Production of Be^7 in 30–42 Mev He-Ion Bombardment of Oxygen, Aluminum, and Copper*†

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The production of Be^7 in targets of oxygen, aluminum and copper bombarded with 30- to 42-Mev He ions has been studied using radiochemical techniques. At 40-Mev He-ion bombarding energy the formation cross sections are 2.4 mb, 0.22 mb, and 0.018 mb, respectively. For aluminum and oxygen targets the Be^7 fragments are emitted sharply forward, implying a direct-interaction mechanism. Estimations of the energies of the Be^7 fragments, along with the observation that for Al^{27} target the yield of Na^{24} is equal to the yield of Be^7, suggests that in this particular case interaction involves the pickup of a He^3 fragment from the nucleus by the impinging He^4 ion with the deposition of less than 7 Mev of excitation energy in the Na^{24} residual nucleus.

I. INTRODUCTION

AMONG the very light nuclei Be^7 is one of the few which are radioactive with a conveniently long half-life. The only detectable radiation which is emitted is a 0.48-Mev γ ray, which along with its chemical properties makes it a rather easy species to identify radiochemically. The formation of Be^7 has been studied, using radiochemical techniques, in nuclear reactions induced by rather high-energy protons[1–5] ($E\sim$30–3000 Mev) and He^4 ions[1] ($E>\sim$50 Mev). Several possible mechanisms have been suggested to account for the yields of Be^7 observed at these rather high bombarding energies. These include fragmentation and evaporation mechanisms,[1,5,6] as well as the formation of Be^7 as the residuum from a spallation reaction,[2,4,5] in the case of a light element target.

In the present paper we present the results of some radiochemical measurements of Be^7 produced in light elements by bombarding with moderate energy He ions (30–42 Mev). At least for oxygen and aluminum target nuclei the results show that Be^7 was produced in some kind of direct interaction mechanism. The formation of Be^7 probably occurs through the pickup of a He^3 particle from the target nucleus by the impinging He^4 particle.

II. EXPERIMENTAL PROCEDURE

Thin foils of Al, Cu, Ag, Au, Pb, or films of CuO on Ag or Au foil, when an oxygen target was required, were bombarded for periods of several hours in the external beam of the University of Washington 60-inch cyclotron. The entire beam passed through the target foil and into an aluminum target plate to which the foil was clamped. The target plate was insulated so that the beam current incident upon it could be measured with a microammeter. In most cases, particularly for aluminum or oxygen targets, 0.001-in.-thick silver foils were used to catch Be^7 fragments which might have recoiled out of the target foil.

Following a bombardment the target was processed radiochemically[7] to recover Be^7. Frequently the target foil, and each of the catcher foils placed on either side of it, were processed separately in order to obtain information on the angular distribution of the Be^7 fragments emitted from the target. The heavy-element foils, Ag, Au, and Pb, also were bombarded separately so as to have "blanks" for those experiments where they served as catcher foils for light element targets. There was no detectable production of Be^7 from these three heavy elements.

Following the radiochemical separation procedure for Be, the sample was checked for the presence of particle radiations, which would indicate the presence of a radioactive impurity. (A β^+-emitting impurity would be particularly undesirable.) If no significant particle radiation was present, the sample was counted inside the well of a 2-inch NaI scintillation counter connected to a scintillation spectrometer. The spectrometer was first calibrated by means of the 0.51-Mev annihilation photopeak of a Na^{22} standard source, after which the spectrum of the Be sample was measured from about 0.7 Mev down to about 0.3 Mev. With a resolution of 12% for a 0.5-Mev photopeak, there would have been no difficulty in distinguishing the 0.48-Mev γ ray of Be^7 from a comparable intensity of 0.51-Mev annihilation quanta had the latter been present as a radioactive impurity. With the spectrum confirmed to

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be that expected for Be^7, the base line was set and the spectrometer window was opened so as to bracket the 0.48-Mev photopeak of the γ ray of Be^7. Pulses occurring within the window of the spectrometer were fed into a conventional scaler.

The strength of the Na^{22} standard source was determined by direct comparison with a Na^{22} standard from the National Bureau of Standards. Using the same window width as for Be^7, the base line of the spectrometer was set so as to bracket the 0.51-Mev photopeak. It was assumed that there was no difference in the detection efficiency of the scintillation spectrometer for 0.48- and 0.51-Mev γ rays. Contributions from the tail of the 1.28-Mev Compton peak to the counting rate under the 0.51-Mev photopeak were estimated to amount to 17% by interpolation between the counting rates observed on either side of the photopeak. Losses of 0.51-Mev quanta owing to coincidences with complementary 0.51-Mev annihilation quanta or with the 1.28-Mev coincident γ rays were estimated to be negligible.

As a further check on the radioactive purity of the Be samples, the activity of the samples was measured periodically for many weeks. The decrease in activity agreed very satisfactorily with the known 54-day half-life[8] in every case.

In order to try to learn more about the nature of the reaction producing Be^7 in the He-ion bombardment of Al, Na was also separated radiochemically[9] in one experiment at one particular bombarding energy in order to look for Na^{24} from the reaction $Al^{27}(He^4,Be^7)Na^{24}$. This species was indeed found; and in addition, Na^{22} was also observed. The former species was counted using a thin end-window counter and corrections were applied to the counting data for counter geometry and absorption and scattering of the radiations. The yield of Na^{22} was obtained by direct comparison in the γ-ray spectrometer with the Na^{22} standard source. The disintegration rates of all species were then corrected for chemical yield, for bombardment duration, and for radioactive decay in order to compute reaction cross sections for the species being measured. The branching ratio for the decay of Be^7 to the 0.48-Mev excited state of Li^7 was taken to be 12%.[8]

TABLE I. Yields of Be^7 from targets bombarded with various energies of He ions.

Target material	Average He-ion energy (Mev)	Cross section cm^2
CuO[a]	30.0	$<5.6\times10^{-30}$
CuO[a]	33.8	2.1×10^{-28}
CuO[a]	33.8	1.2×10^{-28}
CuO[a]	39.4	2.4×10^{-27}
Al	32.5	$<2.7\times10^{-30}$
Al	35.0	1.4×10^{-29}
Al	39.3	2.0×10^{-28}
Al	40.0	2.1×10^{-28}
Al	40.0	2.3×10^{-28}
Al	41.5	2.6×10^{-28}
Al	42.0	2.6×10^{-28}
Cu[b]	37.2	1.3×10^{-29}
Cu[b]	40.8	1.8×10^{-29}
Ag	41.0	$<1.9\times10^{-30}$
Au	41.1	$<5.2\times10^{-32}$
Pb	40.0	$<2.5\times10^{-30}$

[a] Cross sections were computed under the assumption that Be^7 came only from reactions with oxygen.
[b] See text.

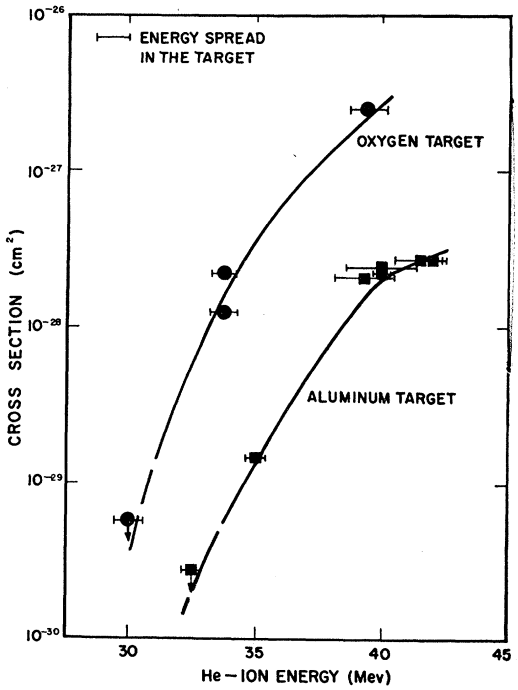

FIG. 1. Cross sections for production of Be^7 from oxygen and aluminum targets by He^4 ions of various energies.

III. EXPERIMENTAL RESULTS

Table I lists the targets which were studied and the cross sections for production of Be^7 from them. For the three heavy elements, Ag, Au, and Pb, the tabulated values of the cross sections represent generous upper limits calculated on the assumption that 10 counts/min of activity within the window of the spectrometer might have escaped detection. The activity observed from electrolytic copper target was very much less than that observed for CuO target, which demonstrates the suitability of CuO as an oxygen target material. It is possible that the Be^7 which was observed in the pure Cu target came from the activation of a trace of oxygen impurity on the surface of the Cu foil which was used. The oxide film that forms on aluminum is reported[10] to be less than 90 A thick, i.e., less than a few $\mu g/cm^2$ of oxygen. It follows from the data of Table I that this amount of oxygen impurity would give rise to a negligible amount of Be^7 from the aluminum target. The excitation functions for formation of Be^7 from Al and oxygen targets, in which its production is unambiguous, are shown in Fig. 1.

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TABLE II. Cross sections for the production of Na isotopes in 40-Mev He-ion bombardment of Al^{27}.

Nuclide observed	Cross section (cm^2)
Na^{24}	2.5×10^{-28}
Na^{22}	5.2×10^{-27}

Table II gives the cross sections for production of Na^{22} and Na^{24} in Al target by 40-Mev He ions. The cross section for production of Na^{22} is a factor of 20 larger than that of Na^{24}. The reason for this is probably that the former species is produced by the reaction $(\alpha,2\alpha n)$, a rather simple reaction with a lower threshold than the reaction which produces Na^{24} (see below).

In the case of Na^{24} it is necessary to show that this nuclide was not produced by fast neutrons in the reaction $Al^{27}(n,\alpha)Na^{24}$, which is known to proceed with a high cross section. That the Na^{24} observed in the He-ion bombardment came predominantly from a He-ion-induced reaction was shown in a separate experiment in which a stack of several Al foils was bombarded with He ions: the last foil in this stack, which received the lowest He-ion bombarding energy and presumably the highest flux of fast neutrons, showed only a relatively small amount of Na^{24}. The cross section for production of Na^{24} by He ions in Table II has been corrected for the estimated contribution from the $Al^{27}(n,\alpha)Na^{24}$ reaction.

Table III shows a breakdown of the yield of Be^7 in which forward and back Ag catcher foils were processed separately from Al and oxygen targets. In both cases the high ratio of activity caught in the front catcher foil (fragments emerging at angles between 0° and 90° to the beam direction) to the back catcher foil is to be noted. However, with such light-target nuclei as these there is a considerable amount of forward folding of the angular distribution due to center-of-mass motion. Figure 2 shows the angular distribution of Be^7 fragments to be expected for three selected cases, assuming isotropic emission of Be^7 in the center-of-mass system.

IV. DISCUSSION

An examination of the data of Table III in the light of Fig. 2 indicates quite clearly that for Al target, at least, the Be^7 fragments are not emitted isotropically in the center-of-mass system. Only if the Be^7 fragments were emitted with very low kinetic energies could the distribution be strongly anisotropic, and in that event the ranges of the Be^7 fragments would be very small and relatively few fragments would escape from the target. This is contrary to the experimental observation that a large fraction of the Be^7 fragments escape from even rather thick targets, and these must therefore have rather high energies. Even if the fragments were emitted at 90° in the center-of-mass system an appreciably smaller fraction of the fragments would be expected to escape from the target foil than is observed experimentally.

TABLE III. Distributions of Be^7 fragments in Al and oxygen targets and Ag catcher foils.

	Counts/min of Be^7 for 40-Mev He ions on 3.1-mg/cm^2 Al	Counts/min of Be^7 for 39.4-Mev He ions on 10.0-mg/cm^2 CuO
0° catcher	212	3963
Target	100	2014
180° catcher	<5	55

The absence of symmetry about 90° in the center-of-mass system implies that the mechanism of the reaction does not involve the formation of a compound nucleus. The sharply forward distribution of the Be^7 fragments is evidence for their formation in some kind of direct interaction mechanism. One can imagine several different ways for this to happen. The simplest way would be for the bombarding He^4 particle to pick up a He^3 aggregate of nucleons, possibly part of an α particle, from the nucleus as it passes through the surface layers of the nucleus. This would correspond to the $Al^{27}(He^4,Be^7)Na^{24}$ reaction. The threshold for this reaction occurs at a He-ion bombarding energy of 25.4 Mev. During the interaction it is reasonable to expect that some excitation energy would be deposited in the Na^{24} residual nucleus. If excitation energy in excess of 6.96 Mev were deposited during the interaction producing Be^7, the Na^{24} would probably lose a neutron and one would have the $Al^{27}(He^4,Be^7n)Na^{23}$ reaction. This reaction has a threshold at a He-ion bombarding energy of 33.5 Mev. A closely similar result to this one would be obtained if the incoming He ion collided with an α-particle aggregate in the nucleus and the pair of

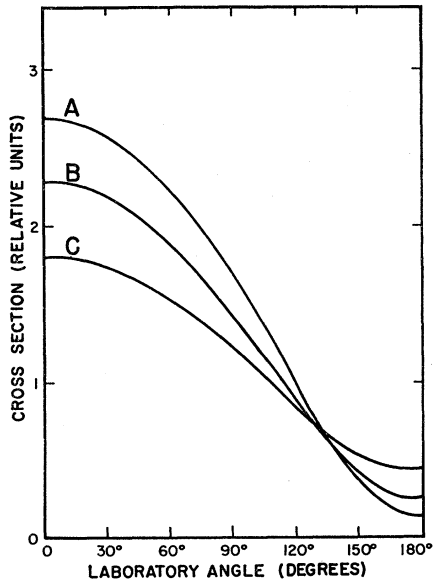

FIG. 2. Angular distributions of Be^7 fragments in the laboratory system assuming isotropic emission in the center-of-mass system for three selected cases. Curve A: O^{16} target with residual C^{13} being left in its ground state. Curve B: Al^{27} target with residual Na^{24} being left with 7 Mev of excitation energy. Curve C: Al^{27} target with residual Na^{24} being left in its ground state.

α particles came out of the nucleus in the form of a highly excited Be^8 fragment. Be^8 formed with an odd-number spin cannot decay into two α particles. If the excitation energy of the Be^8 aggregate is in excess of 19 Mev a neutron will be lost, forming Be^7. The threshold for this reaction occurs at 32.6-Mev He-ion bombarding energy.

In addition to the thresholds for the various reactions which might be responsible for the observed production of Be^7, the kinetic energies of the Be^7 fragments have to be considered. The Be^7 fragments could scarcely be expected to have kinetic energies much less than their Coulomb energy at the surface of the residual nucleus. For Al^{27} target the Be^7 fragments would be expected, on this basis, to have at least 8 Mev of kinetic energy. Addition of 8 Mev to the above-mentioned thresholds for the postulated mechanisms for producing Be^7 in Al target gives the bombarding energies below which the cross section for production of Be^7 would be expected to drop to zero very rapidly. From the effective thresholds calculated in this way it is evident that only the pickup of He^3 with deposition of less than 7 Mev of excitation energy in residual Na^{24} is to be expected for Al^{27} bombarded with 40-Mev He ions. This is in agreement with the observation that the yields of Na^{24} and of Be^7 are the same, within 12%, for Al^{27} bombarded with 40-Mev He ions. The reaction proceeding according to the pickup mechanism would be expected to show a strong drop in cross section below about 33 Mev, the bombarding energy at which about 8-Mev Be^7 fragments would be emitted leaving Na^{24} in its ground state. The excitation function for production of Be^7 in Al target, shown in Fig. 1, would seem also to be in agreement with the pickup mechanism.

The data of Table III can be analyzed to give information on the approximate energies of the Be^7 fragments by providing approximate estimates of their ranges. Experimental observations indicate that the fragments are emitted strongly in the forward direction. If to a first approximation it is assumed that the fragments are all emitted at 0° to the beam, then the average range of the fragments in the target material is the same fraction of the target thickness as the fraction of all the fragments which escape from the target. If some of the fragments are emitted at oblique angles as well, which would seem very likely, then the average range of the fragments will be underestimated. By making reasonable assumptions about the range-energy relations of Be^7 in various materials the average fragment kinetic energies or a lower limit thereto, may be computed.

This was done for the data of Table III on the assumption that all fragments are emitted at 0°. The range of a Be^7 fragment of energy E was assumed, to a first approximation, to be $\frac{7}{16}$ that of a He^4 ion of energy $(4/7)E$. This approximation is probably good for Be^7 fragments of energies greater than about 2 Mev. The resulting lower limits for the average fragment kinetic energies were 8.2 Mev for the aluminum target and about 9 Mev for the oxygen target.

Provided the sensitivity of the experiment could be increased somewhat so that thinner targets could be used, it would be interesting to look at the energy distribution and angular distribution of the Be^7 fragments in greater detail. Particularly intriguing is the possibility of studying a target element which gives a residual nucleus having widely spaced levels near the ground state, so that the Be^7 fragments which leave these levels populated might be distinguishable from lower energy Be^7 fragments. From such a study one might hope to learn more about the pickup mechanism leading to the production of Be^7.

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APPENDIX: RADIOCHEMICAL PROCEDURE FOR BERYLLIUM

The target foil, or catcher foil, is dissolved in acid and 10 mg of beryllium carrier is added. Hold-back carriers for Cu, Zn, Cd, In, Au, Hg, and Tl are added where silver catcher foils are used. (The presence of copper and gold impurities in the silver foil which was used gave rise to troublesome radioactive impurities which could be eliminated by the use of the hold-back carriers.) The acid solution is diluted with water, saturated with H_2S, and the precipitated sulfides are centrifuged and discarded. The supernatant solution is then made basic with NH_4OH, precipitating $Be(OH)_2$ and more sulfides. After centrifuging the precipitate and discarding the solution, the $Be(OH)_2$ is dissolved away from the sulfides by treatment with NaOH. After centrifuging and discarding the sulfide precipitate, the solution containing beryllium is then acidified and 5 ml of 10% versene solution is added. Beryllium is then precipitated with NH_4OH. [Versene complexes most other metal ions except beryllium, and three or four precipitations of $Be(OH)_2$ with NH_4OH in the presence of versene gave a radiochemically pure product.] The final precipitate of $Be(OH)_2$, contained in a lusteroid centrifuge tube, is dissolved in a small amount of 12N HCl, 1 ml of 48% HF is added, and the solution is diluted to 25 ml with water. After heating on a water bath excess Ba^{++} is added to precipitate $BaBeF_4$, isomorphous with $BaSO_4$. The precipitate is centrifuged and the aqueous phase discarded. The precipitate is taken up in a little water and filtered through a Millipore RA filter. After washing, drying, and weighing, the sample is mounted for counting.