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D.J. Clark and G.J. Wozniak

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Fast Energy Changes with a Cyclotron*

D. J. Clark and G. J. Wozniak
Nuclear Science Division, Lawrence Berkeley Laboratory
1 Cyclotron Road, Berkeley, CA 94720, U.S.A.

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D. J. Clark and G. J. Wozniak
Nuclear Science Division, Lawrence Berkeley Laboratory
1 Cyclotron Road, Berkeley, CA 94720, U.S.A.

Abstract
A technique is described to quickly change the energy of a cyclotron by accelerating different charge states of a heavy ion, or different isotopes with the same charge state. This technique requires keeping all the magnetic fields constant and scaling all voltages proportional to the ion charge/mass ratio. An ECR source was used to produce ions as heavy as uranium with a wide range of charge states.

1. Introduction

The sector-focused cyclotron can produce various particle species at a wide range of energies. For efficient use of accelerator time, changes in particle species and/or energy should be made quickly. The minimum time required for these changes is limited by several factors. The magnet is normally unlaminated and takes a few minutes to reach its new value, within the required accuracy. At the Lawrence Berkeley Laboratory 88-Inch Cyclotron there are about 30 parameters to be set for the ECR source and injection line, 40 to be set for the cyclotron and another 10-20 for the external beam transport. Some of these have adequate pre-set values but most have to be optimized for best transmission. So the tune-up time from source to target for a new beam is about 2-4 hours.

Some techniques have been previously developed to reduce the time required for a particle or energy change. In 1966 at the LBL 88-Inch Cyclotron a series of fast energy changes were made in an alpha particle experiment, where 120 energies from 24 to 54 MeV were run during a 70 hour experiment [1]. This was done by minimizing the number of parameters changed in each step. The internal ion source was used, so tuning of the injection line was not required. With a second technique [2] used at the same cyclotron, "analog beams" with essentially the same charge/mass (Q/A) ratio were accelerated under almost identical conditions, and could be selected by making a small change in the cyclotron frequency. Since all other injection, cyclotron and transport parameters could remain the same, this gave very fast changes (< 1 min) in particle species, all with the same energy/nucleon, and thus with energy proportional to mass.

We describe here a third technique, which can be used for modest energy changes of a given isotope, or for changes between two different isotopes.

2. Technique

In the technique presented here, we take advantage of the wide range of charge states available for the heavier ions from the ECR source [3] and the fact that most elements have more than one stable isotope. Fig. 1 shows an A/Q spectrum for ions produced in an ECR source with a Cu oven feed and oxygen support gas. Intense peaks of $^{16}O^{3+,4+,5+}$ ions are observed due to the oxygen support gas. Background carbon beams of $^{12}C^{2+,3+,4+}$ are also produced ($^{12}C^{3+}$ coincides with $^{16}O^{4+}$). At reduced intensities pairs of peaks due to charge states of the two naturally abundant isotopes ^{63}Cu and ^{65}Cu are observed. The charge states shown for copper range from 11^+ to 19^+. In this case the source was tuned to optimize the production of high charge states. It can also be tuned to optimize the production of lower charge states if desired.

In the cyclotron, energy/mass is proportional to $(Q/A)^2$ at constant magnetic field, so we can change the energy of an isotope by switching from one charge state to another, or we can switch from one isotope to another at constant charge state. The injection transport line settings can remain unchanged, by scaling the injection accelerating voltage proportional to the charge/mass, so that the magnetic rigidity is unchanged. Keeping the main cyclotron magnetic field constant, eliminates the settling time after changes. The cyclotron trim coils normally have to be changed to keep the field isochronous. By keeping the magnetic rigidity of the beam constant, all the beam transport magnets to the target can be left unchanged.

We use cyclotron scaling laws [4] to make the beams as similar as possible. According to these scaling laws, if we change all the voltages in the system proportional to the charge/mass ratio, Q/A, of the ion, and leave all the magnetic fields constant, the particle trajectories will remain constant in the injection system, the cyclotron acceleration region and the external beam transport system. The voltages in the system include the ECR source accelerating voltage, the voltage on the electrostatic inflector in the cyclotron center region, the dee voltage and the voltages on the electrostatic deflector which extracts the cyclotron beam. The only part of the system which doesn't scale is the plasma surface in the extraction region of the ECR source. This can be compensated somewhat with the ECR focusing lens. The rf frequency must also be changed, since Q/A changes. The scaling is better when we remain on the same accelerating harmonic of the rf frequency, because the transit time of the beam in the center region changes with harmonic number.

This technique has the limitation of having discrete steps in energy, corresponding to one unit of charge state change or a change in mass from one isotope to another. Since the cyclotron energy/mass is proportional to $(Q/A)^2$, changing the charge state by one unit can give a sizeable change in energy for small values of Q and a more modest change for larger values of Q (see Table 1.). For example, for $Q = 8$ and $\Delta Q = 1$, then $(\Delta Q/Q)x100 = 13$ % and the beam energy change is 27 %. However, as the mass of the beam increases, larger values of Q are possible and changing the charge state by one unit gives a correspondingly smaller change in the beam energy. For $Q = 30$ and $\Delta Q = 1$, $(\Delta Q/Q)x100 = 3$ % and the beam energy changes by 7%. Thus for heavy projectiles in high charge states, modest energy changes are possible by changing the charge state by one unit. Energy changes for an isotope mass change of one unit are shown in Table 2. For smaller energy changes than are possible with these techniques, the magnetic field must be changed, as in the alpha particle experiment mentioned above, but this can be planned to minimize the tuning time.

The scaling described here is specifically for fast energy changes. Our normal cyclotron operation is non-scaling, to maintain a high acceleration voltage for all heavy ion beams and thus reduce charge exchange losses. Some other cyclotrons use scaling of the dee voltage to give constant turn number for their normal operation, either for simplicity of operation or because they have a fixed center region geometry. Several also scale the injection line as described above, for the same reasons.

3. Results

In Fig. 2 are shown 3 examples of experiments where energy changes were made by changing charge states. The ions were ^{63}Cu, ^{235}U and ^{209}Bi. Not all of the charge points shown were used in the experiments. The groups of points for each of the experiments are shown within one harmonic only, since this maintains better scaling due to a constant transit time factor in the cyclotron center region. The energy range can be extended to the adjoining harmonic, but additional tuning is required. The K value is the cyclotron energy (E) constant: $E/A=K(Q/A)^2$.

In the first experiment there were several runs with a beam of ^{63}Cu ions at energies of 7-13 MeV/nucleon. A high cyclotron field was used: K=140. Charge states ranged from 12^+ to 19^+. See Fig. 2. These beams are relativistic enough that the cyclotron trim coils have to be changed. The shortest time observed for switching energy was a change from 15^+ to 14^+, 7.9 to 6.9 MeV/nucleon. For this change all voltages were scaled proportional to Q, as described above. The tuning time for the injection line and cyclotron was about 50 minutes, but the tuning time to the target was only 8 minutes. The transport from the cyclotron to the target included 4

bending magnets, 4 quadrupole doublets and 3 X-Y steering magnets over of distance of 40 meters. In this test, tuning was used only for the final elements of the transport line. So the tuning time of 8 minutes is a considerable reduction compared to the normal tuning time for this line of 30-60 minutes. The tuning time of 50 minutes for the injection line and cyclotron was partly to re-optimize the ECR source with its oven. This time would be reduced if the oven didn't need tuning. When the harmonic was switched from first to third while going from 14^+ to 12^+ charge states, the transport system had to be retuned because the cyclotron beam emittance characteristics changed. But the injection line tuning time was reduced due to the proper scaling used. If an automated system for setting the parameters were used, the change time could be reduced further.

For experiments at very low energy/nucleon, the relativistic effects are small enough that the trim coils don't have to be changed, simplifying the energy change even further. See Fig. 2. ^{235}U beams at some of the charge states between 21^+ and 28^+ have been run at 0.7 - 1.3 MeV/nucleon in this way at K=90 on third harmonic. More careful scaling was done for an experiment using beams of ^{209}Bi at some of the charge states between 11^+ and 18^+, at energies of .24-.65 MeV/nucleon and K=88 on fifth harmonic. A shorter beamline was used than in the copper experiment. In the bismuth run the beam appeared on target as soon as the voltages and rf frequency had been changed, without adjusting any injection line, cyclotron or transport magnets. Normally a high intensity analog beam such as oxygen or neon is used for the initial tuning of the very high charge state beams. It is found that when the intensity is changed by a large amount, some of the injection line transport elements have to be adjusted. This is probably due to a space charge effect in the line.

4. Discussion

There are two major reasons driving the need for fast energy/ion switching. The first is the requirement of nuclear physics research for beams of a wide range of energies and ion species. The second is the need for economic and efficient operation of the accelerator.

Nuclear physics is the study of the properties of nuclei and nuclear reactions. Many nuclear properties depend strongly on the bombarding energy or excitation energy of the resultant products. Thus, in many instances, the measurement of an excitation function is required to extract the underlying physics. Such excitation functions require measurements at a number of bombarding energies. In addition, the nuclear structure of a nucleus can change dramatically with the addition or subtraction of a single nucleon. Thus, nuclear structure studies require measurements with a variety of projectile-target combinations.

Recently, with the advent of ion sources capable of producing highly ionized heavy ions, it is possible to study a reaction in reverse as well as normal kinematics. For an asymmetric entrance channel, a light projectile on a heavy target is normal kinematics, whereas a heavy projectile on a light target is reverse kinematics. Of course, in the center-of-mass (c.m.) system the physics is identical. However, in the laboratory system there can be significant advantages depending on the physics to be studied. For example, in studies of complex fragment emission from compound nuclei, the c.m. boost from reverse kinematics, causes the decay products to be energetic and focussed at small angles. This alleviates detector threshold problems and enables almost 4π solid angle measurements to be made with modest size detectors.

Recently, we have utilized the $^{63}Cu + ^{12}C$ reaction to produce fast moving and highly excited ^{75}Br nuclei which subsequently decayed into a variety of final products [5]. An excitation function of its decay products was measured (see Fig. 3) and conditional barriers extracted. Six bombarding energies were measured in a 12 shift experiment. All the energy changes were made utilizing the above described fast switching technique.

Due to the high cost of operating a cyclotron, where machine time may cost $500/hr, and the large demand for beam time, it is important to minimize the time spent on beam tuning and changes, and to maximize the beam on target time. Thus, one would like cyclotron energy or ion species changes to require less than one hour.

5. Conclusions

We have demonstrated that fast energy changes can be made by selecting different charge states of highly charged heavy ions produced in an ECR source. By keeping all the magnetic fields constant and scaling all the voltages proportional to the ion charge, rapid energy changes were made by selecting different charge states of ^{63}Cu, ^{209}Bi and ^{235}U. By keeping the magnetic rigidity of the beam constant, all the beam transport magnets to the target could be left unchanged.

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Table 1. Energy change from a unit change of charge state.

A	Typical Q	ΔQ	ΔQ/Q (%)	[Δ(E/A)]/[E/A] (%)
20	8	1	13	27
50	13	1	8	16
100	21	1	5	10
150	27	1	4	8
200	30	1	3	7

Table 2. Energy change from a unit change of mass.

A	ΔA	ΔA/A (%)	[Δ(E/A)]/[E/A] (%)
20	1	5	10
50	1	2	4
100	1	1	2
150	1	.7	1.3
200	1	.5	1.0

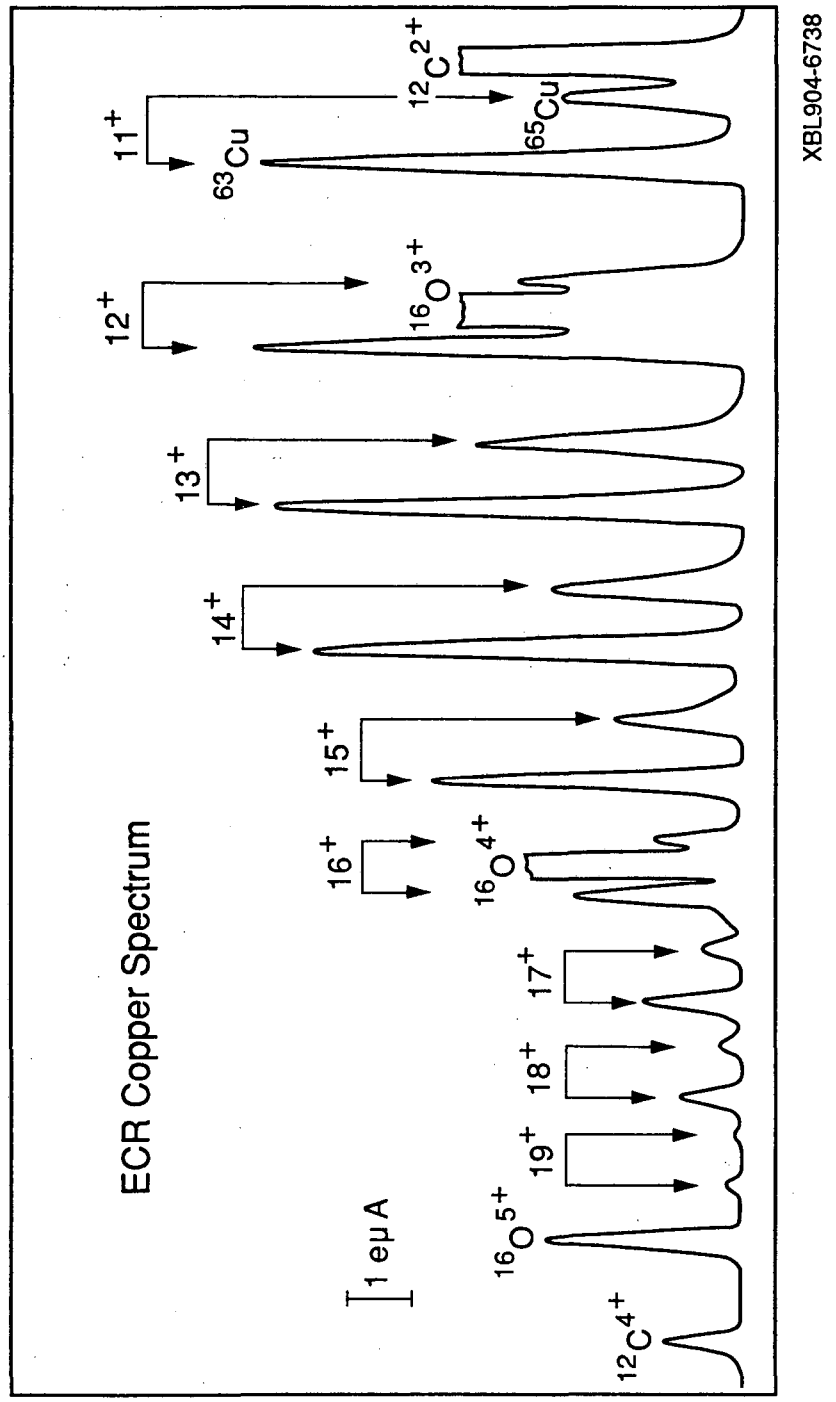

Fig. 1. The intensity of ions produced from the ECR source with a copper feed and oxygen support gas as a function of their mass to charge ratio (A/Q), scanned with the ECR analyzing magnet. See text.

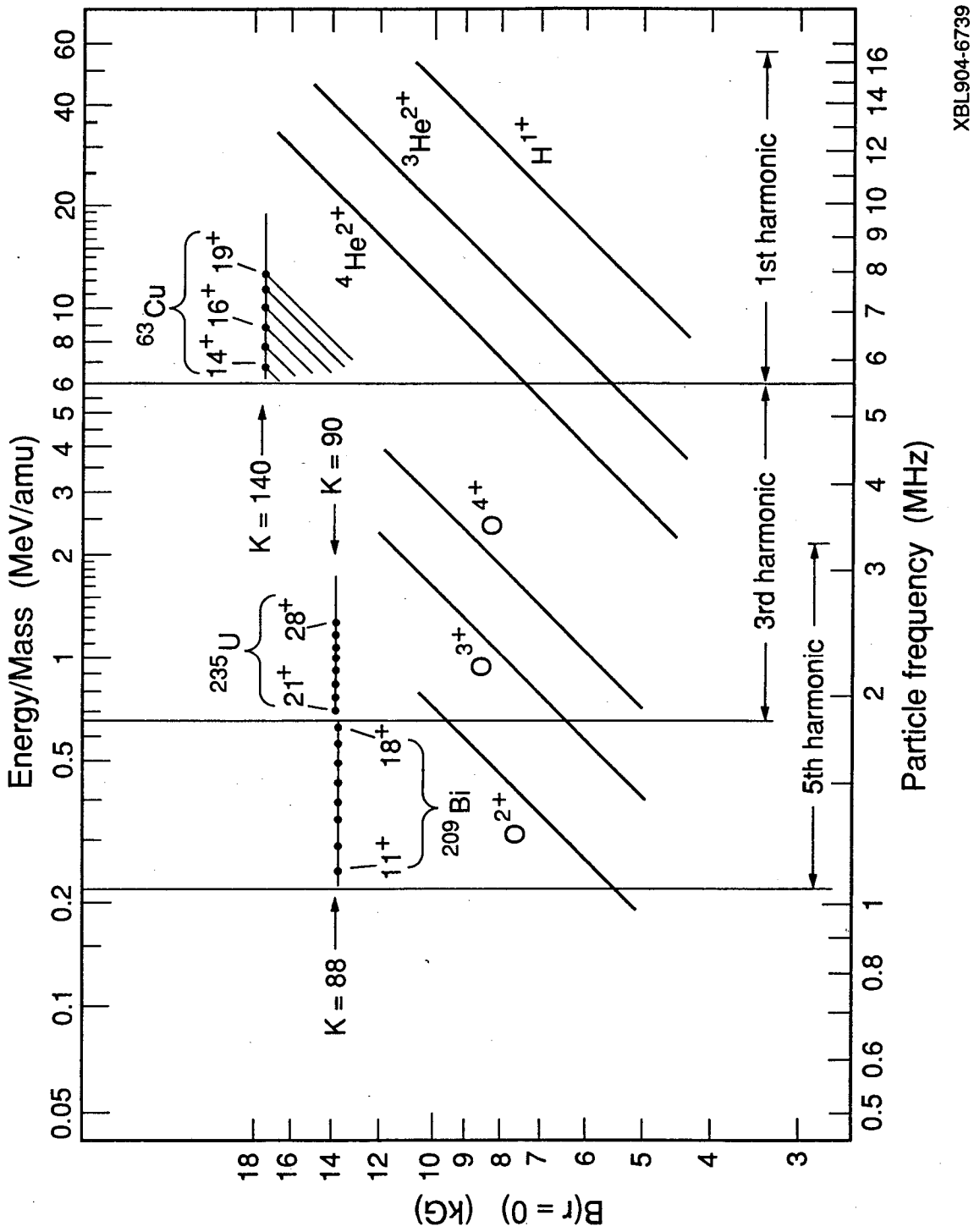

Fig. 2. Resonance chart of cyclotron magnetic field vs. frequency. The available tuning points for ions used in 3 experiments are shown for ^{63}Cu, ^{209}Bi and ^{235}U.

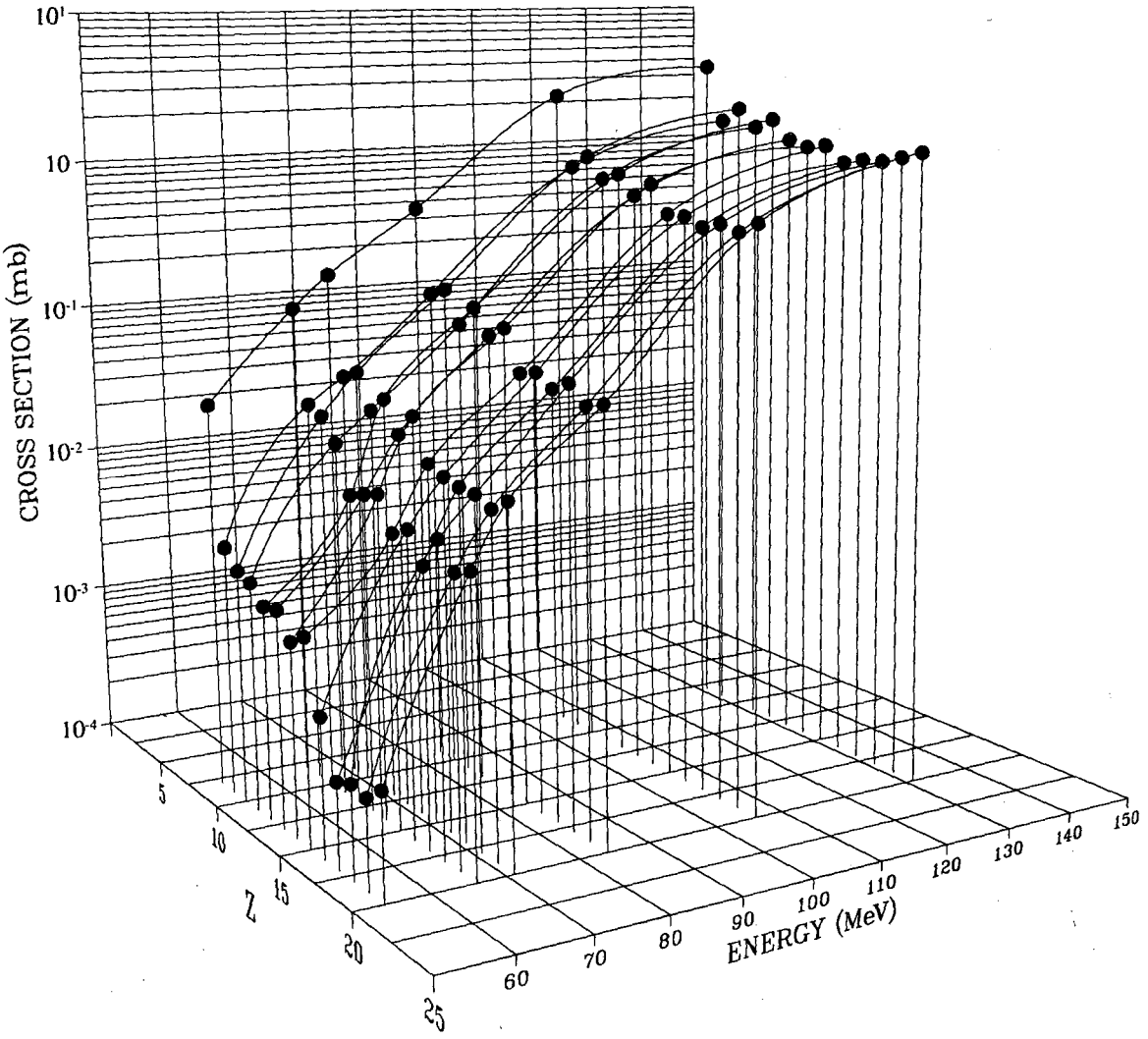

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Fig. 3. An excitation of the yield of complex fragments emitted from the $^{63}Cu + ^{12}C$ reaction at six center-of-mass bombarding energies.

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UNIVERSITY OF CALIFORNIA
INFORMATION RESOURCES DEPARTMENT
BERKELEY, CALIFORNIA 94720