He-Ion Induced Reactions of Aluminum and Magnesium*

RICHARD H. LINDSAY†
Department of Physics, Washington State University, Pullman, Washington

AND

ROBERT J. CARR
Department of Chemistry, Washington State University, Pullman, Washington

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The $Al^{27}(\alpha,3p)Mg^{28}$ and $Mg^{26}(\alpha,2p)Mg^{28}$ reactions produced by the bombardment of aluminum and magnesium targets with 42-Mev He ions have been studied. The excitation functions for these reactions are presented. At 40-Mev He-ion bombarding energy, the cross section for the $(\alpha,3p)$ is about 80 microbarns and the peak yield of the $(\alpha,2p)$ reaction observed at 34 Mev is 1.65 mb. Excitation functions are also given for the production of Na^{22} from the bombardment of aluminum with 30–42 Mev He ions, which proceeds chiefly through the reaction $Al^{27}(\alpha,2\alpha n)Na^{22}$, and of Na^{24} from the bombardment of natural magnesium, primarily through the $Mg^{25}(\alpha,\alpha p)Na^{24}$ reaction.

I. INTRODUCTION

EXTENSIVE study of proton-induced reactions up to cosmic-ray energies in a number of elements has been carried out over the past decade. Disintegration of aluminum by protons, deuterons and He ions to form products such as Na^{24}, Na^{22}, F^{18}, N^{13}, C^{11}, lithium and beryllium isotopes,[1–5] and interactions of aluminum and other nuclei with protons and He ions to form radiochemically detectable Be^{7},[1,3,6,7] have received attention and produced interesting results with rewarding glimpses of higher levels of understanding about the extent of fragmentation, evaporation, and direct mechanisms occurring in nuclear reactions. Gugelot, in his survey of scattering and reaction experiments,[8] has discussed the extent of understanding about the features of the reaction mechanisms. There is far less data available on reactions induced by He ions than by nucleons, and it seems advisable to extend the investigation of the strong interaction of He ions with nuclei.

In the present study, the results of some nuclear reactions produced in aluminum and magnesium by bombardment with He ions up to 42 Mev are presented. Excitation functions for the $Al^{27}(\alpha,3p)Mg^{28}$ and $Mg^{26}(\alpha,2p)Mg^{28}$ reactions and for the production of Na^{22} and Na^{24} from aluminum and natural magnesium, respectively, have been measured. Absolute values of the cross sections are based on a direct measurement of the He-ion current to the targets or from a comparison with other He-ion induced reactions set to monitor the beam intensity.

II. EXPERIMENTAL

Thin foils of natural aluminum and magnesium were bombarded for periods of several hours in the external beam of the University of Washington 60-inch cyclotron. Sufficient activities were produced with irradiations of from 20 to about 60 microampere hours. In a number of bombardments, the beam current impinging on the target was measured with a Faraday cup arrangement.

A. The $Al^{27}(\alpha,3p)Mg^{28}$ Reaction

A target stack consisting of 0.001-inch 99.99% pure aluminum foils was exposed to a total beam of 39.3 microampere-hours. Radiochemical processing of the foils eliminated the interfering Na^{24} activity as follows: The targets were dissolved in 6*M* HCl with H_2O_2 in the presence of Mg^{++} carrier. Four $Mg(OH)_2$ precipitations served to remove the radioactive sodium isotopes. Magnesium hydroxyquinolate was then precipitated by the method of Miller and McLennan[9] and weighed as the dihydrate after heating at 105–110°C. The precipitates were mounted in the form of circular disks with an estimated 2–3% geometry error. The gamma-ray spectrum of the Mg^{28}-Al^{28} source, allowed to reach equilibrium, was analyzed by means of a 128-channel NaI crystal scintillation spectrometer. No contaminants were detectable, and the complete differential pulse-height spectrum of one of the samples is shown in Fig. 1. The gamma-ray peak at 1.78 Mev, following the beta decay to the excited level of Si^{28}, is in 100% abundance.[10] The gamma rays at 1.35 Mev and 0.95 Mev follow the beta decay of Mg^{28} to excited states of

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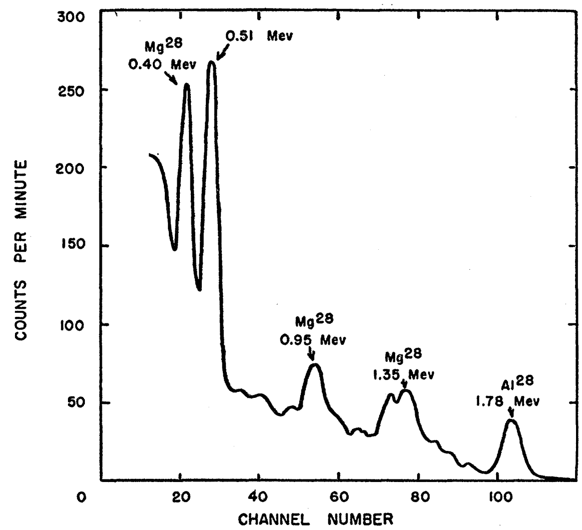

FIG. 1. Spectro-analysis of a radiochemically separated Mg^{28} yield from the $Al^{27}(\alpha,3p)Mg^{28}$ reaction.

Al^{28}. The aluminum activity, counted on the 1.78-Mev photopeak, was followed over a period of several days. A standard Na^{22} source was used for calibration purposes. The efficiency for counting on the photopeak was taken from the published efficiency curves for NaI.[11]

B. The $Mg^{26}(\alpha,2p)Mg^{28}$ Reaction

Natural magnesium rolled to about 3 mg/cm^2 and a number of 0.0035-inch foils were irradiated for 3 hour periods with He-ion beams having average currents ranging up to 10 microamperes. After bombardment the foils were dissolved in 6*M* HCl and three precipitations of $Mg(OH)_2$ were performed by addition of concentrated NaOH and supplementary amounts of NaCl carrier. The final step was a double precipitation of $MgNH_4PO_4$ without sodium hold-back. The precipitate was transferred to a filter tube and collected on a weighed filter membrane. Following washings with alcohol and ether, the precipitates were air-dried and weighed to constant weight as $MgNH_4PO_4\cdot 6H_2O$. The Al^{28} activity was counted on the 1.78-Mev photopeak.

C. Production of Na^{22} from Aluminum

The target consisted of a number of 0.001-inch aluminum foils with an arrangement of 0.0005-inch copper foils in the stack for the purpose of monitoring the He-ion beam by means of the 245-day Zn^{65} activity produced in the copper foils by the (α,pn) reaction on Cu^{63} and by decay of the 5-minute Ga^{65} from the $Cu^{63}(\alpha,2n)Ga^{65}$ reaction. The Zn^{65} yields were normalized to the $Cu^{63}(\alpha,2n)Ga^{65}+Cu^{63}(\alpha,pn)Zn^{65}$ excitation functions of Porile and Morrison.[12] The monitor foils were located at stack positions corresponding to energies in the 28–32 Mev region, where the Zn^{65} yield is nearly constant, in order to minimize errors due to uncertainties in energy.

Zinc-65 decays[10] by electron capture (98.5%) and positron emission (1.5%) with 44% of the disintegrations proceeding to the 1.114-Mev excited state of Cu^{65} and 56% to the ground state. The 1.28-Mev gamma ray of the 2.6-year Na^{22} activity was counted on the photopeak with a single-channel NaI scintillation spectrometer. Absolute values were obtained by comparison of this activity with the 1.114-Mev photopeak count in the monitor foils. Correction for differences in the photopeak efficiency of the two gamma rays was taken from the published efficiency curves. No radiochemical separations were required for this target, since the interfering 15-hour Na^{24}, 21.3-hour Mg^{28}, and daughter Al^{28} activities were allowed to decay out for about two weeks before counting. The interfering activities in the copper foils vanished in a few weeks leaving the pure Zn^{65} spectrum. All samples were counted under the same geometrical conditions.

D. Production of Na^{22} and Na^{24} from Natural Magnesium

A stack of 0.0035-inch magnesium and 0.0005-inch copper foils was irradiated for approximately 26.5 microampere-hours. The copper foils, positioned in the target for a maximum yield from the $Cu^{63}(\alpha,pn)Zn^{65}$ $+Cu^{63}(\alpha,2n)Ga^{65}$ reactions, again monitored the He-ion beam. The target was set in a bell-jar apparatus in which the beam centerline passed through 0.002-inch of stainless foil, 1.375 inches of air at 5 psi above atmospheric pressure and 1.50 inches of helium at 5 psi below atmospheric pressure, to allow high beam current through the target without melting it.

Absolute values for the cross section for the production of Na^{22} were measured at three energies by the method described above and are given in Table I. In the production of Na^{24}, the decay of the 2.75-Mev photopeak was followed over a period of several days. No interfering activities were present at this energy. The photopeak efficiency was estimated by extrapolation of the published curves. Energy losses in all foils were computed from the range-energy curves and range-energy equations for alpha particles.[13]

TABLE I. Cross sections for the production of Na^{22} by bombardment of natural magnesium by He ions.

Average He-ion energy (Mev)	Cross section (cm^2)
35.8	8.3×10^{-28}
33.3	1.6×10^{-28}
30.8	0.65×10^{-28}

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III. RESULTS AND DISCUSSION

The results are shown in Figs. 2–4 and Table I. Cross sections for the $Mg^{26}(\alpha,2p)Mg^{28}$ and the $Al^{27}(\alpha,3p)Mg^{28}$ reactions were corrected for chemical yield. All cross sections were corrected for radioactive decay during and after bombardment, counting yield of the scintillation arrangement, and the relative intensities of the gamma rays. Uncertainties in the chemical yields are 2%, and random errors of 1% in counting alignment and 1–2% in counting statistics are inherent in all absolute determinations. The cross sections are estimated to be accurate to within 20% with less than 5% point to point variation.

We have neglected the straggling corrections to the energy spectrum of the beam and also any loss by recoil of the radioactive products such as Na^{22}, Na^{24}, Mg^{28}, etc., out of the target foil. Catcher foils inserted behind the target foils in a number of the bombardments indicated that losses due to recoil from the thinner targets which were used (7 mg/cm² Al, 3 mg/cm² Mg) were <5% and negligible in the thicker targets (14 mg/cm² Mg and 11 mg/cm² Cu). The 3 mg/cm² Mg foils were used only below 28 Mev, and it was assumed that the recoil effect was tending to cancel out.

The center of mass Q values for the various reactions are listed in Table II. The Q values were obtained from the available mass and decay data. Approximate barriers for Li^6 and heavier fragments were computed from the usual relationship, $V=Z_1Z_2e^2/r_0(A_1^{1/3}+A_2^{1/3})$, where A_1,Z_1 and A_2,Z_2 are mass and atomic numbers of residual nucleus and emitted particle, respectively, and r_0, the nuclear radius parameter, was taken as 1.4 fermis.

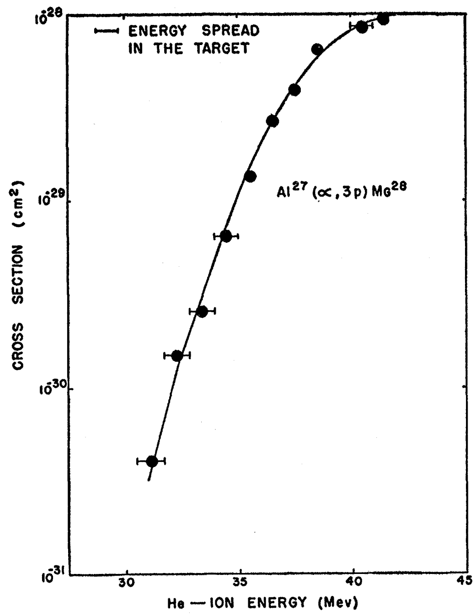

FIG. 2. Excitation function for the reaction $Al^{27}(\alpha,3p)Mg^{28}$.

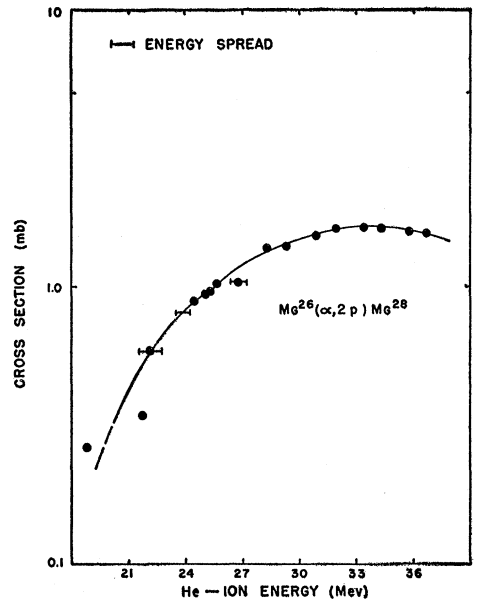

FIG. 3. Excitation function for the reaction $Mg^{26}(\alpha,2p)Mg^{28}$.

The $(\alpha,3p)$ reaction rises from about 3 microbarns at 31 Mev to about 80 microbarns at 40 Mev. The $(\alpha,2p)$ cross section rises from about 0.3 mb at 20 Mev to a maximum of about 1.65 mb at 34 Mev. Hudis[14] found a value of about 0.2 mb for the $(\alpha,3p)$ cross section at 41 Mev, as compared to our value of about 0.1 mb.

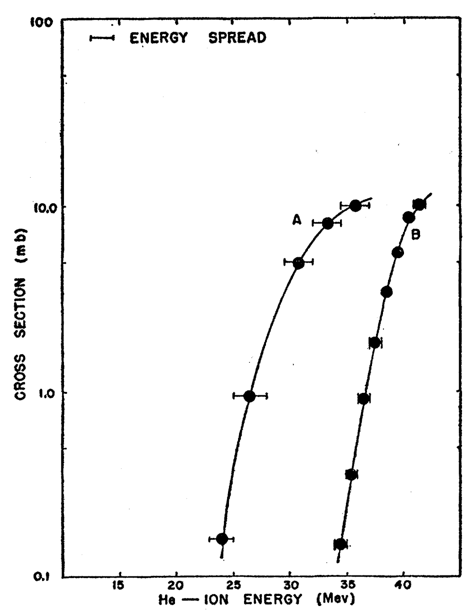

FIG. 4. Curve A: Cross sections for the production of Na^{24} in He-ion bombardment of natural magnesium. Curve B: Cross sections for the production of Na^{22} in the He-ion bombardment of aluminum.

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There is relatively little information available about $(\alpha,2p)$ and $(\alpha,3p)$ reactions. Excitation functions for the former in various nuclides at energies to about 40 Mev have been calculated on the basis of statistical models by Porile[15] and by Sharma,[16] while experimental measurements have been carried out by Sharma,[16] by Amiel,[17] and by Porile and Morrison.[12] The calculated functions are in general agreement with the measured ones, and there is nothing to indicate that the reactions do not proceed primarily by a compound nucleus mechanism.

The $Mg^{26}(\alpha,2p)Mg^{28}$ reaction is not favored energetically over the competing (α,pn) and $(\alpha,2n)$ reactions, the Q values for these three reactions being -13.3, -12.3, and -8.4 Mev, respectively. The depressing effect of the Coulomb barrier, the relatively high Q value, and the effect of nuclear type in the competition with the (α,pn) reaction should account for the observed small cross sections. The shape of the function is in qualitative agreement with what one expects; in particular it is similar to that of the $Al^{27}(\alpha,2p)Al^{29}$ reaction,[16] both having peak yields at an energy of about 34 Mev.

There have been no previous measurements of excitation functions for $(\alpha,3p)$ reactions, and only one calculation, that for the reaction in Zn^{64}.[15] The similarity in shape of this function and our measured one suggests that a compound-nucleus mechanism is predominant in Al^{27}. Evaporation theory has previously been shown to be approximately valid even in light elements for explaining the proton $(p,2p)$ and nitrogen $(N^{14},2p)$ induced reactions through the same compound-nucleus (Al^{26}).[18,19]

No calculated excitation functions are presented for the reactions reported here because the detailed shape of the functions is too sensitive to choice of parameters to make comparisons very meaningful. It is hoped that more detailed treatment will be possible when further excitation function measurements of He-ion induced light element reactions are completed.

The cross section for the production of Na^{22} from aluminum rises sharply to a value of about 7 mb at 40 Mev. A value of 5.2 mb has been observed[7] previously at this bombarding energy. Small corrections were applied for counting on the 1.28-Mev photopeak in the presence of the coincidence spectrum of the 1.28-Mev and 0.511-Mev annihilation gamma rays. The possible reactions producing Na^{22} from the He-ion bombardment of aluminum are $Al^{27}(\alpha,2\alpha n)Na^{22}$, $Al^{27}(\alpha,Be^8 n)Na^{22}$, and $Al^{27}(\alpha,Be^9)Na^{22}$. The first reaction suggests that the incoming He ion may interact directly with an alpha-particle aggregate in the nucleus with both emerging and leaving the residual Na^{23} nucleus with enough excitation energy for a neutron to be given off. The two alpha particles may emerge from the nucleus as a highly excited Be^8 fragment with enough excitation energy imparted to the residual nucleus for it to lose a neutron. Be^8 is unstable with respect to alpha decay unless formed with an odd-number spin. The third energetically possible reaction, if occurring, will produce the stable Be^9 fragment.

TABLE II. Q values and approximate barrier heights for He-ion induced reactions yielding Na^{22} and Na^{24} from bombardment of aluminum and magnesium.

Reaction	$-Q$(Mev)	Barrier (Mev)	$-Q$+barrier (Mev)
$Al^{27}(\alpha,2\alpha n)Na^{22}$	22.5	11.0	33.5
$Al^{27}(\alpha,Be^8 n)Na^{22}$	22.6	9.4	32.0
$Al^{27}(\alpha,Be^9)Na^{22}$	21.0	9.3	30.0
$Mg^{24}(\alpha,\alpha pn)Na^{22}$	24.1	9.5	33.6
$Mg^{24}(\alpha,\alpha d)Na^{22}$	21.9	9.1	31.0
$Mg^{24}(\alpha,Li^6)Na^{22}$	20.4	7.4	27.8
$Mg^{25}(\alpha,\alpha p2n)Na^{22}$	30.0	9.3	39.3
$Mg^{25}(\alpha,\alpha dn)Na^{22}$	29.2	9.0	38.2
$Mg^{25}(\alpha,\alpha T)Na^{22}$	23.0	8.7	31.7
$Mg^{25}(\alpha,Li^7)Na^{22}$	20.5	7.8	28.3
$Mg^{26}(\alpha,Li^7 n)Na^{22}$	31.6	7.7	39.3
$Mg^{26}(\alpha,Li^8)Na^{22}$	29.6	7.2	36.8
$Mg^{24}(\alpha,pHe^3)Na^{24}$	25.3	10.7	36.0
$Mg^{25}(\alpha,\alpha p)Na^{24}$	12.1	9.4	21.5
$Mg^{26}(\alpha,\alpha pn)Na^{24}$	23.2	9.3	32.5
$Mg^{26}(\alpha,\alpha d)Na^{24}$	21.0	8.9	29.9
$Mg^{26}(\alpha,Li^6)Na^{24}$	19.5	7.3	26.8
$Mg^{26}(\alpha,2p)Mg^{28}$	13.3	8.4	21.7
$Al^{27}(\alpha,3p)Mg^{28}$	21.6	12.9	34.5

Natural magnesium is an isotopic mixture of 78.8% Mg^{24}, 10.1% Mg^{25}, and 11.1% Mg^{26}. The production of Na^{22} in the energy range 20–38 Mev may proceed from many reactions. In view of threshold considerations (see Table II) the chief contributions will come from the $Mg^{24}(\alpha,\alpha pn)Na^{22}$, $Mg^{24}(\alpha,\alpha d)Na^{22}$ and $Mg^{24}(\alpha,Li^6)Na^{22}$ reactions. The cross section for the formation of Na^{24} from magnesium may be attributed to the $Mg^{25}(\alpha,\alpha p)Na^{24}$ reaction below 30 Mev, with other reactions listed in Table II beginning to compete to an unknown extent above this energy. A small contribution from the $Mg^{24}(n,p)Na^{24}$ reaction has been neglected in the corrections. Foils in the rear of the target stack, where the neutron flux is reputed to be a maximum and where the He-ion energy has been reduced below thresholds of all reactions producing Na^{24}, showed a small yield.

In contrast to the $(\alpha,2p)$ and $(\alpha,3p)$ reactions, the nature of the $(\alpha,\alpha n)$ and $(\alpha,\alpha p)$ reactions would lead one to predict a considerable contribution from a direet interaction process at the nuclear surface. It is known[12,13] that the excitation functions from direct interaction mechanisms often show an initial rise followed by a very broad or flat peak because the energy transferred to the emerging particles is such that the residula nucleus is left in a low-lying state and in general less susceptible to further particle emission. The direct

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process in which the incident alpha-particle collides as a whole with a surface nucleon knocking it out and itself being scattered is a likely contributing mechanism. On the basis of a statistical model the $(\alpha,\alpha p)$ reaction becomes possible when the alpha particle is emitted with a low enough energy to leave proton emission energetically possible.

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Energy Spectra and Angular Distribution of Photoneutrons from Carbon

V. Emma, C. Milone, and A. Rubbino
Istituto di Fisica dell'Università, Centro Siciliano di Fisica Nucleare, Catania, Italy

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Energy spectra and angular distribution of photoneutrons from carbon are studied by irradiation with a 30-Mev bremsstrahlung beam. The spectra exhibit a fine structure from which the following levels in C^{12} may be distinguished: 21.4, 22.2, 22.9, 23.6, (24.3), 24.8, and 25.6 Mev. Many of these coincide with levels found in the $C^{12}(\gamma,p)$ and $C^{12}(\gamma,3\alpha)$ reactions.

Photoneutron emission occurs predominantly by transition to the ground state of C^{11}.

The angular distribution is of the form $1+1.5\sin^2\theta$ for all neutrons having energy $E_n>3$ Mev. This distribution agrees with that expected according to Wilkinson's independent-particle model for ejection from the $l=1$ orbit.

1. INTRODUCTION

In previous work[1,2] it has been shown that while the photoneutron emission from heavy nuclei occurs mainly by evaporation, in a nucleus as light as oxygen the direct process prevails in photoneutron emission.

The aim of present work is to study in some detail the energy spectrum and the angular distribution of photoneutrons from carbon. These data are needed in order to study the prediction of direct interaction theories and the levels in C^{12}. This work has been suggested to us also by the analysis of the known data on the photodisintegration of C^{12}.[3–26]

As shown in Table I it may be observed that for the photoneutrons from C^{12}: (i) the energy spectra have not yet been studied; (ii) the angular distributions are given only for angles θ between 60° and 160°[16] and for $E_{\gamma\,\max}=23$ Mev.

2. EXPERIMENTAL PROCEDURE

A cylindrical target of C of ~40 g was irradiated with a 31-Mev collimated γ-ray beam of the B.B. betatron of Turin. The photoneutrons were detected by means of the proton recoil tracks in Ilford L4 plates 400 μ thick, placed, respectively, at angles $\theta=30°$, 60°, 90°, 120°, and 150° with the γ-ray beam. The experimental arrangement was the same as that used in a previous work.[27] The methods used for scanning the plates with the ⟨slow⟩ and the ⟨fast⟩ method and for analyzing the proton recoil tracks are described in previous work.[2,28] The measured background[27] was quite negligible.

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