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HEAVY ION REACTIONS WITH HEAVY ELEMENTS

Albert Ghiorso* and Torbjørn Sikkeland†

INTRODUCTION

Most of the quantitative information on nuclear reactions in the heavy element region has been confined to investigations with helium ions or lighter particles because of the difficulties of obtaining intense monoenergetic beams of heavier ions. Heavy ions such as carbon, nitrogen, oxygen, and neon have been accelerated in many cyclotrons[1-7] but the broad energy spectra obtained has made quantitative interpretations of the experimental results almost impossible. More recently, by making use of a new type of ion source, the 150 cm cyclotron of ANSSR in Russia has been able to produce monoenergetic beams of carbon, nitrogen, and oxygen ions. Using these ions a group at that location has studied the fission cross section of U^{235} and U^{238} as a function of energy.[8]

The results presented here were obtained with the Berkeley Heavy Ion Linear Accelerator (HILAC)[9,10] during the last 18 months as part of a general program concerned with the interactions of heavy ions with the heavy nuclides. This program is confronted with certain specialized problems such as the small amounts of target materials available and their very high specific alpha activities together with the short half-lives of the nuclides to be studied and their small formation cross sections. These difficulties have been surmounted to some extent because of the unique advantages of the linear accelerator for heavy ions. The HILAC has proved capable of delivering highly focused microampere beams to an external target free of any hindering field conditions. It has accelerated a wide range of particles with well-defined energies.

A very large fraction of the products of the reaction between a heavy nucleus and a heavy ion (I) consists of fission products. This fission reaction is being studied by several groups in this laboratory by chemical and physical methods but will not be reported upon here. In the complex spectrum of spallation products which survive fission, we have observed nuclides both with lower atomic number (Z) than the target nucleus and those with Z up to that corresponding to the compound nucleus. The present paper will deal only with the production of isotopes with at least as high a Z as the target nucleus.

A. EXPERIMENTAL METHODS

1. Bombardments

The HILAC accelerates all ions to energies of 10 Mev per nucleon; thus to obtain lower energies it was necessary to use degrading foils and evaluate the subsequent energies from calculated range-energy curves.[11] Unfortunately up to the present time the absolute energy of the ions from the machine is known only within 5% and there is some question as to the validity of the theoretical range-energy relationship. The accelerator delivered beam pulses

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*Radiation Laboratory, University of California, Berkeley, California.

†On leave from Joint Establishment for Nuclear Energy Research, Kjiller, Norway.

of 2 milliseconds duration at a repetition rate of 10 per second. The average beam current through a 0.3 x 0.5 cm collimator was several hundred meter milli-microamperes for fully stripped C^{12}, C^{13}, N^{14}, and O^{16} ions. To keep the aluminum degrading foils from melting in this highly concentrated beam, it was necessary not only to helium cool the absorbers and necessary windows between the HILAC vacuum and the target chamber but also to continuously wobble the complete assembly in two directions to minimize the effects of beam "hot spots".

Excitation functions were studied when possible with the stacked foil technique. The individual foils were made by vaporizing UF_4 to a thickness up to 1 mg/cm^2 onto thin aluminum or nickel. For each foil the UF_4 layer was facing the beam so that all spallation recoils were stopped either in the UF_4 or in the backing material.

2. Recoil Techniques

The general technique of taking advantage of the recoil momentum imparted by the fast moving bombarding nucleus was first used by Ghiorso et al.[12] in the experiments in which element 101, mendelevium, was discovered. The reaction products obtain high enough momentum to escape from the target and are stopped in a foil placed directly behind it. For HILAC bombardments a convenient foil material has been found to be palladium because none of the products from the reaction between heavy ions and palladium are alpha emitters. It is also readily dissolved in a few drops of aqua regia and sorbed on anion resin.[13]

It has also been found[14] that the recoils when stopped in a gas remain positively charged and thus can be readily directed by an electrostatic field to a plate for subsequent alpha pulse analysis. Because these atoms are on the surface of the plate they can easily be taken up in solution without dissolving the plate.

The recoil technique is essential wherever a highly active or rare target is used since it greatly simplifies the chemical separation of the products and allows the target to be used over and over again. Hor heavy ions the recoil methods are found to be quite efficient since the large momentum transfer and consequent large recoil range allow targets which are quite "thick" to be used. One disadvantage is the difficulty in estimating the recoil yields and thus absolute cross sections. Leachman and Atterling[15] have measured the range straggling of the reaction products Au(C^{12},4n)At^{211} and Au(C^{12},6n)At^{209} in aluminum and obtained a good fit of the experimental data to the formula suggested by Lindhard and Scharff,[16] by assuming the recoils to be produced by a compound nucleus formation followed by neutron evaporation. Using their data one may estimate the recoil yield of such products from any target thickness and any heavy ion energy.

More uncertain is the estimation of recoil yields for products which are formed by other reaction mechanisms. In these cases the momentum transfer is not known and one therefore has to measure their recoil ranges. In the heavy element region this is difficult to do by conventional methods because of the low cross sections. We have obtained differential range curves by allowing the recoil products to expend their energies in helium at a low pressure and then be attracted at the ends of their ranges to an adjacent plate by a uniform electric field. The catcher plate when sectioned seems to give a very faithful

range curve. Since the method has not been fully proven we have not corrected for loss in the targets of the products of some of the new reactions presented in this paper and the cross sections given must represent a lower limit. In the case of Cm^{244} an additional loss is due to a 50 microgram per cm^2 aluminum foil placed over the target to depress the amount of curium "knockovers".

3. Target Preparations

Targets were prepared by electroplating or by an electrostatic spray method developed by Carswell and Milsted.[17] Their method consists of electrically charging the evaporation droplets of an acetone solution of the nitrate salt of the target so that they can be attracted to the target backing material. This is accomplished by inserting a fine wire in a vertical capillary containing the solution. For our purposes it was necessary to considerably modify this procedure. It was found that by mounting the capillary horizontally and the target vertically it was possible to use a larger capillary, a shorter distance, and a lower voltage and thus to obtain a more controlled fine spraying. For those cases where thick targets had to be dehydrated and converted to the oxide it was found advantageous to keep the target backing (usually 0.03 - 0.10 mil nickel) at a high temperature so that the nitrate could be continuously converted to the oxide. By these means targets up to 0.5 mg/cm^2 with a fairly uniform adherent deposit were made and have withstood hundreds of hours of bombardment in a hundred or more experiments.

4. Chemistry

Conventional chemical separation methods for actinides were used.[31] In order to improve the resolution of the elution curves with ammonium alpha-hydroxy-isobutyrate a platinum tube with a small opening was inserted at the end of the glass column to give a reproducible drop size of about 15 microliters. When a fast operation was necessary a special heating device was introduced to speed up the evaporation of the drops. A hot aluminum plate with perforated holes was used as a turntable and over the area where the drops were falling air was directed. The platinum plates were placed over the holes and the drops were adjusted to fall inside the area defined by the holes. A drop was evaporated within seconds without splattering. For careful identification several actinide and lanthanide isotopes were added as tracers.

5. Counting

All of the isotopes were identified and measured by means of alpha pulse height analysis. Five different samples could be analyzed simultaneously in a multiplex assembly consisting of five Frisch grid chambers, amplifiers, a single Wilkinson type "kick-sorter", coding electronics, and a paper tape printer. With this equipment it was easily possible to obtain good elution curves for short-lived emitters and thus their chemical identifications.

B. NEUTRON EVAPORATION REACTIONS

Very sharp peaks in the excitation functions have been observed for those reactions involving compound nucleus (CN) formation followed by neutron evaporation. Examples are the $(C^{12},4n)$ reaction on U^{238} and Pu^{242} and the (C,6n) reaction on U^{238}.[18] as seen in Fig. 1. A similar curve is obtained for the $(C^{13},5n)$ reaction on U^{238}.[8] Jackson was able to show reasonable agreement with experimental results for the (p,xn) cross-sections in lead and bismuth for calculations using a simplified evaporation model based on the assumption of a constant nuclear temperature, T, together with Monte Carlo calculations.[19] By neglecting direct

processes and charged particle evaporation in (I,xn) reactions, Jackson's evaporation formula can be modified to include fission. The final formula[18,20] for the cross section for the (I,xn) reaction is then:

$$(1) \qquad \sigma(I,xn) = \sigma_C(I) \cdot G_1 \cdot G_2 \cdots G_x P(E^*, x)$$

where:

1. $\sigma_C(I)$ is the cross section for formation of the compound nucleus. To a first approximation $\sigma_C(I) \simeq \sigma_f(I)$ where $\sigma_f(I)$ is the fission cross section. At bombarding energies $E_I > 1.2\ V_C$ (V_C = Coulombic barrier) Blatt and Weisskopf's formula[21] can be used:

$$\sigma_C(I) = \pi (R_T + R_I)^2 \left(1 - \frac{V_C}{E_I}\right)$$

where $R = r_o A^{1/3}$. A reasonably good fit to experimental data gives the value $r_o = 1.5$ fermis for the nuclear parameter both for helium[20] and heavy ion induced reactions[18] with heavy nuclides. To a first approximation, for isotopes of not too widely different atomic number, $\sigma_C(I)$ for the same ion will be equal at the same value of the parameter $x = E_I/V_C$. The curve for carbon ions which has been used in connection with formula (1)[18] is shown in Fig. 1.

2. $$G_i = \left(\frac{\Gamma_n}{\Gamma_t}\right)_i \cong \left(\frac{\Gamma_n}{\Gamma_f + \Gamma_n}\right)_i$$

is the particle level width for the emission of the i^{th} neutron from the compound nucleus. The product $G^x = G_1 \cdot G_2 \cdots G_x$ therefore is the fraction which can evaporate x or more neutrons. G_i is found to be independent of excitation energy[22] and also independent of the way of formation.[18] G_i varies with Z^2/A in a systematic manner[22,23] and unknown values can be estimated.

3. $$P(E^*,x) = I(\Delta_x, 2x-3) - I(\Delta_{x+1}, 2x-1)$$

gives the probability for the evaporation of exactly x neutrons in an initial excitation energy E^*.

I (z,n) is Pearson's incomplete gamma function:

$$I(z,n) = \left(\frac{1}{n!}\right) \int_0^z x^n e^{-x} dx \quad \text{and} \quad \Delta_x = \left(E^* - \sum^x Bi\right)/T,$$

Bi being the binding energy of the i^{th} neutron and can be obtained from the compilations by Glass et al.[24]

$$\Delta_{x+1} = \left(E^* - \sum^{x+1} Bi\right)/T \text{ or } \left(E^* - \sum^x Bi - E_{Th}\right)/T \text{ when } E_{Th} < B_{x+1} \text{ where } E_{Th} \text{ is}$$

the activation energy for fission.[23,25,26] The nuclear temperature for fission is assumed to be equal to that for neutron evaporation. A value of T = 1.35 Mev is found to fit well for helium ion[20] and also for heavy ion[18] induced reactions. In Fig. 1 are given the calculated curves using formula (1) and we see a reasonably good fit to the experimental points. It must be pointed out that, because of high errors in G (of the order of 50%), calculations by formula (1) only give an order of magnitude estimation of the cross section.

C. REACTIONS INVOLVING CHARGED PARTICLE EMISSION

1. Reactions Increasing Target Nucleus by Two Units in Z.

Among the reactions where charged particles are emitted, those leading to isotopes with Z two units higher than the target nucleus take place with relatively large cross sections. Excitation functions for some of these reactions involving C^{12}, C^{13}, and O^{16} on Cm^{244} have been measured. The target thickness was 400 $\mu g/cm^2$. A single cross section point using N^{14} has also been observed which is consistent with a similar excitation function (see Fig. 2). The thresholds are below the Coulomb barrier for the heavy ions and also far below those corresponding to charged particle emission from a compound system in which they obtain a kinetic energy equal to or bigger than the Coulomb barrier. The particle or particles are therefore emitted from outside the top of the barrier. This suggests that the disintegration of the ion into two fragments is probably the first step in this type of reaction. The breakup into three or more particles has lower probability than the breakup into two because this implies a many body process and is also energetically more unfavorable. The ions may therefore break up into an alpha particle and a heavier fragment according to the schemes:

$$C^{12} \longrightarrow Be^{8} + He^{4} - 7.4 \text{ Mev}$$
$$C^{13} \longrightarrow Be^{9} + He^{4} - 10.7 \text{ Mev}$$
$$N^{14} \longrightarrow B^{10} + He^{4} - 11.6 \text{ Mev}$$
$$O^{16} \longrightarrow C^{12} + He^{4} - 7.1 \text{ Mev}$$

The breakup of C^{12} into He^{4} and Be^{8} has actually been observed in nuclear emulsions.[27] Splitting into other helium isotopes gives a higher disintegration energy and is thus more unfavorable.

The penetration probability of the alpha particle now is higher than that of the heavier fragment at a certain impact parameter. The penetration of the alpha particle is also favored in certain geometrical orientations by Coulombic repulsion by the other fragment at the point of disintegration. This type of reaction therefore may take place at energies below the Coulombic barrier for the heavy ion, where competition with penetration of the heavy ion is less severe. The reaction therefore may take place at low angular momentum, and the recoil atoms thus may obtain considerable range. The momentum of the recoil may be as high as that of the heavy ion plus the momentum of the recoiling heavy fragment. At higher energies the reactions proceed at higher angular momentum due to competition with the complete amalgamation of the heavy ion. The reaction leading to the same product now takes the character of a stripping and lower momentum is transferred. This effect shows up in the range measurements. In some preliminary experiments a curium target (70 $\mu g/cm^2$) was bombarded with oxygen at 90 and 150 Mev and the range curves for the Cf^{245} and Cf^{246} recoils in helium gas were measured. At both energies, the concentration of the recoils had a maximum at zero range and decreased with the range. This is in contrast with range curves for products from compound nucleus formation where a Gaussian distribution curve around a most probable range is observed. Severe angular spread of the recoils was also noticed, whereas in experiments with recoils from the reaction $Pr^{141}(C^{12},4n)Tb^{149}$ a strong forward peak was observed. In the low energy bombardment some long range recoils were observed which were lacking at high energy. Although one has to be careful to draw quantitative conclusions from these results, we can say that the observations are not in contradiction to the model just described.

The range measurements indicate that the experimental cross sections for these reactions given in Fig. 2 are low by a factor of three because of recoil loss in the 400 $\mu g/cm^2$ curium target. Approximately this same ratio was obtained for the relative recoil yield between thick and thin Cm^{244} targets when bombarded by C^{12} ions to produce Cf^{246}. The above-mentioned experiments clearly demonstrate that the charged particles cannot be evaporated from a compound nucleus system. Most excited nuclei in the heavy element region decay by fission and the measured fission cross section therefore also will include fission by nuclei which were initially formed by the discussed reaction mechanism. The assumption that $\sigma_f = \sigma_c$ is therefore not fully justified. It is of interest to make an order of magnitude estimation of the error involved. Above the Coulomb barrier the thin target yield of the reaction $Cm^{244}(C^{12},Be^{8}2n)Cf^{246}$ is approximately 4 millibarns. After correcting for loss due to fission (see following section), we find that the total cross section involving the emission of a heavy fragment is of the order of 200 millibarns. For this region σ_c is roughly 1-2 barns so that the error involved should be 10-20%. Closer to the barrier the errors will be even higher.

2. (I,αxn) Reactions

Certain orientations will favor the penetration of the heavier part and reject the alpha particle. In Fig. 2 is the given function for the $(C,\alpha 4n)$ reaction on U^{238}. Energy considerations reveal that at low bombarding energies the alpha particle is not evaporated from a compound system. If now the alpha particle is emitted promptly, no competition with fission will occur at that momentum. The alpha particle is emitted with an energy spectrum leaving the struck nuclei without a distinct excitation energy. If we again assume $\bar{G}$ to be constant and independent of excitation energy and the neutrons to be evaporated, we have the cross section:

$$(1) \quad \sigma\,(I,xn) = \sigma_c\,(I,\alpha)\,\bar{G}^x \int P\,(E^*,x)\,\frac{dN(E^*)}{dE}\,dE$$

Here $\sigma_c\,(I,\alpha)$ is the total cross-section for reactions where an alpha particle is emitted. $\bar{G}^x$ and $P\,(E^*,x)$ are previously defined, and $dN(E^*)/dE$ is the excitation energy spectrum of the strick nucleus after the emission of the alpha particle and before the evaporation of the neutrons.

Using formula (1) we may, by inserting experimental values for $\sigma\,(I,\alpha xn)$, obtain information concerning the excitation energy spectrum and thus the alpha energy spectrum. A convenient experimental series is the $Pu^{240}(C^{12},\alpha xn)Cf^{248-x}$ and $Pu^{242}(C^{12},\alpha xn)Cf^{250-x}$, where one obtains cross sections for reactions with $x = 2$ up to $x = 6$. Formula (1) also gives information about the variation of the $\sigma\,(I,\alpha xn)$ cross section with the target nuclei. At a certain bombarding energy $\sigma_c(I,\alpha)$ will be, to a close approximation, equal for nuclei not too far apart on the nuclear chart. The alpha spectrum will also be similar. We will therefore obtain the following relation:

$$(2) \quad \log\,(I,\alpha xn) = A + x \log \bar{G} \quad .$$

We have obtained experimental values for $\sigma\,(C,\alpha 4n)$ on U^{238} and Pu^{242} and, when plotted on a log log scale, they fall on a line showing a fourth power dependence on $\bar{G}$. Finally, Formula (1) gives an order of magnitude estimation of $\sigma_c(I,\alpha)$ from the experimental value of $\sigma\,(I,\alpha xn)$. We find these cross sections for carbon and oxygen ions above the barrier to be of the order of 100 microbarns and are thus 10 - 100 times lower than the reaction where the alpha particle is amalgamated.

3. Other Reactions

Reactions also occur in which charged particles, other than those already mentioned, are emitted. In terms of a breakup mechanism, these imply that the heavy ions disintegrate in a way in which alpha particles are not involved. By bombarding an Am^{241} target (280 mg/cm^2) with O^{16} we have observed Cf^{245} and Cf^{246} which might be produced by the amalgamation of a lithium ion and the emission of a boron ion. At 80 Mev the cross section was 30 microbarns for the production of Cf^{245} and only 3 microbarns for Cf^{246}. The relatively low cross section for the latter is explained by the higher probability of the emission of more than one neutron at these excitation energies. With correction for fission loss, we obtain the total cross section for reactions where boron ions are emitted, to be of the order of a few hundred microbarns. This is a factor of 100 lower than the (O^{16},C^{12}) reaction and of the same order of magnitude as the (O^{16},α) reaction. There is a higher disintegration energy for the splitting into beryllium and lithium than into carbon and helium; this balances the higher penetration probability of the lithium versus the carbon ions.

We have also observed the product Fm^{250} from the reaction which can be written as $Cm^{244}(O^{16},Be^{8}2n)Fm^{250}$ with a maximum cross section of the order of 1 microbarn. This will correspond to a total cross section for the (O^{16},Be^{8}) reaction of the order of 0.1 millibarn. This is roughly 1000 times smaller than the (O^{16},C^{12}) reaction. The reason might again be explained in terms of a lower penetration probability for Be^{8} and the higher disintegration energy of the reaction $O^{16} \longrightarrow 2\ Be^{8} - 14.6$ Mev.

D. DISCOVERY OF ELEMENT 102

The discovery[28] of element 102 evolved from a unique application of the experimental and theoretical considerations that have been outlined. In many careful experiments conducted in many ways over a long period of time it was found that a prior claim[29] to the discovery of element 102 could not be confirmed.[30] Subsequently, by the use of a radically new method Ghiorso, Sikkeland, Walton, and Seaborg succeeded in unambiguously identifying for the first time an isotope of element 102.

The method used to detect the new element was essentially a continuous milking experiment wherein the atoms of the daughter element 100 were separated from the parent element 102 by taking advantage of the recoil due to the element 102 alpha particle decay. The target consisted of a mixture of isotopes of curium (95% Cm^{244} and 4.5% Cm^{246}) mounted on a very thin nickel foil. The curium was bombarded with monoenergetic C^{12} ions at energies of 60 - 100 Mev. The transmutation recoils were absorbed in helium and electrically attracted to a moving metallic belt placed directly beneath the target. These atoms were then carried on the conveyer belt under a foil which was charged negatively relative to the belt. Approximately half of the atoms undergoing alpha particle decay would cause their daughter atoms to recoil from the surface of the belt to the catcher foil (see Fig. 3). After a time of bombardment suited to the half-life of the daughter atom to be examined, the catcher foil was cut transversely to the direction of the belt motion into five equal length sections. These five foils were then alpha pulse analyzed simultaneously, from the relative amounts of activity and the belt speed the half-life of the parent atoms could be deduced. The method was first successfully used in the bombardment of Pu^{240} with C^{12} ions to identify a new isotope of element 100, Fm^{248} (Fig. 4). It was shown to have a half-life of 0.6 minutes by analysis of the amounts of the 20-minute Cf^{244} caught on the catcher foils.

The most likely isotope of element 102 that could be detected with this method was deemed to be 102^{254} with a predicted half-life of seconds leading to the known 30-minute 7.43-Mev alpha-particle-emitter, Fm^{250}. In a series of experiments it was found that Fm^{250} could be collected on the catcher foils in accordance with a parent half-life of about 3 seconds produced by the reaction Cm^{246} (C^{12},4n)102^{254} $\xrightarrow{\alpha}$. The excitation function for producing Fm^{250} in this manner was found to peak sharply at 70 ± 5 Mev corresponding to a (C^{12},4n) reaction. That the atoms collected are ejected by alpha recoil of atoms from the belt was proved by the fact that neither Cf^{246} nor Cf^{245}, which are collected with high yield on the belt, are found prominently on the catchers. Changing the belt speed was found to change the distribution of Fm^{250} on the catcher foils in a manner conforming to a 3-second parent. The number of Fm^{250} counts observed in a single experiment was as high as 40 and corresponded to a maximum cross section of a few microbarns for the reaction with Cm^{246}.

The final identification of the activity ascribed to Fm^{250} was carried out by dissolving the activity from the catcher foil and separating it from the other actinide elements by means of an ion exchange column. In one experiment 2 atoms of Fm^{250} were identified and in another 9 atoms were observed in the element 100 position.

E. SEARCH FOR ELEMENTS WITH ATOMIC NUMBER GREATER THAN 102

Some very crude preliminary experiments have been reported[28] which were designed to look for alpha activity from element 103. The same curium target was bombarded in the conveyer belt apparatus with ca. 0.3 microamperes of (+7) N^{14} ion. Atoms of 103, such as 103^{256} from the Cm^{246}(N^{14},4n) reaction, would presumably be collected on the conveyer belt as in the other experiments. The belt speed was set at three inches per second since the half-life of an isotope such as 103^{256} would be expected to be a fraction of a second. Nuclear emulsions placed just above the belt to receive the expected long range alpha particles from the decay of this nuclide were examined carefully for such corresponding tracks. There were found 16 tracks with an energy of 9 ± 1 Mev and positions in the nuclear emulsion consistent with a half-life of approximately 1/4 second. These tracks could be due to an isotope of element 103 but the conditions of the experiment did not rule out the very good possibility that they could be due to the production of new nuclides between polonium and thorium from tiny lead or bismuth impurities or to prompt alpha particles arising from interaction of high energy neutrons with the belt material.

The very great difficulties of continuing these experiments which make use of nuclear emulsions as detectors have prompted us to try a more versatile method. An apparatus is being tested in which the transmutation recoils are conducted by properly shaped electrostatic fields to a very thin window. The window is mounted on the high voltage electrode of a gridded ionization chamber. Approximately half of the short-lived atoms that reach the window emit their alpha particles through the window into the chamber volume and thus produce electron pulses which can be analyzed as usual. Since the HILAC beam is presently being pulsed on only 2% of the time, it is expected that even though the alpha particle pulse analysis must be confined to the time between beam pulses a high counting efficiency should be obtainable by this method. Half-life determinations will be made by simultaneous time and pulse height observations.

Another variant of this system makes use of a very long conducting tape, instead of a continuous short belt, together with an alpha grid chamber. The atoms are collected on the tape surface and carried either through the chamber for immediate analysis or through a volume where daughter atoms from alpha recoil of atoms on the belt may be delivered to the thin window of the grid chamber. This allows one to either discriminate against longer lived activities or to analyze the short-lived daughter atoms produced by very short-lived parents. This method potentially should allow the identification of Z of some of the isotopes of elements with atomic number greater than 102. In general, we expect that by means such as these it should be possible to work with alpha activities with half-lives as short as a millisecond and thus it should be possible to identify isotopes of elements as high as 103 and 104. Beyond this point both yield and half-life will become serious problems and will probably demand new advances in techniques.

F. SUMMARY

In the reaction between heavy ions and heavy nuclides a great number of spallation products are observed with atomic numbers all the way from below that of the target nucleus up to that corresponding to the compound nucleus. For reactions which involve charged particle emission, the excitation functions are predominently broad. In contrast, those involving only neutron emission give sharp peaks and a prediction of their positions and cross sections is possible. For the production and study of new isotopes by (I,xn) reactions the excitation function determination is of importance for mass identification purposes. This stresses the importance of a monoenergetic heavy ion beam to prevent the (I,xn) peaks from being smeared out. When dealing with very heavy elements an intense beam also is necessary because of the severe fission competition and consequently low production cross sections for the (I,xn) reactions.

In the energy range studied, reactions where charged particles are emitted, apparently do not proceed by the amalgamation of the heavy ion with the target nucleus. These reactions can be explained in terms of a breakup mechanism in which the disintegration energies and the penetration probabilities of the fragments play an important role in determining the magnitude of the cross section. Because fission is the dominant mode of decay for excited heavy nuclei, the measured fission cross section will be higher than the cross section for compound nucleus formation. Above the barrier it is of the order of 10% higher and below the error may be even higher.

Some radically different experimental approaches have been developed which will probably make possible the positive identifications of new elements with atomic number as high as 104.

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It is a privilege to acknowledge the helpful collaboration of J. R. Walton and G. T. Seaborg in many of these experiments.

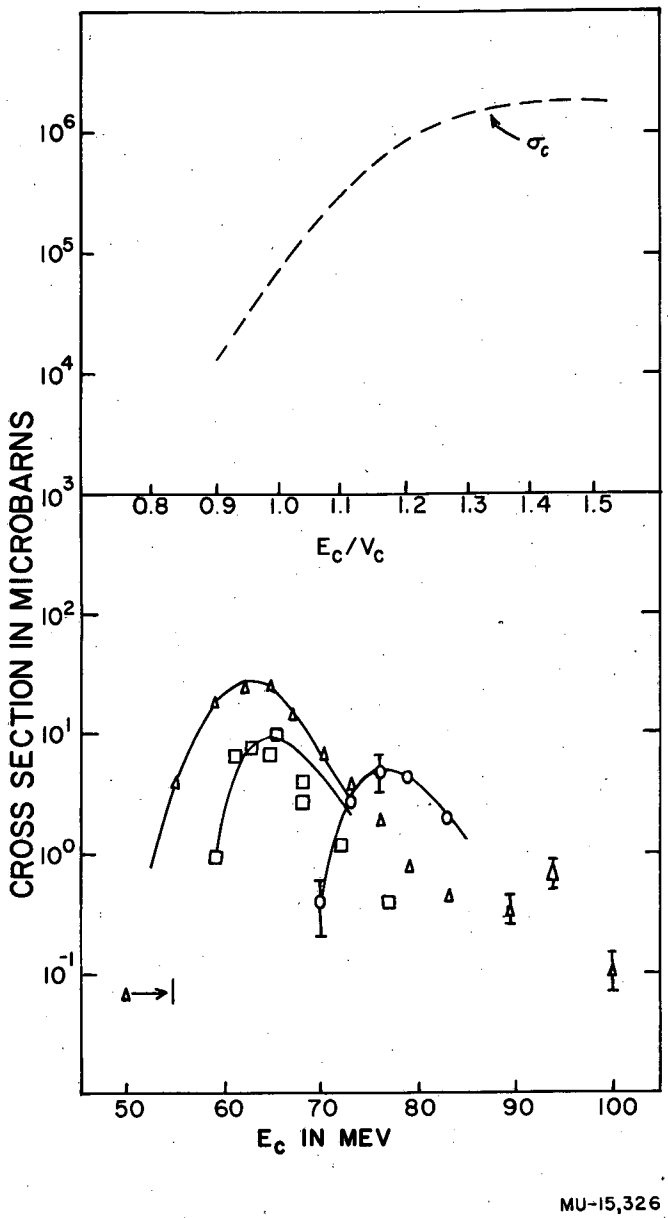

Fig. 1. Comparison of calculated and experimental excitation functions for (C^{12}, xn) reactions. A nuclear temperature T = 0.96 Mev has been used. The dashed curve represents compound nucleus formation cross section for carbon induced reactions with heavy nuclides.

△ $U^{238}(C^{12}, 4n)Cf^{246}$
○ $U^{238}(C^{12}, 6n)Cf^{244}$
□ $Pu^{242}(C^{12}, 4n)Fm^{250}$

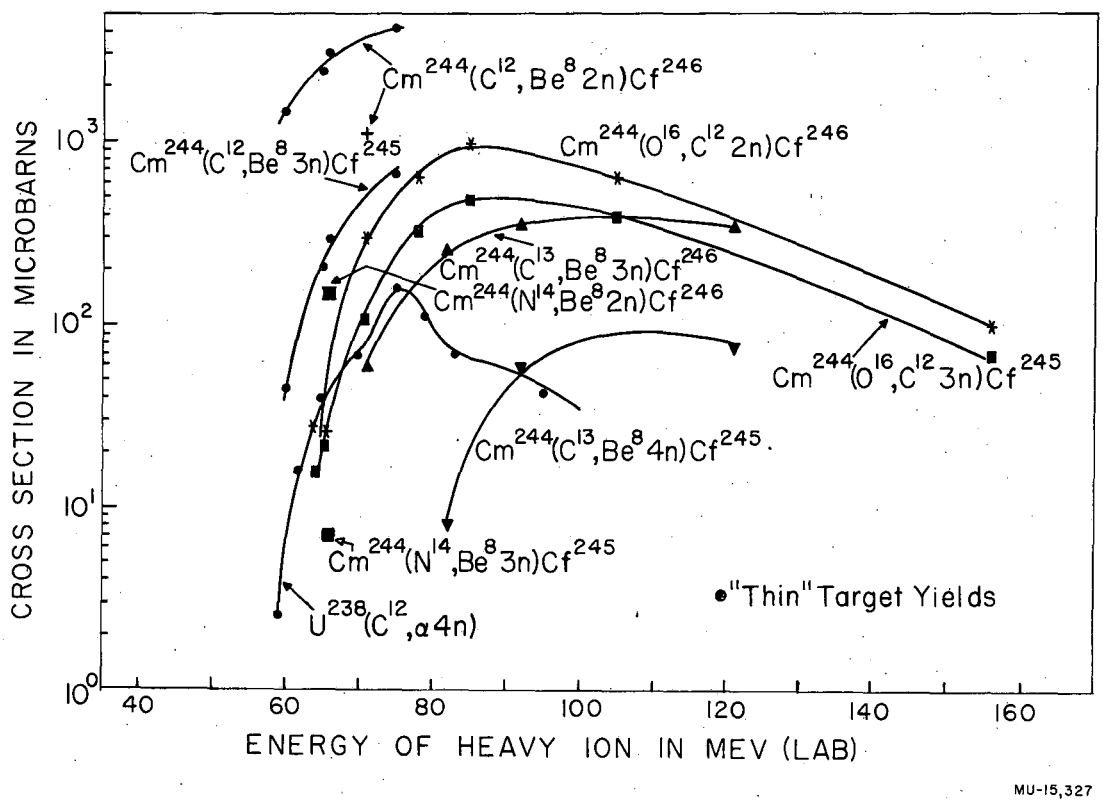

Fig. 2. Reaction involving charged particle emission.

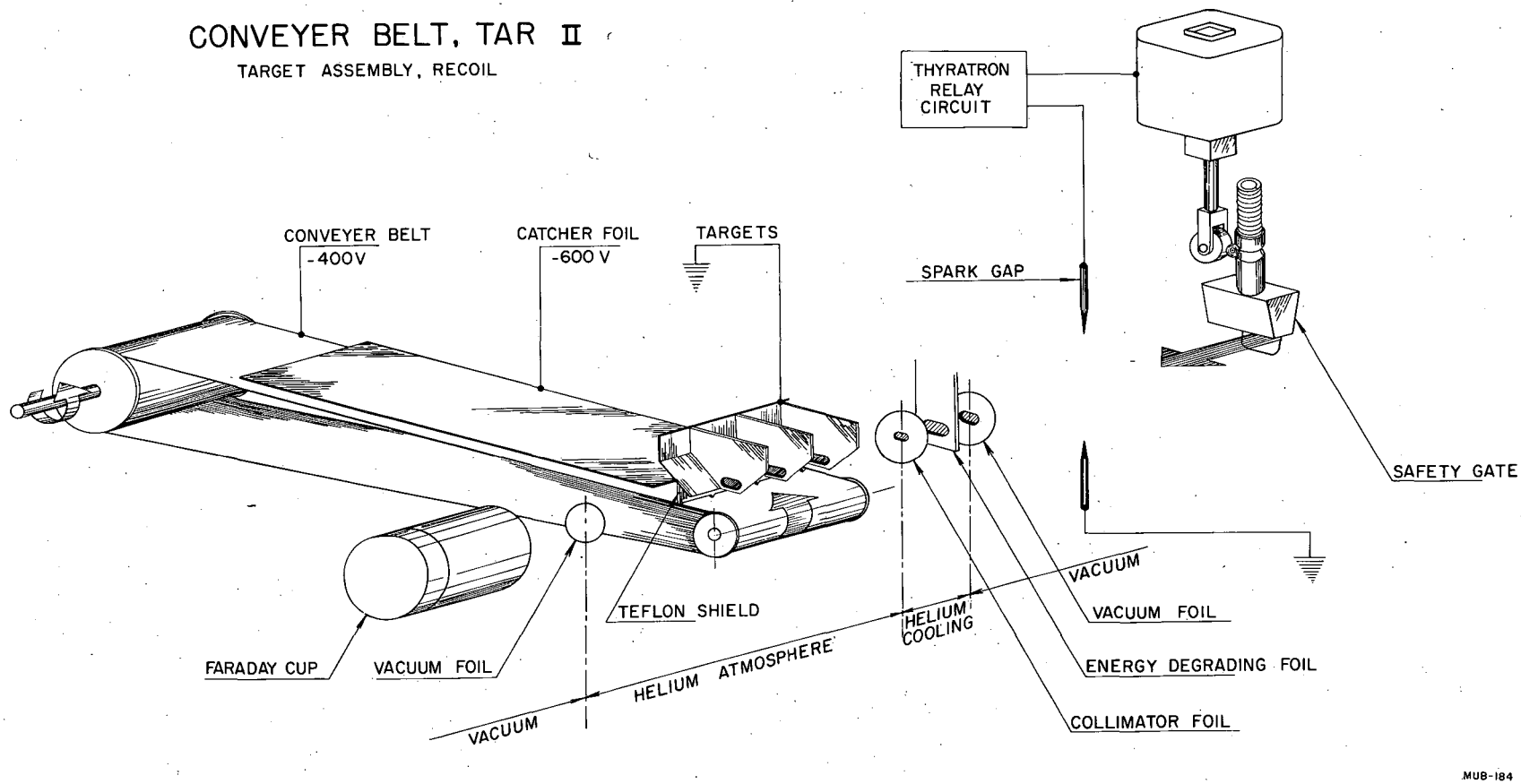

Fig. 3. Schematic diagram of conveyer belt experiment.

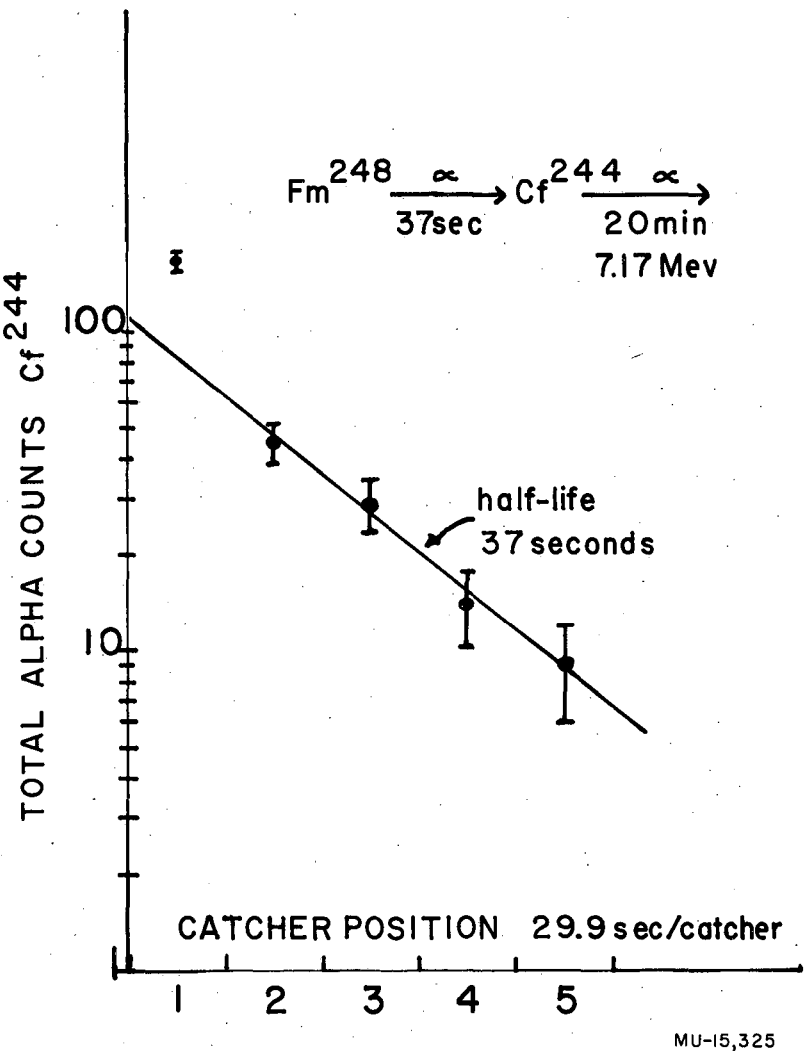

Fig. 4. Alpha recoil milking experiment.

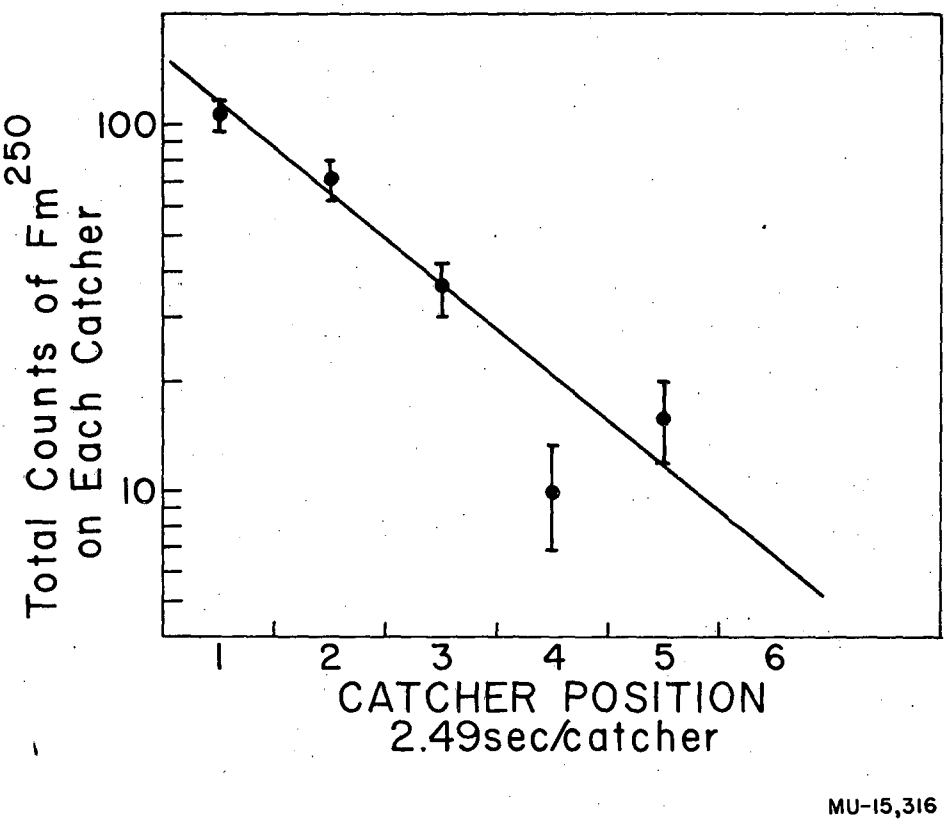

Fig. 5. Determination of half-life of 102^{254}. Data from combined results of many experiments.

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