(p,Be^7) Reaction in Al and Mg from 27 to 31.5 MeV

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A study has been made of the cross sections for the $Al^{27}(p,Be^7)$ and the $Mg(p,Be^7)$ reactions in the energy range 27 to 31.5 MeV. The $Al^{27}(p,Be^7)$ data are contrasted with the known $Mg^{24}(He^4,Be^7)$ reaction cross sections using 30- to 42-MeV He ions, both of which lead to the same compound nucleus. It is seen that the reactions proceed chiefly by a compound nuclear mechanism in this energy range. A three-nucleon transfer direct-interaction mechanism is a possible contributor to the He-ion-induced reaction.

I. INTRODUCTION AND THEORY

COMPOUND nuclear processes have been shown to be important in the emission of complex nuclei such as Be^7, Li^7, Li^6, etc., at high excitation energies.[1–3] Using light element targets (C, N, O, F, Ne, Mg, Al, etc.), the (He^4,Be^7) reaction has been extensively studied at 30 to 42 MeV.[4–6] The Be^7 center-of-mass energy distributions look like evaporation spectra, and the angular distributions of the Be^7 nuclei are approximately symmetrical about 90° in the center-of-mass system.[6] Chiefly because of low cross sections and the very thin targets required, angular distribution measurements of the mass-seven particles emitted in He-ion-induced reactions which would be sensitive to the states of the residual nucleus have not been attempted with success. It is expected that a direct-interaction mechanism would be important in the (He^4,Li^7) or (He^4,Be^7) reactions leading to low-lying levels of the final nucleus. Slightly higher forward than backward Be^7 yields for the $Al^{27}(He^4,Be^7)$ reaction from measurements which are not sensitive to the final state but to the spectrum of states of Na^{24} below about 10-Mev excitation suggest small contributions from direct interaction mechanisms to the total yield.[6] Recent experiments at the University of Washington with the Li^6 angular distributions from the (He^4,Li^6) reaction at 40 MeV using various light-element targets show marked direct-interaction behavior for reactions leading to low-lying states, a manifestation of a two-nucleon pickup reaction with the He ion.[7]

The most important single factor controlling the cross sections for the emission of complex nuclei at these energies (30- to 60-MeV excitation energy of the compound nucleus) is the Coulomb barrier, suppressing the low-energy evaporation spectra. The classical barrier height varies, for example, from 8.2 MeV for the $Mg^{24}(He^4,Be^7)Ne^{21}$ reaction to about 17.8 MeV for the $Cu^{63}(He^4,Be^7)Co^{60}$ reaction. If one looks at the measured cross sections at 40-MeV He-ion bombarding energy for all the targets studied, a rapid decrease with increasing atomic number for $Z>11$ is noted. The Q values do not change markedly with increasing Z for the stable isotopes, varying approximately ± 3 MeV from an average value over the range which has been investigated.

In order to investigate concepts in reactions involving emission of complex nuclei at energies slightly above threshold it was suggested that other projectiles be employed. From energy considerations, 30-MeV protons would be useful in the investigation of the (p,Be^7) reaction in light nuclei. Cohen[8] investigated the reason why complex particles were emitted in nuclear reactions nearly as frequently as nucleons (if one makes corrections for Coulomb barrier penetration and energetics). It was shown that the difference between cluster evaporation by nuclei and the (never occurring) cluster evaporation by water droplets is accounted for by quantum statistics calculations for each system. Ignoring barrier considerations and energetics, the relative probability for the emission of a cluster of seven nucleons p_7 and a single nucleon p_1 are in ratio as the densities of states available to the reaction partners after the evaporation has occurred.[8] If W represents the density of available states, we have

$$p_7/p_1=W(7)/W(1). \quad (1)$$

Li^7 and Be^7 each have one bound excited state, at 0.477 MeV and 0.430 MeV, respectively. This may be approximately accounted for by considering a particle in its excited state as a discrete evaporating entity. The density of states, $W(7)$, may be written as $W(7)=W_{g.s.}(7)+W_{e.s.}(7)$. The spin of the ground state of

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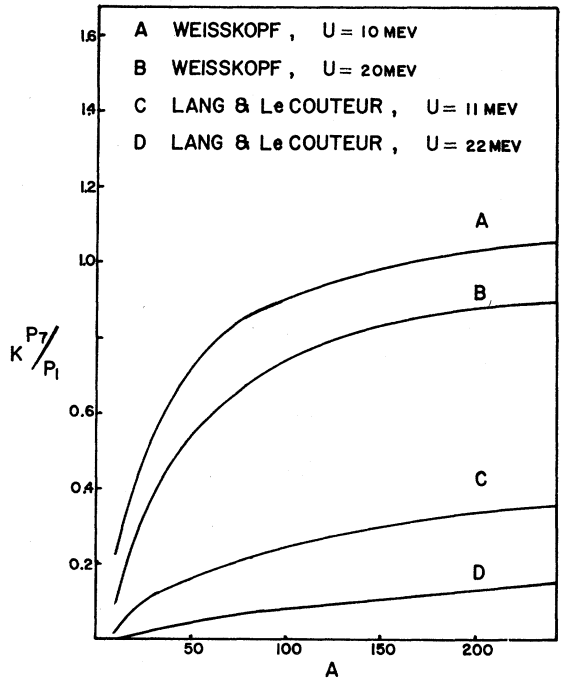

FIG. 1. The ratio of the probability for the emission of a mass-seven nucleus to the probability of the emission of a single nucleon (the constant k is of order 0.2), as a function of the mass number A and the excitation energy U of the residual nuclei. Two different level density expressions are used. These curves are illustrations of what is to be expected from quantum statistical considerations only.

Be^7 and Li^7 is 3/2, and 1/2 for the first excited states. The number of spin states are $(2J+1)=4$ for the ground states and 2 for the excited states. Therefore a statistical weight of 2:1 for ground state to excited state emission is assumed as a first approximation. If we take the variation of nuclear level density with excitation energy to be

$$w(E)=C\exp[2(aE)^{\frac{1}{2}}], \tag{2}$$

where $a=A/20$, we find

$$p_7/p_1=1.5k^{-1}\exp\left[\left(\frac{A-6}{5}E\right)^{\frac{1}{2}}-\left(\frac{A}{5}E\right)^{\frac{1}{2}}\right], \tag{3}$$

where k^{-1} is the ratio of the momentum space degeneracies of the outgoing particles times a factor of 2 introduced to take account of the spin degeneracy of the nucleons.[8] Figure 1 illustrates the variation of the ratio of emission probabilities (kp_7/p_1) with mass number A and with excitation energy of the residual nuclei. The Lang and LeCouteur expression for the level density is also used to compute the ratio.[9] It is seen that for increasing A the result of considering the nucleus as a highly degenerate Fermi gas leads to larger values of p_7/p_1 for all A. Since k^{-1} is of order 5 (see reference 8), the curves show what is to be expected from quantum statistical considerations only, that when comparing the emission probabilities from compound nuclei into states available to each decay mode the clusters of nucleons would be emitted approximately as frequently as nucleons.

II. EXPERIMENTAL PROCEDURE

Thin foils of aluminum and magnesium were bombarded in the 31.5-MeV proton beam of the University of Southern California linear accelerator. About 1 μA-h exposure was necessary in order to conveniently investigate the Be^7 production in this energy range. Beryllium nuclei which had enough kinetic energy to penetrate out of the target foils were stopped in silver catcher foils inserted between targets. From the reaction energetics, no yield from the (p,Be^7) reaction in silver was expected at these bombarding energies because barrier penetrabilities would be very small for the Be^7 nuclei.

Standard procedures were used to chemically separate out the beryllium and the radiochemical purity of the final precipitates were checked with a pulse height analyzer.[5] All absolute counting was done using a 4π scintillation spectrometer set to accept photopeak counts on the 0.477-MeV gamma ray emitted following the Be^7 decay. The spectrometer was calibrated with standard gamma sources obtained from the National Bureau of Standards. The uncertainties in the absolute cross sections result primarily from counting statistics and the spectrometer calibration procedure, with com-

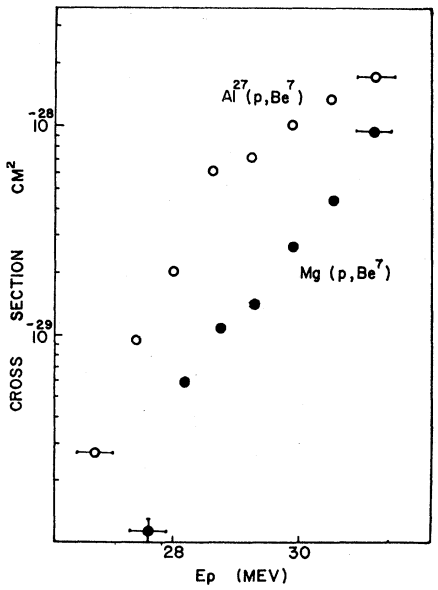

FIG. 2. Excitation functions for the (p,Be^7) reaction in aluminum and magnesium at laboratory energies 27 to 31.2 MeV.

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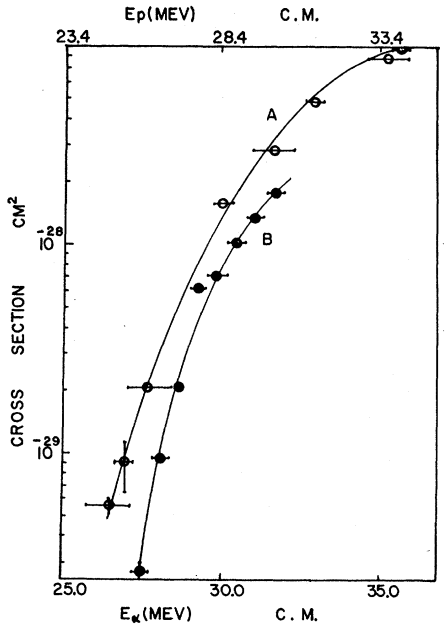

FIG. 3. Curve A: The Mg(He^4,Be^7) reaction cross sections at He-ion energies 26 to 36 MeV. Curve B: The Al^{27}(p,Be^7) reaction cross sections at proton energies 25 to 30 MeV. All energies are in the center-of-mass reference system. The same compound nucleus is formed in each reaction (see text) at equal excitation energies when $E_\alpha = E_p + 1.6$ MeV.

paratively small uncertainties in chemical yields, beam energies, total beam measurements, and radioactive decay information.[10] The net uncertainty in the various measurements increased, of course, at lower energies, but is estimated to be less than 20%.

III. RESULTS AND DISCUSSION

The excitation functions for the (p,Be^7) reaction in aluminum and magnesium are given in Fig. 2. As is usually the case in working with bombarding energies slightly above threshold, the cross sections are obtained from data taken under conditions of very low count rates and are observed to increase rapidly. Cross sections at 31.2-MeV average proton energy were measured to be 1.74×10^{-28} cm^2 for the Al^{27}(p,Be^7) reaction and 9.43×10^{-29} cm^2 for the (p,Be^7) reaction using a natural magnesium target. Natural magnesium consists of about 79% Mg^{24} and approximately 10% each of Mg^{25} and Mg^{26}. Since the Mg^{24}(p,Be^7) reaction has a Q value which is about 3.1 MeV higher than the Mg^{25}(p,Be^7), the lower energy magnesium data (<29 MeV) would be expected to be principally from the latter reaction. Above 30 MeV the reaction with the more abundant Mg^{24} isotope begins to dominate rapidly, an effect noticeable in the data.

In Fig. 3, the Al^{27}(p,Be^7) data is contrasted with the previously measured Mg(He^4,Be^7) cross sections using 30- to 42-MeV He ions. The (He^4,Be^7) reaction is known to be principally of compound nuclear origin in Mg and other light elements when sufficient energy is available to populate states of the residual nucleus up to 7- or 8-MeV excitation.[5,6] It should be noted that one can roughly estimate the relative magnitudes of the cross sections for the isotopes of the very light elements by counting available states into which the reaction may proceed. Such an analysis proves fruitful in explaining the difference in the absolute magnitudes of the Be^7 cross sections for the He-ion-induced reactions in N, O, F, and Ne at 32 to 42 MeV, where barrier considerations alone cannot account for the differences.[6] Thus, consider the residual nuclei Ne^{21}, Ne^{22}, and Ne^{23} from the (He^4,Be^7) reaction in the respective magnesium isotopes. Ne^{21} has about 9 levels below 7 MeV, Ne^{22} and Ne^{23} have considerably less than this total.[11] We expect, therefore, that the Mg^{24} (He^4,Be^7) cross sections should be nearly the same as the Mg(He^4,Be^7) cross sections from level density considerations and because of the approximately 8 to 1 isotopic abundance of the Mg^{24} isotope.

The same compound nucleus Si^{28} is formed in the proton induced reaction on Al^{27} and in the He-ion-induced reaction on Mg^{24}. We would expect on the basis of the Bohr assumption, Eq. (4) below, that the cross sections would differ only by the difference in the cross section σ_c for formation of the compound nucleus when compared at center-of-mass energies $E_\alpha = E_p + 1.6$ MeV. The same excitation in the compound nucleus is then produced because of the masses of the reactants Al^{27}+p and Mg^{24}+He^4 differing by about 1.6 MeV. Using the method of Dostrovsky *et al.*[12] for computing the charged-particle capture cross sections of the reactants, we find at $E_p = 30$ MeV and $E_\alpha = 31.6$ MeV capture cross sections of 85.6×10^{-26} cm^2 and 55.7×10^{-26} cm^2, respectively. Using Weisskopf's method, we find 78.9×10^{-26} cm^2 for $E_p = 30$ MeV and 90.2×10^{-26} cm^2 for $E_\alpha = 31.6$ MeV.[13] Noting the discrepancy, we may assume the capture cross sections to be approximately equal. The data in Fig. 3 show the (He^4,Be^7) reaction to be larger than the (p,Be^7) reaction by about a factor of 2 in the measured energy range. We contemplate no direct interaction mechanisms contributing to the (p,Be^7) yield, therefore the difference in the absolute cross sections is due to three possible factors. It is clear that the experimental conditions are not ideal since we have more than one isotope in the magnesium target. Approximately 10 to 20% of the magnesium cross sections observed could be attributed to reactions with Mg^{25} and Mg^{26}. A direct interaction–three-nucleon pickup mechanism leading to the low-

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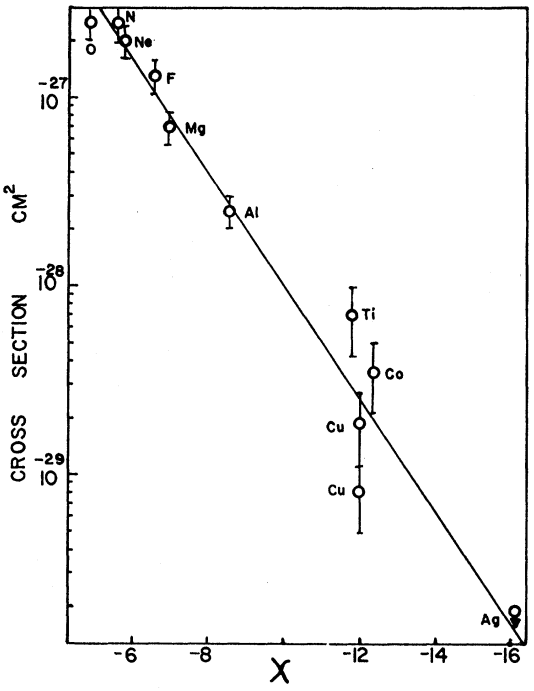

FIG. 4. Experimental cross sections for the (He^4,Be^7) reaction in N, O, F, Ne, Mg, Al, Ti, Co, Cu, and Ag at 40 MeV. A straight line should result when the data is plotted against the parameter χ (see text) according to the statistical model. The two copper measurements are from different investigators and the silver cross section represents an upper limit at 41 MeV.[4-6]

lying levels of Ne^{21} may account for some of the Be^7 yield. Thirdly, a charged-particle capture cross section which is somewhat larger for incident He ions on Mg^{24} than protons on Al^{27} is possible. All of these factors suggest that the Mg^{24}(He^4,Be^7) cross sections are lower at these energies than that given in Fig. 3, bringing the two curves into closer agreement. These data are considered to be a good proof of the validity of the Bohr assumption in the emission of complex nuclei.

It is interesting to compare the measured (He^4,Be^7) cross sections at 40 MeV with calculations from the statistical model. As is well known, the cross section for single particle emission from the statistical model is given by

$$\sigma(\mathrm{He}^4,x)=\sigma_c(\mathrm{He}^4)f_x/\textstyle\sum_j F_j, \qquad (4)$$

where σ_c is the cross section for formation of the compound nucleus by an alpha particle, f_x is the emission function for particle x over a particular energy interval, and F_j is the emission function for particle j over the total energy interval. The emission functions may be taken as

$$f_x \text{ or } F_x=2M_x(2J_x+1)\int_{E_x\min}^{E_x\max} E_x\sigma_{cx}(E_x)W(E_x)dE_x, \qquad (5)$$

where M_x and E_x are the reduced mass and kinetic energy in the center-of-mass system and J_x is the spin of particle x. $\sigma_{cx}(E_x)$ is the inverse cross section for formation of the compound nucleus by particle x with energy E_x and $W(E_x)$ is the level density of the residual nucleus taken as Eq. (2). The use of the empirical equations suggested by Dostrovsky *et al.*[12] for the inverse cross sections leads to a closed form for f_x

$$f_x \text{ or } F_x=\frac{2M_x(2J_x+1)}{8a^2}(\pi R_f^2)(1+C_x)$$
$$\times[\exp(\gamma-4aE_x)^{\frac{1}{2}}]$$
$$\times\{(4aK_xB_f+6-\gamma)[(\gamma-4aE_x)^{\frac{1}{2}}-1]$$
$$+(\gamma-4aE_x)^{\frac{3}{2}}-3(\gamma-4aE_x)\}\cdots, \qquad (6)$$

where the upper limit is $E_x=E^*-S_x$ and the lower limit is K_xB_f. In Eq. (6) we have placed $\gamma=4a(E^*-S_x)$, where a is the level density parameter taken to be $A/20$. S_x is the separation energy of x, E^* is the highest channel energy in any outgoing channel of an X(He^4,x)Y reaction, corresponding to leaving the residual nucleus Y in its ground state. R_f is the channel radius for the final reaction partners, C_x and K_x are Dostrovsky parameters.[12] For Be^7 emission we have used $K_x=0.7$.

If we assume the cross section for the formation of the compound nucleus is given by $\sigma_c(\mathrm{He}^4)=\pi R_i^2\times(1-KB_i/E)$, where R_i is the channel radius for the initial reaction partners, and KB_i is the effective barrier for the incoming He ions, and for this calculation consider only neutron evaporation in competition with Be^7, we obtain

$$\sigma(\mathrm{He}^4,\mathrm{Be}^7)=\frac{\exp[A(E^*-S_x-K_xB_f)/5]^{\frac{1}{2}}}{\exp[(A+6)(E^*-S_n)/5]^{\frac{1}{2}}}G, \qquad (7)$$

where G contains all the other factors in Eq. (4) using the emission functions in Eq. (6) after insertion of the given limits. The exponentials in Eq. (7) are the most rapidly varying part of the expression. Taking logarithms of Eq. (7), we have

$$\log_{10}\sigma\propto[A(E^*-S_x-K_xB_f)/5]^{\frac{1}{2}}$$
$$-[(A+6)(E^*-S_n)/5]^{\frac{1}{2}}+\log_e G. \qquad (8)$$

If we denote the right-hand side of Eq. (8) by χ and plot the logarithms of the observed cross sections vs χ, we should obtain a straight line if the assumptions from the statistical model leading to Eq. (6) are correct. The (He^4,Be^7) data at 40 MeV are compared with Eq. (8) in Fig. 4 for natural N, O, F, Ne, Mg, Al, Ti, Co, Cu, and Ag targets. Some of the targets have more than one isotope which may contribute substantially to the cross section. The calculations from Eq. (8) have been weighted according to percent abundance of the isotope for Cu, Ag, and Ti. Figure 4 shows that the evaporation theory gives a fairly straight line for the light elements and a considerable departure from this line for Co and

Ti targets, which could be due principally to uncertainties in the cross section measurements. Errors in the cross-section measurements for the light element targets are less than 20%, but for Ti, Co, and Cu could be as high as 40%. Small amounts of light element impurities in these targets are possible, a problem particularly unavoidable in the metallurgical processing of Ti, and the surface oxide also contributes to the total Be^7 yield from the O^{16}(He^4,Be^7) reaction.

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Photoneutron Cross-Section Measurements on Gold Using nearly Monochromatic Photons*

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Continuously variable monochromatic gamma rays with an energy spread of 3% have been produced using the annihilation in flight of positrons accelerated in a linear electron accelerator. These gamma rays have been employed to measure the (γ,n) and (γ,2n) cross sections for gold. A neutron counting method was used to determine the neutron multiplicity. The photoneutron yield for Au has a maximum of 535±37 mb at 13.7±0.3 MeV. The (γ,2n) cross section was observed to have a threshold at 14.5±0.5 MeV and a maximum of approximately 100 mb at 18 MeV. The integrated (γ,n) and (γ,2n) cross sections, up to 25 MeV, were found to be 2.14±0.15 and 0.83±0.16 MeV-b, respectively. The value of $\int_0^\infty \sigma E^{-2} dE$ was determined to be 15.3±1.5 mb/MeV. The level density parameter a was found to be 17.1±0.5 MeV^{-1}. The total cross section $\sigma(\gamma,n)+\sigma(\gamma,2n)+\sigma(\gamma,pn)$ can be fitted with a single Lorentz curve having a peak cross section of 535 mb at 13.90 MeV and a width of 4.2 MeV.

INTRODUCTION

CROSS-SECTION measurements for nuclear photodisintegration have been undertaken in recent years by use of several sources of gamma rays. These include monochromatic gamma rays obtained from radioactive sources or charged-particle reactions, and continuous bremsstrahlung from betatrons.[1] All three have disadvantages. The photon energies available from radioactive sources are low, which greatly limits the scope of photonuclear studies made by their use. Gamma rays from charged-particle reactions are obtainable with energies up to about 20 MeV, but they are usually discrete or in some cases have a limited range of variability and are of low intensity. Most photonuclear studies have been made by use of electron bremsstrahlung produced by betatrons. The betatron energy can be accurately controlled and is continuously variable. However, the bremsstrahlung is continuous in distribution up to the energy of the electrons and has its greatest intensity at low energies. Because of the continuous nature of the bremsstrahlung spectrum, the reduction of photonuclear data consists of a complex unfolding procedure in order to reduce a yield curve to an excitation function for the reaction being studied. Since the yield curves have a small slope on the high side of the giant resonance, the analysis involves taking small differences between large numbers, which leads to large uncertainties and sources of error which are difficult to evaluate. In order to determine the formation cross section, the multiplicity of neutrons above the (γ,2n) and (γ,3n) thresholds must be known. These have been determined only in a few cases—by measuring radioactivity induced in the sample materials. This procedure, however, compounds the errors of activation analysis with those of unfolding bremsstrahlung. Some attempts have been made to calculate the multiplicity, but such calculations are subject to large errors.

The method described below for measuring photoneutron cross sections overcomes many of the disadvantages of the techniques commonly used. It consists of employing essentially monochromatic photons of variable energy as the source of gamma radiation. The monochromatic photons are created through the annihilation in flight of a beam of monoenergetic fast positrons. In addition, multiplicities of neutrons are determined experimentally, thus making possible determination of (γ,n) and (γ,2n) cross sections.

EXPERIMENTAL EQUIPMENT AND METHOD

A 22-MeV, high-current, linear electron accelerator[2] has been used to produce positrons through pair

* This work was done under the auspices of the U. S. Atomic Energy Commission.

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