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Proceedings of the Workshop on the Physics Using Compound Nucleus Separators

Ernest Orlando Lawrence Berkeley National Laboratory

April 10–12, 1997

Kenneth E. Gregorich, Editor

Nuclear Science Division

April 1997

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Workshop on the Physics Using Compound Nucleus Separators

Kenneth E. Gregorich, Editor

Nuclear Science Division
Ernest Orlando Lawrence Berkeley National Laboratory
University of California, Berkeley, California 94720 USA

Lawrence Berkeley National Laboratory
April 10-12, 1997

Conference 9704-118

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Workshop on the Physics Using Compound Nucleus Separators
Lawrence Berkeley National Laboratory
April 10-12

Thursday April 10, Morning Session

9:00 AM	Lee Schroeder	Welcome
	Paul Fallon	Workshop Introduction
	Victor Ninov	World's Compound Nucleus Separators
10:05 AM	BREAK	
	Ken Gregorich	BGS Design and Capabilities
	Paul Fallon	GFS Design Goals
12:00 PM	LUNCH	

Thursday April 10, Afternoon Session (Jim Waddington)

2:00 PM	Witek Nazarewicz	Theory : Drip-line to Super-Heavies
	Monique Bernas	Fission of Relativistic Nuclei
3:30 PM		BREAK
	Phil Woods	RDT and Proton Emitters
	Ken Toth	Short Lived Particle Emitters
5:05 PM	END	

Friday April 11, Morning Session (Peter Armbruster)

9:00 AM	Peter Möller	The Stability of Superheavy Elements and the Valleys that get us there !
	Sigrud Hofmann	Population and Identification of Superheavy Elements
	Matthias Schädel	Hot Fusion: Results and Prospects
		General Discussion
11:00 AM	BREAK	
	I-Yang Lee	The 8Pi at the BGS Focal Plane
	Michael Hass	Electromagnetic Studies at the Focal Plane
	Andreas Türler	BGS as a Preseparator for Chemical Studies
12:30 PM	LUNCH	

Friday April 11, Afternoon Session (David Fossan)

2:00 PM	Rauno Julin	Merits and Limitations of RDT with RITU
	Peter Butler	Gamma+Electron Spectroscopy A>220
	Denis McNabb	Search for SD in light Actinides
3:20 PM	BREAK	
	Bill Gelletly	A Birds Eye View of Nuclei Near N=Z
	Mike Carpenter	Gamma-Ray Spectroscopy Beyond the Proton Drip Line for N>82 and Z<82
	Matt Devlin	Channel Selection with Charge Particle Detector Arrays
	Cyrus Baktash	Spectroscopy and Channel Selection Near the Proton Drip Line.
		General Discussion
5:40 PM	END	

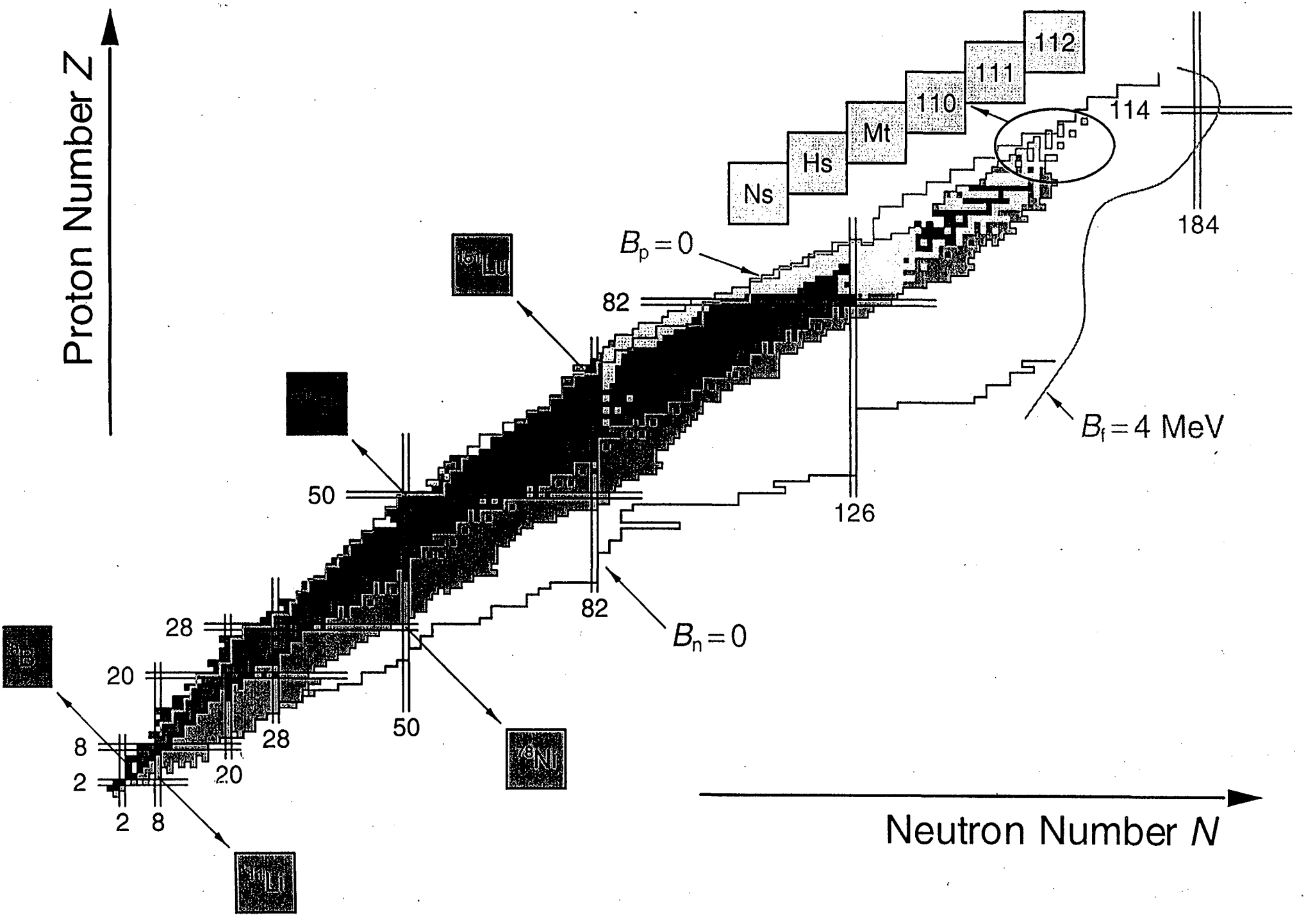
Saturday April 12, Morning Session

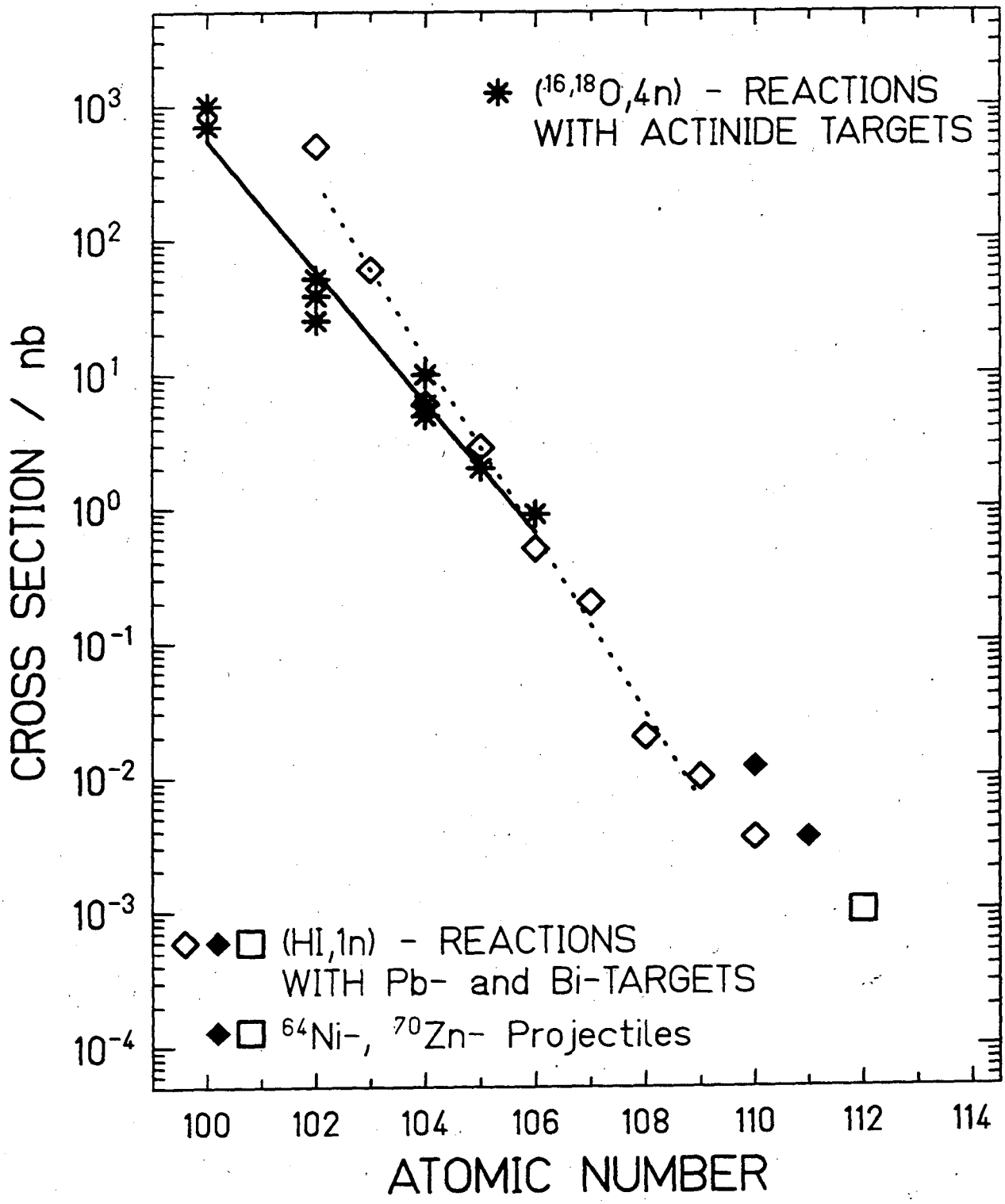
9:30 AM	INFORMAL DISCUSSION / OPEN QUESTIONS
	BGS - Physics/Design
	GFS - Physics Design
12:00 PM	END

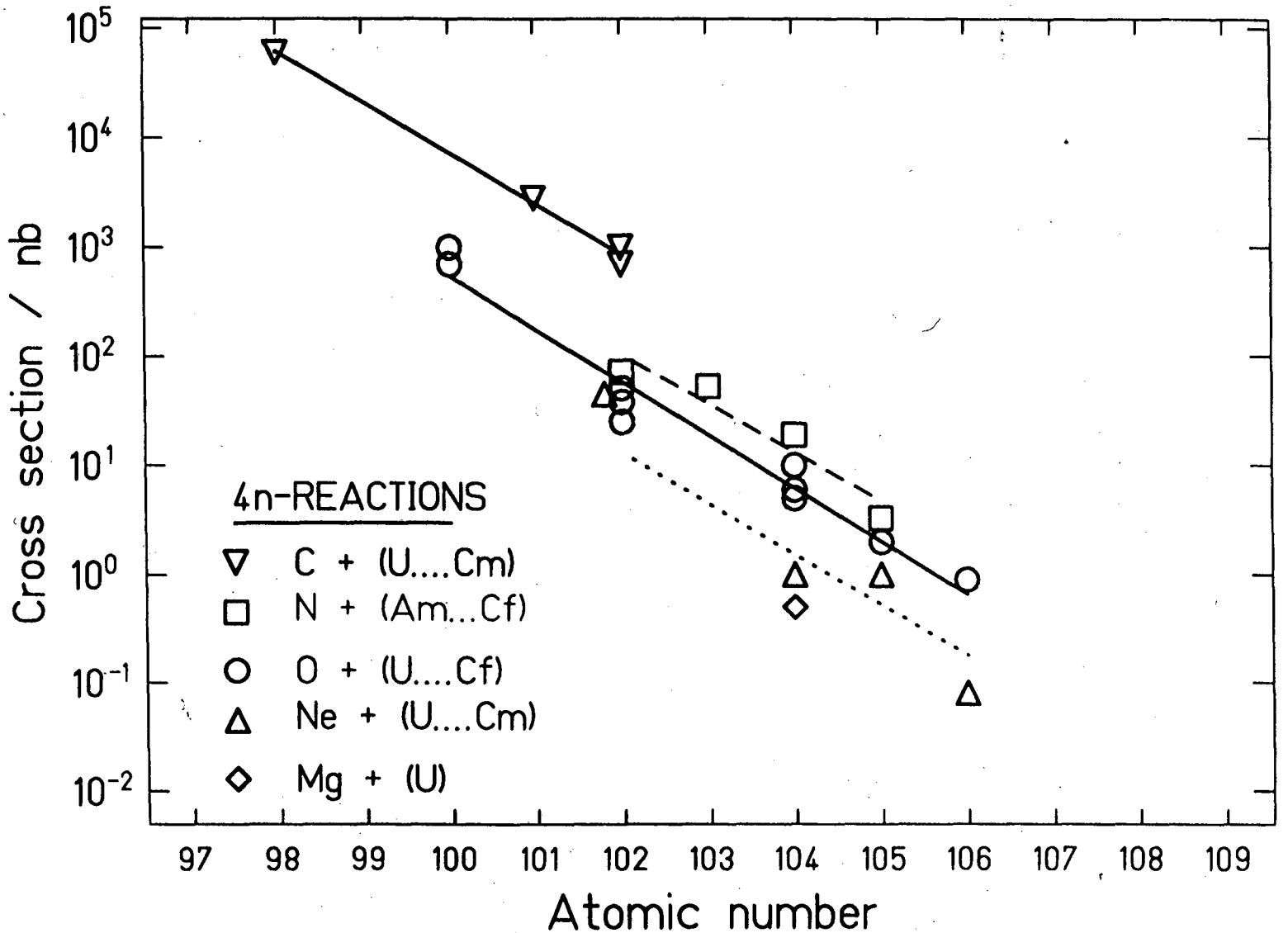
Victor Ninov
Lawrence Berkeley National Laboratory

World's Compound Nucleus Separator

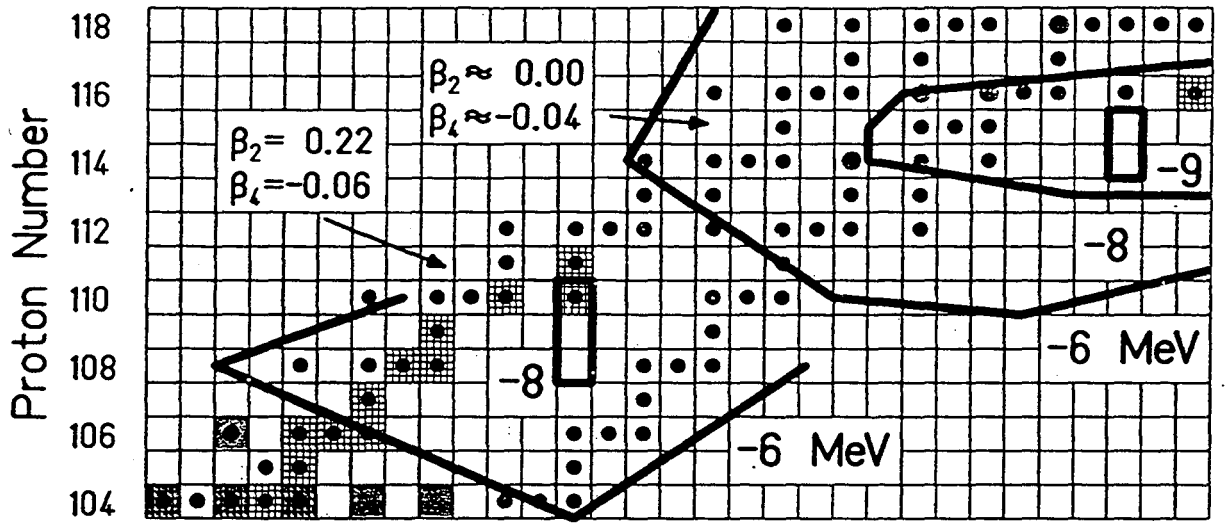
- *Why we need Recoil Separators*
- *Demands for a Recoil Separator*
- *Principle of Kinematic Separation*
- *Velocity Separators*
- *Gas-Filled Separators*
- *Mass Separators*

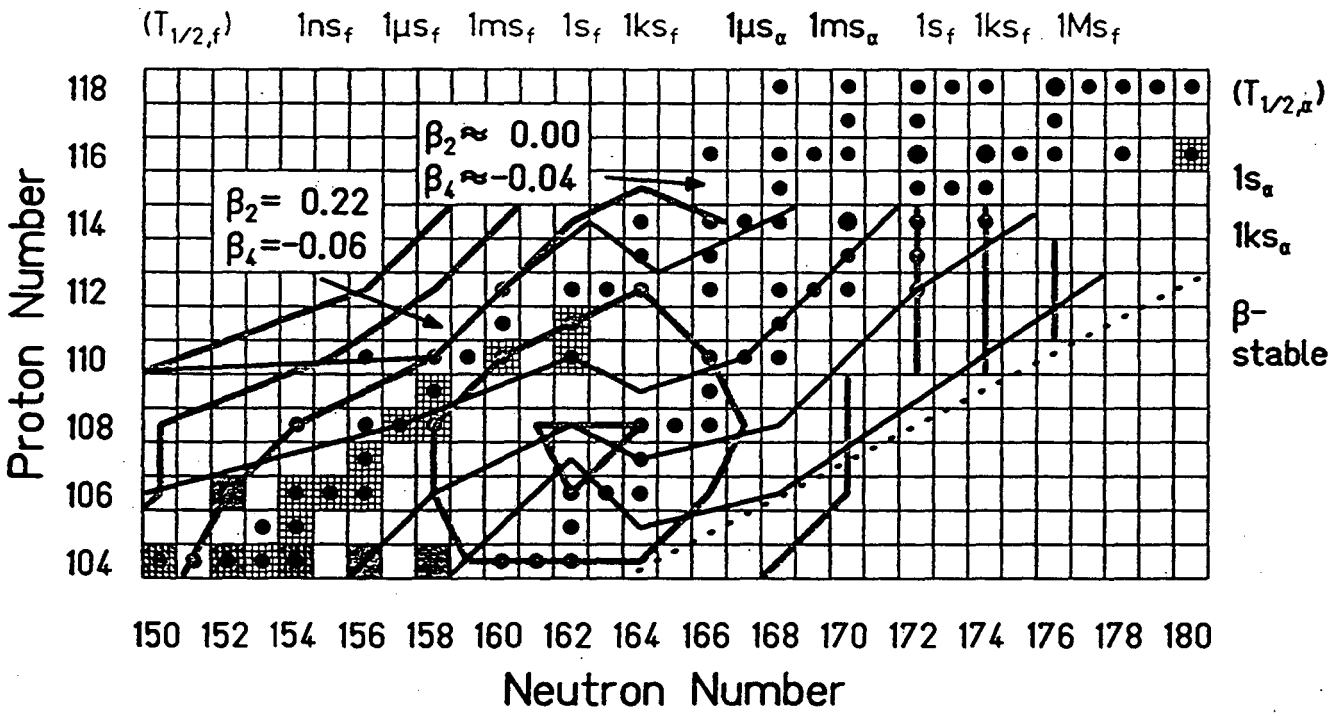

Proton Number Z
Neutron Number N
112
111
110
Mt
Hs
Ns
114
184
$B_p = 0$
82
50
126
82
$B_n = 0$
$B_f = 4$ MeV
28
20
8
2
2
8
20
28
50


✱ (^{16,18}O,4n) - REACTIONS
WITH ACTINIDE TARGETS
◇◆□ (HI,1n) - REACTIONS
WITH Pb- and Bi-TARGETS
◆□ ^{64}Ni-, ^{70}Zn- Projectiles
CROSS SECTION / nb
10^3
10^2
10^1
10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
100
102
104
106
108
110
112
114
ATOMIC NUMBER


4n-REACTIONS
C + (U....Cm)
N + (Am...Cf)
O + (U....Cf)
Ne + (U....Cm)
Mg + (U)
Cross section / nb
Atomic number
10^5
10^4
10^3
10^2
10^1
10^0
10^{-1}
10^{-2}
97
98
99
100
101
102
103
104
105
106
107
108
109

Ground-State Shell-Correction Energies





● : (Ti-Kr) + ^{208}Pb → (Z=104-118)

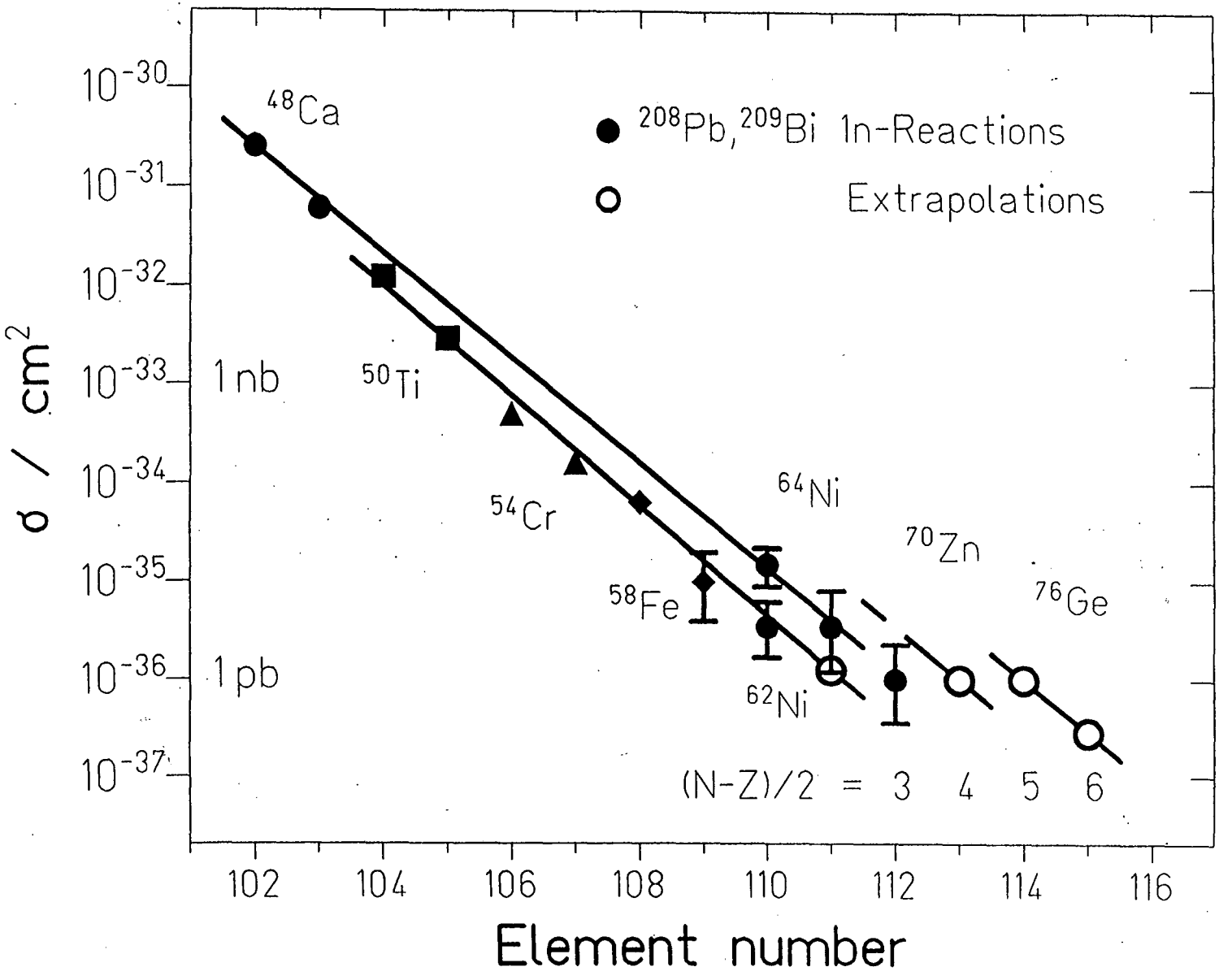
● : (O-Ti) + ^{248}Cm → (Z=104-118)

□ ■ : Known nuclei, α decay, fission

□ : Investigated compound nuclei

S. PATYK
A. SOBICZEWSKI

Cross Section Systematics for Production of Heavy Elements



Demands for a Recoil Separator

1. • luminosity should be as high as possible
2. • mass resolving power as large as possible
3. • separation time as short as possible
4. • angular and momentum acceptance as large as possible
5. • yield of separated nuclei not dependant on their chemical properties

Principle of Kinematic Separation

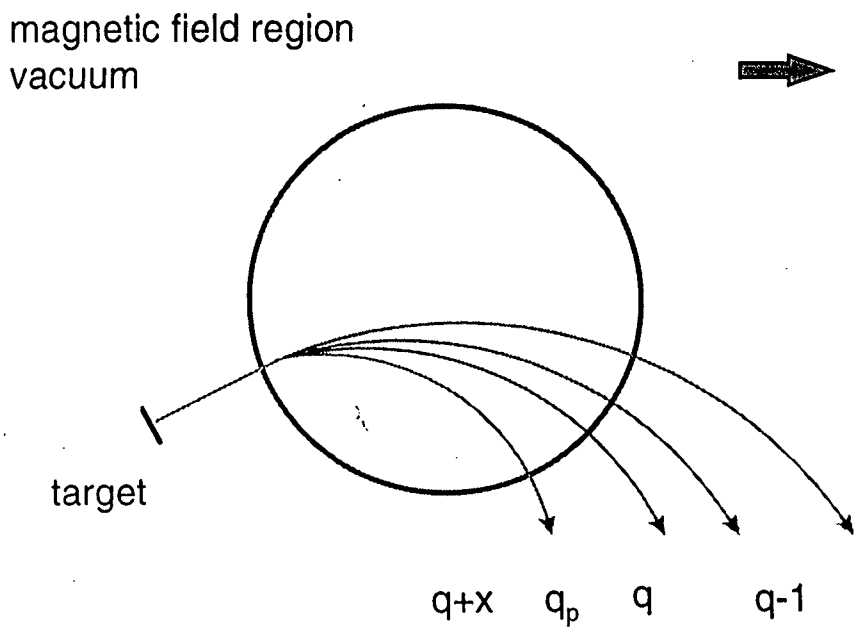
$$p_{\text{proj.}} = p_{\text{cn}}$$

eg. complete fusion

$$v_{cn} = \frac{m_{proj.}}{m_{proj.} + m_{tar.}} \cdot v_{proj.}$$

$$\Rightarrow \quad v_{cn}, E_{cn} < v_{proj.}, E_{proj.}$$

$$\Rightarrow \quad B\rho = \frac{m \cdot v_{cn}}{q} \quad \text{for} \quad v_{cn} \quad B$$



separation of *cn* and projectiles in a B-field is in principle possible

<u>problem:</u> ***q - distribution***

Velocity Filters

Magnetic field : $\vec{F}_{magn.} = q \cdot (\vec{v} \times \vec{B})$

Electric field : $\vec{F}_{el.} = q \cdot \vec{E}$

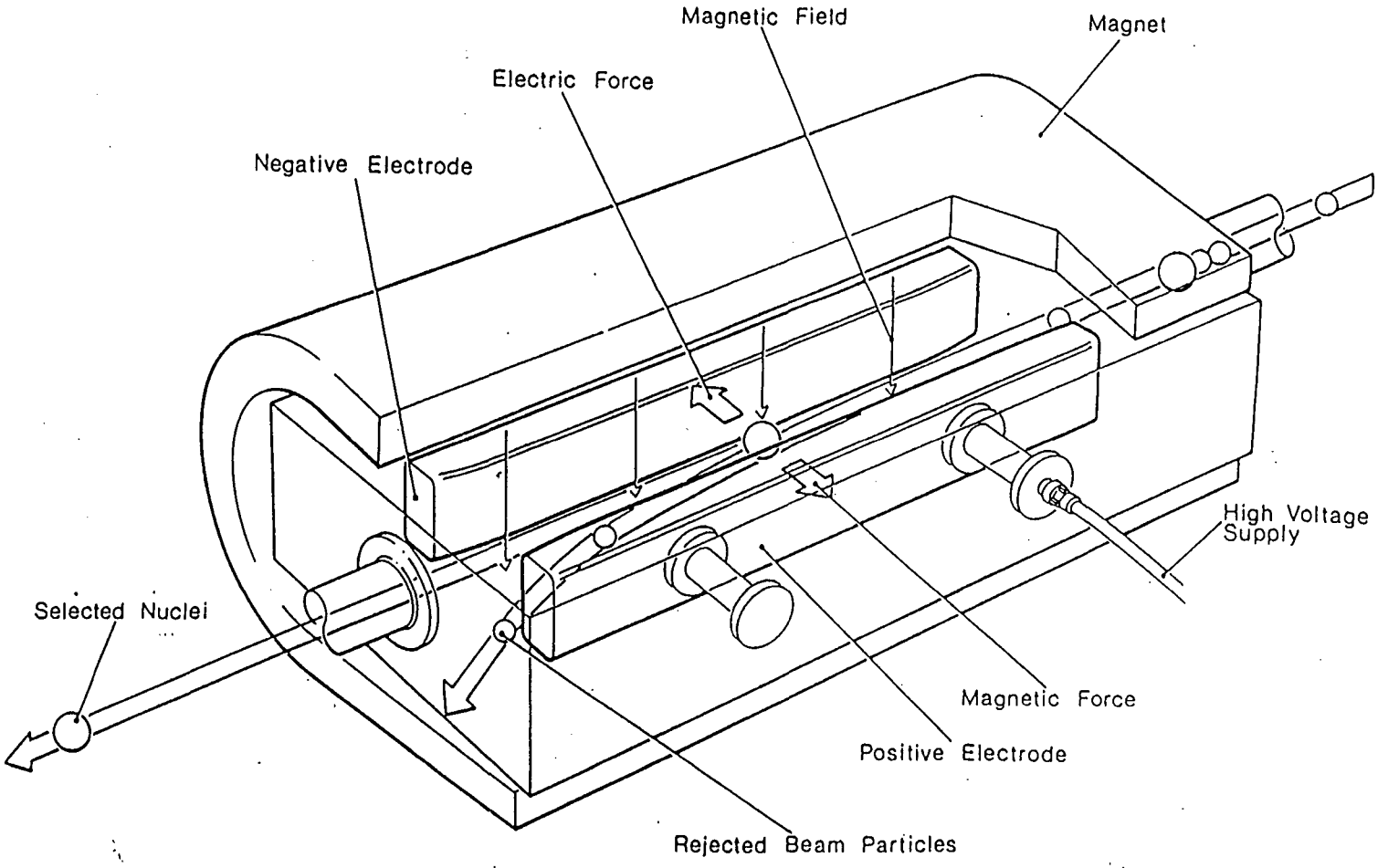
combined B- and E- fileds: $F_{tot.} = q(E + v \cdot B)$ for $\vec{E}$ $\vec{B}$

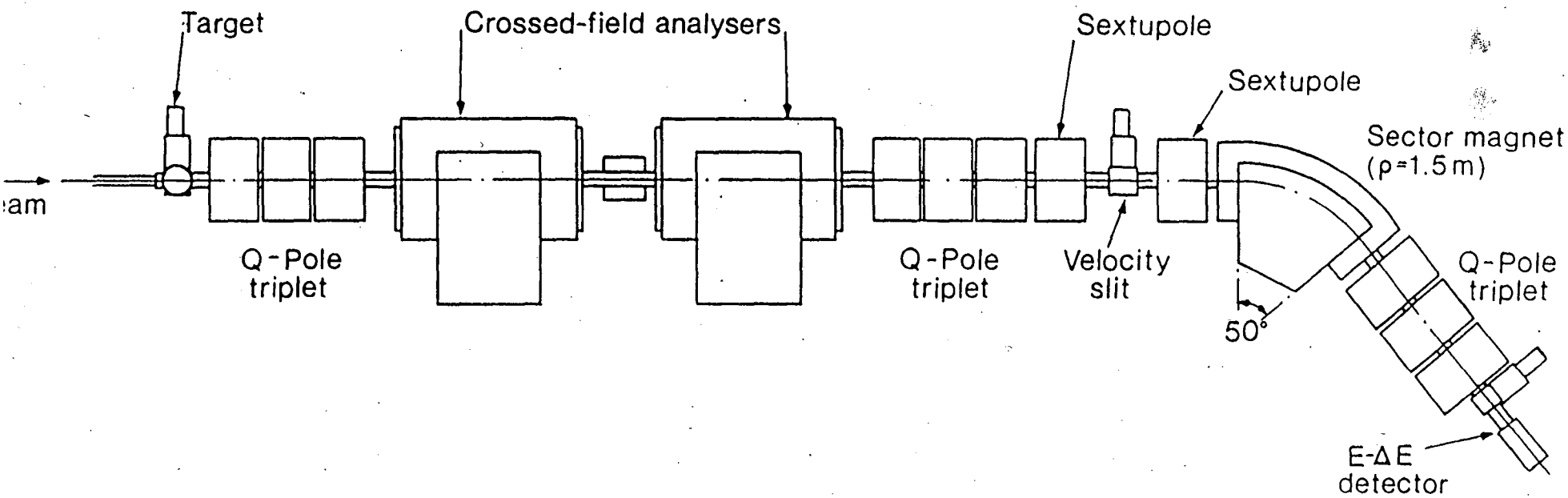
$F_{tot.} = 0$ for $v = E/B$

$F_{tot.} \neq 0$ for all other velocities

- complete sepration of the cn from the projectiles
- collection of all charge states of the cn
- stigmatic focussing
- high transport efficiency

- small angular acceptance
- velocity dispersion in the focal plane

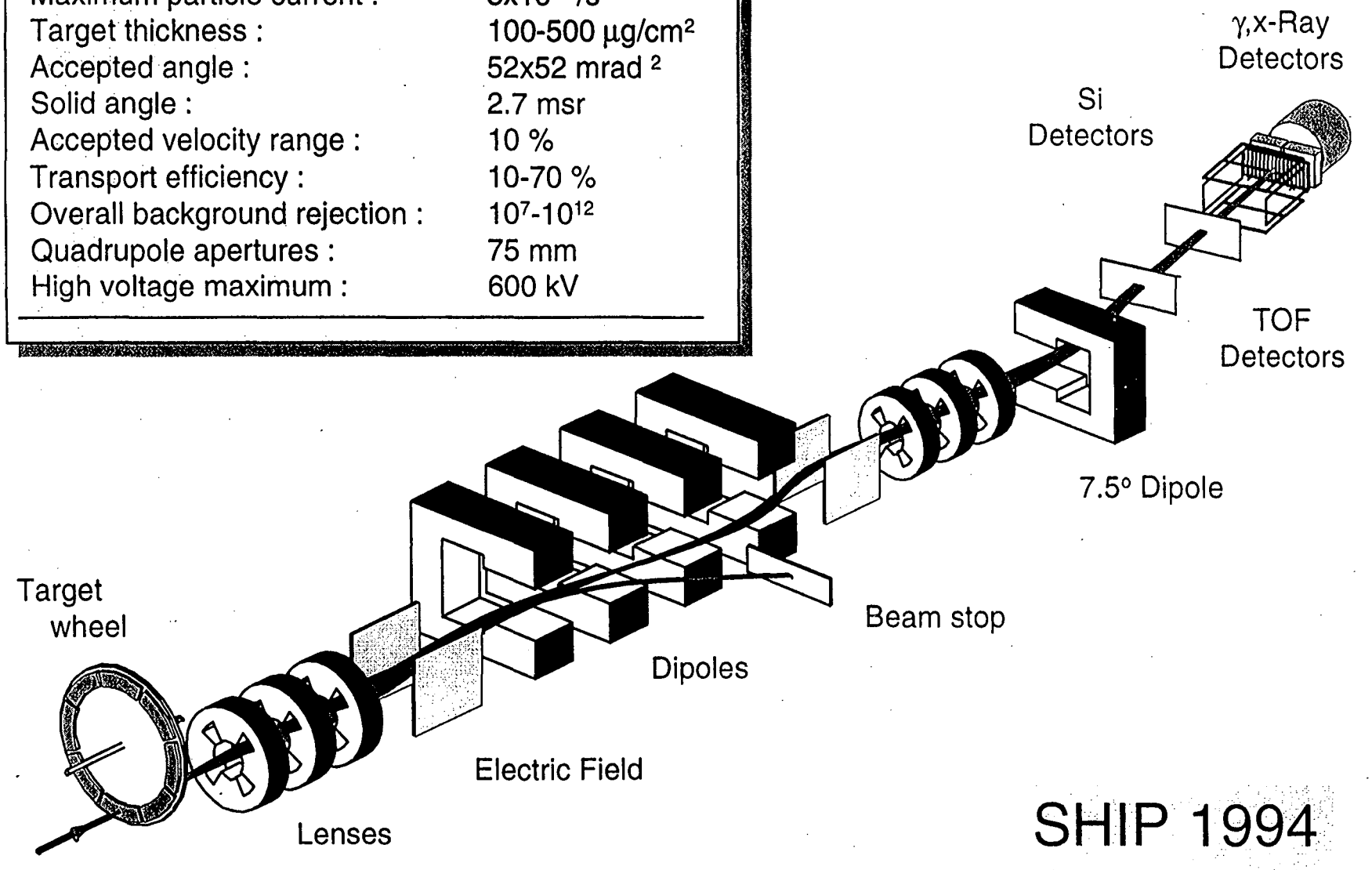

Magnetic Field
Magnet
Electric Force
Negative Electrode
High Voltage Supply
Selected Nuclei
Magnetic Force
Positive Electrode
Rejected Beam Particles



2.1 Layout of the recoil separator showing its main components.

Operating parameters

Maximum particle current :	5×10^{12} /s
Target thickness :	100-500 μg/cm²
Accepted angle :	52x52 mrad ²
Solid angle :	2.7 msr
Accepted velocity range :	10 %
Transport efficiency :	10-70 %
Overall background rejection :	10^{7}-10^{12}
Quadrupole apertures :	75 mm
High voltage maximum :	600 kV



SHIP 1994

SEPARATOR
VASILISSA
DUBNA

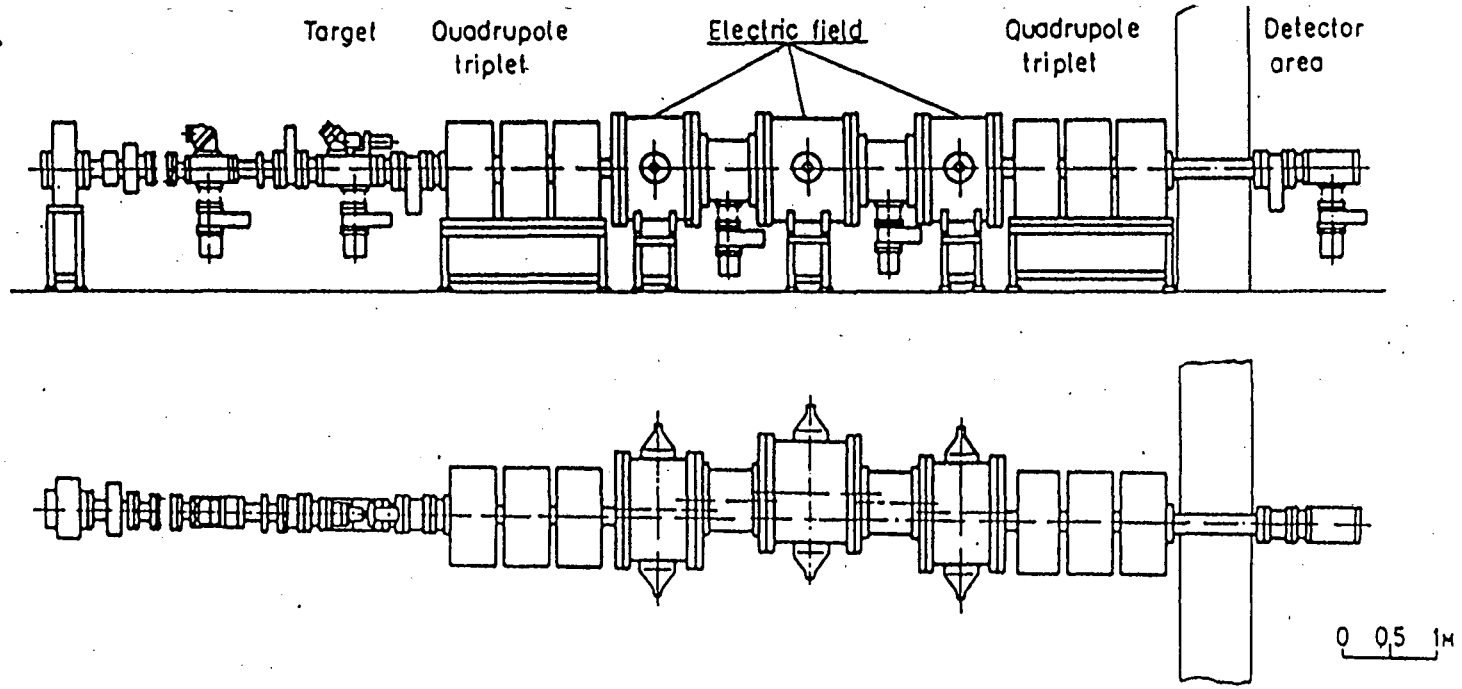
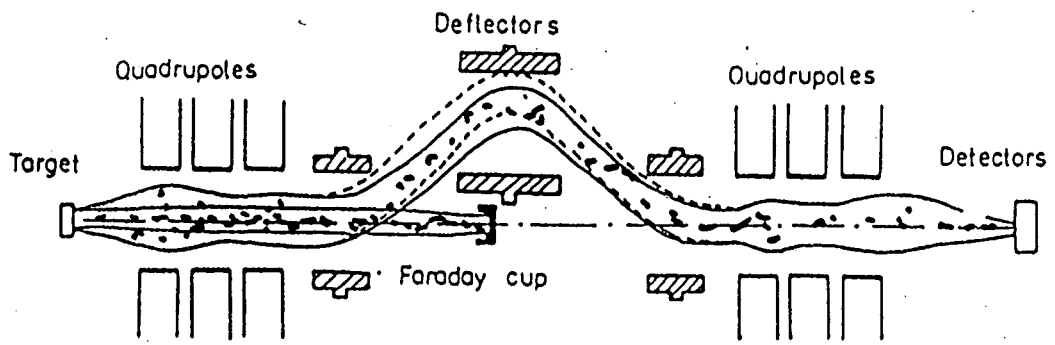


Table 1
Parameters of the ion-optical system

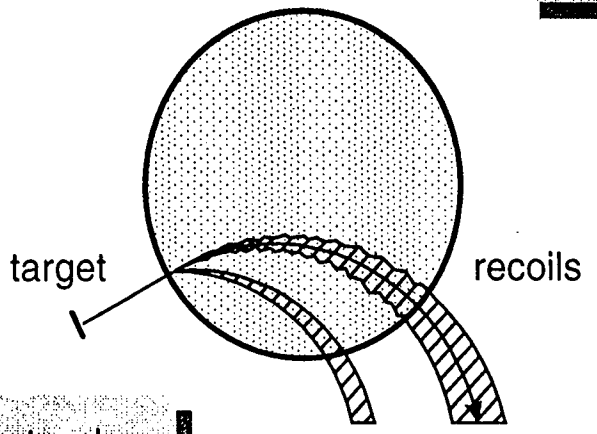
Angular acceptance	±3°
$\Delta E/E$	±10°
$\Delta q/q$	±10°
$\Delta p/p$	±5°
Transport time	3×10^{-6} s
Distances between:	
target and first triplet	0.4 m
target and first condenser	3.5 m
target and second triplet	7 m
target and detectors	12 m
Effective length of quadrupole lenses	35 cm
Aperture radius	10 cm
Maximum field gradient	10 T/m
Effective lengths of first and third condensers	47 cm
Effective length of second condenser	82 cm
Distance between plates	15 cm
Maximum value of electric field strength	20 keV/cm
Target diameter	1 cm



E/q - SEPARATION
upgraded with a dipole

Gas-Filled Separators

magnetic field region
filled with dilute gas



Bohr's approximation

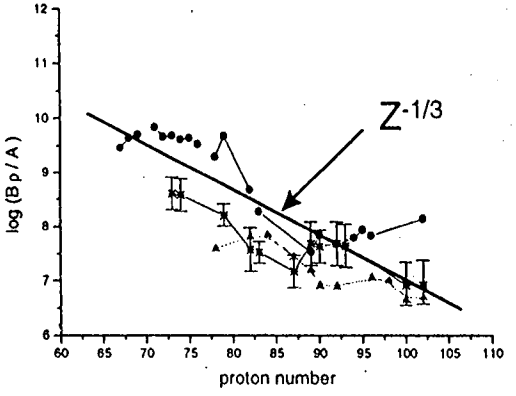
$$\bar{q} = \frac{v}{v_0} \cdot Z^{\frac{1}{3}} \qquad v_0 = \frac{c}{137} \qquad B\rho \approx \frac{A}{Z^{\frac{1}{3}}}$$

first order :

- independent of cn-velocity
- separates *cn* from projectiles according their difference in Bρ

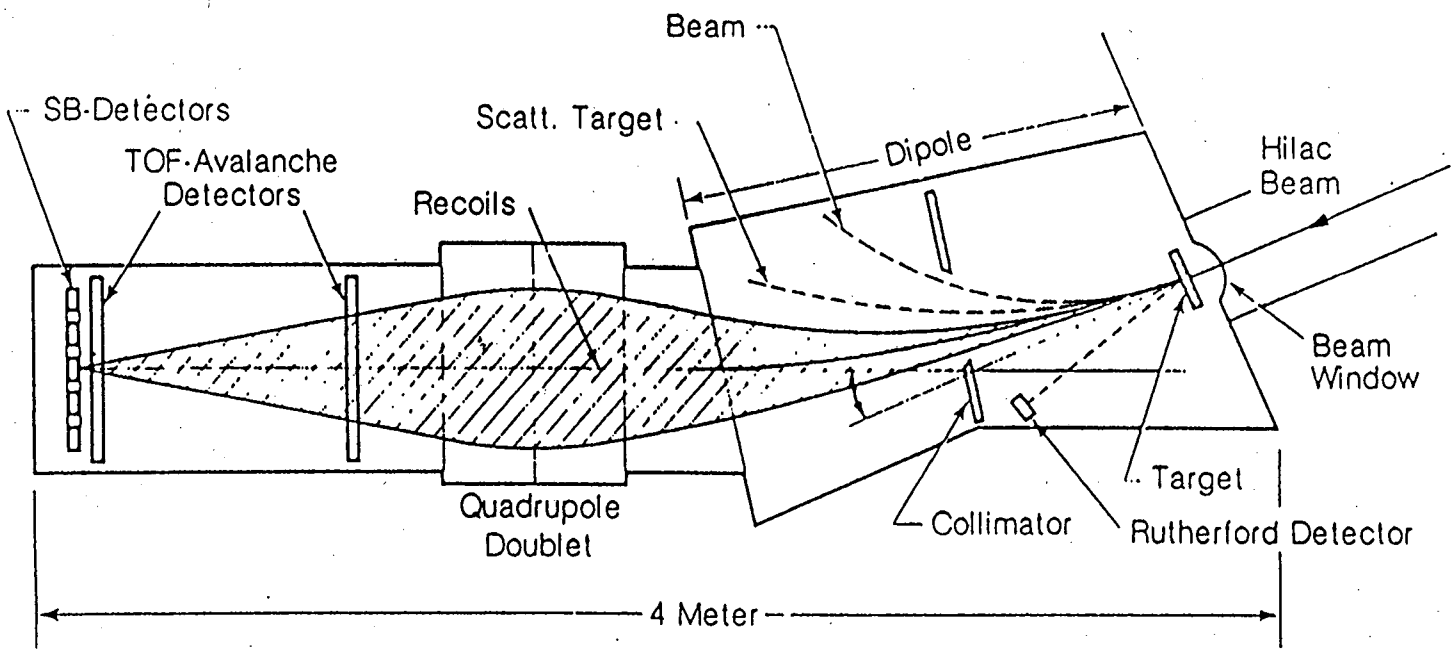
reality :

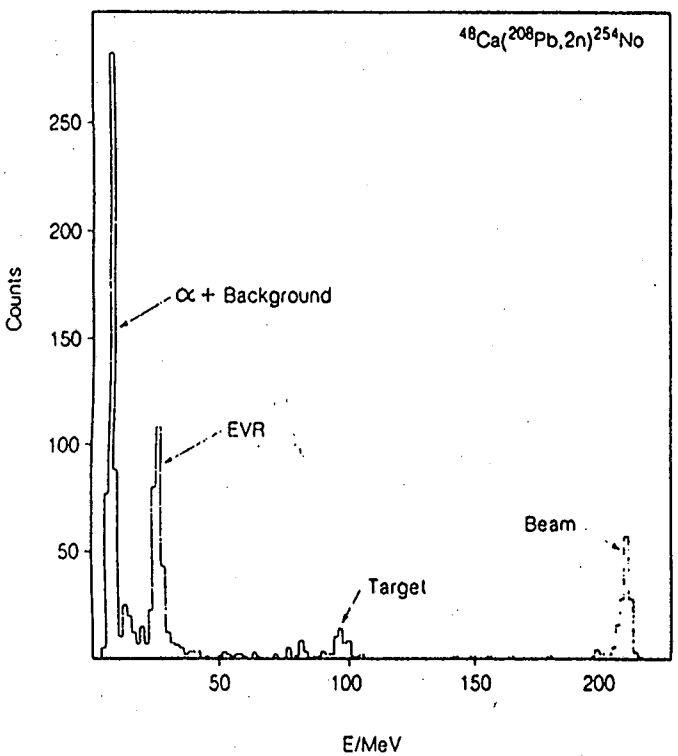
$$\bar{q} = Z \cdot (1 - c_1 \cdot e^{-c_2 \frac{v}{v_0} \cdot Z^{\frac{1}{3}}})$$

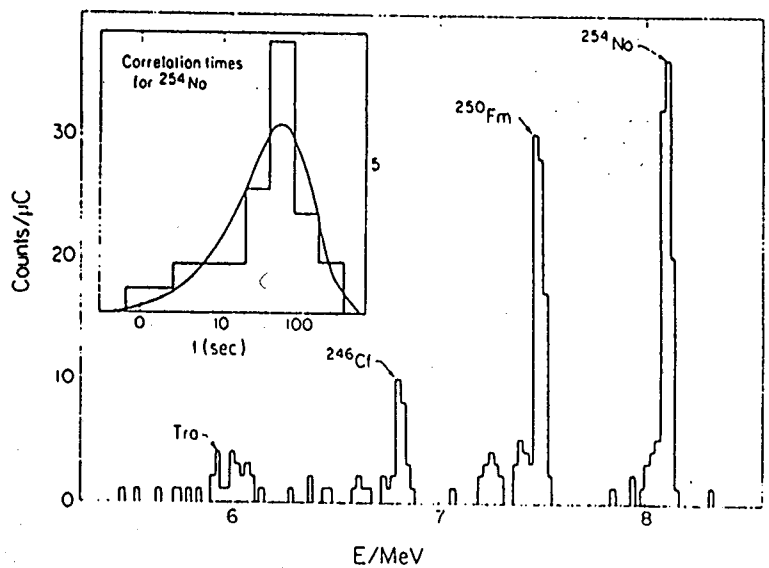


Problems:

q	is a complex function of v,Z
q	shows fluctuations depending on the atomic shell structure of *cn*

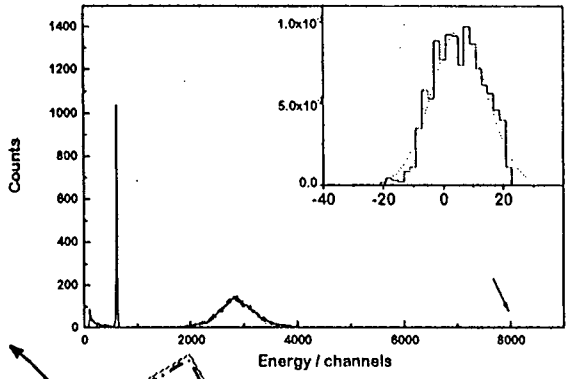

Beam
SB-Detectors
Scatt. Target
TOF-Avalanche Detectors
Recoils
Dipole
Hilac Beam
Beam Window
Target
Quadrupole Doublet
Collimator
Rutherford Detector
4 Meter


$^{48}Ca(^{208}Pb,2n)^{254}No$
Counts
α + Background
EVR
Beam
Target
E/MeV


Correlation times for ^{254}No
t (sec)
Counts/μC
^{254}No
^{250}Fm
^{246}Cf
Tro
E/MeV

GSI Gas-Filled Separator (*HECK*)

- ☺ operable under 0° - 150°
- ☺ wide angular acceptance
- ☺ wide velocity acceptance
- ☺ wide charge acceptance
- ☺ high efficiency
- ☹ dependant on chemical properties of the recoils
- ☹ difficult calibration
- ☹ "weak" mass resolution



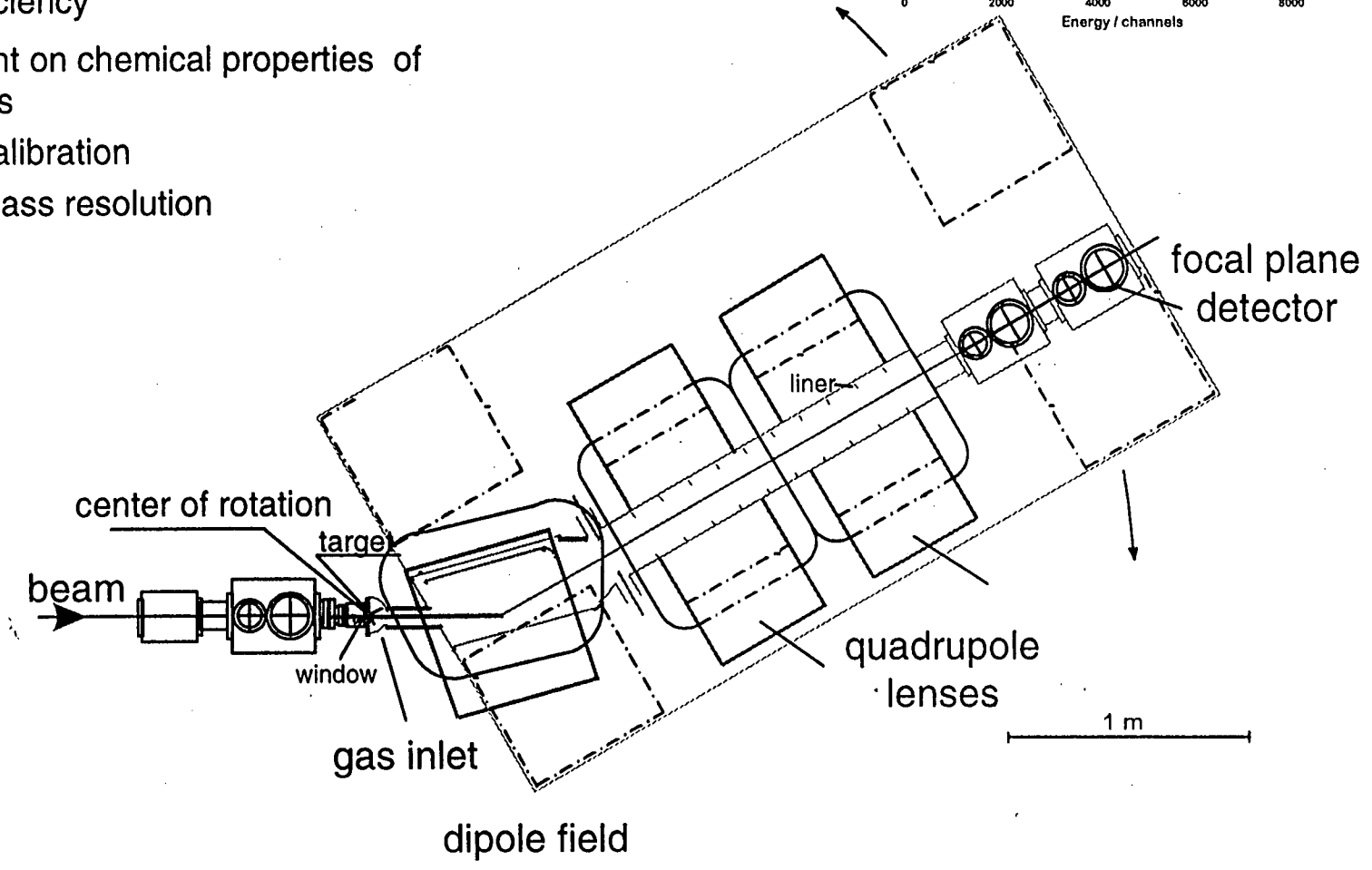
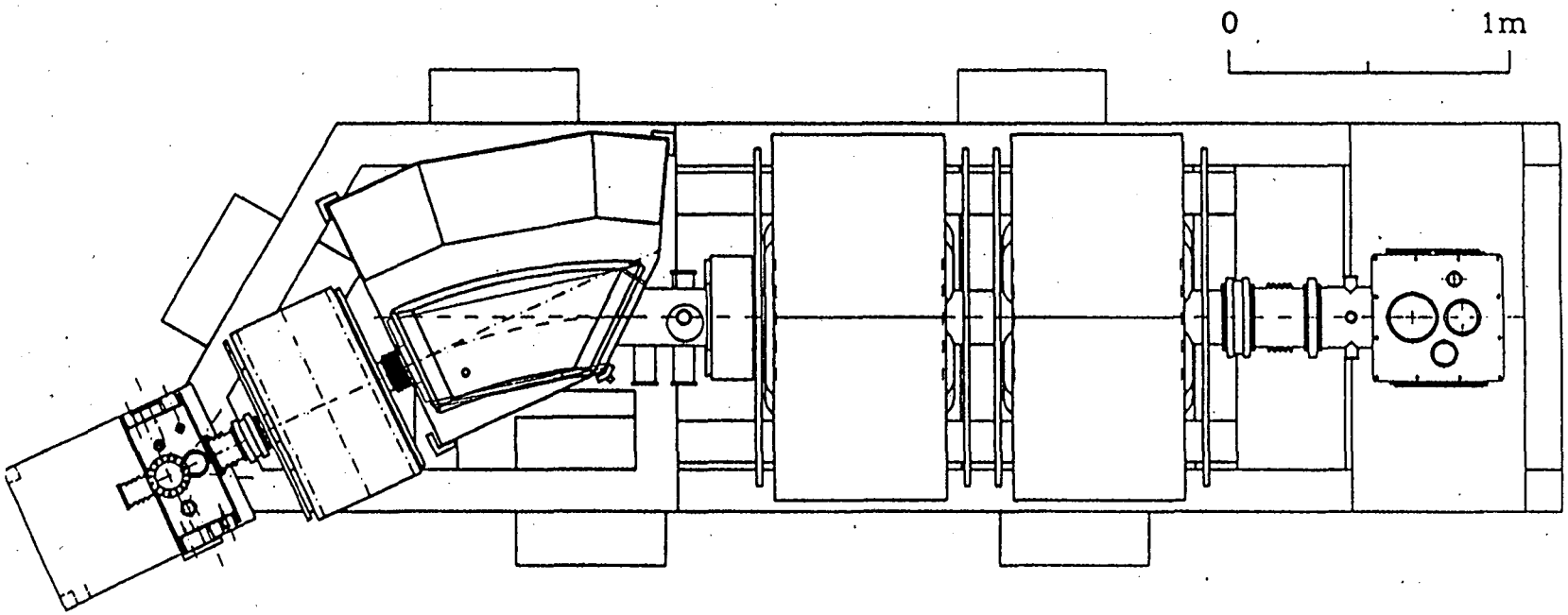
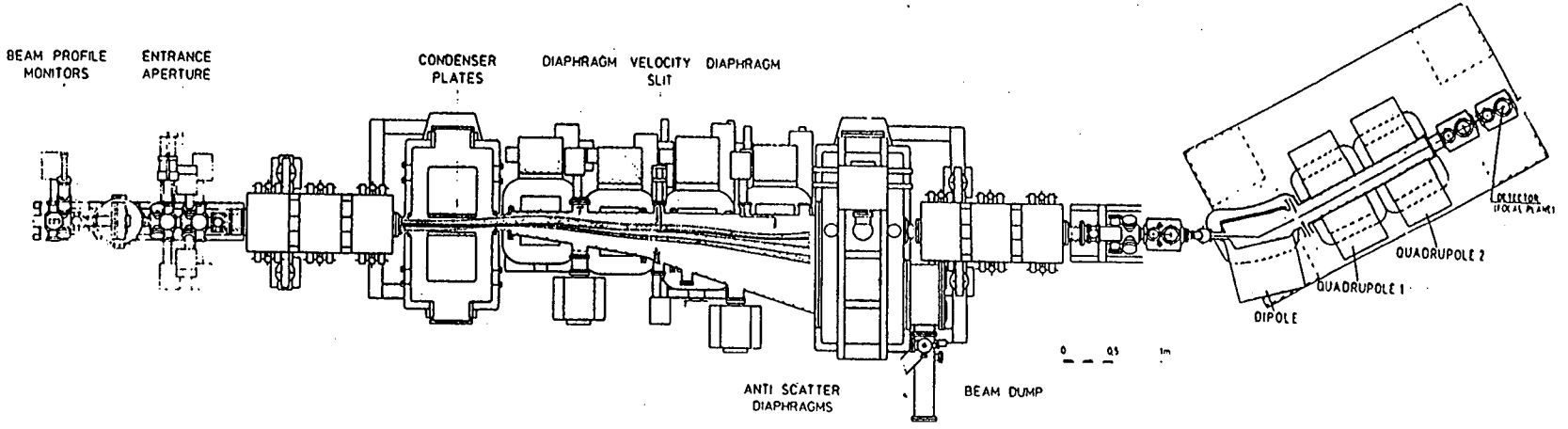


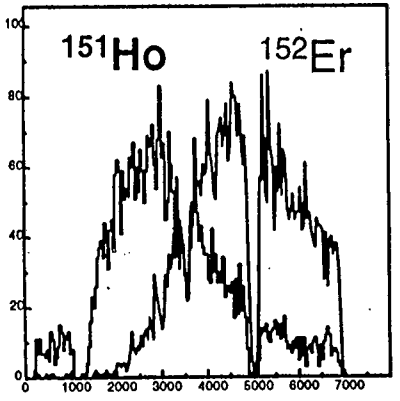
Fig. 1



RITU / Jyväskylä
now combined with TESSA

Combination of two Separators



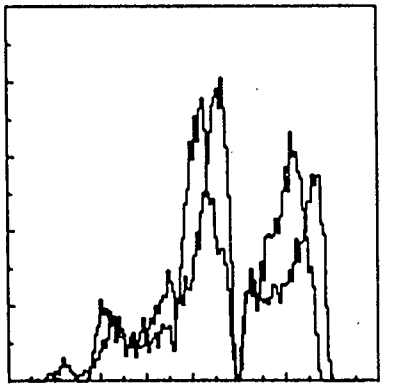


$^{58}Ni + ^{96}Ru$

high-resolution mode

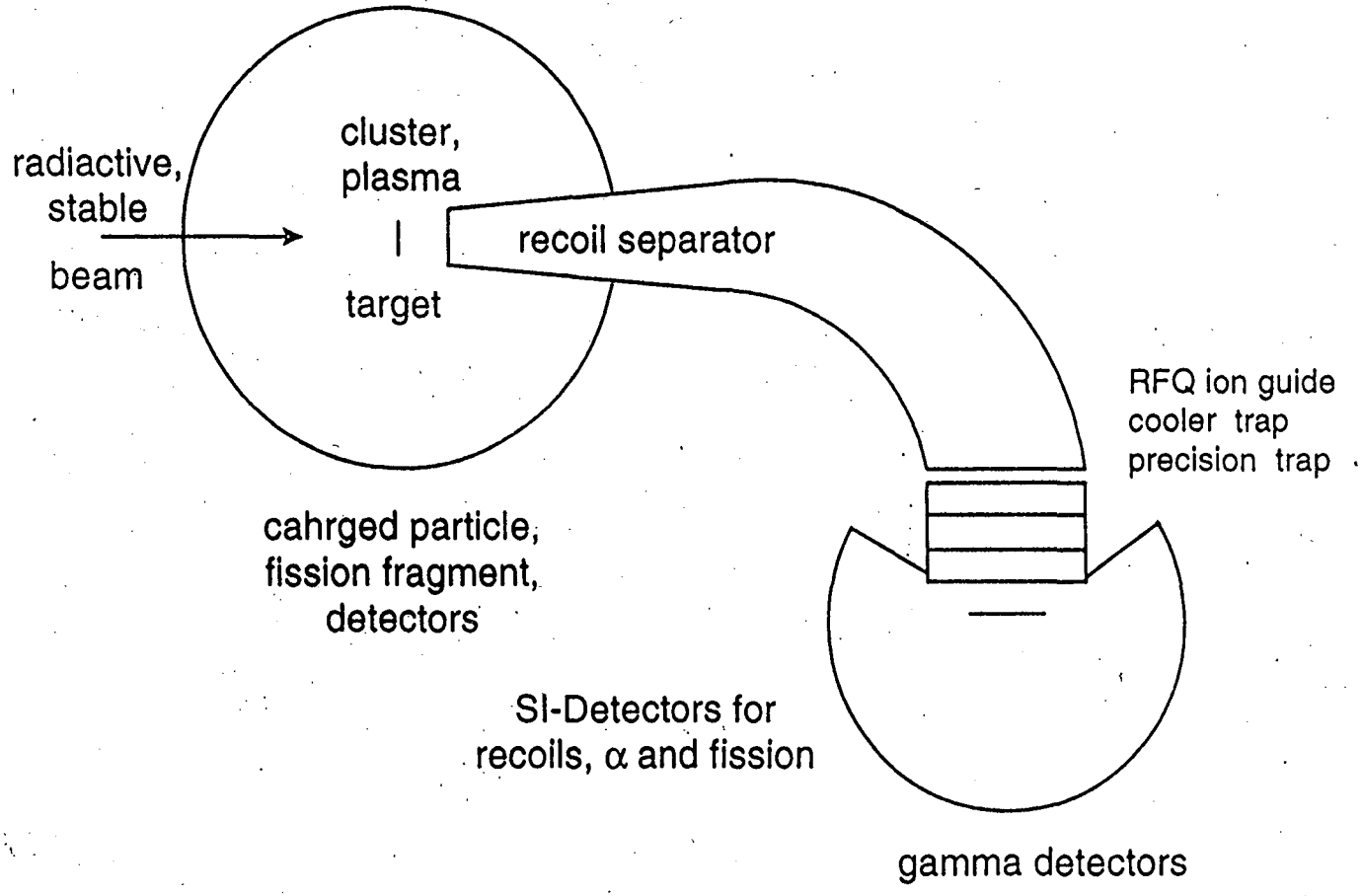
- m/q focussing

m/Δm =130±12



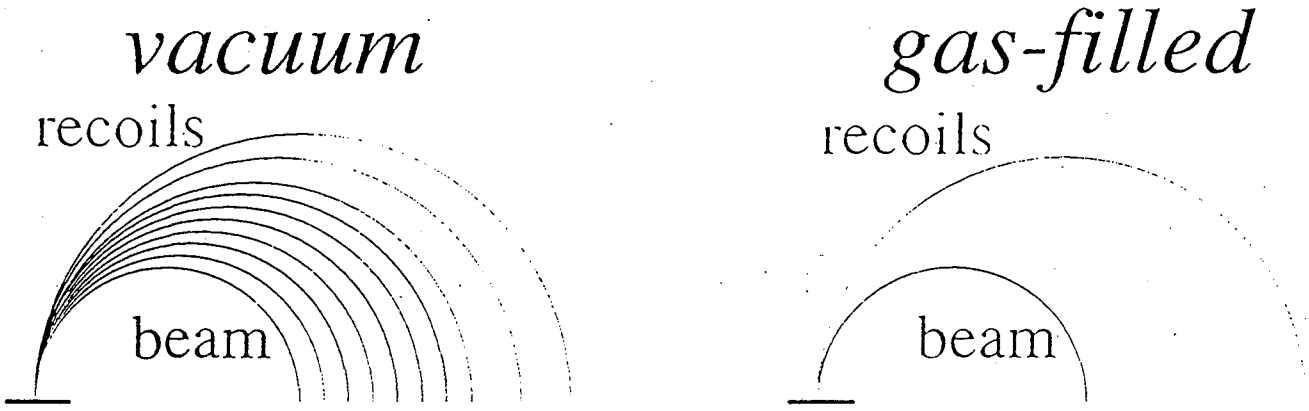
m/q-focussing mode or **charge focussing mode**
m/q-dispersion <u>minimized</u>
ER focussed onto the detector (3 charges)

Recoil Separators are Useful Tools



Ken Gregorich
Lawrence Berkeley National Laboratory

Gas-filled Separator Operating Principles

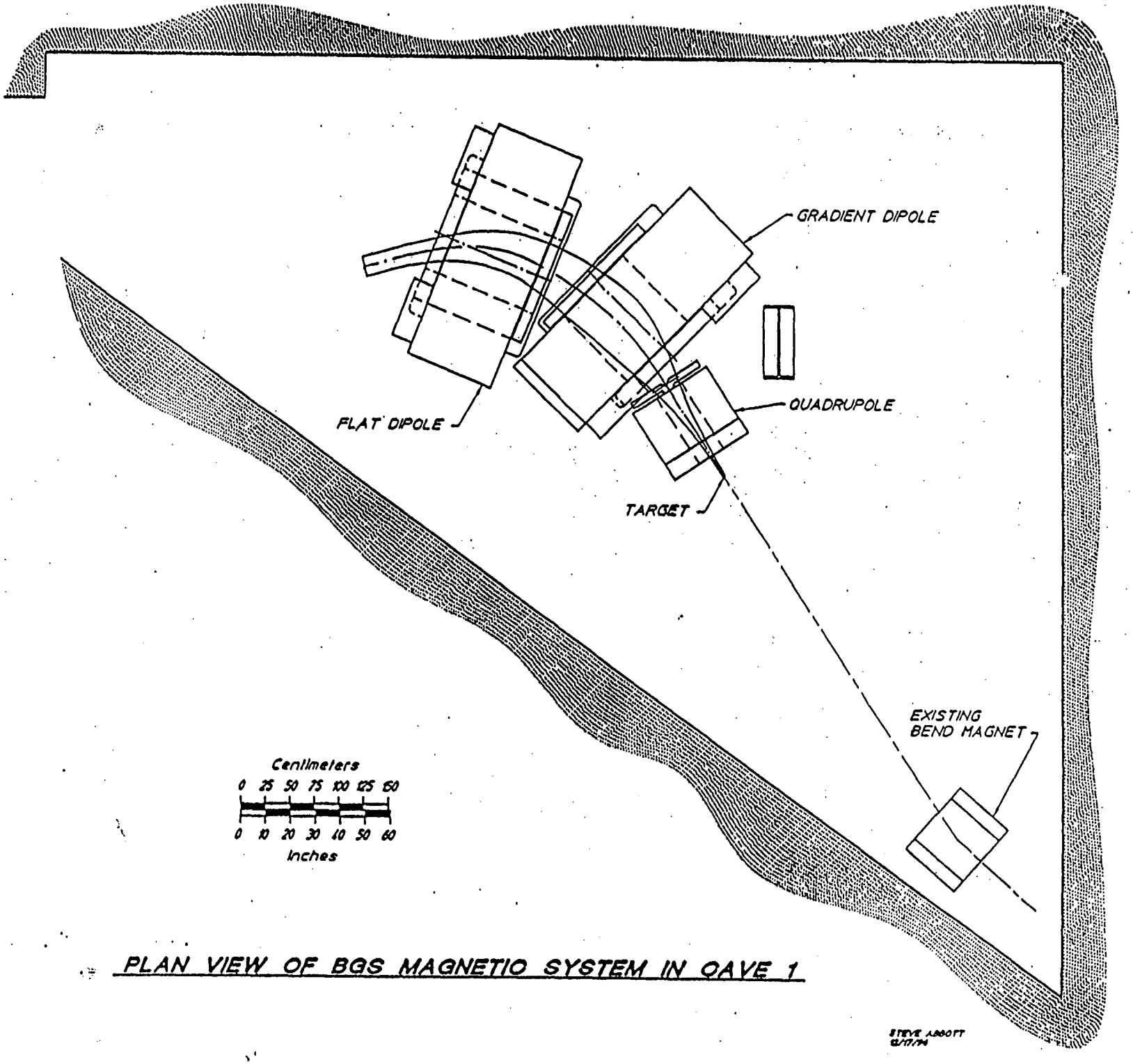


Gas-Filled Separator Advantages

- **average charge state** — Recoils experience many charge-changing collisions, taking on a well-defined average charge state
- **velocity independent** — Average charge is proportional to velocity, making the magnetic rigidity independent of velocity. Charge momentum [illegible]
- **lower beam rigidity** — Projectiles, scattered projectiles, and cluster products all have lower magnetic rigidities than compound nucleus recoils
- **target cooling** — Since the separator is filled with He [illegible] He can be flowed past the target to give better cooling (higher beam current)
- **larger acceptance** — The BGS has a larger angular acceptance than other compound nucleus separators

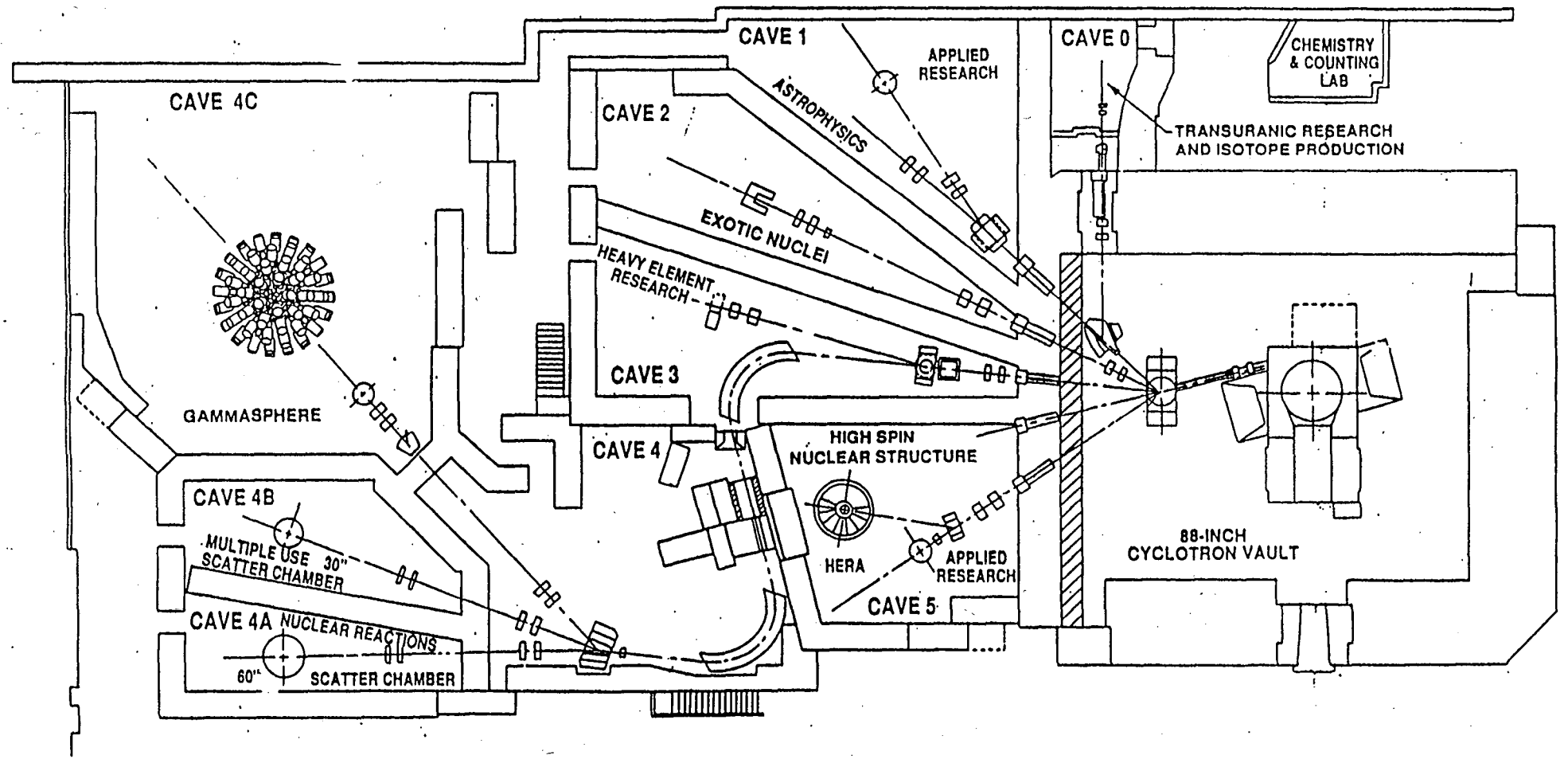
Disadvantages

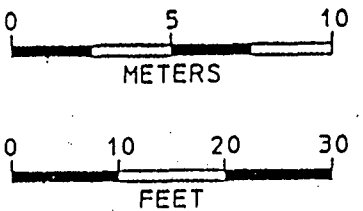
- **scattering in gas** — A mixture of the gas and charge [illegible] gives large beam spots, [illegible] and limit mass resolution [illegible]
- **windows** — Vacuum windows are necessary to contain the separator fill gas, leading to some [illegible] and beam [illegible]



PLAN VIEW OF BGS MAGNETIC SYSTEM IN CAVE 1

STEVE ABBOTT
12/17/94





88–INCH CYCLOTRON FACILITY

Berkeley Gas-Filled Separator

A World-Class Facility:

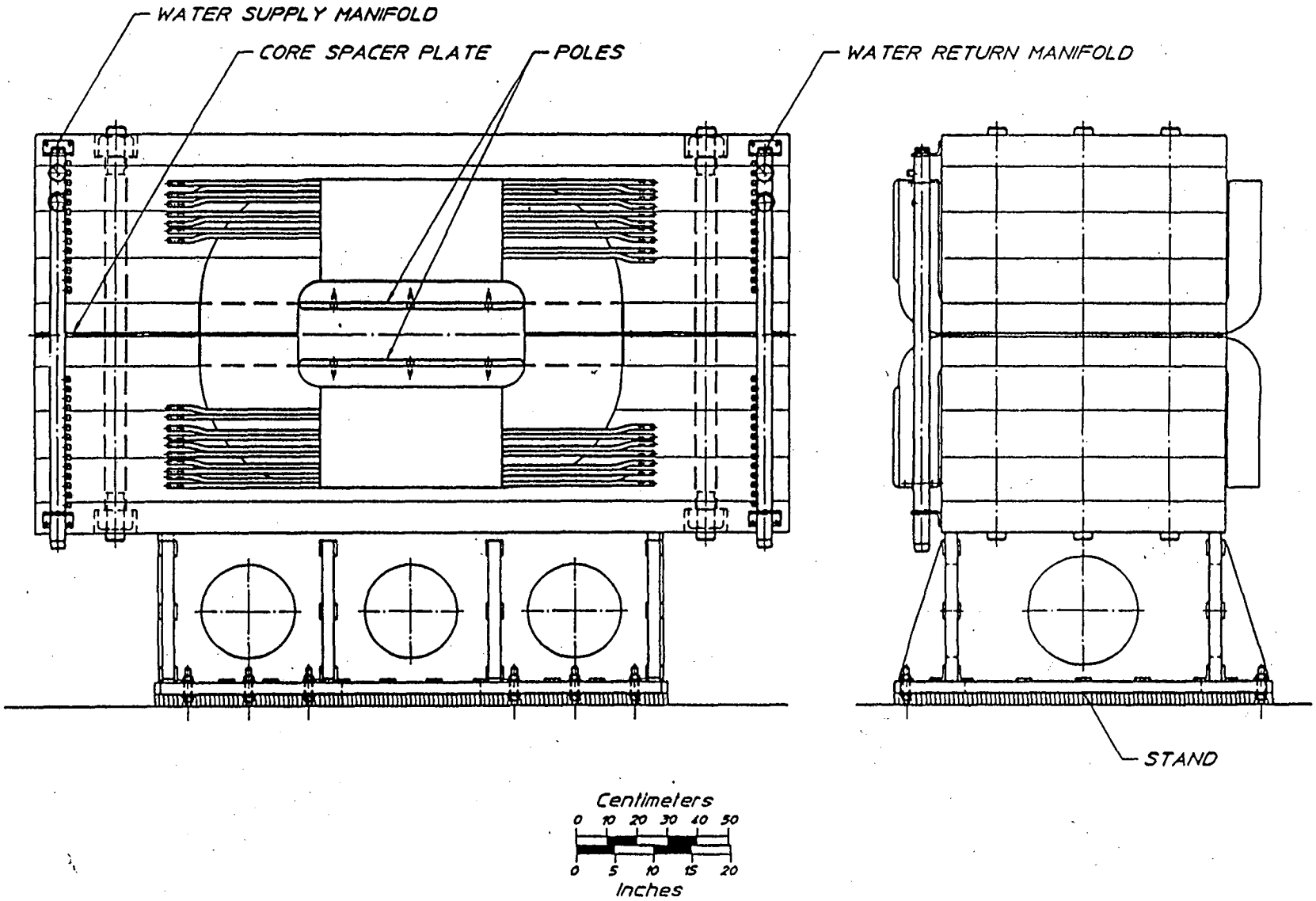
High-Intensity Beams from the 88	Samll Cross Sections
Large Angular Acceptance	Asymmetric Reactions
Large Bending Angle	Better Separation
Large Momentum Acceptance	High Effic., Thick Tgts.

Present Status:

3-D B-Field Simulations Have Been Colpleted
Full Monte-Carlo Simulations of Trajectories are Running
Magnet System Construction is Under Way
Vacuum System and Target Area are Being Designed
Data Acquisition Work has Begun
Magnets & Vacuum Chamber Installation Scheduled for August
First Experiments Planned for Late 1997

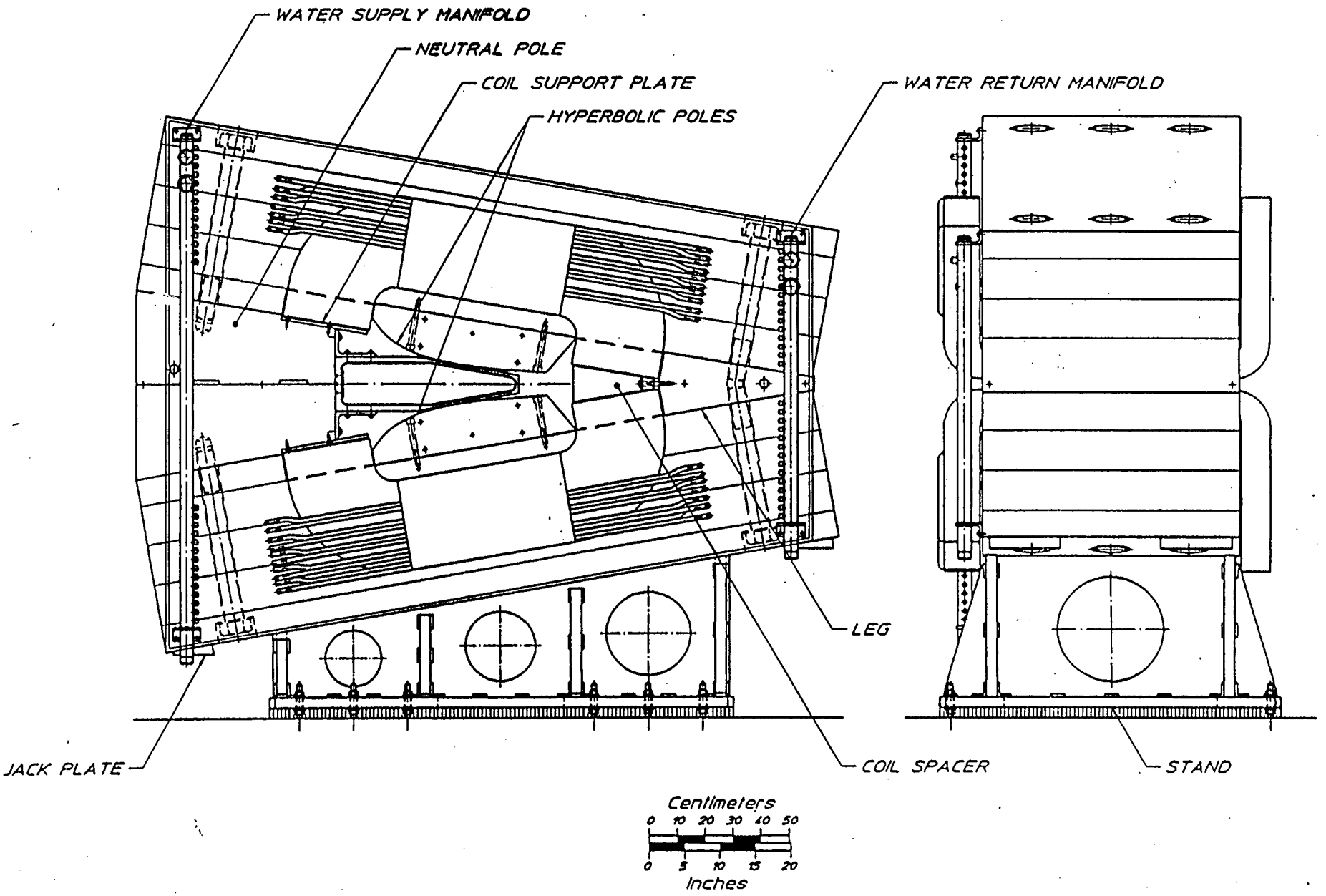
Early Heavy Element Experiments with the BGS:

$^{248}Cm(^{26}Mg,4n)^{270}Hs$	at the center of N=162 Z=108 shell
$^{238}U(^{36}S, 4n)^{270}Hs$	what are the α- and SF-halflives?
$^{248}Cm(^{48}Ca,4n)^{292}116$	spherical superheavies, do they exist?
$^{244}Pu(^{48}Ca,4n)^{288}114$	100 times better sensitivity
$^{209}Bi(^{24}Mg,3n)^{230}Am$	electron capture-delayed fission
$^{209}Bi(^{28}Si,3n)^{234}Bk$	with Q_{EC} > fission barrier
$^{238}U + ^{86}Kr$	binary transfer to produce new neutron-
$^{248}Cm + ^{76}Ge$	rich nuclides: BGS followed by chemistry



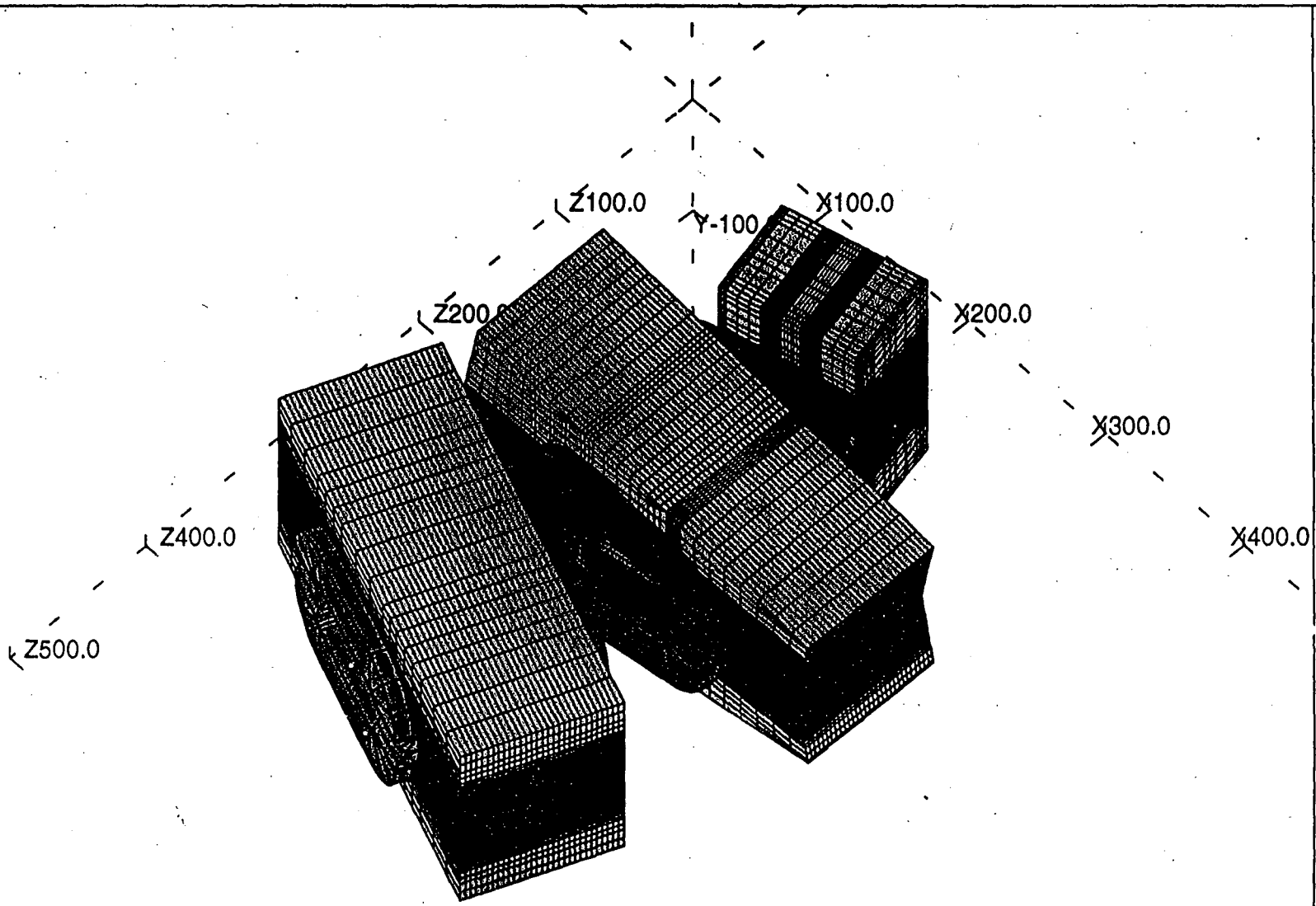
BGS 29 X, 36 H MAGNET

STEVE ABBOTT
4/8/97



BGS 29 X 36 GRADIENT MAGNET

STEVE ABBOTT
4/8/97



UNITS

Length	: cm
Flux density	: gauss
Magnetic field	: oersted
Scalar potential	: oersted·cm
Vector potential	: gauss-cm
Conductivity	: S cm^{-1}
Current density	: A cm^{-2}
Power	: W
Force	: N
Energy	: J
Electric field	: V cm^{-1}

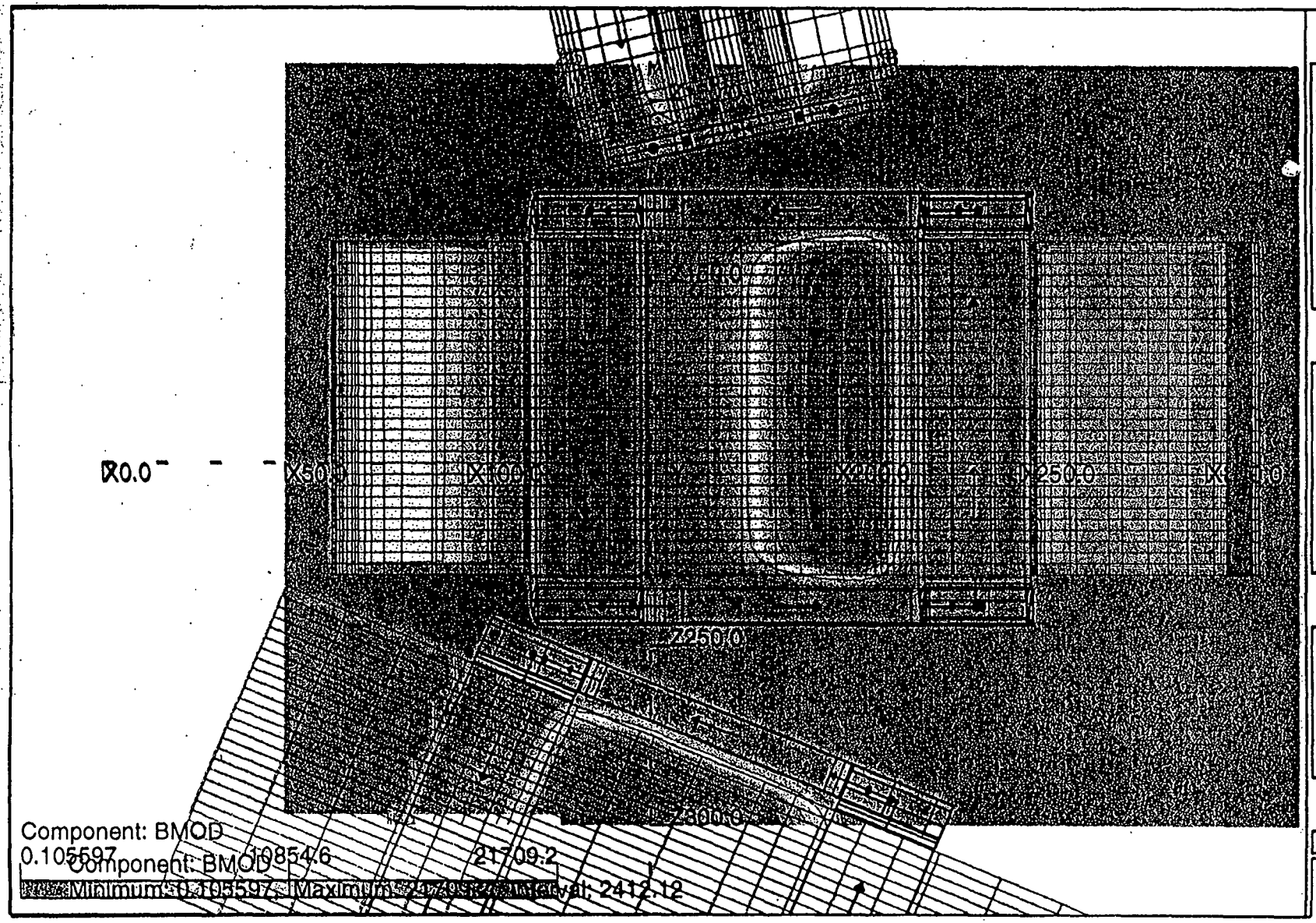
PROBLEM DATA
k14j18.toscab
TOSCA analysis (nl)
Magnetostatics
Case No 1
123057 elements
120699 nodes
Nodal fields
Nodal coil fields

LOCAL COORDS.

Xlocal	= 0.0
Ylocal	= 0.0
Zlocal	= 0.0
Theta	= 0.0
Phi	= 0.0
Psi	= 0.0

28/Sep/96 20:20:22 Page 30

OPERA-3d
Post-processor 2.601



UNITS

Length	: cm
Flux density	: gauss
Magnetic field	: oersted
Scalar potential	: oersted-cm
Vector potential	: gauss-cm
Conductivity	: S cm^{-1}
Current density	: A cm^{-2}
Power	: W
Force	: N
Energy	: J
Electric field	: V cm^{-1}

PROBLEM DATA

k14j18.toscab
TOSCA analysis (nl)
Magnetostatics
Case No 1
123057 elements
120699 nodes
Nodal fields
Nodal coil fields

LOCAL COORDS.

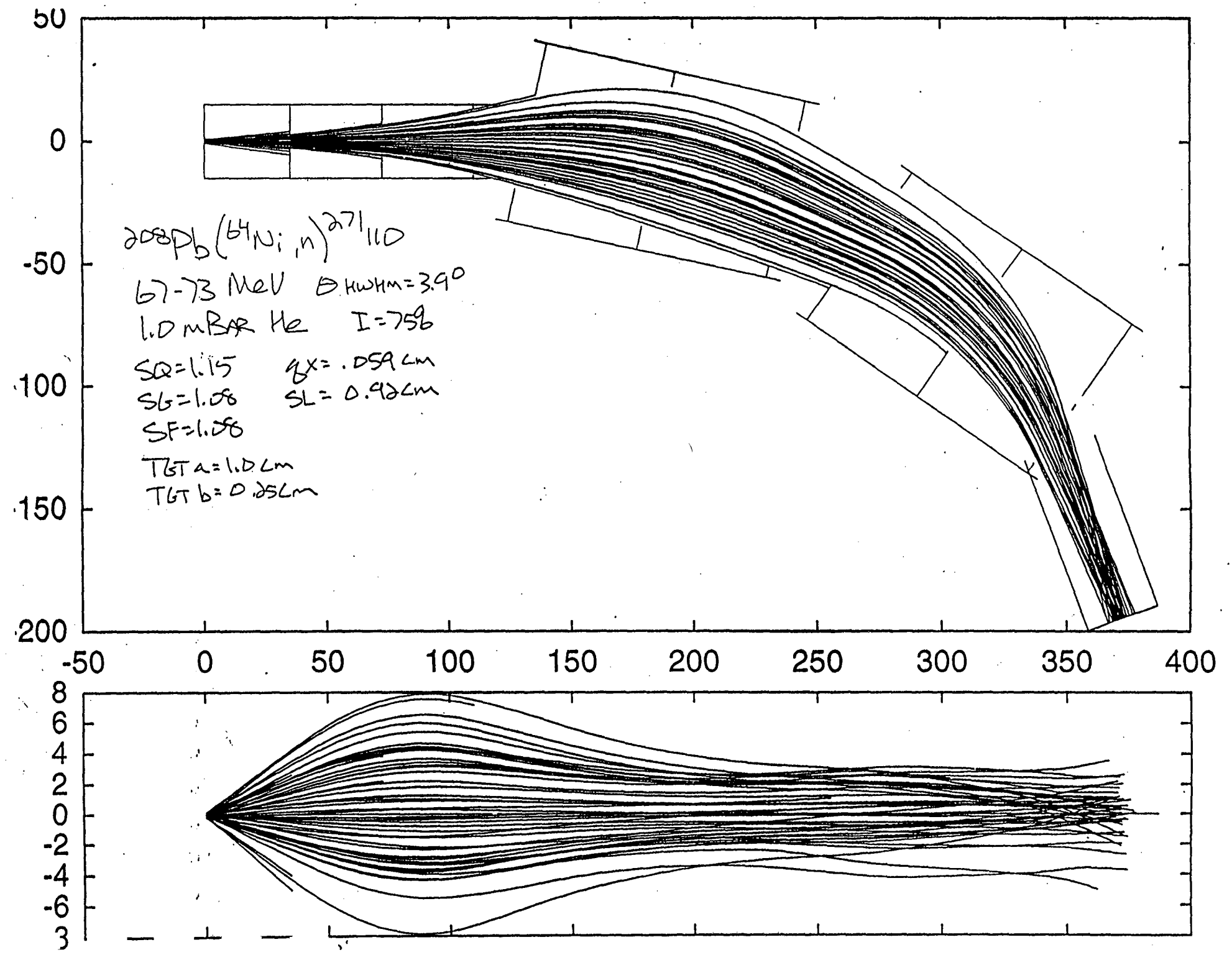
Xlocal	= 0.0
Ylocal	= 0.0
Zlocal	= 0.0
Theta	= 0.0
Phi	= 0.0
Psi	= 0.0

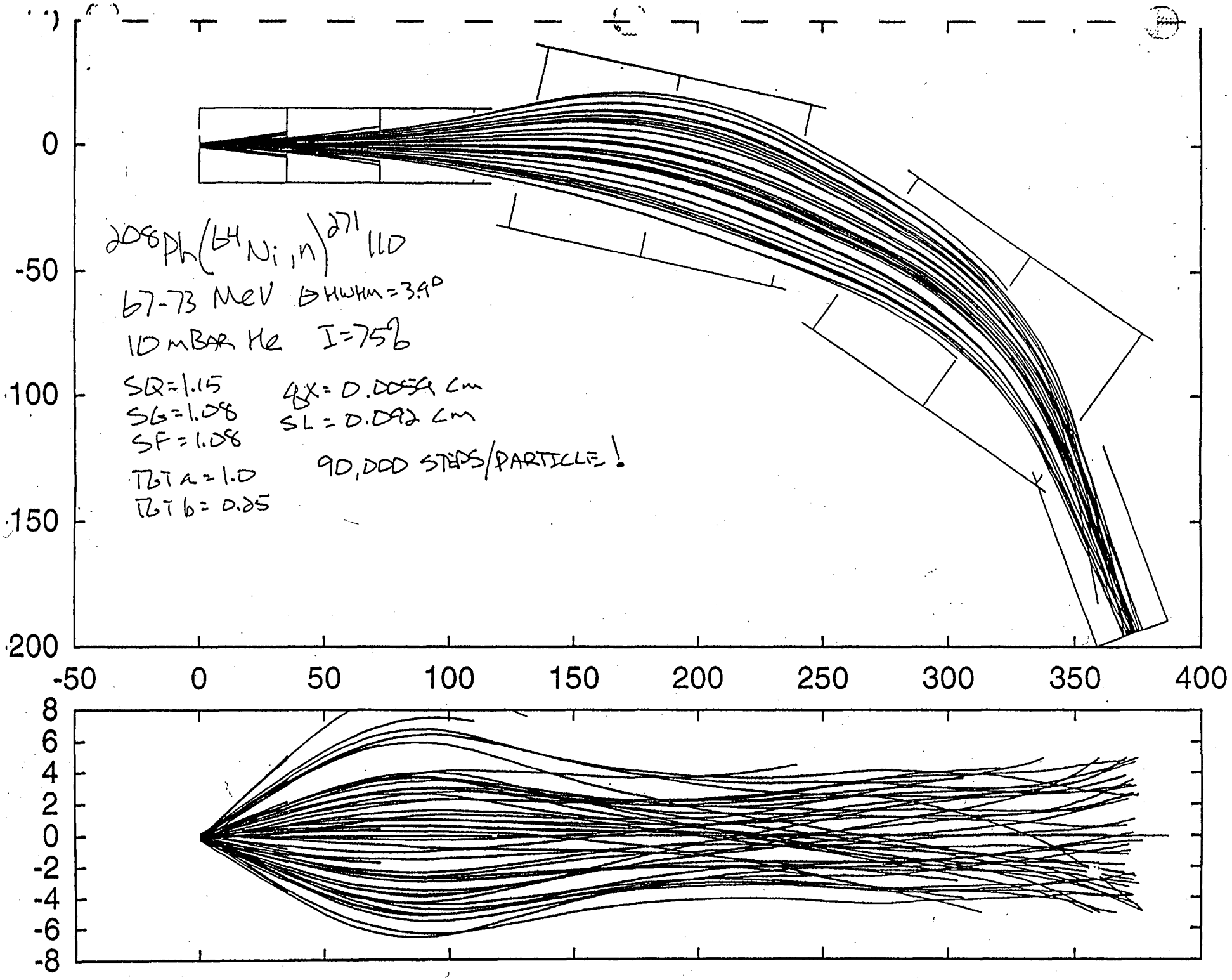
28/Sep/96 19:15:56 Page 8

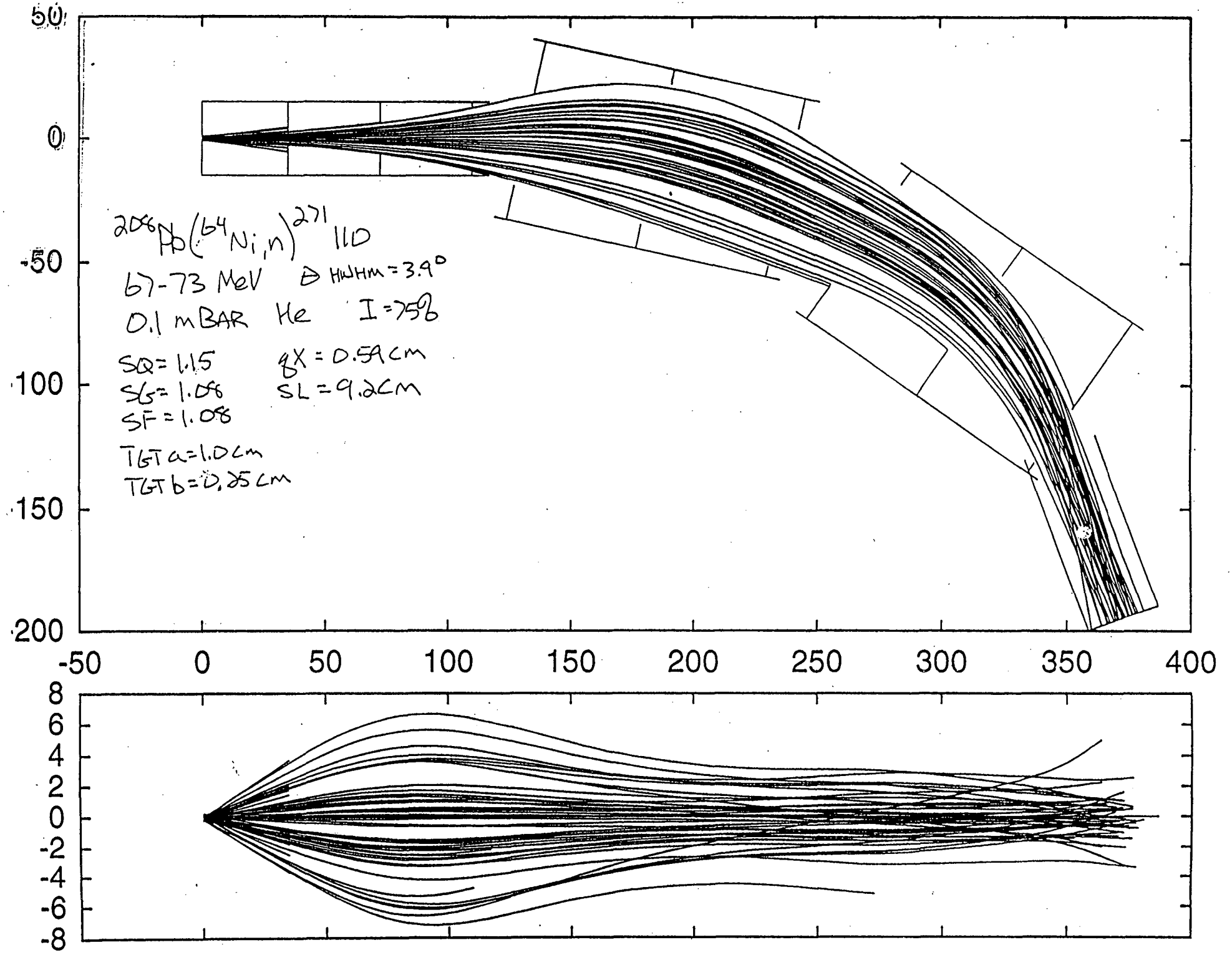
OPERA-3d
Post-processor 2.601

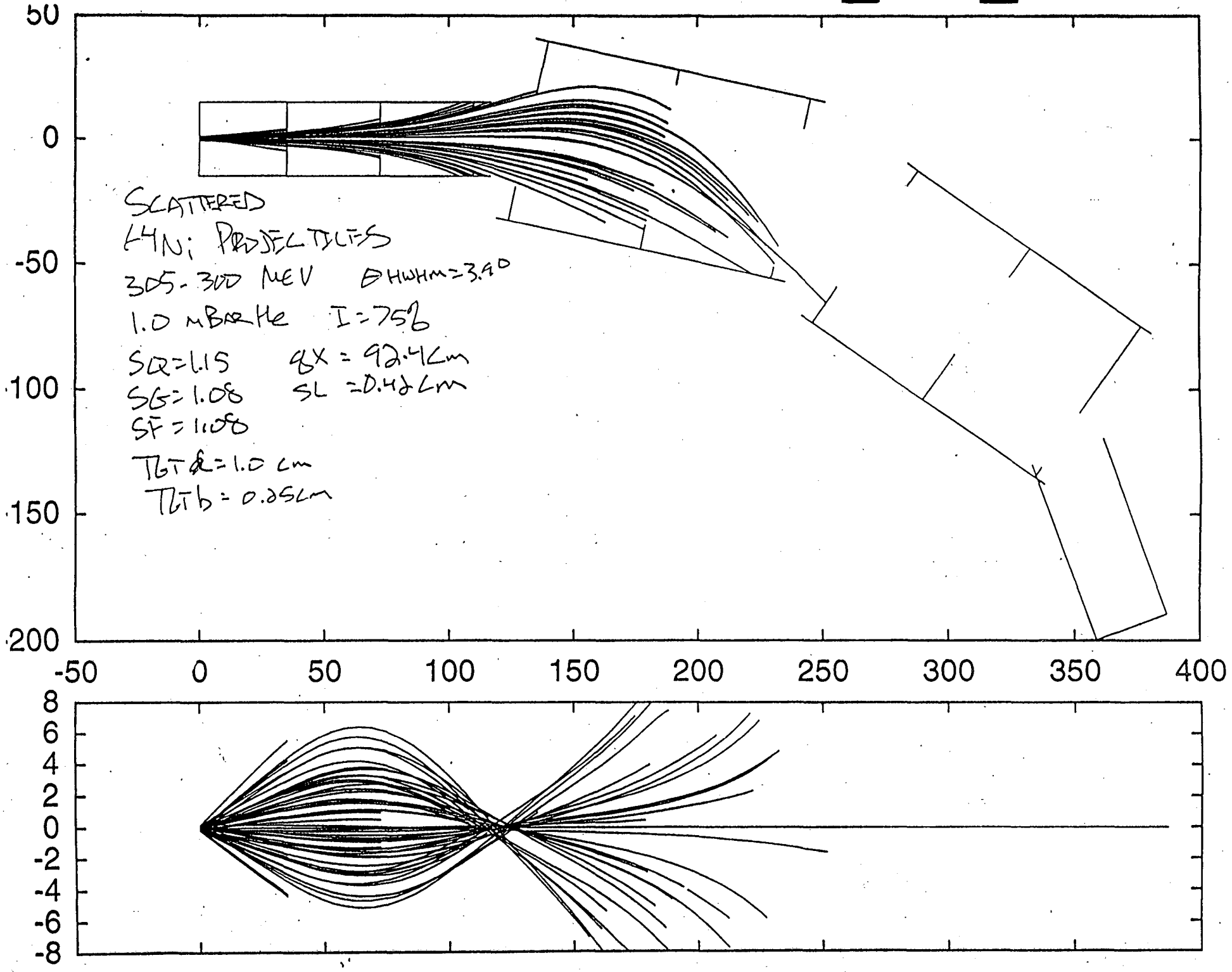
Comparison of Separators for Unslowed Compound-Nucleus Recoils

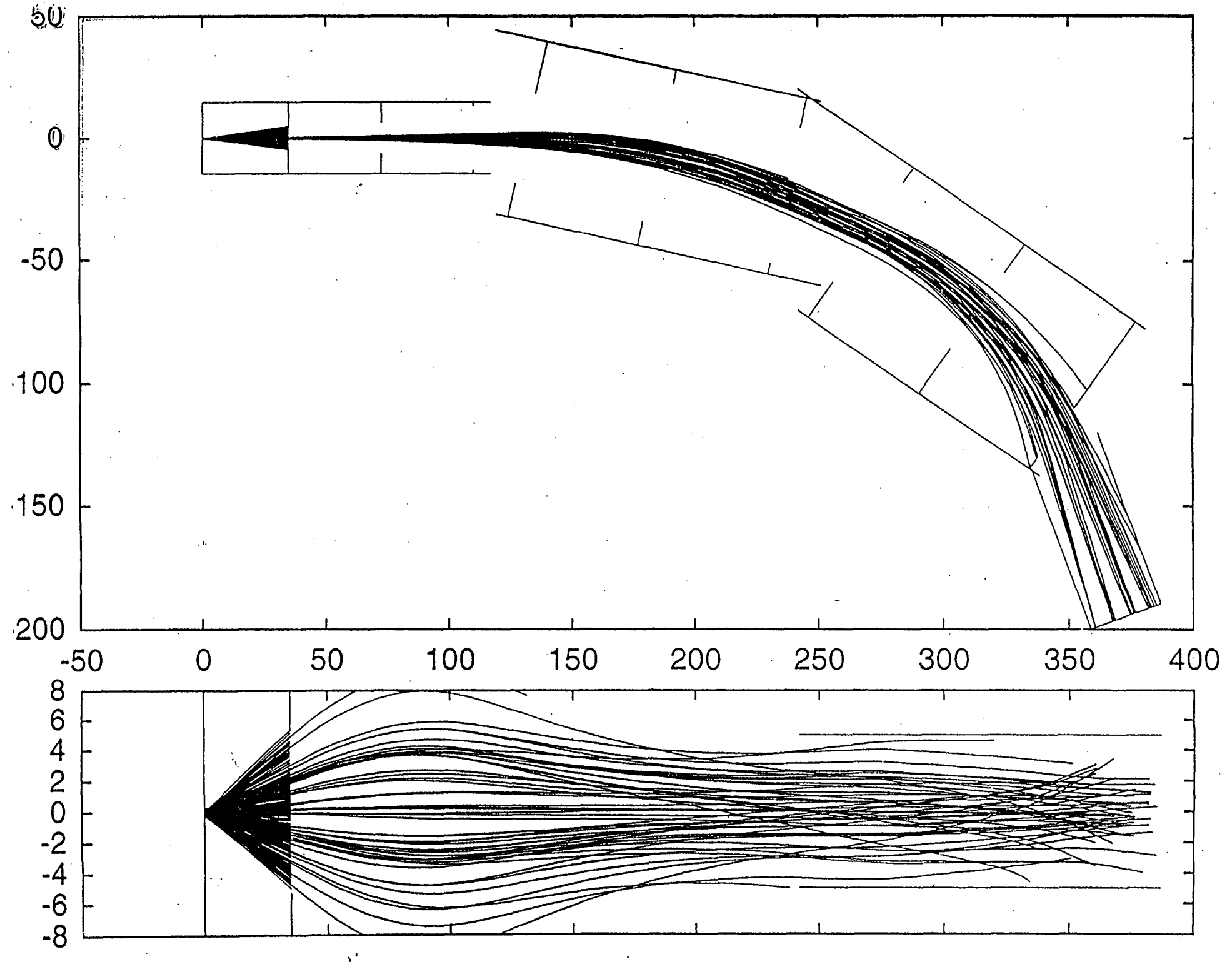
Separator	Magnet. Config.	Angular Accept.	Solid Angle	Bend Angle	Max. Bρ	Length	Horizontal Dispersion
SASSY I	DQ_hQ_v	±3°	11.0 msr	22°	2.2 Tm	4.0 m	0.67 cm/%
SASSY II	$D_vQ_hD_v$	±3°	11.0 msr	55°	2.2 Tm	2.5 m	0.74 cm/%
RITU	$Q_vDQ_hQ_v$	±2.8°	9.5 msr	25°	2.2 Tm	4.7 m	1.00 cm/%
DUBNA	DQ_hQ_v	±2.9°	10.2 msr	22°	3.1Tm	4.3 m	0.92 cm/%
HECK	DQ_hQ_v	±2.8°	9.5 msr	30°	2.2 Tm	3.4 m	0.75 cm/%
SHIP	vel. filter	±1.8°	3.9 msr	n/a	n/a	12. m	0.22 cm/% (v)
FMA	QQEDEQQ	±2.5°	8.0 msr	-20 +40 -20	1.1 Tm	8.2 m	1.00 cm/%
BGS	Q_VD_HD	±6.1°	45.0 msr	70°	2.5 Tm	4.6m	2.00 cm/%

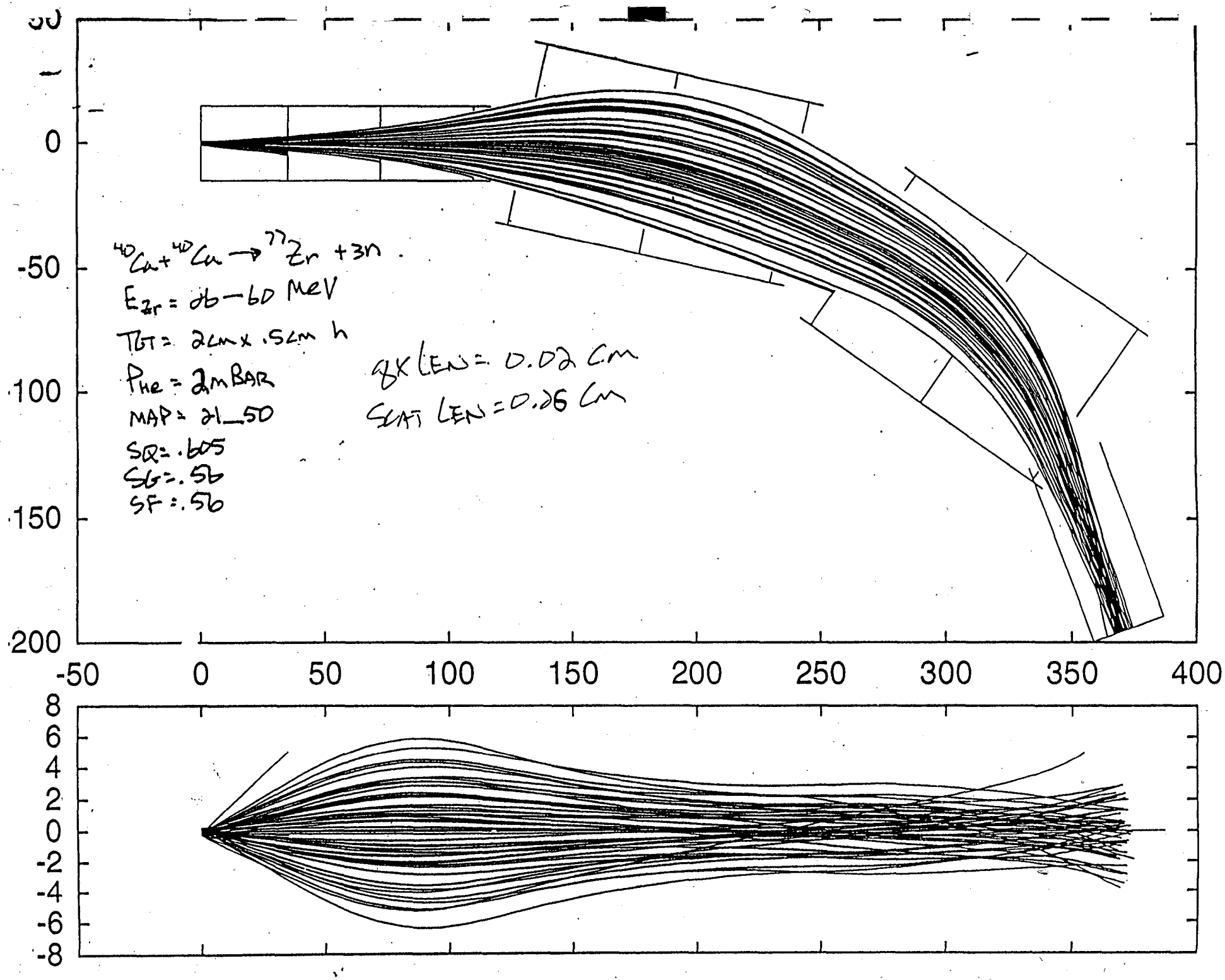

$^{208}Pb(^{64}Ni,n)^{271}110$
67-73 MeV θ HWHM=3.9°
1.0 mBAR He I=75%
SQ=1.15 qx=.059 cm
SG=1.08 SL=0.92 cm
SF=1.08
TGT a=1.0 cm
TGT b=0.25 cm
50
0
-50
-100
-150
-200
-50
0
50
100
150
200
250
300
350
400
8
6
4
2
0
-2
-4
-6
3

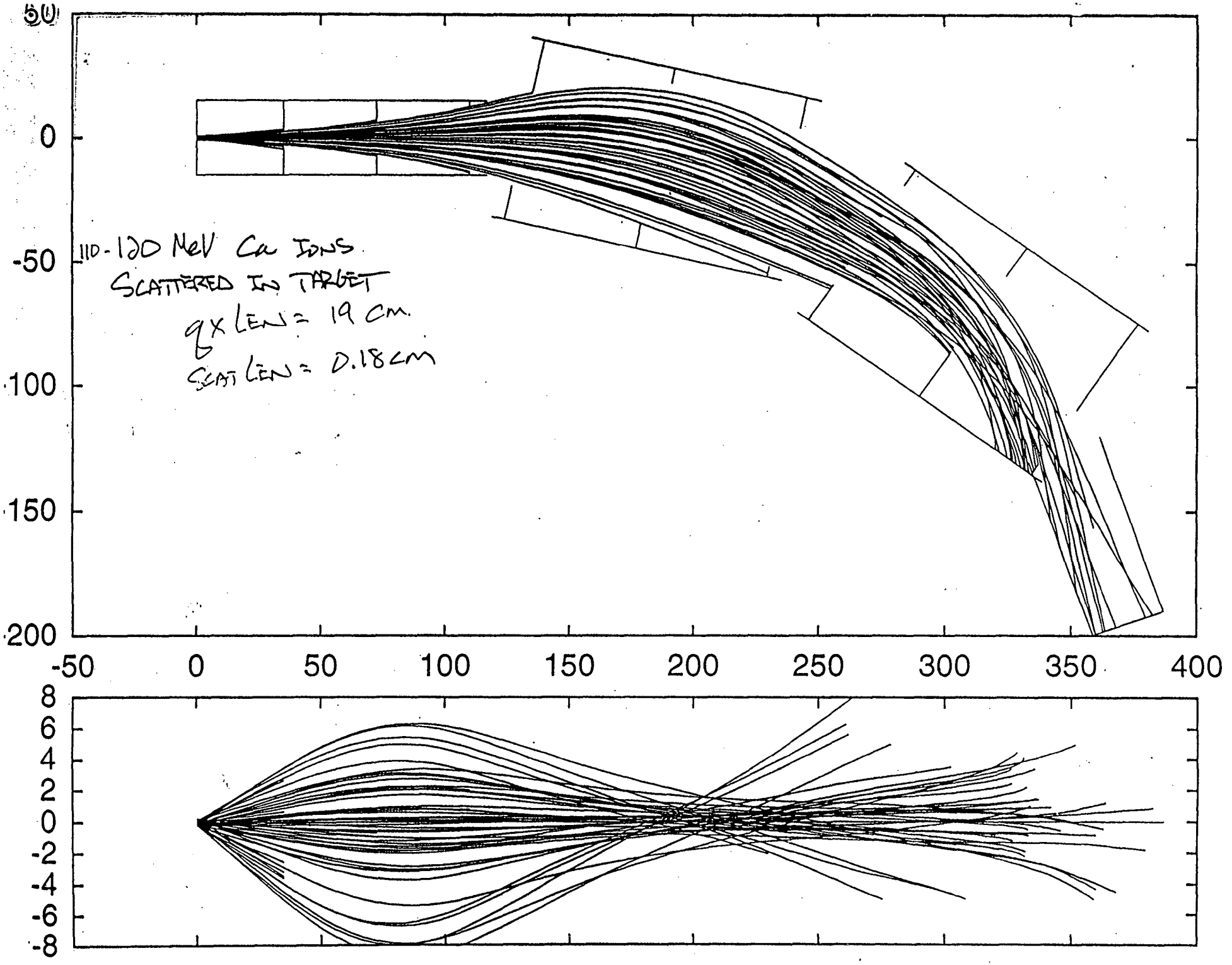

$^{208}Pb(^{64}Ni,n)^{271}110$
67-73 MeV ΘHWHM=3.9°
10 mBar He I=75%
SQ=1.15
SG=1.08
SF=1.08
TGT A=1.0
TGT b=0.25
ΔX=0.0059 cm
SL=0.092 cm
90,000 STEPS/PARTICLE!
0
-50
-100
-150
-200
-50
0
50
100
150
200
250
300
350
400
8
6
4
2
0
-2
-4
-6
-8

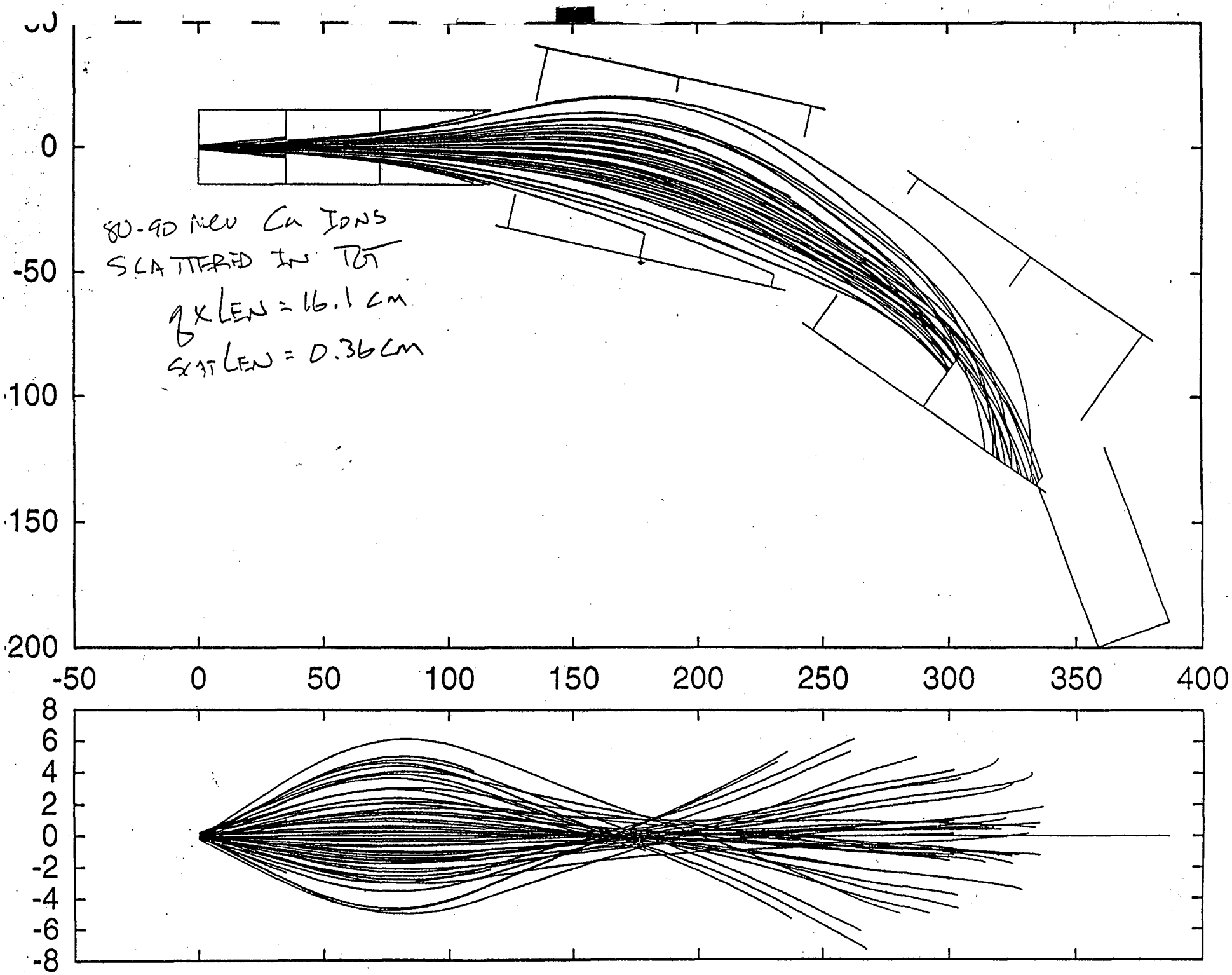

$^{208}Pb(^{64}Ni,n)^{271}110$
67-73 MeV
Δ HWHM = 3.9°
0.1 mBAR He
I = 75%
SQ = 1.15
SG = 1.08
SF = 1.08
gX = 0.59 cm
SL = 9.2 cm
TGT a = 1.0 cm
TGT b = 0.25 cm
50
0
-50
-100
-150
-200
-50
0
50
100
150
200
250
300
350
400
8
6
4
2
0
-2
-4
-6
-8

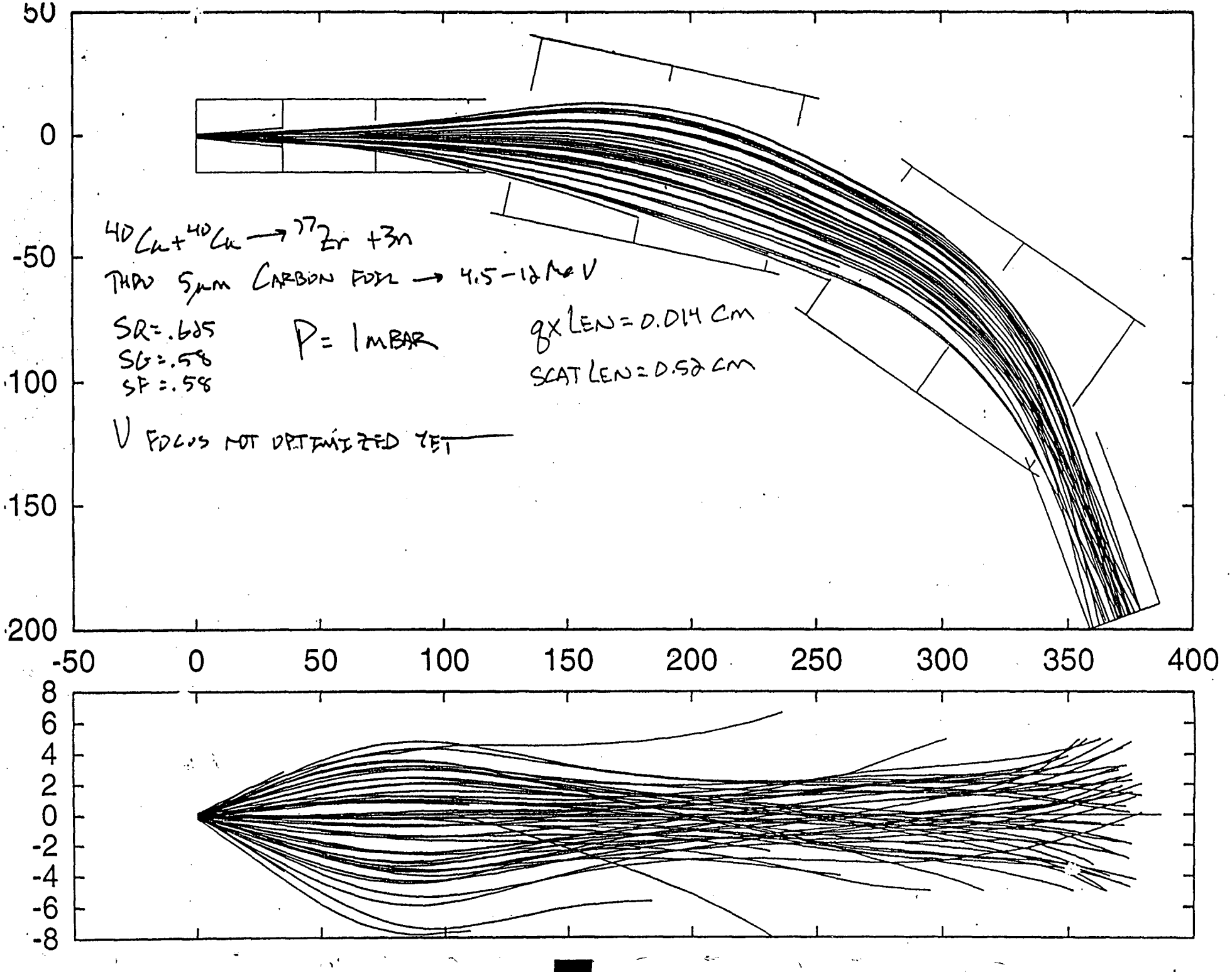

SCATTERED
44N; PROJECTILES
305-300 MEV θHWHM=3.9°
1.0 mBAR He I=75%
SQ=1.15 QX = 92.4cm
SG=1.08 SL =0.42cm
SF=1.08
TGT d=1.0 cm
TGT b=0.25cm


50
0
-50
-100
-150
-200
-50
0
50
100
150
200
250
300
350
400
8
6
4
2
0
-2
-4
-6
-8


$^{40}Ca + ^{40}Ca \rightarrow ^{77}Zr + 3n$
E_{Zr} = 26–60 MeV
TGT = 2cm x .5cm h
P_{He} = 2mBAR
MAP = 21_50
SQ = .605
SG = .56
SF = .56
GX LEN = 0.02 cm
SCAT LEN = 0.26 cm
50
0
-50
-100
-150
-200
-50
0
50
100
150
200
250
300
350
400
8
6
4
2
0
-2
-4
-6
-8


50
0
-50
-100
-150
-200
-50
0
50
100
150
200
250
300
350
400
8
6
4
2
0
-2
-4
-6
-8
110-120 MeV Ca IONS
SCATTERED IN TARGET
gx LEN = 19 cm.
SCAT LEN = 0.18 cm


80-90 MeV Ca IONS
SCATTERED IN TGT
gx LEN = 16.1 cm
SCAT LEN = 0.36 cm
0
-50
-100
-150
-200
-50
0
50
100
150
200
250
300
350
400
8
6
4
2
0
-2
-4
-6
-8


$^{40}Cu + ^{40}Cu \rightarrow ^{77}Zr + 3n$
THRU 5 μm CARBON FOIL → 4.5–12 MeV
SR = .685
SG = .58
SF = .58
P = 1 MBAR
qx LEN = 0.014 cm
SCAT LEN = 0.52 cm
V FOCUS NOT OPTIMIZED YET
50
0
-50
-100
-150
-200
-50
0
50
100
150
200
250
300
350
400
8
6
4
2
0
-2
-4
-6
-8

$i := 1..24$

$Z_i := 5 \cdot i \qquad A_i := Z_i \cdot 2 + 0.0045 \cdot (Z_i)^2$

$v0 \equiv 2.189 \cdot 10^6 \cdot \frac{m}{sec} \qquad qe := 1.602 \cdot 10^{-19} \cdot coul \qquad MeV := 1.602 \cdot 10^{-13} \cdot joule \qquad AMU := 1.66 \cdot 10^{-27} \cdot kg$

$j := 1..13 \qquad v_j := j \cdot v0$

$$qSAS_{i,j} := Z_i \cdot \left[1.0 - 1.04 \cdot e^{\left[-0.91 \cdot \frac{v_j}{v0} \cdot (Z_i)^{-0.666667}\right]}\right]$$

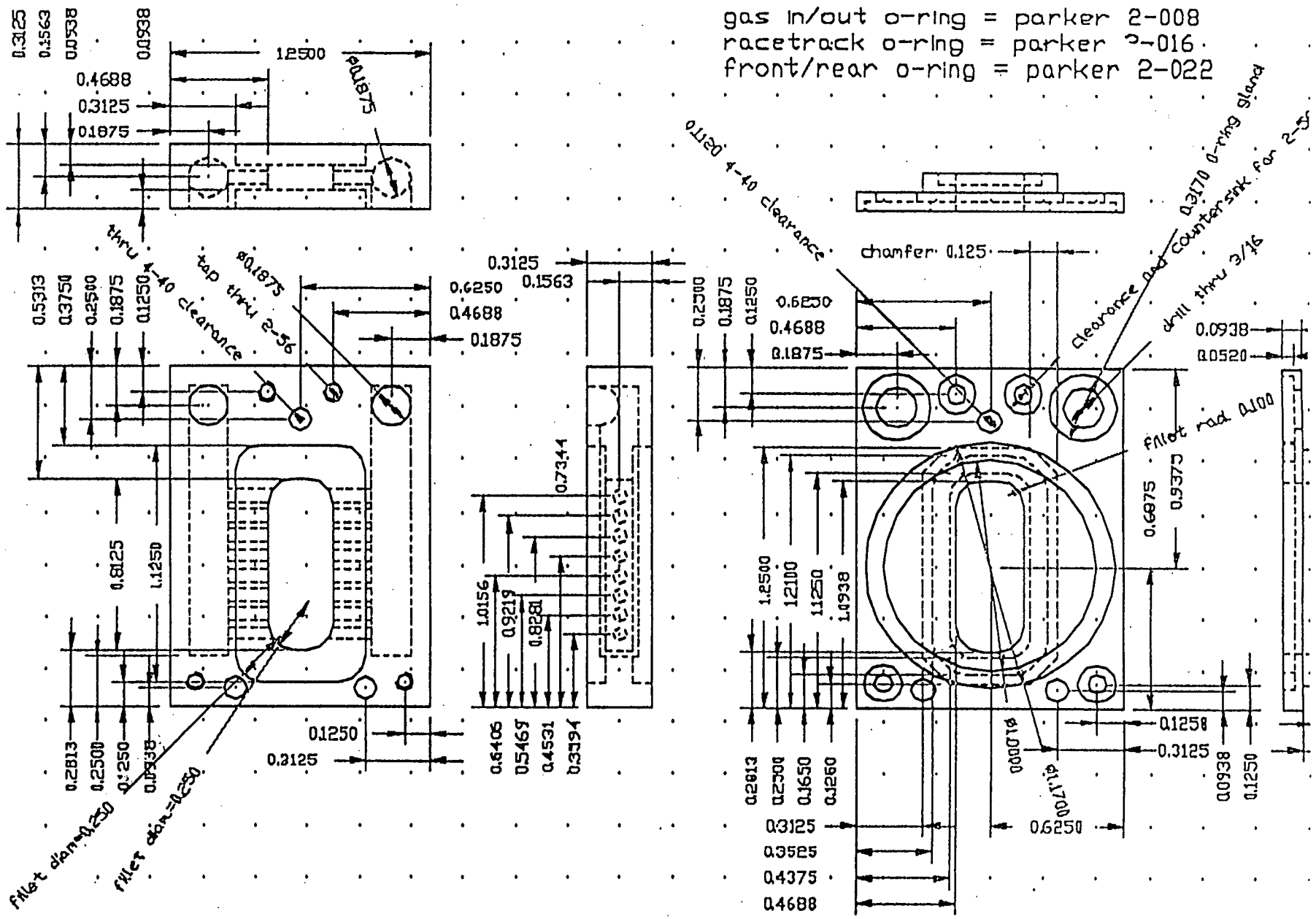
$$qSLO_{i,j} := 0.394 \cdot \frac{v_j}{v0} \cdot (Z_i)^{0.33333} + 1.65$$

$$q_{i,j} := if(qSLO_{i,j} > qSAS_{i,j}, qSLO_{i,j}, qSAS_{i,j})$$

$$q_{i,j} := if\left(\frac{v_j}{v0} > 4.0, qSAS_{i,j}, q_{i,j}\right) \qquad B\rho_{i,j} := \frac{A_i \cdot AMU \cdot v_j}{q_{i,j} \cdot qe \cdot tesla \cdot m}$$

	E/A =	0.025	0.099	0.223	0.397	0.621	0.894	1.216	1.589	2.011	2.483	3.004	3.575	4.196
	v/v0 =	1.0	2.0	3.0	4.0	5.0	6.0	7.0	8.0	9.0	10.0	11.0	12.0	13.0
Z =	5	0.099	0.153	0.187	0.211	0.294	0.328	0.364	0.402	0.441	0.481	0.522	0.565	0.607
	10	0.186	0.277	0.329	0.353	0.38	0.41	0.441	0.474	0.508	0.543	0.58	0.618	0.656
	15	0.268	0.392	0.419	0.438	0.462	0.488	0.517	0.547	0.579	0.611	0.645	0.68	0.716
	20	0.349	0.5	0.504	0.519	0.54	0.564	0.591	0.619	0.649	0.68	0.712	0.745	0.779
	25	0.428	0.601	0.588	0.598	0.616	0.638	0.662	0.689	0.718	0.747	0.778	0.81	0.843
Bρ =	30	0.505	0.698	0.672	0.676	0.69	0.71	0.733	0.759	0.786	0.814	0.844	0.875	0.906
	35	0.583	0.798	0.756	0.753	0.764	0.782	0.803	0.827	0.853	0.881	0.909	0.939	0.97
	40	0.66	0.9	0.84	0.831	0.838	0.853	0.872	0.895	0.92	0.947	0.975	1.004	1.034
	45	0.737	1.006	0.926	0.908	0.911	0.924	0.942	0.963	0.987	1.013	1.04	1.068	1.098
	50	0.814	1.108	1.013	0.986	0.985	0.995	1.011	1.031	1.053	1.078	1.105	1.132	1.161
	55	0.891	1.207	1.101	1.065	1.059	1.066	1.08	1.098	1.12	1.144	1.17	1.197	1.225
	60	0.968	1.305	1.191	1.145	1.133	1.137	1.149	1.166	1.187	1.21	1.235	1.261	1.289
	65	1.045	1.403	1.283	1.226	1.209	1.209	1.219	1.234	1.253	1.276	1.3	1.326	1.353
	70	1.123	1.501	1.377	1.308	1.284	1.281	1.289	1.302	1.321	1.342	1.365	1.39	1.417
	75	1.201	1.599	1.473	1.391	1.361	1.354	1.359	1.371	1.388	1.408	1.431	1.455	1.481
	80	1.279	1.698	1.571	1.475	1.439	1.428	1.43	1.44	1.456	1.475	1.497	1.521	1.546
	85	1.358	1.796	1.672	1.561	1.517	1.502	1.501	1.51	1.524	1.542	1.563	1.586	1.611
	90	1.437	1.895	1.775	1.648	1.597	1.577	1.574	1.58	1.593	1.61	1.63	1.652	1.677
	95	1.517	1.994	1.881	1.737	1.677	1.653	1.646	1.651	1.662	1.677	1.697	1.719	1.742
	100	1.597	2.094	1.99	1.827	1.759	1.729	1.72	1.722	1.731	1.746	1.764	1.785	1.809
	105	1.678	2.194	2.102	1.919	1.841	1.807	1.794	1.794	1.801	1.815	1.832	1.853	1.875
	110	1.76	2.295	2.216	2.012	1.925	1.885	1.869	1.866	1.872	1.884	1.901	1.92	1.942
	115	1.842	2.396	2.334	2.108	2.01	1.964	1.944	1.939	1.944	1.954	1.97	1.988	2.01
	120	1.924	2.497	2.455	2.205	2.097	2.045	2.021	2.013	2.016	2.025	2.039	2.057	2.078

gas in/out o-ring = parker 2-008
racetrack o-ring = parker 2-016
front/rear o-ring = parker 2-022



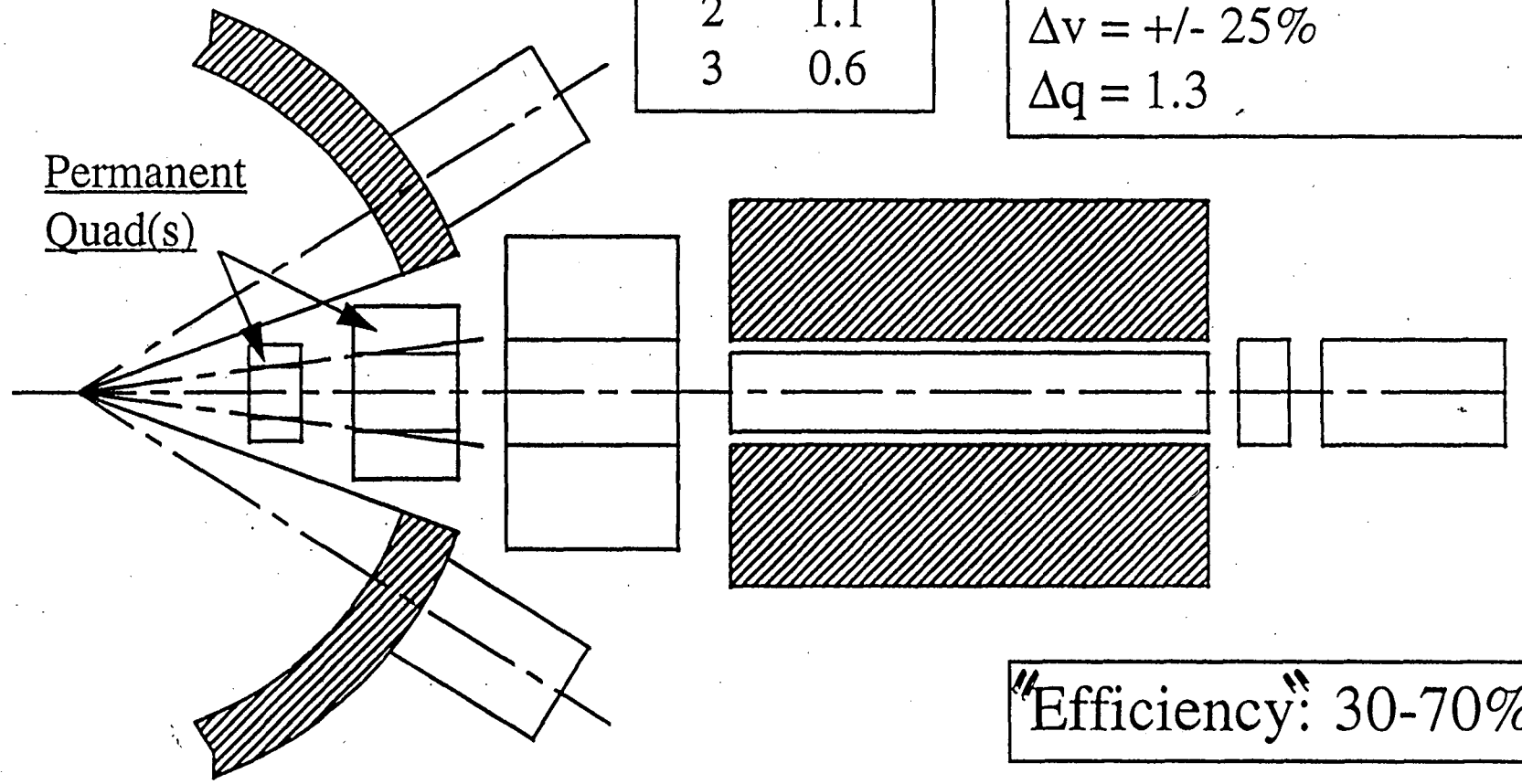
Paul Fallon
Lawrence Berkeley National Laboratory

Quad Triplet + Wien Filter

Recoil Bρ=0.8Tm

Quad	Tesla
1	0.6
2	1.1
3	0.6

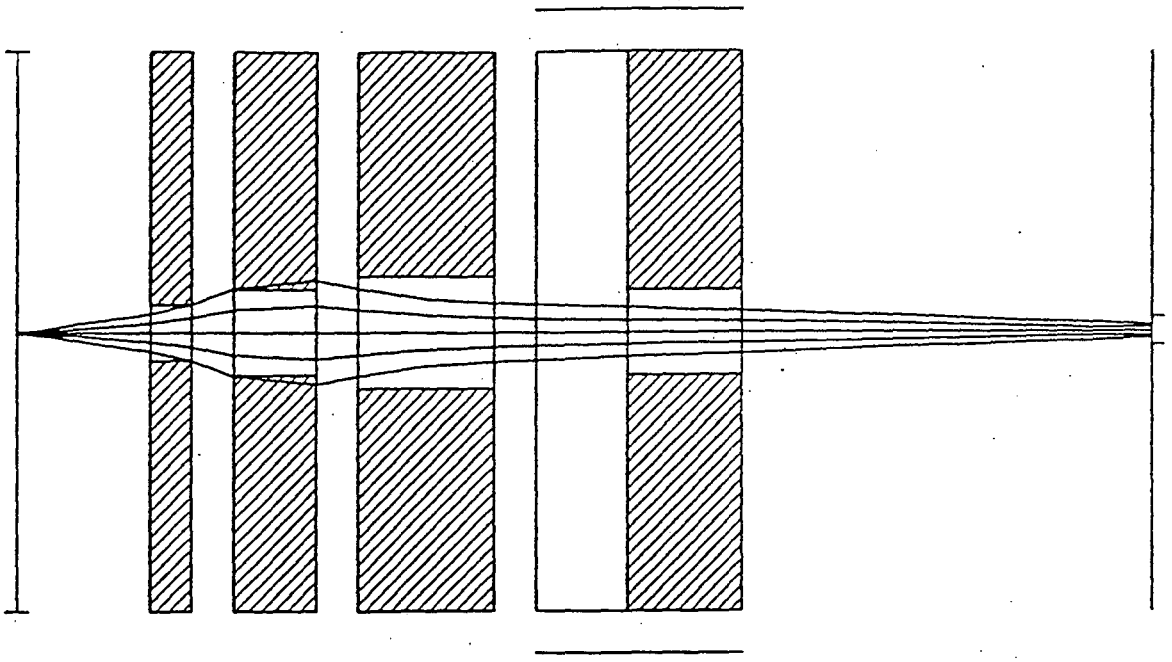
Angular Acceptance ~ +/- 6°
Δp = +/- 10%
Δv = +/- 25%
Δq = 1.3



"Efficiency": 30-70%

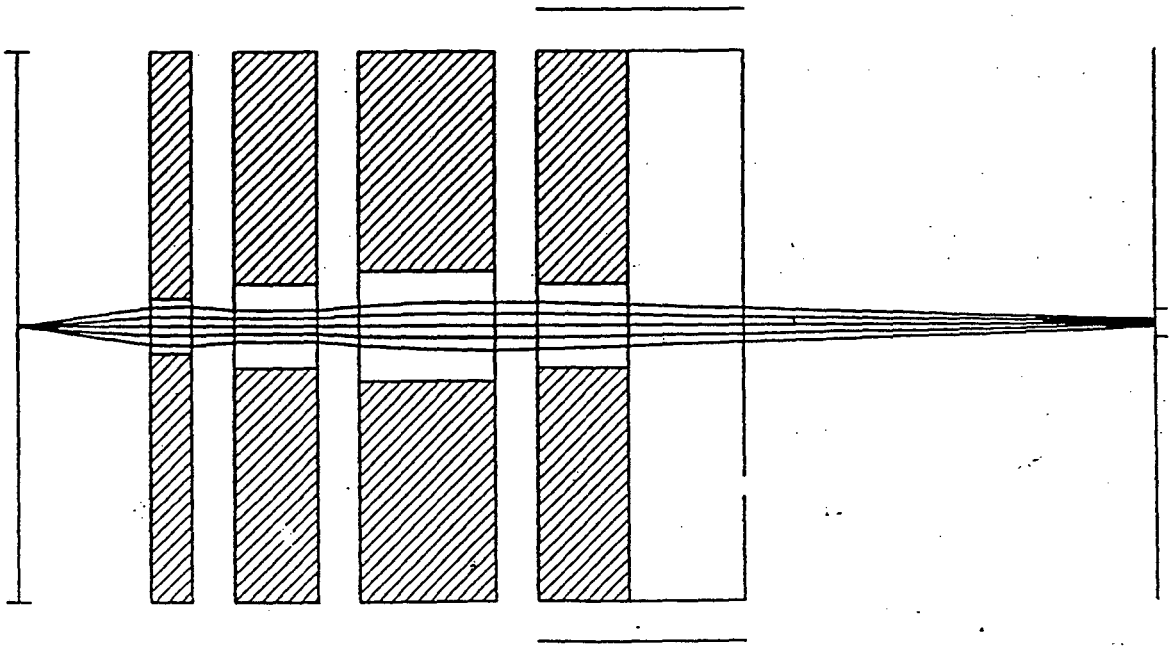
3m

Y



Y-MAX = +/- 0.500 TLU Z-MAX = 2.742 LLU

X



X-MAX = +/- 0.500 TLU Z-MAX = 2.742 LLU

GFS

Gammasphere Fusion Separator

(FRAGMENT)

(GAS FILLED SOLENOID)

Physics

1. Reduce Background

- ***Fission***

  A>190

  - Rich Variety of Shapes/Collective Excitations
  - Weak Structures in ~1mb Channel.
    - Superdeformation : Pb ➡ U
    - Octupole Deformations
    - Hyperdeformations !

- ***Mass Identification***

  Decay Tagging: Identify the Nucleus via p, α-decay energies.

- ***Gamma Identification***

  Gate on the gamma-ray, look at centroid of "recoil-peak" at the focal plane:

2. Doppler Correction

(a) Determine the recoil angle

(b) Correct the Doppler shift

» Significant Improvement in Resolving Power

AIM : Collect "all" recoils from a fusion-evaporation reaction originating from the target position of gammasphere

Design Goals

- **Large Acceptance/Transmission**
- **Good Beam Rejection**
- Recoil (Mass) Identification
- Doppler Correction

Constraints

- Fit with/within Existing Gammasphere Frame
- COST

→ Accept +/- 7 degree Recoil Cone
Beam Rejection : 10^7

GAS FILLED →

- Focus "all" Charge States
- Velocity Compensation
- Low Resolution

Devices Studied :

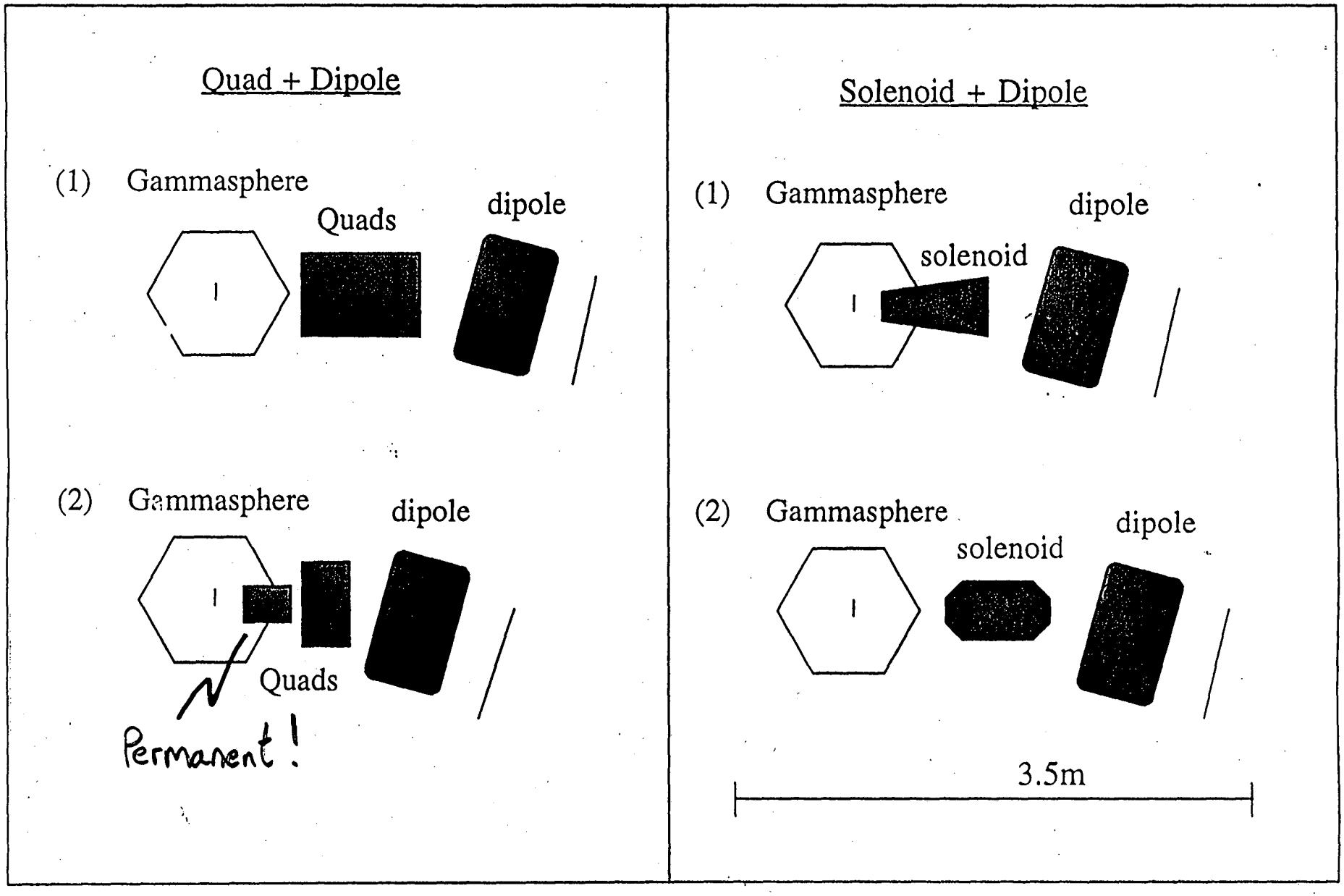
History : (Al Ghiorso) Considered GAS SYSTEMS.

Two "Element" Design :

1. Focus Products
2. Dispersive (Reject Beam)

Focusing	Dispersive
QUADS (Cu-Fe/ Per.)	DIPOLE
SOLENOID	DIPOLE

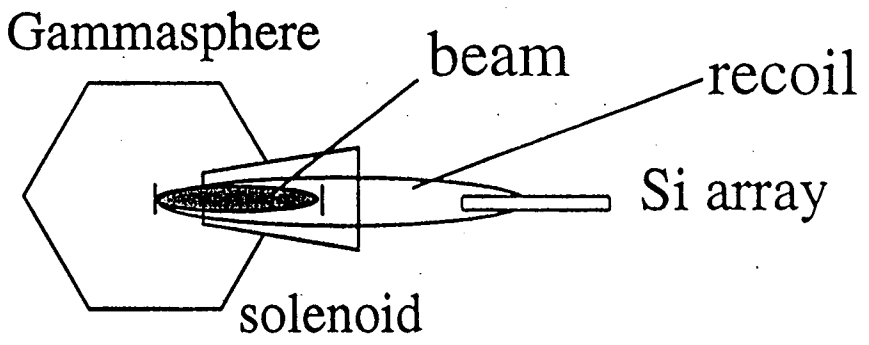
~~SOLENOID ONLY~~


Quad + Dipole
(1) Gammasphere
Quads
dipole
(2) Gammasphere
dipole
Quads
Permanent!
Solenoid + Dipole
(1) Gammasphere
solenoid
dipole
(2) Gammasphere
solenoid
dipole
3.5m

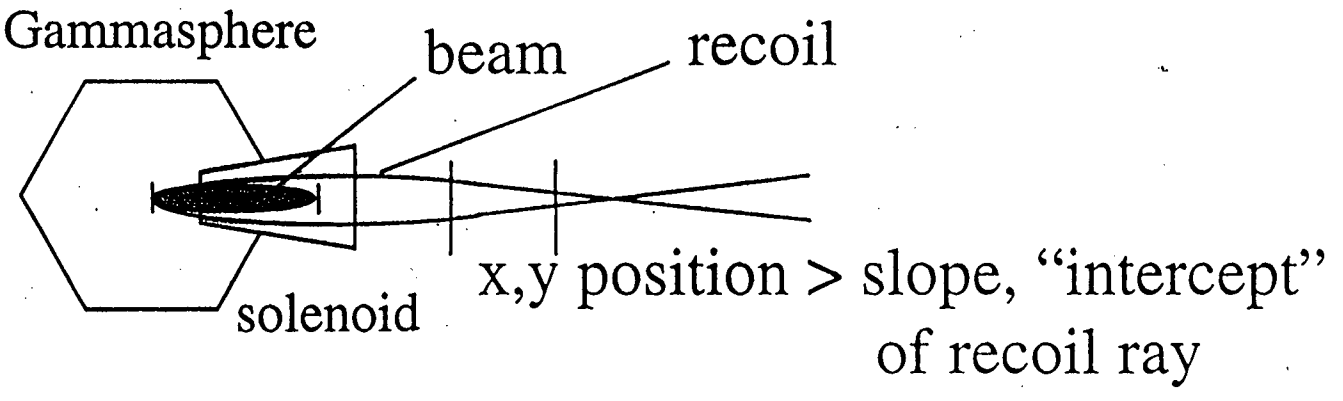
Solenoid Only

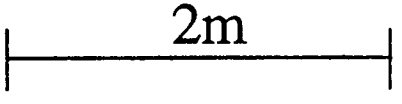
1 Silicon Array and/or 2 "x,y,z Tracking" Information

(i)



(ii)





[redacted] WARM , P.013

⊥ to axis

MULTILAYER INSULATION

VAC. JACKET

20-LAYERS

LN SHIELD

10-LAYERS

HELIUM VESSEL

NEAREST PHOTOMULTIPLIER LOCATION

SPLIT RING

VAC. WALL

LN. SHIELD

WEIGHT, IRON = LBS.

WEIGHT (COLD MASS) = LBS.

SPACE AVAILABLE BOUNDARY

VAC.

68.5'

1.500" EXISTING STEEL PLATE

EXISTING PIT 36" DEEP

NOTE:
DIAGONAL FRAME STRUTS AND SEISMIC TIE-DOWNS ARE OMITTED.

NOTE: SOME ( ), DIMS.:
COIL AXIAL LENGTH: 1000 mm (39.4")
C'STAT O.A. LENGTH: 1769.3mm (69.7")

AREA OUTSIDE HELIUM VESSEL.

NOTE: DIM. IN mm EXCEPT WHERE NOTED.

9-17-96

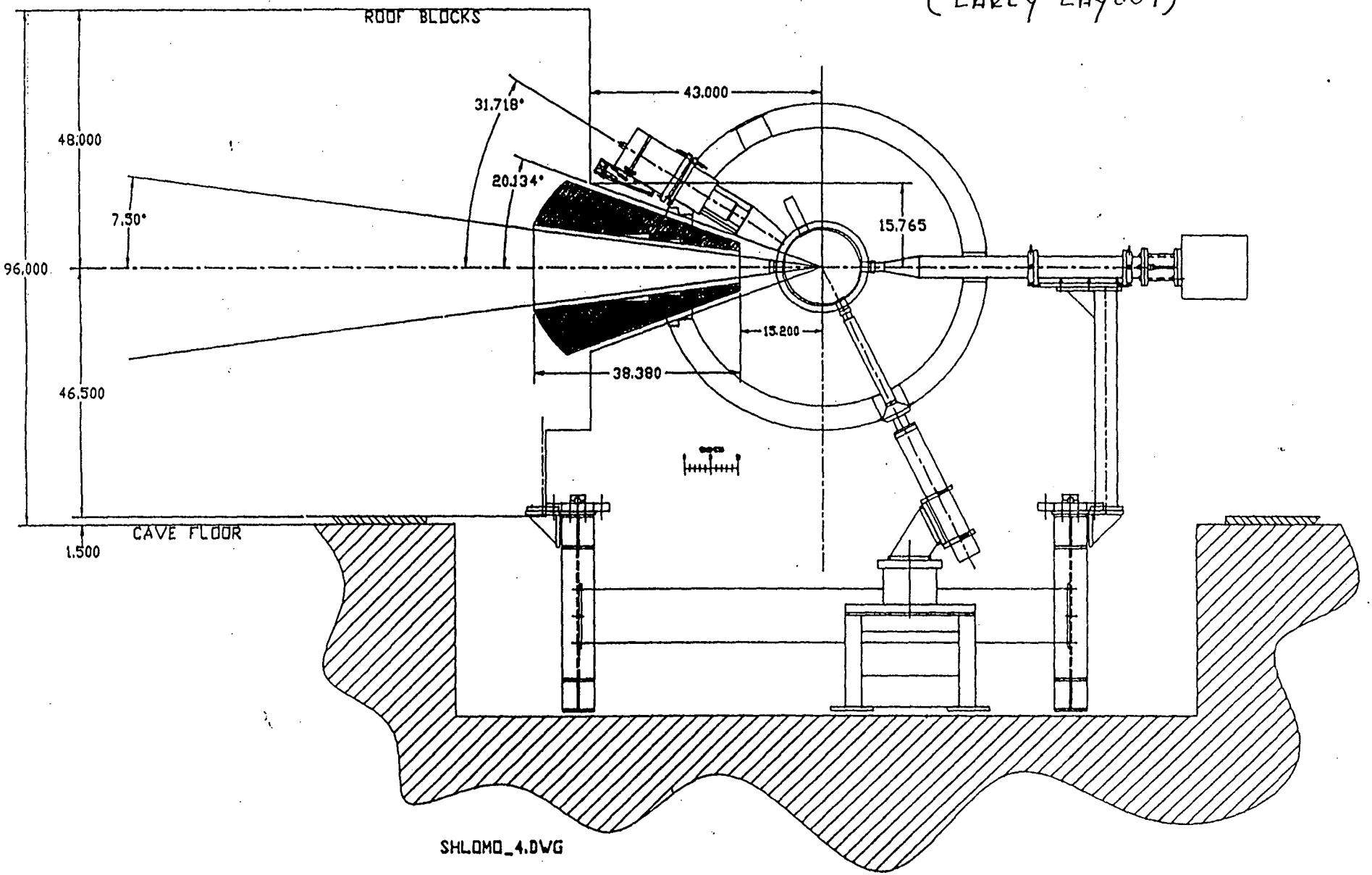
LAWRENCE BERKELEY LABORATORY

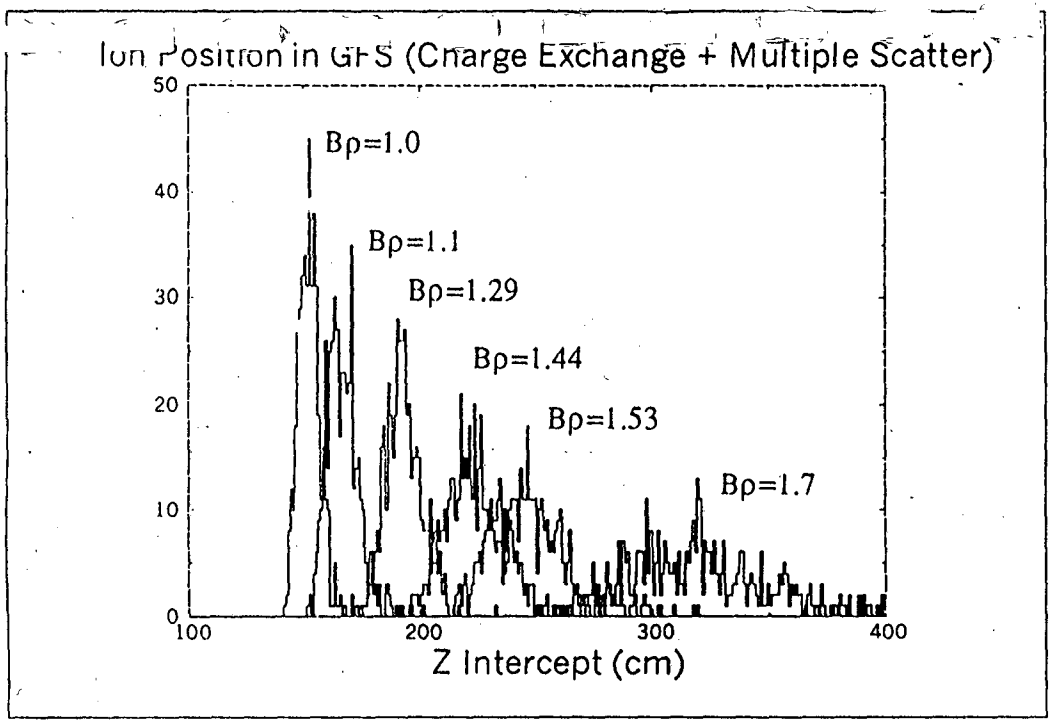
GAMMASPHERE SPECTROMETER

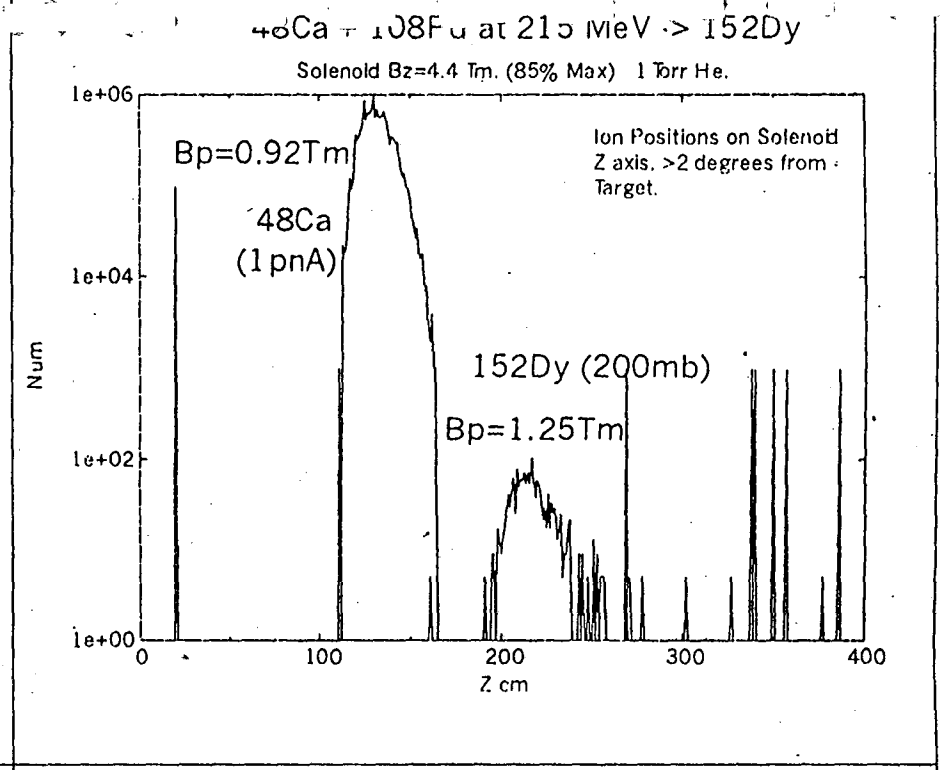
LOCAL X SOLENOID WARM BOX

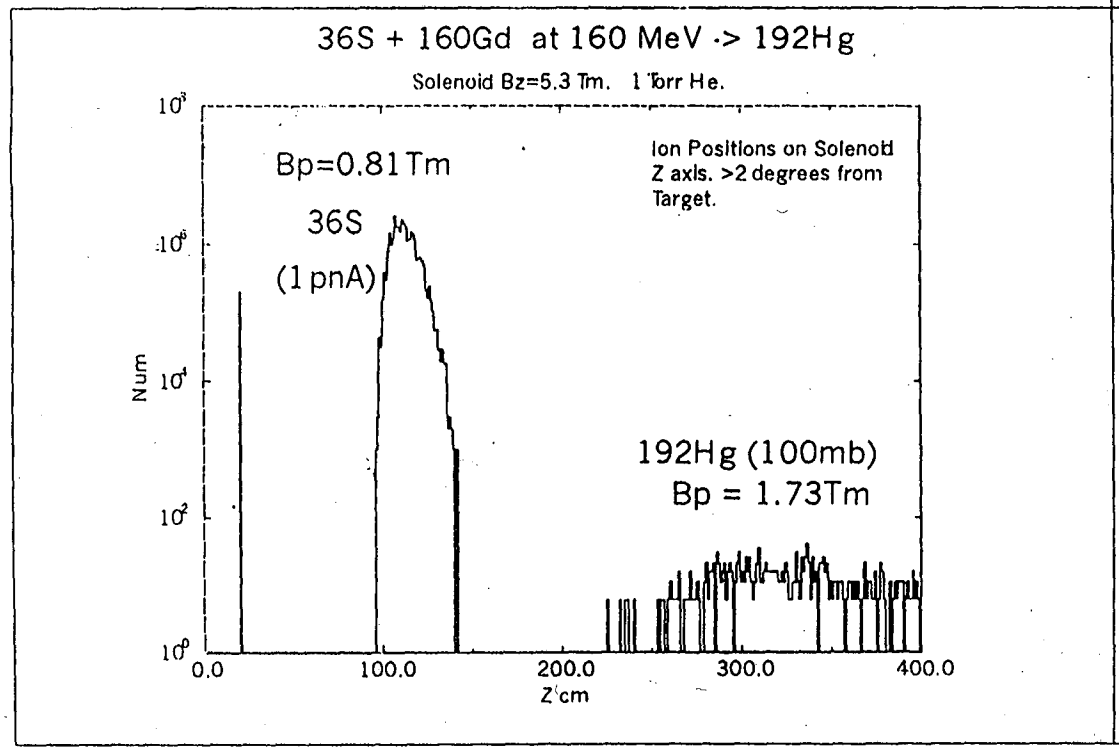
23F3736

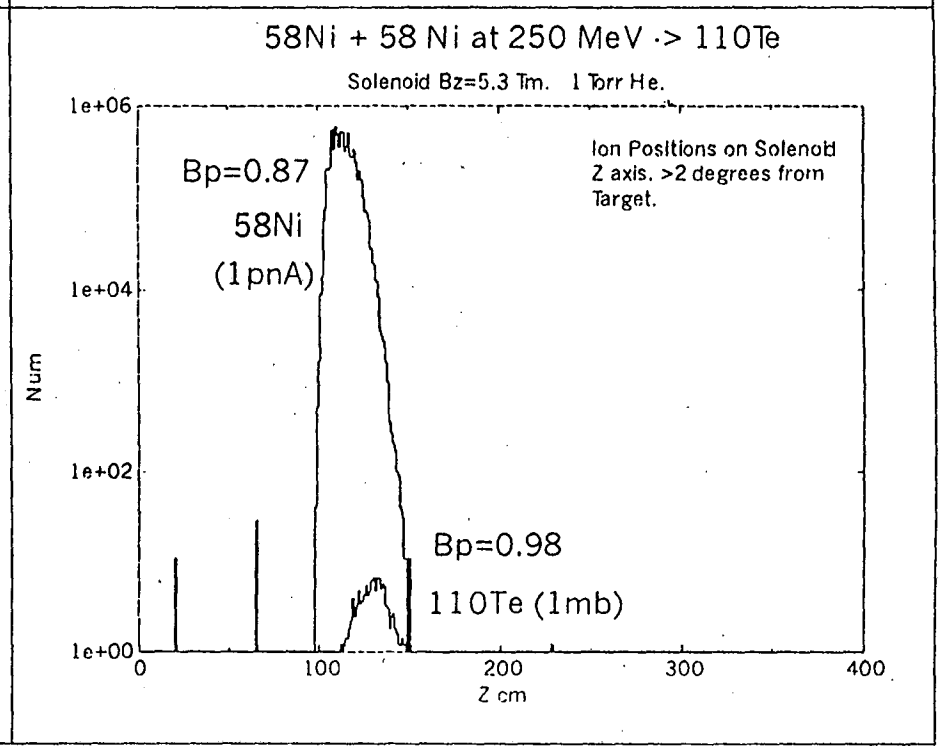
GAS FILLED SOLENOID + GAMMASPHERE
(EARLY LAYOUT)

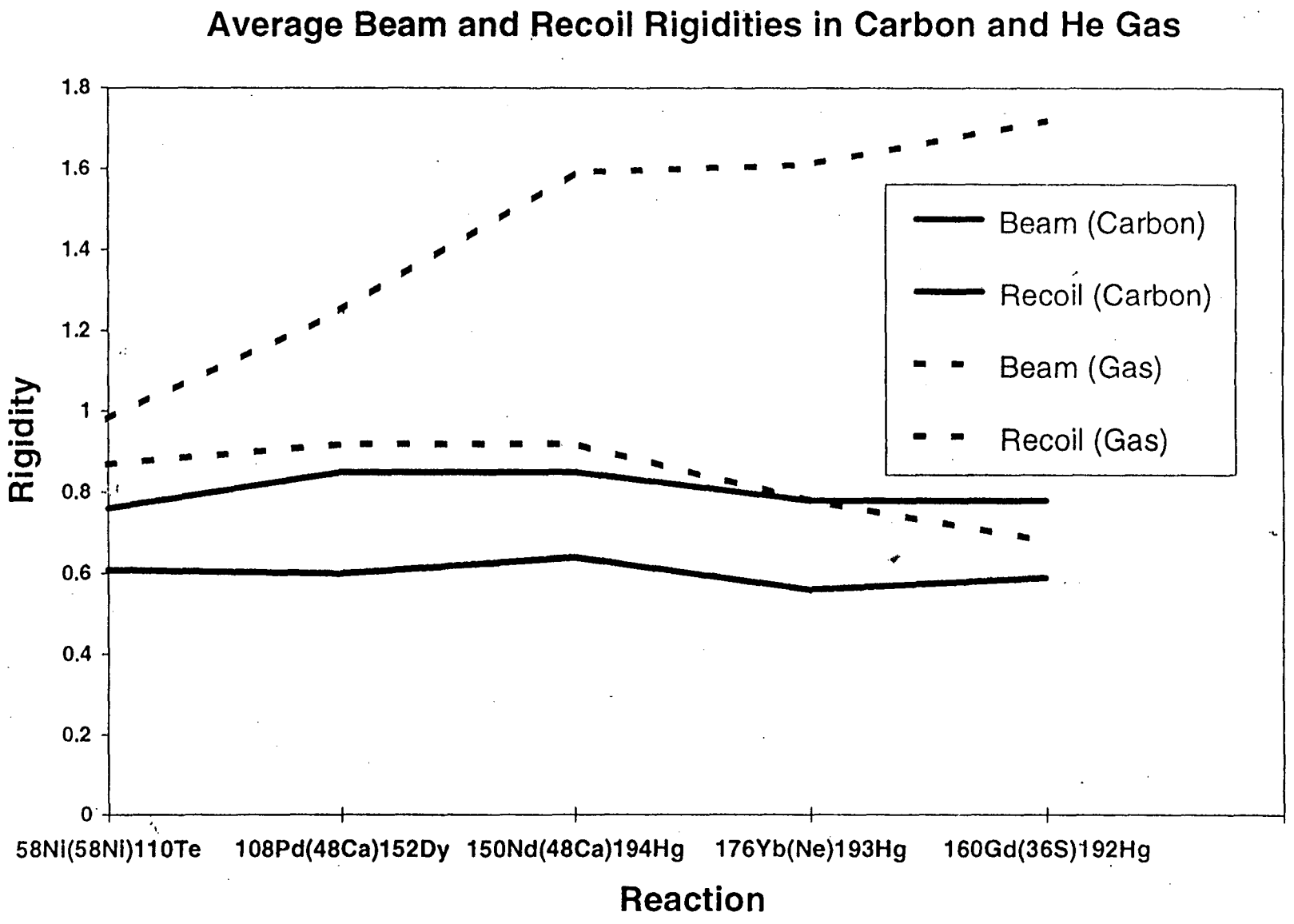



Ion Position in GRS (Charge Exchange + Multiple Scatter)
Bρ=1.0
Bρ=1.1
Bρ=1.29
Bρ=1.44
Bρ=1.53
Bρ=1.7
Z Intercept (cm)

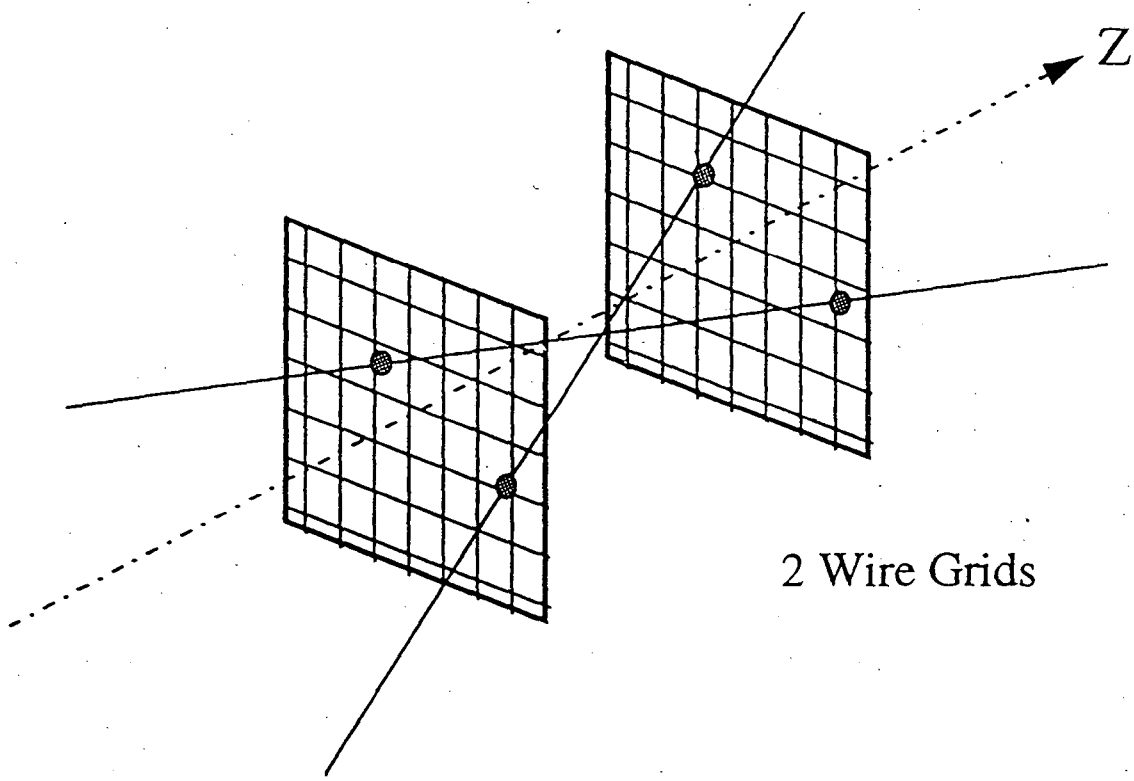

48Ca + 108Pd at 215 MeV -> 152Dy
Solenoid Bz=4.4 Tm. (85% Max) 1 Torr He.
Ion Positions on Solenoid Z axis. >2 degrees from Target.
Bp=0.92Tm
48Ca
(1 pnA)
152Dy (200mb)
Bp=1.25Tm
Num
Z cm


36S + 160Gd at 160 MeV -> 192Hg
Solenoid Bz=5.3 Tm. 1 Torr He.
Ion Positions on Solenoid Z axis. >2 degrees from Target.
Bp=0.81Tm
36S
(1 pnA)
192Hg (100mb)
Bp = 1.73Tm
Num
Z cm

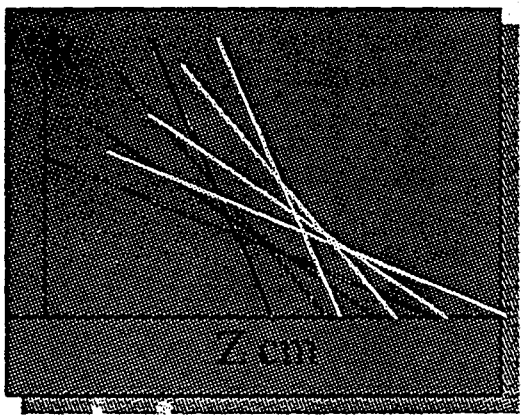

58Ni + 58 Ni at 250 MeV -> 110Te
Solenoid Bz=5.3 Tm. 1 Torr He.
Ion Positions on Solenoid Z axis. >2 degrees from Target.
Bp=0.87
58Ni
(1 pnA)
Bp=0.98
110Te (1mb)
Num
Z cm

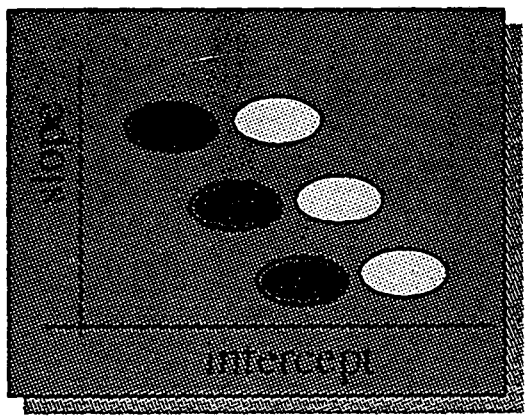

Average Beam and Recoil Rigidities in Carbon and He Gas
Rigidity
1.8
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
Beam (Carbon)
Recoil (Carbon)
Beam (Gas)
Recoil (Gas)
58Ni(58Ni)110Te
108Pd(48Ca)152Dy
150Nd(48Ca)194Hg
176Yb(Ne)193Hg
160Gd(36S)192Hg
Reaction

Reconstruct Ion Path



- Extract $(X,Y,Z)_1$ $(X,Y,Z)_2$ - Θ,Φ
- Doppler Correct.
- Reduce/Remove Solenoid's Aberrations

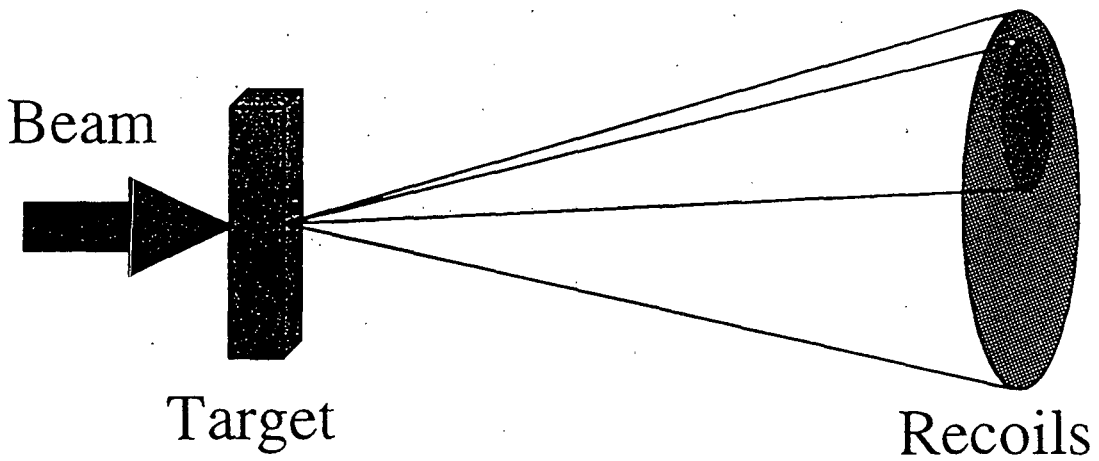




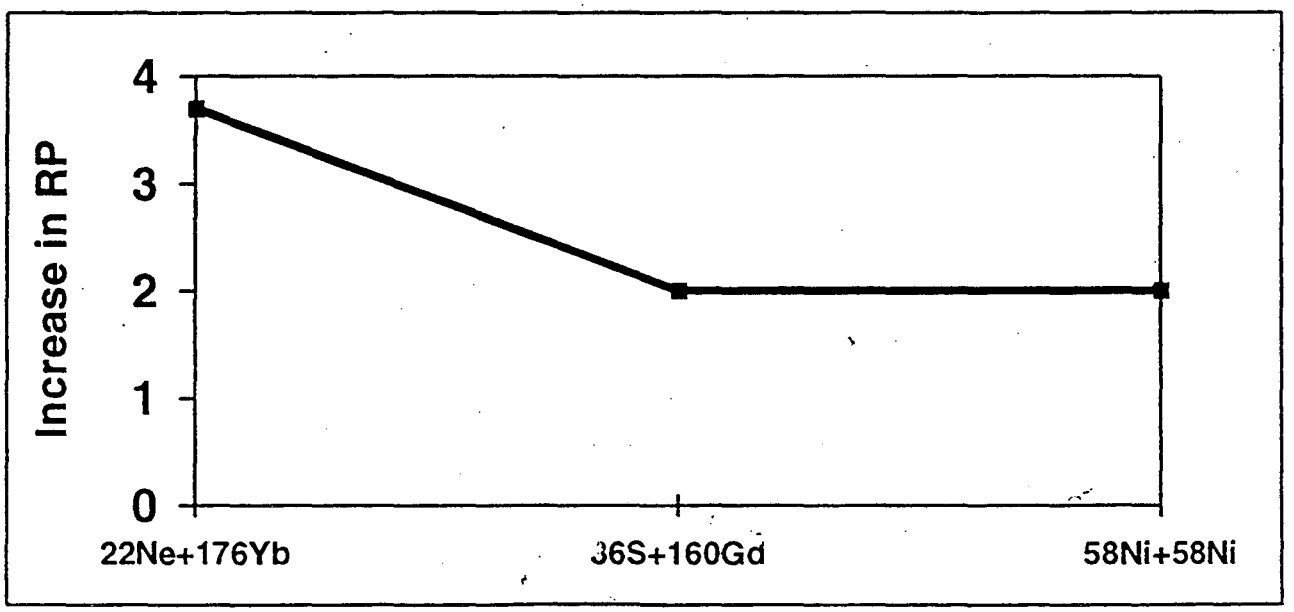
Determining the Recoil Cone Angle

- Track recoil - obtain exit angle.
- Reconstruct emitted angle.

$\Delta\phi=40^o \quad \Delta\theta=1^o$



Effect on Resolving Power for γ^4 (0.5mg/cm^2 Targets)



Summary

- Tapered S.C. Solenoid - Technically Feasible
  - Design Review (OK), Vendors willing to bid.
  - Optics : Ray Tracing - "Realistic" Mag. Field, Charge Exchange and Scatter in the Gas.
  - Beam Rejection OK for $\Delta B\rho \sim 30\%$ (20%)
  - Resolution ~ 10%
- No Gas Option.
  - Solenoid ?
  - Quads (perm) + Wien Filter

Witek Nazarewicz
Oak Ridge National Laboratory/University of Tennessee

W. Nazarewicz LBNL, April '97

- BGS physics
- GFS physics

Probing the effective Hamiltonian

Effective forces for heavy nuclei
--- issues....

- Density dependence
- Effective mass
- Spin-orbit
- Range

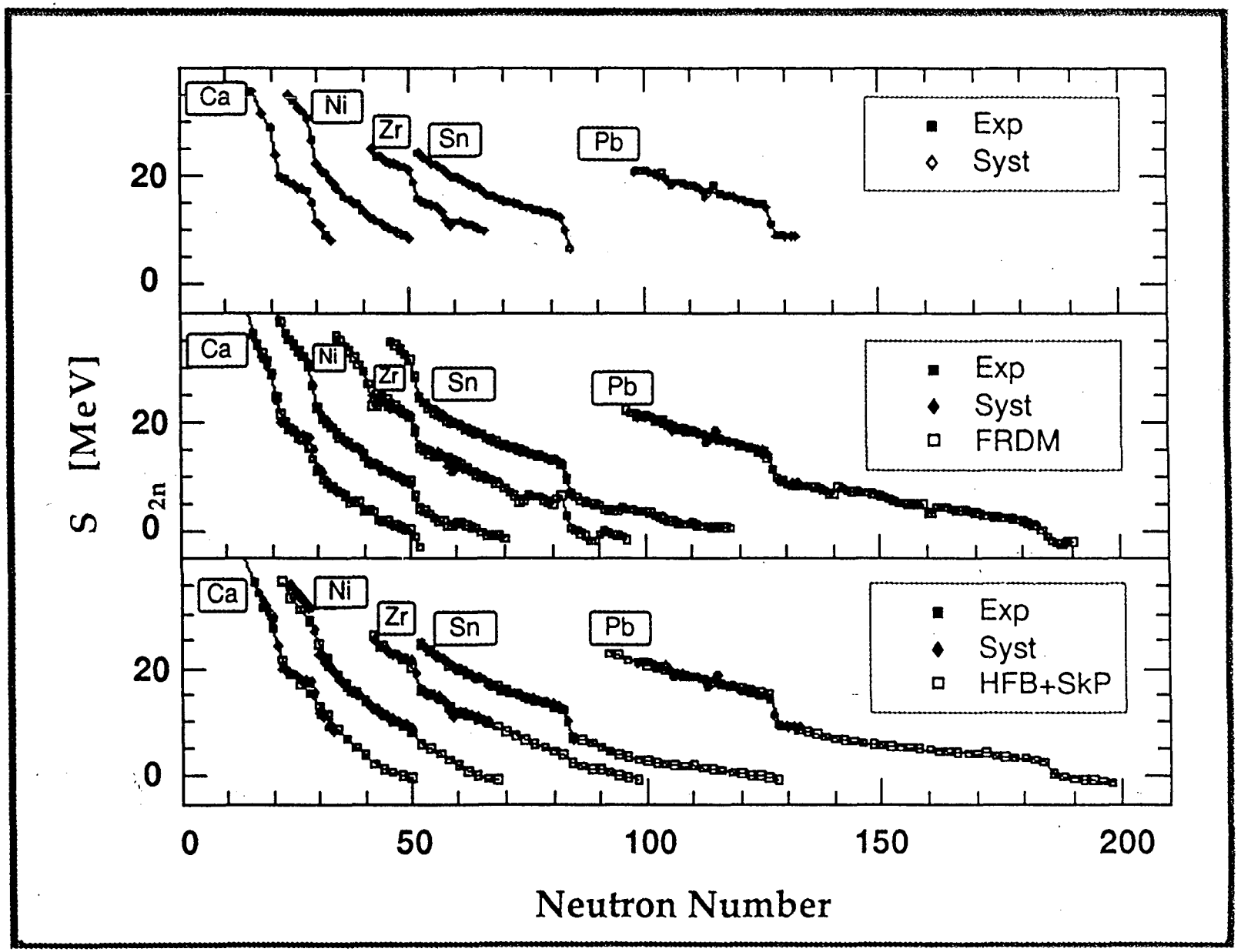
} Extrapolation properties

Superheavy elements

Heaviest elements & actinides

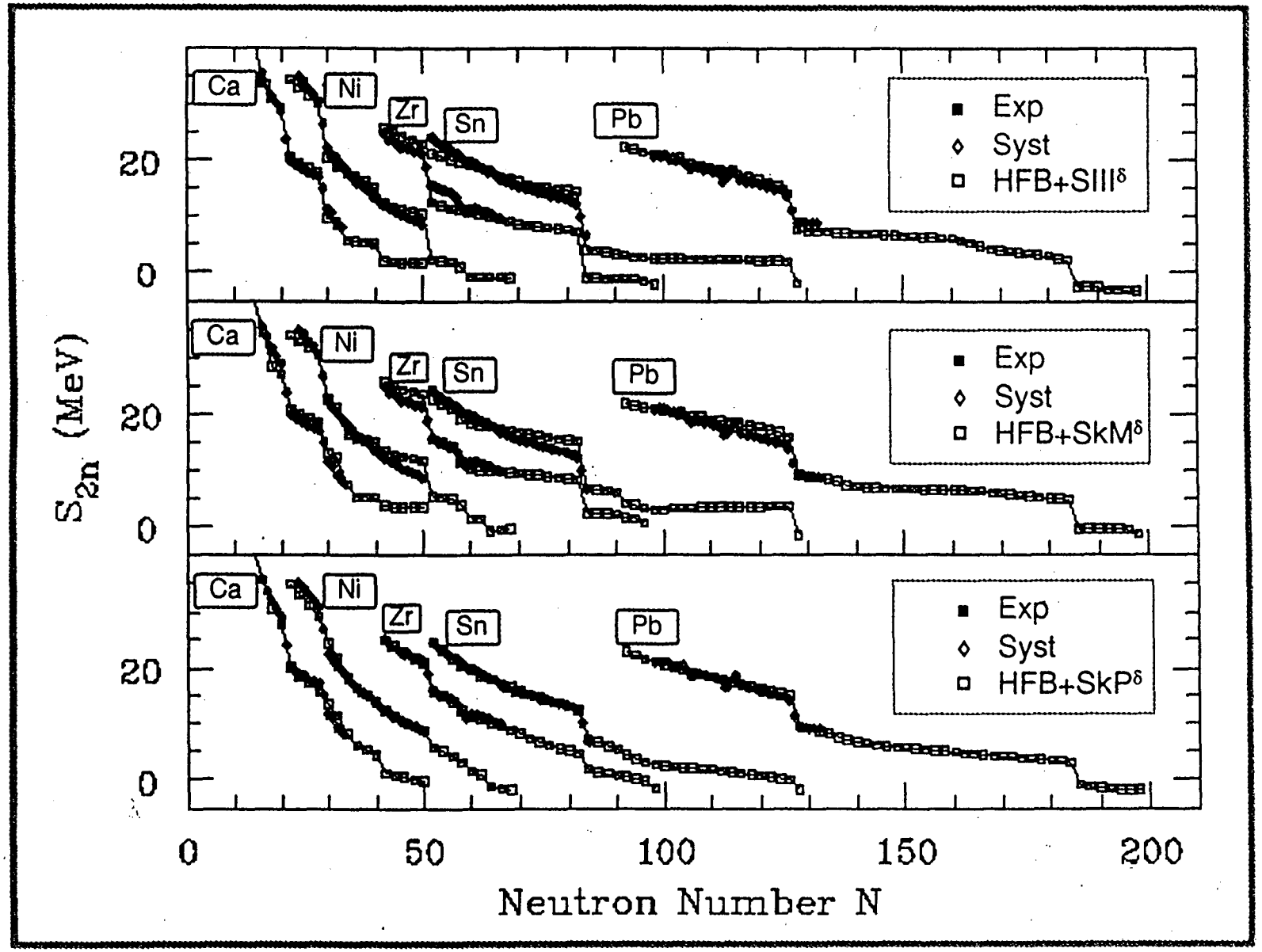
Proton emitters

Global comparison of S_{2n}



Dobaczewski, Nazarewicz, Werner, Phys. Scr. **T56**(1995)15

Global comparison of S_{2n}



Dobaczewski, Nazarewicz, Werner, Phys. Scr. **T56**(1995)15

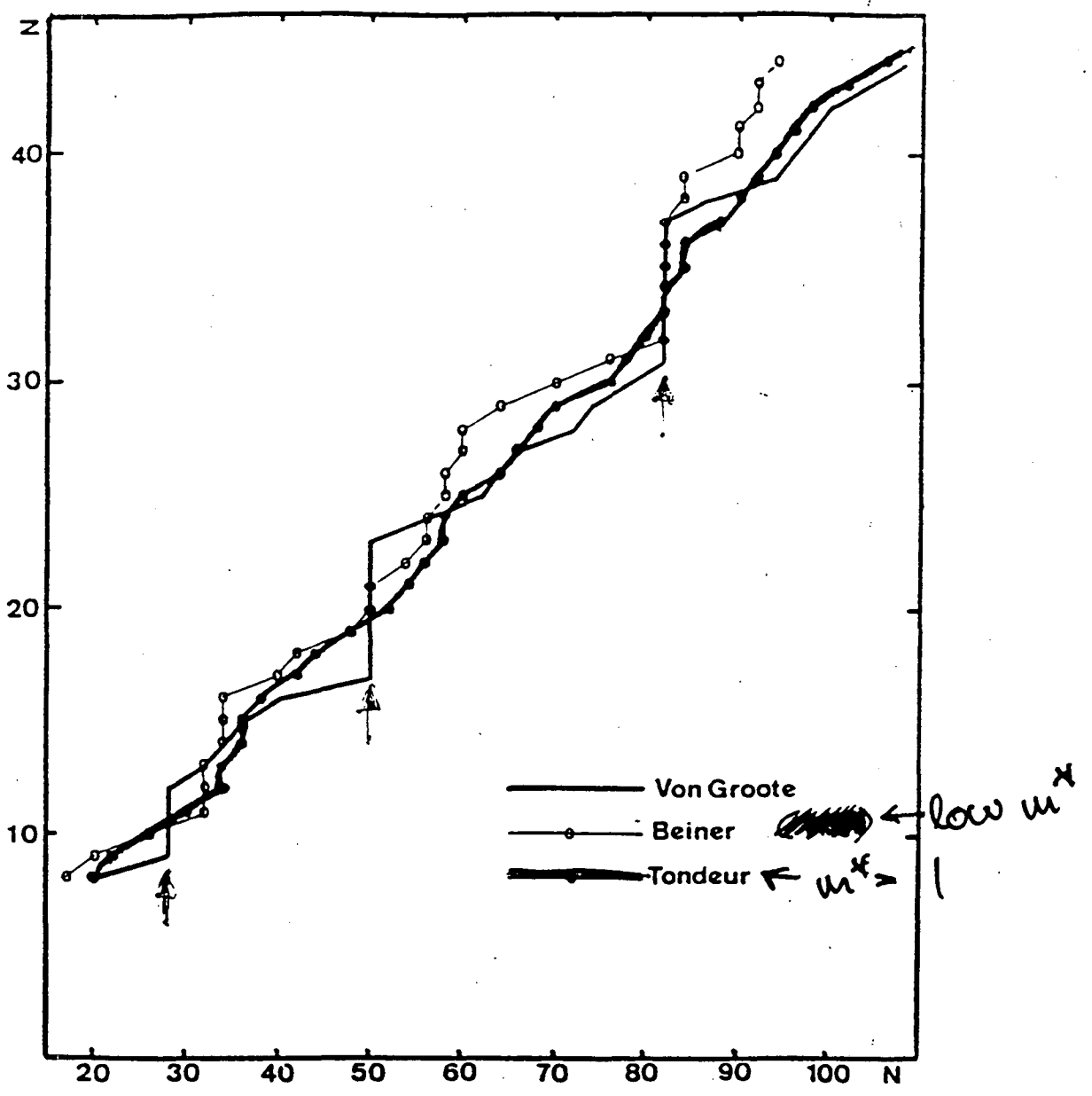


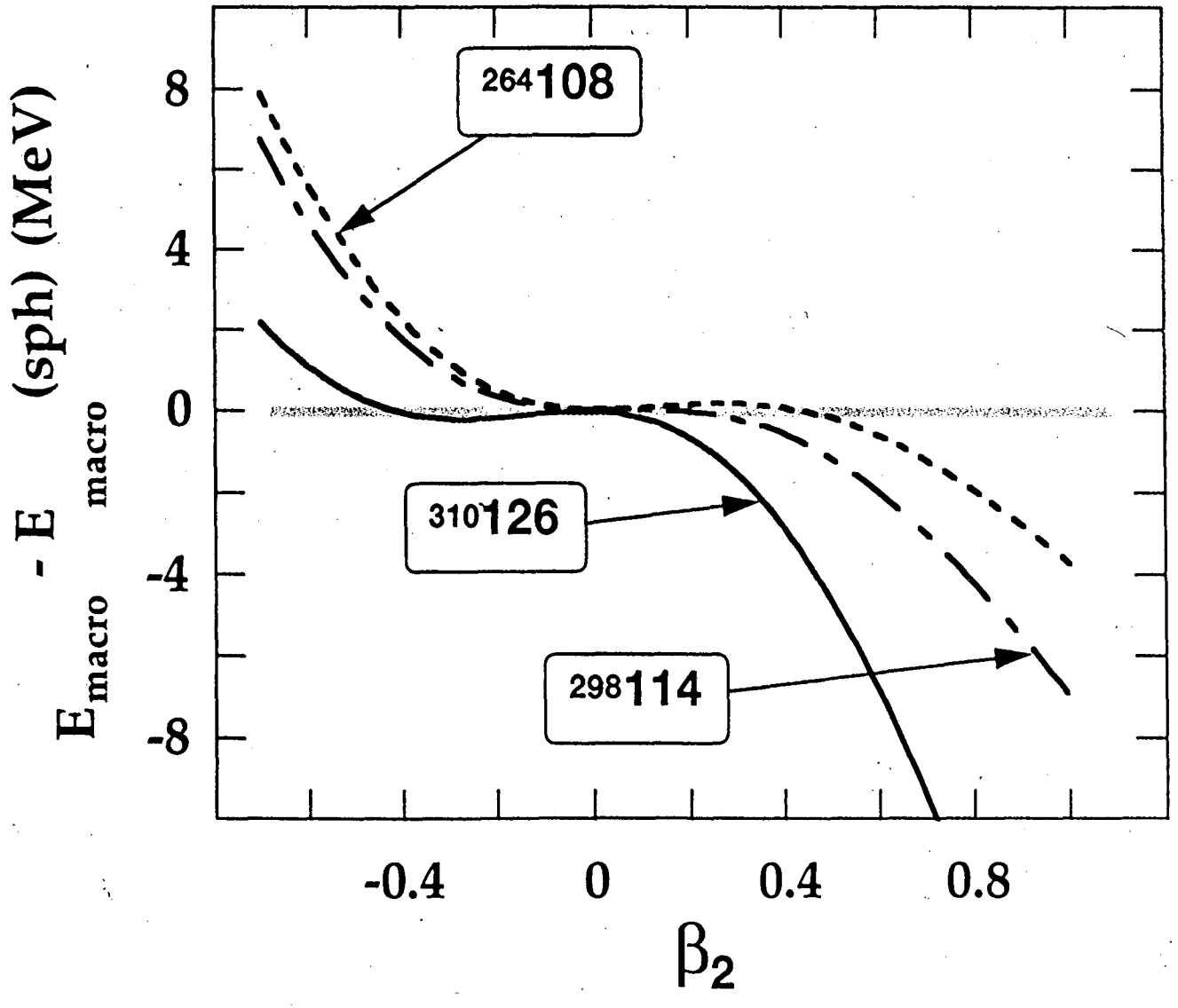
Fig. 3. Comparison of the neutron drip lines obtained with three mass formulae. The curves indicate the position in the (N, Z) plane of the last even isotope stable against two neutrons emission

F. Tondeur (Z. Phys. A288, 97 (1978))
Energy density mass formula

→ Vanishing of shell effects at N=28, 50, and 82

→ Importance of m^*

Liquid-drop energy



How well can HF do for known α-decay chains?

Table 6
Calculated and experimental values of Q_α for the ^{264}Mt→ . . . →^{248}Fm α-decay chain

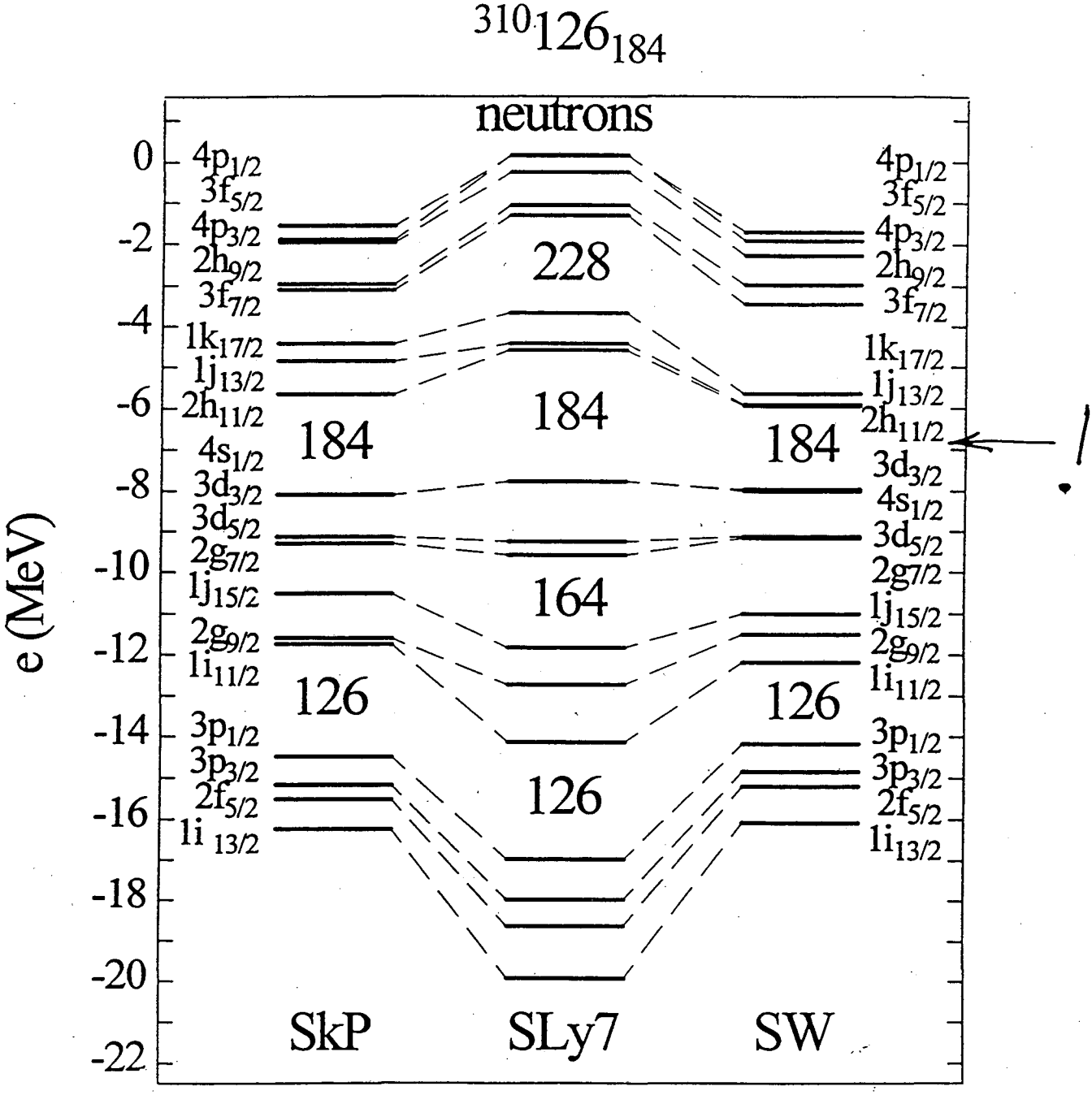
Nucleus	HF+SkP	HF+SLy7	WS	exp [a]
^{264}Mt	10.82	10.81	11.11	10.80
^{260}Nh	10.16	10.21	10.12	9.92
^{256}Rf	9.63	8.77	9.18	8.95
^{252}No	9.04	7.97	8.51	8.55

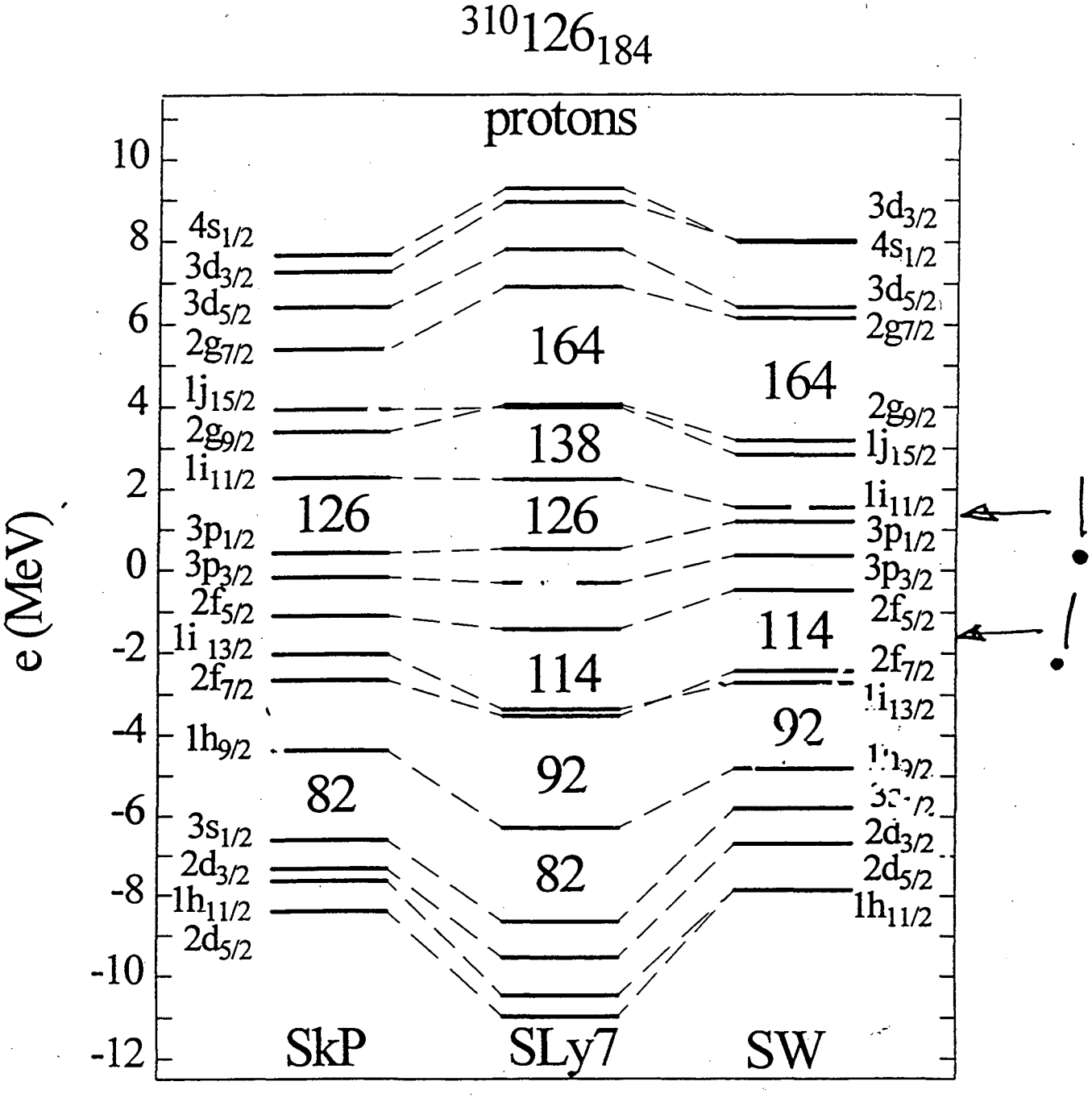
[a] Ref. [41].

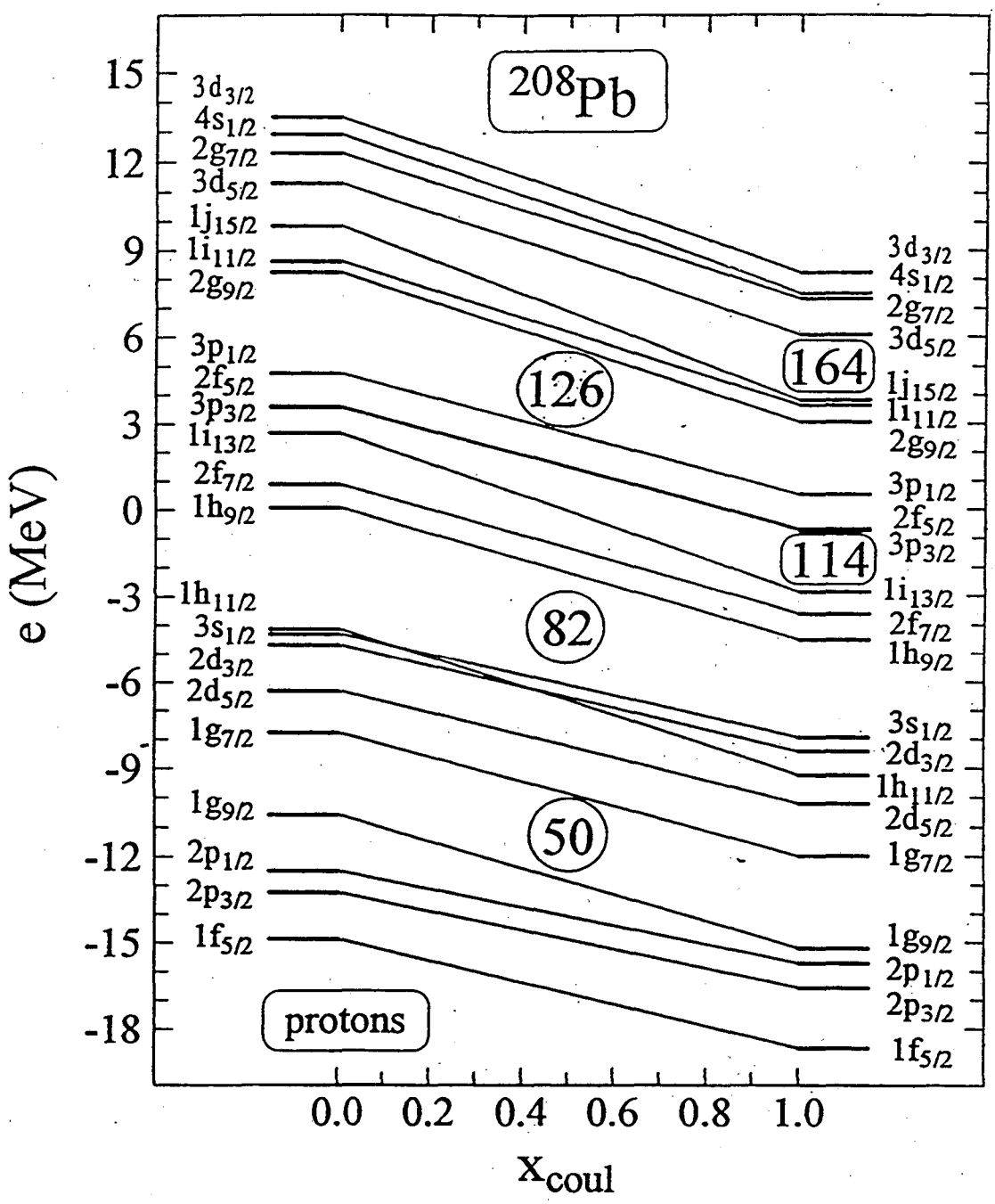
macro-
-micro

S. Ćwiok et al.

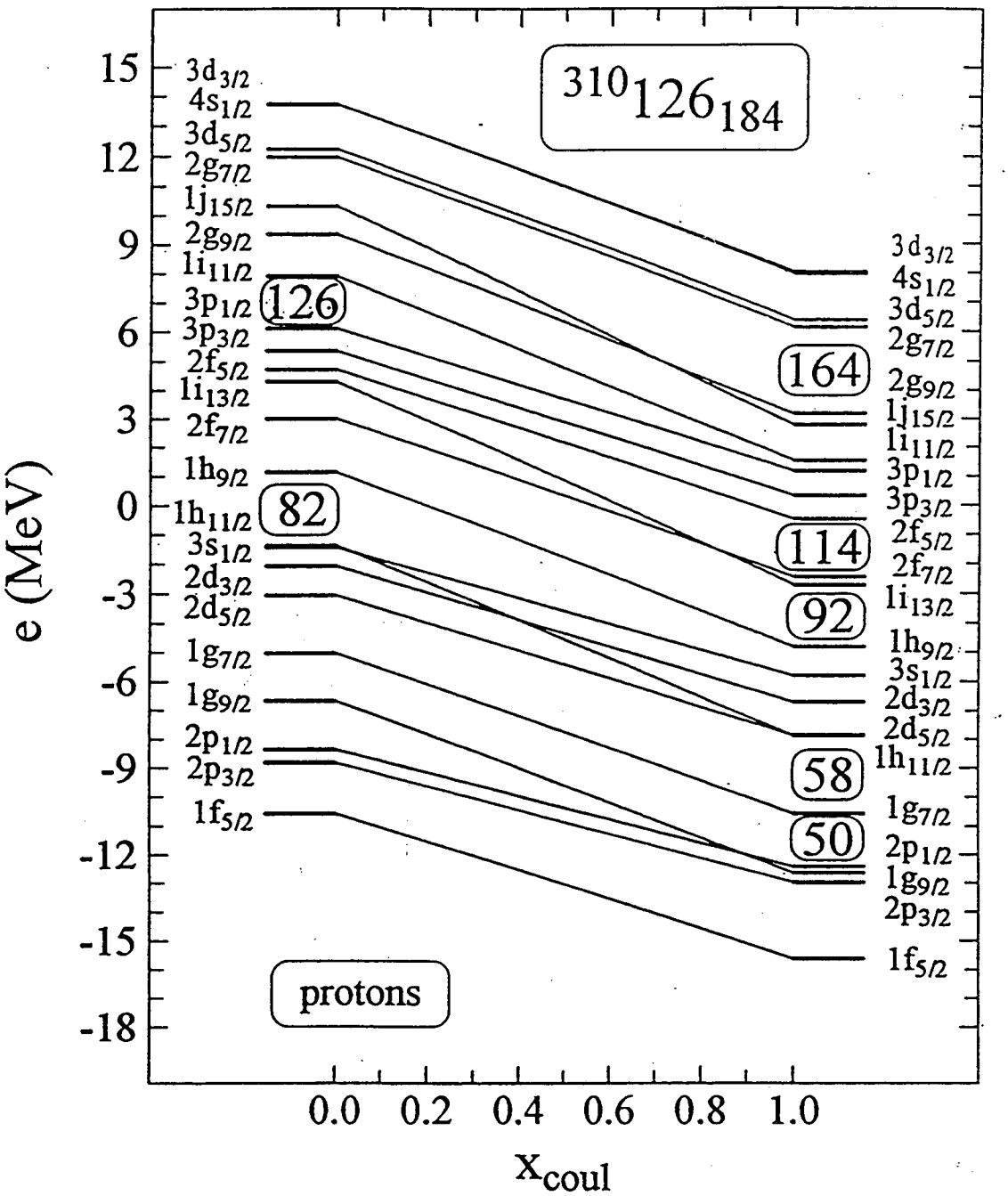
HF + SkP + δ-pairing (LN)
HF + SLy7 + δ-pairing (LN)
WS

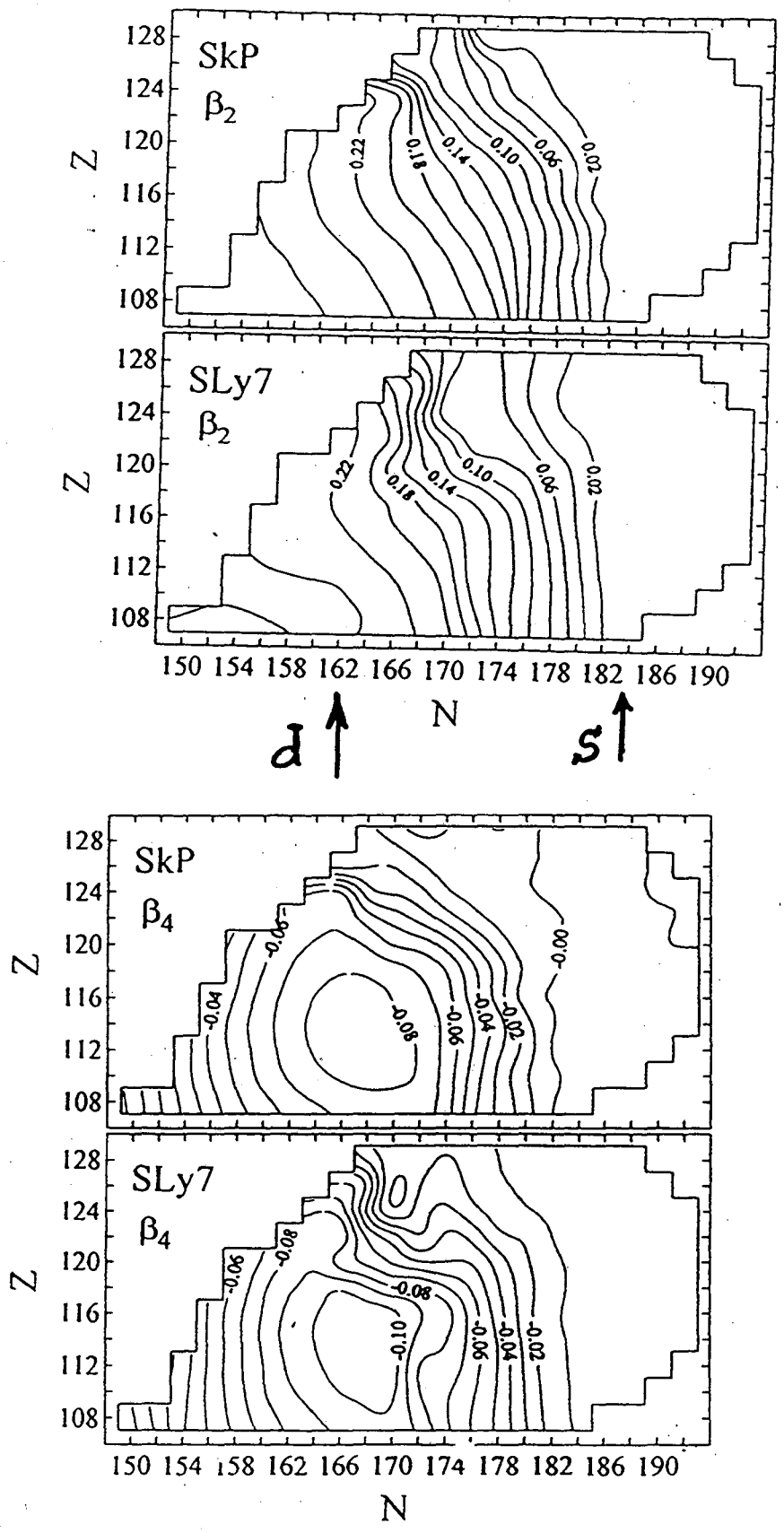


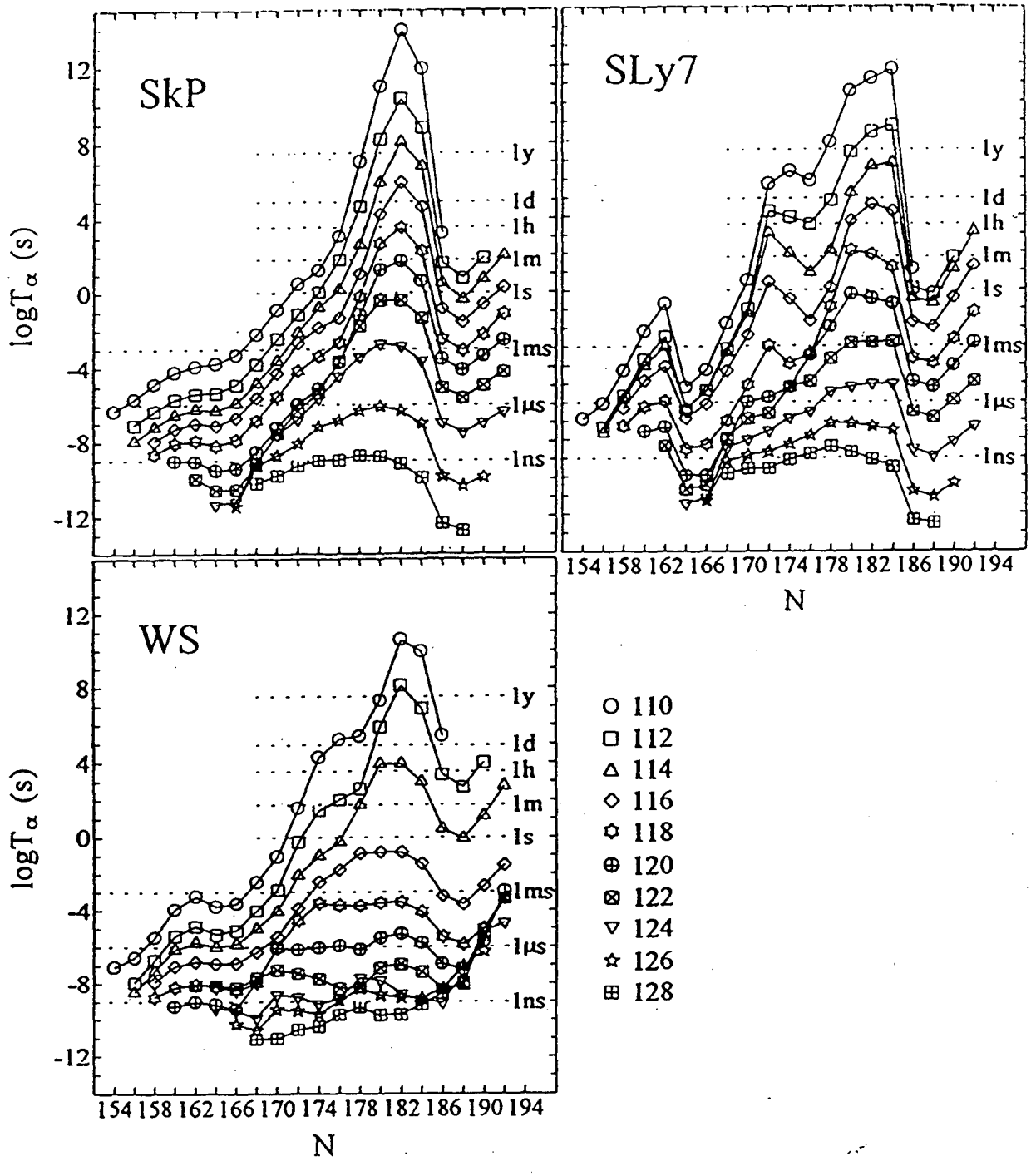

$^{310}126_{184}$
protons
e (MeV)
10
8
6
4
2
0
-2
-4
-6
-8
-10
-12
$4s_{1/2}$
$3d_{3/2}$
$3d_{5/2}$
$2g_{7/2}$
$1j_{15/2}$
$2g_{9/2}$
$1i_{11/2}$
$3p_{1/2}$
$3p_{3/2}$
$2f_{5/2}$
$1i_{13/2}$
$2f_{7/2}$
$1h_{9/2}$
$3s_{1/2}$
$2d_{3/2}$
$1h_{11/2}$
$2d_{5/2}$
126
82
164
138
126
114
92
82
164
114
92
$3d_{3/2}$
$4s_{1/2}$
$3d_{5/2}$
$2g_{7/2}$
$2g_{9/2}$
$1j_{15/2}$
$1i_{11/2}$
$3p_{1/2}$
$3p_{3/2}$
$2f_{5/2}$
$2f_{7/2}$
$1i_{13/2}$
$2d_{3/2}$
$2d_{5/2}$
$1h_{11/2}$
SkP
SLy7
SW



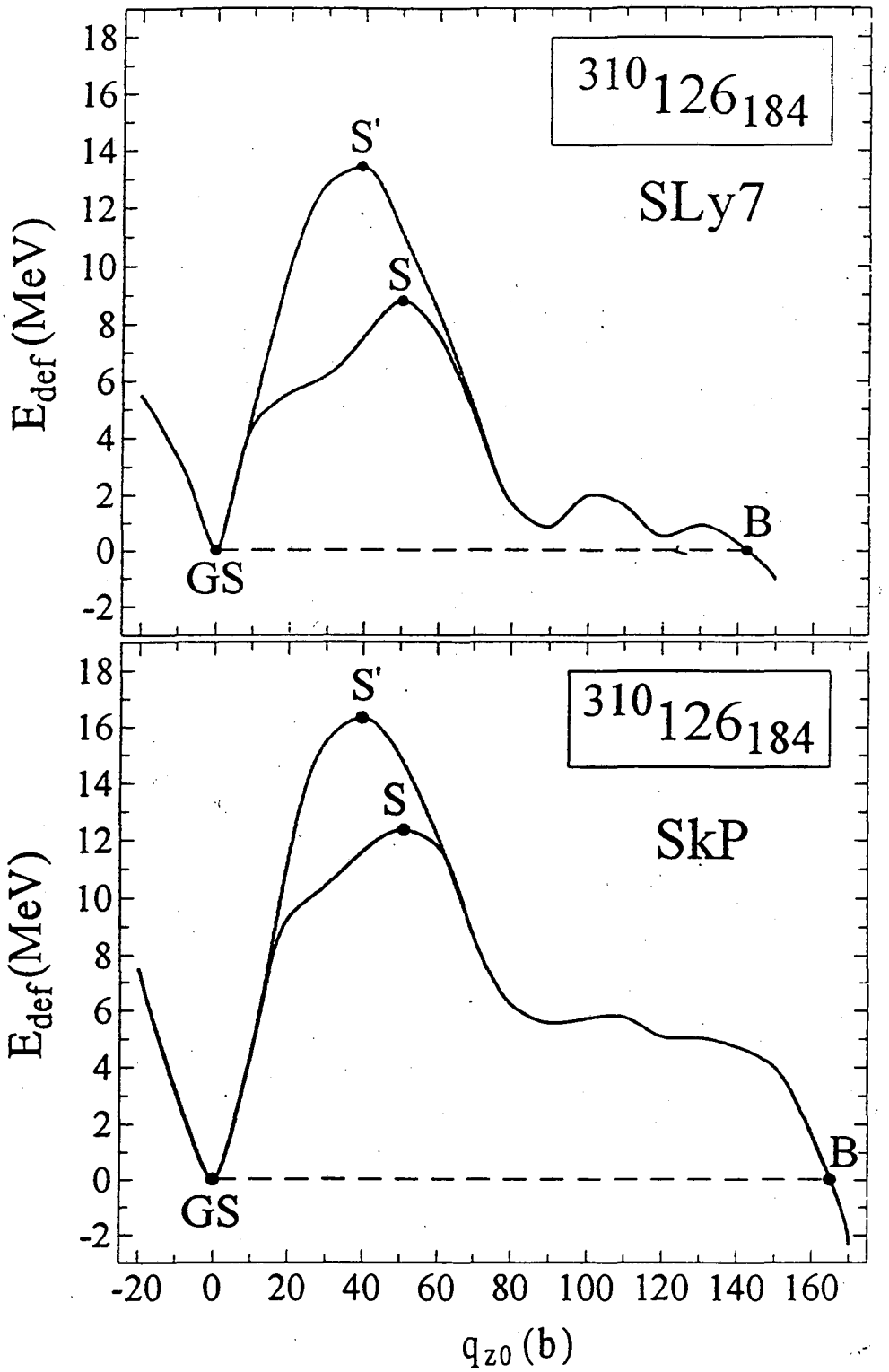
$$\hat{h} = \hat{h}_{WS} + \hat{h}_{s.o.} + \left\{ V_{coul} - V_{coul}(0) \right\} x_{coul} + V_{coul}(0)$$

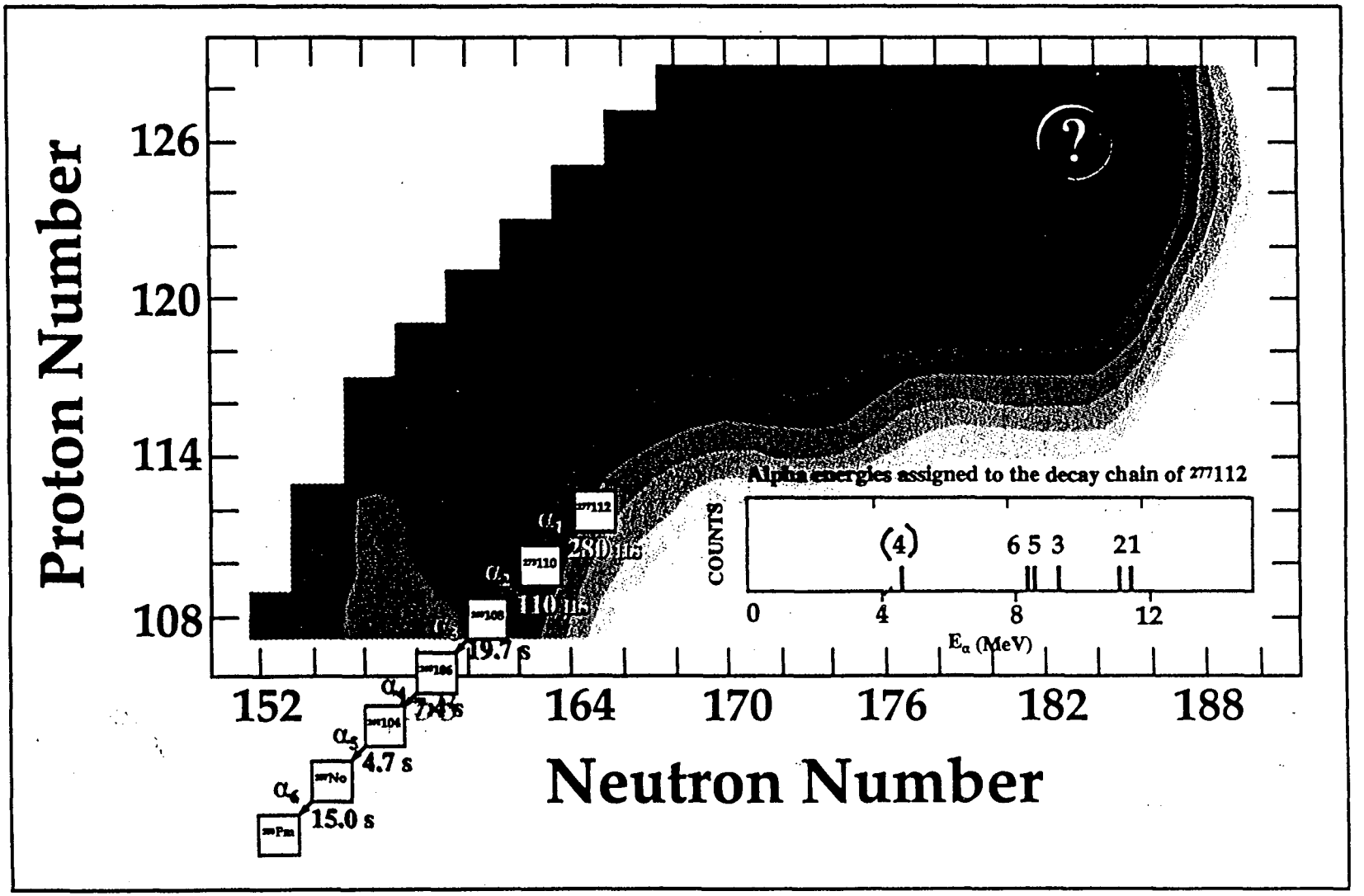

$^{310}126_{184}$
protons
e (MeV)
x_{coul}
15
12
9
6
3
0
-3
-6
-9
-12
-15
-18
0.0
0.2
0.4
0.6
0.8
1.0
126
82
164
114
92
58
50
$3d_{3/2}$
$4s_{1/2}$
$3d_{5/2}$
$2g_{7/2}$
$1j_{15/2}$
$2g_{9/2}$
$1i_{11/2}$
$3p_{1/2}$
$3p_{3/2}$
$2f_{5/2}$
$1i_{13/2}$
$2f_{7/2}$
$1h_{9/2}$
$1h_{11/2}$
$3s_{1/2}$
$2d_{3/2}$
$2d_{5/2}$
$1g_{7/2}$
$1g_{9/2}$
$2p_{1/2}$
$2p_{3/2}$
$1f_{5/2}$


SkP
β_2
SLy7
β_2
SkP
β_4
SLy7
β_4
Z
N
d
s
128
124
120
116
112
108
150 154 158 162 166 170 174 178 182 186 190
0.22
0.18
0.14
0.10
0.06
0.02
-0.00
-0.02
-0.04
-0.06
-0.08
-0.10

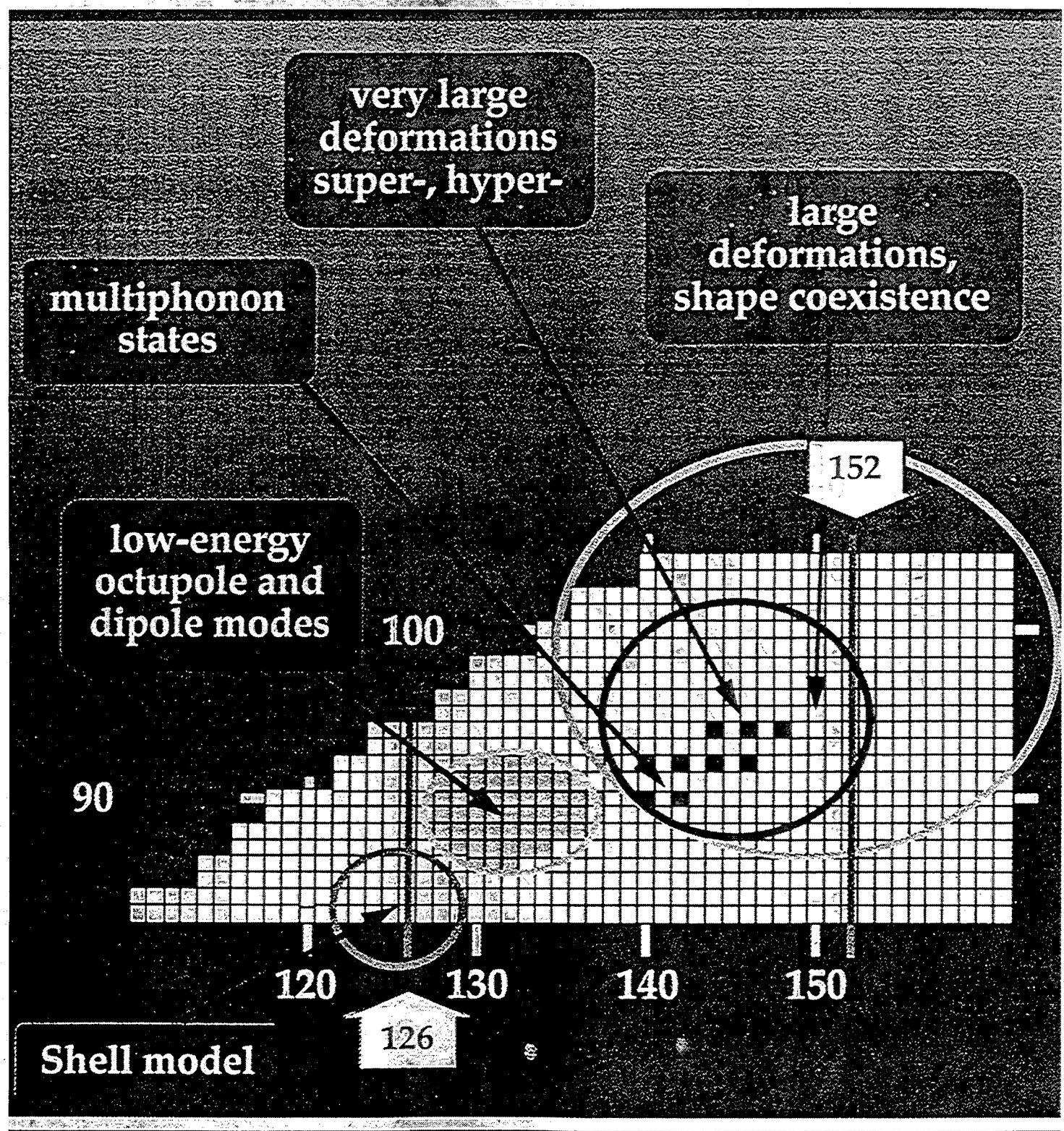


	SkP	SLy7	WS	
^{288}118	2.8	8.6	0.9	μs
^{280}114	1.3	3.8	1.4	μs


$^{310}126_{184}$
SLy7
S'
S
GS
B
E_{def}(MeV)
$^{310}126_{184}$
SkP
S'
S
GS
B
E_{def}(MeV)
q_{z0} (b)


Proton Number
126
120
114
108
152
164
170
176
182
188
Neutron Number
?
Alpha energies assigned to the decay chain of 277112
COUNTS
(4)
6 5 3
21
0
4
8
12
Eα (MeV)
α1
α2
α3
α4
α5
α6
280 ms
110 ms
19.7 s
4.7 s
15.0 s

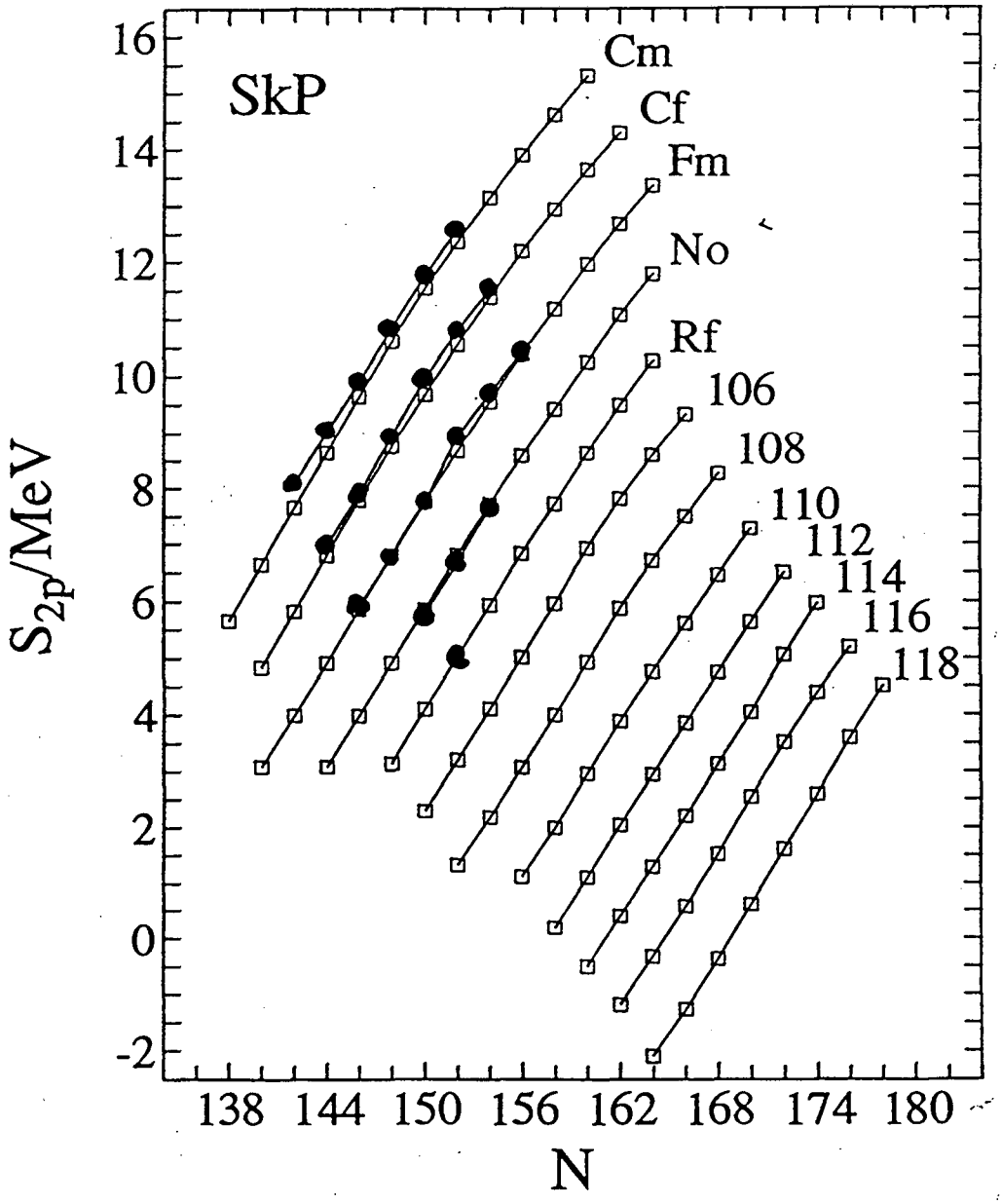
Nuclear Structure in the Actinides



Physics Division ORNL/Dept. of Physics UT

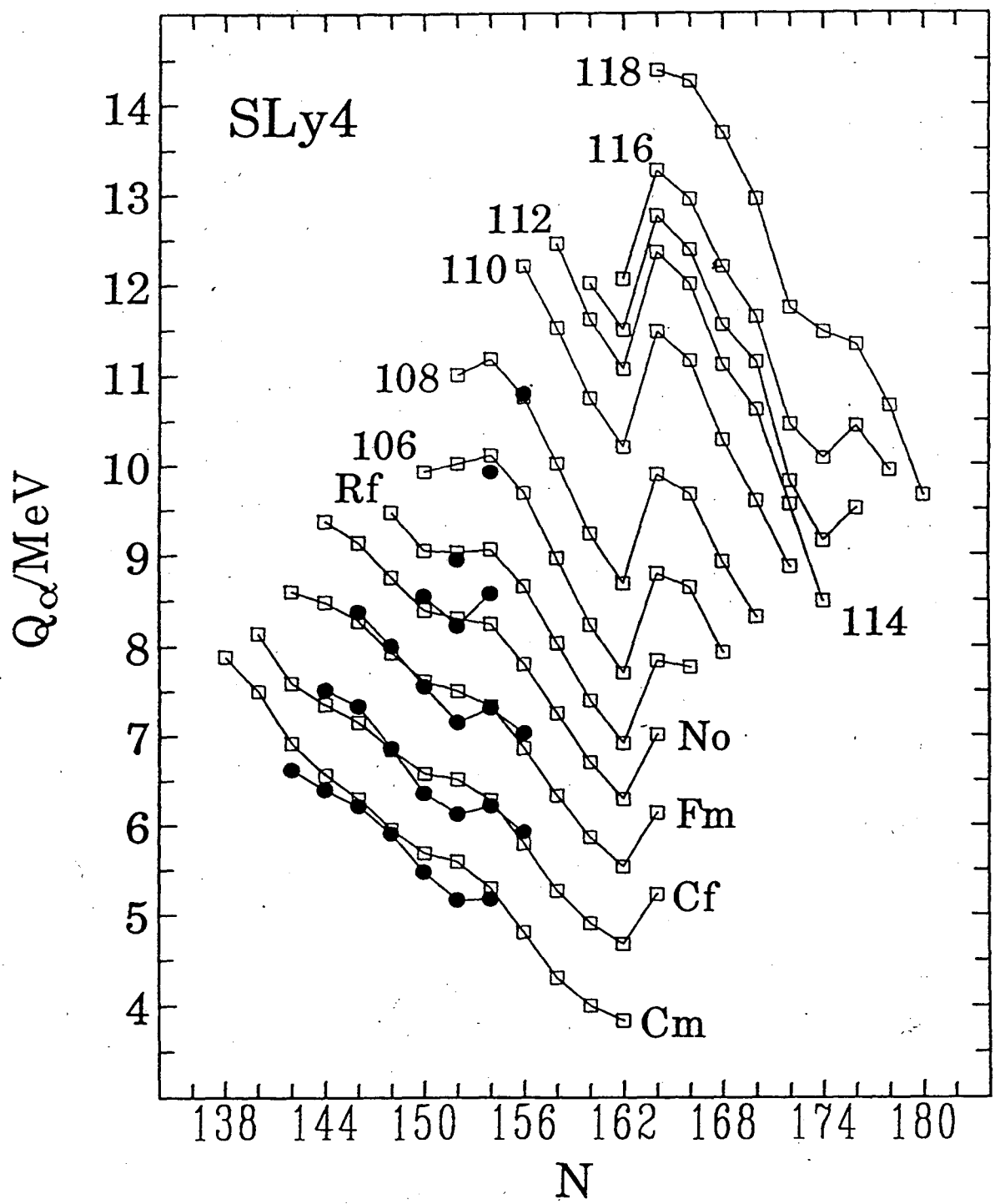
S. Ćwiok et al.

HF + δ + LN



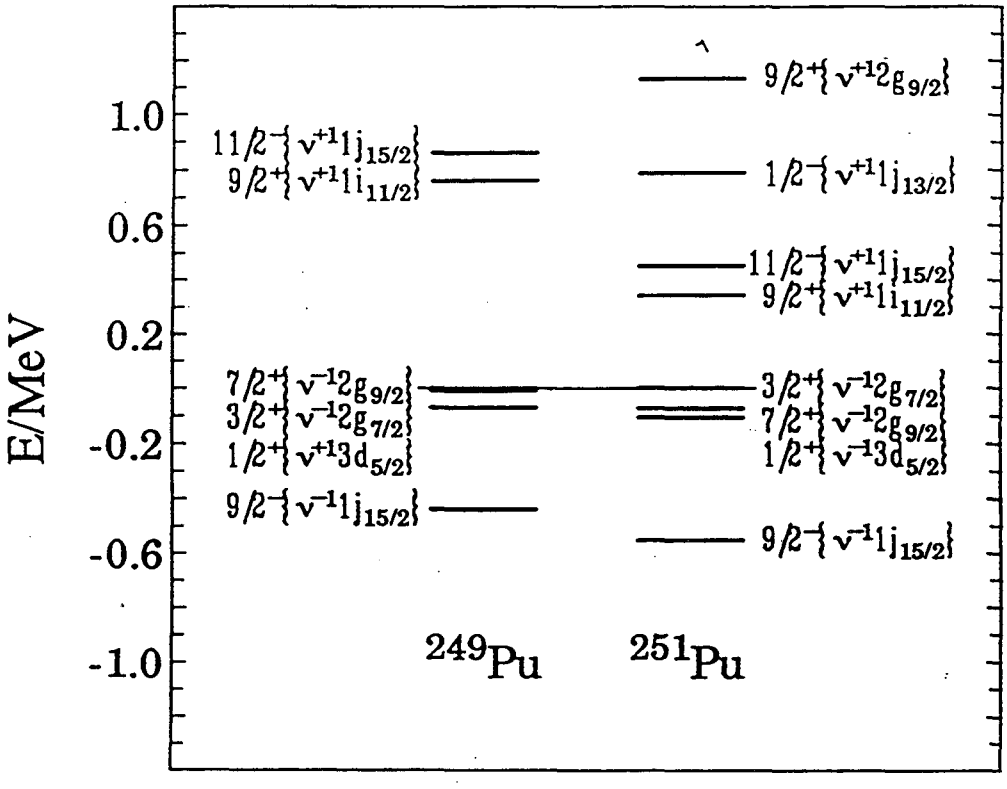
S. Ćwiok et al.

HF + δ + LN



S. Ćwiok et al.

HF + δ + LN (with odd-T terms)



S. Ćwiok et al., PL B322, 304

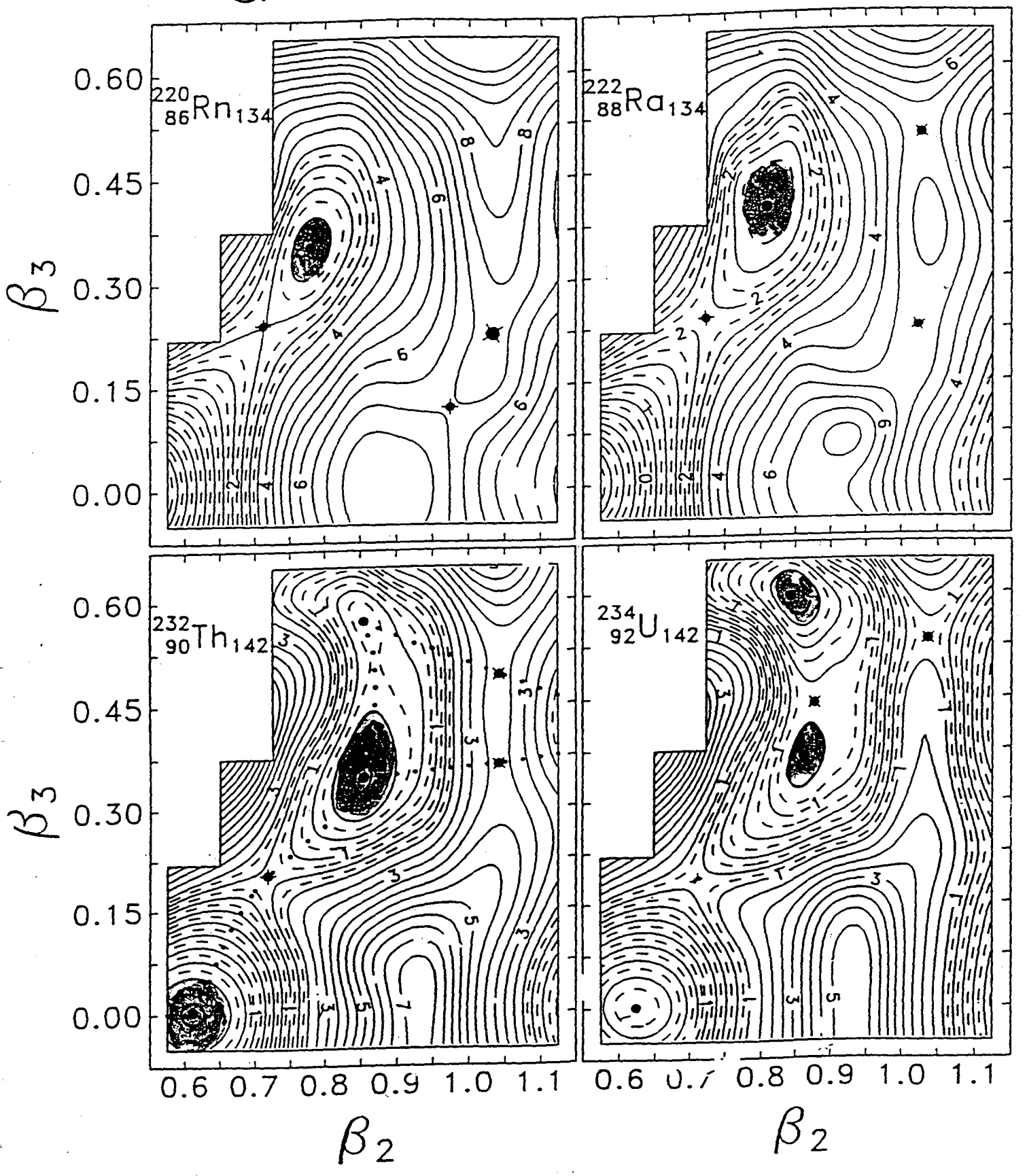


Figure 2

S. Ćwiok et al., Phys. Lett. B322 (1994) 304

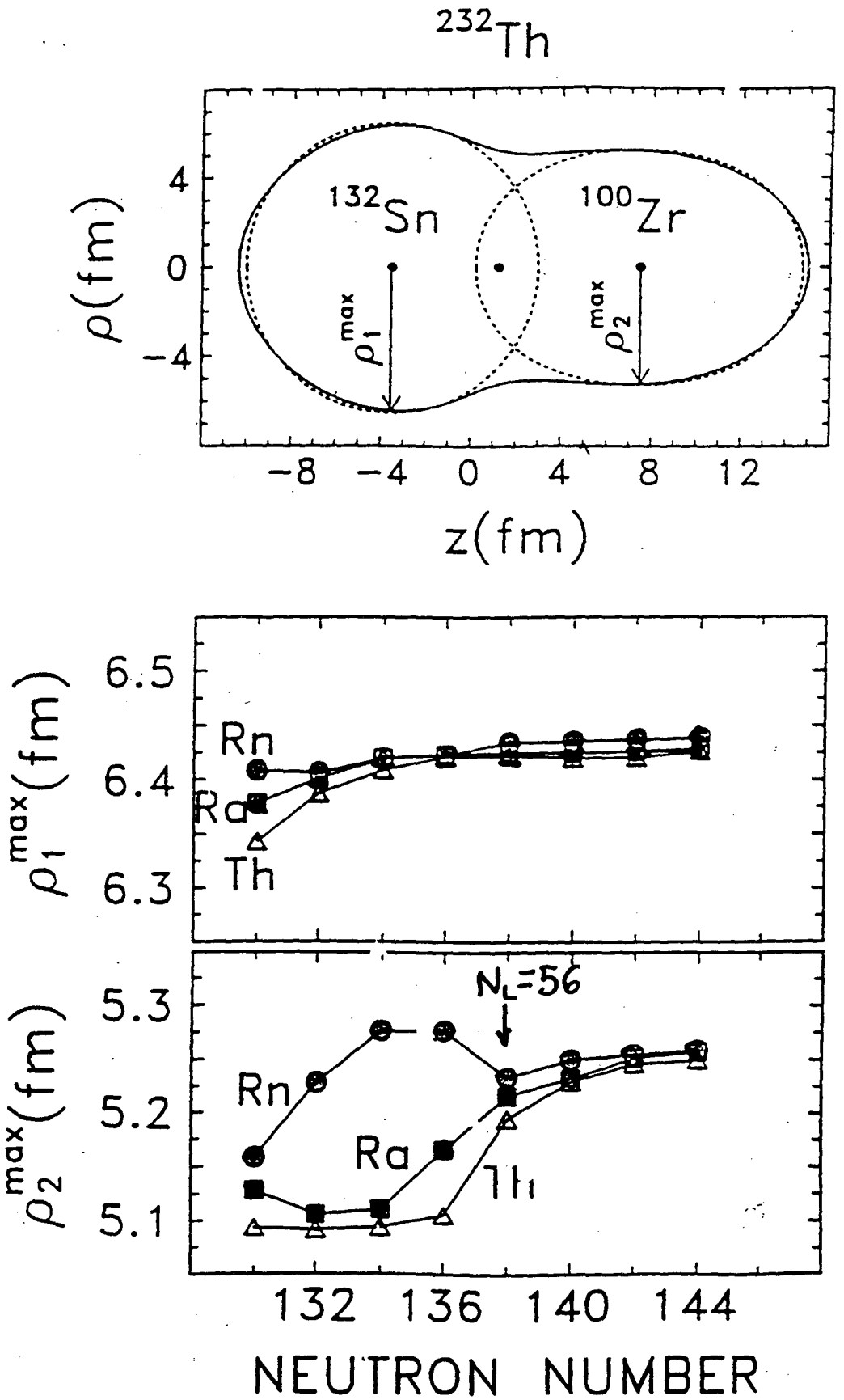
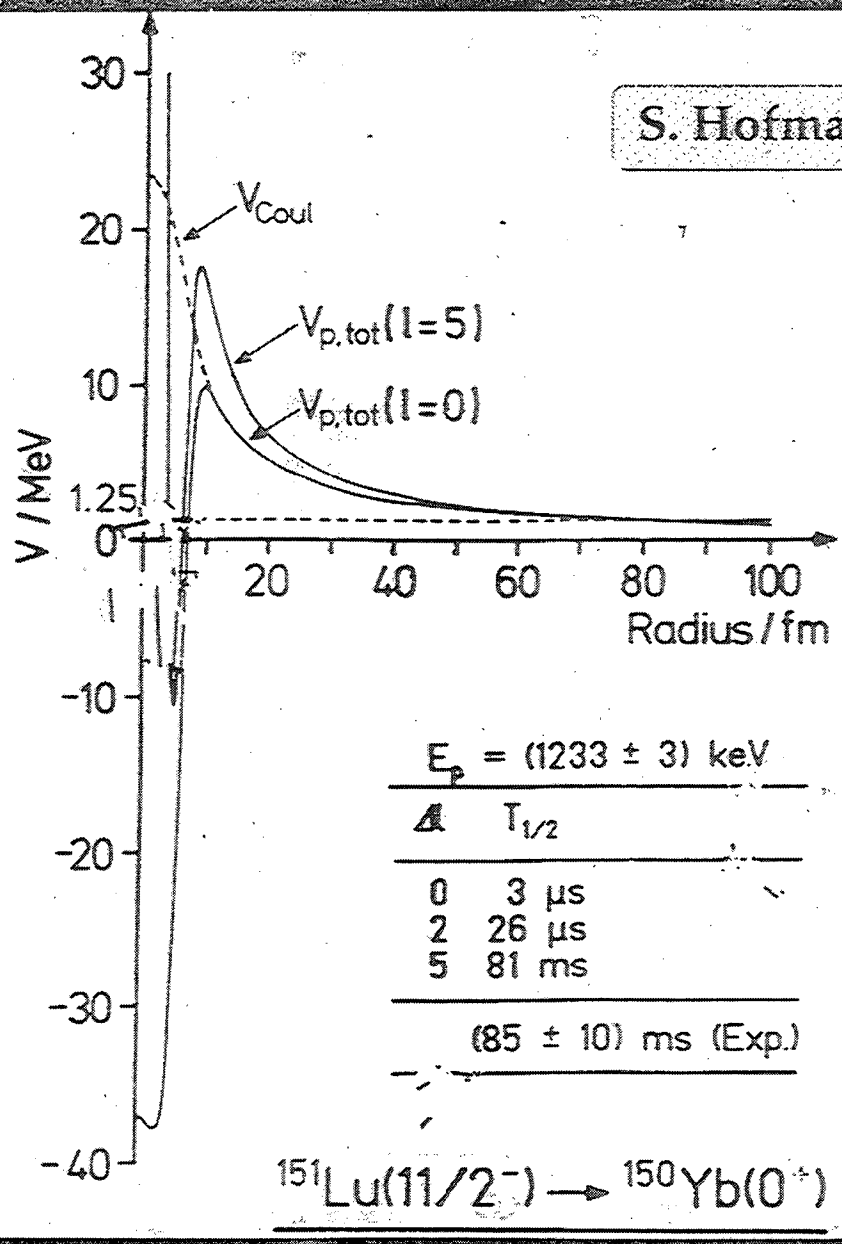


Figure 4

Proton emitters

$$\ln 2 / T_{1/2} \propto \left(Ze^2 / R_c - Q_{p,nucl}\right)^{-1/2} \exp\left(-2G_{jl}\right)$$

$$G_{jl} = \sqrt{2m/\hbar^2} \int_{R_{in}}^{R_{out}} dr \sqrt{V_{jl}(r) + V_{Coul}(r) + V_l(r) - Q_{p,nucl}}$$



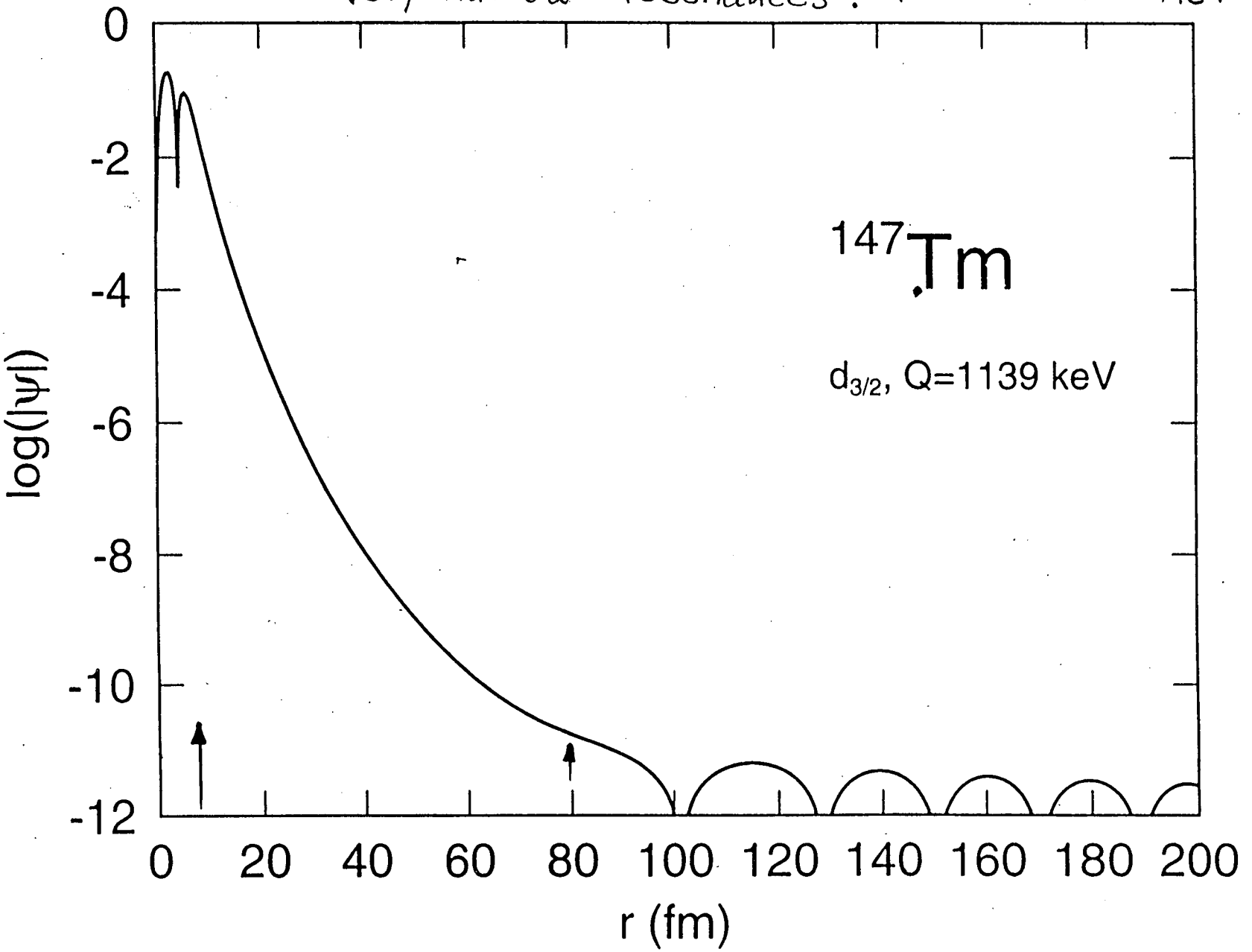
E_p = (1233 ± 3) keV

Δl	$T_{1/2}$
0	3 μs
2	26 μs
5	81 ms

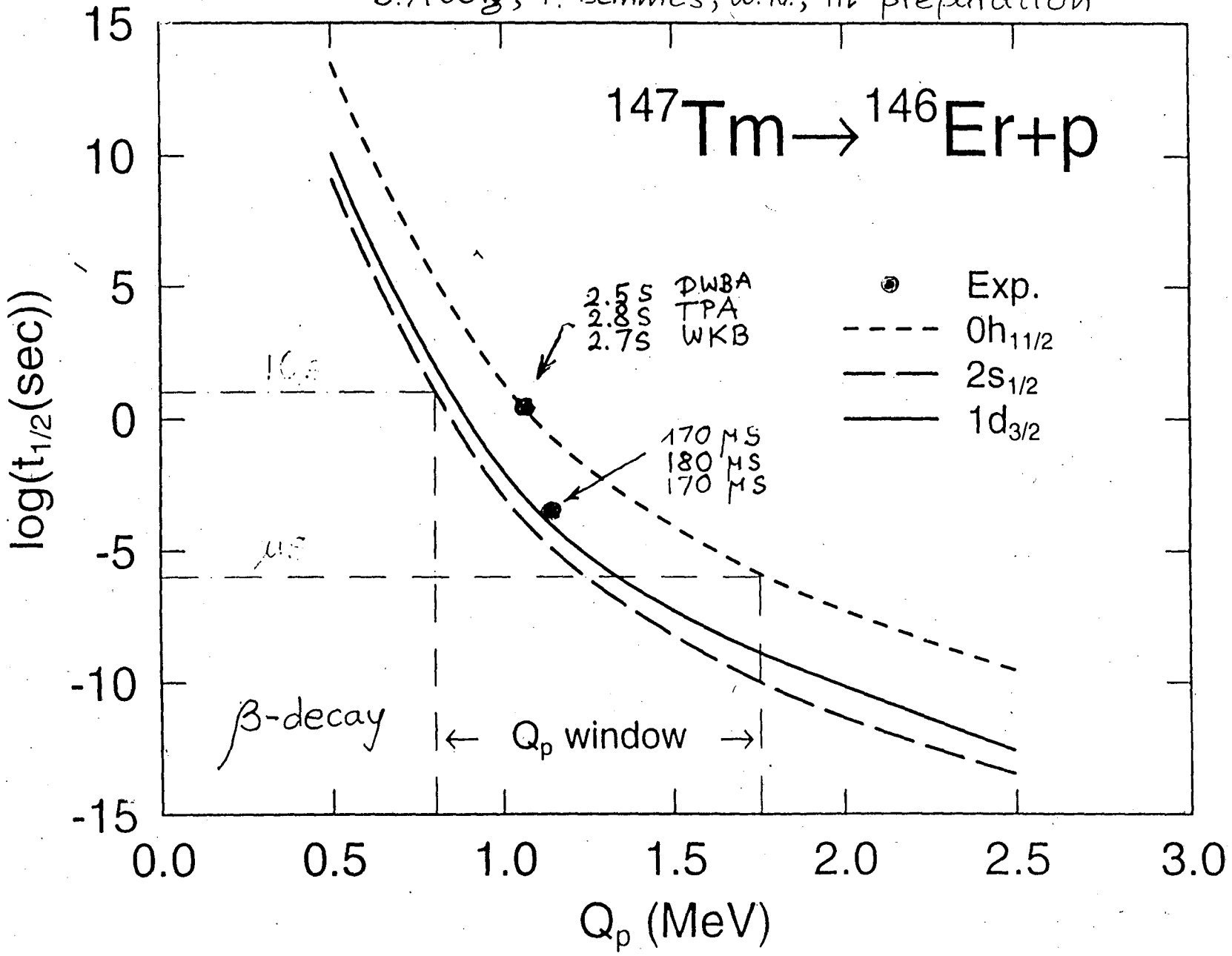
(85 ± 10) ms (Exp.)

$^{151}Lu(11/2^-) \rightarrow {}^{150}Yb(0^+)$

Very narrow resonances : $\Gamma \sim 10^{-22} - 10^{-15}$ MeV



S. Åberg, P. Semmes, W.N., in preparation



Åberg
Semmes
W.N.

$$t_{1/2} = \frac{1}{S_p} \frac{\hbar}{\Gamma} \ln 2$$

t_{calc}/t_{exp} u_ν^2

Nucleus	Q_p (keV)	orbit	$t_{1/2,p}$ Exp.	$t_{1/2,p}$ Calc.	S_p^{exp}	S_p^{th}
$^{109}_{53}I_{56}$	829 ±4	$1d_{5/2}$	(100 ±5) μs	(10 ±1) μs	0.10 ±0.01	0.76
$^{113}_{55}Cs_{58}$	977 ±4	$1d_{5/2}$	(17 ±2) μs	(0.540 ±0.06) μs	0.032 ±0.005	0.59
$^{147}_{69}Tm_{78}$	1071 ±3	$0h_{11/2}$	(2.8 $^{+3.1}_{-1.2}$) s	(2.6 ±0.2) s	0.9 ±0.7	0.64
$^{147}_{69}Tm_{78}$	1132 ±4	$1d_{3/2}$	(360 ±40) μs	(210 ±20) μs	0.58 ±0.0[illegible]	0.79
$^{151}_{71}Lu_{80}$	1255 ±3	$0h_{11/2}$	(130 $^{+160}_{-50}$) ms	(60 ±5) ms	0.5 ±0.4	0.54
$^{157}_{73}Ta_{84}$	947 ±7	$2s_{1/2}$	(300 ±110) ms	(220 ±60) ms	0.74 ±0.34	0.66
$^{161}_{75}Re_{84}$	1214 ±6	$2s_{1/2}$	(370 ± 40) μs	(190 ±30) μs	0.51 ±0.10	0.59
$^{161}_{75}Re_{84}$	1338 ±7	$0h_{11/2}$	(325 ± 44) ms	(86 ±14) ms	0.27 ±0.06	0.33
$^{165}_{77}Ir_{88}$	1733 ±7	$0h_{11/2}$	(350 ±70) μs	(100 ±10) μs	0.29 ±0.07	0.23
$^{167}_{77}Ir_{90}$	1086 ±6	$2s_{1/2}$	(110 ±15) ms	(36 ±7) ms	0.33 ±0.08	0.51
$^{167}_{77}Ir_{90}$	1261 ±7	$0h_{11/2}$	(7.5 ±1.9) s	(2.0 ±0.4) ms	0.27 ±0.09	0.23
$^{171}_{79}Au_{92}$	1718 ±6	$0h_{11/2}$	(2.22 ±0.29) ms	(0.35 ±0.04) ms	0.16 ±0.03	0.14

Phil Woods
Edinburgh University

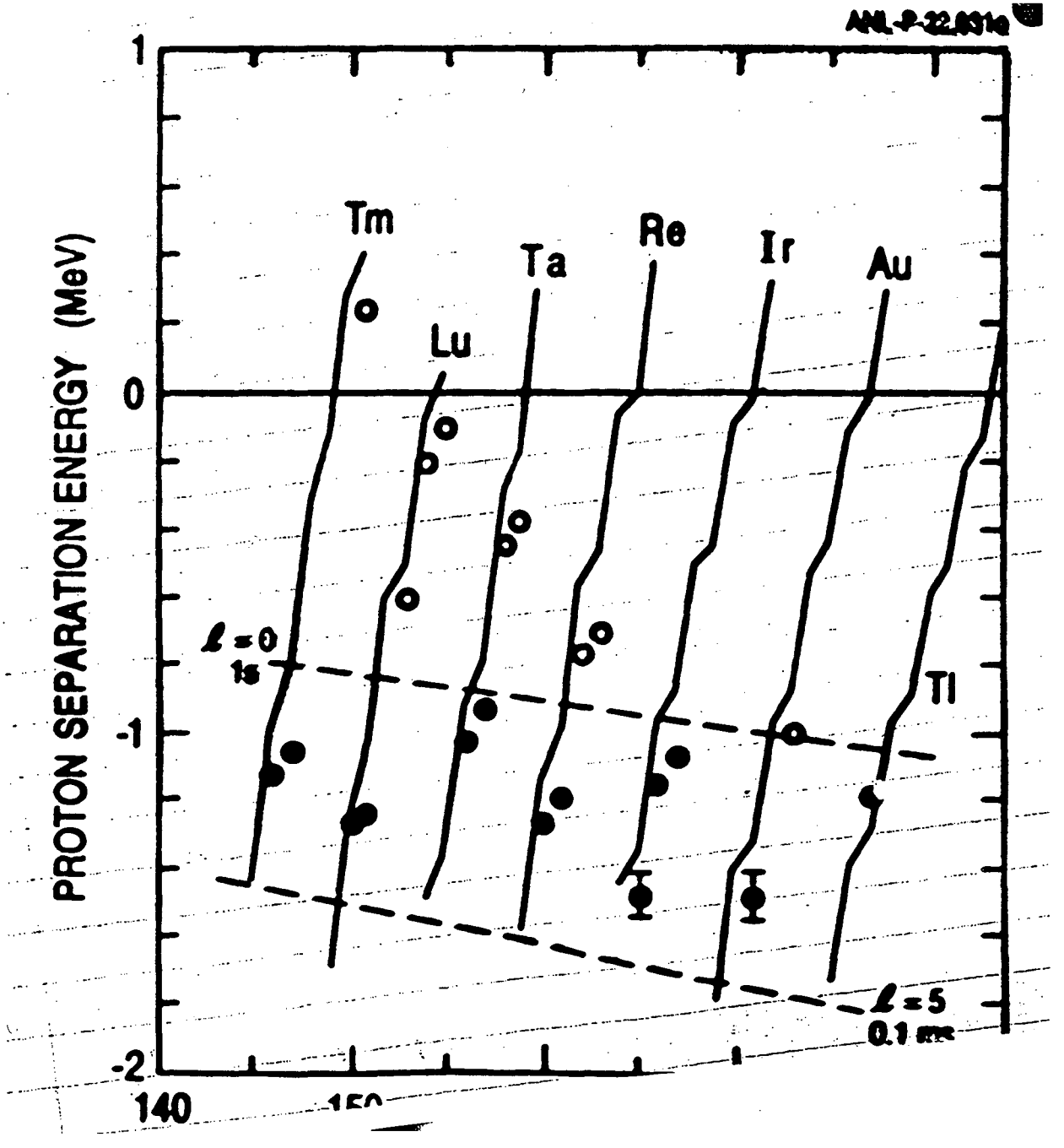
P. Woods

Holistic Studies Beyond the Proton Drip-Line

- (near) ground-state properties of proton unbound nuclei

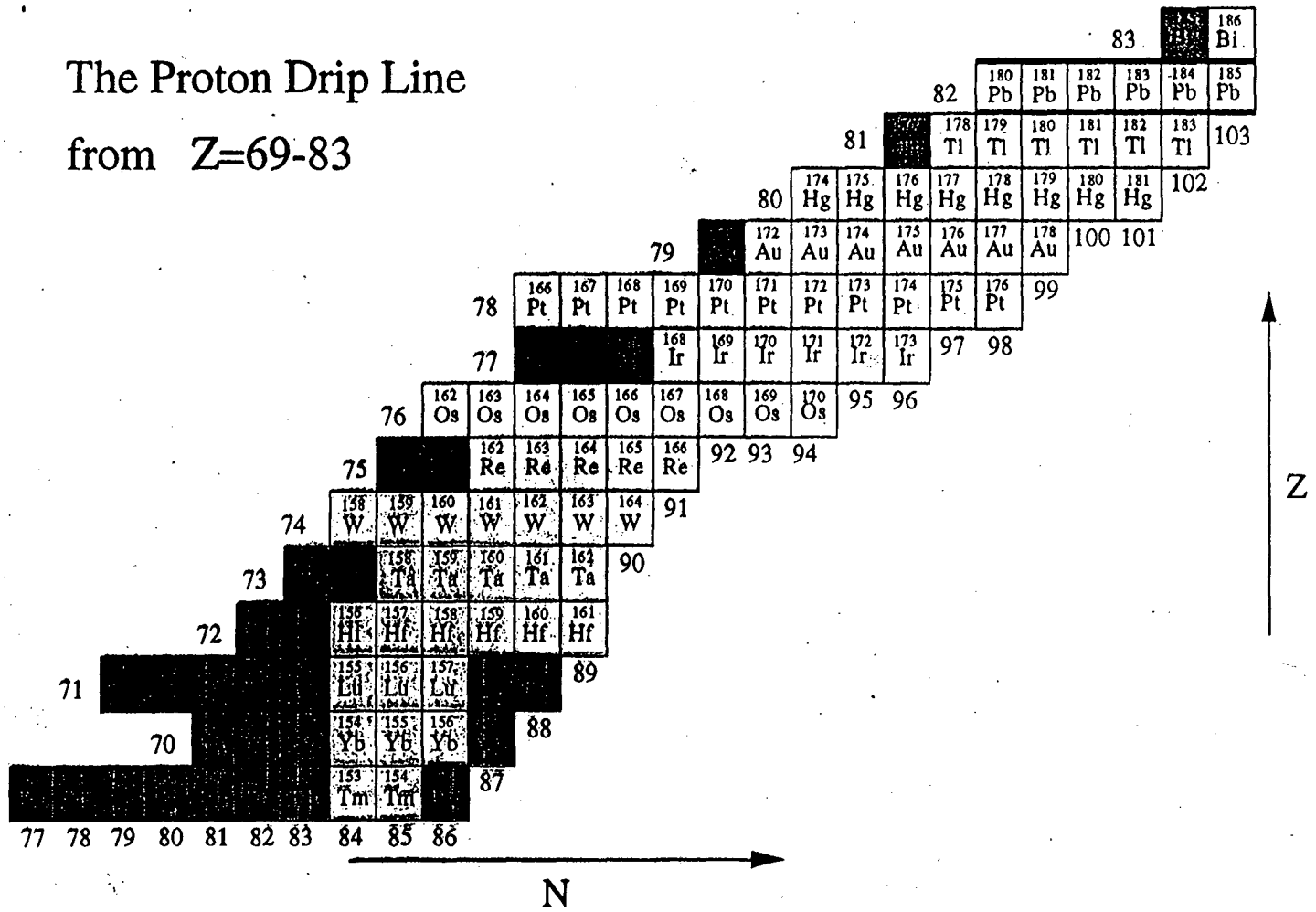
$$\Updownarrow$$

- structure of excited states of proton unbound nuclei — the development of Recoil Decay Tagging, RDT


ANL-P-22,831a
PROTON SEPARATION ENERGY (MeV)
1
0
-1
-2
140
Tm
Lu
Ta
Re
Ir
Au
Tl
ℓ = 0
1s
ℓ = 5
0.1 ms

The Proton Drip Line

from Z=69-83



Proton Spectroscopic Factors

for $82 > Z > 64$

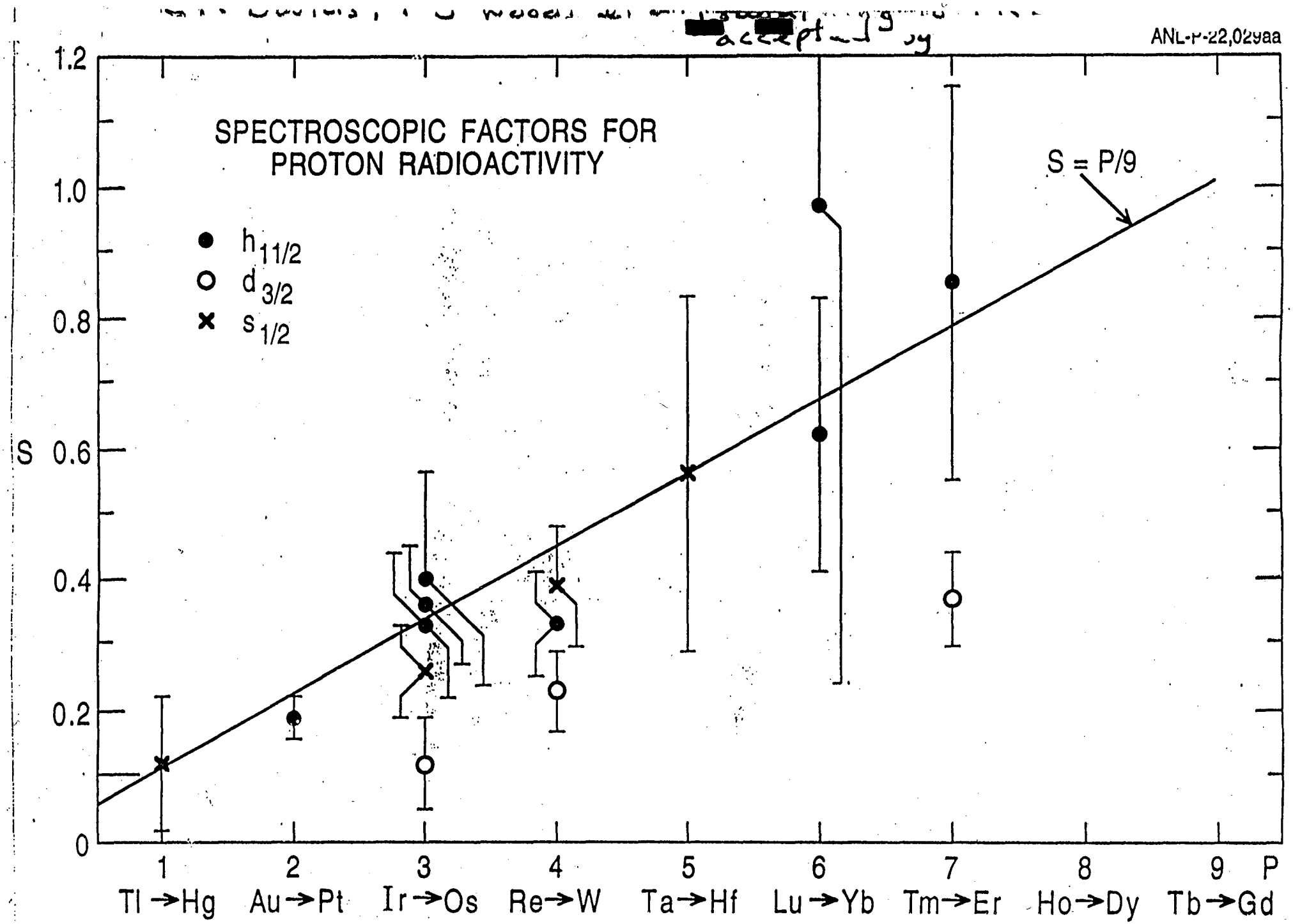
$$S_j^{exp} = \frac{t_{\frac{1}{2}p}^{calc}}{t_{\frac{1}{2}p}^{exp}}$$

$$S_j^{theory} = \frac{P}{9}$$ — D. Kurath

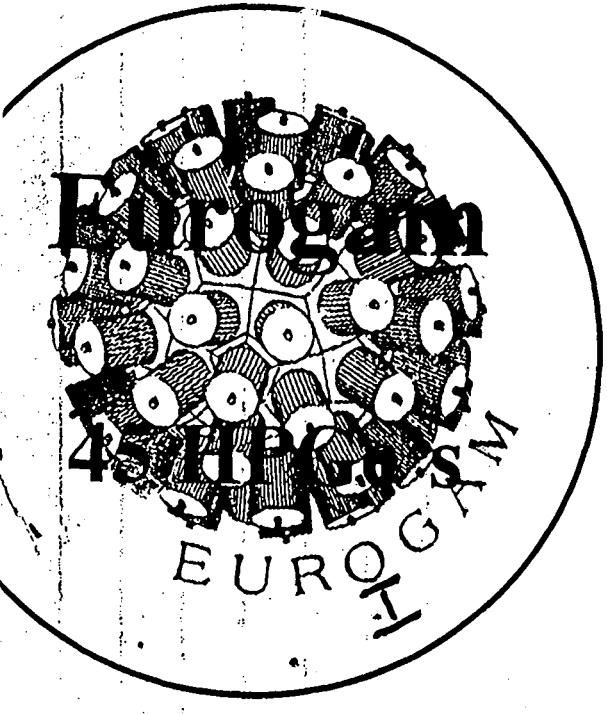
low seniority shell model calculation

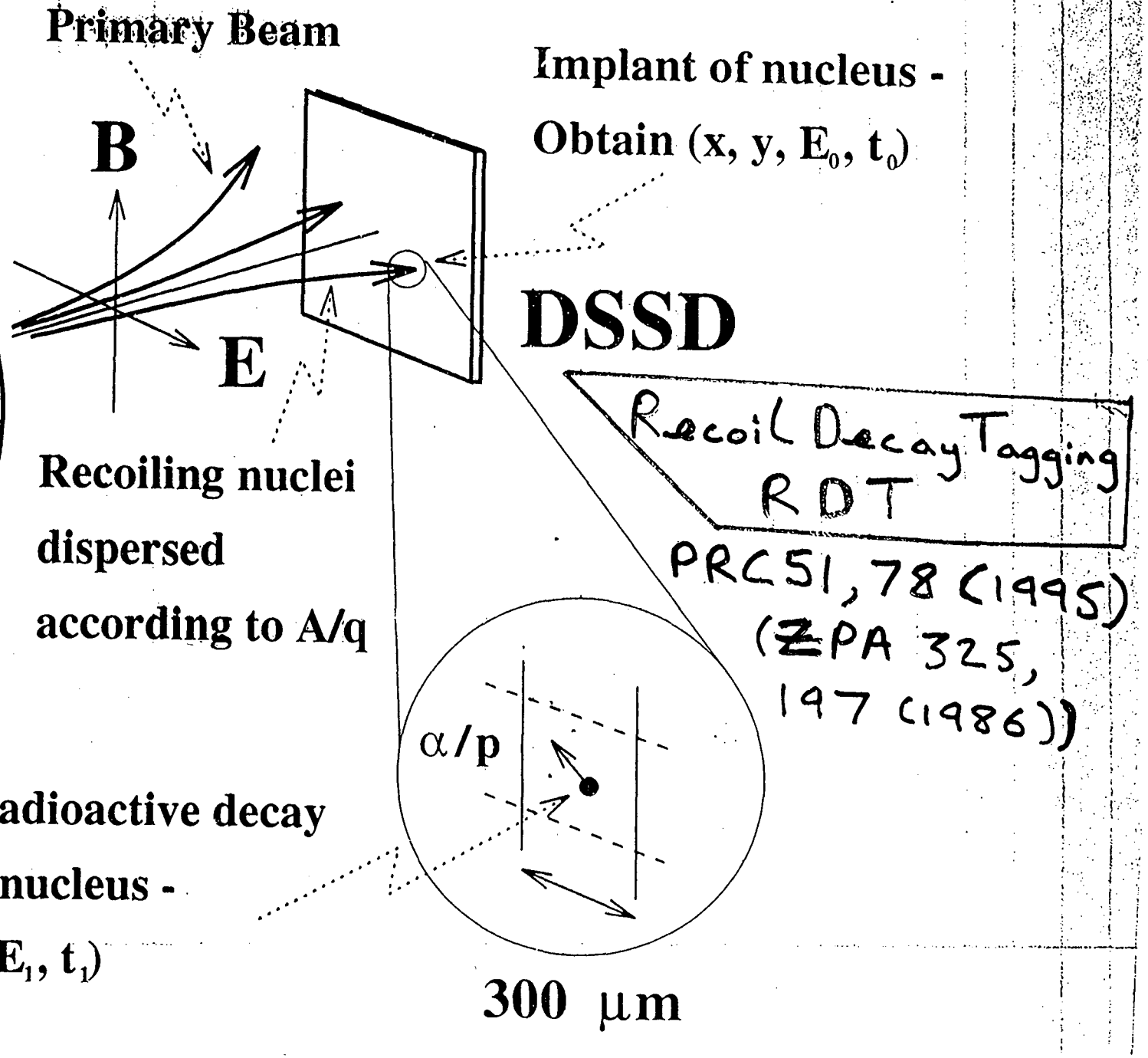
P = number of proton hole pairs in daughter relative to $Z = 82$ shell

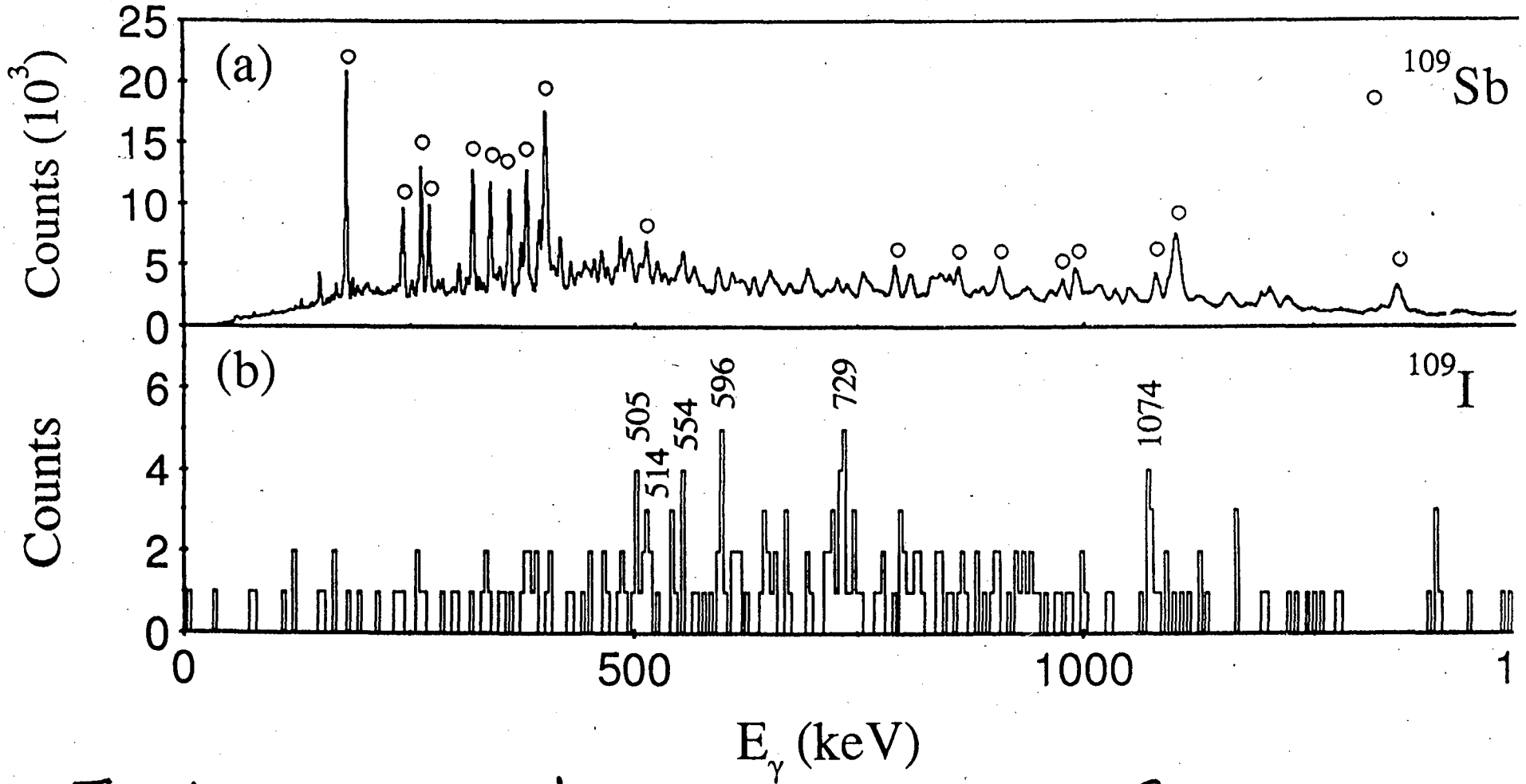
eg $P = \frac{1}{9}$ for $^{177}_{81}Tl$


ANL-P-22,029aa
SPECTROSCOPIC FACTORS FOR
PROTON RADIOACTIVITY
S = P/9
$h_{11/2}$
$d_{3/2}$
$s_{1/2}$
S
1.2
1.0
0.8
0.6
0.4
0.2
0
1
2
3
4
5
6
7
8
9
P
Tl→Hg
Au→Pt
Ir→Os
Re→W
Ta→Hf
Lu→Yb
Tm→Er
Ho→Dy
Tb→Gd

beam γ-ray detection





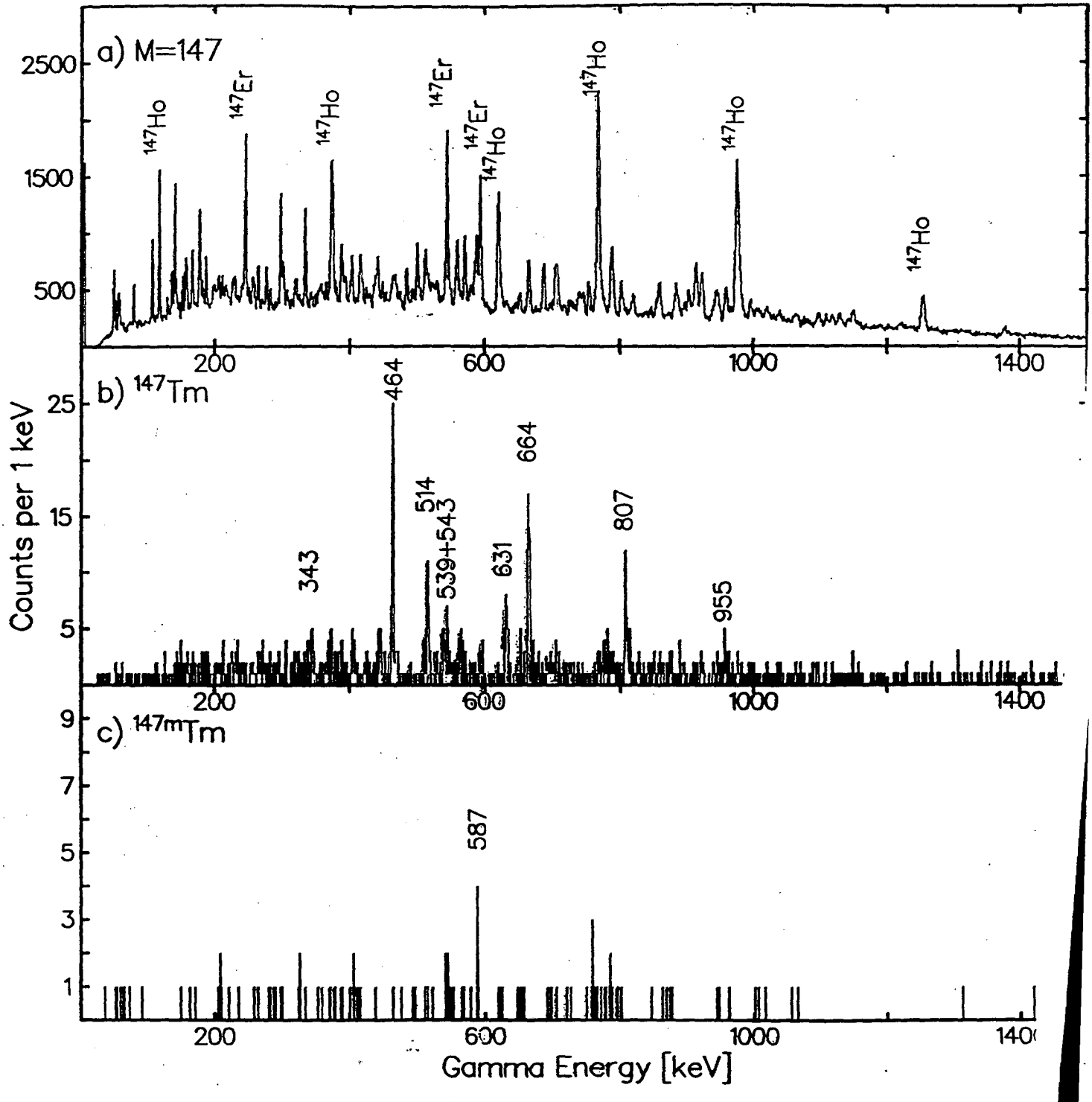


First observation of in-beam γ-rays from a ground-state β-emitter! $\sigma_{^{109}I} \sim 3\,\mu b$

/text/figs/te108/fig7.psk

Fig.

O. Sewerynniak et al., ~~paper in preparation~~ accepted by PRC, Rap Com.



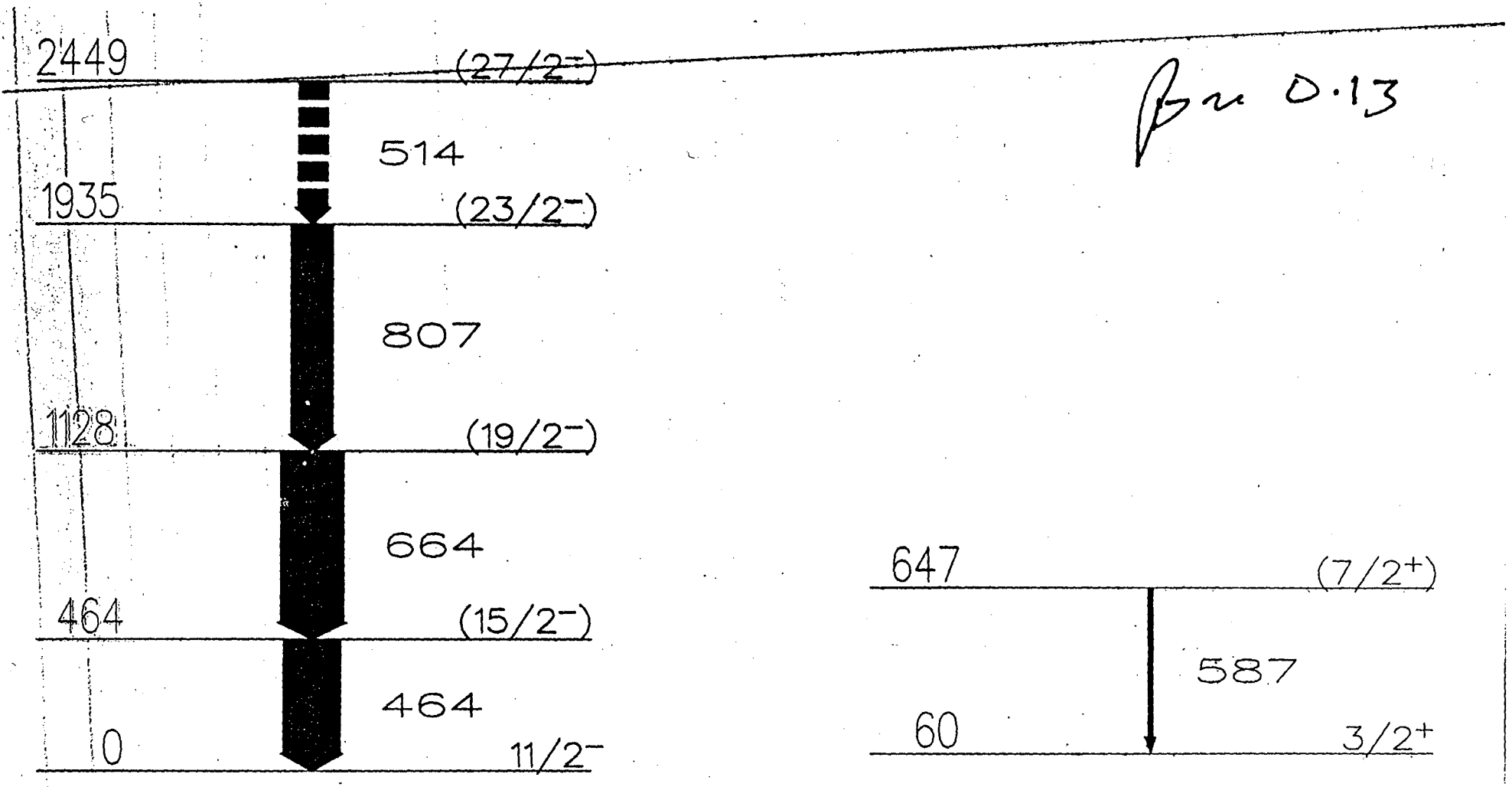
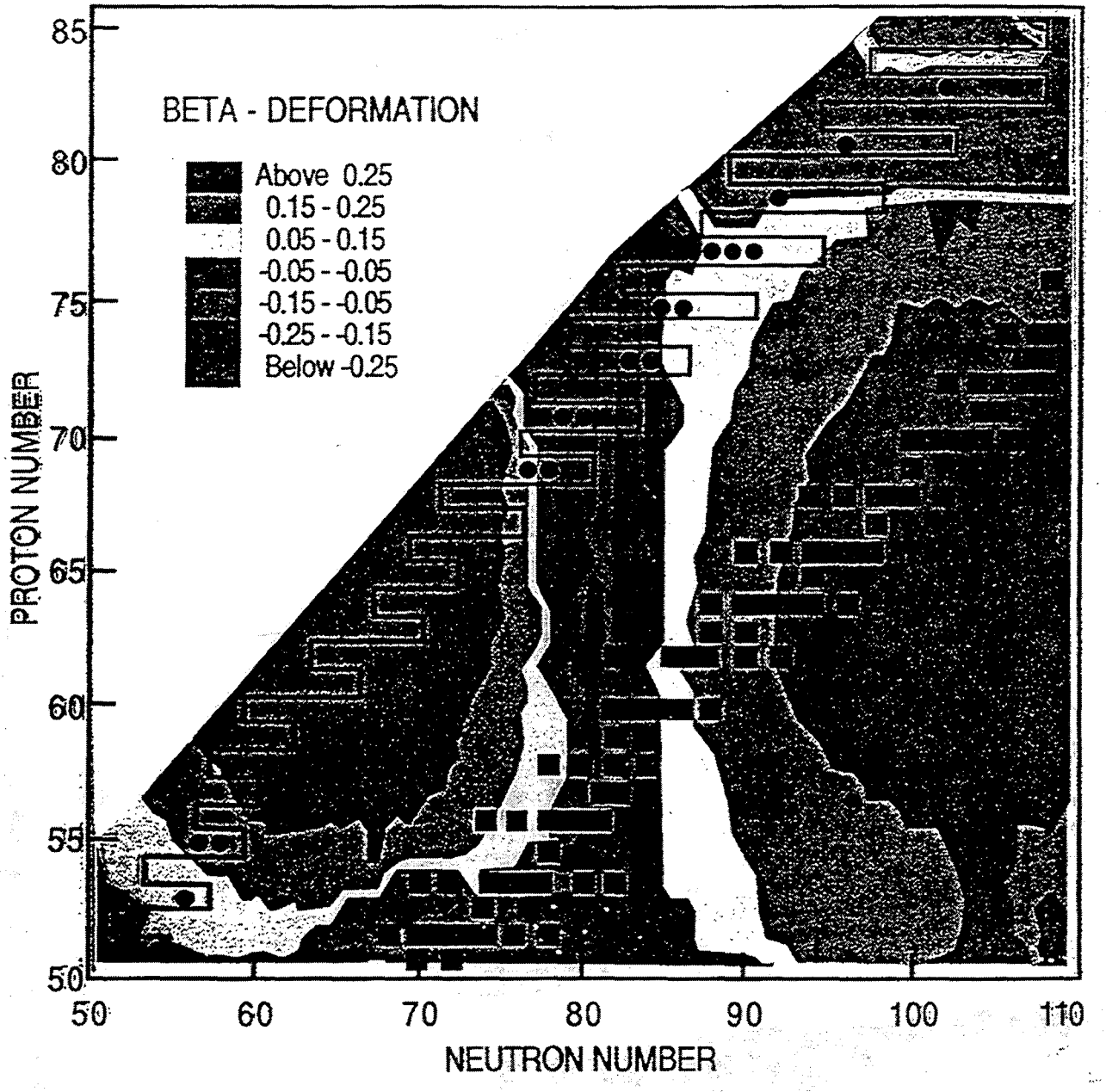


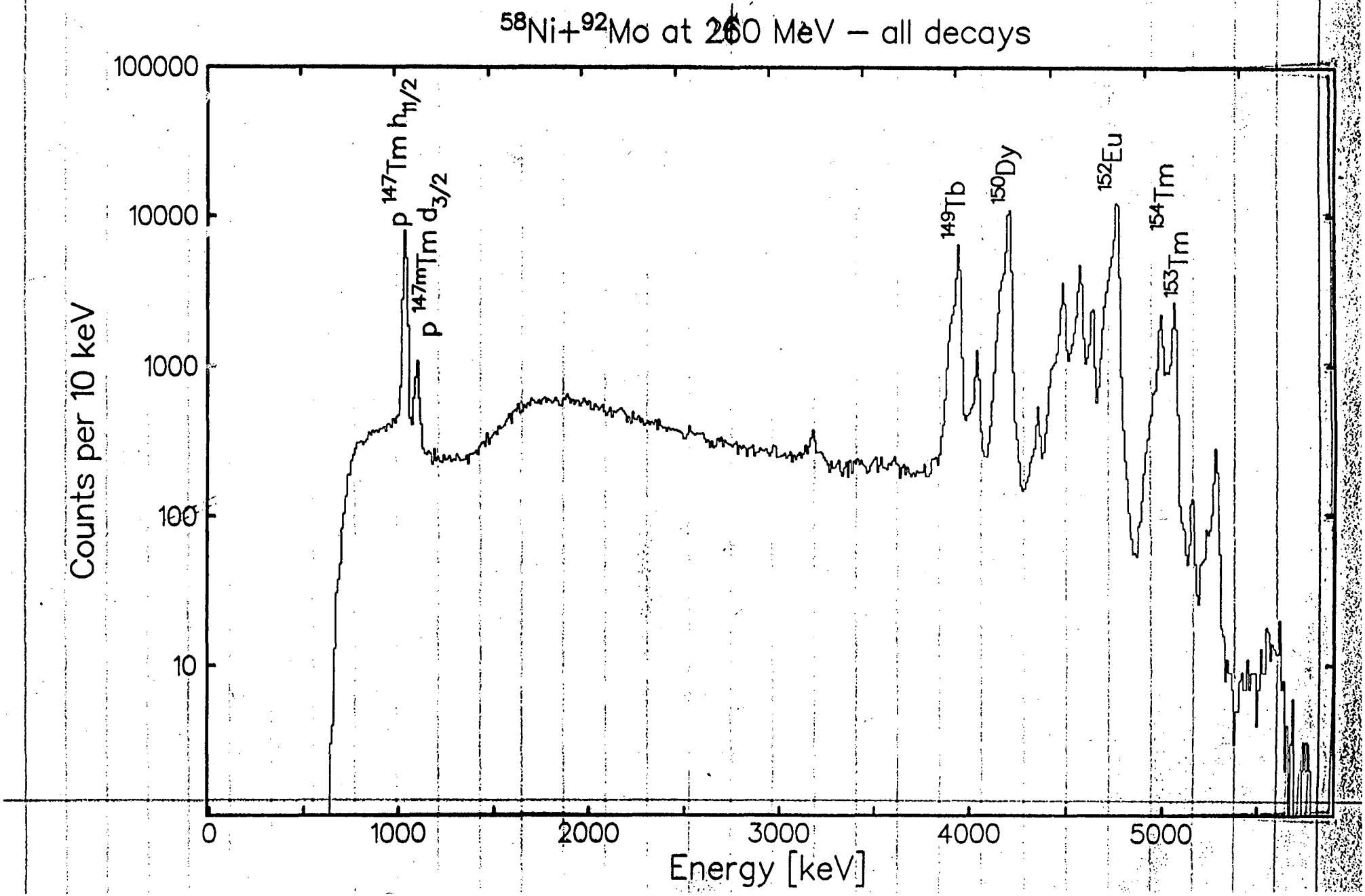
Fig 0.13

^{147}Tm

ANL-P-22,108

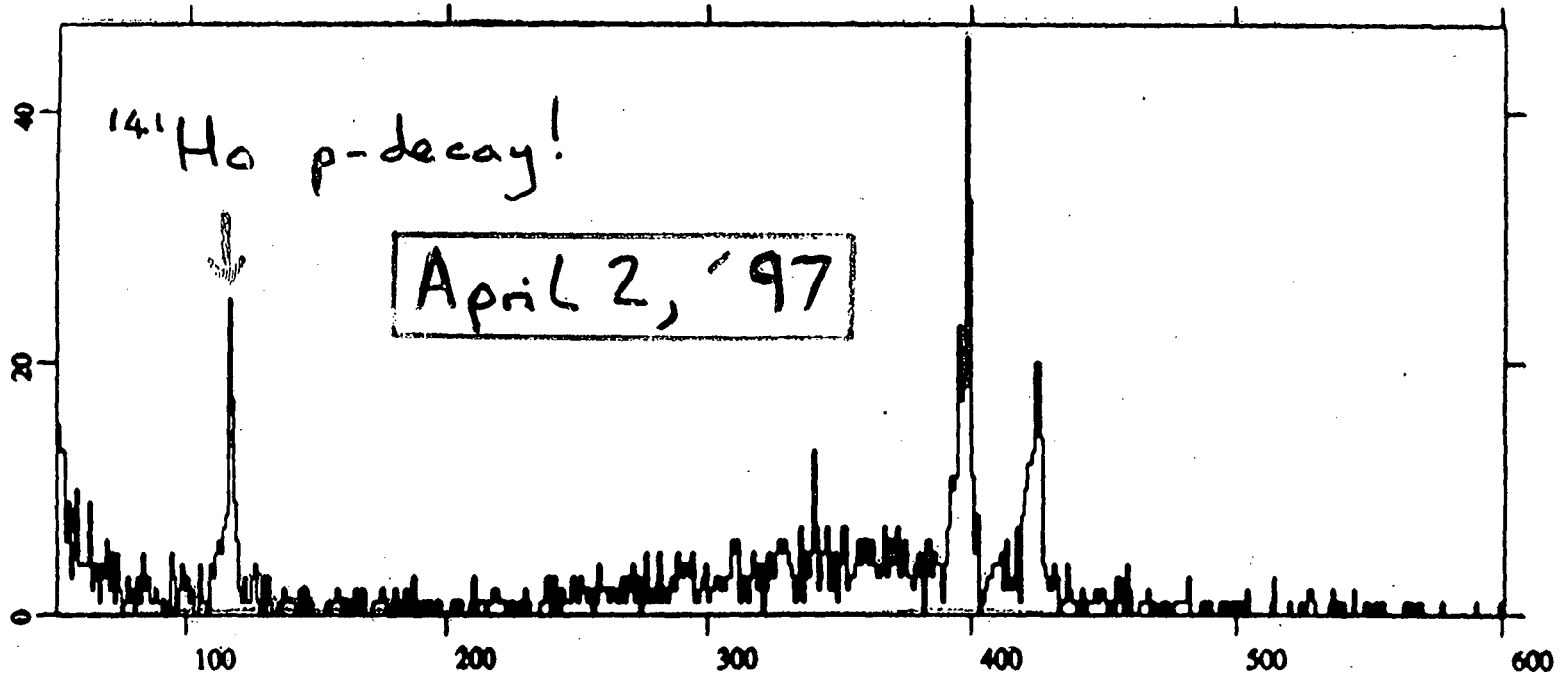

BETA - DEFORMATION
Above 0.25
0.15 - 0.25
0.05 - 0.15
-0.05 - -0.05
-0.15 - -0.05
-0.25 - -0.15
Below -0.25
PROTON NUMBER
85
80
75
70
65
60
55
50
NEUTRON NUMBER
50
60
70
80
90
100
110

FMA + AYEBALL (~1%)

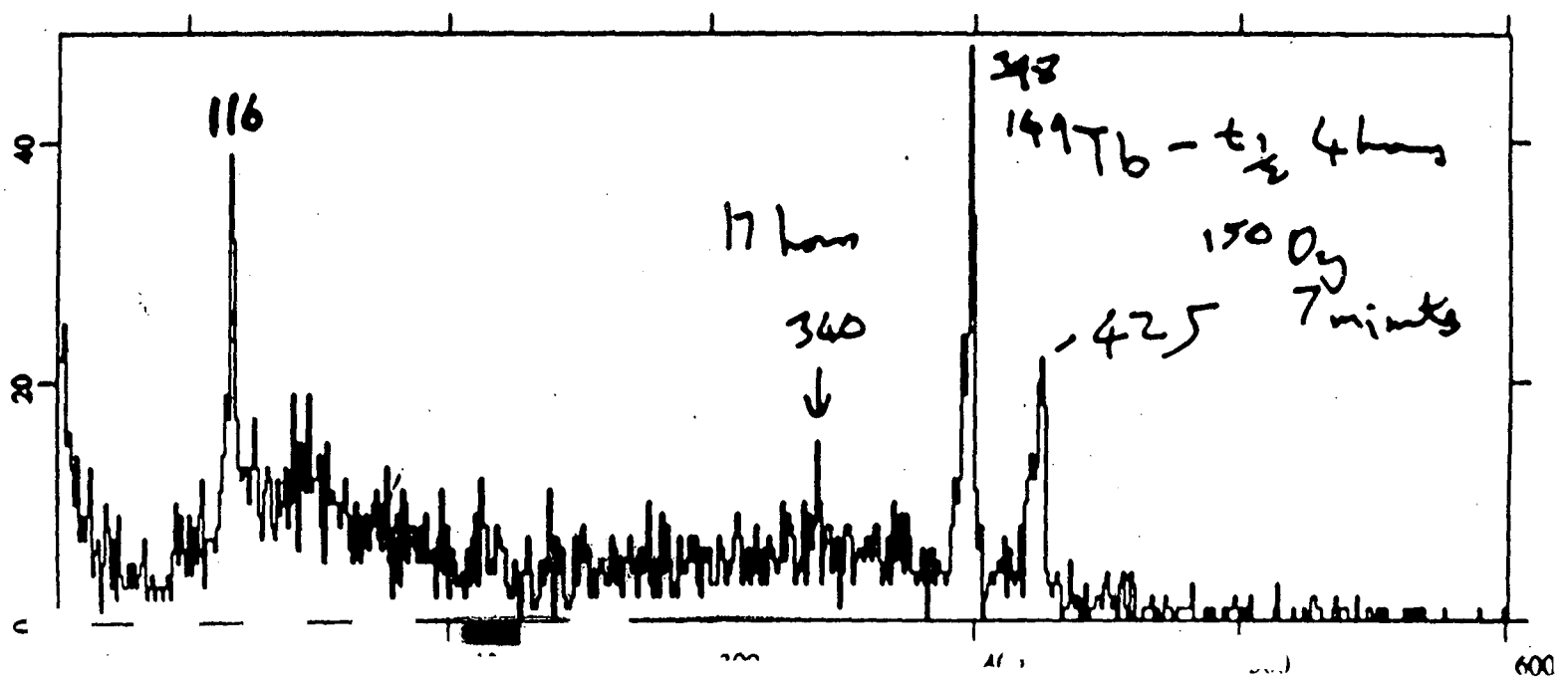


$^{54}Fe + ^{92}Mo \rightarrow ^{146}Er^{*}$

EDFNOBOXSI Run 14 Sum 1,346



EDF Run 14 Sum 2,842



Ken Toth
Oak Ridge National Laboratory

K TOTH

STUDY OF Pb, Po, Pt α Emitters NEAR THE DRIP LINE

FMA

^{78}Kr, Mo Beams Incident on Zn and Mo Targets.

180, 181, 182 Pb.	Also,
166, 167, 168 Pt.	186-189 Bi.
190, 191 Po.	

MASS DIFFERENCES
(MASSES)

HALF-LIVES

α-DECAY RATES

STRUCTURE INFORMATION
(SHELLS)

- $\underline{Z=82}$ STABILITY MIDWAY BETWEEN $\underline{N=126}$ AND $\underline{N=82}$.

α-DECAY REDUCED WIDTH:

$$\delta^2 = \frac{\lambda \hbar}{P}$$

"λ" is decay constant.

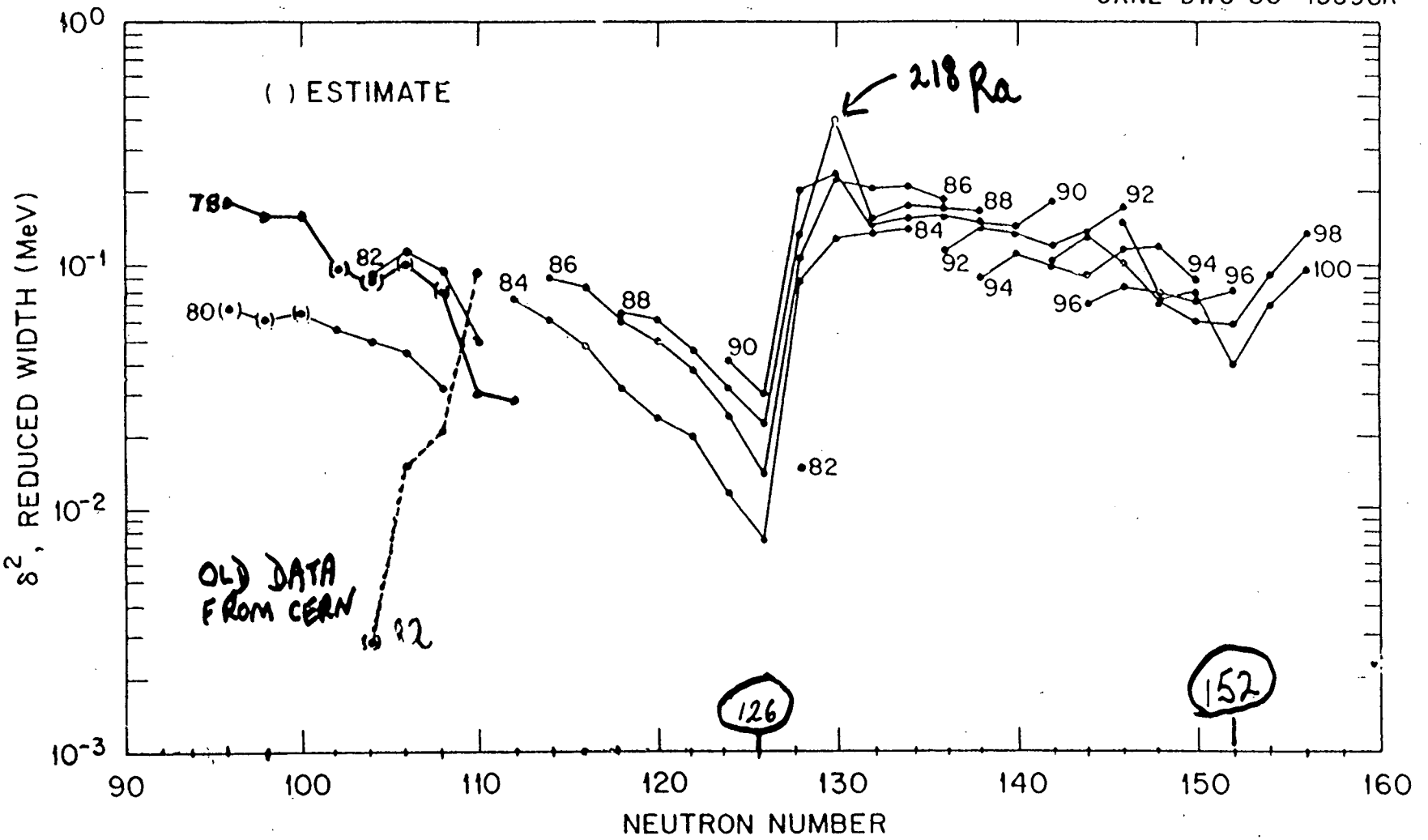
"P" is penetrability factor.

$\delta^2 \approx$ transition probability, where dependence of decay rate on E_α, Z, A, has been removed.

---

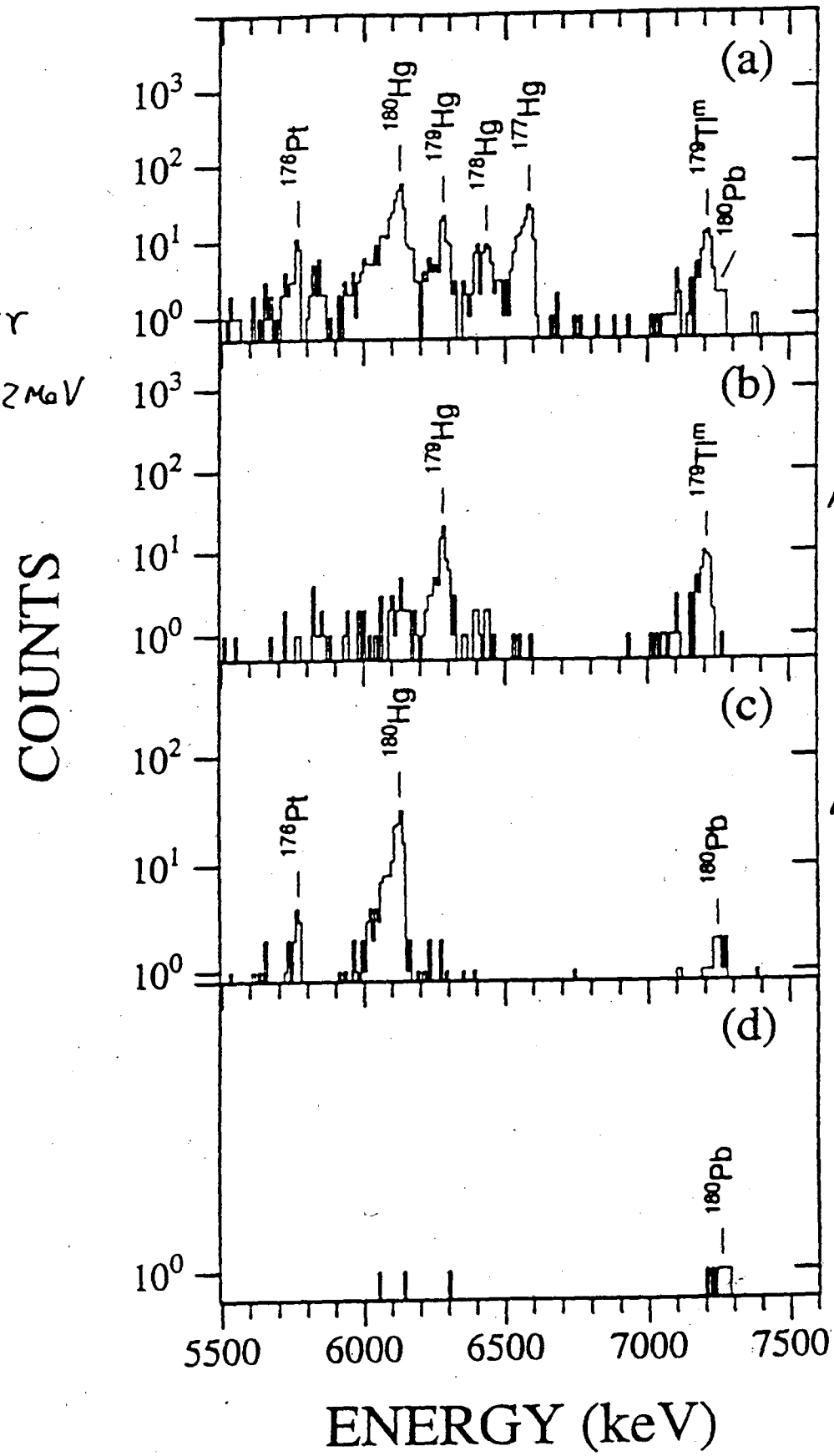
s-wave α-decay transitions; gr. state → gr. state of e.-e. nuclei.

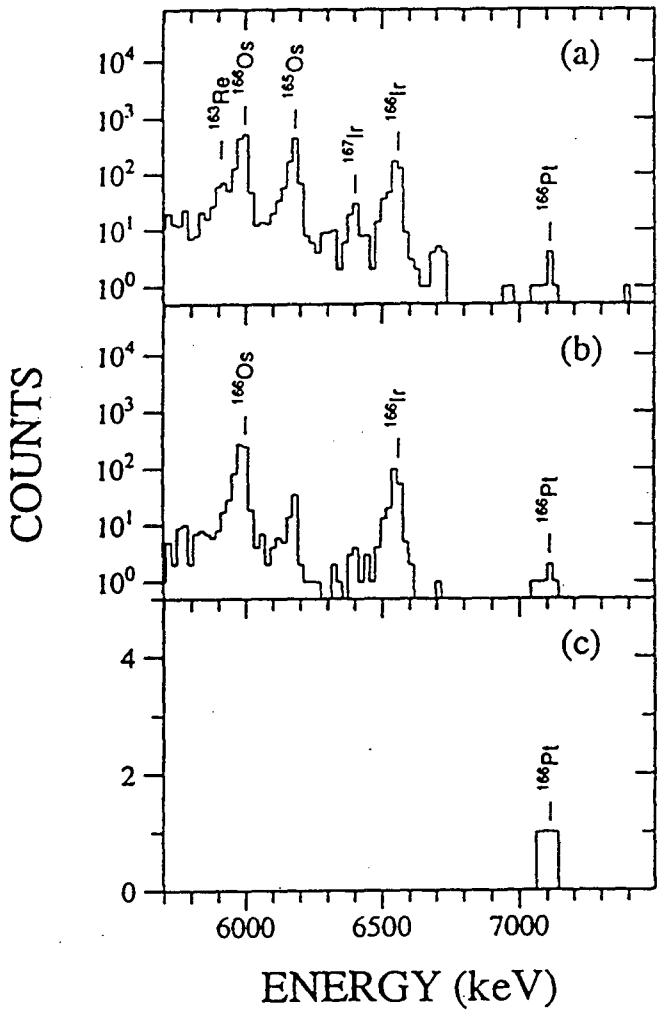
ORNL-DWG 80-15898R



$^{92}Mo + ^{90}Zr$

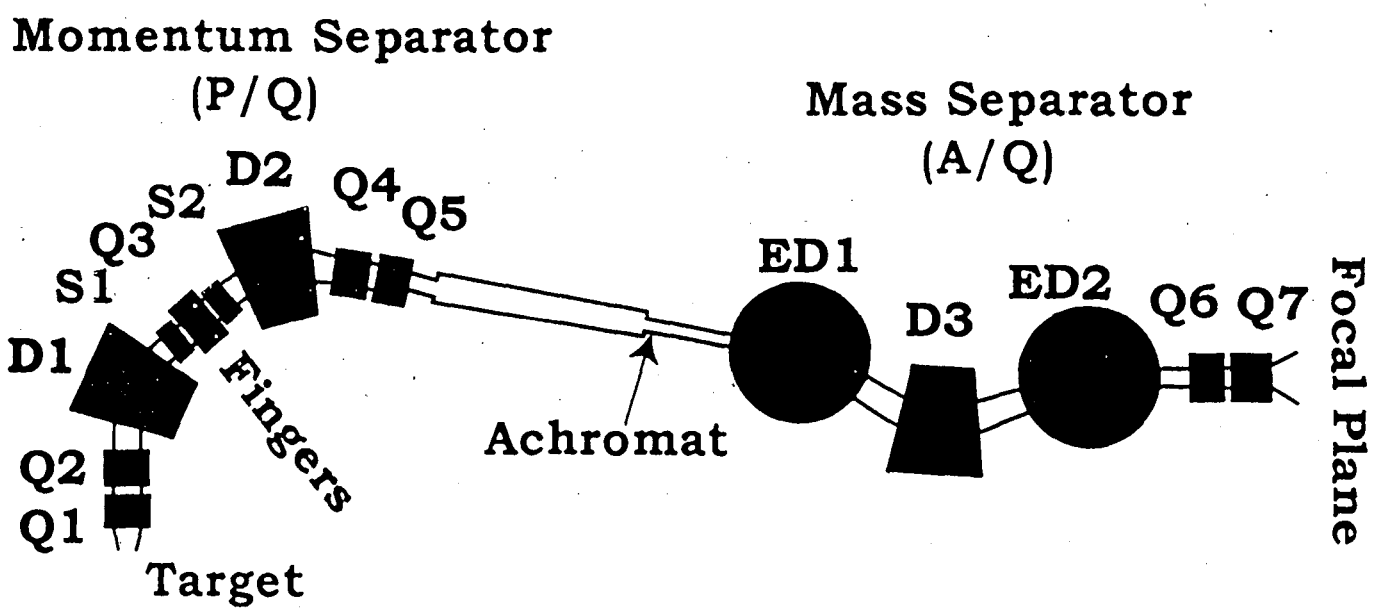
$E(^{92}Mo) = 422\ MeV$





(a) All Alphas, t<2 ms
(b) Gated with M 166
(c) Cor. with ^{162}Os

HRIBF Recoil Mass Spectrometer

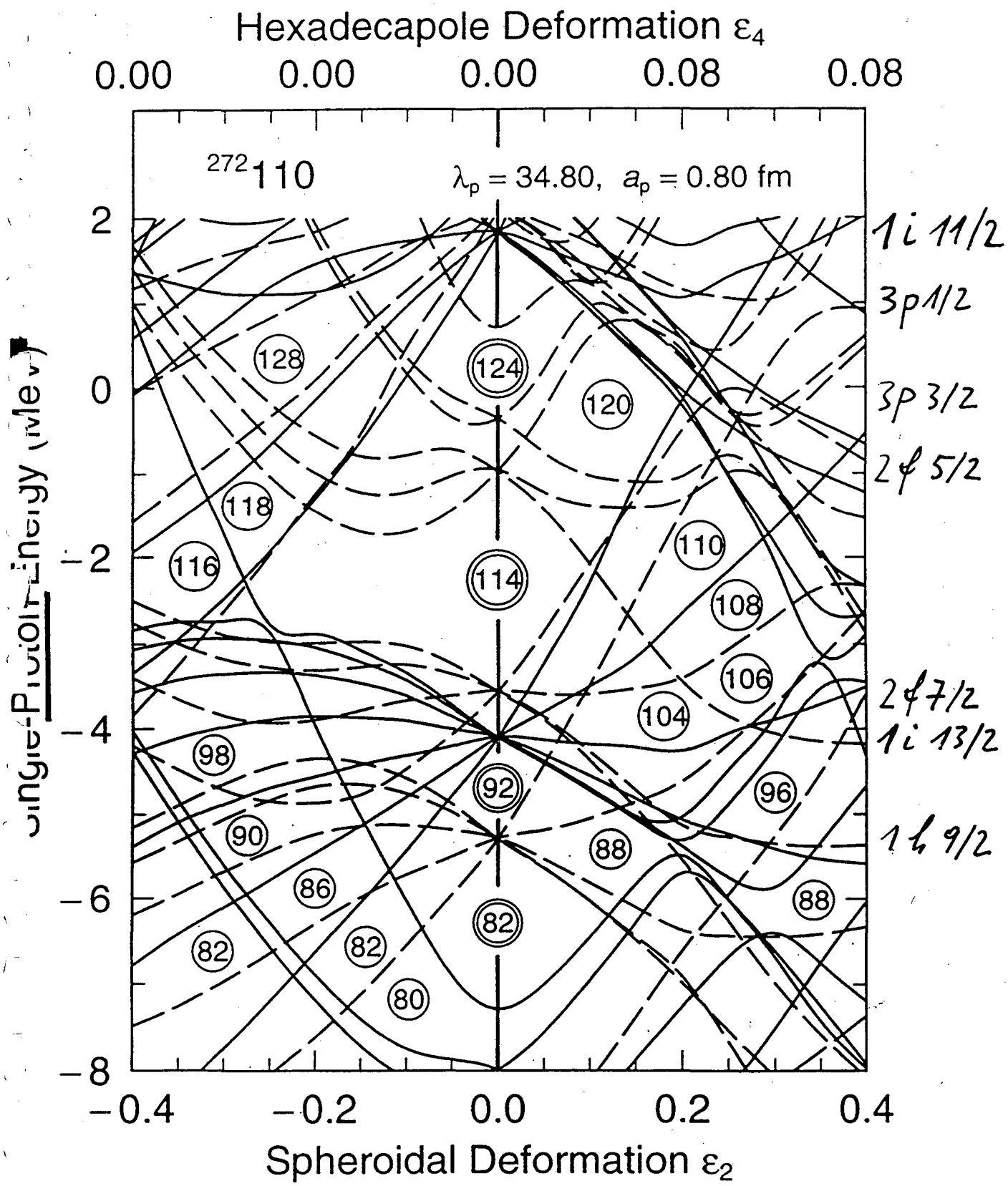


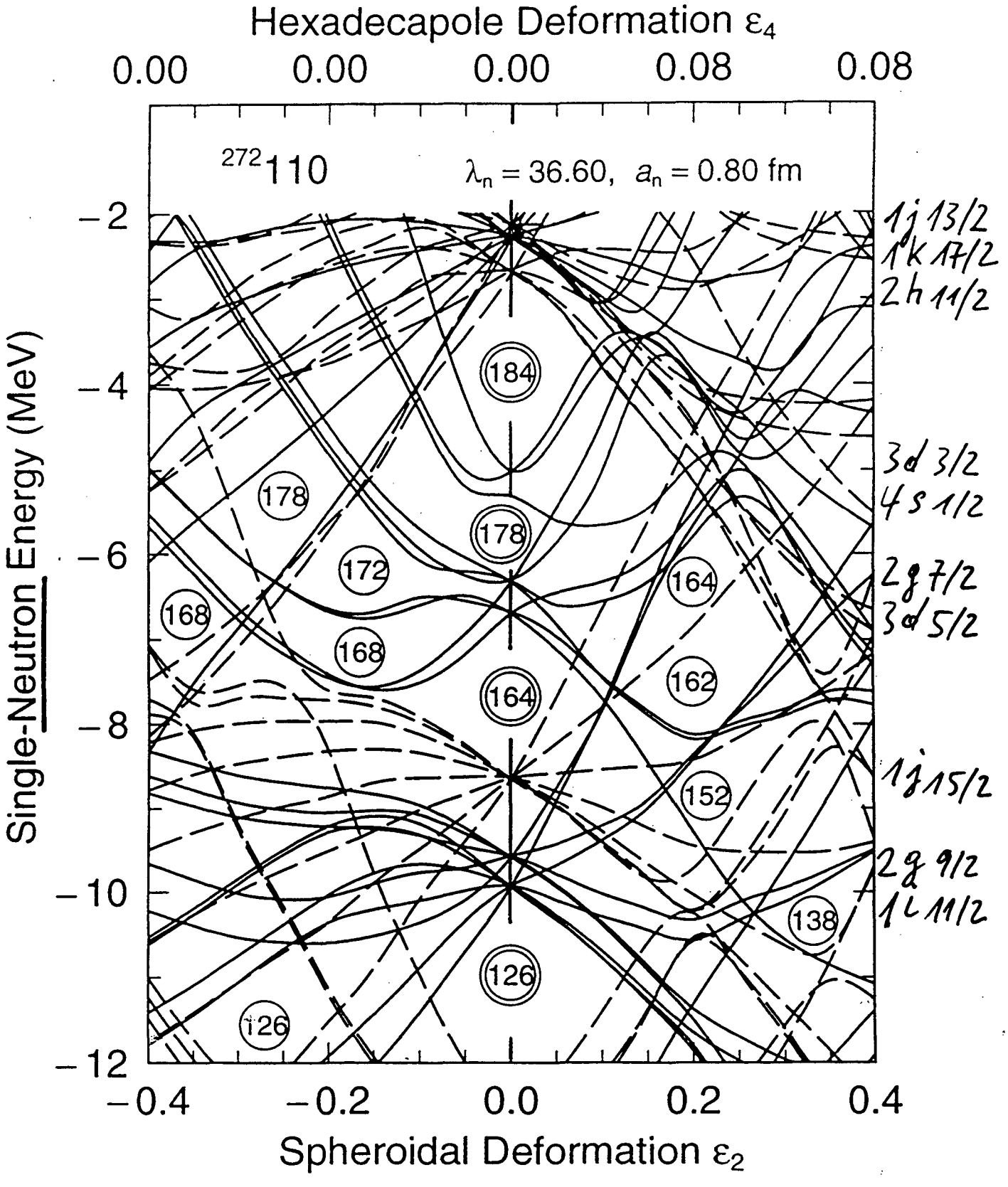
Beam

- Inverse reactions
- High rigidity beams (K=100)
- Excellent beam rejection ($>10^{12}$)
- Excellent mass separation ($M/\Delta M=450$)
- Large energy acceptance
- Large solid angle
- Large A/Q acceptance

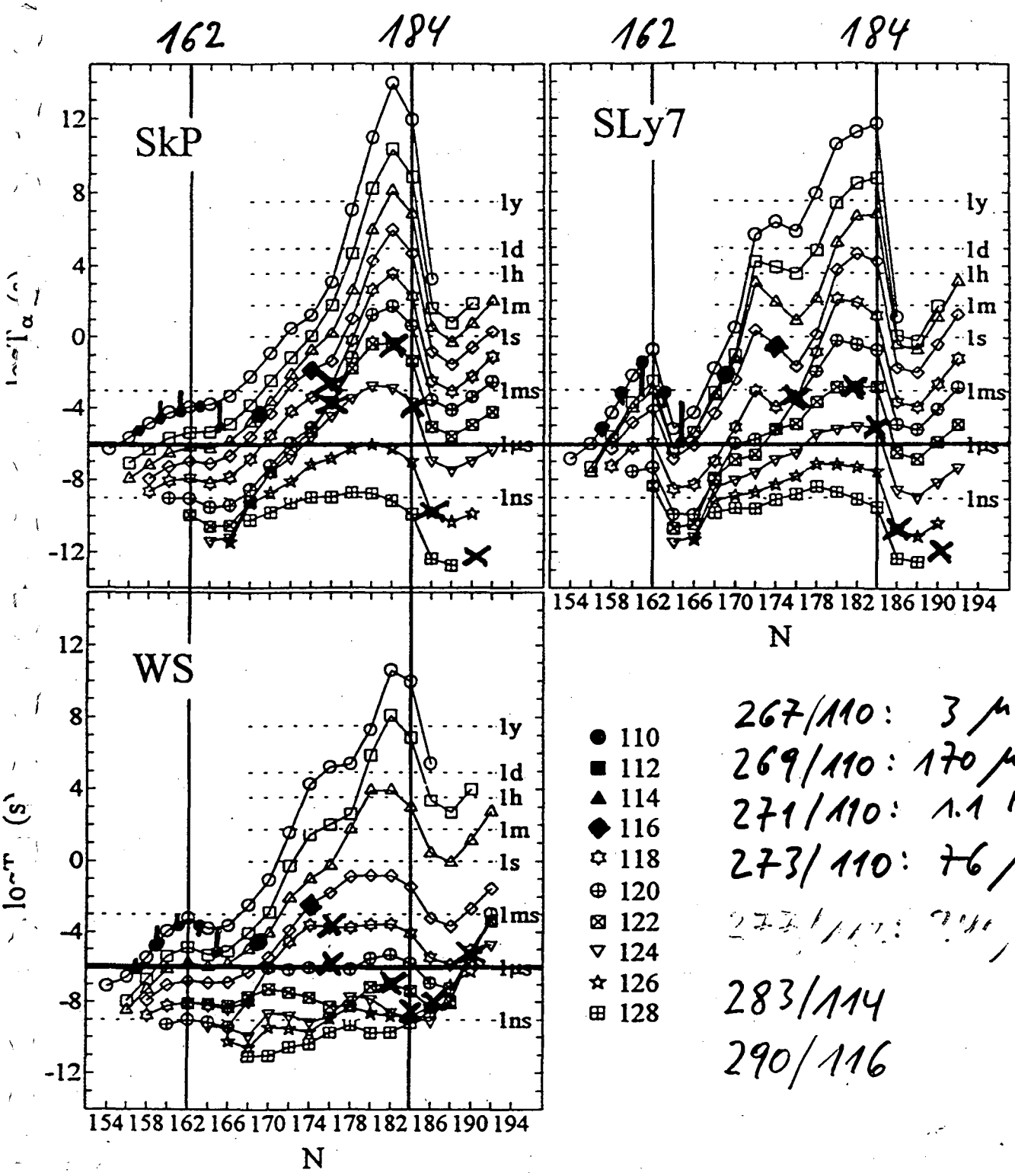
Sigurd Hofmann
GSI

S. Hofmann 1


Hexadecapole Deformation ε4
0.00
0.00
0.00
0.08
0.08
272110
λp = 34.80, ap = 0.80 fm
Single-Proton Energy (MeV)
2
0
−2
−4
−6
−8
128
124
120
118
116
114
110
108
106
104
98
92
96
90
88
86
88
82
82
82
80
1i 11/2
3p1/2
3p 3/2
2f 5/2
2f7/2
1i 13/2
1h 9/2
−0.4
−0.2
0.0
0.2
0.4
Spheroidal Deformation ε2


Hexadecapole Deformation ε4
0.00
0.00
0.00
0.08
0.08
272110
λn = 36.60, an = 0.80 fm
Single-Neutron Energy (MeV)
−2
−4
−6
−8
−10
−12
184
178
178
172
168
168
164
164
162
152
138
126
126
1j 13/2
1k 17/2
2h 11/2
3d 3/2
4s 1/2
2g 7/2
3d 5/2
1j 15/2
2g 9/2
1i 11/2
−0.4
−0.2
0.0
0.2
0.4
Spheroidal Deformation ε2

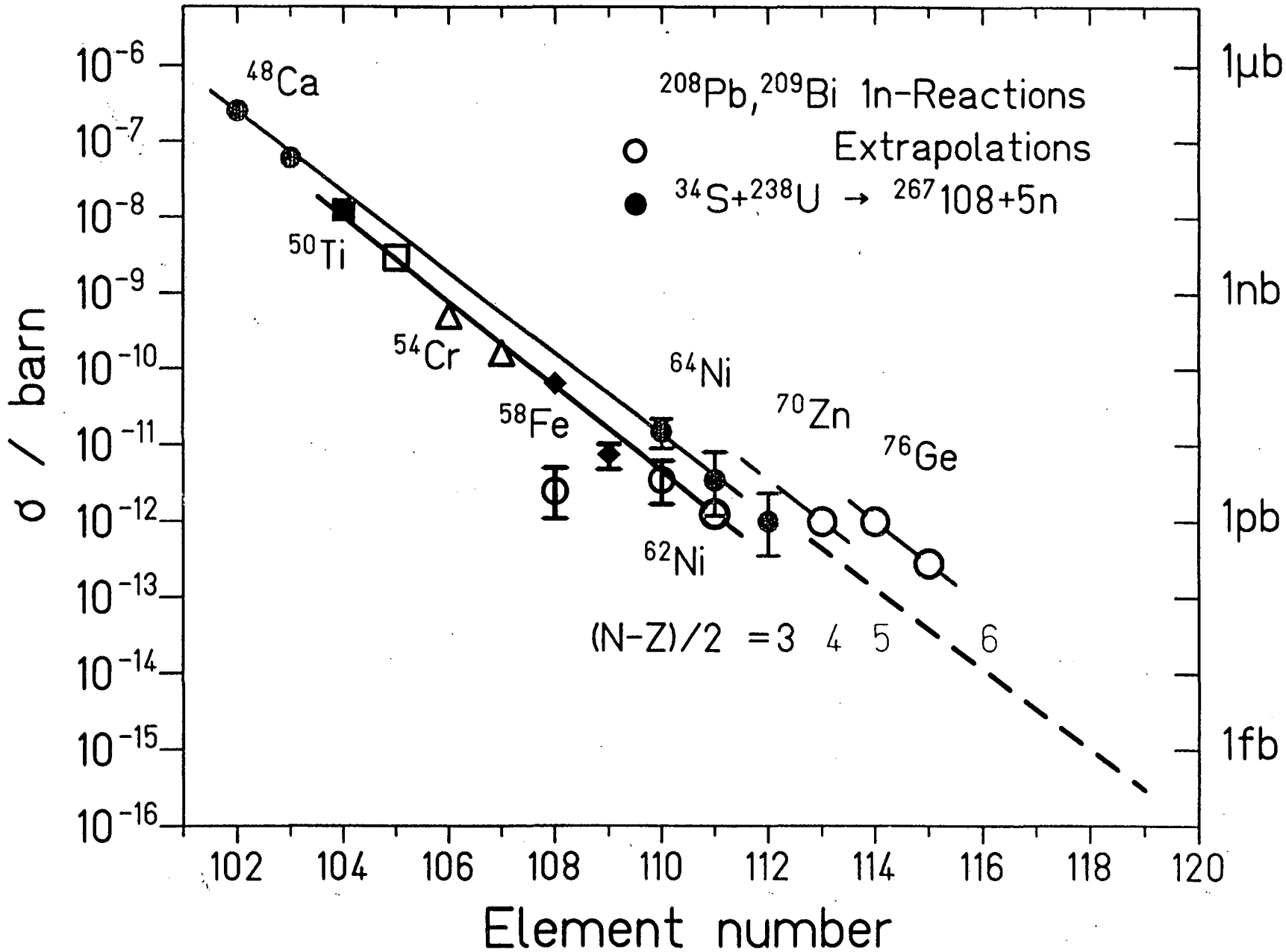
S. Cwiok et al. 1996



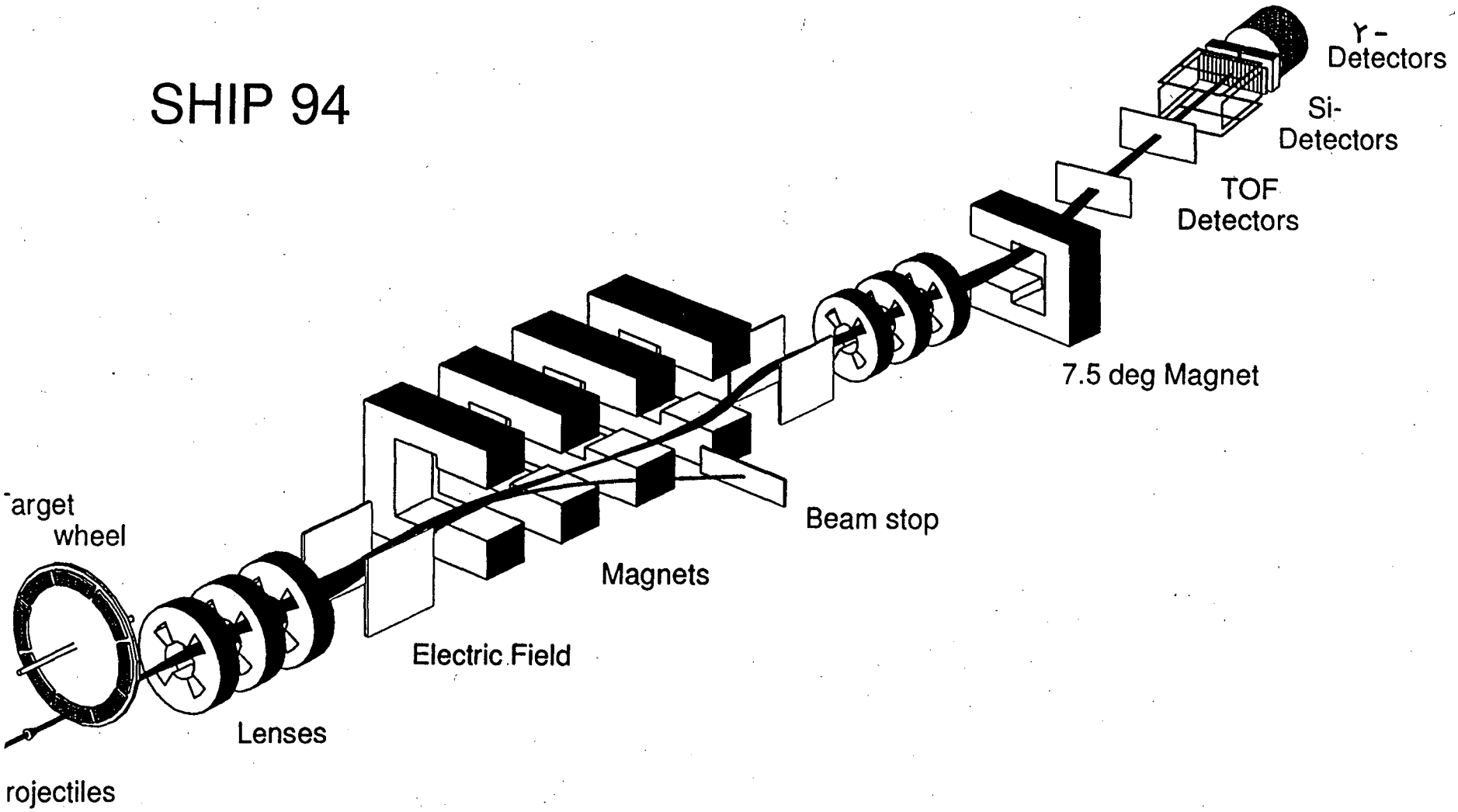
267/110: 3 μs
269/110: 170 μs
271/110: 1.1 ms
273/110: 76 μs
[illegible]
283/114
290/116

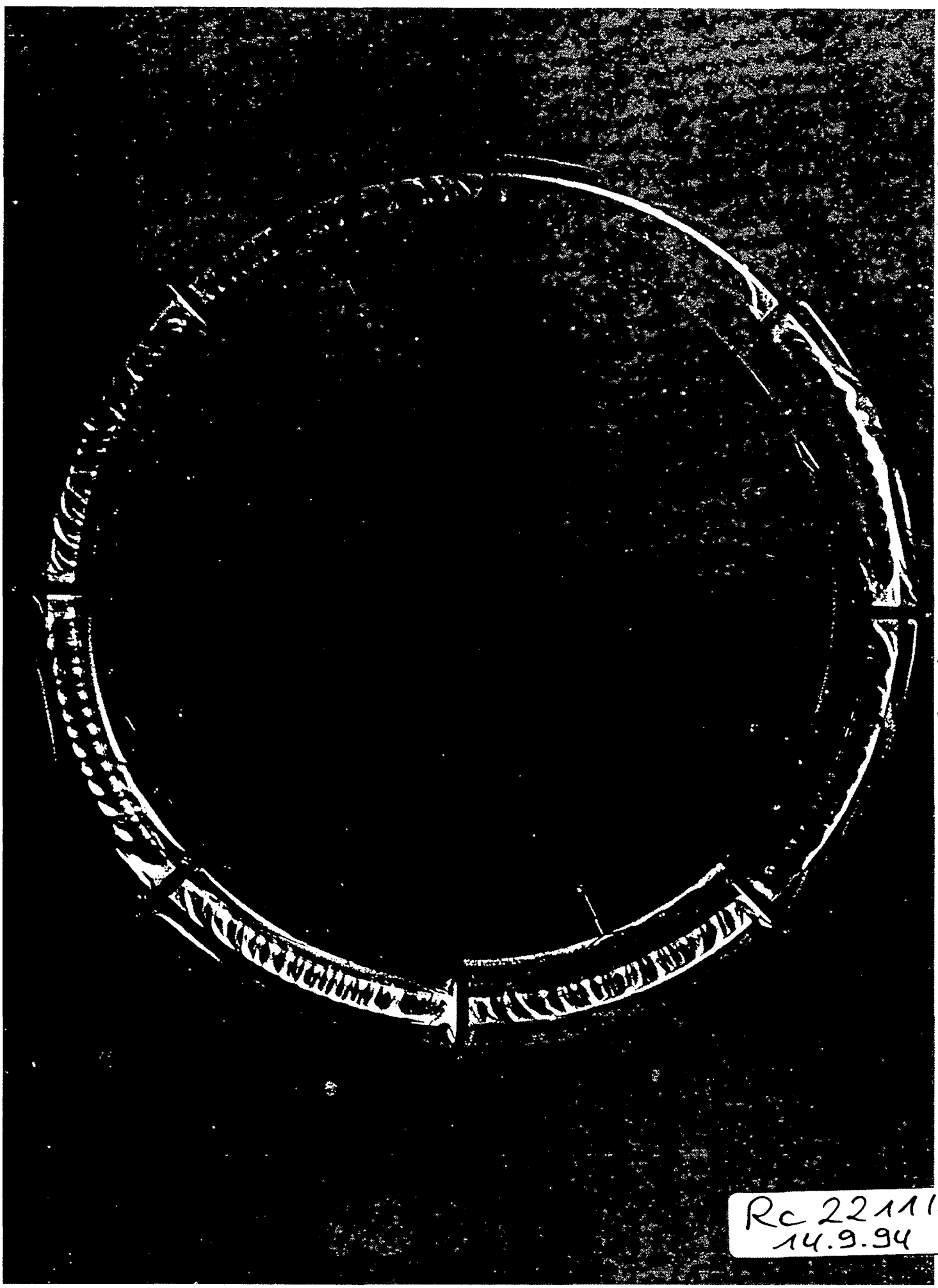
× heaviest isotopes Z = 118 to 128

beam: ^{86}Kr to ^{110}Pd


^{208}Pb,^{209}Bi 1n-Reactions
Extrapolations
^{34}S+^{238}U → ^{267}108+5n
^{48}Ca
^{50}Ti
^{54}Cr
^{58}Fe
^{62}Ni
^{64}Ni
^{70}Zn
^{76}Ge
(N-Z)/2 =3 4 5 6
σ / barn
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{-11}
10^{-12}
10^{-13}
10^{-14}
10^{-15}
10^{-16}
1μb
1nb
1pb
1fb
102 104 106 108 110 112 114 116 118 120
Element number

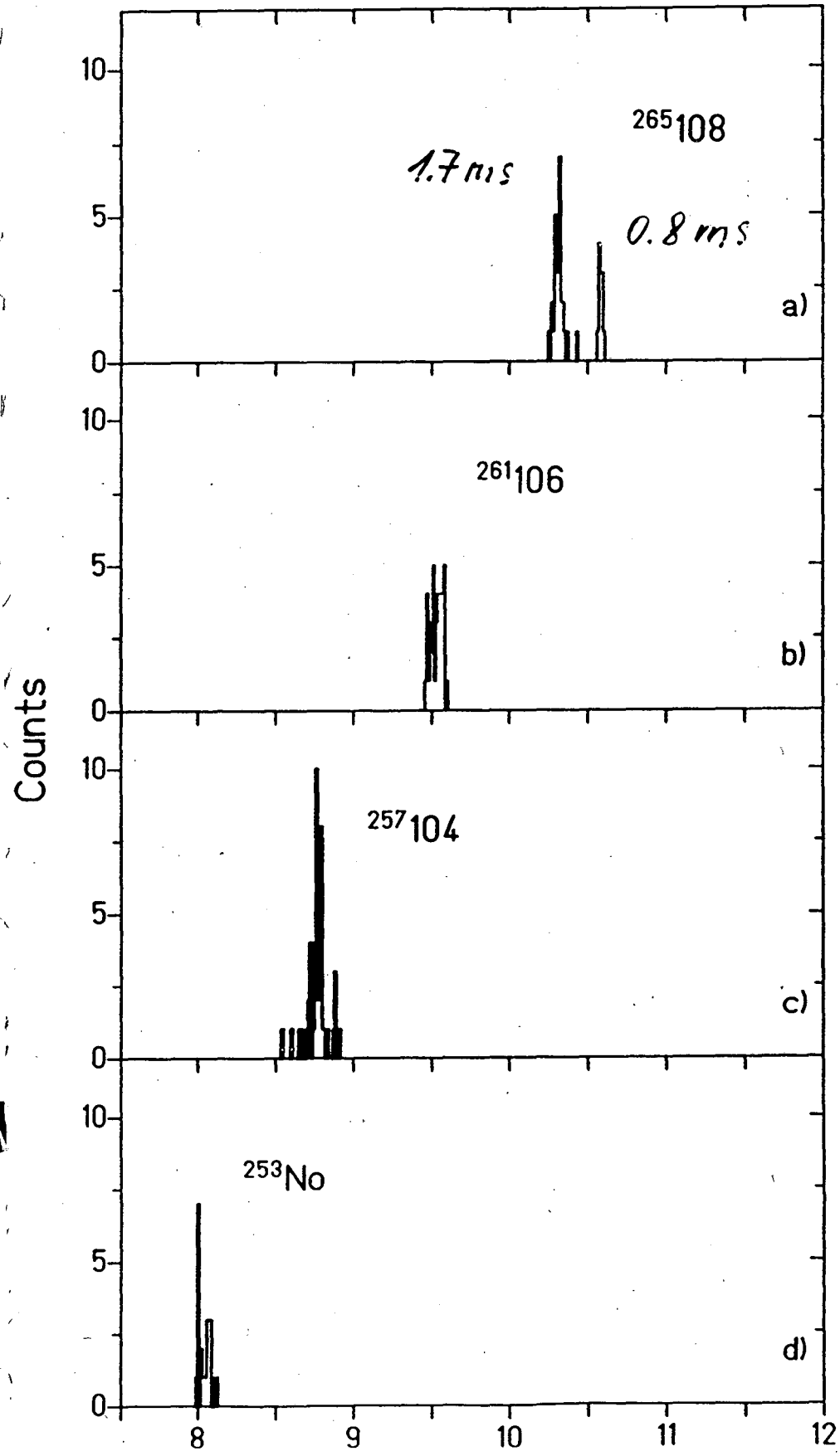
SHIP 94

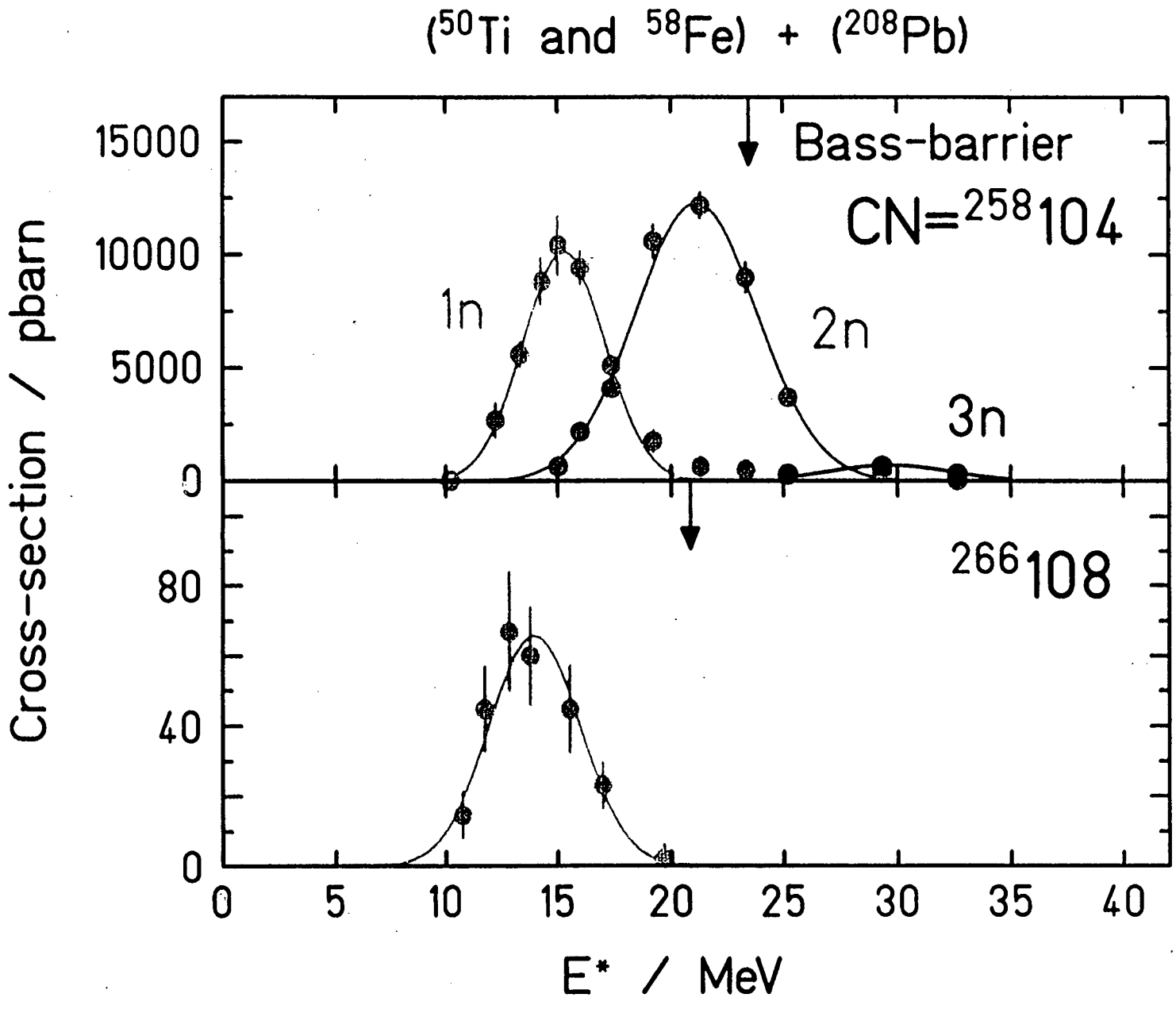

γ-
Detectors
Si-
Detectors
TOF
Detectors
7.5 deg Magnet
Beam stop
Magnets
Electric Field
Lenses
arget
wheel
rojectiles



Rc 22111
14.9.94

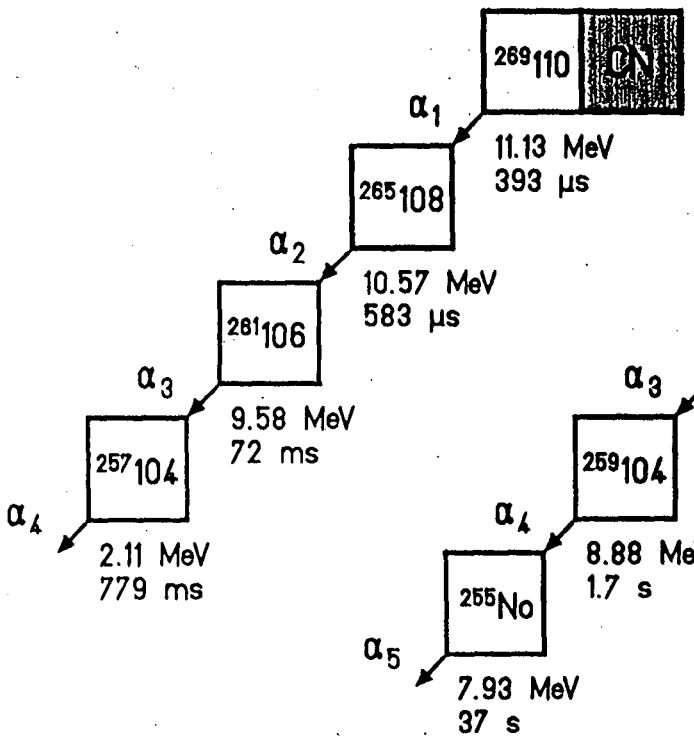
α-α correlated particles for $^{208}Pb(^{58}Fe,1n)^{265}108$




(^{50}Ti and ^{58}Fe) + (^{208}Pb)
Bass-barrier
CN=^{258}104
1n
2n
3n
^{266}108
Cross-section / pbarn
15000
10000
5000
0
80
40
0
0
5
10
15
20
25
30
35
40
E* / MeV

4 events
3.5 pb

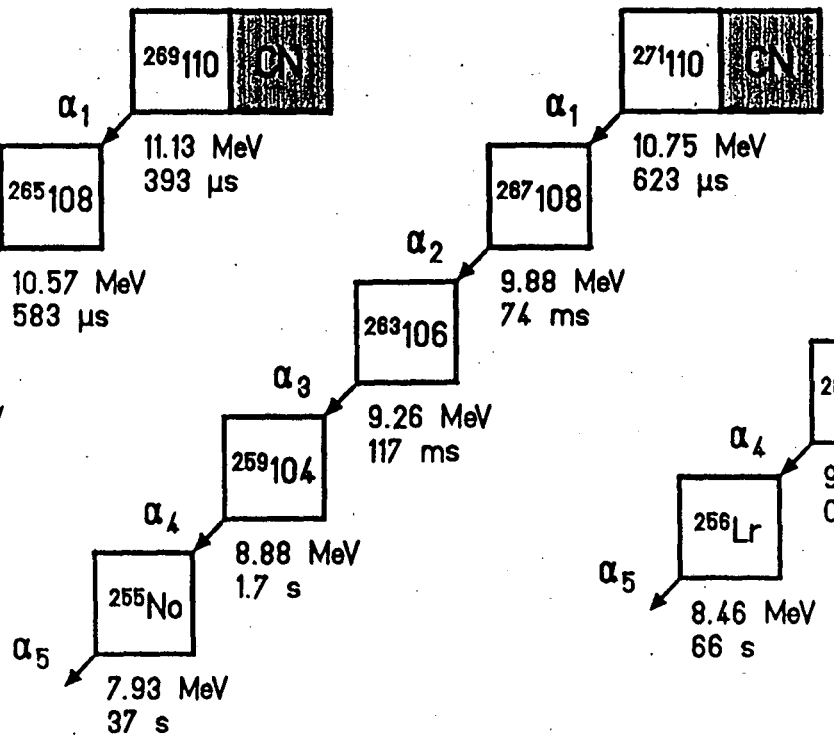
$^{62}Ni + ^{208}Pb \rightarrow ^{269}110 + 1n$



Date: 09-Nov-1994
Time: 16:39 h

9 events
15 pb

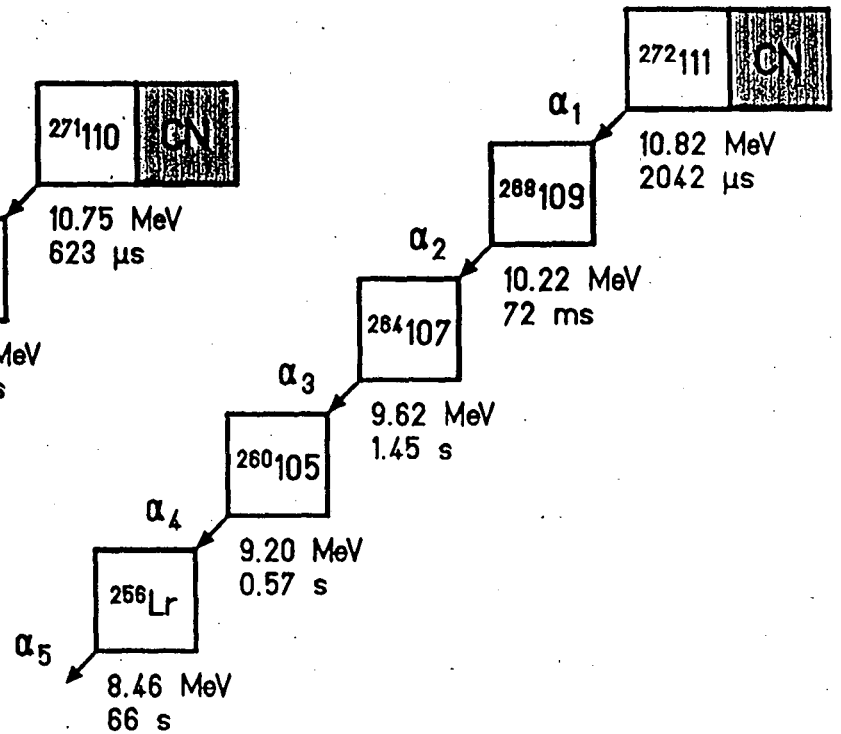
$^{64}Ni + ^{208}Pb \rightarrow ^{271}110 + 1n$



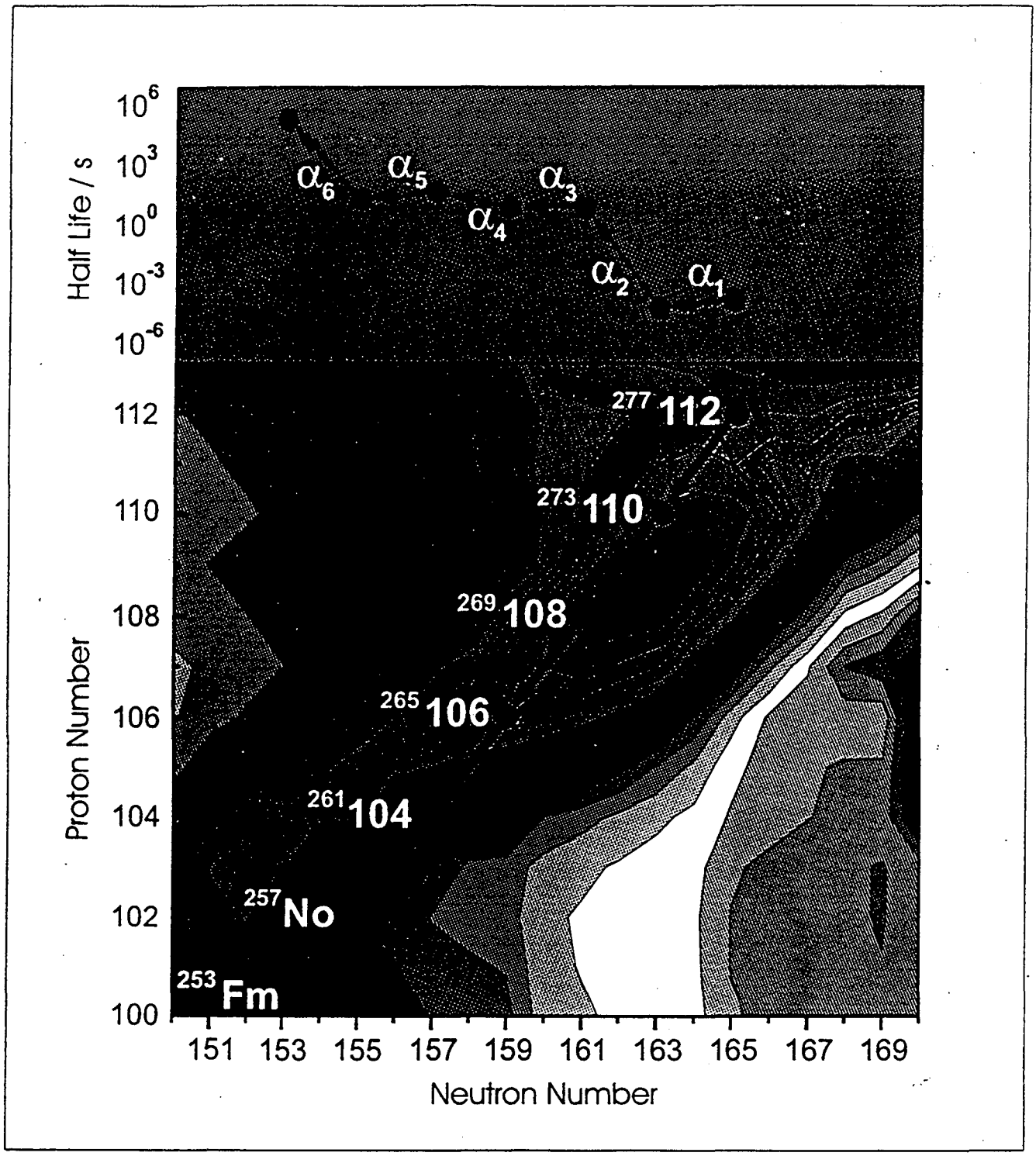
Date: 19-Dec-1994
Time: 05:13 h

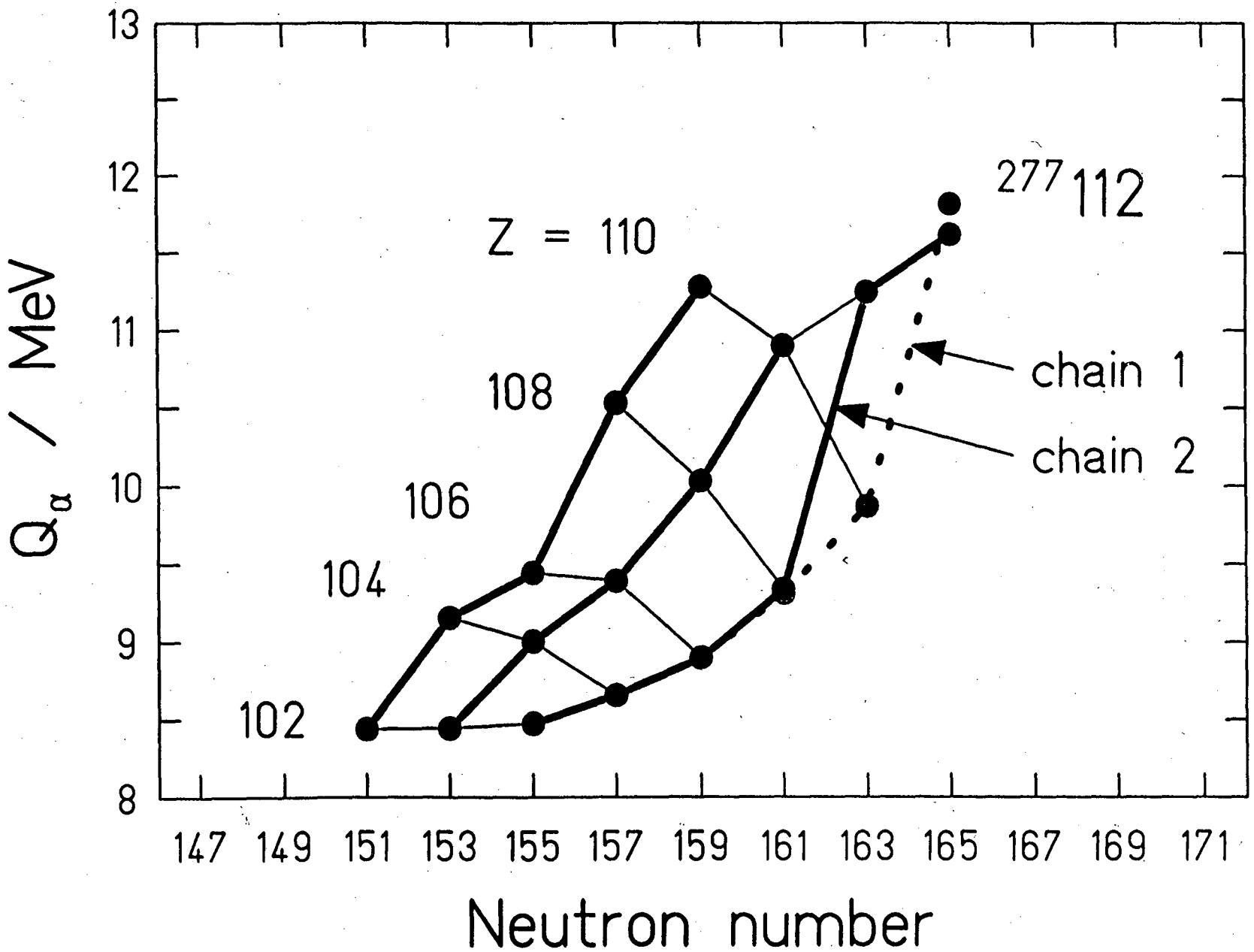
3 events
4 pb

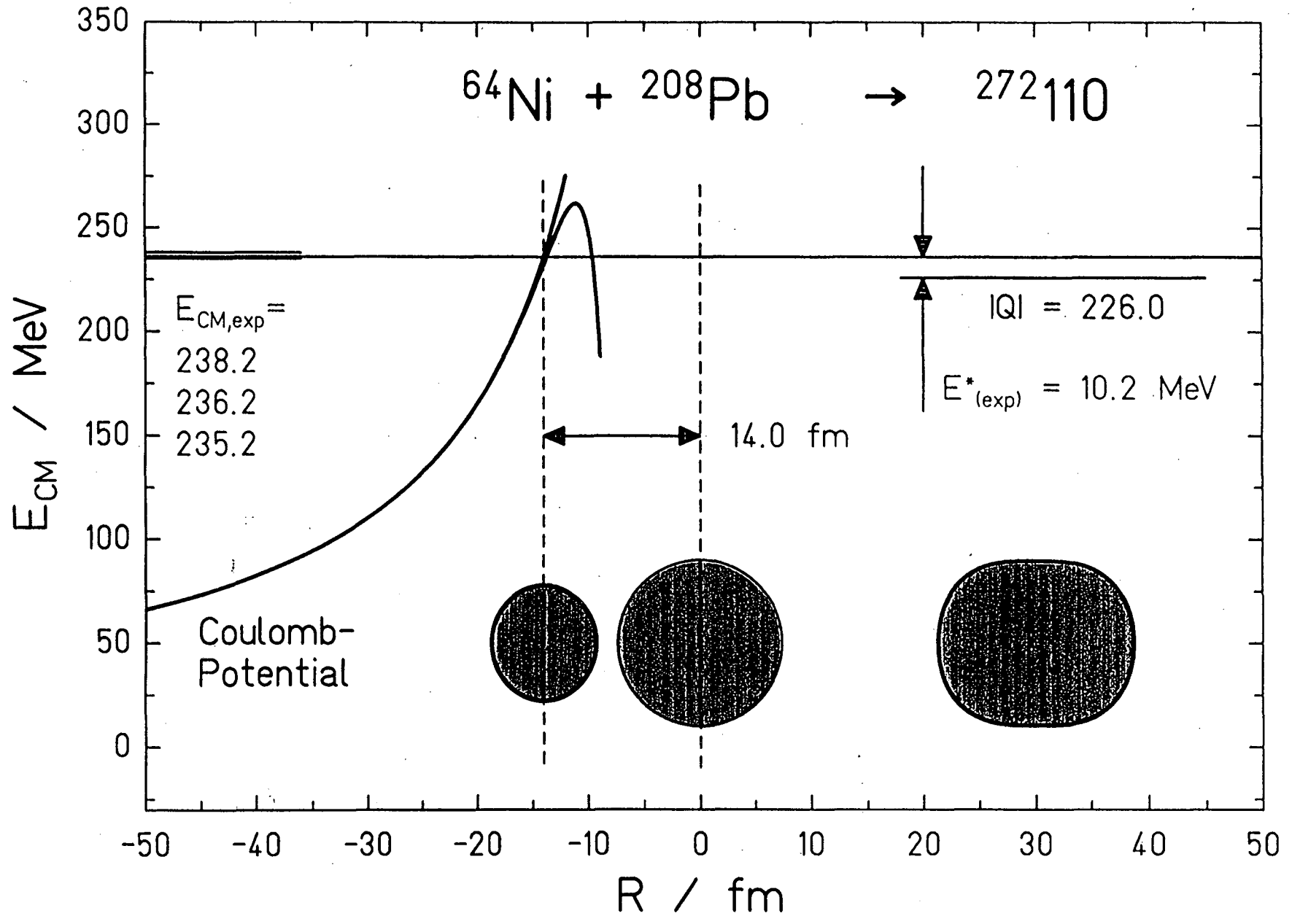
$^{64}Ni + ^{209}Bi \rightarrow ^{272}111 + 1n$



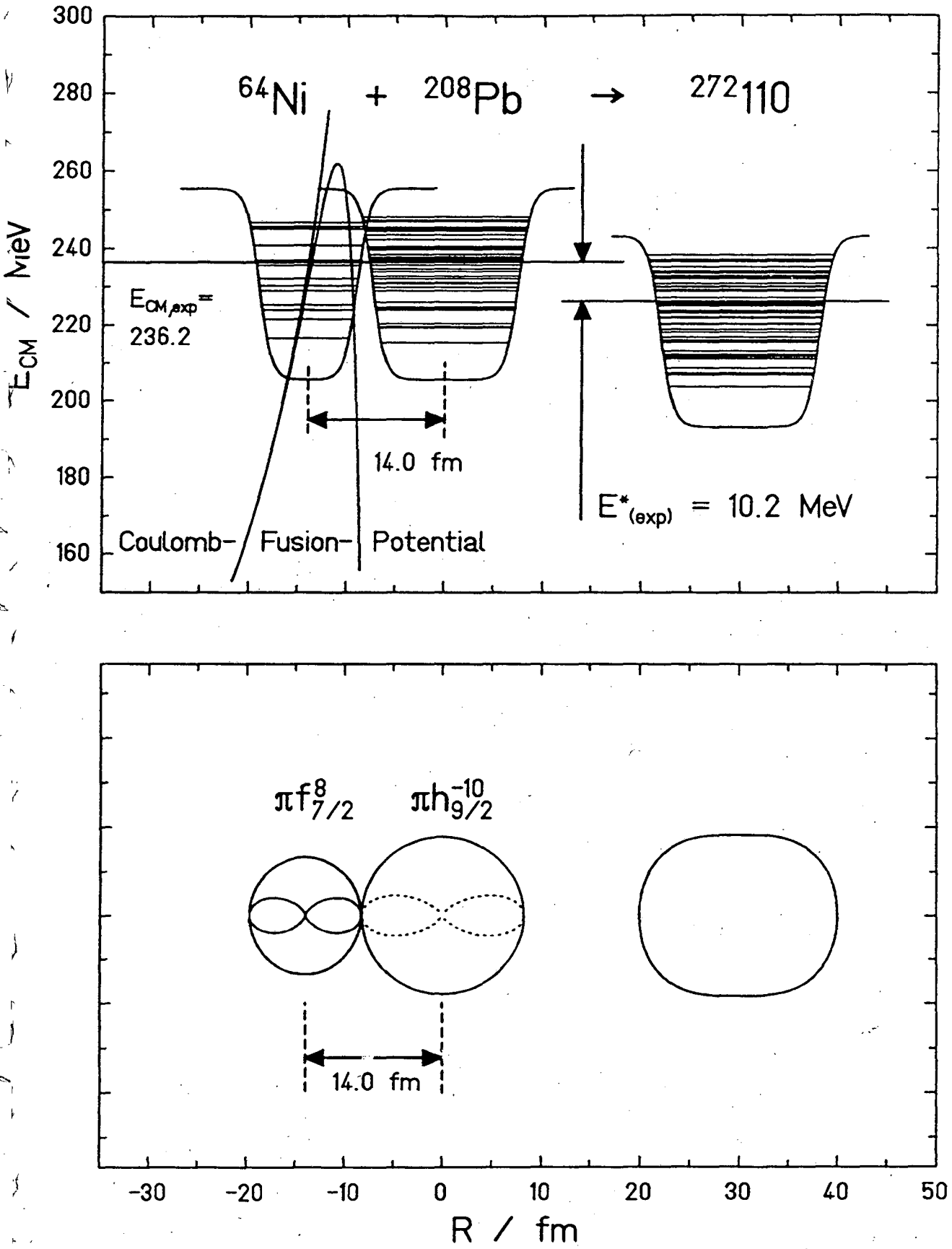
Date: 17-Dec-1994
Time: 06:03 h

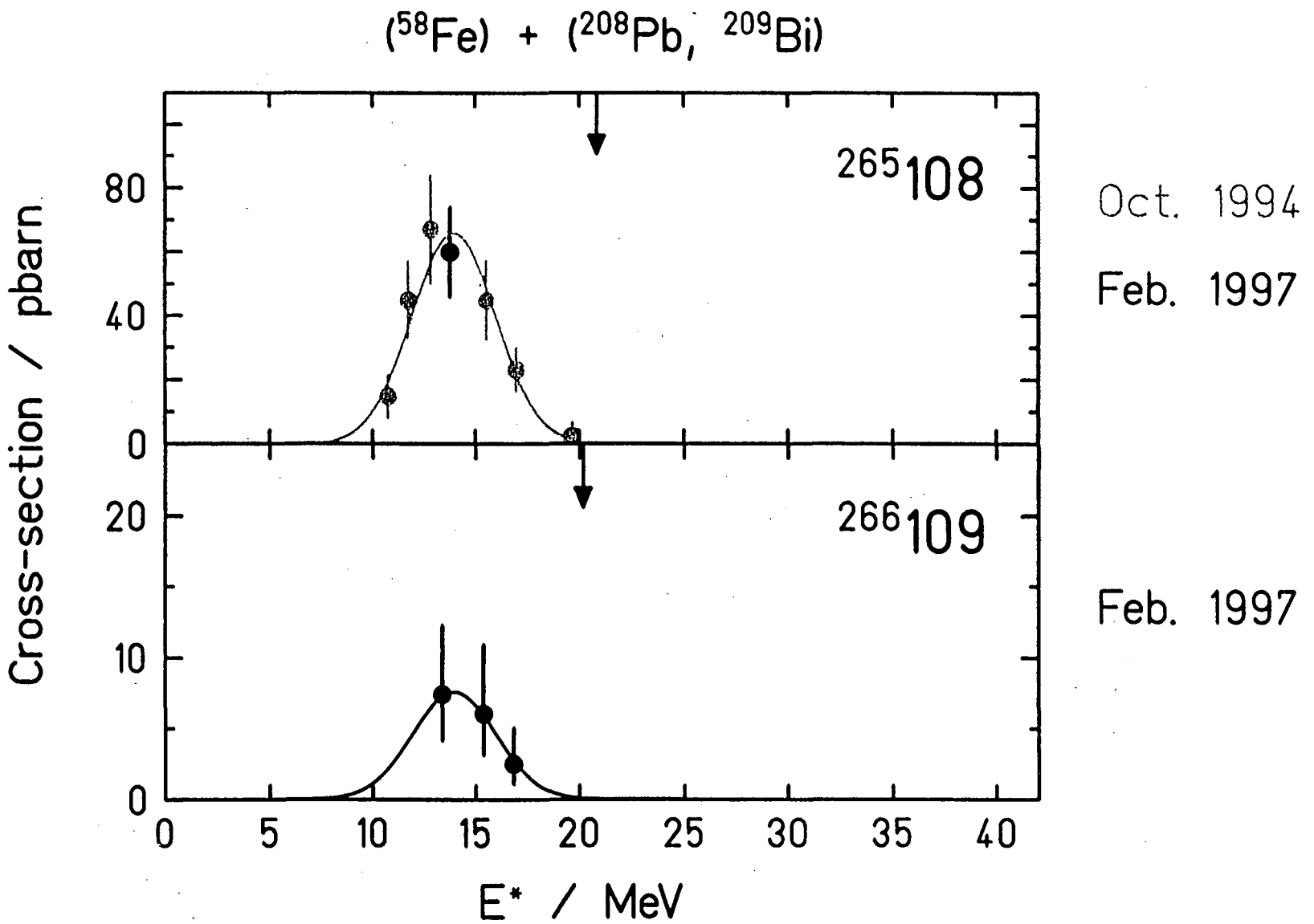

Half Life / s
10^6
10^3
10^0
10^{-3}
10^{-6}
α_6
α_5
α_4
α_3
α_2
α_1
Proton Number
112
110
108
106
104
102
100
^{277}112
^{273}110
^{269}108
^{265}106
^{261}104
^{257}No
^{253}Fm
151 153 155 157 159 161 163 165 167 169
Neutron Number


13
12
11
10
9
8
Q_α / MeV
147 149 151 153 155 157 159 161 163 165 167 169 171
Neutron number
Z = 110
108
106
104
102
^{277}112
chain 1
chain 2

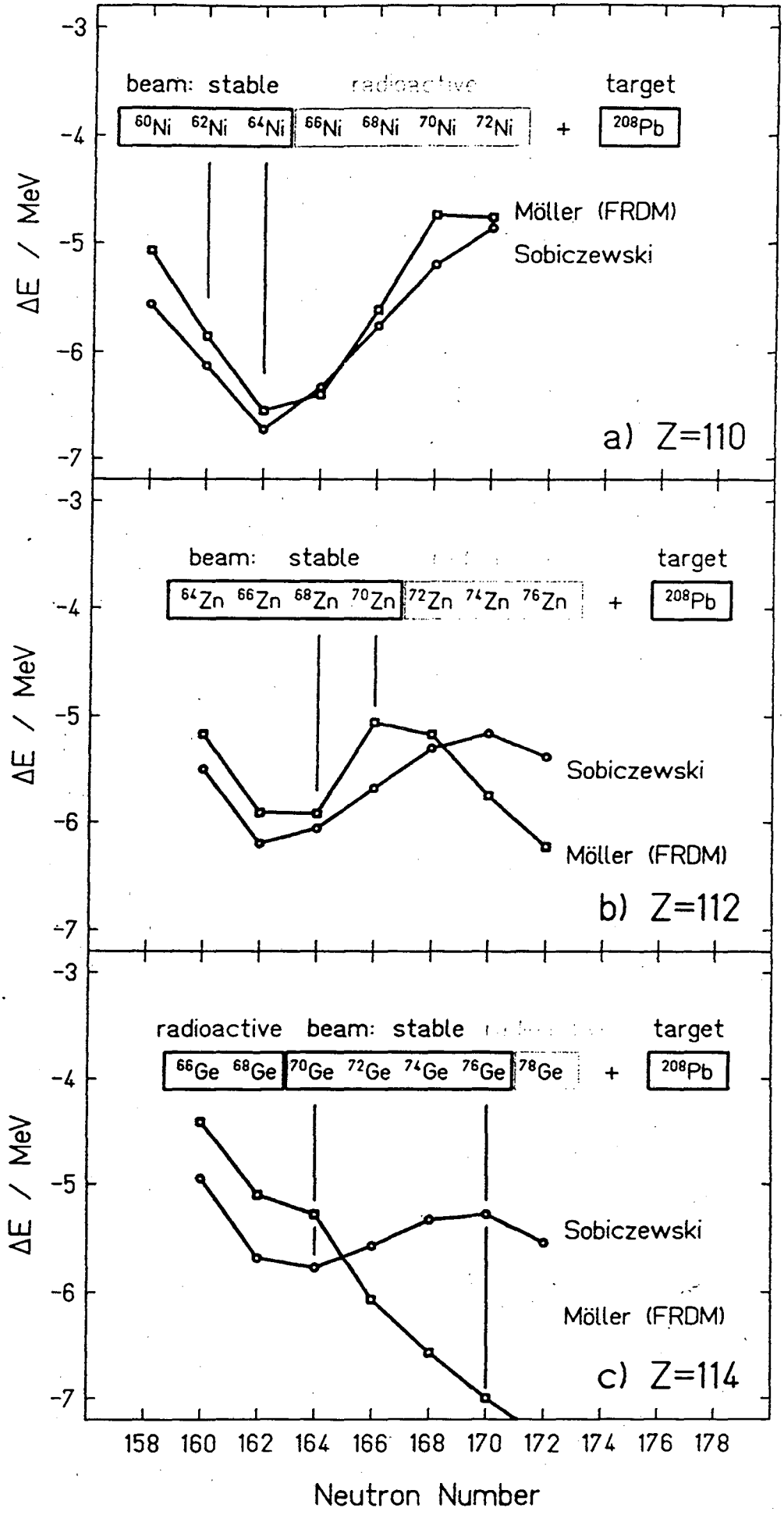

$^{64}Ni + ^{208}Pb \rightarrow ^{272}110$
$E_{CM,exp}$=
238.2
236.2
235.2
Coulomb-
Potential
14.0 fm
|Q| = 226.0
$E^*_{(exp)}$ = 10.2 MeV
E_{CM} / MeV
R / fm
350
300
250
200
150
100
50
0
-50
-40
-30
-20
-10
0
10
20
30
40
50

Fusion Initiated by Transfer (FIT)



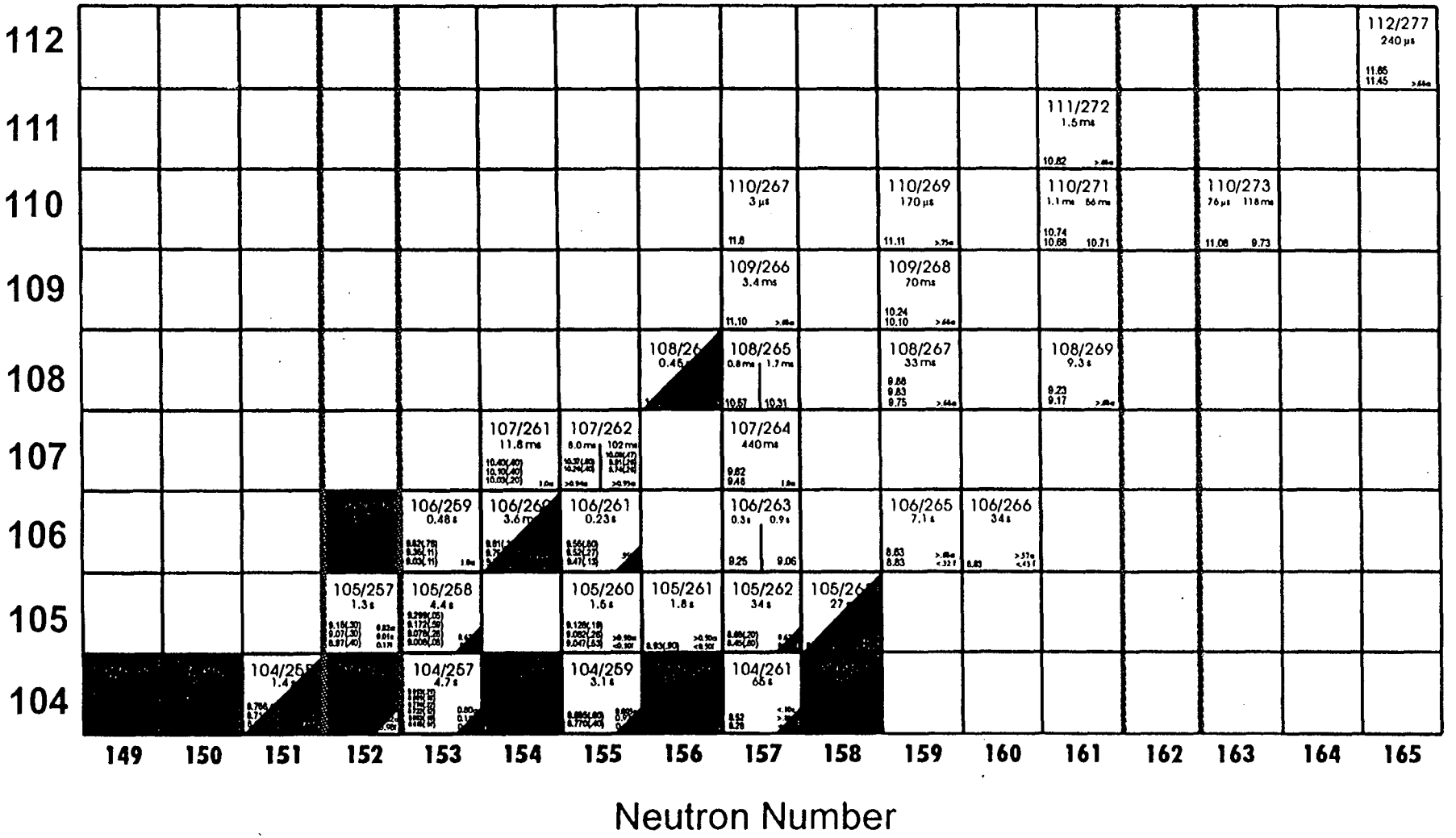

(^{58}Fe) + (^{208}Pb, ^{209}Bi)
^{265}108
Oct. 1994
Feb. 1997
^{266}109
Feb. 1997
Cross-section / pbarn
80
40
0
20
10
0
0
5
10
15
20
25
30
35
40
E* / MeV

Ground-State Shell-Correction Energies



IKC51.SGISHEBE110.Z100 IKC51.SGISHEBE112.Z100 IKC51.SGISHEBE114.Z100

CHART OF THE NUCLIDES 1996



Neutron Number

Participants

Peter Armbruster
Helmut Folger
Fritz-Peter Heßberger
Sigurd Hofmann
Rudo Janik
Matti Leino
Gottfried Münzenberg
Viktor Ninov
Andre Popeko
Stefan Saro
Hans-Jochen Schött
Christelle Stodel
Alexander Yeremin

Institutes:

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JINR Dubna
University Bratislava
University Jyväskylä

Matthias Schädel
GSI

M Schädel

HOT FUSION: RESULTS AND PROSPECTS

- HOT FUSION IN HEAVY ELEMENT RESEARCH -

Matthias Schädel, GSI, Darmstadt

Regions of Interest - Paths to enter

"Cold -" vs. "Hot - Fusion"

- borderline or transition region
  - characteristica
    - differences
      - regions of nuclei
        - σ (Z) - dependence

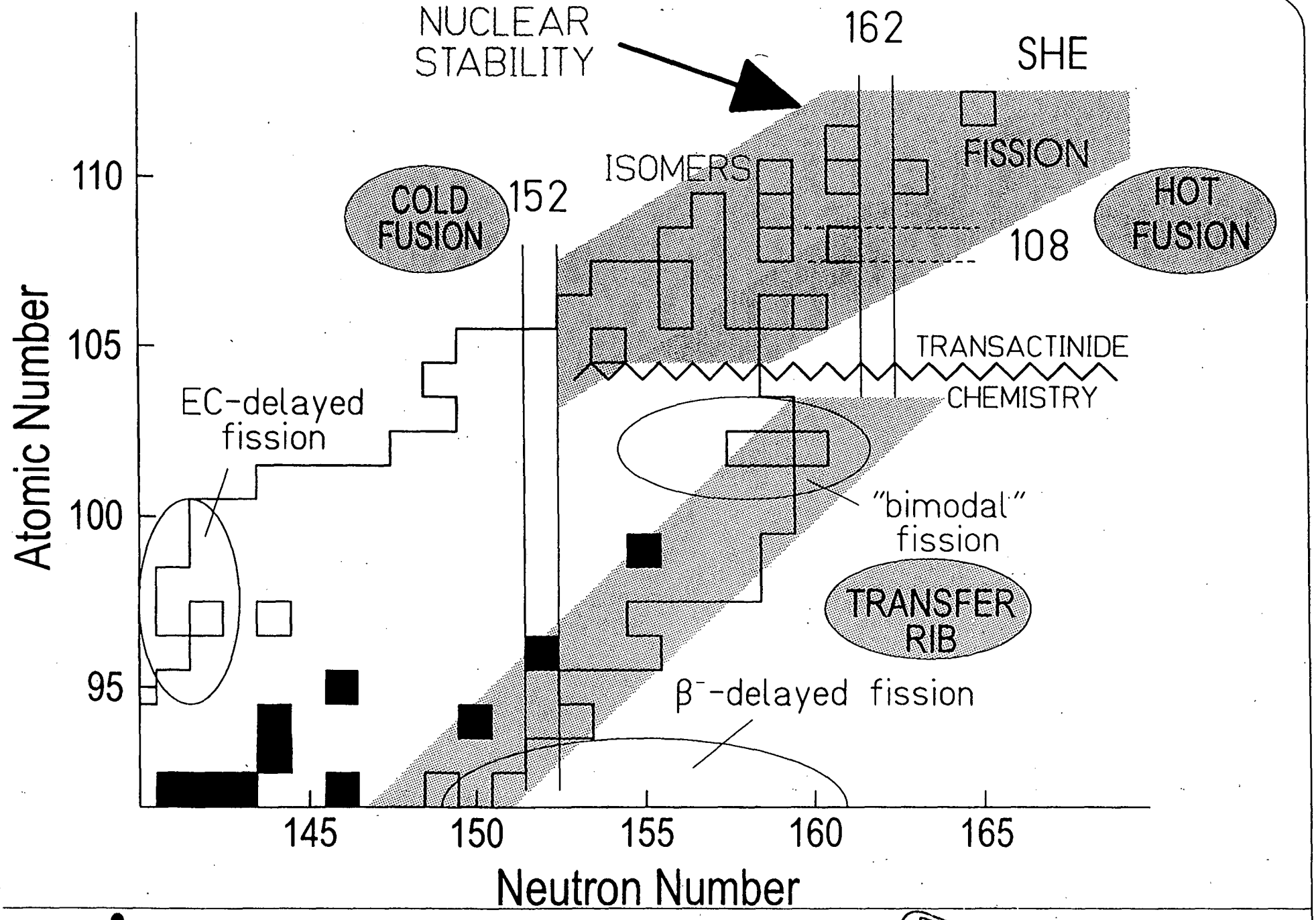
Important Special Aspects

- Γ_n/Γ_f
  - fission times
    - pre - equilibrium particle emission

Alternative Approaches

- (αxn) - reactions

Workshop on Gas - Filled Separators, Berkeley, April 10-12, 1997


NUCLEAR STABILITY
162
SHE
FISSION
ISOMERS
COLD FUSION
152
108
HOT FUSION
TRANSACTINIDE CHEMISTRY
EC-delayed fission
"bimodal" fission
TRANSFER RIB
β⁻-delayed fission
Atomic Number
110
105
100
95
145
150
155
160
165
Neutron Number

FUSION

"hot"

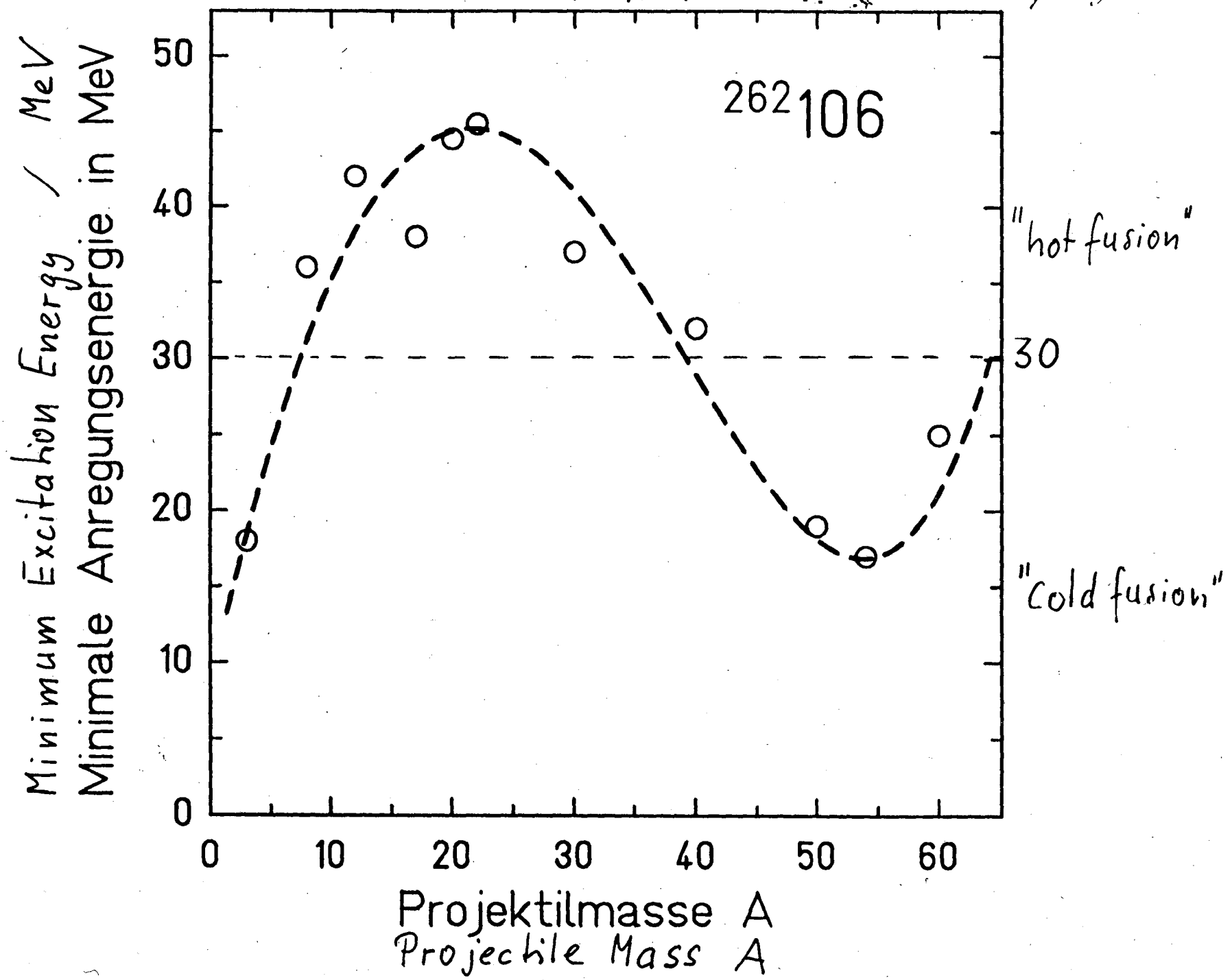
$^{232}_{90}Th$ ..... $^{254}_{99}Es$ + $^{13}_{6}C$ ..... $^{48}_{20}Ca$ → S

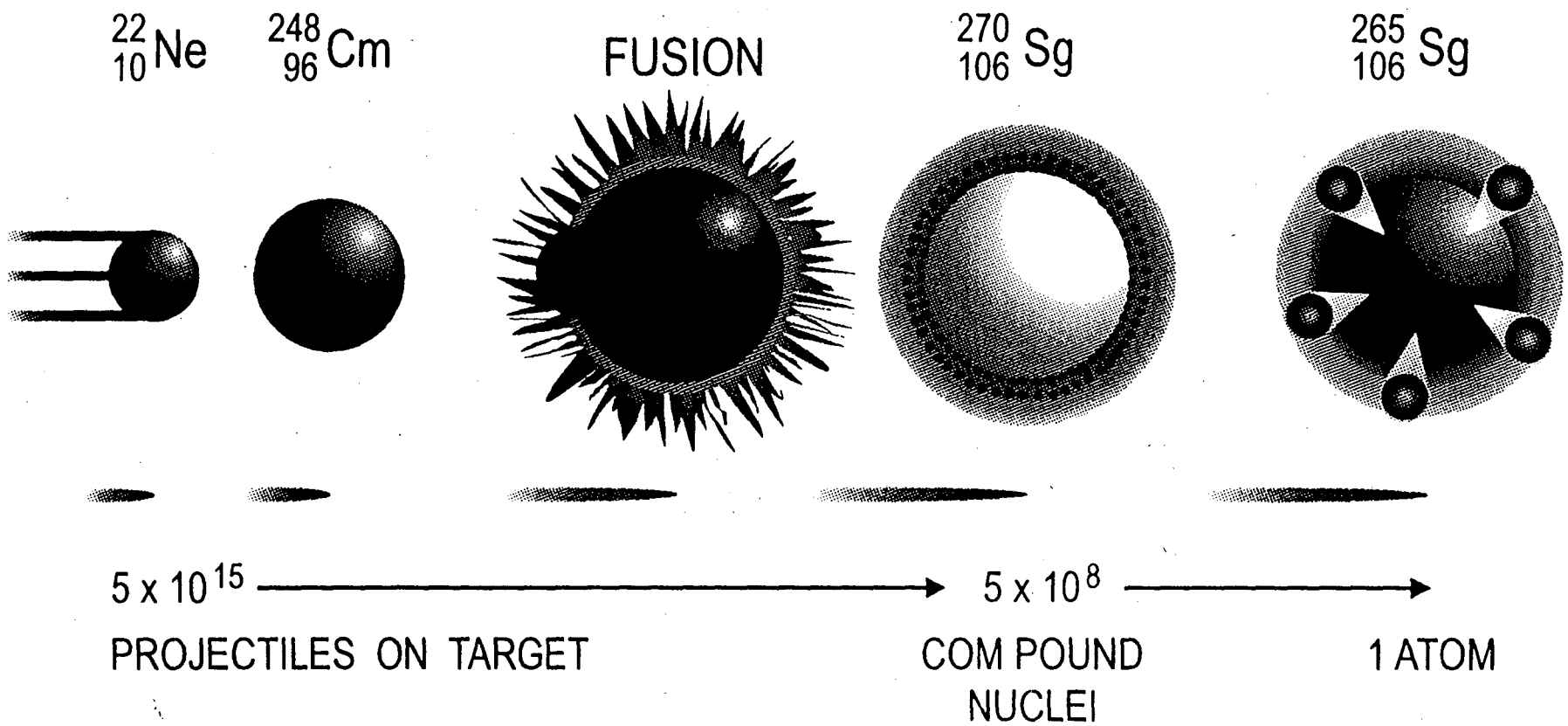
"cold"

$^{208}_{82}Pb$, $^{209}_{83}Bi$ + $^{50}_{22}Ti$ ..... $^{86}_{36}Kr$ → H

"alternative"

$^{154}_{62}Sm$ ..... $^{160}_{64}Gd$ → E


Minimum Excitation Energy / MeV
Minimale Anregungsenergie in MeV
$^{262}106$
"hot fusion"
30
"Cold fusion"
0
10
20
30
40
50
0
10
20
30
40
50
60
Projektilmasse A
Projectile Mass A


$^{22}_{10}$Ne
$^{248}_{96}$Cm
FUSION
$^{270}_{106}$Sg
$^{265}_{106}$Sg
5×10^{15}
5×10^{8}
PROJECTILES ON TARGET
COM POUND NUCLEI
1 ATOM

Do we understand "HOT FUSION"?

I. Semi-empirical approaches (educated guesses)

e.g., fusion-evaporation codes like HIVAP:

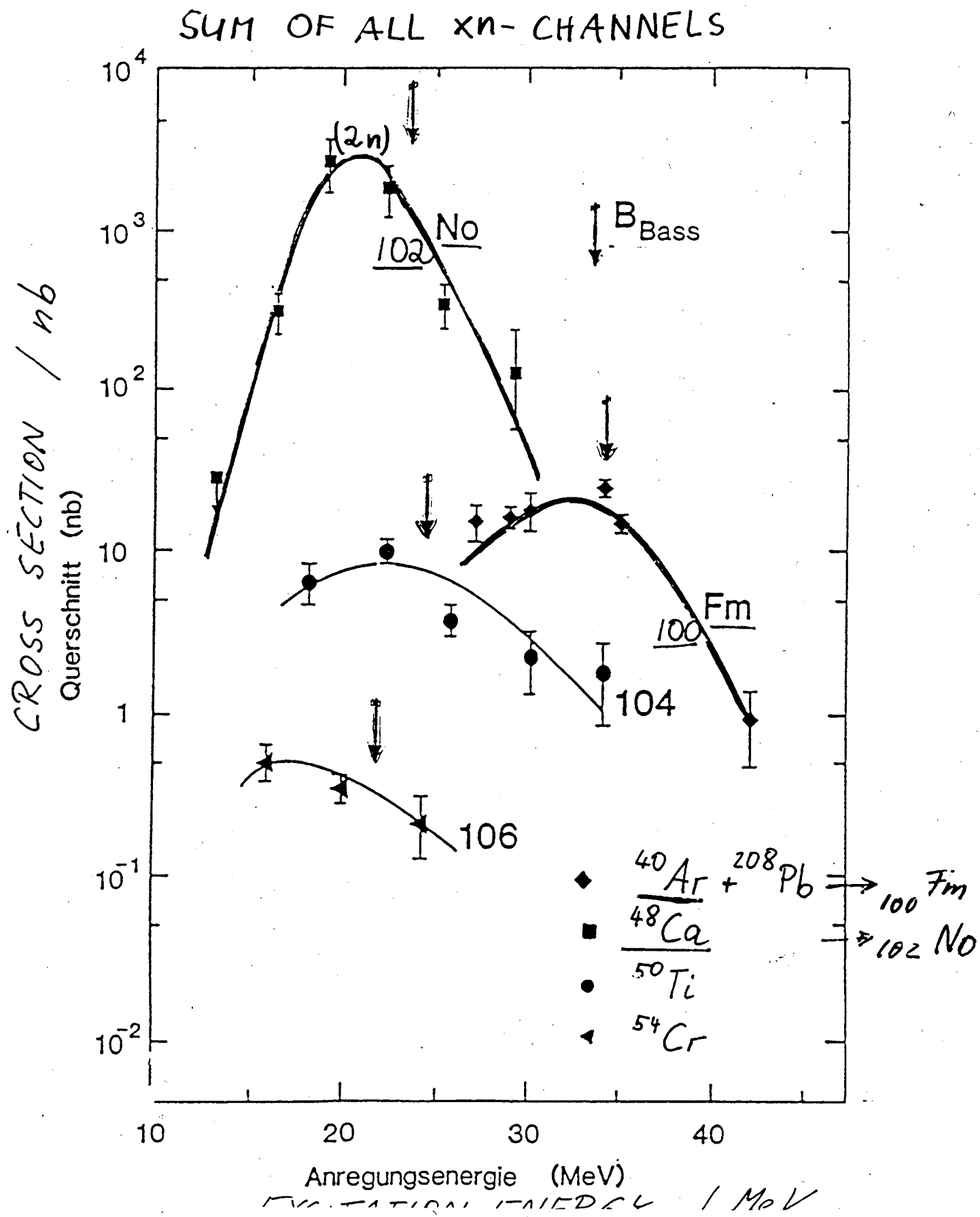
Parameters

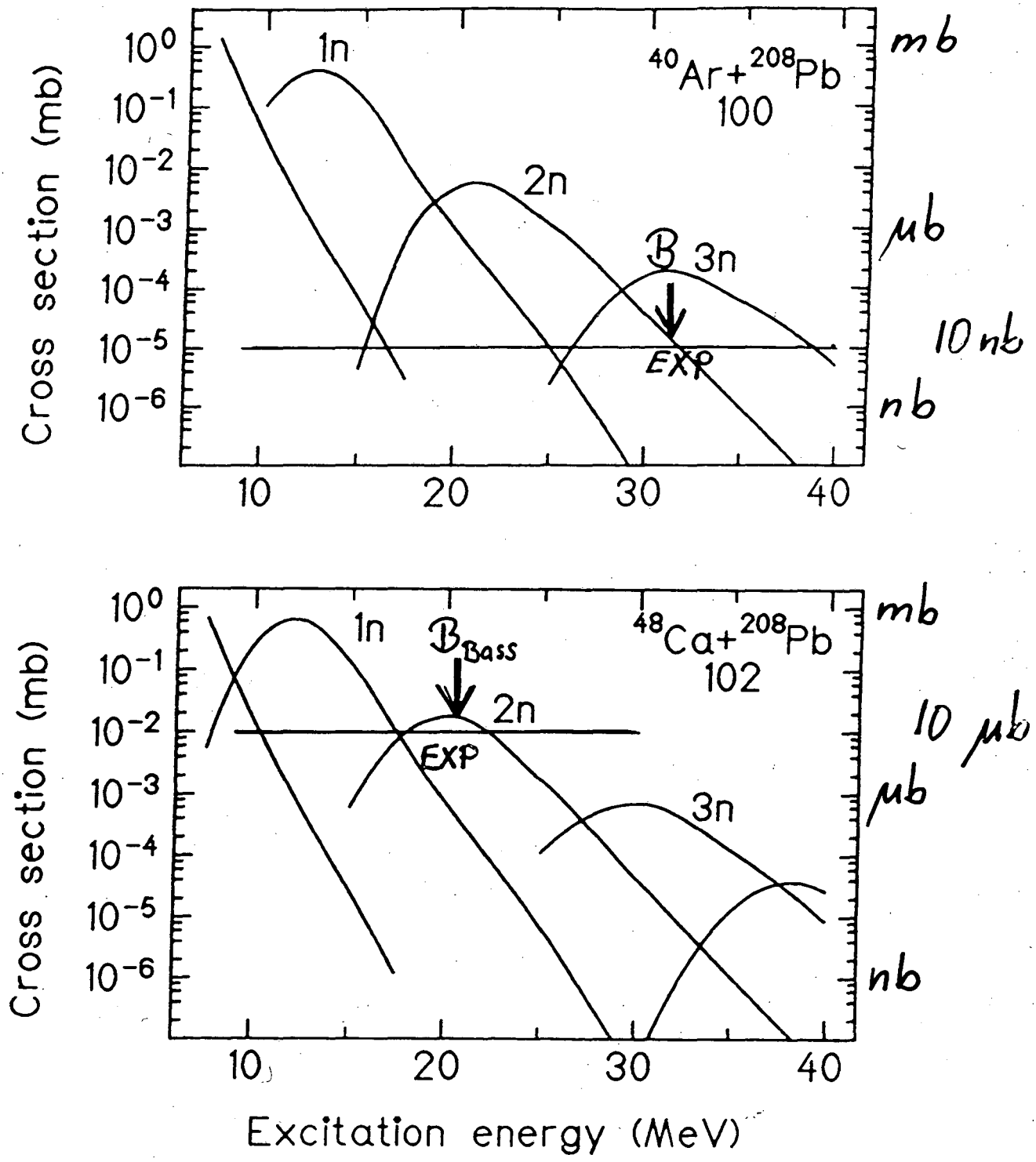
Masses	- particle separation energies
	- shell effects, $S = M_{exp} - M_{LD}$
Fission barriers	$B_f = B_{fLD} - S$
Level densities	$\rho(E, J) \approx \exp[2(aE_J)^{1/2}]$
	$a = \hat{a}[1 + f(E)S/E]$
	$f(E) = 1 - \exp(-E/E_d)$
Damping constant	$E_d = 18$ MeV

II. Empirical descripitions

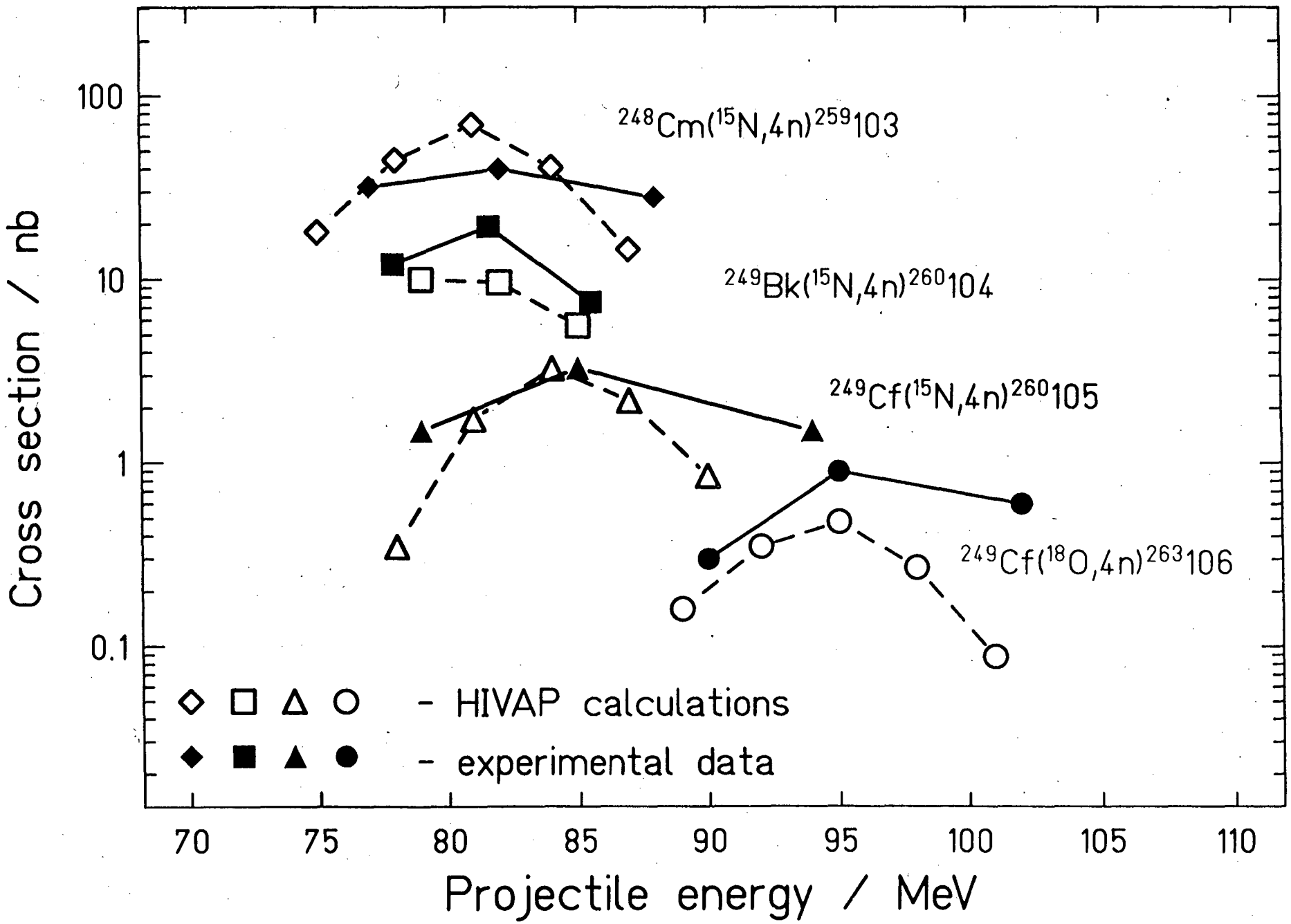
$\Longrightarrow$ No! We can describe it

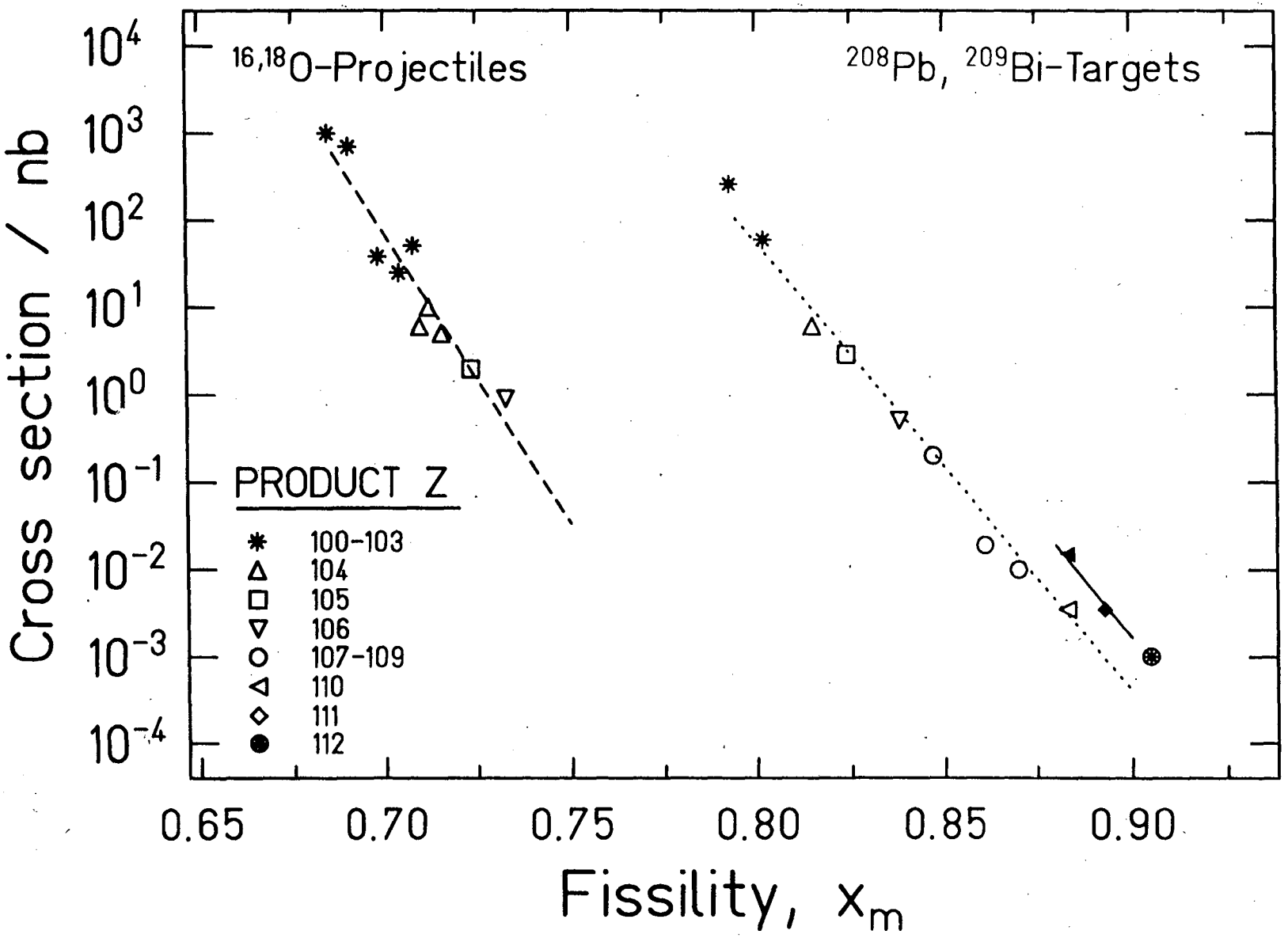
from H.W. Gäggeler '88





—— HIVAP "without" fusion barrier


Cross section / nb
100
10
1
0.1
$^{248}Cm(^{15}N,4n)^{259}103$
$^{249}Bk(^{15}N,4n)^{260}104$
$^{249}Cf(^{15}N,4n)^{260}105$
$^{249}Cf(^{18}O,4n)^{263}106$
- HIVAP calculations
- experimental data
70
75
80
85
90
95
100
105
110
Projectile energy / MeV


16,18O-Projectiles
208Pb, 209Bi-Targets
PRODUCT Z
100-103
104
105
106
107-109
110
111
112
Cross section / nb
Fissility, xm
10^4
10^3
10^2
10^1
10^0
10^-1
10^-2
10^-3
10^-4
0.65
0.70
0.75
0.80
0.85
0.90

Cold – and Hot Fusion: Common Feature?!

Important,
i.e., mainly determining the σ(Z)-dependence,
is only the fission competition in the
evaporation of <u>the last neutron</u>.

"Second order " effects:

– fusion hindrance in cold fusion.
– fission competition in the evaporation
of the first neutrons in hot fusion.
($\Gamma_n/\Gamma_f \approx 0.5$)

BUT:

This is in contradiction to calculations
which indicate a strong influence of
fusion hindrance for Pb-based systems.

Fission Competition, Time Scales, and Pre-Equilibrium Reactions

A.N. Andreyev et al. Proceedings Taormina, 1994

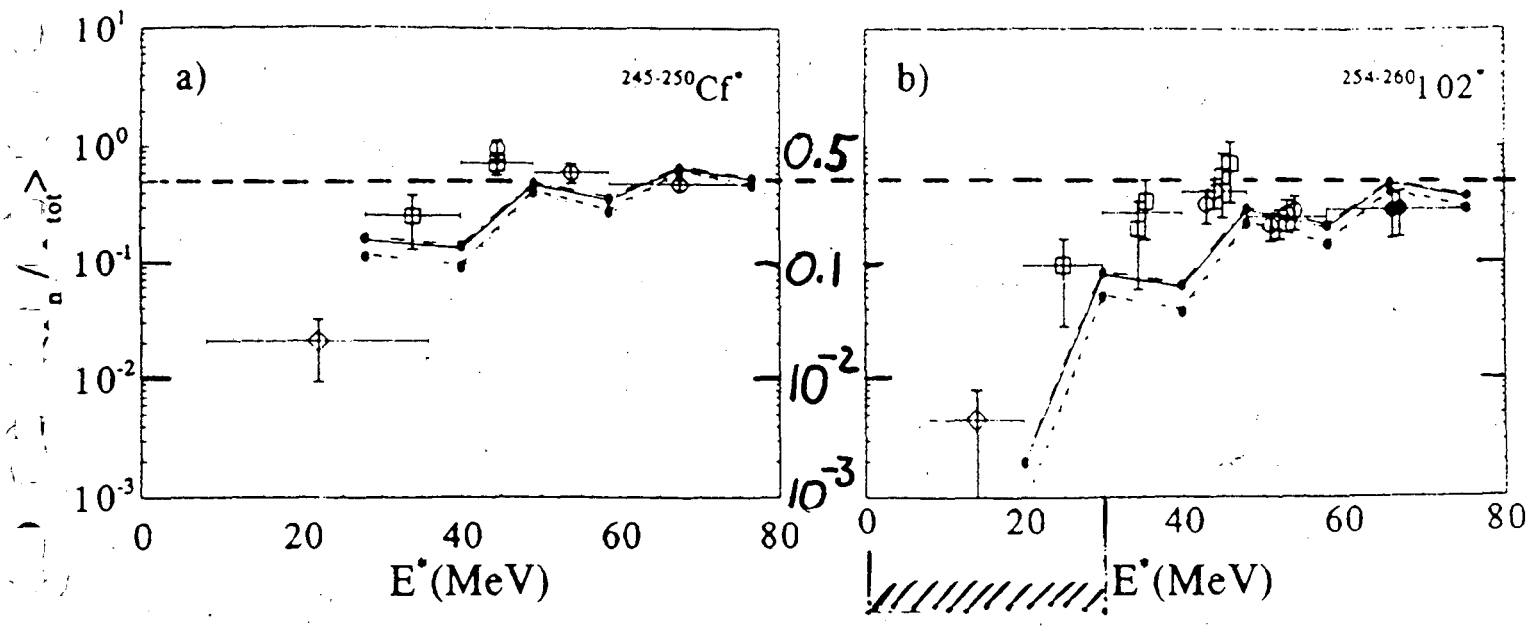
^{22}Ne, ^{26}Mg, ^{27}Al, ^{31}P on ^{232}Th, ^{236}U; ^{238}U(^{22}Ne,8n)^{252}No

"... conclude that ... the main losses in the yields of transcurium ER formed in heavy ion "hot" fusion reactions arise at the final steps of the deexcitation cascades."

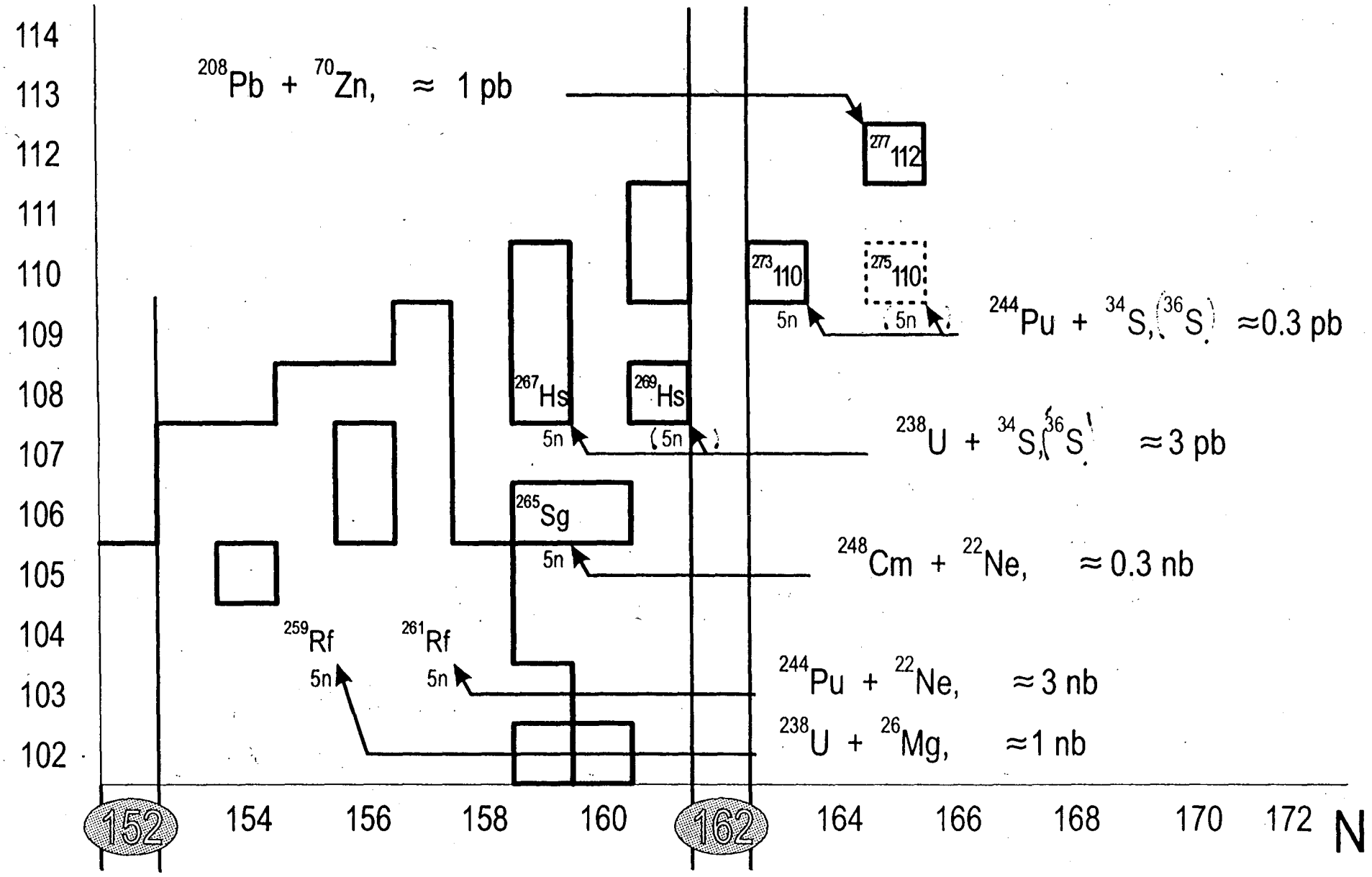
"... qualitative conclusion that fission does not play decisive role in their formation, at least, at the first step of the deexcitation process."

for evaporation of 6n, 7n, 8n (E* 40 MeV)
leading to ^{242}Cf, ^{248}Fm, ^{250}Md, ^{252}No: $\Gamma_n/\Gamma_{tot} \approx 0.5$!

i.e., 50 % survival probability for each step, or
"only" f = 10-20 loss for 4n-evaporation.

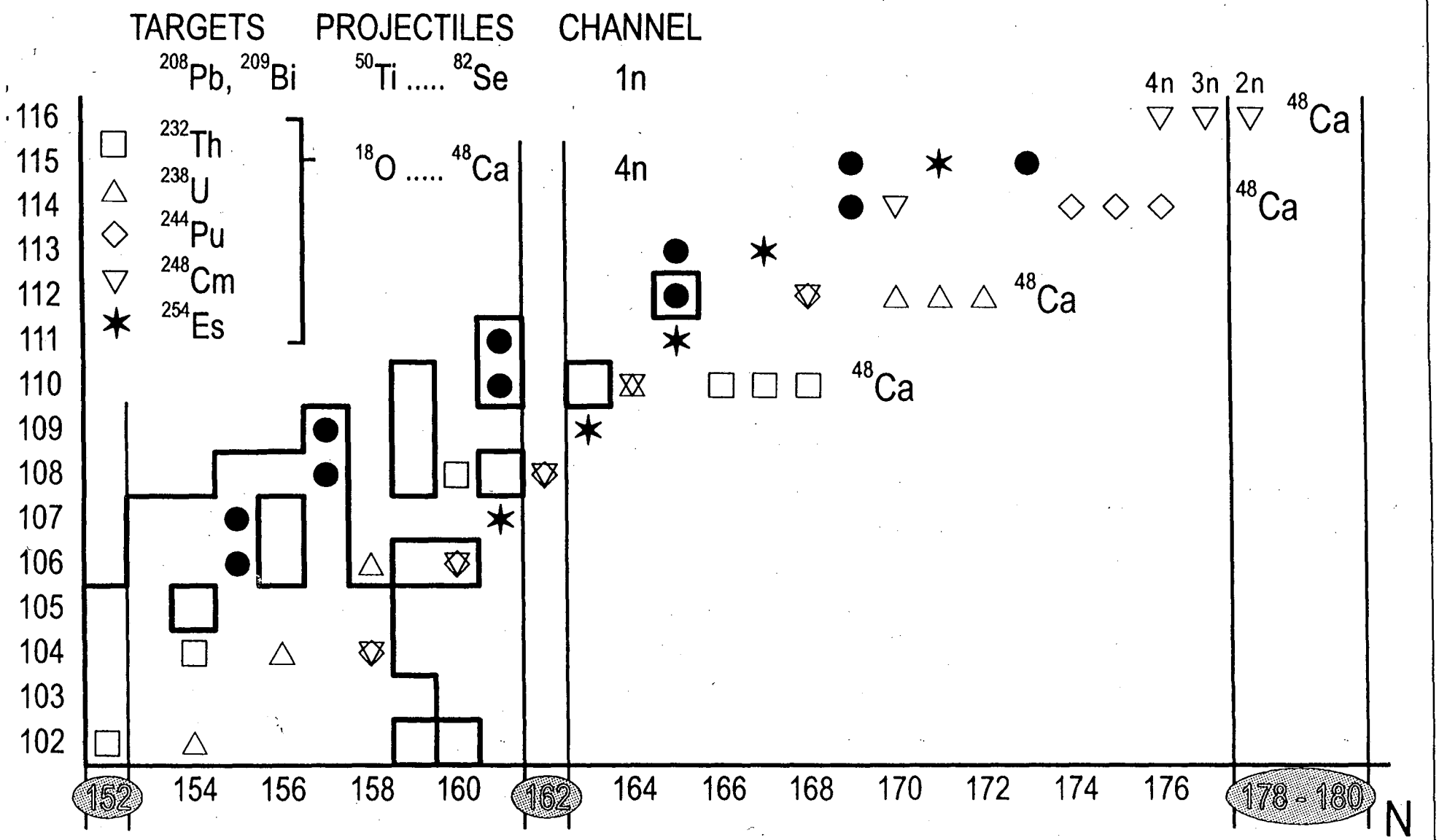


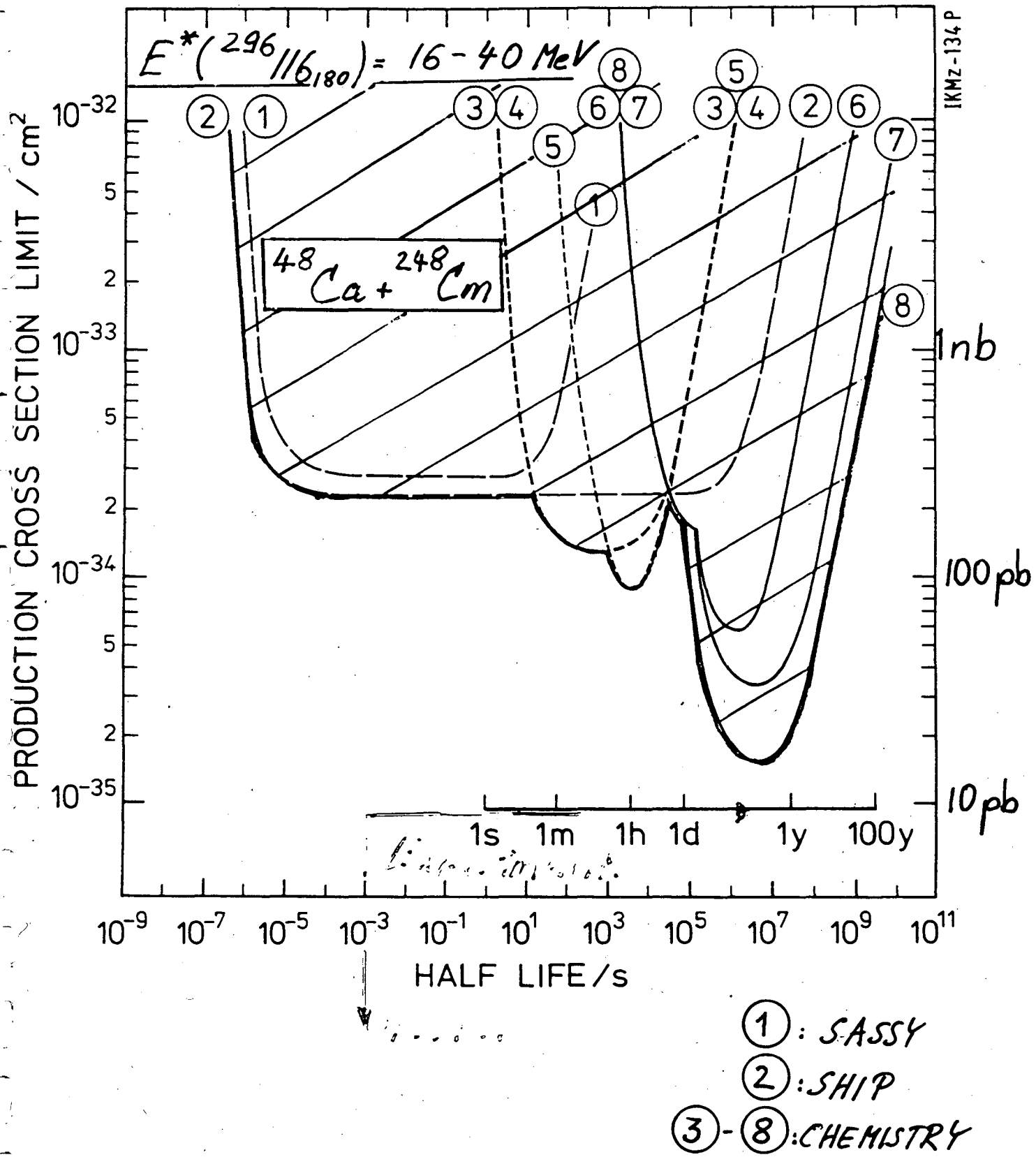
REGION OF CATASTROPHE



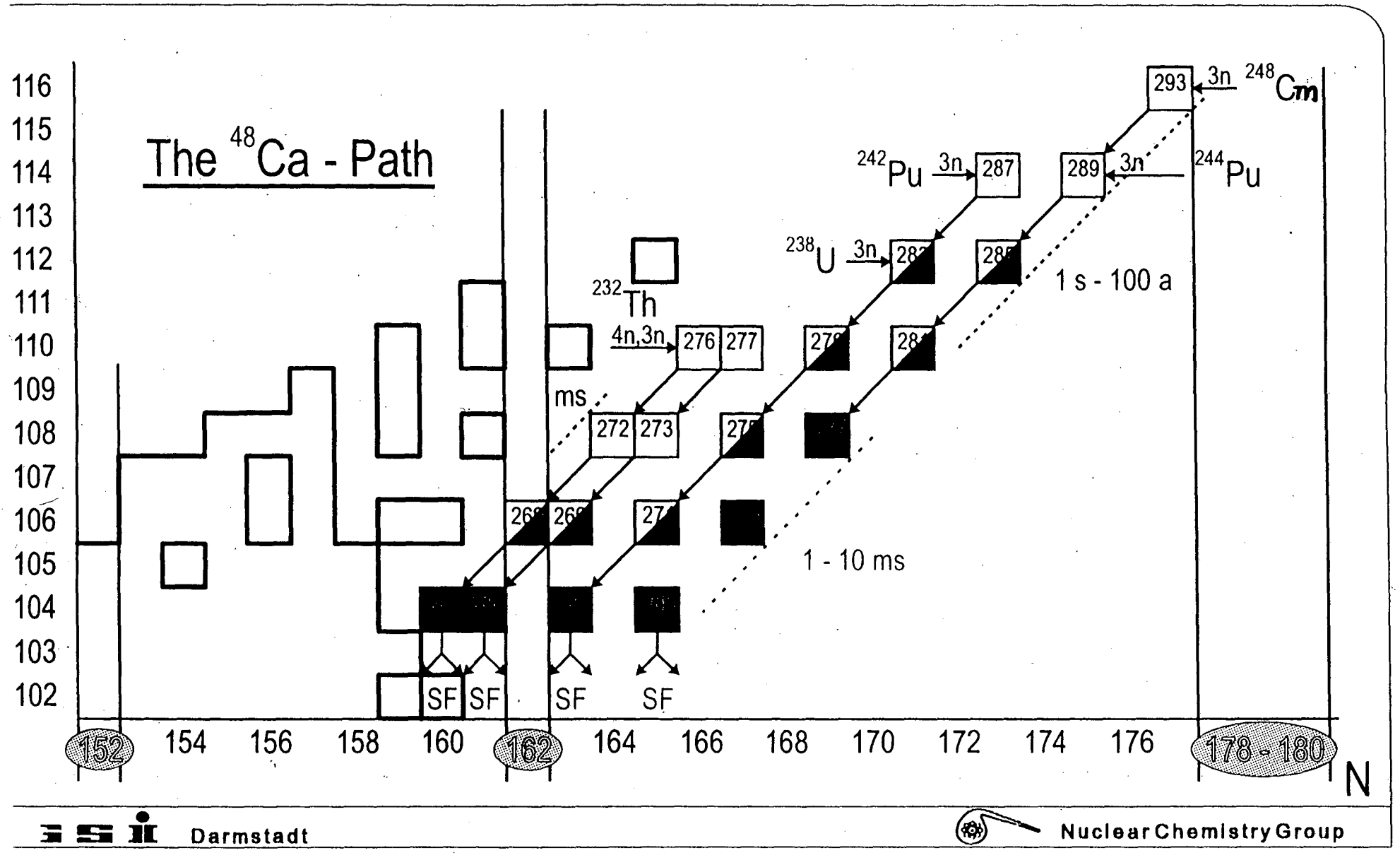
Yuri A. Lazarev, Hirschegg Proceedings 1996

EVAPORATION RESIDUES





P. Armbruster et al. Phys Rev. Lett 54 (1985) 406


The 48Ca - Path
116
115
114
113
112
111
110
109
108
107
106
105
104
103
102
293
3n
248Cm
242Pu
3n
287
289
3n
244Pu
238U
3n
232Th
4n,3n
276
277
272
273
ms
1 s - 100 a
1 - 10 ms
SF
SF
SF
SF
152
154
156
158
160
162
164
166
168
170
172
174
176
178 - 180
N

(αxn)–REACTIONS

H.C. Britt and A.R. Quinton, Phys. Rev. C 124 (1961) 877

7.1 – 10.5 MeV/u ^{12}C, ^{14}N, ^{16}O on ^{197}Au, ^{209}Bi:

E, θ, σ of α-particles measured:

"... direct projectile breakup reactions occur in interactions between the projectile and the surface of the target nucleus and, thus, involve the larger impact parameter. These reactions would then leave residual nuclei that are excited to energies considerably below the excitations involved in the full compound nucleus reactions."

R.J. Silva et al., Nucl. Phys. A 216 (1973) 97

^{248}Cm(^{18}O,α3n)^{259}No discovered

R.L. Hahn et al., Phys. Rev. C 10 (1974) 1889

^{239}Pu(^{12}C,α2n)^{245}Cf measured

factor $\approx$ 5–10 higher σ than 4n- and 3n-channel

A. Ghiorso et al., Phys. Rev. Lett. 22 (1969) 1317

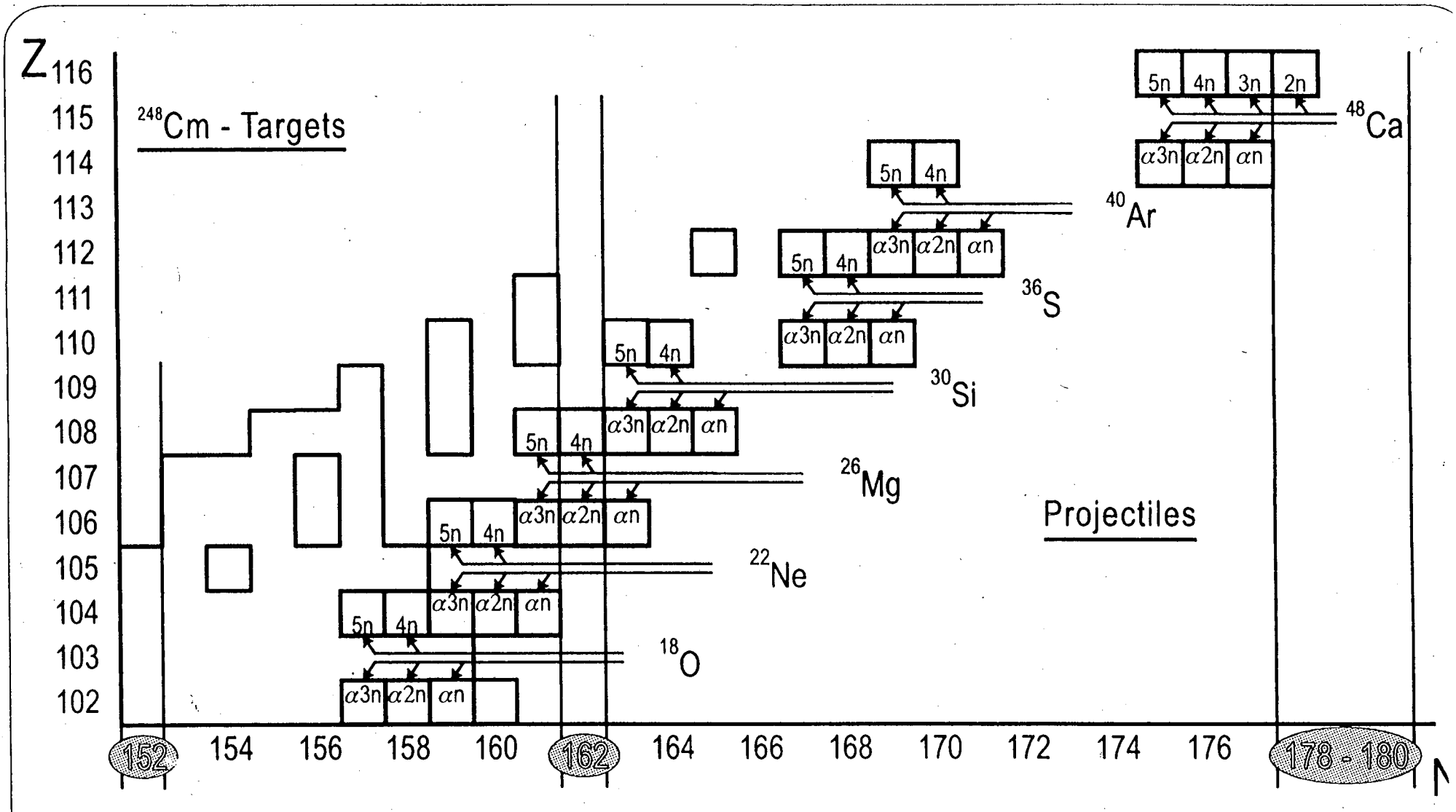
^{249}Cf(^{12}C,α1n)^{256}No measured

factor $\approx$ 10 higher σ than 4n-channel

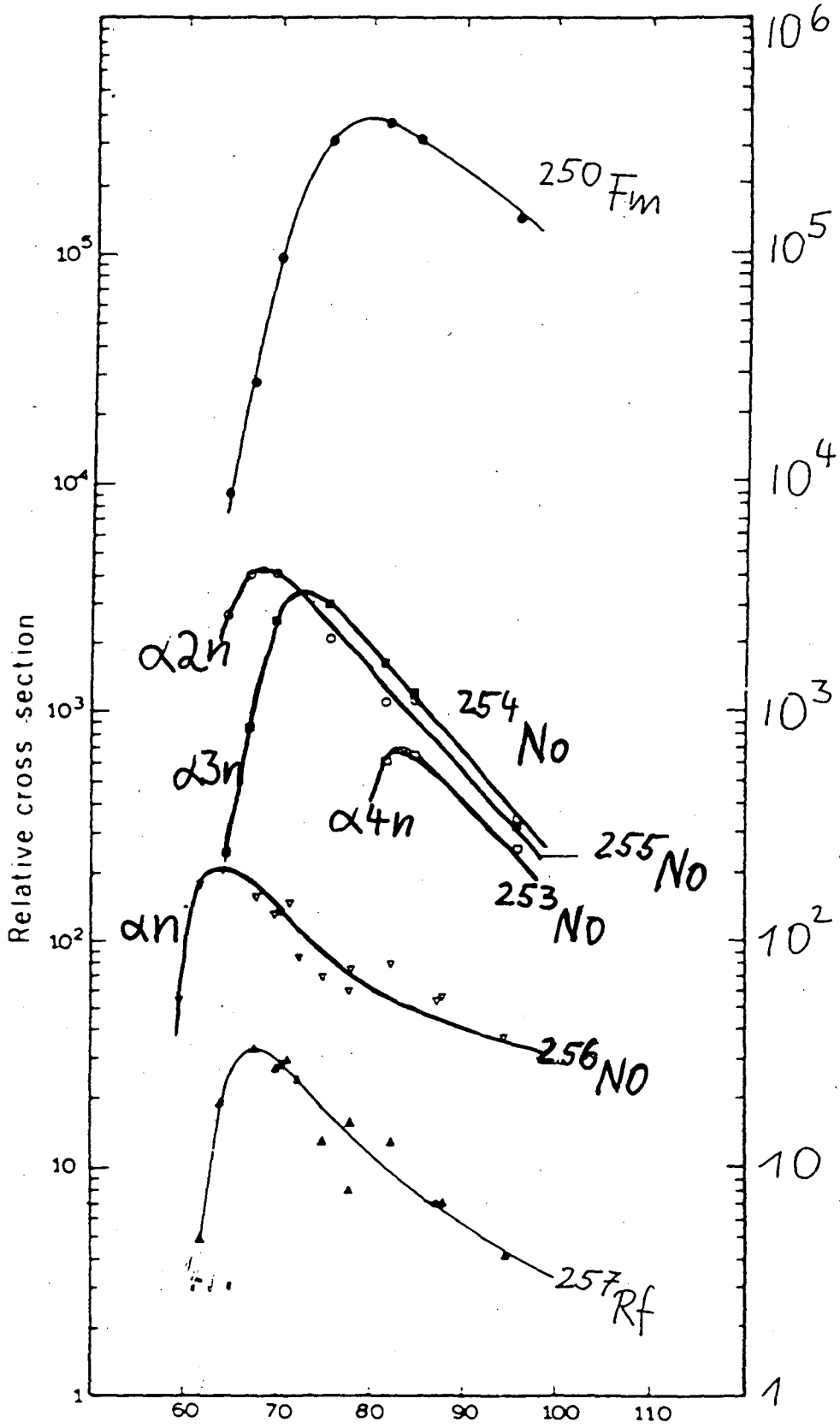
H. Bruchertseifer et al., JINR P 7-80-666 (1980)

^{176}Lu(^{22}Ne,α0n)^{194}Au measured

broad excitation function


Z
116
115
114
113
112
111
110
109
108
107
106
105
104
103
102
248Cm - Targets
5n
4n
3n
2n
α3n
α2n
αn
48Ca
40Ar
36S
30Si
26Mg
22Ne
18O
Projectiles
152
154
156
158
160
162
164
166
168
170
172
174
176
178 - 180
N

$^{12}C + ^{249}Cf \rightarrow ^{261}Rf^*$



αxn - EVR?
or
transfer products?
...

Data A. Ghiorso et al. Phys Rev. Lett 22 (1969) 1317

WHAT'S NEEDED

Targets (facilities, expertise, new technologies):

^{232}Th, ^{236,238}U, ^{242,244}Pu, ^{248}Cm; – ^{249}Bk, ^{254}Es.

Beams (intense):

^{18}O, ^{22}Ne, ^{26}Mg, ^{30}Si, ^{40}Ar, and ^{34,36}S, ^{48}Ca.

Techniques:

* Recoil separators with large angular and momentum acceptance (gas-filled or not), and a good supression of near-target transfer products.

* Sensitive radiochemical techniques; high separation factor, fast

Reaction Studies:

more dedicated studies in the region of highly fissile nuclei; e.g. E_α, Θ_α in coincidence with heavy-element EVR.

Motivated young scientists,
support (financial) from authorities, and
support from THEORY !

I-Yang Lee
Lawrence Berkeley National Laboratory

I-Y. LEE

γ -Ray Studies at Focal Plane of BGS

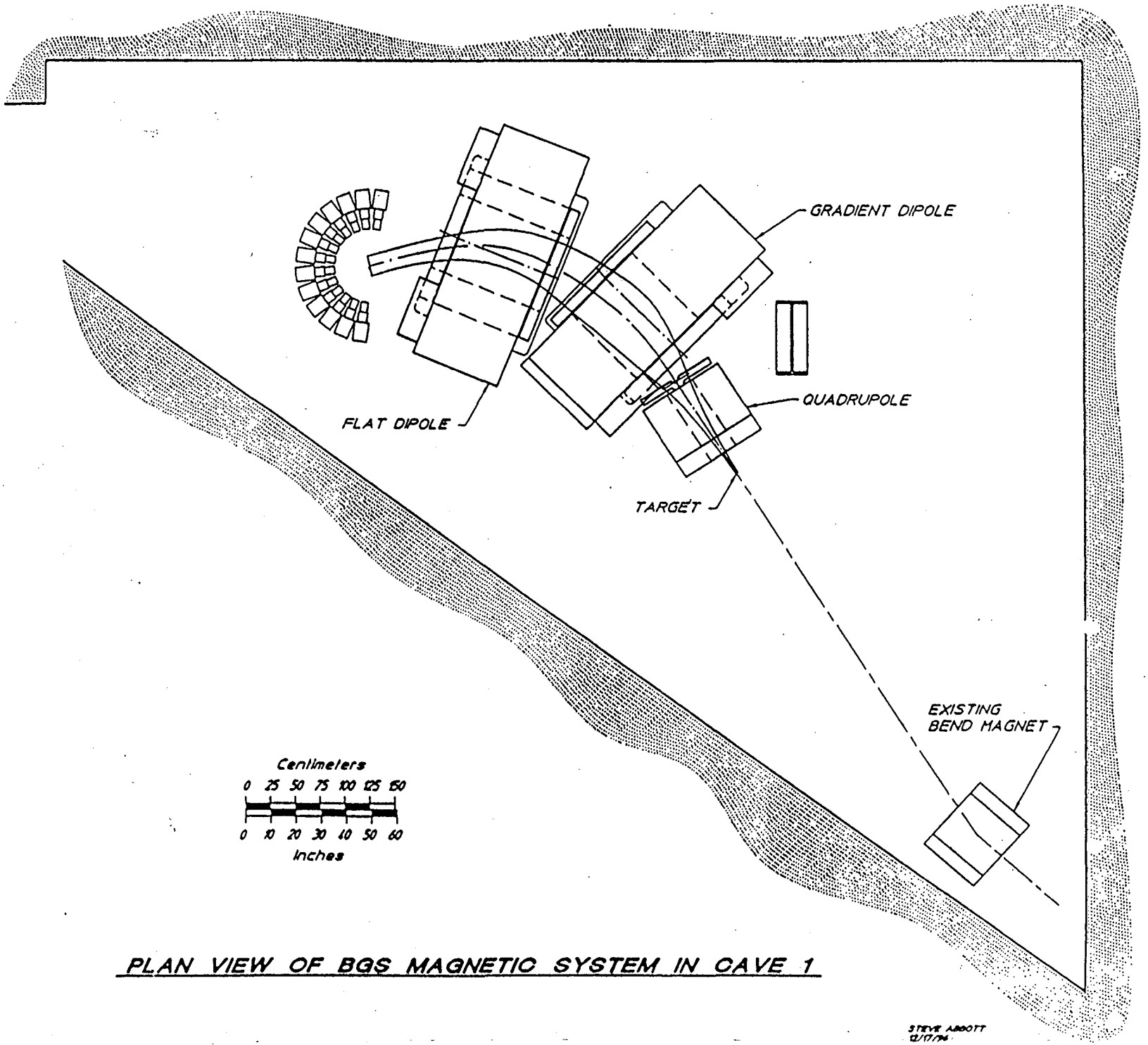
Delayed γ - ray, $\tau > 1$ μsec

- **isomeric states**
- **following α–, β–, or p–decay**

- **N=Z nuclei**
  - **n-p pairing**
  - **Single particle states near ^{100}Sn**

- **β– decay**
  - **Low spin, high excitation energy states**
  - **Order to chaos**

- **Proton activity**
  - **From excited states**
  - **To excited states**



PLAN VIEW OF BGS MAGNETIC SYSTEM IN CAVE 1

8 π array at BGS
Properties

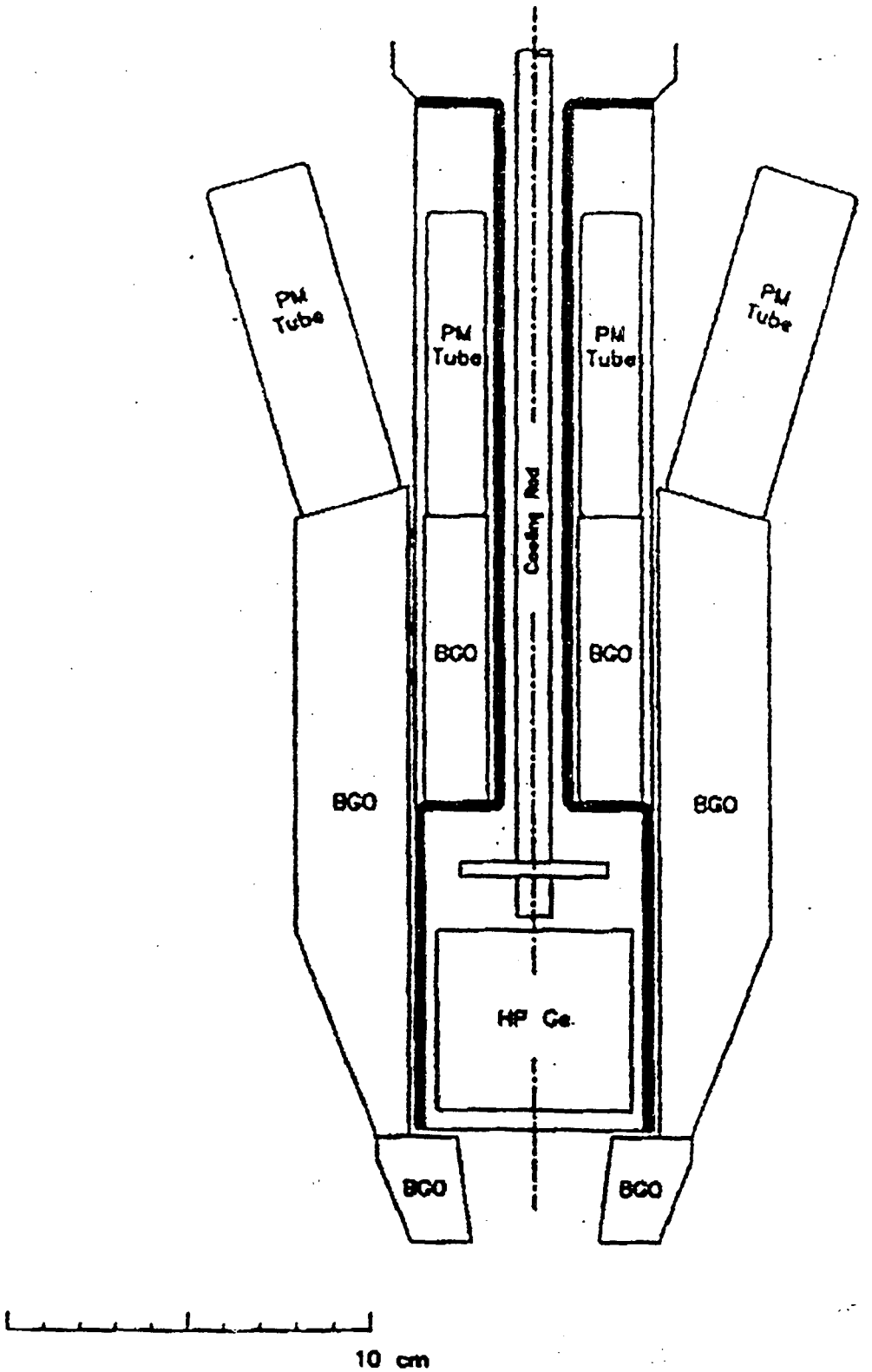
Compton Shielded Ge detector

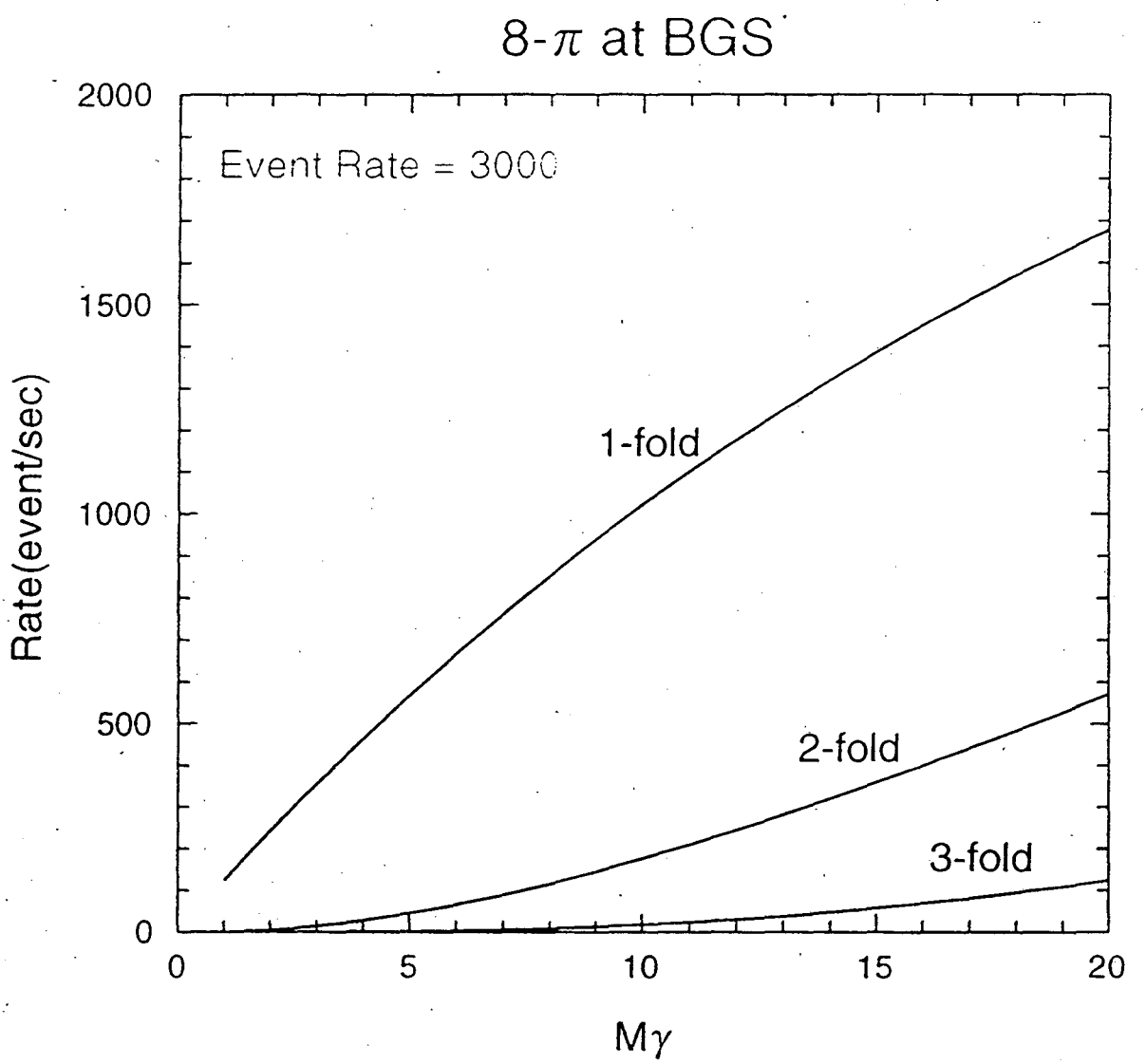
Number of detectors	N = 20
Source to Ge distance	= 15 cm
Solid angle	Ω = 0.0076 %
Peak efficiency	ε_p = 0.15 (1.33 MeV)

Total efficiency	$N \Omega \varepsilon_p$ = 0.023
Peak-to-total	= 0.55
Resolving power	= 1000

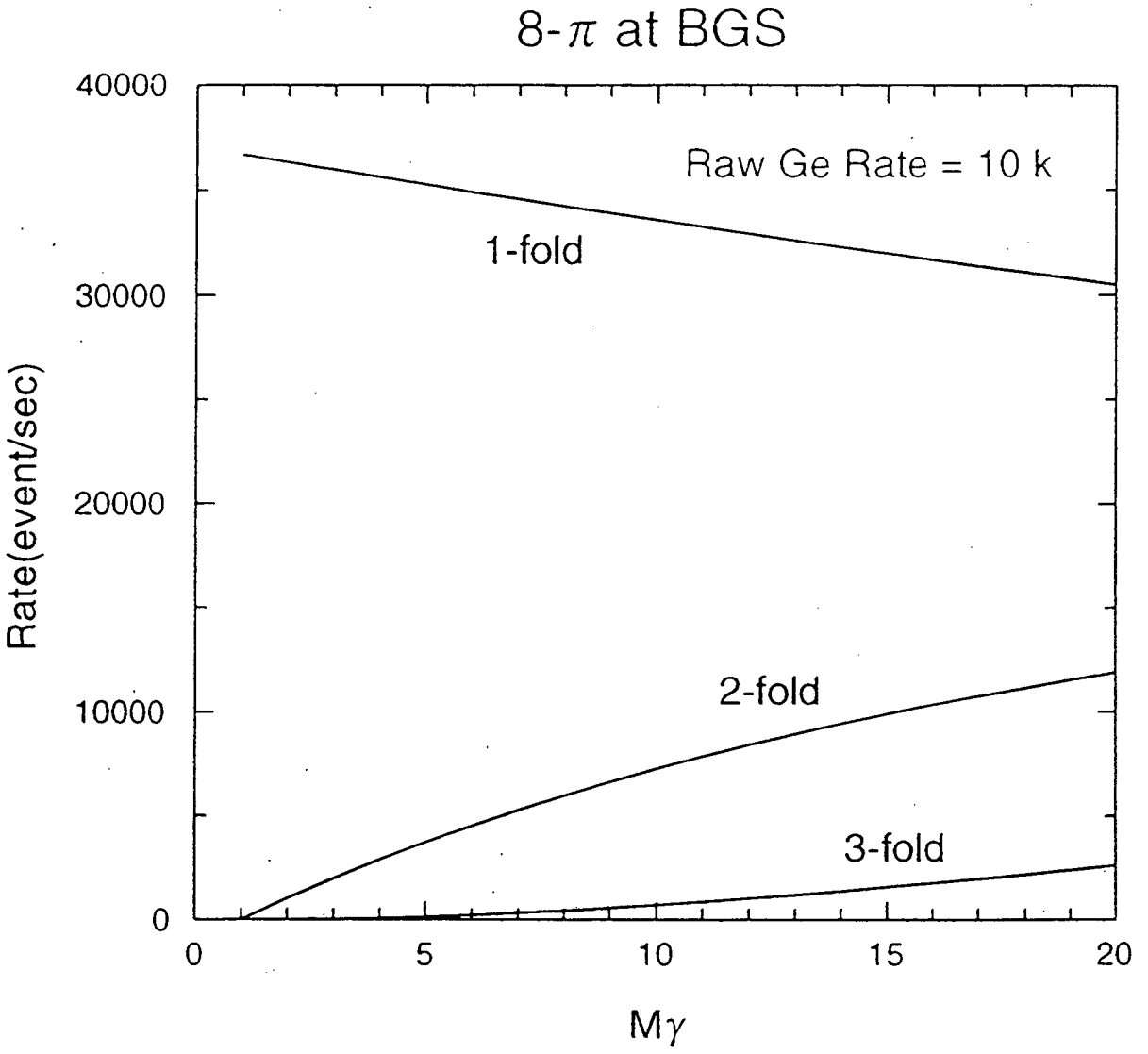
one detector at closest distance

$\Omega \varepsilon_p$ = 0.015


PM Tube
PM Tube
PM Tube
PM Tube
Cooling Rod
BGO
BGO
BGO
BGO
HP Ge
BGO
BGO
10 cm



FILE: plot_8pirate_ev.dat


8-π at BGS
Raw Ge Rate = 10 k
1-fold
2-fold
3-fold
Rate(event/sec)
40000
30000
20000
10000
0
0
5
10
15
20
Mγ

8 π array at BGS

Counting Rate

Cross section = 1 μb
Target thickness = 1 mg/cm^2 (A=100)
Beam intensity = 1 pμA
BGS efficiency = 80 %

Focal plane event rate = 30 /sec

M_γ	Raw Ge singles rate	total clean rate γ	$\gamma-\gamma$
5	1 /sec	5.7/sec 490 k/day	0.45/sec 39 k/day
10	2 /sec	10.2/sec 880 k/day	1.76/sec 152 k/day

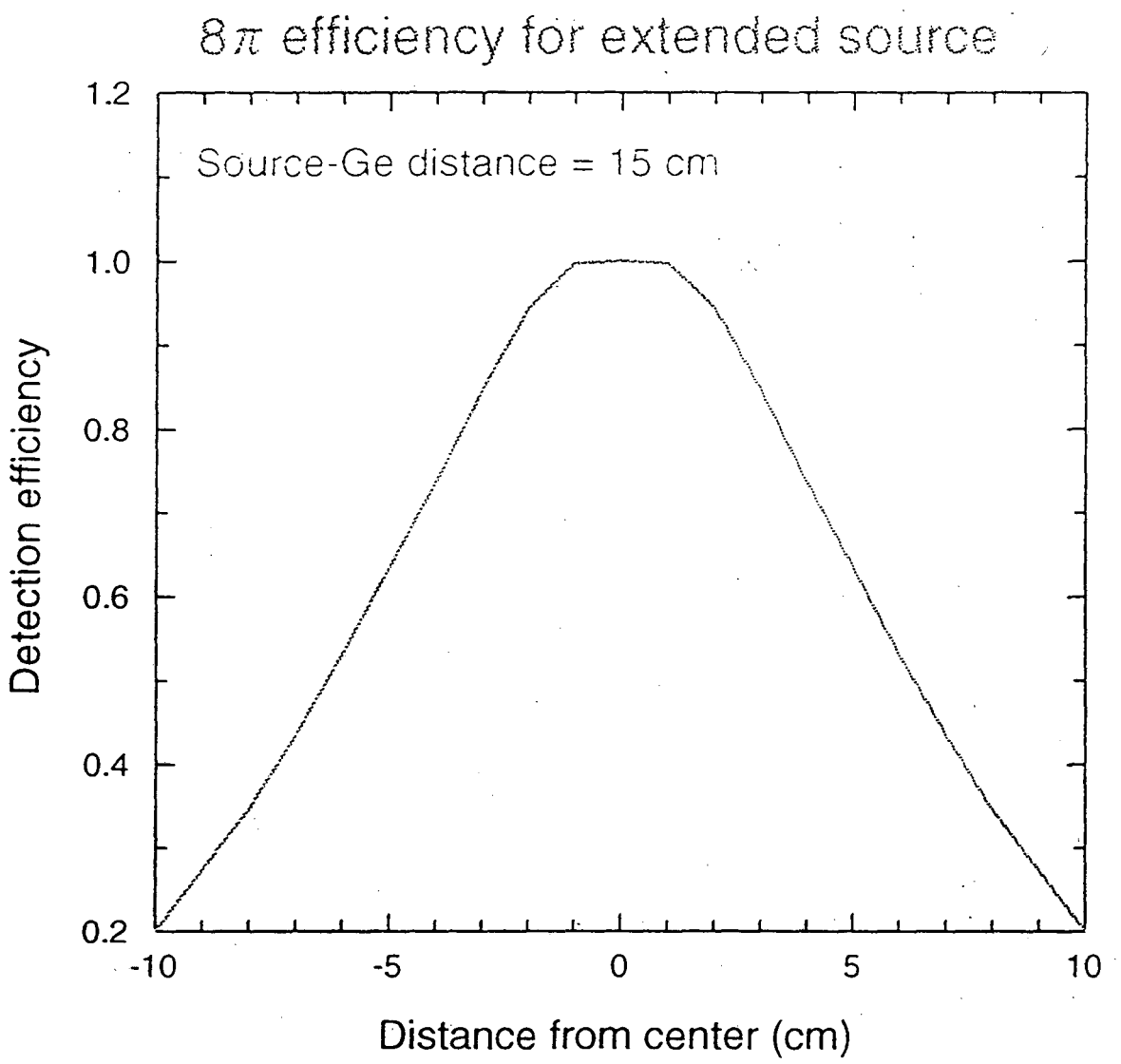
8 π array at BGS
Counting Rate

Cross section = 1 b
Target thickness = 1 mg/cm^2 (A=100)
Beam intensity = 1 pμA
BGS efficiency = 80 %

Focal plane event rate = 3 10^7 /sec

Raw Ge single rate < 10 k/sec

M_γ	event rate	total clean rate γ	total clean rate $\gamma-\gamma$
5	3.1 10^5/sec	59.2 k/sec 5115 M/day	4.7 k/sec 406 M/day
10	1.6 10^5/sec	54.4 k/sec 4700 M/day	9.3 k/sec 804 M/day



FILE: plot_bigs.dat

Selection of Weak Decay Channel

α–, p–decay

- Energy specific
- RDT

Isomeric γ–decay

β–decay

- Energy nonspecific
- Long lived
- γ–ray multiplicity
- γ–ray sum energy
- moving tape select lifetime

8π array at BGS
Status

- Arrived at LBNL on 4/3/97 from Chalk River.
- In storage at Buildings 51 and 88.
- To operate at BGS requires :

  Supporting structure.

  Liquid nitrogen filling system.

  Cables.

Michael Hass
The Weizmann Institute

Structure Studies of Isomers and Ground States with

LBL Gas-Filled-Magnets

BGS
GFS

Michael Hass
Department of Particle Physics
The Weizmann Institute

Gamma-decay studies of isomers
^{182}Os(I=K=25)

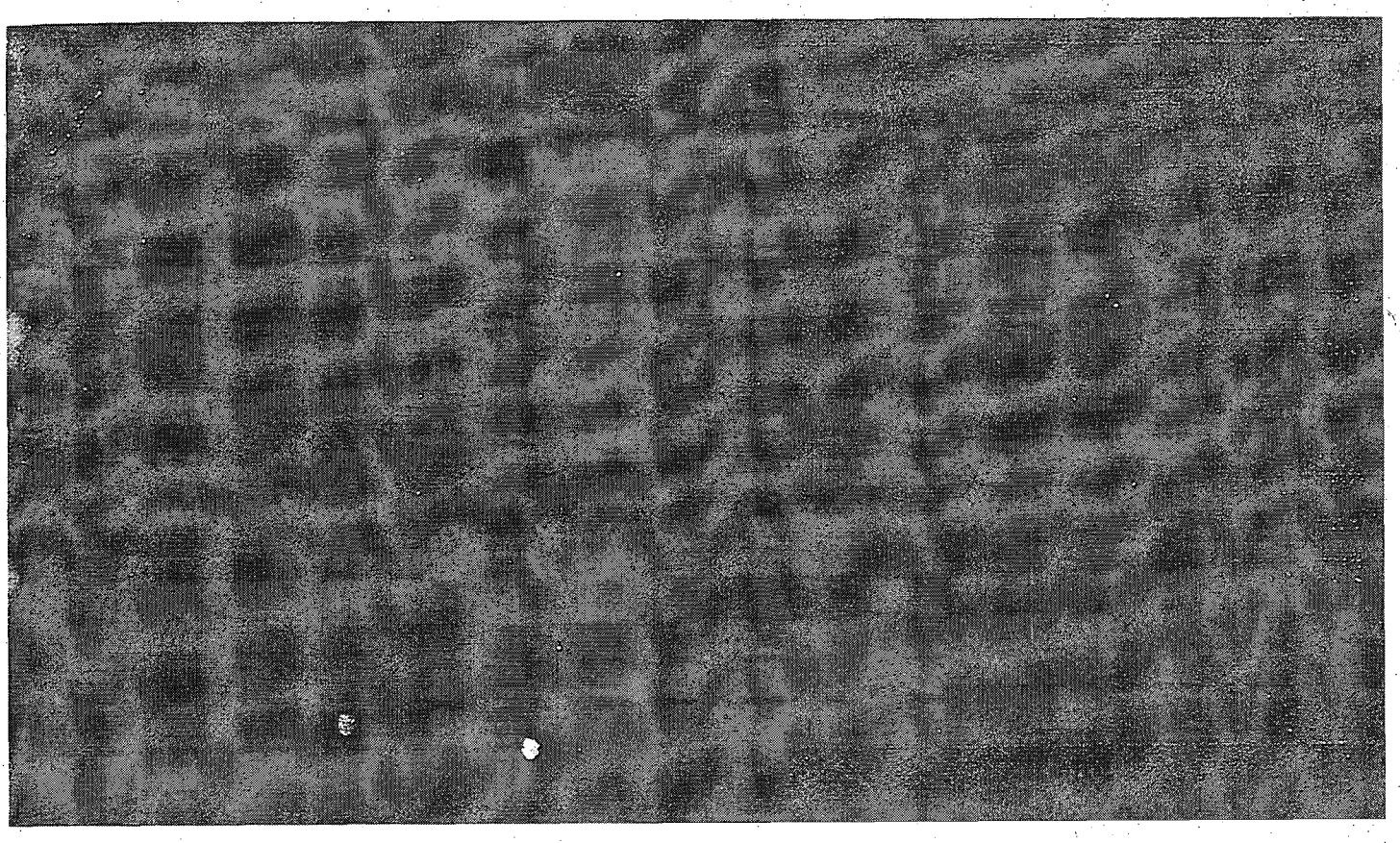
- Quadrupole moments (*signs*) of high-spin isomers.
- Magnetic moments of ground states in mirror nuclei (f-shell).
- PNC in ^{93}Tc (GSI + Legnaro) ✓

ADVANTAGES

1) High transmission efficiency
2) Short transit time!! → GFS!
3) "Good" beam-products separation

^{182}Os (I=K=25)

- Decay-path, and in particular a branch from K=25 to gsb(K=0), established; but **ONLY very partially**.
- Magnetic moment measured [g= +.425(8)]
- Quadrupole moment measured [|Q|=4.2(2) eb]



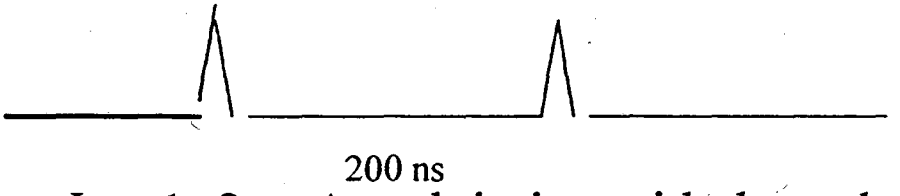
Picture of "tunneling in the γ–plane" still unsettled.

^{182}Os (K=I=25)

- τ = 216 ns

- ^{150}Nd(^{36}S,4n)^{182}Os at E(^{36}S)=160 MeV
  ==> v/c[recoils]= 0.6 cm/ns
  ==> For GFM length of 200 cm,
  t(flight)=350 ns.
  ==> about 20% K=25 isomers reach fp.
  Timing at the fp with *individual* nuclei.

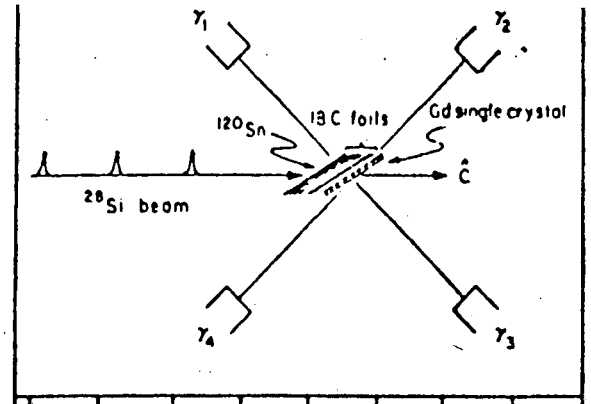
Previous experiments at Daresbury:

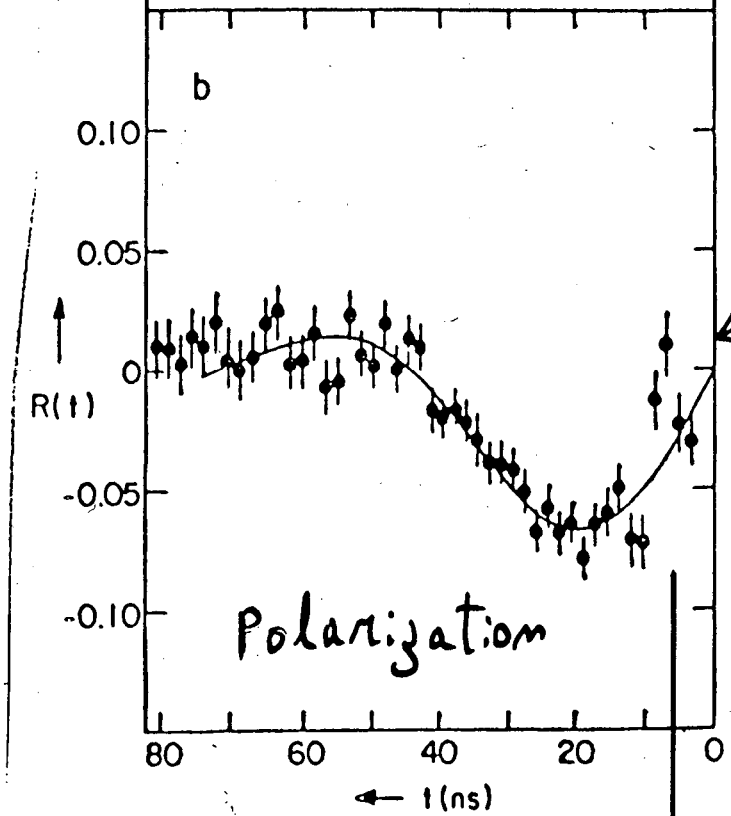


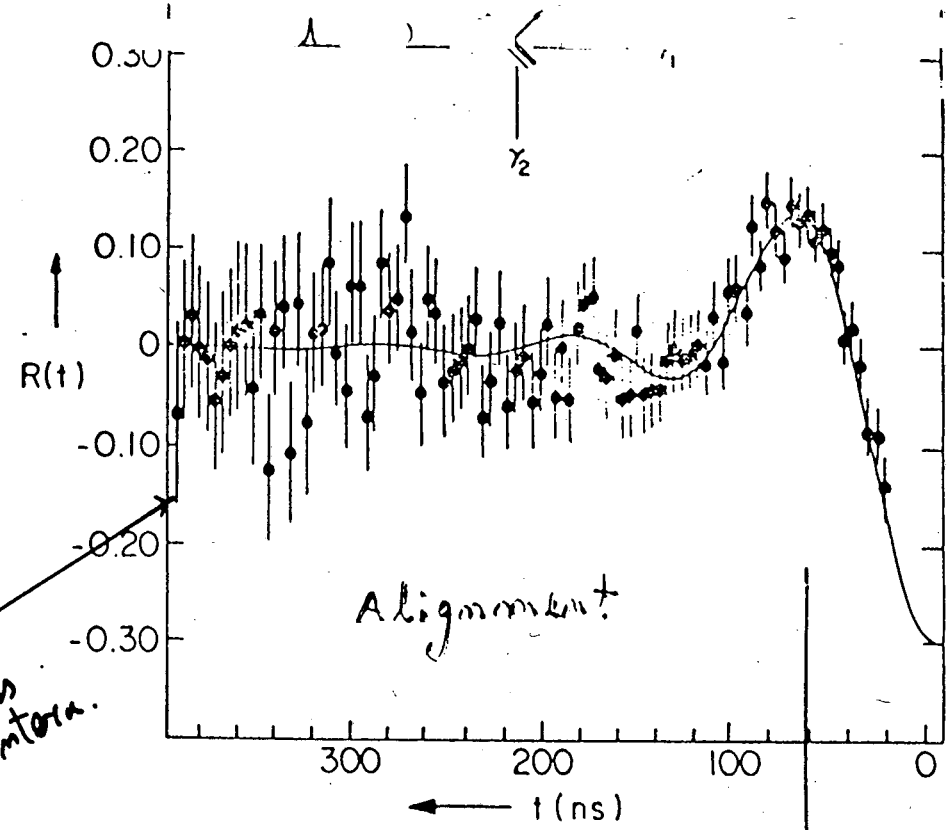
I=~ 1–2 pnA and timing with the pulsed beam.

- Particular and immediate aim:
  level scheme below isomer

Similar considerations also for measuring sign-of-Q.for this case and others as well.







Identical parameters for Q-interac.

Ratio function for aligned ^{144}Gd(10$^+$) isomers

$$R(t) = \frac{Y(0^\circ,t) - Y(90^\circ,t)}{Y(0^\circ,t) + Y(90^\circ,t)} = \frac{3}{4} A_{22} \sum S^{22}_{n1} \cos(n\omega_0 t).$$

a. The experimental set-up (shown for the ^{144}Gd case).

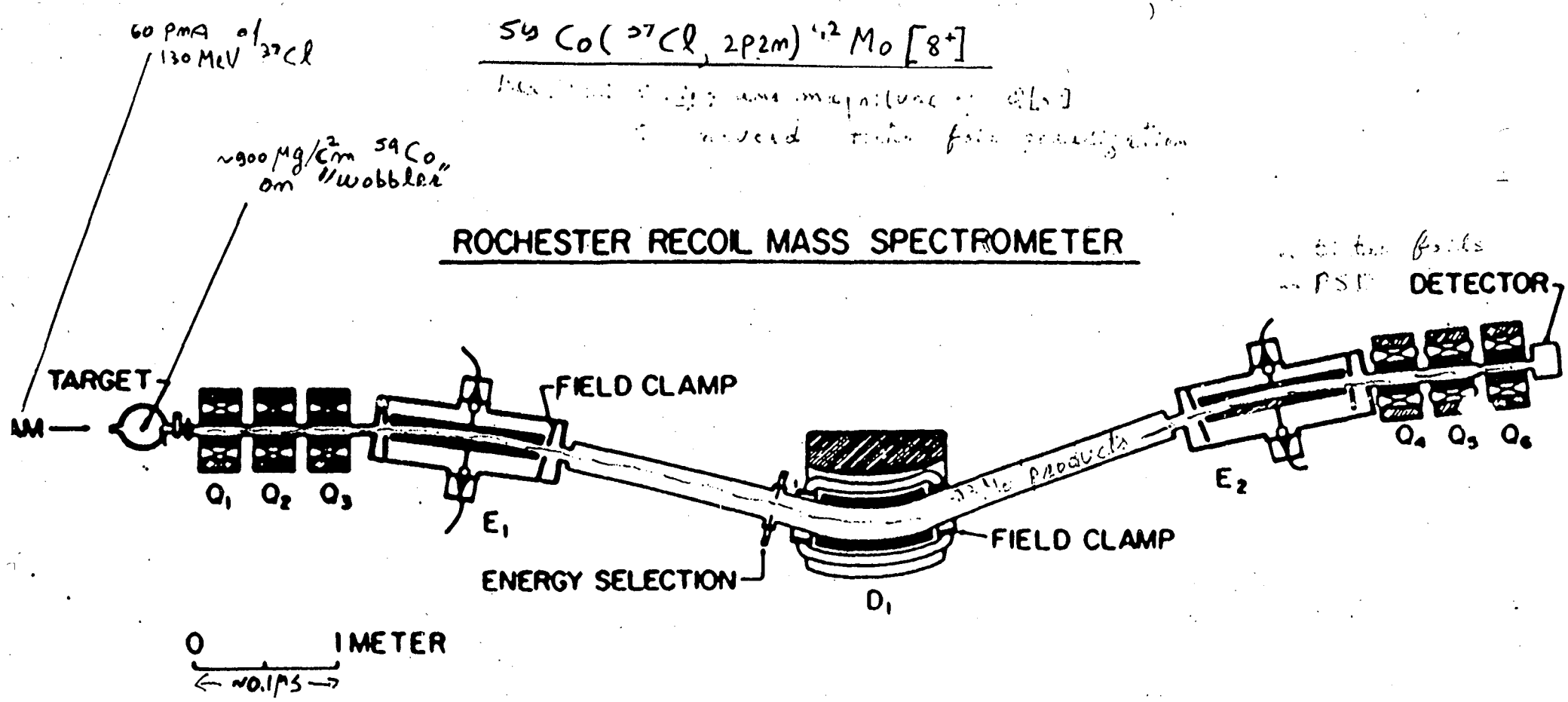
b. Ratio functions (eq.2) for polarized ^{144}Gd(10$^+$) isomers

$$Y_a(t) = Y_{1u}(t) + Y_{2d}(t) + Y_{3u}(t) + Y_{4d}(t)$$

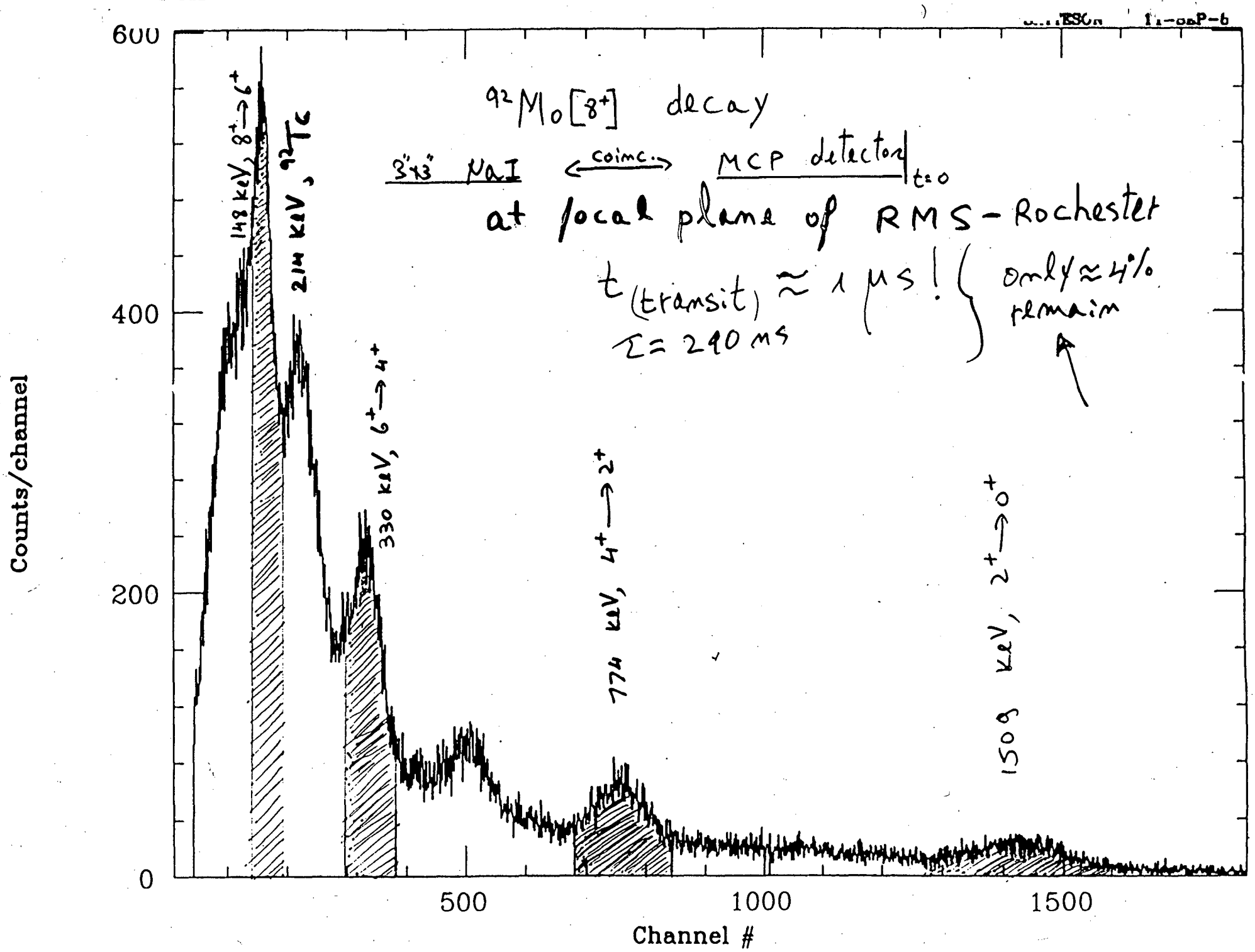
$$Y_b(t) = Y_{1d}(t) + Y_{2u}(t) + Y_{3d}(t) + Y_{4u}(t)$$

$$R(t) = \frac{Y_a(t) - Y_b(t)}{Y_a(t) + Y_b(t)} = -\frac{3}{2} p_I^{eff} F_2 \sum_{n \geq 0} S^{12}_{n1} \sin(n\omega_0 t)$$

$^{59}Co(^{37}Cl, 2p2n)^{92}Mo\,[8^+]$



The PSD detector is for initial identification and diagnostic purposes. It is then replaced by the tilted-foil apparatus and MCP. γ counters are placed at the focal-plane area.


^{92}Mo[8$^+$] decay
3"x3" NaI ⟷ coinc. ⟷ MCP detector|$_{t=0}$
at focal plane of RMS-Rochester
$t_{(transit)} \approx 1\ \mu s$!
$\tau = 240$ ms
only ≈ 4% remain
148 keV, 8$^+$→6$^+$
214 keV, ^{92}Tc
330 keV, 6$^+$→4$^+$
774 keV, 4$^+$→2$^+$
1508 keV, 2$^+$→0$^+$
Counts/channel
Channel #
0
200
400
600
500
1000
1500

Magnetic Moments of Mirror Nuclei

Isoscaler component:

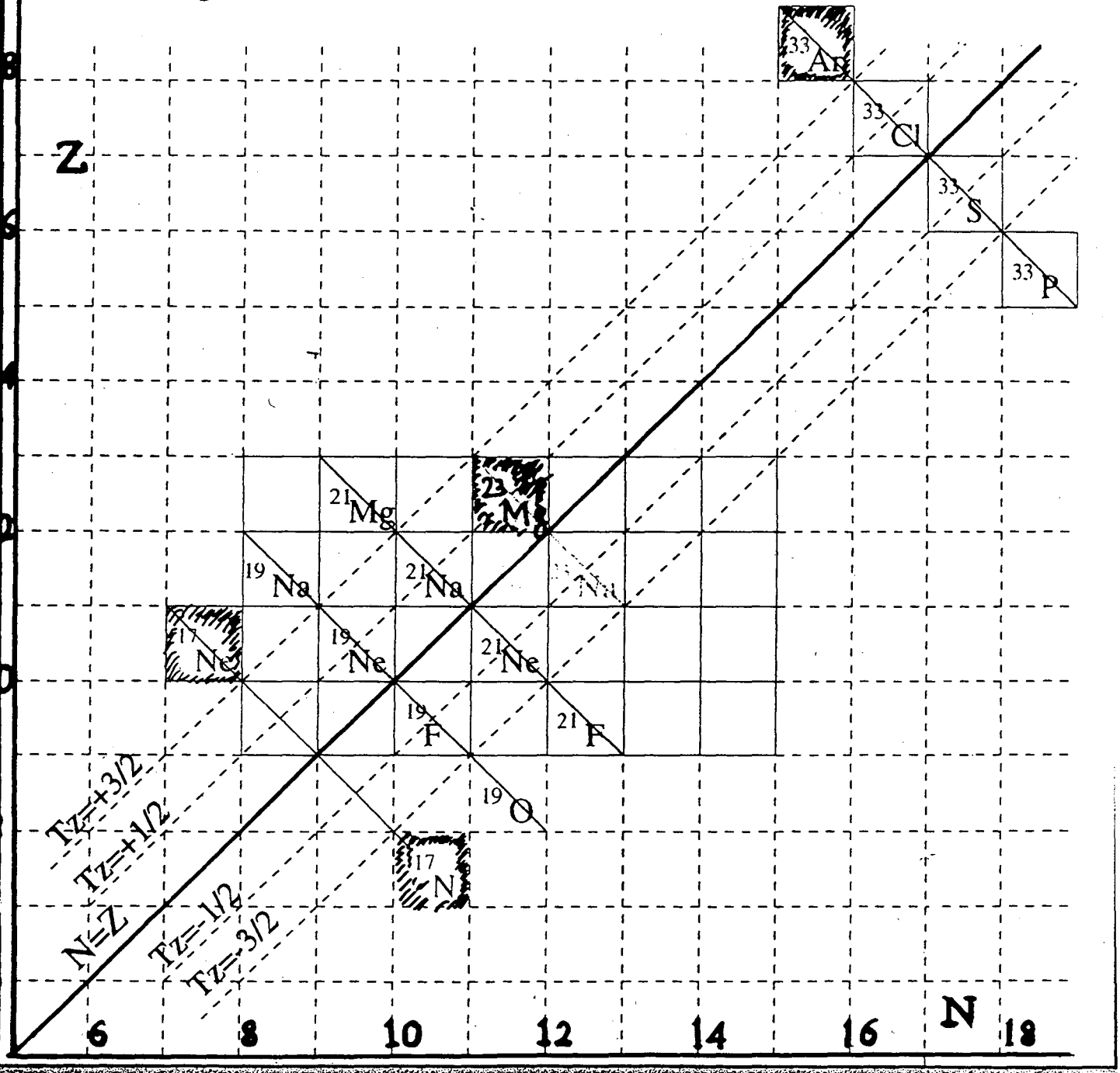
$$\mu(M_T) + \mu(-M_T) = \mu_0[I+(g_n + g_p -1)\langle S_z\rangle]$$
$$= 2\,\mu(T=0)$$

Isovector Component:

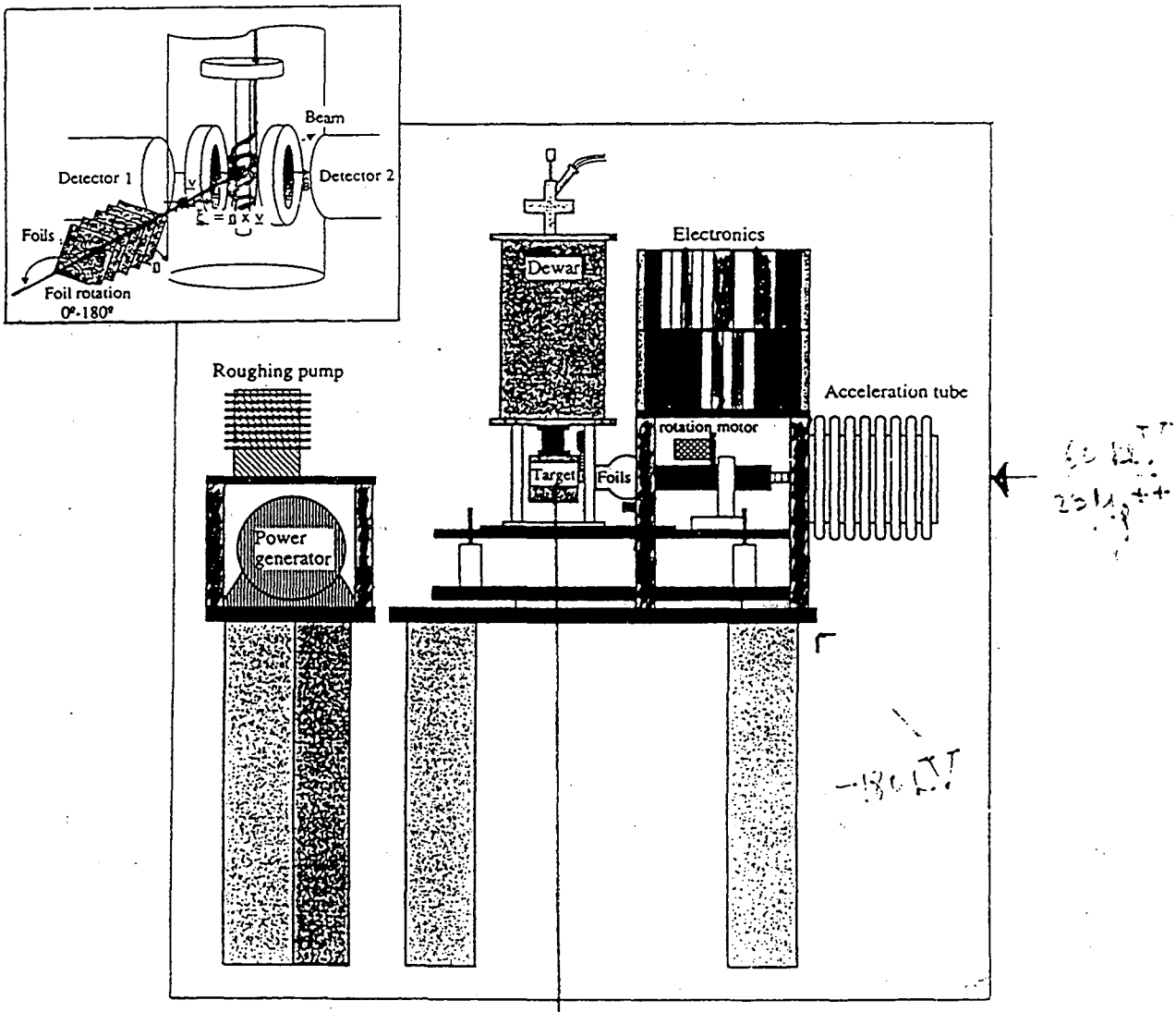
$$\mu(M_T) + \mu(-M_T) = \mu_0[\langle \Sigma\tau_3(k)\, i_z(k)\rangle + (g_p-g_n-1)\langle \Sigma\tau_3(k)s_z(k)\rangle]M_T$$

Connected to Gamow-Teller Strength

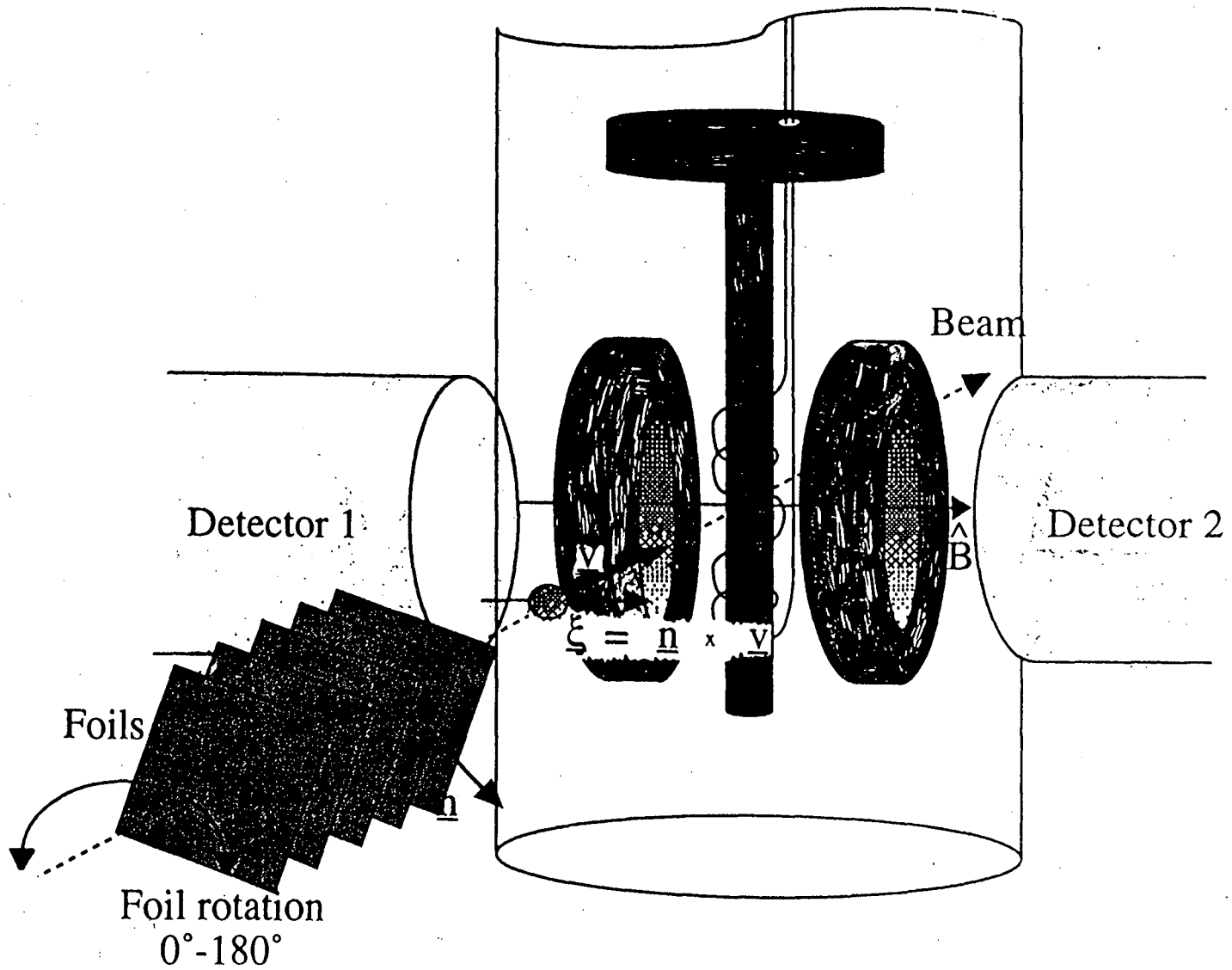
Picture complete for T=1/2 nuclei in the s-d shell. Virtually nothing is known about T=3/2 nuclei and T=1/2 in the f shell.



- Schematic figure of the ISOLDE setup on the HV platform.
- The inset shows the tilted-foil and beta-NMR geomtry.

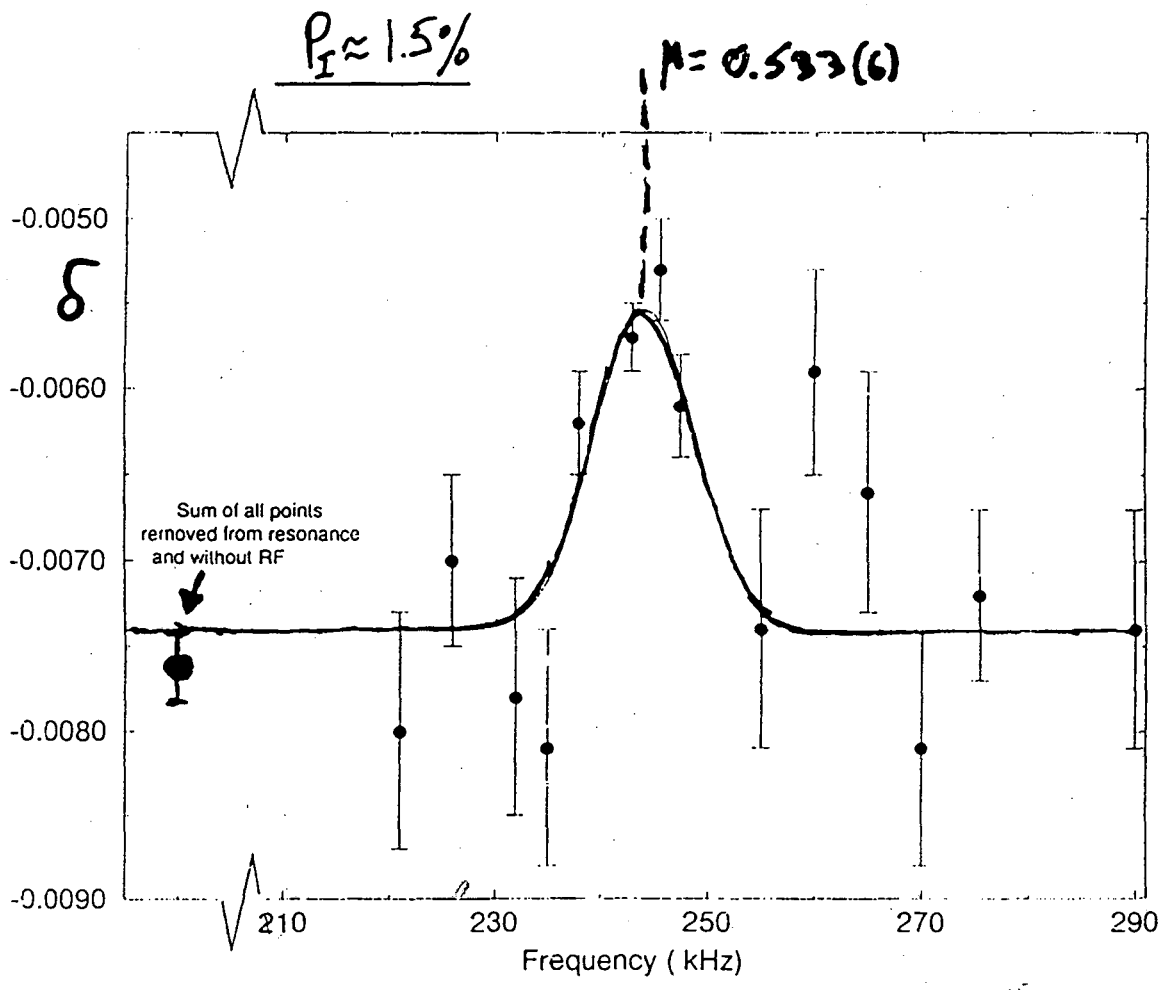


E = 480 kV 23 Mg


Beam
Detector 1
Detector 2
$\hat{B}$
$\underline{v}$
$\underline{\xi} = \underline{n} \times \underline{v}$
Foils
$\underline{n}$
Foil rotation
0°-180°

RESULTS OF AUG. '96 RUN

$^{23}Mg(I=3/2^+, \tau=16\ s)$



FMA/ANL '97

$^{32}S + {}^{12}C \xrightarrow{1m} {}^{43}Ti \longrightarrow$ f-shell!
$N \sim Z$

Need high rate!

Andreas Türler
Paul Scherrer Institute

BGS
as a Preseparator for Chemical Studies

A. Türler

Paul Scherrer Institute

Why chemical studies?

Chemical separator systems

Why combine a physical with a chemical separator?

Chemistry in the gas phase:

- Prospects for chemical studies Z=107 to 109
- Future developments in gas phase chemistry
- A proposal for a 108 chemistry experiment in 3 years from now

Periodic Table of the Elements

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
1 H																	2 He
3 Li	4 Be											5 B	6 C	7 N	8 O	9 F	10 Ne
11 Na	12 Mg											13 Al	14 Si	15 P	16 S	17 Cl	18 Ar
19 K	20 Ca	21 Sc		V	24 Cr	25 Mn	26 Fe	27 Co	28 Ni	29 Cu	30 Zn	31 Ga	32 Ge	33 As	34 Se	35 Br	36 Kr
37 Rb	38 Sr	39 Y		Nb	42 Mo	43 Tc	44 Ru	45 Rh	46 Pd	47 Ag	48 Cd	49 In	50 Sn	51 Sb	52 Te	53 I	54 Xe
55 Cs	56 Ba	57-71 La		Ta	74 W	75 Re	76 Os	77 Ir	78 Pt	79 Au	80 Hg	81 Tl	82 Pb	83 Bi	84 Po	85 At	86 Rn
87 Fr	88 Ra	89-103 Ac		Db	106 Sg												
						107 Ns	108 Hs	109 Mt	110	111	112						

Lanthanides	57 La	58 Ce	59 Pr	60 Nd	61 Pm	62 Sm	63 Eu	64 Gd	65 Tb	66 Dy	67 Ho	68 Er	69 Tm	70 Yb	71 Lu
Actinides	89 Ac	90 Th	91 Pa	92 U	93 Np	94 Pu	95 Am	96 Cm	97 Bk	98 Cf	99 Es	100 Fm	101 Md	102 No	103 Lr

Heavy Elements

$Z \geq 104$

Physics

Nuclear properties:

Decay mode: α, EC, SF
Half-lives?
Branching ratios?
Nuclear structure?
Deformations?
Reaction mechanism?

Better understanding of the influence of shells on stability and structure of heavy elements

Chemistry

Chemical properties:

Group?
Electronic structure?
Influence of relativistic effects?
Stability of compounds?
Single atom chemistry?

Better understanding of the fundamental principles governing the periodic table

Separator

SHIP, BGS

OLGA, ARCA, SISAK

Chemical Separator Systems

Nickname	OLGA	ARCA	SISAK
Affiliation	PSI Villigen University of Bern FZ Rossendorf	GSI Darmstadt University of Mainz TU Dresden	Chalmers University University of Mainz University of Oslo
Separation time	≥ 3 s	≥ 10 s	≥ 1 s
Separation principle	gas - solid chromatography	extraction or ion exchange chromatography	liquid - liquid extraction
Operation principle	continuous	batch wise	continuous
Chemical yield	≅ 60 %	60 - 80 %	60 - 80 %
Decontamination from actinides	$\cong 10^3$	$\cong 10^4$	
Detection system	Wheel (ROMA, MG) Tape system	Counting chambers	Liquid scintillation flow through cells
Detection efficiency	70 %	70 %	≅ 100 %
Smallest detected cross section	≅ 50 pb	≅ 250 pb	> 5 nb
Transactinides studied	104, 105, 106	104,105,106	

OLGA ↔ Dubna Gas Filled Separator

Beam Energy: 121, 123 MeV

Beam Dose: 4.6×10^{17}

Targets: 950, 690 $\mu g/cm^2$

$N_{^{265}Sg}$ = 241 (260 pb)

^{265}Sg decay chains = 5

Overall efficiency = 2.1 %

Beam Energy: 121 MeV

Beam Dose: 6×10^{18}

Target: 240 $\mu g/cm^2$

$N_{^{265}Sg}$ = 910 (260 pb)

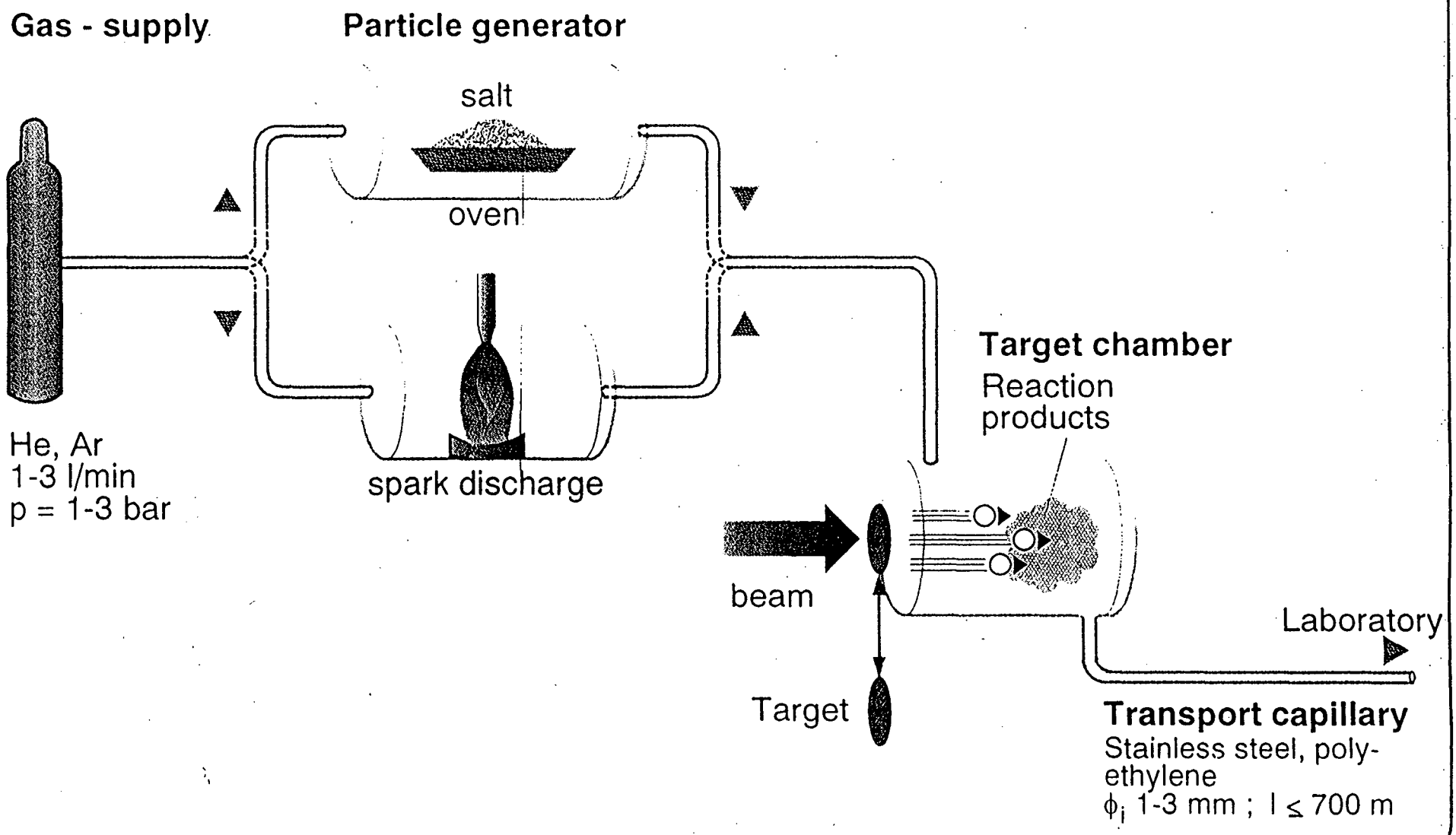
^{265}Sg decay chains = 4

Overall efficiency = 0.5 %

OLGA is factor 4 more efficient!

(Compared to beam dose even factor 16!)

Schematic of a gas-jet device



Disadvantages of Gas-Jet Transport Systems

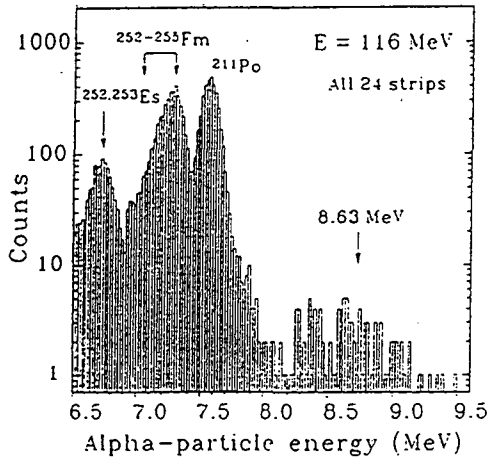
- ☹ Strong fluctuations in gas-jet yield (10 - 60%)
- ☹ Varying performance of aerosol generators
- ☹ Yield dependence on beam intensity and possibly beam structure (DC ↔ macropuls)
- ☹ Relatively long transport times (≥ seconds)
- ☹ No separation from unwanted reaction products
- ☹ Aerosol material interferes with desired clean chemical conditions
- ☹ High gas flow rates (≥ 1 l/min He)

Separation Factors

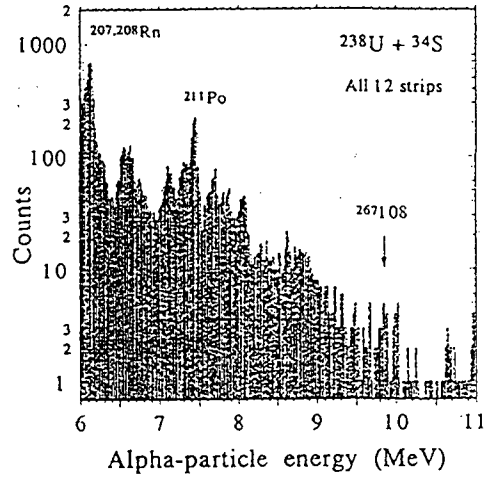
Example: Dubna Gas Filled Separator

Separation Factor: Transferproducts 10^4 - 10^5

$^{22}Ne(^{248}Cm, 5n)^{265}106$



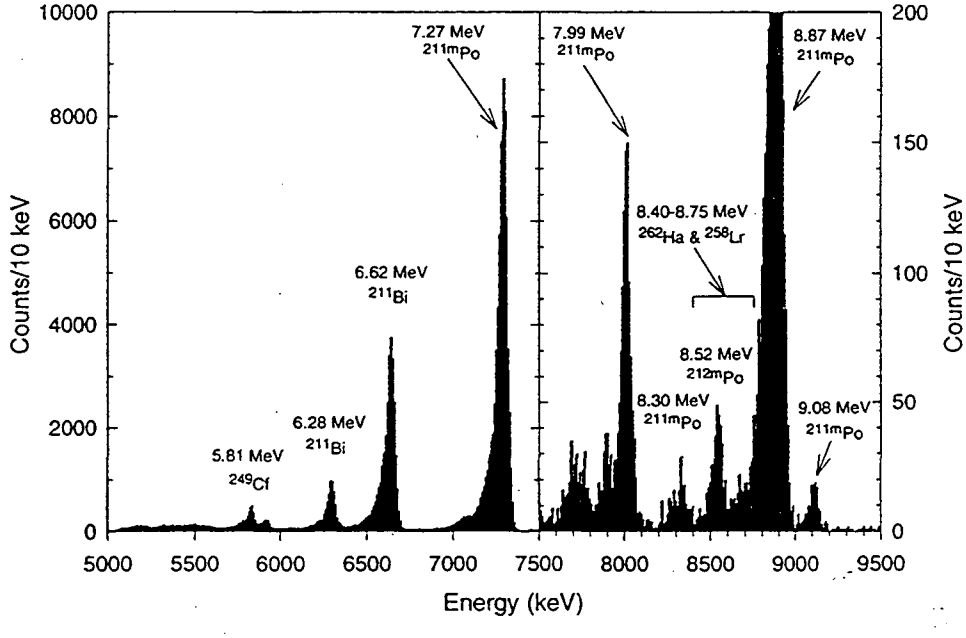
$^{34}S(^{238}U, 5n)^{267}108$



Example: OLGA

Separation Factor: Actinides:10^3 - 10^4; Pb, Bi, Po: 0 - 10^1

$^{18}O(^{249}Bk, 5n)^{262}105$



Problem: Target Impurities (Pb → Bi, Po, Ra, Ac) !!!

Why combine a physical with a chemical separator?

Chemistry profits from:

Good separation of transfer products from target impurities.

Fast and reliable transport.

Will allow special chemical environment (e.g. pure O_2)

Physics profits from:

Enhanced separation factors for separation from actinides with $T_{1/2} \geq 1s$. Especially interesting for enhancing separation from long-lived SF activities.

BGS + Chemistry = 10^7-10^9

Production cross sections and predicted decay modes, decay energies and half-lives for elements Z=107-109 suitable for chemistry experiments.

	Q_α (MeV) [1,2]	$T_{1/2}$ (s) [1,2]	Q_α (MeV) [3]	$T_{1/2}(\alpha)$ (s) [3]	$T_{1/2}(EC)$ (s) [3]	Q_α (MeV) [exp.]	$T_{1/2}$ (s) [exp.]	Cross section (pb) extrapolated
Ns (Element 107)								
$^{22}Ne(^{249}Bk, 5n)^{266}Ns$	n.a.	n.a.	8.82	377	>100			250
$^{22}Ne(^{249}Bk, 4n)^{267}Ns$	8.94	63	8.47	2475	>100			100
Hs (Element 108)								
$^{26}Mg(^{248}Cm, 5n)^{269}Hs$	n.a.	n.a.	8.84	632	>100	9.34	≈ 10	10
$^{36}S(^{238}U, 5n)^{269}Hs$	"	"	"	"		"	"	3
$^{26}Mg(^{248}Cm, 4n)^{270}Hs$	9.44	5	8.69	168	>100			4
$^{36}S(^{238}U, 4n)^{270}Hs$	"	"	"	"				1
$^{136}Xe(^{136}Xe, 1n)^{271}Hs$	n.a.	n.a.	8.82	745	>100			n.a.
Mt (Element 109)								
$^{25}Mg(^{249}Bk, 5n)^{269}Mt$	9.60	0.6	9.62	3	7			10
$^{26}Mg(^{249}Bk, 5n)^{270}Mt$	n.a.	n.a.	9.53	12	19			10
$^{26}Mg(^{249}Bk, 4n)^{271}Mt$	9.45	1.6	9.30	27	39			4

[1] Cwiok et al., Nucl. Phys. A573, 356 (1994)
[2] Patyk et al., Nucl. Phys. A533, 132 (1991)
[3] Möller et al., Nucl. Data Tables 59, 185 (1995)

Chemical systems suitable for gas chromatographic studies

	Element									
	103	104	105	106	107	108	109	110	111	112
Element	X								X	X
Chloride	(X)	X	X					X	X	
Oxychloride		(X)	X	X	(X)					
Oxide					X	X	X	X		
Hydroxide				X	X		X			

Future Developments in Gas Phase Chemistry

Improvements in the chemistry:
For the chemistry of element 107,108 and 109 the hydroxides and the oxides are best suited for a gas chromatographic separation:

- Good separation from actinides
- Good separation from early transactinides 104, 105 and 106
- Good separation from Pb and Bi and probably also Po (compared to chloride and oxychloride chemistry).

Improvements in the current detection system:
Tape system with thin foils and movable detectors

- 80% detector efficiency
- lower background compared to wheel
- α - recoil technique: measurement of interesting samples in low background environment

⇒ **With these improvements we should be able to perform a first chemical separation of element 107**

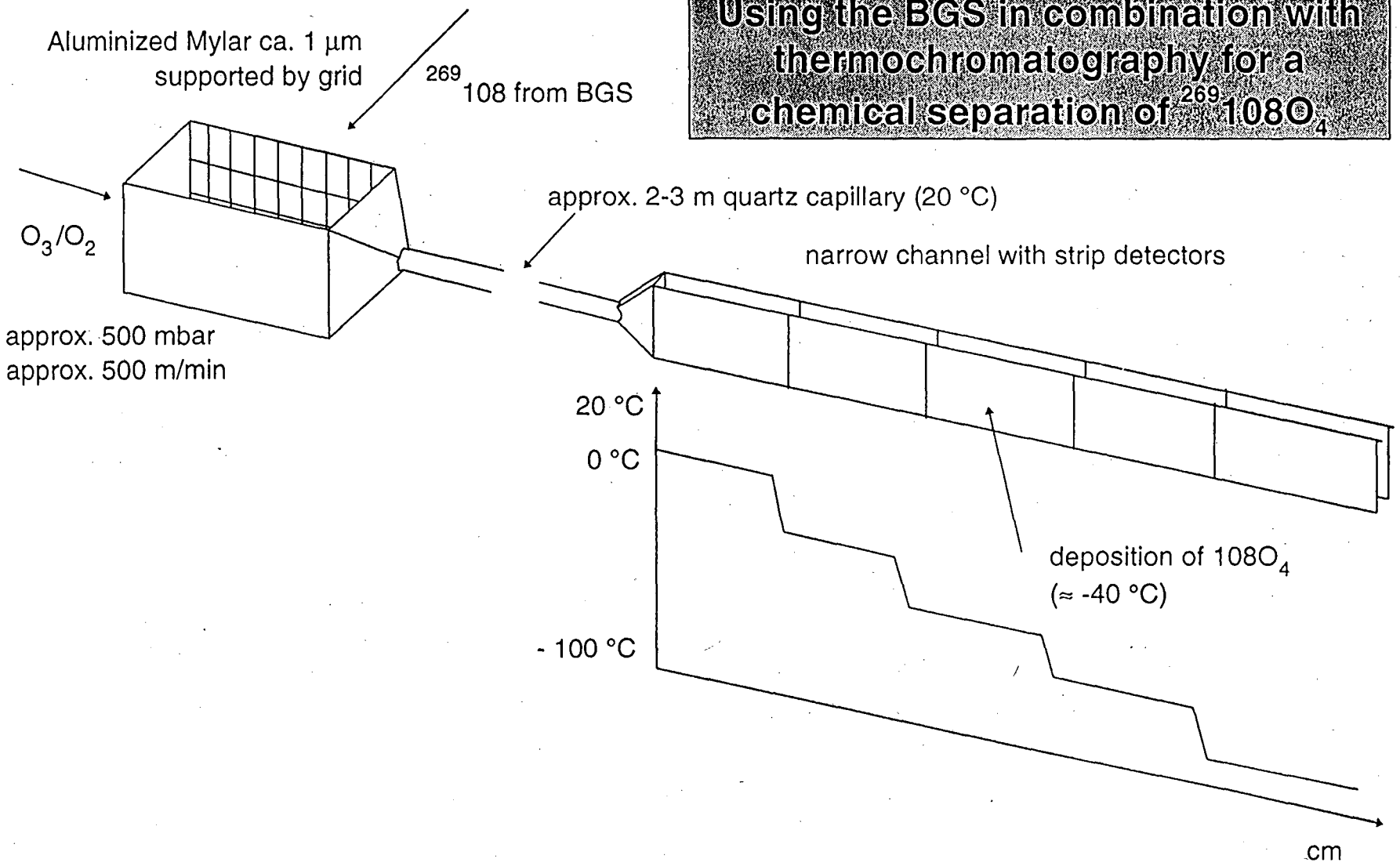
However:

⇒ The low production cross sections of elements 108 and beyond require better separation factors than what can be accomplished with chemistry alone!

Improvements in the transport system:
Replace aerosol gas-jet with chromatography column coupled directly to the BGS!:

- Transport time ≈ 1 μs !
- Transport yield ≈ 10% - 40%
- Separation from unwanted reaction products (transfer products with target and target impurities
- Clean chemical conditions (no aerosol material)
- Remote controlled chemistry inside the cave

Using the BGS in combination with thermochromatography for a chemical separation of $^{269}108O_4$



Chemical Separation of $^{269}108O_4$ using the BGS as preseparator

108 Experiment:

Half-life:	$^{269}108$ $T_{1/2} \approx 10$ s
Production reaction:	$^{26}Mg(^{248}Cm, 5n)^{269}108$; Cross section ≈ 10 pb
Production rate:	8.4 / day (0.5 mg/cm^2 target, 0.5 pμA beam)
Separator Efficiency:	20%
Chemical Yield:	80%
Detection Efficiency:	80%
Overall Efficiency:	12.8 %
Detection Rate:	**1 / day**

Testexperiment

Test experiment:	$^{171}OsO_4$
Production reaction:	$^{24}Mg(^{152}Gd, 5n)^{171}Os$
Half-life:	^{171}Os $T_{1/2} = 8.2$ s, $E_\alpha = 5.24$ MeV

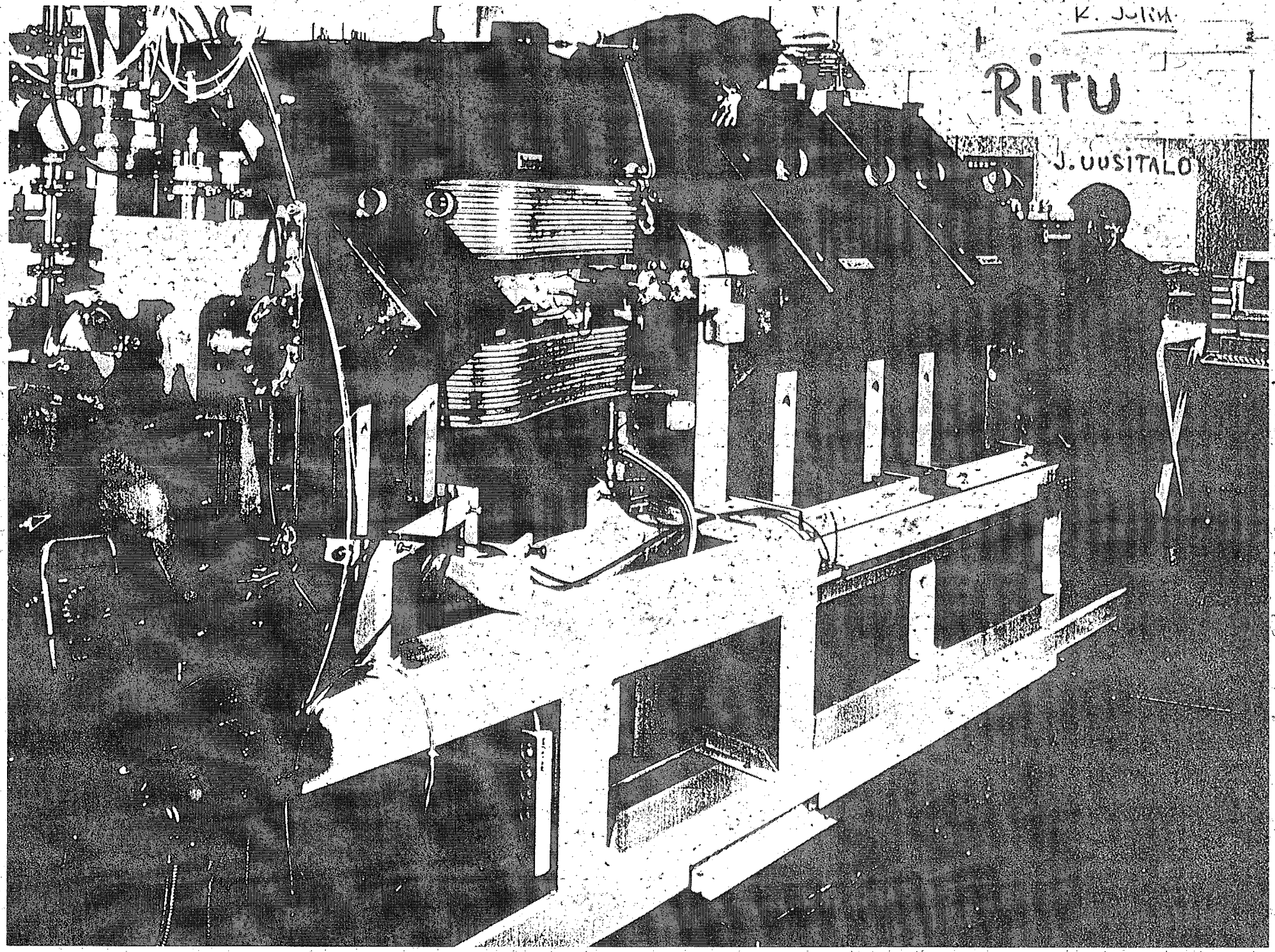
Determine Chemical Yield

Check if Detector Setup works

Results:

Chemistry:	Adsorption enthalpy of $108O_4$ on Si surface
	Relative volatility compared to lighter homologs
Physics:	Determine possible SF-branch
	Disadvantage of thermochromatography:
	No half-life measurements possible for 108 nuclide unless the separator can provide a start signal (TOF ?)

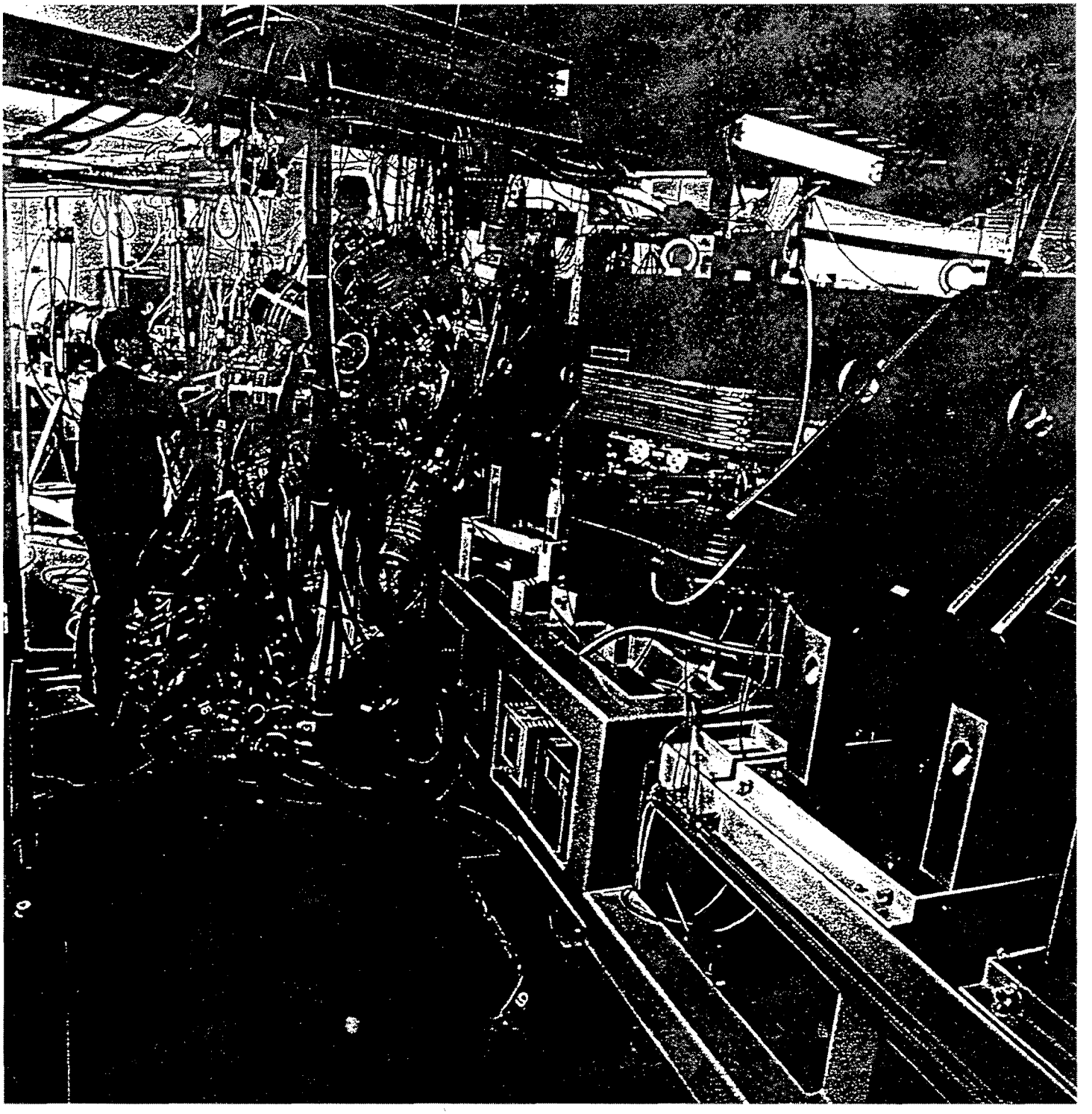
Rauno Julin
University of Jyvaskyla


K. Julin
RITU
J. UUSITALO

Isotopes found with RITU

	108	110	112	114	116	118	120	122	124	126
										^{218}U, ^{219}U
									^{215}Pa	^{216}Pa, ^{217}Pa, ^{218}Pa
							^{210}Th, ^{211}Th	^{212}Th	^{213}Th, ^{214}Th	^{215}Th, ^{216}Th, ^{217}Th
						^{206}Ac, ^{207}Ac, ^{208}Ac	^{209}Ac	^{210}Ac, ^{211}Ac	^{212}Ac, ^{213}Ac	^{214}Ac, ^{215}Ac, ^{216}Ac
				^{203}Ra, ^{204}Ra	^{205}Ra	^{206}Ra, ^{207}Ra	^{208}Ra	^{209}Ra, ^{210}Ra	^{211}Ra, ^{212}Ra	^{213}Ra, ^{214}Ra, ^{215}Ra
			^{200}Fr	^{201}Fr, ^{202}Fr	^{203}Fr	^{204}Fr, ^{205}Fr	^{206}Fr, ^{207}Fr	^{208}Fr, ^{209}Fr	^{210}Fr, ^{211}Fr	^{212}Fr, ^{213}Fr, ^{214}Fr
		^{197}Rn	^{198}Rn	^{199}Rn, ^{200}Rn	^{201}Rn, ^{202}Rn	^{203}Rn, ^{204}Rn	^{205}Rn, ^{206}Rn	^{207}Rn, ^{208}Rn	^{209}Rn, ^{210}Rn	^{211}Rn, ^{212}Rn, ^{213}Rn
	^{193}At, ^{194}At, ^{195}At	^{196}At	^{197}At	^{198}At, ^{199}At	^{200}At, ^{201}At	^{202}At, ^{203}At	^{204}At, ^{205}At	^{206}At, ^{207}At	^{208}At, ^{209}At	^{210}At, ^{211}At, ^{212}At
	^{192}Po (35 ms), ^{193}Po, ^{194}Po (0.7 s)	^{195}Po	^{196}Po	^{197}Po, ^{198}Po	^{199}Po, ^{200}Po	^{201}Po, ^{202}Po	^{203}Po, ^{204}Po	^{205}Po, ^{206}Po	^{207}Po, ^{208}Po	^{209}Po, ^{210}Po, ^{211}Po
^{190}Bi	^{191}Bi, ^{192}Bi, ^{193}Bi	^{194}Bi	^{195}Bi	^{196}Bi, ^{197}Bi	^{198}Bi, ^{199}Bi	^{200}Bi, ^{201}Bi	^{202}Bi, ^{203}Bi	^{204}Bi, ^{205}Bi	^{206}Bi, ^{207}Bi	^{208}Bi, ^{209}Bi, ^{210}Bi
^{189}Pb	^{190}Pb, ^{191}Pb, ^{192}Pb	^{193}Pb	^{194}Pb	^{195}Pb, ^{196}Pb	^{197}Pb, ^{198}Pb	^{199}Pb, ^{200}Pb	^{201}Pb, ^{202}Pb	^{203}Pb, ^{204}Pb	^{205}Pb, ^{206}Pb	^{207}Pb, ^{208}Pb, ^{209}Pb

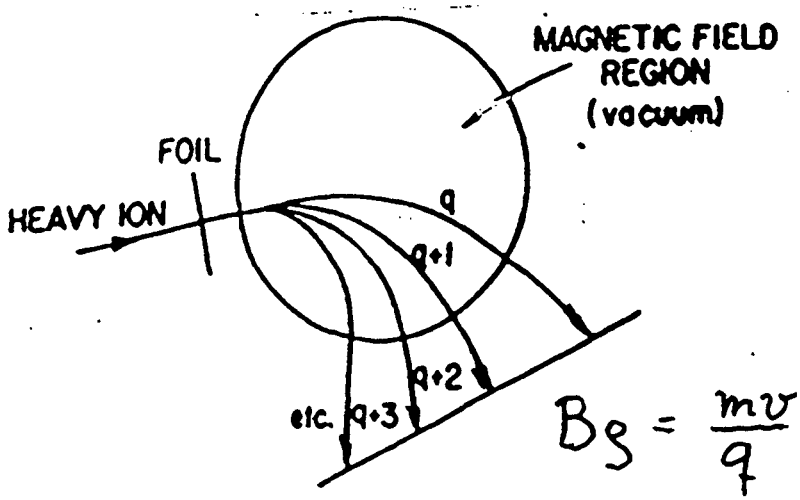
JUROSPHERE + RITU



GAS-FILLED SEPARATOR

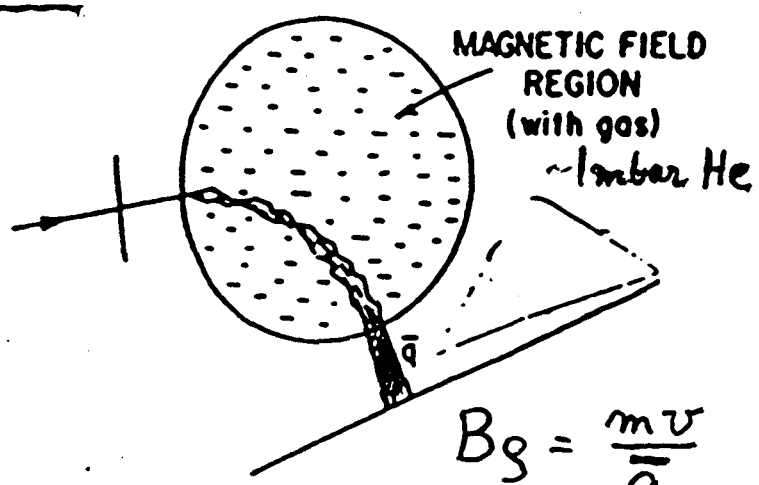
FOR HEAVY-ELEMENT STUDIES

IN VACUUM



$$B\rho = \frac{mv}{q}$$

IN GAS



$$B\rho = \frac{mv}{\bar{q}}$$

$$\bar{q} = \frac{v}{v_0} Z^{1/3} = \text{mean charge}$$

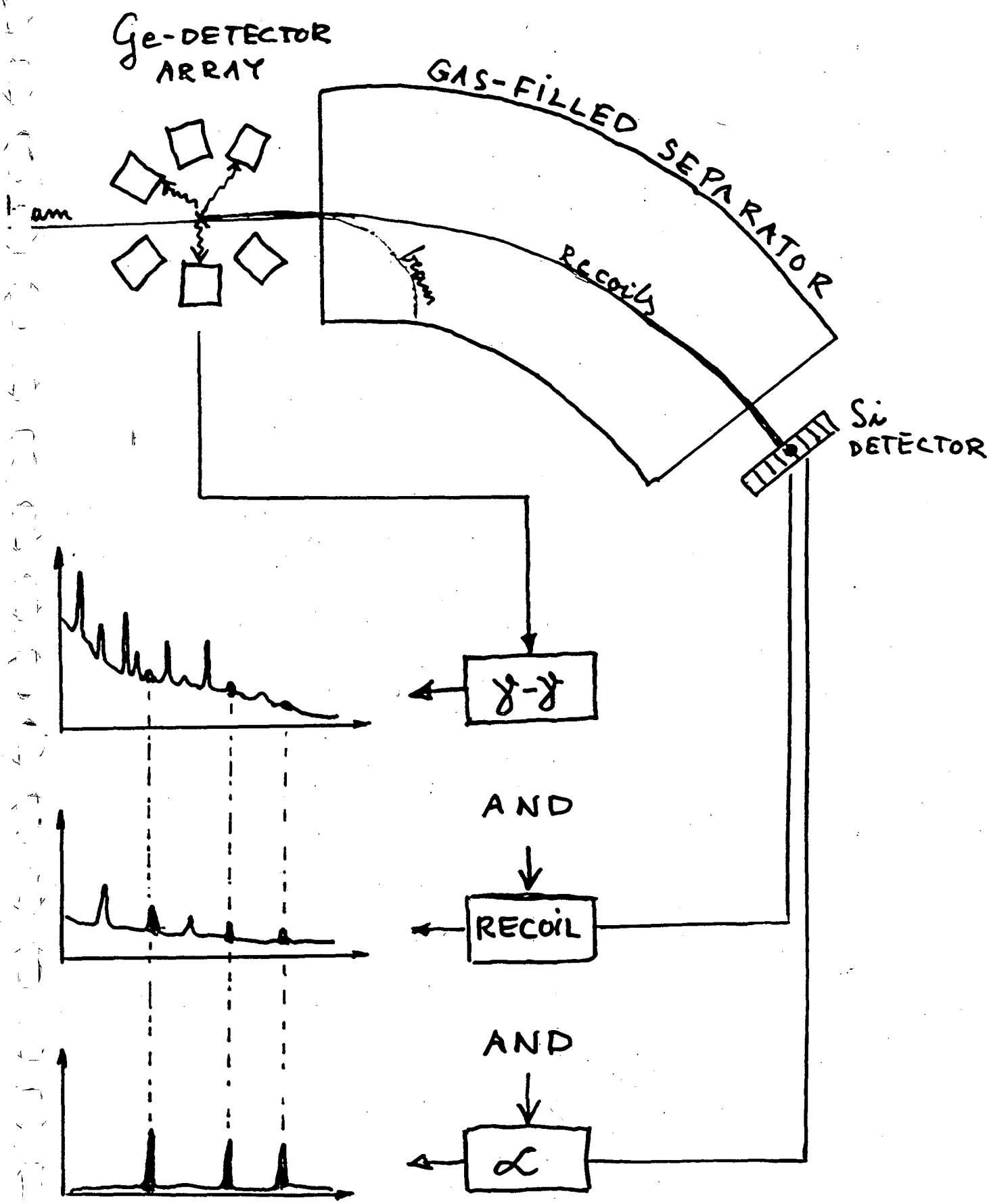
$$\Rightarrow B\rho \propto A/Z^{1/3}$$

HIGH TRANSMISSION!

$\Rightarrow$ charge, velocity — focusing

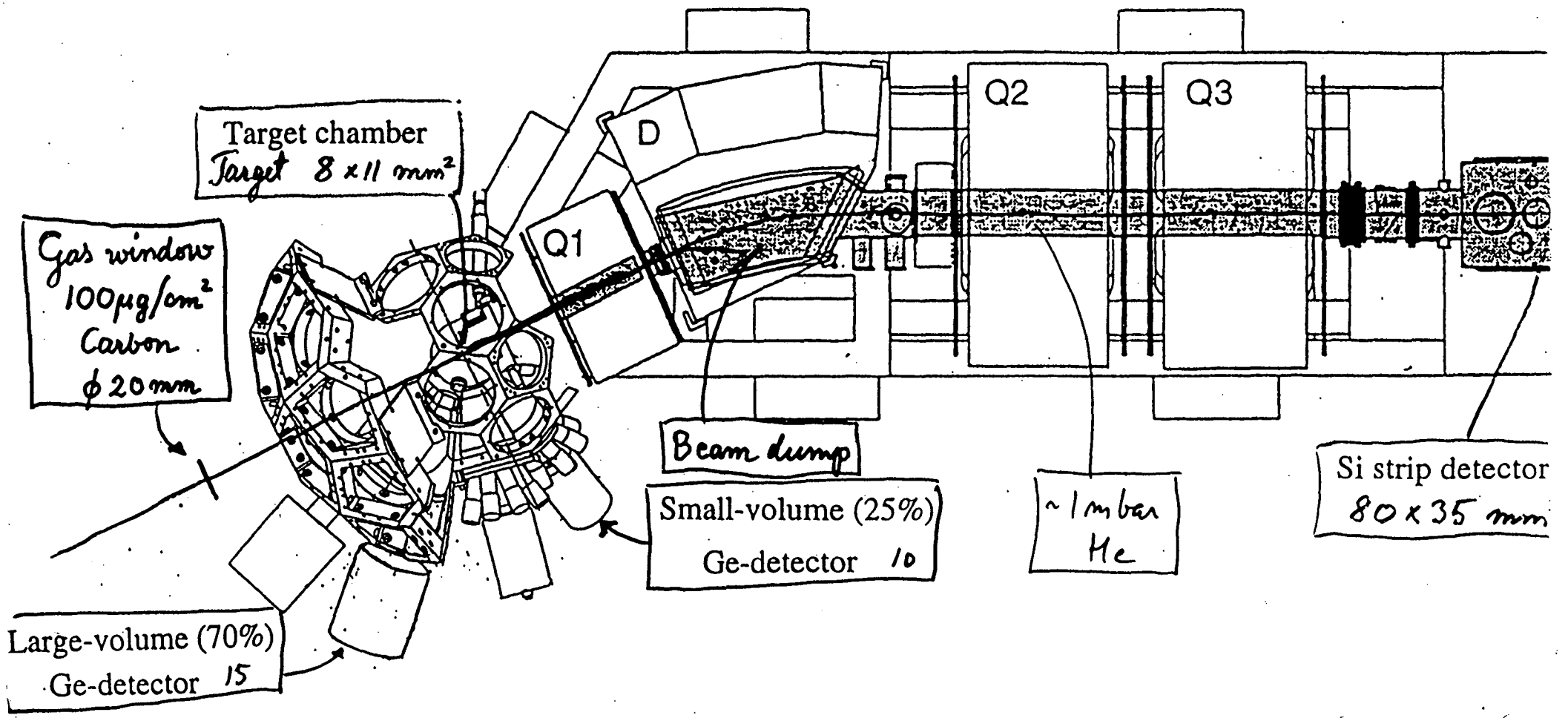
RECOIL-DECAY TAGGING METHOD

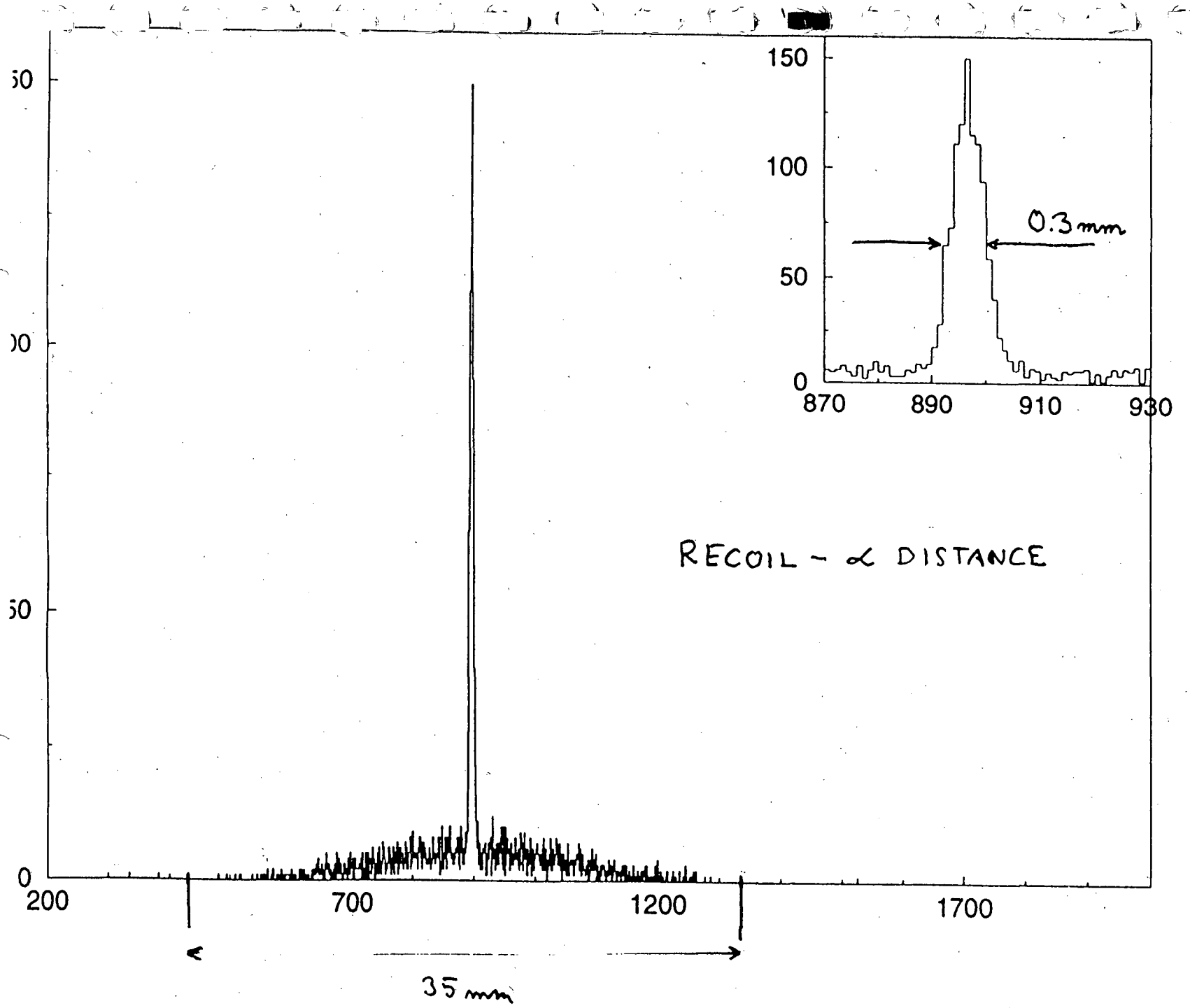
R.S. Simon .. ZP A325 (86) 197
E. Paul .. PR C51 (95) 78



JUROSPHERE

RITU

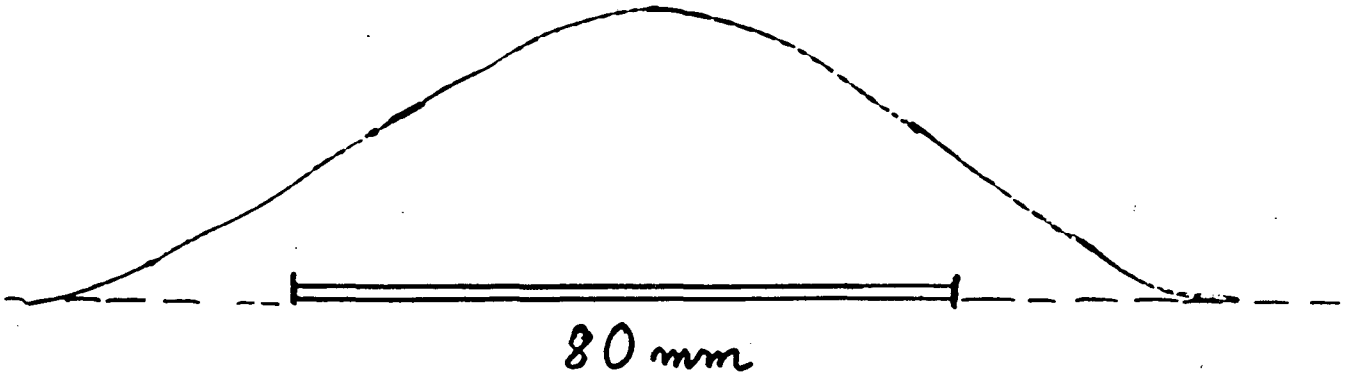


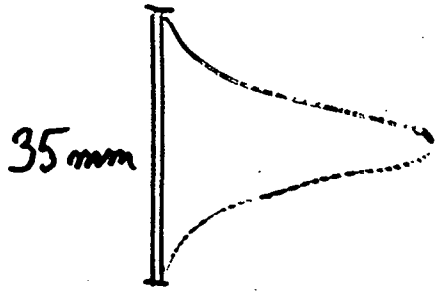

150
100
50
0
870
890
910
930
0.3 mm
RECOIL ~ α DISTANCE
0
200
700
1200
1700
35 mm

RITU

focal plane

recoil distribution

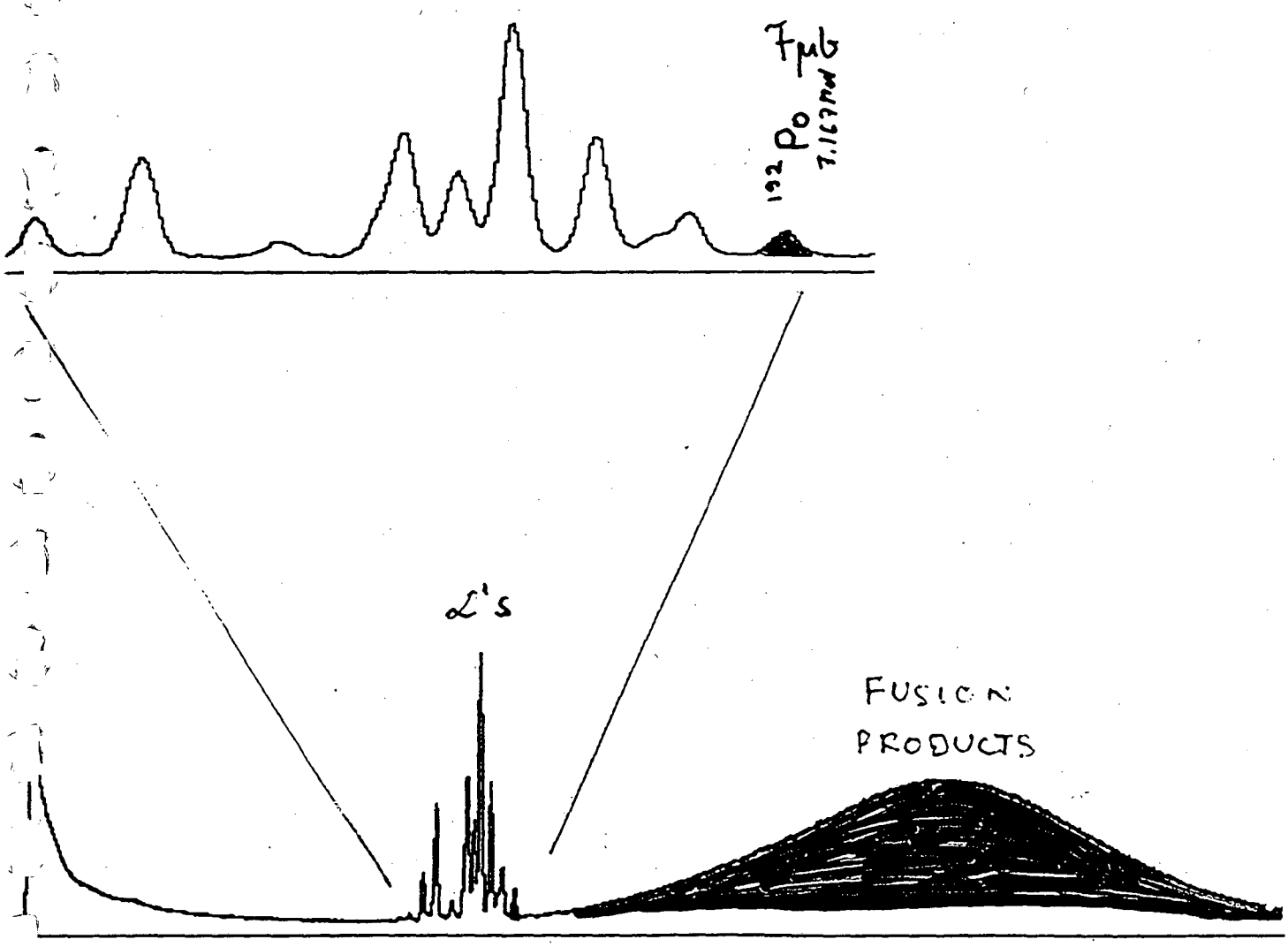




⇒ granularity ~100

FOCAL PLANE Si-DETECTOR SPECTRUM FROM

$$^{160}Dy + {}^{36}Ar \xrightarrow{xn} Po \xrightarrow{\alpha}$$
$$176\ MeV \xrightarrow{pxn} Bi \xrightarrow{\alpha}$$

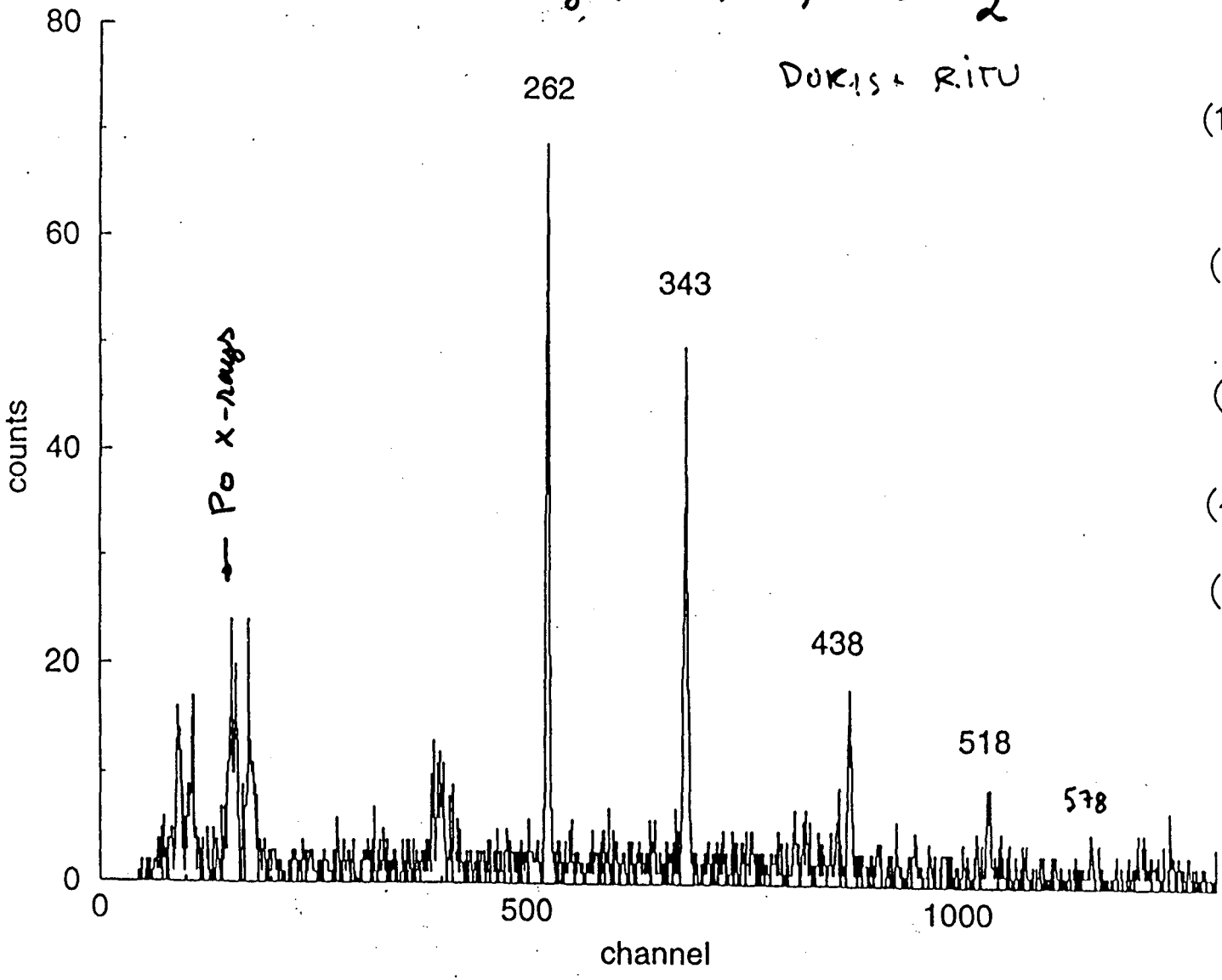


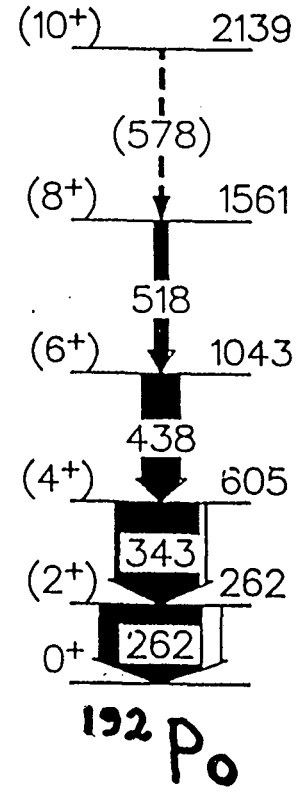
RECOIL GATED α-TAGGED γ RAYS

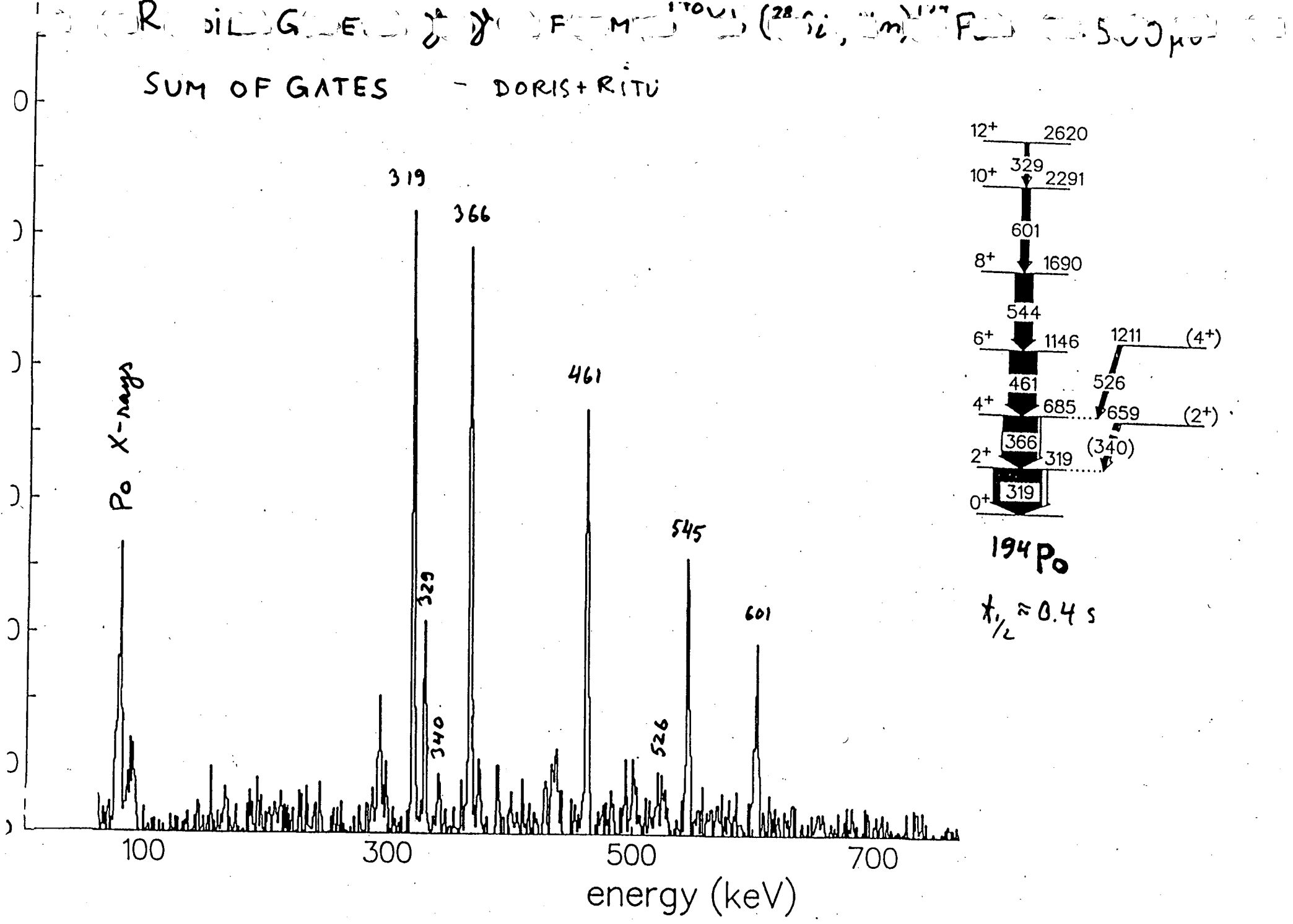
FROM $^{160}Dy(^{36}Ar, 4n)^{192}Po \xrightarrow[\alpha]{35ms}$

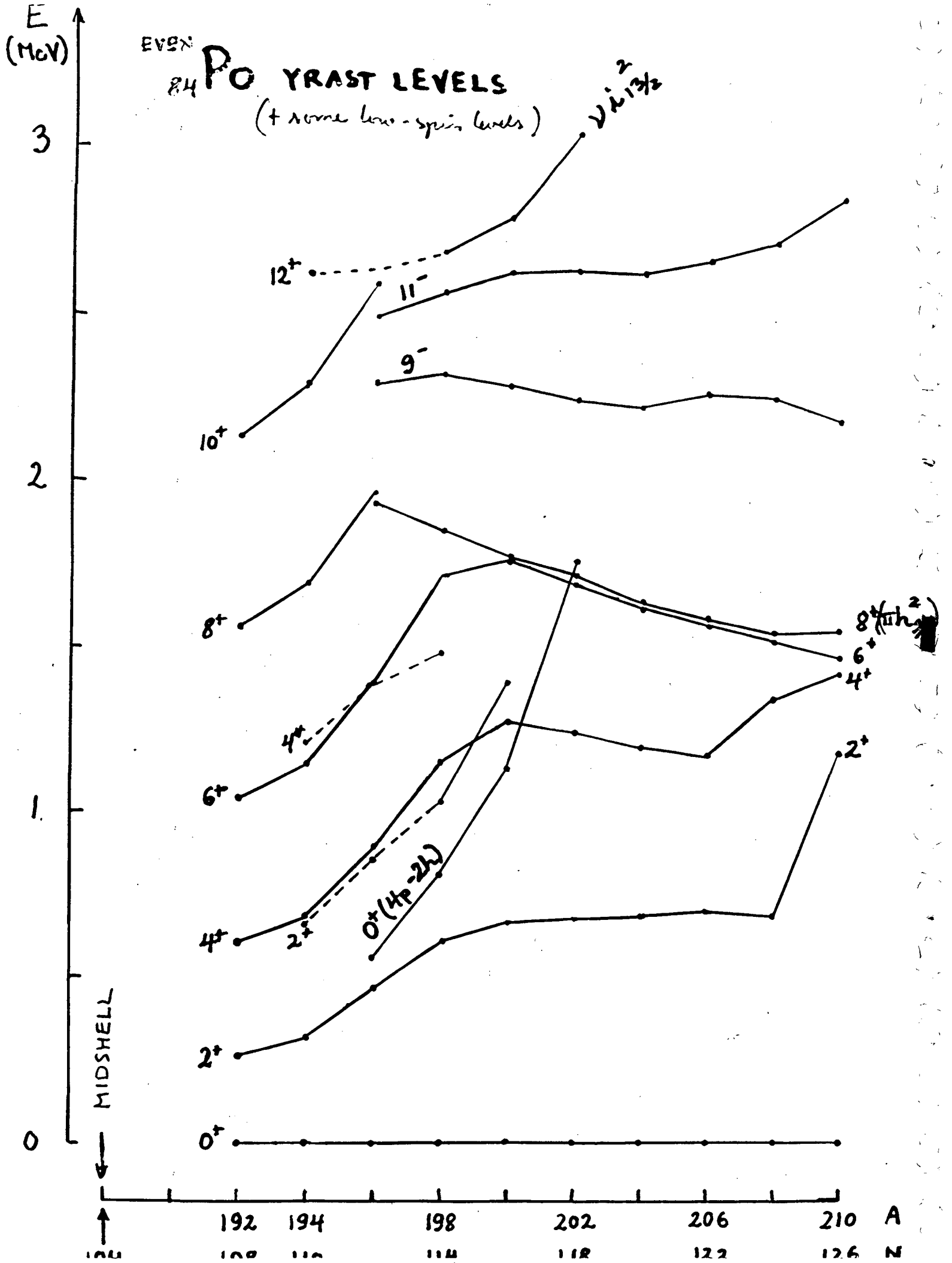
~ 7μb !

DORIS + RITU

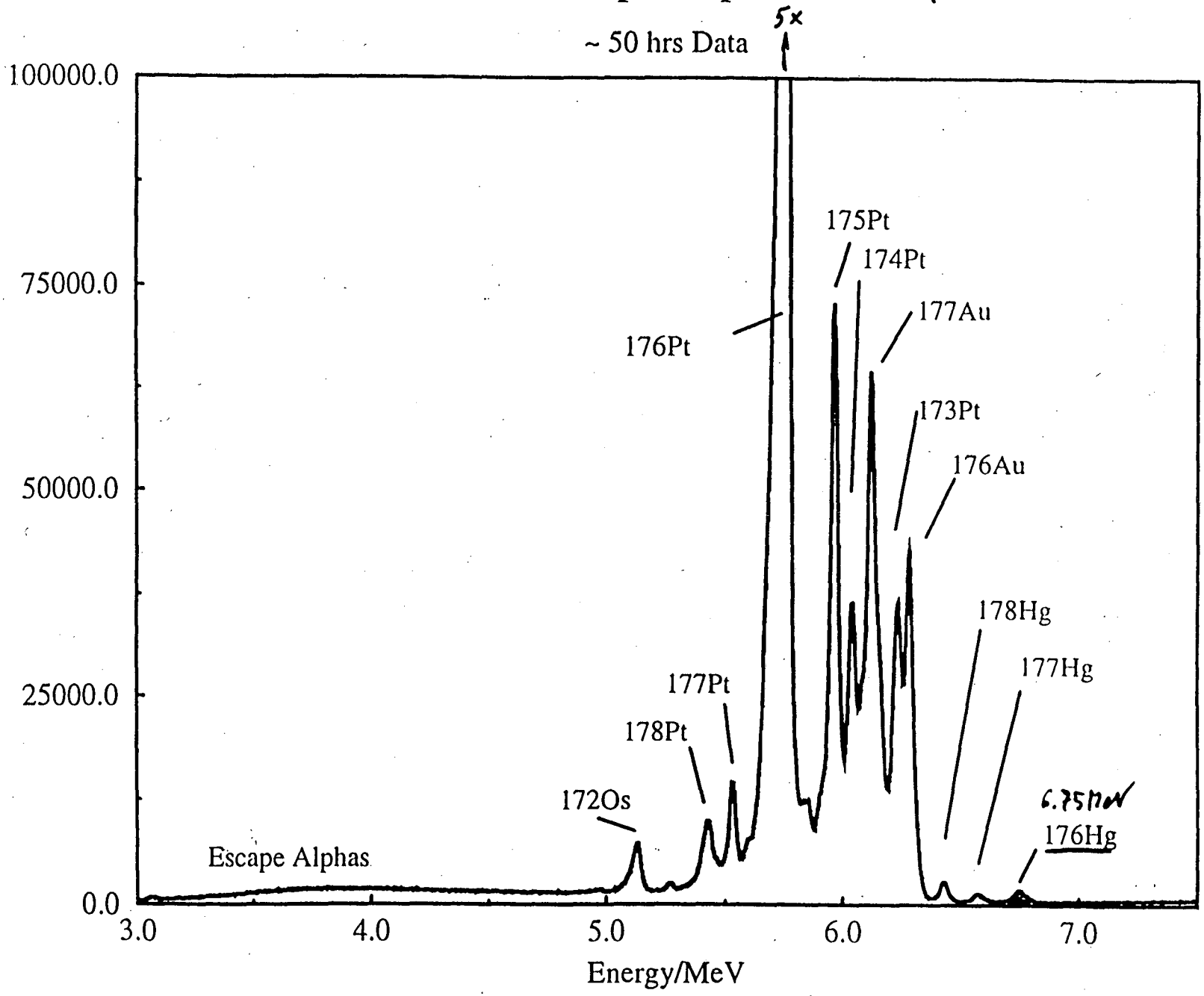





SUM OF GATES - DORIS + RITU
Po X-rays
319
366
461
545
601
329
340
526
100
300
500
700
energy (keV)
12+ 2620
329
10+ 2291
601
8+ 1690
544
6+ 1146
1211 (4+)
461
526
4+ 685
659 (2+)
366
(340)
2+ 319
319
0+
194Po
t1/2 ≈ 0.4 s

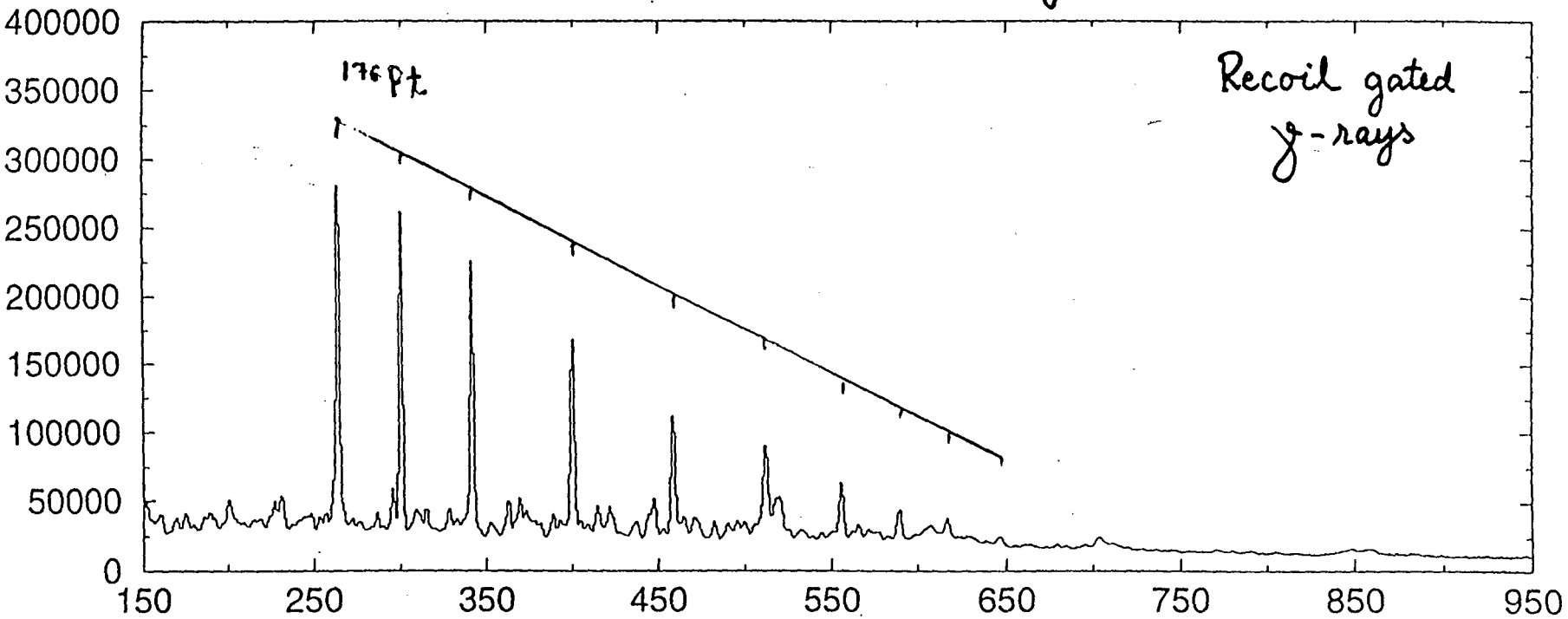

EVEN
84 Po YRAST LEVELS
(+ some low-spin levels)
E (MeV)
3
2
1
0
12+
11−
9−
10+
8+
6+
4+
2+
0+
4+
2+
0+(4p-2h)
8+(πh²)
6+
4+
2+
MIDSHELL
192
194
198
202
206
210
A
N

Total Alpha Spectrum from $^{36}Ar + ^{144}Sm \rightarrow ^{180}Hg^*$

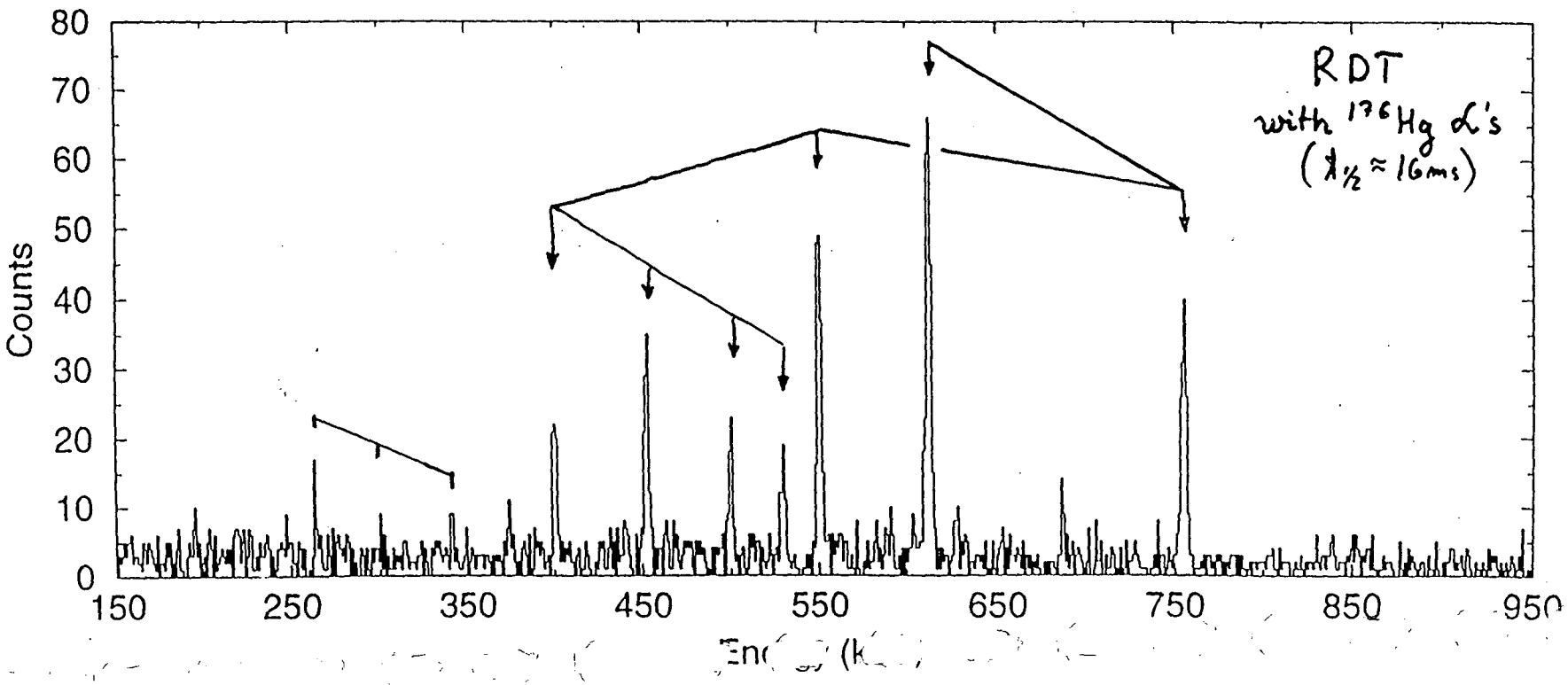


JUROSPHERE + RITU
~50h run

$^{36}Ar + ^{144}Sm \rightarrow ^{180}Hg^{*} \rightarrow$



2p 2n ch
dominat

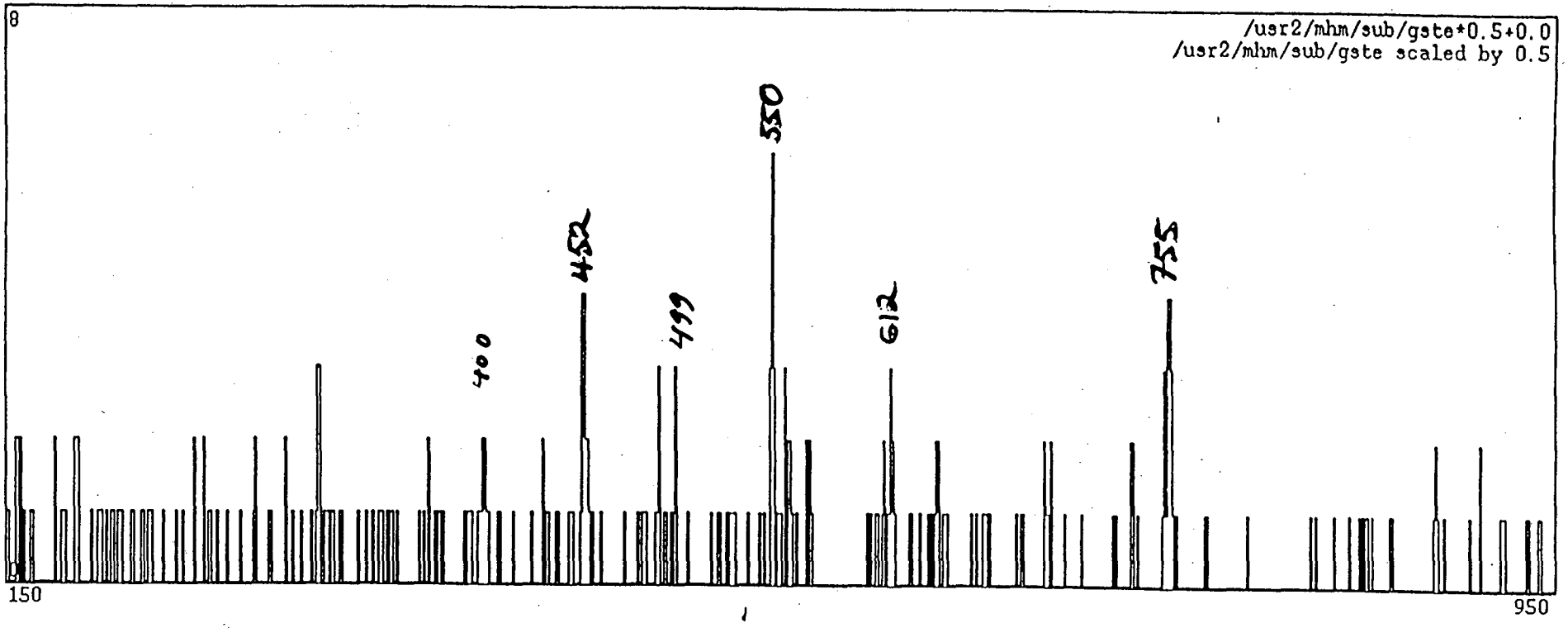


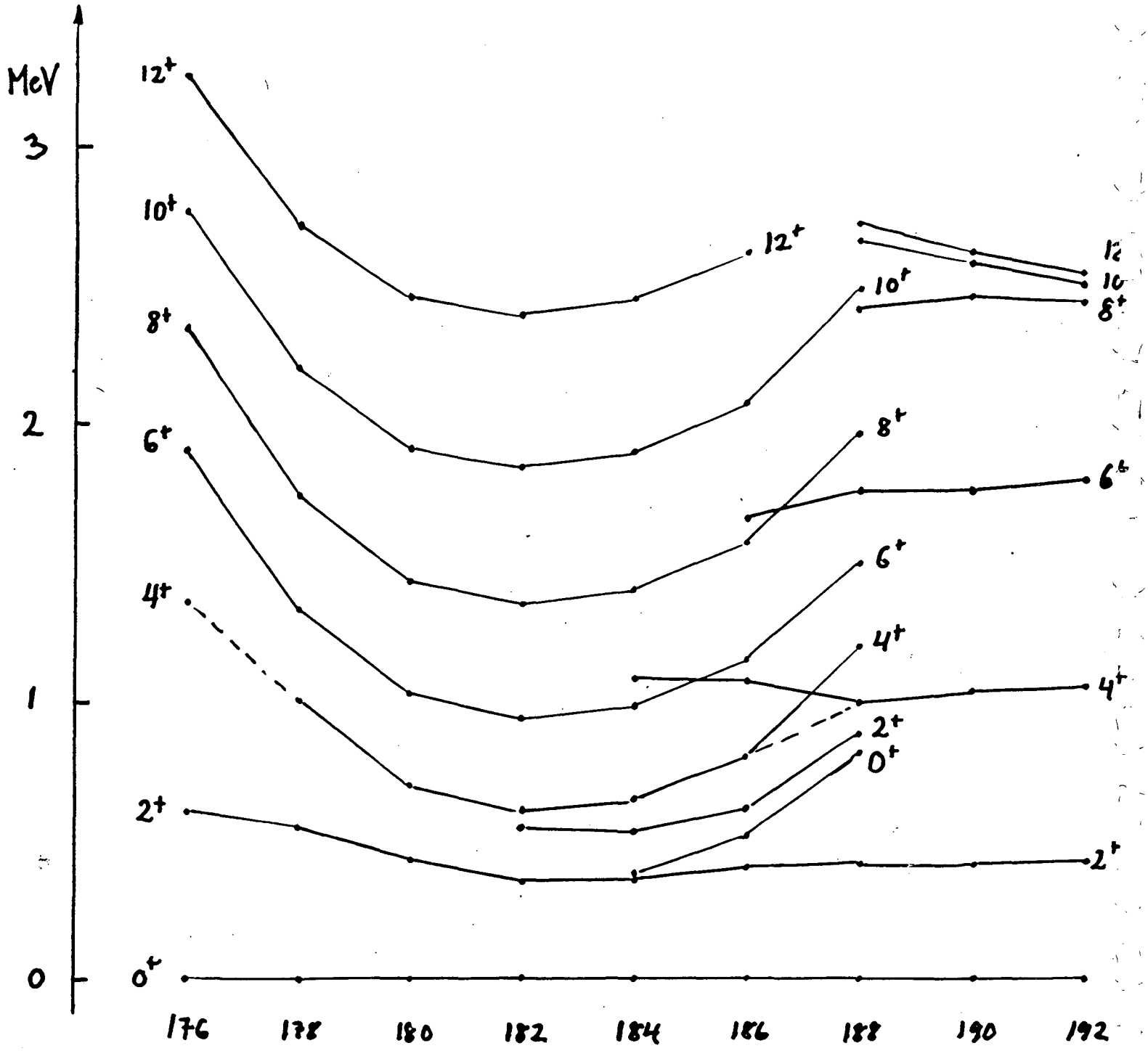
4n channe
~ 2μb

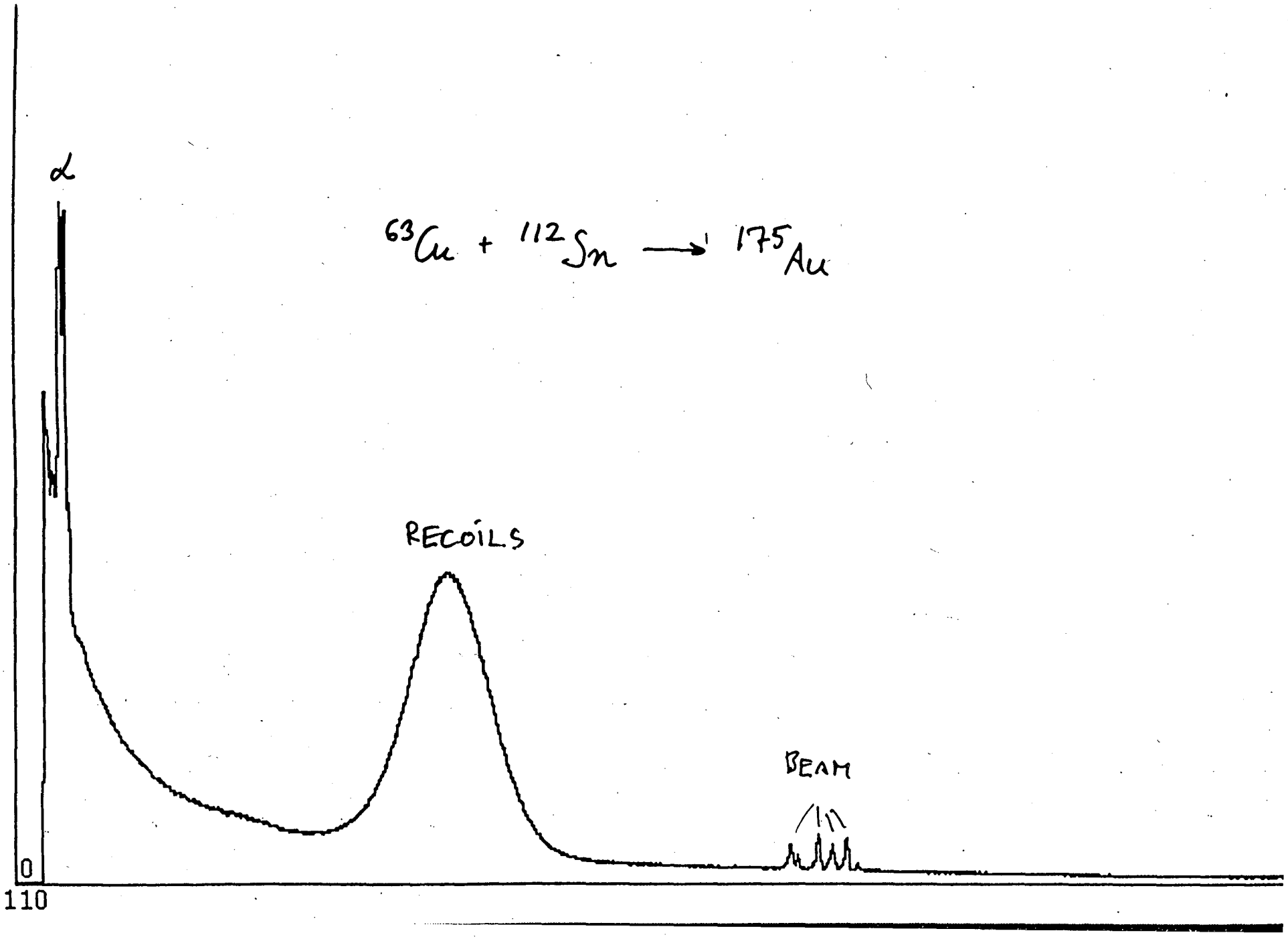
RDT γγ

with ^{176}Hg α's

Sum of gates




MeV
3
2
1
0
12+
10+
8+
6+
4+
2+
0+
176
178
180
182
184
186
188
190
192


α
$^{63}Cu + ^{112}Sn \rightarrow ^{175}Au$
RECOILS
BEAM
0
110

RITU

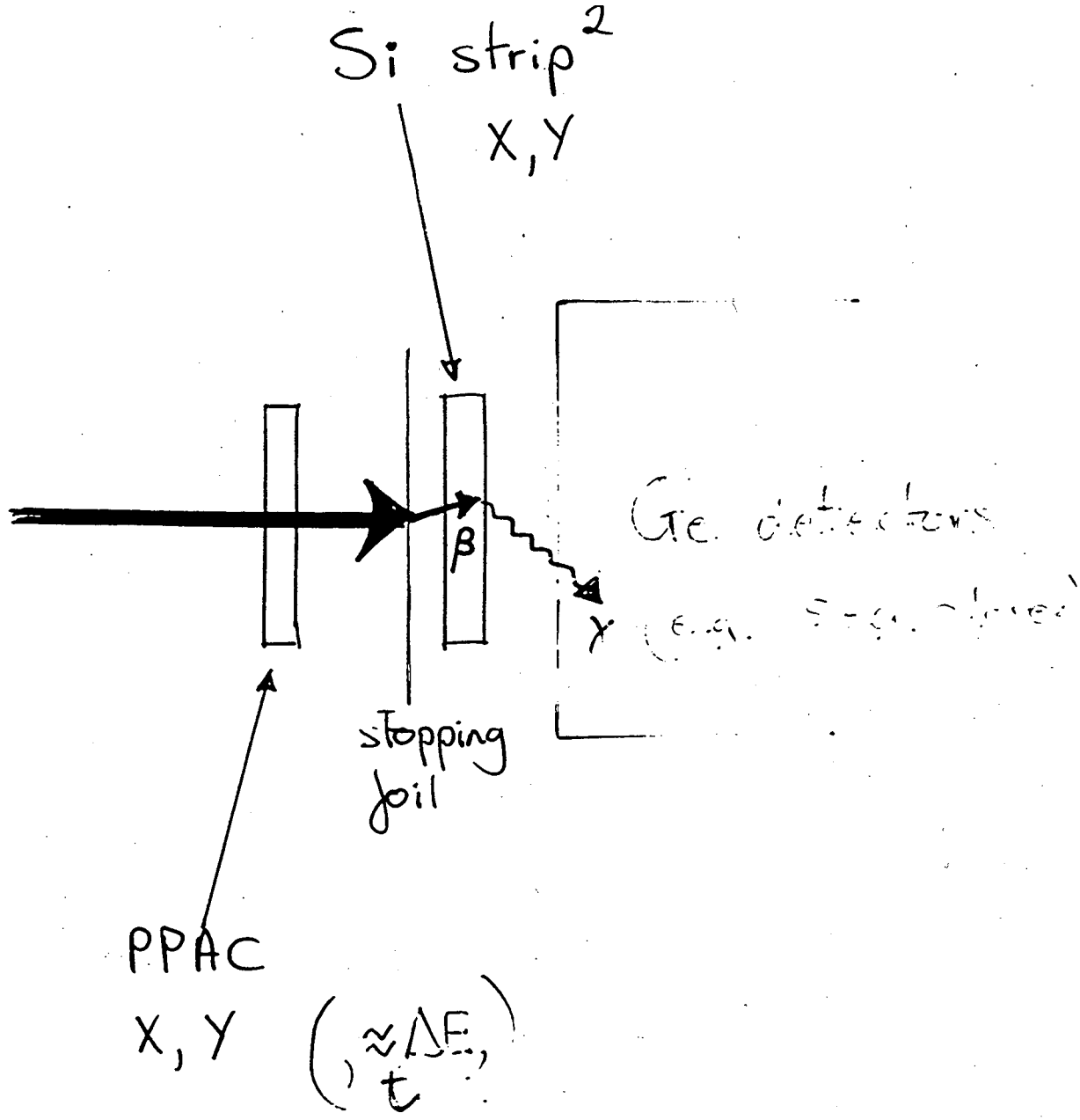
GAS-FILLED SEPARATOR FOR FUSION EVAP. RECOILS

+

- HIGH TRANSMISSION (< 50%)
- SIMPLE TO OPERATE
- PERFECT BEAM DUMP ($< 10^{-12}$)
- INEXPENSIVE
- TARGET COOLING

−

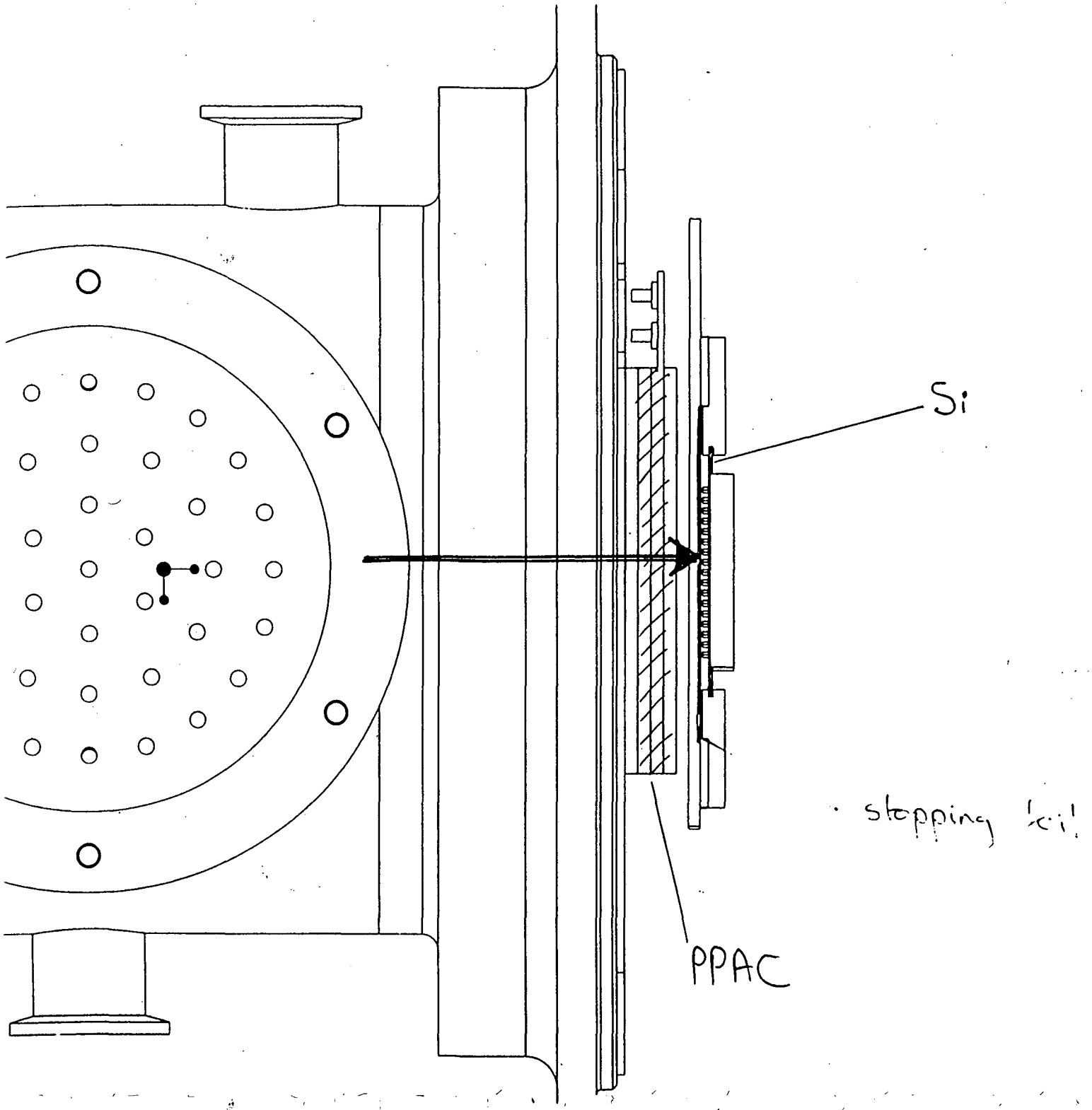
- NO A AND Z SELECTION (WITHOUT ADD. DETECTORS)
- SYMMETRIC REACTIONS (SO FAR $^{63}Cu + ^{106}Cd$)



Prompt γ – Recoil

Recoil – β

β – delayed γ


Si
stopping foil
PPAC

R1

PHYSICAL REVIEW C VOLUME 54, NUMBER 6 DECEMBER 1996

First observation of excited states in ^{192}Po

K. Helariutta, T. Enqvist, P. Jones, R. Julin, S. Juutinen, P. Jämsen, H. Kankaanpää, P. Kuusiniemi, M. Leino, M. Muikku, M. Piiparinen, A. Savelius, W. H. Trzaska, S. Törmänen, and J. Uusitalo
University of Jyväskylä, Department of Physics, P.O. Box 35, 40351 Jyväskylä, Finland

R. G. Allatt, P. A. Butler, P. T. Greenlees, and R. D. Page
Oliver Lodge Laboratory, Department of Physics, University of Liverpool, Liverpool, L69 3BX, United Kingdom
(Received 13 September 1996)

γ-rays following the ^{160}Dy(^{36}Ar,4n)^{192}Po reaction have been identified by employing a high-transmission gas-filled separator in recoil decay tagging measurements. The deduced level scheme reveals a flattening of the energy systematics, when going towards the neutron midshell indicating that the deformed intruder structures have become yrast. [S0556-2813(96)50212-8]

Peter Butler
University of Liverpool

P. Butler

γ AND e^- SPECTROSCOPY

$A \gtrsim 220$

1. Octupoles

   CN reactions - U

   Deep inelastic - Rn, Ra etc

2. SD and HD

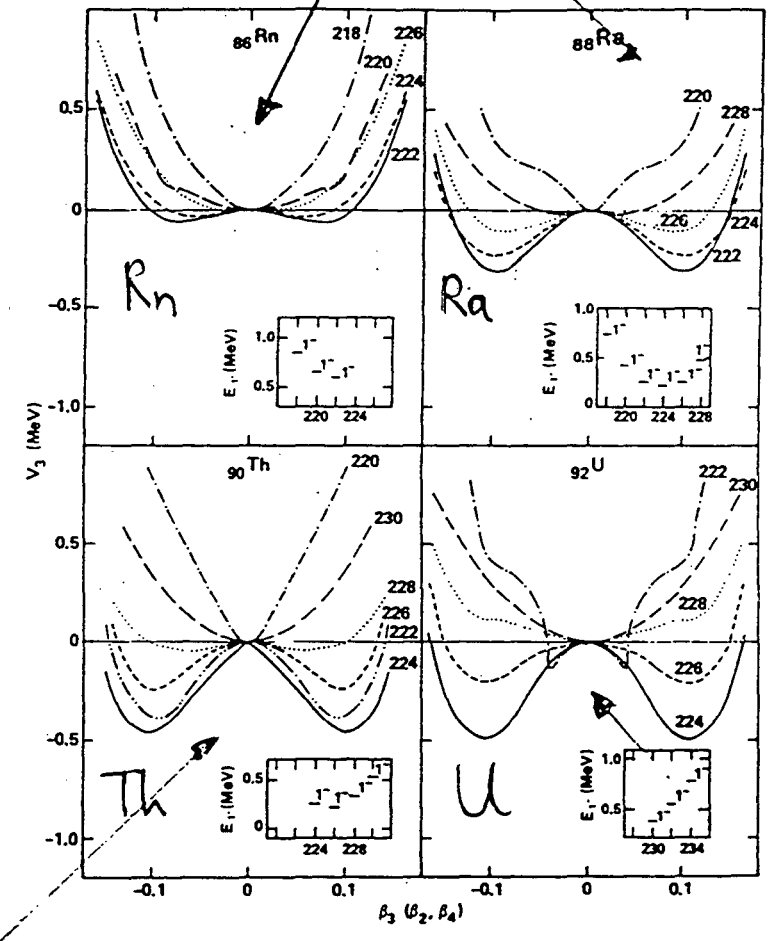
   e^- coincidences

   γ coincidences

transfer reactions

$\sigma \lesssim 1$ mb

V (MeV)



β_3

CN reactions

$\sigma \sim 10$ mb

OR

Transfer

$\sigma \sim 10$ mb

CN reactions

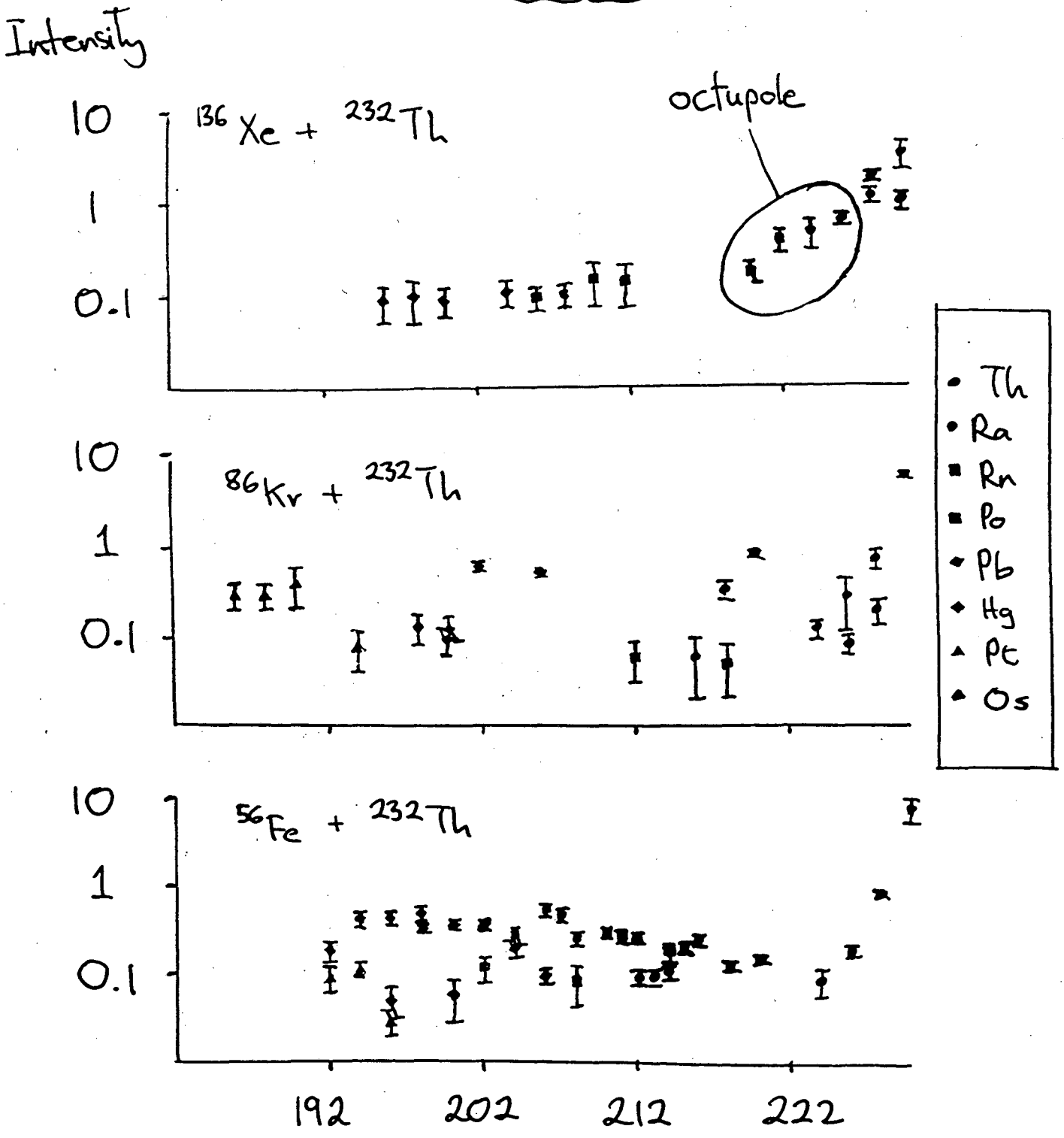
$\sigma \sim 1$ μb

Fig 1

W. Nazarewicz et al

Nucl. Phys. A429 (1984) 269

REACTIONS

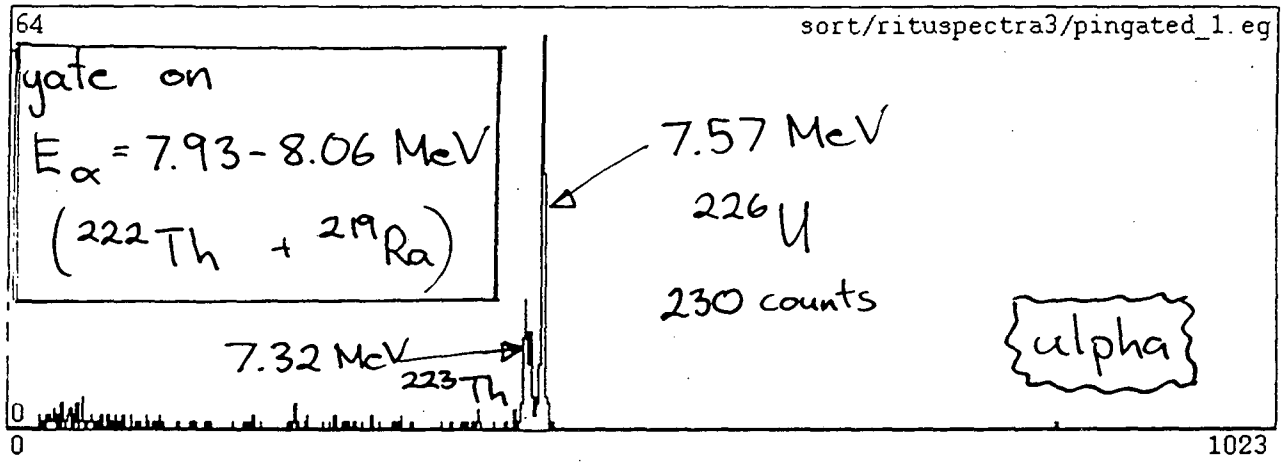

Intensity
10
1
0.1
$^{136}Xe + ^{232}Th$
octupole
$^{86}Kr + ^{232}Th$
$^{56}Fe + ^{232}Th$
192
202
212
222
Th
Ra
Rn
Po
Pb
Hg
Pt
Os

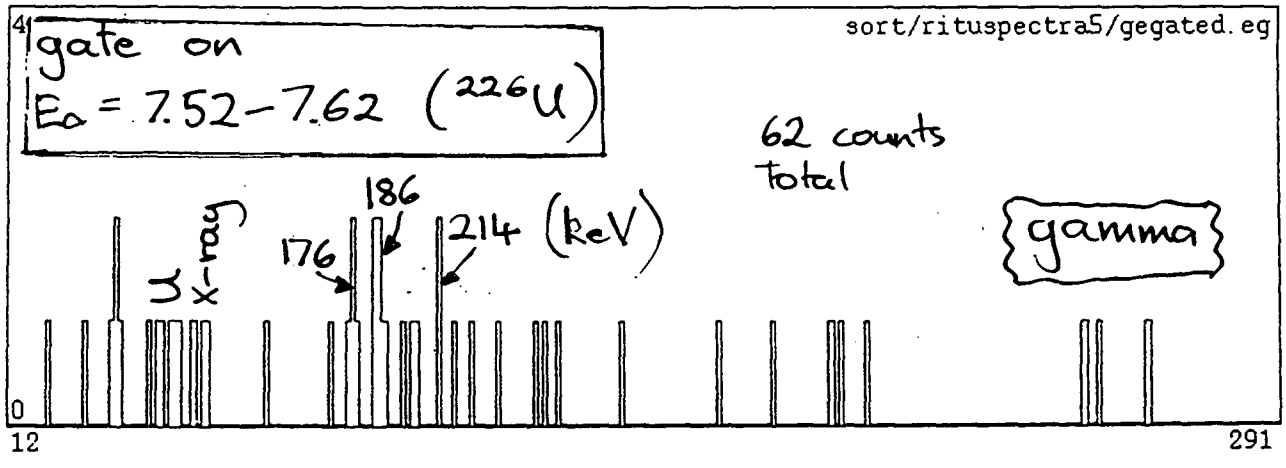
112 MeV $^{208}Pb(^{22}Ne, 4n)^{226}U$

$\sigma \sim 5\mu b$

DORIS + RITU (Jyväskylä)

12 hour run

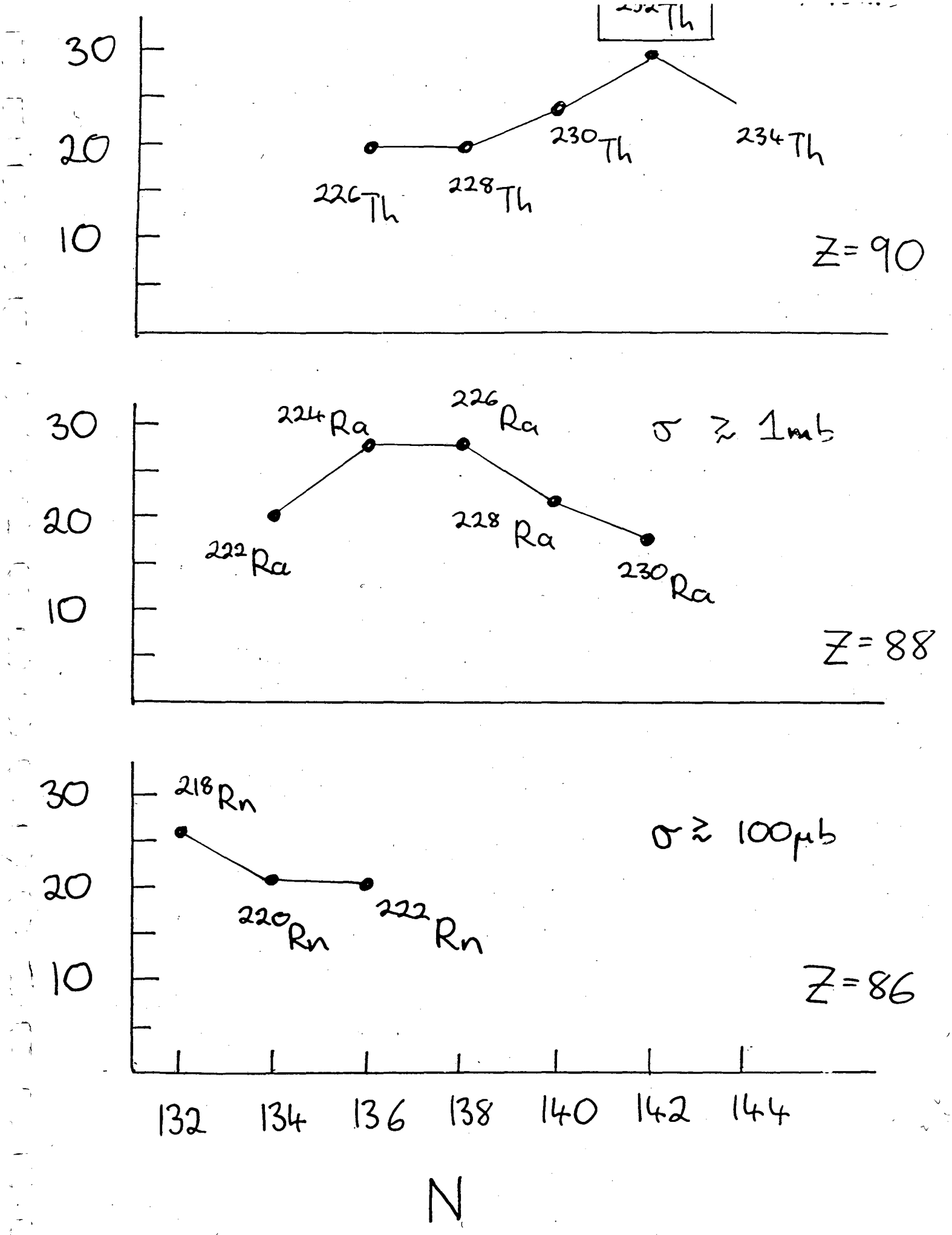


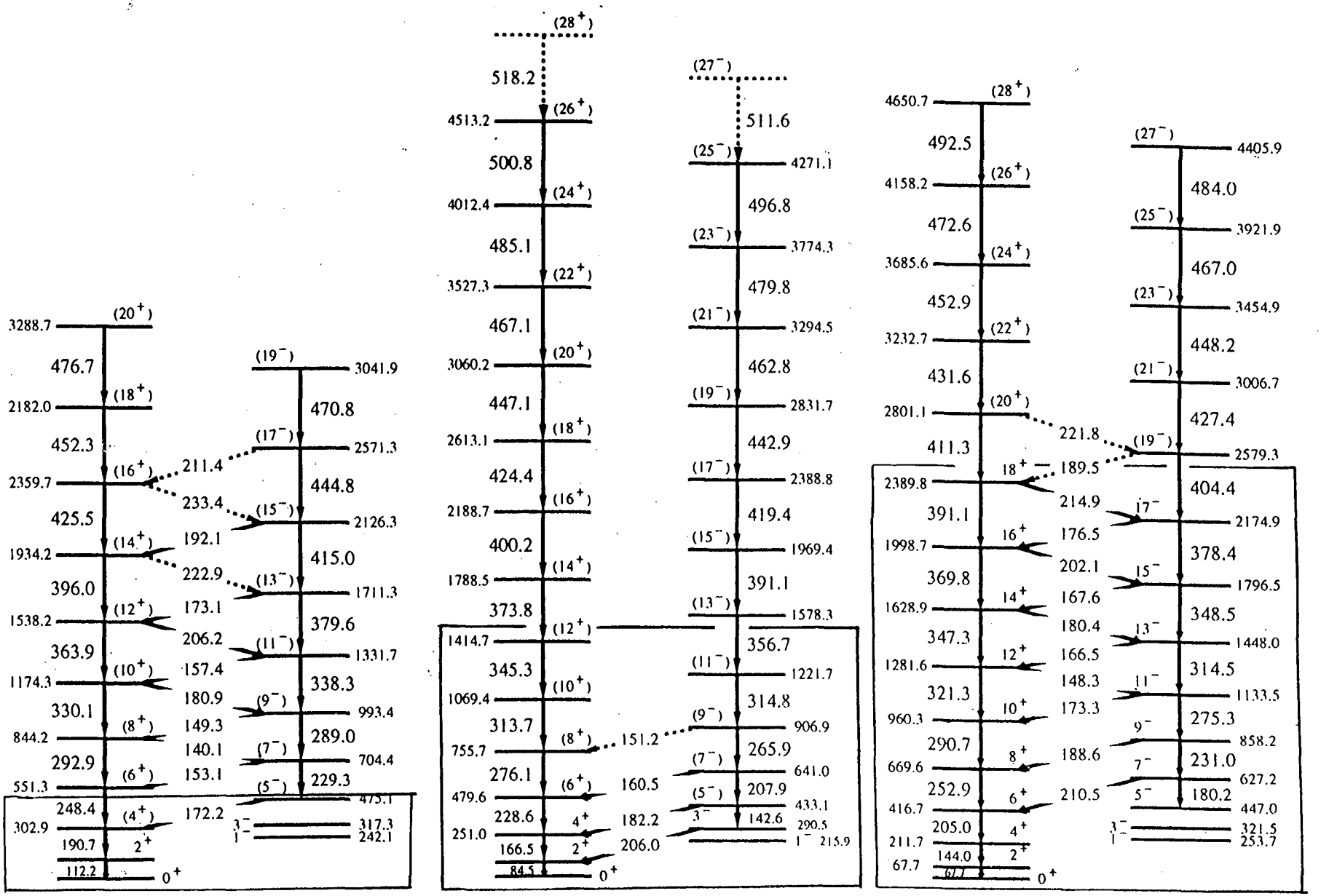


(^{224}U : $\sigma \sim 1\mu b$)

JUROSPHERE EXPT SCHEDULED

21 APRIL - 4 MAY 1997


232Th
30
20
10
226Th
228Th
230Th
234Th
Z=90
30
20
10
224Ra
226Ra
σ ≳ 1mb
222Ra
228 Ra
230Ra
Z=88
30
20
10
218Rn
σ ≳ 100μb
220Rn
222Rn
Z=86
132
134
136
138
140
142
144
N


3288.7 (20+)
476.7
2182.0 (18+)
452.3
2359.7 (16+)
425.5
1934.2 (14+)
396.0
1538.2 (12+)
363.9
1174.3 (10+)
330.1
844.2 (8+)
292.9
551.3 (6+)
248.4
302.9 (4+)
190.7 2+
112.2 0+
211.4
233.4
192.1
222.9
173.1
206.2
157.4
180.9
149.3
140.1
153.1
172.2
(19−) 3041.9
470.8
(17−) 2571.3
444.8
(15−) 2126.3
415.0
(13−) 1711.3
379.6
(11−) 1331.7
338.3
(9−) 993.4
289.0
(7−) 704.4
229.3
(5−) 475.1
3− 317.3
1− 242.1
222 88 Ra
(28+)
518.2
4513.2 (26+)
500.8
4012.4 (24+)
485.1
3527.3 (22+)
467.1
3060.2 (20+)
447.1
2613.1 (18+)
424.4
2188.7 (16+)
400.2
1788.5 (14+)
373.8
1414.7 (12+)
345.3
1069.4 (10+)
313.7
755.7 (8+)
276.1
479.6 (6+)
228.6
251.0 4+
166.5 2+
84.5 0+
151.2
160.5
182.2
206.0
(27−)
511.6
(25−) 4271.1
496.8
(23−) 3774.3
479.8
(21−) 3294.5
462.8
(19−) 2831.7
442.9
(17−) 2388.8
419.4
(15−) 1969.4
391.1
(13−) 1578.3
356.7
(11−) 1221.7
314.8
(9−) 906.9
265.9
(7−) 641.0
207.9
(5−) 433.1
3− 142.6 290.5
1− 215.9
224 88 Ra
4650.7 (28+)
492.5
4158.2 (26+)
472.6
3685.6 (24+)
452.9
3232.7 (22+)
431.6
2801.1 (20+)
411.3
2389.8 18+
391.1
1998.7 16+
369.8
1628.9 14+
347.3
1281.6 12+
321.3
960.3 10+
290.7
669.6 8+
252.9
416.7 6+
205.0
211.7 4+
144.0
67.7 2+
67.7 0+
221.8
189.5
214.9
176.5
202.1
167.6
180.4
166.5
148.3
173.3
188.6
210.5
(27−) 4405.9
484.0
(25−) 3921.9
467.0
(23−) 3454.9
448.2
(21−) 3006.7
427.4
(19−) 2579.3
404.4
17− 2174.9
378.4
15− 1796.5
348.5
13− 1448.0
314.5
11− 1133.5
275.3
9− 858.2
231.0
7− 627.2
180.2
5− 447.0
3− 321.5
1− 253.7
226 88 Ra

SUMMARY OF RESULTS SO FAR

(J.F.C. Cocks et al.
Phys Rev Lett. April 1997)

#1 I_x (−ve parity) − I_x (+ve parity)

= 3 Octupole Vibration

218, 220, 222 Rn

228 Ra

228, 230, 232, 234 Th

→ 0 Octupole Deformed

222, 224, 226 Ra

(224), 226 Th

#2 D_0 remains constant with spin

Dip seen at ^{224}Ra

− shell cancellation

DEEP INELASTIC REACTIONS

$E \sim 15\text{-}20\%$ above Coulomb barrier

Require $d\Omega \sim 1\,sr$ (at least 100m)

$\Delta p \sim 15\%$

% of products $\sim 5\text{-}10\%$

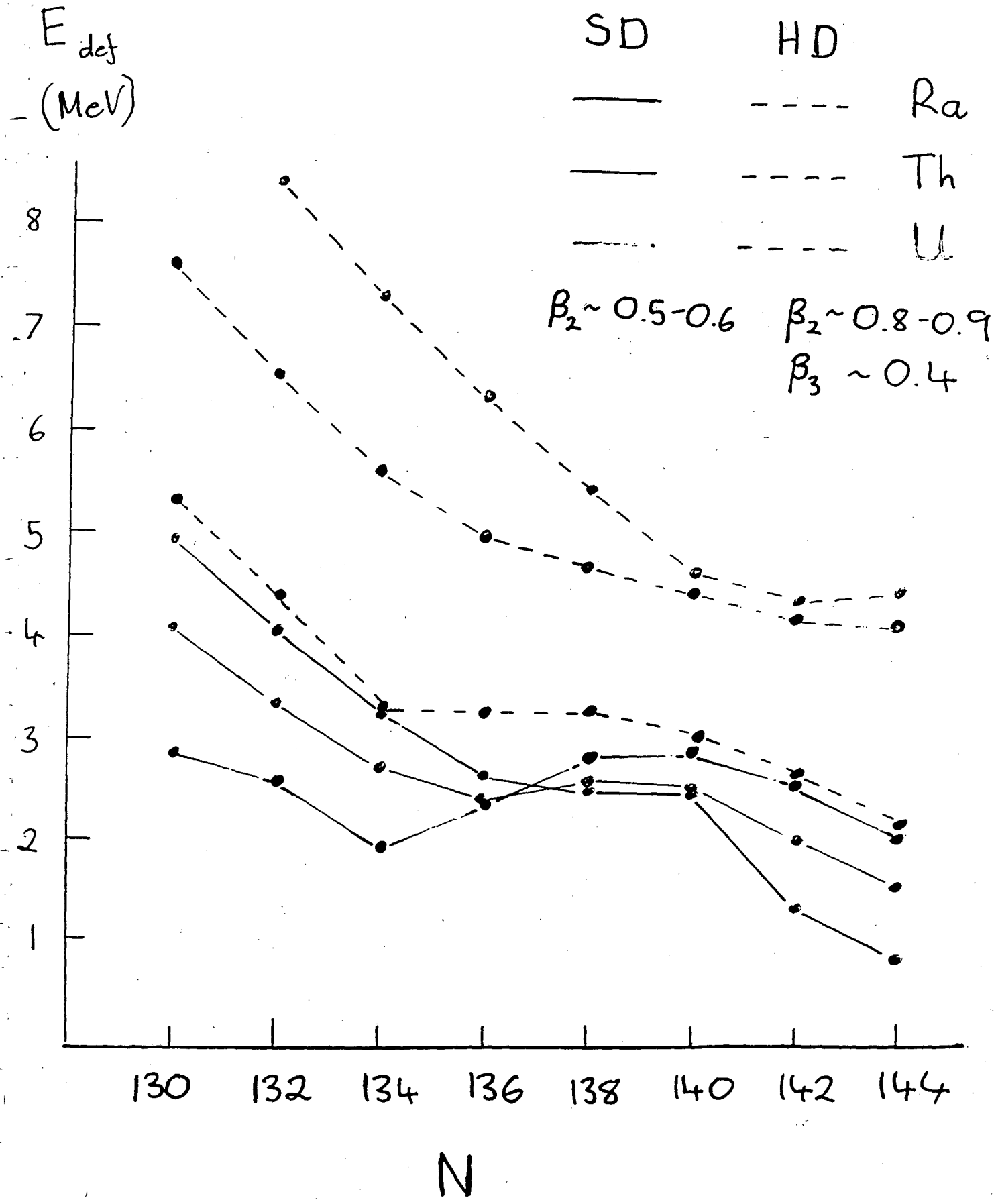
$\therefore \Delta\bar{v}/\bar{v}$ 1%

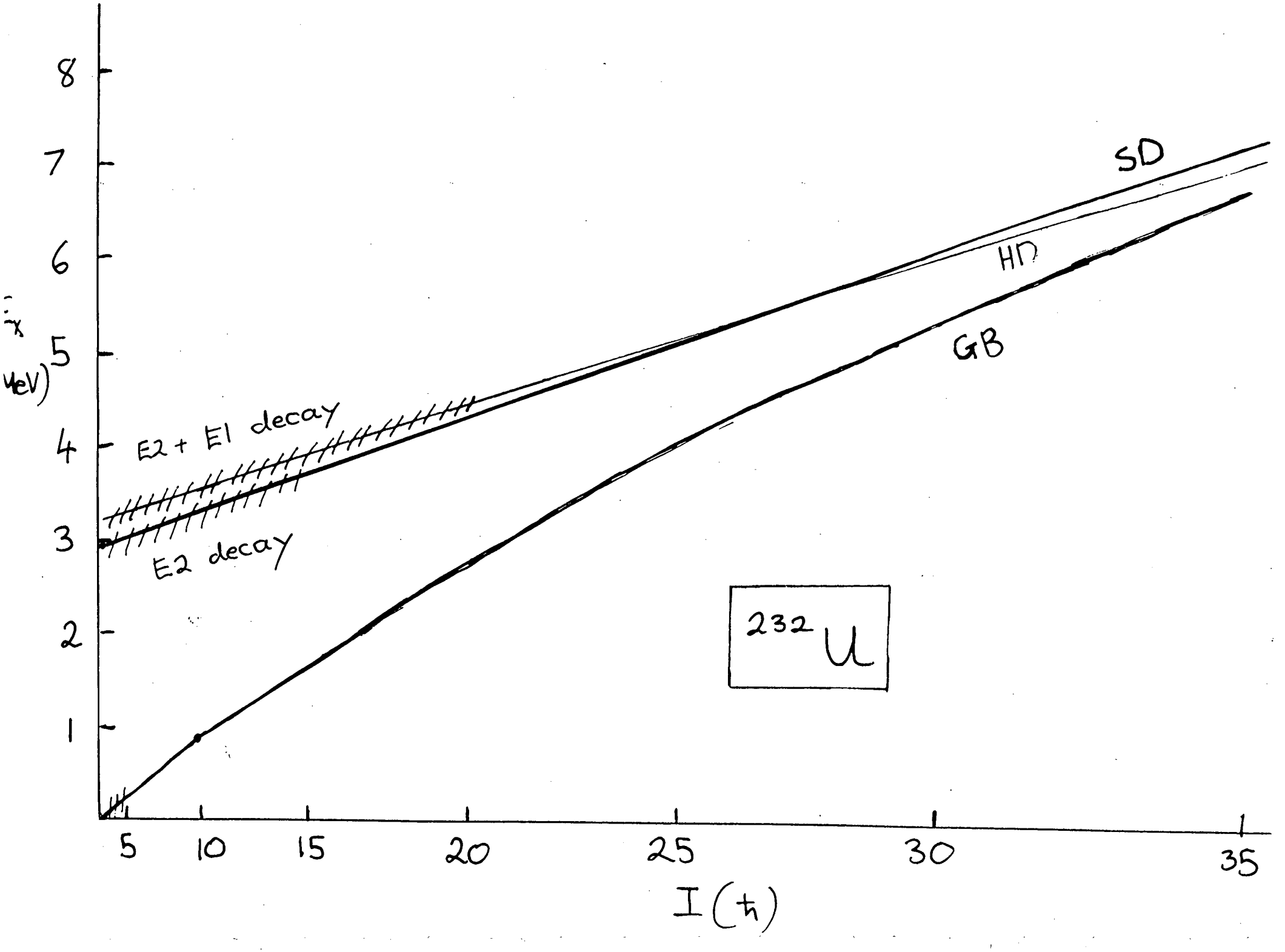
$\Delta Z/Z$ 1%

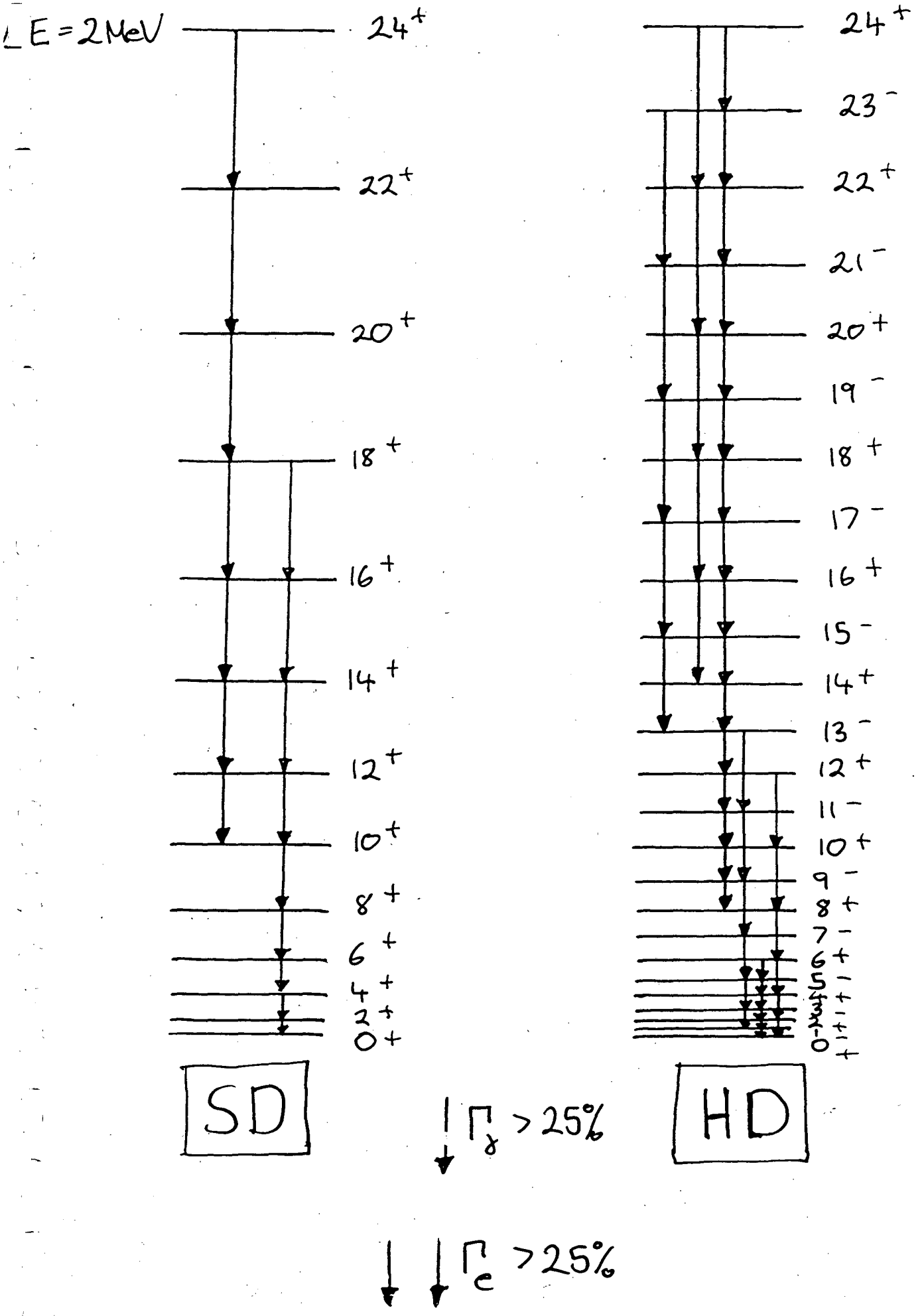
$\Delta A/A$ 0.5%

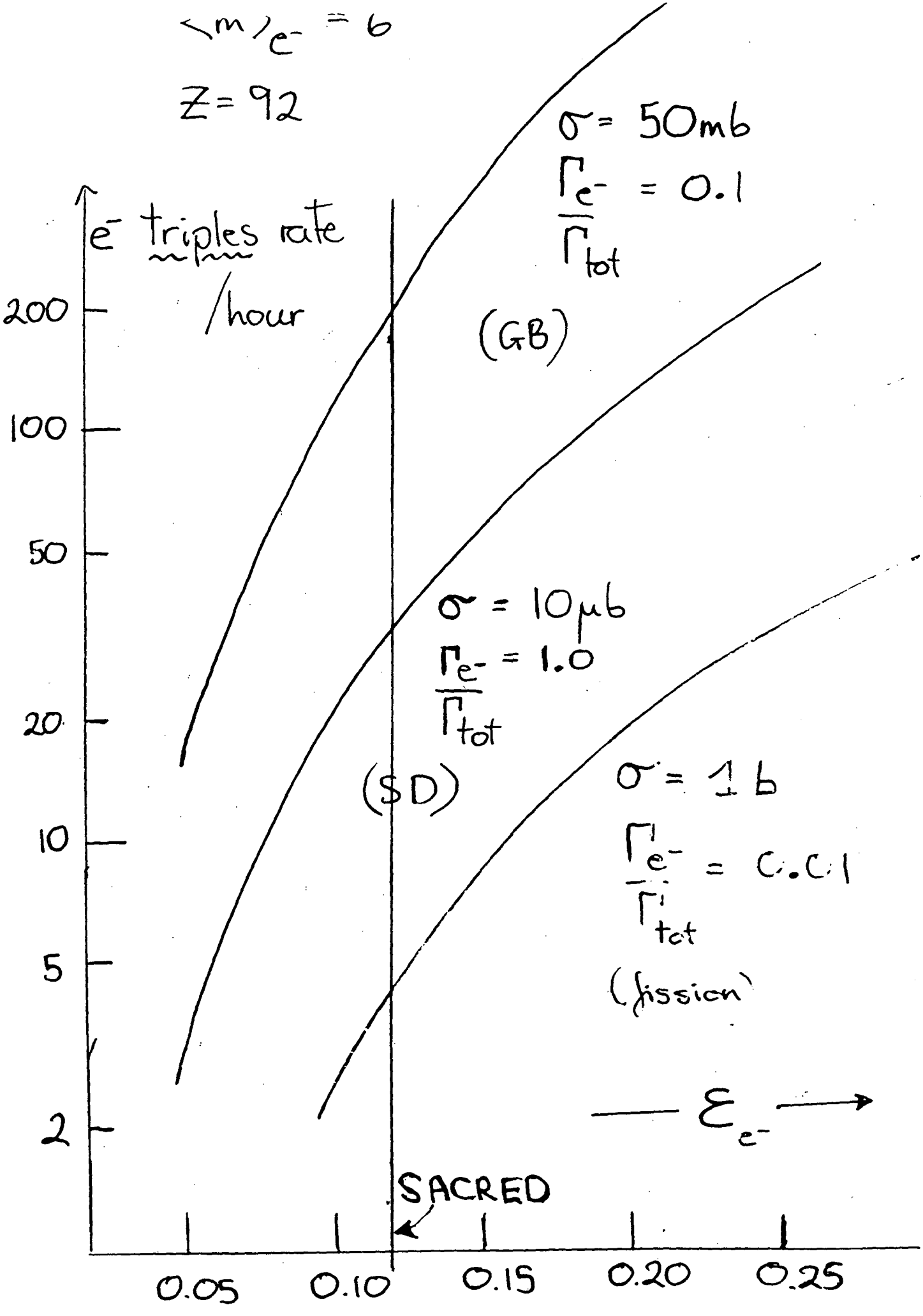
GFS requires dipole etc.

↑ fragment

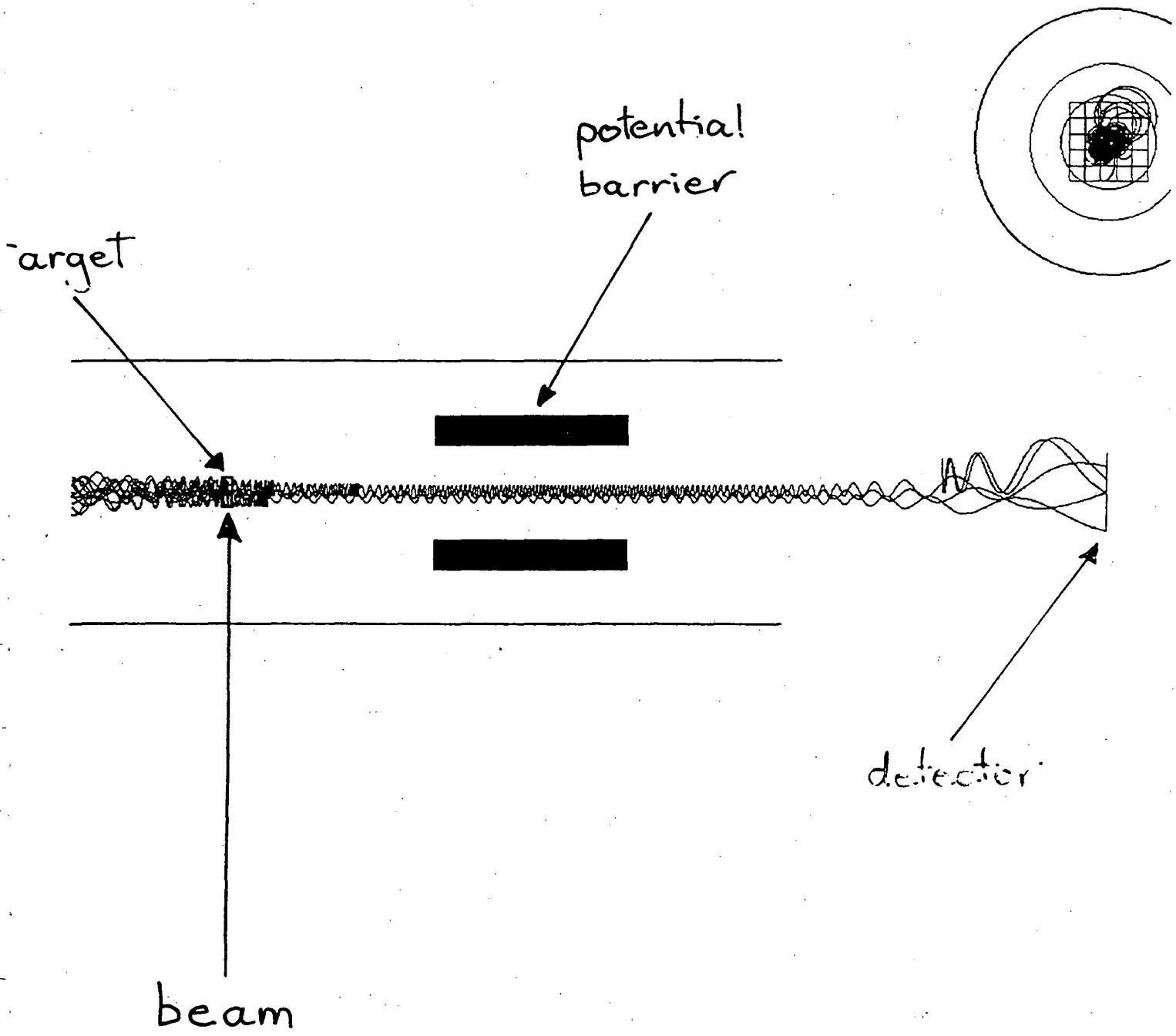

E def
(MeV)
SD
HD
Ra
Th
U
β2 ~ 0.5-0.6
β2 ~ 0.8-0.9
β3 ~ 0.4
8
7
6
5
4
3
2
1
130
132
134
136
138
140
142
144
N


8
7
6
5
4
3
2
1
MeV)
SD
HD
GB
E2 + E1 decay
E2 decay
232 U
5
10
15
20
25
30
35
I (ħ)


E = 2MeV
24+
22+
20+
18+
16+
14+
12+
10+
8+
6+
4+
2+
0+
SD
24+
23−
22+
21−
20+
19−
18+
17−
16+
15−
14+
13−
12+
11−
10+
9−
8+
7−
6+
5−
4+
3−
2+
1−
0+
HD
Γγ > 25%
Γe > 25%


$\langle m \rangle_{e^-} = 6$
$Z = 92$
$\sigma = 50\,mb$
$\frac{\Gamma_{e^-}}{\Gamma_{tot}} = 0.1$
e^- triples rate /hour
200
100
50
20
10
5
2
(GB)
$\sigma = 10\,\mu b$
$\frac{\Gamma_{e^-}}{\Gamma_{tot}} = 1.0$
(SD)
$\sigma = 1\,b$
$\frac{\Gamma_{e^-}}{\Gamma_{tot}} = 0.01$
(fission)
$\mathcal{E}_{e^-}$
SACRED
0.05
0.10
0.15
0.20
0.25

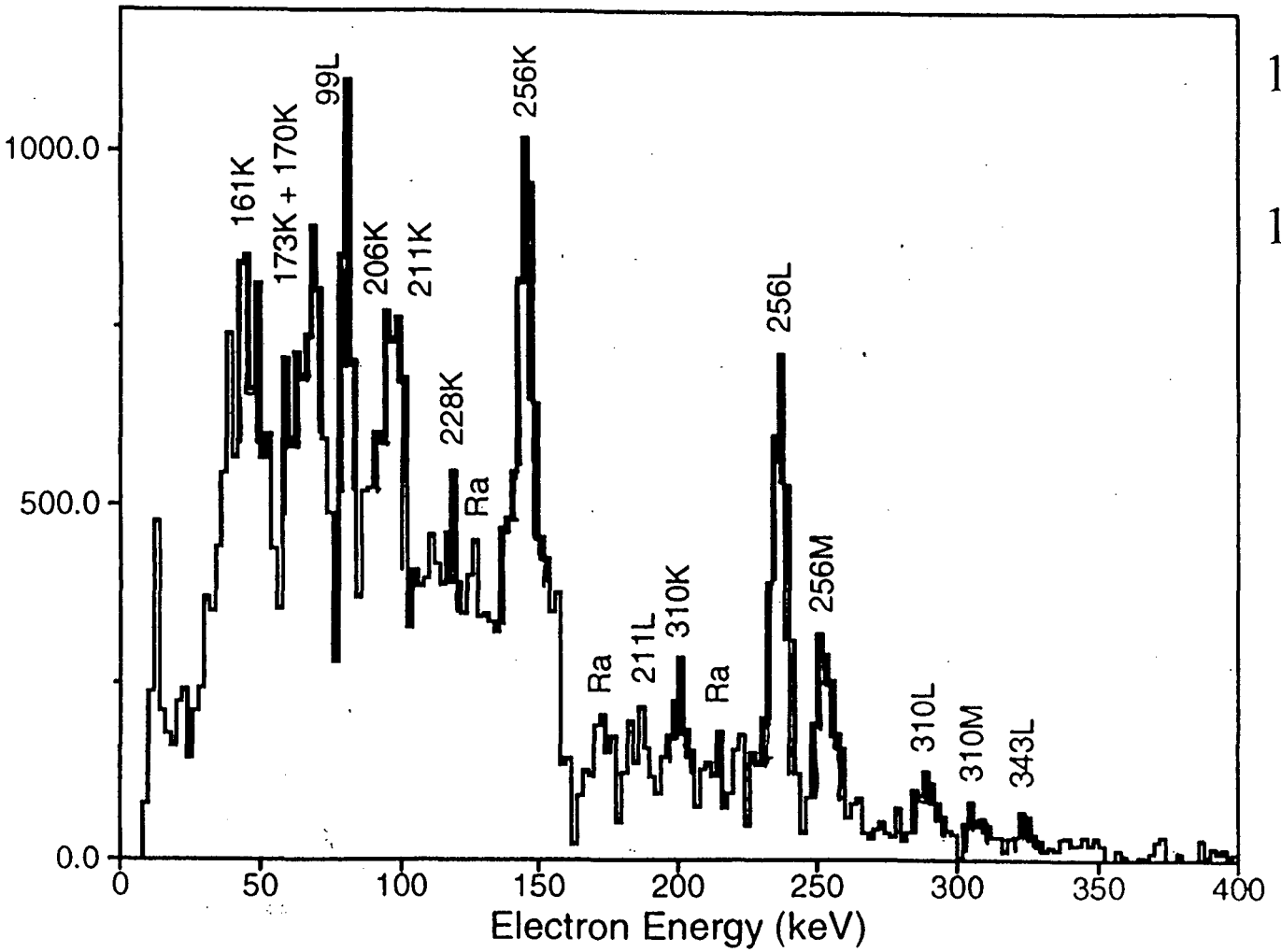
SACRED

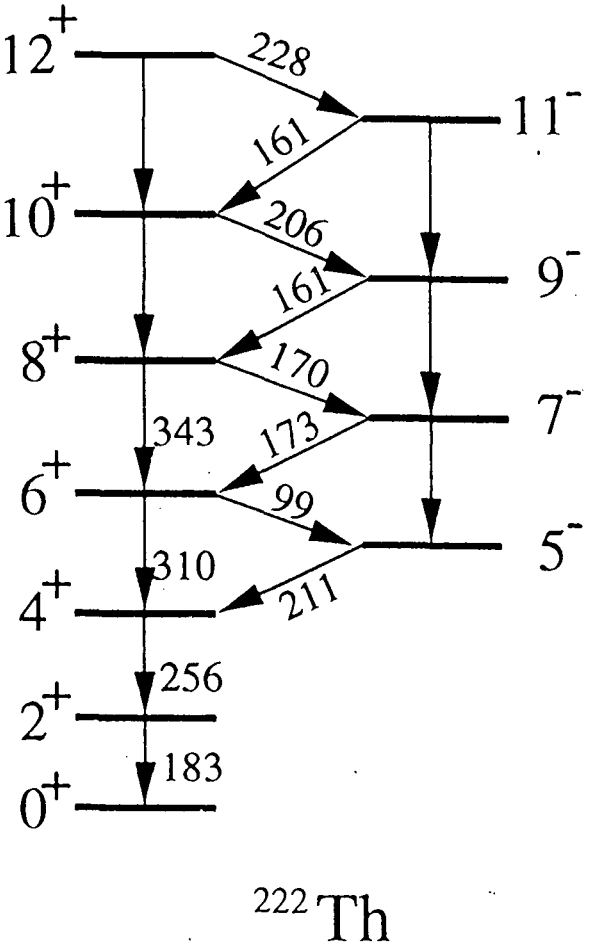


P. A. Butler et al.
NIM A381 (1996) 433

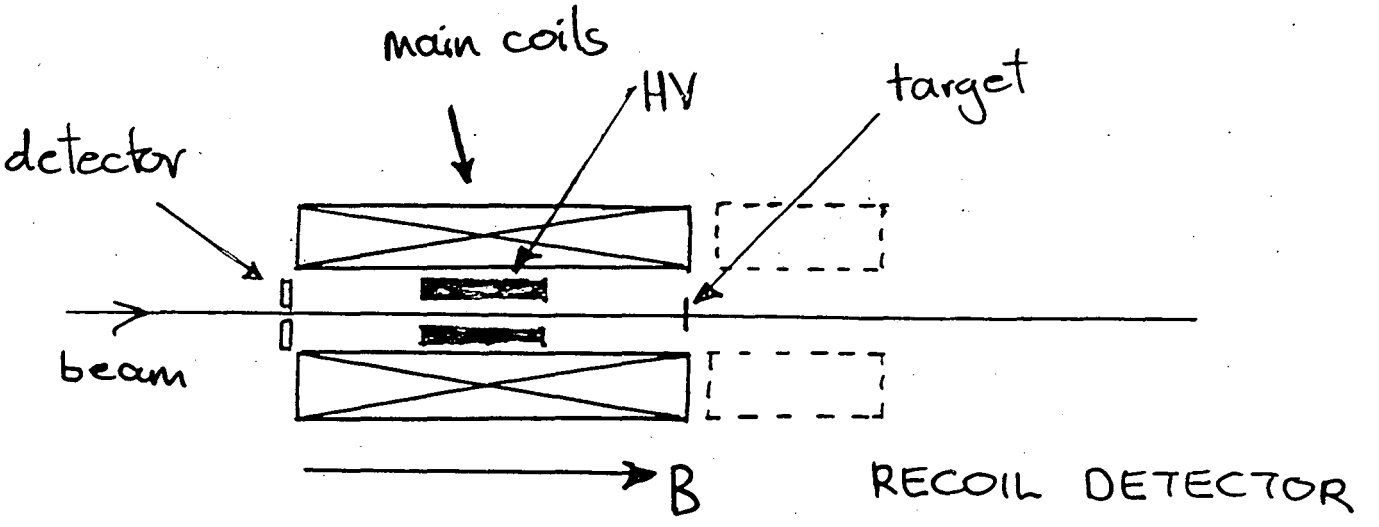
$^{208}Pb(^{18}O, 4n)^{222}Th$ $\sigma \sim 15mb$

Spectrum from Electron-Electron Matrix gated on 183L ($2^+ \rightarrow 0^+$)





SACRED electron array



OR

GAMMASPHERE

high γ-fold detection

Reactions

CN reactions are:

$$^{18}O + {}^{208}Pb \rightarrow {}^{222}Th$$

$$\alpha + {}^{232}Th \rightarrow {}^{230,232}U$$

$$\alpha + {}^{238}U \rightarrow {}^{237,239}Pu \qquad T_{if} \sim \mu s$$

α induced reactions [illegible]

1. DO NOT NEGLECT TRANSFER PRODUCTS

2. DO NOT NEGLECT CONVERSION ELECTRONS

Bill Gelletly
University of Surrey

W. Gelletly (University of Surrey)

Bird's Eye View of N = Z line.

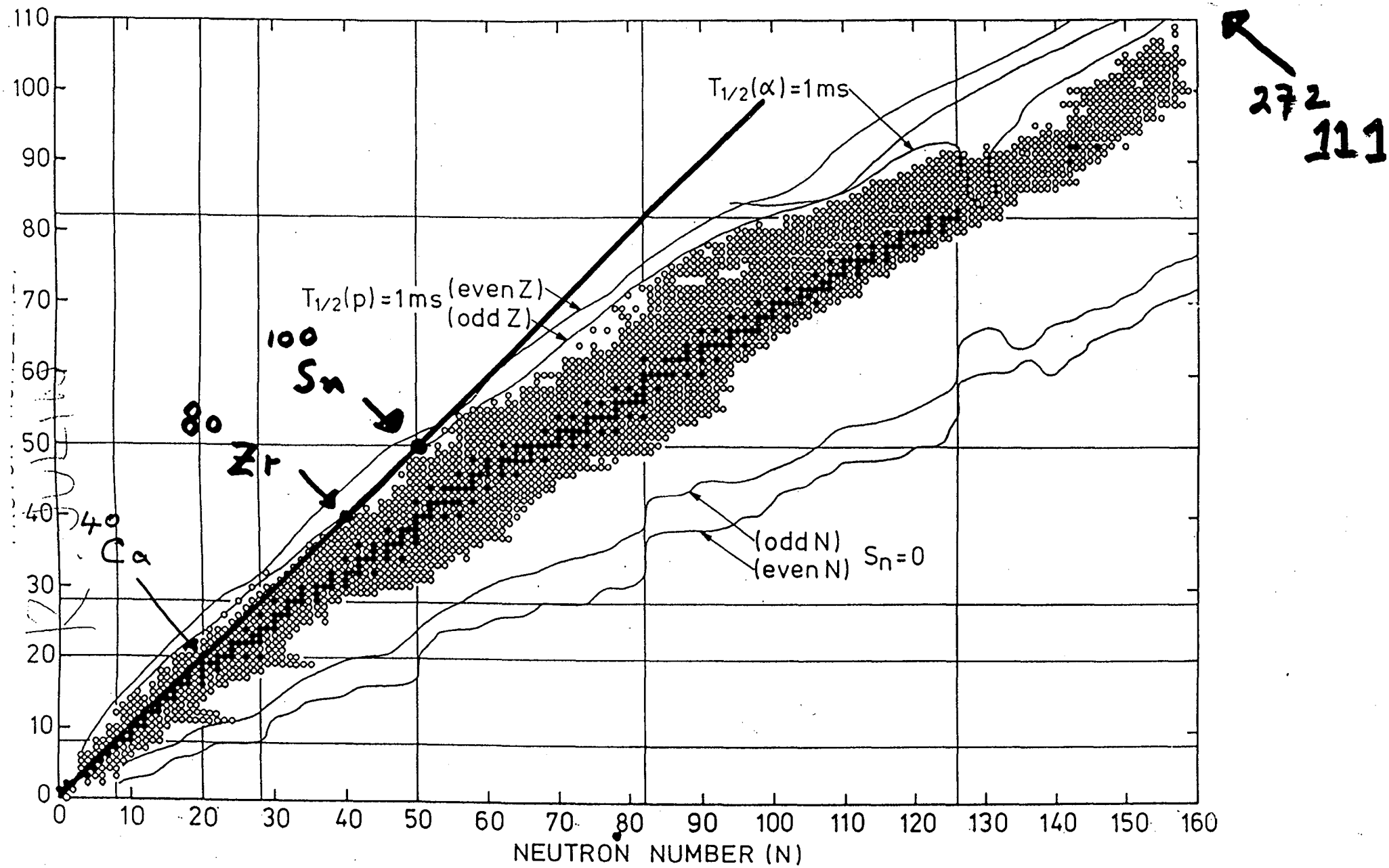
OUTLINE

1. INTRODUCTION
   - Why study N=Z nuclei?
   - How can we study N=Z nuclei?

2. STUDIES WITH FUSION-EVAPORATION REACTIONS
   - Mirror Nuclei
   - Isospin Mixing
   - Shape changes along N=Z line
   - n-p pairing

3. FUTURE OF FUSION-EVAPORATION REACTION STUDIES

4. STUDIES WITH FRAGMENTATION REACTIONS
   - Nature of Experiments
   - New Isotopes
   - Gamma-gating and Identification of Isomers
   - ^{74}Kr
   - Future Studies


$T_{1/2}(\alpha)=1$ms
$T_{1/2}(p)=1$ms (even Z)
(odd Z)
(odd N)
(even N)
$S_n=0$
100
Sn
80
Zr
40
Ca
NEUTRON NUMBER (N)
272
111

Why study N = Z nuclei?

1 Up to ^{100}Sn neutrons and protons fill the same shells

2 Strong dependence of deformation on Z, N and angular momentum

3 Co-existence of prolate, oblate and triaxial shapes

4 Evidence of n-p pairing

5 Mirror pairs at high spin

6 Astrophysical rp-process passes this way

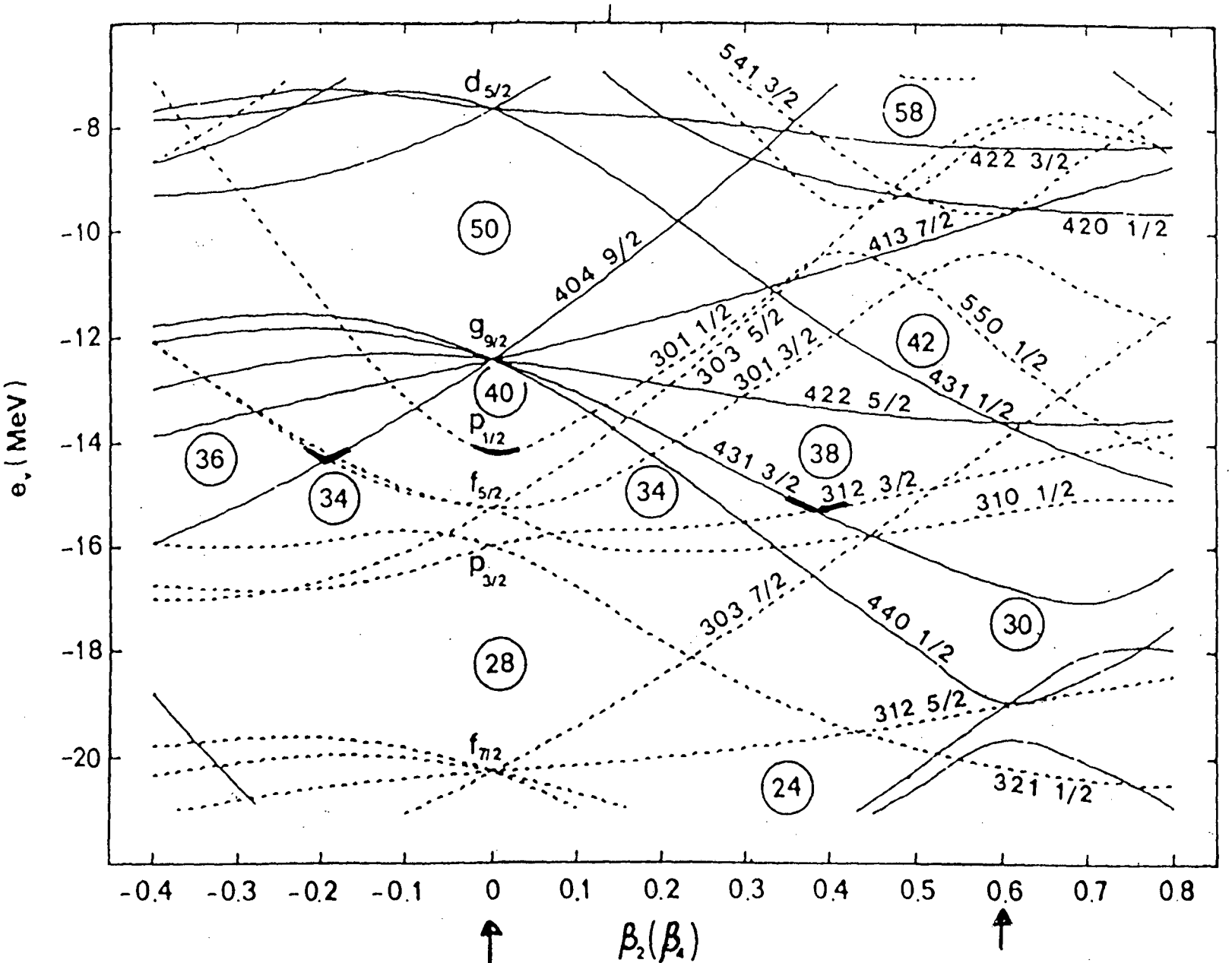
Successfully studied by:

1 Beta-decay following spallation

2 Heavy ion fragmentation

3 Gamma rays from fusion - evaporation reactions

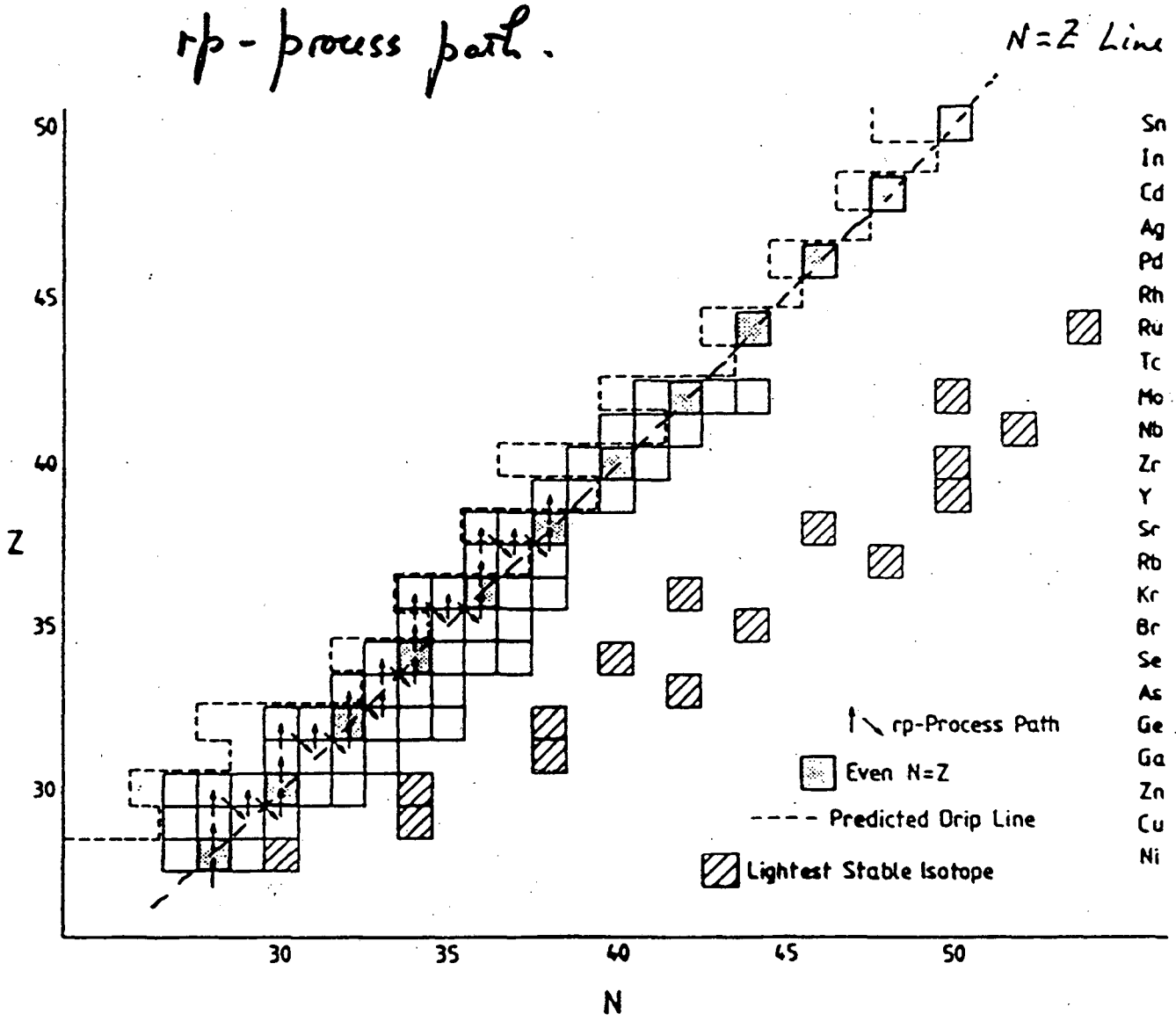
Single Particle Levels as fn. of β_2 from WOODS-SAXON CRANKING CALCULATION.



$^{76}_{38}Sr_{38}$ - Minimum

- Prolate $\beta \simeq 0.4$

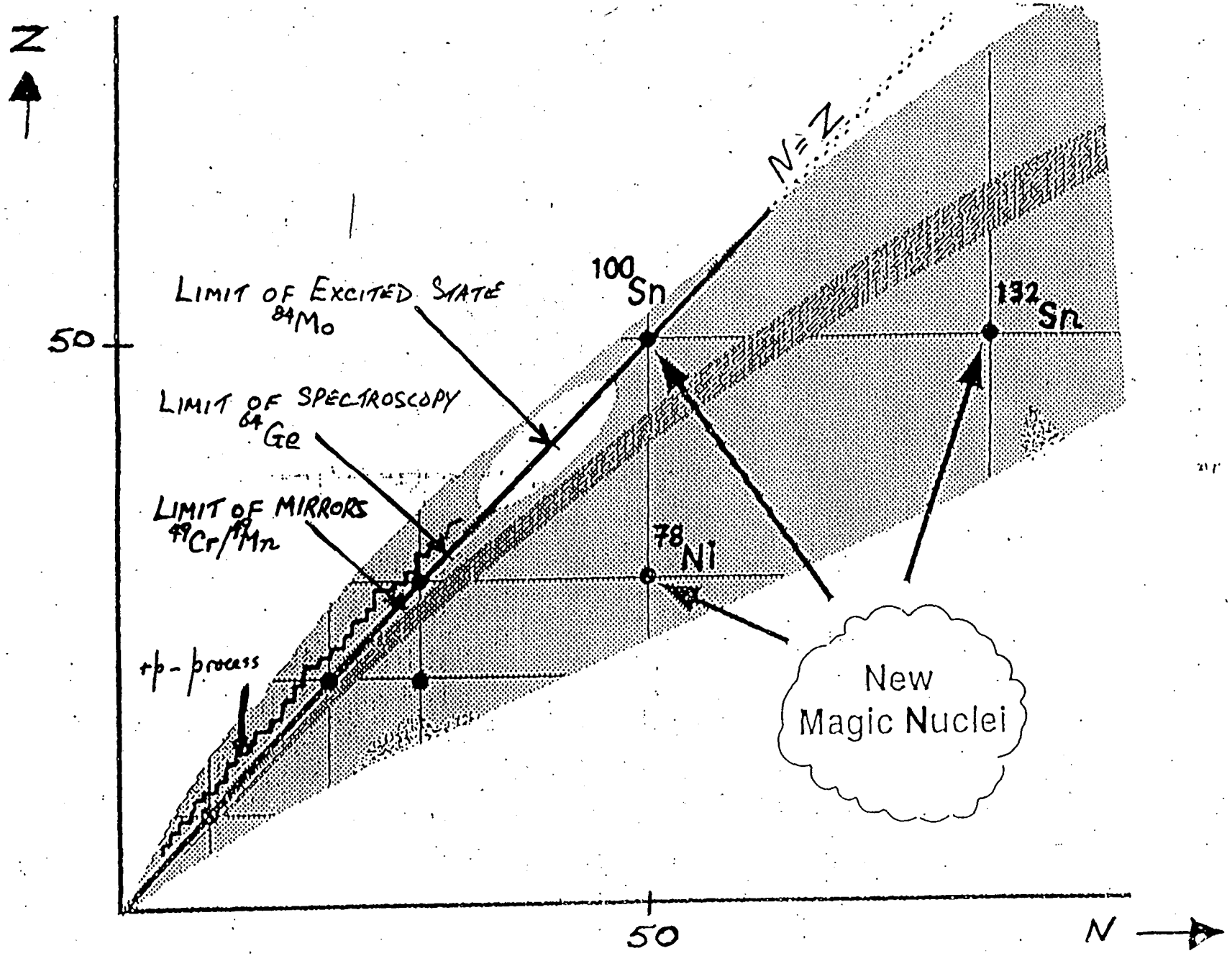
rp-process path.



- rp-process path lies close to the N = Z line.
- At every stage there is competition between (p,γ)/β⁺ Decay
- 2p capture is important
- Inter alia we require

Masses – ^{65}As, ^{68}Se, ^{69}Br, ^{73}Rb

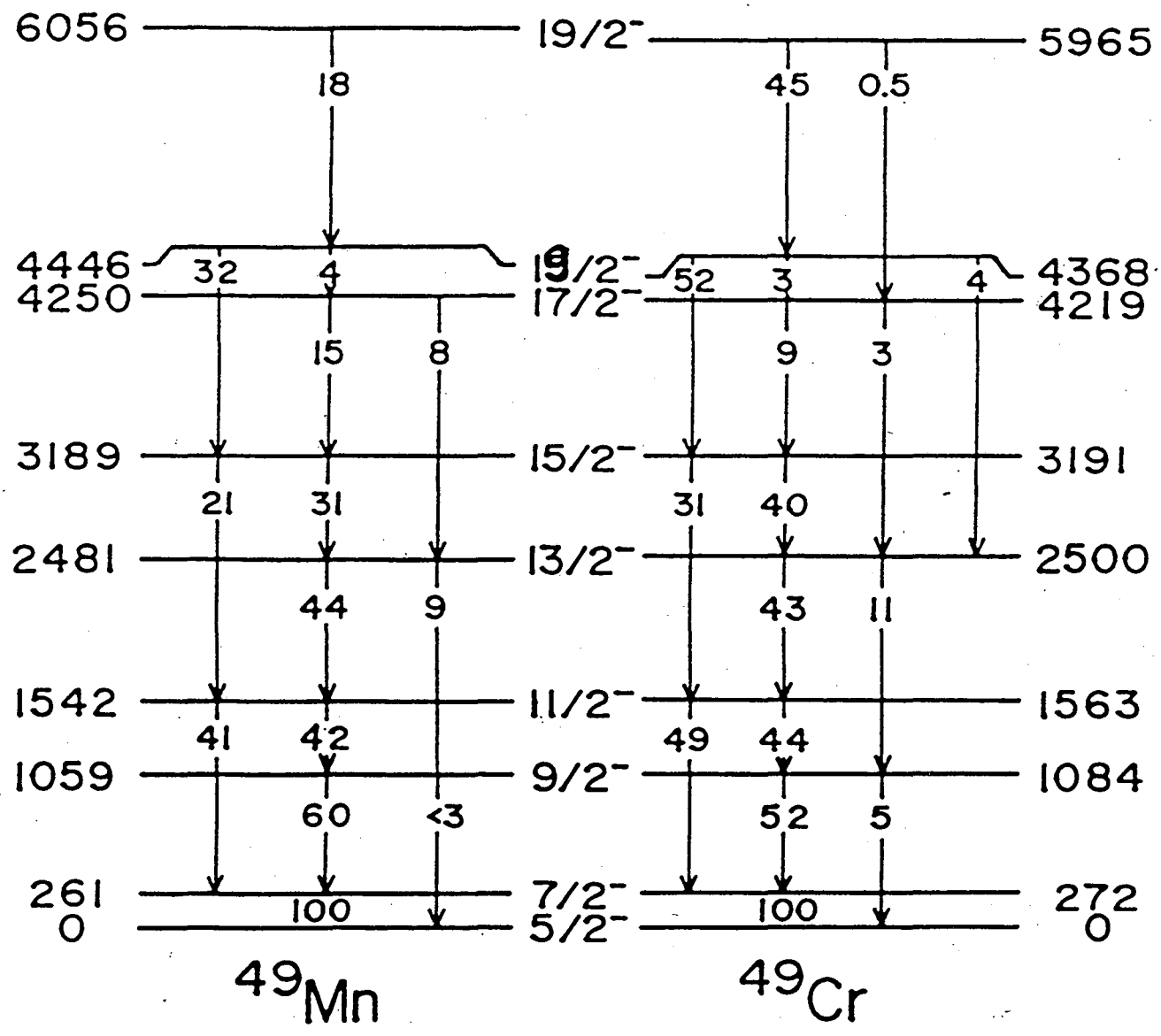
β-Decay – ^{80}Zr, ^{88}Ru, ^{92}Pd, ^{96}Cd



Where have we reached?

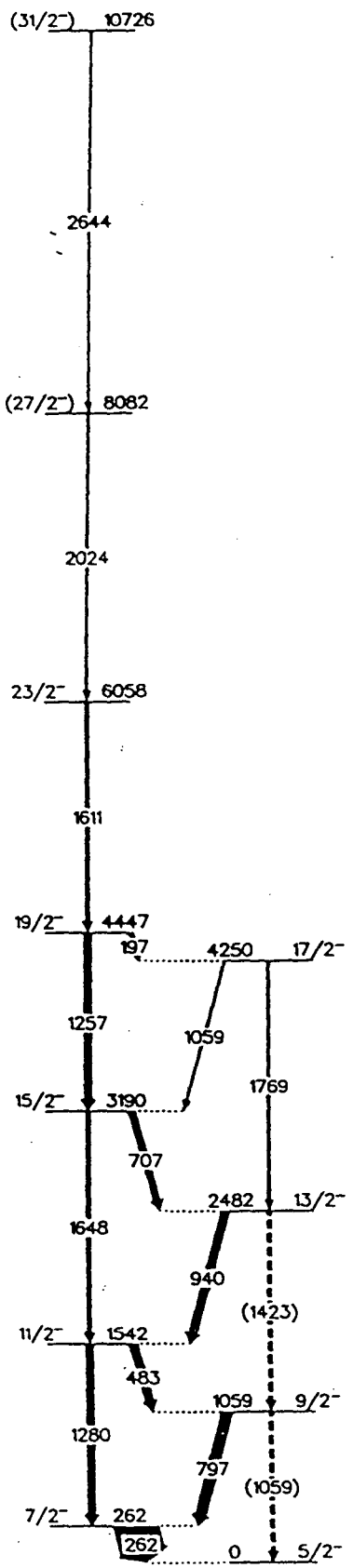
^{49}Mn / ^{49}Cr Mirror Pair

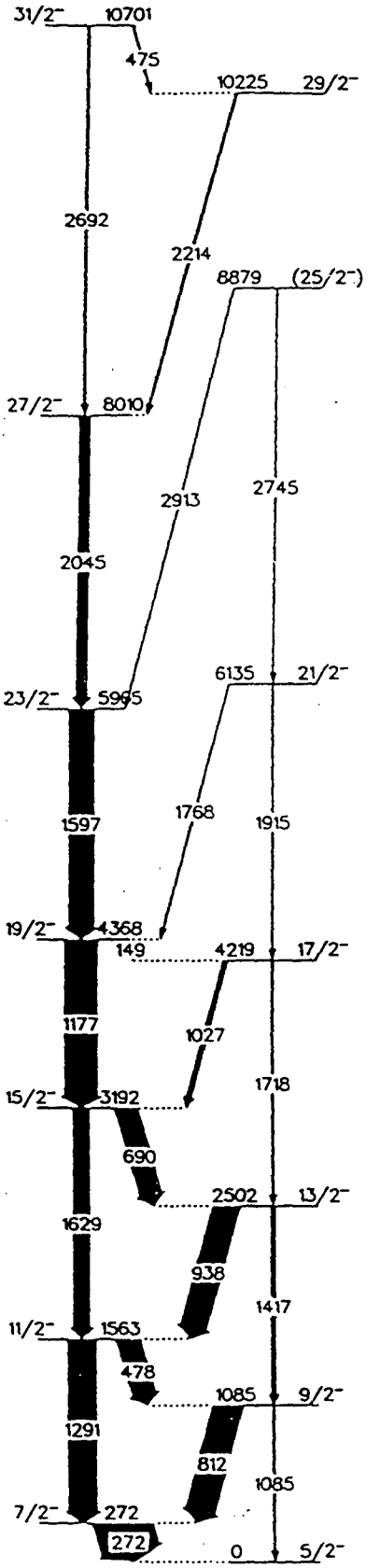
^{12}C (^{40}Ca, p2n) ^{49}Mn — 16ESS + Daresbury Rec. Sep.



- CHARGE INDEPENDENCE
- COLLECTIVE
- G. MARTINEZ-PINEDO et al — Full pf shell model

^{49}Mn from ^{28}Si on ^{24}Mg [PEX]

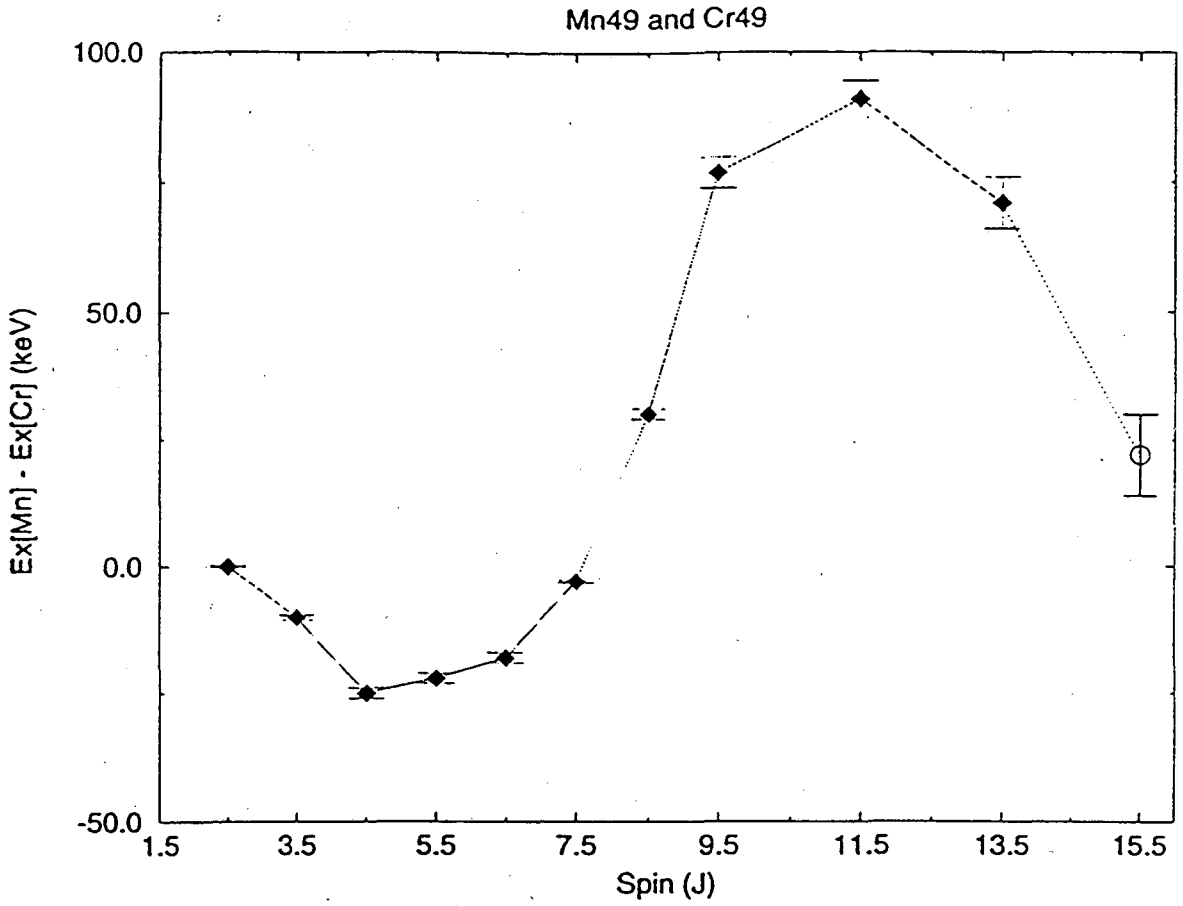


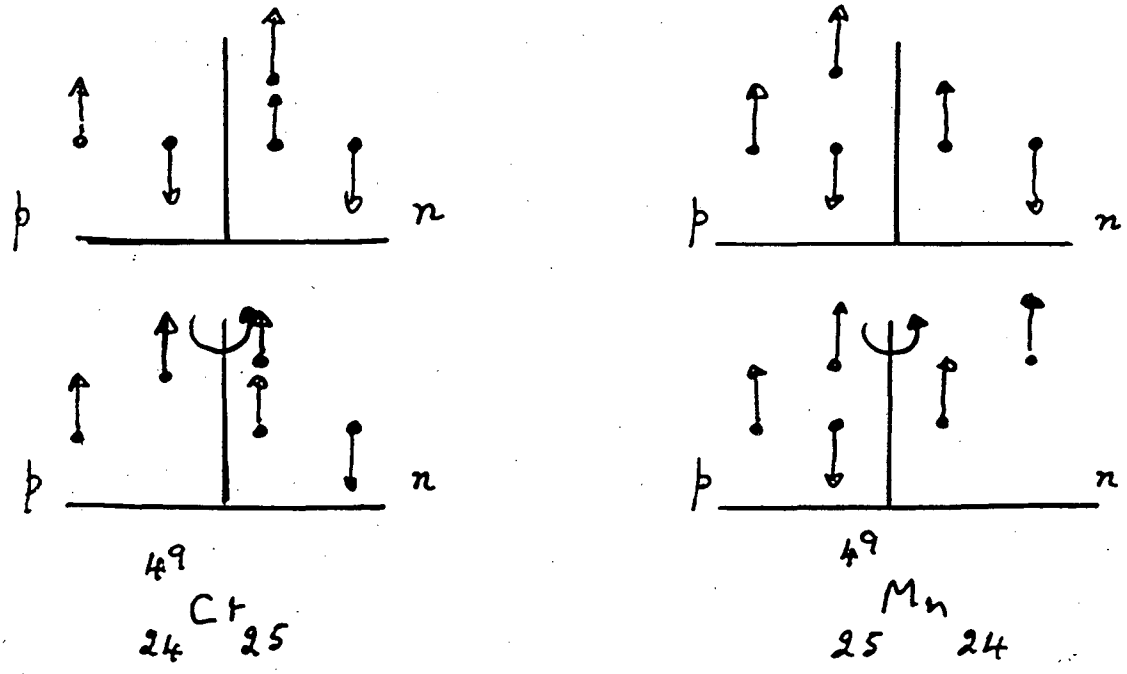


C. O'LEARY, M. BENTLEY (STAFFORDSHIRE) et al.

– PEX Array.

Plot of level energy difference with spin for mirror pair



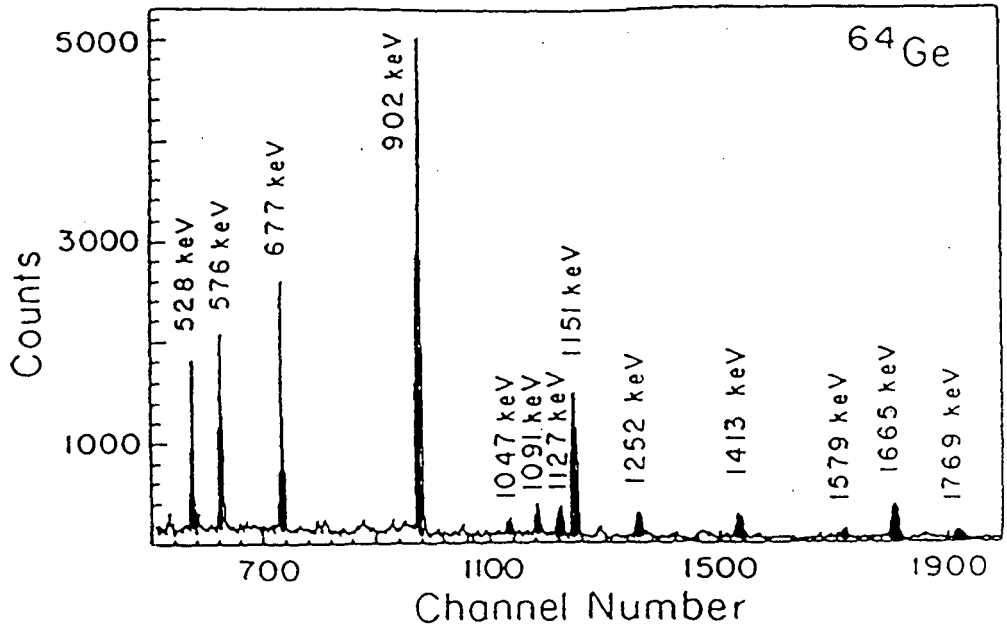


Protons align.

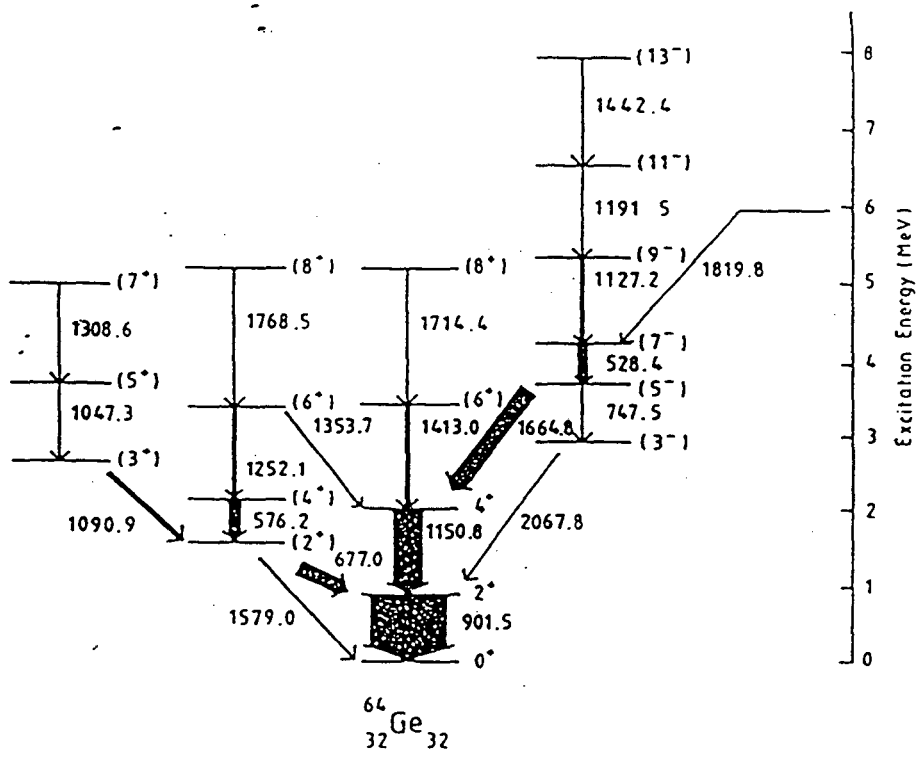
ΔV_c – Negative

Neutrons align.

ΔV_c – Zero.

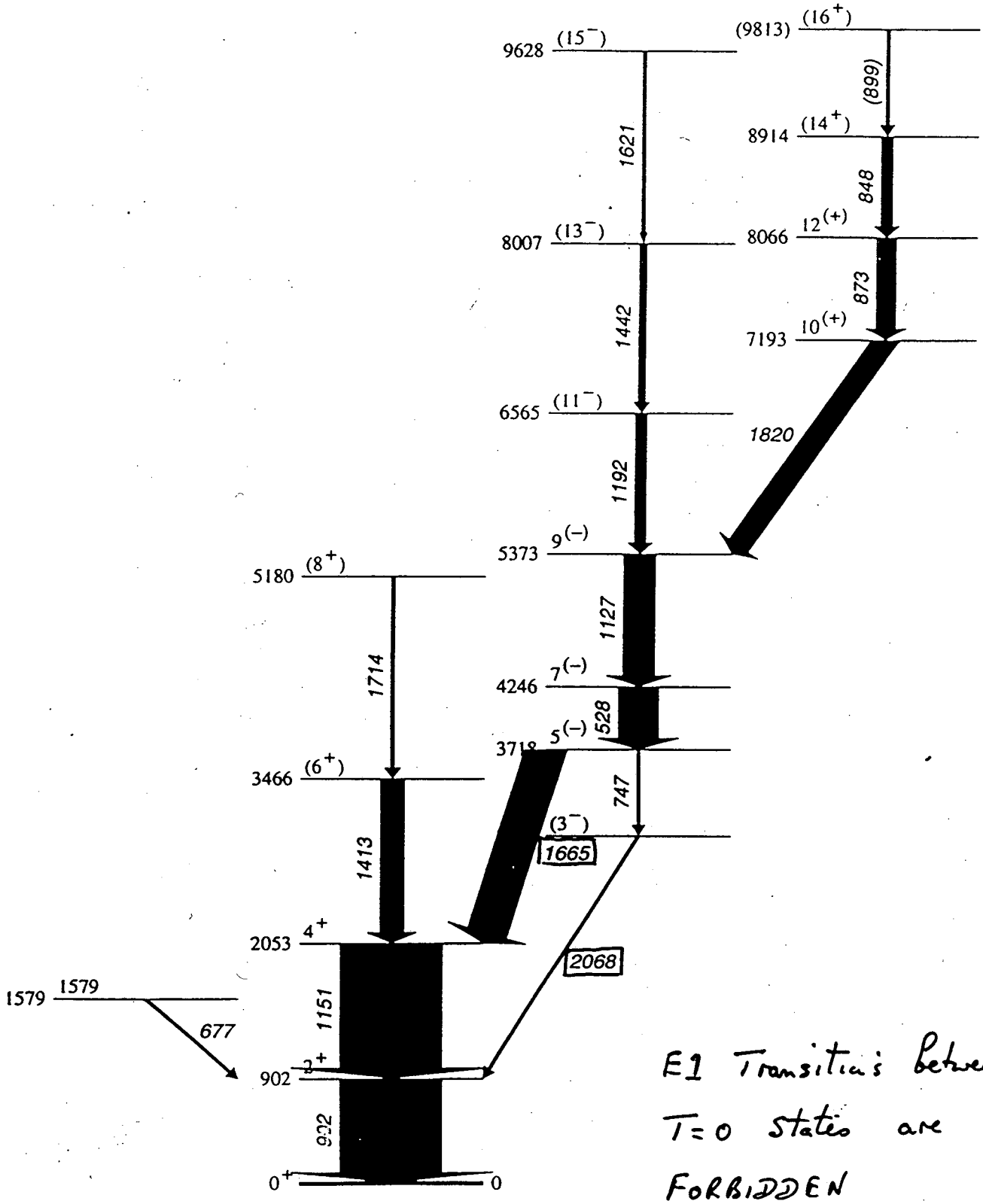


Recoil - γ



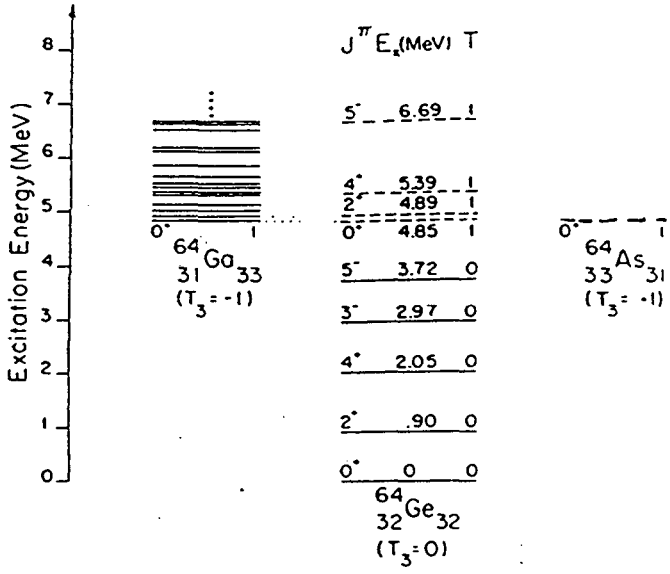
- In SELF-CONJUGATE NUCLEI E1 TRANSITIONS BETWEEN T=0 States ARE FORBIDDEN BY ISOSPIN SELECTION RULE.

G. de Angelis et al (- To be published.)



$^{64}_{32}Ge_{32}$

E1 Transitions between T=0 states are FORBIDDEN



- B A BROWN, J.Phys G8 (1982) 679

- We need 3 things:

  - Relative position of lowest T=0 and T=1 states of each spin involved.

  - $\langle J, T=1 | V_c | J, T=0 \rangle$

  - Anticipated strength of non-retarded E1 matrix element $[\langle 5^- | E_1 | 4^+ \rangle]$

- Position of lowest T=1, T_z=0 state we get from masses of isobars corrected for n-p mass difference and Coulomb shifts. Calc^N gives $J^{\pi T}=0^+$ at 4.85(20 MeV). The 4^+ and 5^- states are then at 3.34 MeV and 2.97 MeV.

- Strength we get from unperturbed p-h states in A=63 and 65

- E1 strength = $1.0^{1.0}_{-0.5}$ W.U. from average over A=56-74

CRUDELY

Mixing amplitudes ~ 1·2%

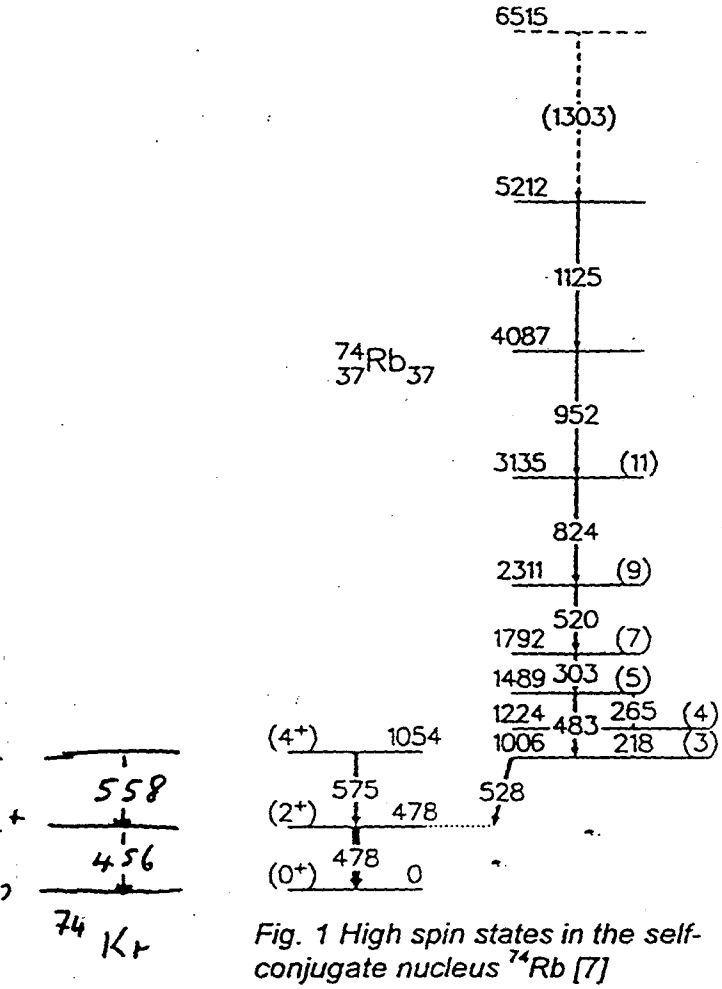
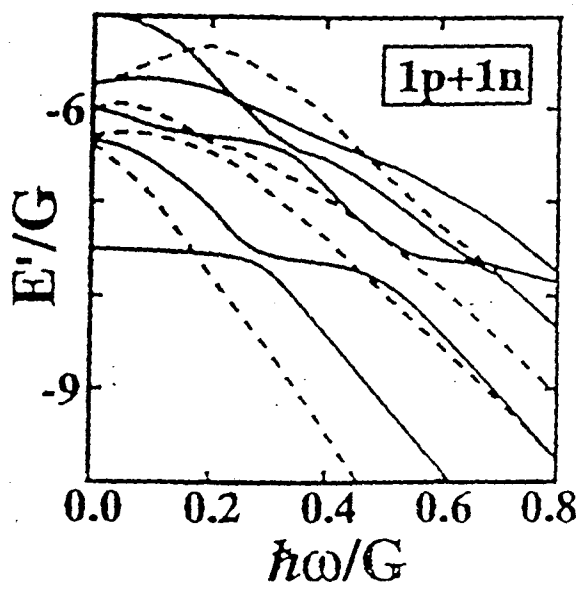


Fig. 1 High spin states in the self-conjugate nucleus ^{74}Rb [7]



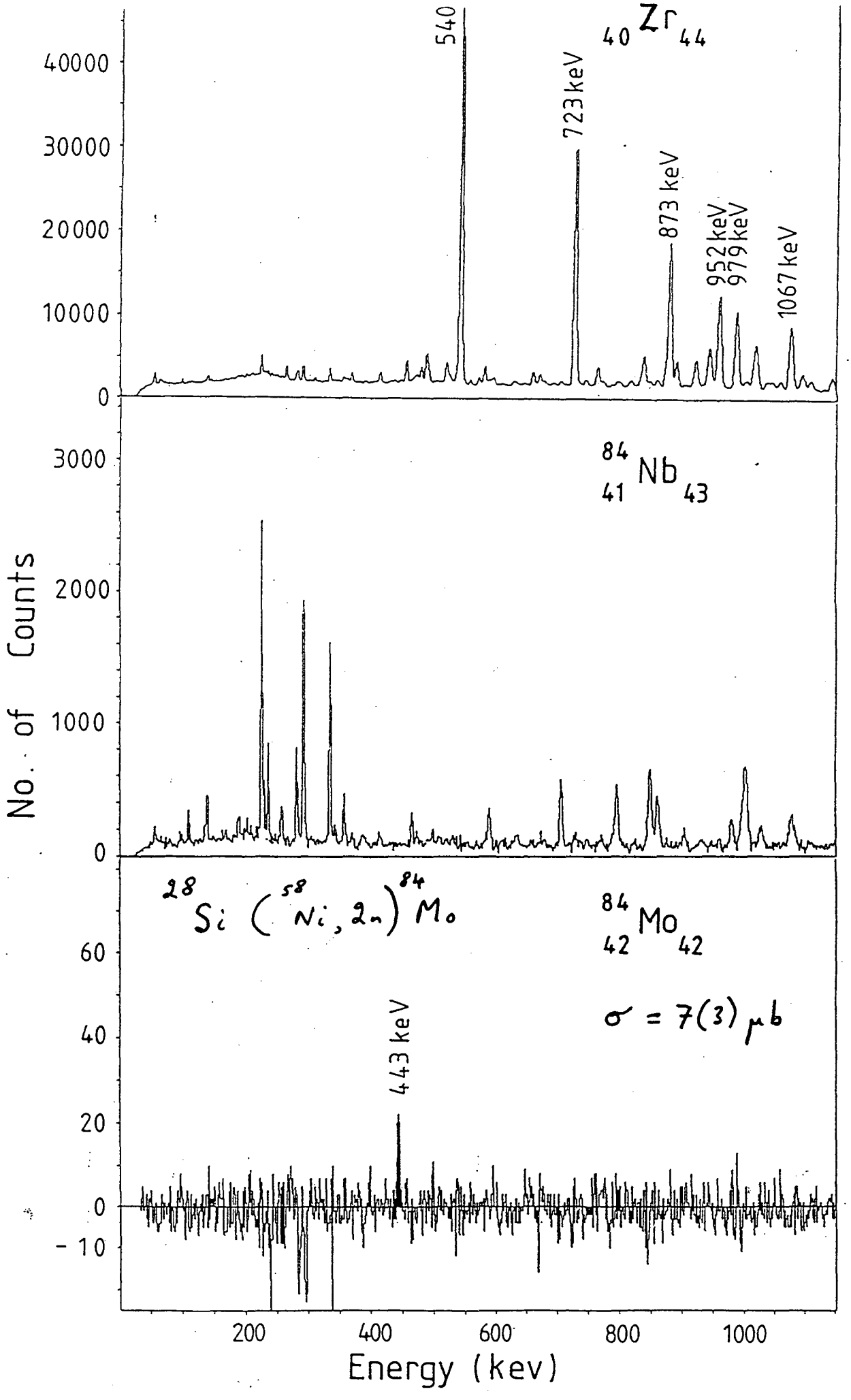
CRANKING CALCULATION

- EUROGAM I + RECOIL SEPARATOR and PEX + Charged Particle Ball.
- $4^+ - 2^+ - 0^+$ sequence resembles sequence in $^{74}_{36}Kr$ ($T_z = +1$)

g.s. is $T=1$.

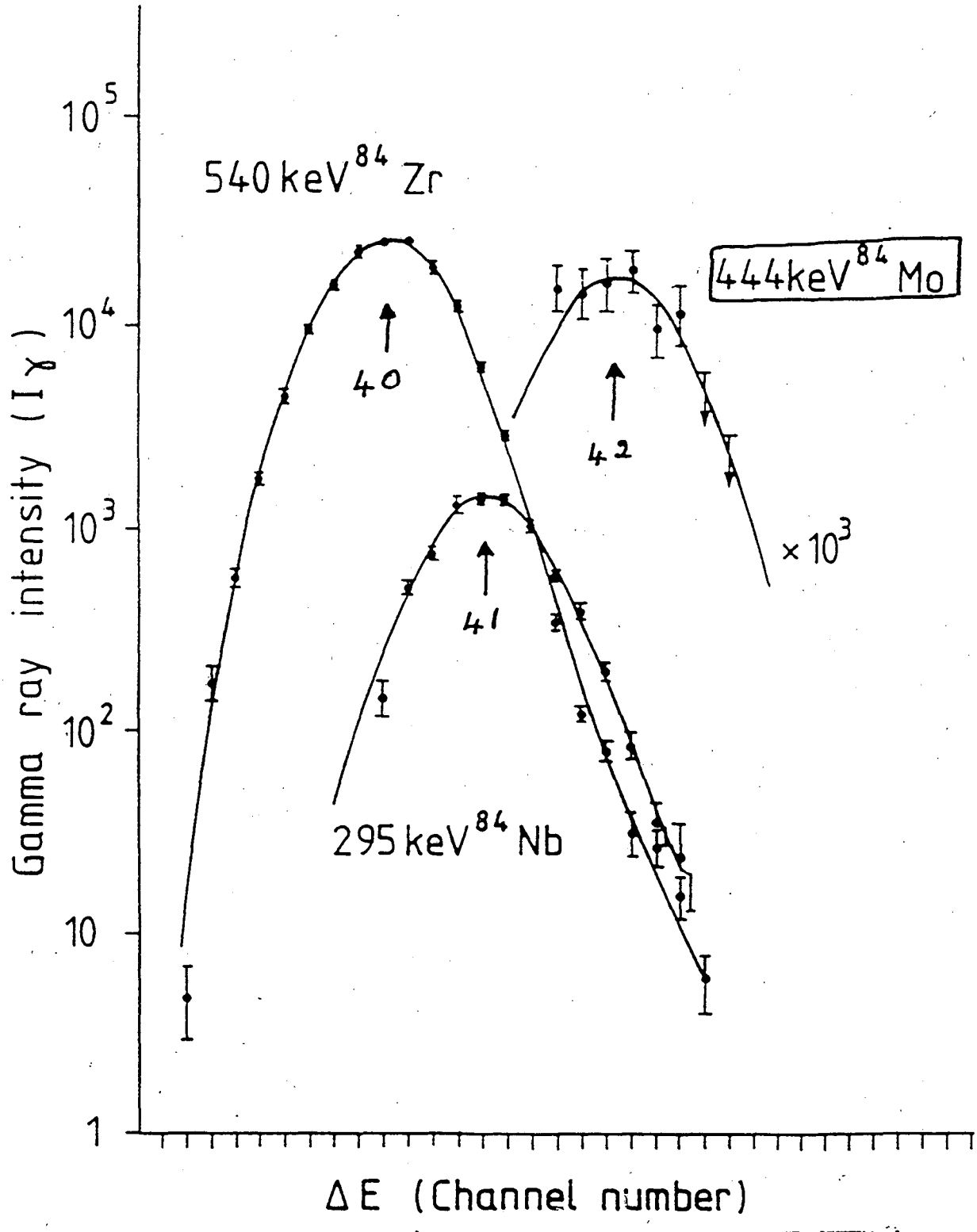
Cranking Calc^n with residual np-interaction.

- At $\hbar\omega/G = 0.2$ lowest $T=1$, odd spin branch crosses $T=0$, even spin ROUTHIAN.


$^{40}Zr_{44}$
540
723 keV
873 keV
952 keV
979 keV
1067 keV
$^{84}_{41}Nb_{43}$
$^{28}Si(^{58}Ni, 2n)^{84}Mo$
$^{84}_{42}Mo_{42}$
$\sigma = 7(3)\ \mu b$
443 keV
No. of Counts
Energy (kev)

^{40}Ca (^{40}Ni, 2n) ^{84}Mo — I_γ vs. ΔE in ION CHAMBER

Gated on A = 84 Gamma Rays



The Way Forward

1 Increased Efficiency – 2n channel.

EUROBALL/GAMMASPHERE - 10% FMA - 10%

In principle we can do spectroscopy up to Zr/Mo

2 Selection by charged particle detector array

Allows use of (α2n) channel

Improvement with EUROBALL - 5×10^3

but it depends on cleanliness of target

3 Recoil Decay Tagging

Here we use subsequent radioactive decay to identify source of γ-rays

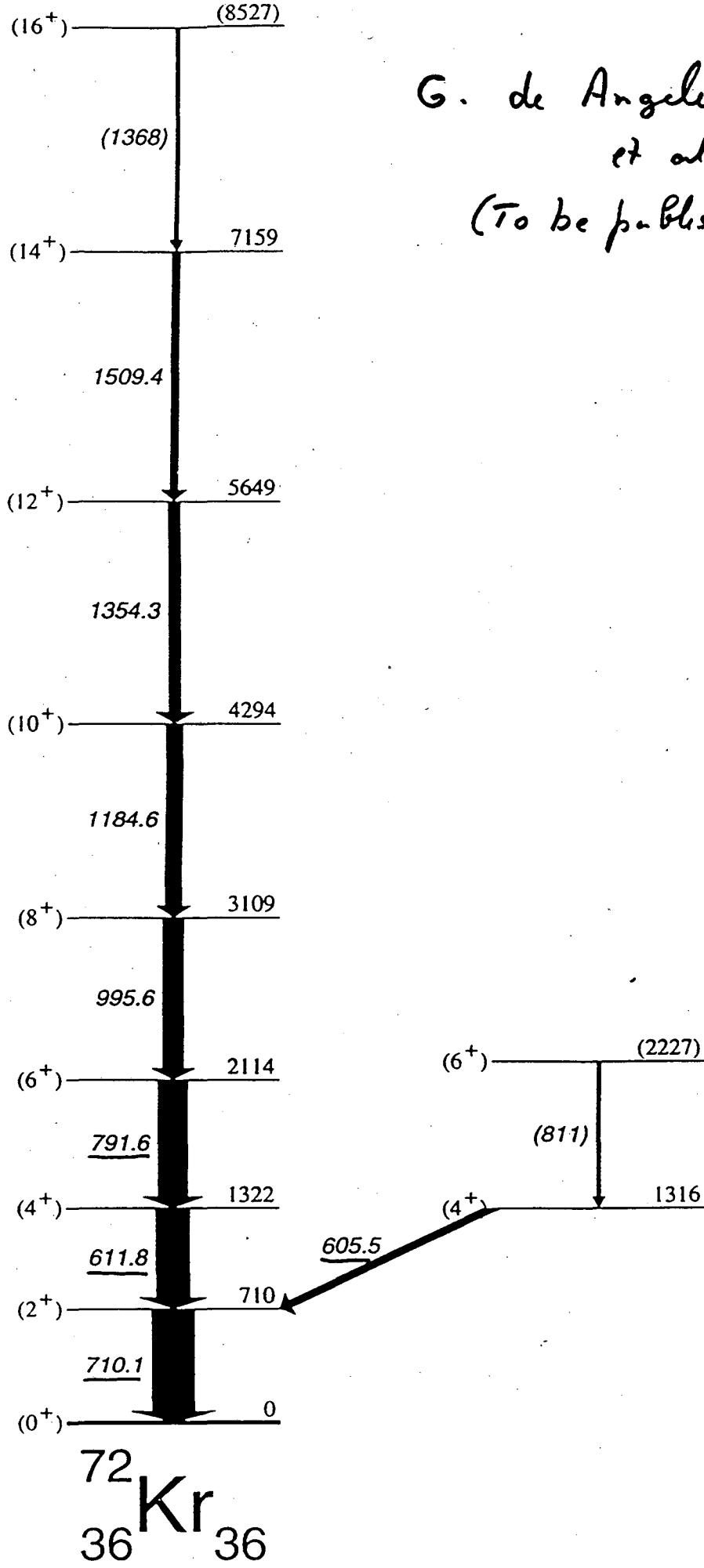
4 Radioactive beams

(a)	$^{12}C(^{54}Fe, 2n)^{64}Ge$	155 MeV	640(70)μb
(b)	$^{40}Ca(^{34}Ar, 2p2\alpha)^{64}Ge$	130 MeV	50 mb

$^{40}Ca(^{40}Ca, 2\alpha)^{72}Kr$

GaSp + ISIS

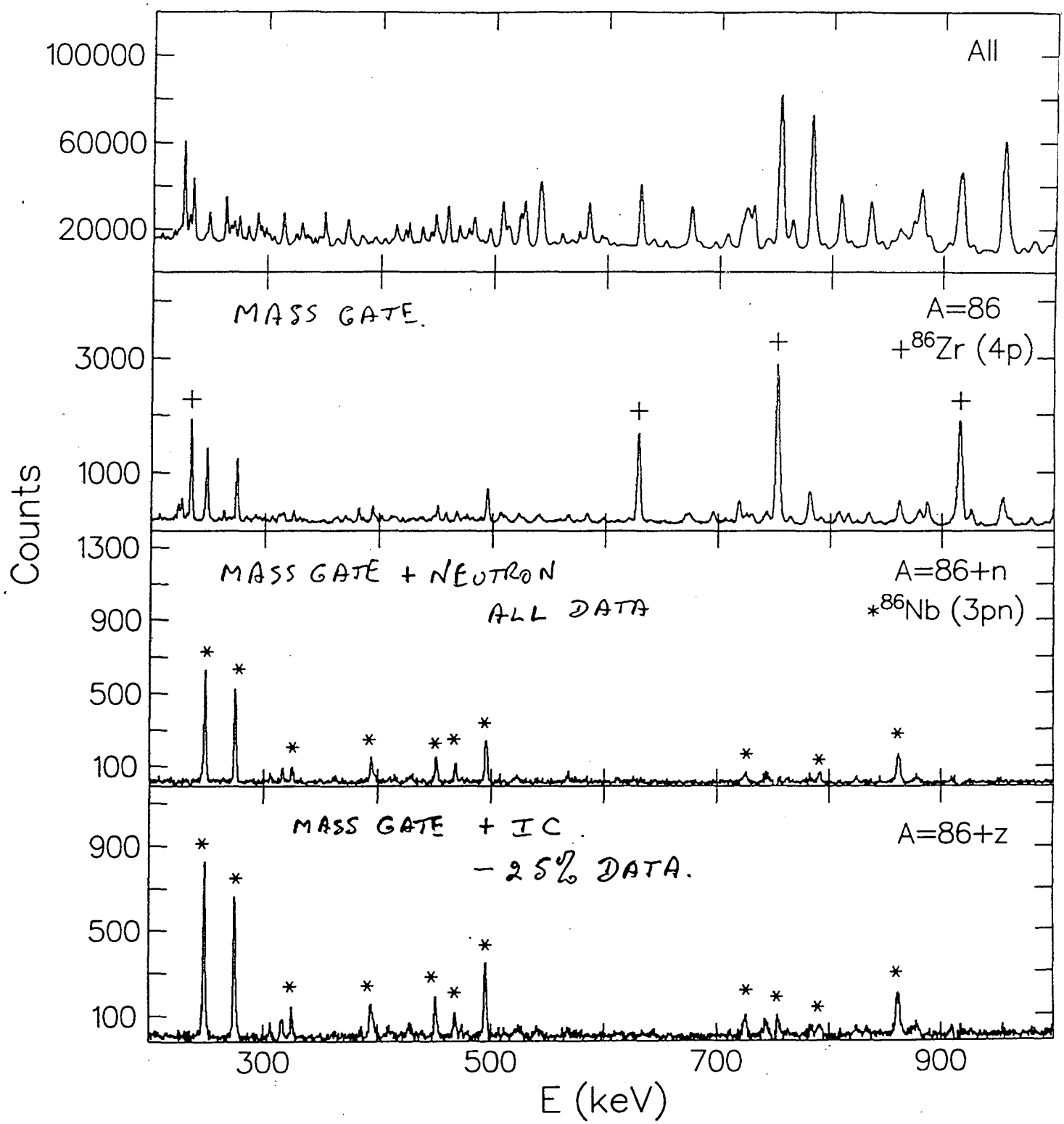
G. de Angelis et al. (To be published)



$^{54}Fe(Ar, 2n)^{90}Ru$ — 120-125 MeV

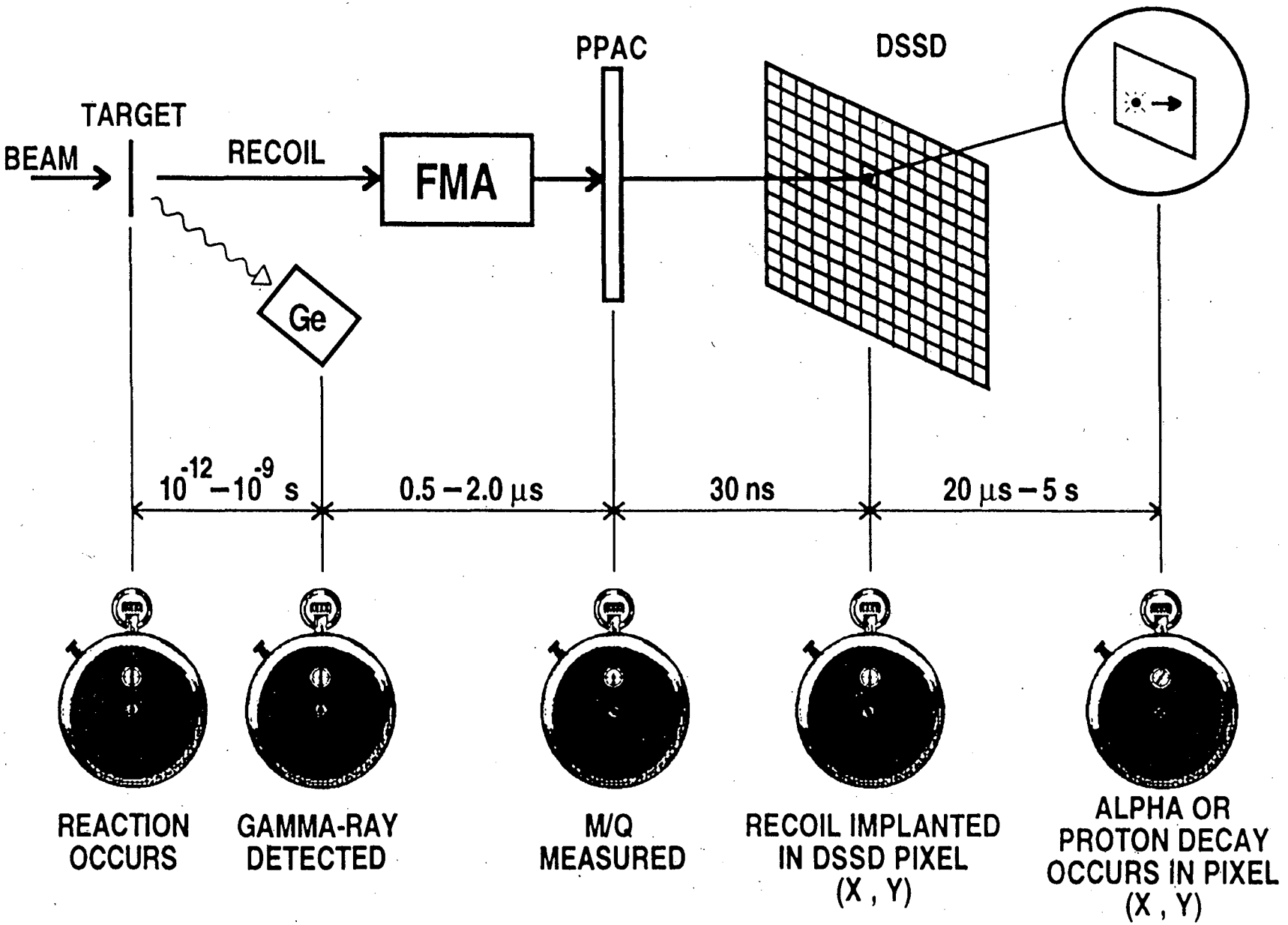
$v/c \sim$

AYEBALL. — 1.0 % efficiency.



- Sufficient ΔZ resolution — statistics required.
- Improvement — Channel Plates not PPAC — Increased %.

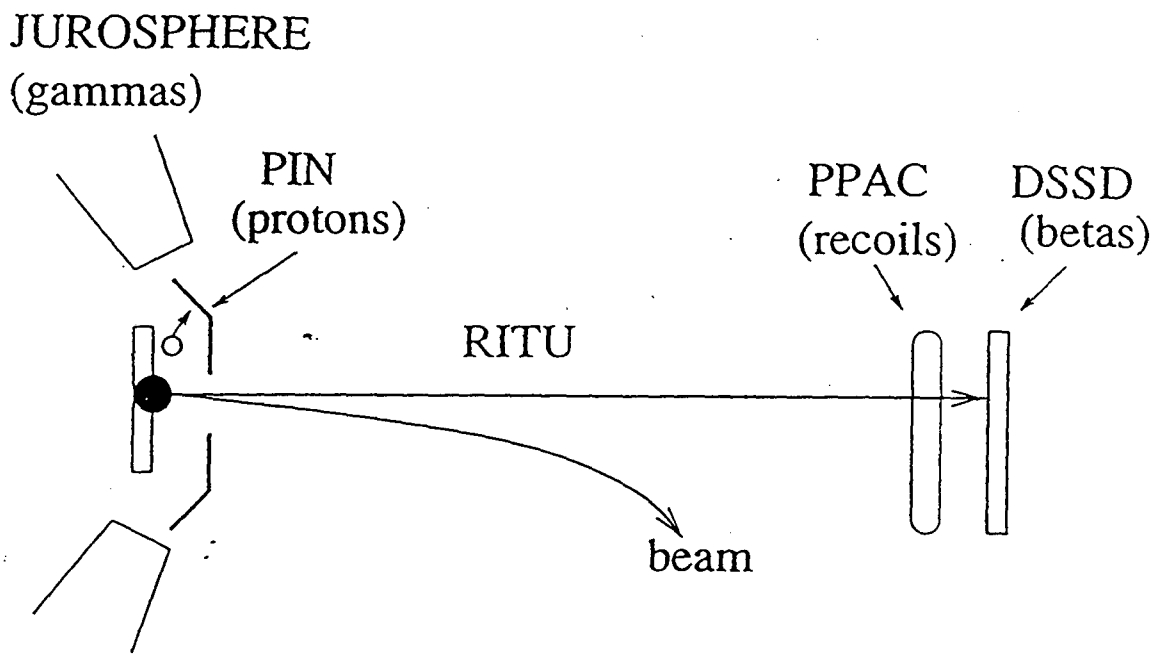
RECOIL DECAY TAGGING METHOD



- Prompt γ-rays correlated with M/Q and (X , Y) position of recoil in DSSD
- Decay proton or alpha identifies nucleus that emitted the γ-rays

Proposal

^{71}Kr/^{71}Br - Surrey/Daresbury/Valencia/ Legnaro/Liverpool/Jyvaskyla



- **^{40}Ca (^{36}Ar, αn)^{71}Kr - 105 MeV - σ = 60 μb**

  JUROSPHERE - ε = 1%

  RITU separates beam from recoils

  PPAC and DSSD record arrival of recoil

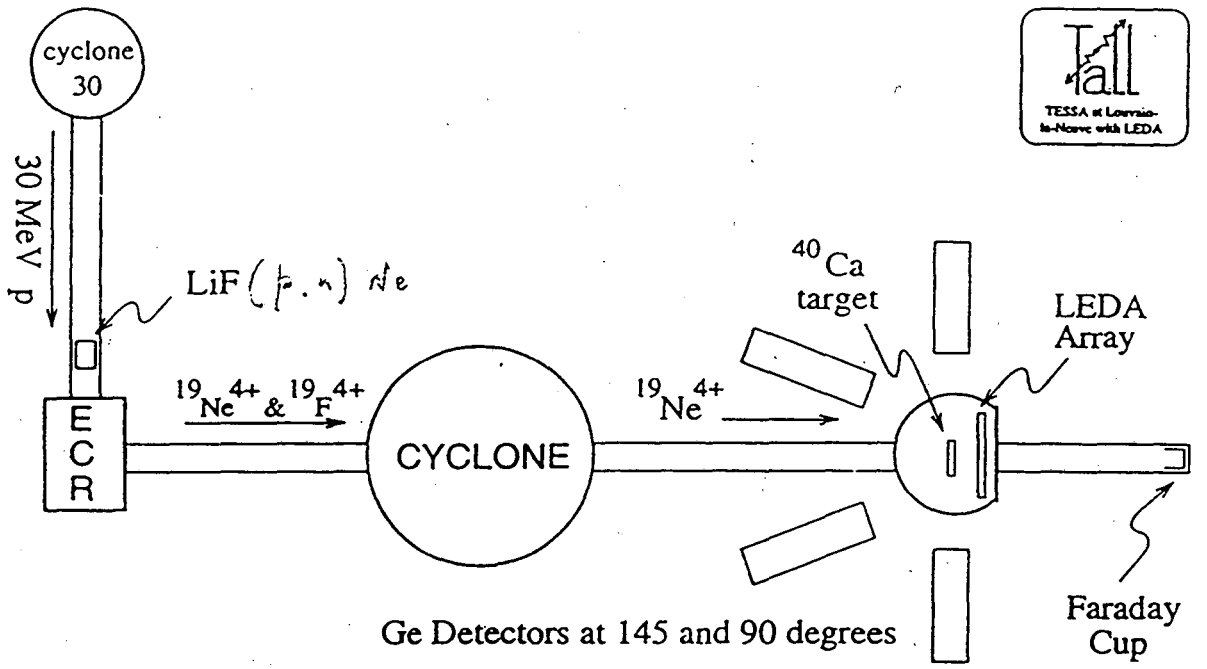
- **DSSD has 2304 pixels**

- **^{71}Kr- 100 ms, ^{70}Br - 80 ms**

- **β^+ decay correlated with gammas at target**

- **1000 counts in 5 days**

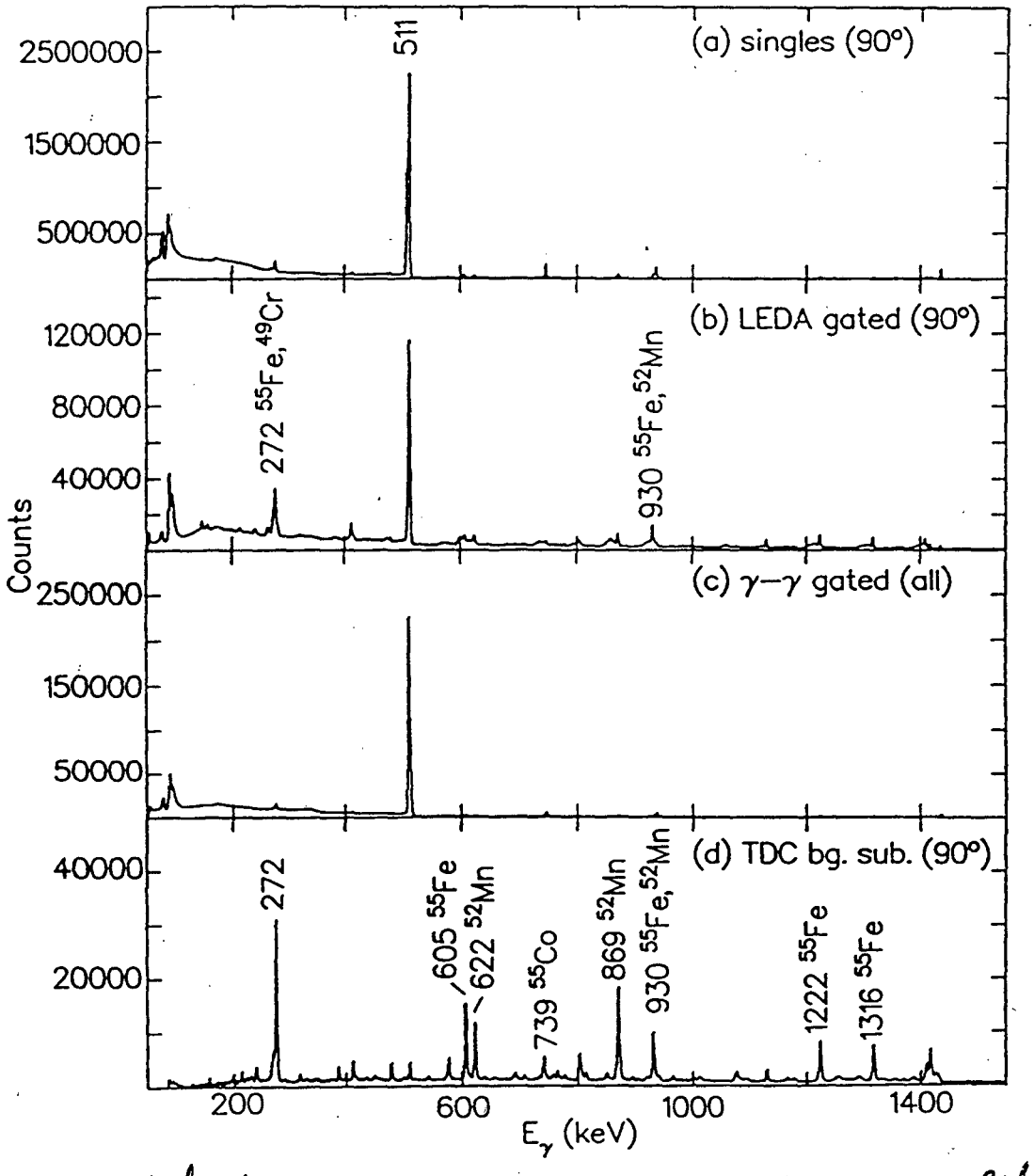
ive + Ca → Zn 30 ← 55 Ni 28 (2p2n)



- Beam – 80 MeV, 150 pnA
- Target – 1.6 mg cm^{-2}
- Pb to shield BGO from collimators and beam dump
- Al foil to stop beam hitting LEDA.
- Beam dump 2m away.

$^{19}Ne + ^{40}Ca$ – 80 MeV

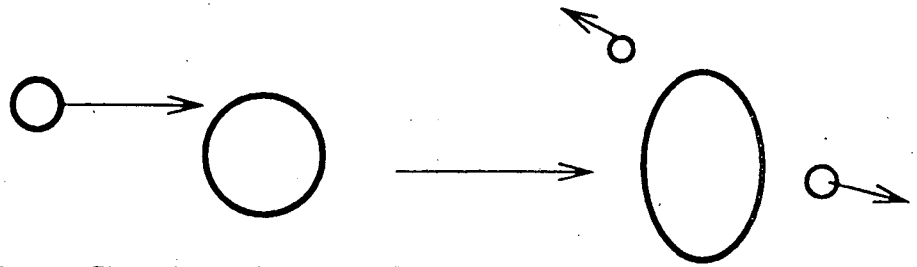
Data from 90° detectors except (c) where 145° detectors are included



- a) Dominated by e^+e^- but Compton Suppression worked

HOW DO YOU MAKE N~Z NUCLEI ?

(A) SOFTLY.....Heavy-Ion Fusion-Evaporation



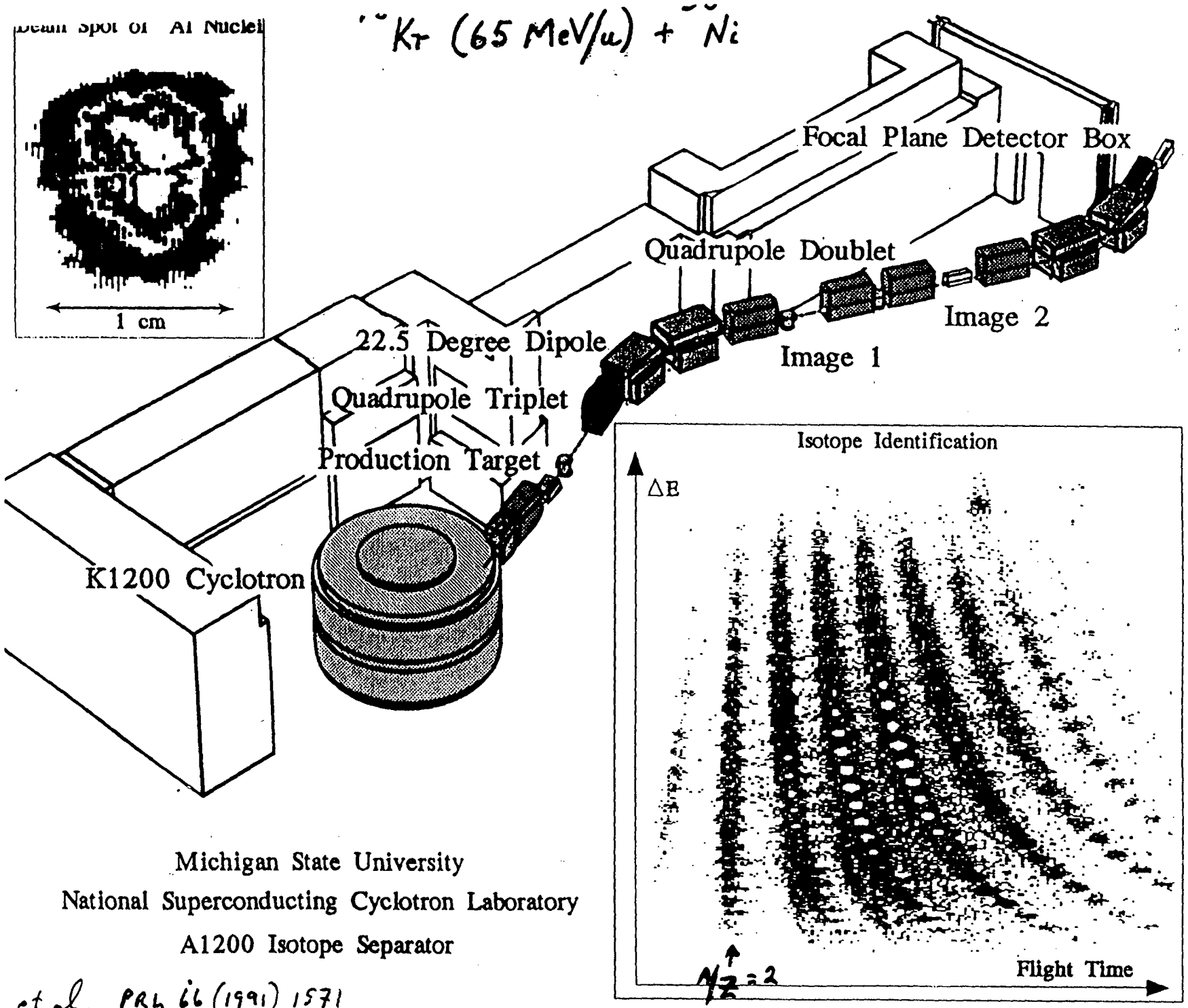
Eb ~ Coulomb Barrier
(~4 MeV/A)

2n out channel for
heavy N=Z upto 96-Cd

(B) BANG!!!! Fragmentation Reactions

Eb ~ 50 MeV/A

Many channels
Need LISE3 to
id all recoils
(~200 N,Z combinations)



Michigan State University
National Superconducting Cyclotron Laboratory
A1200 Isotope Separator

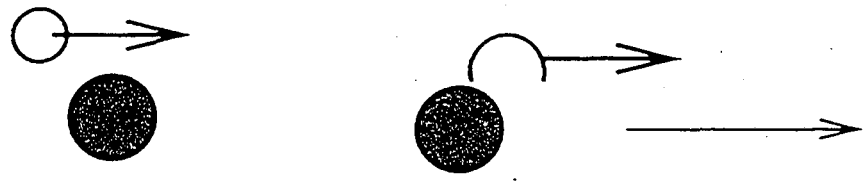
R et al. PRL 66 (1991) 1571

SPECIFIC RESEARCH GOALS

(2) Structure of N~Z Nuclei With Radioactive Ion Beams.

(a) Along the N=Z Line Using Projectile Fragmentation.

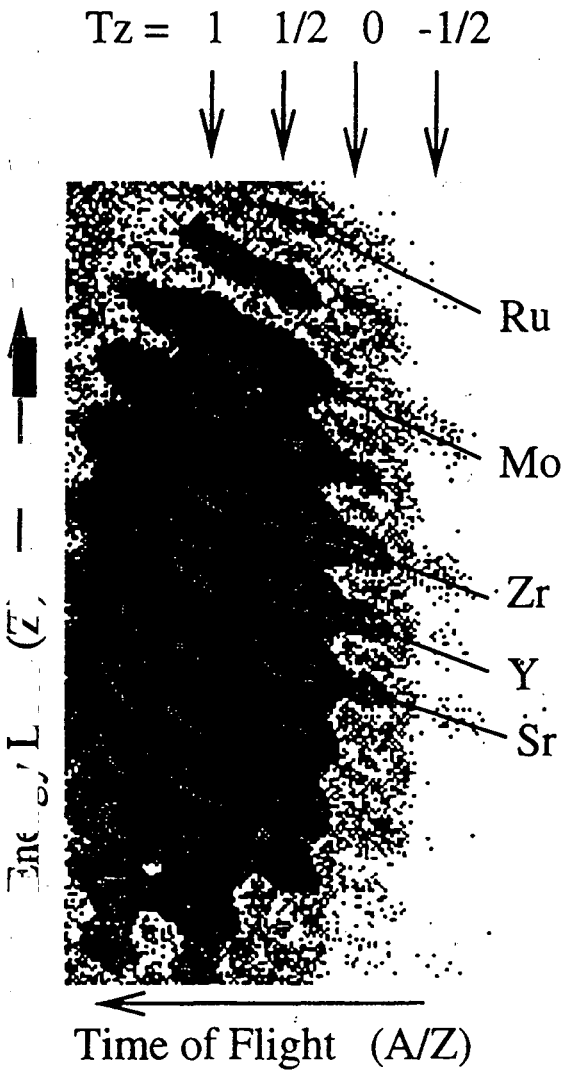
Nuclear collision causes beam to FRAGMENT.

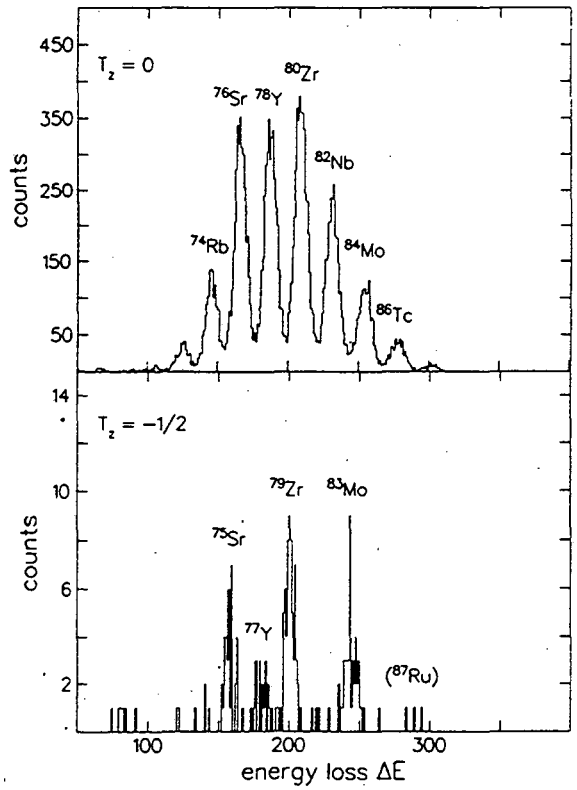


secondary beam to mass spectrometer

Fragments form a SECONDARY BEAM of r-active nuclei.

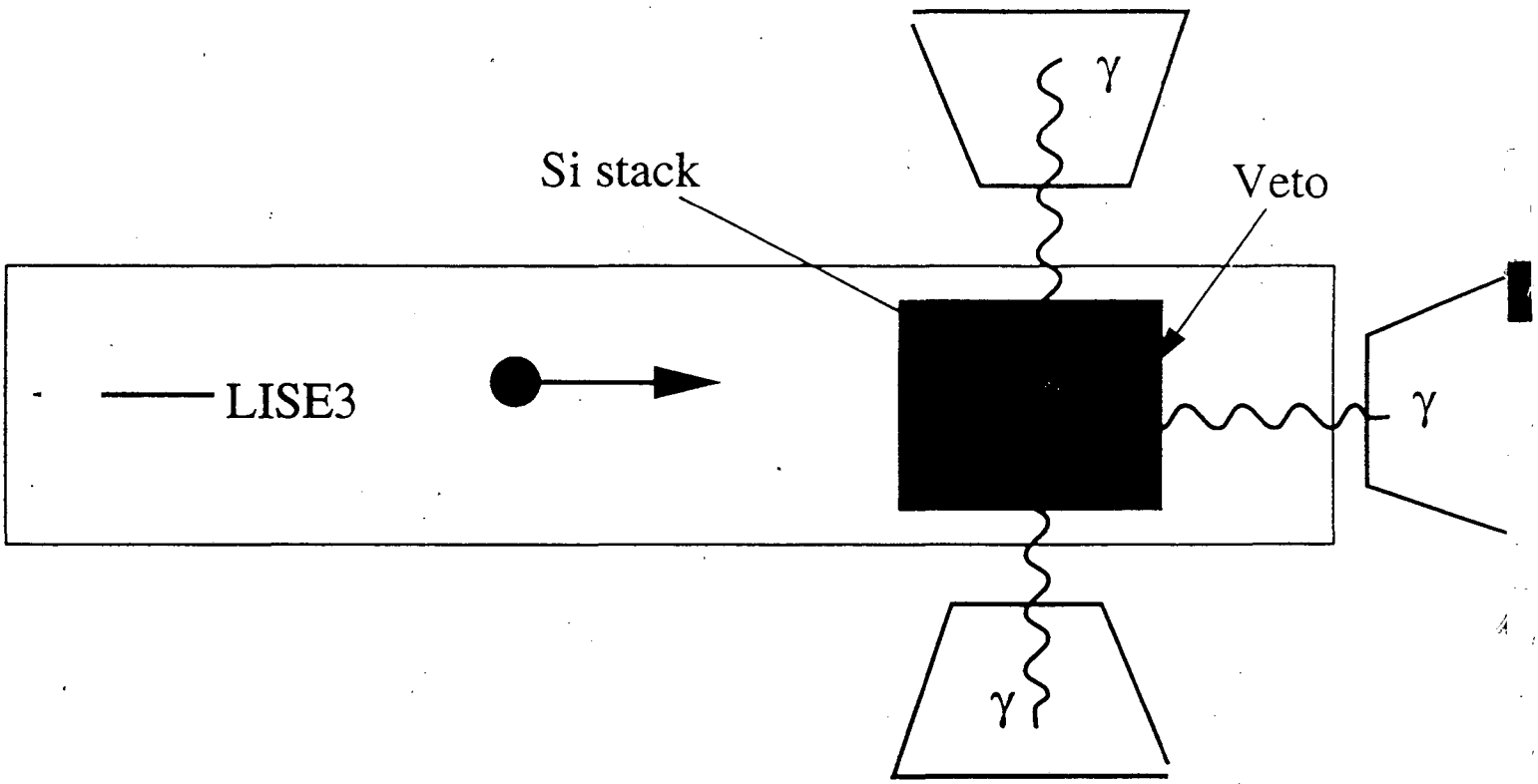
These can be selected and separated by their A and Z eg.



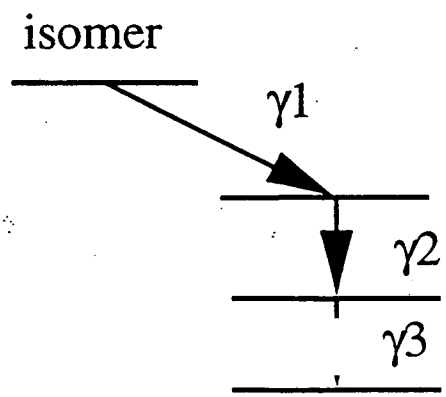


Defines the limits of nuclear stability ...very imp. for nucleosythesis and creation of the elements above A=56

Identify recoils using LISE3 + Si stack



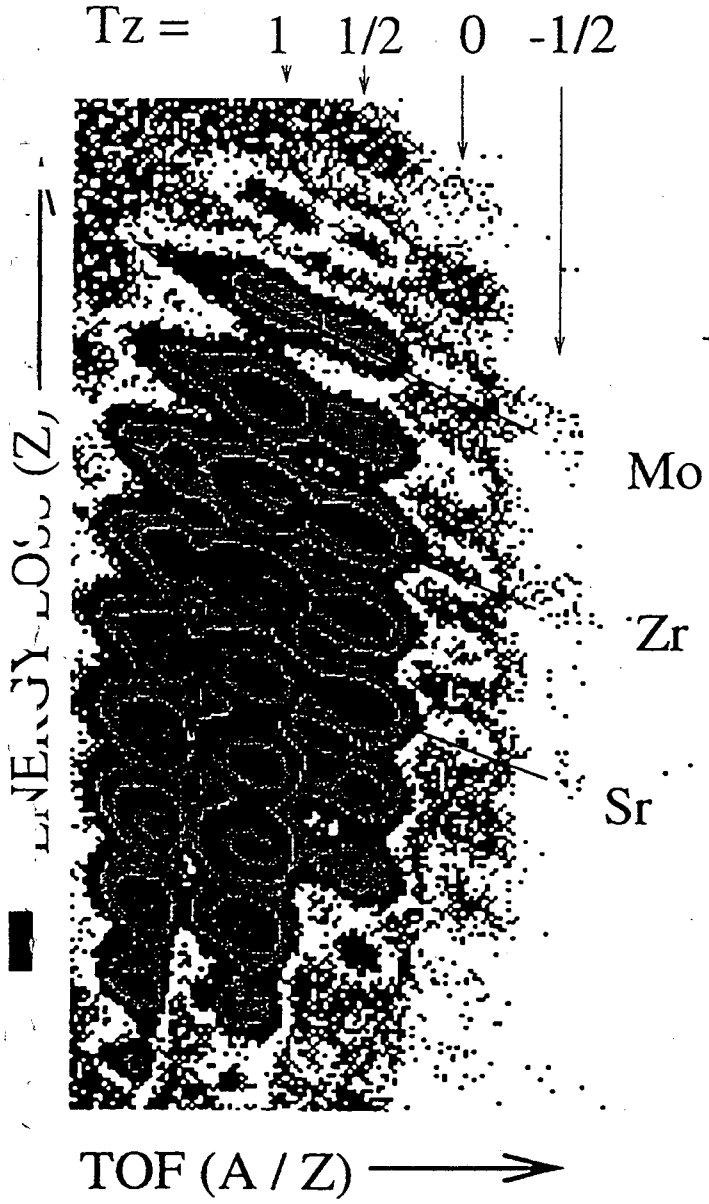
Measure delayed gamma-rays using Clover + Leps detector

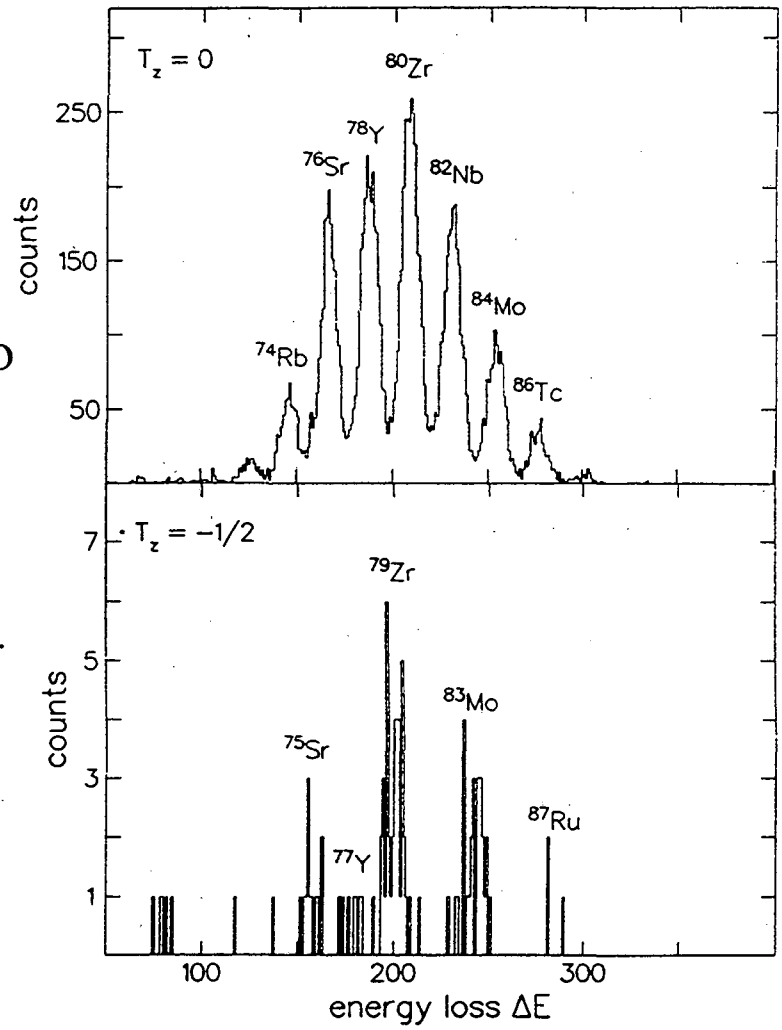


Total Gamma-efficiency for
4 clovers and 1 clover Leps
= 15% for 1.33 MeV gamma-ray

FIRST IDENTIFICATION OF 'NEW' ISOTOPES.

$$Tz = \frac{(N - Z)}{2}$$





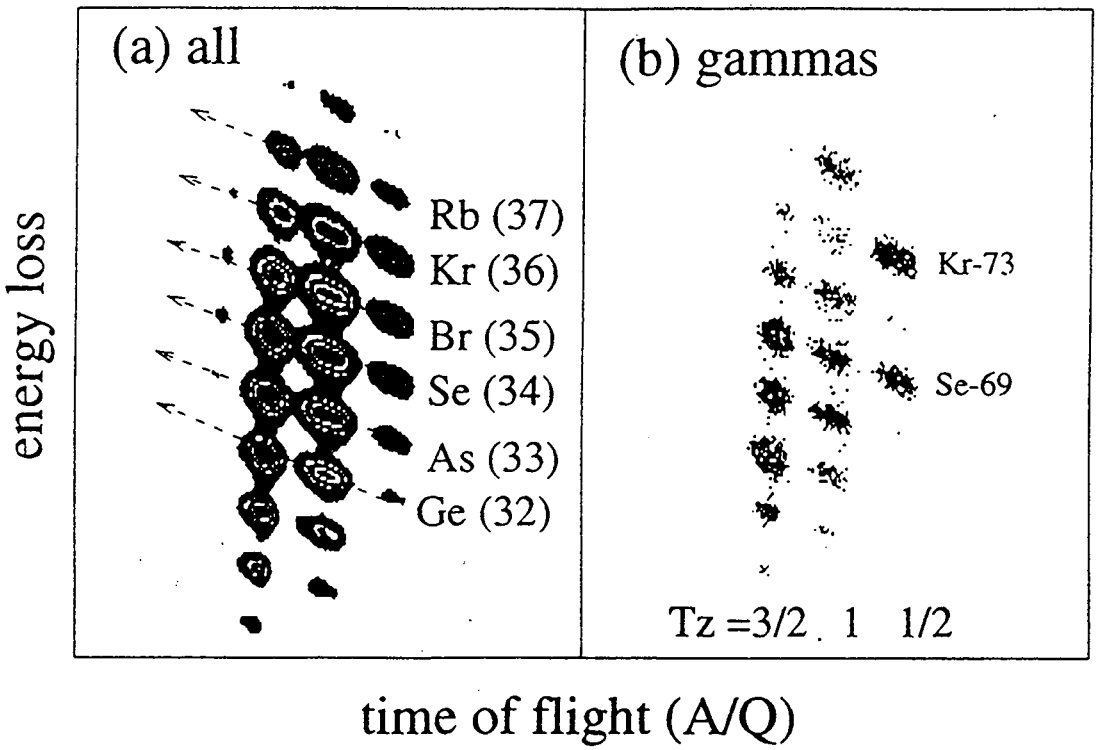
First identification of 77Y, 79Zr, 83Mo and 87Ru.....

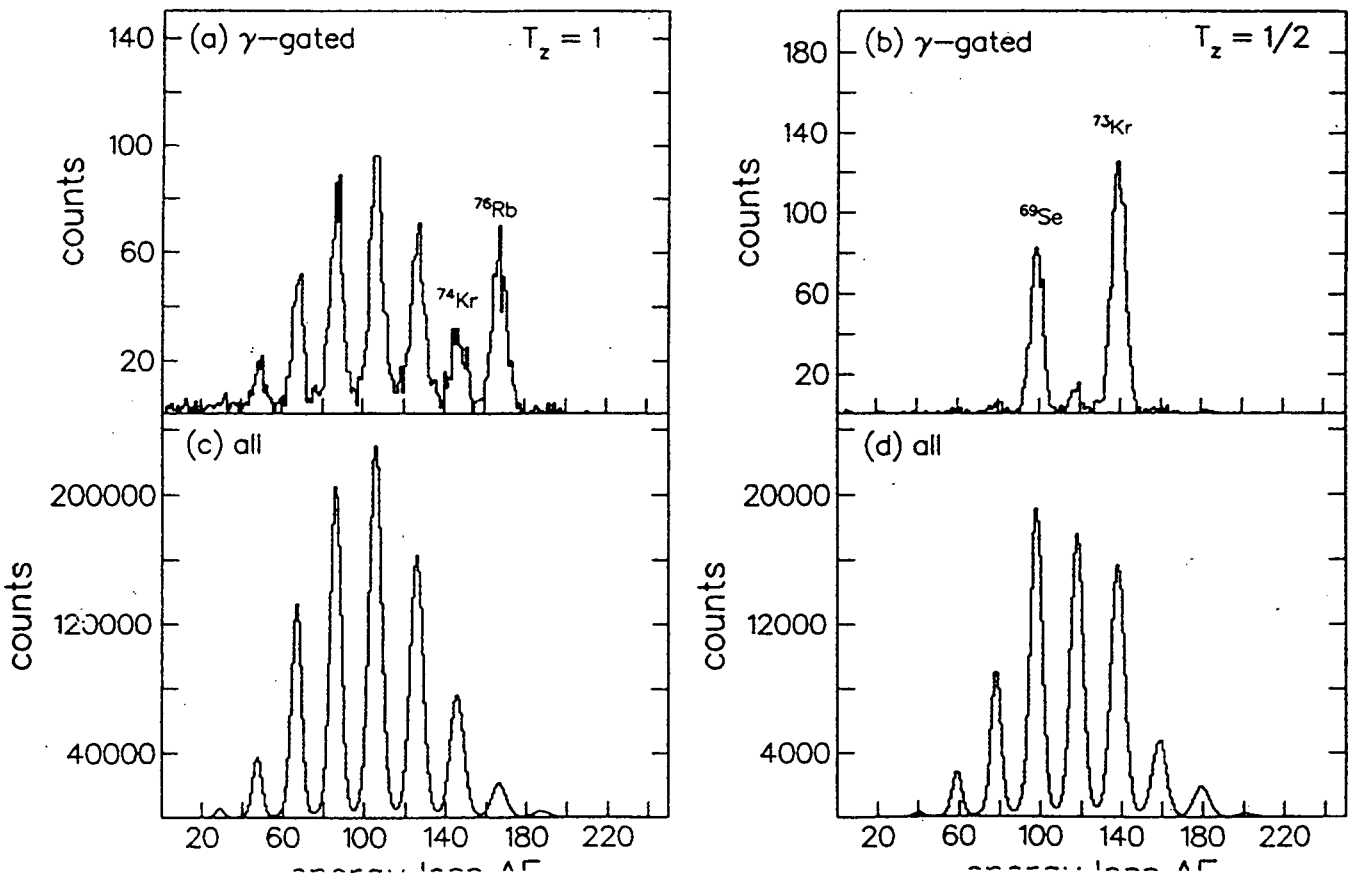
isomeric spectroscopy across the N=Z line is possible.....

(Evidence of new isomeric decays in Tz=0, 82Nb and 86Tc).

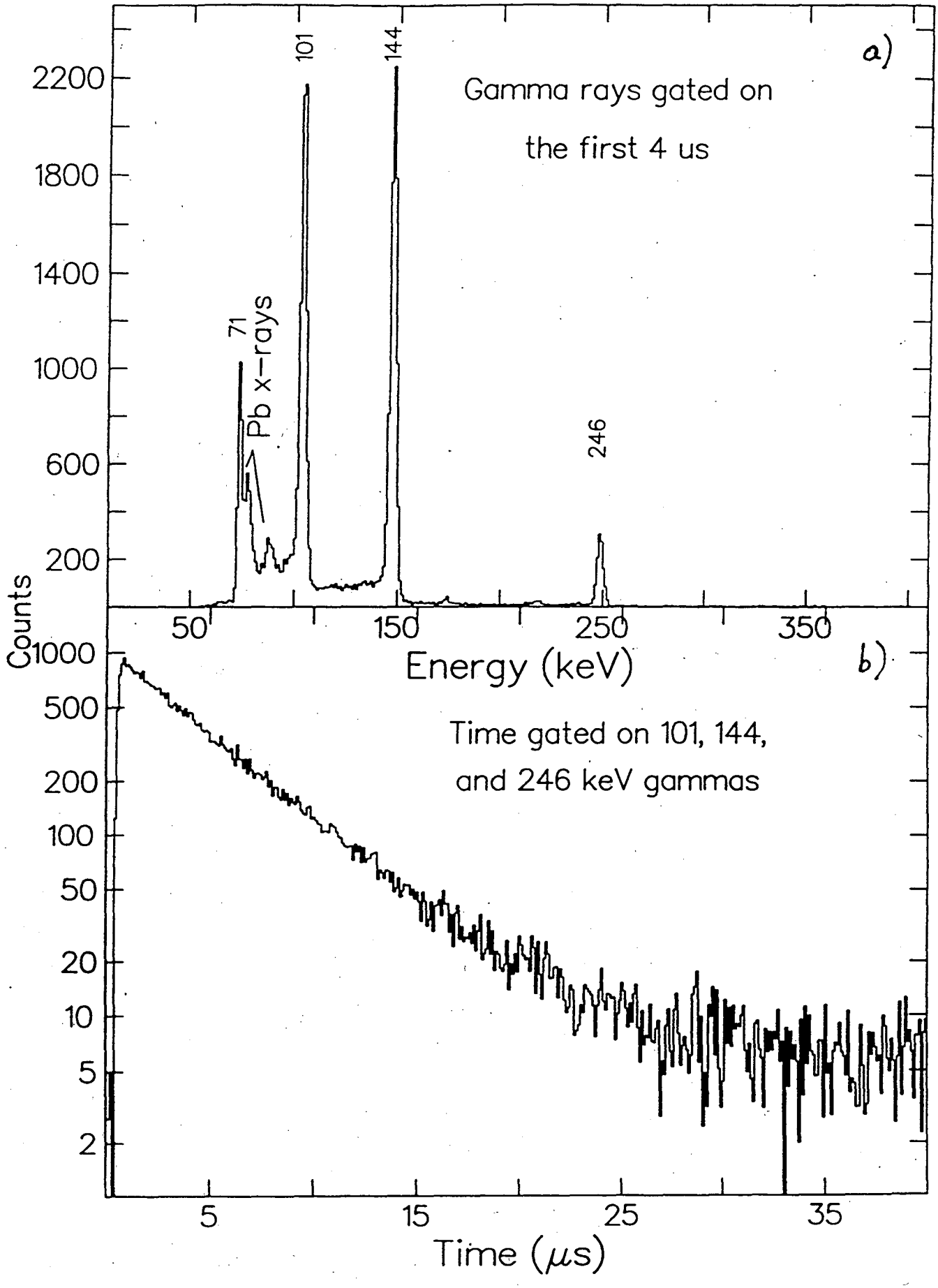
'GRZYWACZ PLOT' TO ID ISOMERS

92-Mo @ 60 MeV/A on Ni target at GANIL



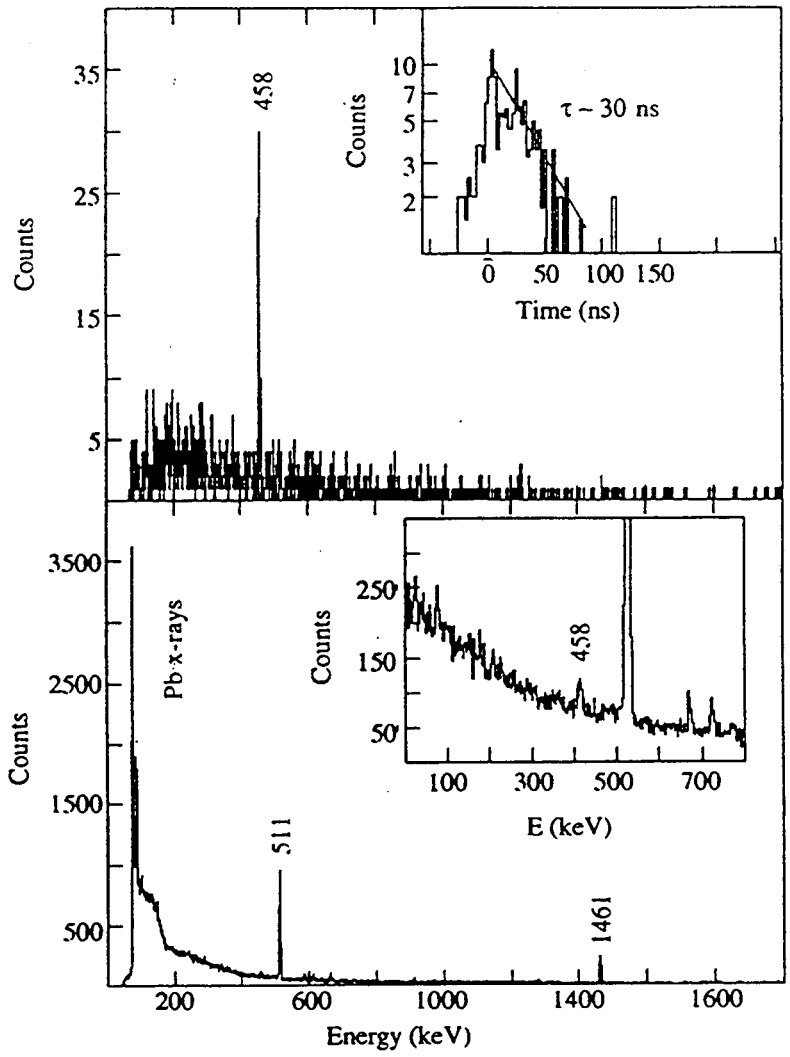


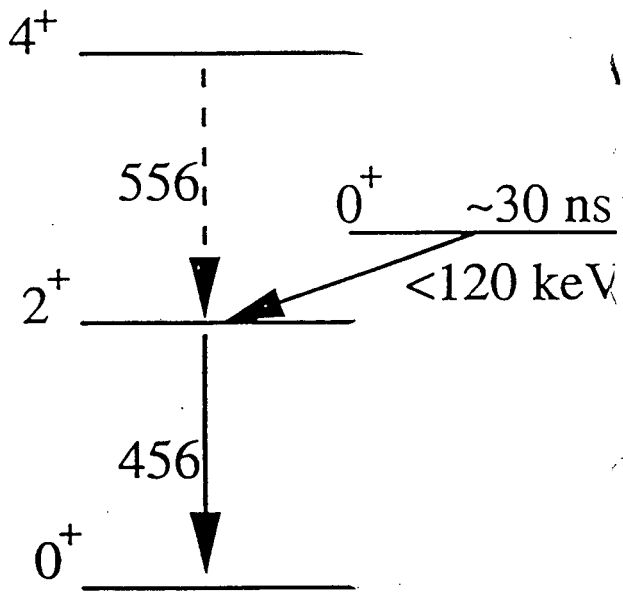
a) γ-ray spectrum within 4 μs. b) Time spectrum.



C. Chandler et al. – to be published

SHAPE COEXISTENCE IN KRYPTON-74





CONCLUSIONS

A. More efficient γ-ray arrays.

B. 1) Improved Recoil Mass Separators.

2) Recoil Decay Tagging < α- and p-decay / β^+/β^--decay ?

3) Charged Particle / Neutron arrays

4) Inner balls – E_γ(Total) vs. Fold

5) Isomer Tagging

6) X-rays and Conversion electrons etc.

C. β^+/EC Decay

D. Radioactive Beams

– COULEX / Transfer

– Fusion – evaporation

Mike Carpenter
Argonne National Laboratory

M CARPENTER

γ-Ray Spectroscopy Beyond the Proton Drip Line for N > 82 and Z < 82

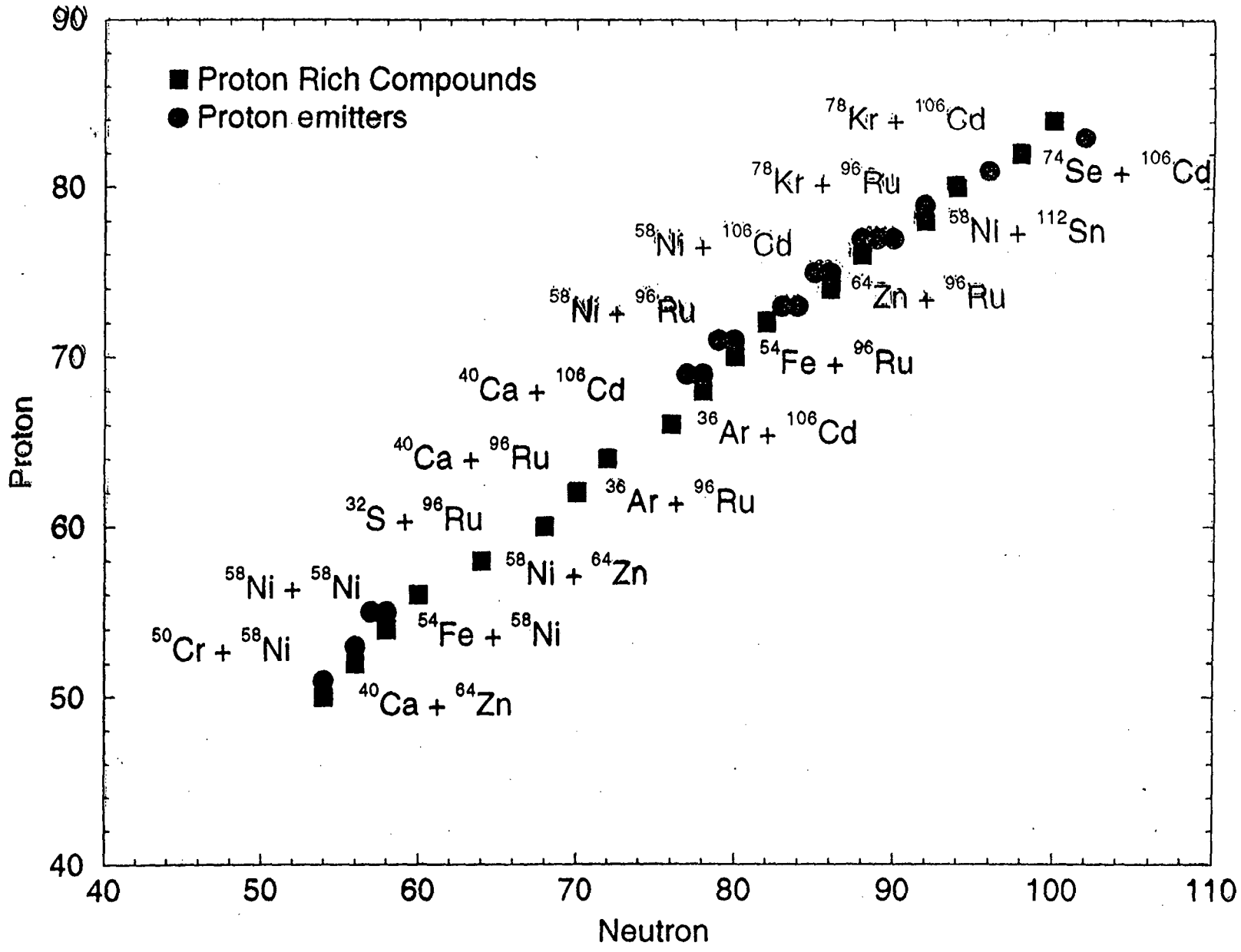
(Oasis for proton and alpha radioactivity)

Current Results

Gammasphere + FMA

Gammasphere + GFS

! RDT !


Proton Rich Compounds
Proton emitters
78Kr + 106Cd
78Kr + 96Ru
74Se + 106Cd
58Ni + 112Sn
58Ni + 106Cd
64Zn + 96Ru
58Ni + 96Ru
54Fe + 96Ru
40Ca + 106Cd
36Ar + 106Cd
40Ca + 96Ru
36Ar + 96Ru
32S + 96Ru
58Ni + 64Zn
58Ni + 58Ni
54Fe + 58Ni
50Cr + 58Ni
40Ca + 64Zn
Proton
Neutron
90
80
70
60
50
40
40
50
60
70
80
90
100
110

Gammasphere + FMA

<u>Conditions:</u> Beam current = 3pNa
Run Time = 5 days
Target: A~100 0.5 mg/cm^2

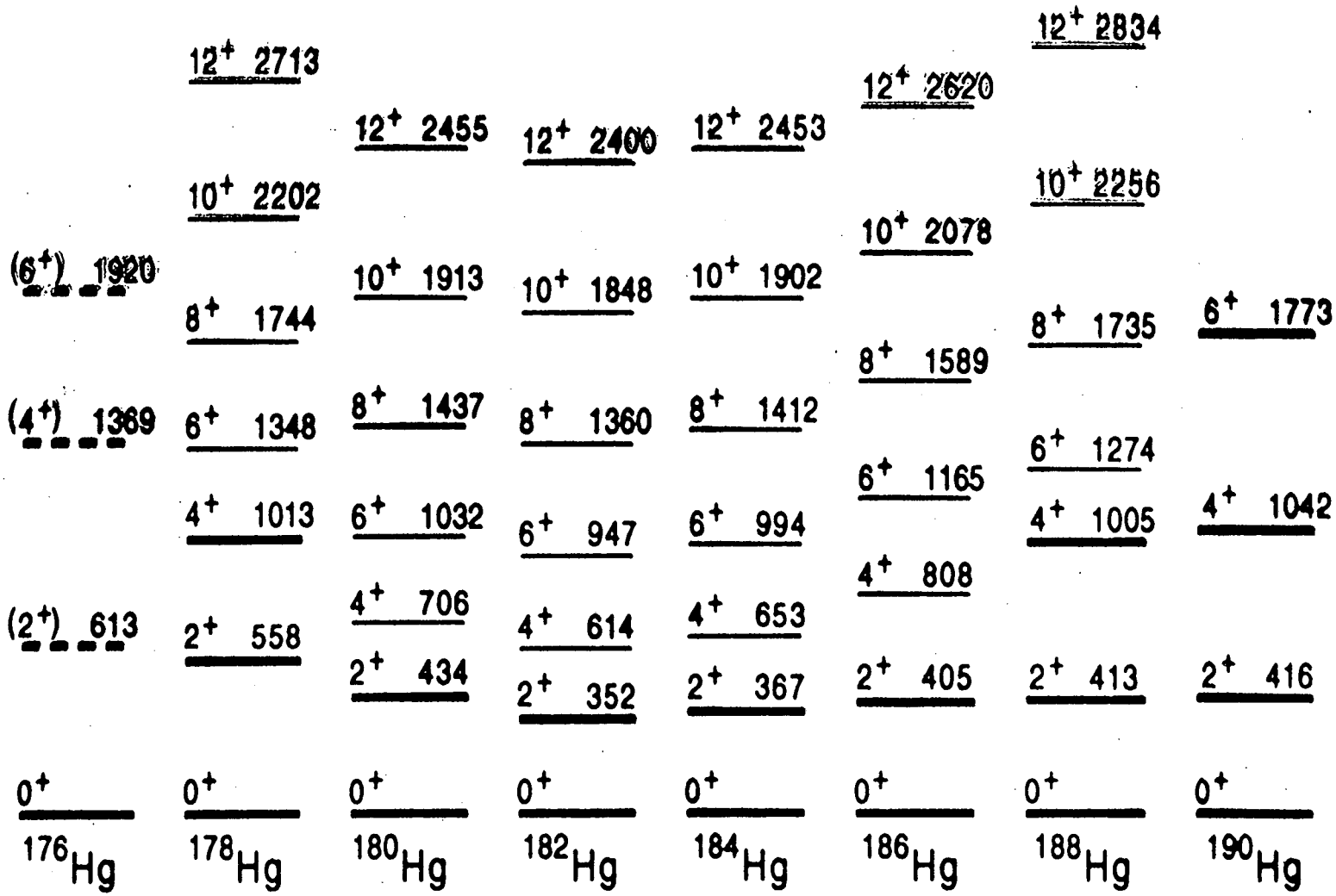
Expected yield in $2^+ \to 0^+$ transition for 1 mb = σ.

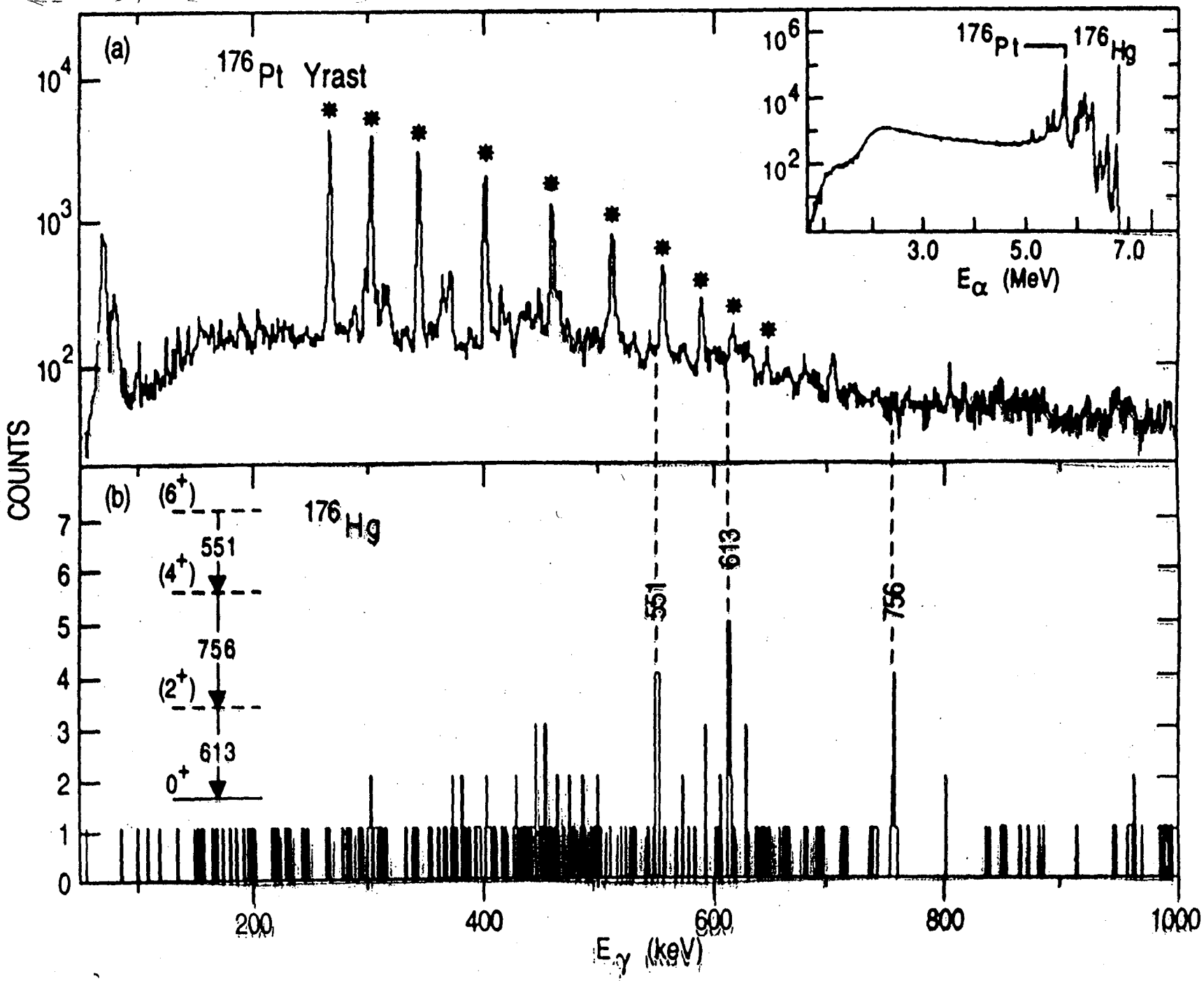
* Residues ~ 65×10^6
* Residues to FMA Focal Plane ~ 6.5×10^6 (10%)
* Implanted in DSSD ~ 4.9×10^6 (75%)
* ~ 5/sec. <= Decays detected ~ 2.0×10^6 (40%)
* $2 \to 0$ transition detected by GS ~ 2.0×10^5 (10%)

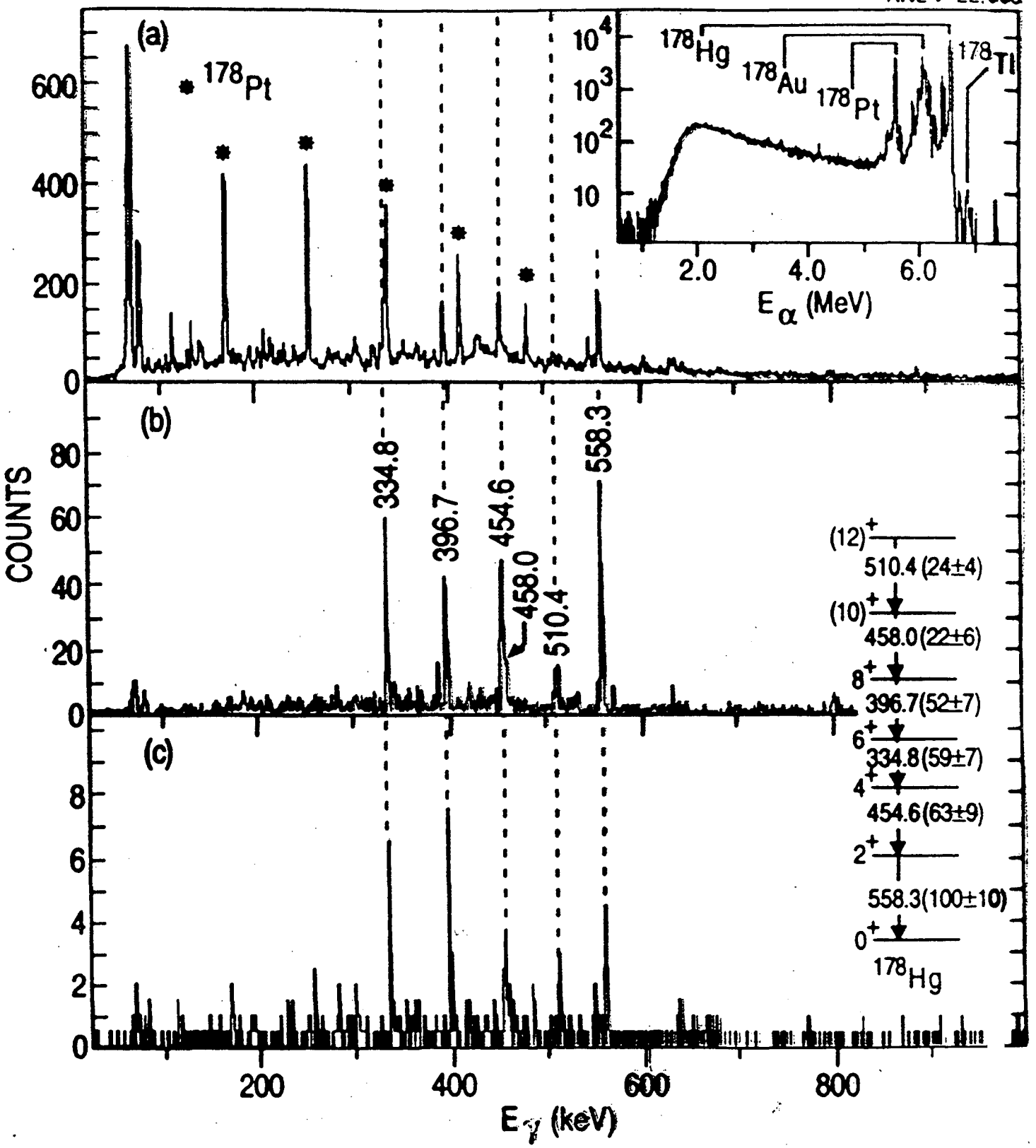
σ	γ-RDT	γ-γ-RDT *	γ-γ-FMA *
1mb	200,000	18,000	44,000
1mb	200	18	44
100mb	20	~2	~4

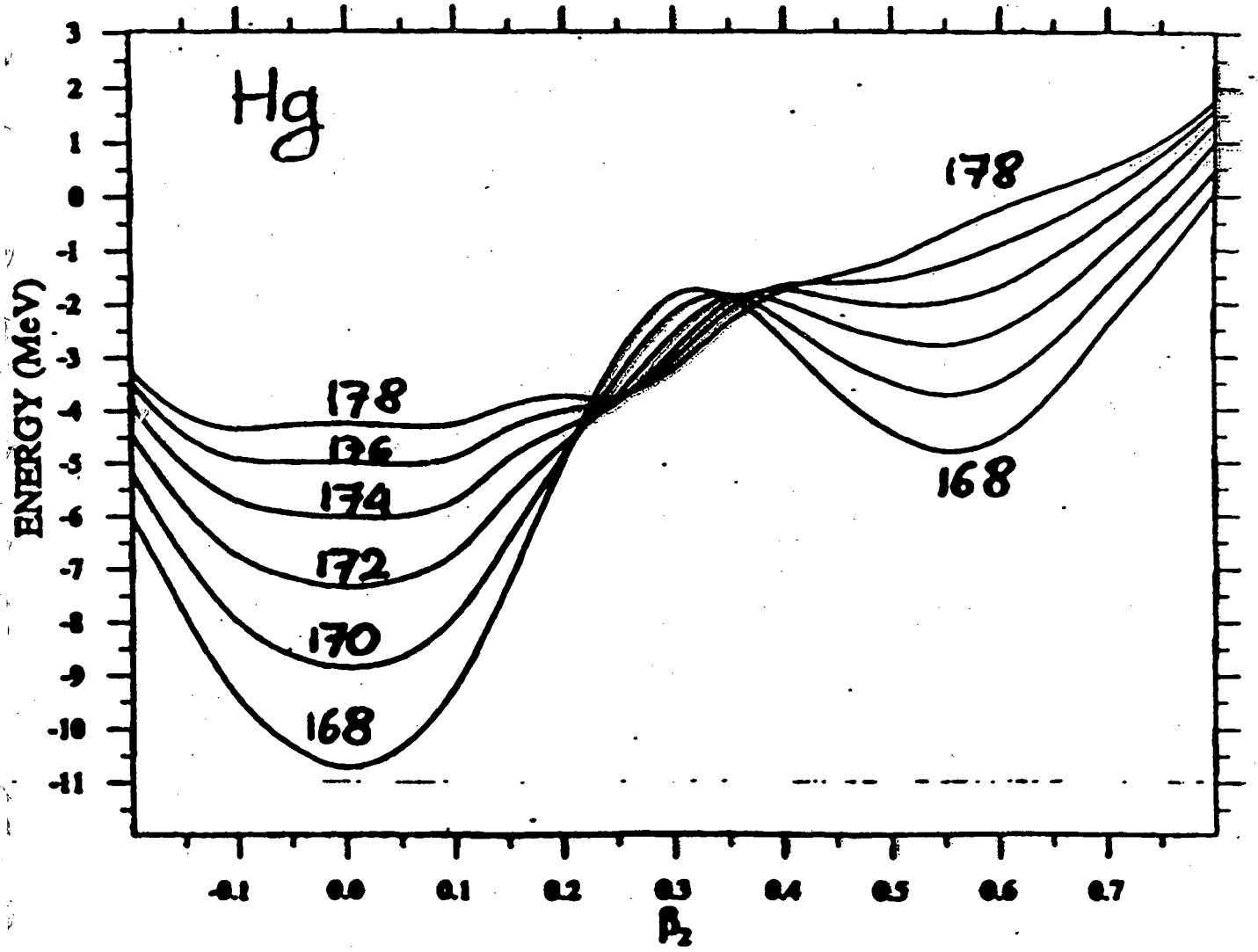
For GFS 50% transmission + 2x target thickness = x10

* * 4^+-2^+ (90%) transitions in coincidence with 2^+-0^+ (100%)

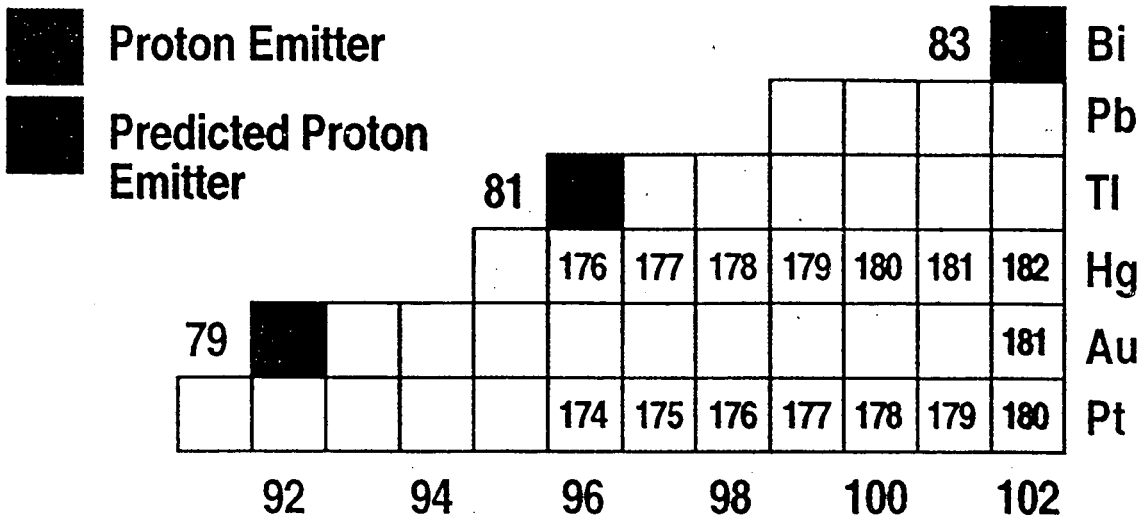

12+ 2713
12+ 2455
12+ 2400
12+ 2453
12+ 2620
12+ 2834
10+ 2202
10+ 1913
10+ 1848
10+ 1902
10+ 2078
10+ 2256
(6+) 1920
8+ 1744
8+ 1437
8+ 1360
8+ 1412
8+ 1589
8+ 1735
6+ 1773
(4+) 1369
6+ 1348
6+ 1032
6+ 947
6+ 994
6+ 1165
6+ 1274
4+ 1013
4+ 706
4+ 614
4+ 653
4+ 808
4+ 1005
4+ 1042
(2+) 613
2+ 558
2+ 434
2+ 352
2+ 367
2+ 405
2+ 413
2+ 416
0+
176Hg
178Hg
180Hg
182Hg
184Hg
186Hg
188Hg
190Hg


(a)
176Pt Yrast
176Pt
176Hg
Eα (MeV)
COUNTS
(b)
176Hg
(6+)
(4+)
(2+)
0+
551
756
613
Eγ (keV)


(a)
178Pt
600
400
200
0
178Hg
178Au
178Pt
178Tl
10^4
10^3
10^2
10
2.0
4.0
6.0
Eα (MeV)
(b)
COUNTS
80
60
40
20
0
334.8
396.7
454.6
458.0
510.4
558.3
(12)+
510.4 (24±4)
(10)+
458.0(22±6)
8+
396.7(52±7)
6+
334.8(59±7)
4+
454.6(63±9)
2+
558.3(100±10)
0+
178Hg
(c)
8
6
4
2
0
200
400
600
800
Eγ (keV)



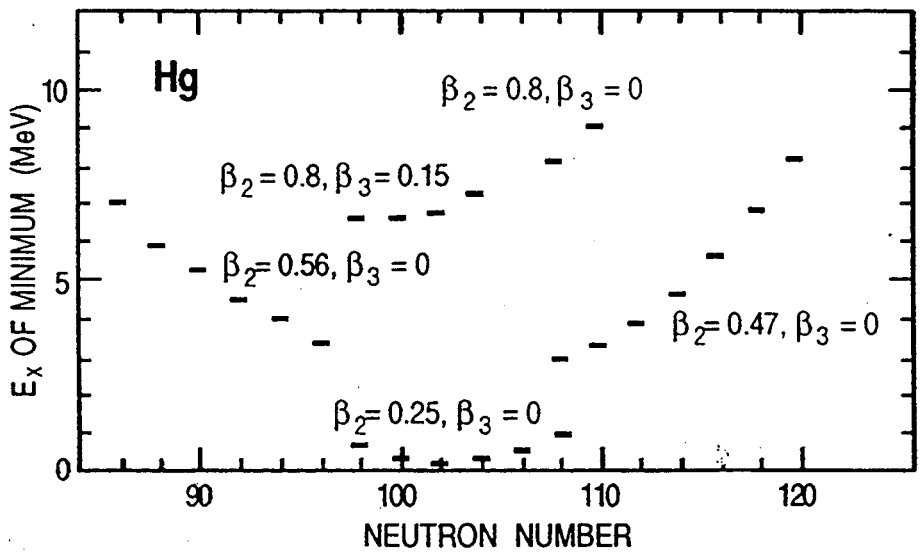
$\beta_2(\beta_4, \beta_6, \beta_8)$



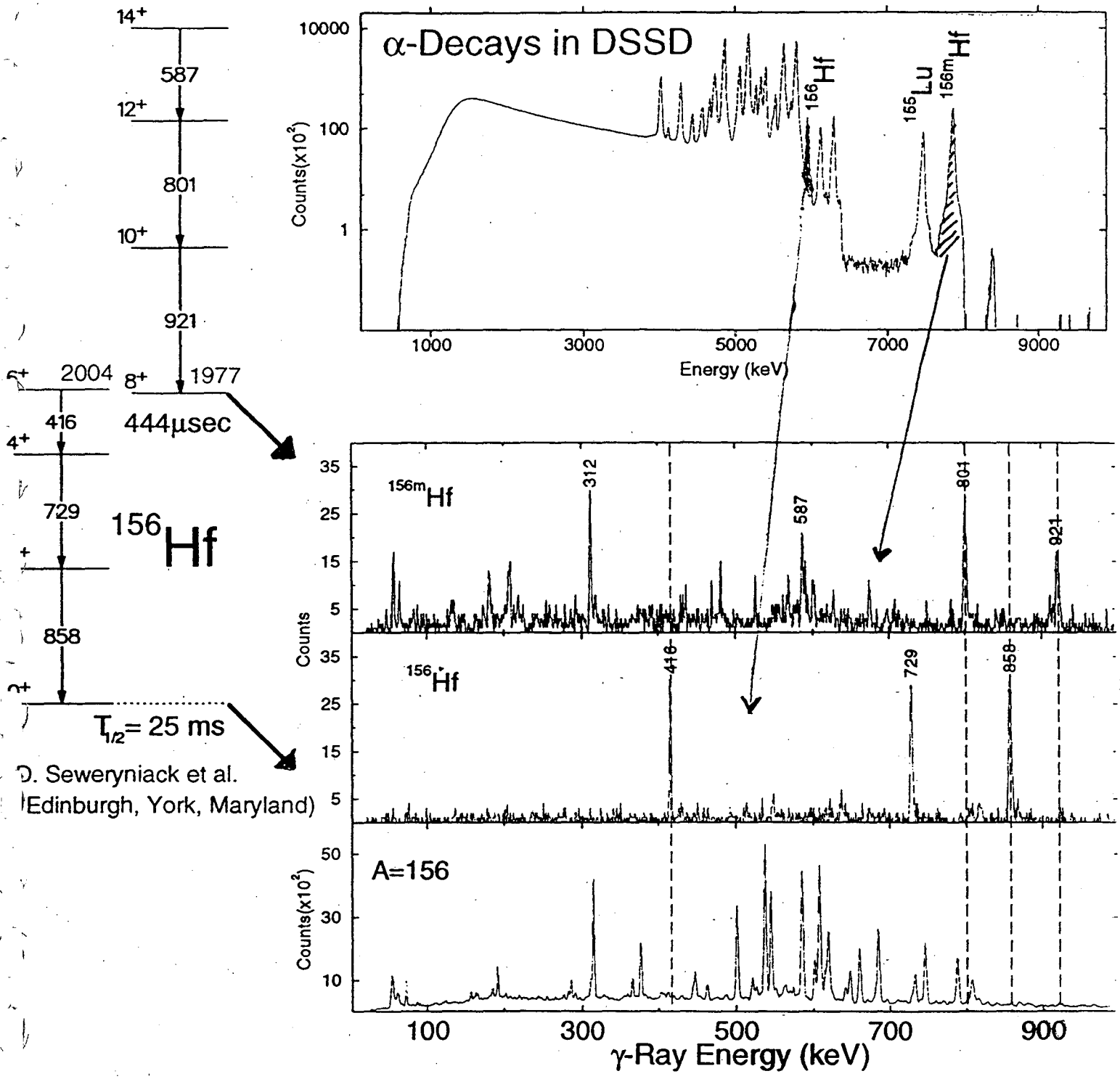
^{78}Kr + ^{103}Rh @ 340, 360 and 380 MeV

Theoretical Calculations Predict Variety of Shapes in Light Hg and Pb Isotopes

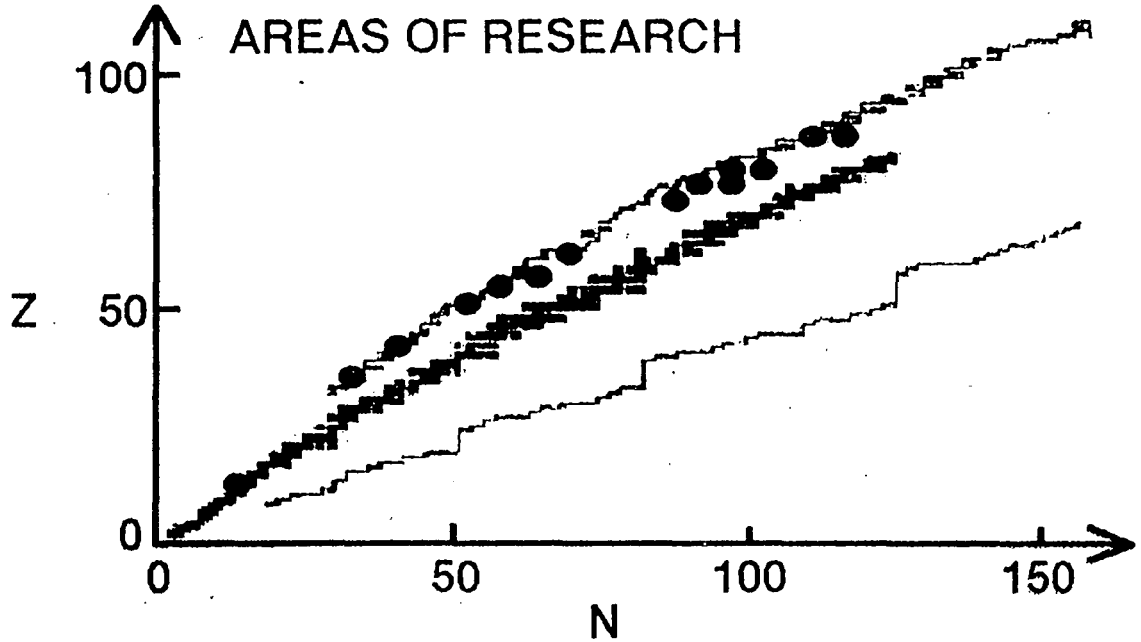
W. Nazarewicz, Phys. Lett. B 305 (1993) 195-201



RDT on ^{156}Hf



D. Seweryniack et al.
N Edinburgh, York, Maryland)



13 experiments from A=24 to 226

40 scientists from 13 countries

Mass Gated

C14.06	W. F. Mueller	179Au first results
L11.07	G. J. Lane	110Sb intruder bands

RDT

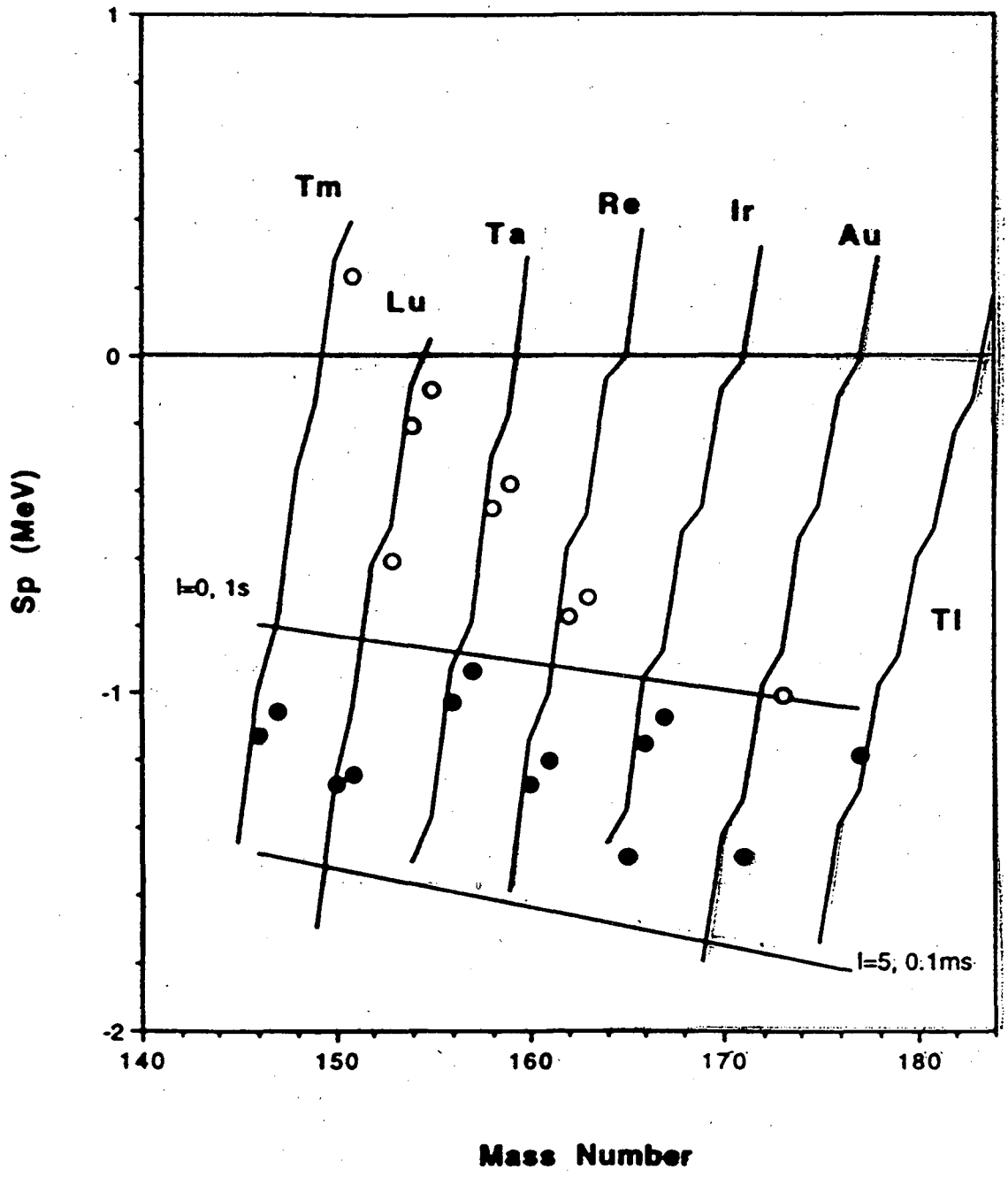
C14.03	M. P. Carpenter	103Rh(78Kr,pxn)176-179Hg
L11.09	D. Seweryniak	102Pd(58Ni,2p2n)156Hf

Ion Chamber Gated

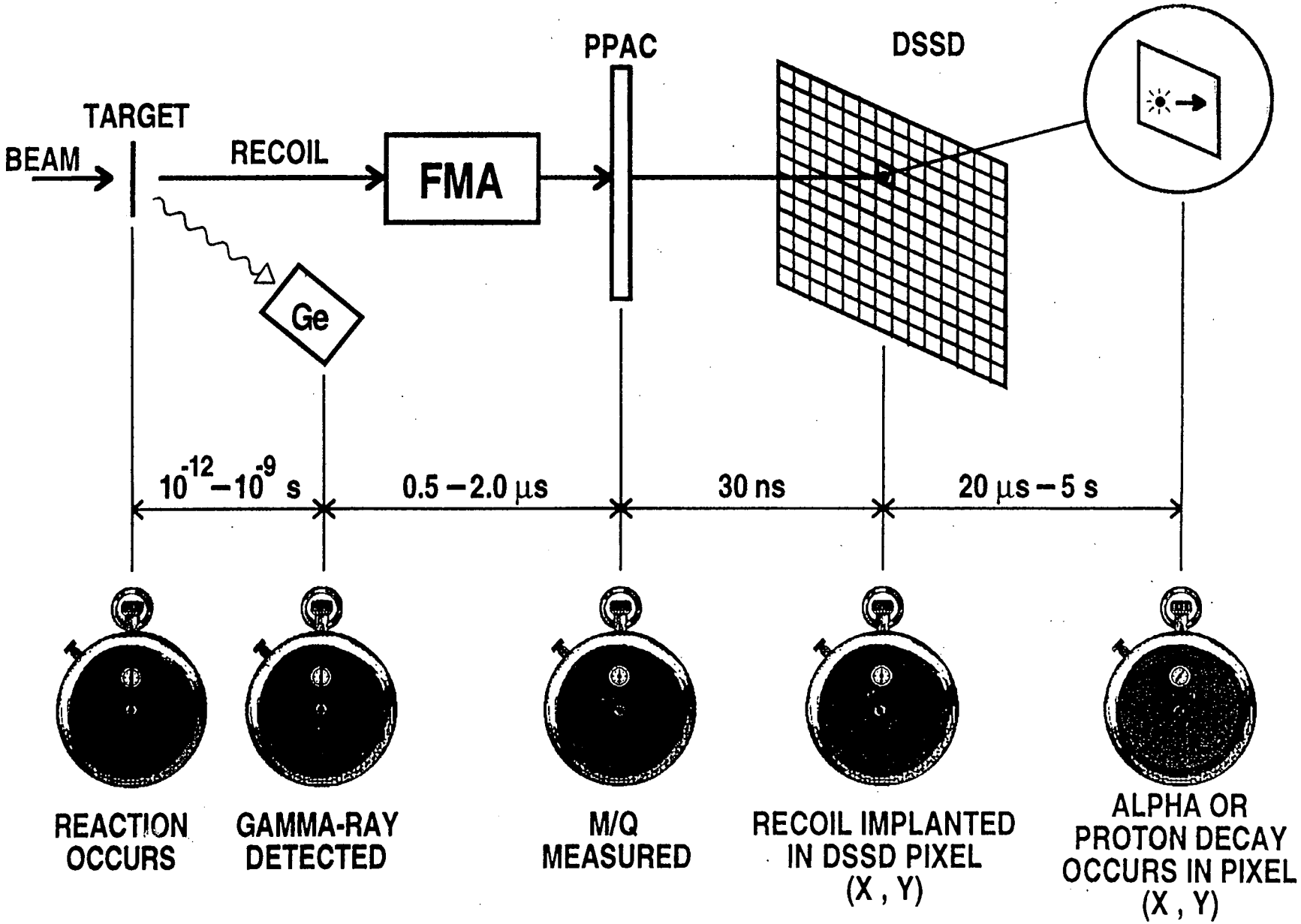
K7.05	J. Schwartz	12C(16O,a)24Mg High-spin states
N7.10	M. P. Carpenter	12C(58Ni,X)Y ----> 40Ca(Y,X)Z Development of secondary reactions

. . . and much more to come

Studies of N=Z nuclei: 62Ga, 88Ru, 92Pd
New regions of deformation: 200Rn, 204Ra
First observation of excited states in other nuclei using the RDT method


Tm
Lu
Ta
Re
Ir
Au
Tl
I=0, 1s
I=5, 0.1ms
Sp (MeV)
Mass Number
1
0
-1
-2
140
150
160
170
180

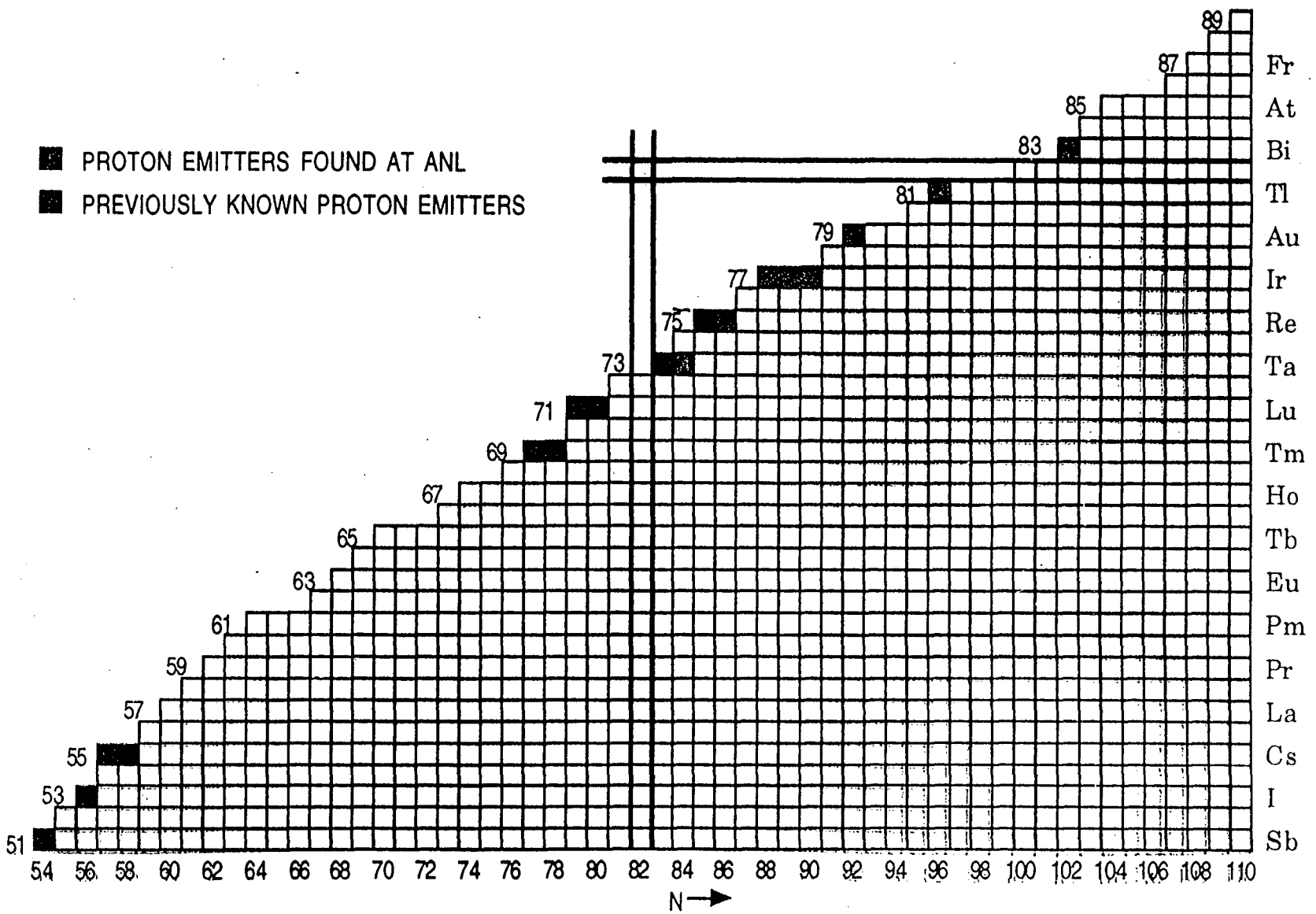
RECOIL DECAY TAGGING METHOD



● Prompt γ-rays correlated with M/Q and (X , Y) position of recoil in DSSD

Decay proton or alpha identifies nucleus that emitted the γ-rays

PROTON RADIOACTIVITIES

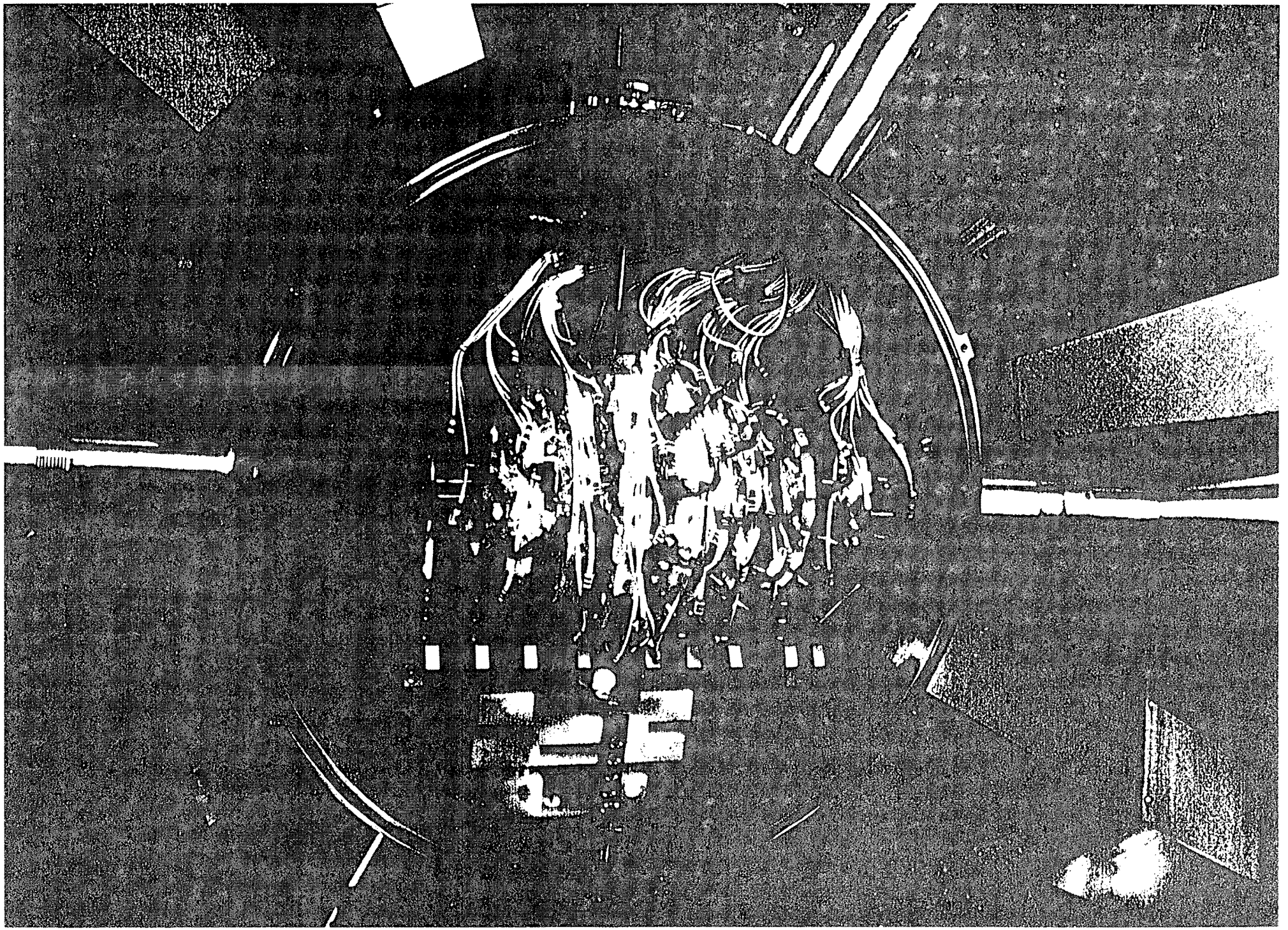


Channel selection with charged-particle detector arrays

Talk given at the
Workshop on the Physics of using
Compound-Nucleus Separators
LBNL

M. Devlin

April 11, 1997



Photographic & Digital Services

95 28

Design goals of charged-particle detector arrays

High efficiency

High degree of segmentation

Good particle identification

Able to handle high count rates

Low particle detection energy thresholds

Low total mass

Properties of the Microball

- It consists of 95 CsI(Tl) scintillators with Si photodiode readout arranged in 9 rings covering 96% of 4π

- It resolves and identifies charged particles with 80-95% efficiency

- It provides the charged particle energies

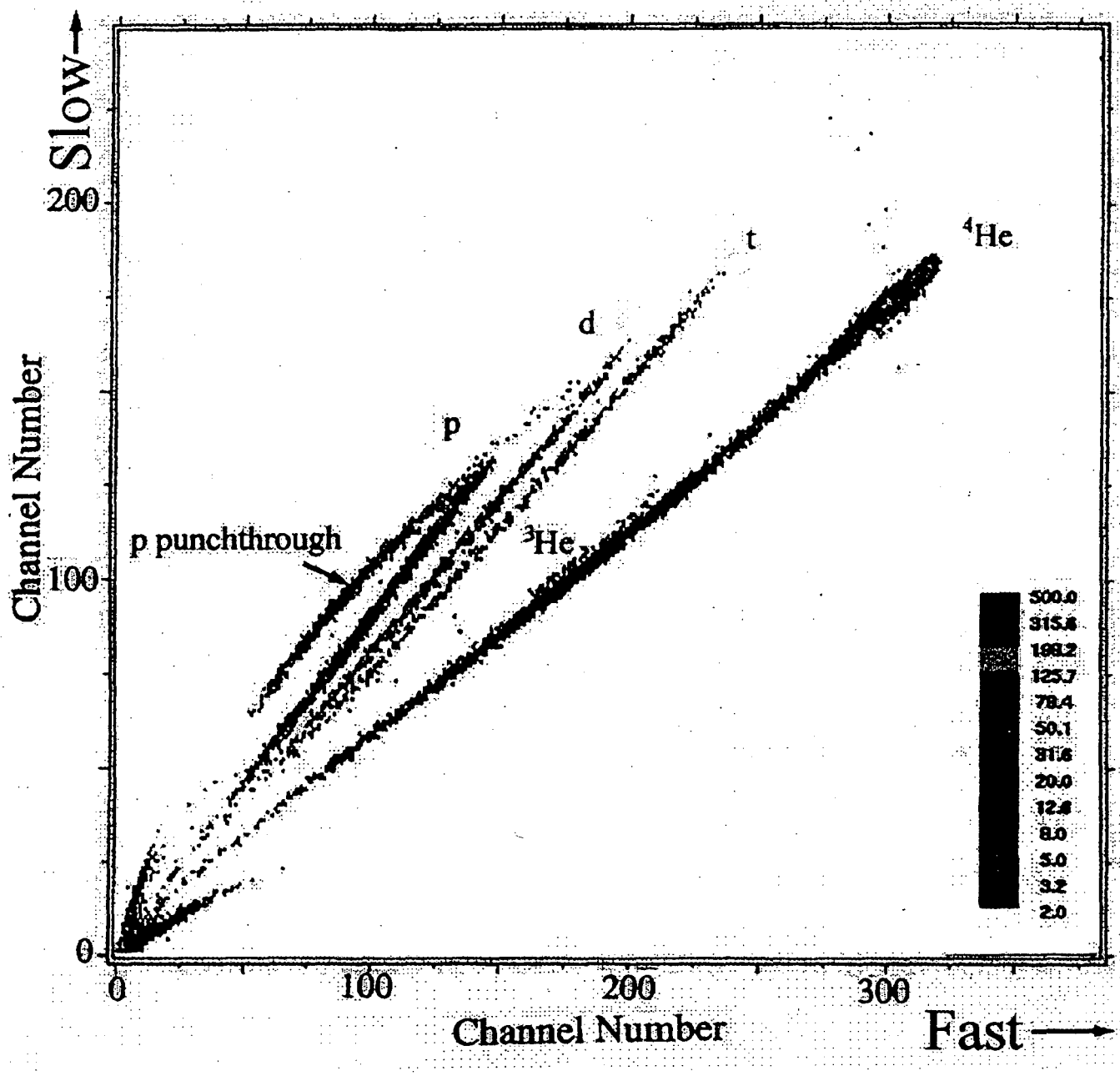
- It selects the exit channels with high efficiency

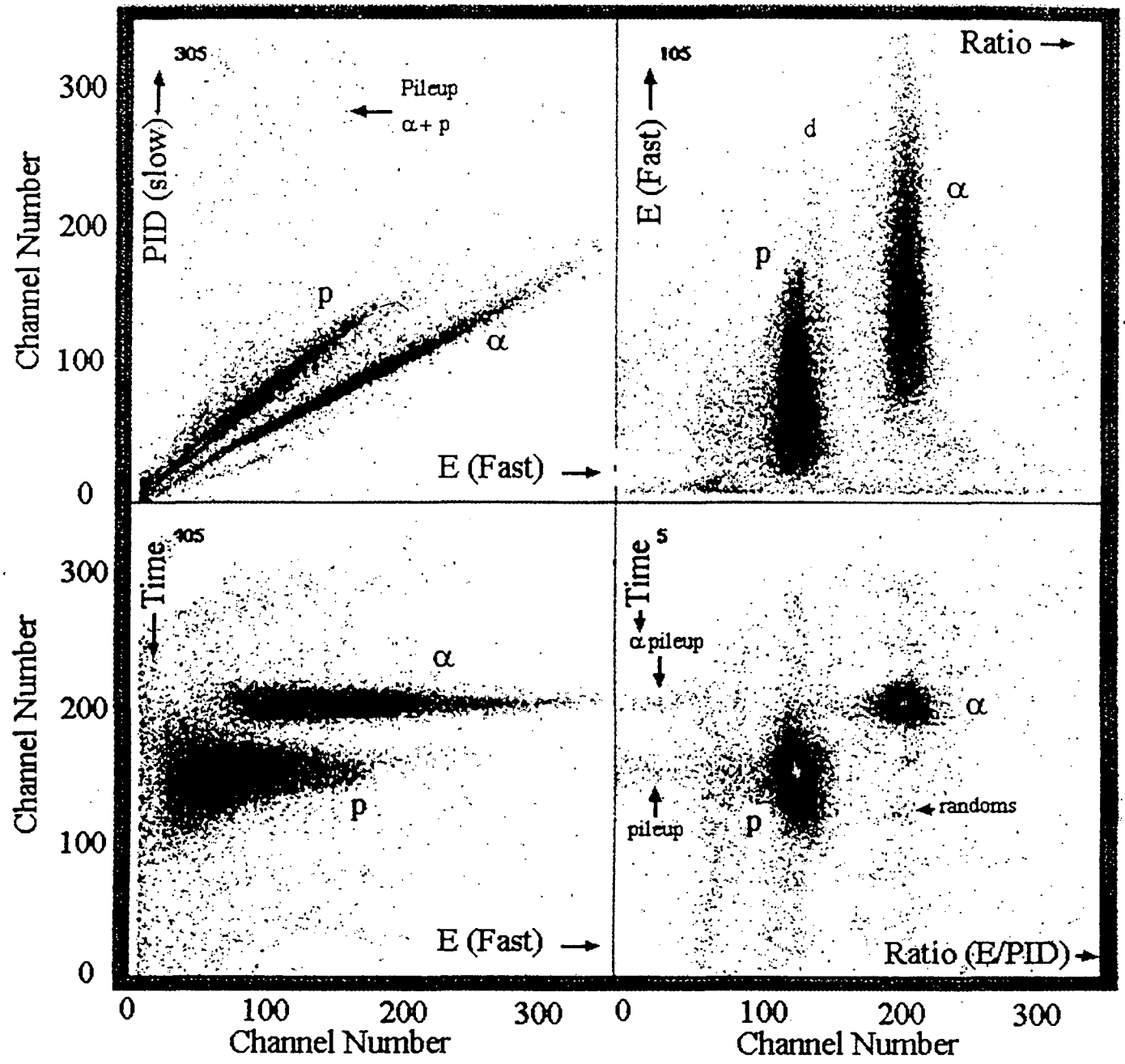
- It allows precise Doppler corrections to be made from the measurement of the recoil direction that improve substantially the energy resolution

  For the ^{58}Ni(^{29}Si,α2p) reaction channel the FWHM goes from 24.0 to 6.5 keV at 2.0 MeV!

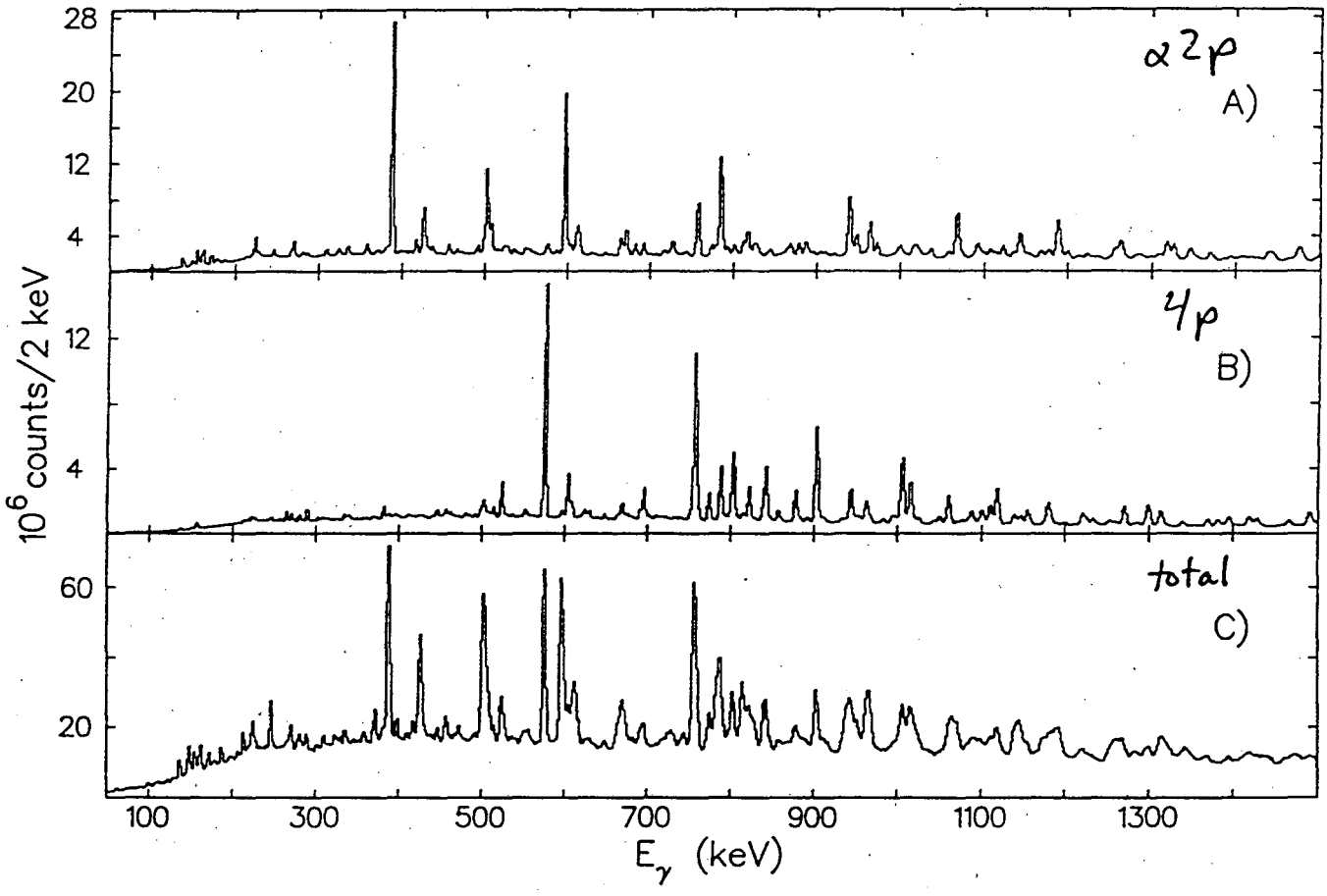
- It improves the peak to background by factors of 4 -10 depending on the channel.

48 MeV alphas on Au

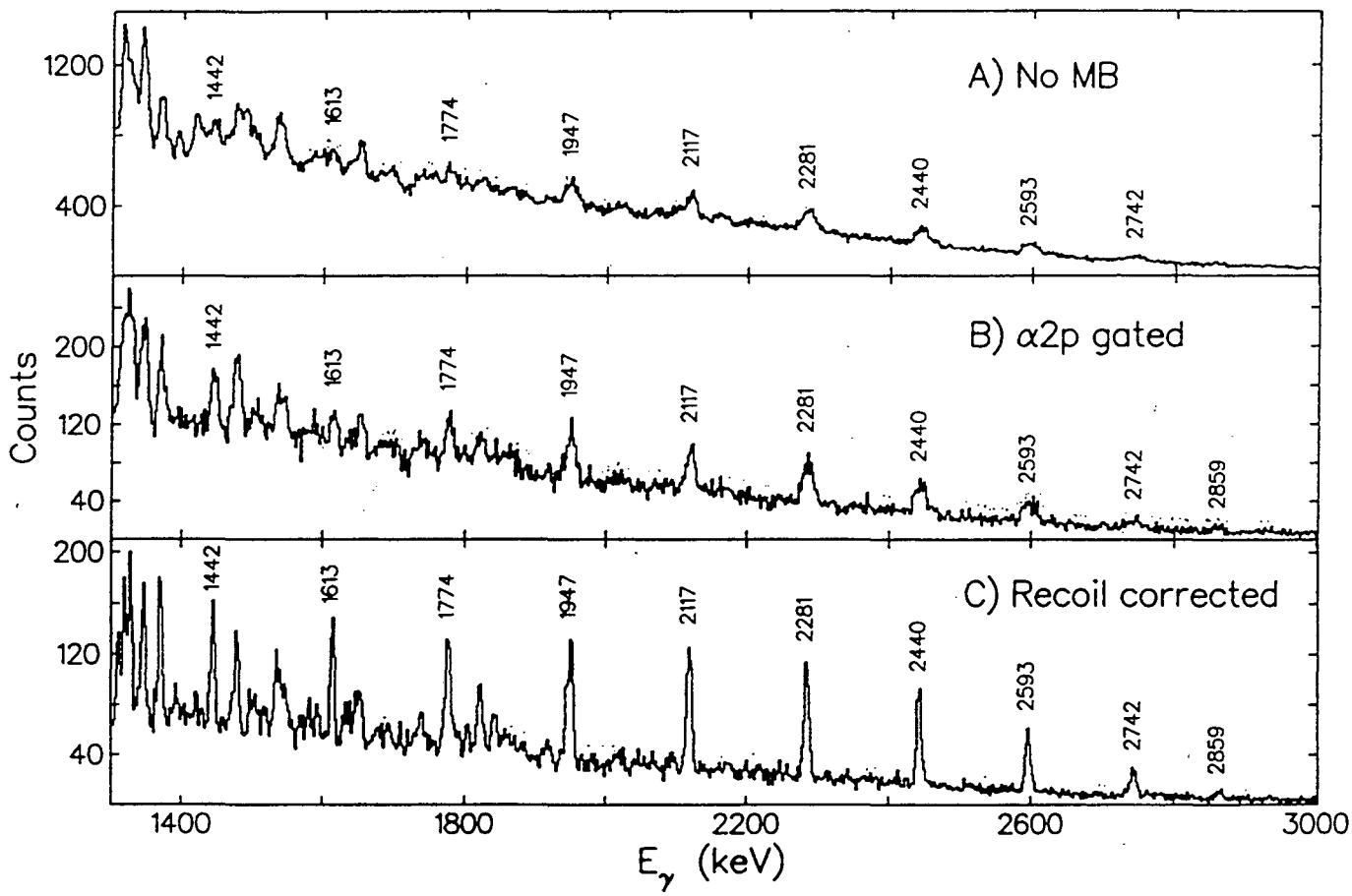



305
Pileup
α + p
PID (slow)
p
α
E (Fast)
105
Ratio
E (Fast)
d
α
p
305
Time
α
p
E (Fast)
5
Time
α pileup
α
pileup
p
randoms
Ratio (E/PID)
Channel Number
0
100
200
300
Channel Number
0
100
200
300
Channel Number
0
100
200
300
Channel Number

$^{28}Si + ^{58}Ni$ @ 130 MeV



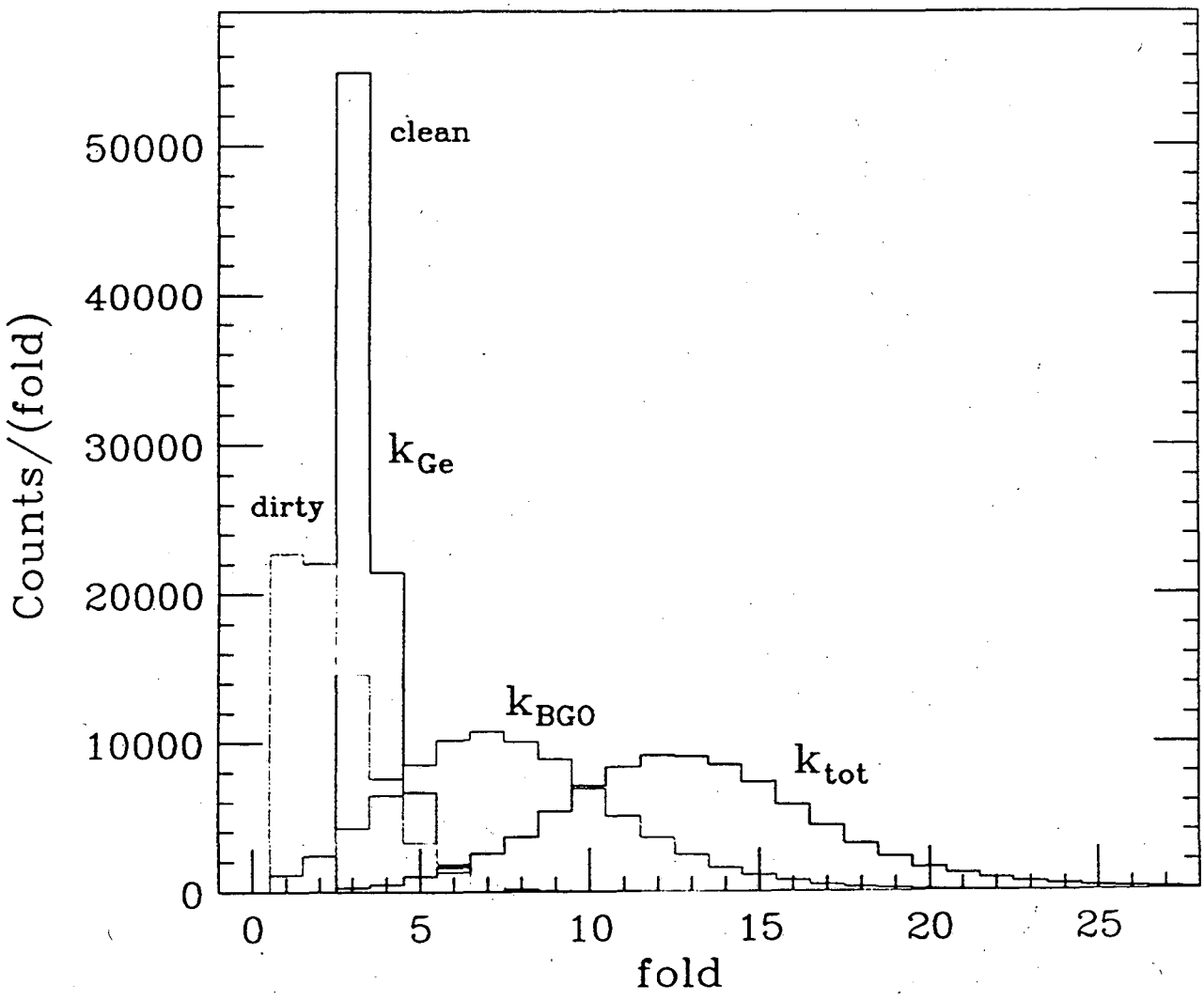
^{80}Sr great SD

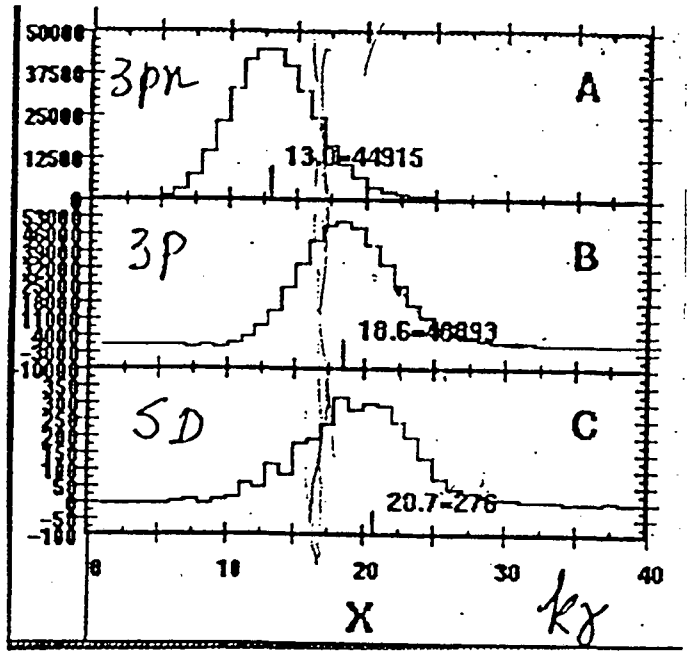


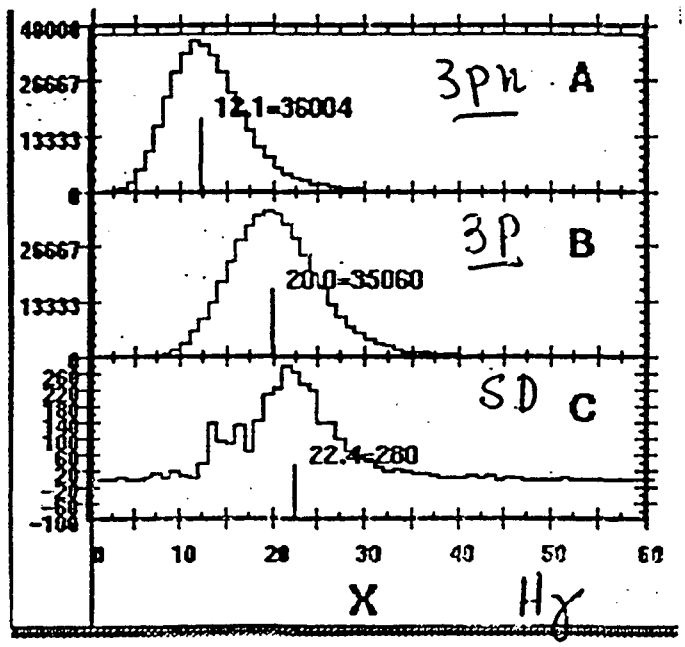
P/B ≈ 0.4

1.3

4.5


clean
dirty
k_{Ge}
k_{BGO}
k_{tot}
Counts/(fold)
fold
0
10000
20000
30000
40000
50000
0
5
10
15
20
25


3pn
A
13.0-44915
3P
B
18.6-46893
5D
C
20.7-276
X
kγ


3pn
A
12.1-36004
3P
B
20.0-35060
5D
C
22.4-280
X
Hγ

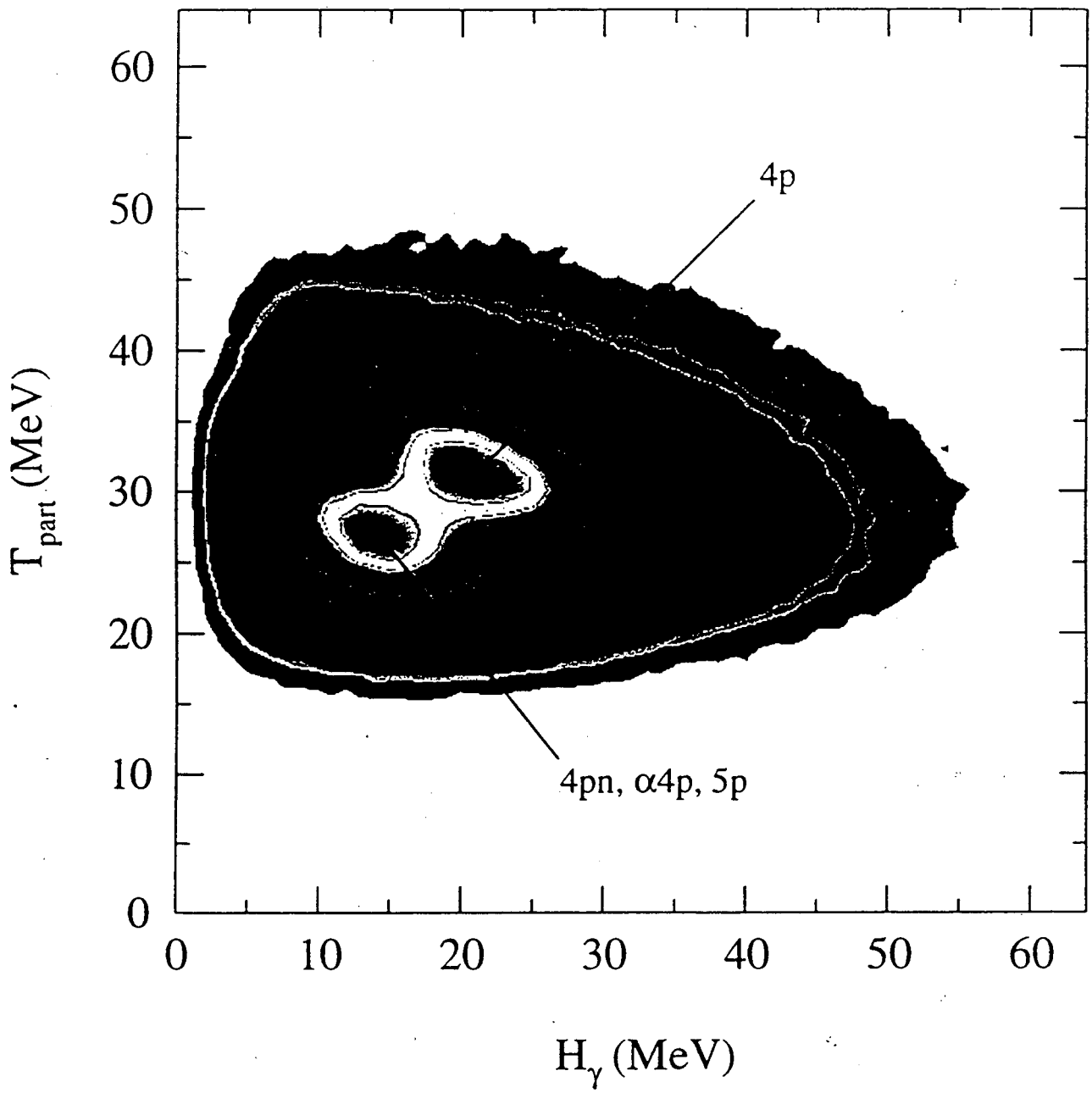
k_γ, H_γ, E^* gating

- 137 MeV $^{31}P + ^{58}Ni = ^{89}Tc^* \rightarrow$
- 18% in $^{85,86}Zr$ the 3p particle gate
  - with 12% as ^{85}Zr+3pn, and 2.0% as ^{86}Zr+3p
  - The Yrast SD was 2.8% of the ^{86}Zr or 0.056% of the total
- After gating by $k_\gamma \geq 17$
  - 90% of the 3pn+^{85}Zr was removed
  - 35% of the total ^{86}Zr was lost
  - and only 25% of the SD was lost
- In the end the SD was 0.042% of total and 4.0% of 3p, but only 2% of the initial background remained

Gammasphere + Microball

83 HPGe - Hevimets Removed

$^{28}Si + ^{40}Ca$ at E_{lab} = 125 MeV - 4 protons detected



Carl Svensson

$^{28}Si + ^{58}Ni$ @ 130 MeV

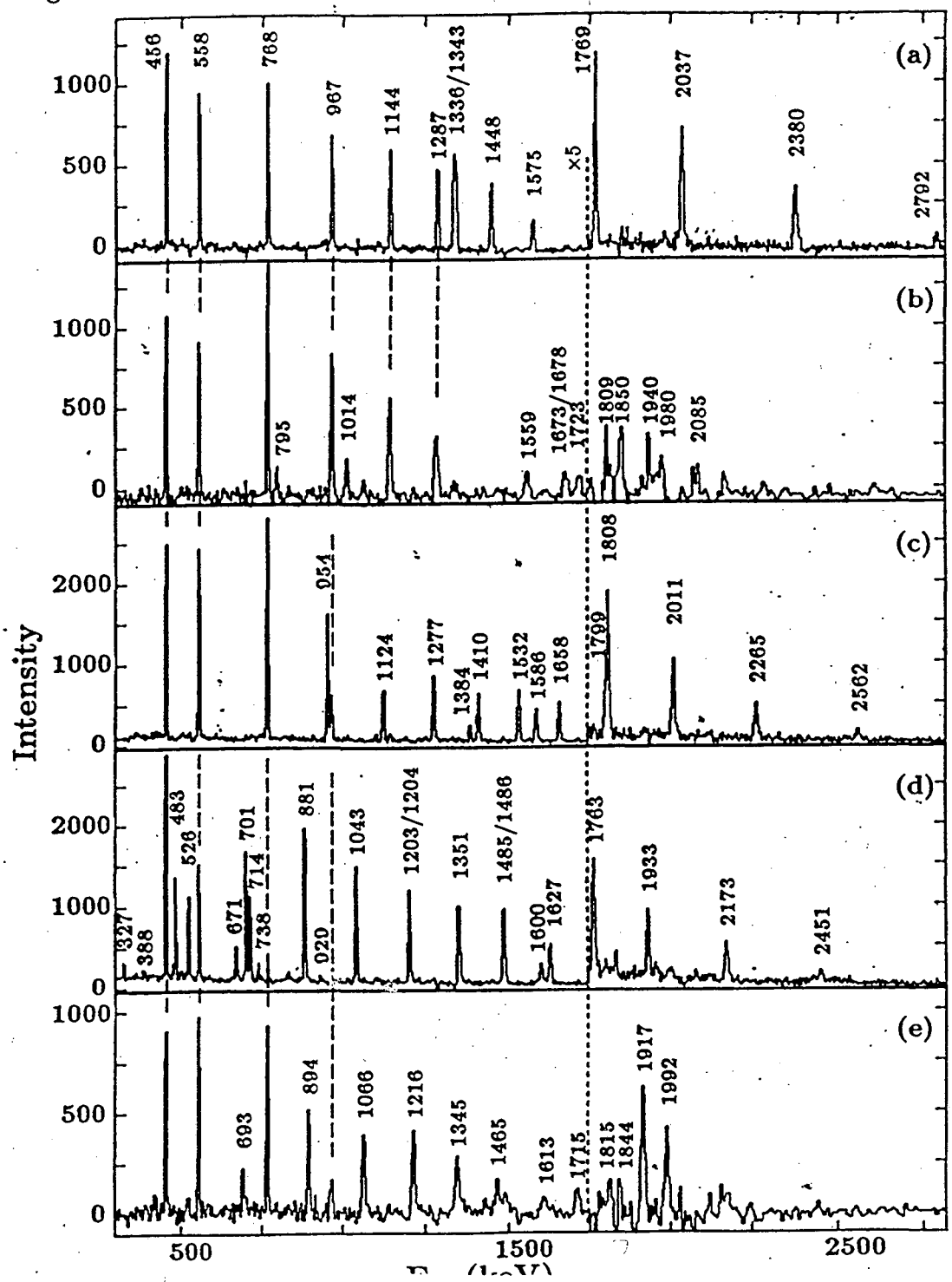
$3\alpha^-$ channel $\Rightarrow$ ^{74}Kr

$\approx 0.2\%$ of ER cross section

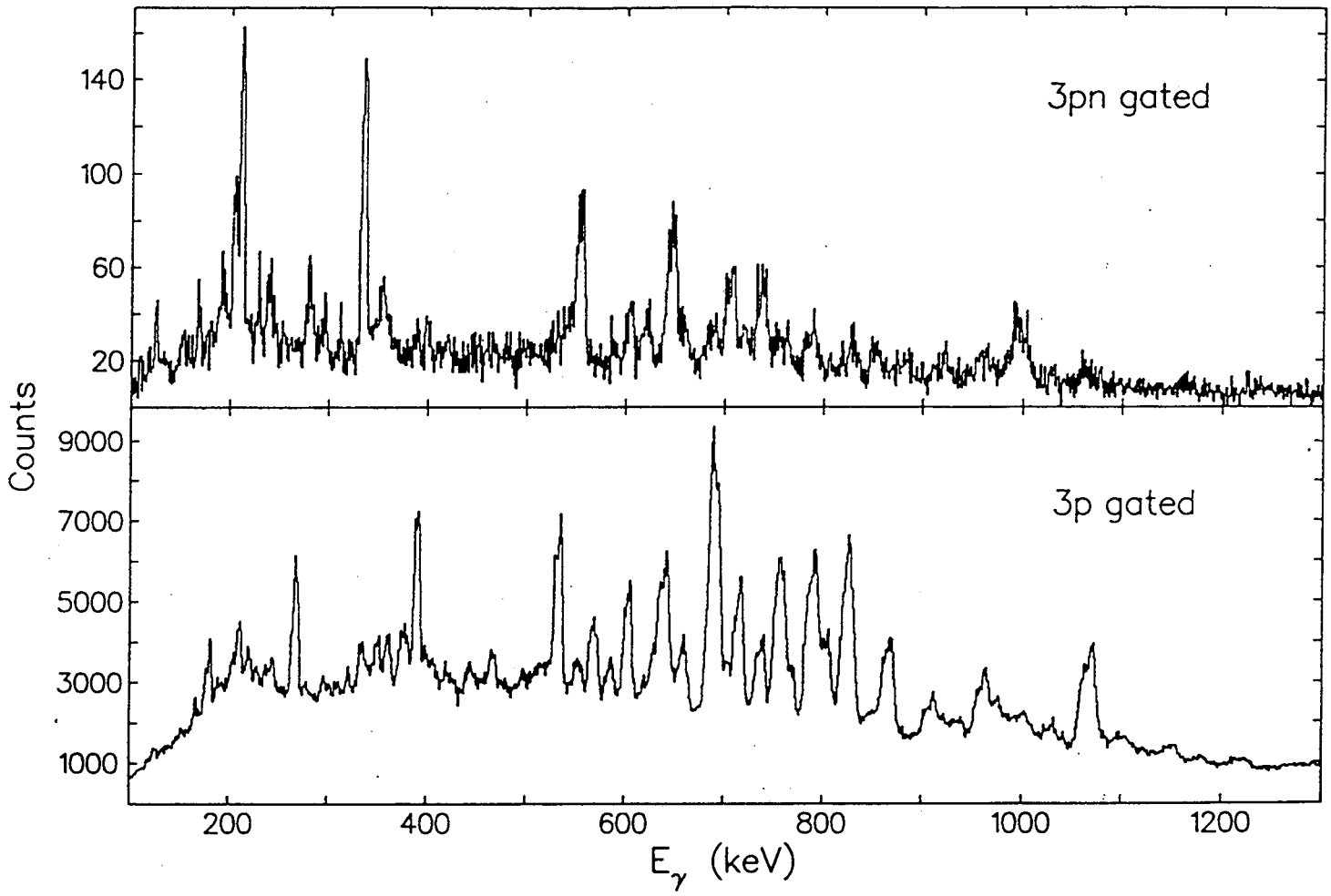
≈ 2 mb

D. Rudolph *et al.*, Systematics of $T_z = 1$ nuclei in the $A = 80$ region ...

Figure 2



$^{58}Ni + ^{58}Ni$ @ 250 MeV



GS + MB + n detectors

J.F. Smith, D.R. LaFosse, et al.

	σ	
<u>GS + MB</u> (some spectroscopy)	$<200\,\mu b$	(in favorable cases: multiple charged particle evaporation)
(high spin spectroscopy)	$\lesssim .1$ mb	SD ($\simeq 1\%$) of a 1% channel
<u>GS + MB + n det</u>	$<50\,\mu b$	"N = Z"

MB suppresses fission for pxn and αxn reactions in light and moderate mass nuclei

Cyrus Baktash
Oak Ridge National Laboratory

Spectroscopy and Channel Selection Near Proton-Drip Line

Cyrus Baktash
ORNL

Important Considerations in the Choice of Tools and Techniques:

- Objectives:
  - New isotope/element production, decay studies:
    High beam intensitis
  - → Gamma spectroscopy
    Few pna of beam

- Reactions:
  - Transfer and DIC (grazing angle) n-rich
  - → Compound nucleus (forward angles) p-rich
    Evaporation particles may be used for tagging

- Partial Cross section:
  Determines requisite *selectivity* { ~50 mb, ~.5 mb, ~5 μb

- Count-rate requirements:
  A function of beam intensity and cross section;
  Determines requisite *efficiency*

F.O.M ~ selectivity x efficiency

Tools:

- Magnetic Recoil Separators

- Ge arrays, charged-particle det., n-det., (H,K) at the target position

  - Recoil Mass Separators (RMS)

    - Focal-Plane detectors:
      >Ionization chamber, X and γ-det. for Z-sel.;
      >DSSD;
      >Recoil-Decay (p, α, isomers) Tagging
      > others (decay scheme)

Outline

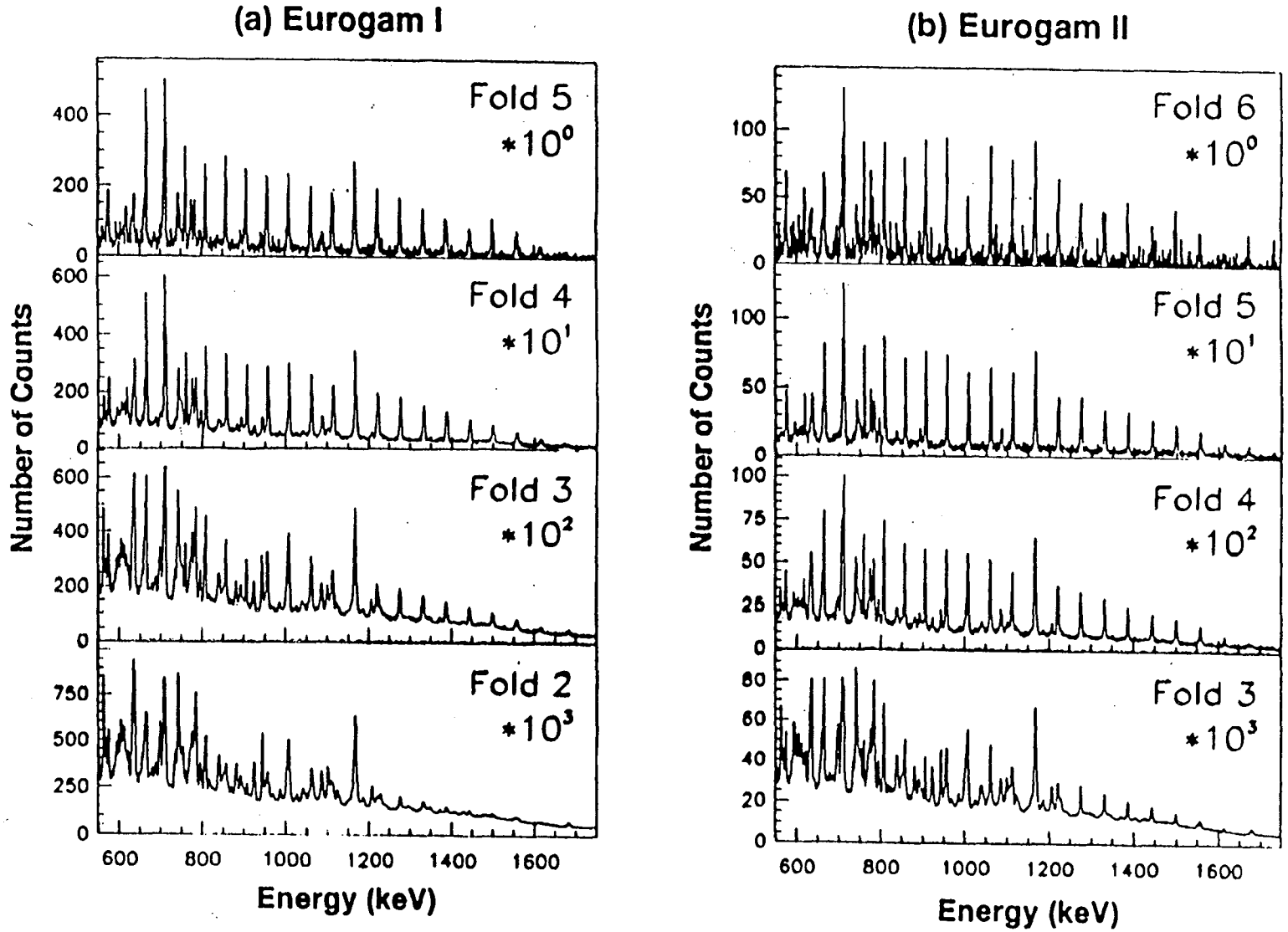
Experiences from:

(1)	GS + γBall	$A \simeq 80$	SD
(2)	GS + γBall + n	$A \simeq 60$	$N=Z \simeq 30$
(3)	RMS + Aux. det		$N=Z \gtrsim 40$
			p, α emitters
			Radioactive Ion Beams

(4) Summary

few X.R channels

(H,K) selection is good enough.



• Large σ
• Regular pattern

⇒ High-fold γ

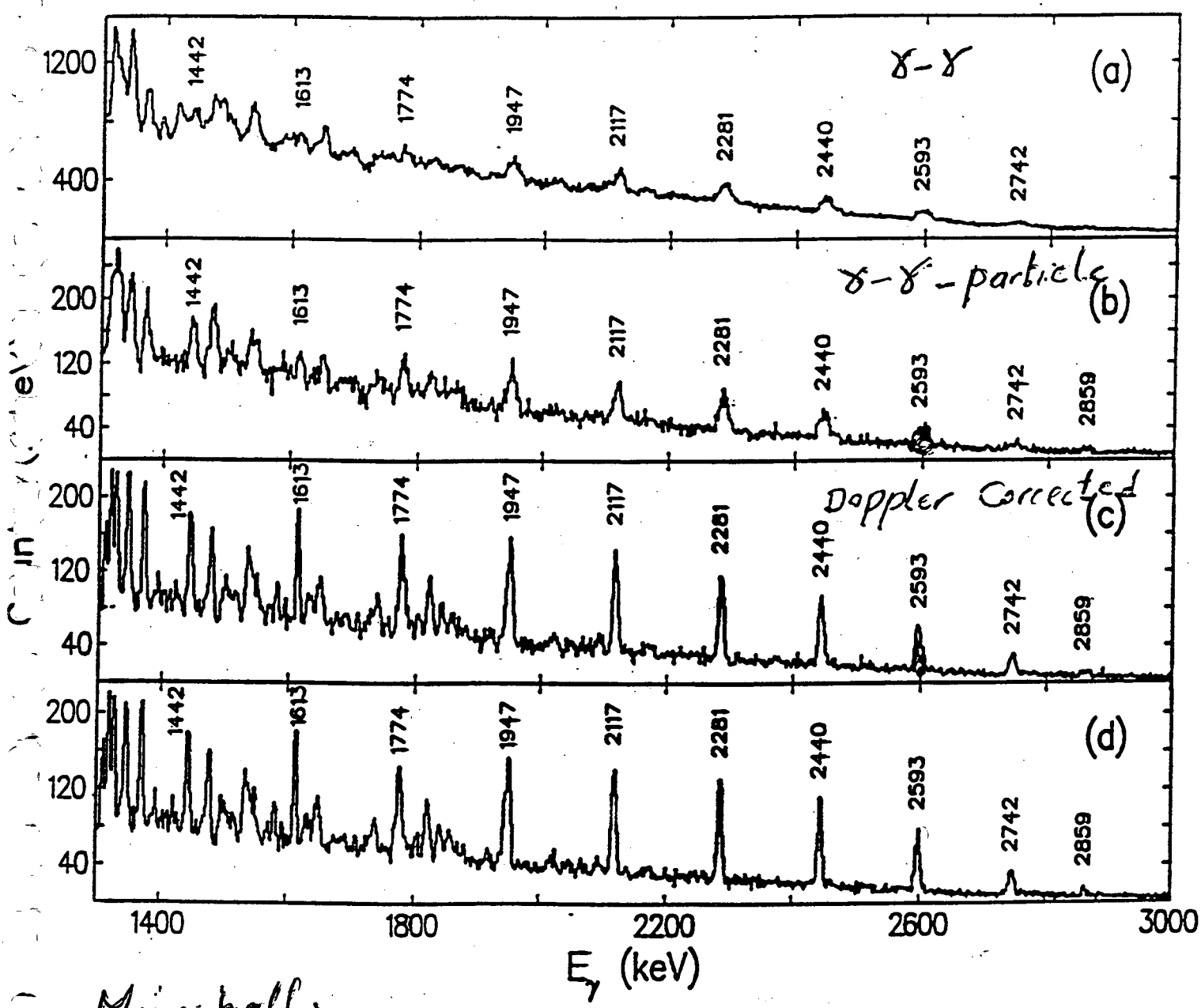
$$R.P. = \frac{\text{Peak}}{\text{Tot.}} \times \frac{\gamma\ \text{sep.}}{\gamma\ \text{Res.}}$$

≃ 10–15 for SD

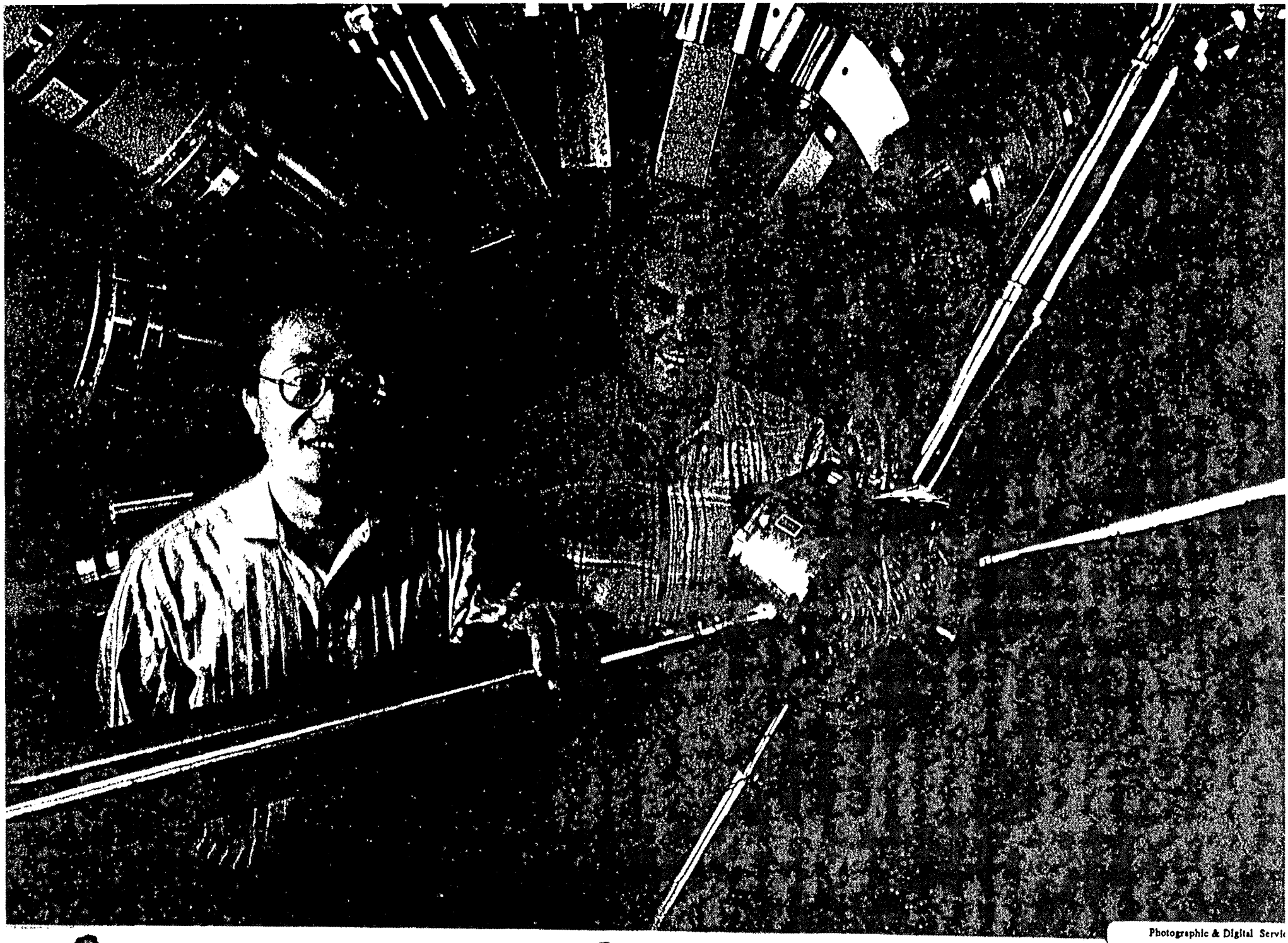
limits σ ≃ 100 μb

Figure 6. Spectra of the yrast SD band in ^{149}Gd when one, two, three, four and five coincidence requirements (gates, fold two corresponds to one gate) are demanded from a gate list of 10 transitions. The data are taken from Eurogam I (a) and Eurogam II (b) [31]. No background has been subtracted from these spectra.

- $A \simeq 80$
- charged-particle evaporation Dominates
- Typically $\gtrsim 20$ exit channels



Microball:
- Channel Selection
- Better resolution ⇒ improved RP



Photographic & Digital Servi
XBC 958-4278
BNCB BE TIONAL

Reaction $^{28}Si + ^{58}Ni$ at 130 MeV

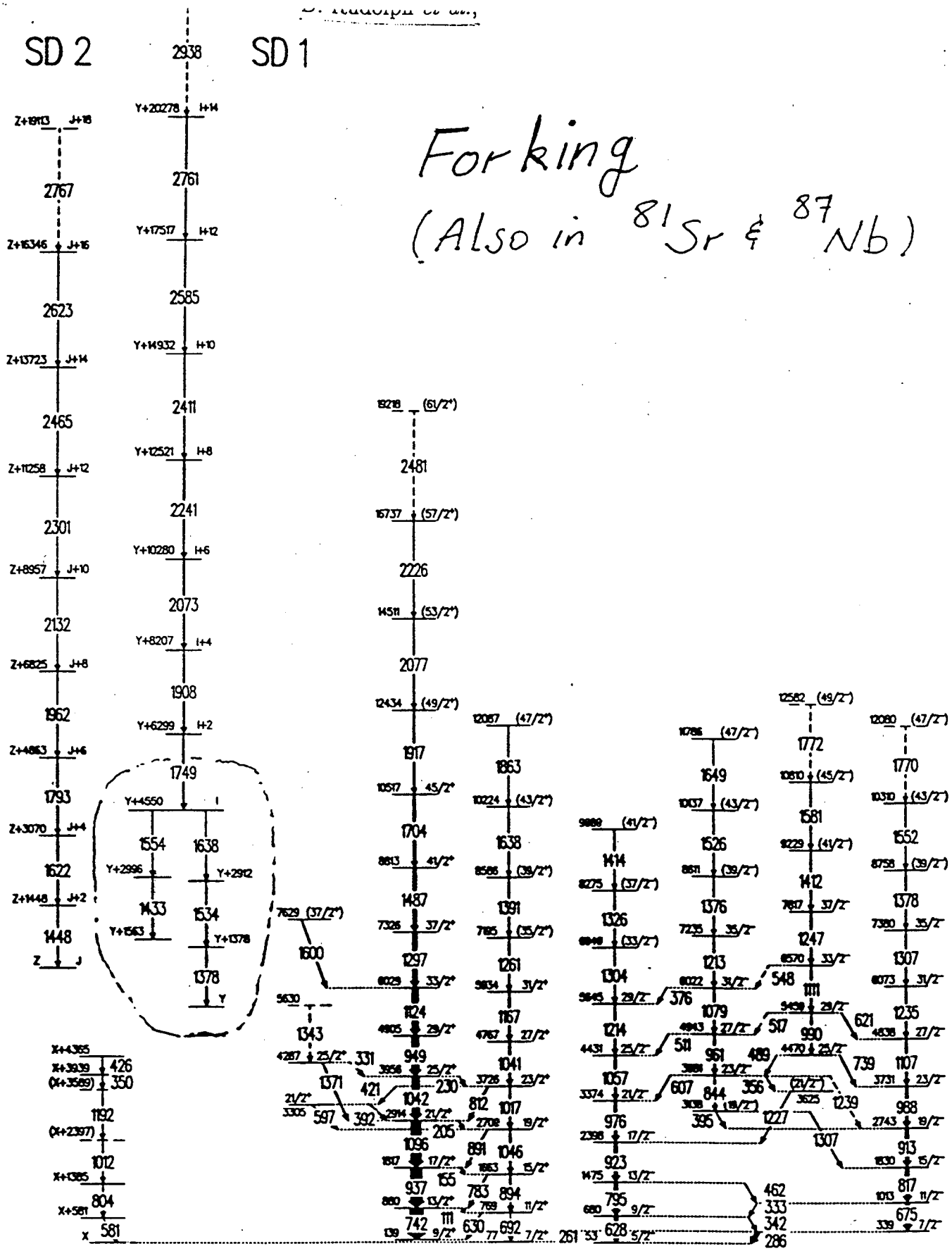
GAMMASPHERE (57) plus MICROBALL

2.5×10^9 particle-$\gamma\gamma\gamma$ events

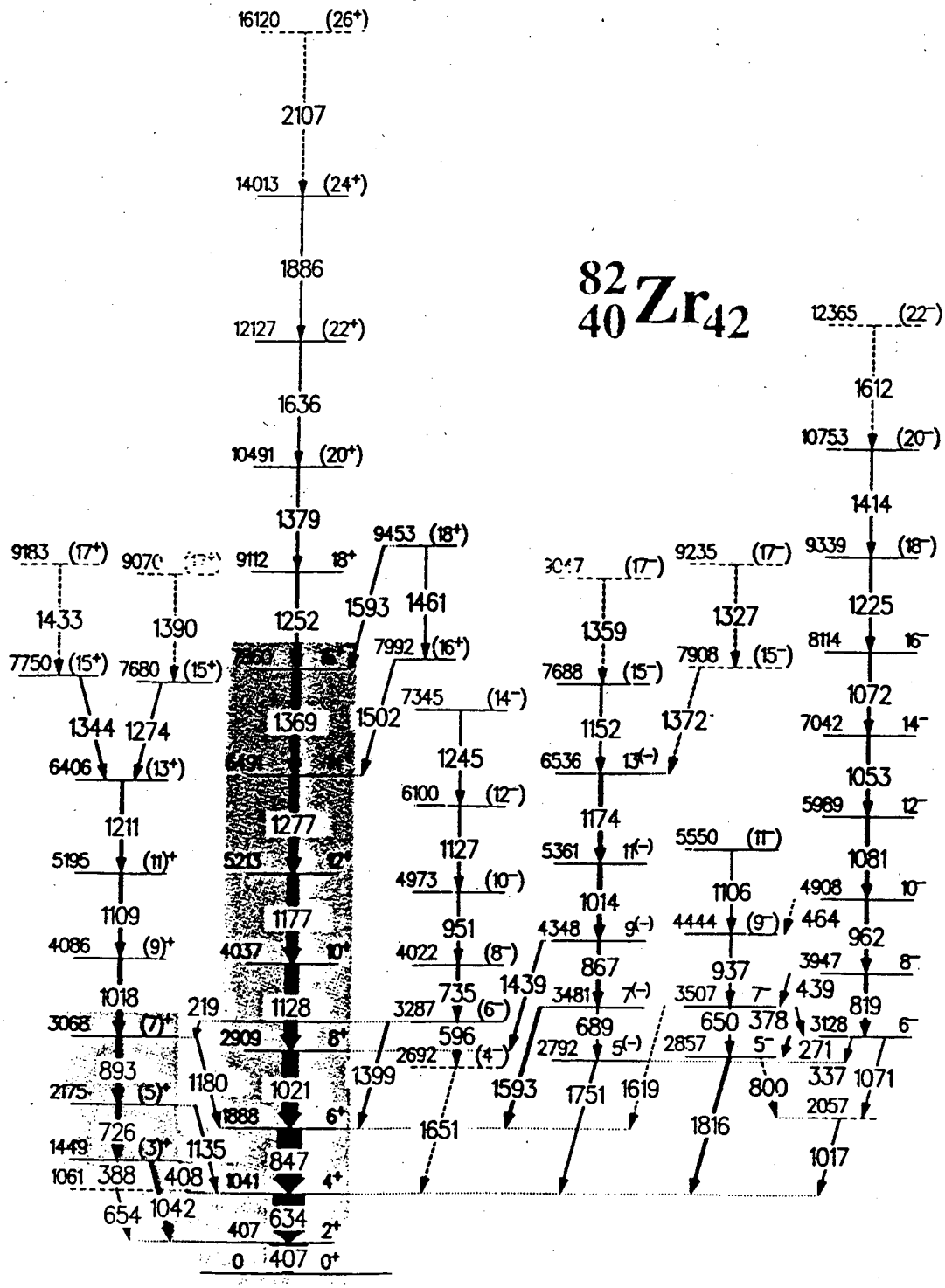
Relative Cross-Sections (%)

						CN	Mo
							Nb
		80 0.001	81	82 0.40	83 0.58	84 0.10	Zr
	78	79 0.02	80 0.28	81 1.2	[illegible]	[illegible]	Y
76 0.001	77 0.02	78 0.14	[illegible]	80 [illegible]	81 [illegible]	[illegible]	Sr
75	76 0.09	[illegible]	78 0.80	[illegible]	80 0.03	81 0.77	Rb
74 0.21	75 0.01	[illegible]	77 0.05	78 1.1	79	80 0.005	Kr
73 0.08	74	75 0.05	76	77	78	79	Br
38	39	40	41	42	43	44	

Forking
(Also in ^{81}Sr & ^{87}Nb)

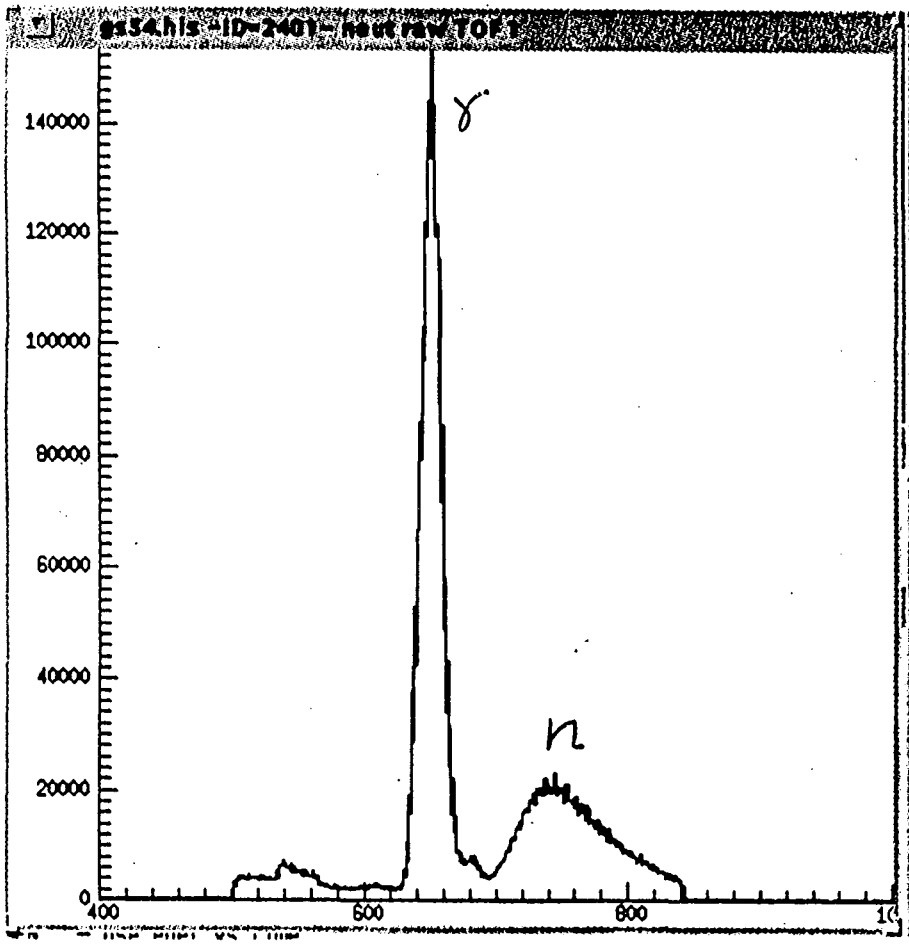


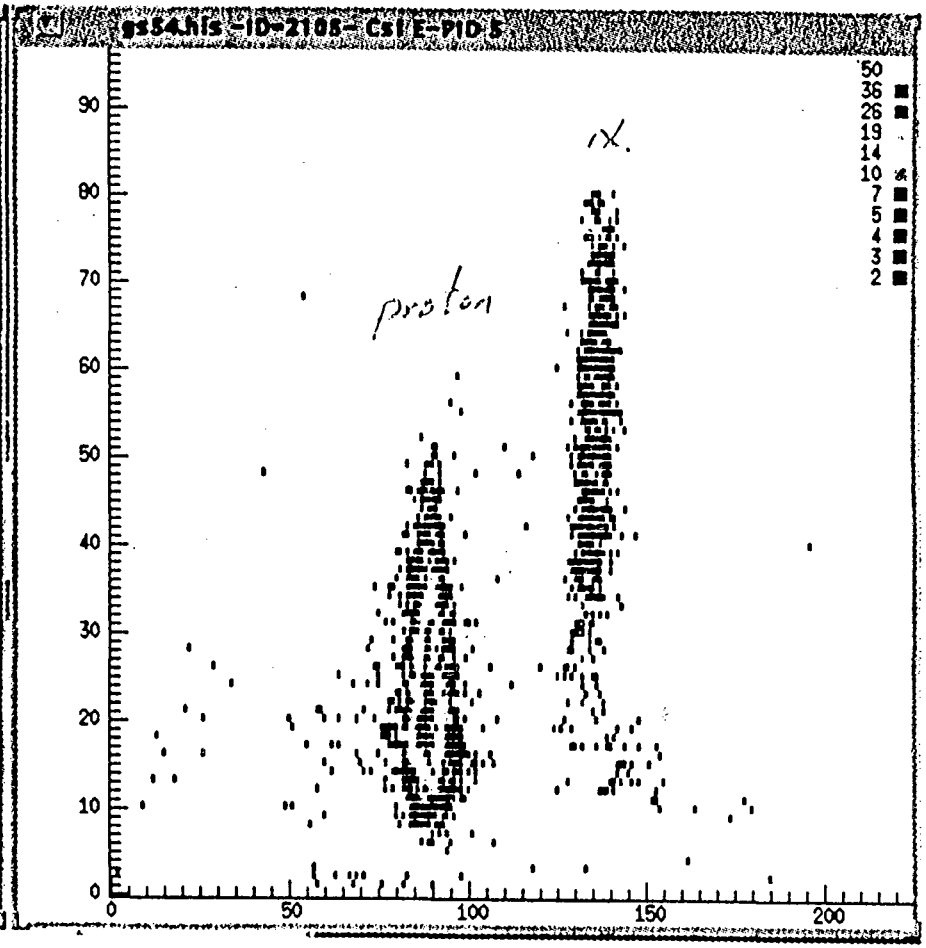
^{83}Zr


82 40 Zr 42
16120 (26+)
2107
14013 (24+)
1886
12127 (22+)
1636
10491 (20+)
1379
9112 18+
1252
1369
1277
1177
1128
1021
847
634
407 2+
0 407 0+
9183 (17+)
1433
7750 (15+)
1344
6406 (13+)
1211
5195 (11)+
1109
4086 (9)+
1018
3068 (7)+
893
2175 (5)+
726
1449 (3)+
388
1061
654
1042
408
1135
1180
219
1888 6+
1041 4+
9453 (18+)
1593
1461
7992 (16+)
1502
7345 (14-)
1245
6100 (12-)
1127
4973 (10-)
951
4022 (8-)
735
3287 (6-)
596
2692 (4-)
1399
1651
1439
1593
1390
7680 (15+)
1274
2909 8+
4037 10+
5213 12+
6491 14+
9070
3047 (17-)
1359
7688 (15-)
1152
6536 13(-)
1174
5361 11(-)
1014
4348 9(-)
867
3481 7(-)
689
2792 5(-)
1751
1619
9235 (17-)
1327
7908 (15-)
1372
5550 (11-)
1106
4444 (9-)
937
3507 7-
650
2857 5-
1816
378
800
12365 (22-)
1612
10753 (20-)
1414
9339 (18-)
1225
8114 16-
1072
7042 14-
1053
5989 12-
1081
4908 10-
464
962
3947 8-
439
819
3128 6-
271
337
1071
2057
1017

Liquid Scintillator n-det.

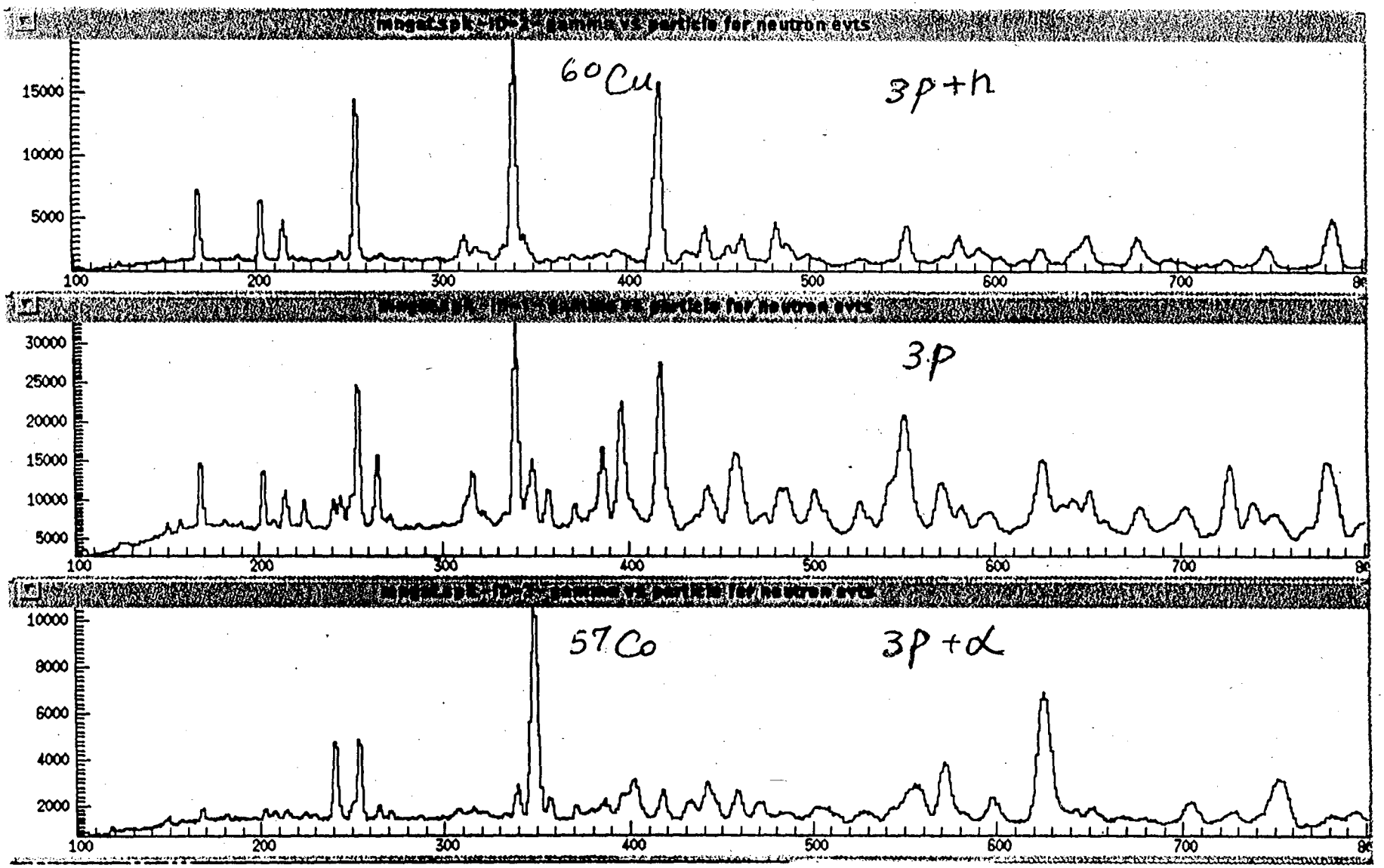
Microball





PID vs $\frac{\text{Fast}}{\text{slow}}$ ratio

(145MeV $^{36}Ar + ^{28}Si$)



(1) ^{36}Ar + ^{28}Si 136 MeV

(2) 28 Si + ^{40}Ca 125 MeV

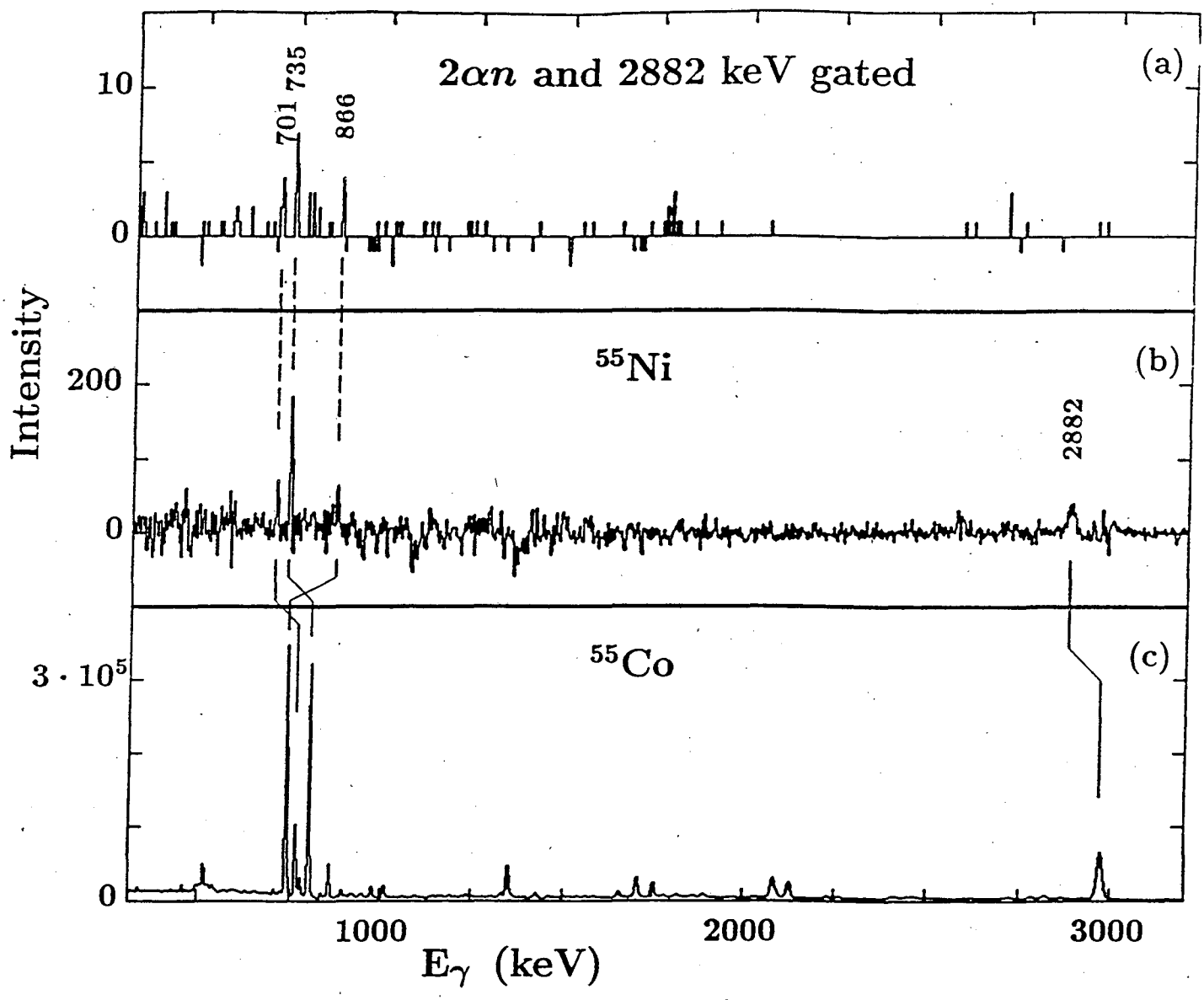
N=Z

Type II
p-emitter

Heaviest
mirror pair

							63	64 CN	Ge
						61	62	63	Ga
					59	60 2p2n 0.3 SD	61 2pn 1.8	62	Zn
				57	58 αpn 0.3 D	59 αp 2.8 D	60 3pn 12	61 3p 16	Cu
			55 2αn 0.004	56 2α 0.02	57 α2pn 3.8	58 D α2p 33	59 4pn 4.2	60 4p 11	Ni
		53	54 2αpn 0.1	55 2αp 2.0	56 α3pn 1.2	57 α3p 9.0	58	59 5p 0.01	Co
	51	52 3α 0.03	53 2α2pn < 0.01	54 2α2p 1.0	55	56 α4p 0.1	57	58	Fe
49	50	51 3αp 0.1	52	53 2α3p 0.02					Mn
48	49	50	51	52					Cr

Figure 1: Experimental relative cross-sections [%] of the reaction ^{36}Ar + ^{28}Si at 136 MeV beam energy deduced from the thin target GAMMASPHERE experiment. The total cross section amounts to $\sigma_{tot} \approx 1000$ mb and the uncertainties reach from 5 % (strong channels) to 20 % (weak channels). The proposed reaction ^{24}Mg + ^{40}Ca leads to the same compound nucleus ^{64}Ge.


2αn and 2882 keV gated
(a)
10
0
701
735
866
Intensity
200
0
55Ni
(b)
2882
3 · 10^5
0
55Co
(c)
1000
2000
3000
Eγ (keV)

C. Svensson
INL Conf.

(H,K) + Charged particles
- Suppress leak Thru
- cheap "n-det"

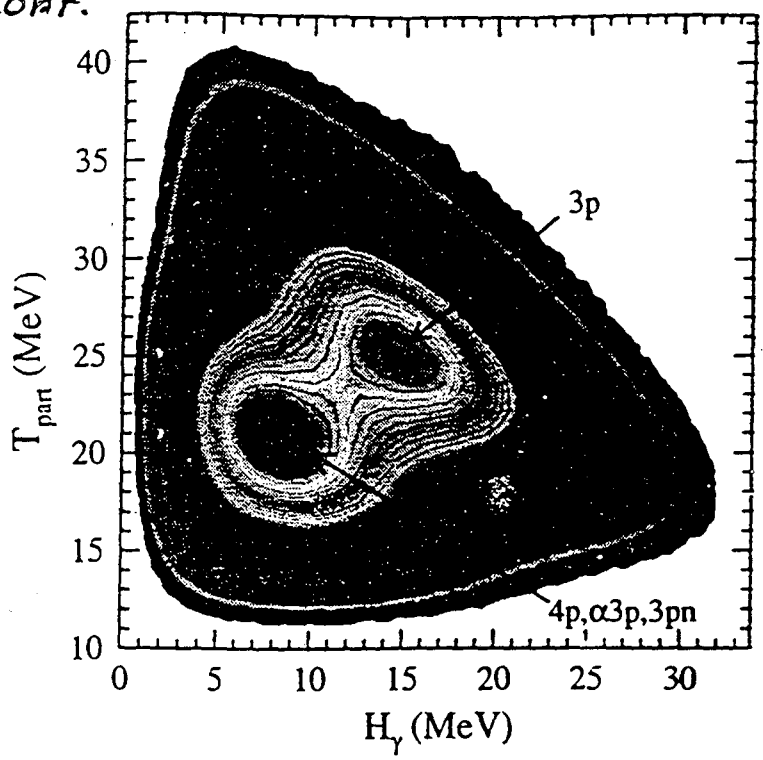


Fig. 1. Total Energy Plane contour plot for all events in which 3 protons were detected. The real 3p events are cleanly separated from the contaminating four-particle channels.

3pn, 4P, α3P
leak Thru

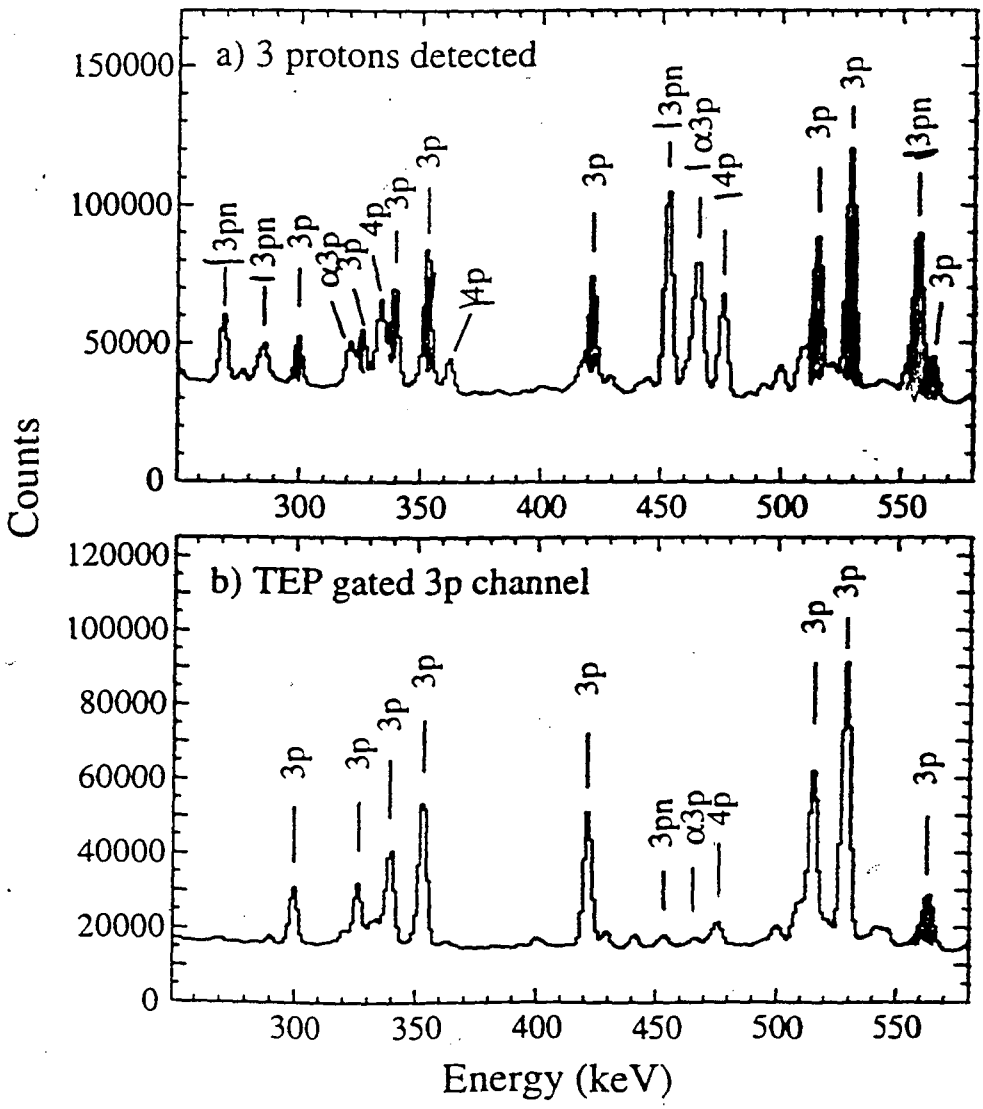
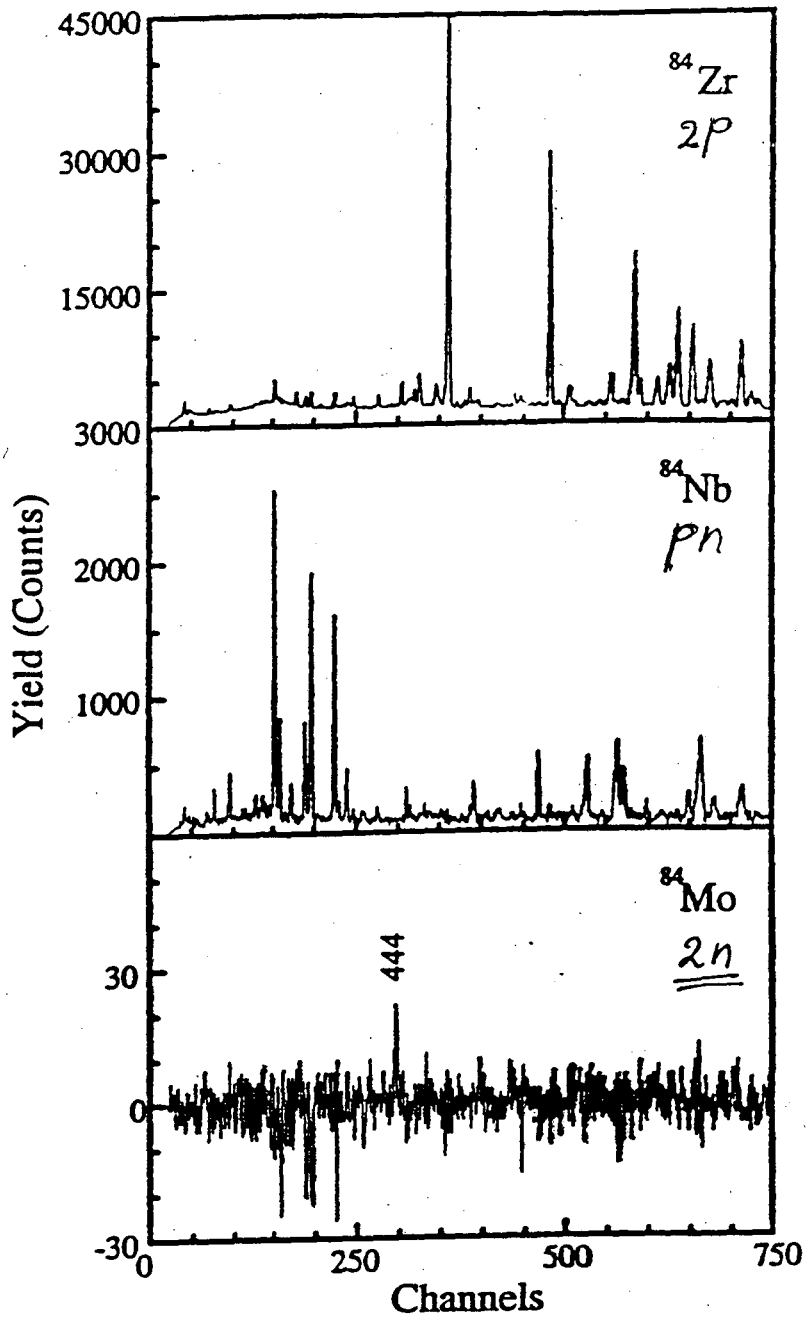


Fig. 2. Portion of the γ-spectra produced by a) gating on 3 detected protons, and b) setting a gate around the real 3p region of the 3p gated Total Energy Plane (Fig. 1).

Gelletly et al

Heavier N=Z ; σ ~10 μb ⇒ Requires High selectivity

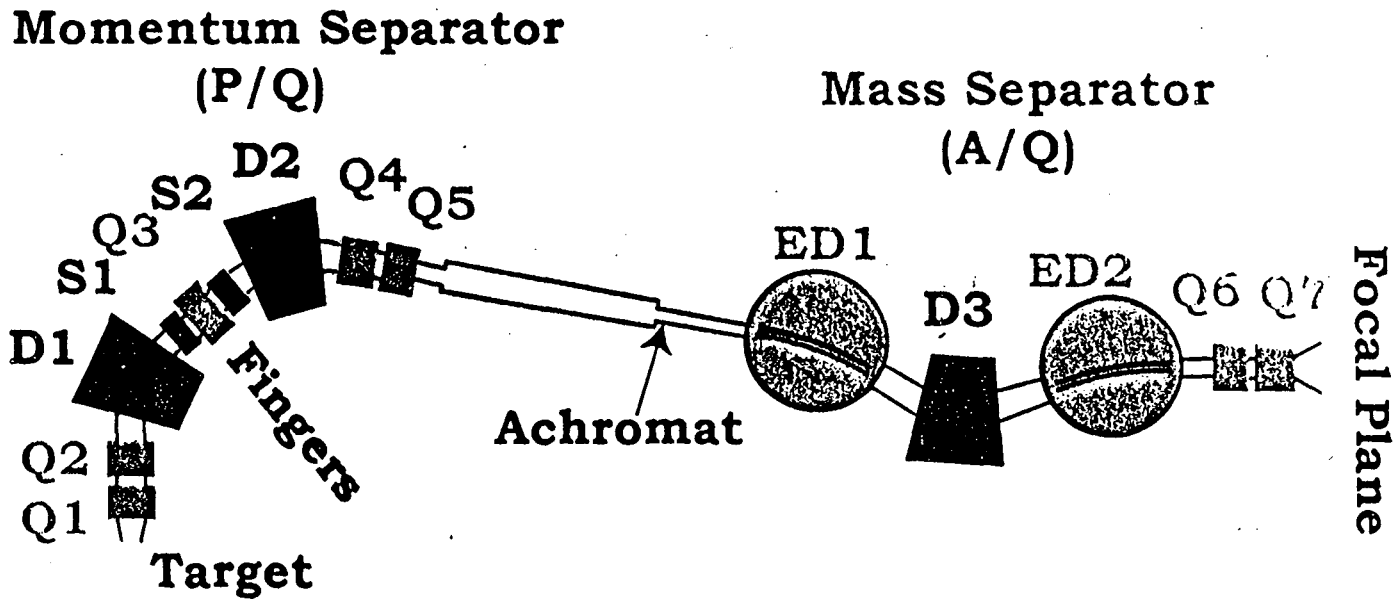
- Mass separator
- * Z-selector



Recall that GS + μBall was not good enough

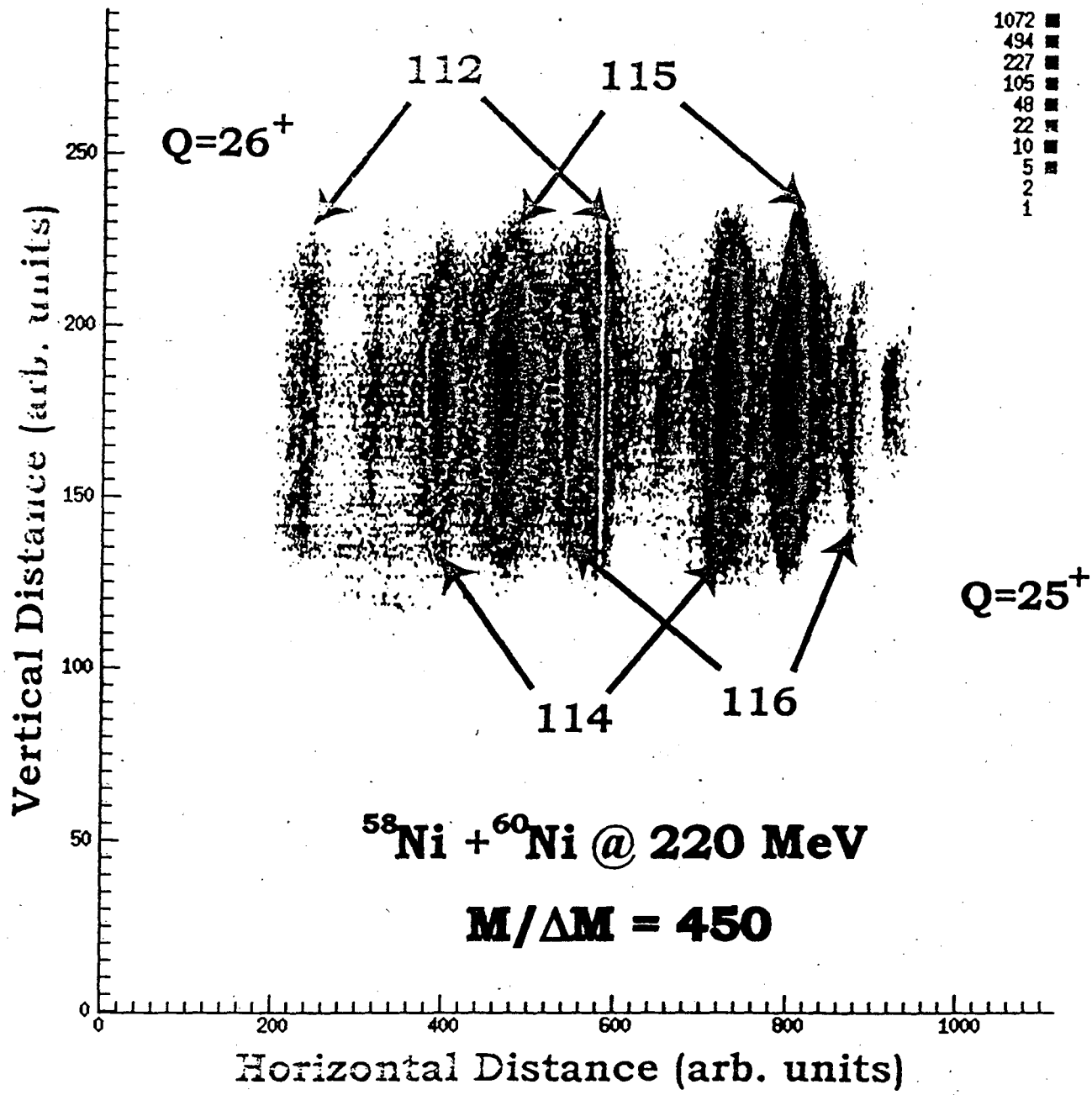
Remains to be seen if addition of n detector would help.

HRIBF Recoil Mass Spectrometer

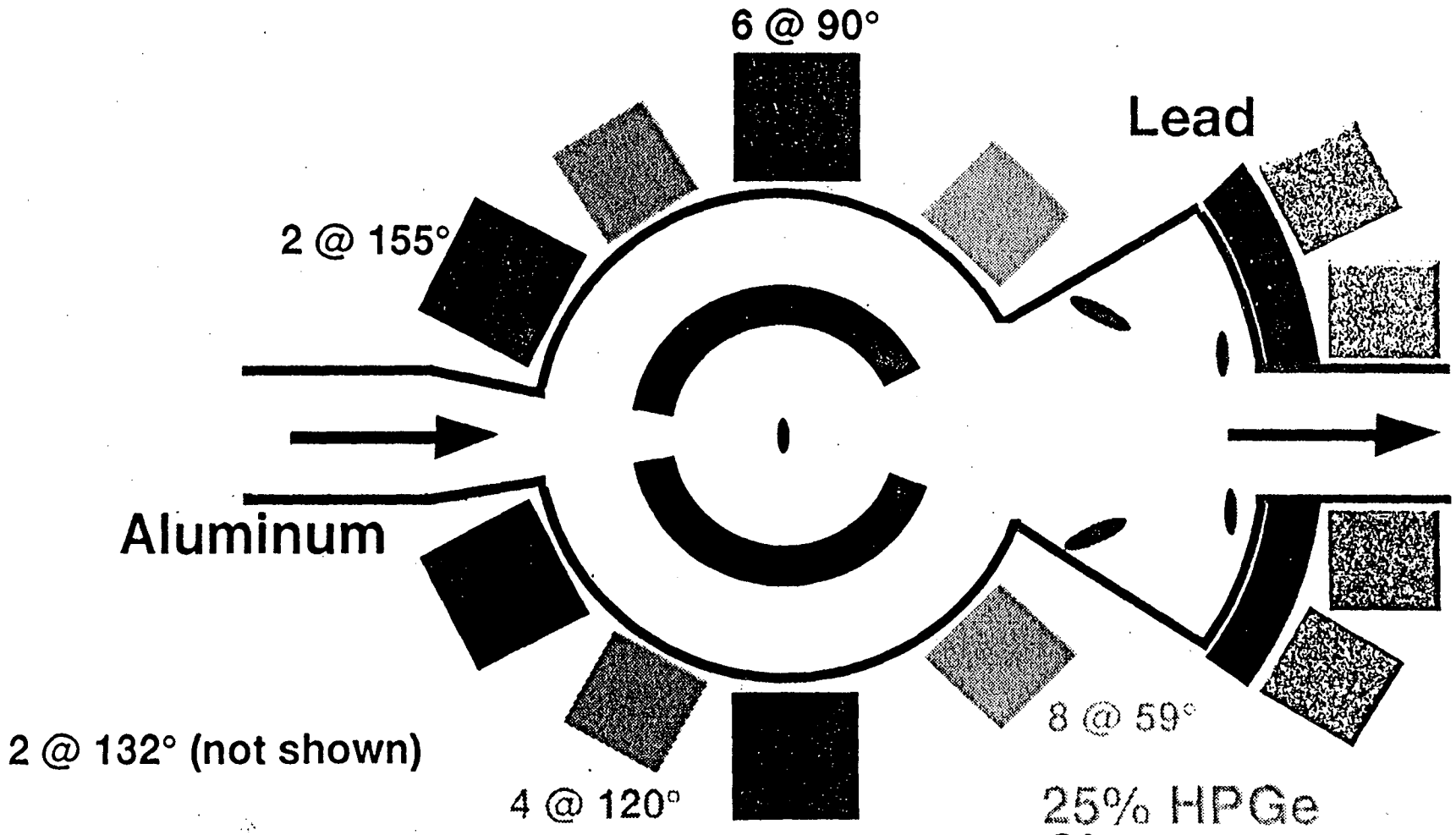


Beam

Inverse reactions
High rigidity beams (K=100)
Excellent beam rejection (>10^{12})
Excellent mass separation ($M/\Delta M$=450)
Large energy acceptance
Large solid angle
Large A/Q acceptance


1072
494
227
105
48
22
10
5
2
1
112
115
Q=26+
Q=25+
114
116
58Ni + 60Ni @ 220 MeV
M/ΔM = 450
Vertical Distance (arb. units)
Horizontal Distance (arb. units)
0
50
100
150
200
250
0
200
400
600
800
1000

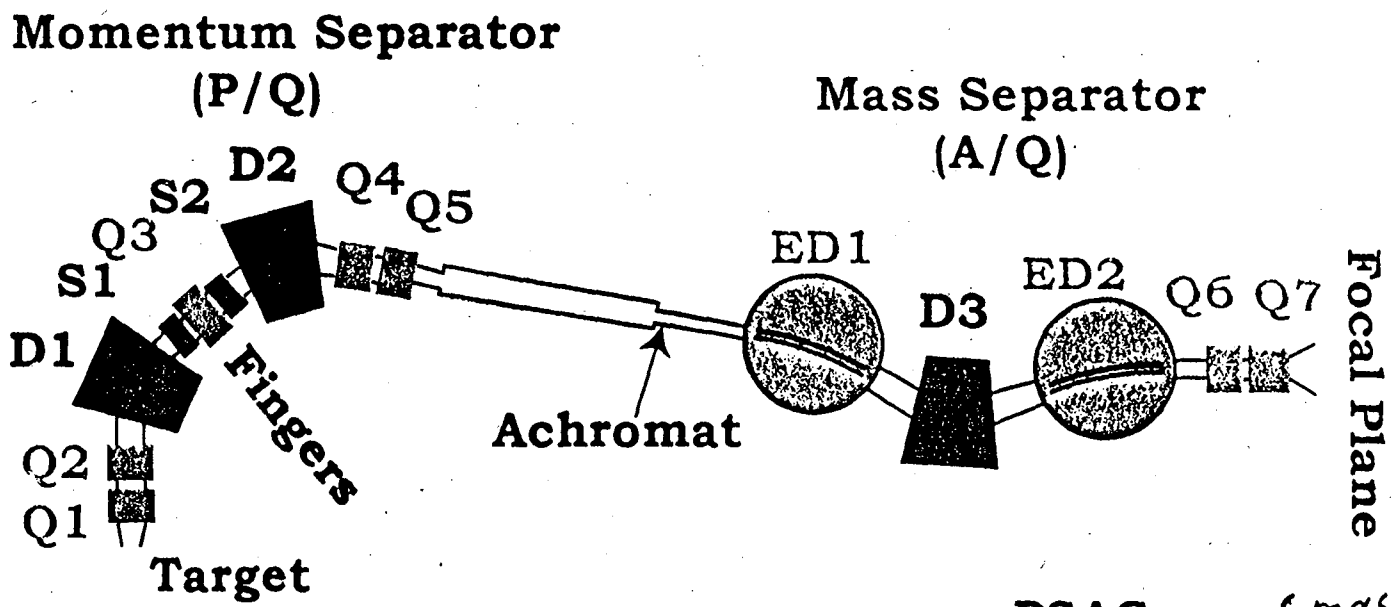
Target Position Detectors



25% HPGe
Clover
CsI
Fast Plastic/Inverted Si
Neutron Detectors

mjb:DNP:10/27/95

HRIBF Recoil Mass Spectrometer



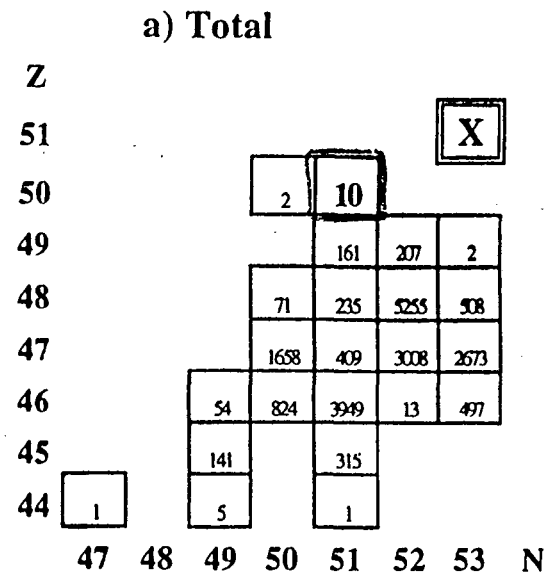
$\epsilon_{photo} \simeq 4\%$

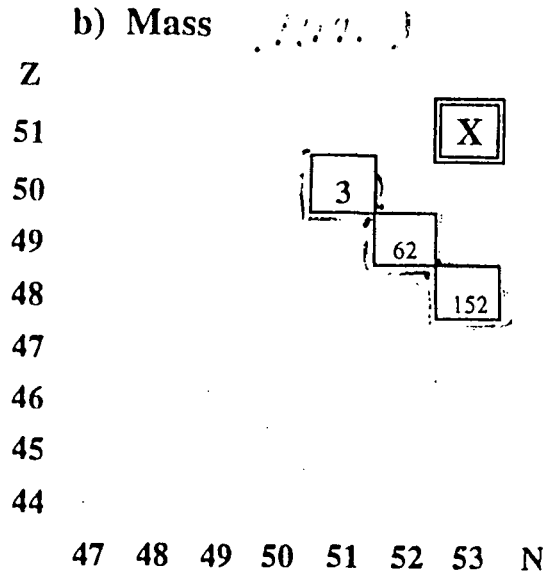
- 11 Clover Ge
- 12 Duet Ge (25%)
- Hyball (CsI + Silicon)
- NE-213 Array

- PSAC (mass information)
- Strip Detectors (charged-particle
- Tape System
- Pair Spectrometer
- Ion Chamber (Z-information)
- Isomer Catcher

Selectivity

10/20,000





3/217

improvement ≈ 27

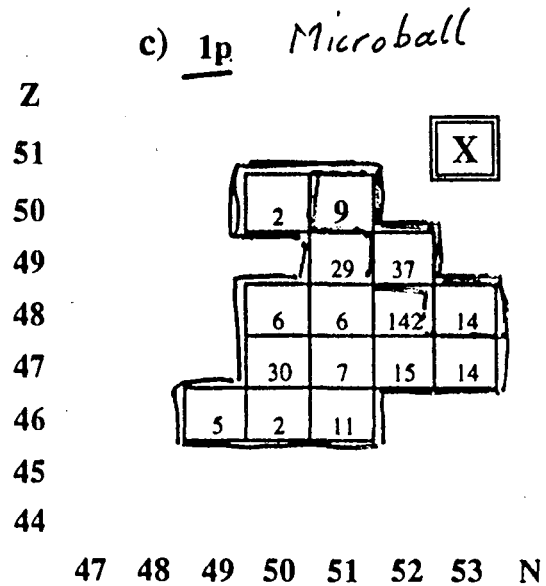
μball: 9/329

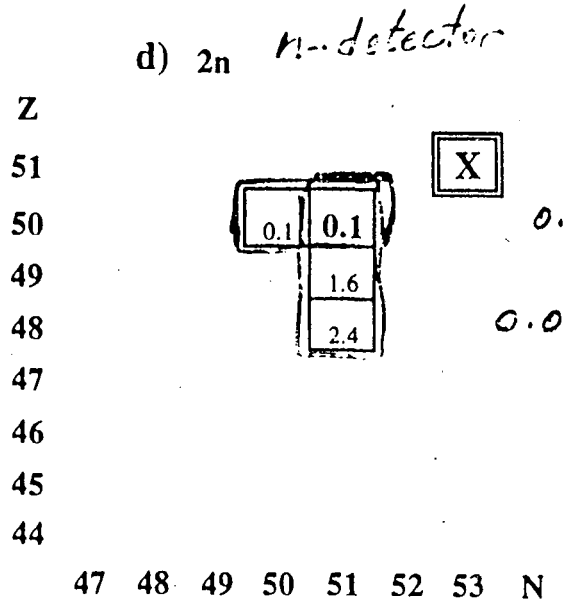
improvement ≈ 55

μball + RMS

3/20

improvement ≈ 300





improvement

0.1/4.2 → 47

0.03/0.3 → 2000

20

Table 1: Detection Efficiency of Ancillary Systems Separately and Combined for a Typical RIB Experiment[a]

Eff. Selectivity ε × selectivity

	Distinct Residues[b]	ε[c]	% Yield[d]	Enhancement[e]	F.O.M.[f]
Total[g]	23	1.00	0.05	*not applicable*	*not applicable*
RMS[h]	3	0.30	1.4	28	8.4
HB[i]	15	0.90	2.7	54	48.6
NW[j]	4	0.01	2.4	48	0.2
RMS + HB	3	0.27	15	300	81.0
RMS + NW	1	0.0030	100.0	2000	6.0
HB + NW	4	0.0090	10	200	1.8
RMS+HB+NW	1	0.0027	100.0	2000	5.4

OK if γ's known

may be needed if no γ's known

a) Values calculated from a statistical model calculation for the $^{40}Ca(^{64}Ga,p2n)^{101}Sn$ reaction at a beam energy of 235 MeV. The total fusion cross section is calculated to be 341 mb.

b) The number of reaction channels which survive the gating conditions.

c) Efficiency of the auxiliary detection system(s) in place. See Appendix B for discussion.

d) Percentage yield of the ^{101}Sn channel with respect to the total channels within the gating conditions.

e) Enhancement of the relative yield of the ^{101}Sn channel with respect to its ungated relative yield.

f) The Figure Of Merit (F.O.M.) for the detector, which is equivalent to the efficiency of the detector multiplied by the enhancement it provides for ^{101}Sn.

g) The values with no ancillary detector gating.

h,i,j) The values for the Recoil Mass Separator (RMS), the Hybrid Ball (HB), and the Neutron Wall (NW), respectively.

Summary

(1) No universal solution.

∴ Need as many tools as possible

→ use the most selective technique (inefficient) to establish few γ-rays

→ go to the setup with best F.O.M. to build level scheme

(2) Guidelines:

- $\sigma \simeq$ mb	high-fold γ	(SD in $A \simeq 150$)
- $\sigma \simeq 100\,\mu b$	GS + μBall	(SD in $A \simeq 80$)
- $\sigma \simeq 10\,\mu b$	GS + μBall + n	($N = Z \lesssim 36$)
- $\sigma \lesssim \mu b$	mass separators + Z-selectors	($N = Z \gtrsim 36$)
- $\sigma \leq 0.1\,\mu b$	RDT	

(3) For $\sigma_{stable} < \mu b$; use Radioactive Ion Beams

- gain in σ is offset by reduced beam intensity
- But partial σ improves; ~~expecting~~ RMS-based Techniques would work again.

GFS

(1) Q. of mass resolution

- In lo-res. mode (gas filled), would help reduce countrate in DSSD, and hence dead time:
  - Readout time $\sim 10^{-5}$
  - Count rate $\sim \underline{\underline{10}}^{5}$ $\Big\}$ ~ 1

  Also, less hit/pixel helps shorten the recovery time

- In Hi-res. mode (mass-separator), would be nice to achieve $\sim 1:150$

(2) Countrates & physics

with 100% transmission eff., 10% ϵ_{photo} for GS:

$\simeq 1$ Count / day / nb / few pna

Can get 50 counts in 5 days @ 10nb

→ $Z = 104$; Few levels ←

Karl-Heinz Schmidt
GSI

K.-H. SCHMIDT

FISSION OF EXOTIC NUCLEI

Experiments performed at GSI by:

C. Böckstiegel, H.-G. Clerc, A. Grewe, M. de Jong
A. Junghans, J. Müller, S. Steinhäuser
IKDA, TH Darmstadt, Germany

M. Pfützner
University of Warsaw, Poland

J. Benlliure, A. Heinz, K.-H. Schmidt, B. Voss
GSI Darmstadt, Germany

FISSION OF EXOTIC NUCLEI

Limitations of conventional techniques

The secondary-beam facility of GSI

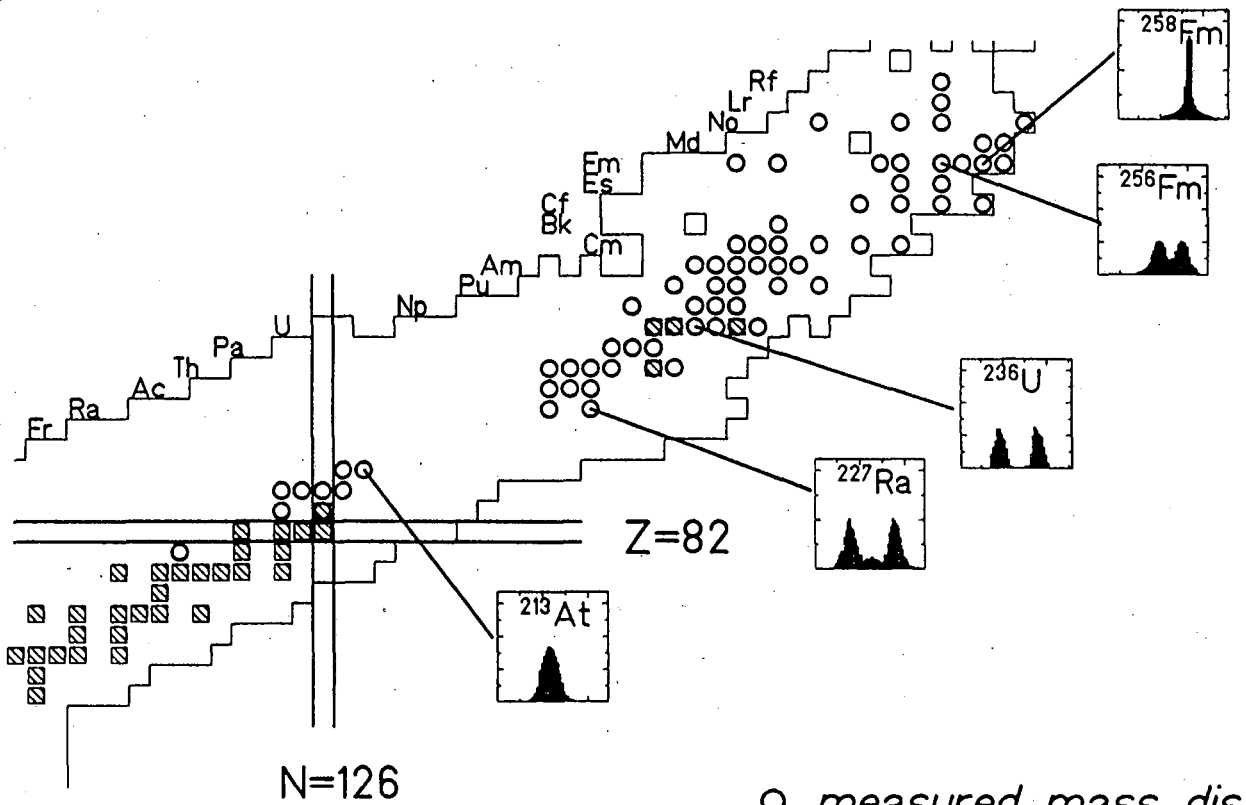
A fission experiment with exotic beams
- Experimental set-up
- Excitation mechanism

Results
- Z yields and TKEs in bimodal fission
- New insight into pair breaking in fission

Perspectives

Illustration of present knowledge on low-energy fission

max. 10 MeV above the fission barrier



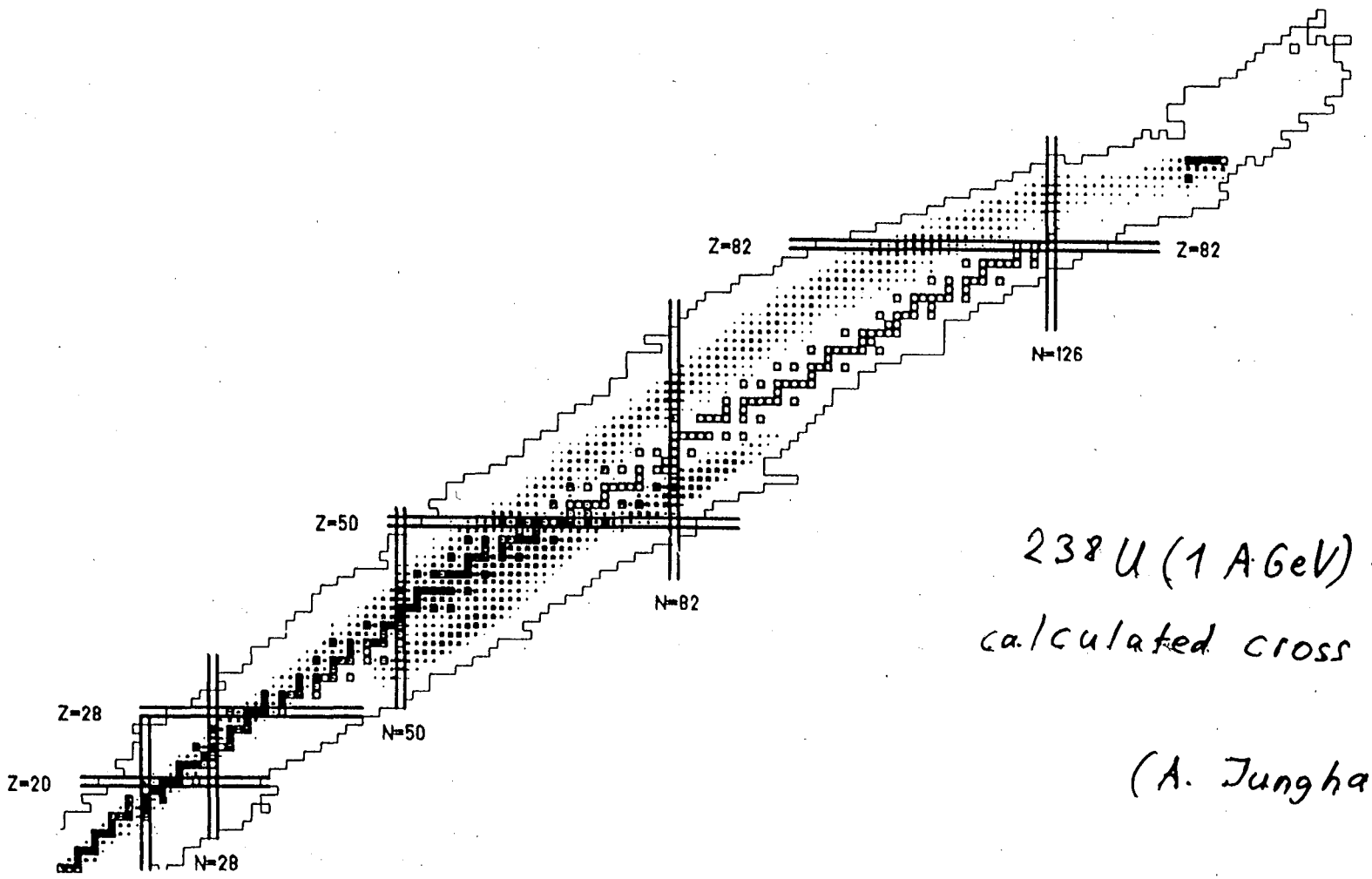
○ *measured mass distributions (n,f) (sf) etc.*

Our knowledge of low-energy fission relies on a very limited number of fissioning systems.

Difficulties to populate states close to the fission barrier:

spontaneous fission	restricted !
(n,f) (γ,f) (d,pf) etc.	need stable or long-lived nuclei !

New options by the use of secondary beams?



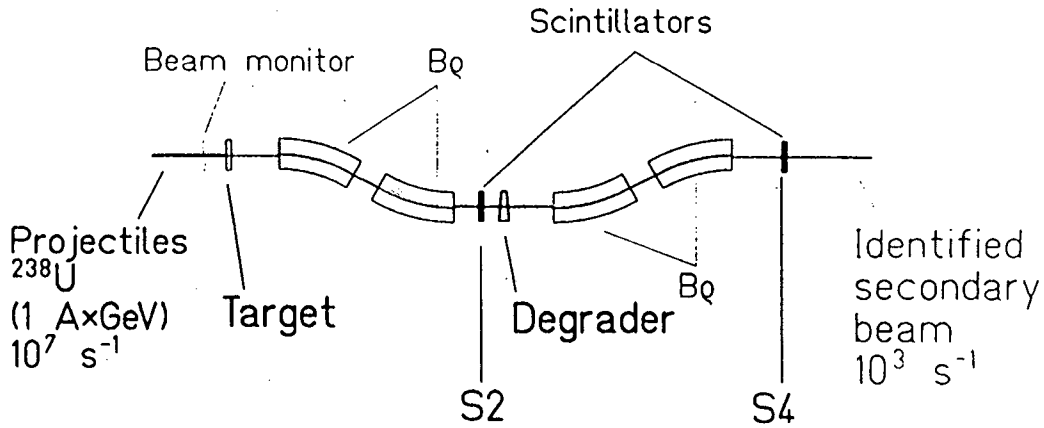
^{238}U (1 A·GeV) + Pb

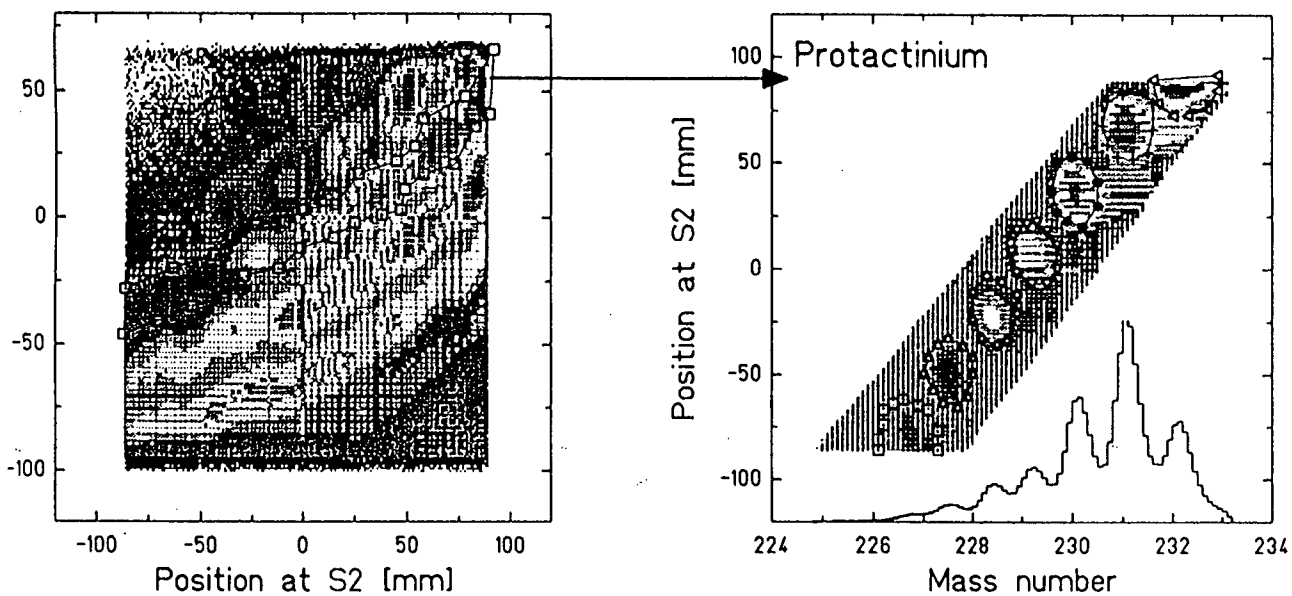
calculated cross sections

(A. Junghans)

'KC52.GRAPH.DATA(NUCDIFF)'

Isotopical separation at the fragment separator (FRS)

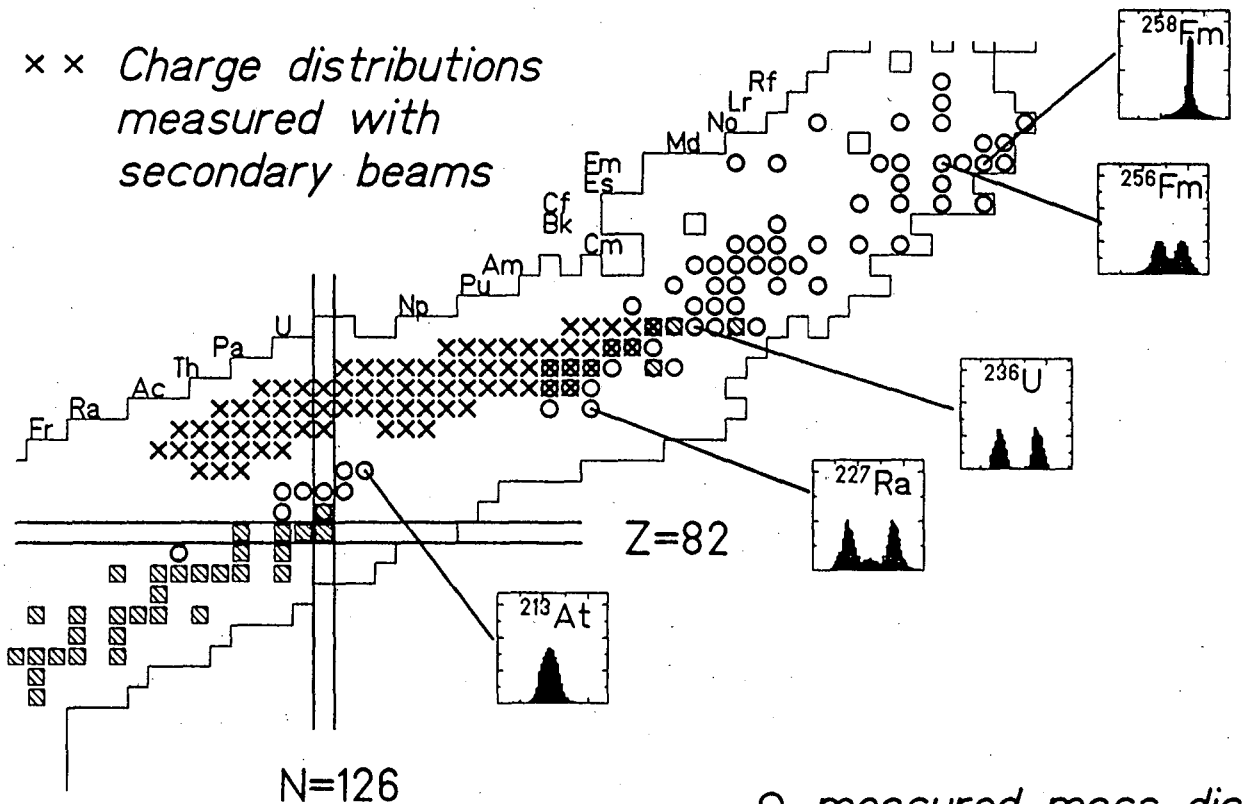




Low-energy fission

max. 10 MeV above the fission barrier

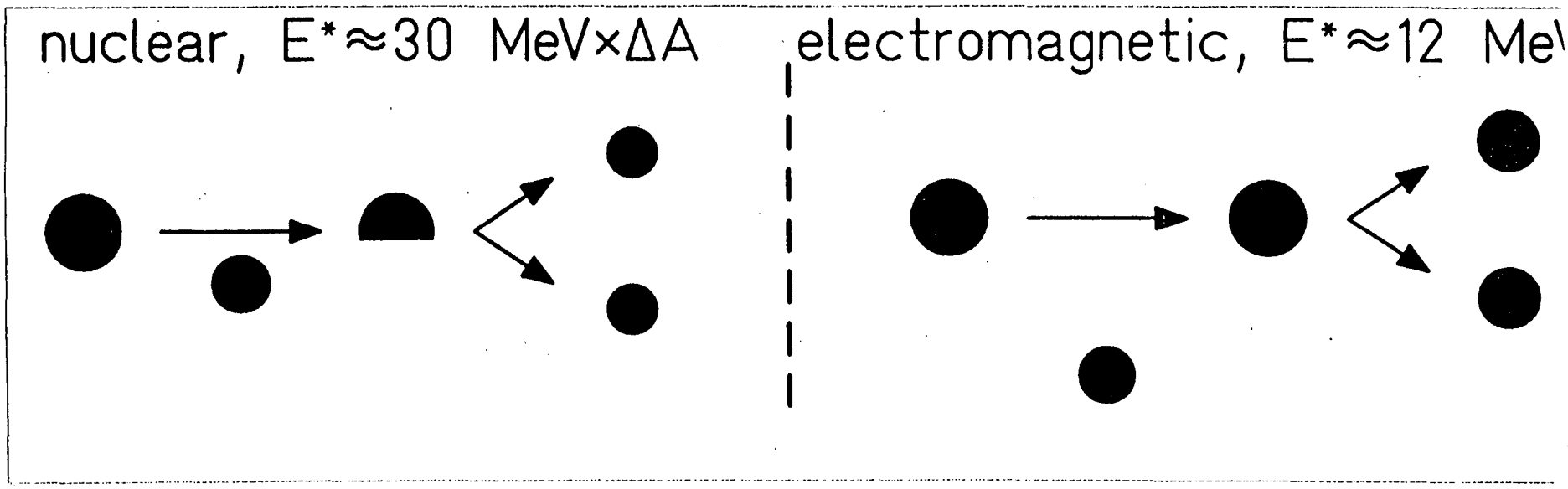
× × Charge distributions measured with secondary beams



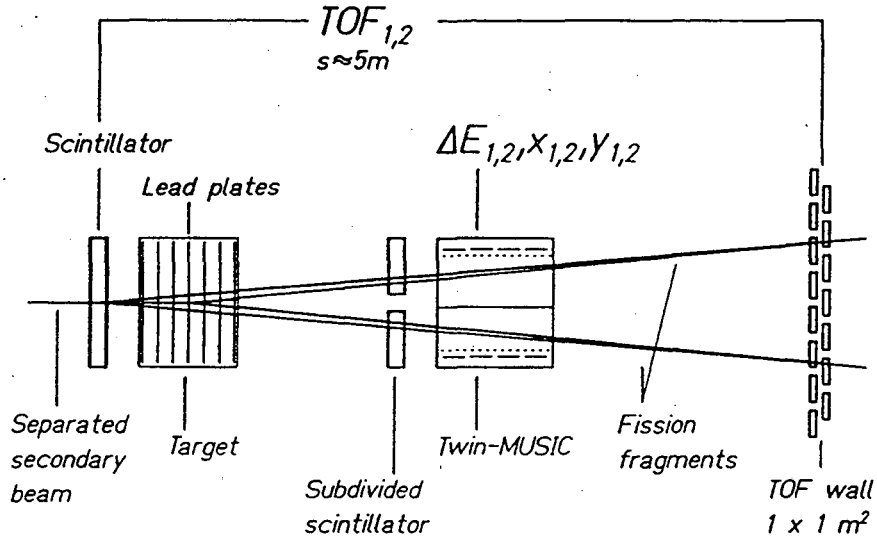
○ measured mass distributions (n,f) (sf) etc.

Fission in inverse kinematics at relativistic energies:

excitation mechanisms



Setup for the fission experiment



Method:

electromagnetic excitation → fission
(fission after nuclear contact is suppressed)

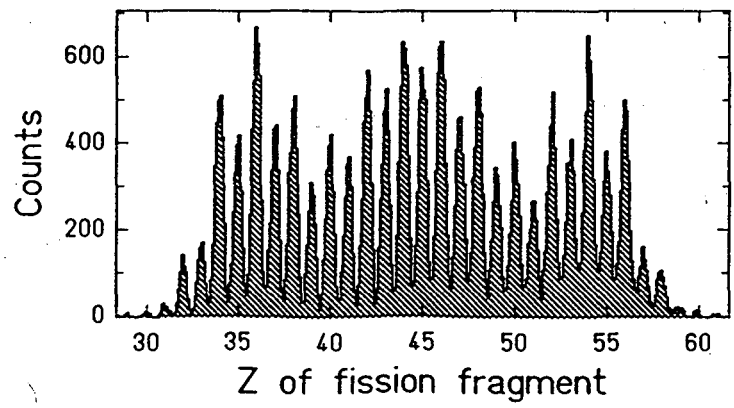
Features:

forward focussing (almost 100% detection efficiency)
excellent Z resolution
kinematic analysis

Results:

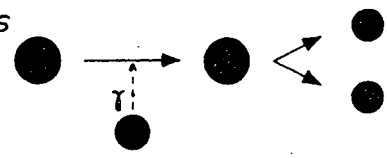
Z yields
total kinetic energies

Z response (sec. beam ^{226}Th)

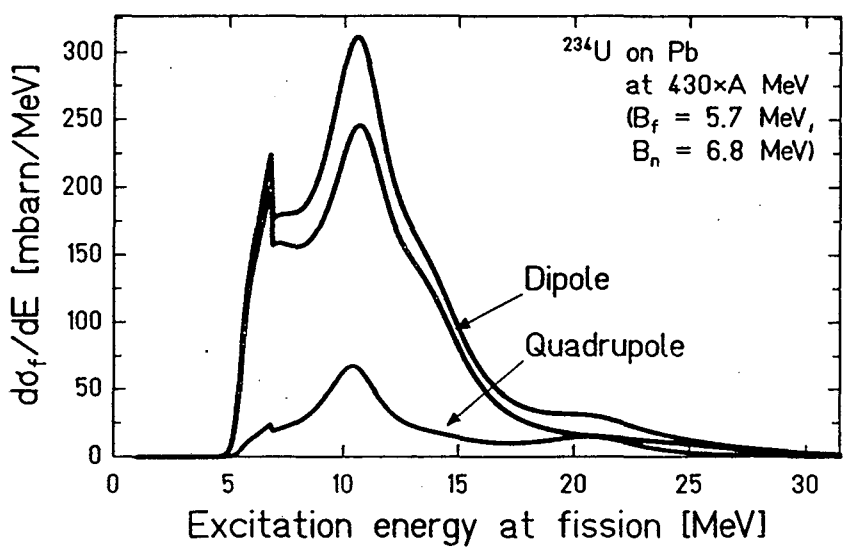


Excitation mechanism:

- *electromagnetic interaction*
  - *Excitation of the giant resonances (dipole-, quadrupole-)*
    - *11 MeV mean excitation energy (FWHM = 5 MeV)*



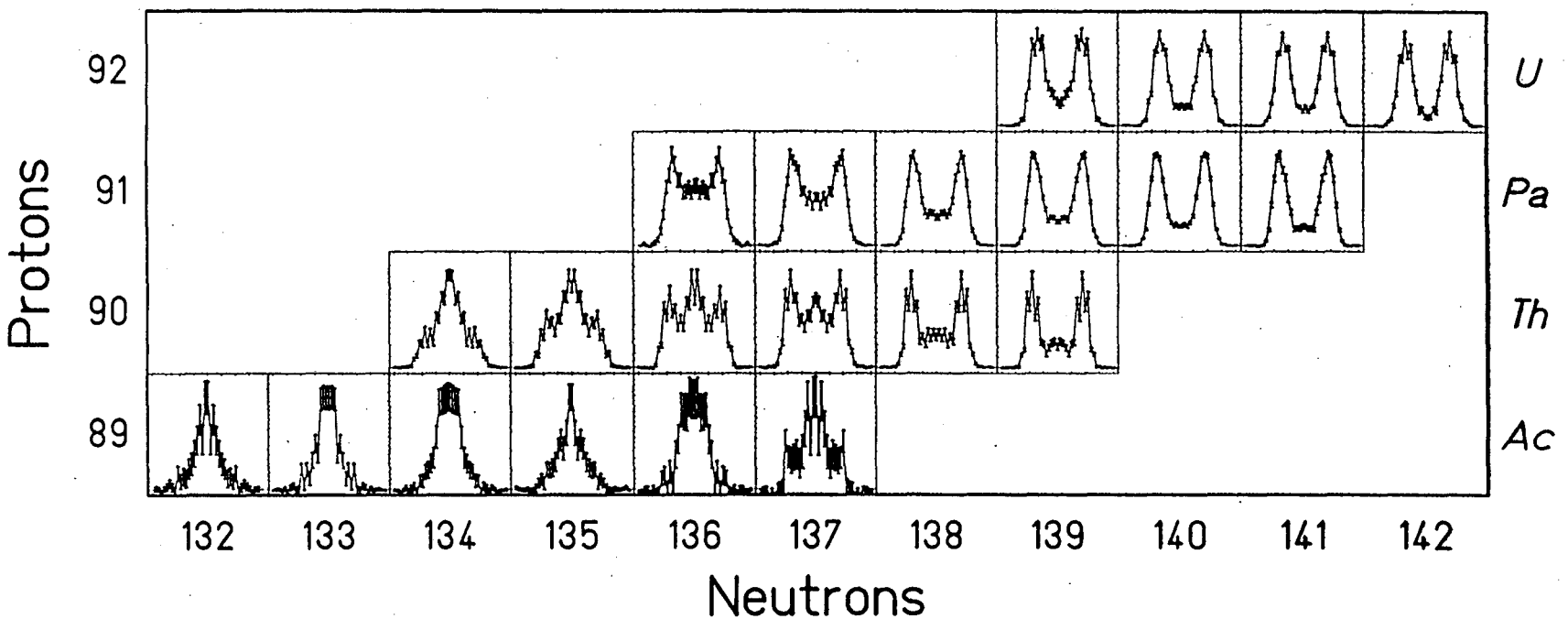
Multichance fission of ^{234}U after e.m. excitation



- *≈ 3 barn excitation cross section*
- *3 g lead target -> ≈ 1% e.m. fission*

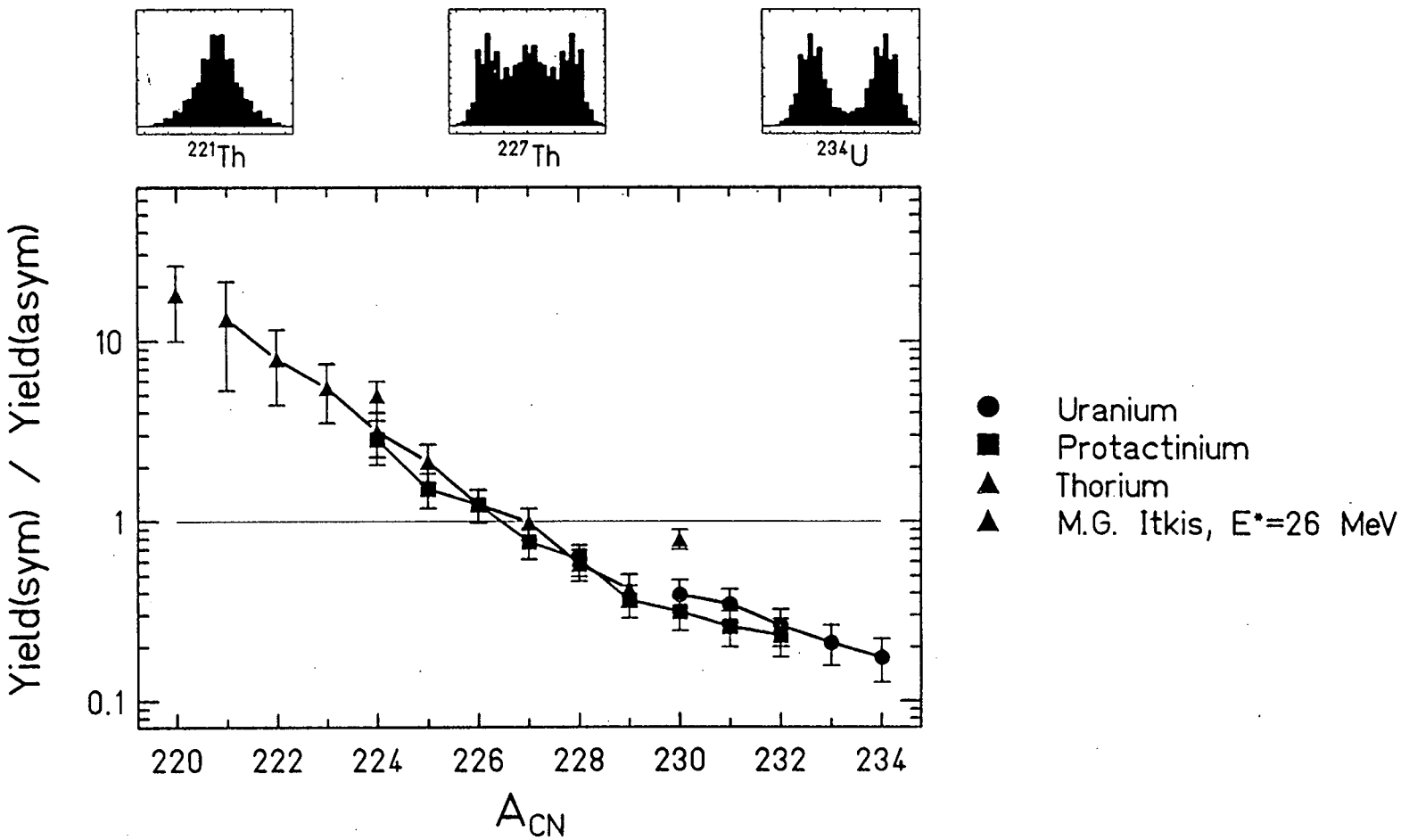
A. Grewe et al., Nucl. Phys. A614 (1997) 400

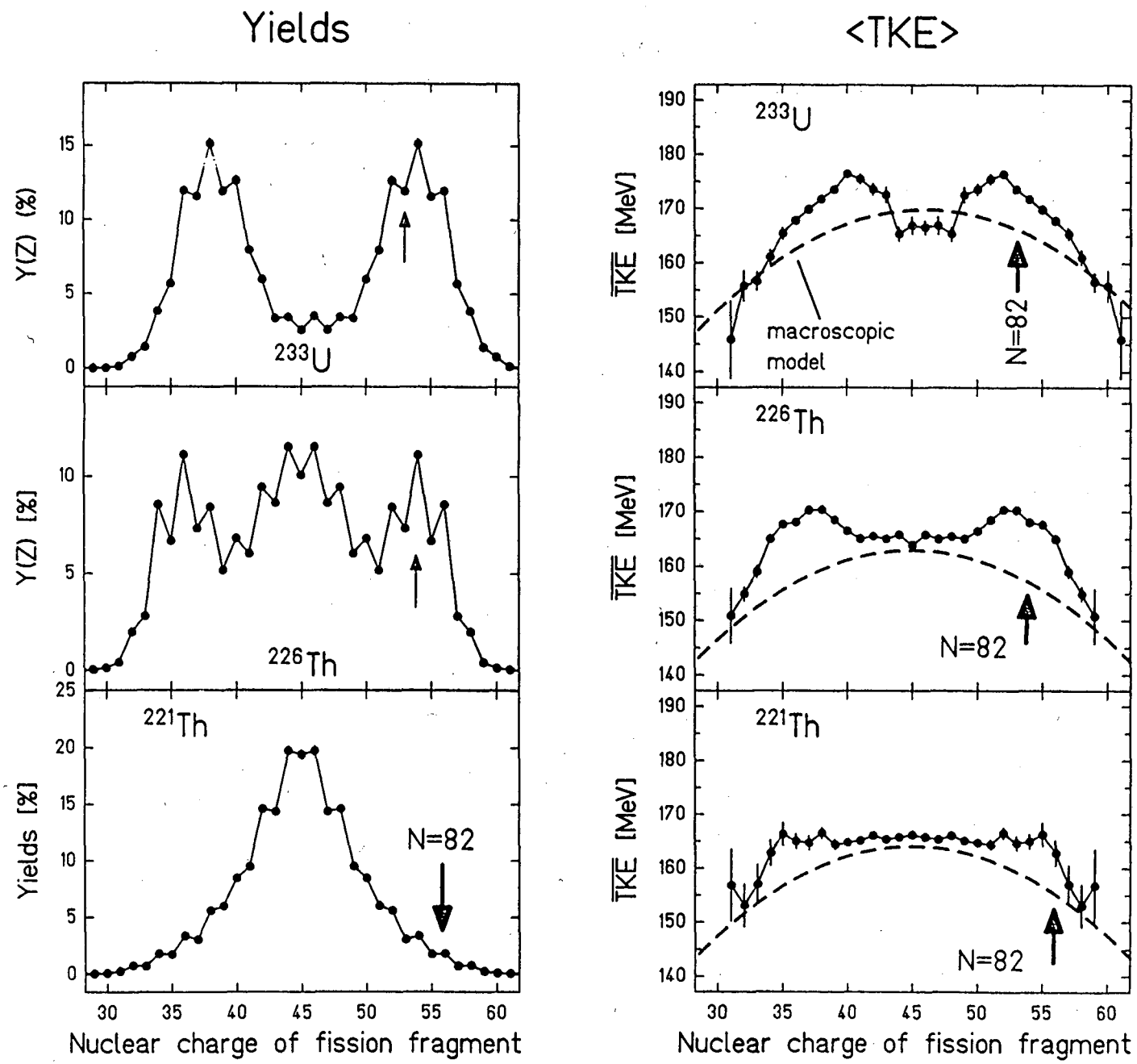
Charge yields (e.m. induced bimodal fission)



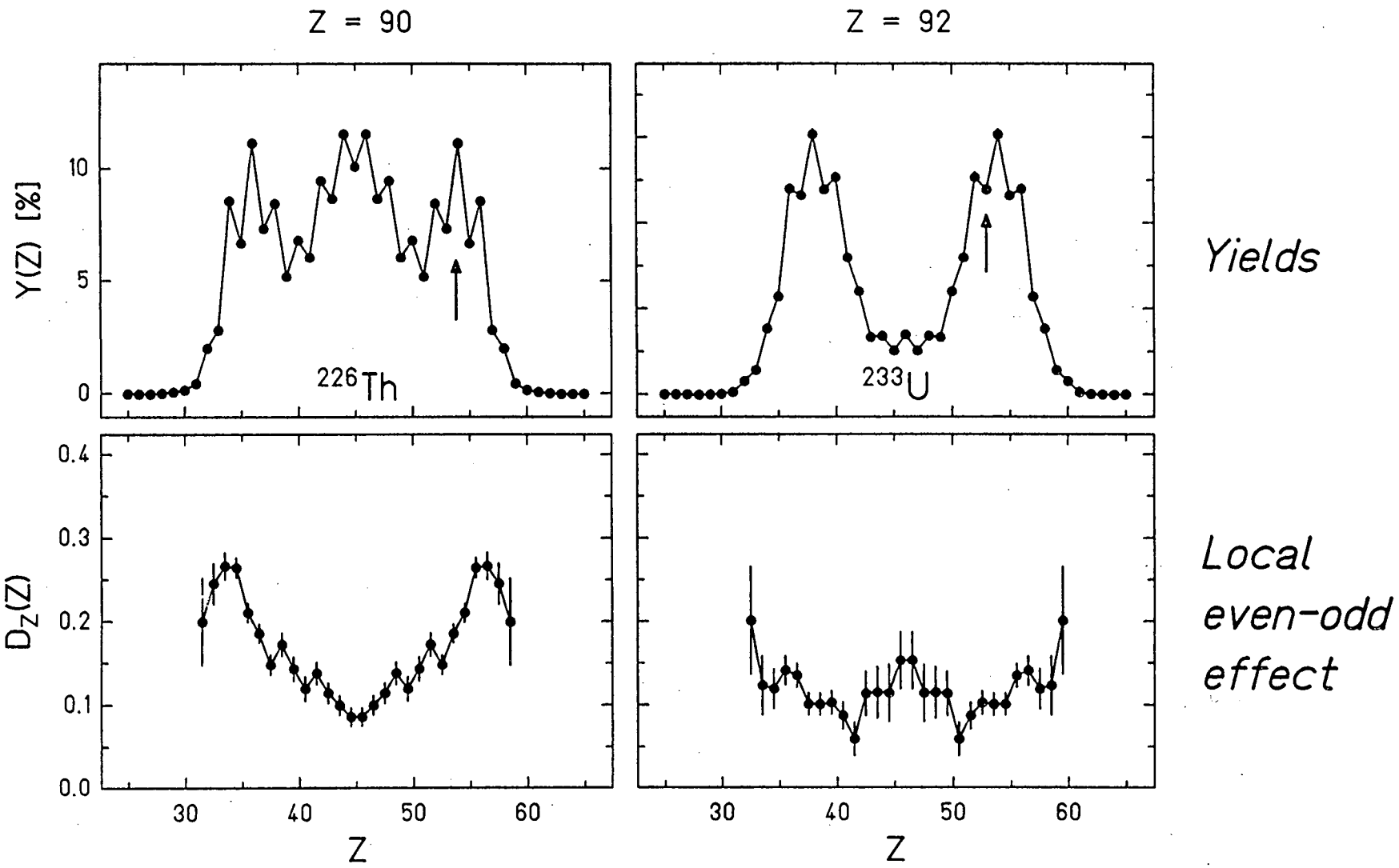
S. Steinhäuser et al., Dyn. Asp. Nuc. Fission, Casta-Papiernicka (Slovak Rep.), 1996

Relative strength of the 2 fission modes

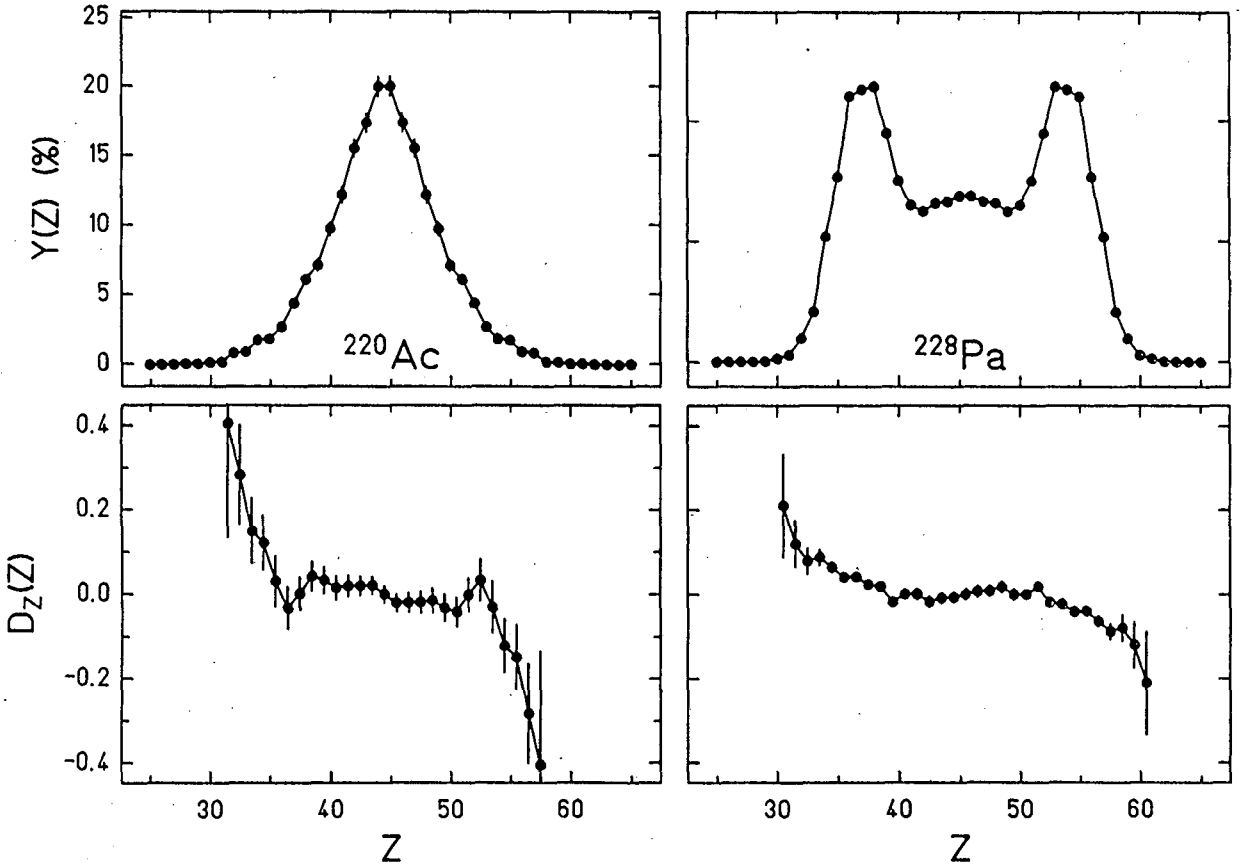




C. Böckstiegel et al., Phys. Lett. B



$$D_Z(Z+1.5) = (-1)^{Z+1}\,[\ln Y(Z+3) - 3\ln Y(Z+2) + 3\ln Y(Z+1) - \ln Y(Z)] \,/\, 8$$

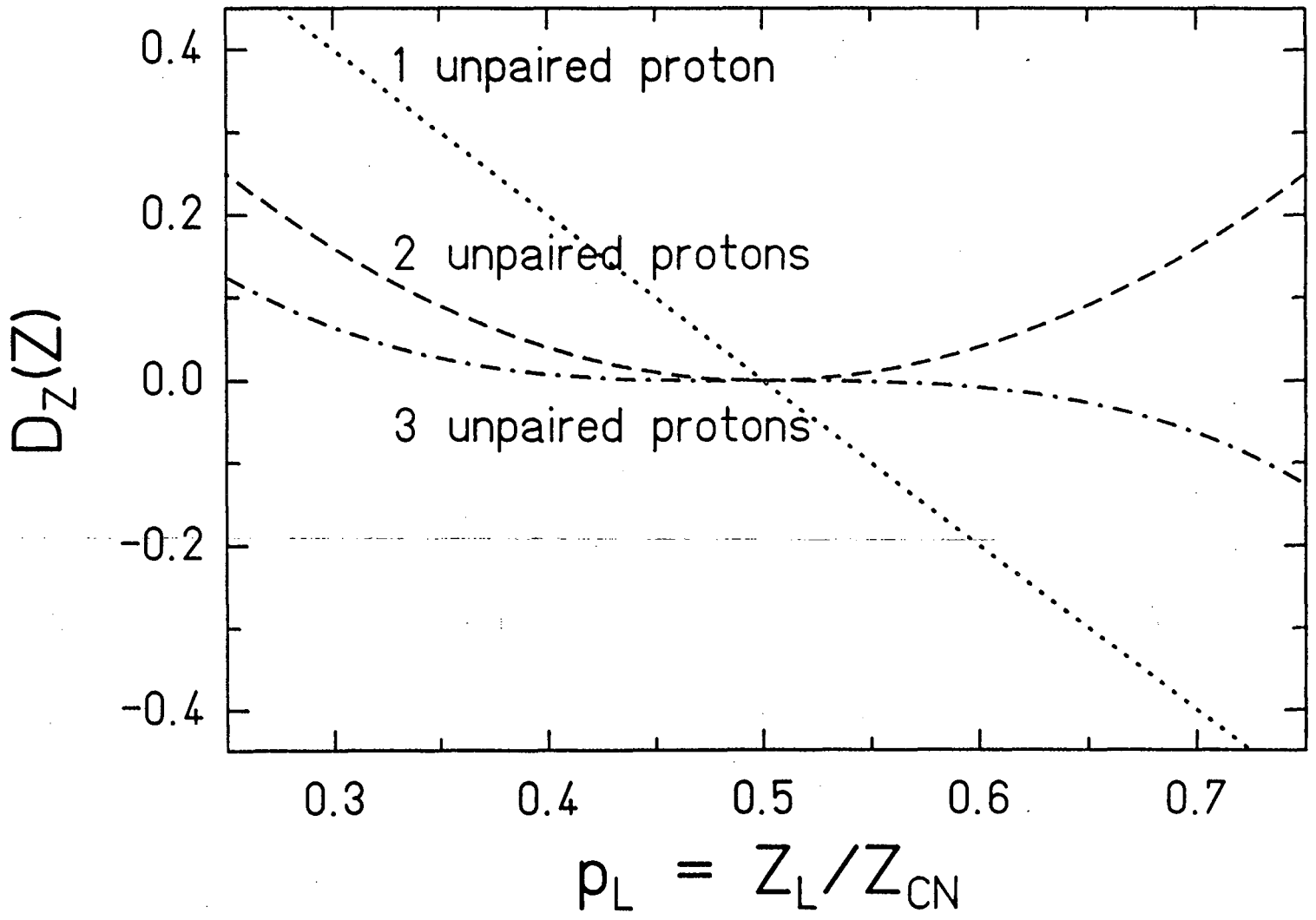


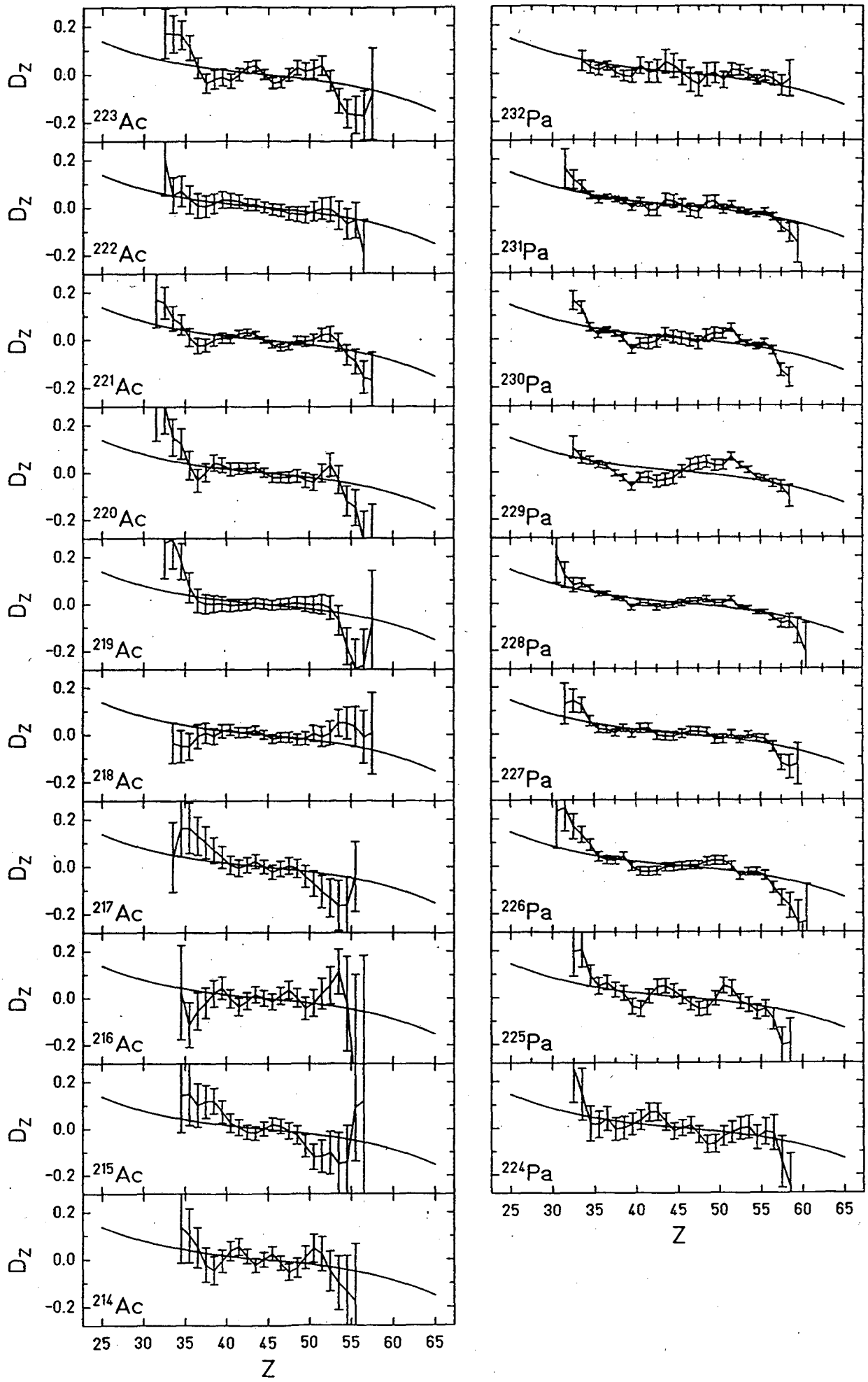
Yields

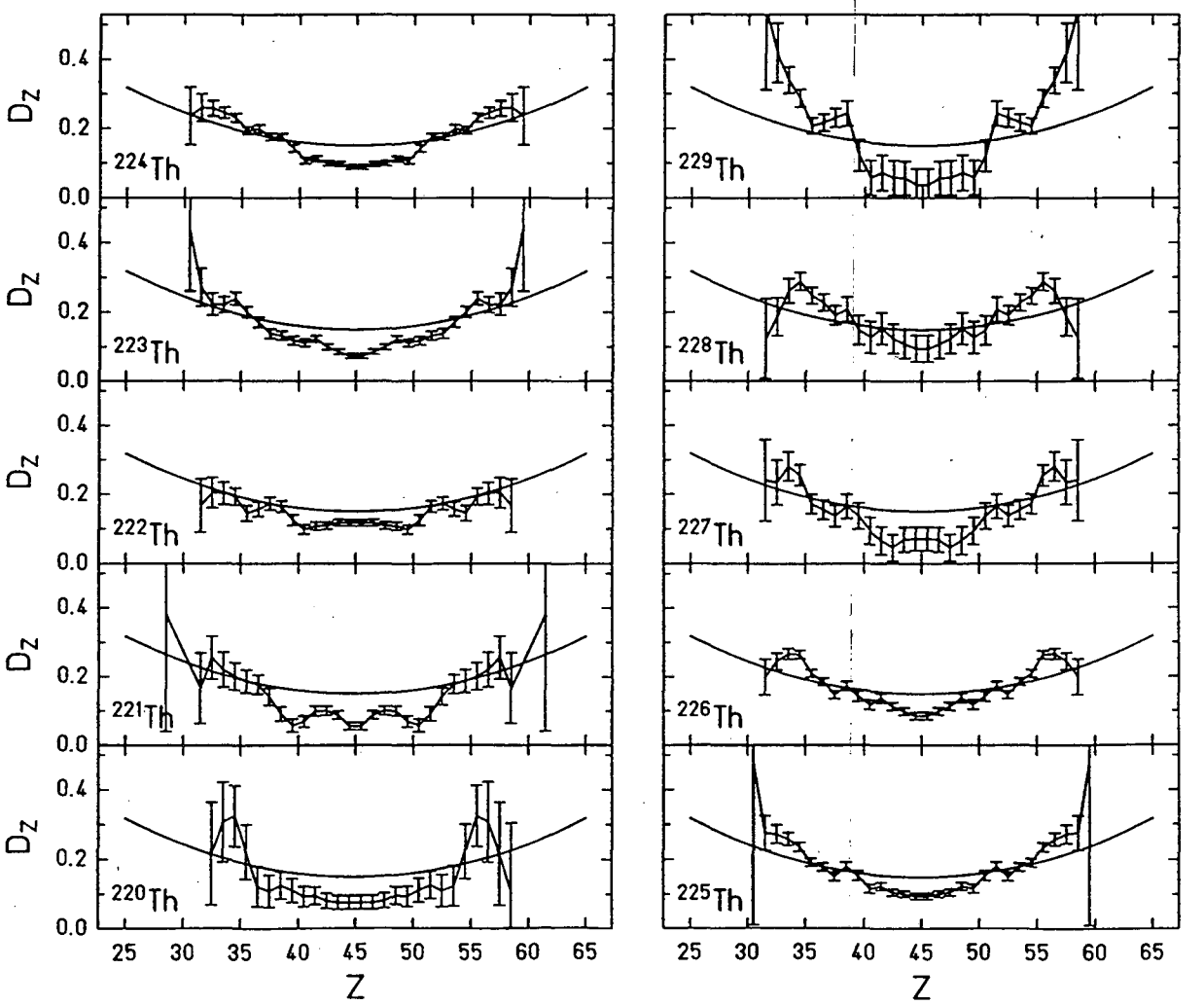
Local even-odd effect

$$D_Z(Z+1.5) = (-1)^{Z+1}\,[\ln Y(Z+3) - 3\ln Y(Z+2) + 3\ln Y(Z+1) - \ln Y(Z)] \,/\, 8$$

Prediction based on single-particle excitations




^{223}Ac
^{222}Ac
^{221}Ac
^{220}Ac
^{219}Ac
^{218}Ac
^{217}Ac
^{216}Ac
^{215}Ac
^{214}Ac
^{232}Pa
^{231}Pa
^{230}Pa
^{229}Pa
^{228}Pa
^{227}Pa
^{226}Pa
^{225}Pa
^{224}Pa
D_Z
0.2
0.0
-0.2
25 30 35 40 45 50 55 60 65
Z


D_Z
0.0
0.2
0.4
^{224}Th
^{223}Th
^{222}Th
^{221}Th
^{220}Th
^{229}Th
^{228}Th
^{227}Th
^{226}Th
^{225}Th
25 30 35 40 45 50 55 60 65
Z

Perspectives

Secondary beams make short-lived nuclei available for of low-energy fission studies.

Challenge to develop adaquate experimental techniques for the new specific conditions.

A new door for fission studies is open and will give new life to this unique research field on large-amplitude collective motion.

CONCLUSION

Transition from symmetric to asymmetric fission around A = 226 systematically mapped

Weights of modes governed by A

Compact asymmetric mode around N = 82 observed for all nuclei

First determination of superfluid component in symmetric mode (10% to 15%)

First systematic observation of even-odd structure for odd-Z fissioning nuclei (Z even-odd effect in the presence of unpaired protons!)

Evidence that pair breaking occurs in an early stage of fission (not during snapping-in at scission)

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