Formation of Be^7 in Interactions of Various Nuclei with High-Energy Protons*

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Cross sections are reported for the formation of Be^7 in interactions of C, Al, Cu, Ag, and Au with protons of energies between 1 and 3 Bev. They are compared with previous data at 0.34-Bev proton energy. The carbon cross section is strikingly constant at 11 to 14 mb from 0.1 to 3.0 Bev. The other cross sections rise with increasing proton energy and are all in the neighborhood of 10 mb at 3 Bev. Beryllium-7 may be considered as a spallation residue from carbon, and the same mechanism probably accounts for at least a large part of its formation from Al. However, Monte Carlo calculations show that this mechanism predicts much too low cross sections from the higher Z targets. Other mechanisms must be invoked, the most promising being the evaporation of Be^7 nuclei discussed in the following paper.

INTRODUCTION

THE production of lithium and beryllium nuclei in high-energy nuclear reactions has been investigated by various methods at energies up to cosmic-ray energies.[1–6] The rapid decay of Li^8 to Be^8 which then decays immediately into two α particles requires the use of nuclear emulsion or coincidence counting techniques for the determination of Li^8 formation cross sections. Formation of Be^7, which has a 53-day half-life, may be studied by usual radiochemical techniques. Marquez and Perlman[1] have determined the formation cross sections of Be^7 from a number of targets bombarded with 335-Mev protons. They conclude on the basis of these results and of indirect evidence for formation of Li^8 nuclei with energies >40 Mev, that these light nuclei must be considered as ejected fragments rather than spallation residues when formed in the irradiation of targets such as copper, silver, and gold with 335-Mev protons.

In the investigation of copper[5] and aluminum[6] spallation reactions induced by 2.2-Bev protons, it was again noted that the formation cross sections for Be^7 were higher than would be expected if Be^7 were a spallation residue. In copper interactions with 2.2-Bev protons, for example, the yield of Be^7 is higher than that of any other nuclide investigated in the range $10<A<40$. Furthermore, the cross sections for Be^7 formation from aluminum and copper were found to be higher at 2.2 Bev than at 335-Mev by factors of about 8 and 20, respectively. The present investigation was undertaken to obtain additional data on Be^7 formation in irradiations of various elements with protons of kinetic energies between 1 and 3 Bev, and thus perhaps to shed some light on possible mechanisms for the production of light fragments in these interactions.

TARGETS AND IRRADIATIONS

Pure foils of polystyrene (166 mg/cm²), aluminum (21 mg/cm²), copper (46 mg/cm²), silver (138 mg/cm²), and gold (166 mg/cm²) were irradiated with 1.0 to 3.0-Bev protons in the circulating beam of the Cosmotron. Targets were prepared as shown in Fig. 1. Recoil loss of Be^7 and cross contamination of one target foil with Be^7 produced in another were minimized by the thickness of the target foils, the use of guard foils, and the arrangement of the foils with respect to the proton beam. Details of the irradiation procedure have been described previously.[6] Irradiations of two to five hours' duration at beam intensities between 10^9 and 10^{10} protons/sec yielded Be^7 samples with sufficiently high counting rates for positive identification and measurement.

Absolute cross sections were based on a value of 10.7 ± 0.6 mb for the $Al^{27}(p,3pn)Na^{24}$ monitor reaction between 0.4 and 3.0 Bev.[7] Since Na^{24} can also be made in high yield by the (n,α) reaction on aluminum, secondary neutron production in thick targets leads to erroneously high Na^{24} yields in the aluminum monitors. In the actual target stacks used, this secondary effect was shown to raise the Na^{24} yields by about 20% at any energy between 1 and 3 Bev, and the observed Na^{24} cross sections were corrected accordingly. The measurements of this secondary effect were based on the use of another monitoring reaction which is not sensitive to low-energy secondaries. This is the production of 4.1-hour Tb^{149} from gold which has a thresh-

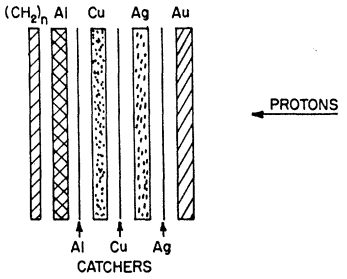

FIG. 1. Arrangement of target stack.

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[5] Friedlander, Miller, Wolfgang, Hudis, and Baker, Phys. Rev. **94**, 727 (1954).
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old of 600 Mev.[8] About 2 hours after irradiation, the Tb^{149} α activity can be measured in unseparated gold targets without interference from other activities and thus provides a convenient relative monitor for primary high-energy protons. A measurement of the ratio of Na^{24} activity in aluminum to Tb^{149} activity in gold in a target similar to that shown in Fig. 1, but with an additional 0.0005-in. gold foil on the upstream side of the stack served to measure the secondary contribution to the Na^{24} production, when this ratio was compared with a similar ratio determined in a target consisting only of a 0.0005-in. gold foil and a 0.003-in. aluminum foil.

SEPARATION AND MEASUREMENTS

No chemical separation of beryllium was necessary from the polystyrene foils since only Be^7 activity was discernible in the foils after the decay of the 20-min C^{11} activity.

The only interfering activity in the aluminum targets was Na^{22}. A procedure was developed to measure the intensity of the 480-kev gamma ray of Be^7 in the presence of the 510-kev annihilation γ rays of Na^{22} by γ-ray spectroscopy. The relative intensities of the 0.51-Mev and 1.28-Mev γ rays of Na^{22} were measured with a Na^{22} standard. On the basis of the 1.28-Mev peak observed in the γ spectrum of the aluminum target foil, it was then possible to subtract the contribution of Na^{22} annihilation radiation from the combined 480–510-kev peak of the complex spectrum to yield the 480-kev photopeak of Be^7. When a chemically pure beryllium fraction was desired, beryllium and aluminum were separated from sodium by precipitation of beryllium and aluminum hydroxides with ammonia. The bulk of the aluminum was than precipitated as $AlCl_3 \cdot 6H_2O$ by the addition of ether and HCl (gas). Beryllium was then purified by the extraction of basic beryllium acetate with chloroform.

To separate beryllium from copper, silver, and gold targets the targets were dissolved in the appropriate acid and $Be(OH)_2$ was precipitated a number of times with ammonia. The final precipitate was dissolved in concentrated hydrochloric acid and the solution was passed through a Dowex A-1 ion exchange column. A ferric hydroxide scavenging precipitation with NaOH, followed by an acetylacetone extraction of the beryllium ethylene diammine tetraacetic acid complex at pH 4–5 completed the separation. All chemically separated beryllium samples were finally converted to BeO which was weighed to determine the chemical yield of the purification steps. The BeO was used for the activity measurements.

The only readily detectable radiation of Be^7 is a 0.48-Mev gamma ray emitted in 11% of all Be^7 disintegrations.[9] Thus absence of β radiation and decay of the γ rays with a 53-day half-life were used as criteria for the radiochemical purity of the samples. Scintillation counters employing NaI(Tl) crystals were used to detect the γ radiation. When sufficient Be^7 activity was present, a gamma-ray spectrometer was used to check the purity of the γ radiation. Even when the initial counting rate was too low for the detection of possible contaminating γ rays at other energies, the scintillation counter was used in conjunction with a dual discriminator set to count only pulses in the region of the 0.48-Mev photopeak. This method not only discriminated against possible contaminants, but also appreciably increased the ratio of counting rate to background over that achieved without pulse-height analysis. The detection efficiencies of the scintillation counters for 0.48-Mev γ rays were measured by means of a Na^{22} source of known disintegration rate. The small difference in photopeak efficiencies for 0.51-Mev and 0.48-Mev γ rays was neglected.

RESULTS AND DISCUSSION

The counting rates of the beryllium samples, corrected for decay, chemical yield, counter efficiency, and the 11% abundance of the 0.48-Mev gamma ray, were converted to Be^7 disintegration rates at end of bombardment. These disintegration rates, together with the Na^{24} disintegration rates in the aluminum monitors, yielded the formation cross sections of Be^7. The results are listed in Table I, together with the data of Marquez and Perlman[1] at 0.34 Bev. The cross sections determined in the present work are estimated to be accurate to $\pm 25\%$. In the few instances where duplicate determinations were made, the agreement obtained tends to corroborate this estimate.

The data of Table I show several striking features. The cross section for Be^7 formation from carbon is remarkably constant over the entire energy range. Dickson and Randle[10] have investigated this process at lower energies and found that it has a threshold at 32 Mev and that its cross section levels off at about 14 mb

TABLE I. Formation cross sections (in mb) of Be^7.

Target	Proton energy (Bev) 0.34[a]	1.0	1.4	1.8	2.2	3.0
C	12	10.6		11.5	10.8	11.1
Al	1.4	7.6[b]	8.3[b]		12.6[b], 9.1[b]	11.7[b]
Cu	0.6	5.0, 3.7			9.2, 13.0, 13.0[c]	11.9
Ag	0.1	2.9, 2.2			11.3	12.1
Au	0.01	1.7, 1.0			5.9	8.4

[a] Data of Marquez and Perlman, reference 1.
[b] Previously reported in reference 6, but recalculated with the revised values (reference 7) of the Al(p,3pn) monitor cross section.
[c] Previously reported in reference 5, but recalculated with the revised value (reference 7) of the Al(p,3pn) monitor cross section.

[8] R. B. Duffield and G. Friedlander, data reported in Brookhaven National Laboratory Report BNL-303, July 1, 1954 (unpublished), p. 27.

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in the energy range from 100 to 140 Mev. This reaction which can probably be interpreted largely as a $C^{12}(p,3p3n)$ or a $C^{12}(p,\alpha pn)$ process with Be^7 as a residue, thus furnishes another example of the relatively simple light-element reactions with cross sections which are almost energy independent in the range from a few hundred to a few thousand Mev. Other such proton-induced reactions reported earlier are the formation of C^{11} from carbon,[7,11] of F^{18} from fluorine,[12] of F^{18} from aluminum,[6] and of Na^{24} from aluminum.[6,7] It appears that this energy independence is a rather general phenomenon which to date has not been adequately explained in terms of any model.

Turning attention to the target elements other than carbon, one sees that in all these cases the cross sections for Be^7 formation increase with increasing proton energy. However, the magnitude of this increase is very different for the different target elements. Whereas, at 0.34-Bev bombarding energy, the cross section was found to drop rapidly with increasing Z of the target (by a factor of 10^2 from Al to Au), at 3 Bev all the cross sections are nearly equal to each other, and equal to the carbon cross section.

As discussed before,[6] the formation of Be^7 from aluminum is likely to result, at least in part, from processes in which Be^7 is the residue of cascade and evaporation steps. Such a spallation reaction would require, on the average, the deposition of about 200 to 300 Mev of excitation energy in the aluminum nucleus, or rather in the end product of the fast cascade, and such deposition energies are quite probable at Bev bombarding energies, as indicated by recent Monte Carlo calculations.[13] The results of these calculations, for the interaction of Al^{27} with 1.84-Bev protons, when taken together with an estimate of 17 Mev for the average de-excitation per mass number in the evaporation process, lead to a cross section of 12 mb for the production of nuclei of $A=7$. It is not unreasonable to assign about half of this cross section or 6 mb to Be^7. A similar analysis for 0.46-Bev protons incident on Al^{27} leads to a predicted cross section of <0.3 mb for formation of Be^7 as a spallation residue. In view of the very approximate nature of the calculations one can conclude only that this mechanism probably contributes significantly to the formation of Be^7 from aluminum, but it is not clear whether it can account for the entire cross section.

In the cases of copper, silver, and gold it is quite clear that a spallation mechanism with Be^7 as residual nucleus cannot account for the observed cross sections. This can again be seen by comparison of the experimental data with the Monte Carlo cascade calculations.[13] The calculated mass-yield curve for the products resulting from interactions of copper with 2-Bev protons agrees reasonably well with experimental data for products of $A>20$, but is at least an order of magnitude too low at mass 7. At lower bombarding energies, and from heavier target nuclei, Be^7 is of course even less likely to result as a spallation residue.

Other mechanisms must thus be invoked for the formation of Be^7 from heavy nuclei, as was already suggested by Marquez and Perlman.[1] One possibility is the fragmentation mechanism proposed[14,15] to account for the production of other light nuclei from heavy-element targets. Another possible mechanism, suggested by J. M. Miller, is the direct evaporation of Be^7 nuclei, in competition with evaporation of neutrons, protons, helium nuclei, etc., from excited nuclei. Evaporation calculations which are reported in the following paper[16] have shown that this mechanism can, indeed, account for the approximate magnitudes of the cross sections as well as for the shapes of the excitation functions for Be^7 production from copper, silver, and gold in the energy range studied.

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