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PROCEEDINGS OF THE WORKSHOP ON PROSPECTS FOR RESEARCH WITH RADIOACTIVE BEAMS FROM HEAVY ION ACCELERATORS

Washington, DC,
April 26–27, 1984

April 1984

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Proceedings of the Workshop on

Prospects for Research with Radioactive Beams

From Heavy Ion Accelerators

Washington, DC April 26-27, 1984

Edited by J. Michael Nitschke

This work was supported by the Director, Office of Energy Research, Division of Nuclear Physics of the Office of High Energy and Nuclear Physics of the U.S. Department of Energy under contract DE-AC03-76SF00098.

The SuperHILAC Users Executive Committee organized a workshop on Prospects for Research with Radioactive Beams from Heavy Ion Accelerators. This workshop was held on April 26 and 27 subsequent to the American Physical Society Meeting in Washington, DC. This was the second workshop of this kind, the first one was organized by R. N. Boyd and C. Rolfs from August 31 to September 4, 1981 at Burr Oak State Park, Ohio.

The main purpose of the workshop was to bring together a diverse group of scientists who had already done experiments with radioactive beams or were interested in their use in the future. The topics of the talks ranged from general nuclear physics, astrophysics, production of radioactive beams and high energy projectile fragmentation to biomedical applications. The talks were followed by a discussion.

This publication contains the abstracts of the talks given at the workshop and copies of the viewgraphs as they were supplied to the editor. The discussion was transcribed from a tape recording that had less than studio quality.

It is hoped that this material will be useful despite the informal nature of is presentation.

J. Michael Nitschke, editor

PROSPECTS FOR RESEARCH WITH RADIOACTIVE BEAMS FROM HEAVY ION ACCELERATORS WORKSHOP

Washington, DC U.S.A.

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(2) "Radioactive Ion Beam Studies at Livermore" G.J. Mathews, R.C. Haight, and R.W. Bauer (Lawrence Livermore National Laboratory)	14:50-15:20	21
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THE OHIO STATE UNIVERSITY RADIOACTIVE ION BEAM FACILITY,

R.N. Boyd, L. Rybarcyk, M. Wiescher, H.J. Hausman and W. Kim,
Department of Physics, Ohio State University

The possibility that radioactive ion beams (RIBs) could be produced with intensities sufficient that nuclear reactions involving them could be observed was proposed three years ago, and two schemes for producing such beams, those used at OSU and at Livermore, have been presented in detail. While there are numerous physics motivations for producing such beams, two of the more obvious ones are studies of reactions important to nuclear astrophysics and of reactions of significance to nuclear structure.

The situation for nuclear astrophysics has been investigated theoretically by Wallace and Woosley and by others. At the elevated temperatures (and densities) which can occur in a variety of stellar situations, e.g., collapse or accretion by a neutron star, the reactions one must consider in order to understand the processes of nucleosynthesis and energy generation often involve reactions on short lived nuclei. Two specific examples emerge from this work as being of particular interest, those of $^{13}N(p,\gamma)$ and $^{14}O(\alpha,p)$. The first represents a basic departure from the usual CNO cycle. The second involves a nucleus, ^{14}O, on which the (p,γ) reaction is endothermic, and so studies of reactions such as (α,p) become crucial. While the thermonuclear reaction rates for those processes can be estimated from general features of nuclear reactions, accurate values require knowledge of the possible interferences which can occur; these are not possible to estimate.

Another possible use for RIBs is that of nuclear structure investigations. Consider, for example, the $^{40}Ca(p,p')$ and $^{40}Ca(3^-, 3.74\ MeV)(p,p')$ reactions. In the first case, elastic scattering occurs in the ground state, while the 3^-, 3.74 and 5^-, 4.49 MeV states are strongly excited by 1p-1h excitations. All other states are much less strongly excited. However, if the ^{40}Ca could be produced in the 3^- state, then the peak for that state would represent elastic scattering. The ground state would be (de)excited by 1p-1h (de)excitation, and the 2p-2h states would be excited with strengths much like those seen for the 1p-1h states when ^{40}Ca was in the ground state. Thus RIBs of excited state nuclei would provide a rather extraordinary way of establishing the characteristics of previously weakly excited nuclear structures. The possibilities for transfer reactions are similarly interesting and diverse. It should be noted, though, that many of the excited state RIBs one would like to produce would require very relativistic heavy ions.

The general features associated with production of RIBs can best be illustrated by examing the production of a particular beam, e.g., ^{15}O. The OSU scheme will use the $^{3}He(^{16}O,^{15}O)^{4}He$ reaction to produce this RIB. Use of the heavier ion as the primary beam throws all of the reaction products into a forward cone, thus providing a large enhancement of the yield over that in the center of mass. For production of low energy ^{15}O beams (having energies appropriate to astrophysics), the ^{16}O energy is chosen to coincide with a resonance so as to produce as large

an ^{15}O flux as possible: a convenient energy is 12.9 MeV. At that energy the ^{15}O yield for any angle less than 10.9° will be at least several orders of magnitude less than the yield of elastically scattered ^{16}O ions. However, the ^{15}O reaction products are scattered back to 23.7°. Thus the elastic background can be virtually eliminated by designing the RIB apparatus so that it selects only back scattered particles. The disadvantage of this design choice is that the ^{15}O ions so chosen have a large energy spread, about 40%, whereas those in the forward cone have a much smaller spread. The RIB facility thus must either be designed to eliminate a large elastic background or to accommodate a large energy spread.

The OSU RIB facilty is based on the back angle scheme. For purposes of discussion, the facility will be assumed to be configured so as to study the $^{4}He(^{15}O,\gamma)^{19}Ne$ reaction. The 12.9 MeV ^{16}O beam from the OSU CN van de Graaff accelerator will impinge on a semiwindowless ^{3}He target cell. Prior to reaching that cell the beam passes through several differentially pumped regions in which the pressure changes from 400 torr to 1×10^{-6} torr. The 12 pumps in this system are coupled so that those on the higher pressure regions act as forepumps for those acting on the higher vacuum regions. This allows a closed loop system for recycling of the ^{3}He gas.

Many of the ^{15}O ions produced in the ^{3}He target enter a 60° dipole magnet, which focusses the energetically disparate ^{15}O ions. Adjustable pole faces allow some adjustment of the location of the RIB waist. Just past the magnet the ions will pass through two thin foils, separated by 30 cm, which comprise a time of flight (TOF) system. Electrons knocked out of the foils will be accelerated, reflected and focussed by an electrostatic mirror (through which the ions pass) and detected by channel plate detectors. The time difference between the signals from those detectors will give the velocity, hence energy, of each ^{15}O ion.

Following the second TOF foil, the ^{15}O ions will pass into a ^{4}He target cell. That cell will be surrounded by NaI γ-ray detectors, so any γ-rays produced therein by $^{15}O(\alpha,\gamma)^{19}Ne$ reactions will have a high probability of being detected. The fast signals from the NaI detectors will be used, together with the signal from the channel plate detector at the second TOF foil, to determine the time the ^{15}O ion spent traversing the ^{4}He target cell before the radiative capture reaction occurred. This, together with energy loss information, gives the relative ^{15}O-^{4}He energy at which the reaction occurred. Each ^{15}O ion passes through a significant fraction of the excitation function one would like to measure. The tagged ion scheme thus provides a large enhancement on what would be, with a monoenergetic beam and a thin target, an impossibly low count rate.

In this context it is worth considering some limits on improvements on the facility. The anticipated RIB intensities from the OSU facility are about 1×10^{6} ions/sec. Transit times through the system are long enough that frequent event confusion will occur at rates slightly in excess of 1×10^{7} ions/sec. Thus that intensity represents an approximte upper limit on the useful beam intensity with this tagged ion scheme. This upper limit

could be circumvented with a monoenergetic pulsed beam, thereby alleviating the need for ion tagging. However the reaction products at the first target cell would then have to be restricted so as to have good energy definition. This would require a considerably greater primary beam intensity, probably several orders of magnitude in the pulse peaks (depending on the duty cycle), to be competitive. A monoenergetic CW beam would have to be even more intense, as it would require use of either a thin target or a high resolution γ-ray detector, either of which would reduce the detectable reaction yield considerably.

RADIOACTIVE ION BEAMS (RIBs)

A. PHYSICS MOTIVATION
   1. NUCLEAR ASTROPHYSICS
   2. NUCLEAR REACTIONS

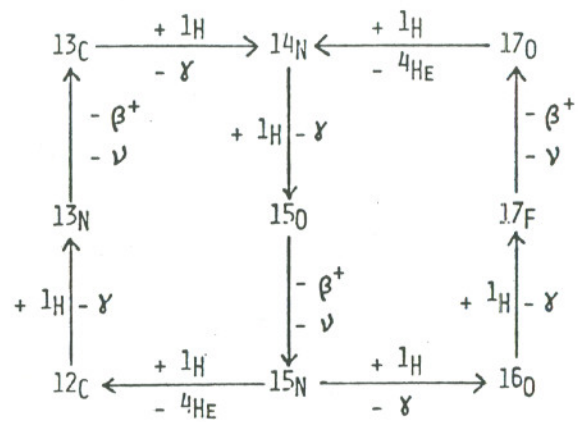
   ⋮

B. GENERAL FEATURES OF FACILITIES

C. RISOAR - THE OSU RIB

D. FUTURE IMPROVEMENTS

THE CNO CYCLE



BASIC CNO CYCLE REQUIRES:

A) 4 ^{1}H + 2 β DECAYS $\rightarrow$ ^{4}He.

B) DECAY TIMES OF, E.G., ^{13}N AND ^{15}O, ARE MUCH SHORTER THAN TYPICAL TIMES BETWEEN SUCCESSIVE REACTIONS.

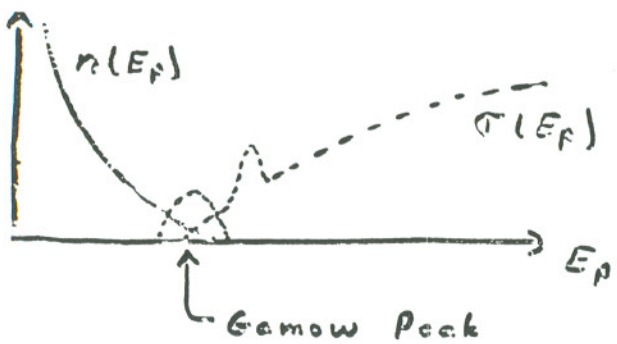
For example: $[^{13}N]$

$$\frac{d[^{13}N]}{dt} = [^{12}C][^{1}H]\langle\sigma v\rangle_{p+^{12}C\to^{13}N}$$

$+$ other production processes

$-$ diminution processes

$$\langle\sigma v\rangle = 4\pi\left(\frac{M}{2\pi kT}\right)^{3/2}\int_0^\infty v^3\sigma(v)\exp\left(-\frac{Mv^2}{2kT}\right)dv$$



So measure $\sigma(E)$, calculate $\langle\sigma v\rangle$ for all relevant reactions.

Fast Nucleosynthesis

When ^1H is nearly gone: stellar collapse. Temperature and density increase.

Or, accreting neutron star: high T in infall region.

Then:

$^{12}C + {}^1H \to {}^{13}N + \gamma$

$^{13}N + {}^1H \to {}^{14}O + \gamma$

$^{14}O + {}^1H \not\to$

$\quad + {}^4He \to {}^{17}F + {}^1H$

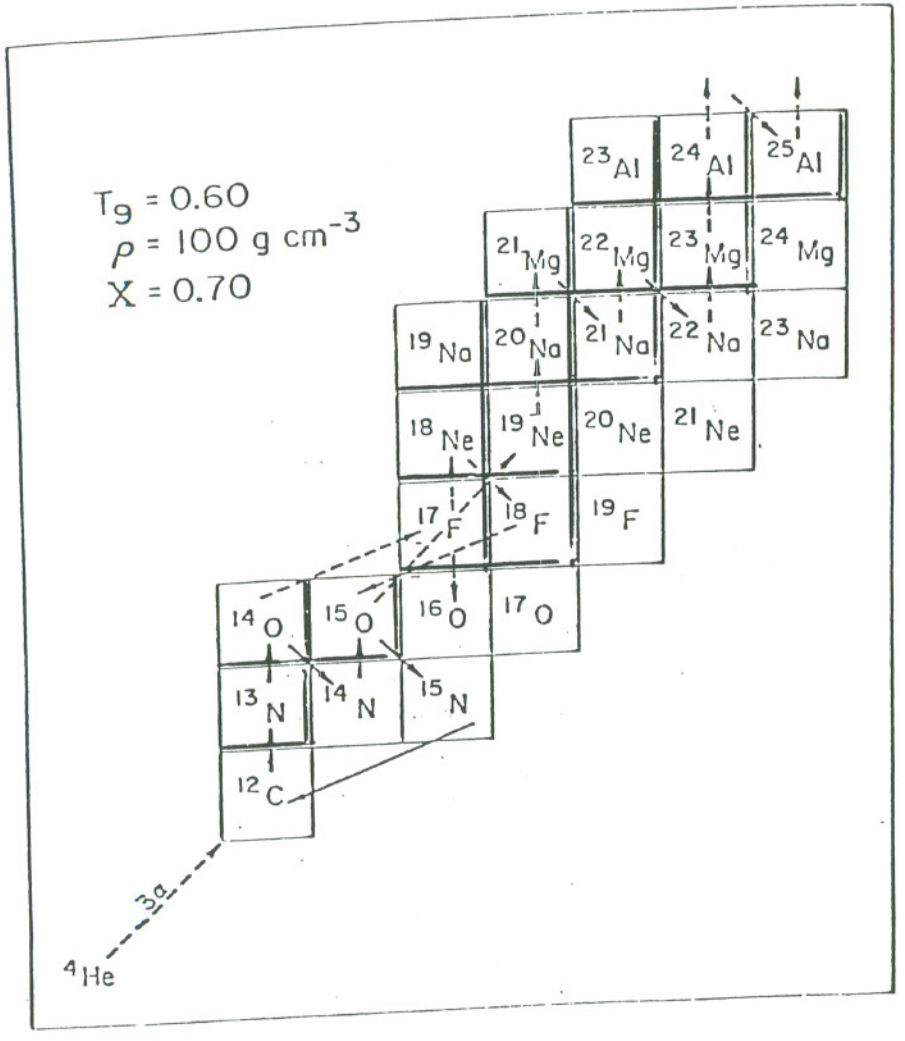
$^{17}F + {}^4He \to {}^{20}Ne + {}^1H$

$\qquad\qquad \to {}^{21}Ne + \gamma$

$\vdots$

Life times >> typical times between reactions. B ≳ N, so no cycles!

Need, e.g., $\sigma(^{13}N + {}^1H \to {}^{14}O + \gamma)$. But $\tau(^{13}N) \approx 10$ min: tough target.



Isomeric States

e.g., ^{26}Al (5+) and ^{26}Al* (0+)
.229 keV

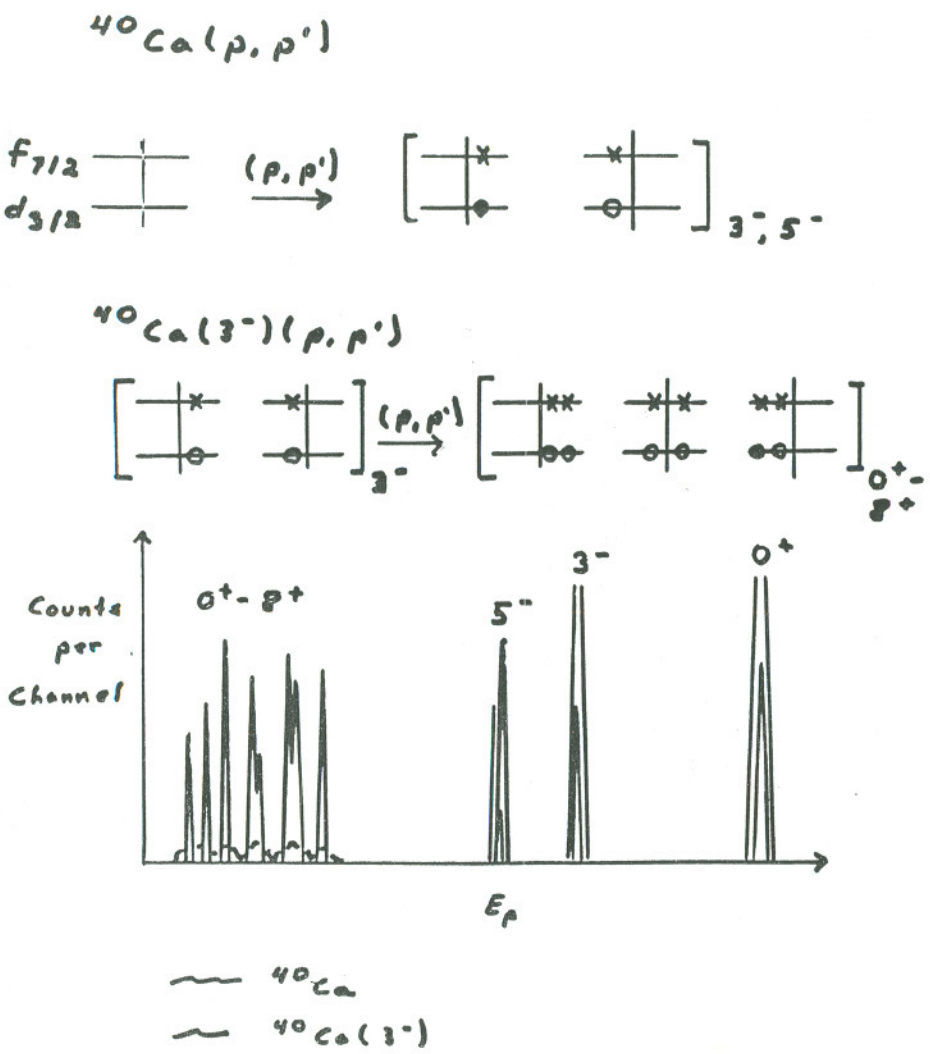
At high T, some ^{26}Al in 0+:

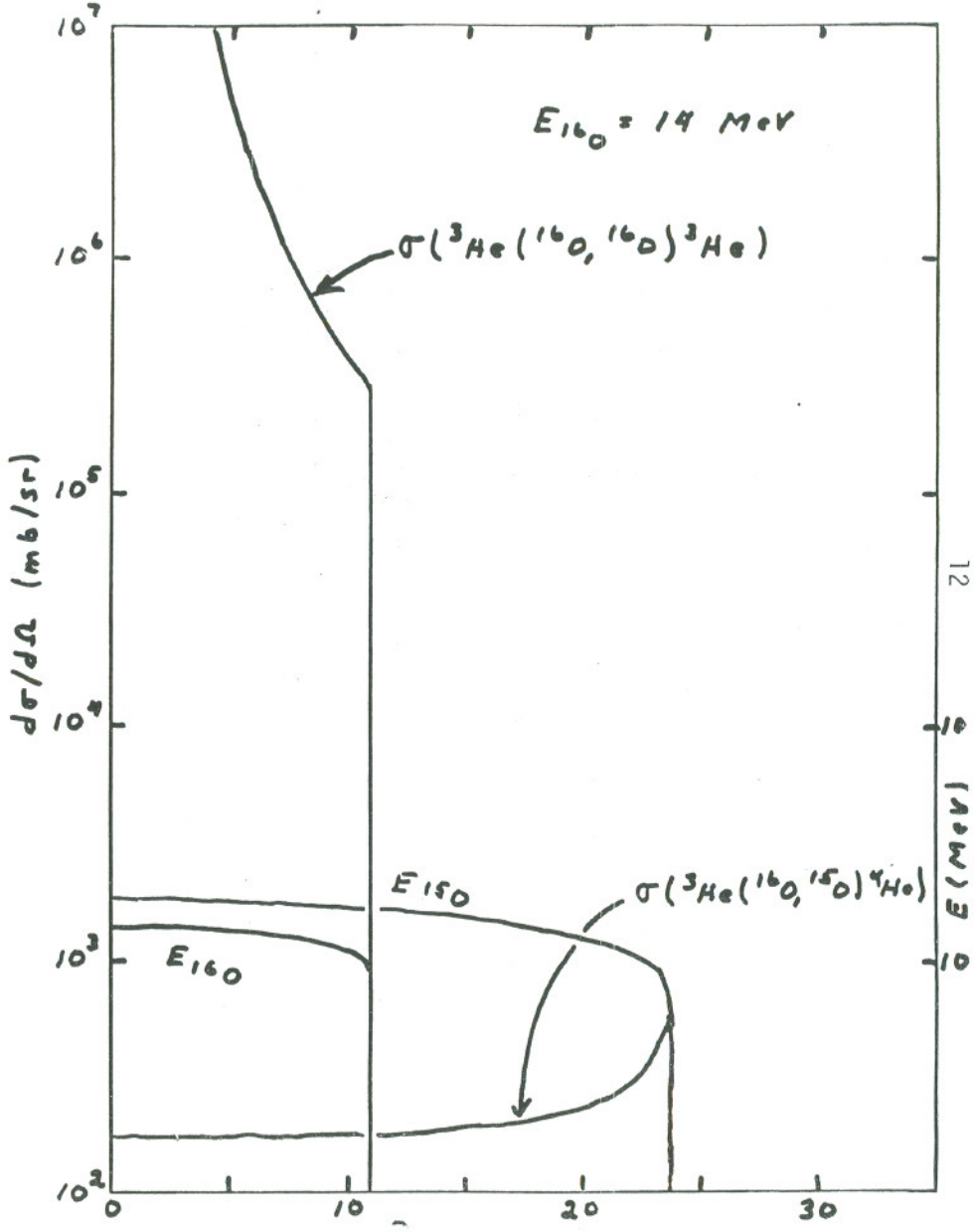
$$^{25}\mathrm{Mg} \xrightarrow{(p,\gamma)} {}^{26}\mathrm{Al}^{*},\ {}^{26}\mathrm{Al} \xrightarrow{(p,\gamma)} {}^{27}\mathrm{Si} \ \ldots$$

Other Isomers

34m Cl	146	keV	32 m (g.s.: 1.5 s)
38m Cl	671	keV	.7 s
38m K	131	keV	.9 s
42m Sc	618	keV	62 s (g.s.: 0.6 s)
44m Sc	271	keV	2.4 d (g.s.: 3.9 h)

Isomer Th. Rect. Rates large?
In some cases, reactions may be just through Isomers!


$^{40}Ca(p,p')$
$f_{7/2}$
$d_{3/2}$
(p,p')
$3^-, 5^-$
$^{40}Ca(3^-)(p,p')$
3^-
(p,p')
0^+
2^+
Counts per Channel
$0^+ - 2^+$
5^-
3^-
0^+
E_p
^{40}Ca
$^{40}Ca(3^-)$


$E_{^{16}O} = 14$ MeV
$\sigma(^3He(^{16}O,{}^{16}O)^3He)$
$E_{^{15}O}$
$\sigma(^3He(^{16}O,{}^{15}O)^4He)$
$E_{^{16}O}$
$d\sigma/d\Omega$ (mb/sr)
E (MeV)
10^7
10^6
10^5
10^4
10^3
10^2
0
10
20
30
10
10

OBSERVATIONS

FORWARD ACCEPTANCE CONE:

SMALL ENERGY VARIATION.

GOOD FOR FORWARD PEAKED (HIGH ENERGY) PRODUCTION REACTIONS.

BUT

HUGE ELASTIC BACKGROUND.

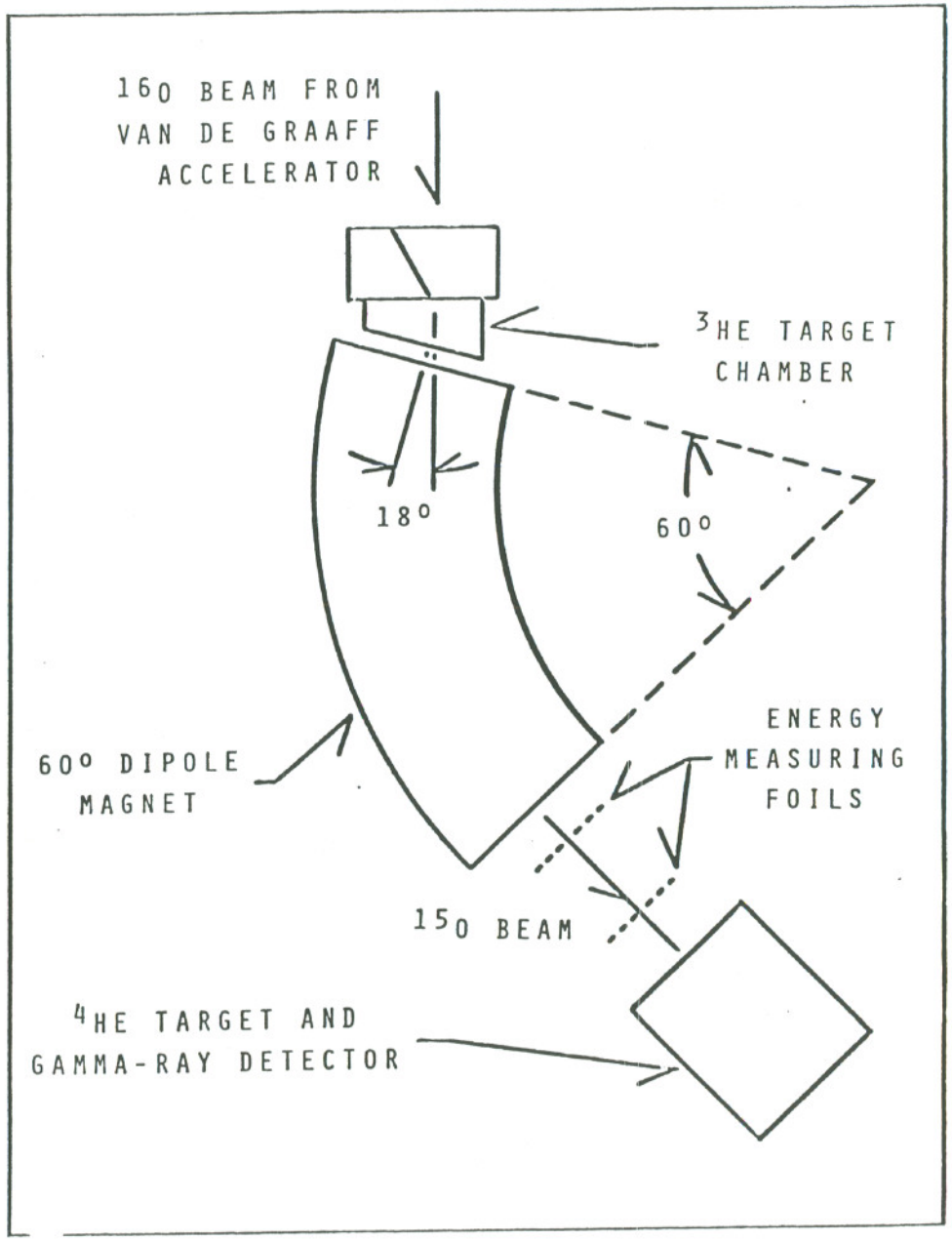
BACKWARD ACCEPTANCE CONE:

VERY SMALL ELASTIC BACKGROUND.

GOOD FOR RESONANT (LOWER ENERGY) PRODUCTION REACTIONS.

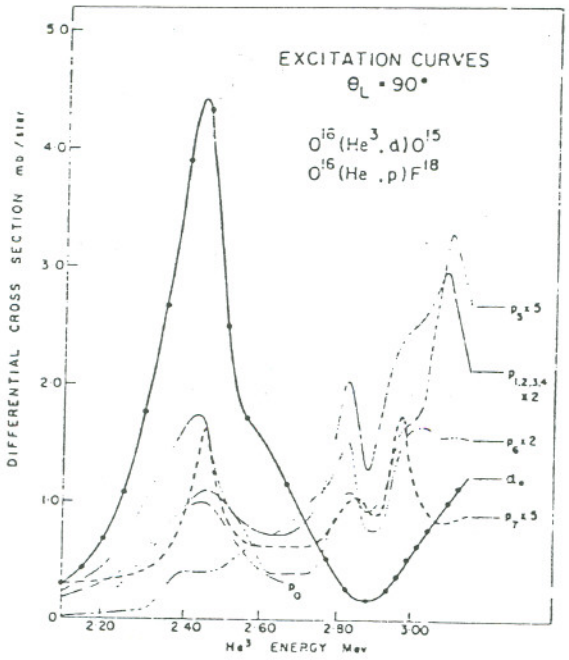
BUT

HUGE ENERGY SPREAD.



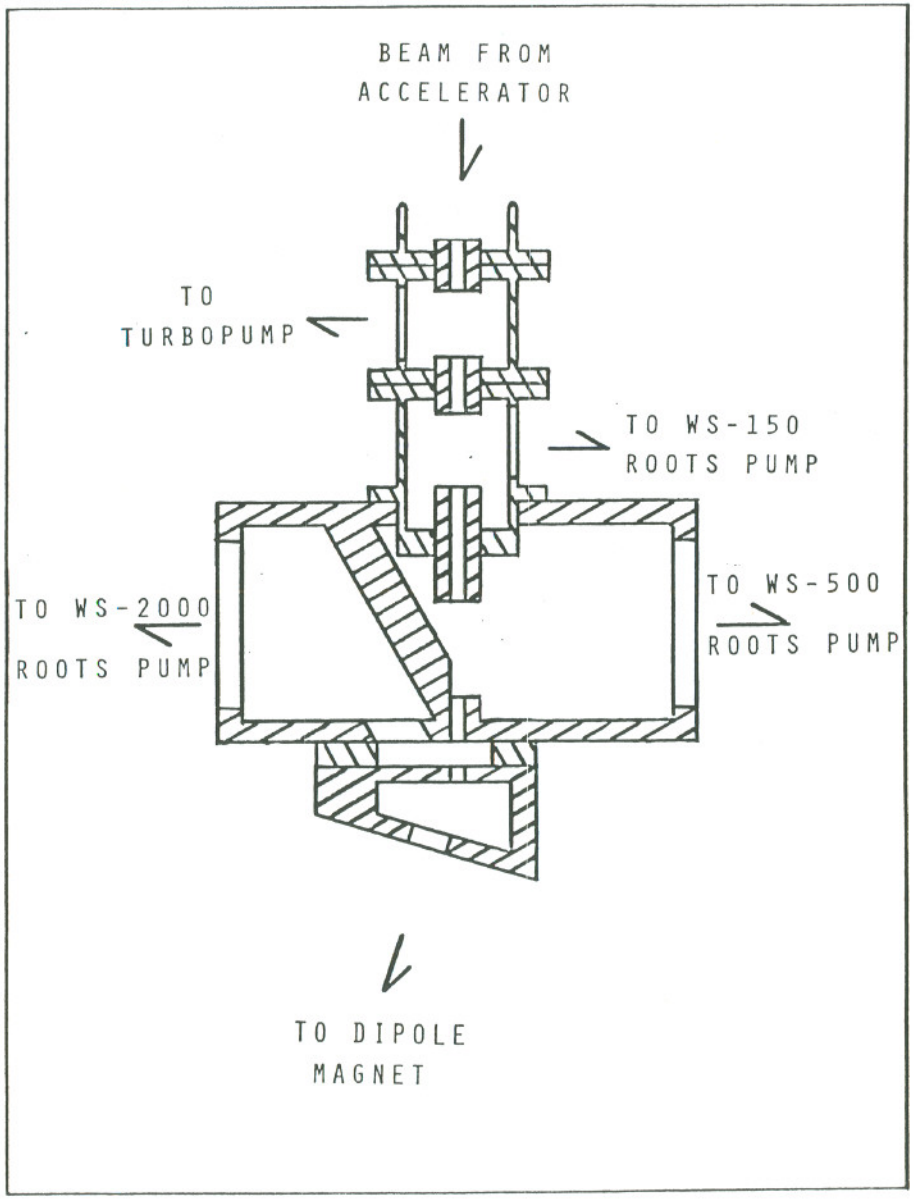
D.A. Bromley, J.A. Kuehner and E. Almqvist,

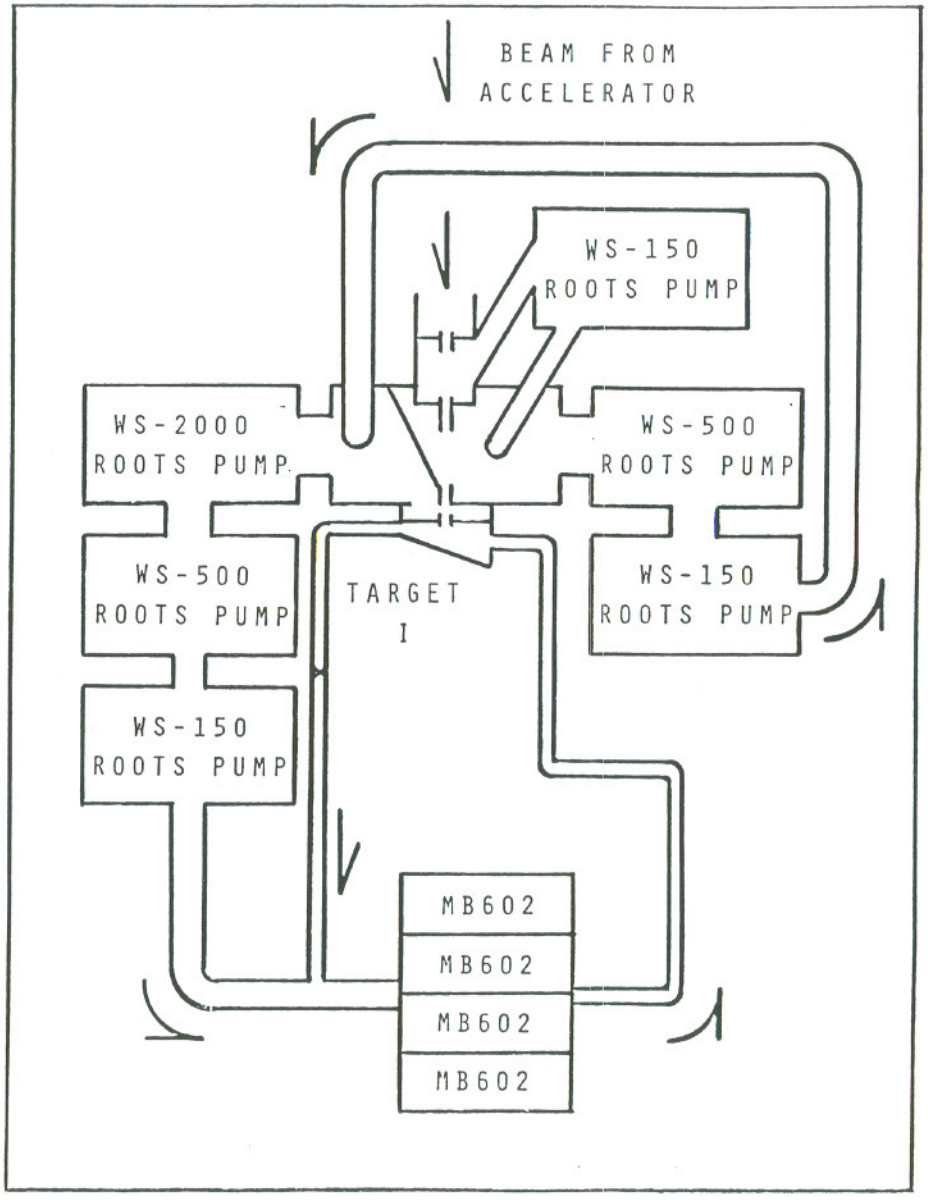
Nuclear Physics 13 (1959) 1.

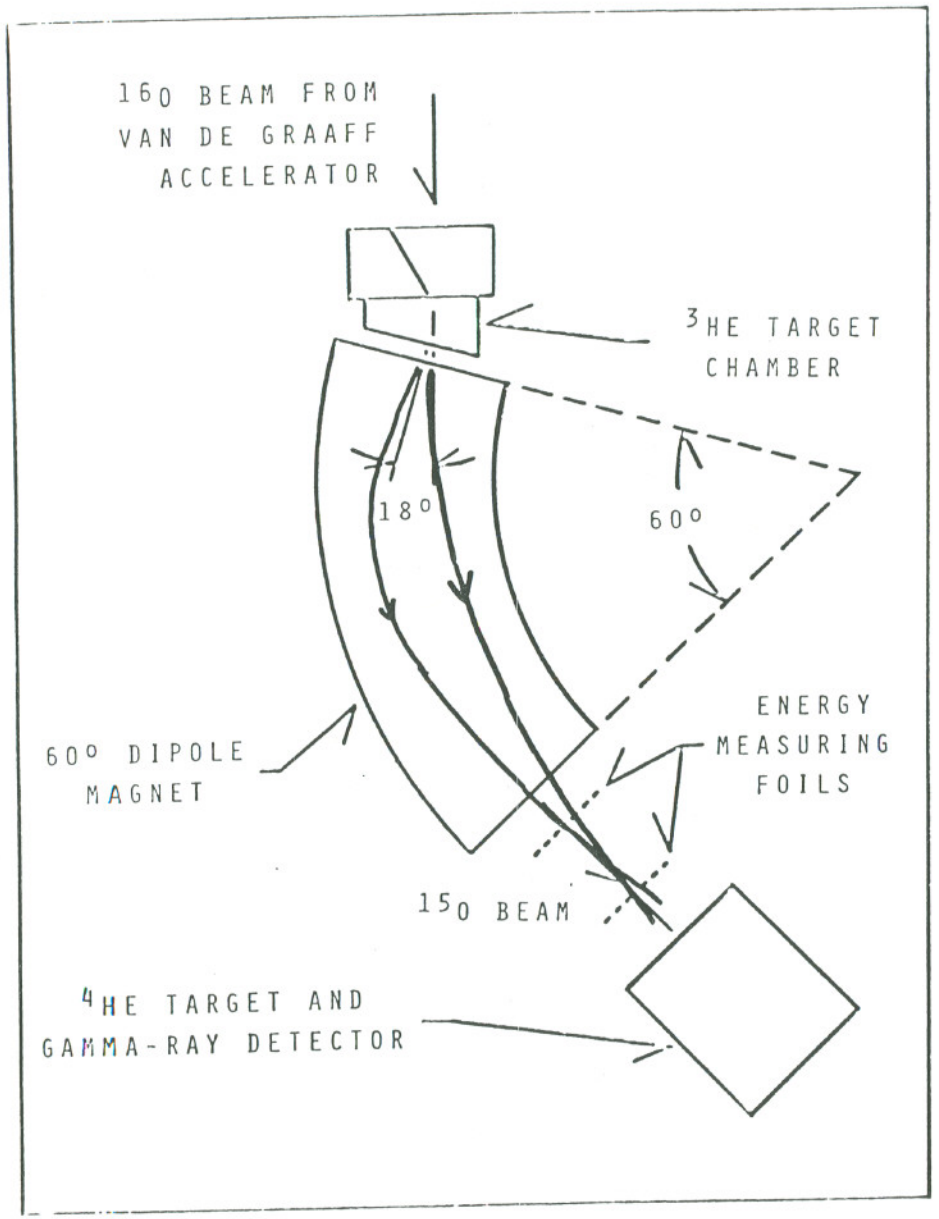


$E_{^3He}$ = 2.42 MeV for $^{16}O(^3He,\alpha)^{15}O$ → →

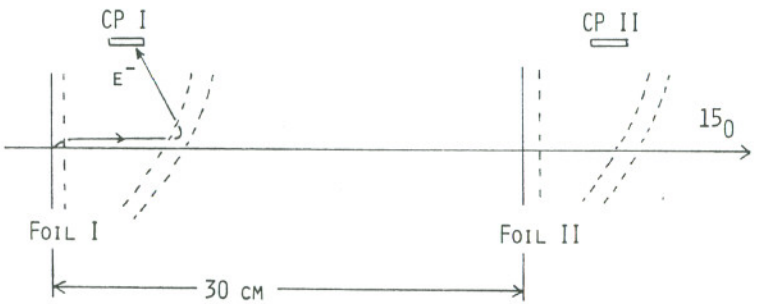
$E_{^{16}O}$ = 12.9 MeV for $^3He(^{16}O,\alpha)^{15}O$.


BEAM FROM
ACCELERATOR
TO
TURBOPUMP
TO WS-150
ROOTS PUMP
TO WS-2000
ROOTS PUMP
TO WS-500
ROOTS PUMP
TO DIPOLE
MAGNET


BEAM FROM
ACCELERATOR
WS-150
ROOTS PUMP
WS-2000
ROOTS PUMP
WS-500
ROOTS PUMP
WS-500
ROOTS PUMP
TARGET
I
WS-150
ROOTS PUMP
WS-150
ROOTS PUMP
MB602
MB602
MB602
MB602



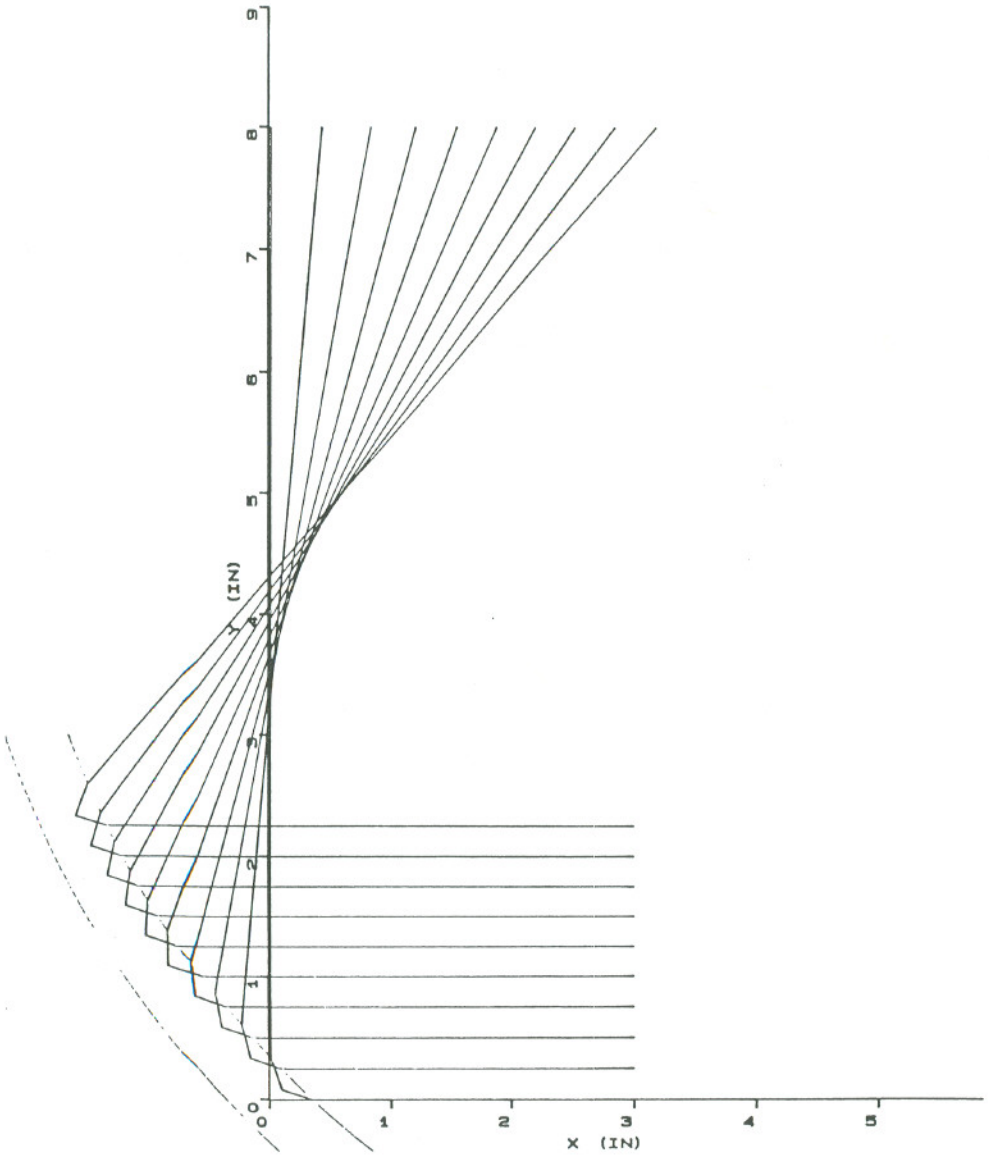
TIME OF FLIGHT SYSTEM



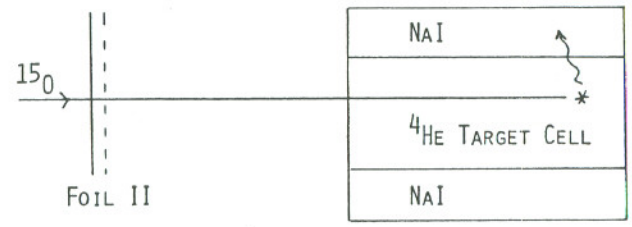
E^-S KNOCKED FROM FOILS ARE ACCELERATED TO 1 KEV, REFLECTED AND FOCUSSED BY THE MIRRORS, AND DETECTED IN CHANNEL PLATE DETECTORS.

TOF GIVES v_{15_O}, WHICH GIVES E_{15_O}.

SECOND FOIL GIVES "START" FOR ENTRANCE TO ^{4}HE TARGET CELL.



THE SECOND TARGET CELL



TIME BETWEEN CP II AND FAST SIGNAL FROM THE NAI DETECTOR GIVES FLIGHT TIME IN ^{4}HE TARGET CELL.

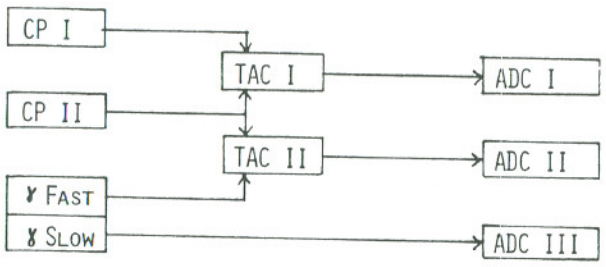
$$E(T) = E_{INC} - \int_{T_{II}}^{T_\gamma} \frac{DE}{DX}(T)\sqrt{2E/M}\ DT$$

THUS $T_\gamma - T_{II}$ GIVES $E_{REACTION}$.

STRAGGLING IMPOSES A PRACTICAL LIMIT:

$$\frac{E_{INC} - E(T)}{E_{15_O}} \lesssim 0.3.$$

Abbreviated Electronics Scheme



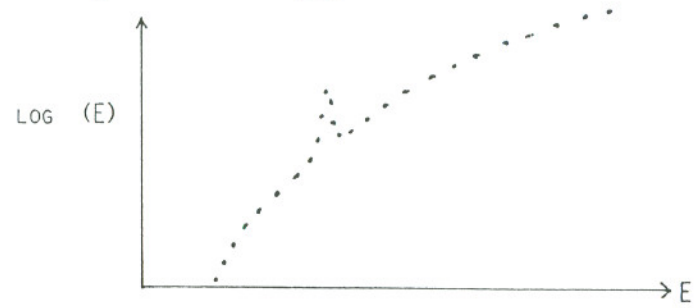
Also:

TAC II needs to accept during 30 nsec possible coincidence between CP II and γ Fast timing signals.

Pile up rejection vetoes ADCs.

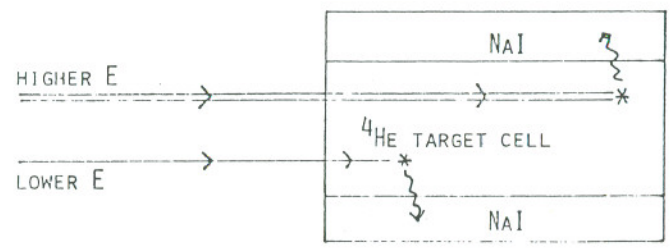
Acceptable coincidence between CP II and γ Fast gates TACs.

For $^{A}X_{Z} + {}^{4}He \rightarrow {}^{A+4}XX_{Z+2} + \gamma$



With monoenergetic beam and thin target, 1 accelerator setting per energy is needed.

But, with thin target, tagged ions, and large energy variation:



Thus entire (viable) excitation function is done at a single setting.

Production Reactions

$^{7}Li(^{3}He,T)^{7}Be$
$^{12}C(^{3}He,^{4}He)^{11}C$
$^{14}N(^{3}He,^{4}He)^{13}N$
$^{16}O(^{3}He,^{4}He)^{15}O$
$^{19}F(^{3}He,^{4}He)^{18}F$
$^{20}Ne(^{3}He,^{4}He)^{19}Ne$
$^{26}Mg(^{3}He,T)^{26}Al^{*}$
$^{27}Al(^{3}He,^{4}He)^{26}Al$

Reactions to Study

(p,γ), (α,γ) and (α,p), whenever exothermic or nearly so, on all of the above beams.

Some Observations

^{16}O incident beam gives factor of 20 enhancement in yield into dipole magnet.

$E_{CM} = E_{INC} \times 4/19$ for (α,γ)

$= E_{INC} \times 1/16$ for (p,γ)

Thus, even though E_{LAB} is about 12 MeV, E_{CM} is the order of 1 MeV.

Straggling, timing uncertainties, etc. give E of about 0.4 MeV. But that's about 80 keV in the cm for (α,γ), and 25 keV in the cm for (p,γ).

Thus there are big practical advantages to using the heavier ion as the incident projectile.

Potential Upgrades

More primary beam means more secondary beam?

Saturation effects?

Limits: Event confusion at 2×10^7 ions/sec from 50 nsec flight times.

Different schemes:

Pulsed beam eliminates need for tagging.

But now need good energy resolution, so restrict angular range (and reduce the beam intensity).

Duty cycle, bunching efficiency?

Need 1 to 2 orders of magnitude from the source.

CW beam beats duty cycle, but not requires thin target or good gamma-ray energy resolution: need 2 to 3 orders of magnitude from source, or $$$.

RADIOACTIVE ION BEAM STUDIES AT LIVERMORE

G. J. Mathews, R. C. Haight, R. W. Bauer
University of California
Lawrence Livermore National Laboratory
Livermore, CA 94550

Radioactive ion beam research (RIR) [1-4] introduces for the first time the possibility of reaction studies with the >1300 known nuclei with decay lifetimes >1 μsec. There are pressing needs in nuclear astrophysics [5-9], as well as nuclear structure, heavy-ion physics, materials science, and medicine for research with such unstable nuclei.

At LLNL [2-4] our approach to RIR has been to produce secondary beams using primary production reactions with large cross sections and favorable kinematics. The design emphasis has been to maximize secondary beam production and yet maintain overall simplicity, economy, and flexibility. The result is the Quadrupole-Sextuplet Beam Transport System (QSBTS) shown in Fig. 1.

Heavy ion primary beams from the LLNL EN tandem Van de Graaff facility impinge on a primary production target. Some of the production reactions investigated so far have been $^{1}H(^{7}Li,^{7}Be)n$, $^{2}H(^{7}Li,^{8}Li)p$, $^{2}H(^{12}C,^{13}N)n$, and $^{2}H(^{14}N,^{15}O)n$. The properties of a few of the beams investigated are summarized in Table I.

The $(^{2}H,n)$ reactions in the comoving frame of the heavy ion seem to be particularly well suited for production since they have favorable Q values (usually positive), high cross sections (∿100 mb), and large center-of-mass motion which confines the secondary reaction products to forward angles. Most of the secondary beams investigated thus far have been chosen because of particular importance in nuclear astrophysics.

Production targets used to date have been thin (∿0.5-1.0 mg/cm^2) foils of polyethylene or deuterated polyethylene. These targets offer the advantages of simplicity and economy over gas targets and can easily be produced with sufficient thickness for primary target purposes. But there are also some disadvantages. One is that these targets begin to deteriorate after ∿100 μC of incident primary beam. We minimize this deterioration by occasionally stepping the target position. Thus, a single target can survive several thousand μC. As many as 10 separate targets can be accommodated on the present target ladder. Another disadvantage is the scattering of the primary beam from carbon in the polyethylene. This tends to increase the background of scattered primary beam relative to that from a gas target. This background

is easily maintained at less than or equal to the secondary beam of interest by utilizing a well defined beam spot. For future low-cross section measurements we anticipate a further reduction in background by utilizing a windowless gas cell of sufficient thickness ($\sim$100 $\mu g/cm^2$ of H_2 or D_2) or a conventional gas cell oriented such that the primary beam scattered at the windows can not be observed in the detectors.

The secondary beam is isolated, focused, and directed onto a secondary target by means of the QSBTS shown in Fig. 1. This transport system has been designed to maximize transmission of the secondary beam while inducing a substantial reduction of the primary beam. Most of the incident primary beam passes through the target at 0° and therefore impinges on a centrally placed shadow bar which also acts as a split Faraday cup to monitor primary beam current, focus, and position. The secondary particles which emerge at lab angles between $\sim$1° and 4° (about 10-15% of the total angular distribution) are transported by the QSBTS onto a secondary target 3 m away.

Polyethylene is also used for the secondary targets. Radiation damage is not a problem for these targets; however, background due to the reactions of secondary beam with carbon in the target must be subtracted.

Reaction products are measured directly in a ΔE-E telescope mounted at 0° immediately behind the secondary target, rather than indirectly (e.g. by capture gamma rays). This approach has the advantage of 100% detection efficiency for reaction products. Since a single detector acts as both the secondary current monitor and the tertiary product detector, cross sections can be easily inferred from the ratio of tertiary products to incident radioactive beam. A disadvantage, however, is that considerable care must be exercised to isolate the tertiary reaction products which account for only 10^{-9} to 10^{-5} of the total detected events.

To eliminate background from radiation damage during extended exposures to the secondary beam, a gas ionization-chamber ΔE detector [10] is utilized in the present setup. An example of the charge resolution for the ionization chamber is shown in Fig. 2. These spectra were obtained by accelerating the various beams indicated and "detuning" the spectrometer to observe the inelastic scattering. The charge resolution is quite good (0.2 charge units FWHM) in the energy range of interest (0.1 to 3 MeV/A).

Examples of the 20-MeV ^{7}Be beam (observed [4] in a solid-state telescope), and a 34-MeV ^{13}N beam (gas-ΔE solid-state E telescope) are shown in Figs. 3 and 4. These figures also show the background due to inelastically scattered primary beam at lower charge states. This background

can be virtually eliminated from the analysis by pulsing the primary beam and measuring the time of flight through the spectrometer. Events corresponding to flight times of the secondary beam can be exclusively selected. Thus, only the secondary beam and its reaction products are counted. An example of the ^{13}N beam of Fig. 4 gated by the flight time is shown in Fig. 5. For this beam the flight time was 140 ns and the time resolution as determined by the beam buncher was 8 ns.

A summary of some of the primary to secondary conversion efficiencies is given in Table I. At present the maximum secondary beam intensity is limited by the count rate acceptable in the ΔE-E telescope. Pile up in the ΔE detector begins to be a problem for count rates greater than 4000-5000 cts/sec. Under realistic runing conditions this corresponds to only $\sim$10-50 nA of primary beam, although as much as 10 μA of primary beam is presently available. Thus, the intensity of primary beam current does not now determine the lower limit for the cross sections which can be measured.

Expected counting rates for various reactions with the secondary beam intensity which can now be accommodated are given in Table I. Although the count rates are low they are not prohibitive as long as the background rates are small in comparison. This is the main thrust of the current development efforts at LLNL. At present the background for detection of ^{8}B from the $^{1}H(^{7}Be,^{8}B)\gamma$ or $^{2}H(^{7}Be,^{8}B)n$ reactions is at the level of 1 mb. This is adequate for comoving (d,n) measurements. (A measurement of the (d,n) cross section for ^{7}Be at 3.8 MeV c.m. has previously been reported by our group [2].) This background, however, precludes the (p,γ) measurement. Similarly the background for detection of ^{14}O nuclei from reactions with ^{13}N is at the level of 1 b due to scattered ^{16}O from alpha transfer to the primary beam. In the next developement stage it is anticipated that these backgrounds can be more than adequately eliminated by using a variant of the QSBTS which is more energy selective to direct the secondary beam into an Enge split-pole spectrometer for further isolation from scattered primary beam. The flight path will be enlarged by a factor of 3 to 4 and, if necessary, the time pick-off can be obtained with associated secondary beam particles (rather than beam bursts) via a channel plate placed in the beam line behind the QSBTS. This latter improvement alone could improve the timing resolution by at least two orders of magnitude. Also detection methods for the secondary beam which can accomodate higher count rates are presently under consideration.

Work performed under the auspices of the U.S. Department of Energy by the Lawrence Livermore National Laboratory under contract number W-7405-ENG-48.

Table I. Some beams which have been studied and their characteristics.

Production Reaction	Primary Beam Energy (MeV)	E (FWHM) (MeV)	Conversion Efficiency	(d,n) rate cts/hr	(p,γ) rate cts/day
$^{1}H(^{7}Li,^{7}Be)n$	24	20 (0.5)	$3 \cdot 10^{-6}$	∿100	0.1
$^{2}H(^{12}C,^{13}N)n$	36	34 (1.6)	$1 \cdot 10^{-7}$	∿100	6
$^{2}H(^{14}N,^{15}O)n$	36	16 (2.1)	$1 \cdot 10^{-7}$	-	-

References

1. R. N. Boyd, Proceedings of the Workshop on Radioactive Ion Beams and Small Cross Section Measurements, Burr Oak, Ohio (1981); IEEE Trans. Nucl. Sci. NS-30, 1387 (1983).
2. R. C. Haight, G. J. Mathews, R. M. White, L. A. Aviles, and S. E. Woodard, Nucl. Instrum. Methods 212, 245 (1983); IEEE Trans. Nucl. Science NS-30, 1160 (1983).
3. R. C. Haight, G. J. Mathews, R. A. Ward, and S. E. Woosley, Lawrence Livermore National Laboratory report UCRL-89382 (1983).
4. G. J. Mathews, R. C. Haight, R. G. Lanier, and R. M. White, Phys. Rev. C 28, 879 (1983).
5. R. K. Wallace, and S. E. Woosley, Ap. J. 45, 389 (1981).
6. J. N. Bachall, et al., Rev. Mod. Phys. 54, 767 (1982).
7. F. Hoyle and W. A. Fowler, "Quasi-Stellar Sources and Gravitational Collapse," ed. I. Robinson, A. Schild, and E. L. Schucking, Chicago: Univ of Chicago Press, p. 12 (1965).
8. R. A. Ward and W. A. Fowler, Ap. J. 238, 266 (1980).
9. R. A. Ward, M. J. Neuman, and D. D. Clayton, Ap. J. Suppl. 31, 33 (1976).
10. M. M. Fowler and R. C. Jared, Nucl. Instrum. Methods 124, 341 (1975).

Figure Captions

Fig. 1 The Quadrupole Sextuplet Secondary Beam Transport System. Typical trajectories are indicated for the horizontal (H) and vertical (V) planes. The central shadow bar intercepts the primary beam.

Fig. 2 An illustration of the charge resolution in the gas ionization-counter telescope. The lines corresponding to different atomic numbers were obtained by accelerating that beam and detuning the spectrometer to observe the scattered primary beam.

Fig. 3 An example of a 20-MeV ^{7}Be beam. The $^{7}Li^{3+}$ component is due to scattered primary beam.

Fig. 4 An example of a gated 34-MeV ^{13}N beam. This corresponds to a center-of-mass (p,γ) energy of 2.4 MeV and a FWHM of 110 keV.

Fig. 5 The same beam shown in Fig. 4 gated by requiring that events of all energies travel through the spectrometer with the flight time of the ^{13}N peak.

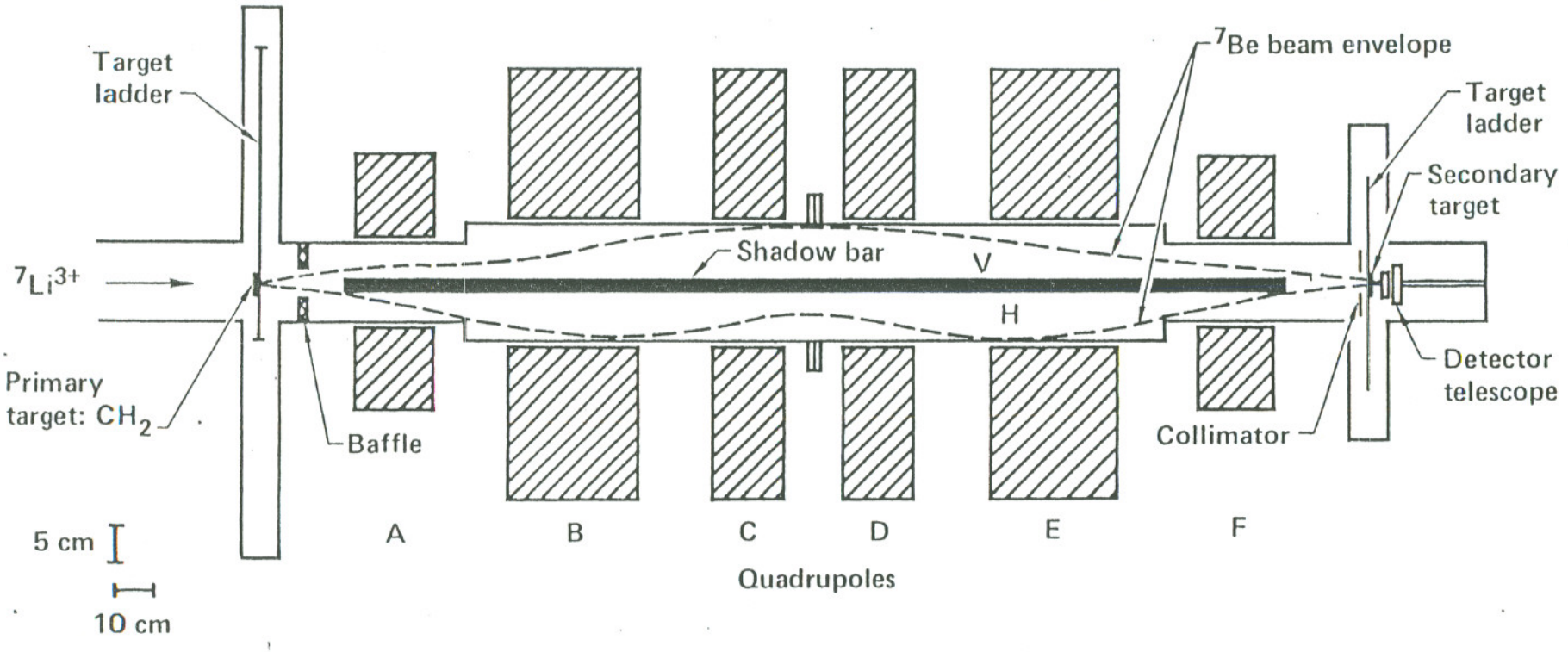

Target ladder
$^7Li^{3+}$
Primary target: CH_2
Baffle
Shadow bar
V
H
^7Be beam envelope
Target ladder
Secondary target
Detector telescope
Collimator
5 cm
10 cm
A
B
C
D
E
F
Quadrupoles

Figure 1

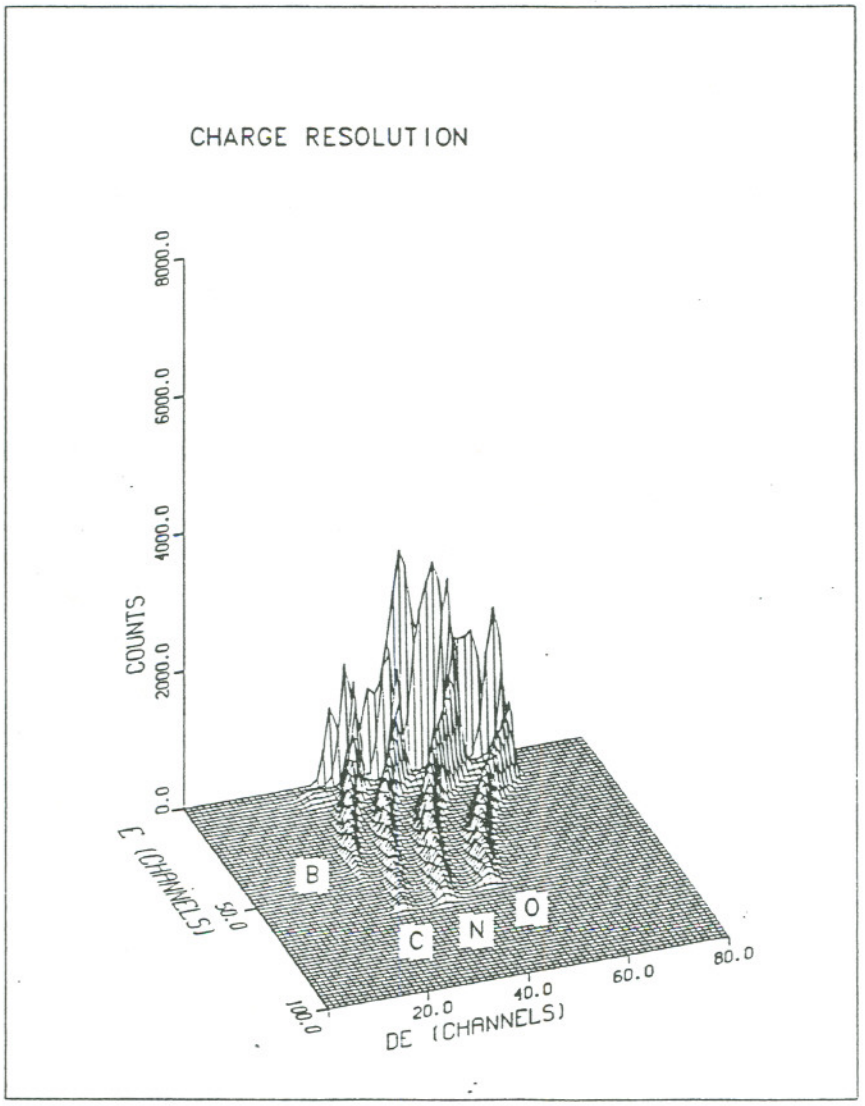
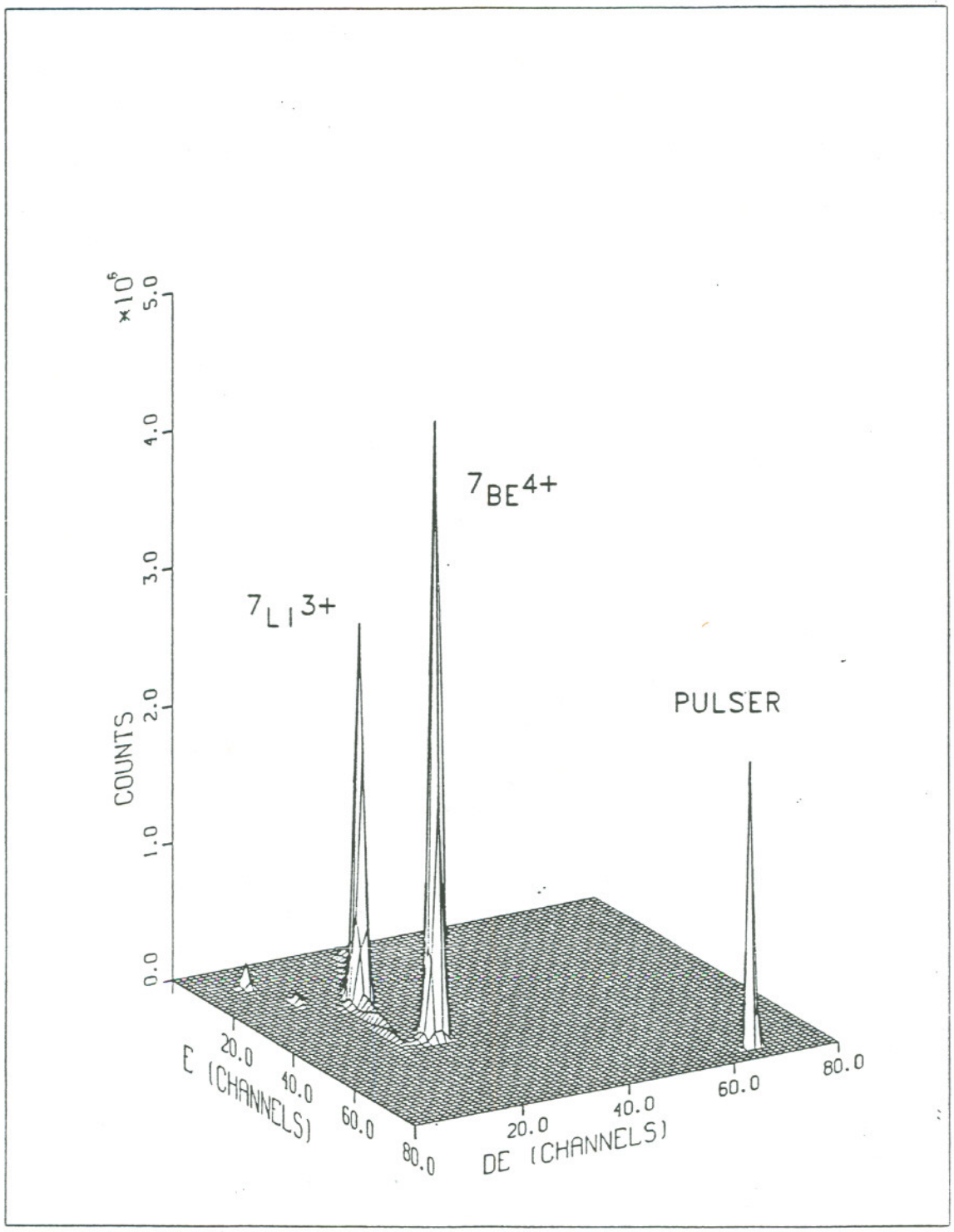

CHARGE RESOLUTION
COUNTS
0.0
2000.0
4000.0
6000.0
8000.0
E (CHANNELS)
50.0
100.0
DE (CHANNELS)
20.0
40.0
60.0
80.0
B
C
N
O

Figure 2


COUNTS
×10^6
0.0
1.0
2.0
3.0
4.0
5.0
7LI3+
7BE4+
PULSER
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40.0
60.0
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DE (CHANNELS)
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40.0
60.0
80.0

Figure 3

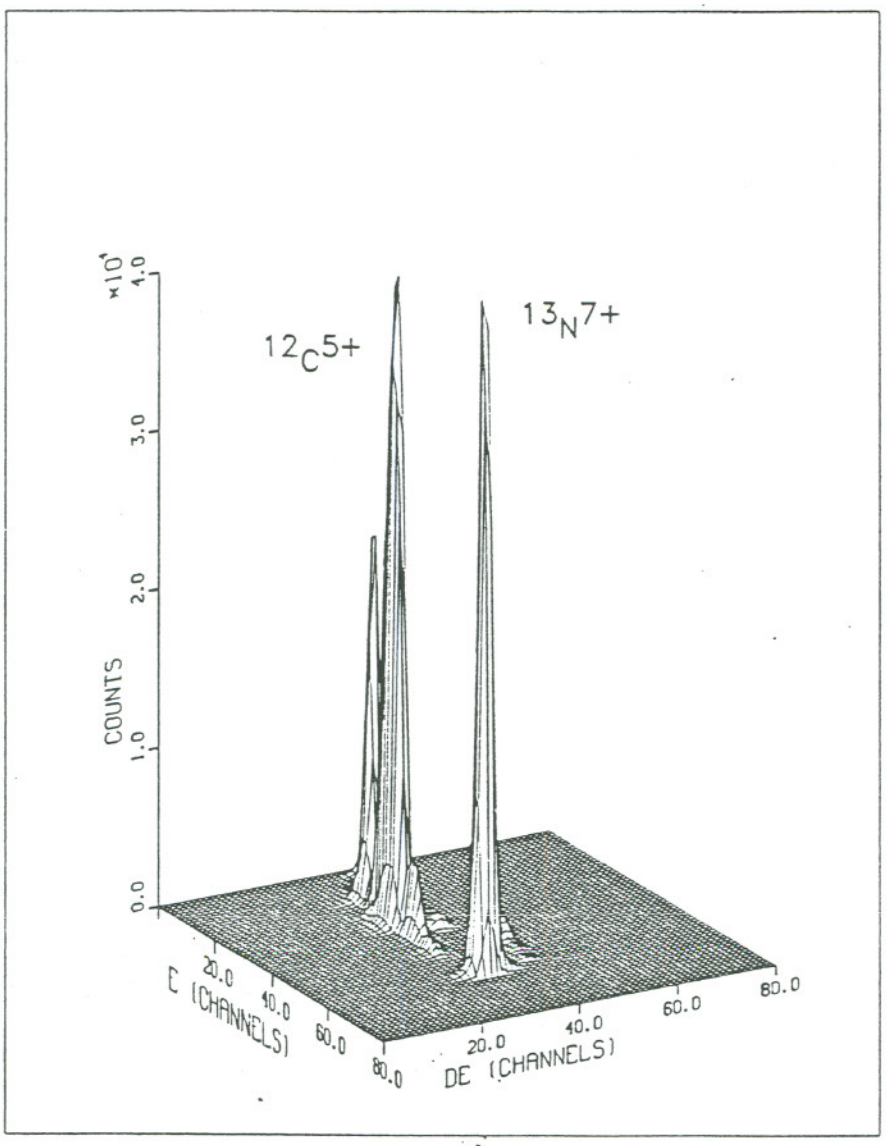
×10¹
4.0
3.0
2.0
1.0
0.0
COUNTS
12C5+
13N7+
20.0
40.0
60.0
80.0
E (CHANNELS)
20.0
40.0
60.0
80.0
DE (CHANNELS)

Figure 4

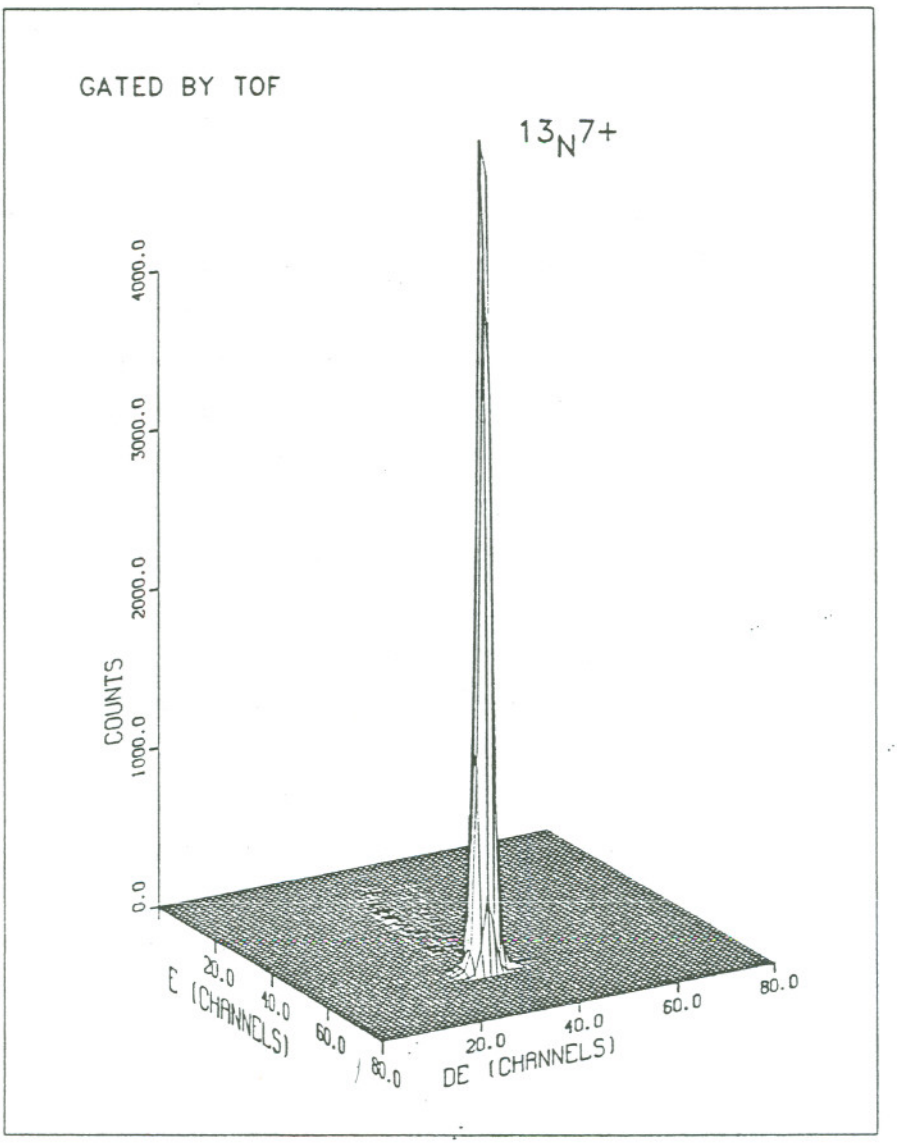
GATED BY TOF
$^{13}N^{7+}$
COUNTS
0.0
1000.0
2000.0
3000.0
4000.0
E (CHANNELS)
20.0
40.0
60.0
80.0
DE (CHANNELS)
20.0
40.0
60.0
80.0

Figure 5

Nuclear Astrophysics Experiments with Radioactive Nuclei

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In cases where the half-life ($t_{1/2}$) of a radioactive nucleus is greater than about one day, it is often more feasible to produce a radioactive target rather than a radioactive beam. This is especially true when measurements of small cross sections ($<\mu b$) and low energies ($<$1MeV) are required. In particular, three radioactive nuclei of recent interest to nuclear astrophysics (^{7}Be: $t_{1/2}$=53 d., ^{26}Al: $t_{1/2}$= 7.2x10^{5} yr., ^{22}Na: $t_{1/2}$= 2.6 yr.) have convenient half-lives for the production of a target.

The $^{7}Be(p,\gamma)^{8}B$ reaction, which is expected to occur in the p-p chain in the solar interior, leads directly to the production of high energy neutrinos following the ^{8}B decay. It is these neutrinos in the sun which provide $\simeq$ 80% of the capture rate in the on-line ^{37}Cl solar neutrino experiment.[1] A reliable prediction[2] of the flux of these neutrinos requires a knowledge of the cross section for the above reaction at low center-of-mass energies. Results from a recent measurement of the $^{7}Be(p,\gamma)^{8}B$ reaction cross section[3] utilizing a radioactive ^{7}Be target will be described.

The discovery of isotopic anomalies in certain meteoritic inclusions has led to much speculation regarding the circumstance and timescale for the formation of the Solar System. In particular ^{26}Mg excesses in the Allende meteorite were found by Lee, Papanastassiou, and Wasserburg[4] to be correlated with the elemental Al to Mg ratio. This has been attributed to the decay, in situ, of ^{26}Al. This discovery, in addition to the reported observation of a cosmic γ-ray line in the galactic plane attributed to ^{26}Al decay[5], has sparked much interest in ^{26}Al nucleosynthesis. While the major production reaction -- $^{25}Mg(p,\gamma)^{26}Al$ -- is well understood, the chief destruction reaction in proton-rich environments, $^{26}Al(p,\gamma)^{27}Si$, has only recently been measured[6] using an ^{26}Al target.

An interesting parallel with the above occurs in the case of ^{22}Na. The interstellar decay of ^{22}Na could possibly produce both an observable

γ-ray line as well as an enhanced abundance of ^{22}Ne. The former is of interest to γ-ray astronomy while the latter could account for the meteoritic anomaly known as Ne-E (a nearly pure ^{22}Ne isotopic abundance). Here, little is known of the destruction reaction ^{22}Na(p,γ)^{23}Mg, which requires development of a ^{22}Na target.

More detailed measurements of the ^{26}Al(p,γ)^{27}Si reaction in collaboration with J. H. Thomas and R. W. Kavanagh and of the ^{22}Na(p,γ)^{23}Mg reaction in collaboration with M. Wiescher, in progress at Caltech, will be described.

REFERENCES

1. R. Davis, Jr., B. T. Cleveland, and J.K. Rowley, in Science Underground, Proceedings of the Workshop on Science Underground, Los Alamos, 1982, edited by M. M. Nieto et al., AIP Conf. Proc. No. 96 (AIP, New York, 1983).

2. B. W. Filippone and D. N. Schramm, Astrophys. J. 253, 393 (1982) and J. N. Bahcall et al., Rev. Mod. Phys. 54, 767 (1982).

3. B. W. Filippone et al., Phys. Rev. Lett. 50, 412 (1983) and B. W. Filippone et al., Phys. Rev. C 28, 2222 (1983).

4. T. Lee, D. A. Papanastassiou, and G. J. Wasserburg, Astrophys. J. (Letters) 211, L107 (1977).

5. W. A. Mahoney et al., Astrophys. J. 262, 742 (1982).

6. L. Buchmann et al., Nucl. Phys. A415, 93 (1984).

Nuclear Astrophysics Experiments with Radioactive Nuclei

if $t_{1/2} > 1\text{-}10$ days $\Rightarrow$ target feasible
↳ [chemical separation + cross section measurement limit]

I. Pros & Cons of Rad. target

II. Production of Rad. Target

III. Examples:

A. ^{7}Be ($t_{1/2} = 53d$): Solar ν Problem

B. ^{26}Al ($t_{1/2} = 7.2 \cdot 10^5$ yr.): γ-ray line Astronomy
^{26}Mg meteorite anomaly

C. ^{22}Na ($t_{1/2} = 2.6$ yr.): γ-ray line Astronomy
Ne-E meteorite anomaly

Target vs. Beam:

For Nuclear Astrophysics Exps. (ie low E & big $\frac{d\sigma}{dE}$) Rad. Target has higher "Luminosity":

for Nominal Rate of 100 $\frac{\text{events}}{\text{day}}$

Rad. beam: $\sim 10^{8}/\text{sec} \times 10^{19}/\text{cm}^2 \Rightarrow \underline{1\ \mu b^{-1}}$

Rad. target: $\sim 10^{14}/\text{sec} \times 10^{17}/\text{cm}^2 \Rightarrow \underline{100\ pb^{-1}}$

But:

Rad. targets have

1. LARGE! backgrounds (β's, γ's)

2. Significant Chemical Contaminants
Dilute reaction yield (Res. & Non-Res.)

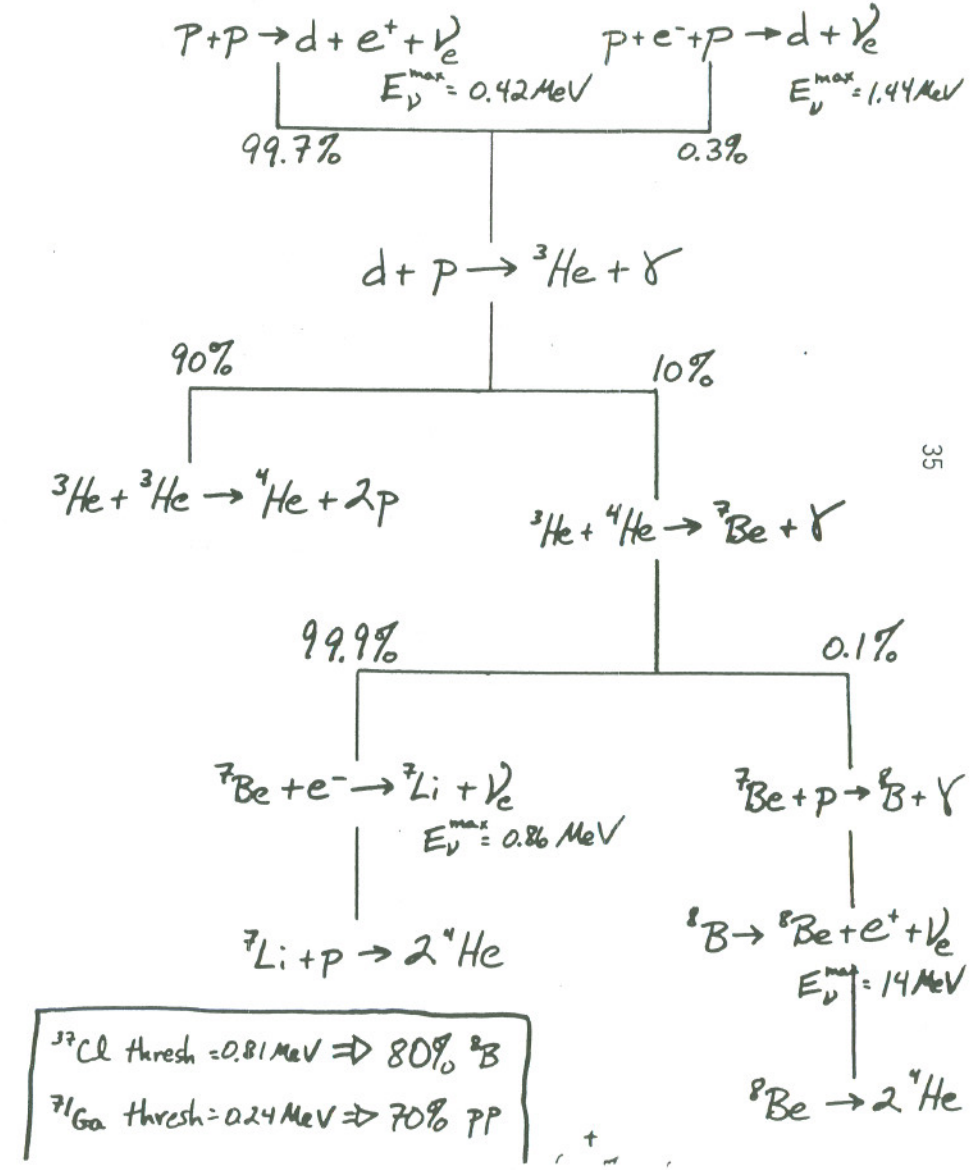
Production of Radioactive Targets:

1. Need ≈ μg amounts of Rad. Material
   - Reactor
   - High Current light ion reactions
     - Sometimes Commercially Available (Med.)
   - or Do it yourself

2. Clean, efficient chemistry
   - For separation & concentration

3. Effecient, Uniform deposition scheme
   - Evaporation
     - Distillation
     - Efficiency ~ 10 - 20%
   - Electrodeposition
     - 90 - 95% efficiency

P-P Chain



^{37}Cl Results:

$1\ SNU \equiv 10^{-36}\ \nu$ captures / target atom - sec

Davis et al measure

$$\underline{\underline{1.9 \pm 0.3\ SNU}}$$

Above known Background

Predict

$$\underline{\underline{\sim 6.0\ SNU}}$$

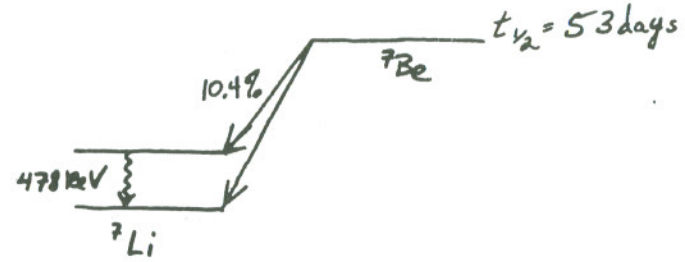
from Standard Solar Model

"Solar Neutrino Problem"

$^7Be + p \rightarrow {}^8B + \gamma$:

$t_{1/2} = .77s \rightarrow {}^8Be^* + e^+ + \nu_e$

$\hookrightarrow 2\alpha$



For Absolute σ's need # targets / cm^2

1. Count 478 keV γ's & measure area

$$\dot{N}_{^7Be} = -\lambda N_{^7Be}(0)\, e^{-\lambda t}$$

2. Watch buildup of ^7Li

$$N_{^7Li}(t) = N_{^7Be}(0)\left(1 - e^{-\lambda t}\right)$$

$\sigma_{^7Li/^7Be}(.77\,MeV) = 157\,mb$

$^7Be(p,\gamma)^8B$ at ANL

A. Elwyn ; ANL
C. Davids; ANL
D. Koetke; Valpo.
W. Ray Jr.; ANL
B.F.

① Produced 120 mCi ^7Be (0.34 μg)

$^7Li(p,n)^7Be$

1mm thick ← ^7Li; ↓ 200 μg; → 50 ng

② Chemically separate, purify, & electrodeposit

80 mCi ^7Be (~70%)

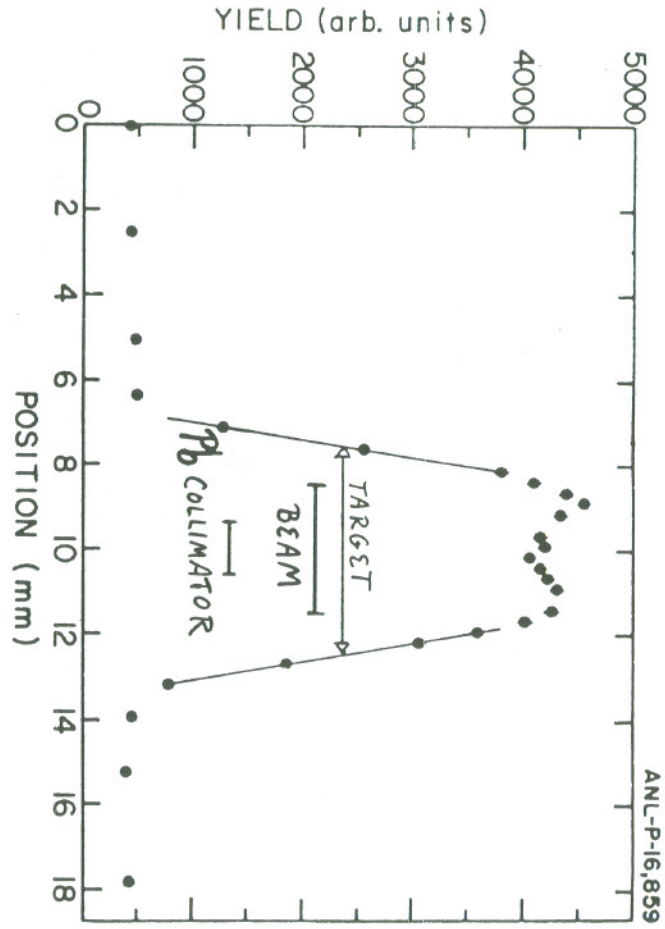
③ Detect Delayed α particles

④ Measure ^7Be Density:

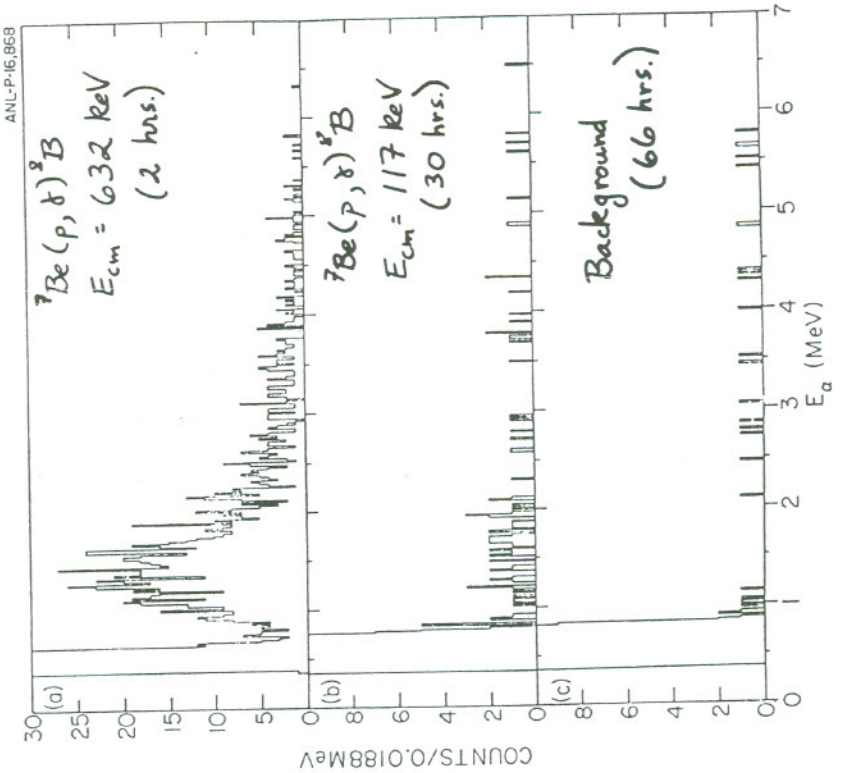
A. $^7Li(d,p)^8Li$
$N_{^7Li}(t)$

B. Total Activity (γ rays) + Area.

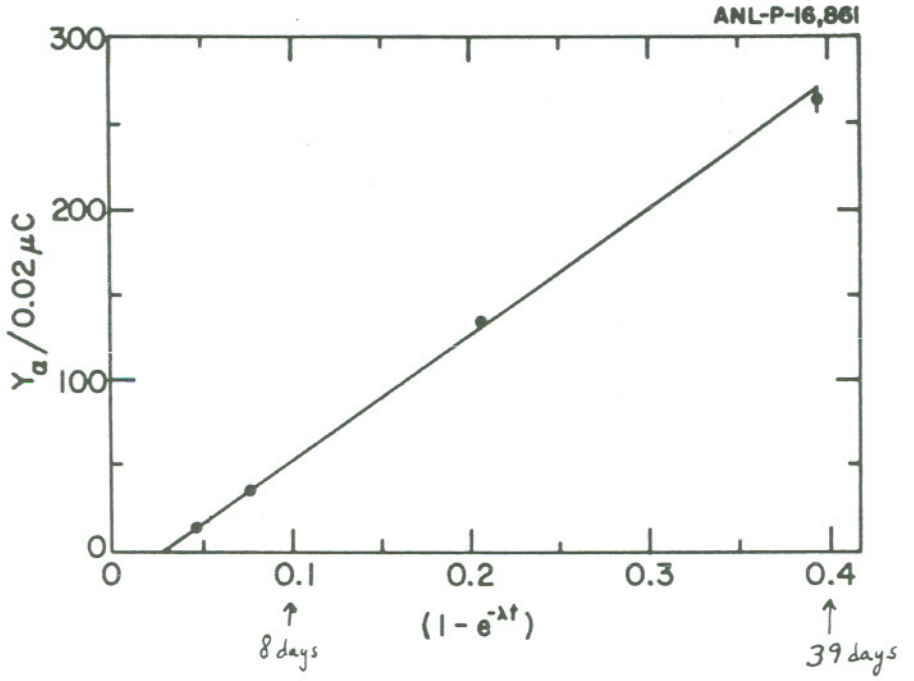
A + B consistent with $\langle \sigma_{^7Li(d,p)^8Li} \rangle$



γ 478 keV ; 1.3 mm Collimator



$^7Be \rightarrow {}^7L(d,p)^8Li \rightarrow {}^8Be^* \rightarrow 2\alpha$



λ = ^7Be decay constant

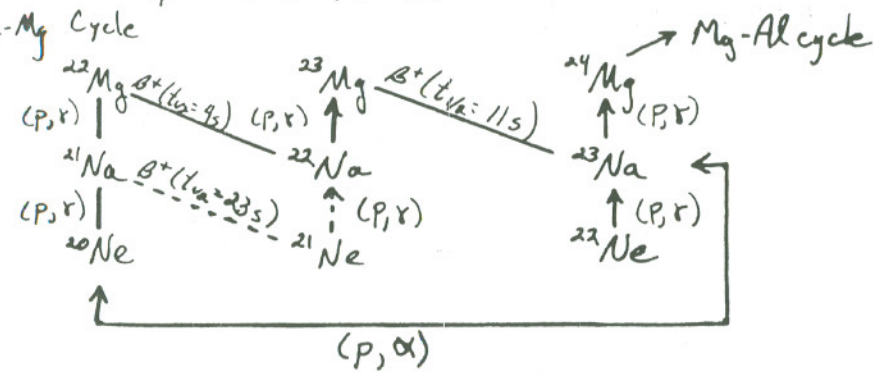
Nucleosynthesis of ^{26}Al & ^{22}Na in Novae

W. Hillebrandt & F.-K. Thielemann
Ap. J. 255, 617 ('82)

R. K. Wallace & S. E. Woosley
Ap. J. Supp. 45, 389 ('81)

$T_p \simeq 2-3 \cdot 10^8$ °K

Ne-Na-Mg Cycle



Mg-Al cycle

Similar to above

$^{26}Al(p,\gamma)^{27}Si$

Decay of ^{26}Al & ^{22}Na will give:

1. ^{26}Al : 1809 keV γ ray

   ^{22}Na : 1275 keV γ ray

Note: Mahoney et al see 1809 keV γ from gal. plane
Ap. J. 262, 742 ('82)
Priv. Comm.

2. ^{26}Al : ^{26}Mg

   ^{22}Na : ^{22}Ne

There exist anamolous abundances of ^{26}Mg & ^{22}Ne [Ne-E] in meteorites

$^{26}Al(p,\gamma)^{27}Si$ @ CIT:

R.W. Kavanagh
J. H. Thomas
B.F.

20 μg of ^{26}Al on loan from LANL
from $p + {}^{28}Si$ @ LAMPF

1. Molecular Plating seems to work

2. Detection of ^{27}Si decay

$t_{1/2} = 4.1$ sec ; $E_{\beta^+}^{max} = 4$ MeV

Look for resonances below $T_q = 0.2$

$^{26}Al(p,\gamma)^{27}Si$

Buchmann et al Nucl. Phys. A415, 93 ('84)

^{26}Al from $^{26}Mg(p,n)^{26}Al$

Vacuum distillation & evaporation
↳ 0.06 μg/cm² target

Measured Yield of Resonant γ rays
↳ must know branching ratios
to determine $(\omega\gamma)_{TOT.}$

$^{22}Na(p,\gamma)^{23}Mg$:

M. Wiescher
B.F.

Preliminary Exps. @ Mainz & Münster

$^{23}NaCl$ in aqueous soln. dried on Ta backing w 100 μg/cm² Ni substrate

little deterioration w 7 Cb p @ 0.3 MeV

Can detect γ's (?!) or ^{23}Mg β^+'s

Conclusions:

1. Nucleosynthesis Calculations need reaction cross sections with Radioactive Nuclei in incident Channel.

2. If $t_{1/2}$ > days radioactive target can be feasible.

3. For $t_{1/2}$ < days need Radioactive Beam

Astrophysical Processes Involving Proton-Rich Nuclei

by

Richard K. Wallace

Abstract

The most frequently encountered astrophysical process that involves proton-rich nuclei far from stability is explosive hydrogen burning. Specifically, we are interested in scenarios where hydrogen-helium mixtures burn at temperatures well above 10^8K. Examples of such scenarios are listed in Fig. 1. These include thermonuclear runaways on the surfaces of accreting neutron stars, supermassive star interiors, novae, and red giants, which have produced a bubble of hot material that mixes into the cool stellar envelope.

The main reaction chain responsible for hydrogen burning at high temperatures is the "β-limited" CNO cycle: $^{12}C(p,\gamma)^{13}N(p,\gamma)^{14}O(e^+\nu)^{14}N(p,\gamma)^{15}O(e^+\nu)^{15}N(p,\alpha)^{12}C$, which produces energy at a rate limited by the weak decay lifetimes of ^{14}O and ^{15}O, independent of temperature and density. For higher temperatures and densities ($T>3\times10^8$K), ^{15}O can capture an α particle, and under the same conditions, ^{19}Ne captures a proton, thus producing a leak out of the closed cycle: $^{15}O(\alpha,\gamma)^{19}Ne(p,\gamma)^{20}Na$. A complicated chain of (p,γ) and weak decays then leads to the production of iron-group nuclei. This process is illustrated in Fig. 2. Note that the flow path near the proton drip line includes mostly nuclei with lifetimes less than 300ms. Such an "rp-process"[1] can produce up to 100 times the energy generation rate of the β-limited CNO cycle at early times, however, it destroys seed nuclei, thus decreasing the energy generation at late times.

Many (p,γ), (α,γ), and (α,p) rates for unstable proton-rich nuclei are needed to calculate the rp-process correctly. Currently these rates are taken from Hauser-Feshbach statistical calculations, or from individual resonance analysis for known states in the compound nucleus or its isobaric analog.

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[1]Wallace, R. K. and Woosley, S. E., 1981, Ap. J. Supp., 45, 389.

Figure 3 illustrates the nuclear flows occurring during a nova outburst. The final abundances for ^{22}Na (a γ-line astronomy candidate and source for the neon-E meteritic anomaly) and ^{26}Al (another important meteoritic anomaly) depend strongly upon the poorly known $^{21,22}Na(p,\gamma)$ $^{22,23}Mg$ and $^{26}Al(p,\gamma)$ ^{27}Si rates. Some published calculations have differed by 10^{10} in their estimate of the Na rates!

Figure 4 illustrates some astrophysically important rates for stable targets. Most of these reactions occur in supernovae, rather than explosive hydrogen burning. Figure 5 lists some important reactions involving long-lived targets. In Fig. 6, reactions 1 and 5 determine the leakage from the β-limited CNO cycle, and thus represent fundamental uncertainties in the rp-process. Reactions 2 and 3 determine the rate at which material is processed out of the iron group (^{56}Ni), and have important effects on x-ray burst calculations.

Finally, Fig. 7 illustrates our ultimate goal: all (p,γ), (α,p), and $(e^+\nu_e)$ rates for low-mass nuclei up to the proton drip line!

ASTROPHYSICAL PROCESSES INVOLVING PROTON-RICH NUCLEI

by

Richard K. Wallace

April, 1984

Los Alamos

X-7
COMPUTATIONAL PHYSICS

-3-

EXPLOSIVE H-BURNING: T_8>5

1. NOVAE: Accreting White Dwarf. ρ_4>1. H,He,C.
2. X-RAY BURSTS (I): Accreting Neutron Star. ρ_6>1.
3. γ-RAY BURSTS: 5<T_7<100. ρ_{10}>1. B>10^{12}.
4. SUPERNOVAE: "failed" core bounce with rot. ejection.
5. SUPERMASSIVE ($M>10^5 M_\odot$) STARS: Low-Z Explosion.
6. COSMOLOGICAL MODELS with low entropy ($\rho_b c^2 = aT^4$).
7. CORE He-FLASH RED GIANTS: Bubble-Envelope.

Los Alamos

X-7
COMPUTATIONAL PHYSICS

-4-

Fig. 1

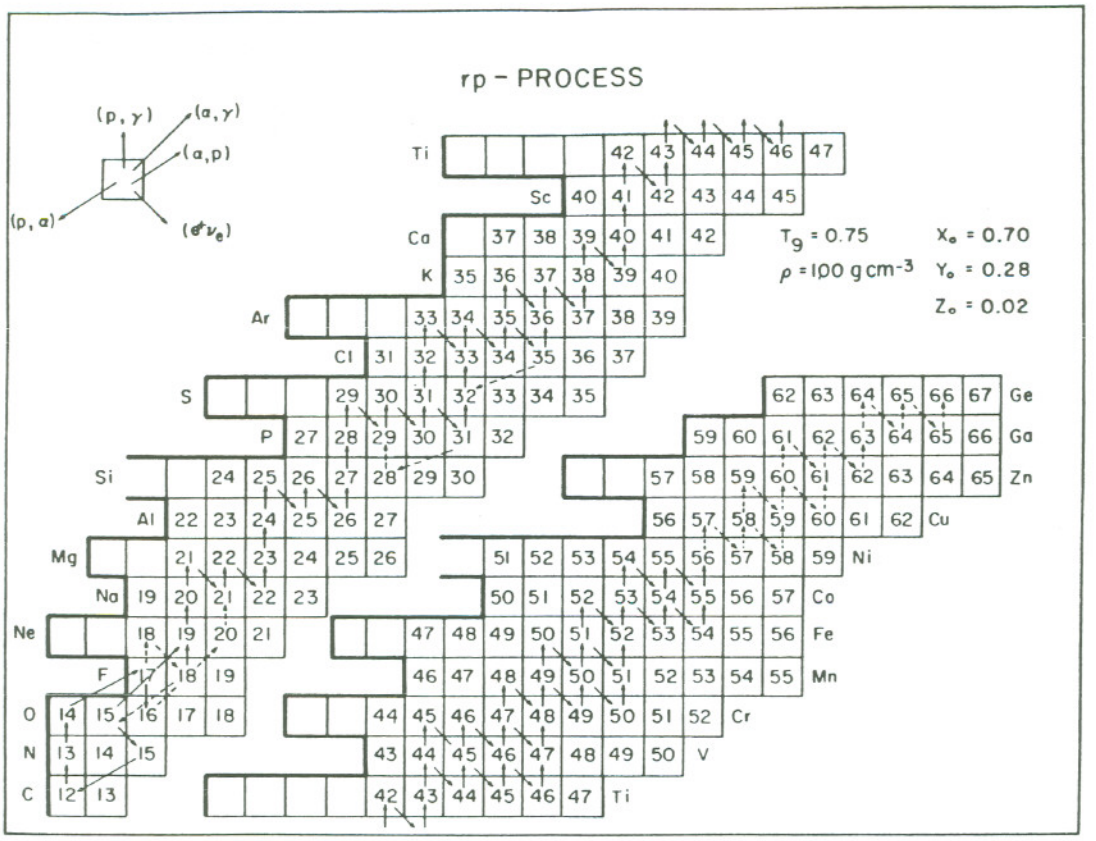
rp - PROCESS
(p, γ)
(α, γ)
(α, p)
(p, α)
(e⁺ν_e)
T_9 = 0.75
ρ = 100 g cm⁻³
X_o = 0.70
Y_o = 0.28
Z_o = 0.02
Ti
Sc
Ca
K
Ar
Cl
S
P
Si
Al
Mg
Na
Ne
F
O
N
C
Ge
Ga
Zn
Cu
Ni
Co
Fe
Mn
Cr
V
Ti

Fig. 2

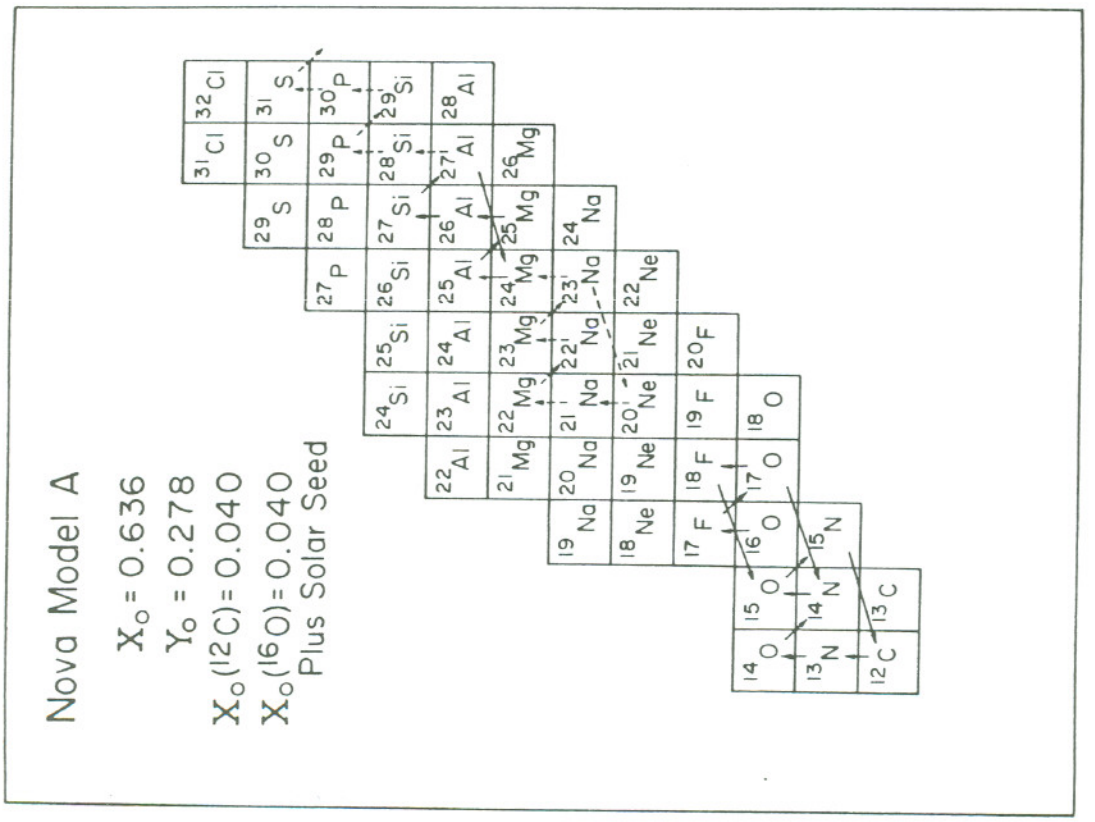
Nova Model A
X_o = 0.636
Y_o = 0.278
X_o(12C) = 0.040
X_o(16O) = 0.040
Plus Solar Seed

Fig. 3

STABLE TARGETS -- SUPERNOVAE

1. $^{20}Ne(\alpha,\gamma)^{24}Mg$ - Ne, Si, C burning.

2. $^{20,21,22}Ne(n,\gamma)^{21,22,23}Ne$ - affect n flux during He burning, and ^{23}Na prod.

3. $^{46,48}Ca(n,\gamma)^{47,49}Ca$ - give production of $^{46,48}Ca$ -- n-rich core ejection? Ca meteoritic anomalies.

4. $^{187}Os(n,n)^{187}Os$ - cosmochronology.

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Fig. 4

LONG-LIVED TARGETS ($t_{1/2}$> 1 yr)

1. $^{22}Na(p,\gamma)^{23}Mg$ - affects ^{22}Na prod., esp. in Novae. Important for γ-line astronomy and Ne-E meteoritic anom.

2. $^{26}Al(n,p)^{26}Mg$ - ^{26}Al synthesis during C burning and expl. Ne burning. γ-line astronomy and meteorites.

3. $^{26}Al(p,\gamma)^{27}Si$ - ^{26}Al in novae.

4. $^{22}Na(n,p)^{22}Ne$ - ^{22}Na in C burning.

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Fig. 5

SHORT-LIVED TARGETS ($t_{1/2}$< 1 yr)

1. $^{15}O(\alpha,\gamma)^{19}Ne$ - leakage from hot CNO cycle.
2. $^{56}Ni(p,\gamma)^{57}Cu$ - heavy rp-process flow rate.
3. $^{64}Ge(p,\gamma)^{65}As$ - heavier rp-process flow rate.
4. $^{19}Ne(p,\gamma)^{20}Na$ - competes w/ ^{19}Ne decay.
5. $^{14}O(\alpha,p)^{17}F$ - another leak from hot CNO.
6. $^{13}N(p,\gamma)^{14}O$ - hot H burning, esp. Novae.
7. $^{18}F(p,\gamma)^{19}Ne$ and $^{18}F(p,\alpha)^{15}O$ - ratio.

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Fig. 6

ULTIMATE GOAL

Mass, (p,γ), (α,p), and $(e^{+}\nu_{e})$ rates for all nuclei between stabiliy and the proton drip line.

from O_6 to Cd_{48}.

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Fig. 7

Prospects for the Production of Radioactive Beams at the Berkeley SuperHILAC/Bevalac

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University of California
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The SuperHILAC/Bevalac complex is capable of accelerating all stable isotopes to energies between a few MeV/A to over 1 GeV/A. Many branches of nuclear-, solid state-, and astrophysics as well as biology and medicine would, however, benefit from the availability of radioactive beams (RIB). Such beams have already been produced for biomedical purposes at the Bevalac (c.f. contributions by J. Alonso and A. Chatterjee) through high energy projectile fragmentation.

The "conversion efficiency" for RIB's of nuclei near stability is on the order of 10^{-2} to 10^{-3} for target thicknesses of about 10 g/cm^2 and energies in the 100 to 1000 MeV/A range. At the highest energies the electromagnetic dissociation of the projectile may aid in the production of unstable beams (c.f. the contribution by B. L. Berman to this workshop). The kinematic focussing of the projectile fragments makes it possible to analyse and "purify" these beams with monochromators consisting of dispersive magnetic elements and a position dependent absorber (wedge). These high energy RIB's can be used for experiments directly, but can also be injected very

efficiently into a general purpose accumulator and storage ring that is equipped with an RF accelerating or decelerating section and capabilities to cool the circulating beams.

The cooling can either be achieved with electrons, lasers or by a stochastic method depending on the mass of the beam, its charge state, energy and intensity, and the required time constant. The net result of any of the cooling methods is a vast improvement of the emittance and the associated luminosity of the beam. The RF section would allow the deceleration of the beam (while it is being cooled?!) to energies as low as 5 MeV/A for low energy nuclear physics experiments. These can be done with thin (10-100 ng/cm^2) internal targets or with an extracted, external beam in the conventional way. The addition of a second ring would of course greatly improve the operational flexibility of such a facility.

A completely different approach for RIB's at LBL is, to start with, the SuperHILAC. A comparison of different RIB production methods shows that the combination of a high intensity, low energy, commercial cyclotron with a target/ion source and an RFQ booster injecting into the SuperHILAC would deliver RIB's of light elements with intensities in the 10^8 to 10^{11} s^{-1} range, and energies from .1 to 8.5 MeV/A. The same cyclotron could also be used to irradiate a UC_2 target to produce fission fragments. In this way neutron rich isotopes with intensities of 10^8 s^{-1} (after acceleration) for masses near the peak of the fission distribution can be produced. All these beams could of course be "postaccelerated" in the Bevatron. In another method, instead of using the external cyclotron, a heavy ion beam from the SuperHILAC itself could be taken to produce exotic isotopes in a target/ion source. After pre-acceleration in an RFQ these RIB's could be accelerated in the HILAC during machine pulses "stolen" from the primary beam. This method

would lend itself particularly well to the production of neutron deficient RIB's via compound nucleus reactions and neutron rich beams via damped reactions. Intensities are limited due to thin targets. RIB's of interest in astrophysics could also be generated by starting with a high intensity primary beam and converting it via a gas target using resonance reactions (c.f. contribution of R. N. Boyd). RIB intensities in this case are limited by the small effective target thickness and the low conversion factors.

An alternative to RIB's is in some cases the use of radioactive targets; this subject will be covered in detail by the contributions of E. Hagberg et al. and B. Filippone.

This work was supported by the U.S. Department of Energy under Contract Number DE-AC03-76SF00098.

Table I: Comparison between RIB Production Methods

	High Energy Projectile Fragmentation w. Storage Ring	High Intensity Cyclotron w. Heavy Ion Accelerator	High Energy Proton Accelerator w. Heavy Ion Accelerator
Primary Beam:	Heavy Ions	Light Ions	Protons
Energy:	100-1000 MeV/A	50 MeV	400-800 MeV
Intensity:	10^{11} s^{-1}	6×10^{15} s^{-1}	$10^{13}/10^{15}$ s^{-1}
Target Thickness:	10 g/cm^2	.5 g/cm^2	100 g/cm^2
Target:	Be	C	A = 100
Cross Section:	10 mb	100 mb	10 mb
Acceleration Losses:	10^{-1}	10^{-4}	10^{-4}
RIB Intensity:	3×10^{8} s^{-1}	2×10^{9} s^{-1}	$10^{7}/10^{9}$ s^{-1}

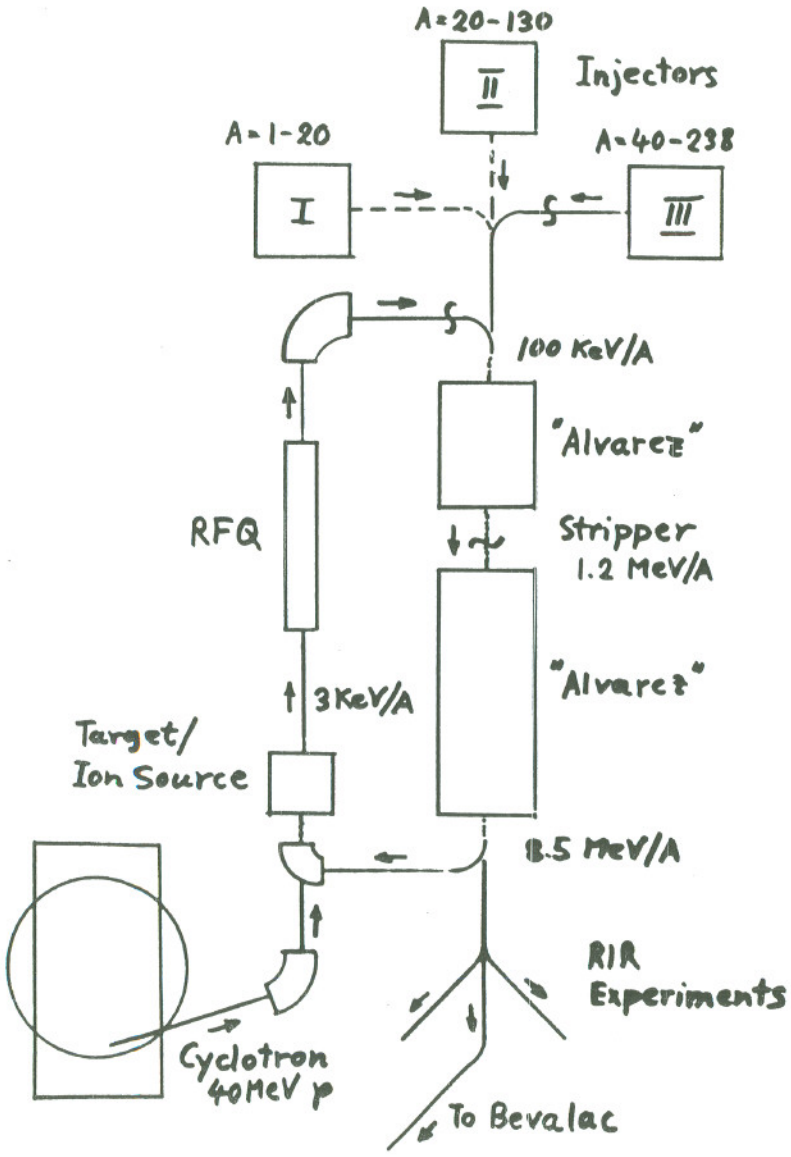
Table II: RIB's of interest in astrophysics (E = 1-10 MeV/A) that can be obtained from a combination of a cyclotron and a heavy ion accelerator. The cyclotron parameters are: K = 50, 200 μA of p and d, and 100 μA of α. Accelerator losses are included in the final average beam intensities.

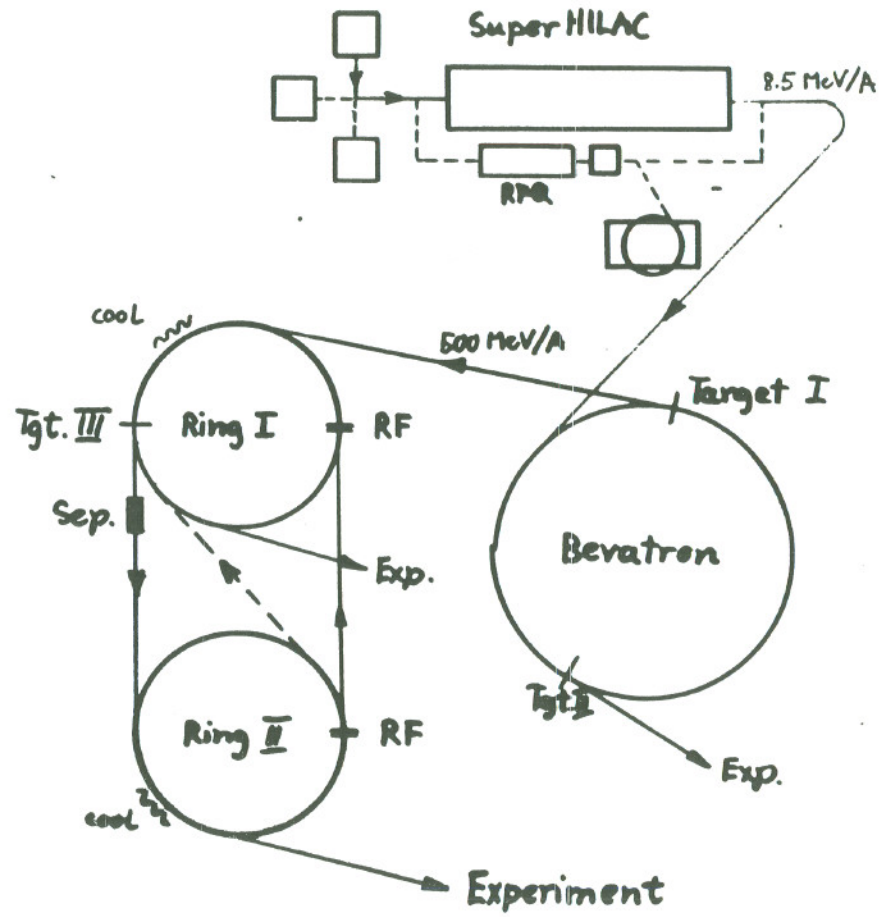
Isotope	Target (M.P.)	Reaction	Compound	Beam Intensity (s^{-1})
^{8}B	$^{9}BeO(2530)$	(p,2n)	$^{8}B,(B_2O_3)$	5×10^{10}
^{11}C	$^{9}BeO(2530)$	(α,2n)	^{11}CO	3×10^{9}
^{13}N	$^{13}C(3550)$	(α,2n)	^{13}CN	1×10^{11}
$^{14,15}O$	$^{12}C(3550)$	(α,xn)	C^{14} ^{15}O	$4 \times 10^{9}, 1 \times 10^{9}$
$^{17,18}F$	$Be^{18}O(2530)$	(p,xn)	$^{17,18}F$	2×10^{10}
$^{18,19}Ne$	MgO(2800)	(α,xn)	$^{18,19}Ne$	$2 \times 10^{9}, 5 \times 10^{8}$
^{21}Na	MgO(2800)	(p,α)	^{21}Na	4×10^{8}
		Fission		
A = 100	$^{238}UC_2(2400)$	(p,f)	---	1×10^{8}/AMU/s

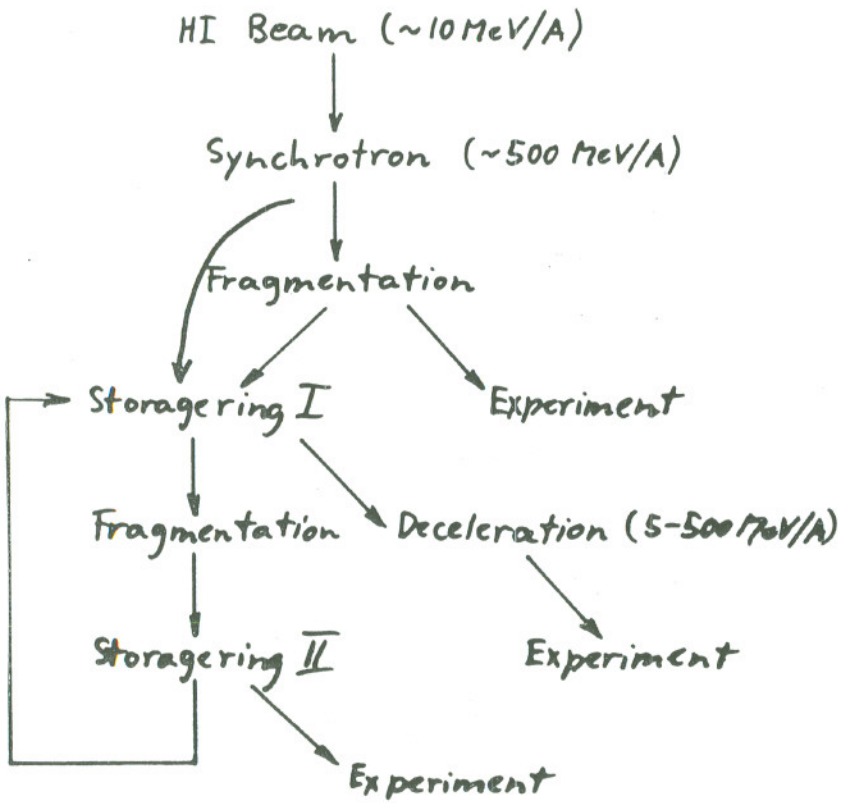
Table III: Typical RIB's that can be obtained from high intensity, low energy (~ 10 MeV/A) HI beam induced reactions. The primary HI beam is delivered by a typical linac operated at its space charge limit. The RIB is accelerated by the same or a similar linac. Acceleration losses are included in the final average beam intensities.

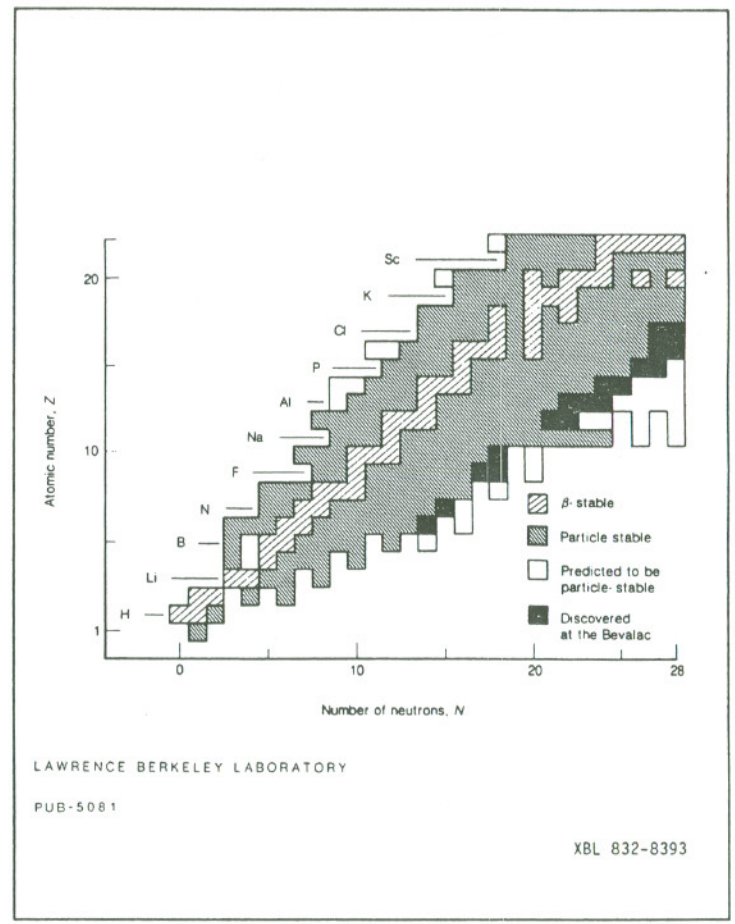
Isotope	Target (M.P.)	Reaction	Beam Intensity (s^{-1})
		CN-Reactions	
$^{22,23}Mg$	$^{12,13}C(3550)$	$(^{12}C,xn)$	2×10^{8})
^{26}Al	$^{12,13}C(3550)$	$(^{15}N,xn)$	1×10^{8}
^{56}Ni	TiC(3140)	$(^{12}C,xn)$	4×10^{7}
$^{120,122}Cs$	$Y_2O_3(2410)$	$(^{40}Ar;2p,xn)$	$10^{3},10^{4}$
		Damped Reactions	
^{44}Ar	$ThO_2(3050)$	$(^{50}Ti;4p,2n)$	5×10^{5}

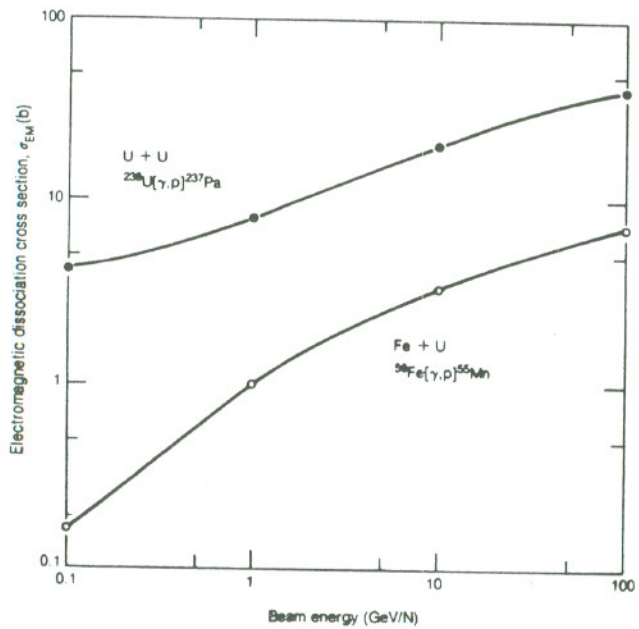
Radioactive Beam Facility

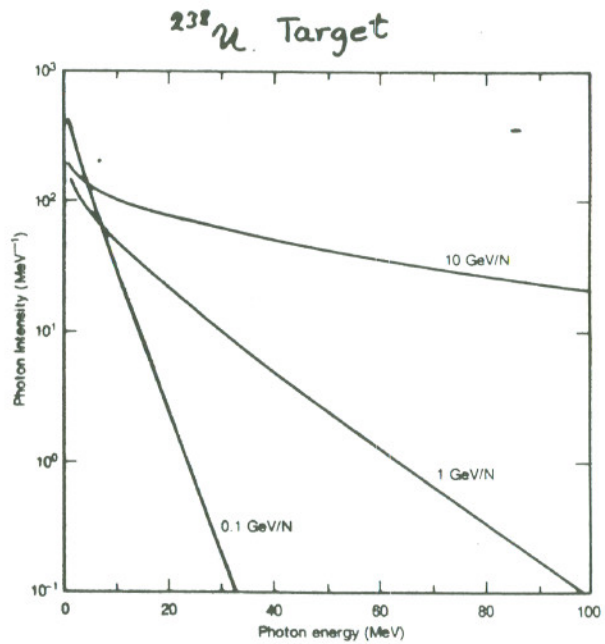


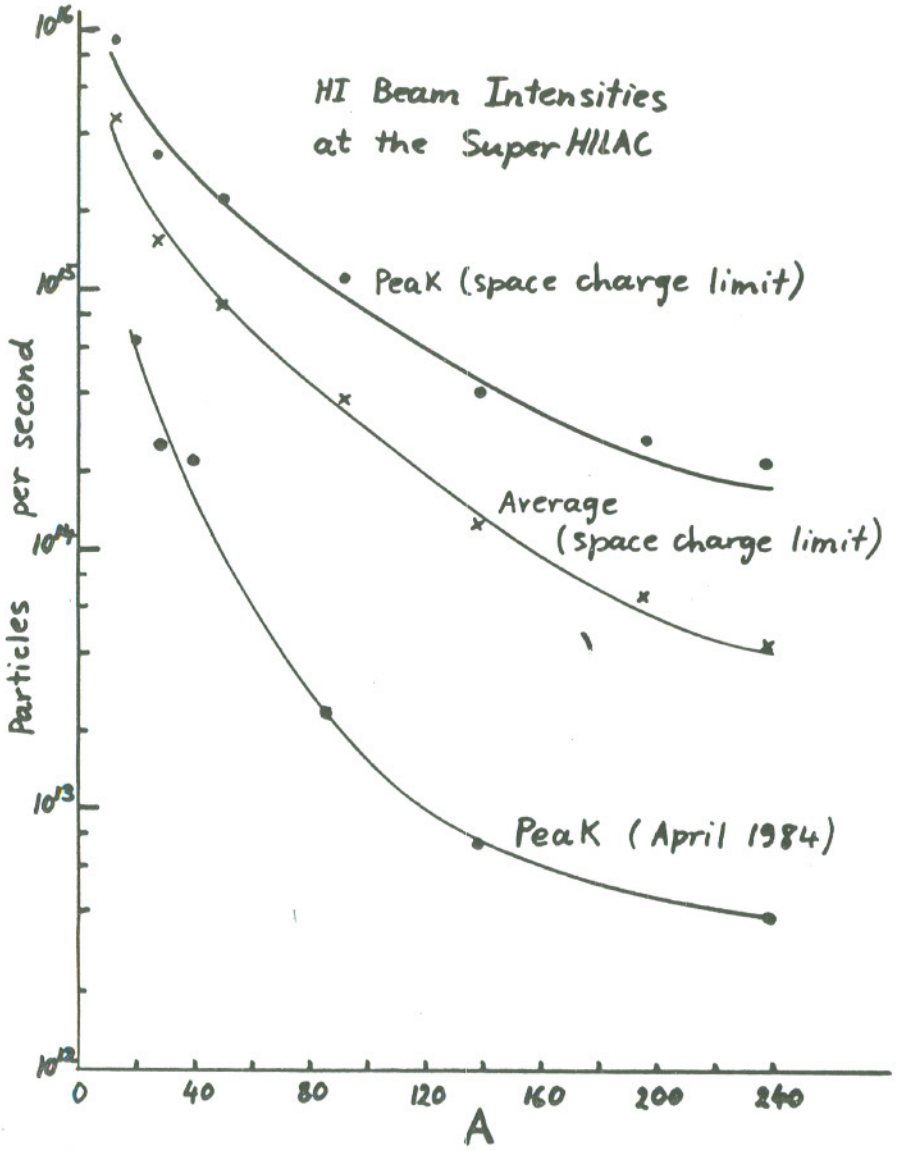


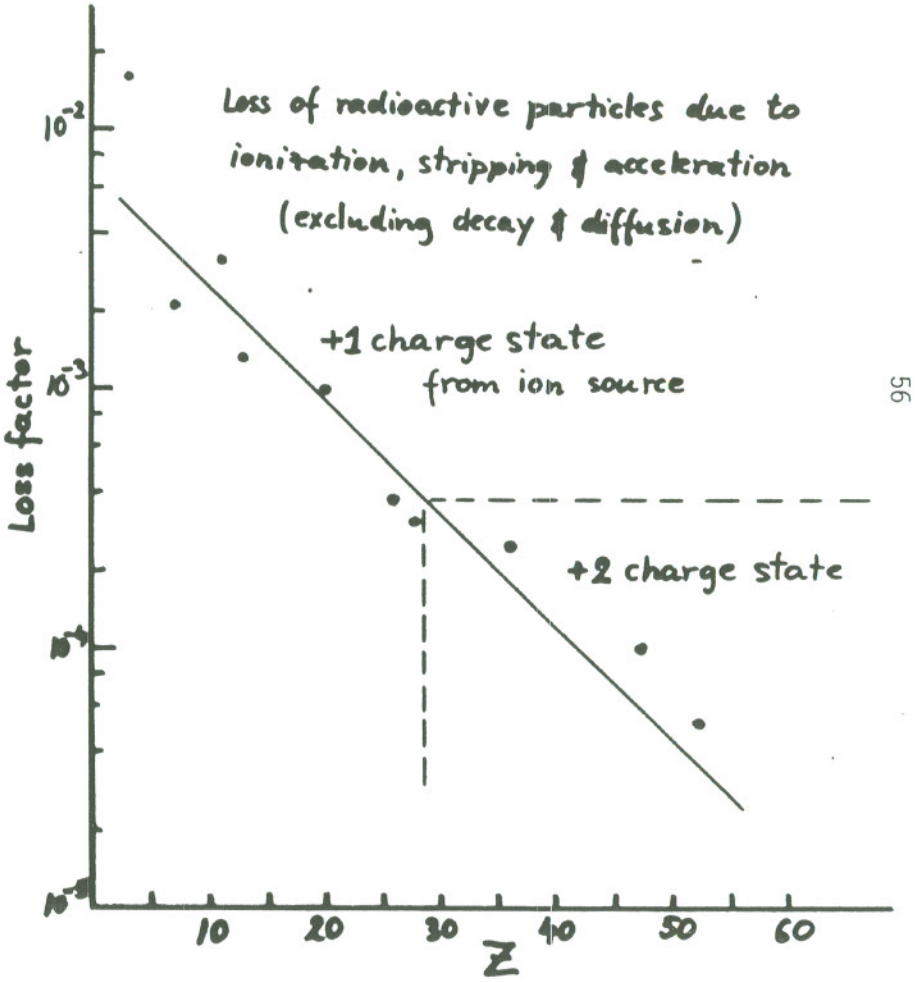

HI Beam (~10 MeV/A)
Synchrotron (~500 MeV/A)
Fragmentation
Storage ring I
Experiment
Fragmentation
Deceleration (5-500 MeV/A)
Storage ring II
Experiment
Experiment


Atomic number, Z
Number of neutrons, N
H
Li
B
N
F
Na
Al
P
Cl
K
Sc
β- stable
Particle stable
Predicted to be particle-stable
Discovered at the Bevalac
LAWRENCE BERKELEY LABORATORY
PUB-5081
XBL 832-8393


Electromagnetic dissociation cross section, σ_{EM} (b)
100
10
1
0.1
U + U
$^{238}U[\gamma,p]^{237}Pa$
Fe + U
$^{56}Fe[\gamma,p]^{55}Mn$
0.1
1
10
100
Beam energy (GeV/N)

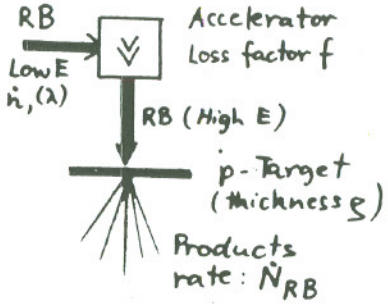

^{238}U Target
Photon intensity (MeV^{-1})
10^3
10^2
10^1
10^0
10^{-1}
10 GeV/N
1 GeV/N
0.1 GeV/N
0
20
40
60
80
100
Photon energy (MeV)


HI Beam Intensities
at the Super HILAC
Peak (space charge limit)
Average
(space charge limit)
Peak (April 1984)
Particles per second
A
0
40
80
120
160
200
240

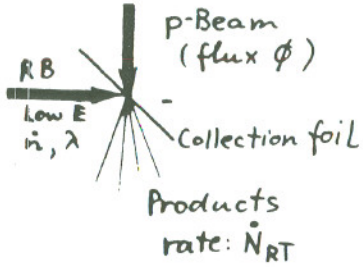

Loss of radioactive particles due to
ionization, stripping & acceleration
(excluding decay & diffusion)
+1 charge state
from ion source
+2 charge state
Loss factor
Z
10
20
30
40
50
60

Radioactive Beam (RB) vs. Target (RT)

RB (p, x)



p (RT, x)



RT saturation number

$$N = \dot{n}/\lambda$$

$$\dot{N}_{RB} = f\,\dot{n}\,\sigma\,\rho \qquad \dot{N}_{RT} = \phi\,\sigma\,\dot{n}/\lambda$$

$$\dot{N}_{RB} \overset{!}{=} \dot{N}_{RT}$$

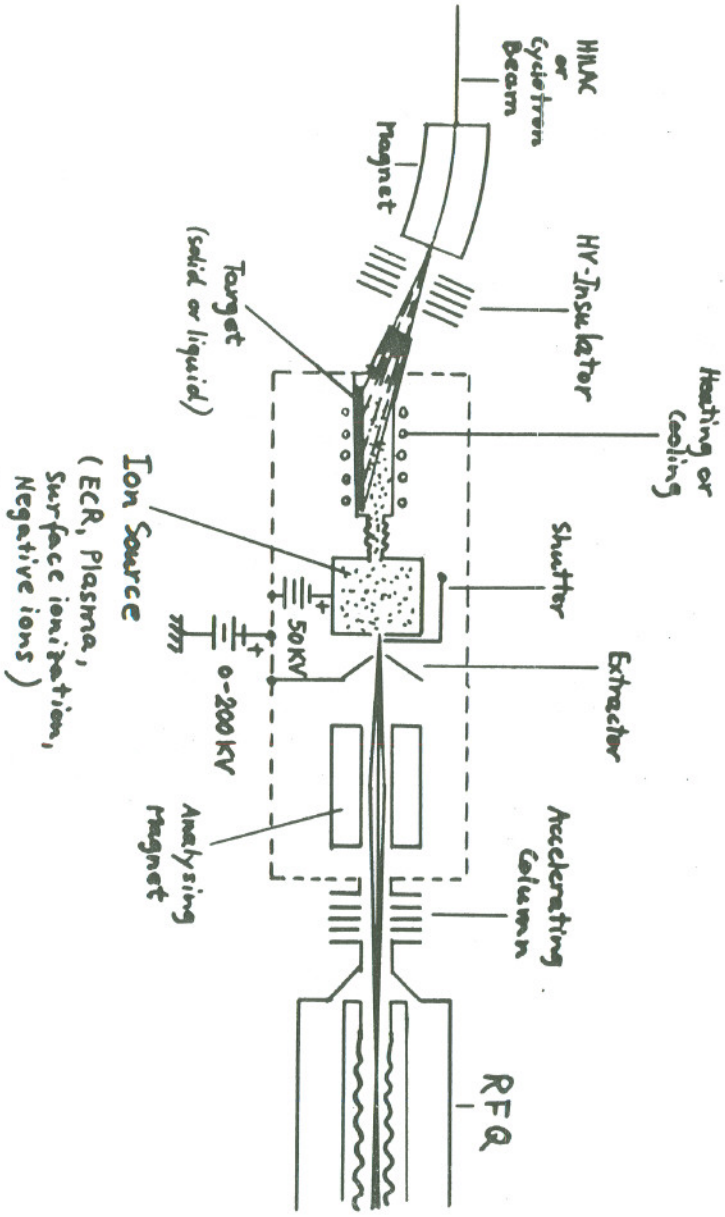
$$\boxed{\lambda \underset{\text{lim}}{=} \frac{\phi}{f\rho}}$$ independent of $\dot{n}$, σ

For $\rho = 100\,\mu g/cm^2 \approx 2\cdot 10^{18}\ p/cm^2$, $f = 10^{-3}$

and $\phi = 1\ p\mu A/cm^2\,s = 6\cdot 10^{12}\ s^{-1}\,cm^{-2}$

$\therefore\ \lambda = 3\cdot 10^{-3}\ s^{-1}$ or $T_{1/2} \approx 200\,s$

RADIOACTIVE BEAM SOURCE



New Technologies that make Radioactive Beams possible

(1) High intensity proton accelerators
(Isochronous cyclotron, sector cyclotron, synchro cyclotron, linear accelerators).

(2) New, high current, high charge state ion sources for heavy ion accelerators.

(3) New, high efficiency, low charge state ion sources for isotope separators.
(ECR, electron beam generated plasma ion sources, surface ionization, negative ions).

(4) Radio Frequency Quadrupoles ("RFQ's")

(5) "Cooled" Storage Rings

R/D Areas

(1) Target technology
(power dissipation (10-50 KW), (200 KW) matrices, diffusion, chemical selectivity, fluorination)

(2) Ion sources
(pulse mode, efficiency)

(3) Radioactivity hazards
(activation, contamination of accelerator, robots)

(4) RFQ's

(5) MI Storage Rings

(6) Beam cooling

Presentation at the Workshop on Prospects for Research with Radioactive Beams from Heavy-Ion Accelerators, Washington, D.C., 26-27 April 1984

Expectations for Radioactive Beams at a Proposed ISOL Facility at LAMPF

W. L. Talbert, Jr. and M. E. Bunker, Los Alamos National Laboratory

ABSTRACT

An on-line He-jet coupled mass separator system has been conceived for installation at the LAMPF beam stop area, with the target in the main 800-MeV beam. Estimates have been made for the production cross sections of nuclei expected to be available from spallation and proton-induced fission reactions.

Spallation cross sections were estimated using the Rudstam systematics.[1] Fission cross sections cannot be estimated using an established similar approach. An empirical approach was taken, fitting two gaussian distributions to existing data for Rb and Cs isotopic distributions,[2,3] one for the neutron-rich portion of the distribution and one for the neutron-deficient portion. The parameters of the gaussians were varied with A and Z to account for the mass yield variations and the differences between the Rb and Cs data. In all the distributions, interpolations were made for 800-MeV protons from the existing data for protons at 156 or 170 MeV and 1 GeV.

The production cross-section estimates indicate that many radionuclides not now available at any other ISOL facility could be provided in quantities necessary for detailed nuclear decay studies out to near the limits of particle stability. Closer to stability, production rates are high enough that the use of the system to provide targets for reaction studies may be possible.

Collection of radioactive isotopes for use in charged-particle reactions of interest to nuclear theorists and astrophysicists seems feasible, pending expected improvements in overall system efficiency. On-line efficiencies for a He-jet coupled mass separator have been reported in the few per cent range, and seem to be limited by the spacing between the He-jet skimmer and ion source entrance. A factor of less than ten improvement in these reported efficiencies make a LAMPF system attractive for the production of many charged-particle reaction targets.

Radioactive targets produced at ISOLDE have been used for (n,p) and (n,α) reaction studies at the ILL in Grenoble.[4] Even at the efficiencies presently achievable for a He-jet coupled mass separator at LAMPF, many targets could be made for such studies.

One field of great interest in astrophyics is the study of nucleogenesis from various processes thought to occur in stellar environments. The lack of experimental data to guide r-process calculations is a marked deficiency in these considerations. A He-jet coupled mass separator at LAMPF would enable the study of needed nuclear properties and decay processes systematically out to the r-process path from roughly A=70 to 170, using high-energy proton-induced fission of ^{238}U for nuclide production. Proton-rich nuclei can also be made available through spallation reactions.

Finally, the systematic study of nuclei far from stability would provide data for crucial tests of nuclear models that have been developed to explain nuclear behavior near stability but often fail in explaining decay processes and excited-state characteristics farther from stability. Many regions of Z are not accessible for such studies using existing on-line facilities, and a He-jet coupled mass separator at LAMPF would provide a means of extending significantly the present coverage.

The uniquely intense proton beam available at LAMPF compensates for the thin targets needed to enable recoiling radionuclides to be transported to a mass separator by means of a He-jet. Some estimates of the separated isotope production rates for the above uses will be presented.

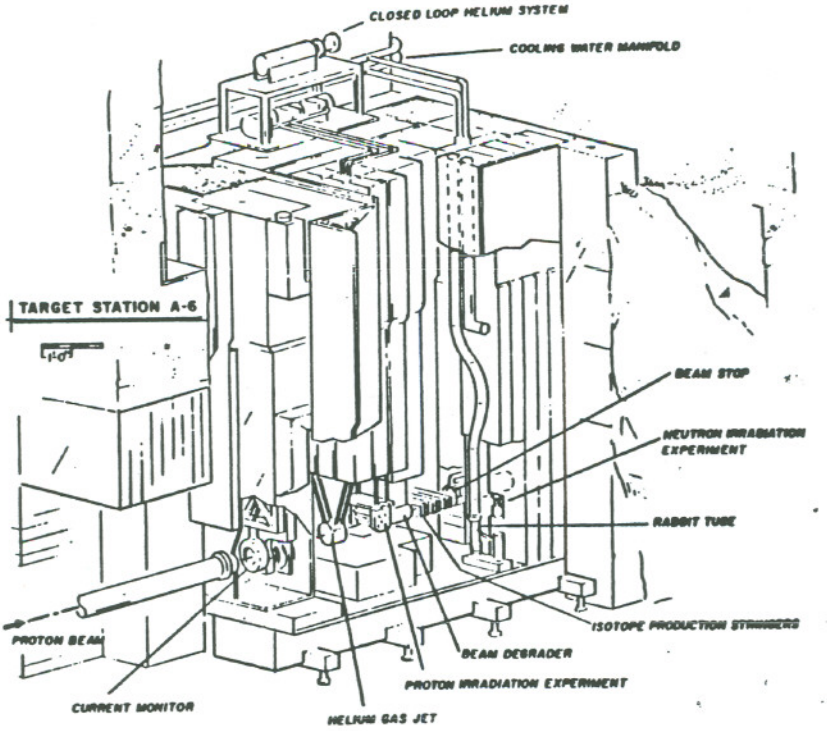
References:

1. G. Rudstam, Z. Naturforsch. 21a, 1027 (1966).

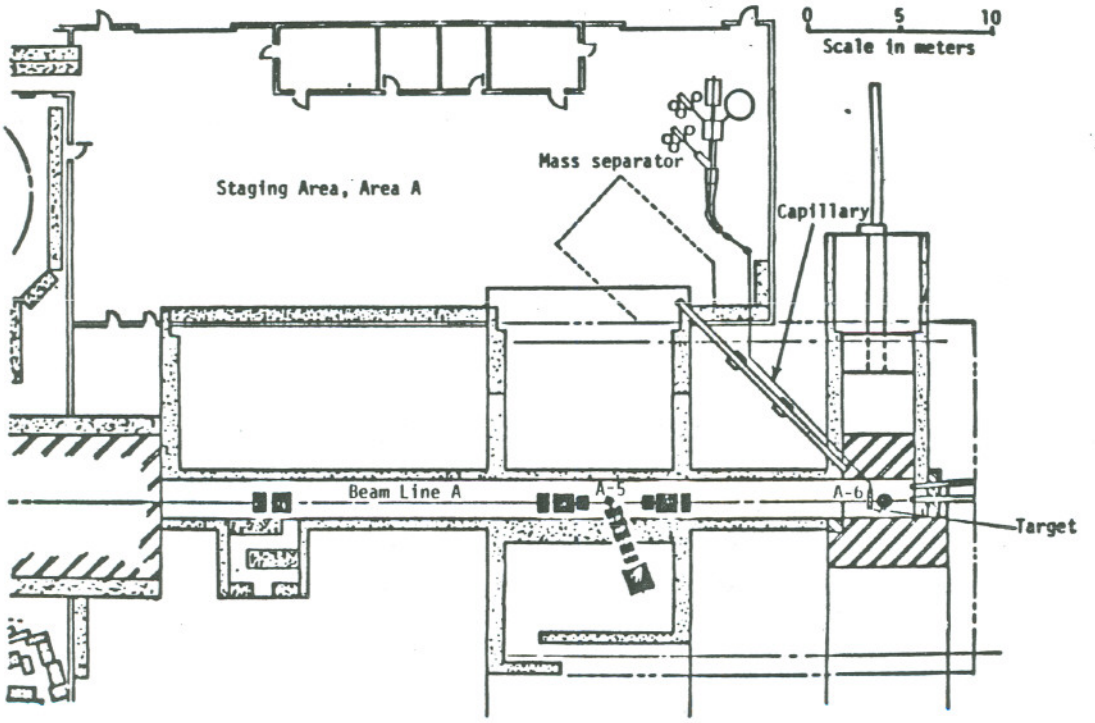
2. B. L. Tracy, J. Chaumont, R. Klapisch, J. M. Nitschke, A. M. Poskanzer, E. Roeckl and C. Thibault, Phys. Rev. C 5, 222 (1972).

3. B. N. Belyaev, V. D. Domkin, Yu. G. Korobulin, L. N. Androneko and G. E. Solyakin, Nucl. Phys. A348, 479 (1980).

4. G. Andersson and E. Hagberg, in Future Directions in Studies of Nuclei Far From Stability, J. H. Hamilton et al. (eds.), North Holland, 1980, p.121.



Conceptual Design of Area A-6 Target
Area showing He-jet Target Placement



Conceptual Layout of LAMPF Area A-6
He-jet/ISOL System

Production Processes at LAMPF

1. Spallation – mostly neutron–deficient
2. High–energy p–induced fission – mostly neutron–rich
3. Fragmentation – light (A<70) neutron–rich

Challenges to Making Predictions

1. Very little data at all – essentially no systematic data on yields
2. Fission process at 800 MeV contains at least two components
3. But, plausible spallation predictions possible using Rudstam systematics

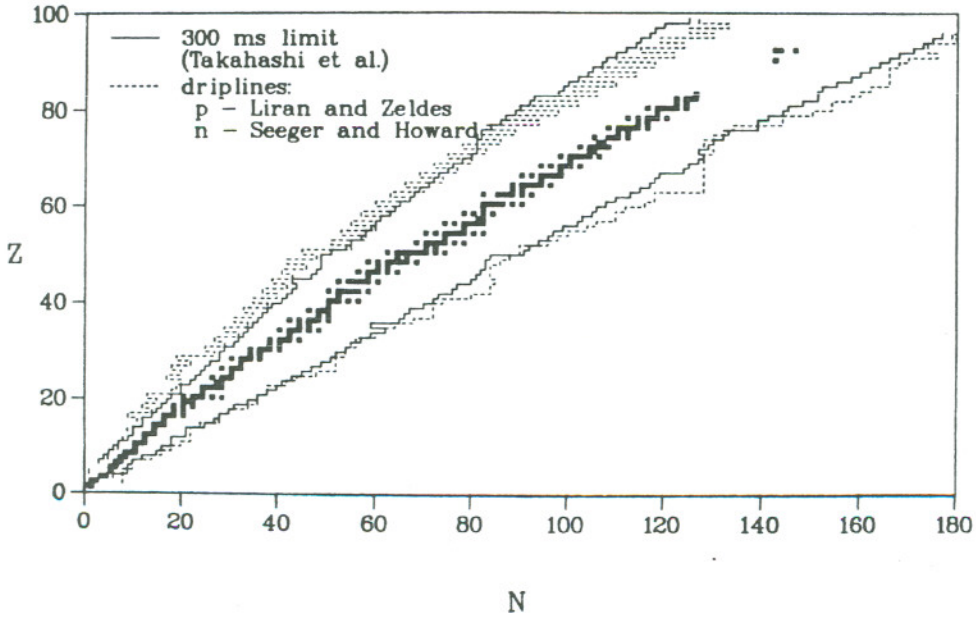
What Cross-Sections Are Needed?

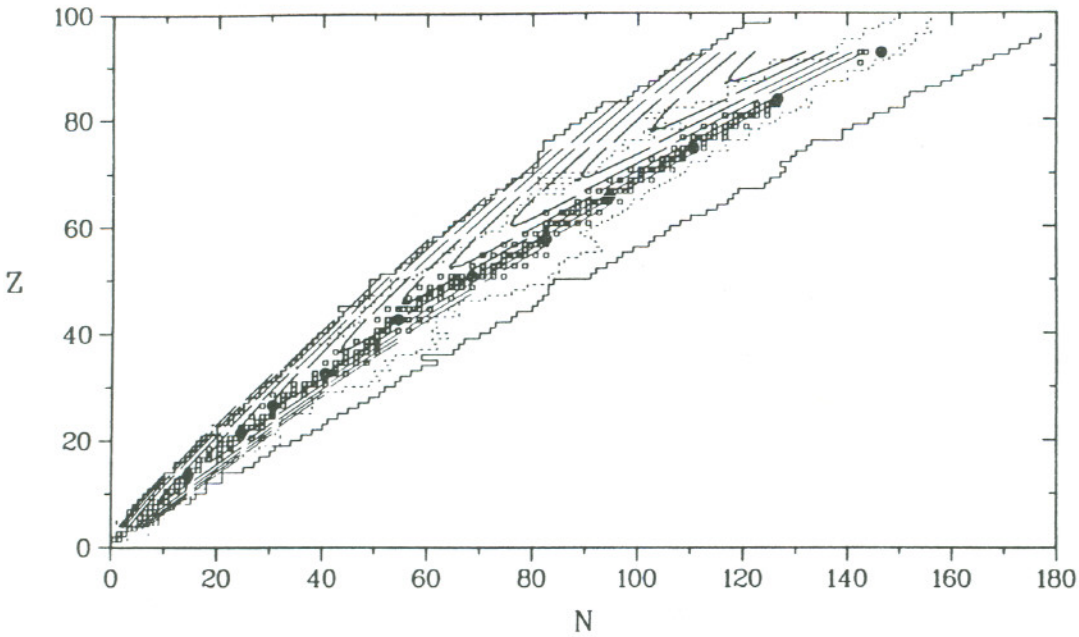
1. Reasonably detailed measurements are possible with 1000 atoms/s availability.

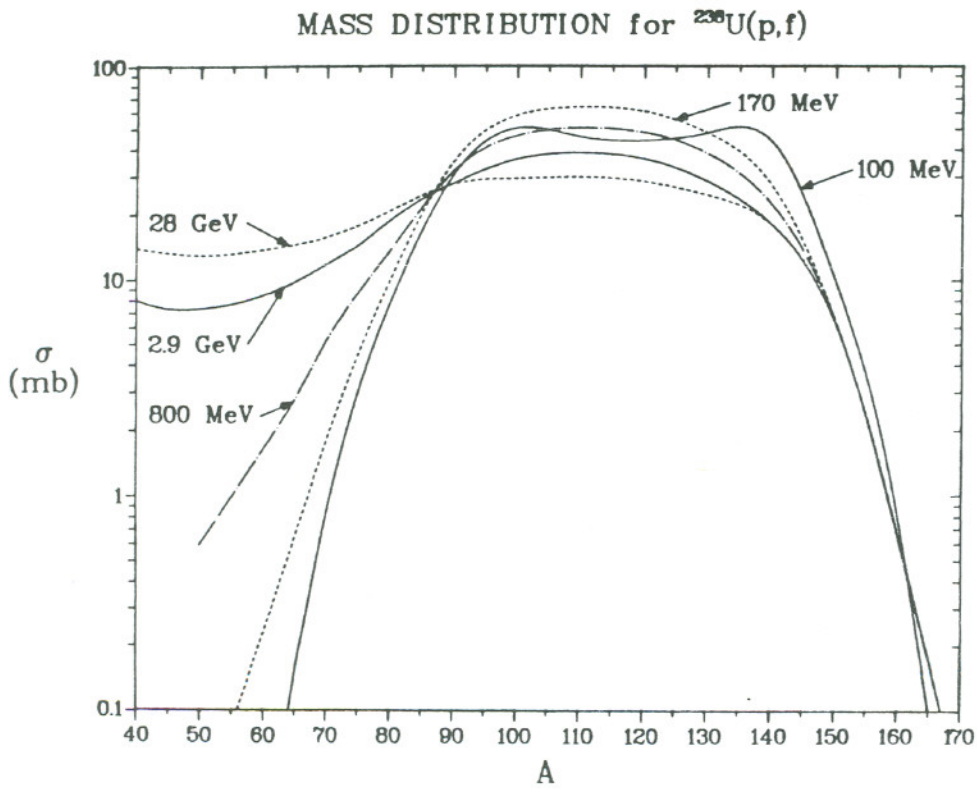
2. Consider: 60% activity transport efficiency
   1% mass separator efficiency
   two 10 mg/cm^2 U targets
   800 μA proton beam current

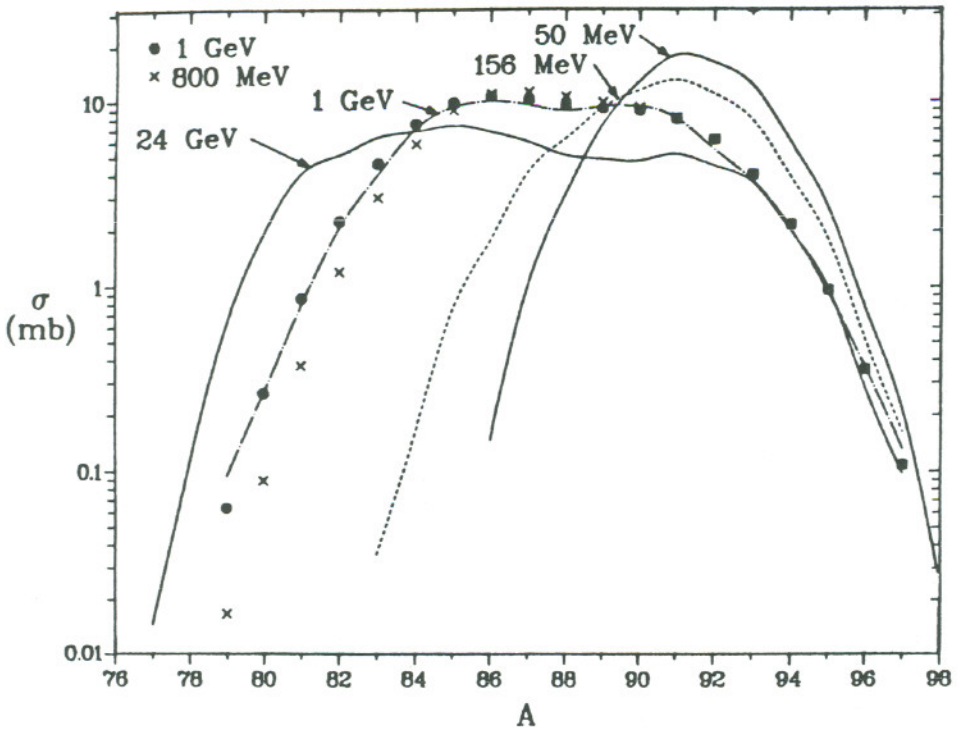
Then, 1000 atoms/s availability requires a cross-section of 0.66 μb. Predictions are not made below 1 μb.

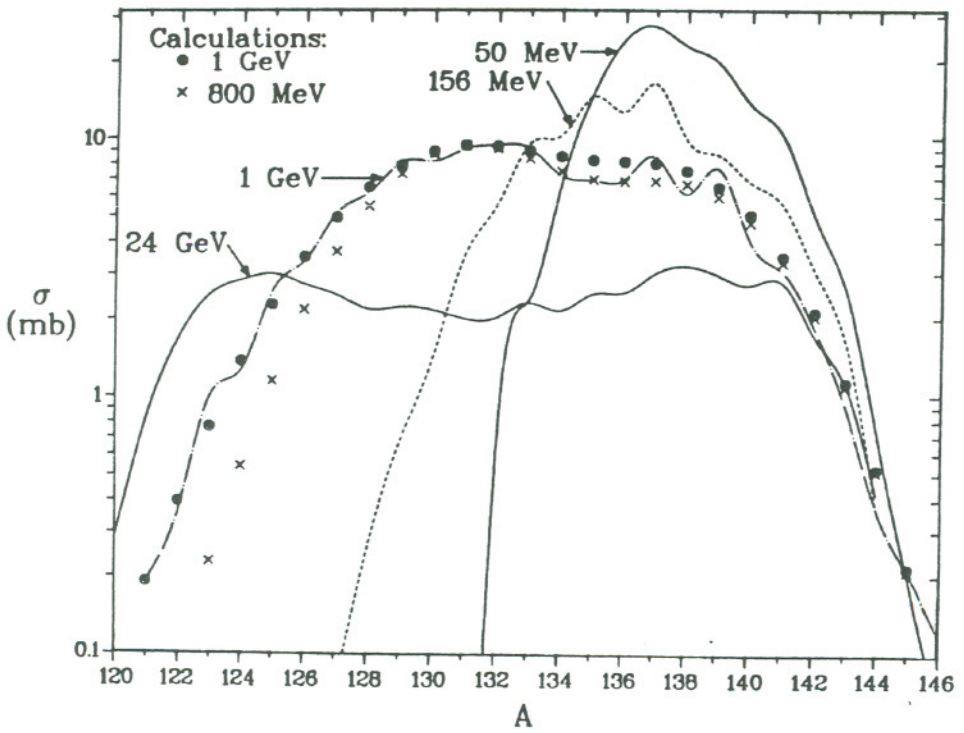
THEORETICAL DRIP LINES AND 300 ms LIMIT

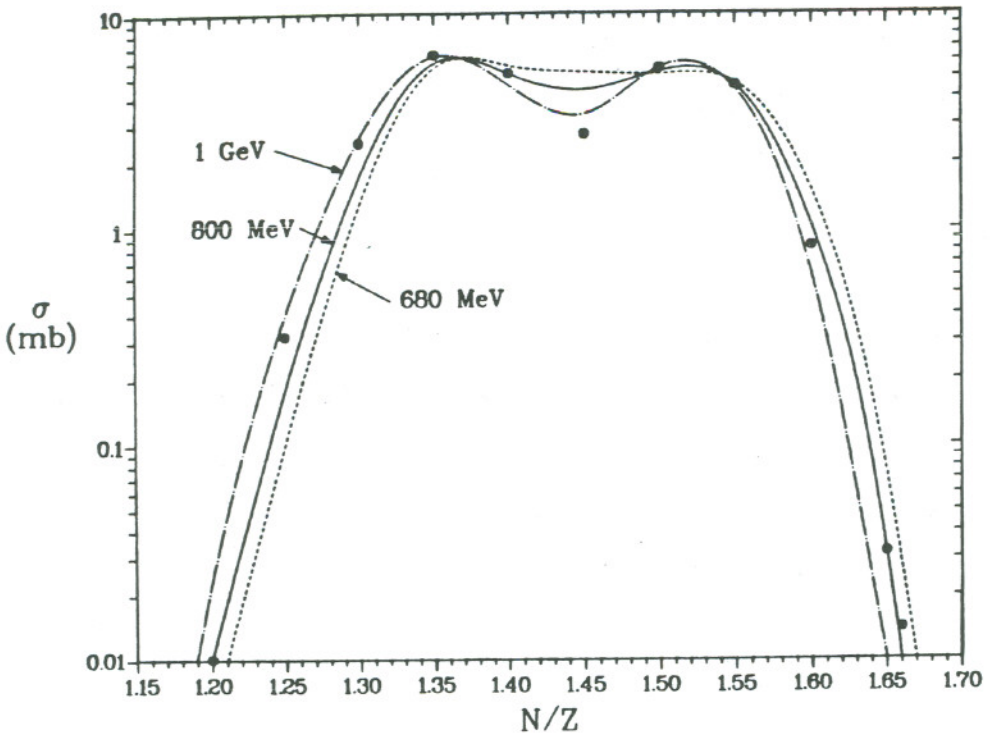


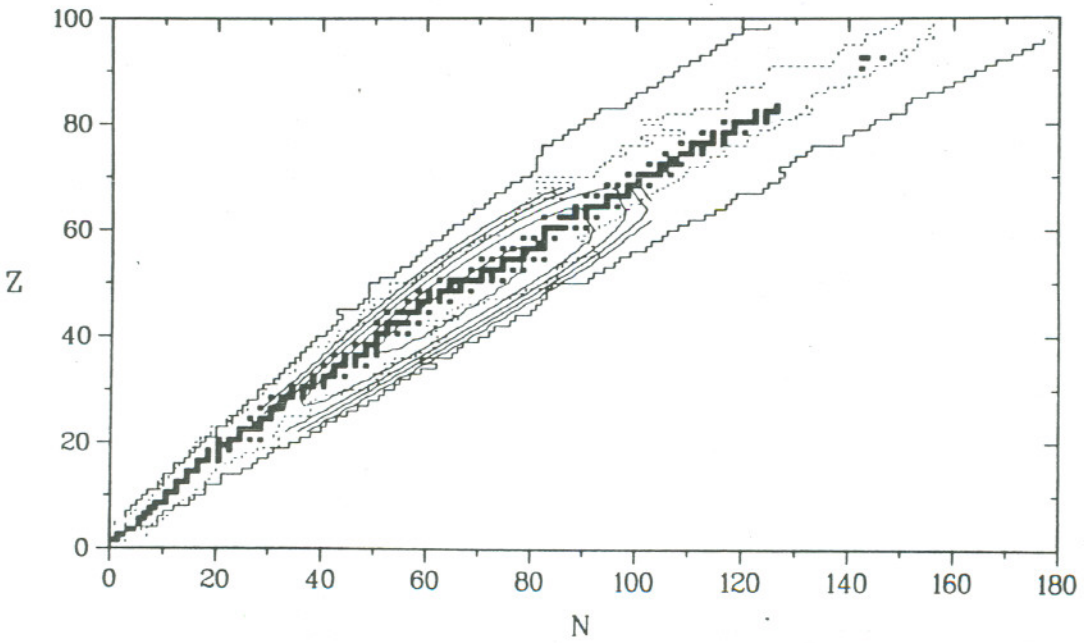

Z
N
0
20
40
60
80
100
120
140
160
180

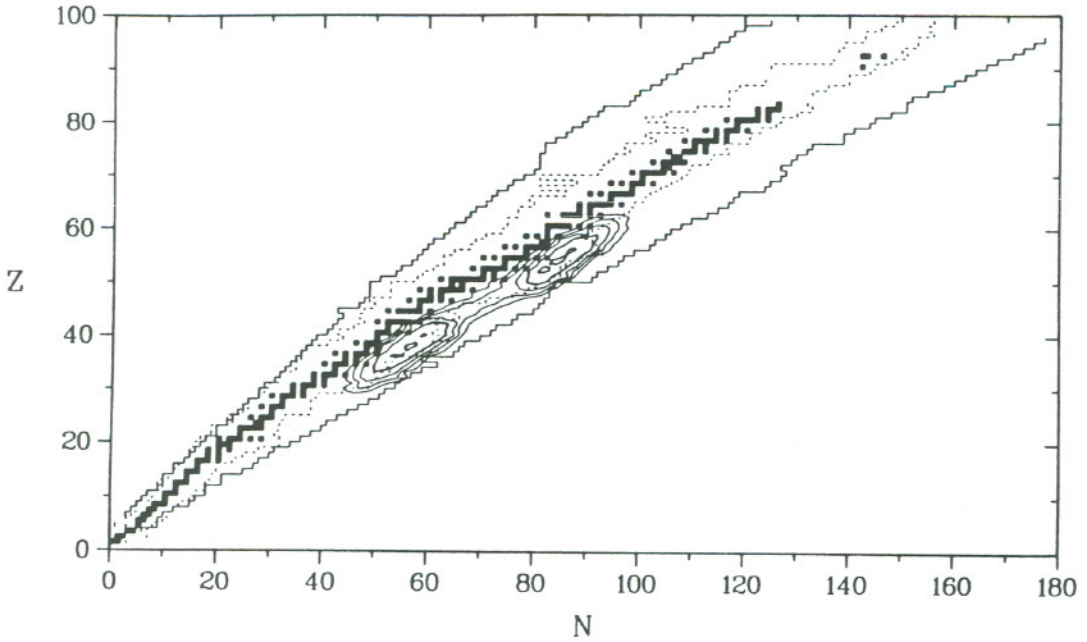

MASS DISTRIBUTION for ^{238}U(p,f)
170 MeV
100 MeV
28 GeV
2.9 GeV
800 MeV
σ
(mb)
A
100
10
1
0.1
40
50
60
70
80
90
100
110
120
130
140
150
160
170


• 1 GeV
× 800 MeV
50 MeV
156 MeV
1 GeV
24 GeV
σ
(mb)
10
1
0.1
0.01
76
78
80
82
84
86
88
90
92
94
96
98
A


Calculations:
• 1 GeV
× 800 MeV
50 MeV
156 MeV
1 GeV
24 GeV
σ
(mb)
10
1
0.1
120
122
124
126
128
130
132
134
136
138
140
142
144
146
A


10
1
0.1
0.01
σ
(mb)
1 GeV
800 MeV
680 MeV
1.15
1.20
1.25
1.30
1.35
1.40
1.45
1.50
1.55
1.60
1.65
1.70
N/Z


100
80
60
40
20
0
Z
0
20
40
60
80
100
120
140
160
180
N



Four Uses of Radioactive Beams Are Envisioned:

1. Make separated isotope targets for charged particle reactions. Given:

   20 mb cross section,
   1% total efficiency,
   two 10 mg/cm^2 ^{238}U target foils,
   800 μA proton beam,
   50 hours collection time,

   get 10^{13} atoms = 1.6 ng at A=100.

2. Make separated isotope targets for neutron reactions (n_{th},α) and/or (n_{th},p).

3. Study far-from-stability nuclei of importance to astrophysics calculations, especially r-process phenomena.

4. Study nuclei far from stability - major use.

Accelerator Targets

1. Charged particle reactions require 10–100 ng (~0.1μg/cm^2) deposits.

2. LAMPF He–jet/ISOL system can reasonably provide 10^{13} atom targets – 1.6 ng at A=100. This assumes a one per cent system efficiency. Other on–line systems operate at considerably higher efficiencies – up to 90% (ISOLDE), ignoring decay corrections in activity release from target. Technological developments may improve He–jet/ion–source coupling to an adequate level for provision of charged particle reaction targets moderately away from stability.

3. Provision of targets for possible simulation of neutron capture processes of interest to astrophysicists must await efficiency improvements, but are not altogether ruled out.

Reactor Targets

1. Targets of 10^{13}–10^{14} atoms have been used in moderate neutron fluxes (10^9 n/cm^2–s). Using spallation–produced targets from ISOLDE, studies have been made of the reactions ^{76}Br(n_{th},p), ^{84}Rb(n_{th},p), ^{37}Ar(n_{th},p), ^{37}Ar(n_{th},α), ^{109}Cd(n_{th},α), ^{125}Xe(n_{th},α), ^{127}Xe(n_{th},α) and ^{132}Cs(n_{th},α).

2. LAMPF He–jet/ISOL system should be able to provide targets for some studies even with pessimistic efficiency.

Studies of Interest to Astrophysics *

1. $T_{1/2}$'s may be possible for ^{78}Ni, ^{129}Pd, ^{129}Ag and ^{130}Ag (σ<100 nb).

2. Q_β, $T_{1/2}$ may be possible for ^{79}Cu, ^{79}Ga, ^{80}Cu, ^{80}Zn, ^{80}Ga, ^{129}Cd, ^{130}Cd, ^{130}Sn, ^{131}Cd and ^{131}Sn.

3. Level structure information as well as $T_{1/2}$ and Q_β should be possible for ^{79}Zn, ^{81}Ga, ^{130}In and ^{131}In.

These studies are considered using only the ^{238}U(p,f) reaction with 800-MeV protons. The r-process region near N=126 is difficult to approach by any means.

*G. J. Mathews, UCRL-89914, Oct. 1983

Studies of Interest to Nuclear Physics

1. Essentially all nuclei with production cross sections greater than one μb in spallation and high-energy fission that are not available elsewhere are uniquely provided by a LAMPF He-jet/ISOL system for study of ground- and excited-state properties.

2. Of initial interest are the ^{100}Sn and ^{80}Zr regions and the neutron-rich region of A=150 to 160.

Some Interesting Cases to Study:

1. ^{100}Sn – a true test of magic number far from stability. N,Z equal and large; symmetry is broken only by Coulomb effects. Using a ^{116}Sn target, σ=0.4 μb.

2. ^{80}Zr – similar test, using semishell at N=Z=40. There are conflicting theoretical predictions of deformation. Using a ^{92}Mo target, σ=7 μb.

3. A=150–160 fission–product region. Many of the most neutron–rich known nuclei have $T_{1/2}$'s of minutes. A σ of 1 μb carries one close to the 300–ms limit. Of interest is to study the extent of the well–known deformed region at larger neutron numbers.

PROSPECTS FOR NUCLEAR PHYSICS WITH RADIOACTIVE BEAMS AND TARGETS

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One approach to a study of the prospects for research with radioactive beams is to consider the possibility of using beams from an on-line isotope separator. Many modern separators provide high intensity beams of radioactive isotopes with excellent purity and a well-defined energy. A selected low-energy beam can either be collected on a thin backing and used as a radioactive target or it can be further accelerated and turned into a radioactive beam useful for nuclear spectroscopy. The purpose of the present study is to explore the possibilities and limitations of a scenario in which a medium energy accelerator, such as a tandem, is located adjacent to a high production separator. (Fig. 1)

The first question to be dealt with is that of intensity. Whether it is for radioactive targets or beams, a minimum number of atoms is required in order to permit the successful study of any particular nuclear reaction. We have estimated these minimum amounts for a number of standard nuclear reactions using typical values of cross sections, minimum acceptable counting rates, detection efficiencies and beam currents for the reactions investigated. (Fig. 2) Specifically, the reactions considered were resonant capture, transfer and pickup reactions, neutron induced reactions and Coulomb excitation. We found 10^{14} atoms to be a rough value for the minimum number required in a radioactive target. Similar rough estimates of the minimum intensity required for a useful radioactive beam, based on a target of 10^{19} stable atoms/cm^2 and other typical data found in Fig. 2, yielded a value of $\approx 10^9$ atoms/sec.

The second question to be dealt with is that of the respective merits of radioactive targets and radioactive beams. Suppose that we have a separated beam of the radioactive nuclide A and that we want to study the reaction A + B where B is a stable nuclide. Should we collect A, let it form a target and bombard it with B or should we accelerate A and let it impinge on a target of B type nuclei? (Fig. 3) If we disregard any technical difficulties, then a decision can be made, again based on assumptions of typical values for stable target thicknesses and areas, stable beam intensities and a duration of 1 week for the experiment. The decision on the most advantageous way of studying the reaction A + B is found to be a function of the half-life of A. (Fig. 4) If this half-life is shorter than an hour, then the radioactive beam experiment is more advantageous. If it is longer than an hour then a radioactive target experiment is the way to go. It should be noted that this conclusion is independent of the intensity of the primary radioactive beam.

A criterion has thus been established that for each selected unstable nuclide indicates the best strategy and the minimum primary radioactive beam intensities required for nuclear physics experiments. A comparison can now be made between these requirements and today's reality, represented by the radioactive-beam intensities that are available from a thick target separator such as the ISOLDE facility at CERN. (Fig. 4) For short-lived nuclides we find that there are a few cases where the available beam intensities are sufficient for a radioactive beam experiment. On the other hand, many of the longer-lived activities are produced in quantities large enough to permit a successful radioactive target experiment.

Although a large number of radioactive-target experiments thus appears possible, it is not guaranteed that they will be interesting or provide any new information. As an example, let us consider mass determinations of nuclides through capture, transfer and pickup reactions on radioactive targets. A search through the neutron-deficient region of the chart of nuclides for promising radioactive target candidates for a mass measurement program yields 45 such cases. (Fig. 5) For fourteen of these cases the known production rates are high enough to permit a measurement to be done. For each promising radioactive target, 11 simple reactions were considered and for each of these reaction channels it was established whether the nuclide produced through that particular channel has an unknown mass. The different reaction channels appear as 11 separate columns in the centre section of Fig. 5 and, from left to right, they correspond to the (p,α), (d,α), $(d,{}^3He)$, (p,t), (p,d), (n,γ), (t,p), $({}^3He,t)$, (p,γ), $(t,{}^3He)$ and $({}^3He,p)$ reactions. Out of our 45 promising cases only 8 fulfill both the production criterion and the unknown mass criterion, allowing in total the possibility of determining 30 new masses. This is a fair number although maybe not as high as we would have thought initially. Similar scans performed among proton-deficient nuclei and for prospects other than mass measurements, such as determinations of level schemes and rotational bands, yield similar conclusions.

A global attack on the entire chart of nuclides with present-day technology might be difficult to motivate considering the investment involved. However, there are undoubtedly specific areas of the chart of particular interest. As examples of such cases, ${}^{56}Ni$ and ${}^{146}Gd$ are both promising candidates for radioactive targets. The interest in these two nuclides lies in the fact that they occur at double shell closures, a situation which they share with very few other nuclides. Information on the masses and level schemes of some nuclides in the vicinity of ${}^{56}Ni$ and ${}^{146}Gd$ is not available (Fig. 6) but would be attainable, together with invaluable spectroscopic data, through reaction studies on both nuclides. The new data would be important to an understanding of the shell structure in these two regions.

Finally, one use of large quantities of radioactive nuclei is in the production of other far-unstable nuclei. Nuclides close to the proton drip line have been produced with stable beams and targets. (Fig. 7) An even higher yield of such nuclides is to be expected if the starting point is a beam of nuclei already removed from stability. However, the gain in cross section has to be compared to the loss in beam intensity arising from the use of a radioactive beam. The

latter loss can be estimated to be typically three orders of magnitude. The cross sections for the production of neutron-deficient nuclides with a ^{58}Ni target have been calculated with the ALICE code for beams of either stable ^{58}Ni, ^{63}Cu and ^{64}Zn or radioactive ^{56}Ni, ^{61}Cu and ^{62}Zn. A comparison between the production rates of neutron-deficient nuclides in the Xe region with stable and with radioactive beams has been made based on the calculated cross sections and the estimated difference in beam intensities. (Fig. 7) For nuclides reasonably close to stability the stable beam production wins by three orders of magnitude. However, the advantage of the stable beam production gets less and less pronounced the further away from stability we move. Close to the proton drip line the radioactive beam production mode lacks a factor of 10 in intensity, a factor that could be regained if a separator were located at a high intensity accelerator facility such as LAMPF, TRIUMF or SIN.

In summary we conclude that, so far as conventional nuclear physics is concerned, with existing machines and technology to produce radioactive nuclei, accelerated beams of such nuclei can lead to:

1) a modest number of reaction studies,
2) a fair quantity of new information, and
3) some cases in which the new information will be interesting and exciting.

But they cannot:

1) compete effectively with radioactive targets of species with half lives greater than ≈ 1 hr, or
2) increase our production rate of exotic nuclei.

*CNRS-NRC exchange fellow at AECL, Chalk River.

Prospects for Nuclear Physics with Radioactive Beams and Targets

E. Hagberg, G. Audi, J.C. Hardy and H. Schmeing

The following boundary conditions were used in this study

Radioactive nuclides obtained from on-line isotope separators

High intensity, very pure, radioactive beams are produced by many on-line isotope separators

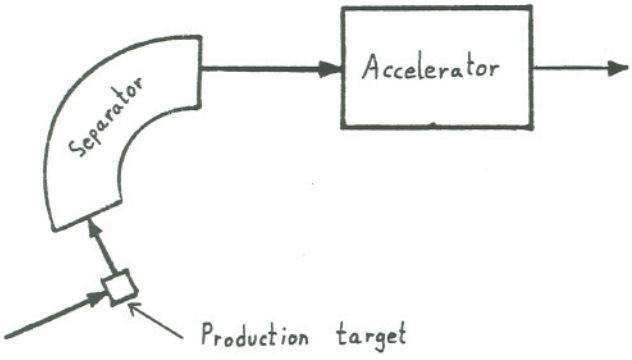
Nuclear spectroscopy by standard, well proven methods

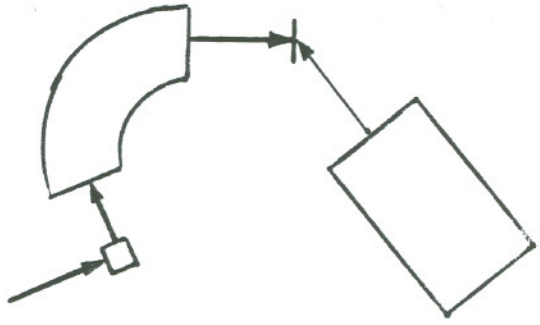
Simple reaction and excitation mechanisms considered
Interest is Nuclear Physics rather than Astrophysics

Present day technology

Consider the possibilities that would come about if a high production isotope separator and a medium sized accelerator were located adjacent to each other.

Look at both radioactive beams and radioactive targets





Radioactive targets

A radioactive target is bombarded by a stable beam. What is the minimum number of radioactive atoms required to form an acceptable target for some commonly used reactions ?
Assume target area is 2×2 mm and target nuclei are mass 50
Assume close geometry, limited resolution, no magnetic spectrometers

Reactions	typical cross section (mb)	minimum peak countrate required (s^{-1})	detection efficiency (%)	bombarding beam intensity (μA)	minimum number of atoms	($\mu g/cm^2$)
Resonant capture	10	0.1	0.5	10	$3 \cdot 10^{13}$	0.07
Transfer and pickup	0.1	0.01	1	2	$8 \cdot 10^{14}$	1.5
Coulomb excitation	100	0.1	1	2	$8 \cdot 10^{12}$	0.015
(n,p):(n,α):(n,γ)	1000	0.1	1	(10^{11} s^{-1})	10^{14}	0.2
Production	1	100	-	5	$3 \cdot 10^{15}$	6

On the average lets say 10^{14} atoms constitute a useful target

Comparison between radioactive targets and radioactive beams

Suppose we have a primary beam of the radioactive nuclide A
We want to study the reaction between A and the stable nuclide B

We have a choice	Bombard A with B	Radioactive target
	Bombard B with A	Radioactive beam

Disregarding technical problems what is the best approach
In both cases we have the same cross section, σ
the same primary production rate of A, n_A

In the radioactive target case we assume
beam, $n_B = 10\,\mu A$
target area, $a = 4\,mm^2$

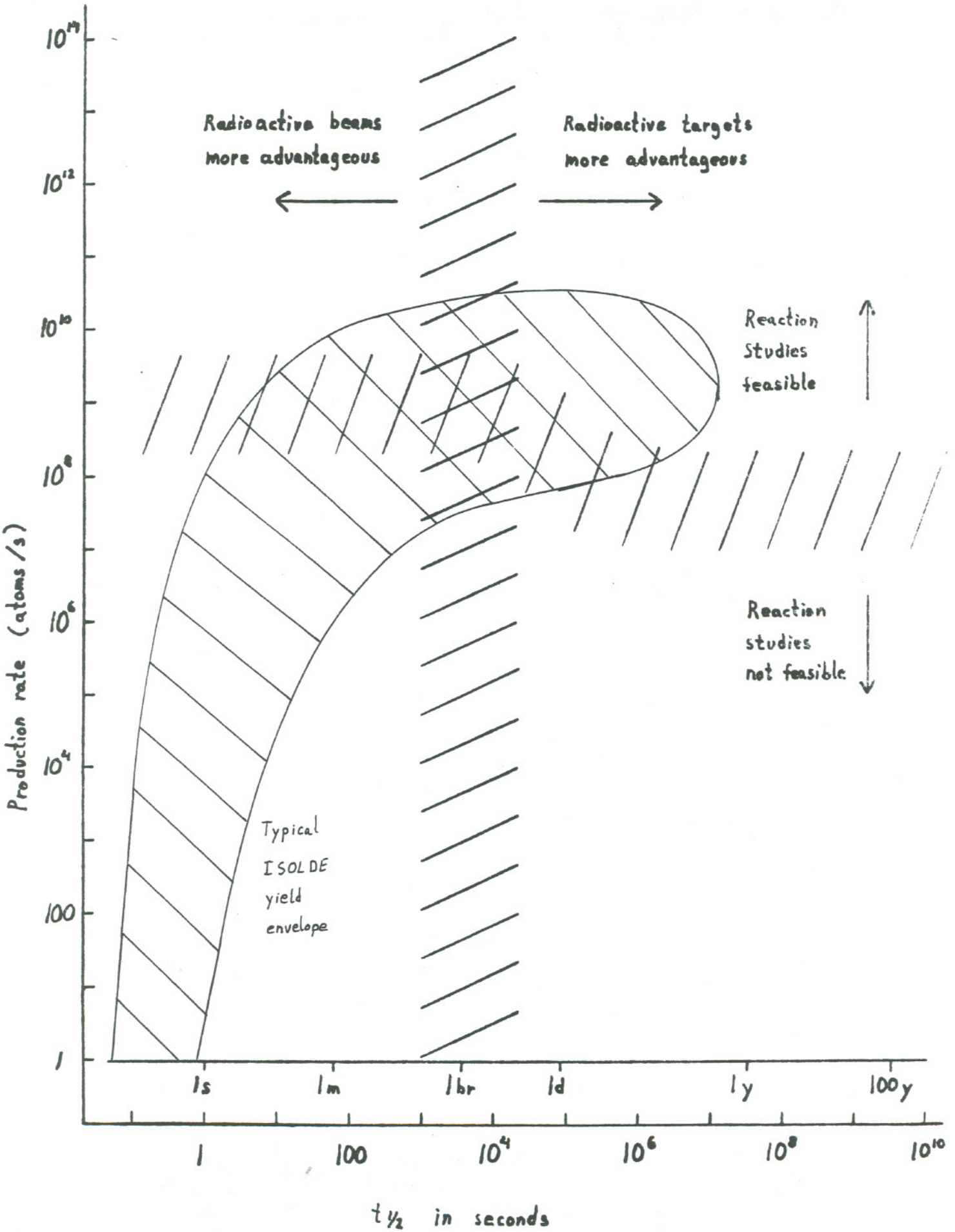
The total number of reactions, N_t, that will take place during a bombarding time T is $N_t = \int_0^T \frac{\sigma n_B n_A}{a \lambda_A}(1-e^{-\lambda_A t})\,dt$

In the radioactive beam case we assume
number of target nuclei, $b = 10^{19}\ cm^{-2}$ $(1\,mg/cm^2)$

The total number of reactions, N_b, that will take place during a bombarding time T is $N_b = \sigma n_A b T$

For a given value of the decay constant, λ_A, of the radioactive nuclide A and of the bombarding time T we can now compare N_b and N_t and find out which approach is the most advantageous one.

4


Radioactive beams more advantageous
Radioactive targets more advantageous
Reaction Studies feasible
Reaction studies not feasible
Typical ISOLDE yield envelope
Production rate (atoms/s)
10^{14}
10^{12}
10^{10}
10^{8}
10^{6}
10^{4}
100
1
1s
1m
1hr
1d
1y
100y
1
100
10^{4}
10^{6}
10^{8}
10^{10}
$t_{1/2}$ in seconds

Mass determinations with neutron-deficient radioactive targets

Promising cases	Sufficient production rate	Nuclide with unknown mass can be reached through a simple reaction channel	Both conditions met	
^{44}Ti		X		
^{48}Cr		X		
^{56}Ni		X X		
^{62}Zn				
^{66}Ge				
^{68}Ge				
^{76}Kr				
^{80}Sr		X X X		
^{82}Sr				
^{86}Zr		X X X		
^{90}Mo		X X X		
^{100}Pd				
^{110}Sn		X X		
^{116}Te		X X X		
^{121}I	X			
^{122}Xe	X			
^{127}Cs	X			
^{128}Ba		X X		
^{132}Ce		X X X X X X X X		
^{134}Ce		X X X X X		
^{138}Nd		X		
^{146}Gd	X	X	X	1
^{148}Gd	X			
^{154}Dy		X		
^{158}Er	X	X X X X X	X	5
^{170}Hf		X X X X		
^{166}Yb	X	X	X	1
^{172}Hf		X X X X X		
^{173}Ta		X X X X X X X X X X		
^{176}W		X X X X X X X X X		
^{182}Os		X X X X X X		
^{185}Ir	X	X X X X X	X	5
^{188}Pt	X	X X X X X	X	5
^{192}Hg	X	X X X X X	X	5
^{193}Hg	X	X X X	X	3
^{194}Hg	X	X X X X X	X	5
^{198}Pb		X X X X		
^{203}Bi		X X		
^{204}Po		X		
^{206}Po		X		
^{209}At	X			
^{211}Rn	X			
^{224}Ac				
^{227}Th				
^{228}Pa				
Σ 45	14 X	103 X	8 X	30

Production of extremly neutron-deficient nuclides

Compare $^{58}Ni + ^{58}Ni$ both stable

$^{56}Ni + ^{58}Ni$ ^{56}Ni is radioactive

The contour lines indicate the expected ratio between the radioactive beam production mode and the stable beam production mode

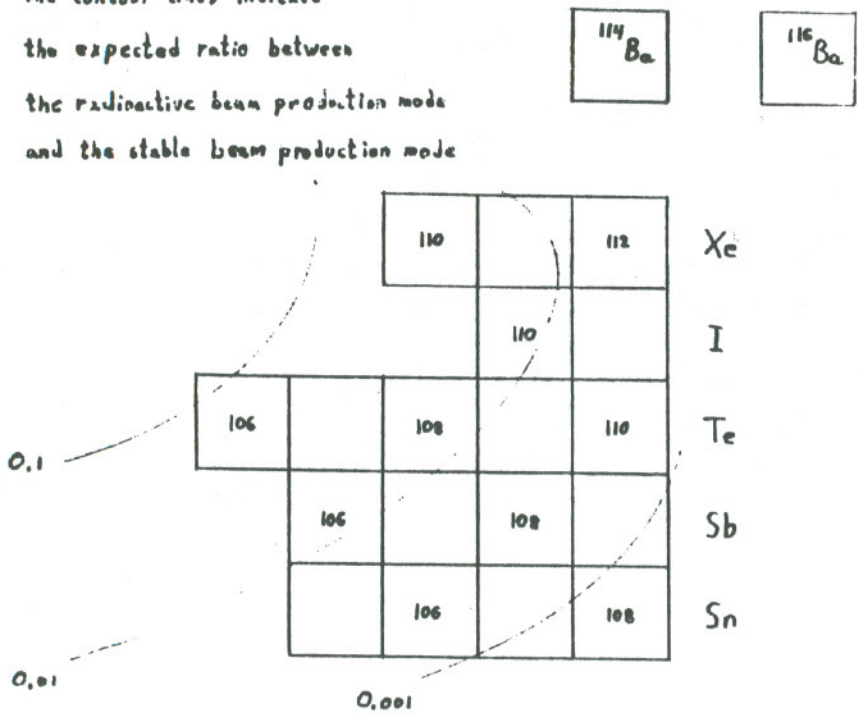
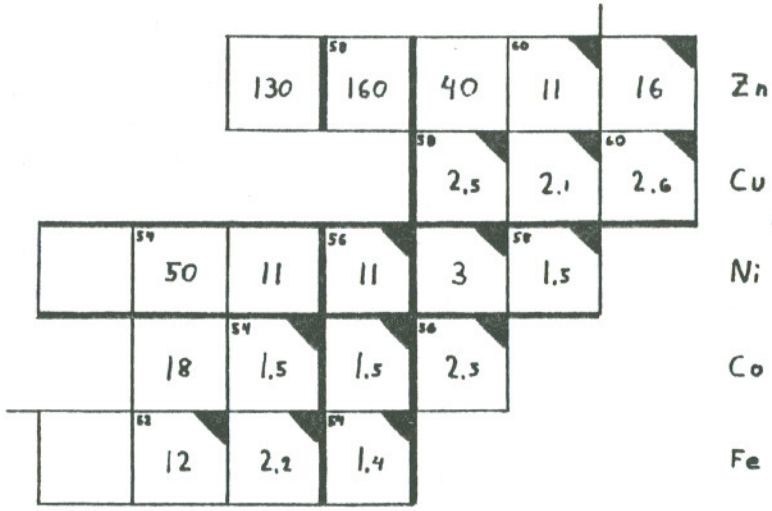
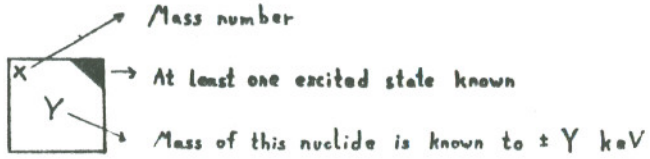


Chart of the nuclides in the vicinity of doubly magic ^{56}Ni





Nucleon Exchange Studies with Beams Far from Stability

A. C. Mignerey, J. J. Griffin and H. Breuer
University of Maryland, College Park, MD 20742

Two very basic questions remain unanswered in the field of deep-inelastic heavy-ion reactions. First, what is the role of the driving force as represented by the potential energy surface of the combined target-projectile system and second, how is the total excitation energy of the system divided between the primary products. Unfortunately, these two questions are intimately related. The centroids of the measured product mass and charge distributions must be corrected for particle evaporation before estimates of the primary mass and charge drifts can be made. However, the particle evaporation process in turn depends on the excitation energy of the primary fragments. Alternatively, if the mass and charge centroids could be accurately predicted from the potential energy surface, then the difference between the measured and predicted drift would determine the average number of protons and neutrons evaporated, and, hence, the average fragment excitation energy.

The potential energy surfaces for a wide variety of asymmetric heavy-ion systems predict that the driving forces should lead to more symmetric mass splits of the combined target-projectile system. In contrast, experimental results suggest that even more asymmetric products are usually favored. The disparate neutron-to-proton ratios of the target and projectile lead to protons transferring preferentially from the projectile to the target rather than net neutron transfer from the target to the projectile. In the Fe-induced reactions studied (1), the conclusions of zero neutron drift and large asymmetric proton drift were arrived at after correcting the measured distributions for neutron evaporation, assuming an excitation energy division according to the product masses (probably valid for final energies near the

Coulomb barrier corresponding to long interaction times.) However, the potential energy surfaces predict neutron drifts towards symmetry. If charged particle evaporation is also important the predicted primary distributions would then show less proton drift and asymmetric neutron drifts.

The initial asymmetric target-projectile combinations available using stable beams and targets usually place the projectile injection point on the proton rich side of the β stability valley, where there is a relatively large gradient for asymmetric proton drift. Hence, it is desirable to study a series of systems which provide different injection points on the same or similar potential energy surfaces. The systems $^{37}Cl + ^{209}Bi$ and $^{40}Ca + ^{238}U$ studied at bombarding energies of 7.2 MeV/nucleon (2) have injection points which lie close to the minimum of the potential energy surface for the charge degree of freedom and should drift towards symmetry along the stability valley. Instead both systems are characterized by experimental product charge and mass distributions which show a strong drift along the valley but against the potential to more asymmetric products. To quantitatively measure the differences in drifts between these two systems charged particle evaporation must also be considered.

Neutron rich beams are highly desirable in these studies because they lead to injection points on the proton deficient side of the potential energy surface. This allows the study of the effect of a strong driving force to larger proton numbers in the projectile-like fragment, which has yet to be observed experimentally. In addition, proton evaporation from the products would be less likely and the uncertainties associated with these corrections would be reduced.

The point has frequently been raised whether the potential energy surface

really has any influence over the nucleon exchange process and if not what does provide the driving force for net particle transfer? In a kinetic pressure picture developed by J. Griffin based on solutions to a simple particle in a box model, the driving force for the net exchange of nucleons between two potential wells of length L with energy E_{TOT} is proportional to the kinetic pressure $\frac{\partial E_{TOT}}{\partial L}$ in each well. This has the functional form $(X^{2/3})/A$, where X is either the number of neutrons or protons in the well and A is the atomic number. Nuclei with higher kinetic pressures will show a net drift towards nuclei with lower kinetic pressures. This is in agreement with the asymmetric drifts observed in the systems studied. It would be particularly interesting to study a variety of systems where the potential picture and the kinetic pressure picture predict opposite proton drifts. Neutron rich beams would provide this opportunity.

Experiments using secondary beams must be designed to operate at very low incident beam intensities. The cross sections for deep-inelastic reactions are on the order of mb and, since it is the large scale features of the mass and charge distributions which are of interest, the data can be summed over a rather large range of fragment energies. This is a great advantage since the energy resolution of secondary beams may be considerably poorer than that of primary beams. It is also possible to take data over a large angular range since it has been shown that, while the absolute yield may vary, the shapes of the mass and charge distributions in deep-inelastic reactions are independent of angle. This allows the use of large solid-angle ion chambers and timing detectors which have recently been developed. Combining all these factors it is believed that an experiment could be completed with several days of beam-time which would provide important data towards our understanding of the mass and charge drifts in the deep-inelastic heavy-ion reaction mechanism.

References

1. H. Breuer *et al.*, Phys. Rev. *C28*, 1080 (1983).

2. H. Breuer *et al.*, Proc. of Winter Workshop on Nuclear Dynamics III, Copper Mountain, Colorado, March 1984.

①

Nucleon Exchange Studies with Beams far from Stability

A. Mignerey
J. J. Griffin
H. Breuer

Two basic unsolved problems in Damped Heavy-Ion Reactions

① Role of the potential energy surface

② Division of excitation energy between primary fragments

Unfortunately these two problems are related -

Evaporation of particles from primary products depends on the excitation energy

Overall drift of primary effected by evaporation to secondaries

②

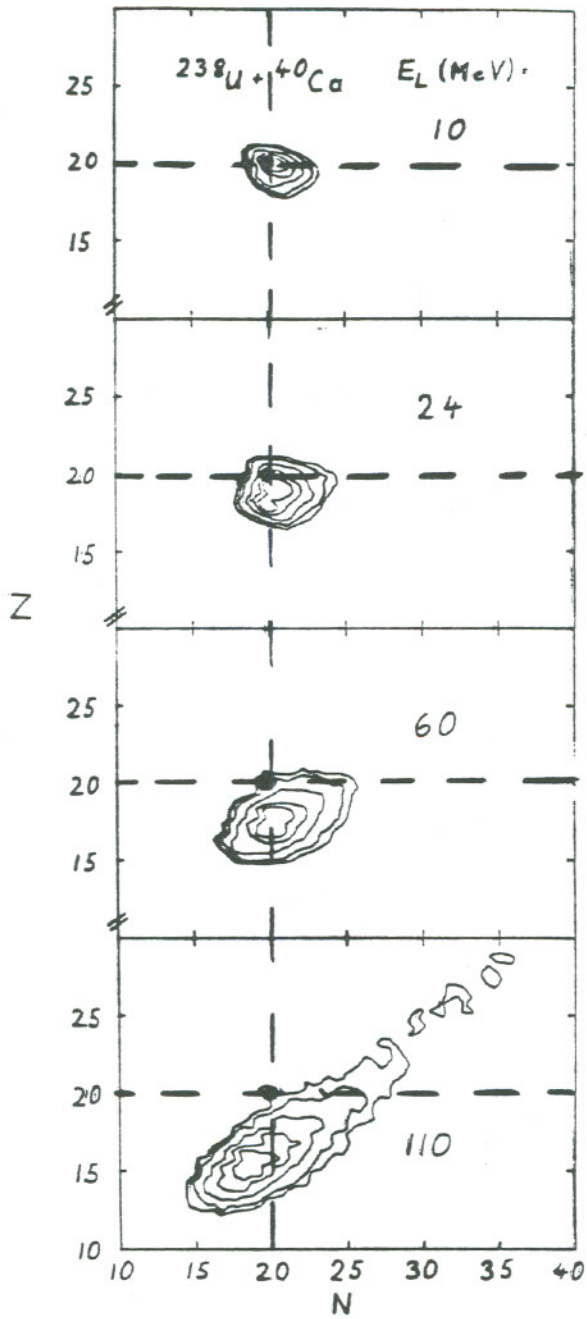
From systems studied know that the mass and charge drift do not follow the driving force indicated by the potential energy surface

	$(N/Z)_P$	$(N/Z)_T$
Fe + Ho	1.15	1.46
Fe + Bi	1.15	1.52
Fe + U	1.15	1.59
Cl + Bi	1.18	1.52
Ca + U	1.00	1.59

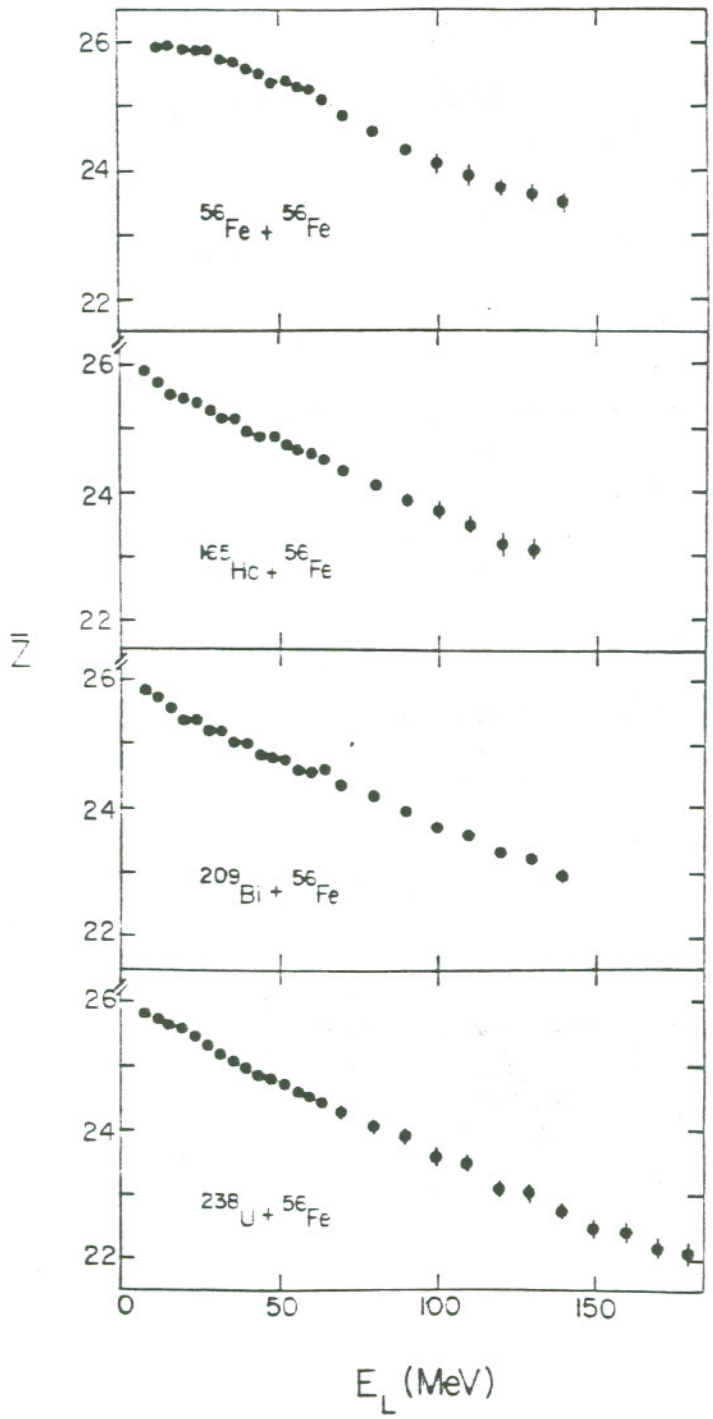
Large difference in N/Z ratios of the target and projectile -

Driving force to equilibrize the N/Z

Done by net proton drift from light to heavy - <u>not</u> neutron from heavy to light

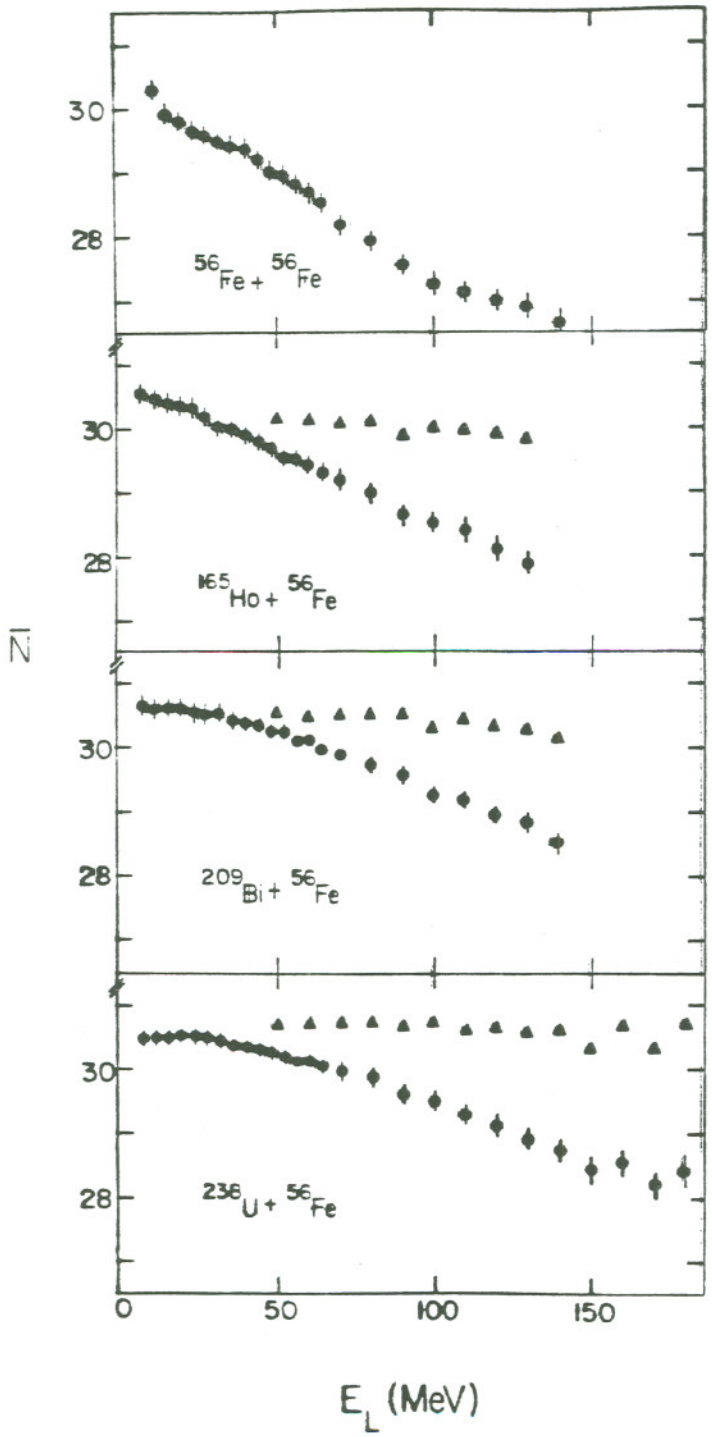

238U + 40Ca
EL (MeV)
10
24
60
110
Z
N
25
20
15
10
10
15
20
25
30
35
40

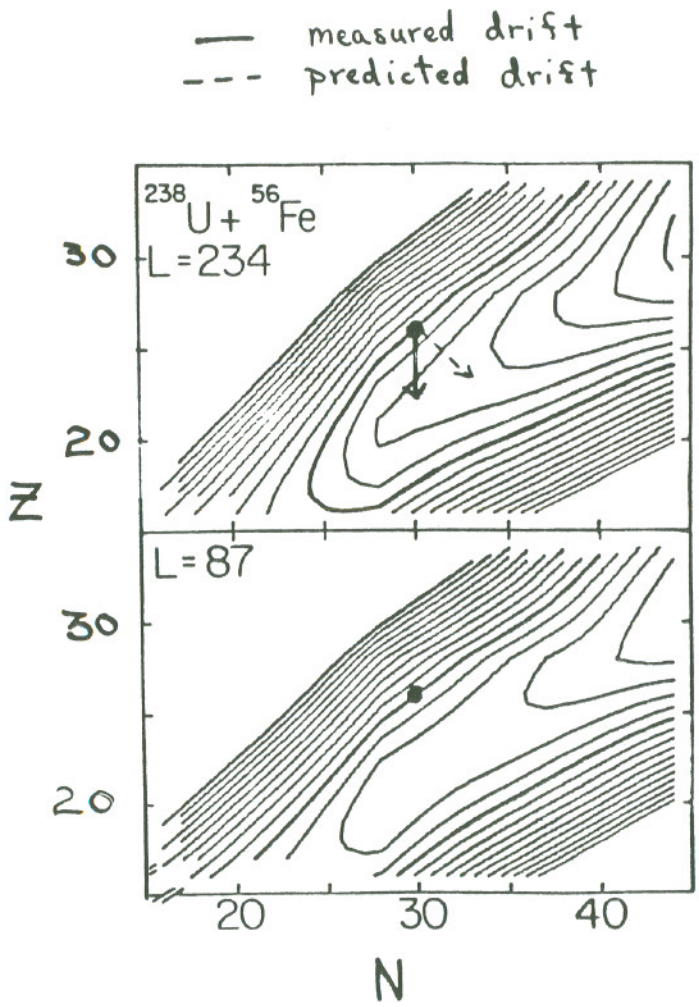
8.3 MeV/u ^{56}Fe

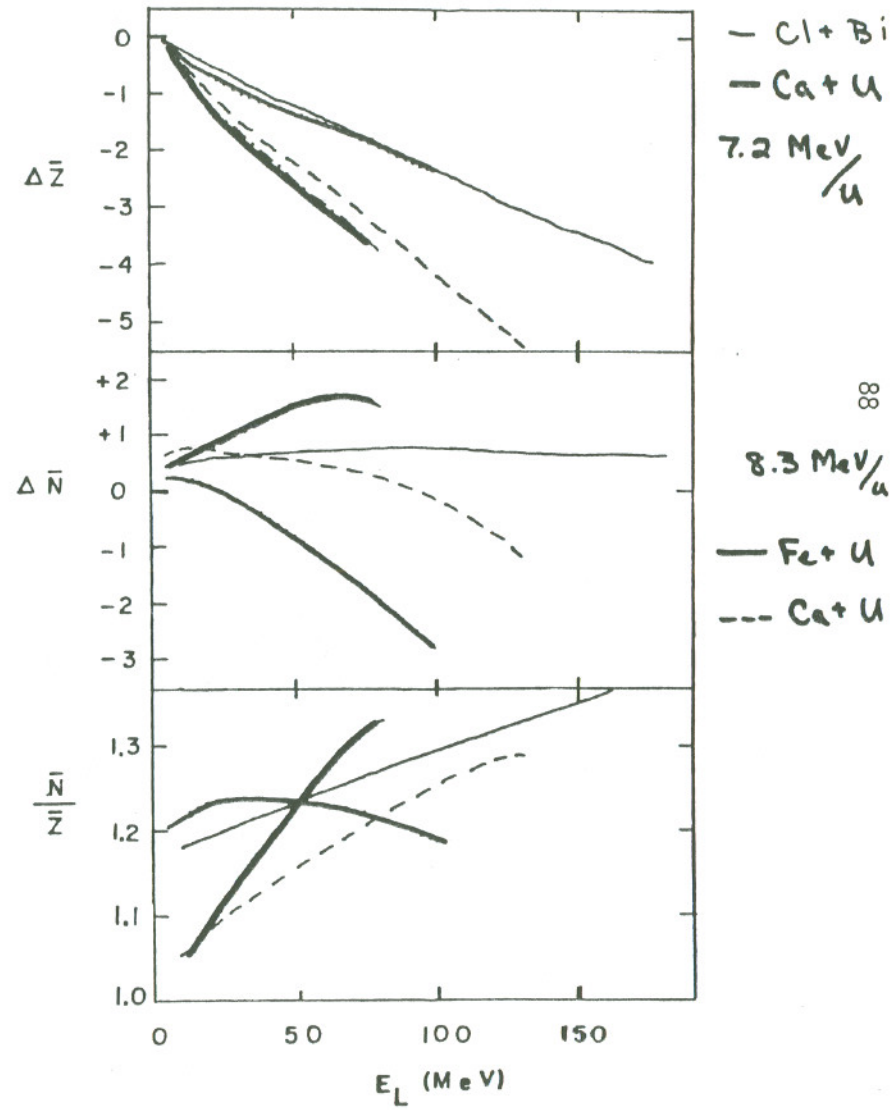

26
24
22
^{56}Fe + ^{56}Fe
^{165}Ho + ^{56}Fe
^{209}Bi + ^{56}Fe
^{238}U + ^{56}Fe
$\bar{Z}$
0
50
100
150
E_L (MeV)

(5)

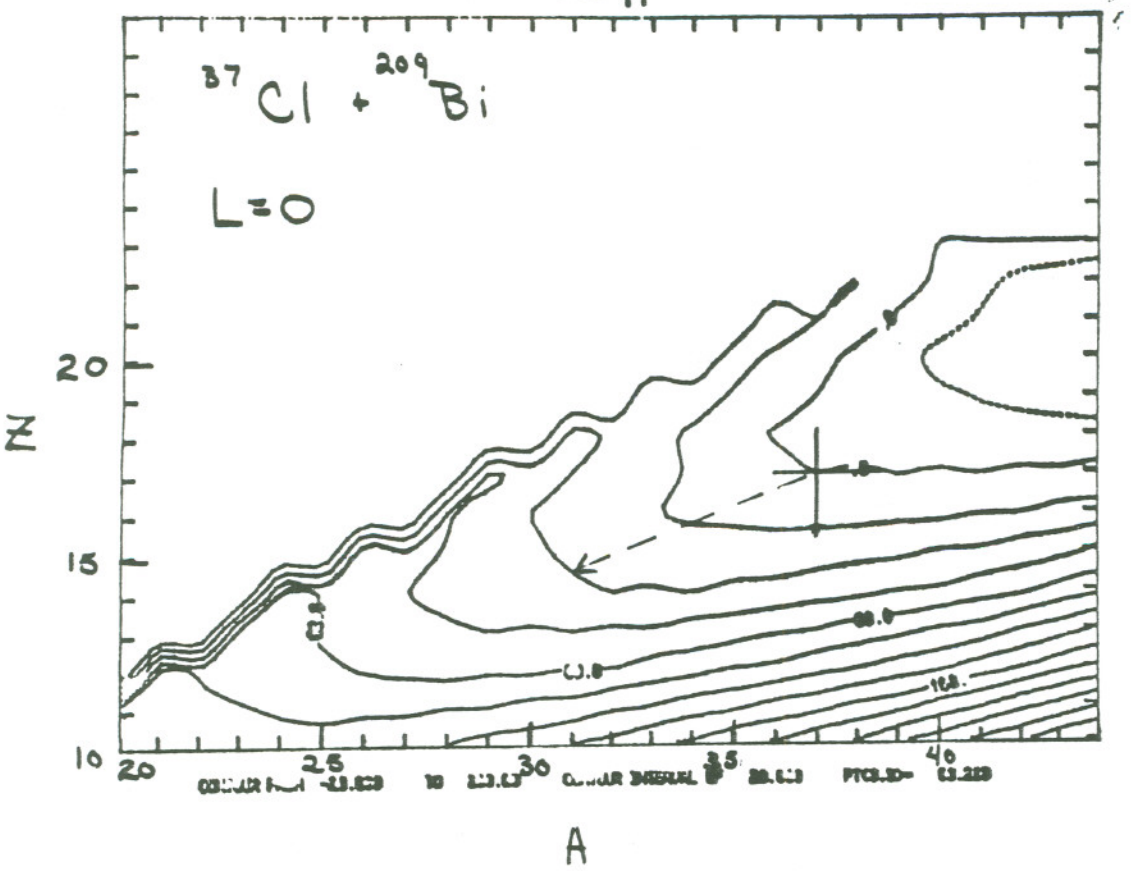
8.3 MeV/u ^{56}Fe



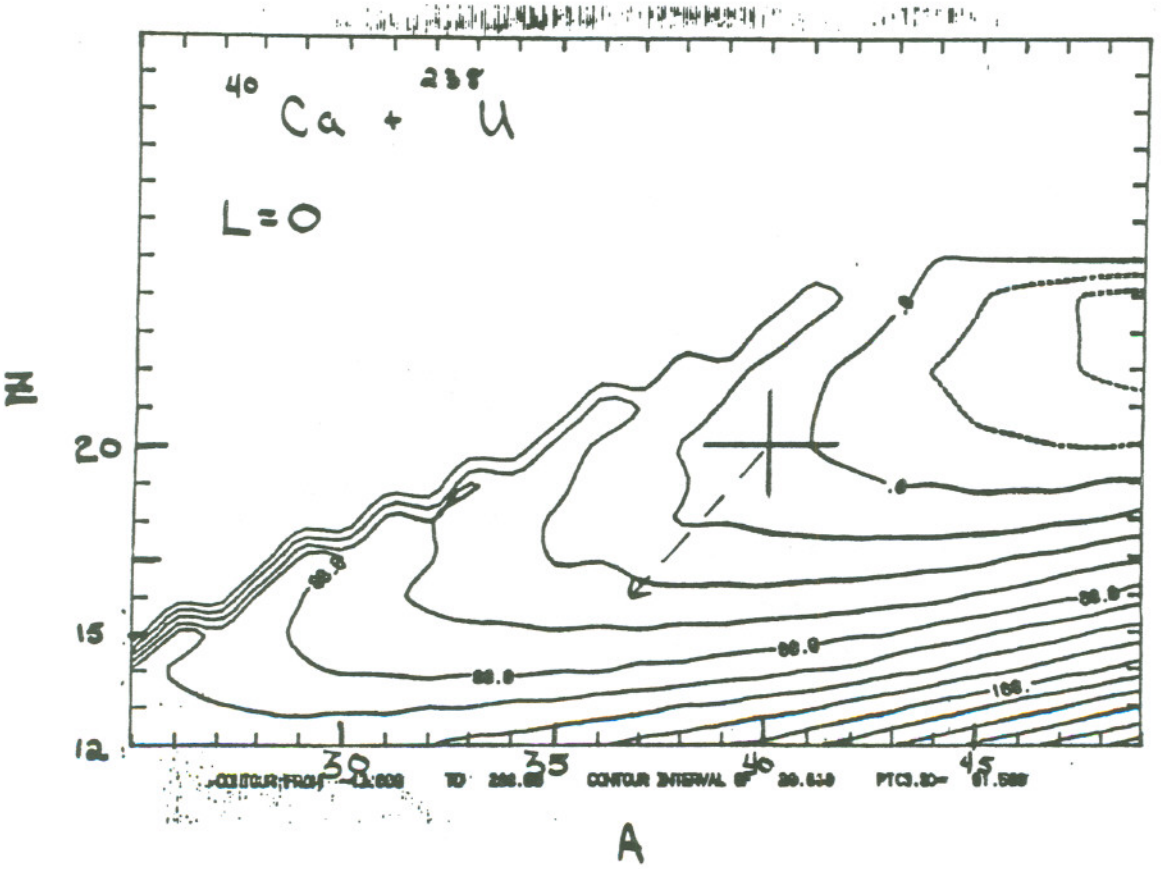

measured drift
predicted drift
238U + 56Fe
L=234
L=87
Z
N
30
20
20
30
40


— Cl + Bi
— Ca + U
7.2 MeV/u
8.3 MeV/u
— Fe + U
--- Ca + U
ΔZ̄
ΔN̄
N̄/Z̄
E_L (MeV)
0
50
100
150

Potential Energy Surface



Potential Energy Surface



Griffin Kinetic Pressure

Driving force determined by the kinetic pressure in each well

$$\frac{\partial E_{TOT}}{\partial L} \propto \frac{N^{2/3}}{A} \quad \text{or} \quad \frac{Z^{2/3}}{A}$$

System will try to equalize the kinetic pressures

	$^{37}_{17}Cl + ^{209}_{83}Bi$	$^{40}_{20}Ca + ^{238}_{92}U$
P	.18	.18
n	.20	.18

	$^{56}_{26}Fe + ^{165}_{67}Ho$	$^{56}_{26}Fe + ^{238}_{92}U$
P	.16	.09
n	.17	.12

Other systems which form the same CN

$^{53}_{23}V + ^{168}_{70}Yb$ $\qquad$ $^{173}_{73}Ta + ^{48}_{20}Ca$

(12)

Feasibility

Current experiments -

1 nA $= 6.2 \times 10^9$ particles/sec

1 mg/cm^2 target

$\sigma \sim$ mb/MeV-Z-sr

Rate = 22.5 counts/sec

Typically ~3 N for a given Z

Ratioactive beams

10^7 particles/sec

Increase detector acceptance -

New Large area ion chambers → 1 sr

Large area timing detectors

Larger energy binning ~ 50 MeV bins

3.6×10^3 sec/hr

Electromagnetic Dissociation of Radioactive Heavy-Ion Beams

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University of California
Livermore, California 94550

The bombardment of a high-Z target by a beam of relativistic projectile nuclei produces a situation in which, for impact parameters greater than the range of nuclear forces, the projectile nucleus can be dissociated by the electromagnetic field of the target nucleus and thus in effect sees a (virtual) photon target. The virtual-photon spectrum (almost entirely transverse for incident energies much larger than the Coulomb barrier) can be calculated by the Weiszäcker-Williams technique or a refinement thereof, and if the photonuclear cross section corresponding to the detected breakup mode of the projectile nucleus is known, the electromagnetic-dissociation cross section can be computed (from the product of the virtual-photon spectrum and the photonuclear cross section). If the photonuclear cross section is not known, the measured electromagnetic-dissociation cross section gives its virtual-photon-spectrum-weighted moment.

We have measured the peripheral fragmentation cross sections for ^{18}O (projectiles) incident upon a number of target species (Be, C, Al, Ti, Cu, Sn, W, Pb, and U), using a beam of 1.7 GeV/nucleon ^{18}O ions from the Lawrence Berkeley Laboratory Bevalac (Refs. 1). The fragment species detected include isotopes of Li, Be, B, C, N, O, and F, and in particular include ^{17}O, ^{16}O, and ^{17}N, which are the product nuclei of the principal photonuclear breakup modes of ^{18}O [corresponding to the (γ,n), $(\gamma,2n)$, and (γ,p) channels, respectively], for which in turn the photonuclear cross sections had been measured previously, with monoenergetic (real) photons, at the Lawrence Livermore National Laboratory Electron-Positron Linear Accelerator (Refs. 2). The nuclear part of the fragmentation cross sections was determined from the cross sections for the isotopes of Li, Be, B, etc., which do not result from photodisintegration of ^{18}O, and was subtracted from the total cross sections for ^{17}O, ^{16}O, and ^{17}N production to yield the electromagnetic-dissociation cross sections for these latter nuclear species. (This procedure depends upon the

validity of nuclear factorization, which was shown in this experiment to hold true to within 4%, and upon the assumption that interference between the nuclear and electromagnetic processes can be neglected at energies larger than 100 times the Coulomb barrier, which was the case for these measurements).

Several noteworthy examples of the potential uses of β-unstable beams for electromagnetic-dissociation experiments come readily to mind; in fact, the availability of such beams often would make it possible to carry out studies which otherwise would be very difficult or impossible.

The determination of the isospin distribution of the giant dipole resonance (GDR) requires the study of isobaric series of non-self-conjugate nuclei, only one of which is normally stable. Further, in practice one is limited to light nuclei (having ground-state isospin T of 1/2 or 1) because the strength of the $T_> = T + 1$ component of the GDR is proportional (presumably) to $1/(T + 1)$. To date, ^{18}O is the only nucleus for which a thorough analysis has been made[2] of the isospin decomposition of the GDR (except for the trivial cases of self-conjugate nuclei, for which the entire GDR is $T_>$ and of very heavy nuclei, for which it is $T_<$). In order to see if the isospin composition of the GDR varies with (N-Z), it is necessary to know it for ^{18}Ne, which is β-unstable. [In this connection, measurements on ^{18}F also would be helpful, to isolate the $T_< = 1$ part of the GDR for ^{18}O and ^{18}Ne; ^{18}F, too, is β-unstable.] The next-best-known case is that of ^{13}C (Refs. 3); here we need to study the β-unstable nucleus ^{13}N as well.

Another vital topic in nuclear physics concerns the question of the existence (and strength) of short-range correlations in nuclear ground states, which can be determined from the enhancement of electric-dipole absorption strength over the TRK sum-rule value. There is, currently, strong disagreement, particularly for ^{16}O, between the large values reported from total photon-absorption measurements[4] and the small ones deduced from summing the measurements of all the partial photonuclear-reaction channels.[5] (Large values require the existence of strong short-range correlations.) (Also, the former method gives a large value for ^{40}Ca and the latter gives a small one for ^{4}He.) Since the GDR strength for

self-conjugate nuclei is entirely $T_>$ (= 1), one expects the energy distribution of the dipole strength to be at least roughly the same for all light self-conjugate nuclei. Hence it would be very valuable to perform systematic measurements on these nuclei, especially the β-unstable species ^{18}F, ^{22}Na, ^{26}Al, ^{30}P, ^{34}Cl, and ^{38}K, in order to bridge the gap between ^{16}O and ^{40}Ca.

Finally, one of several more exotic reaction channels which can be studied, that of photopion production by charge exchange, can be used to test the charge symmetry of the strong interaction <u>in many-body nuclei</u>, where there already is evidence of its breakdown.[6] For example, the mirror reactions $^{16}O + \gamma + \rightarrow {}^{16}N + \pi^+$ and $^{16}O + \gamma \rightarrow {}^{16}F + \pi^-$ can be compared with $^{16}N + \gamma \rightarrow {}^{16}O + \pi^-$ and $^{16}F + \gamma \rightarrow {}^{16}O + \pi^+$; the measured super-ratio then gives a very clean-cut measure of the charge asymmetry.[7] This experiment (or any other like it) requires β-unstable beams, in this case ^{16}N and ^{16}F.

Space considerations preclude a discussion here of other examples of useful electromagnetic-dissociation experiments using radioactive beams; but in any case, it certainly can be claimed that the availability of β-unstable high-energy beams of light nuclear species would make possible measurements which could throw light upon many important problems concerning nuclear structure, nuclear reactions, and nuclear forces.

References

1. D. L. Olson, B. L. Berman, D. E. Greiner, H. H. Heckman, P. J. Lindstrom, G. D. Westfall, and H. J. Crawford, Phys. Rev. C 24, 1529 (1981) and D. L. Olson, B. L. Berman, D. E. Greiner, H. H. Heckman, P. J. Lindstrom, and H. J. Crawford, Phys. Rev. C 28, 1602 (1983).

2. B. L. Berman, D. D. Faul, R. A. Alvarez, and P. Meyer, Phys. Rev. Lett. 36, 1441 (1976) and J. G. Woodworth, K. G. McNeill, J. W. Jury, R. A. Alvarez, B. L. Berman, D. D. Faul, and P. Meyer, Phys. Rev. C 19, 1667 (1979).

3. J. W. Jury, B. L. Berman, D. D. Faul, P. Meyer, K. G. McNeill, and J. G. Woodworth, Phys. Rev. C 19, 1684 (1979) and D. Zubanov, R. A. Sutton, M. N. Thompson, and J. W. Jury, Phys. Rev. C 27, 1957 (1983).

4. J. Ahrens, H. Borchert, K. H. Czock, H. B. Eppler, H. Gimm, H. Gundrum, M. Kröning, P. Riehn, G. Sita Ram, A. Zieger, and B. Ziegler, Nucl. Phys. A251, 479 (1975).

5. B. L. Berman, R. Bergère, and P. Carlos, Phys. Rev. C 26. 304 (1982) and references therein.

6. J. R. Calarco, B. L. Berman, and T. W. Donnelly, Phys. Rev. C 27, 1866 (1983) and references therein.

7. B. M. K. Nefkens, W. J. Briscoe, A. D. Eichon, D. H. Fitzgerald, J. A. Holt, A. A. Mokhtari, J. A. Wightman, M. E. Sadler, R. L. Boudrie, and C. L. Morris, Phys. Rev. Lett. 52, 735 (1984).

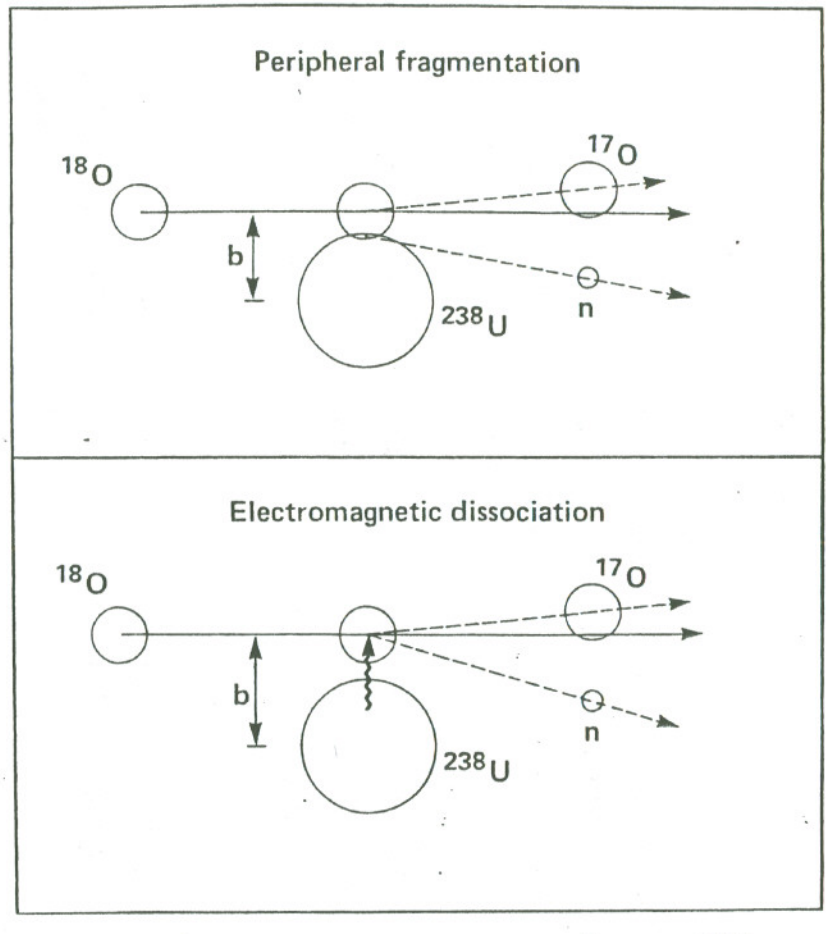
References

- D.L. Olson, B.L. Berman, D.E. Greiner, H.H. Heckman, P.J. Lindstrom, G.D. Westfall, and H.J. Crawford "Electromagnetic Dissociation of Relativistic ^{18}O Nuclei" Phys. Rev. C 24, 1529 (1981)
- D.L.O., B.L.B., D.E.G., H.H.H., P.J.L., and H.J.C. "Factorization of Fragment-Production Cross Sections in Relativistic Heavy-Ion Collisions" LBL-15837; Phys. Rev. C ~~(in press)~~ 28, 1602 (1983)

— on ^{18}O Photodisintegration:
- B.L. Berman et al., Phys. Rev. Lett. 36, 1441 (1976)
- J.G. Woodworth et al., Phys. Rev. C 19, 1667 (1979)

— on ^{12}C and ^{16}O:
- H.H. Heckman and P.J. Lindstrom, Phys. Rev. Lett. 37, 56 (1979)

— on ^{56}Fe:
- G.D. Westfall et al., Phys. Rev. C 19, 1309 (1979)



Projectile Target Fragment(s)

$b_{min}(em) \cong b_{max}(nuc)$

Correspondences between charged particle interactions and photon interactions

Particle Process	Incident Particle	Struck System	Radiative Process	b_{min}
Bremsstrahlung in electron (light particle)-nucleus collision	Nucleus	Electron (light particle)	Scattering of virtual photons of nuclear Coulomb field by the electron (light particle)	$\hbar/2Mv$
Collisional ionization of atoms (in distant collisions)	Incident particle	Atom	Photoejection of atomic electrons by virtual quanta	d
Electron disintegration of nuclei	Electron	Nucleus	Photodisintegration of nuclei by virtual quanta	Larger of $\hbar/\gamma mv$ and R
Production of pions in electron-nuclear collisions	Electron	Nucleus	Photoproduction of pions by virtual quanta interactions with nucleus	
nuclei		Nucleus	nucleons	$A_P^{1/3} + A_T^{1/3}$ + cons

Assumes

1. No interference

$$\sigma(T,F) = \sigma_{nuc}(T,F) + \sigma_{em}(T,F)$$

2. Nuclear factorization (at least weak)

$$\sigma_{nuc}(T,F) = \gamma_T \gamma_F$$

3. Can calculate virtual-photon spectrum

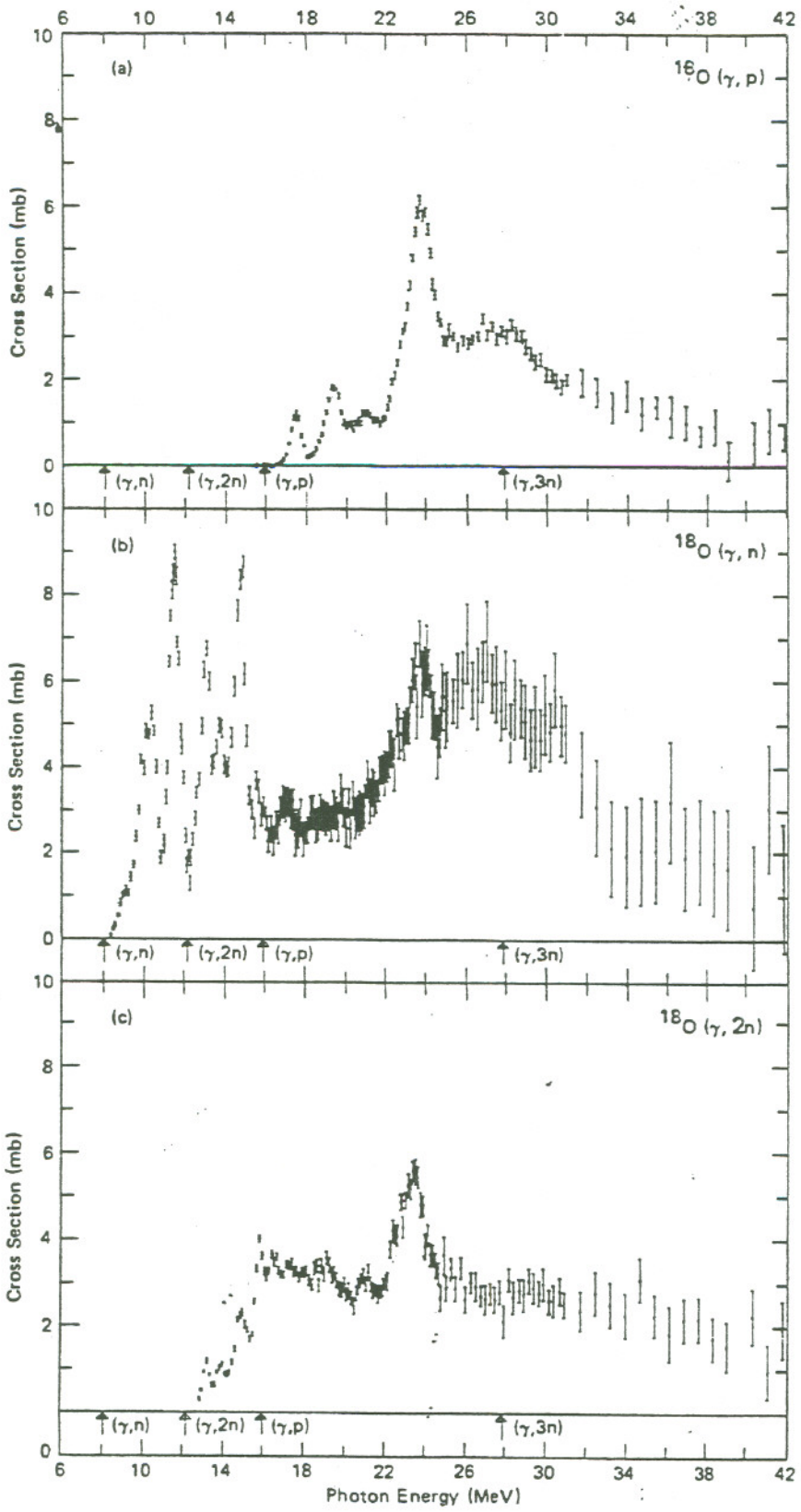
$$N_\gamma(E_\gamma)$$

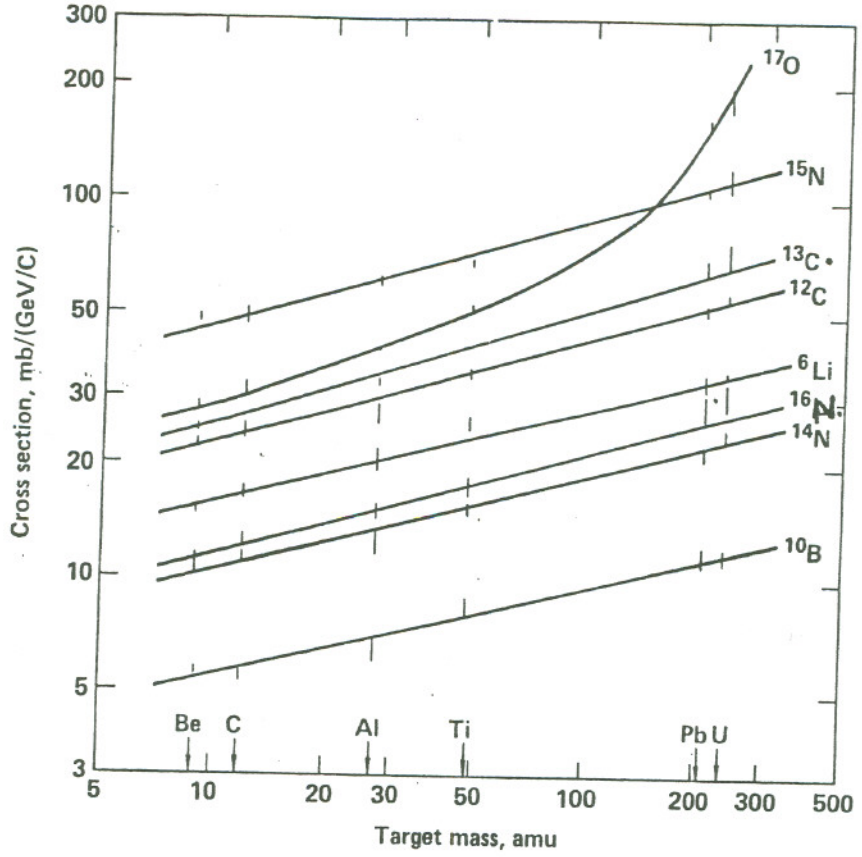
Predicts

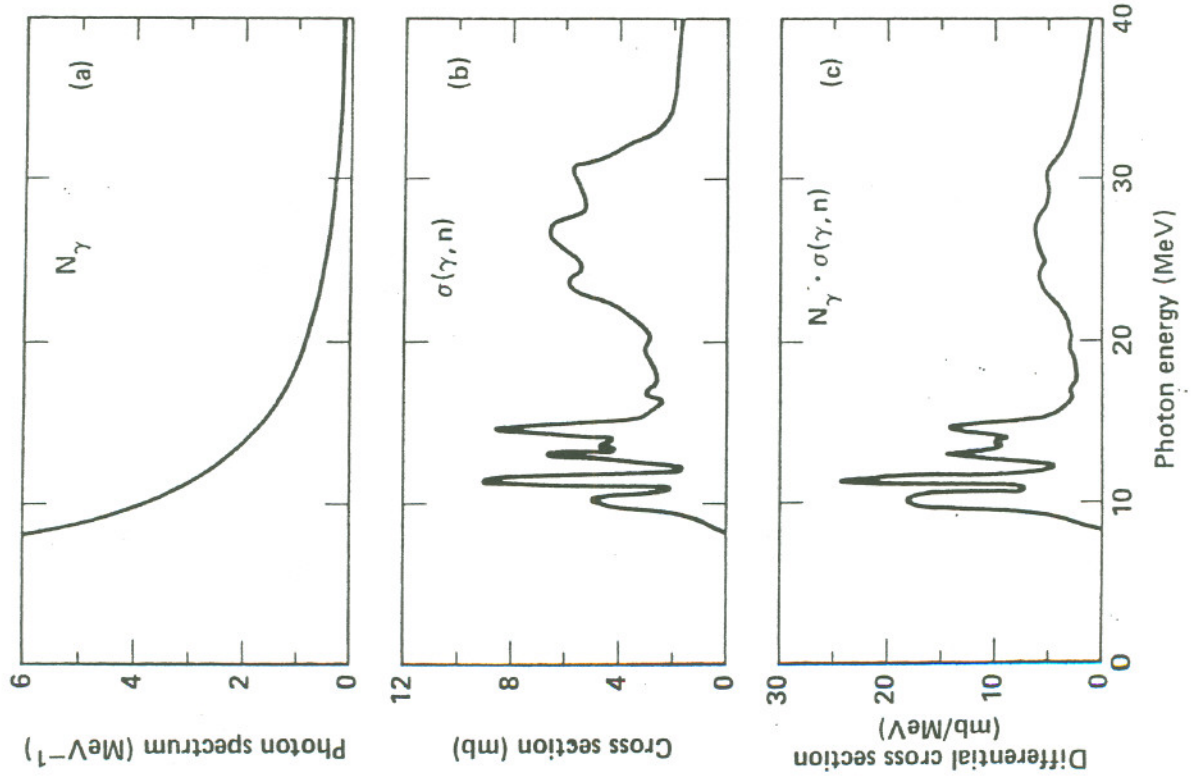
1. $\sigma_{em}(T,F) = \int N_\gamma \, \sigma_T(\gamma,F) \, dE_\gamma$

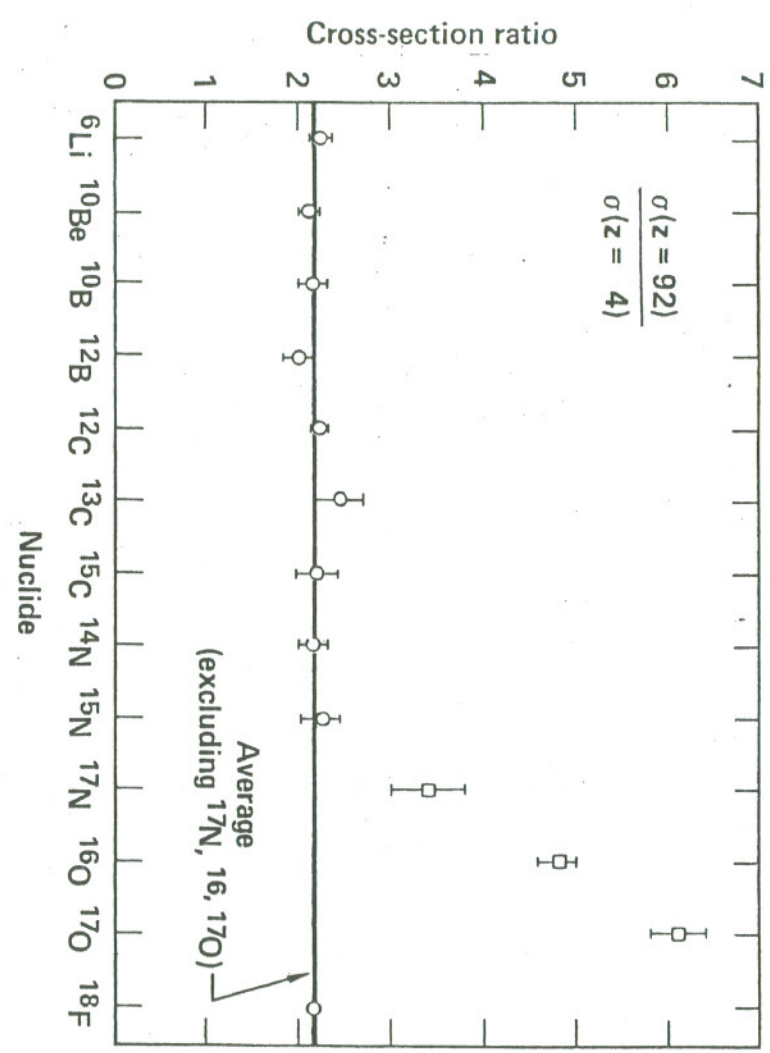
$\sigma_T(\gamma,F)$ = photonuclear cross section

2. $\sigma_{em}(T,F) \propto Z_T^{1.8}$


(a)
^{16}O (γ, p)
(b)
^{18}O (γ, n)
(c)
^{18}O (γ, 2n)
(γ,n)
(γ,2n)
(γ,p)
(γ,3n)
Cross Section (mb)
Photon Energy (MeV)


Cross section, mb/(GeV/C)
Target mass, amu
300
200
100
50
30
20
10
5
3
5
10
20
30
50
100
200
300
500
Be
C
Al
Ti
Pb
U
17O
15N
13C
12C
6Li
16N
14N
10B


(a)
Nγ
Photon spectrum (MeV−1)
(b)
σ(γ, n)
Cross section (mb)
(c)
Nγ · σ(γ, n)
Differential cross section (mb/MeV)
Photon energy (MeV)



Nuclear Factorization Results

$$r \equiv \frac{\gamma_T \gamma_F}{\sigma(T,F)}$$

1) Use 48 selected values (high-quality data, large σ_{em} fragments omitted):

$$\Rightarrow \quad r = 1.003 \pm 0.038$$

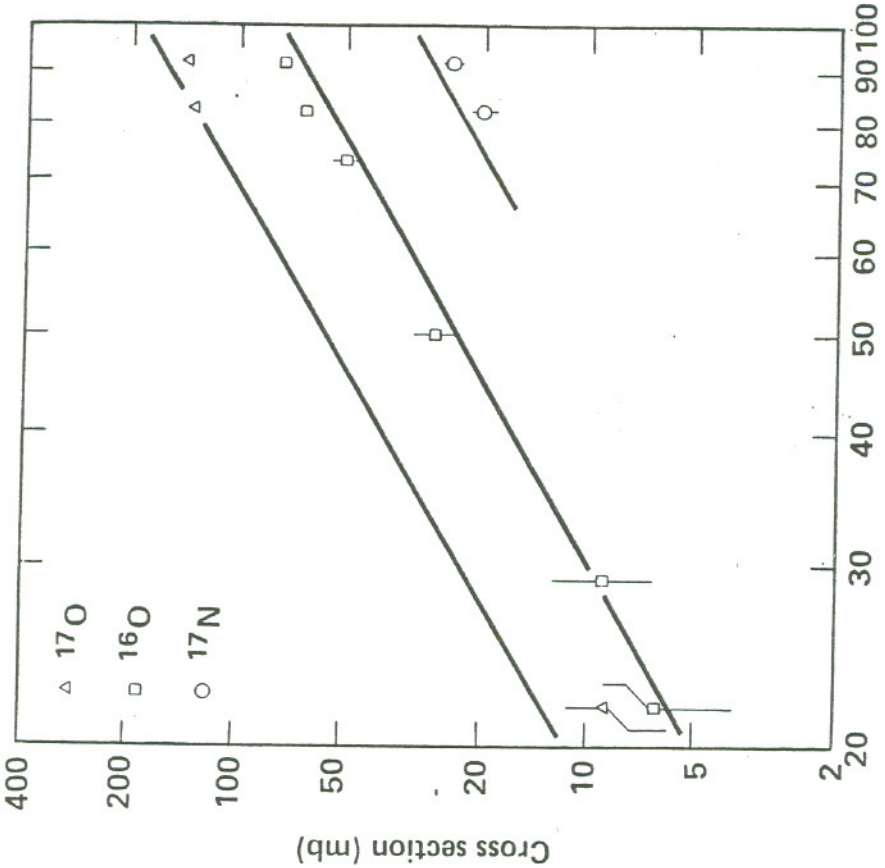
2) Use 77 values (all measured $\sigma(T,F)$ except ^{6}Li fragment and large σ_{em} fragments):

$$\Rightarrow \quad r = 0.996 \pm 0.044$$

Conclusion: $r = 1$ to within $\sim 4\%$

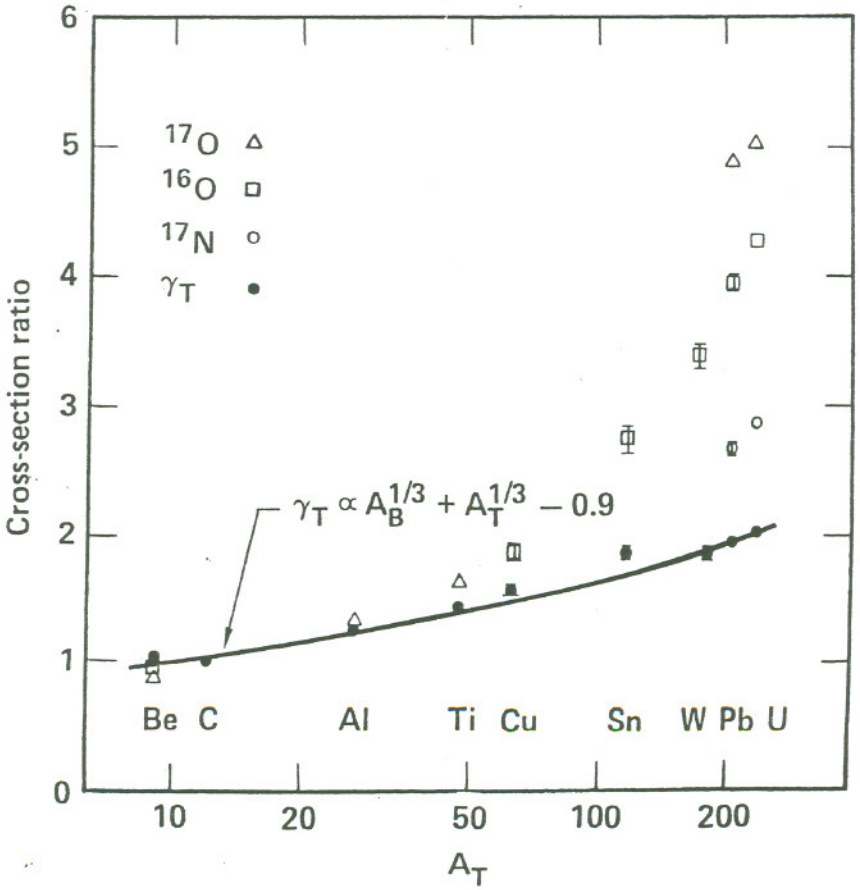
(Previous experimental result: $\gtrsim 15\%$)

For further details, see Phys. Rev. C 28, 1602 (1983)



Curves from N_{JPEI}

$\sigma_{em}(T, {}^{16}O) \propto Z_T^{1.67 \pm 0.15}$



$\left.\frac{\sigma_{em}}{\sigma_{nuc}}\right|_{T=2}$

1.51

1.14

0.44

Table IV. Electromagnetic dissociation cross sections (mb).

Fragment	Target	Measured σ_{em}	Calculated JPE1[a]	Calculated WW[b]
(a)				
^{17}O	Ti	8.7 ± 2.7	13.4	12.5
	Pb	136.0 ± 2.9	132.	135.
	U	140.8 ± 4.1	162.	167.
^{16}O	Ti	6.3 ± 2.5	5.8	5.4
	Cu	9.0 ± 3.5	9.4	9.0
	Sn	27.5 ± 4.0	24.0	23.7
	W	50.0 ± 4.3	46.1	46.8
	Pb	65.2 ± 2.3	53.9	55.2
	U	74.3 ± 1.7	66.1	68.1
^{17}N	Ti	-0.5 ± 1.0	2.9	2.4
	Pb	20.2 ± 1.8	23.3	23.8
	U	25.1 ± 1.6	28.5	29.2
(b)				
^{16}N	Ti	2.7 ± 2.1		
	Pb	12.7 ± 4.4		
	U	11.3 ± 5.1		
^{14}C	Ti	8.8 ± 1.1		
	Pb	33.7 ± 4.0		
	U	35.1 ± 2.7		
^{13}C	Ti	-1.6 ± 1.5		
	Pb	21.9 ± 2.4		
	U	17.6 ± 2.6		

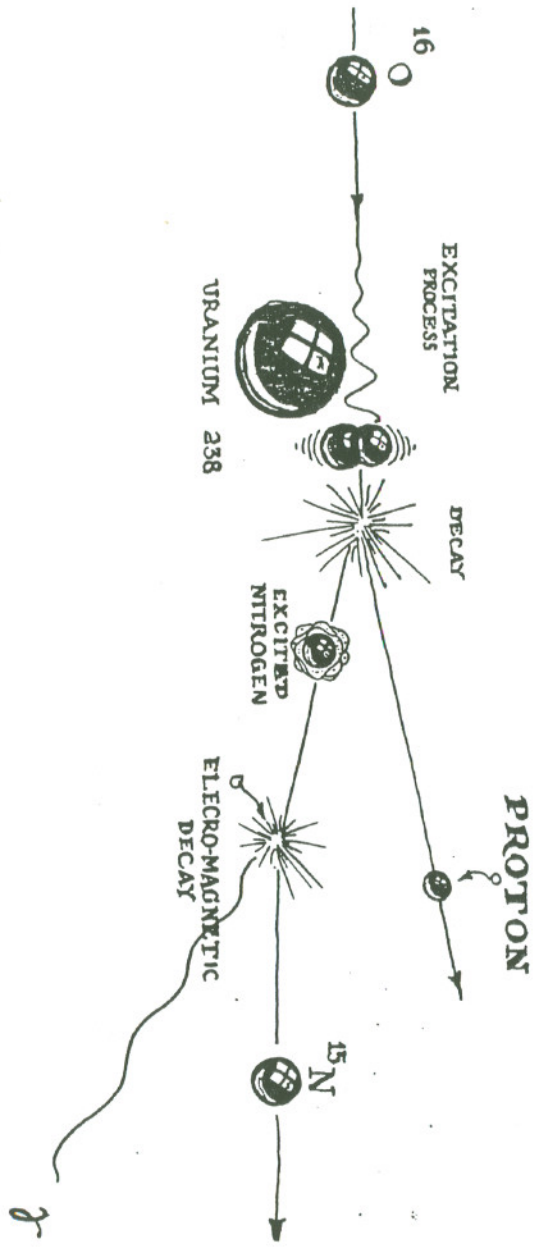
Summary of Results

1) Nuclear factorization holds to within ~4%.

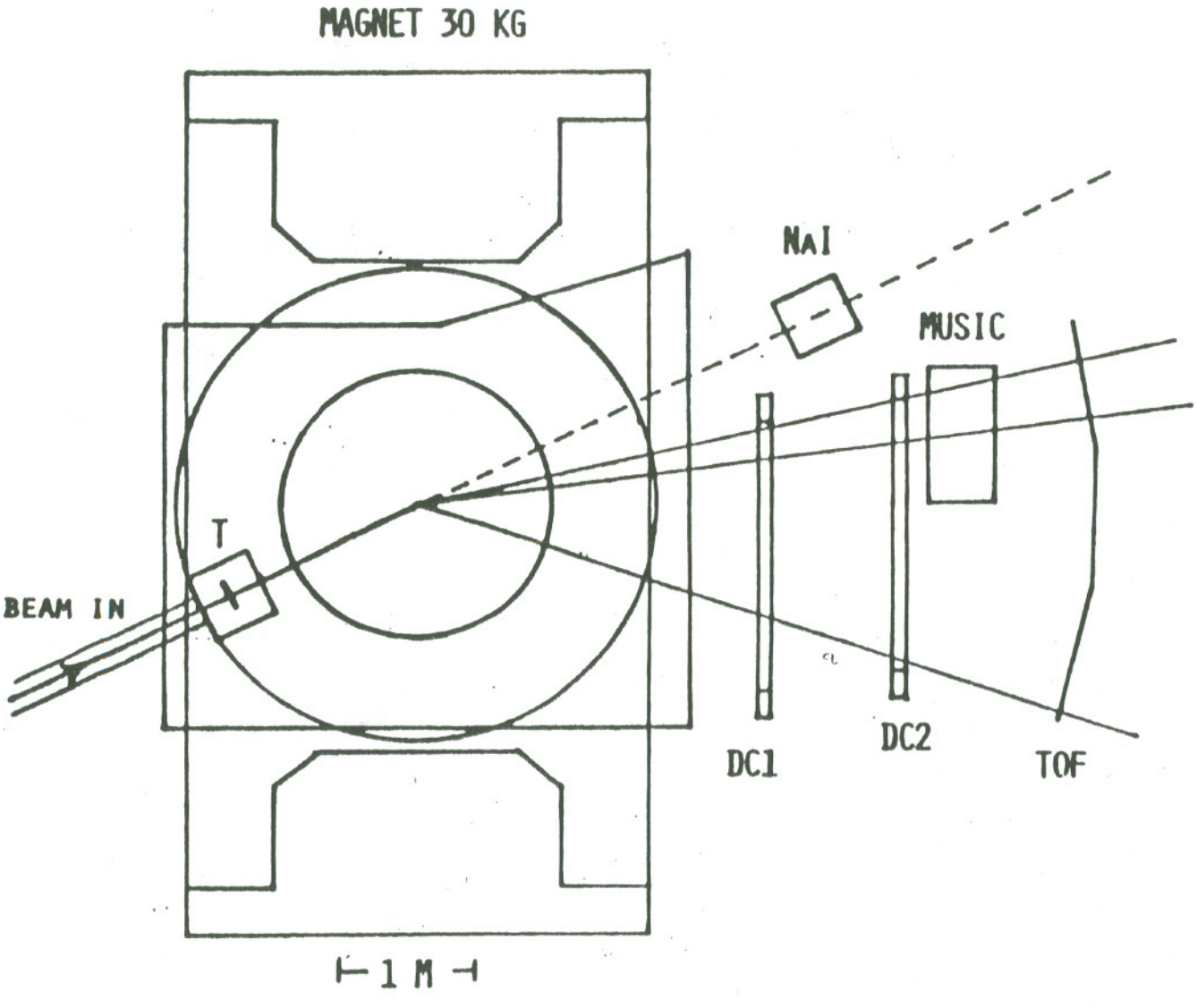
2) σ_{em} (measured) = σ_{em} (calculated from photonuclear cross sections and virtual-photon theory) to within ~10%.

3) $\sigma_{em}(T, F) \propto Z_T^{1.8}$ to within ~8%.

THE REACTION
BILLIARD BALL REPRESENTATION



HISS SETUP



T - TARGET

DC1 - DRIFT CHAMBER 1

DC2 - " " 2

NaI - 49 CELL NaI ARRAY

TOF - TIME-OF-FLIGHT WALL, PLASTIC SCINTILLATORS

MUSIC - MULTIPLE SAMPLING IONIZATION CHAMBER

Advantages:

- All reaction products detected simultaneously
- Coincidence experiments possible
- Unstable beams available
- High cross sections / low backgrounds

Disadvantages:

- No photon-energy specificity
- Dependence upon virtual-photon theory

Can Measure

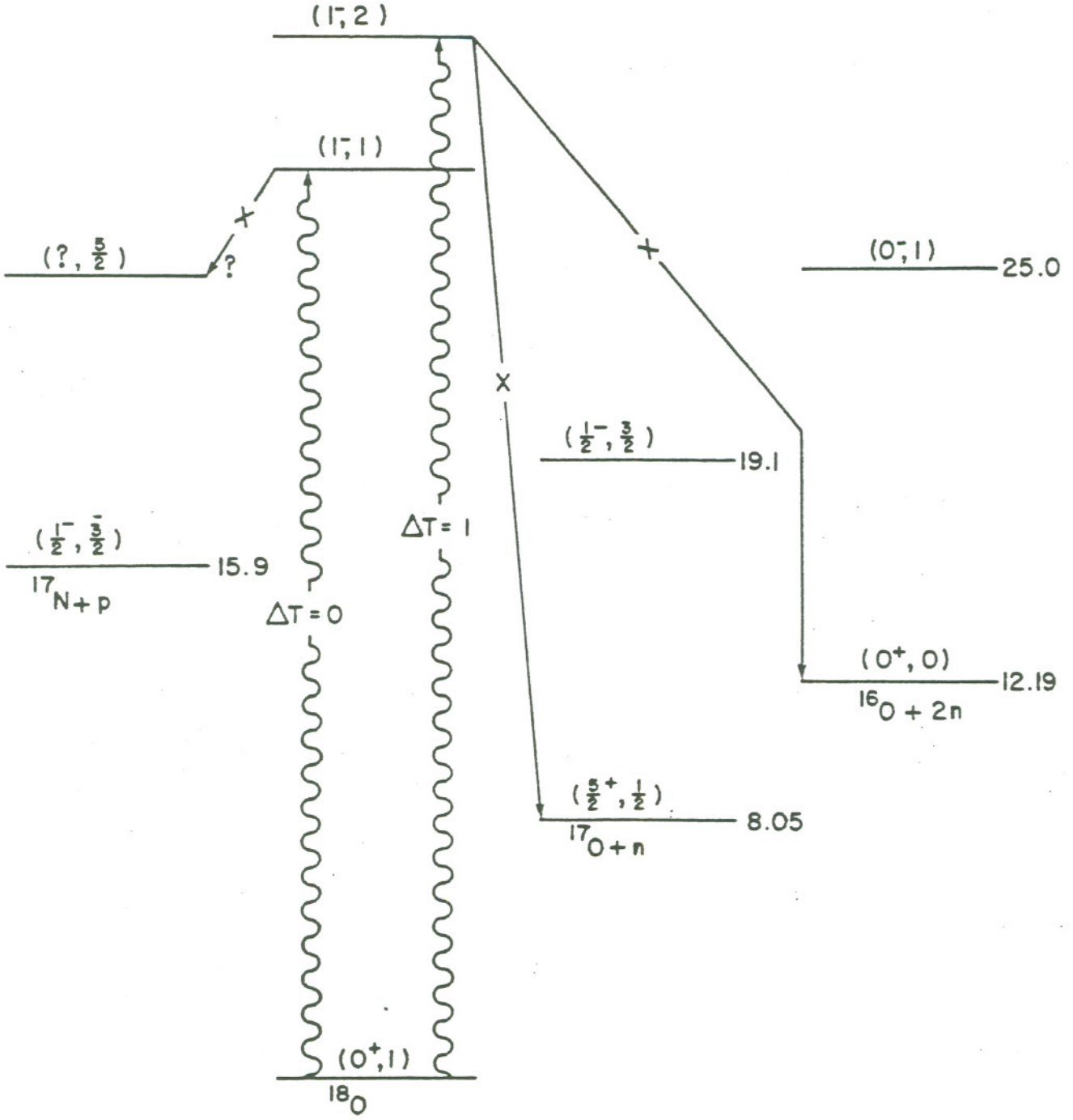
- Reaction products (including neutrons) in coincidence
- Missing energy of reaction products [Excitation energy of residual (daughter) nuclei]
- De-excitation photons (Doppler-shifted up in energy)

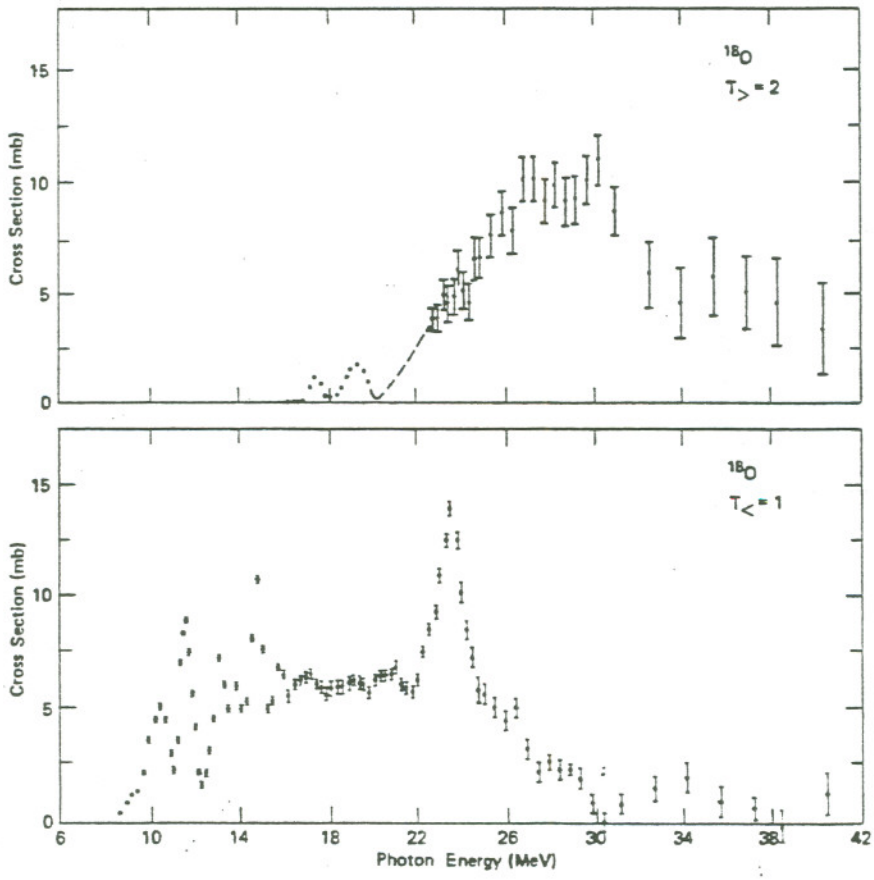
Can Study

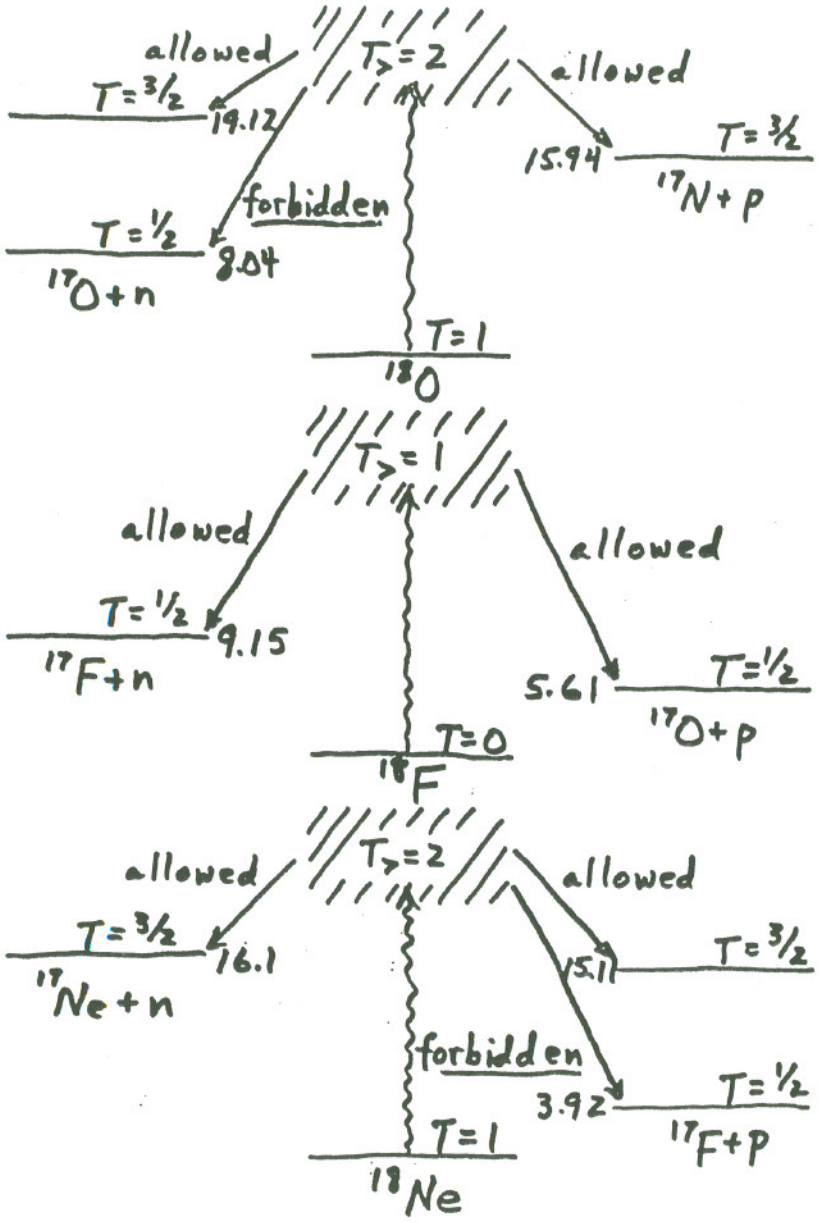
- Isospin distribution of the GDR
- Energy distribution of E1 strength
- Exotic reaction channels
- Lots of other things

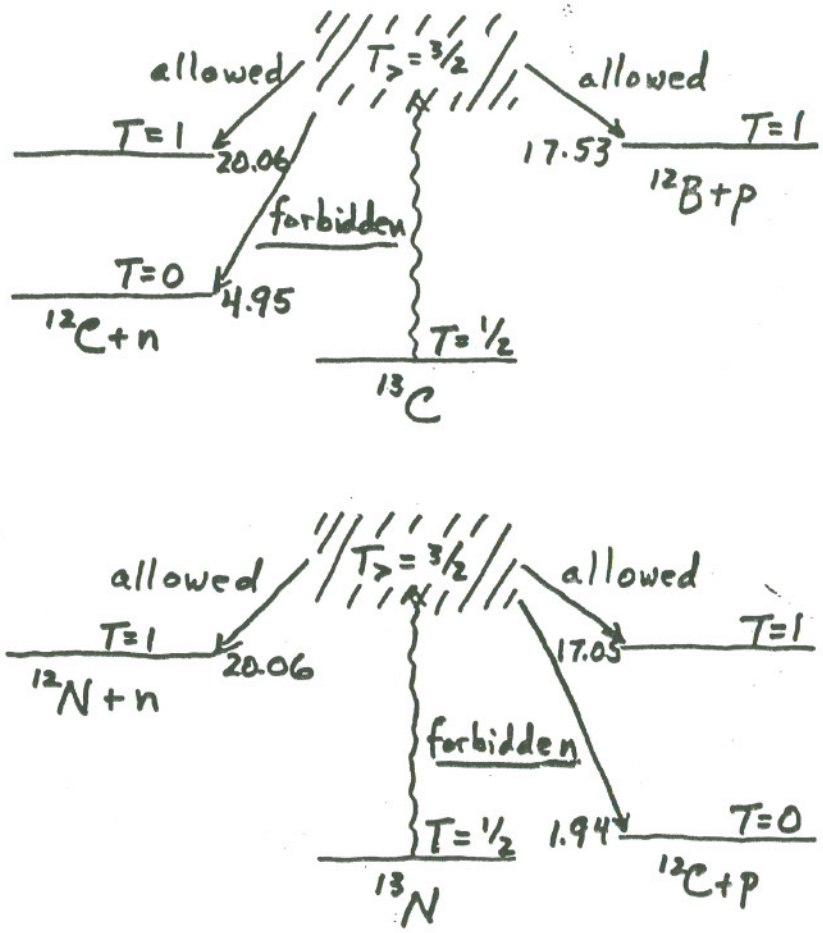
Isospin Distribution of the GDR

- What are the systematic properties of the $T_>$ giant resonance?
  - Where is it?
  - How strong is it?
  - How does it decay?
- Need light nuclei, because its strength varies (presumably) as $\frac{1}{T+1}$.
- Need non-self-conjugate nuclei in order to take advantage of selection rules.
- Isobaric series most instructive; e.g. ^{13}C, ^{13}N or ^{18}O, ^{18}Ne


(1⁻, 2)
(1⁻, 1)
(?, 5/2)
?
(0⁻, 1)
25.0
(1/2⁻, 3/2)
19.1
(1/2⁻, 3/2)
15.9
17N + p
ΔT = 1
ΔT = 0
(0⁺, 0)
12.19
16O + 2n
(5/2⁺, 1/2)
8.05
17O + n
(0⁺, 1)
18O


^{18}O
$T_> = 2$
Cross Section (mb)
^{18}O
$T_< = 1$
Cross Section (mb)
Photon Energy (MeV)


allowed
$T_> = 2$
allowed
$T = 3/2$
19.12
15.94
$T = 3/2$
$^{17}N + p$
forbidden
$T = 1/2$
8.04
$^{17}O + n$
$T = 1$
^{18}O
$T_> = 1$
allowed
allowed
$T = 1/2$
9.15
$^{17}F + n$
5.61
$T = 1/2$
$^{17}O + p$
$T = 0$
^{18}F
$T_> = 2$
allowed
allowed
$T = 3/2$
16.1
$^{17}Ne + n$
15.11
$T = 3/2$
forbidden
3.92
$T = 1/2$
$^{17}F + p$
$T = 1$
^{18}Ne


$T_> = 3/2$
allowed
allowed
$T = 1$
20.06
17.53
$T = 1$
$^{12}B + p$
forbidden
$T = 0$
4.95
$^{12}C + n$
$T = 1/2$
^{13}C
$T_> = 3/2$
allowed
allowed
$T = 1$
20.06
$^{12}N + n$
17.05
$T = 1$
forbidden
$T = 1/2$
1.94
$T = 0$
$^{12}C + p$
^{13}N

Energy Distribution of E1 Strength

- How much dipole strength is there for self-conjugate nuclei?
- Where does it go?

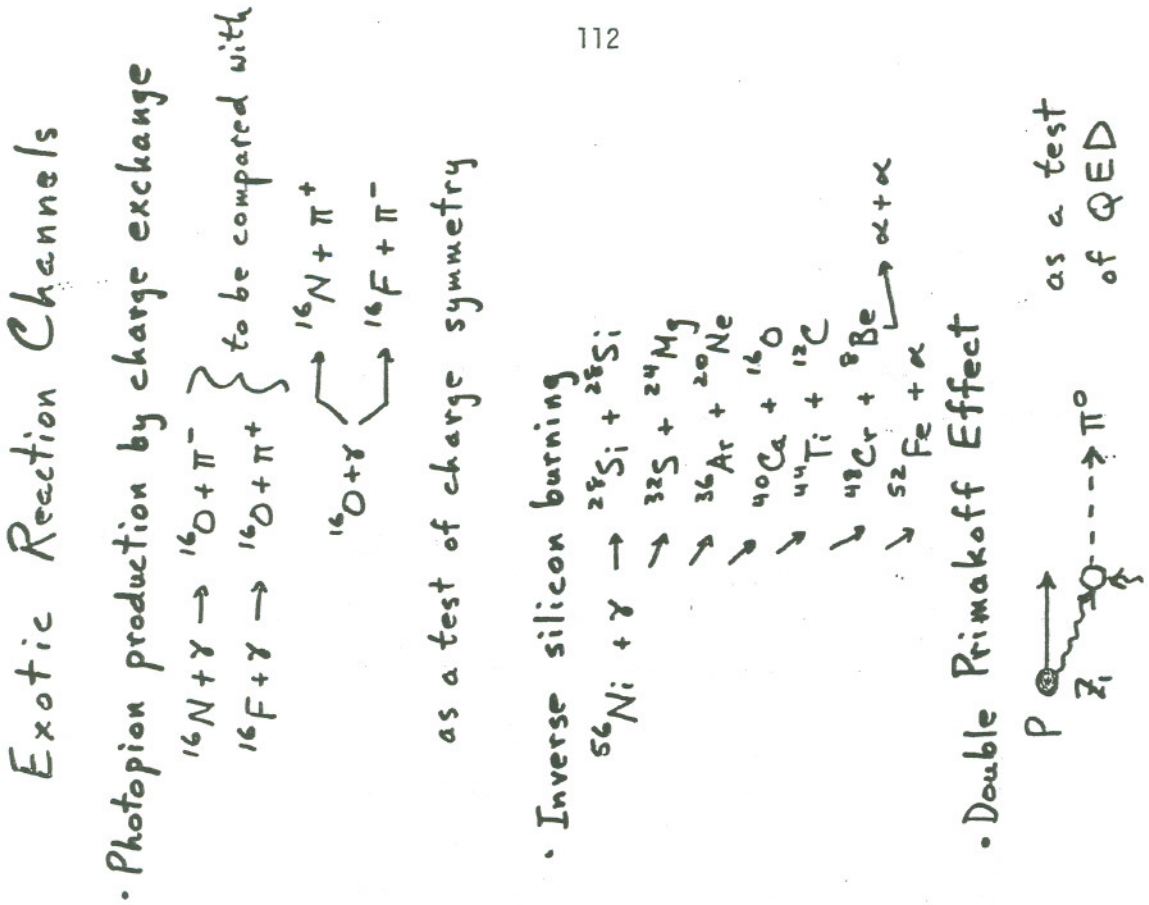
There seems to be a pattern for the C, N, O, Mg, and Si isotopes.

- Is it followed for ^{18}F, ^{22}Na, ^{26}Al, ^{30}P, ^{34}Cl, and ^{38}K?
- What about for isobars of self-conjugate nuclei?
- In view of the controversy over ^{16}O, what about for ^{16}C and ^{16}Ne?

Table I. Integrated photonuclear cross sections up to 30 MeV (Refs. 14, 16, 17).

Nucleus	$\int\sigma(\gamma,n_{tot})dE_\gamma$ (MeV mb)	$\int\sigma(\gamma,n_{tot})dE_\gamma$ TRK units	$\int\sigma(\gamma,p)dE_\gamma$ (MeV mb)	$\int\sigma(\gamma,p)dE_\gamma$ TRK units	SUM TRK units
^{12}C	42	0.23	72	0.40	0.63
^{13}C	95	0.49	55	0.28	0.77
^{14}C	109	0.53	not	available	
^{14}N	99	0.47	15	0.07	0.54
^{15}N	90	0.40	70	0.31	0.71
^{16}O	55	0.23	91	0.38	0.61
^{17}O	95	0.37		(*)	
^{18}O	142	0.53	31	0.12	0.65
^{24}Mg	57	0.16	170	0.47	0.63
^{25}Mg	257	0.69	115	0.31	0.99
^{26}Mg	254	0.65	90	0.23	0.89
^{28}Si	91	0.22	243	0.58	0.79
^{29}Si	168	0.39	274	0.63	1.02
^{30}Si	235	0.52	111	0.25	0.77

*Data analysis for $^{17}O(\gamma,p)$ is currently in progress.


Exotic Reaction Channels
• Photopion production by charge exchange
$^{16}N + \gamma \rightarrow {}^{16}O + \pi^-$
$^{16}F + \gamma \rightarrow {}^{16}O + \pi^+$
to be compared with
$^{16}O + \gamma$
$^{16}N + \pi^+$
$^{16}F + \pi^-$
as a test of charge symmetry
• Inverse silicon burning
$^{56}Ni + \gamma \rightarrow {}^{28}Si + {}^{28}Si$
$^{32}S + {}^{24}Mg$
$^{36}Ar + {}^{20}Ne$
$^{40}Ca + {}^{16}O$
$^{44}Ti + {}^{12}C$
$^{48}Cr + {}^{8}Be \rightarrow \alpha + \alpha$
$^{52}Fe + \alpha$
• Double Primakoff Effect
P
Z_i
π^0
as a test of QED

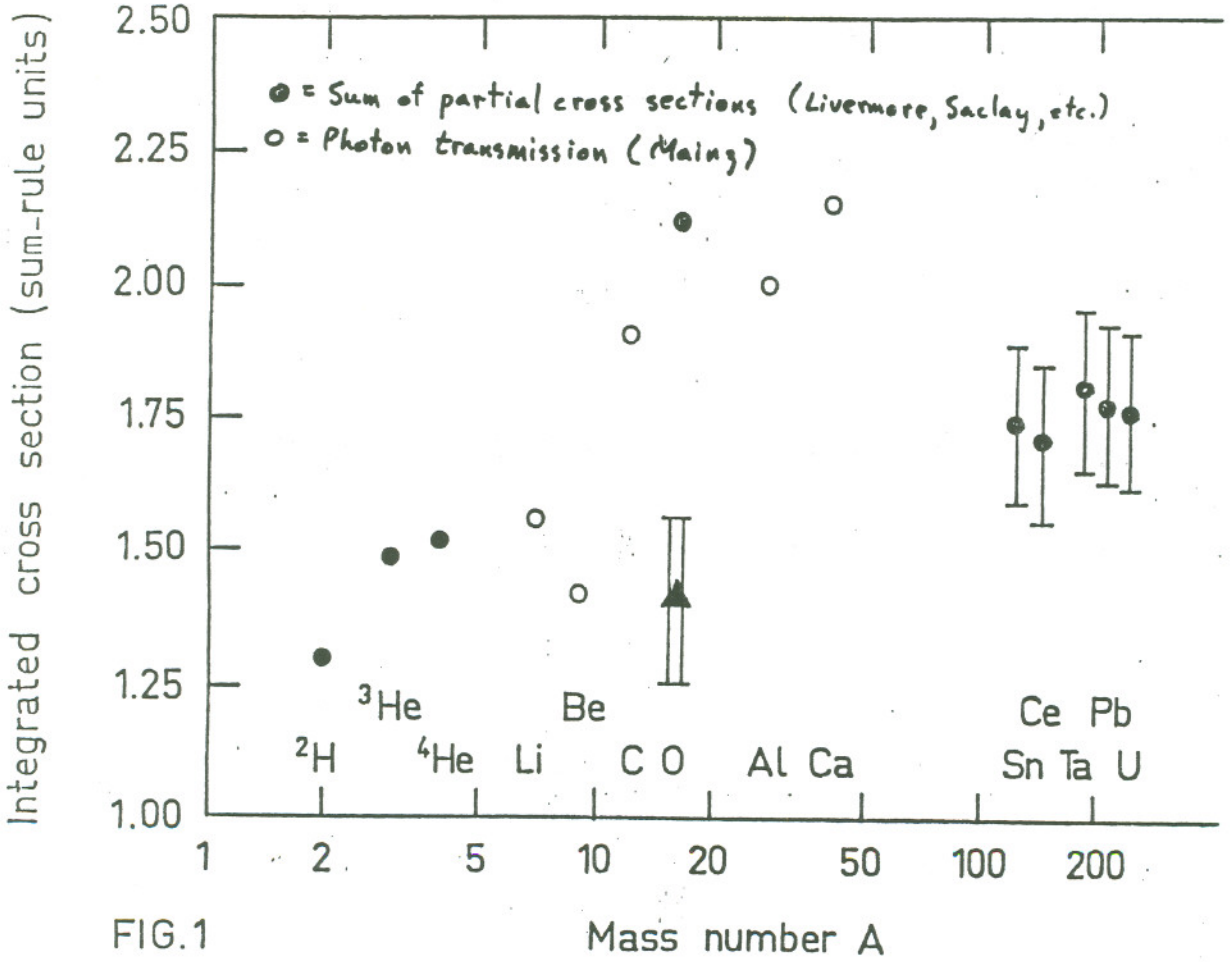

Integrated cross section (sum-rule units)
2.50
2.25
2.00
1.75
1.50
1.25
1.00
● = Sum of partial cross sections (Livermore, Saclay, etc.)
○ = Photon transmission (Mainz)
^2H
^3He
^4He
Li
Be
C
O
Al
Ca
Ce
Pb
Sn
Ta
U
1
2
5
10
20
50
100
200
Mass number A

FIG.1

Resonant Charge Exchange Effects Between Mirror Nuclei

J. P. Vary
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Iowa State University
Ames, Iowa 5011, USA

and

M. A. Nagrajan
Daresbury Laboratory
Warrington, England

INTRODUCTION

Charge exchange (CEX) reactions between a stable projectile and target and even single and double CEX reactions with pions incident on stable targets are well established spectroscopic tools. We indicate that CEX reactions between mirror nuclei offer unique kinematic and structure enhancement factor. Elastic and inelastic, single and multiple CEX reactions between mirror nuclei are relatively simple to analyze in a coupled channels formalism. We outline the analytical procedure for the simplest case of elastic scattering. Our primary purpose is to show that these reactions are ideal candidates for resonances, are sensitive to interesting and non-trivial wave function components, may be calculated in a straightforward formalism and hence may provde a powerful new spectroscopic tool. We discuss a specific example (^{17}F - ^{17}O) to illustrate a major gap in our current knowledge and how it may be resolved with the CEX reactions.

Resonant Charge Exchange Effects Between Mirror Nuclei

M.A. Nagarajan – Daresbury
J.P. Vary – Iowa State

I. Motivation:

- Search for a nuclear reaction which is sensitive in a specific way to details of the microscopic wave function and where the reaction theory is realistic and calculable

- Charge exchange between mirror nuclei

- Why: a) $Q \simeq 0$
  b) $E_{cm} \simeq$ Coulomb barrier
  c) Coupled channel formalism ≈ exact + simple

  ⇓

  Reaction times long, No kinematic suppression, Absorption minimized, $V_{np}(^3S_1 - ^3D_1)$ strong

  ⇓

  Non perturbative effects i.e. resonances possible.

- Theoretical ingredients All accessible!
  Coupled channels formalism (see example below)
  Microscopic wave functions
  Optical potentials from microscopic thy (dbl. fold.)

- What to obtain: new knowledge of g.s. w.f.
  " " " excited state w.f.'s
  i.e. a new spectroscopic tool.

$^{17}O - ^{17}F$ example

II. Coupled Channels Formalism – Example

$$\underbrace{(C_1+n)}_{A} + \underbrace{(C_2+p)}_{B} \longrightarrow \overbrace{(C_1+n)}^{A} + \overbrace{(C_2+p)}^{B}$$

$$\longrightarrow \underbrace{(C_1+p)}_{A'} + \underbrace{(C_2+n)}_{B'}$$

i.e. elastic charge exchange and we take $C_1 = C_2$ to get $Q \simeq 0$

$$H = H_A + H_B + K_{AB} + \underbrace{V_{AB}}_{V_{C_1C_2} + V_{C_1p} + V_{C_2n} + V_{np}}$$

same

$$(H-E)\,\psi^{(+)} = 0$$

$$\psi^{(+)} = \left[\Phi_A(C_1+n)\,\Phi_B(C_2+p)\,F_1(\vec{R}_i) + \Phi_{A'}(C_1+p)\,\Phi_{B'}(C_2+n)\,F_2(\vec{R}_f) \right]$$

$\vdots$ ← ≈ Standard Theoretical Manipulations + invoke "no-recoil" approximation

$$\& \qquad F^{\pm}(\vec{R}) \equiv \left[F_1(\vec{R}) \pm F_2(-\vec{R}) \right]$$

$$\Rightarrow \left[K_{AB} + V_{C_1C_2}(R) + \frac{\Delta V^D(R) \pm \Delta V^E(R)}{1 \pm S(R)} \right] F^{\pm}(R) = 0$$

$$F^{\pm}(\vec{R}) \xrightarrow[R\to\infty]{} \exp(i\vec{k}\cdot\vec{R}) + \left[f_d(\theta,\phi) \pm f_{ce}(\pi-\theta, \pi+\phi) \right] \frac{e^{ikR}}{R}$$

Beliefs (Hopes ?):

Have chosen case where ΔV^E important $\Rightarrow f_{ce}$ is significant compared to f_d. Hence interference and/or resonances are possible and achieve a spectroscopic tool with great sensitivity to microscopic ground state wave functions.

Note: Above formalism applicable to simple case of elastic scattering of Core ± 1 nucleon systems

e.g. $^{15}N - ^{15}O$
$^{17}F - ^{17}O$
$^{39}K - ^{39}Ca$
$^{41}Sc - ^{41}Ca$ (10^5 years)
⋮

And we look at resonant <u>elastic</u> <u>single</u> <u>CEX</u>

Extensions possible for:

A. Resonant <u>elastic</u> <u>double</u> <u>CEX</u>

$^{18}O - ^{18}Ne$ ($Q \simeq 7$ MeV)

$^{14}C - ^{14}O$ ($Q \simeq 6$ MeV)

⋮

triple ?

B. Resonant <u>inelastic</u> <u>single</u> (double) <u>CEX</u>

^{17}O Self-consistent structure calculation

ref: Phys. Rev. C21, 1626 (1980)

$H = T + V$, V = Reid soft-core potential

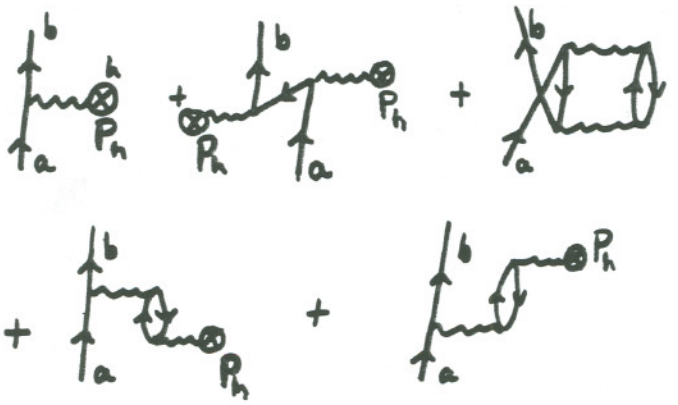
$\downarrow$

$H_{eff} = H_0 + \mathcal{V}_{eff}$

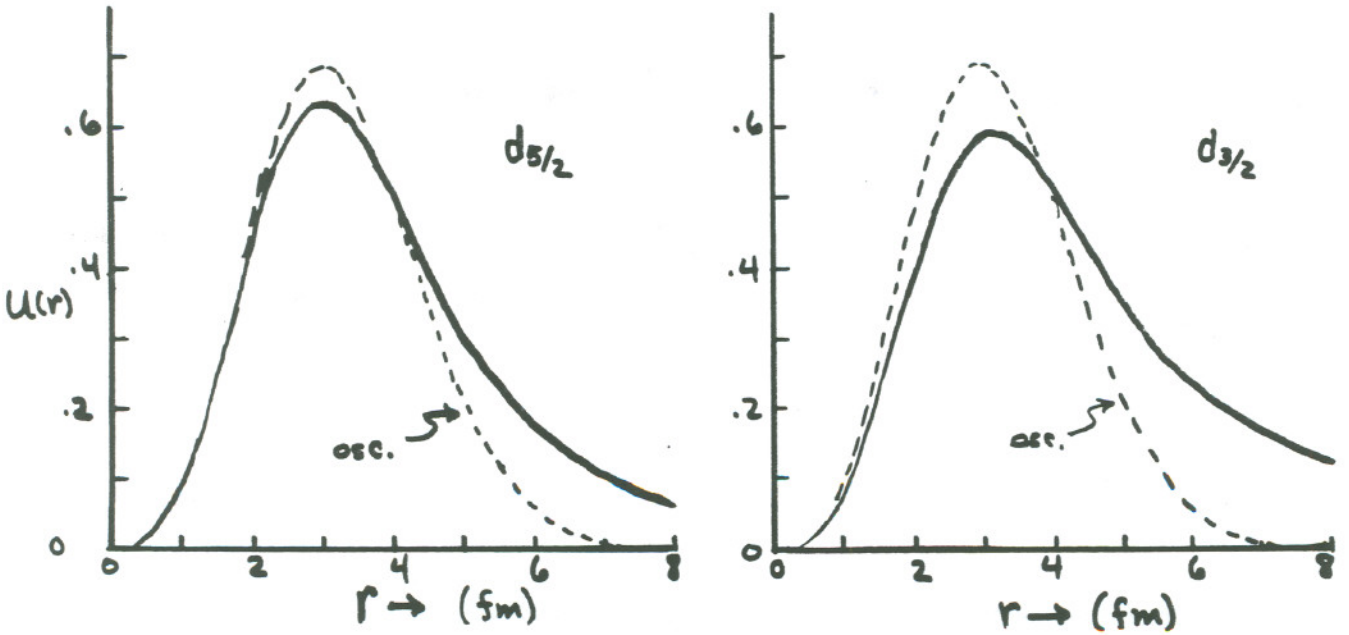
where

H_0 = Renormalized Brueckner calculation for $A = 16$

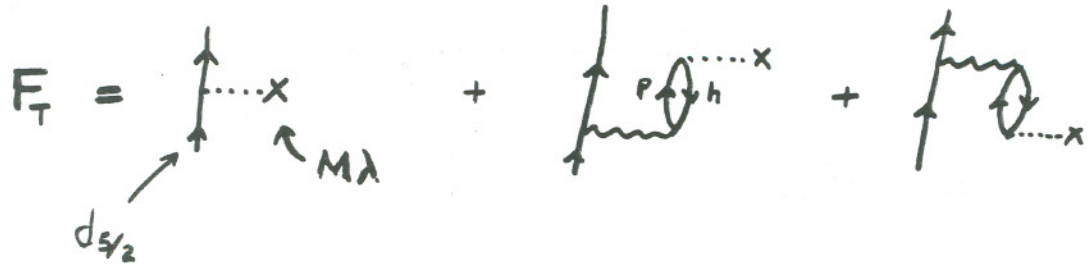
$\mathcal{V}_{eff} =$



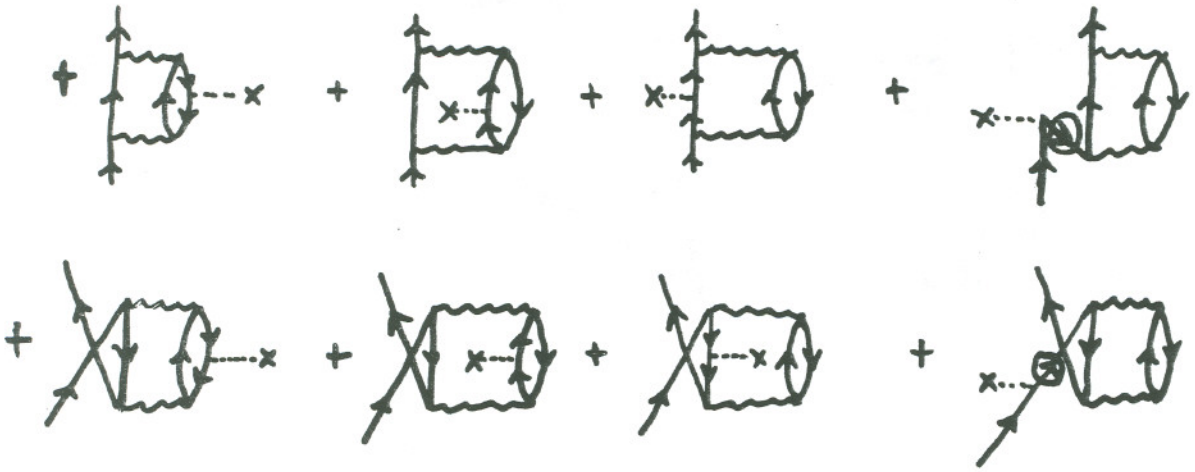
Results



Magnetic Form Factor of ^{17}O : Effective Operator Method

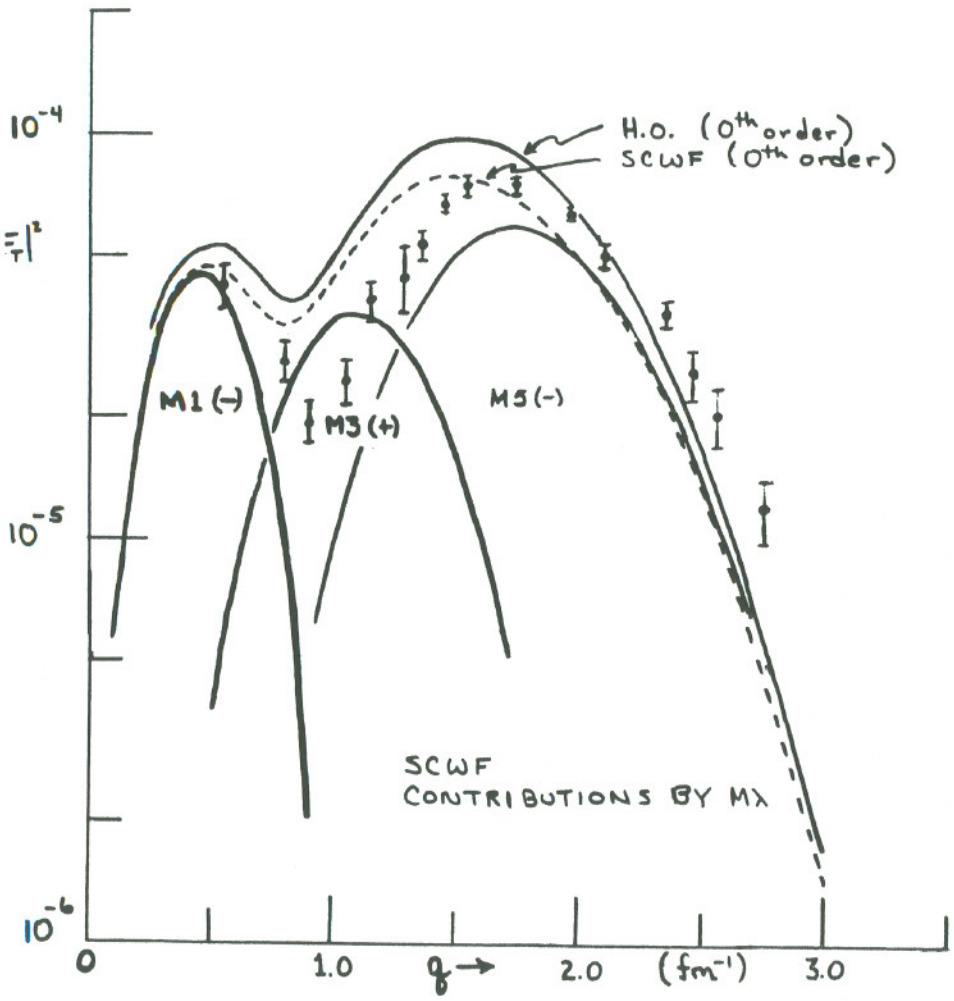


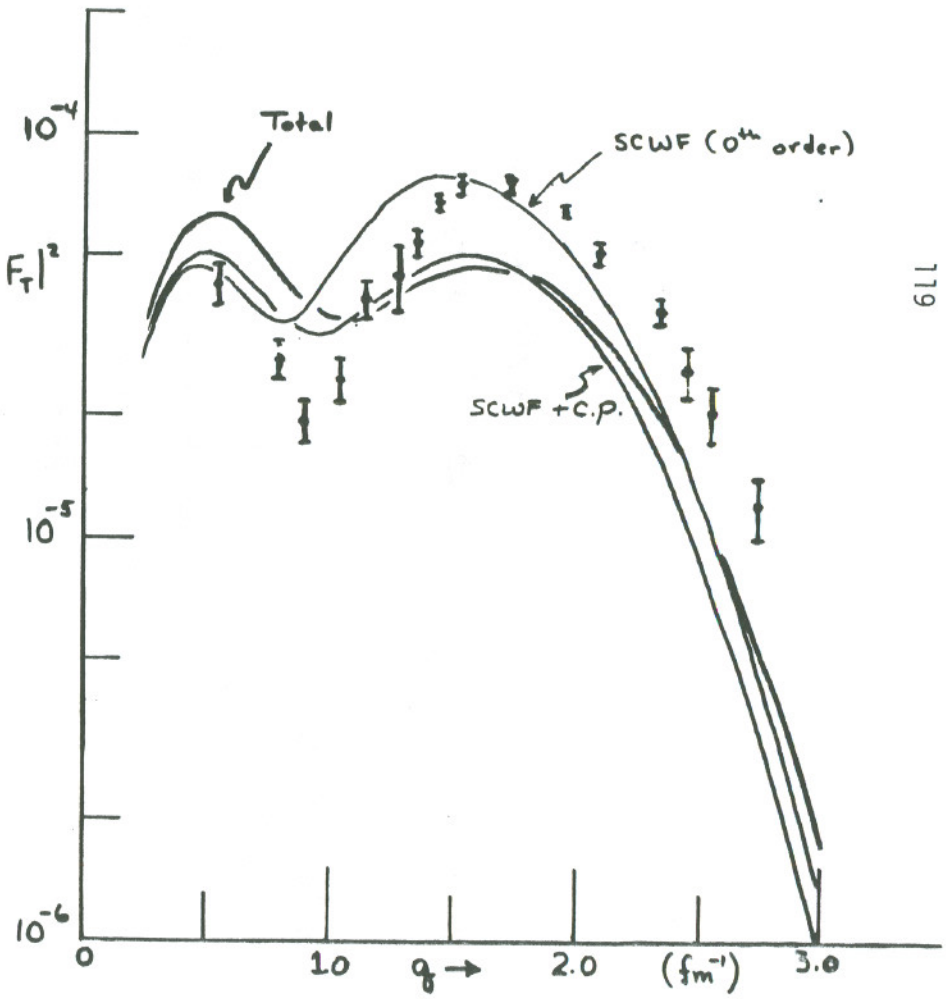
+ second order number conserving sets



But <u>no</u> diagrams with hole insertions due to true self-consistent treatment of structure

<u>Physics</u>: perturbative treatment of 2p-1h and 3p-2h contributions through $n\hbar\omega$ excitations.


10^{-4}
10^{-5}
10^{-6}
$F_T|^2$
H.O. (0th order)
SCWF (0th order)
M1 (-)
M3 (+)
M5 (-)
SCWF
CONTRIBUTIONS BY Mλ
0
1.0
q →
2.0
(fm⁻¹)
3.0


10^{-4}
10^{-5}
10^{-6}
$F_T|^2$
Total
SCWF (0th order)
SCWF + C.P.
0
1.0
q →
2.0
(fm⁻¹)
3.0

Summary

$$F_T = F_0 + F_1 + F_2 + F_{exch}$$

in a realistic, self-consistent, approach ⇒ inadequate to explain the data! ⇒ Mystery

Future Work

A. Other corrections

i) New 2-body potential (e.g. Paris)
ii) Higher order effects (e.g. coupled cluster w.f.)
iii) Effect of 3-body forces
iv) Relativistic effects (nucleons)
v) Collective core admixtures (non-perturbative)
vi) Δ's in ^{17}O
vii) Exotic effects : mesonic, ...

B. Other experiments

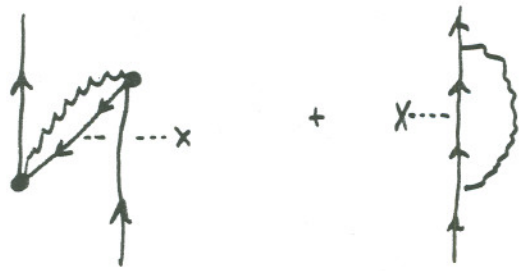
i) (e, e')
ii) (p, n)
⋮

Collective Core Effects in ^{17}O g.s. w.f.

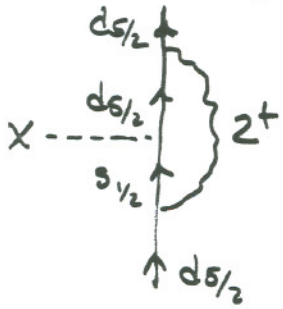
S. Reich CNEA - Buenos Aires
J.P. Vary Iowa State

- Invoke collective ρ-vibration coupling model of Bohr and Mottleson.
- Calculate <u>additional</u> set of diagrams

e.g.



- Carefully examine role of each diagram and each collective core state
- Find : Enormous M3 suppression from



That's <u>good</u> news but M5 not improved

and fully microscopic calc'n of the M3 suppression will require enormous effort

⇒ Clues found but Full mystery not solved

⇒ Resonant single CEX

How will resonant single CEX help or even resolve the mystery?

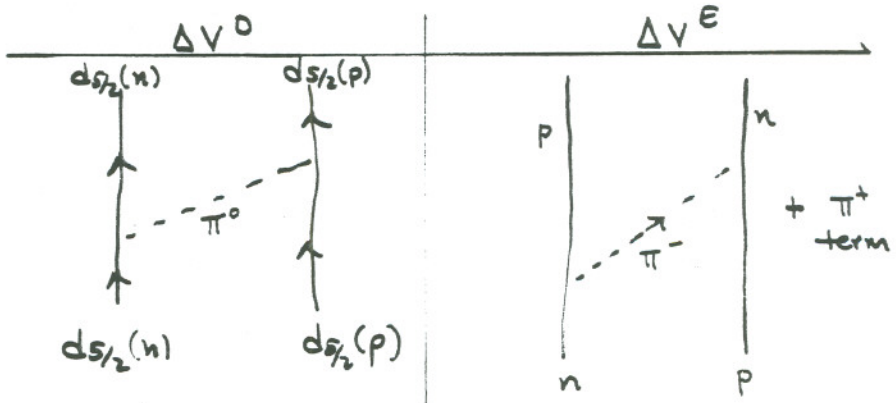
$$|^{17}O\rangle = \alpha\, |d_{5/2} \times 0^+_{core}\rangle + \beta\, |s_{1/2} \times 2^+_{core}\rangle$$

is suggested to be very important

$$|^{17}O\rangle \simeq |^{17}F\rangle$$

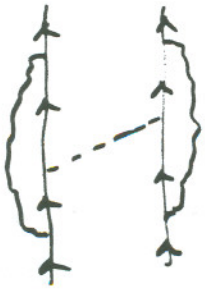
All processes that contribute to ΔV^D, ΔV^E are calculable with the coll. p-core vibration vertices and V_{np} ($^3S_1 - {}^3D_1$) interaction

e.g. α^2 terms



$\alpha\beta$ terms

β^2 terms



etc.

COULOMB EXCITATION OF RADIOACTIVE IONS

R. A. Warner

Pacific Northwest Laboratory

Radioactive ions incident on thick ^{208}Pb targets can be Coulomb excited into states which are difficult to populate in other ways. For some cases of interest, the expected gamma-ray yield is a few photons per 10^6 ions.

High energy fragmentation of heavy targets seems one of the most favorable mechanisms for generating the ions required. The fragmentation cross sections peak for product ions that are slightly neutron-rich, and for kinetic energies in the range 2 to 4 MeV per product nucleon. As shown in Figure 1, many of these raw fragments have energies close to their Coulomb barrier on a suitable target. For soft or deformed even-even projectiles at these energies, multiple excitation will be common, and some limited identification might be done with coincidence techniques. Any identification scheme such as time-of-flight coupled with energy loss, would enable the concurrent accumulation of data for many fragmentation species.

As an alternative, selected fragmentation and fission product nuclides, mass separated on line, are available at several facilities with fluxes adequate for practical Coulomb excitation experiments. They have energies however, that are 1/10 to 1/100 of those required. Acceleration of one of these beams would permit some exciting work.

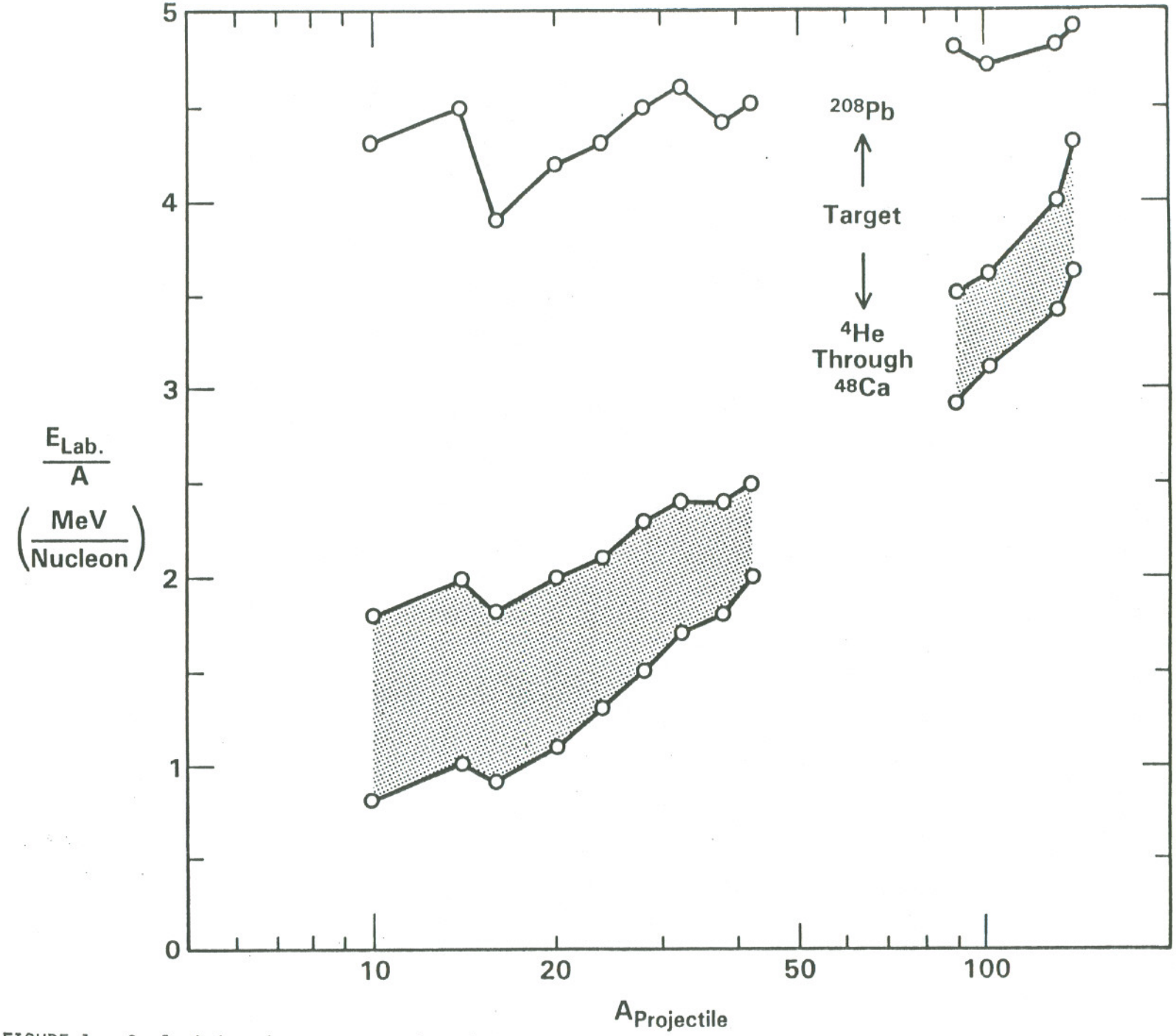


FIGURE 1. Coulomb barriers expressed as laboratory energy per nucleon for a variety of fragmentation and fission product ions incident on selected targets.

APPLICATION OF RADIOACTIVE HEAVY ION BEAMS FOR RESEARCH WITH HEAVY AND SUPER HEAVY ELEMENTS

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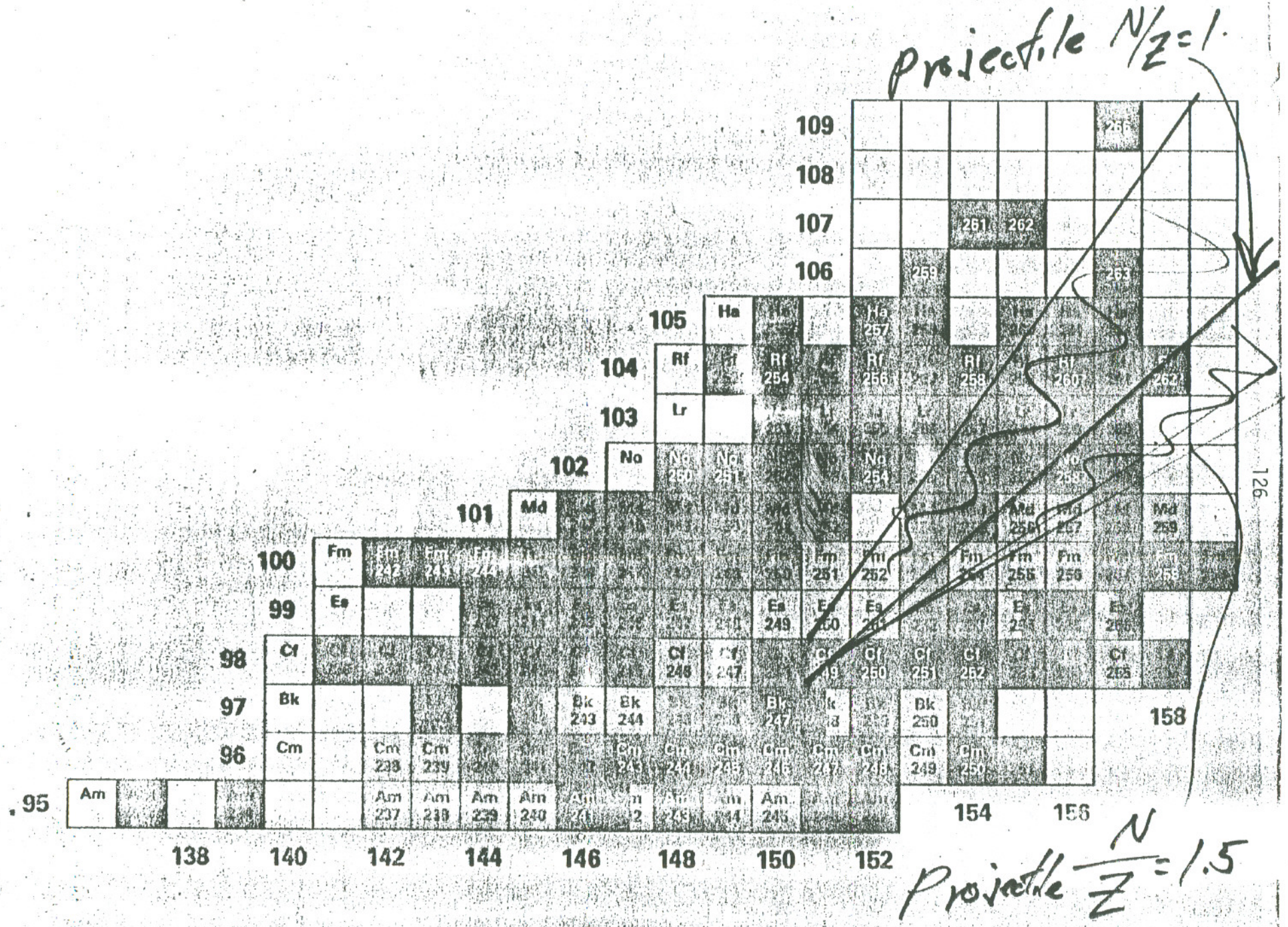
Maximum stability in the heaviest elements is maintained only by the addition of nearly two neutrons for every proton. However, the heavy-ion projectiles available for the production of new nuclides and elements possess N/Z ratios very close to one. Thus, it has not been possible to produce the most stable isotopes of these elements from the naturally occurring isotopes used in heavy-ion beams. Similarly, searches for superheavy elements based upon synthesis in nuclear reactions have failed to reach the most central, and therefore, the most stable region of the Island of Stability. This is because even the most neutron-rich projectiles (^{48}Ca) are still too deficient to reach the 184-neutron shell. An obvious solution to this restriction is the production of intense radioactive ion-beams with projectiles having large neutron excesses.

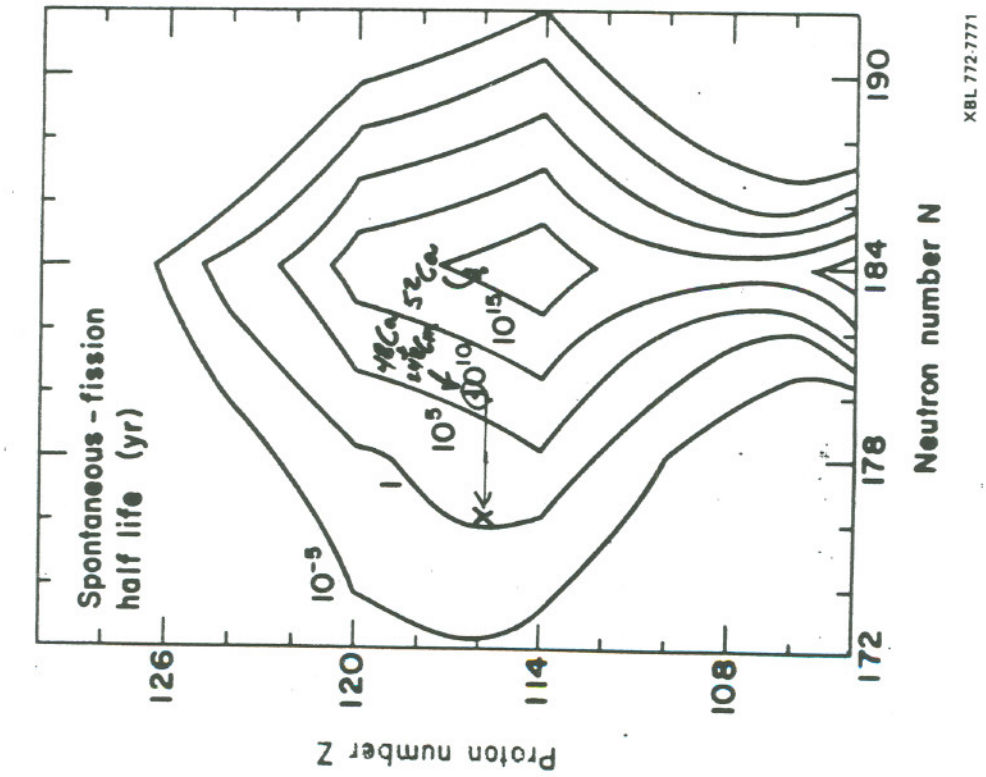
Since the amounts of actinide target isotopes are limited to milligrams or less and the cross section for heavy-ion production reactions are nanobarns or less, it is necessary to have ion beams with intensities of 10^{11} to 10^{12} particles/s. In some experiments it would be feasible to build up longer-lived products by recirculating a radioactive beam many times through a thin actinide target located within a storage ring that confines the beam. There is also the possibility that complete fusion cross sections would increase with highly neutron-rich projectiles because the compound nucleus, as it approaches the minimum in the potential energy valley, would suffer lower losses from prompt fission. We have investigated this possibility by calculating reaction cross sections with the Jackson-Sikkeland model. The results indicate a maximum gain of 10 for some reactions followed by a lower or negative gain as the neutron number in the projective increases (O, Ne, Ca ions). Our conclusion is that the improvement in cross section is insufficient to compensate for ion-beam intensities lower than 10^{11} to 10^{12} particles/s.

This work was performed under the auspices of the U. S. Department of Energy by Lawrence Livermore National Laboratory under contract No. W-7405-Eng-48.


Projectile N/Z=1.
Projectile N/Z=1.5
109
108
107
106
105
104
103
102
101
100
99
98
97
96
95
Ha
Rf
Lr
No
Md
Fm
Es
Cf
Bk
Cm
Am
138
140
142
144
146
148
150
152
154
156
158

$$^{248}Cm + {}_{20}Ca \Longrightarrow [116] + xn$$

Calcium Isotope	X=2 σ (mb)	X=2 rel σ	X=3 σ (mb)	X=3 rel σ
48	3×10^{-9}	1.0	1.3×10^{-10}	1.0
50	5×10^{-9}	1.57	2.4×10^{-10}	1.9
52	1.6×10^{-9}	0.5	2.1×10^{-10}	1.7
54	4×10^{-11}	0.01	2.1×10^{-11}	0.2



XBL 772-7771

$$^{248}Cm + {}_{8}O \Longrightarrow [104] + xn$$

O Isotope	X = 4 σ (mb)	X = 4 rel. σ	X = 5 σ (mb)	X = 5 rel. σ
18	8.7×10^{-6}	1.0	5.8×10^{-6}	1.0
20	1.6×10^{-5}	1.9	1.6×10^{-5}	2.7
22	6.2×10^{-6}	0.7	2.1×10^{-5}	3.6
24	1.3×10^{-6}	0.15	1.3×10^{-5}	2.2

$$^{248}Cm + {}_{10}Ne \Longrightarrow [106] + xn$$

Ne Isotope	X = 5 σ (mb)	X = 5 rel. σ
22	2.1×10^{-8}	1.0
24	9.1×10^{-8}	4.4
26	2×10^{-7}	9.3
28	1.2×10^{-7}	5.7

Polarized Radioactive Atomic Beams

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Intense, radioactive accelerator beams may be used extensively in nuclear magnetic moment and fundamental beta decay studies. We are designing a multipurpose apparatus for producing polarized radioactive atoms using the atomic beam method. In this method, a radioactive accelerator beam is stopped and neutralized in a hot tungsten foil. Atoms diffusing thermally from the foil and through a sextupole atomic beam system are focussed and polarized by atomic spin state ($J \neq 0$) in the usual way. In a weak magnetic field region, the atomic polarization is transferred to the radioactive nucleus via the hyperfine interaction. Depending on nuclear and atomic spins and experimental constraints, nuclear polarizations in the range of 10 to 90% are possible.

A stored polarized atomic gas presents several advantages for any experiment using polarized beta-radioactive nuclei. Not only are expected polarizations and intensities higher than with current experimental arrangements, but also the method does not require polarized accelerator beams or knowledge of polarization transfer reaction mechanisms. The only essential requirement is that a sufficient intensity of the required radioactive nuclide be available. The decay of the polarized nuclei will occur essentially in vaccuum and thus solid state environment effects on magnetic moment studies may be avoided. Undesirable thick target and window scattering effects on nuclear beta decay experiments should be minimal in this configuration. The unique features of this polarized radioactive atom source should suggest improved measurements of many fundamental beta decay parameters.

Polarized Radioactive Atomic Beams

(w/ S. Hanna Stanford)

1. Nuclear physics interests
2. β NMR Magnetic Moment Technique
3. Polarized β-active atomic beams.

^{15}C, ^{16}N, ^{17}N, ^{23}Mg, ^{27}Si .....

I. β NMR Technique

1. Polarized incident beam produces polarized, β unstable product nucleus in nuclear reaction:

e.g. $^{39}K(\vec{p},n)\,^{39}Ca$ $\quad t_{1/2} = 0.87$ sec.

↑ product nucleus polarized

2. Measure asymmetric β decay of polarized nucleus:

β decay angular distribution:

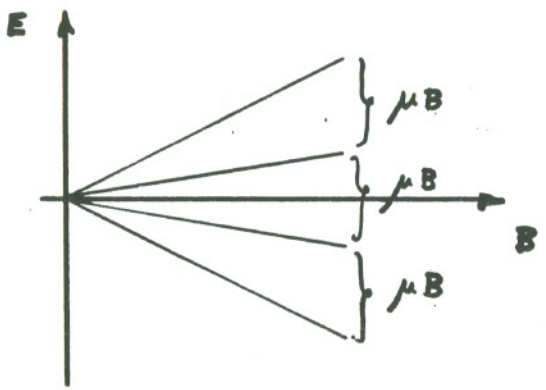
$$w(\theta) \propto 1 + \frac{v}{c} A p \cos\theta$$

⇒ up/down asymmetry

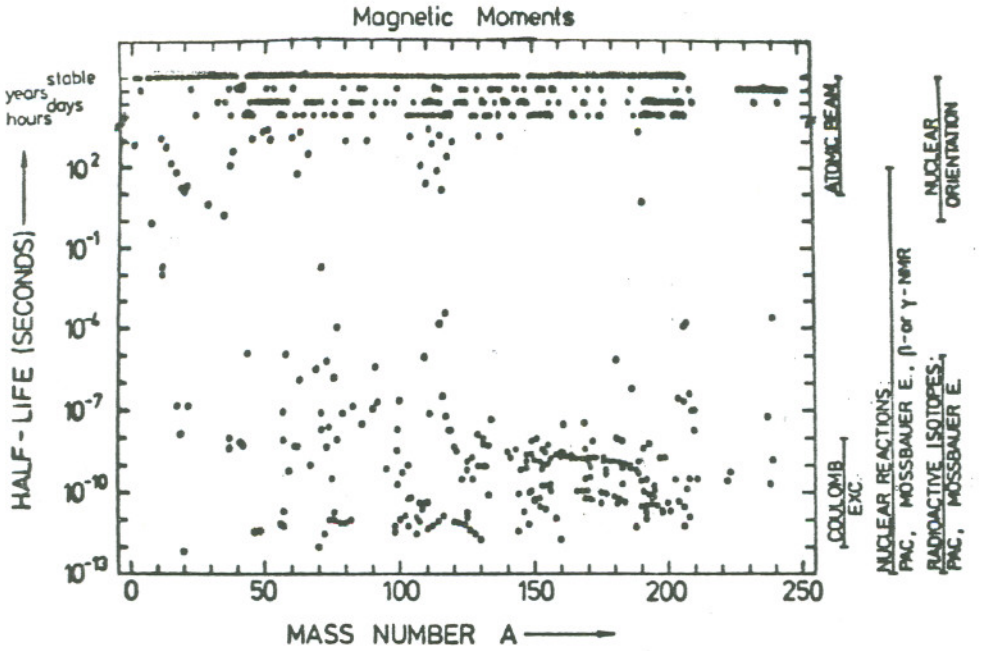
β decay asymmetry: $\varepsilon \equiv \dfrac{n\uparrow - n\downarrow}{n\downarrow + n\uparrow}$

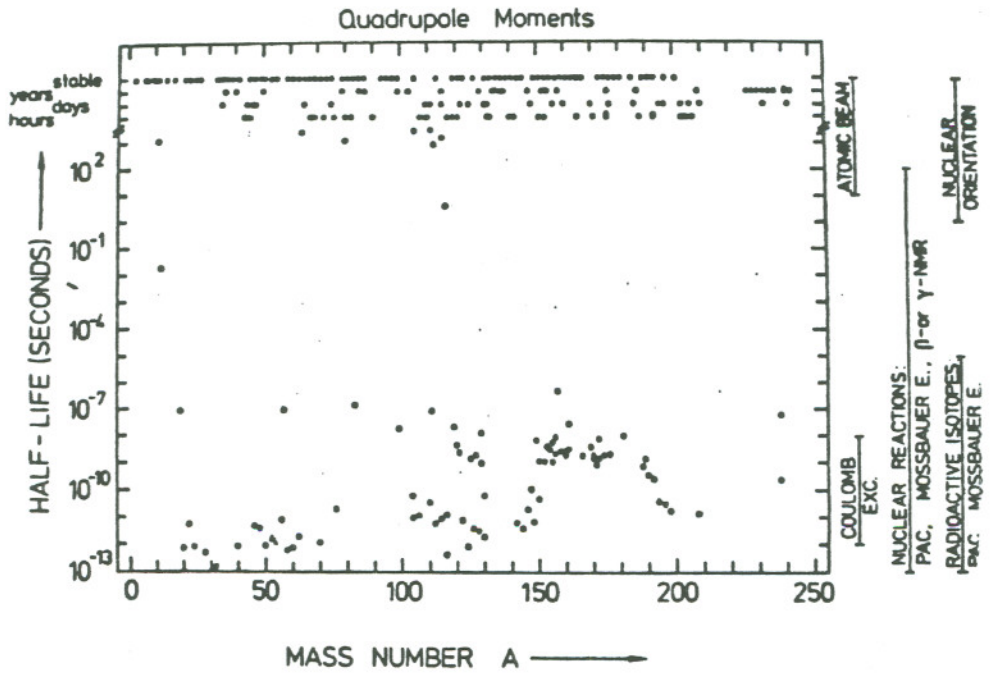
3. By applying oscillating EM field of proper frequency, destroy β decay asymmetry

$\varepsilon \to 0$ when $\omega = \frac{\mu B}{\hbar}$



Spin 3/2


Magnetic Moments
stable
years
days
hours
HALF-LIFE (SECONDS)
10^{2}
10^{-1}
10^{-4}
10^{-7}
10^{-10}
10^{-13}
0
50
100
150
200
250
MASS NUMBER A
ATOMIC BEAM
COULOMB EXC.
NUCLEAR REACTIONS: PAC, MÖSSBAUER E., β-or γ-NMR
RADIOACTIVE ISOTOPES: PAC, MÖSSBAUER E.
NUCLEAR ORIENTATION


Quadrupole Moments
stable
years
days
hours
HALF-LIFE (SECONDS)
10^{2}
10^{-1}
10^{-4}
10^{-7}
10^{-10}
10^{-13}
0
50
100
150
200
250
MASS NUMBER A
ATOMIC BEAM
COULOMB EXC.
NUCLEAR REACTIONS: PAC, MÖSSBAUER E., β-or γ-NMR
RADIOACTIVE ISOTOPES: PAC, MÖSSBAUER E.
NUCLEAR ORIENTATION

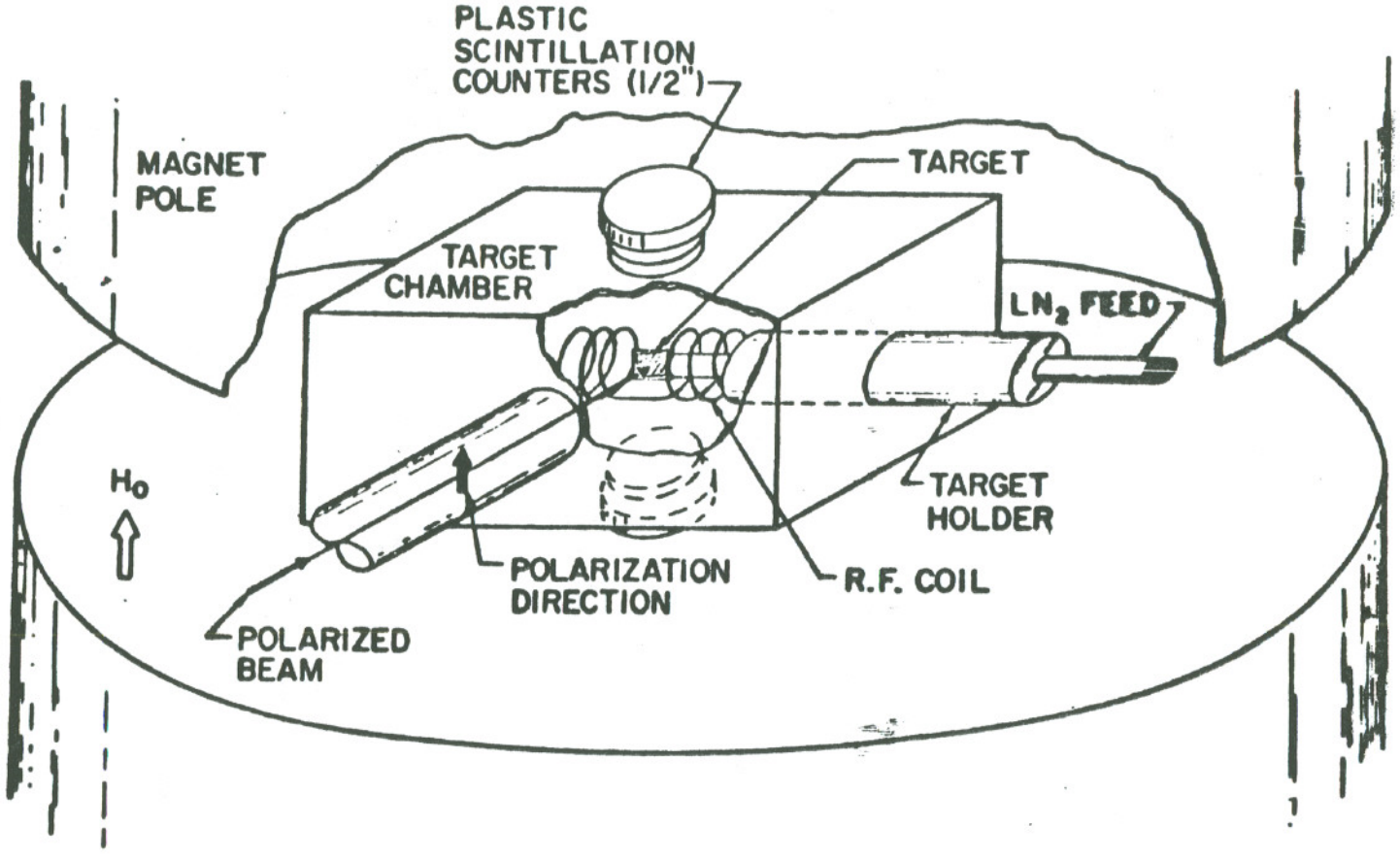
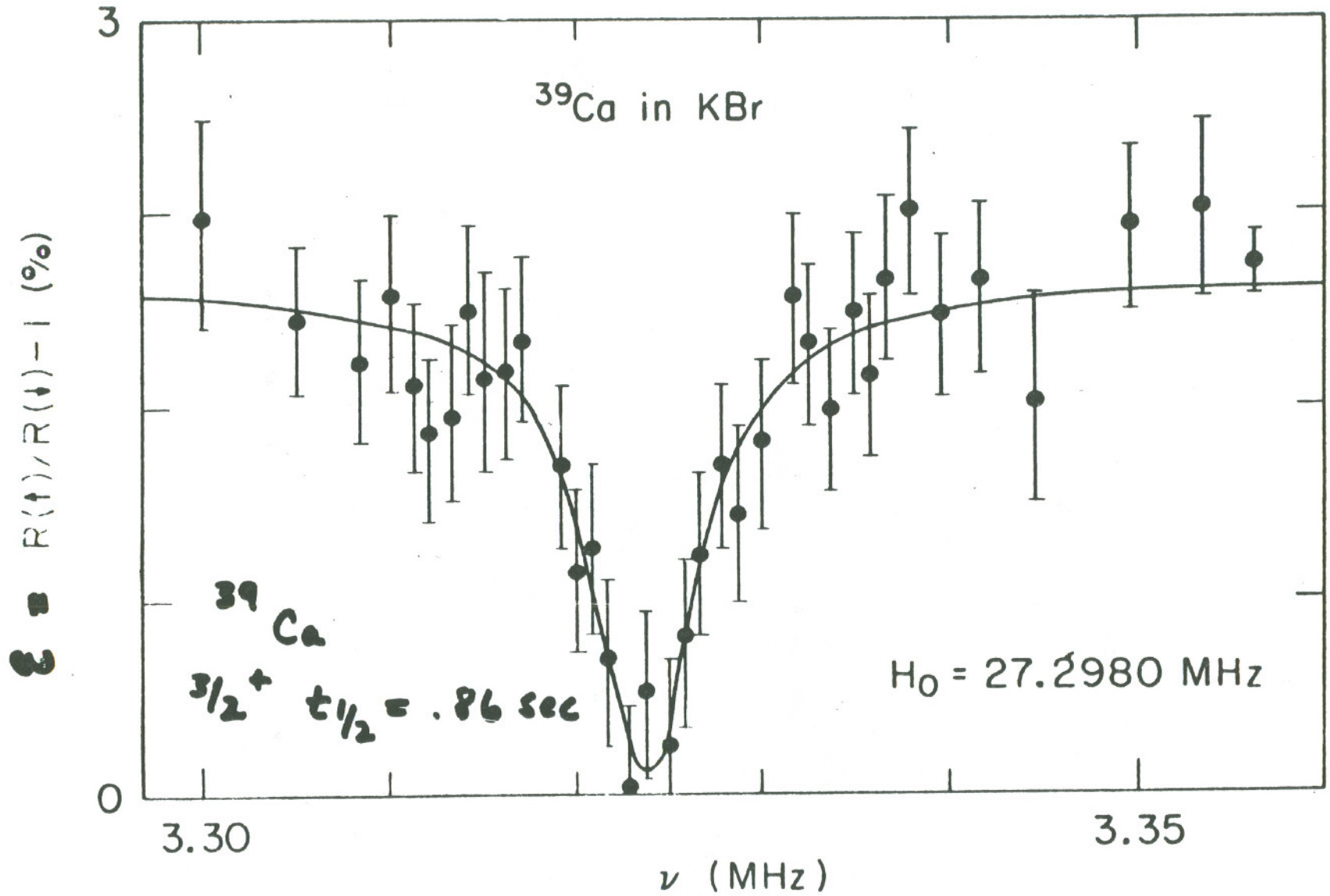
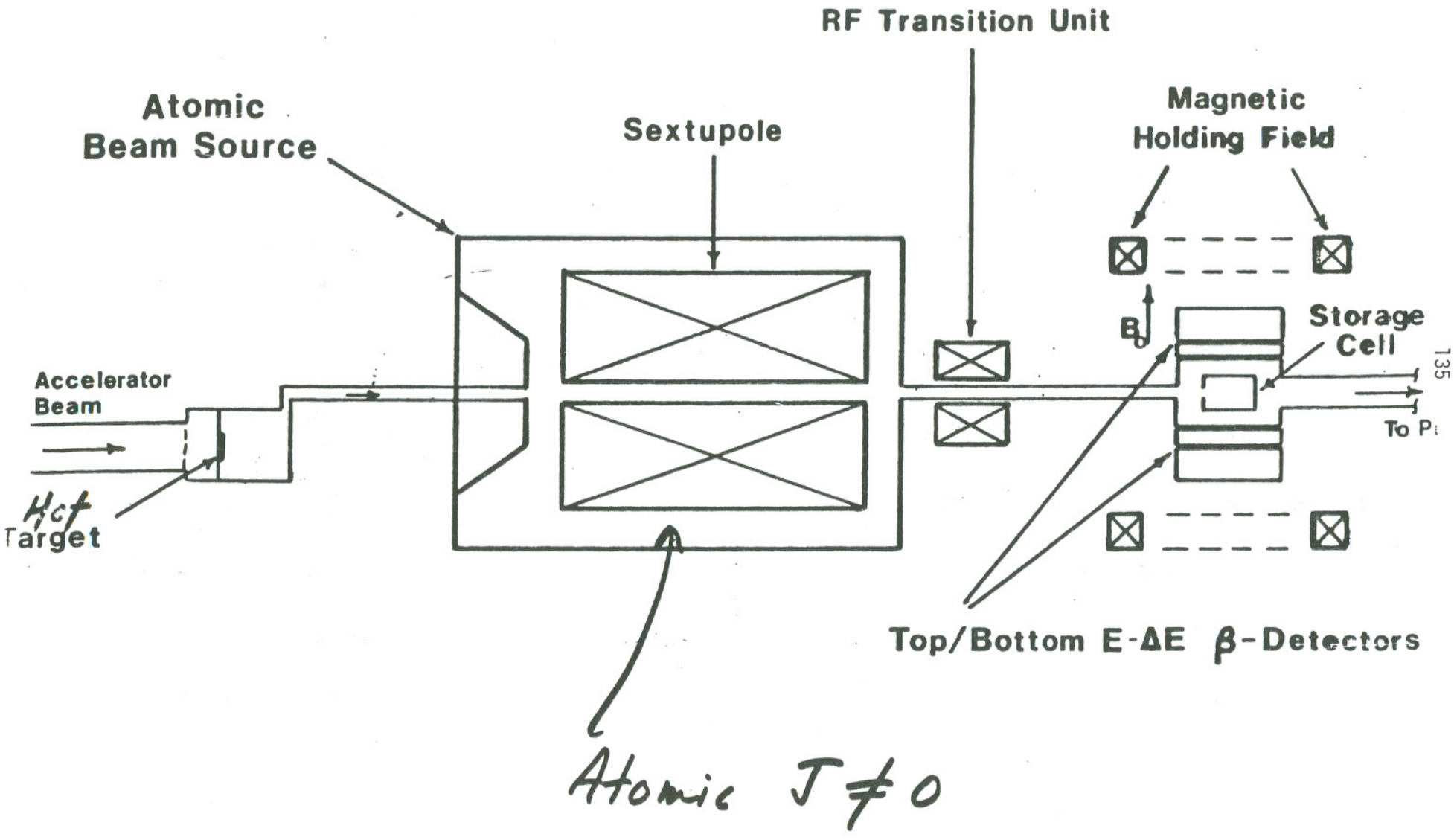


Figure 2.4: Target chamber for beta-decay asymmetry measurements. The components are described in the text. A photograph is shown in [Th 79, Figure 1].



[illegible] (c): Beta decay/NMR measurement of the magnetic moment of ^{39}Ca in ionic K compounds. The KBr sample has cubic [illegible] structure and hence produces a narrow NMR line with [illegible] nearly saturated by an unmodulated rf signal


RF Transition Unit
Atomic
Beam Source
Sextupole
Magnetic
Holding Field
Storage
Cell
Accelerator
Beam
Target
To P
Top/Bottom E-ΔE β-Detectors
Atomic J ≠ 0

Advantages

1. No polarized accelerator beam.
2. High nuclear polarizations

   $P_z \sim 10 - 100\ \%$

   even P_{zz}
3. Windowless β energy measurement
4. High precision μ and beta decay parameters; hyperfine anamolies.
5. $A \geq 50$ now possible

Problems:

1. Polarized accelerator beams
2. Polarization transfer
3. Experimental environment
4. Range of technique: $A \leq 50$

EXOTIC BEAMS AT NSCL

L.H. Harwood, J.A. Nolen Jr., and B. Sherrill

Introduction:

The NSCL coupled cyclotron facility will for the first time provide intense (10^{13} part./sec.) heavy-ion beams with E/A up to 200 MeV. Such beams will be of immediate importance in answering many nuclear physics questions. They could also provide the laboratory with the ability to produce exotic beams (beams of unstable nuclei for nuclear physics experiments and/or one or two electron heavy atoms for atomic physics experiments) with useable intensities. This contribution is a summary of a more detailed presentation given at a workshop at MSU in Dec., 1982 [1]; it's purpose is to outline methods for exotic beam production. Little discussion of the possible experiments using the beams will be made due to time limitations.

Exotic Beam Intensities:

The NSCL Phase II facility is shown in figure 1. Beams will be produced with an ECR ion source, accelerated in the K-500 cyclotron, injected into the K-800 cyclotron and reaccelerated to their final energy. The beams and intensities which will be available are shown in figure 2. From this plot it is clear that beams of stable nuclides of E/A of 200 MeV will be available for A<100 at intensities of 10^{12} part./sec. At these energies the most useful reaction mechanism for making exotic nuclei is fragmentation [2]. Assuming fragmentation as the production mechanism and a primary beam intensity of 10^{12} part./sec. the possible secondary beam intensities are given by:

$$\text{secondary part./sec.} = 7.\text{x}10^{6} \text{ x } \sigma(\text{ mb/sr })$$

where σ is the cross section for fragmentation of the secondary particle. The above expression assumes a 500 mg/cm^2 ^{9}Be production target and 20% efficiency in acceptance of secondary particles. Figure 3 shows the intensities for fragmented particles using a ^{48}Ca beam [2].

For comparison figure 4 shows fragmentation intensities with a 213 MeV/A ^{40}Ar beam [3]. The above expression is only approximate. However, it is conservative given the NSCL facility and thus provides a guide in determining secondary beam intensities. A correct expression would depend primarily on the beam energy, the reaction, and the mass of fragment/mass of beam.

Production of Secondary Beams:

A list of desirable characteristics for a secondary beam facility is given in figure 5. This list is intended to be global, since the requirements for individual experiments may vary widely.

A. Reaction Product Mass Separator

A Reaction Product Mass Separator (RPMS), shown in figure 6, has been designed to operate up to 200 MeV/u. The prototype is operational and will be useful for reaction products with E/A up to 30 MeV/u [4]. This device combines a Wien filter, which disperses according to velocity, and a magnetic dipole, which disperses according to momentum, with appropriate magnetic quadrupole magnets to achieve a system which has a focal plane where the position of the particle depends solely on its mass-to-charge ratio (m/q). It has unit mass resolution and might appear to be the most logical way of getting a clean secondary beam. It does have several problems, however. First, the beam would not truly be pure as it exits the RPMS since particles with the same, or nearly the same, m/q like ^{18}C and ^{15}B would not be separated. An additional clean up is necessary. Second, the location and direction of the beam as it exits the RPMS would be rather inconvenient for using the secondary beams. For mechanical reasons the Wien filter disperses vertically. The dipole must therefore deflect vertically also, resulting in an exiting beam which is no longer in the horizontal plane. A third difficulty comes from the fact that to maintain maximum resolution the dipole bend angle must vary with particle velocity, thereby changing the vertical position of the focal plane and the direction of the beam. Finally, it is necessary to have a large space available downstream for the secondary beam separator in order that the apparatus for the

experiment of interest can be set up. The present full scale RPMS has limited space available at the exit.

B. RPMS and Low Resolution Spectrometer

There are ways to address each of the above problems. The beam direction problem can possibly be overcome by changing the mechanical design of the Wien filter, and the varying dipole deflection can be eliminated by always running with the same dispersion. To remove the m/q ambiguity, the beam exiting the RPMS can be passed through a degrader and then a relatively low resolution magnetic spectrometer (LRS) as shown in figure 7. The particles exiting the RPMS also have the same momentum-to-charge (p/q) ratio since the Wien filter requires them to have the same velocity. Combined with the m/q ambiguity, there is then a p/q ambiguity. Since, by and large, the m/q ambiguities are between different elements, the different particles will have sufficiently large differences in energy loss in the degrader to remove the p/q ambiguity; the LRS could then easily separate them and give a monoiosotopic beam and also serve to limit the energy spread of the separated beam. The LRS could also be used to put the beam back into the horizontal plane if the dispersion is still vertical.

C. Fragmentation RPMS

The present RPMS design is a compromise to allow exploitation heavy-ion reaction mechanisms from 4 to 200 MeV/u and is not optimized for fragmentation. Fragmentation products are fairly localized in velocity-space ($\Delta V/V < 5\%$), thus $p/q \propto m/q$. At energies greater than 50 MeV/A the particles are often fully stripped, hence $p/q \propto m/z$. Thus, it is possible to do surprisingly good beam selection with only momentum selection with an LRS. The products would be spread out over the device's focal plane, however. A dedicated "fragmentation RPMS" is shown in figure 7. This is designed to take advantage of the momentum-mass correlation and do an initial clean-up before the reaction products enter the Wien filter. A system consisting of a LRS followed by another LRS and finally the Wien filter would be quite effective for fragmentation product separation. Of course, this design still has the m/q and p/q ambiguities of the earlier design but would provide a cleaner radiation environment at the exit of the system.

D. Fragmentation Separator

The simplest design for producing isotopically pure secondary beams is the "fragmentation separator," which is illustrated in figure 8. It consists of: 1) an LRS, 2) a degrader, 3) a dispersion matching section, and 4) another LRS. This design incorporates all the ideas used above to enhance the RPMS options and would be cheaper, basically since the total number of elements is smaller. Conceptually, the sections would serve to: 1) separate the particles according to p/q, 2) use the differential degrading trick to remove the p/q ambiguity, 3) match the dispersion of the degraded secondary particles to the dispersion of the final LRS, and 4) remove the unwanted particles and form a dispersionless final focus on the target. A position sensitive counter could be used in place of or following the degrader to measure the particle momentum, as is done at EPICS [5]. This would allow higher resolution experiments to be done with the full intensity secondary beam, in spite of the 5% velocity spread for a given isotope.

E. Modified Beam Line

A major problem with many schemes for producing secondary beams is delivery of the beams to experimental areas. Specifically, a beam's utility increases with the number of different apparati to which it can be delivered. Ideally, the secondary beam production should occur early in the beam distribution system. A relatively inexpensive alternative which fills this need at NSCL can be found by examination of the beamline which exits the K800 cyclotron, or equivalently the beam transport to the S800. A production target could be placed at the beginning of these sections and an appropriate redesign of the beamline would result in a configuration that resembles the "fragmentation separator." The modifications needed for a system of moderate capability would not be large. This beamline separator would also be well suited to providing the atomic physics beams. Such a system at the K800 exit would also make the exotic beams available to any experimental area since the beamline separator is before the main switch-yard magnet. The price to be paid is intensity of the secondary beams. The beamline elements are not sufficient to transmit the entire phase space of the secondary beams; to make them such would be enormously expensive (>1M$). With this scheme one could begin to make and use secondary beams

before investing large sums of money into special, dedicated equipment. This is the course chosen for NSCL.

Conclusions:

A summary of devices and their estimated parameters is shown in figure 9. The most logical alternative for beginning uses of exotic beams seems to be the modified beamline option. More design work on this option is planned.

References:

1. L.H. Harwood, J.A. Nolen Jr., A.D. Panagiotou, Workshop on Phase II Apparatus NSCL, Dec. 1982 p. 52.

2. G.D. Westfall, et al., PRL 43, 1858 (1979).

3. Y.P. Viyogi, et al., PRL 42, 33 (1979).

4. L.H. Harwood, and J.A. Nolen Jr., Nucl. Instr. and Meth. 186, 435 (1981).

5. H.A. Thiessen, et al., Los Alamos Scientific Laboratory Report No. LA-4534-MS (unpublished); H.A. Thiessen, et al., Los Alamos Scientific Laboratory Report No. LA-6663-MS, 1977 (unpublished).

Figure Captions:

Fig. 1: Floor plan for the NSCL phase II program.

Fig. 2: Contours of expected beam intensities for phase II operation.

Fig. 3: Possible secondary beam intensities for ^{48}Ca on ^{9}Be at 200 MeV/u. The figure is taken from reference 2.

Fig. 4: Possible secondary beam intensities for ^{40}Ar on ^{9}Be at 213 MeV/u. The figure is taken from reference 3.

Fig. 5: Considerations for an exotic beam facility.

Fig. 6: Diagram of the prototype RPMS.

Fig. 7: Diagram of the Fragmentation RPMS and a LRS to remove m/q, p/q ambiguities.

Fig. 8: Possible configuration for a Fragmentation Separator.

Fig. 9: Summary of features and expected intensities for the devices discussed in the text. The count rates indicated are assuming a fragmentation cross section of 1mb, and the device characteristics listed in the text.

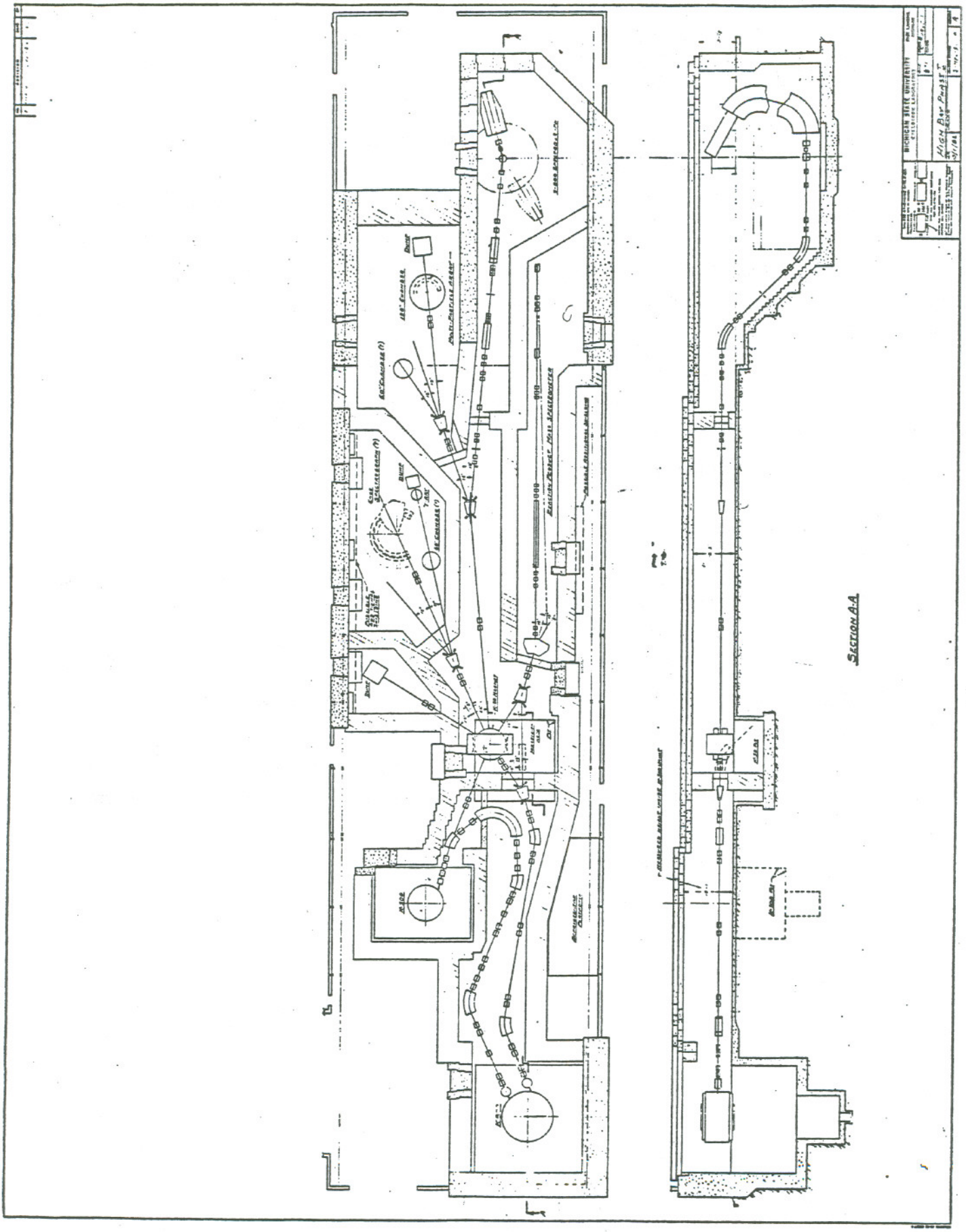


Figure 1

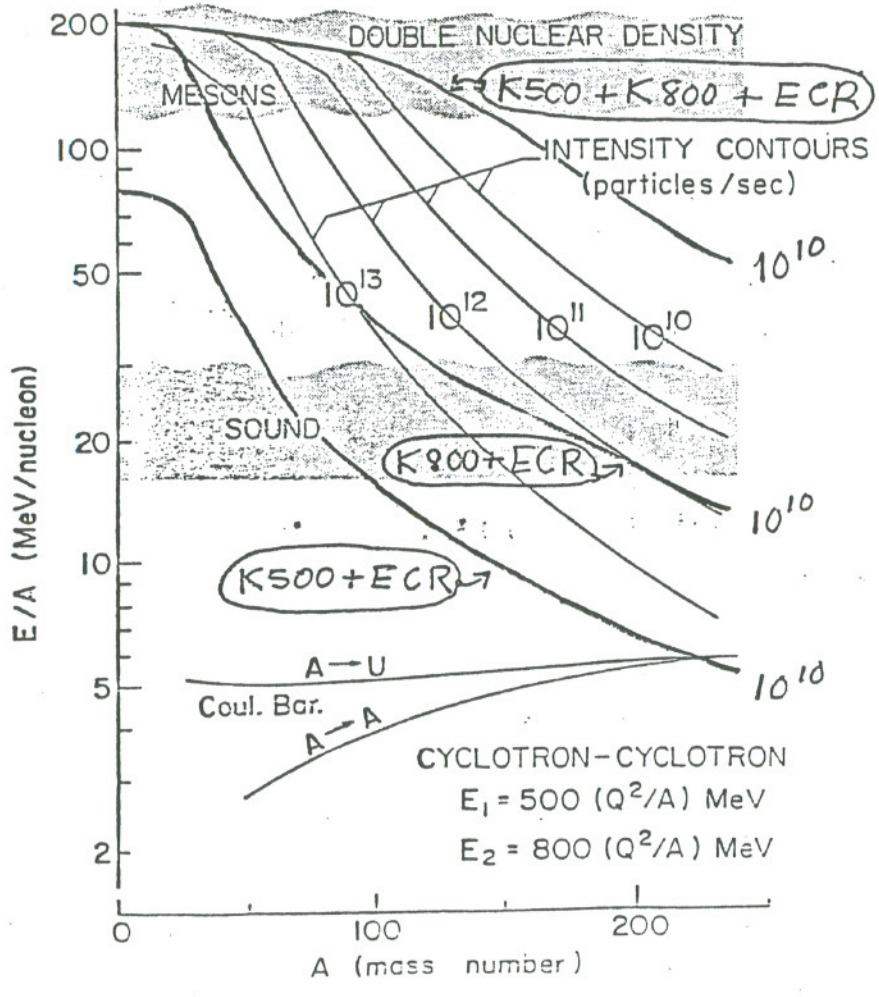


Figure 2

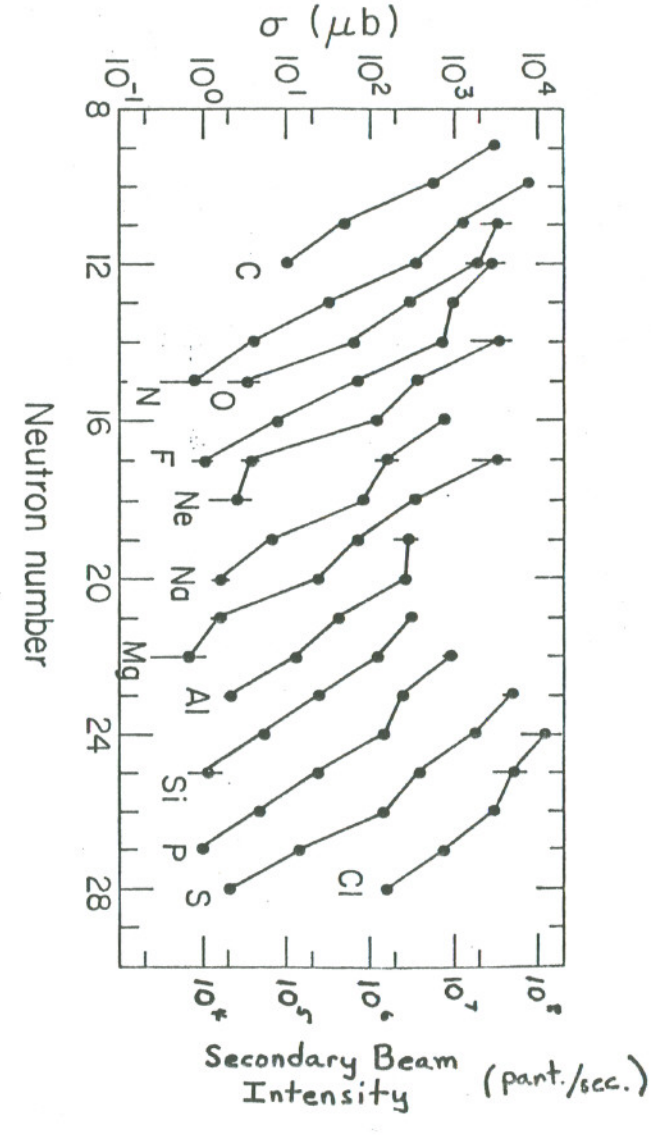


Fig. 2

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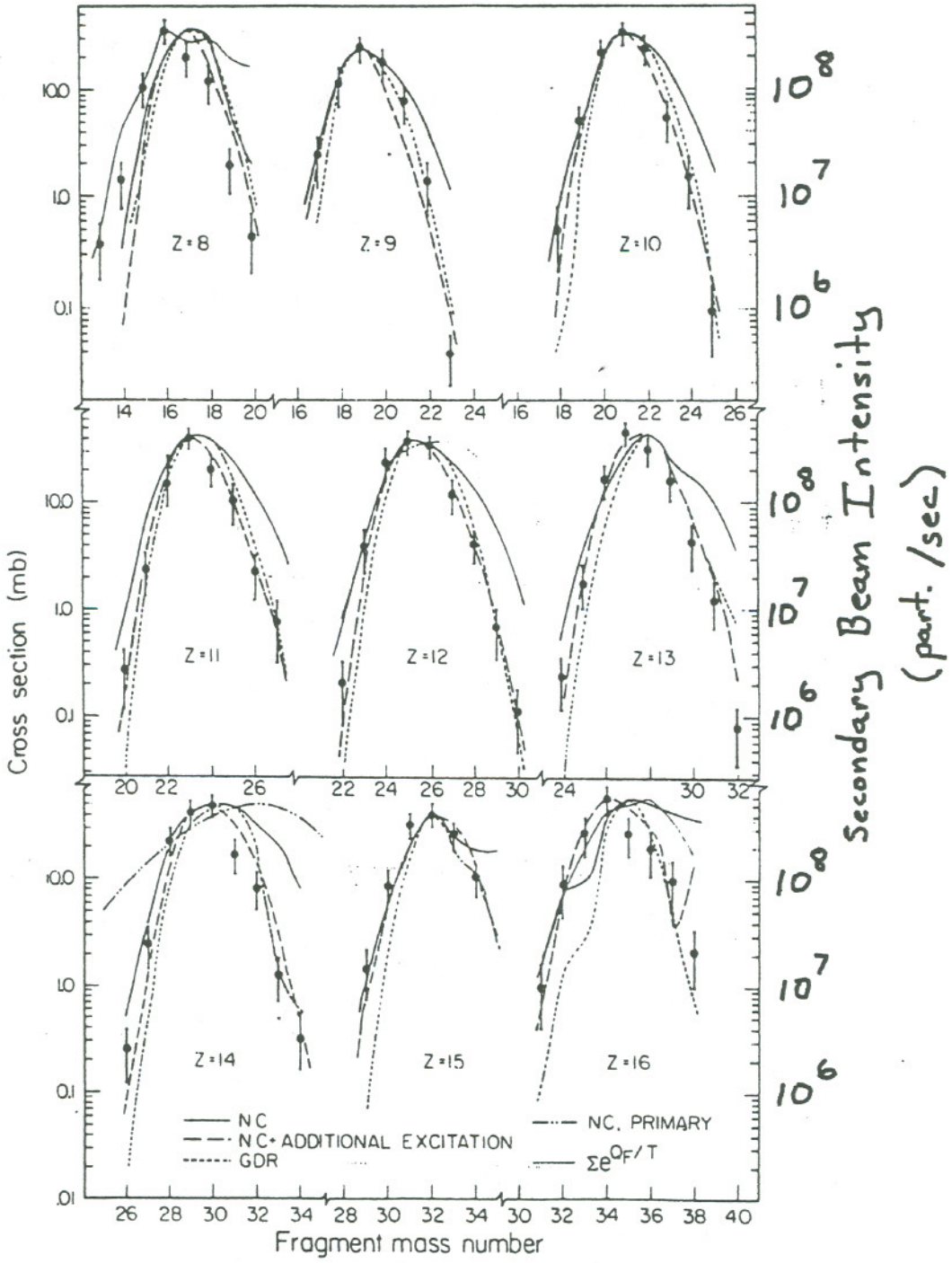

Cross section (mb)
Secondary Beam Intensity (part./sec)
Fragment mass number
Z=8
Z=9
Z=10
Z=11
Z=12
Z=13
Z=14
Z=15
Z=16
NC
NC+ADDITIONAL EXCITATION
GDR
NC, PRIMARY
$\Sigma e^{Q_F/T}$

Figure 4

RPMS

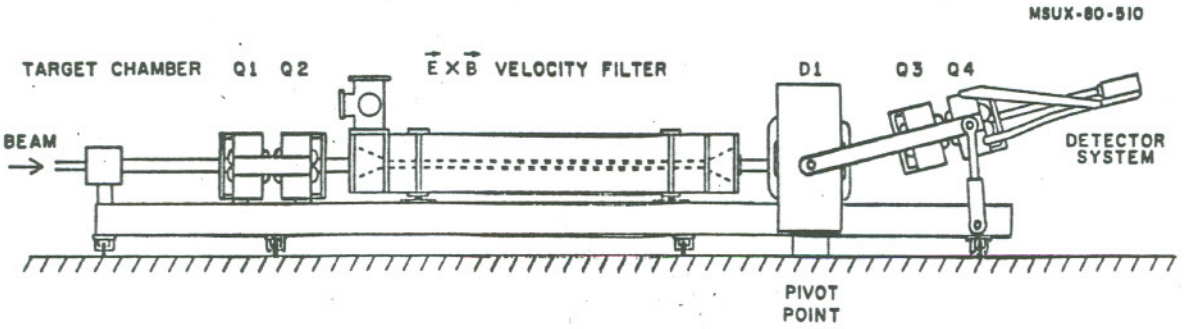


Figure 6

$\Omega = 1$ msr

$\frac{M}{\delta M} = 200$

$0° \leq \theta \leq 30°$

Energy Range

$0 \leq E \leq 30 \frac{MeV}{A}$

Requirements For an Exotic Beam Facility

1). Reasonable intensity (10^8 P/s).

2). $\frac{m}{q}$, $\frac{P}{q}$ resolution.

3). Large velocity acceptance $\pm 5\%$, $\Omega \sim 1$ msr.

4). Achromaticity $(\theta/\delta) = (x/\delta) = 0$.

5). Adequate Energy Range.

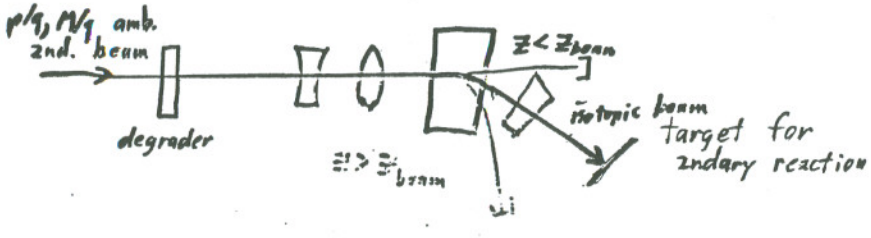
6). Reasonable Cost.

Figure 5

Fragmentation RPMS: fixed at 0°

Costs: Multipoles ≈ 250K
Manpower ≈ 250K
Power supp. ≈ 50K
other ≈ 100K
650K

Low Resolution Spect.: 1) cleans up beam energy spread
2) removes M/q ambiguity

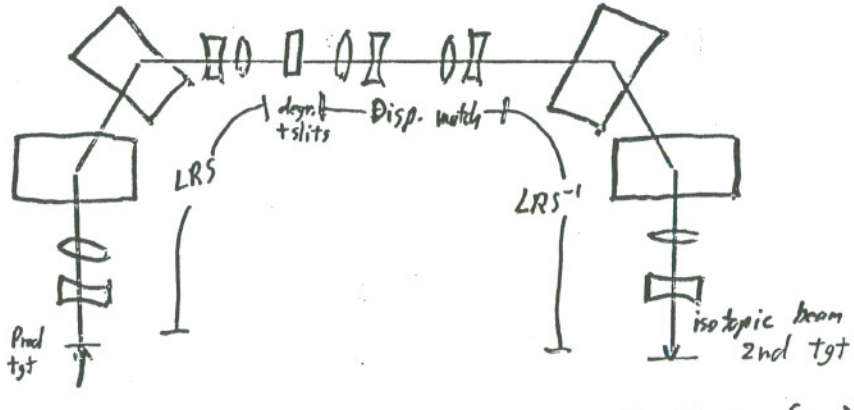


Cost: ≈ 300K

Figure 7

Fragmentation Separator

1) Isotopic beams
2) Can clean up energy spread
3) Atomic physics beams
4) Isochromat



Cost: 2 × (400K) (LR
100K D.M.
$900K

Nice features: 1) combines RPMS, tail, + LRS
2) RPMS still available
3) can be run so 4π of secondary beam is small
4) Maybe in EPICS mode
5) Perfect for atomic beams

Figure 8

DEVICE	Secondary Beam Intensity	$\frac{\Delta P}{P}$	Achromatic	Cost	Comments
RPMS Phase II	10^6 to 10^8	5%	yes	600K	$\frac{p}{q}$, $\frac{m}{q}$ amb.
Fragmentation RPMS	10^6 to 10^8	5%	yes	650K + ½ RPMS	"
RPMS + LRS	10^4 to 10^6	5%	no	300K + RPMS	large emittance
Fragmentation Separator	10^6	5%	yes	900K	"
Phase II Beam Line	10^4 to 10^5	2%	maybe	50K	Could be better with more β

figure 9

SECONDARY BEAMS AND EXOTIC NUCLEI PRODUCED AT CERN AND GANIL

J.P.Dufour. CEN.Bordeaux.

Secondary beams appear very promising for the exotic nuclei production.(1) Such beams may be produced through projectile fragmentation at high energy. This interesting mechanism produces a large number of nuclides, all mainly emitted at zero degree with the beam velocity (2). The purpose of this work was to search for adequate filters of any kind leading to the realisation of a Projectile Fragment Isotope Separator (PFIS). Such a device may be directly used for exotic nuclei studies or as a source of separated beams. Through calculations, the following set of filters was selected:

1) target thickness-magnetic deflection(t-bρ1). The bρ analysis behind the target provides a first selection according to a function close to

2) degrader-magnetic deflection(d-bρ2). In a system like LISE at GANIL, (figure 1), a degrader may be used at the focal plane of the first magnet to differentially slow down the (t-bρ1) selected isotopes. The second magnetic analysis(bρ2) thus provides a selection following a function close to

3) a third selection is provided by the range of the nuclei, if stopped in a solid or gaseous material. This last selection is found to be very similar to that of point 2) and thus mainly provides,if used, an enhancement of selection 2).

Such a principle has been first tested with a 18 O beam(86 A.Mev) at the CERN'synchrocyclotron. The regular heavy ion user's beam line provided the magnetic analysis of point 1), selection 2) was supressed and replaced by selection 3). The secondary beam intensities were measured through the caracteristic beta delayed neutron radioactivity of 17 N and 16C stopped in a 0.5 mm thick Al catcher foil placed behind a 2 to 10 mm thick degrader.

Conversion rates R, defined as the ratio of secondary intensity over the primary intensity, have been found to be :

^{17}N : R= 8 10^{-6} at 70 $\pm$1.4 A.Mev with a 600mg/cm^2 Al target.

^{16}C : R=1.5 10^{-6} at 60$\pm$1.2 A.MEv with a 1200 mg/cm^2 Al target.

In a separate experiment the radioactivity of ^{15}B has been observed for the first time: T=10.5 ms for the beta delayed neutron decay mode (branching ratio larger than 95%).

Another test of the method has been very recently performed at GANIL. The full use of the three criteriums has been made, and in order to achieve a high precision in the second and third ones, a wedge has been used as a degrader. The energy spread has been thus reduced from 4% to 0.5%. The range of ^{35}P, produced with a 40 Ar (44 A.Mev) beam, at the exit of the system had a dispersion(in aluminum) of 3.8 mg/cm^2 :for a total range value of 160 mg/cm^2. The two isotopes 34 P and 35P have been identified through β-γ coincidences; the mass resolution measured in this region is A/ A=100.

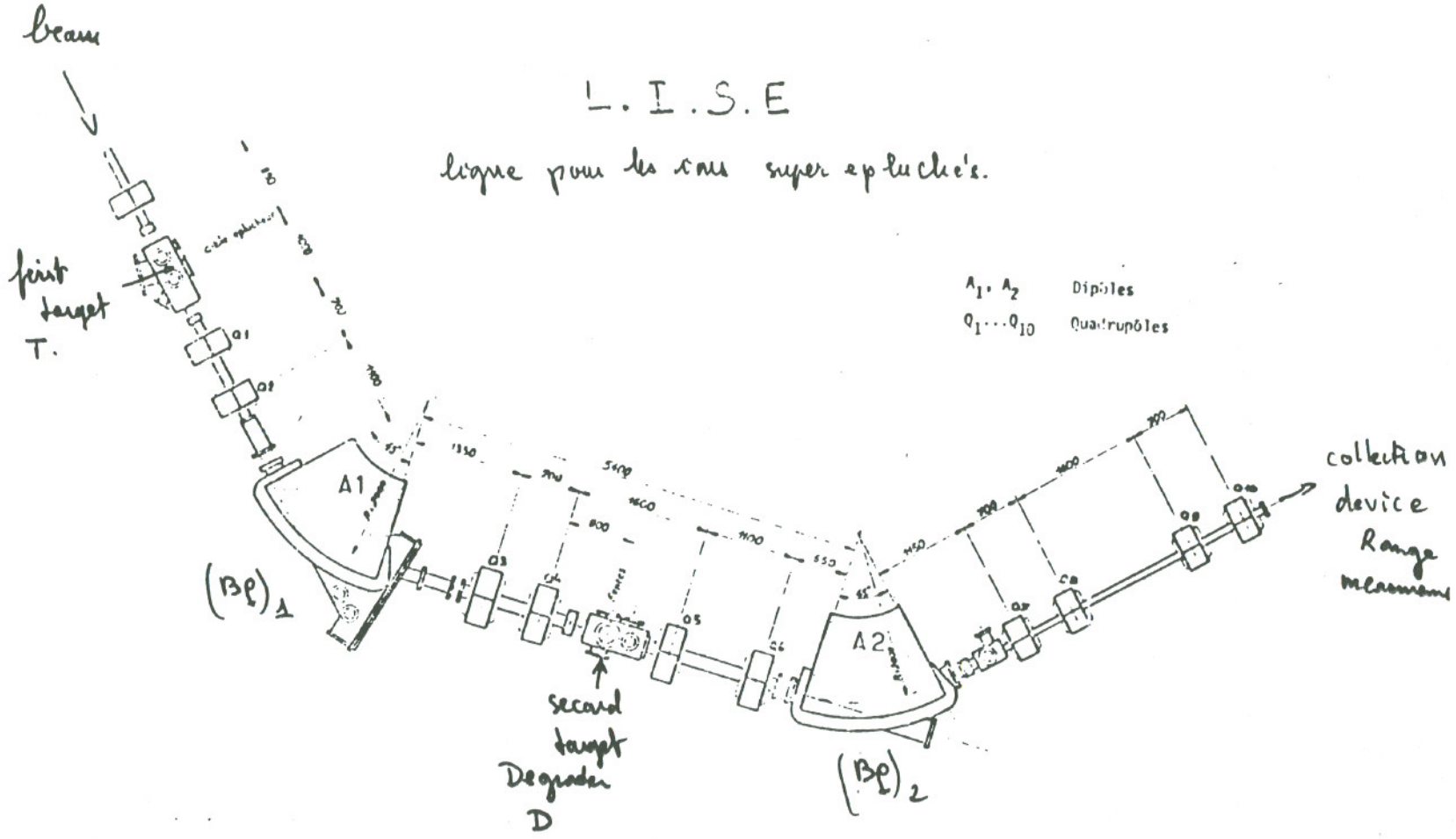
The Projection Fragment Isotopic Separation obtained with a combination of degraders and magnetic dipoles thus appears precise enough to allow both secondary beam and exotic nuclei separation up to mass 100 and probably more.

References: 1) J.P. DUFOUR,A.FLEURY,R.BIMBOT, Phys.Rev. C23,801(1981)

2) T.JM.SYMONS,Y.P.VIYOGI,G.D.WESTFALL,P.DOLL;D.E.GREINER. H.FARAGGI,P.J.LINDSTROM,D.K.SCOTT,H.J.CRAWFORD,C.McPARLAND, Phys.Rev.Lett.42,40(1979).

L.I.S.E

ligne pour les ions super epluche's.



LBL-17829

Relativistic Radioactive Heavy Ion Beams at the Bevalac

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Relativistic heavy ion beams have been available now at Berkeley for over twelve years, and even from the earliest times the possibilities of unstable secondary beams were explored. Work by Tobias and Chatterjee[1] on autoactivation in beryllium catchers, and shortly thereafter extensive studies by Heckman, Greiner et al.[2] on the yields and kinematics of reaction products served to characterize peripheral fragmentation reactions as an important mechanism for secondary beam applications.

In such reactions, these authors found a few nucleons were removed from the projectile, which continued forward with essentially the same velocity it had prior to the collision. In addition, cross section and momentum transfer changed very little over a fairly wide range of beam energies and reaction products, being respectively around 10-40 millibarns and 100 MeV/c.

These high cross sections, and low momentum transfers pointed to the feasibility of using relativistic heavy ions to produce secondary beams of interesting purities and intensities for experimental applications. Beams of ^{11}C and ^{19}Ne were in fact produced and delivered to biomedical users of the Bevalac as early as 1978[3]. Since this time beams of these ion species have been used extensively in biomedical range measurements and implantation studies[4], and other projectile fragmentation nuclear science experiments have further illustrated the power of this technique for producing exotic nuclei. An example of this is Fig. 1 which shows isotopes produced by Westfall et al[5] in a ^{48}Ca fragmentation experiment. In this experiment

lasting only one day, 14 new isotopes were discovered, and cross sections were measured for an extremely wide range of products.

From these experiences certain points can be made about secondary beams of relativistic heavy ions.

Production Considerations

To maximize the yield of a desired secondary ion, one should use the most target material for the least energy loss and multiple scattering of the beam. These both indicate lowest Z materials. Fig. 2 shows calculated yield of ^{11}C from ^{12}C as a function of beryllium target thickness, showing also the primary beam energy loss and multiple-scattering growth. Production peaks at about 1.8% for a 15 g/cm^2 target, then drops off as the secondary ion itself undergoes further reactions, and the primary beam attenuates and can no longer feed the ^{11}C channel. Note that the peak production yield is limited by the ratio of the cross section for the desired ion to the total reaction cross section, a condition reached in the above case. Similar calculations for heavier targets show much more energy loss and scattering for the equivalent production, for the heaviest targets a maximum is not reached before the ion is stopped.

Berman's work on photodissociation[6] indicates huge cross section enhancements for heaviest targets at high energies (2 GeV/amu); this process may yield significant improvements in beam intensities for selected species at high energies. How far down in energy one can gain benefits from this mechanism must still be explored.

Production yields, as indicated, depend critically on relative cross sections. In the 10 mb range we have seen a production efficiency of about 10^{-2}, fully 1% of the primary beam emerges as the desired secondary! From

Fig. 1 one sees large variations in production cross sections for ions far removed from the projectile mass, yields will thus also vary considerably. Note that to estimate the yield in the experimental area, as opposed to the production efficiency, one must also include transport efficiency, which is related to energy and angular spread in the production process. Thus cross section ratios only indicate upper limits of potential yield ratios or delivered beams.

To calibrate the above discussion, typical Bevalac beams are between 10^9 and 10^{10} ions per pulse (.25 Hz) in the light-ion region, so the most favorable secondary beam intensities can be as high as 10^7 to 10^8 ions per pulse. In fact our normal ^{11}C and ^{19}Ne running is with 1×10^7 ions/pulse in the Biomed area.

Transport Considerations

The key factor is that the higher the energy of the production reaction, the smaller the perturbation on the beam momentum and divergence. In fact, at Bevalac energies the qualities of the secondary beam come very close to matching those of the primary beam. The fact that the 1 milli-steradian acceptance Beam 40 spectrometer, where the "low energy" (212 MeV/amu) ^{48}Ca experiment was performed, showed 95% collection efficiency for fragments close to the projectile mass (even 15% for the very-distant carbon isotopes) attests to the benefits of high-energy kinematic focusing.

Higher energy also helps in minimizing target thickness effects. Energy variation in the secondary beam occurs depending on where in the target each ion is produced, as de/dx of primary and secondary ions are in general different. At high energies, though, de/dx for both is smaller, and total energy loss is a smaller fraction of the total energy. These factors all point to very high beam quality for the secondary beams. Note also, that one can apply a number of the normal beam transport techniques to even further

improve the beam quality. For instance, putting the production target at the tightest possible waist, where normal beam divergence is large, will minimize the emittance growth of the beam due to scattering and reaction kicks in the target. We will see later that energy spread can also be improved.

Present Bevalac beam lines, largely inherited from the days of proton running, are not designed as high-acceptance lines, and still we can transport about 30% of the produced ^{19}Ne to the biomedical experimental area. Planned improvements in the next year should make the situation even better.

Beam Purification

Magnetic analysis systems for beam purification are effective for separating by rigidity, the ultimate resolution being dependent on beam quality (transverse emittance) and energy spread. An additional complication for secondary beams is the overlap of charge-to-mass ratios of different reaction products.

As was the case above, higher energies aid in the process of beam purification. In the Bevalac energy range, typical energy spreads of secondary beams are only about a few percent, allowing simple magnetic analysis to be enough to isolate adjacent isotopes of a given (light) element. One will see contaminants of like q/A coming through the slit system, e.g. ^{19}Ne, ^{17}F, ^{15}O are seen together, as were ^{9}Li, ^{6}He, ^{3}H in another recent experiment[7]. One can, however, by means of a degrader at the first analysis point separate the rigidities of the different Z components to allow good purification at a second analysis point. (This has not yet been demonstrated at the Bevalac, but there is little doubt it will work.)

Energy Analysis

The ultimate user of the secondary beam has need for some degree of energy uniformity in the beam. Again, beam optics can come to our aid. By introducing the right dispersive elements the beam can be spread out to an

almost arbitrarily high energy resolution (limited again by transverse emittance). In the Biomed area, energy widths of collimated beams of the order of the range straggling are routinely seen, making ^{19}Ne Bragg curves as sharp as primary ^{20}Ne curves. (See Fig. 3). This resolution is achieved at the cost of intensity; much greater flux is available using a momentum - recombined tune, about a factor of five more beam intensity is obtained in a reasonably small focal spot (<1 cm^2). One can also improve the energy spread in the beam using a wedge at the intermediate (dispersed) waist, with pitch set to match the dispersion so that beam emerges monochromatized. Experiments have indeed shown substantial sharpening in ^{11}C Bragg peaks using this wedge technique[8].

To achieve the highest energy resolutions for, say, low-energy experiments or for reaction studies of interest to astrophysics, may involve an inordinately large degree of effort. Nevertheless, by suitable intermediate degrading and analysis, even relatively large statistical energy fluctuations in the degrading process from the production energy to the energy of interest might be adequately compensated for.

Summary

The Bevalac has been demonstrated to be an efficient source of radioactive beams of good quality, and is attracting a growing body of users of this capability. Immediately on the table are an increasing demand by biomedical experimenters, leading up to eventual clinical use; and two most interesting nuclear science experiments, discussed in the next paper of this workshop. We are anticipating a substantial increase in interest and demand in coming years, and are planning beam line improvements to enhance transmission and purification efficiencies.

The Bevalac and its relativistic secondary beams may not be the panacea for all the desires of the research community, fluxes of 10^{12} ions/sec of ^{52}Ca will probably never be achieved, and half-MeV resolutions may be

unattainable, but nevertheless there is a tremendously broad range of experimental work possible with these beams. Furthermore, active use, and exploration of the usable limits of these beams will go a long way in setting the specifications for the next generation of radioactive-beam facility.

ACKNOWLEDGMENT

This work was supported by the Director, Office of Energy Research, Office of High Energy and Nuclear Physics, Nuclear Science Division, U.S. Department of Energy under Contract Number DE-AC03-76SF00098.

References

1. Tobias, C.A., Chatterjee, A. and Smith, A.R., Phys. Lett. 73A (1971), 119.

2. Greiner, D.E., Lindstrom, P.J., Heckman, H.H., Cork, B., Bieser, F.S., Phys. Rev. Lett. 35 (1975), 152.

3. Alonso, J.R., Chatterjee, A., and Tobias, C.A., IEEE Trans. on Nucl. Sci. NS-26 (1979), 3003.

4. Chatterjee, A., Saunders, W., Alpen, E.L., Alonso, J., Scherer, J. Rad. Res. 92 (1982) 230.

5. Westfall, G.D., Symons, T.J.M., Greiner, D.E., Heckman, H.H., Lindstrom, P.J., Mahoney, J., Shotter, A.C., Scott, D.K., Crawford, H.J., McParland, C., Awes, T.C., Gelbke, C.K., Kidd, J.M., Phys. Rev. Lett. 43 (1979), 1859.

6. Olson D.L., Berman, B.L., Greiner, D.E., Heckman, H.H., Lindstrom, P.J., Westfall, G.T., Crawford, H.J., Phys. Rev. C24 (1981) 1529. See also B. Berman's contribution to this workshop.

7. Tanihata, I., Private Communication, results from preliminary run on joint INS-LBL Bevalac Experiment #690H.

8. Chu, W.T., private communication, results from ongoing Bevalac biomedical research.

Figure Captions

Fig. 1 Production cross sections for isotopes observed in the fragmentation of 212 MeV/amu ^{48}Ca projectiles on a beryllium target.

Fig. 2 Calculated production efficiency for ^{11}C from ^{12}C as a function of beryllium target thickness. Fully 1.8% of the primary beam emerges as ^{11}C. Multiple scattering beam - broadening is also shown; the hashed line represents maximum divergence accepted by the Bevalac transport line to the Biomedical area.

Fig. 3 Bragg curve for (300 MeV/amu) ^{19}Ne delivered to the Biomedical area. Note total absence of primary ^{20}Ne (would have 5% longer range), but presence of ^{17}F and ^{15}O, contaminants with very similar q/A's.

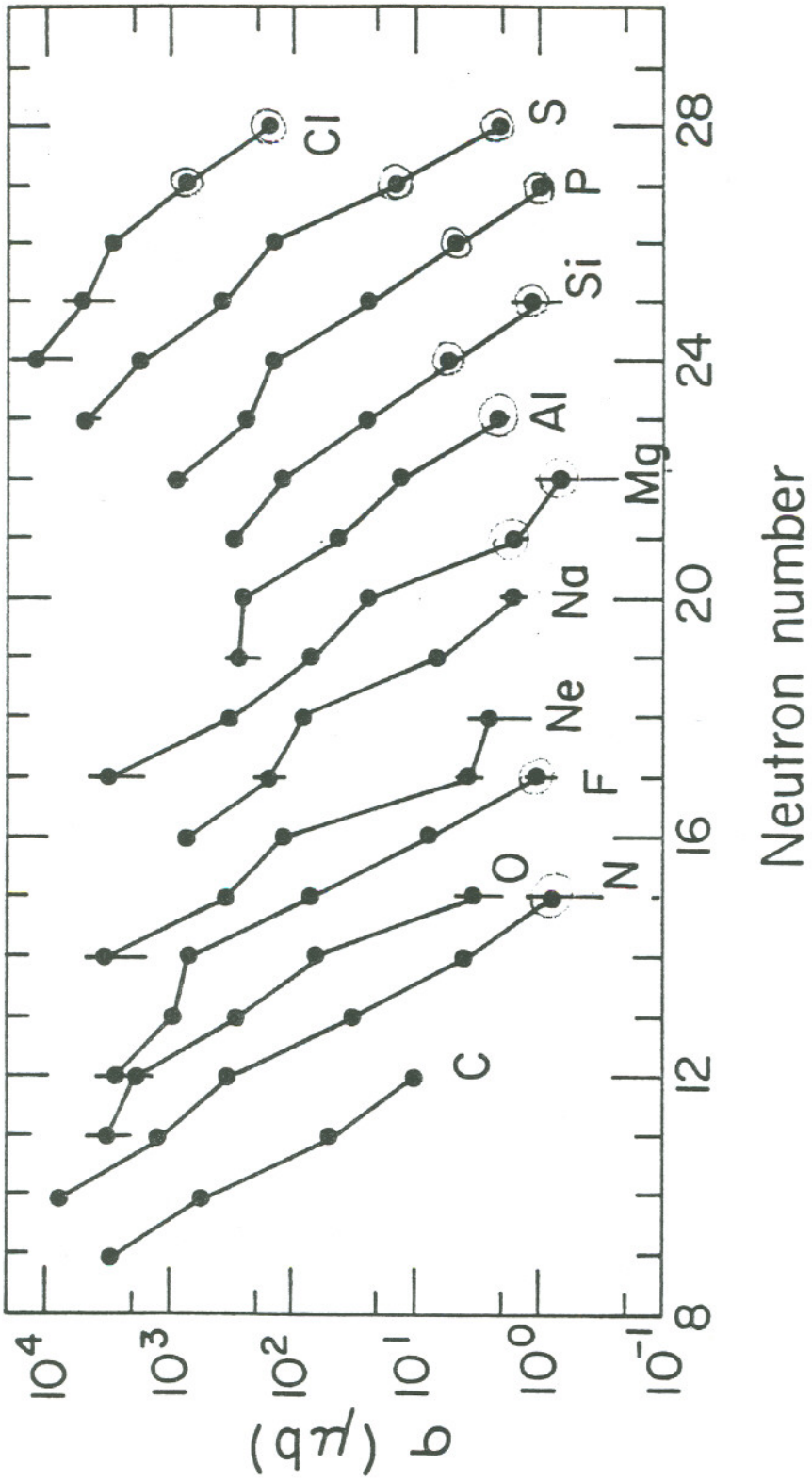

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Figure 1

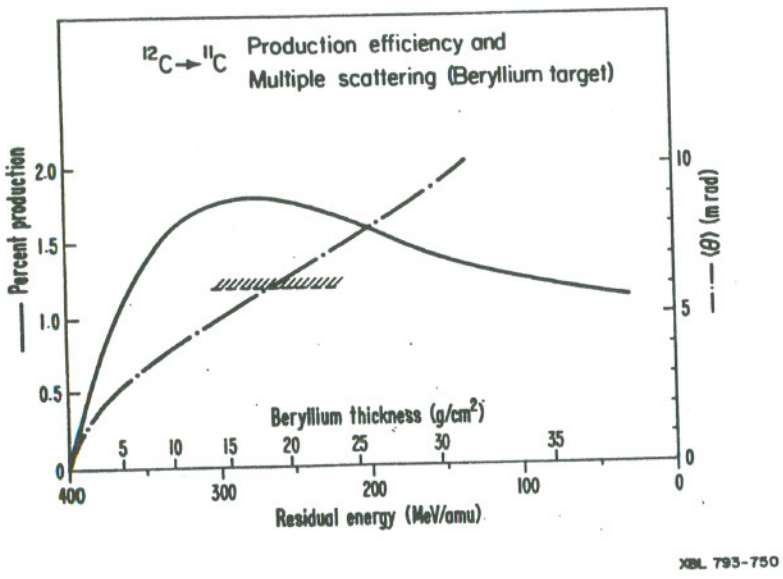

Figure 2

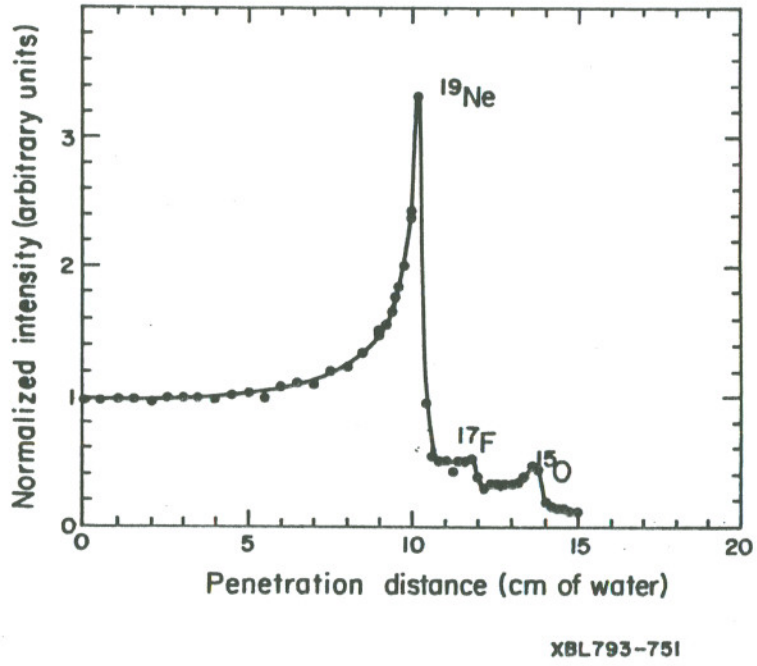

Figure 3

NUCLEAR PHYSICS USING UNSTABLE NUCLEAR BEAM

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1. INTRODUCTION

In these ten years, after high-energy heavy-ion beam became available, projectile fragmentation process has been studied extensively. It is found that many isotopes are produced through the projectile fragmentation with large cross sections and emitted into the very narrow cone of the incident particle direction. They are also emitted in the same velocity as the incident beam. This property of the projectile fragments opens a possibility of producing the beam of the unstable nuclei for study of nuclear reaction.

For example the production cross section of unstable nuclei through the projectile fragmentation of ^{40}Ar ranges from a few hundred mb to μb depending on the beam and the target combination.[1] Wide range of nuclei far from the stability line are produced with more than one μb. The momentum spread of the product nuclei were measured by D. E. Greiner et al..[2] They found that the product nuclei are moving in the same speed as the incident beam. In the rest frame of the projectile, the fragments were found to have a momentum distribution $exp(-P^2/2\sigma^2)$, with

$$\sigma = \sigma_0 \sqrt{\frac{B(A-B)}{(A-1)}} \qquad (1)$$

where A is the mass number of the projectile and B is the mass number of the fragment, and σ_0 = 90 MeV/c. The momentum spread in the laboratory frame is then an order of a few per cent when the projectile of energy of about 1 GeV/A is used. The angular spread of the fragments is an order of a few degrees. Because of these character of the projectile fragment,a very high transmission efficiency is expected when the fragments are used as secondary beams.

In this paper I will represent a secondary isotope beam line ,which is tested recently at Bevalac, Berkeley and an experiment proposed at the Bevalac.

2. A SECONDARY BEAM LINE AT THE BEVALAC

A secondary beam line at the Bevalac is schematically shown in Fig. 1. A primary heavy ions accelerated by the Bevalac are firstly focused at F1. A primary target of Be is positioned at F1. Fragments produced at the target are guided to F2 by a beam line with a bending magnet(X2M5) and a set of Q magnets(X2Q4). The second focusing point F2 supplies an angular focus with momentum dispersion. An isotope separation slit is located at F2 and degrade the energy of the isotopes which have different rigidity from the isotope of interest. A cleaning slit is placed at F3, which is an achromatic focusing point located after another bending magnet(X2M7) and a set of Q magnets(X2Q5). Separated and cleaned secondary isotopes are then guided to the HISS(heavy ion spectrometer system) experimental area by an ordinal beam line.

Fig.2 shows examples of the obtained secondary beams. The scatter plot between the time-of-flight(TOF) from F3 to F6 and the pulse height measured at F6 is shown. The primary beam of 800 MeV/nucleon ^{12}C and a primary target of 4.7 g/cm^2 Be were used. For Fig.2a, the beam line was adjusted to the particle with A/Z=3. Very clean signals of t, ^6He, ^9Li were observed. No mixture of the nuclei other than A/Z=3 was seen. Fig.2b is the data obtained for A/Z=1.8 beam. It is the most difficult case because the primary beam(^{12}C) is sitting next to ^{11}C with only 9% larger momentum. Our data shows that the beam line reduce the primary beam down to less than its 10^{-6} of original intensity. In fact we observed much stronger intensity of ^{11}C than ^{12}C. The ^7Be (A/Z=1.75) were also observed. It is natural because the momentum spread due to the production reaction makes ^7Be of same rigidity as ^{11}C.

3. A MEASUREMENT OF THE INTERACTION CROSS SECTIONS AND THE NUCLEAR RADII

We have proposed two experiments using those unstable nuclear isotopes at Bevalac. One is a measurement of the nuclear radii(E690H)[3] and the other is a meas-

urement of the magnetic moments of mirror nuclei in f-shell(E732H)[4]. Here in this talk I briefly describe a principle and a method of the nuclear radii experiment. Although the measurement of the magnetic moments will not be discussed here, the copies of the proposal of the experiment may be obtained from the author.

Many detailed studies of the nuclear size and shape of stable isotopes have been made by electro-magnetic probes and by nuclear probes. Among them the electron scattering gives most accurate information on the charge distribution over the wide range of stable nuclei. However only the radii of stable isotopes can be measured by the electron scattering.

The isotope-shift measurement has been extended to unstable isotopes, especially at the ISOLDE facility at CERN.[5] Interesting data have been obtained on the Hg-isotope chain, and on alkali isotopes.[6] The data have revealed a sharp shape transition to strong deformation at A=185,183,and 181. The isotopes in the vicinity of the magic neutron number N=82 also show a clear indication of the change of the shape.[5]

Although it already provides a challenging test of our understanding of the nuclear structure, the applicability of the method is restricted to nuclei of certain elements. An experiment was proposed in which we plan to determine the nuclear size by measurering the interaction cross sections with the beam of unstable nuclei.[8] The method makes it possible to expand the area of feasibility to a wide region in (N,Z) plane up to particle drip lines. The principle of the measurement is shown below.

The reaction, or more precisely the transmutation, cross sections have been measured using ^{4}He, ^{12}C, ^{14}N, ^{16}O, and ^{40}Ar beams of 1.05 and 2.1 GeV/A.[7] It is found that the cross sections can be expressed as

$$\sigma_r = \pi r_0^2 (A_p^{1/3} + A_t^{1/3} - \Delta)^2 , \qquad (3)$$

where A_p and A_t are the mass numbers of the projectile and the target nucleus respectively, and Δ is a parameter depend on $A_{min}=min(A_p,A_t)$. If we use r_0=1.29 fm and $\Delta=1.0-0.028A_{min}$ (with $\Delta=0$ for $A_{min}\geq 30$), the formula is known to fit the data within 10 % for all projectile and target combinations so far measured. It is also found that σ_r is independent of incident energy above 150 MeV/A. Supported by the energy

independence of σ_r, we can say that σ_r is directly related to nuclear radius. It has to be noted that σ_r was measured by a charge changing reactions, namely a nucleus is called as interacted when it changes its Z by a collision. To determine the nuclear radii, the interaction cross section(σ_I) , which is defined as the total cross section of the nucleon(proton and/or neutron) removal from the incident nuclei, is more appropriate.

In the experiment, we define effective radii in nucleus-nucleus collisions as

$$\sigma_I = \pi(R_p + R_t)^2 , \qquad (4)$$

where R_p and R_t are the radii of the projectile and the target nuclei, respectively.

Systematic change of R_p can be obtained by a series of σ_I measurements with the same target. The comparison of effective nuclear radii defined here and the RMS radius can be made by σ_I of the collision between two stable isotopes. Among them the interaction cross sections of the collisions between identical nuclei like ^{4}He-^{4}He or ^{12}C-^{12}C are the most important.

If we use the interaction cross sections so far measured[7], the nuclear radii R_I can be fitted by $R_I = 1.21A^{1/3}$. As shown in Fig.3 by a dashed line, the values lies about 0.6 fm above the half density radius line obtained from the electron scattering measurements except the lightest nuclei(d and ^{4}He). It shows that the present measurements are sensitive to the peripheral density distribution of nuclei.

Apart from the absolute values, the precise relative values of nuclear radii, obtainable over a wide range of isotopes and isotones, can give a systematic information which reflects effects of shell closure, deformation, and softness of aggregation of nuclear matter. It is expected to constitutes one of the most stringent test of existing nuclear structure theories when extended into exotic region of nuclei.

Acknowledgment

The beam line described here has become available by a support and a nice work done by the Bevalac and its staff. They are gratefully acknowledged. I would like to thank the member of the experiment for helping and for continuous discussion on the

subject. This work was supported by the Director, Division of Nuclear Physics of High-Energy of the U.S. Department of Energy under Contract DE-AC03-76SF00098 and by the Collaboration Program between Institute for Nuclear Study, University of Tokyo, and Lawrence Berkeley Laboratory.

References

(1) T. J. M. Symons,Y. P. Viyogi, G. D. Westfall, P. Doll, D. E. Greiner, H. Faraggi, H. J. Crawford, and C. McPorland, Phys. Rev. Letters 42 (1979) 40.

(2) D. E. Greiner, P. J. Lindstrom, H. H. Heckman, B. Cork, and F. S. Bieser, Phys. Rev. Letters 35 (1975) 152.

(3) H. Hamagaki, O. Hashimoto, T. Kobayashi, Y. Shida, K. Sugimoto, I. Tanihata, N. Yoshikawa, S. Nagamiya, N. Takahashi, O. Yamakawa, H. Crawford, D. Greiner, P. Linstrom, Proposal to Bevalac experiment (E690H) 1983.

(4) K. Asahi, T. Minamisomo, Y. Nojiri, H. Hamagaki, Y. Shida, K. Sugimoto, I. Tanihata, D. E. Greiner, and J. Symons, Proposal to Bevalac experiment(E732H) 1983.

(5) E. W. Otten, Nucl. Phys. A354 (1981) 471c.

(6) J. Bonn, G. Huber, H.-J. Kluge, V. Kope, L. Kugler, E.-W. Otten, and J. Rodriguez, J. of the Phys. Soc. Japan 34 suppl. (1973) 317.

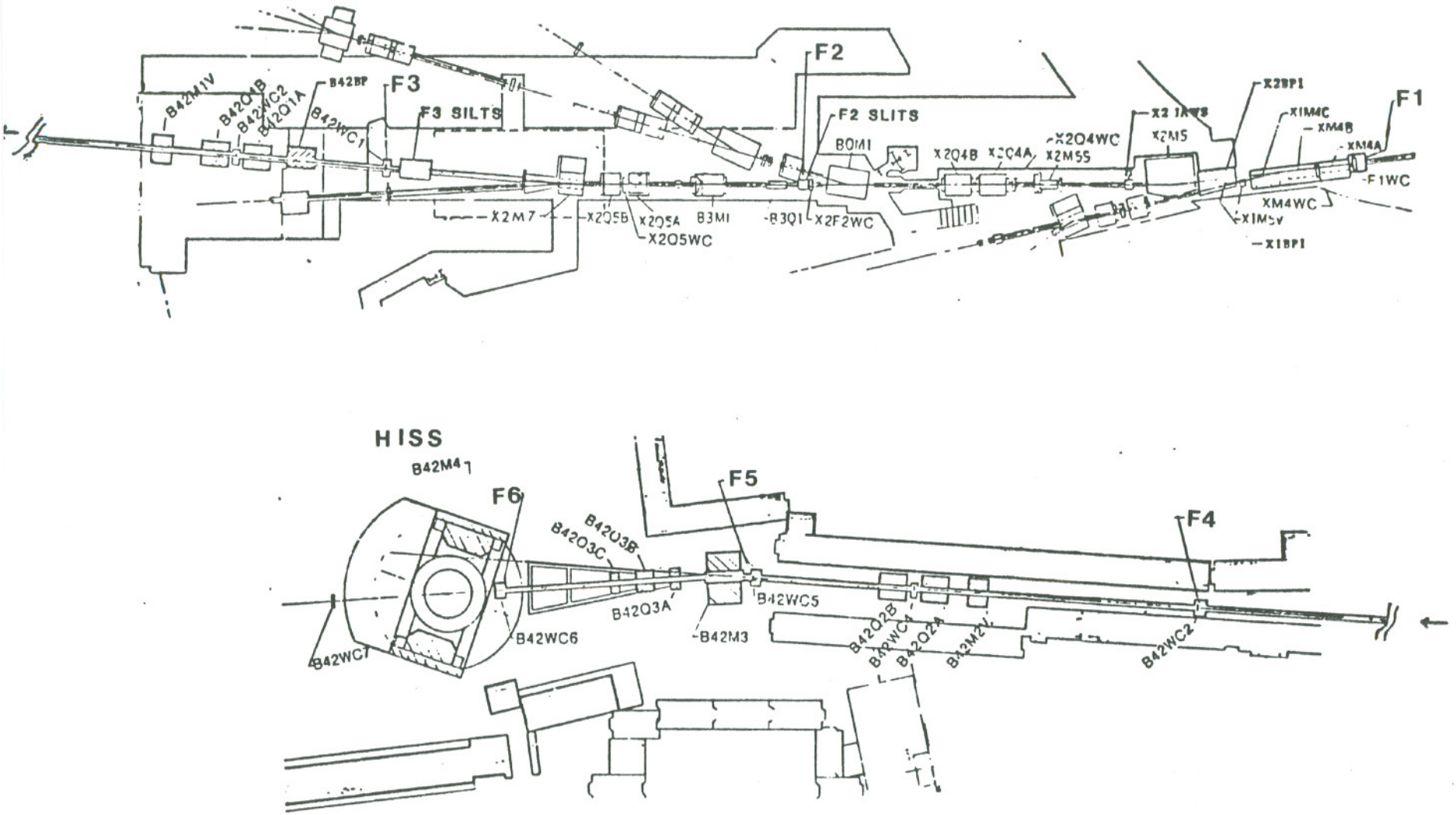
(7) H. H. Heckman, D. E. Greiner, P. J. Lindstrom, and H. Shwe, Phys. Rev.C 17 (1978) 1735.

Figure Captions

Fig.1 A schematic view of the secondary beam line at Bevalac.

Fig.2 Particle identification spectrum of the secondary beam line.

Fig.3 The effective nuclear radii calculated by the eq(4). The half-density radii measured by electron scatterings are also displayed. The figure is made from the Figure 2.0.1 of the article by H. R. Collard, L.R.B. Elton, R. Hofstadter, ed. "Nuclear Radii" H. Schopper, Landolt-Bornstein,New Series, Group1, Vol.2. Springer, 1969.


F1
F2
F3
F3 SILTS
F2 SLITS
F4
F5
F6
HISS
B42M1V
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B42WC2
B42Q1A
B42WC1
B42BP
X2M7
X2Q5B
X2Q5A
X2Q5WC
B3M1
B3Q1
X2F2WC
B0M1
X2Q4B
X2Q4A
X2Q4WC
X2M5S
X2M5
X2BP1
X1M4C
XM4B
XM4A
F1WC
XM4WC
X1M5V
X1BP1
B42M4
B42WC7
B42WC6
B42Q3C
B42Q3B
B42Q3A
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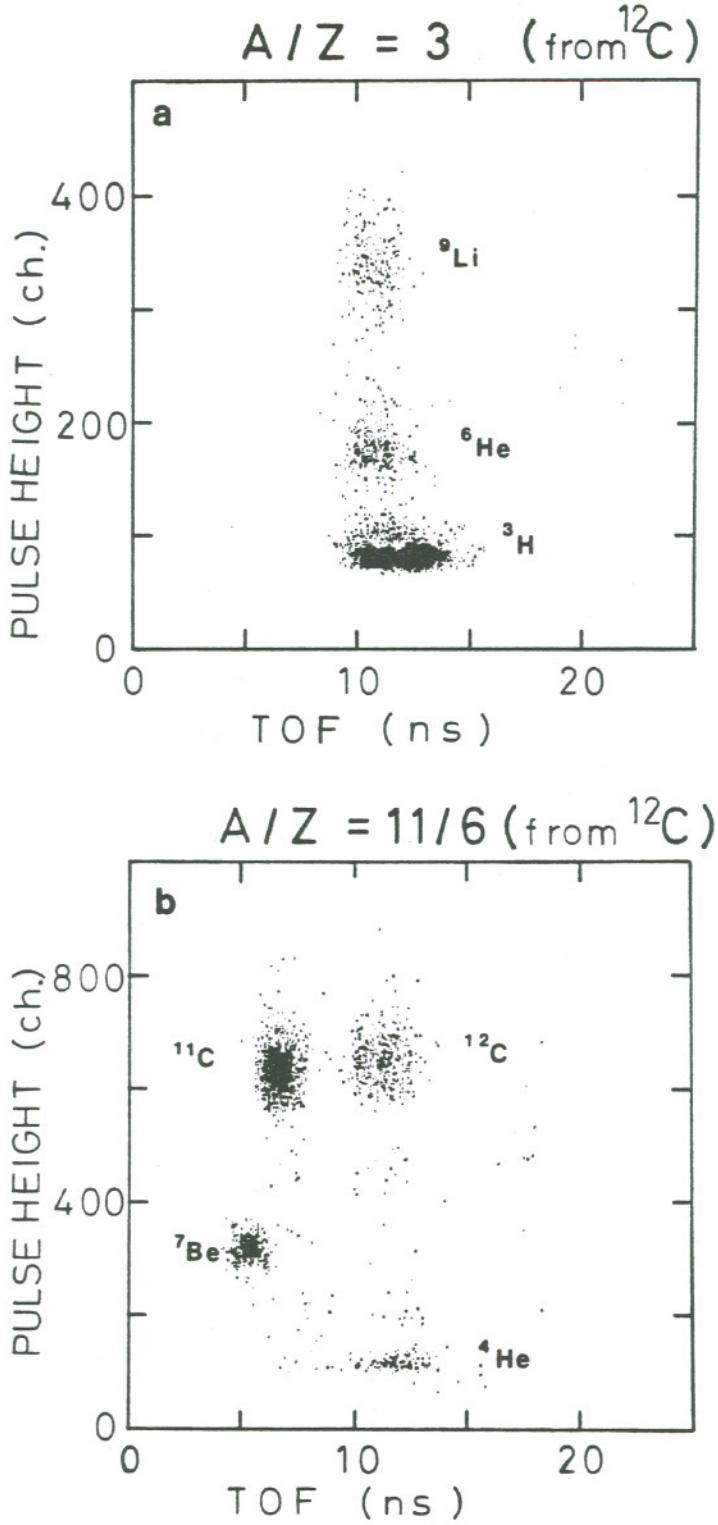
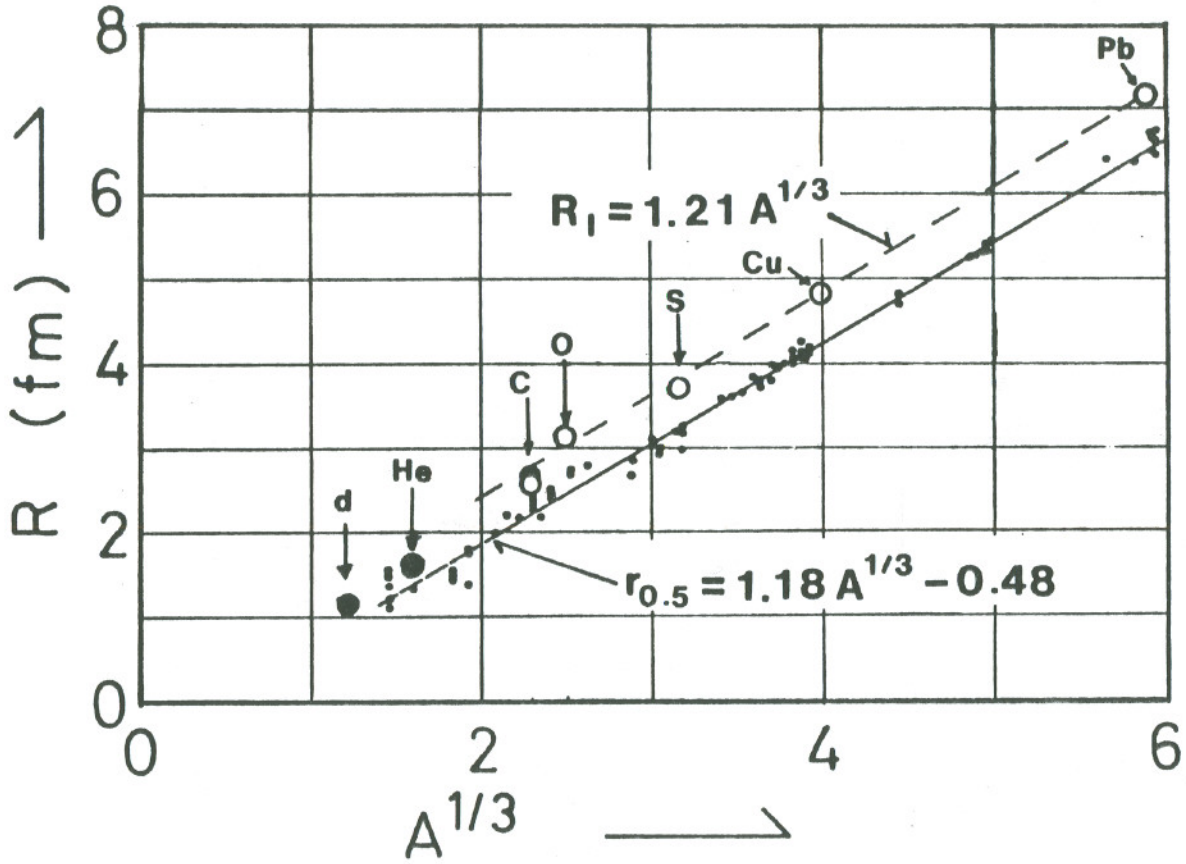
B42WC5
B42Q2B
B42WC4
B42Q2A
B42M2
B42WC2

Fig. 1



XBL 844-1428

Fig. 2



XBL 844-1419

Fig. 3

projectile fragmentation

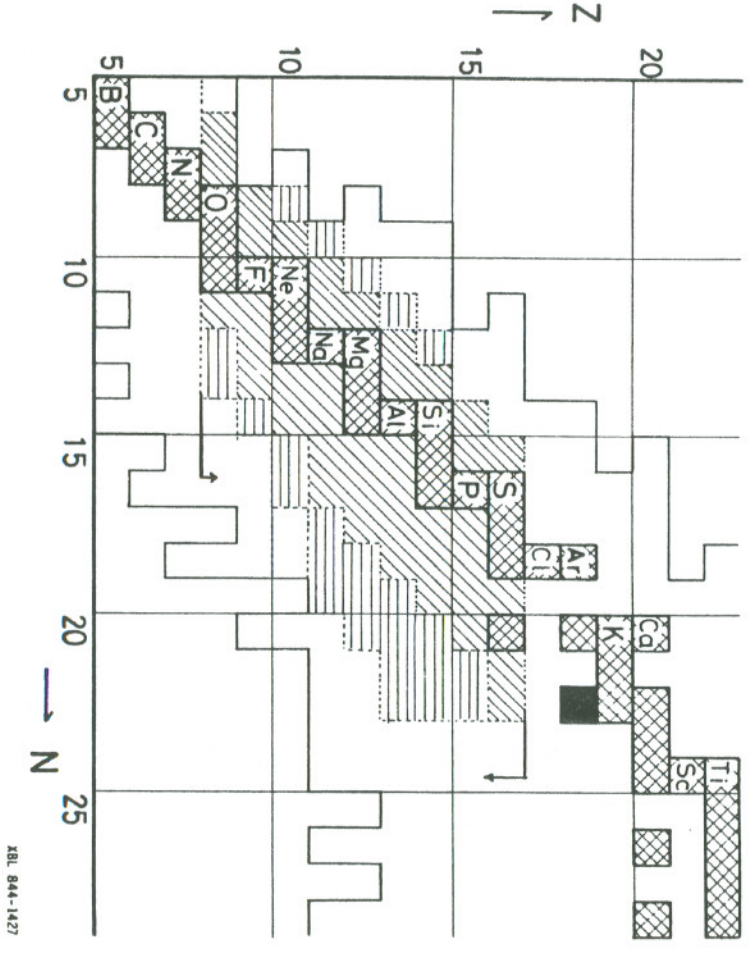
$E_{BEAM} \gtrsim 200$ MeV/nucleon

- Focusing

$$\left[\begin{array}{ll} \dfrac{\Delta P_{\parallel}}{P} & \sim 3\,\% \\ \Delta\theta & \sim 10 \text{ mrad} \end{array}\right.$$

- Intensity

$$\left[\begin{array}{lll} {}^{11}C & \sim 10^{9}\ /s & \text{from } {}^{12}C \text{ of } 10^{11}/s \\ {}^{9}C & \sim 10^{7}\ /s & \text{and } 5\,g/cm^2 \text{ Be target} \\ {}^{8}He & \sim 10^{4}\ /s & \end{array}\right.$$



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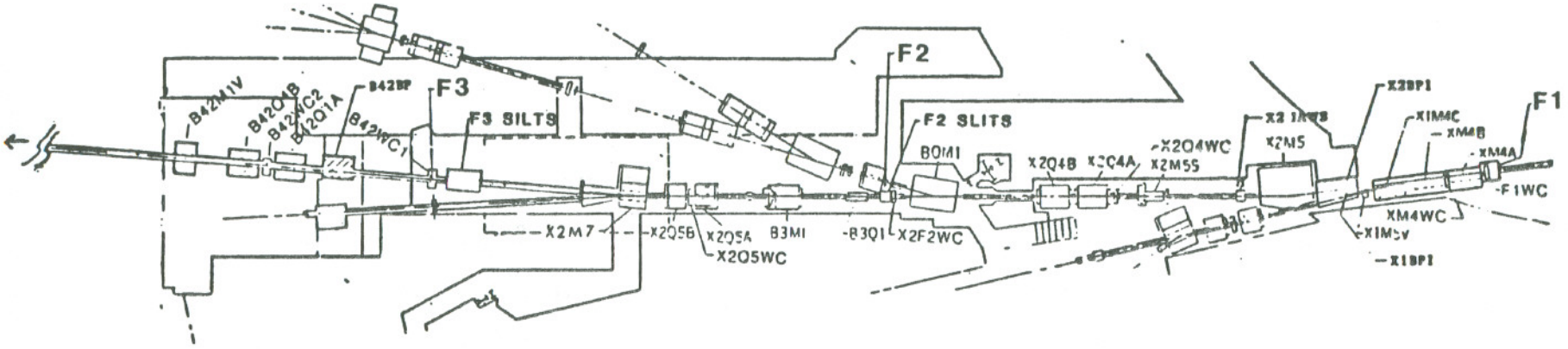
F1
F2
F3
F3 SILTS
F2 SLITS
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B42WC2
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X2M7
X2Q5B
X2Q5A
X2Q5WC
B3M1
B3Q1
X2F2WC
B0M1
X2Q4B
X2Q4A
X2M5S
X2Q4WC
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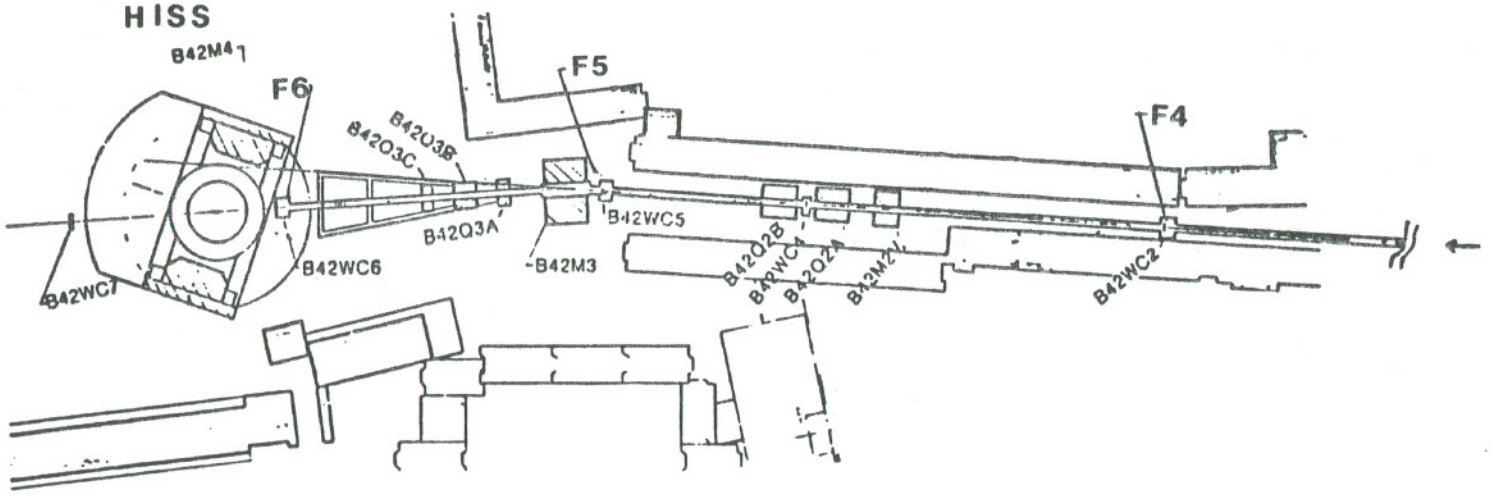
XM4WC
X1M5V
X1BPI


HISS
B42M4
F6
F5
F4
B42Q3B
B42Q3C
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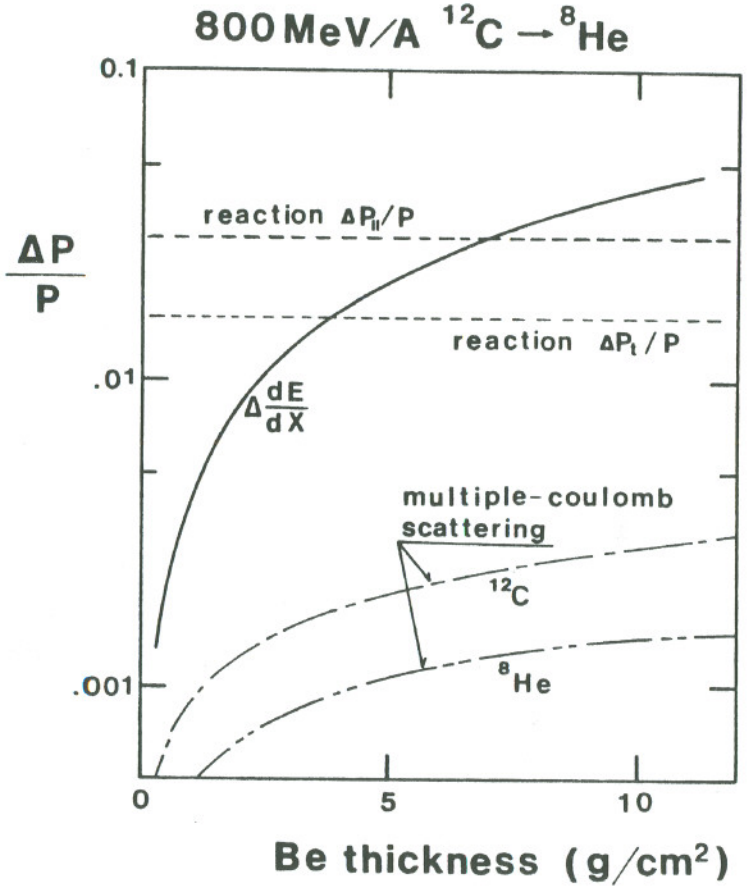
B42M2
B42WC2



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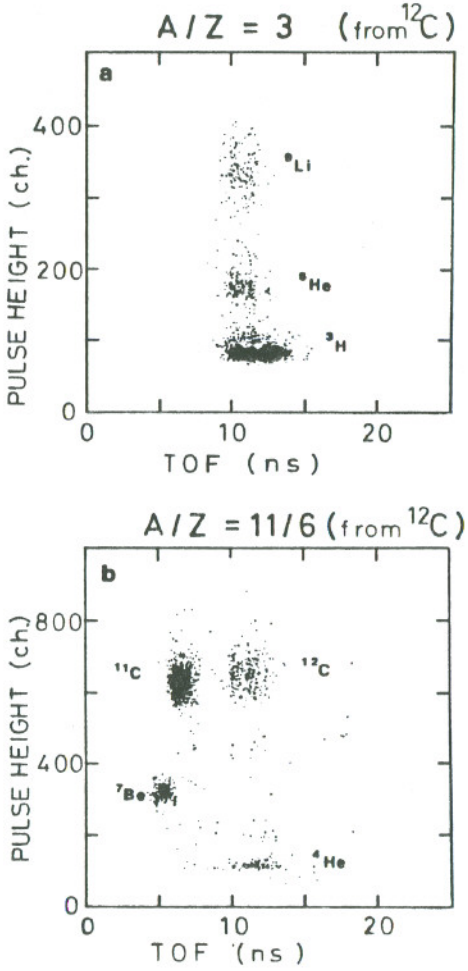

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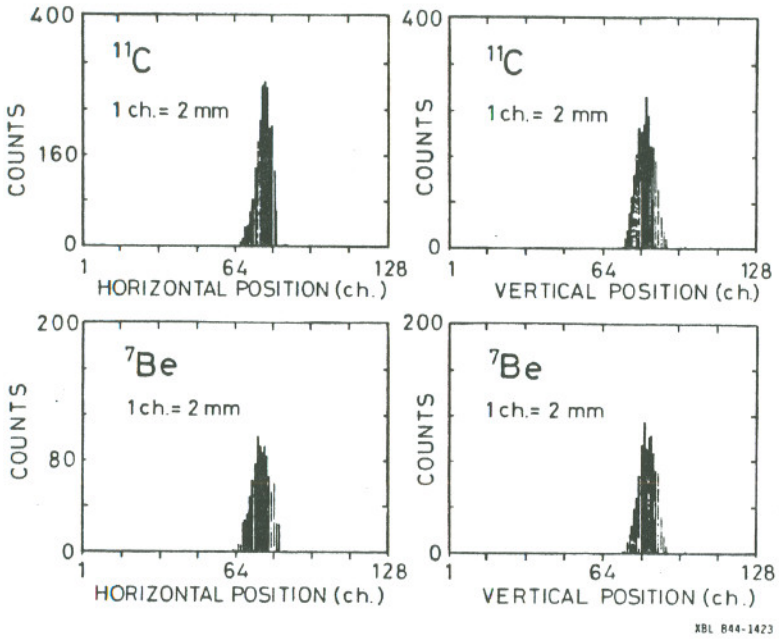
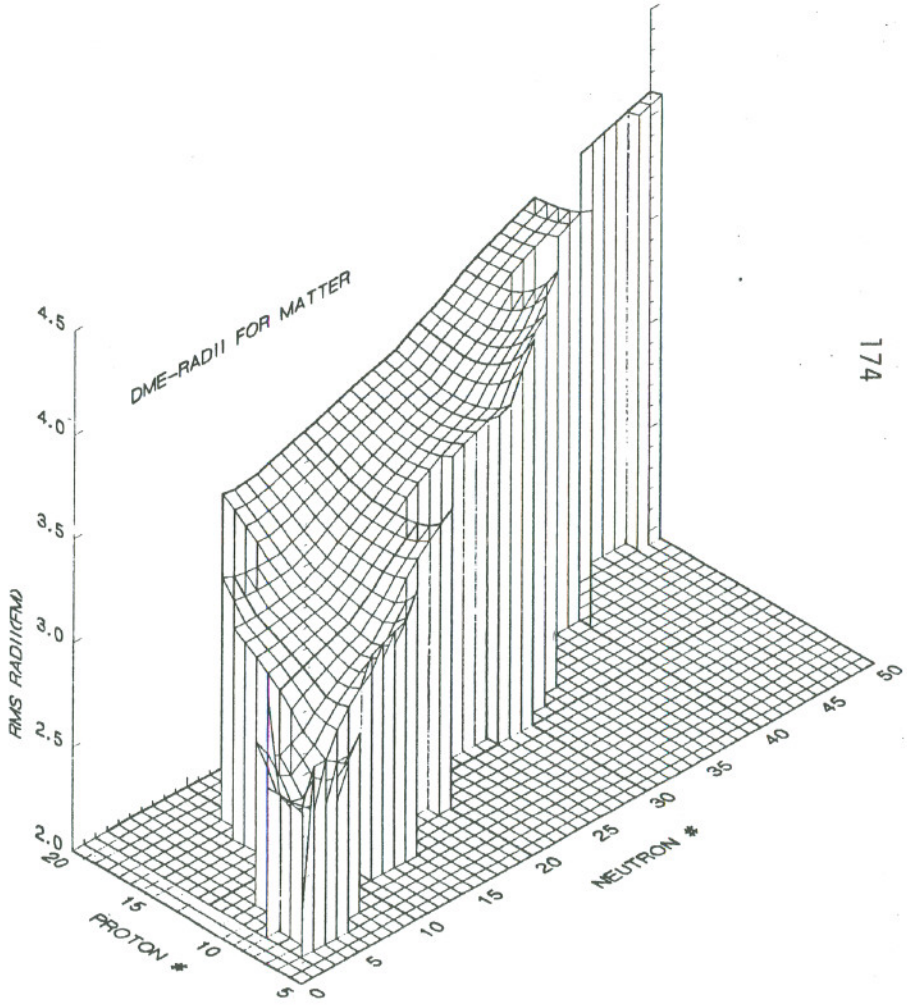

^{11}C
1 ch.= 2 mm
COUNTS
HORIZONTAL POSITION (ch.)
VERTICAL POSITION (ch.)
^{7}Be
XBL 844-1423


DME-RADII FOR MATTER
RMS RADII(FM)
PROTON #
NEUTRON #

- $\sigma_I = \pi r_0^2 \left(A_P^{1/3} + A_T^{1/3} - \delta\right)^2$

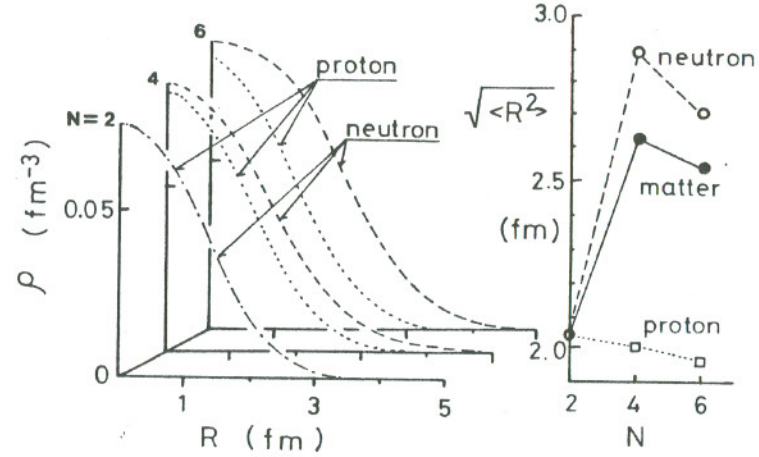
$$\begin{cases} r_0 = 1.31 \\ \delta = 1 - \min(A_P, A_T) * 0.028 \end{cases}$$

- σ_I : Energy Independent ($\geq$ 200 MeV/A.

$$\sigma_I = \pi \left(R_P + R_T\right)^2$$

Optical model

$$\sigma_I = \pi \left\{ r_{0.5P} + r_{0.5T} + \varepsilon \left(\frac{1}{r_{0.5P}} + \frac{1}{r_{0.5T}}\right) \right\}$$



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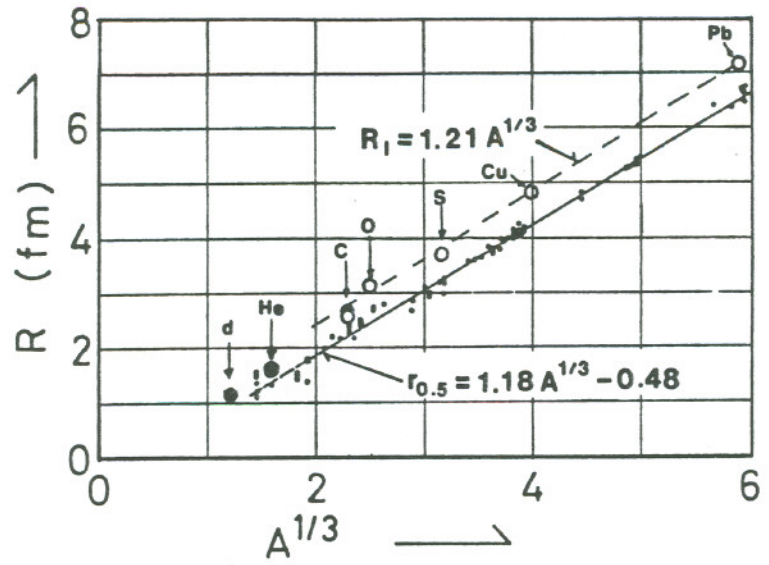
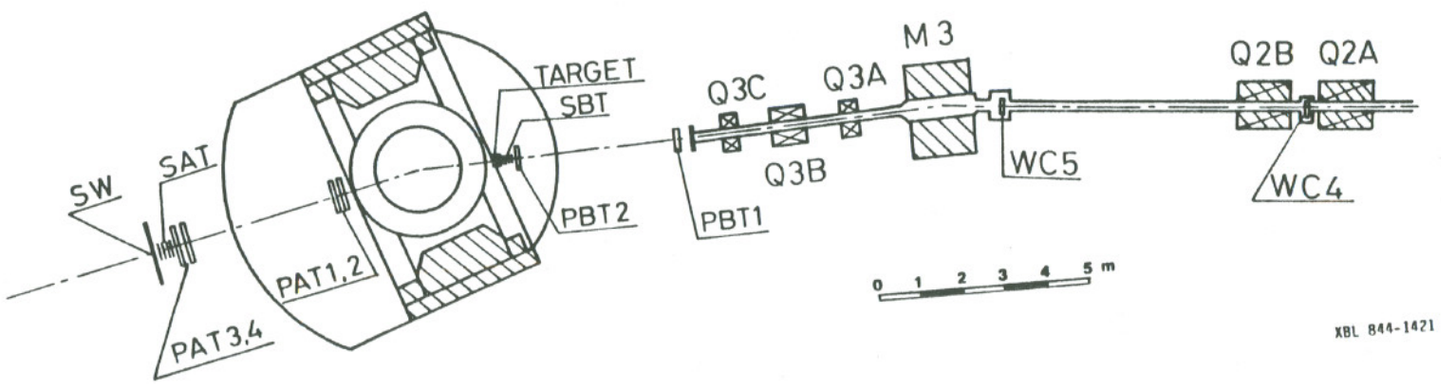


XBL 844-1419

Measured Attenuations by 2" Al target
(Survival rate)

^{12}C	0.624
^{11}C	0.656
^{7}Be	0.717
^{9}Li	0.609
^{6}He	0.527

E690H setup


HISS
SW
SAT
PAT3,4
PAT1,2
TARGET
SBT
PBT2
PBT1
Q3C
Q3B
Q3A
M3
WC5
Q2B
Q2A
WC4
0 1 2 3 4 5 m
XBL 844-1421

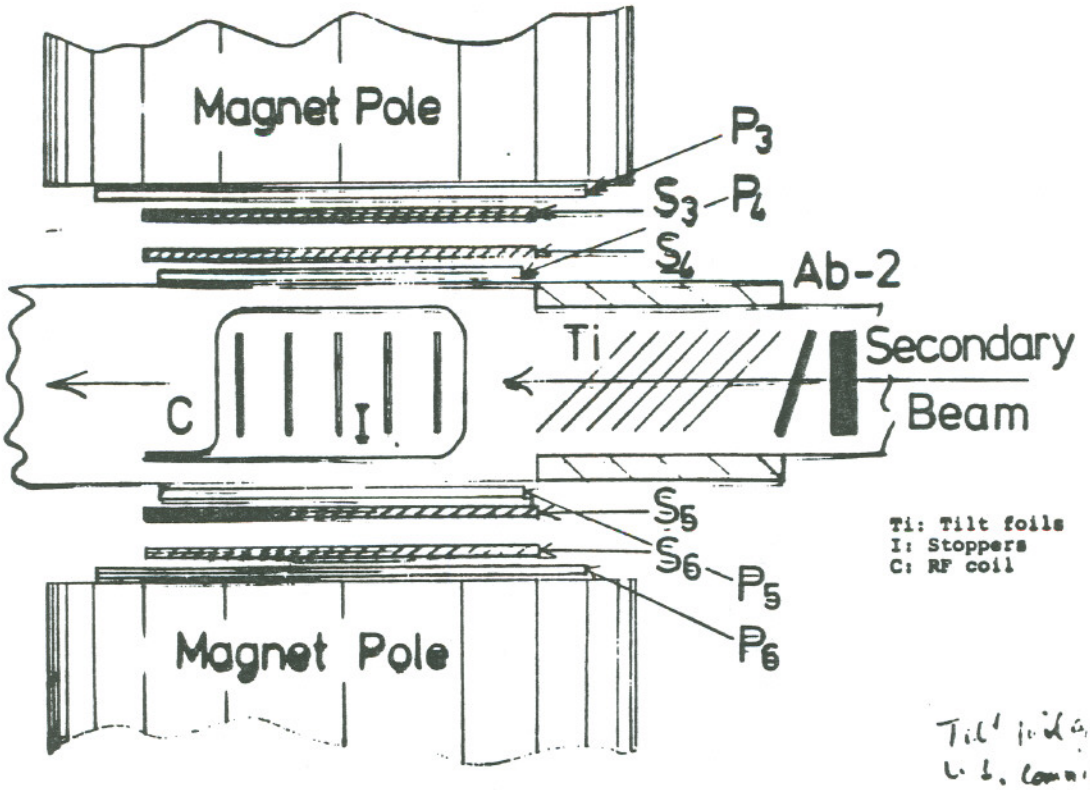
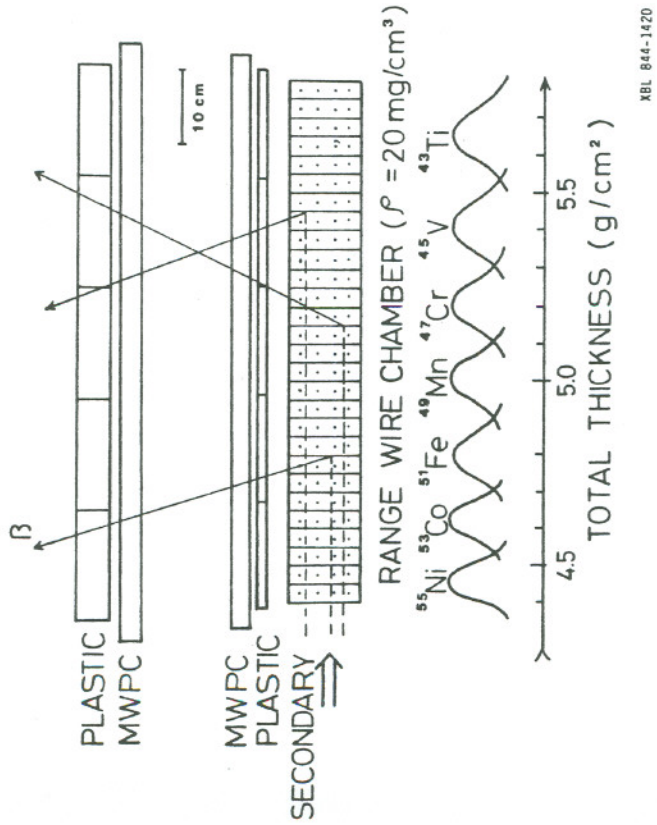


Fig. 2 Experimental setup for MWR.



PROSPECTS FOR RESEARCH WITH RADIOACTIVE BEAMS

FROM HEAVY ION ACCELERATORS WORKSHOP

Production of High Energy Radioactive Beams and Their Biomedical Applications

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The Bragg peak therapy of cancer patients with heavy charged particles requires precise localization of the Bragg peak on a tumor volume. From Fig. 1 we can see that heavy charged particles comparatively deposit a very small dose along their path except at the end of their range. Just near their stopping point there is a great increase in the deposited dose. Hence, a slight error in coinciding the Bragg peak with the tumor volume can cause severe underdosing of the tumor region and overdosing of the nearby critical organs.

For precise localization of the Bragg peak, one requires an experimentally measured value of the water equivalent thickness between the point of entry and the target volume. Between these two end points there can be unknown amounts of bone, tissue, sinus, air etc.

Presently used CT (computerized tomography) techniques may not be as reliable as desired, especially when there is a large amount of thick bone or air path. We have proposed a technique which uses high energy radioactive beam and a sensitive positron camera, which, we expect, will achieve the desired accuracy.

In this technique, radioactive particles such as ^{19}Ne or ^{11}C are used. Both of these particles decay by emitting positrons, which then annihilate

with the medium electrons to produce two gamma rays, separated by 180°. These gamma rays can then be detected in coincidence mode by a positron camera to locate their origin.

Radioactive beams, such as ^{19}Ne and ^{11}C can be produced as secondary particles from the BEVALAC through the process of projectile fragmentation in a nuclear interaction. A preliminary experiment (August, 1971) was done to determine whether cross sections for the multi-nucleon transfer process are large enough to have pure and high-energy radioactive beams. A slab of spectroscopically pure beryllium metal (impurities less than 0.1%) was used to stop 250-MeV/n nitrogen (^{14}N) particles. The slab was long enough to stop ^{11}C (half-life = 20.34 min) and ^{13}N (half-life = 10 min) particles produced in flight as a result of fragmentation of the main beam.

Activity from the beryllium catcher was analyzed by a scintillation spectrometer and confirmed the production of ^{11}C and ^{13}N. The thick target cross-sections for these processes turned out to be 17 ∓ 4 mb for ^{11}C and that for ^{13}N was 6 ∓ 1.5 mb (1). The details of the production of pure radioactive beams are described in an accompanying report by Alonso et al. In Fig. 2, the Bragg ionization curves of radioactive particles are presented. Though there is a small amount of impurities (^{17}F, ^{15}O) associated with the ^{19}Ne beam, they do not interfere in the application for Bragg peak localization because of very different half-lives. Also, their stopping points are different.

If ^{20}Ne is the therapeutic beam, then one can use ^{19}Ne for the diagnostic information. Similarly, for ^{12}C therapy beam, one can use ^{11}C as the diagnostic beam.

By adjusting the energy of the ^{11}C beam, one can image its stopping point by using a two-dimensional positron camera (Figure 3). A typical picture of such a stopping point is shown in Fig. 4 with the coordinates of the center of

the image recorded on the top left hand corner. The idea is to adjust the energy of the radioactive particles such that the coordinates of the center point of the image match with the coordinates of the center of the tumor volume. Since ^{19}Ne and ^{20}Ne have the same atomic numbers, the energy of the ^{20}Ne (therapy) beam has to be (19/20) times greater than the ^{19}Ne beam energy for Bragg peak to be localized. This procedure of localizing Bragg peak is on-line (in the treatment position), unlike in the situation with CAT scanner. The diagnostic dose with ^{19}Ne beam can be kept under 10 rads for the necessary diagnostic information. The radioactive beam technique has been applied and verified in live animals. Application to human patients is underway.

This work was supported by the U.S. Department of Energy under Contract Number DE-AC03-76SF00098.

Figure Captions

Figure 1 Bragg curve for the 400 MeV/u neon beam and a broadened depth-dose distribution in water.

Figure 2 Bragg ionization curve for radioactive beams. The respective widths of the peaks are quite narrow, indicating low momentum spread in the secondary beams has been achieved.

Figure 3 A picture of the positron camera (two-dimensional) is shown here. The crystals used in this device are bismuth germanate (BGO). There are 64 crystals in each bank, placed inside the rectangular boxes.

Figure 4 Image of a radioactive beam stopping point obtained with the positron camera is shown here. The beam was stopped in a head-like human phantom.

References

1. Tobias, C. A., Chatterjee, A., and Smith, A. R.. "Radioactive Fragmentation of ^{14}N Beam Observed in a Beryllium Target." Phys. Letters 73A, 119(1971).

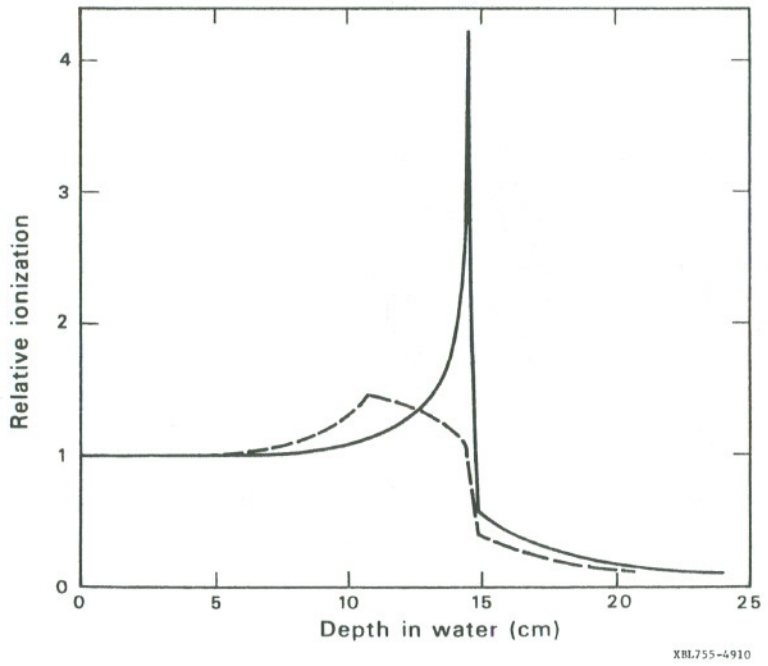

Figure 1.

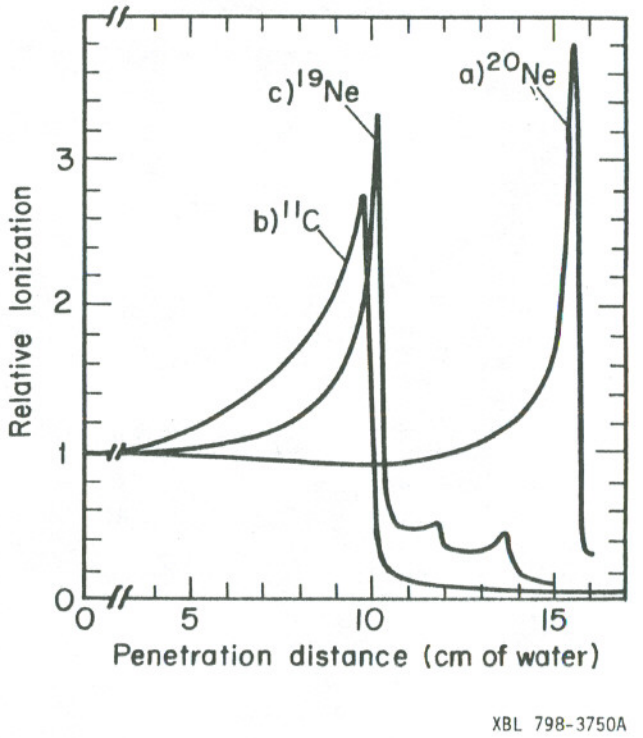

Figure 2

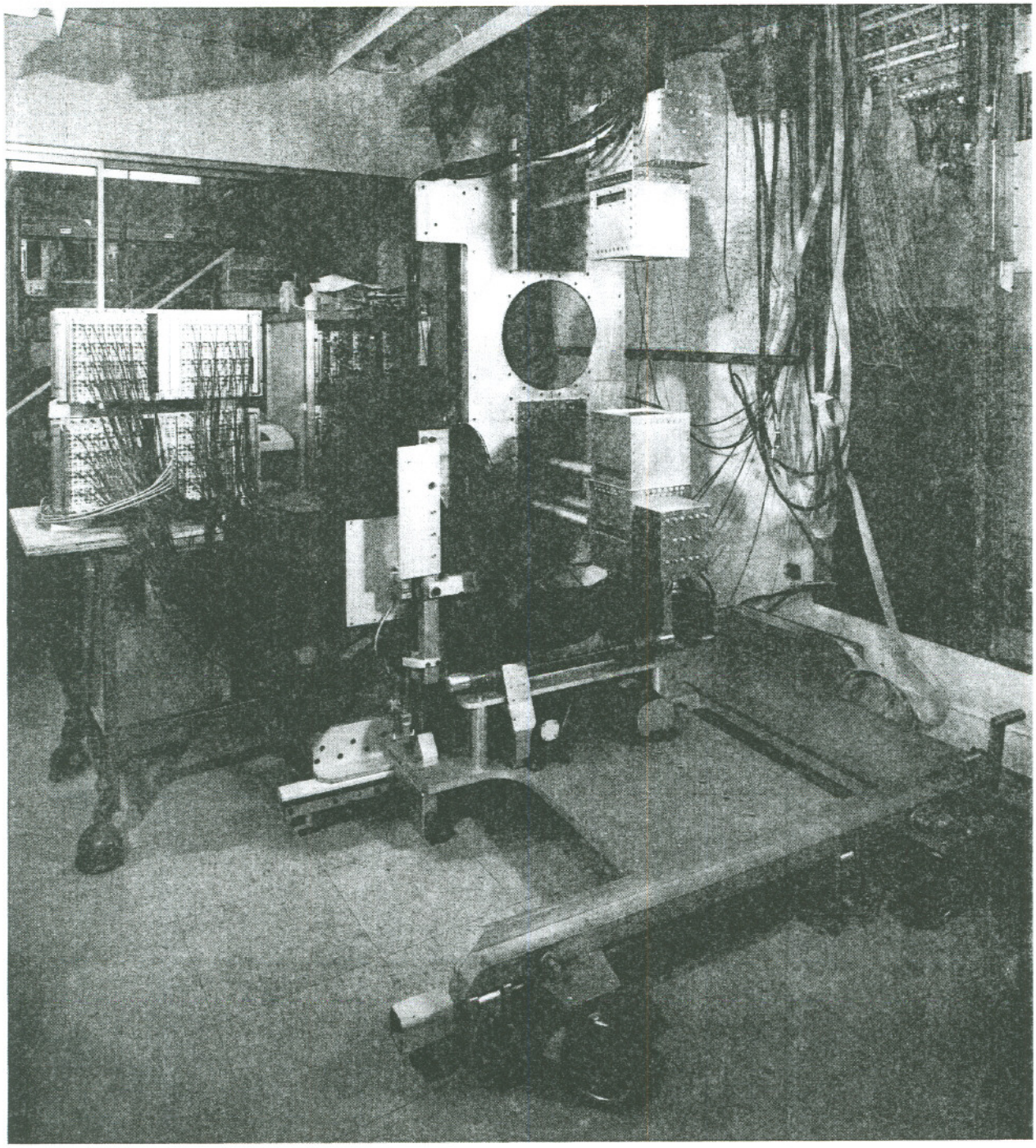

Fig. 3

CBB 831-292

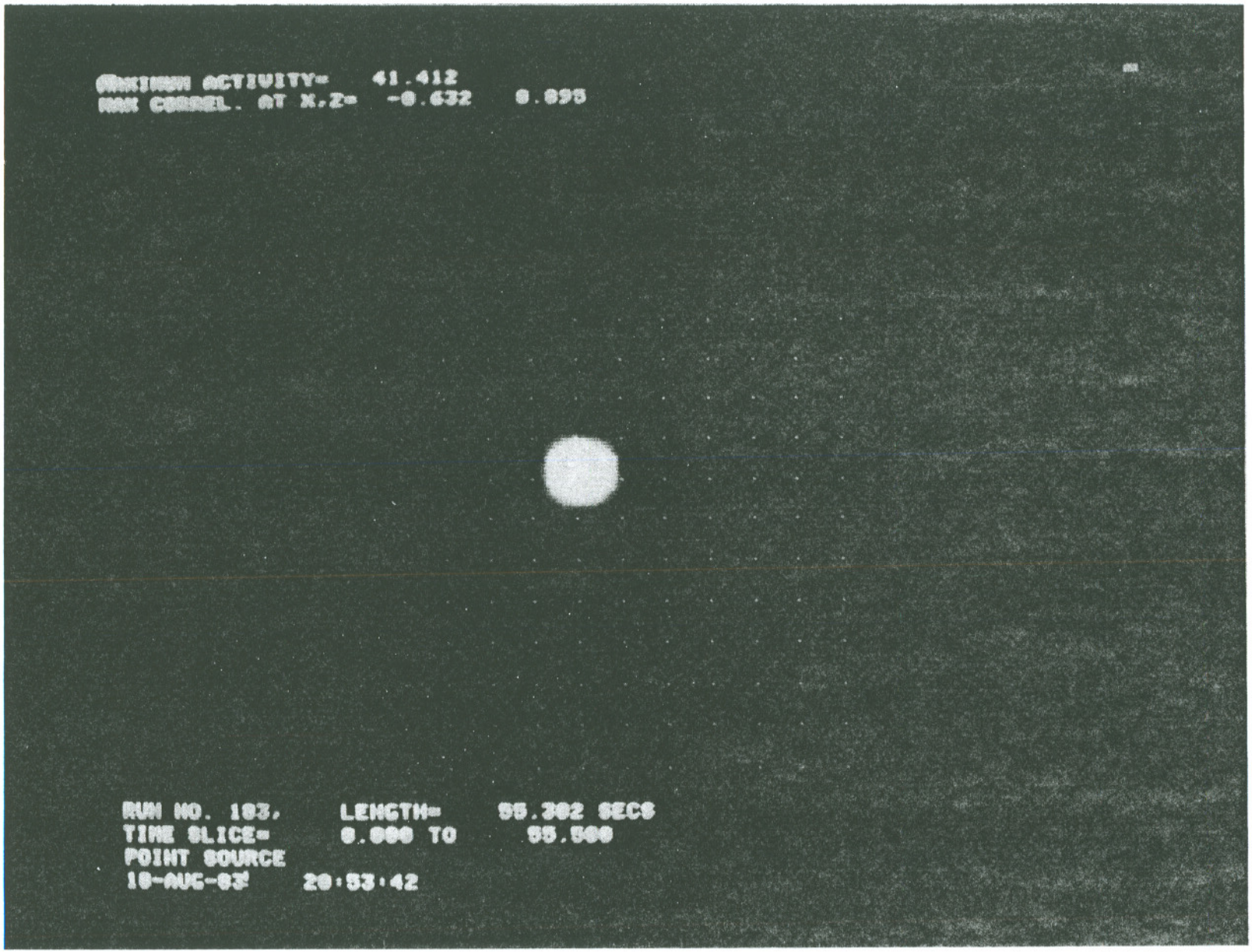

Fig. 4

XBB 839-8101

^{68}Ni SPECTROSCOPY WITH A ^{14}C BEAM

M. Bernas

I.P.N. d'Orsay - France

Radioactive beams of ^{14}C have been accelerated since a few years with tandem accelerators (Los Alamos, Munich, Orsay and recently Brookhaven). The ^{14}C beams have been used to populate exotic nuclei and it can illustrate how it opens new ways for exploring the continent of nuclei.

The ^{14}C beam energy delivered by the Orsay MP is 75 or 87.5 MeV and the intensity currently used some 1 to 5 $\frac{nA}{p}$; the two proton pick up (^{14}C, ^{16}O) transfer reaction clean because of the level structure of ^{16}O and easy because of Q value has been performed on the heavier bound isotopes of Se, Ge, Zn and Ni. Not populated by n induced fission process and far from the alcalin, this region of the map is still poorly known and we have measured or remeasured masses of nuclei such as ^{70}Ge, ^{74}Zn, ^{68}Ni, ^{64}Fe, using a spectrometer to determine the ^{16}O magnetic rigidities.

In order to accurately measure the forward angular distributions, a beam catcher system has been set up in the vacuum chamber of the magnet[1]. This set up allows to measure small angle cross sections, including 0°, with a rejection yield of $\sim 10^9$. It is used with a ray tracing system [2]. From the forward enhancement of the associated angular distribution, a spin 0^+ was assigned to the first excited state of ^{68}Ni, revealing reinforced shell closure effect for $N \doteq 40$. For the first time a spin assignement was performed from heavy ion transfer reactions [1].

The lifetime of this 0_2^+ ^{68}Ni state is large enough since it decays by conversion electrons or positron-electron pair emission. We have determined this lifetime form the measurement of the time distribution of electrons resulting from this decay. A pulsed beam of ^{14}C was sent on ^{70}Zn target, and a TAC was triggered by the ^{16}O associated with the 0_2^+ level and stopped by an electron detected in a plastic scintillator offering a large solid angle and a minimized back ground sensitivity. The 30 events associated with decay have been analysed in term of the Poisson law and have led to $\tau_{1/2} = 211 \pm 50$ ns[3]. This measurement provides a nice insight on the 0_2^+ , 0_1^+ wave functions.

Another example is provided by the ^{62}Fe nucleus spectroscopy. We have measured - with a 50 keV accuracy - the excitation energies of this nuclei. At G.S.I., with a ^{76}Ge beam sent on a heavy W target, deep inelastic transfer products

were separated by the on line mass separator. At mass 62, new lines with a unique period (.88 s) could be related to these ^{62}Fe excitation energies, and the decay spectra of ^{62}Mn was very accurately built up [4].

For (^{14}C, ^{16}O) the cross sections range between 1. to 0.1 mb/sr in the forward angles.

Three nulceon transfer reactions (^{14}C, ^{17}O) were also used to study nuclei poorly known as ^{67}Ni and ^{73}Zn. The cross sections are smaller than for (^{14}C, ^{16}O) by a factor of 5.

For the most complex transfer (^{14}C, ^{15}O), exchange of two charges and one mass unit, the cross section is found strongly Q dependant [5], and the study of more neutron rich nuclei, such as ^{69}Ni and ^{75}Zn becomes very difficult ($\sim$ 100 nb/sr).

All these measurements were made easier or possible by the use of mass separated targets prepared at the C.S.N.S.M. of Orsay. The occurence of isotope contaminants of a few % produces unwanted peaks larger than the ground state peak. Therefore radioactive targets would have to be mass separated and with the thickness of $\sim$ 100 ngr/cm^2, mentioned earlier in this conference, the transfer of more than one nucleon would be very difficult.

However targets as ^{60}Fe (.310^5 years) ^{32}Si(330 y.) ^{28}Mg (21 hours) and ^{38}S (2h.50) are in the range of feasibility.

With an improved control of the small electrostatic accelerators primary radioactive beams can provide the low energy intense beams necessitated for astrophysical purposes in the near future. Secondary beams will always suffer from the large conversion factor 10^{-4} to 10^{-5} necessarily involved but will allow to extend further from the stability line.

REFERENCES

1) M. Bernas, Ph. Dessagne, M. Langevin, J. Payet, F. Pougheon and P. Roussel
Phys. Lett. 113 B, 4 (1982) 279

2) P. Roussel et al
Nucl. Inst. and Meth. 153 (1978) 111

3) Halflife of the first excited state (0^+) of ^{68}Ni
M. Bernas, Ph. Dessagne, M. Langevin, G. Parrot, F. Pougheon, E. Quiniou and P. Roussel, submitted to Phys. Lett.

4) E. Runte et al, Nucl. Phys. A399 (1983) 163

5) Ph. Dessagne et al, To be published in Nucl. Phys.

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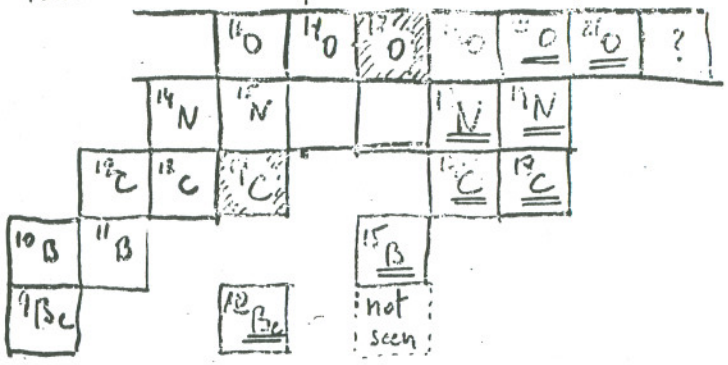
Visiteurs J. C. Peng (Los Alamos)

* students

Quasi elastic transfer at the M-P. tandem with ^{14}C and ^{18}O incident beams have provided masses and spectra of those isotopes;



Need of neutron rich nuclei projectile or target

① target : refering to the target

thicknesses of 100 mgr / cm² → only 3 new masses

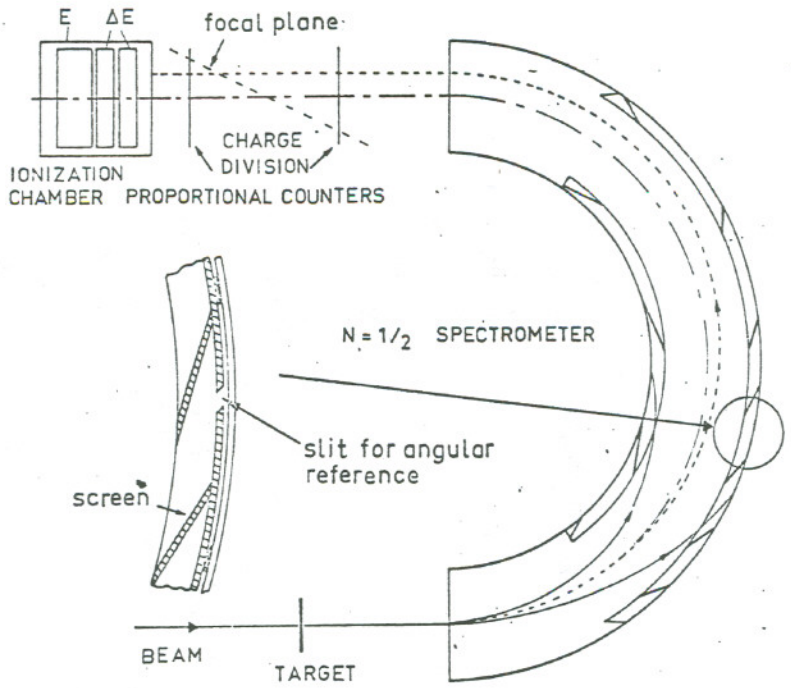
which targets may be considered? With ≈10 μgr/cm² → 5 more new masses

- ^{60}Fe ~ 10^5 ans.
- ^{32}Si 101 ans
- ^{28}Mg 21 h
- ^{38}S 2h 50

② With secondary radioactive beam, lumi-nosity is reduced by ~10^4. . little chance for Q.E. transfer

or primary radioactive beam; ^{60}Fe or ^{32}Si accelerated in a tandem.

or multiplication of beam collisions with the target

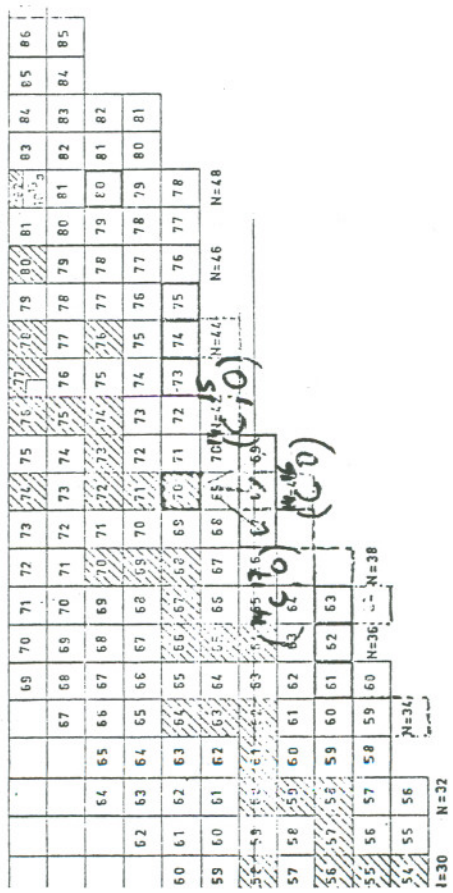


$\delta \Delta E \sim 1\%$ of ΔE
$\delta E \sim 2\%$ of E
$\delta \theta \sim 0.2°$
Rejection yield of primary beam $\sim 10^9$ -

$\Delta\Omega = 5 \text{ m} \, 57°$
$\Delta\theta = 5°$

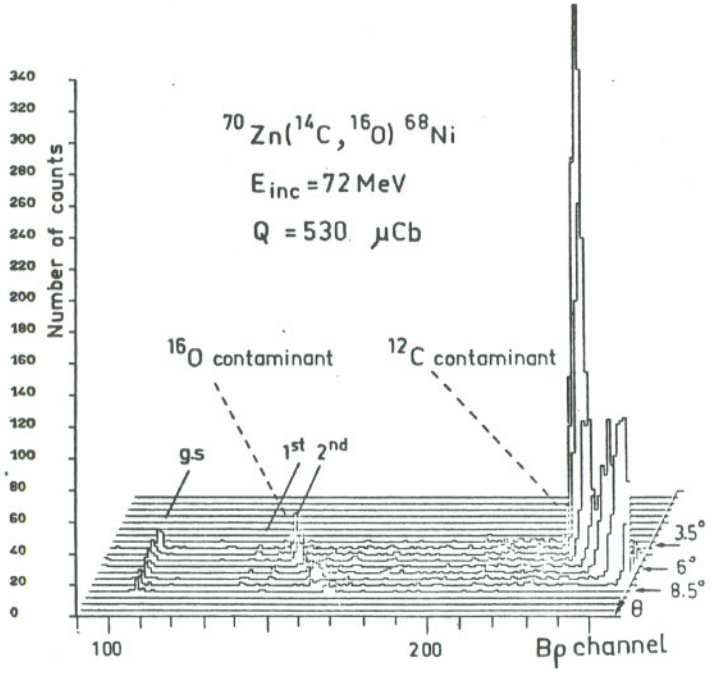
$\frac{\Delta E}{E} \simeq 2 \frac{\Delta p}{p} \sim 14\%$ in the magnet -

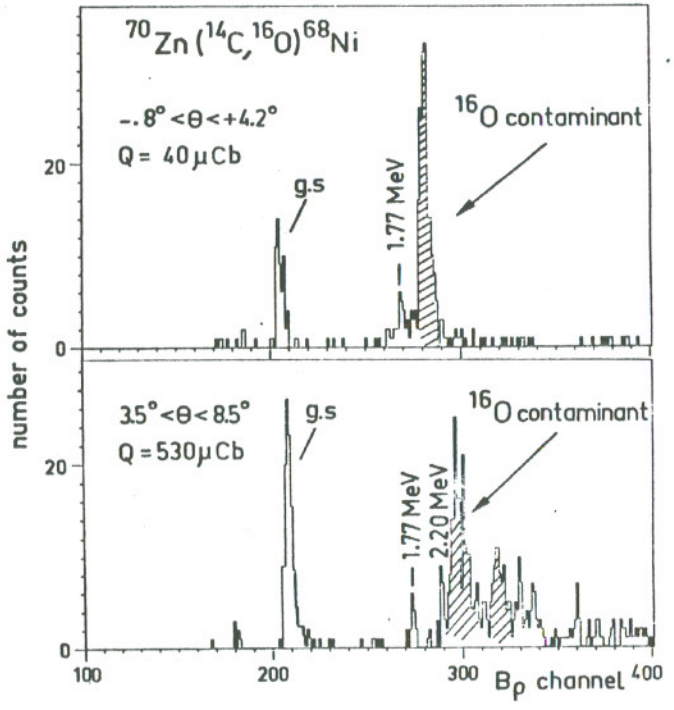
experimental set-up for 0° measurement of transfer reactions.

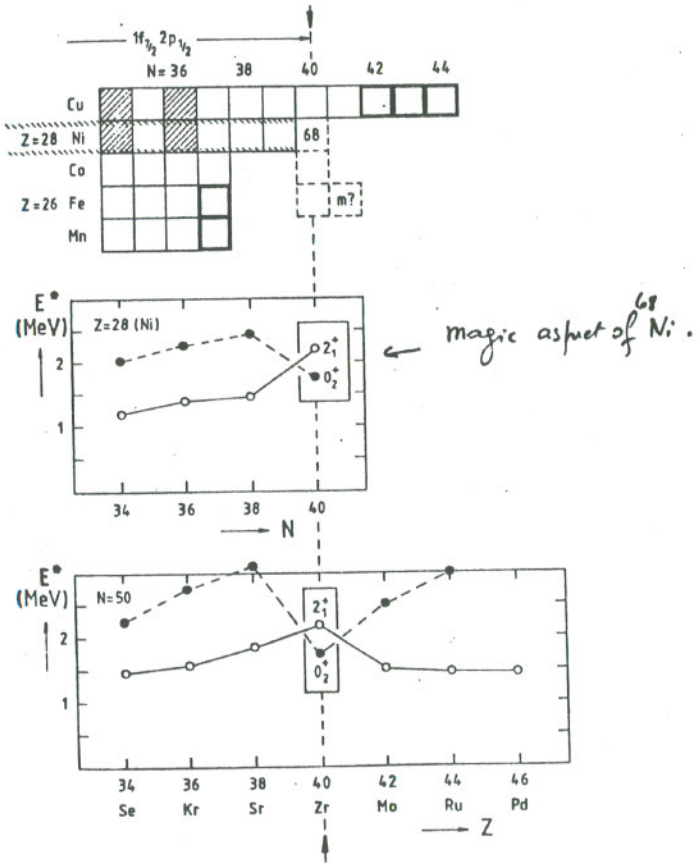


For intermediate nuclei, the neutron rich isotopes are not known since they are not produced by fission and far from the lines of element ~~m~~ efficiently mass separated.

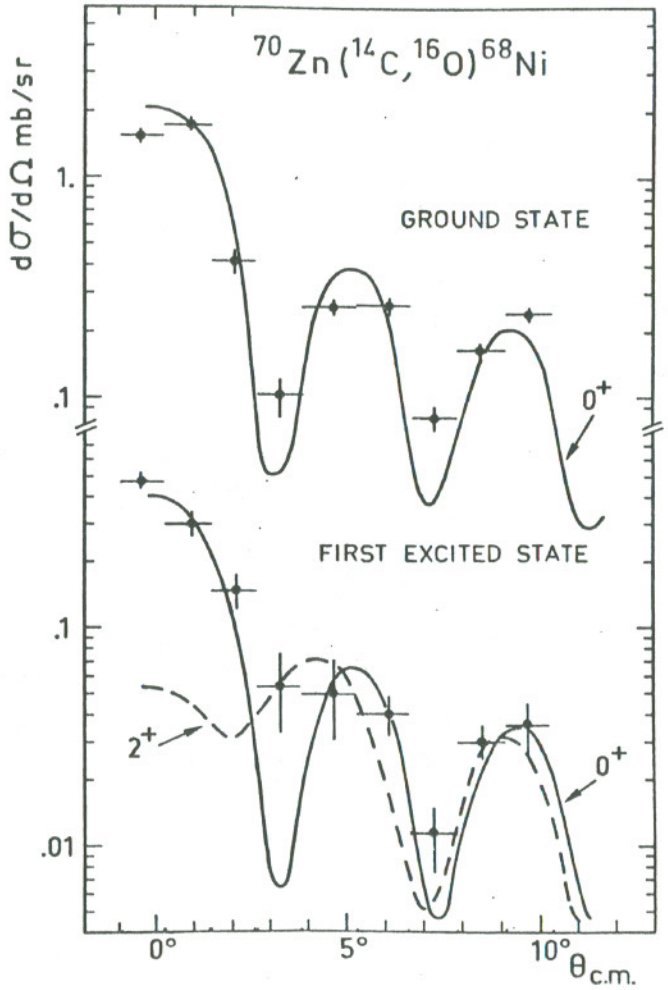
→ These Q.E. transfer reaction still bring valuable information


$^{70}Zn(^{14}C,^{16}O)^{68}Ni$
E_{inc} = 72 MeV
Q = 530 μCb
Number of counts
^{16}O contaminant
^{12}C contaminant
g.s
1st
2nd
3.5°
6°
8.5°
θ
Bρ channel


$^{70}Zn(^{14}C,^{16}O)^{68}Ni$
-.8° < θ < +4.2°
Q = 40 μCb
g.s
1.77 MeV
^{16}O contaminant
3.5° < θ < 8.5°
Q = 530 μCb
g.s
1.77 MeV
2.20 MeV
^{16}O contaminant
number of counts
Bρ channel



magic aspect of ^{68}Ni.



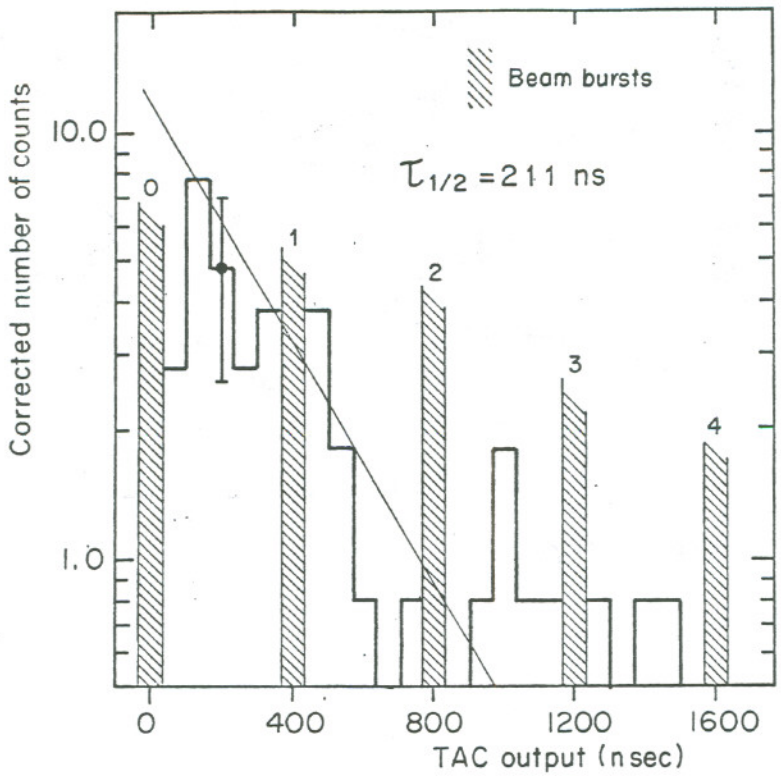
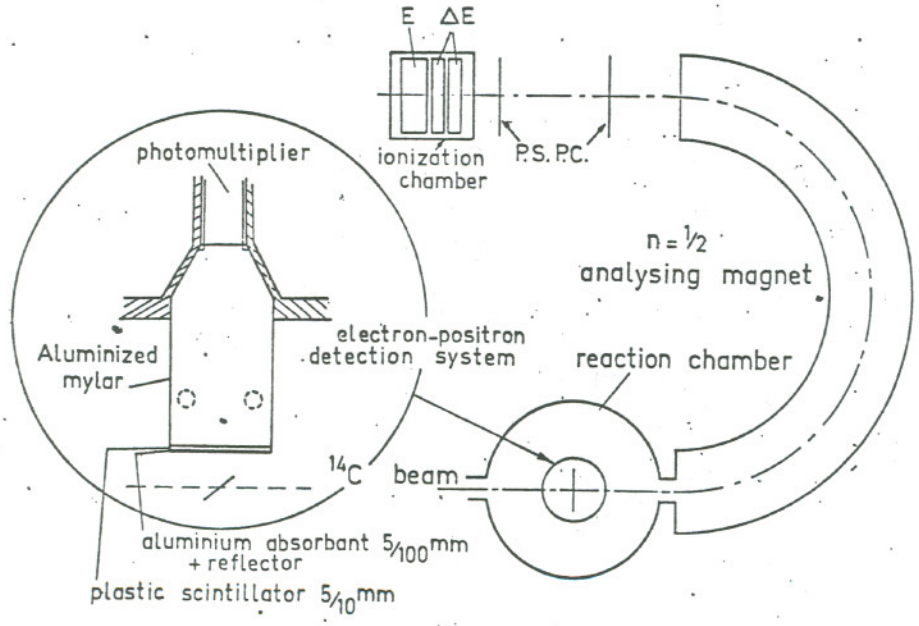


Fig. 2



experimental set-up for measurement of time distribution of E associated to $0^+ \to 0^+$ decay of ^{66}Ni

Complementary spectroscopic investigation

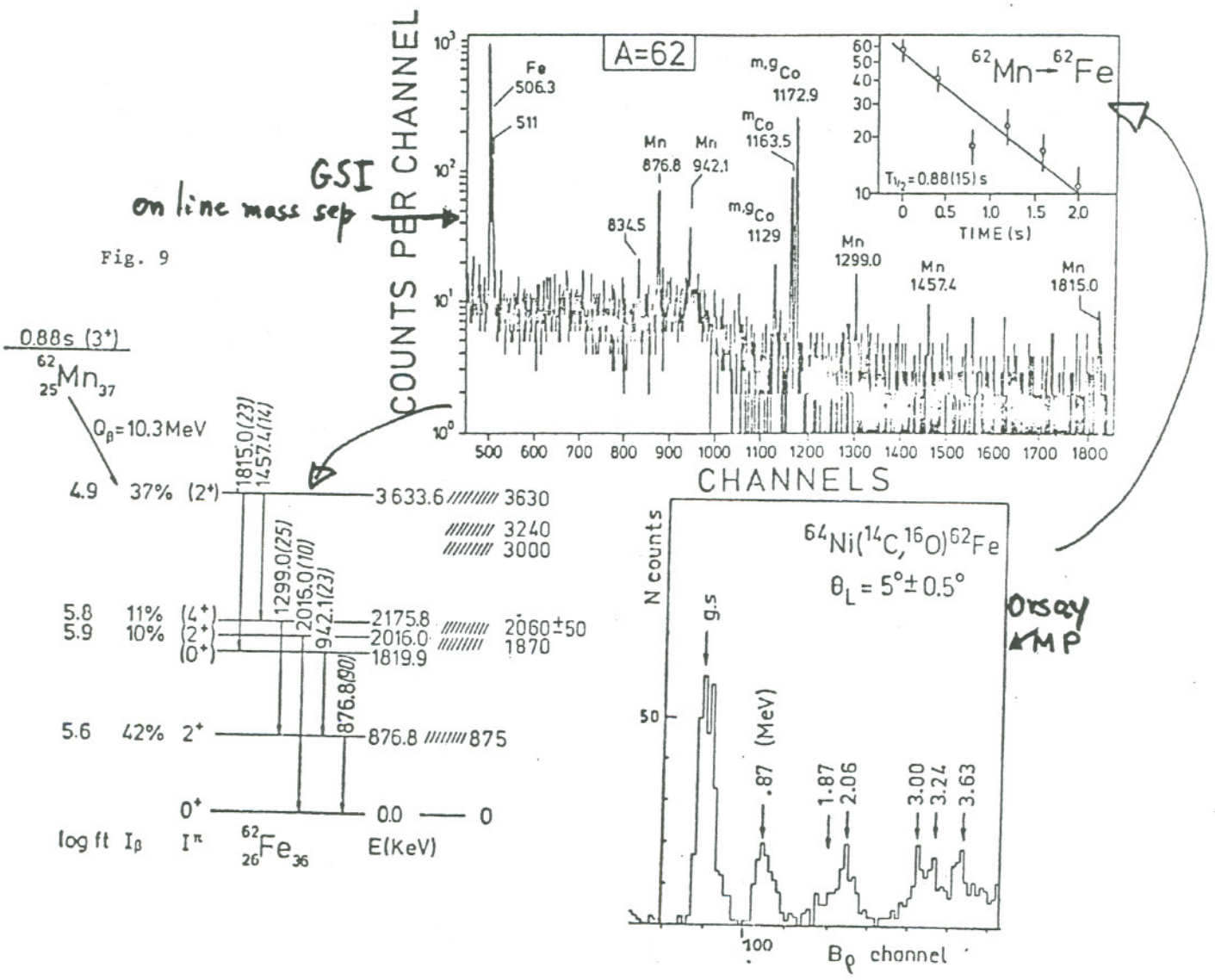
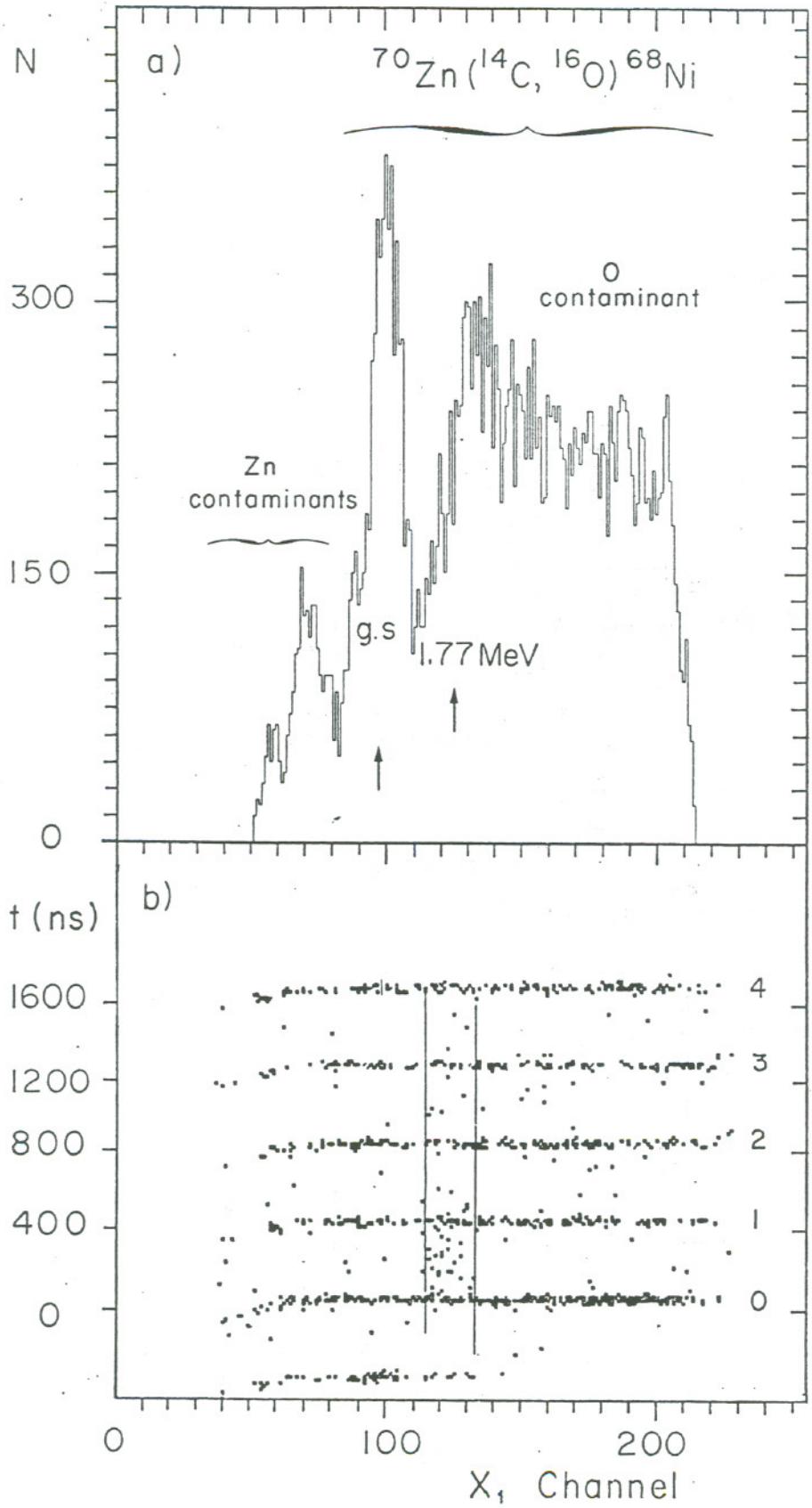


Fig. 9


N
a)
$^{70}Zn(^{14}C, ^{16}O)^{68}Ni$
300
150
0
O
contaminant
Zn
contaminants
g.s
1.77 MeV
t (ns)
b)
1600
1200
800
400
0
4
3
2
1
0
0
100
200
X_1 Channel

$^{27}Al + \alpha \rightarrow {}^{30}P^{*} + n$

First "exotic" nuclei

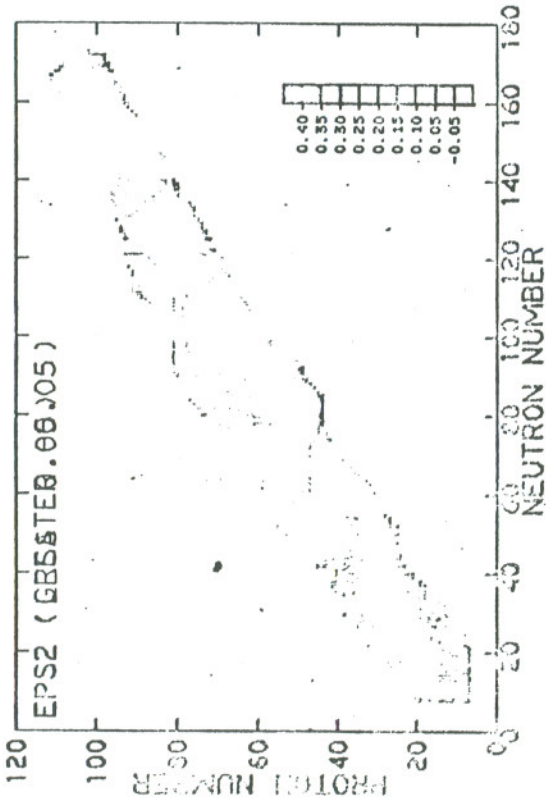
$\hookrightarrow {}^{30}Si + \beta + \nu$

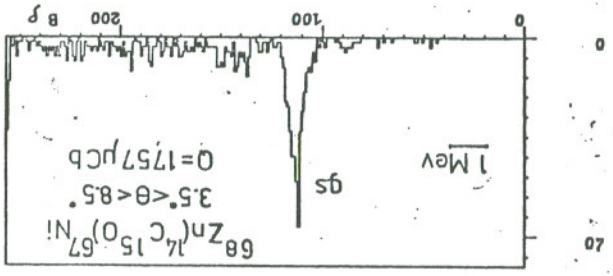
$^{13}N^{*}$

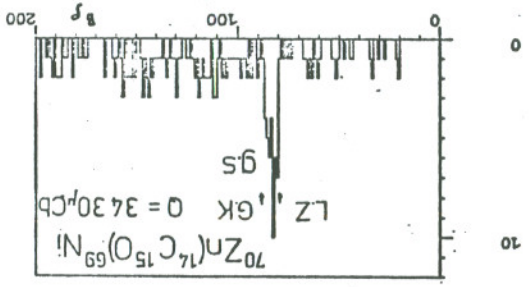
50 years ago.

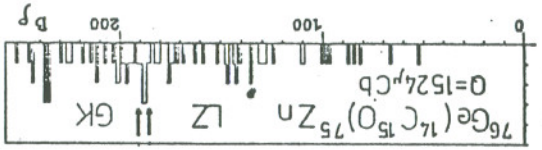
Frederic & Irène Joliot.

Future as dreamed by P. Möller









further exotic species.

DISCUSSION

Nitschke: Before we start the discussion, Peter Armbruster from GSI has agreed to say a few words about their recent plans of extending the UNILAC to higher energies with the addition of a synchrotron and a storage ring.

Armbruster: Let me start out by saying a few words about the SIS-18, the synchrotron ring, which will accept beams of up to 18 teslameter. This synchrotron was part of our proposal during the last years already; it was actually the first accelerator which was proposed after the UNILAC by Professor Schmeltzer in 1978 before he left. The last five years we had long debates on how to proceed and the version which came out now, is to build the best possible machine for future injection into a real high energy superconducting collider system which is not shown here and which will not be ready before 1995, and which is not now part of our plan. The machine we are building now should give us a good injector for a machine where we can have colliding beams with energies between 20 and 30 GeV/nucleon. That's the goal which will be reached perhaps in 10 years if we succeed with these things here. To repeat once more, this is what we have and this is what we want to get in the next five years: the area (of the accelerator and the storage ring) is about the ratio of the costs of the two machines and so you see it's a rather expensive thing. We are going up to 1 GeV/nucleon with this synchrotron; this synchrotron is already a rather big project. The new thing which was not on our project (previously) is the biggest experiment we will undertake in the next five years--to try to store heavy ions. We call it the experimental storage ring. One has to consider that such a storage ring is a new technique; it will open up many new experimental possibilities, but for heavy

ions such a storage ring has not worked so far and it is an experiment in itself and all experiments may fail. In case we succeed we will be able to store ions in this ring which has half the diameter of the SIS-18, we can for instance store bare uranium ions and we can use this ring as a stretcher. It has rather good beam quality already in the synchrotron also has good time structure and we can use this facility to make high intensity beams--beam pulses--which are important in applied projects like for instance in fusion studies. Inertial fusion studies will be part of this game. What is interesting for this group: we think we will put a fragmentation separator somewhere here and then try to catch these fragmented beams, these radioactive beams, in the storage ring and try to cool them down stochastically and get a really good beam quality which will also be achieved with electron cooling. This is also being used for the uranium beam which we have in normal operation. And so these beams then can be stored, and this ring is able to accelerate a little bit and also decelerate downwards again and so the idea which is the most fancy one is to use the de-accelerated beams here and go back to energies near the Coulomb barrier and then use internal targets. We have heard that this idea was already presented, and you may gain with an internal target about a factor of over a thousand; this is perhaps one of the decisive factors which we are still missing.

I would like to say a word about the fragmentation separator, which has already been mentioned by Jose Alonso and Jean-Pierre Dufour, what such a separator could look like. I think the problem is that there are some cases--if the fragment products have the same velocity and the same E/q, just with a magnet you cannot separate them. In this case it helps that you have a first magnet and then an absorber with a wedge and then have a second magnet...which allows you to have something similar to what was done in Berkeley or proposed by Dufour...to do

experiments here or bring them (the radioactive beams) to the storage ring. So there are three games we will play with these beams: we will use them with external targets--OK--and there I think with 10 milligrams per square centimeter we can get a secondary beam of 10^7 per second; and say in a normal Coulomb excitation experiment you get about 100 counts. And then I mentioned internal targets--internal targets in the experimental storage ring--the advantages are the higher rates, but you have to reduce your target thickness from the 100 microgram region to 10 nanograms; there you loose but you turn around 10^6 times per second and you increase the efficiency about--by a factor of 10 to 10^3 depending on the target thickness.

Now about fusion ..., about which I'm asked very often: I'm very pessimistic of fusing these kind of beams to go in the field of superheavy element productions. There are other interesting things to be done in physics but to start experiments where you have nanobarns to 100 picobarns cross section is really not very advisable. This is very very far away and we will concentrate certainly on experiments with lighter ions, and not push too far--it will just be a continuation of present work.

I also wanted to say that I was very happy to be here to profit from the discussions, and it will help us to support our efforts in Germany. Our enthusiasm is based on the fact that there is a lot of good physics to be done.

Nitschke: We would like to proceed now with the discussion, and, if you permit, I have one question that has been on my mind for some time, as you might already have guessed from my talk: whether we have discovered either by thinking at home or from what was presented here that there is enough physics to warrant the planning of a dedicated radioactive beam facility. Originally this idea was brought forth several years ago by Willi Fowler and he has again emphasized it in his Nobel lecture, which you might have heard during the APS meeting; of course <u>he</u> has in mind

radioactive reactions mostly for astrophysical purposes. And it is quite clear that there is a wide range of reactions that one would like to study. During the first part of the workshop; this was emphasized by Dick Boyd's and Grant Mathews' talks, but for a multi-million dollar facility the astrophysics application may not be sufficient and the purpose of the workshop was really to bring together many other aspects of physics that might be of interest. And perhaps the point of the discussion here now is to bring this out: to see what the problems are, what possible parameters we want to discuss, whether there are perhaps two distinct regions where one wants to have a smaller facility built along Van de Graaff's and lighter nuclei on one hand, and a larger facility that can handle heavier beams, higher energies, higher intensities and stored beams. You see that we are talking 80 million Dollars for the GSI facility, an RFQ would cost about a million dollars, and a high intensity cyclotron costs about two million dollars; so we are considering quite expensive facilities and the way the funding situation in most countries is one has to be rather careful in what one is proposing. So please feel free now to pick up any of these leads or other questions that were mentioned.

Alonso: I think the first thing that is needed is perhaps a good compendium of exactly what facilities there are; everybody has talked about what they have but what we need to have should be located in one place. I would suggest an appendix to the proceedings which would consist of a detailed list of what facilities there are available today, what their capabilities are, the kinds of experiments that can be done on these facilities, and to have people that want to do potential experiments come up with some specifications. Then also what plans there are for enhancing these and this would provide a good framework to start first of all the physics that can be done but also to be able to then see what directions to push, what this new dedicated

facility needs to look like, because it may be that in fact we can do a lot of the research that needs to be done for these astrophysics measurements with facilities that are either on-line or close to being on-line around the world. And that would stake out essentially an area that can be reached by existing facilities, so one would concentrate one's limited resources.

Schult: I would like to support this idea. In fact, it seems to me to be very useful if the people that have facilities of this kind would mention which kind of potential they can foresee--to extend their facilities. It may be that somebody by adding a small amount of money could produce more beams and this is an option one has to compare with other means to produce radioactive beams. Also, I think it would be very nice to know, for instance, which intensities one could get by shooting a uranium beam on a beryllium target and make spallation, or fragmentation, because at the Bevalac one could do such an experiment and measure the fragments; then one would find out how far neutron-rich one could really go, and then this information would be extremely valuable for people planning maybe another method because it would not be useful I think to use, say, proton-induced fission at a very intense facility, to do things with lower intensity, then you can do maybe in Berkeley. So this would be very helpful to know.

Boyd: I think it is probably worth pointing out that the facilities that Grant Mathews and I described selected pretty carefully the reactions that we are going to use for the production of the beams that we talked about. More beam intensity would certainly be enormously advantageous to both facilities, not just in improving the reaction studies that we talked about but also improving the variety of beams that can actually be produced. If you have to get two or three nucleons away from the line of stability, for these astrophysically interesting reactions it will be pretty dicey for us to touch these reactions with the

beam intensities and energies that we have right now. However, I also feel that probably a reasonably state-of-the-art tandem Van de Graaff with a lot of beam intensity is probably the ideal facility for most of what we want to do, right now in the astrophysically interesting research. It is pretty clear, though, that there are lots of other interesting things that people like to do and a high intensity tandem is not going to do that. I suspect--and just for the sake of argument let me suggest this--if there are two kinds of facilities that are needed, to do research with radioactive ion beams, one being a high-intensity tandem for the low energy-oriented studies and the other being like a very energetic cyclotron.

Dufour: It seems to me that we have some ideas of how to produce radioactive beams. The mechanisms are known up to the GeV region. What I would say when you speak about tandem--it is possible to think about a very universal facility. You say if you make high energy heavy radioactive beams--sure: you may think of a thick target with the universal production and then cool it (the beam) down and use it, which means you would cover--for instance, with uranium on beryllium--almost the production of all nuclei with almost the best cross section you can have, and then you have a universal facility. The problem is that that proposal costs a lot of money. And so I have been looking around what kind of physics you can do with existing facilities. I was not aware of your work. We also used existing facilities. We should also think of using what we have now, perhaps not with so much intensity. In Berkeley they have improved things a lot and in Ganil we don't have very high energy but we have more intensity. We can do some things, I think. Within 2-3-5 years we may have some more precise ideas about these beams. We are at the very beginning of something that can become very big.

Nitschke: I would like to remind you at this point that in Berkeley we have nearly an electrical milliampere of peak neon beams available, that would also mean that enriched isotopes of, let's say, neon-22 could be used at similar intensities. If one now talks about an inexpensive facility one could think about a gas target being used to change this neon-22 into other isotopes and in this way one could get quite good intensities.

Mathews: I would just like to put two cents' worth in of what I think and what we have seen here. The last couple of days have just been an example of a group of physicists given a chance to let their imagination go for awhile, and we have seen a lot of really great ideas come out. What I get from it is that it would be a great idea to have a kind of a national facility because what we have also learned is that this whole industry of radioactive heavy ion beams is very technology-heavy and it will require a lot of technology development, so two things that we need here are concentrated effort to develop the technology...What we have seen right away is, with a little bit of imagination as the technology develops, who knows what we can do. I mentioned earlier today most of the reactions that we think of that can be measured haven't been measured yet; when we open up this roqm.

Roeckl: Since it has been suggested to put at the end of the proceedings a table with all the facilities, I think it is not necessary; it sounds to me like a bureaucratic exercise. I don't know who will do it. My suggestion is to look up the Zinal Proceedings, which was a conference on electromagnetic isotope separators which includes recoil separators, which is a special volume of nuclear instruments and methods--1980, if I remember correctly. And everything I have heard here is included there--I mean instrumental techniques-- except the Ganil facility and except the beamline for the Helium-6/ Helium-8, maybe a few more developments here and there. It is not worth putting this table

at the end of the proceedings, especially because it is a multi-dimensional affair. If you want to put in the isotope production rates, you may take like you did, Mike, the maximum yield or if then you want to see like Schult said how much you get from uranium on beryllium how does it compare with protons, my comment would be that it depends. If you just take the rates, with something like protons as you have heard in somebody's talk, the advantage of relativistic heavy ion beams is the kinematics. And to put the kinematical properties in such a table I think that is impossible. So I would like to see the proceedings but I don't need the table.

Armbruster: A short comment of what we can do about neutron-rich beams. If you now go from calcium-48 to uranium-238 and fragment ^{238}U you might get something like neutron-rich nuclides and also some neutron-heavy fission fragments but I think that is an illusion. It has been shown in one of the slides by Jean-Pierre Dufour it is quite similar as in spallation reaction. If you do an abrasion-kind of process with such a heavy ion neutrons are evaporated out and you land near the valley of stability. I don't see any means right now except for going in small steps with few nucleon transfer reactions or perhaps by deep inelastic reactions to move out a little bit on the neutron-rich side. I think there is good hope as we have heard to fill in all the nuclides that are in the fission valley. I think that you can get all these nuclides and I'm very optimistic that we can get the light nuclei below the fission fragment group, for instance with calcium-48 where Simon and Company have already filled the chart of nuclides and so we can get all the nuclei below the fission fragment region with charge-to-mass ratios of about the uranium but for the heavier ones I don't see very much of a chance.

Tanihata: I would like to comment on the maximum intensity that we can get from these reactions. It is very important. I think most of us are not quite sure of the maximum intensity that we can get from

any method; we have discussed this in Japan with respect to the Numatron which is at the moment not going very well. The maximum intensity you can get with any kind of accelerator--the total reaction cross section of the nucleus-nucleus reaction to partial cross section of the nucleus of interest--usually you can not reach this limit because you use some energy to shoot the beam in the target and you lose energy and you get less and less but if you have a good machine you can get up to this number; you can get 10^{12} of neon beam, you can get a cross section of about 1 barn and you have a cross section for the secondary beams of millibarns or more and that means you can get 10^{-3} of the original beam intensity in principle. And of course higher energies are possible ... and one way of using a storage ring ... you make a fragmentation and you put that in here ... and you cool it. But rather than doing <u>that</u> you put this beam into this accumulator ring, then you put a thin gas target, but it need not be very thin, it could be a microgram of target; so that you consume this beam in a second almost as fast as you accelerate the next beam. So what you do is you accumulate in here, then take out the fragment from there. This fragment has different rigidity; and you consume the total beam in the time you accelerate the next beam. If you have a fast cycling synchrotron I guess you can get up to 10^{12} of beam easily. That means you can get a decent amount of beam like 10^8 or 10^9 of say 2 neutrons plus from stability. And 4 neutrons plus you may still get 10^7. And after that it is a technical problem that is almost solved in principle; that you can cool down the beam or decelerate it. The cooling of the beam of 7 MeV/A is already done in the ISR (?) ...

Armbruster: Which ion?

Tanihata: I think it is deuteron.

(Some unclear recording)

Dufour: I am not sure that you can really achieve this slowing down to say 5 MeV/nucleon because you have to consider the energy spread and the straggling that is coming out of your magnetic analyzer.

Alonso: Now what I am saying is the following: Let's assume that we have an ideal system where I can spread the beam out, disperse the beam, get a good dispersed focus on the beam, use a wedge to monochromatize it. That gets rid, ideally of everything I don't want. At some point it is not going to satisfy what I need, in which case I actually have to take a slice. So I can use the wedge to monochromatize that slice, and arbitrarily I can cut tighter and tighter and get monochromatic beam at the cost of intensity. I think it is doable and my experience has also been the first time you try it it doesn't work right; if you try it again and you keep trying it and it works.

Dufour: You say that you first degrade; secondly you put the wedge. Now when you first degrade you lose a lot. If you degrade and you start with one percent at several GeV/nucleon, at 100 MeV/nucleon that would become 10 percent in energy spread.

Alonso: Wait. The energy spread is a function only of the P perpendicular, if you will, let's say of the Fermi motion which is independent of the energy of the primary beam, so the natural energy spread from the reaction mechanism doesn't depend on whether you're at 4 MeV or 400. You have a thick target; the thickness of the target is selected so that the momentum contribution is roughly the same as you get from the Fermi momentum.

Dufour: So there's another point. You say it scales as the cross section. That is not true.

Alonso: No, that is not what I said, to first order it scales as the cross section but it also scales as the opening angle which is the acceptance of the spectrometer.

Dufour: (not understandable)

Alonso: However there is something else that can be said. It gets worse the further you get away from the projectile nucleus, but with the accelerator that we have we can get you almost everything you want. I don't want to produce a carbon beam by starting with calcium-48.

Dufour: That's what I mean. If you go neutron-rich, the fragments are always different in energy loss from the beam.

Alonso: Sure.

Tanihata: This is an extreme example. You start from an 800 MeV-carbon beam and you produce heavy isotopes. This is the thickness of the target and this is the broadening due to the reaction. There is a difference in dE/dx and you can still get up to 5 grams of target in this case, just because the energy loss is very low. If you go down to a 50 or 80 MeV/nucleon your energy loss is really huge, but at the high energies your energy loss is very small.

Dufour: (not understandable)

Nitschke: Let me say a few words about the use of internal targets. Let's say we put in a target which does not really go over the full width of the beam intercepts sort of the outer 10 percent and then as the beam hits the target the beam of course loses rigidity and winds up on a path that is further inside of the storage ring. Now we put in an RF section in order to make the particles that have lost energy in the target gain energy again and after a few turns they are back out to the radius of the target where they can interact again and so forth and you see that you don't stop them completely. If you don't stop them

completely with one single blow then you can keep on using the same particles over and over again. And you can take the fragment particles out of the storage ring. That is just one of the possibilities.

Schult: Have you done some beam transport calculations on this?

Nitschke: No, we have not.

Tanihata: You can use a gas jet target also.

Nitschke: A gas jet target in a vacuum of 10^{-12} Torr?

Tanihata: It's difficult.

Schult: Why do you need that good a vacuum?

Nitschke: If you want to store uranium for any extended time.

Armbruster: We thought about the storage of uranium; the extrapolation from protons to uranium is difficult.

Alonso: You don't need such exceptionally high vacuums for storage rings. The electron pickup cross sections for 91-92 plus uranium are about 30 barns. 10^{-9} is fine at energies of about 1 GeV/A. We are thinking of storage times of several hours.

Nitschke: That is somewhat at variance with the calculations that were made for the GSI storage ring: approximately 100 seconds at a vacuum of 7×10^{-12}.

Alonso: What cross sections are you using?

Armbruster: I can send you the cross sections on which these calculations are based.

Alonso: We measured the cross section.

Armbruster: Yeah, OK. Those are your cross sections.

Alonso: There is a numerical error somewhere, either in your or my calculations.

Nitschke: If there are no further questions I'd like to thank all of you again. I think you have made this into a very successful workshop and a good discussion. I thank the speakers, the chairmen, and Jeannette Mahoney who has faithfully taped all of your precious words, has helped with the registration and has made things flow smoothly. I hope that this was not the last workshop on radioactive beams but that the field will expand from here and that starting with Dick Boyd's earlier seminar this series of seminars and workshops will continue with new results, new theories, new machines and equipment and that it will become a new field and will expand into a new dimension of nuclear physics. Because, as I said in the beginning, we have now uranium beams from a few keV per nucleon up to GeV per nucleon; everything that is stable can be accelerated and a very logical extension would now be to start to explore radioactive beams and their applications.