Emission of Be^7 and Competition Processes at 30 to 42 MeV

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A study has been made of cross sections for the reactions $Al^{27}(p,Be^7)$ at 30 to 39 MeV; $V^{51}(p,Be^7)$ at 33 to 39 MeV; $V^{51}(He^4,Be^7)$ and $V^{51}(He,He^4He^3)$ at 40 MeV; $Co^{59}(He^4,Be^7)$ and $Co^{59}(He^4,He^4He^3)$ at 36 to 41 MeV and $Ni(He^4,Be^7)$ at 33 to 41 MeV. The cross sections for the competing modes of Be^7 and He^4+He^3 emission are found to be of the same order of magnitude in V^{51} at bombarding energies where these modes alone can compete in the emission of 7 amu. Significantly different results were obtained with the Co^{59} target where He^4+He^3 emission is favored by a factor of 6 or 7 over Be^7 emission. He-ion- and proton-induced reactions leading to the same compound nucleus with subsequent emission of Be^7 show that the (He^4,Be^7) reaction has a somewhat higher cross section at equivalent excitations of the compound nuclei. Cross sections for other He-ion-induced reactions with V^{51} and Co^{59} involving multicluster alpha emission are reported.

I. INTRODUCTION AND THEORY

THE competing reactions (x,Be^7) and (x,He^4He^3) have nearly the same threshold energy and yield the same residual nucleus. If targets are chosen such that the residual nuclei for these reactions are radioactive and detectable by radiochemical techniques, then because the complex nucleus Be^7 is radioactive and easily detected, the competition between these reactions can be studied. Angular distribution measurements of the mass-seven particles emitted in 40-MeV-proton- and He-ion-induced reactions by direct counting in a scattering chamber are not feasible because of the very low cross sections. Some angular distribution work has been done by Hower[1] on the emission of Be^7 from aluminum using catcher foils to stop the fragments, then separating beryllium radiochemically from the foils. The problem of determining competition in the analogous reactions (x,pn) and (x,d) is difficult because measurement of the two reactions using counter techniques is obviously complicated, and one does not have the convenience of two radioactive products. The emission of a radioactive complex nucleus and the competition with the emission of a pair of lighter fragments gives the experimenter a tool for a further study of the nature of a highly excited compound nucleus. This competition for the reactions $Al^{27}(He^4,Be^7)$ and $Al^{27}(He^4,He^4He^3)$ has been studied earlier.[2] The results indicated that Be^7 emission was slightly favored over the competing reaction at 38–42 MeV. We will not distinguish in the final analysis between reactions which emit Be^7 in a highly excited state unstable to decay into He^4 and He^3 fragments because the experiments are not sensitive to this mechanism. If the Be^7 nucleus has more than 4.5-MeV excitation energy, it is unstable to two-cluster decay. Theoretically, one would not expect this emission of highly excited Be^7 nuclei to be competitive with ground-state emission. To show this, we use the charged-particle emission widths obtained by Dostrovsky *et al.*[3] to find the ratio of ground state to excited state Be^7 emission

$$\frac{\Gamma(Be^7)}{\Gamma(Be^{7*})}=\frac{g\exp[2(aX)^{1/2}]\{2aX-1.5[2(aX)^{1/2}-1]\}}{g^*\exp[2(aX^*)^{1/2}]\{2aX^*-1.5[2(aX^*)^{1/2}-1]\}},$$

where a is the level density parameter, g is the number of spin states of the emitted particle and $X=E-Q-V_{\text{eff}}-\delta$. In this notation E is the maximum excitation energy of the particle, V_{eff} is the effective Coulomb barrier and δ is the appropriate pairing energy.[3] For the $Al^{27}(He^4,Be^7$ or $Be^{7*})$ reaction discussed above the ratio of the ground state to excited state (4.5-MeV) emission widths at 41-MeV bombarding energy is about 10:1. A similar calculation yields a ratio of about 1:1 for the ratio of (He^4,Be^7) to (He^4,He^4He^3) emission, assuming all particles to be emitted in their ground states.

There is another possible mechanism in addition to the double evaporation mode for the (He^4, He^4He^3) reaction which must be examined, the inelastic scattering of the He ion followed by the evaporation of a He^3 particle. However, the inelastic scattering cross sections for 40.2-MeV He ions scattered from Al, V, Cu, and other heavier elements obtained by Igo[4] show that the cross section for excitation of the target nucleus to states of high enough (>30 MeV) for He^3 emission are small. This is due to the fact that the scattered He ion must have sufficient energy to penetrate the barrier. We can expect essentially no He^3 emissions below about 30-MeV excitation because the separation energies of He^3 are on the order of 21 to 25 MeV in the light elements, and enough energy must remain for the He^3 to penetrate the

[1] C. Hower, Ph.D. thesis, University of Washington, 1962 (unpublished).
[2] R. H. Lindsay and R. J. Carr, Phys. Rev. **120**, 2168 (1960).
[3] I. Dostrovsky, Z. Fraenkel, and G. Friedlander, Phys. Rev. **116**, 683 (1959).
[4] G. Igo, Phys. Rev. **106**, 256 (1957).

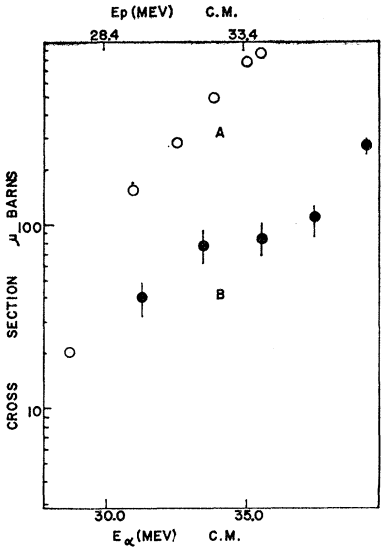

FIG. 1. Curve A for the $Mg^{24}(He^4,Be^7)$ cross sections; curve B, the $Al^{27}(p,Be^7)$ cross sections. The center-of-mass energy scales fix the level of excitation of the compound nucleus Si^{28} formed two ways.

Coulomb barrier. 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 demonstrate this concept.[3]

Using the proton beam of the University of Minnesota linear accelerator, we have extended earlier measurements[5] on the emission of Be^7 from a compound nucleus formed in two different ways, by bombardment with He ions and protons on different targets. Results are reported for the pairs of targets Al and Mg; Ti and V in Figs. 1 and 2. The compound nucleus, Si^{28}, is formed by proton bombardment of Al^{27} and by He-ion bombardment of Mg^{24}. The compound nucleus Cr^{52} is formed both in the proton-induced reaction with V^{51} and in the He-ion-induced reaction on Ti^{48}. Although the experiments were done with the natural metals instead of separated isotopes for Mg and Ti, semiquantitative conclusions can be obtained from the data, because of the high percent abundance of the desired target isotope in the natural form. The results show in each case that when the data are graphed such that equivalent energies of excitation are produced, the He-ion-induced reaction yields are higher. The net difference is great enough to indicate a failure of the independence hypothesis for formation and decay of the compound nucleus.

Measurements of other reaction cross sections involving single or multicluster emission with targets of V^{51}, Co^{59}, and Ni have been made. They include the reactions $V^{51}(He^4,2He^4)$, $V^{51}(He^4,2He^4n)$, $Co^{59}(He^4,2He^4n)$, and $Ni(He^4,Be^7)$ in the energy range 35 to 41 MeV. An analysis of the data is given in Sec. III.

[5] R. H. Lindsay and E. F. Neuzil, Phys. Rev. **127**, 1269 (1962).

II. EXPERIMENTAL PROCEDURE

The University of Washington cyclotron, the University of Minnesota linear accelerator, and the USC linear accelerator were used in the bombardment of thin foils of the target materials with He ions and protons for several hours or more. The target foils were backed by silver or gold foils to stop Be^7 nuclei which escaped from the target. The experiments measuring the (He^4,Be^7) yield in the elements above $Z=20$ are difficult to do with precision for a number of reasons. Among these are low cross sections (0 to 100 μb), the low activity of the Be^7 decay (53 day half-life), only 12% of the Be^7 decays are followed by a gamma ray at 0.48 MeV, and the presence of light element impurities (principally oxygen) in which the cross sections are some 100 to 1000 times higher at these energies. This latter problem will always tend to make the experimental cross section for Be^7 production higher than the correct value. The surface-oxide problem was minimized by using fairly thick metal foils, at the obvious loss of energy resolution. Another problem is the radiochemically pure separations required while maintaining a high chemical yield (at least 40%). The additional problem of the presence of a neutron yield producing through the (n,He^4) reaction the same product we are looking for, was found not to be negligible. The net uncertainty in the cross-section measurements is about $\pm 20\%$.

Whenever possible the cross sections were measured by two methods, an approximately 4π two crystal gamma-ray spectrometer (two crystals separated by a 1-cm gap) or 2π arrangement, and end-window geiger counters calibrated by standards obtained from the National Bureau of Standards. The two methods usually agreed to within 15% and the average value is reported.

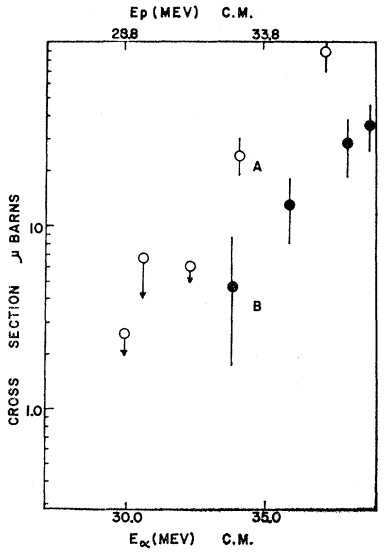

FIG. 2. Curve A for the $Ti^{48}(He^4,Be^7)$ cross sections; curve B, the $V^{51}(p,Be^7)$ cross sections. The center-of-mass energy scales fix the level of excitation of the compound nucleus Cr^{52}.

In the vanadium work, a study of the $V^{51}(He^4,Be^7)Sc^{48}$ reaction was made by observing both the Be^7 and Sc^{48}, isolated by chemical separations. A number of other scandium isotopes were noted to be present, among these were Sc^{46}, Sc^{47}, and Sc^{49}. The decay properties of these radioactive scandium isotopes made each amenable to observation except for Sc^{49}, the yield of which could not be determined because the half-life (57 min) is too short for the time delays involved in our experiments. The counting of the 44-h Sc^{48} was done using the 2π scintillation counter connected to a single-channel analyzer set to count on the 1.32-MeV photopeak following the Sc^{48} decay. Two other gamma rays are emitted in coincidence with the 1.32-MeV gamma ray, at energies of 0.99 and 1.04 MeV, and it was easy to discriminate against them. However, some photopeak counts will be removed by coincidences in the 2π counting arrangement, and, in the absence of angular correlation data, estimates have to be made of the corrections by examining coincidence in the 4π counting geometry.

Estimates of the neutron induced corrections to this data from the $V^{51}(n,He^4)Sc^{48}$ reaction were obtained by observing the Sc^{48} yield at positions in the target stack where Sc^{48} could be formed only through this reaction (10 to 30 MeV). These data showed a markedly constant neutron flux in the target stack, and an average (n,He^4) yield was subtracted from the net Sc^{48} yield at the higher energies. After the Sc^{48} decayed out (about 1 week), data were taken for the yield of the 3.4 day Sc^{47}, which was several orders of magnitude more active than the other isotopes because of the $V^{51}(He^4,2He^4)$ reaction. Samples were counted on the 0.16-MeV photopeak and also using an end-window Geiger counter. Following the decay of the Sc^{47}, the 85-day Sc^{46} was counted on the 1.12-MeV photopeak (which could easily be resolved from a coincident, 0.89-MeV gamma-ray photopeak with the 3-in.-NaI crystal assembly). Small corrections were then applied to the Sc^{47} data for the presence of Sc^{46}.

The $Co^{59}(He^4,Be^7)Mn^{56}$ experiment was done in a similar manner. Following separations of the beryllium and manganese, the samples were counted on the 2.58-h Mn^{56} gamma-ray photopeak at 0.85 MeV in the presence of a 0.84-MeV gamma ray from the decay of the 291-day Mn^{54}, which was later determined and subtracted from the Mn^{56} data. The neutron-induced reaction contribution to the Mn^{56} yield was determined by the same method as described above.

The Be samples were chemically purified by the standard method of holding back various ions that will form complex ions with EDTA in a basic NH_4OH solution which, however, precipitated the $Be(OH)_2$. In addition, various acid insoluble sulfides were precipitated and the solutions were scavenged with $Fe(OH)_3$ in $6N$ NaOH. Any residual iron was removed by solvent extraction of the $FeCl_3$ in $8N$ HCl by means of isopropyl ether. The Be was weighed and counted as the oxide. Some samples were checked for possible impurities with a 400-channel analyzer, and for possible interfering positron activity by examining coincidences at 0.511 MeV. The manganese was separated by repeated oxidation of Mn^{++} to MnO_2 in an acid solution. In addition, $Fe(OH)_3$ and insoluble acid sulfide scavengings were made. The manganese was weighed and counted as MnO_2. The scandium was separated from the vanadium in an acid medium by the repeated precipitation of vanadium by alpha-benzoinoxime. Chromium was removed by conversion of the chromium to the chromate and precipitation of the lead chromate. The Sc^{3+} was extracted into *n*-butyl phosphate in an acid medium and re-extracted into water and precipitated as the hydroxide. The usual decay data were taken to check the half-lives of the observed products.

TABLE I. Cross sections for the production of Be^7 and the residual nucleus in the He-ion bombardment of vanadium and cobalt.

Target element	Average He-ion energy (MeV)	Be^7 cross section (μb)	Residual nucleus cross section (μb)
V^{51}	40.6	6.7	
	40.8		10.9
	36.7	1.0	
	32.5	<0.2	
Co^{59}	40.5	8.5	67
	36.8	3.7	32

III. RESULTS AND DISCUSSION

The data in Table I are the cross sections for the competing reactions (x,Be^7) and (x,He^4He^3) in vanadium and cobalt. The cross sections for the $V^{51}(He^4,Be^7)$ and $V^{51}(He^4,He^4He^3)$ reactions are in the ratio of about 1.6:1 at 40.5 MeV. These data are similar to an earlier study with aluminum, in which the ratio of the Be^7 to the Na^{24} (residual nucleus) produced through the $Al^{27}(He^4,He^4He^3)Na^{24}$ mechanism ranged from about 2:1 to 1.3:1 for various investigators.[2] Hence, the emission of the heavy fragment is favored over the emission of two lighter fragments. Different results were obtained with the cobalt target. The cross section for the beryllium yield at 40.5 MeV is about 8.5 μb. The results for the product Mn^{56} yield, determined independently by beta and gamma techniques give a value of 67 ± 15 μb at the same energy. Hence we obtain a cross section for the competing reaction $Co^{59}(He^4,He^4He^3)Mn^{56}$ of 58 ± 18 μb, indicating that this mode of decay is more frequent than the emission of the single fragment by a factor of about 6.7. The difference in the results with the vanadium and cobalt targets may be a manifestation of energetics. There is about 2.75 MeV more energy available in the cobalt reaction, that is, the threshold for the $Co^{59}(He^4Be^7)$ reaction is about 2.75 MeV lower than the $V^{51}(He^4,Be^7)$. However, the Coulomb barrier for the Be^7 nuclei is approximately 2 MeV higher in the cobalt reaction. Qualitatively, then, one might expect the observed result that the (He^4,Be^7) cross sections should be of the same order in vanadium and cobalt (see Table I), but

TABLE II. Cross sections for the production of Be^7 in the He-ion bombardment of nickel.

Average He-ion energy (MeV)	Cross section (μb)
41.1	30.5
36.6	8.2
33.2	2.2

because of the sharply increasing barrier to the emission of the Be^7 nuclei one might also expect the double evaporation mode (He^4+He^3) to begin to dominate for increasing target Z. Further work must be done to establish the possible validity of this concept. From these experiments it is clear, however, that Be^7 emission is highly competitive with (He^4,He^4He^3) (two fragment emission) for the light elements, and we have no reason to suspect that the emission of Li^7 would not be highly competitive with the emission of a He ion and H^3. For that matter, the same can be said concerning the emission of 6 amu, that is, we would expect that Li^6 emission and He ion+deuteron emission would be the same order of frequency, and experiments are now contemplated to examine this concept. There are, of course, other mechanisms which can produce Li^6, Li^7, or Be^7 when the bombarding projectile is a He ion, the direct interaction multinucleon pickup reaction. At least one experiment has been done to examine the angular distribution of Li^6 particles resulting from He-ion-induced reactions in light elements at 40 MeV to single low-lying states of the residual nucles.[6] The results show marked direct interaction behavior. The experiments reported here are the summed result of the population of many levels of the residual nuclei and compound nuclear processes apparently dominate.

Figures 1 and 2 show the results of the emission of Be^7 from compound nuclei formed in two different ways. In Fig. 1, the Mg^{24}(He^4,Be^7) cross sections are compared with the Al^{27}(p,Be^7) in the center-of-mass energy range from 30 to 36 MeV. The results extend earlier work with the latter reaction up to 30 MeV.[5] In Fig. 2, the V^{51}(p,Be^7) measurements are compared with Ti(He^4,Be^7) cross sections. In each case, the same compound nucleus is formed and one would expect on the basis of the Bohr theory, that the cross sections would differ only by the difference in the cross sections for the formation of the compound nucleus, which from continuum theory and experiment are approximately equal.[3] The proton-induced cross sections are smaller than the He-ion induced, by a factor of about 5 or more, over the energy range 30 to 36 MeV. It is possible that the Bohr independence hypothesis is incorrect, and cannot be applied to this reaction. The He ion can bring into the entrance channel a large amount ($l>6$) of angular momentum at 40 MeV, and although we are graphing our data at fixed energies of excitation of the compound nucleus the average angular momentum of the compound nucleus in the He-ion-induced reactions is considerably larger than that for the proton-induced reactions. The entrance channel angular momentum will manifest itself in high rotational angular momentum of the compound system, an effect which might make the emission width for the Be^7 particle larger for the He-ion-induced reaction, since a large orbital angular momentum may be given up in the emission of the heavy fragment.

TABLE III. Cross sections for the V^{51}(He^4,$2He^4$)Sc^{47} reaction.

Average He-ion energy (MeV)	Cross section (mb)
40.8	2.97
38.3	1.85
35.6	1.34
32.8	0.56

[6] C. D. Zafiratos, Ph.D. thesis, University of Washington, 1962 (unpublished).

TABLE IV. Cross sections for the (He^4,$2He^4n$) reaction in vanadium and cobalt.

Target element	Average He-ion energy (MeV)	Cross section (mb)
V^{51}	40.8	0.61
	38.3	0.11
	35.6	0.021
Co^{59}	40.5	6.2
	36.8	1.7

The Ni(He^4,Be^7) cross sections given in Table II are somewhat larger than the vanadium and cobalt cross sections. This is due to the fact that the Q values for reactions with the more abundant nickel isotopes (Ni^{58} and Ni^{60}) are considerably lower than with V^{51} or Co^{59}. It should be noted that the previously measured copper cross sections for this same reaction are of the same order of magnitude as the vanadium and cobalt values at these energies.[2] The V^{51}(He^4,$2He^4$) reaction cross sections were studied in the energy range 32–41 MeV and the data are given in Table III. A cross section of 2.97 ± 0.50 mb was obtained at 40.8 MeV from the two methods of counting the Sc^{47} activity. The multicluster emission in this reaction can take place in either of two modes. The alpha-inelastic scattering evaporation mode cannot be neglected because the separation energy for the He ion is on the order of only 6 to 10 MeV. A rough indication of the extent of this contribution to the (He^4,$2He^4$) can be calculated from Igo's data. We may assume that there should be some 20-MeV excitation of the target nucleus if subsequent alpha emission is to be a serious competing mode. Igo's data show an approximately constant differential cross-section $d\sigma/dEd\Omega$ at angles around 24° for exciting the target nuclei Al, V, and Cu to all levels up to about 30 MeV. If one integrates the given data for excitation above 20 MeV one obtains a differential cross section $d\sigma/d\Omega$ of about 10 mb/sr for Al and

about 20 mb/sr for V and Cu, at this angle. The cross section drops sharply with angle, and the data indicate that in the backward hemisphere statistical processes dominate, but are several orders of magnitude smaller than the direct interaction processes in the forward hemisphere. Let us assume a conservative average differential cross section for direct interaction processes leading to (He^4, $He^{4\prime}$) events above 20-MeV excitation. From Igo's data, such a conservative cross section would be about 20 mb for these elements. Dostrovsky's emission widths may be used to compute the expected frequency of emission of the He ion by evaporation relative to the emission of other particles. At 30-MeV excitation, we find that about one in thirty total emissions will be an alpha particle. But $(20\text{ mb})\times(1/30)=0.67$ mb, and we see that the (He^4,$2He^4$) reaction through the inelastic scattering-evaporation mechanisms is likely to be highly competitive with the double evaporation mechanism, at 40 MeV.

The (He^4,$2He^4n$) reaction in vanadium and cobalt was investigated in the energy range from 35 to 41 MeV and the results are given in Table IV. At 40.8 MeV average He-ion energy a cross section of 0.61 mb was found for the V^{51} reaction and at 40.5 MeV a value of 6.2 mb for the Co^{59} reaction. This order of magnitude difference between the two cross sections can be explained on the basis of the Q values for the reactions being (−17.2 MeV) for Co^{59} and about −20.9 MeV for V^{51}, a difference of about 3.7 MeV. At 36.8 MeV, the Co^{59}(He^4,$2He^4n$) reaction has a cross section of 1.7 mb, a number much more comparable with the vanadium cross section at 40.8 MeV.

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Studies of Alpha Particles from the Li^6-Li^6 Nuclear Reaction*

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The reaction mechanism and the states in Be^8 in a Li^6-induced reaction $Li^6(Li^6,\alpha)Be^8 \rightarrow 3\alpha$, were studied by a double-coincidence experiment in which angles and energies of the two simultaneous alphas were recorded. The bombarding energy was 1.9 MeV. When the data are transformed to the center-of-mass system, it is shown that a mechanism in which the entire available energy is divided equally between two alphas emitted 180° apart is some 23 times more probable than one in which one of the alphas recoils from Be^8 in its ground state. There are also satellite coincidence maxima at 169° and 192°. The pattern can be interpreted as due to a cluster reaction mechanism in which Li^6 combines with a deuteron cluster to produce a state of Be^8 at 20.95±0.3 MeV which is (Li^6+d)-like. The pattern is fitted best, if a Breit-Wigner probability distribution for the excited Be^8 state is assumed, by a total width of 3.4 MeV. It is estimated that the α-decay width of this state is 260±90 keV. Such a mechanism has previously been suggested by Coste and Marquez, following ideas of Temmer. The angular distribution of the alpha group which leaves Be^8 in its ground state is nearly isotropic in the barycentric system. It seems that the reaction leading to the ground state of Be^8 proceeds through an intermediate compound nucleus, C^{12*}. The absolute total cross section for an intermediate stage involving the ground state of Be^8 is 5.8×10^{-29} cm²; for the 20.85 MeV state it is 13×10^{-28} cm².

I. INTRODUCTION

THIS work is an experimental study of the alpha particles from the nuclear reaction $Li^6(Li^6,\alpha)2\alpha$ as induced by Li^6 ions near 2.0-MeV kinetic energy. Figure 1 shows the energy spectrum of these alphas after transforming the data, taken by a conventional particle selection system, to the barycentric system. A similar result has been published by a group in Saclay, France[1] who studied the spectrum by an emulsion technique.

The most energetic and weakest group at 14.52 MeV arises from the alpha particles that leave the residual Be^8 nucleus in its ground state. The second group at 12.59 MeV corresponds to the first excited state of Be^8, namely, the 2^+ state. The main feature of the spectrum in Fig. 1 is an intense group which is located at

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[1] M. Coste and L. Marquez, Compt. Rend. **254**, 1768 (1962).