TABLE II. Values of l_n, l_p, and r for which Eq. (1) gave angular distributions in good agreement with experimental results.

N^{14} state	l_n	l_p	r (fermis)
Ground	0	0	5.08
	1	1	4.57
	2	0	4.65
	0	2	
	2	2	6.42
3.95 Mev	0	0	4.67
	1	1	4.22
	2	0	4.27
	0	2	

were obtained with all the sets of values of l_n, l_p, and r shown in Table II. Although the shell model requires $l_n=l_p=1$, the fits obtained with the other values shown in Table II were equally good. This unfortunate state of affairs makes it difficult to draw any conclusions about the spectroscopic states of N^{14} formed in the (α,d) reaction.

It has been suggested[27] that the N^{14} levels at 4.91 and 5.69 Mev have the configuration $s^4p^9 2s_{\frac{1}{2}}$, while the 5.10- and 5.82-Mev levels are $s^4p^9d_{\frac{5}{2}}$. Both these configurations would involve entry of the captured proton and neutron into different shell-model levels, or else a rather drastic rearrangement of the C^{12} core. Since at least two of these four levels were formed in high yields, it seems that the (α,d) reaction does not preferentially populate levels in which captured nucleons enter equivalent states.

ACKNOWLEDGMENTS

It is a pleasure to thank the crew of the Crocker Laboratory 60-inch cyclotron both for their efficient operation of the cyclotron and for their willing assistance with all phases of the experiments. We wish to thank Dr. Homer E. Conzett, Dr. Jose Gonzalez-Vidal, and especially Dr. Norman K. Glendenning, for very valuable discussions, and Daniel O'Connell for preparing the carbon targets.

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(He^4, Be^7) Reaction in Magnesium, Aluminum, Titanium, Cobalt, and Copper from Threshold to 42 Mev*

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Cross sections for the production of Be^7 in the He-ion bombardment of Mg, Al, Ti, Co, and Cu have been measured in the 30–42-Mev energy range. The excitation functions for these reactions are presented. A study of the bulk (0°–90°; 90°–180°) laboratory angular distributions by the catcher foil technique of the Be^7 nuclei emerging from 2.0- and 1.85-mg/cm² magnesium targets and an examination of the approximate range-energy curves for the Be^7 particles in aluminum and magnesium indicates that the reaction proceeds through a compound nucleus. The experimental excitation function for the $Al^{27}(He^4,Be^7)Na^{24}$ reaction is compared with calculations based on the nuclear evaporation model. The cross sections for the production of Na^{24} and Be^7 in the He-ion bombardment of aluminum are contrasted and the difference between the yields leads to an excitation function for the (He^4,He^3He^4) reaction.

INTRODUCTION AND THEORY

A STUDY of the production of Be^7 in the light elements with 30–42-Mev He-ions has indicated that a direct-interaction mechanism is responsible for the observed cross sections.[1] An apparent nonisotropic distribution in the center-of-mass system of the Be^7 particles which penetrate out of a thin target produced the above conclusion. A re-examination of the data given in reference one and observations of the bulk (0–90°; 90°–180°) angular distributions using the catcher foil method but thinner targets indicate that the apparent high forward yields observed are due to the fact that much too thick a target was used (3.1 mg/cm² Al) and the less energetic fragments which emerge into the backward hemisphere are unable to escape the target unless the (α,Be^7) event occurs near the rear surface. The comparatively large numbers of Be^7 decays observed in the target blur the angular distributions. An examination of the approximate range-energy curves for Be^7 particles and the kinetic

* Supported in part by the U. S. Atomic Energy Commission under contract.

[1] G. H. Bouchard, Jr., and A. W. Fairhall, Phys. Rev. 116, 160 (1959).

energy vs laboratory angle curves from the conservation laws show that a target of about $\frac{1}{2}$ mg/cm^2 of aluminum or magnesium would have to be used to obtain a good approximation to the bulk angular distributions by a study of the product yields in the front and rear catcher foils. The results of bombarding 2.0- and 1.85-mg/cm^2 magnesium foils and the conclusions from the above considerations indicate that the reaction probably proceeds principally through a compound nucleus.

The present study consists of an investigation of the (α,Be^7) reaction in magnesium, aluminum, titanium, cobalt, and copper. A total of 32 cross sections has been measured. In the case of the $Al^{27}(\alpha,Be^7)Na^{24}$ reaction, excitation functions for both the yield of Na^{24} and Be^7 are presented and discussed in the light of the $Al^{27}(\alpha,\alpha He^3)Na^{24}$ reaction which is expected to contribute to the Na^{24} yield.

Monte Carlo calculations[2,3] based on the nuclear evaporation model have recently been made for proton-induced reactions with emission of particles such as Be^7, Li^6, Li^7, Li^8, and He^6 from various targets at the high energies (340–2000 Mev) and a comparison with the experimental cross sections shows fair agreement with a number of the observed cross sections. However, the evaporation picture for particles as heavy as Be^7 is questionable and the apparent success of the statistical model has not added greatly to the extent of understanding of the detailed mechanism of the nuclear reaction. Despite these well-known difficulties, it is interesting to compute cross sections on the nuclear evaporation model at the low energies for the (α,Be^7) reaction to see if the same qualitative agreement can be found. To this end, the basic assumptions used by Dostrovsky *et al.*[3,4] were applied in a calculation of the (α,Be^7) reaction in aluminum from 30–42 Mev. The variation of nuclear level density $W(E)$ with excitation energy was taken as the usual form:

$$W(E)=C\exp\{2[a(E-\delta)]^{\frac{1}{2}}\}, \quad (1)$$

where the values of δ were taken to be the pairing energies for neutrons and protons tabulated by Cameron.[5] The calculation did not involve any residual nuclei which were at or near closed shells and for simplicity no other level density irregularities were taken into account. The empirical equations for the inverse cross sections for neutrons and the variation of charged particle capture cross sections with atomic number and particle kinetic energy adopted by Dostrovsky *et al.* in reference four were used with suitable change of parameters. The classical barrier was computed from the relation

$$V=zZe^2/r_0(A_1^{\frac{1}{3}}+A_2^{\frac{1}{3}}), \quad (2)$$

where A_1, Z and A_2, z are mass and atomic numbers of residual nucleus and emitted particle, respectively, and r_0, the nuclear radius parameter, was taken to be 1.50 and 1.70 fermis. The possibility of evaporation of the Be^7 particle in its bound excited state at 0.43 Mev was taken into account by assuming a statistical weight of 2:1 for ground state to excited state emission. The results of the calculation are illustrated in Fig. 1, and it is seen that at least qualitative agreement with the data can be found. The calculation tends to add strength to the nuclear radius parameter of 1.70 fermis as a better approximation in computing the interaction radius. The parameter k_{Be} on the curves adjusts the effective barrier, k_jV.

SEPARATIONS AND MEASUREMENTS

Thin foils of magnesium, aluminum, titanium, cobalt, and copper were bombarded for three hour periods in the 42 Mev He-ion beam of the University of Washington 60-inch cyclotron. The beam current through the targets was measured with a Faraday-cup arrangement, and total beams ranged up to about 60 microampere-hours. Since the Be^7 particles produced in the reaction are known to have fairly high laboratory energies (up to 22 Mev in the Mg bombardment) and are able to penetrate out of the target foils, it is necessary to provide catcher foils to collect them in the forward and backward directions. Catcher foils of copper and silver of various thicknesses were used and a preliminary investigation indicated that about 15 mg/cm^2 of copper or 20 mg/cm^2 of silver could stop all the Be^7 nuclei

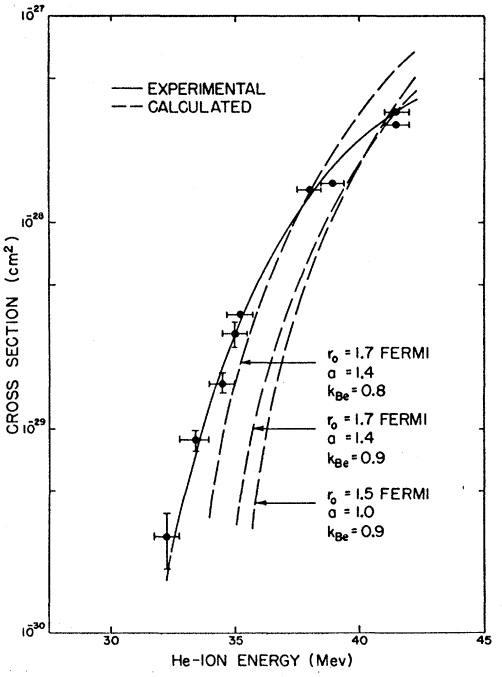

FIG. 1. Experimental and calculated excitation functions for the reaction $Al^{27}(\alpha,Be^7)Na^{24}$.

[2] J. Hudis and J. M. Miller, Phys. Rev. **112**, 1322 (1958).
[3] I. Dostrovsky, Z. Fraenkel, and P. Rabinowitz, Phys. Rev. **118**, 791 (1960).
[4] I. Dostrovsky, Z. Fraenkel, and G. Friedlander, Phys. Rev. **116**, 683 (1959).
[5] A. G. W. Cameron, Can. J. Phys. **36**, 1040 (1958).

TABLE I. Cross sections for production of Be^7 in the He-ion bombardment of magnesium, aluminum, titanium, cobalt, and copper.

Target element	Average He-ion energy (Mev)	Cross section (cm^2)
Mg	41.6	8.64×10^{-28}
	41.1	7.70×10^{-28}
	38.4	4.88×10^{-28}
	36.9	2.82×10^{-28}
	35.0	1.56×10^{-28}
	32.3	2.03×10^{-29}
	31.4	0.90×10^{-29}
	30.8	0.56×10^{-29}
Al	41.4	3.45×10^{-28}
	41.4	2.97×10^{-28}
	38.9	1.57×10^{-28}
	38.0	1.46×10^{-28}
	35.2	3.63×10^{-29}
	35.0	2.92×10^{-29}
	34.5	1.62×10^{-29}
	33.4	0.88×10^{-29}
	32.3	$<2.93\times10^{-30}$
Ti	40.2	8.85×10^{-29}
	36.8	2.42×10^{-29}
	34.9	0.60×10^{-29}
	33.1	6.78×10^{-30}
	31.2	$<2.60\times10^{-30}$
Co	40.5	4.27×10^{-29}
	36.7	2.00×10^{-29}
	37.4	0.74×10^{-29}
	31.8	$<0.14\times10^{-29}$
Cu	40.7	8.73×10^{-30}
	39.1	6.40×10^{-30}
	38.2	3.76×10^{-30}
	37.0	2.87×10^{-30}
	35.6	1.90×10^{-30}
	32.8	$<0.70\times10^{-30}$

emerging from the target foils. Both copper and silver have (α,Be^7) cross sections that are much smaller than the observed cross sections in aluminum and magnesium at corresponding bombarding energies and either could be used as a catcher element without serious corrections to the data. In titanium, cobalt, and copper bombardments, however, it was necessary to collect the Be^7 nuclei emerging out of the target with silver, which has a maximum cross section at 41 Mev reported to be about 1.9 microbarns.[1]

The (α,Be^7) event at He-ion bombarding energies around 40 Mev in light elements such as C, N, or O is known[1,6] to have a comparatively high cross section and a small amount of one of these elements existing as an impurity in the target is undesirable. With 99.9% to 99.99% pure magnesium and aluminum metals, no difficulties were expected, either from remaining volume impurity or from the oxide film that is formed on the surface. However, with copper, considerable care had to be taken to clean up the surface and reduce the oxide film, which builds up to a rather thick layer in a few months. A study[7] of the thickness of oxide films on metals by the methods of optical polarization shows that the oxide layers immediately after exposure to air of 40% to 45% humidity at 25°C are 8–22 A on Al, 12–23 A on Ti, and 10–11 A on Cu. In all cases this amounts to less than one microgram/cm^2 of oxygen and would produce only a negligible amount of Be^7 in the targets used. However, the oxide film on Cu builds up to a rather thick layer (~150 A) in about 140 days and increases so that after a few years the entire surface is covered by a visible layer. It is evident that a 150 A oxide film would be undesirable in view of the fact that the (α,Be^7) reaction in oxygen proceeds with a cross section about 1000 times larger than in copper in the 34–42-Mev range.[1]

In this study, copper foils having a bulk purity of 99.99% were chemically cleaned in hot methanol and then vacuum heated to reduce the oxide layer to an estimated 10–20 A shortly before bombardment. Consistent results were observed in copper bombardments after this was done. In the case of cross sections previously measured in copper,[1] the authors stated that they suspected the presence of an oxide impurity in the target. The cross sections given in Table I for Cu are about a factor of two less than those reported.

The procedures for separation and purification of the beryllium samples, of course, varied with target element, but all relied primarily on anion exchange separations in hydrochloric acid solutions, together with repeated precipitation of $Be(OH)_2$ from ethylenediaminetetraacetate solutions in the presence of appropriate holdback carriers. Beryllium does not form a very strong chloride complex and therefore it is not retained on the anion exchange column in HCl solutions. In all of the targets used, most of the contamination comes from elements which form quite strong chloride complexes and are retained on the column. The final step in the procedure was the precipitation of the beryllium as $BaBeF_4$, which is convenient for mounting and counting in the form of thin disks.

All absolute counting was done by means of a single-channel scintillation spectrometer connected to a 3-inch thallium activated NaI crystal and set to accept photopeak counts on the 0.477-Mev photopeak of Be^7. Some samples were checked for radiochemical purity with a 100-channel analyzer. Determination of absolute values of the cross sections was made by comparison of the samples with a standard Be^7 source under conditions of the same geometry. A source of Sr^{85}, with a gamma ray at 0.513 Mev and calibrated by the National Bureau of Standards was compared at point source geometry with the Be^7 source ($BaBeF_4$) made by bombarding magnesium with He-ions. The correction for the difference in the photopeak counting efficiencies was estimated from the published efficiency curves[8] to be about 0.96.

In the study of the production of Na^{24} from the He-ion bombardment of aluminum, a stack of 1-mil Al foils and an arrangement of $\frac{1}{2}$-mil Cu foils was bombarded and the beam current monitored by means of

[6] A. W. Fairhall and Charles O. Hower (private communication).
[7] V. V. Andreeva, Trudy Inst. Fiz. Khim. Akad. Nauk, S.S.S.R. No. 6. and Novge Metody Fiz-Khim Issledovani, No. 2, 79 (1957).
[8] N. H. Lazar, R. C. Davis, and P. R. Bell, Nucleonics **14**, No. 4, 52 (1956).

the 245-day Zn^{65} activity produced in the copper. The Zn^{65} yields were normalized to the $Cu^{63}(\alpha,2n)+Cu^{63}(\alpha,pn)$ excitation functions of Porile and Morrison.[9] The aluminum and copper foils were mounted intact with no chemical procedures being carried out. The Al foils were counted soon after bombardment on the 2.75-Mev photopeak of Na^{24} with a 100-channel analyzer. No interfering activities were present at this energy. Zinc-65 decays[10] with about 44% of the disintegrations proceeding to the 1.114 Mev excited state of Cu^{65} and the copper targets were counted on this photopeak a few weeks after bombardment when all interfering activities had vanished. The ratio of the photopeak counting efficiencies for these two gamma rays was estimated first from the published curves, and checked by calibrating the spectrometer with an assortment of standard sources obtained from the National Bureau of Standards. The principal difficulty in obtaining accurate data for the yield of Na^{24} from He-ion-induced reactions in aluminum is the presence of a neutron induced contribution from the $Al^{27}(n,He^4)$ reaction, which is uncertain to the degree of variation of the neutron flux in the target stack. The Na^{24} yields in foils at the low-energy end of the target where the He-ion beam has been reduced in energy below threshold for any possible He-ion induced reactions producing Na^{24} indicate that the neutron flux in the target stack is nearly constant (see Table II), and drops slightly with decreasing energy. A constant neutron flux was assumed in correcting the data.

RESULTS AND DISCUSSION

The results are shown in Figs. 1–5 and Tables I–III. All cross sections have been corrected for chemical yield, radioactive decay after bombardment and branching ratios of the gamma rays. Uncertainties in the chemical yields are less than 2%, and random errors of 2–3% in the counting alignment and 1–20% statistics are inherent in various absolute determinations. Small uncertainties in the total beam measurements and the counting method of the comparison with the Be^7 standard source calibrated to about 3% adds to the possible error in absolute cross sections. Straggling corrections have been neglected and the beam energies were computed from the range-energy curves and range-energy equations for alpha particles.[11]

The excitation function for the (α,Be^7) reaction in magnesium is given in Fig. 2. This function includes

TABLE II. Photopeak count rates on the 2.75-Mev gamma-ray peak of Na^{24} converted back to the end of bombardment from a stack of 1-mil Al foils bombarded by 42-Mev He ions.

Foil	Photopeak counts/min	Activity after correction for constant neutron background
1	7990	6700
2	7060	5770
3	5130	3840
4	3830	2540
5	2962	1672
6	2158	868
7	1796	506
8	1518	228
9	1383	93
10	1310	20
11	1295	5
12	1285	...

TABLE III. Be^7 activity observed in the target, front, and back catcher foils in the 41-Mev He-ion bombardment of a 2.0-mg/cm² Mg target. All count rates are converted back to the end of bombardment. The right-hand column gives the approximate minimum kinetic energy that the particle must have in order to penetrate from the target foil into the given catcher. The silver catcher foils were 4 to 5 mg/cm².

Foil	Be^7 activity (counts/min)	Minimum Be^7 K. E. required to reach foil (Mev)
180° Catcher 2	5	
180° Catcher 1	26	
Mg target	90	
0° Catcher 1	44	...
0° Catcher 2	38	8.6
0° Catcher 3	44	13.2
0° Catcher 4	10	17.6
0° Catcher 5	2	21.6

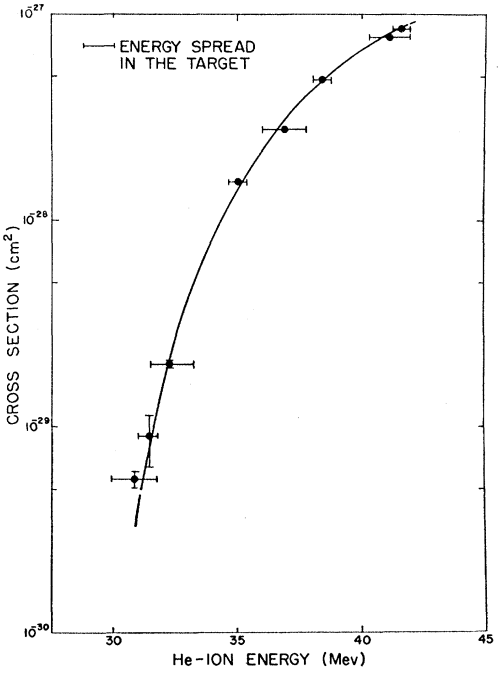

FIG. 2. Excitation function for the production of Be^7 in the He-ion bombardment of natural magnesium.

[9] N. T. Porile and D. L. Morrison, Phys. Rev. **116**, 1193 (1959).
[10] D. Strominger, J. M. Hollander, and G. T. Seaborg, Revs. Modern Phys. **30**, 585 (1958).
[11] W. A. Aron, B. G. Hoffman, and F. C. Williams, U. S. Atomic Energy Commission Unclassified Report No. AECU-663 (unpublished).

any contributions to the Be^7 yield from the (α,Be^7n) reaction, but the threshold of this reaction added to a reasonable classical barrier indicates that negligible contributions are to be expected from this reaction at the energies used in this study. The (α,Be^7) cross sections in aluminum are compared in Fig. 1 with predictions from the nuclear evaporation model. The results of cross section measurements for this reaction in titanium, cobalt, and copper are shown in Figs. 3 and 4. All the measured cross sections, and upper limits, are given in Table I. The vertical bars in the figures indicate uncertainties due to counting only and the horizontal bars are the He-ion beam energy increments for the various points.

In Fig. 5, cross sections for the yields of Be^7 and Na^{24} from He-ion-induced reactions in aluminum are contrasted. Additional points from other investigators are inserted. The triangles represent the data of Lindner and Osborne for the production of Na^{24} from threshold to 40 Mev,[12] the cross sections being determined by counting the target foils by beta-ray techniques. The computed thresholds (see Table IV) for the $Al^{27}(\alpha,Be^7)$ and $Al^{27}(\alpha,Be^7n)$ reactions are about -25.4 Mev and -33.5 Mev, respectively. Addition of about 8 Mev to these numbers from barrier considerations leads to a prediction of effective threshold energies of about 33 Mev and 41 Mev for the two reactions. Consequently, the yield of Na^{24} below about 40 Mev cannot be lower than the Be^7 yield. Indeed, because of another possible

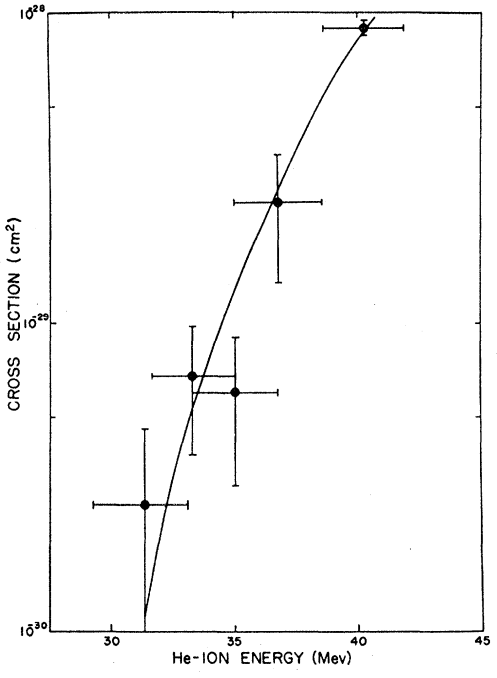

FIG. 3. Cross sections for the production of Be^7 in the He-ion bombardment of natural titanium.

[12] M. Lindner and R. N. Osborne, Phys. Rev. **91**, 342 (1953).

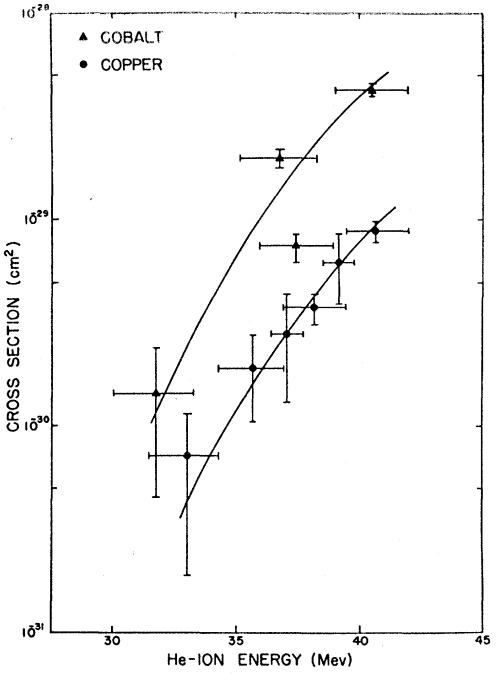

FIG. 4. Upper curve: Cross sections for the reaction $Co^{59}(\alpha,Be^7)Mn^{56}$. Lower curve: Excitation function for the production of Be^7 in the He-ion bombardment of natural copper.

mechanism for Na^{24} production below 40 Mev, i.e., the $Al^{27}(\alpha,\alpha He^3)$ reaction with a threshold of 27.2 Mev, the yield of Na^{24} might be expected to be larger than that of Be^7. The data for the yield of Na^{24} observed by counting on the 2.75-Mev photopeak and given by the open circles in Fig. 5 does indicate that the $Al^{27}(\alpha,\alpha He^3)$ reaction is proceeding and the suggested excitation function for this reaction shown by the dashed line is the difference between the data for the yield of Na^{24} and the solid line drawn through the experimental points in Fig. 1 for the yield of Be^7. From the point of view of the nuclear evaporation model, the evaporation of a He^3 particle from a highly excited (40–50 Mev) compound nucleus is rare in comparison with n, p, d and He^4, but not as uncommon as the formation of heavier particles such as Be^7. The indications from the nuclear evaporation theory can be seen by a reference to the calculated cross sections of Dostrovsky, Fraenkel, and Friedlander for the formation of various particles from different compound nuclei at excitation energies of 30 and 40 Mev.[4] The evaporation of a He^3 particle from a highly excited compound nucleus followed by emission of a He^4 particle from the intermediate nucleus would be rare, but expected from the existing theory. There is always, of course, the possibility of a direct interaction mechanism for this reaction.

A crude estimate of the energies of the Be^7 nuclei emerging from a Mg target of some 2 mg/cm² was obtained by studying the penetration of the particles through thin silver foils. The observed Be^7 activity in

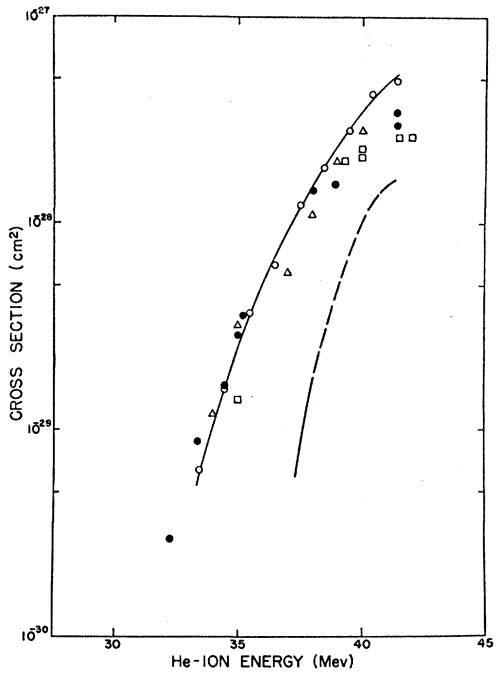

FIG. 5. Cross sections for the yields of Be^7 and Na^{24} from He-ion-induced reactions in aluminum. Darkened circles: The experimental data shown in Fig. 1, for the production of Be^7. Circles: Cross sections for the production of Na^{24} measured by counting on the photopeak at 2.75 Mev. Squares: The experimental data for the yield of Be^7 from reference one. Triangles: The data of reference 12 for the production of Na^{24}. Dashed line: The $Al^{27}(He^4,He^3He^4)Na^{24}$ reaction (see text).

the various foils is given in Table III. Although this target is still too thick to obtain accurate bulk angular distributions by comparing the observed activity in rear and front catcher foils, it is seen from the data that the 31 counts/min observed in the 180° catchers, 90 counts/min in the target and about 138 counts/min in the 0° catchers does not show the very high forward yield expected from a direct interaction mechanism. Rather the data are approaching the expected laboratory angular distributions from a compound nuclear mechanism. The bombardment of a 1.85-mg/cm² magnesium target showed a greater 180° catcher yield (35 counts/min) and these data indicate that if the target could be made considerably thinner one would observe the ~2:1 or 3:1 ratio for forward to backward angular distributions (laboratory) expected from a compound nuclear event. A reference to Fig. 6 and Fig. 7 will indicate the reasons for the conclusions stated above. Figure 6 shows the maximum allowed laboratory kinetic energies of the Be^7 particles as obtained from a solution of the Q equation for various reactions. Figure 7 shows approximate range-energy curves for Be^7 particles in various elements.[13] The range-energy curve for magnesium may be taken as the aluminum curve to a fair approximation. Even if the curves shown in Fig. 7 are in error by more than a factor of two, the conclusions below would be qualitatively valid. Let us first take up a discussion of the catcher foil data of reference one for the bombardment of a 3.1-mg/cm² aluminum target with 40-Mev He-ions. The curve labeled B in Fig. 6 gives the expected maximum Be^7 energies as a function of laboratory angle for the 41-Mev

TABLE IV. He-ion energy thresholds and approximate classical barriers [computed from Eq. (2) with r_0 taken as 1.5 fermis] for reactions yielding Be^7 in the targets used in this study.

Reaction	Threshold (Mev)	Classical barrier (Mev)	Threshold +barrier (Mev)
$Mg^{24}(\alpha,Be^7)Ne^{21}$	25.1	8.2	33.3
$Mg^{24}(\alpha,Be^7n)Ne^{20}$	33.1	8.2	41.3
$Mg^{25}(\alpha,Be^7)Ne^{22}$	21.5	8.2	29.7
$Mg^{25}(\alpha,Be^7n)Ne^{21}$	33.5	8.2	41.7
$Mg^{26}(\alpha,Be^7)Ne^{23}$	28.2	8.1	36.3
$Mg^{26}(\alpha,Be^7n)Ne^{22}$	34.2	8.1	42.3
$Al^{27}(\alpha,Be^7)Na^{24}$	25.4	8.8	34.2
$Al^{27}(\alpha,Be^7n)Na^{23}$	33.5	8.8	42.3
$Ti^{46}(\alpha,Be^7)Ca^{43}$	21.1	14.2	35.3
$Ti^{47}(\alpha,Be^7)Ca^{44}$	18.0	14.1	32.1
$Ti^{48}(\alpha,Be^7)Ca^{45}$	22.8	14.0	36.8
$Ti^{50}(\alpha,Be^7)Ca^{47}$	24.1	13.9	38.0
$Co^{59}(\alpha,Be^7)Mn^{56}$	20.6	16.7	37.3
$Cu^{63}(\alpha,Be^7)Co^{60}$	18.0	17.8	35.8
$Cu^{65}(\alpha,Be^7)Co^{62}$		17.6	

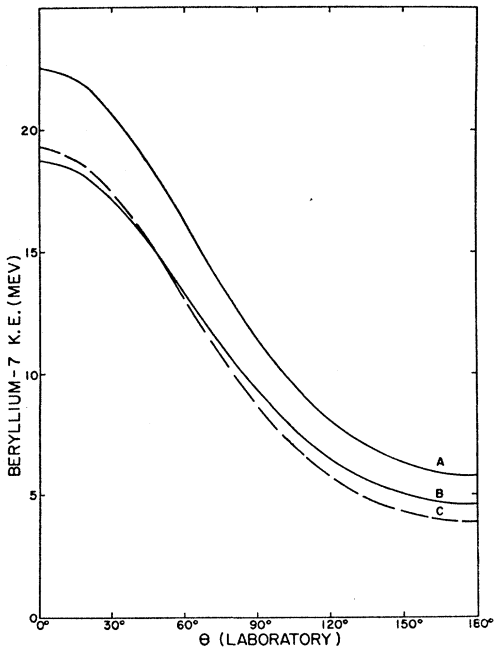

FIG. 6. Predicted maximum energies from the conservation laws for the Be^7 particles from various reactions. Curve A: $Mg^{25}(\alpha,Be^7)$. Curve C: $Mg^{24}(\alpha,Be^7)$. Curve B: $Al^{27}(\alpha,Be^7)$.

[13] These curves were supplied by R. J. Barrett of the University of California Radiation Laboratory and are part of a series of unpublished range-energy curves for particles heavier than He-ions which are used in conjunction with work on the heavy-ion linear accelerator. They are computed from simple assumptions and basic range-energy theory and are expected to be roughly valid.

He-ion-induced reaction $Al^{27}(\alpha,Be^7)$. This corresponds, of course, to a reaction leaving the residual Na^{24} nucleus and the Be^7 particle in their ground states. The maximum energy at 0° is about 18.76 Mev and at 180° about 4.61 Mev. At 150°, a maximum energy of about 5.05 Mev is predicted. From Fig. 7, the range of a 5-Mev Be^7 particle in aluminum is less than 1 mg/cm². Consequently, then, because most of the particles emerging at 150°–180° will have laboratory kinetic energies much less than 5 Mev, only those from events taking place very near the rear surface of the target foil would be able to escape the target and be stopped by the 180° catcher. The higher energy particles emerging into the forward hemisphere would have a much better chance of escaping the target, regardless of where the event occurred. The 3.1-mg/cm² target would not, then, be sufficiently thin to obtain a good approximation to the bulk angular distributions by a study of the product yields in front and rear catcher foils, and, as expected and observed, a considerable number of the Be^7 particles are unable to penetrate out of the target.

It is seen from the threshold considerations for the magnesium target that the reaction which can produce the Be^7 nuclei with the greatest energies is $Mg^{25}(\alpha,Be^7)$.

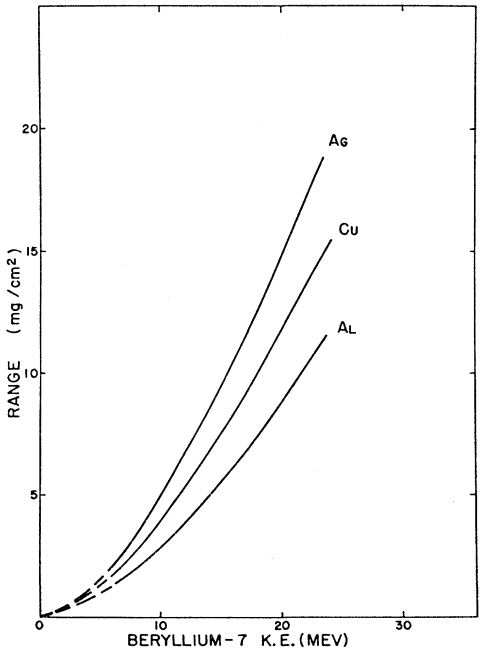

FIG. 7. Approximate range-energy curves for Be^7 particles in various elements.

The activity observed in the fifth silver 0° catcher foil indicated that a few events in the target produced particles which had energies greater than about 21.6 Mev, and were probably emitted very nearly parallel with the incident beam direction. These particles must have come from events with the isotope Mg^{25}. In view of the isotopic abundances, the majority of the Be^7 yield should come from the $Mg^{24}(\alpha,Be^7)$ reaction. The expected maximum energy ($\theta=0$) for this reaction is about 19.4 Mev. In most of the direct pickup reactions which have been observed, the energy distributions of the emitted particles show a peaking at the higher energies, in contrast to stripping reactions which show the opposite behavior.[14] The general crudeness of the catcher foil type of experiment in measuring energy spectra is almost certain to blur any fine details, and the data of Table III could not be used to ascertain whether or not an effect of this type is present. Workers at the University of Washington in a study of the $C^{12}(\alpha,Be^7)$ reaction have indicated that the energy spectrum at each angle showed no peaks.[6]

The discussion given above has indicated that the (α,Be^7) reaction in the light elements at the low energies is compound nuclear, but the possibility of a direct interaction pickup-type reaction in the heavier elements and at higher bombarding energies is not abandoned. Wilkinson's[15] discussion of the evidence from the adsorption of slow K^- mesons by complex nuclei with emission of fast $\Sigma^\pm$ hyperons that the diffuse nuclear surface is rich in nucleon clusters aids in making a pickup mechanism for the (α,Be^7) event tenable. Cohen and Rubin[14] point out that even the (p,He^4) reaction in the heavy elements follows predominantly a direct-interaction mechanism, possibly a pickup reaction resulting from a single interaction at the nuclear surface with a H^3 cluster. Indeed, the experiments which demonstrate the presence of nucleon-nucleon correlations in the nuclear surface and the theory of continually dissolving and reforming surface clusters are expected to simplify the explanation of multinucleon pickup events.

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[15] D. H. Wilkinson, Phil. Mag. **4**, 215 (1959).