Excitation Functions for Deuterons and Protons on Mg*

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Yields of F^{18}, Na^{22}, and Na^{24} have been measured as a function of energy for both deuterons and protons on Mg. In some cases the yield of a single isotope can be attributed to a single nuclear reaction over a certain energy interval, this being done by a consideration of thresholds. These excitation curves are given over the ranges 0 to 20 Mev and 0 to 190 Mev for deuterons and from 0 to 31 Mev for protons.

INTRODUCTION

PREVIOUS work[1] with the 190-Mev deuterons from the 184-inch Berkeley cyclotron has pointed to interesting nuclear reactions which might be investigated with both this machine and the 60-inch Crocker cyclotron, and the Berkeley proton linear accelerator. It has been noticed in particular that at high energy, nuclear reactions which result in a product nucleus of much lower atomic number tend to go more probably by boiling off two or more α-particles plus additional neutrons from the excited nucleus than by evaporation of charged particles of lower binding energy. This process fitted into the picture of the incident high energy particle exciting the target nucleus by inelastic collision,[2] the excited nucleus then decaying by boiling off fragments ranging in size from individual nucleons to "fission fragments."[3] In this picture the nucleus which plays the role of the compound nucleus is simply the target nucleus itself with a large amount of excitation energy. Since several reactions had been found at high energy in which the excitation seemed to be carried away preferentially by two or more α-particles,[1] it was interesting to ask if there were any reactions going by the usual mechanism of formation of a compound nucleus, in which it could be shown that the excitation was lost by boiling off more than one α-particle. At the threshold for such a reaction, when defined to include the height of the coulomb barrier of the compound nucleus to the α's inside it, there is ample energy for neutron evaporation to compete with the process in question, and so one might conclude that if the boiling off of α's does occur, it must compete with neutron evaporation; otherwise the excitation would first be lost by neutron evaporation while the energy is being distributed among the nucleons in the compound nucleus.

TABLE I. Reaction thresholds.

Reaction	Threshold (from masses) (Mev)	Threshold +barrier (Mev)
$Mg^{24}(p,\alpha He^3)F^{18}$	25.0	31.4
$Mg^{24}(n,\alpha H^3)F^{18}$	24.2	29.0
$Mg^{24}(d,2\alpha)F^{18}$	6.6	12.9
$Mg^{25}(p,2\alpha)F^{18}$	11.5	17.7
$Mg^{25}(n,\alpha H^3 n)F^{18}$	31.3	35.4
$Mg^{25}(d,2\alpha n)F^{18}$	13.7	19.0
$Mg^{26}(p,2\alpha n)F^{18}$	23.6	28.9
$Mg^{26}(n,\alpha H^3 2n)F^{18}$	43.4	46.9
$Mg^{26}(d,2\alpha 2n)F^{18}$	25.8	30.4
$Mg^{24}(p,He^3)Na^{22}$	15.3	20.4
$Mg^{24}(d,\alpha)Na^{22}$	−3.1	+1.9
$Mg^{25}(p,\alpha)Na^{22}$	1.7	6.7
$Mg^{25}(d,\alpha n)Na^{22}$	3.9	8.0
$Mg^{26}(p,\alpha n)Na^{22}$	13.8	17.9
$Mg^{26}(d,\alpha 2n)Na^{22}$	11.4	14.9

The reaction studied first was $Mg^{24}(d,2\alpha)F^{18}$, whose energetic threshold (threshold not including coulomb barrier height) is 6.6 Mev. With the 20-Mev deuterons from the 60-inch cyclotron, one could be reasonably sure of getting a yield of F^{18} even for cross sections as low as 10^{-29} cm^2 because of the high beam strengths available. This excitation curve was also investigated with the 190-Mev deuterons from the 184-inch cyclotron, and in the course of this work the excitation curves for $Mg^{24}(d,2p)Na^{24}$ and $Mg^{24}(d,\alpha)Na^{22}$ plus $Mg^{25}(d,\alpha n)Na^{22}$ plus $Mg^{26}(d,\alpha 2n)Na^{22}$ were also found from theshold to 190 Mev, since Na^{24} and Na^{22} activities occurred as a background that had to be subtracted from the total target activity to get the F^{18} activity.

The other reaction of this type that was studied was $Mg^{25}(p,2\alpha)F^{18}$ with the 32-Mev proton beam from the Berkeley linear accelerator. The excitation curve for $Mg^{25}(p,\alpha)Na^{22}$ was also obtained below 18 Mev in this same work, and a composite yield of this and

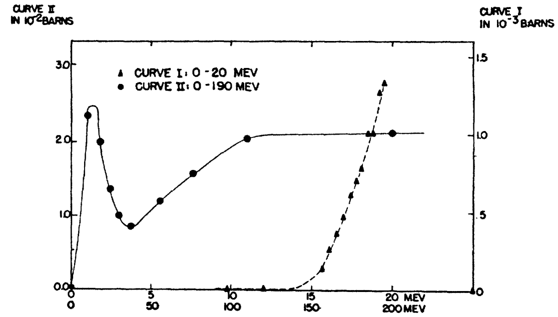

FIG. 1. Deuteron excitation of F^{18} from Mg^{24}.

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[1] Bartell, Helmholz, Softky, and Stewart, Phys. Rev. 80, 1006 (1950).
[2] R. Seber, Phys. Rev. 72, 1114 (1947).
[3] R. Batzel and G. T. Seaborg, Phys. Rev. 79, 528 (1950).

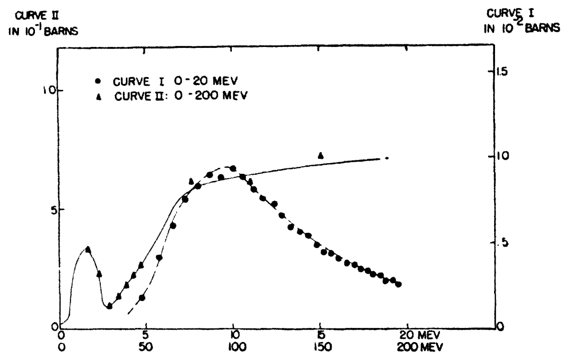

FIG. 2. Deuteron excitation of Na^{22} from Mg^{24}, Mg^{25}, Mg^{26}.

$Mg^{24}(p,He^3)Na^{22}$ and $Mg^{26}(p,\alpha n)Na^{22}$ from 18 Mev to 31 Mev. We notice that we have here a set of four nuclear reactions which represent the formation and decay of the same compound nucleus, Al^{26}, formed by $Mg^{24}+d$ and $Mg^{25}+p$.

METHOD

The excitation curves were measured by the usual method of bombarding stacks of foils and measuring the induced activities in the foils as a function of time in order to identify the radioactive products by their half-lives. The absorber thickness that the incident particles passed through in order to reach a given foil in the stack is then an indication of the particle energy for that foil as found from a range-energy curve. The activity observed, F^{18}, is a 110-min β^+ emitter of about 0.7-Mev maximum energy and with no γ. After a target of Mg or Al had been bombarded by deuterons or protons of sufficient energy and allowed to cool for about an hour, the only activities easily measurable with the thin mica window Geiger counter used were F^{18}, Na^{24}, the well-known β^- emitter of 15-hour half-life, and Na^{22}, a β^+ emitter of about 3-year half-life. These very different half-lives were ideal to measure in the automatic sample-changing and recording counter which is available for this work, and since no chemistry was necessary, many foils could be run at once for greater accuracy in the curves. The 24-sample automatic counter, constructed at this laboratory by H. Robinson

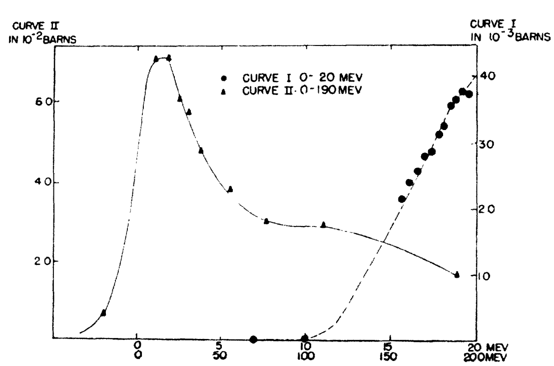

FIG. 3. Deuteron excitation of Na^{24} from Mg^{24}.

and A. Hartzell of the chemistry electronics group, has performed without breakdown for many weeks of operating time, and made it possible to get at least four points per half-life on the composite decay curves, so that resolution of the activities was easy and positive.

The bombardments on the 60-inch cyclotron were carried out with a beam of 20-Mev deuterons collimated to $\frac{1}{8}$ in. by $\frac{1}{2}$ in. and and the energy was measured by an absorber foil wheel and Faraday cup described by E. L. Kelly.[4] Two types of target were bombarded: a stack of 22 Mg metal foils each 9 mg/cm² thick, and a stack of "foils" prepared by pressing the oxide of separated Mg^{24} isotope into 0.015-in. thick beryllium masks. These powder "foils" turned out to be exceptionally uniform in thickness and were about 40 mg/cm² thick. Stacks of each type were bombarded and current-monitored after measuring the beam energy; then the targets were put on the sample-changing counter and their activity was followed down to the long-lived Na^{22}. The possible contaminants in the Mg targets which could also give F^{18} as a product from deuterons of this energy are O^{17}, F^{19}, and Na^{23}. Since the abundance of O^{17} is only 0.039 percent and the Mg metal foil targets gave the same yield of F^{18} as the MgO targets which were 50 percent O, it seems safe to discount $O^{17}(d,n)F^{18}$ as causing the activity. A very sensitive spot test for F in the Mg showed less than 1 part F in 5000, and for $F^{19}(d,dn)F^{18}$ to account for the activity its cross section would have to be the geometrical cross section of F^{19}, 0.5×10^{-24} cm², and it would have to be present in greater than ten times this amount. Finally, spectrographic analysis of the Mg showed less than 0.01 percent Na, so this eliminates $Na^{23}(d,d\alpha n)F^{18}$.

The bombardments on the 184-inch cyclotron also were on both types of Mg target and took place in the internal electrostatically deflected beam of 190-Mev deuterons. It was not possible to measure the incident energy of these deuterons, and so 190 Mev is the figure used as the most probable energy. In these bombardments Cu absorbers of accurately known thickness were inserted between the target foils in order to degrade the beam energy, the beam was collimated by a $\frac{3}{4}$-in. diameter hole in a $1\frac{1}{2}$-in. thick Cu block, and current to the target stack was maximized by adjusting the position of the entire target assembly in the deflected beam. Al metal foils, 0.002 in. thick, were placed coincident with the Mg foils and the excitation curves from Mg monitored by comparing them with the known excitation curve for $Al^{27}(d,\alpha p)Na^{24}$ as measured by Hubbard[5] and by Meinke.[6] The excitation curve for $Al^{27}(d,d2\alpha n)$-F^{18} was incidentally measured, since the F^{18} activity also showed up quite strongly in these Al monitor foils. The entire apparatus used in these 184-inch cyclotron runs is described in great detail by Meinke.[6]

The bombardments on the linear accelerator were

[4] E. L. Kelly and E. Segrè, Phys. Rev. **75**, 999 (1949).
[5] H. Hubbard, Phys. Rev. **75**, 1470 (1949).
[6] W. W. Meinke, Ph.D. thesis, University of California.

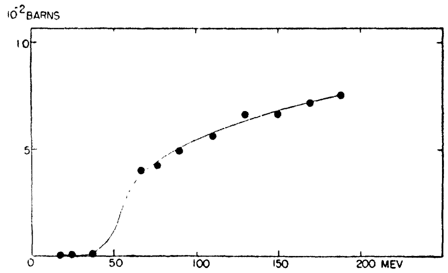

FIG. 4. Deuteron excitation of F^{18} from Al^{27}.

simply on a stack of 24-Mg metal foils, each about 36 mg/cm² thick. The 32-Mev proton beam was monitored by the standard beam monitor which measures current to the stack.

RESULTS

Deuterons

Figure 1 shows the excitation function $Mg^{24}(d,2\alpha)F^{18}$ from 0–20 Mev and from 0–190 Mev. The ordinates for Curves I and II are different. Comparison of the yields from the targets of separated $Mg^{24}O$ and from the metal foils showed conclusively that the reaction is indeed due to Mg^{24}, and the much thinner foils of the metal gave higher energy definition than could ever be obtained with powder pellets. The observed threshold corresponds to that calculated from nuclear masses plus the height of the coulomb barrier of the compound nucleus to the two α-particles inside it. Reference to Table I shows that below 19 Mev $(d,2\alpha)$ is the only energetically possible way to make F^{18} from any of the Mg isotopes. This is therefore a nuclear reaction in which it has been proved that the entire deuteron enters the nucleus, as contrasted to one of the stripping processes such as (d,p), because none of the reactions making F^{18} by neutrons or protons on Mg^{24} are energetically possible in this region. Undoubtedly the curve for the F^{18} yield from Mg^{24} at high energy represents several other reactions as well, such as $(p,\alpha He^3)$, $(n,\alpha H^3)$, $(d,2d\alpha)$, etc. In fact, one might attribute the second rise in the curve to the setting-in of the aforementioned inelastic processes at high energy after the usual compound nucleus process has become less probable.

The composite yield curve for $Mg^{24}(d,\alpha)Na^{22}$, $Mg^{25}(d,\alpha n)Na^{22}$, and $Mg^{26}(d,\alpha 2n)Na^{22}$ is given in Fig. 2 for both 0–20 Mev and 0–190 Mev and those for Na^{24} from Mg^{24}, which might be either $Mg^{24}(d,2p)Na^{24}$ or $Mg^{24}(n,p)Na^{24}$, and for $Al^{27}(d,d2\alpha n)F^{18}$ are given in Figs. 3 and 4. As before, the ordinates for Curves I and II are different.

The deuterons giving Curve II of these excitation functions have a distribution in energy between 190 Mev and 196 Mev when they enter the absorber stack. The 22 g/cm² of Cu absorber broadens this distribution so that deuterons which passed through the stack are distributed between 0 Mev and about 30 Mev, hence the abscissa is badly distorted at energies below 50 Mev and some curves show a yield apparently below zero energy. Neutrons also cause a yield apparently below zero energy.

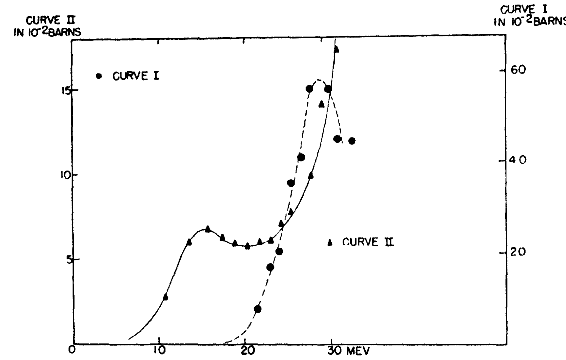

FIG. 5. Curve I: Excitation of F^{18} from Mg^{25} by protons. Curve II: Excitation of Na^{22} from Mg^{24}, Mg^{25}, and Mg^{26} by protons.

Protons

Figure 5, Curve I, shows the excitation function $Mg^{25}(p,2\alpha)F^{18}$ from 0–31 Mev. Reference to Table I will show that this is the only energetically possible reaction to produce F^{18} from any of the Mg isotopes below 29 Mev. In this case, the protons available were of high enough energy so that some of the back side of the characteristic compound nucleus peak was obtained. Figure 5, Curve II, shows the yield of Na^{22} from the natural isotopic mixture of Mg, which is 78.6 percent Mg^{24}, 10.1 percent Mg^{25}, and 11.3 percent Mg^{26}. The part of the curve below 18 Mev must represent only $Mg^{25}(p,\alpha)Na^{22}$, as reference to Table I will show.

CONCLUSIONS

Although the absolute yields are probably not accurate to better than a factor of two due to self-absorption and scattering of the low-energy β-particles counted, it appears that the peak yield of $(d,2\alpha)$ is about 0.020 barn and of $(p,2\alpha)$ about 0.060 barn. We can compare these with a $Na^{33}(d,p)Na^{24}$ peak of about 0.400 barn[7] and with an $Al^{27}(d,\alpha p)Na^{24}$ peak of greater than 0.050 barn[5,6] to get an idea of how these reactions compare with other known ones on nearby nuclei; and while it is obvious that $(d,2\alpha)$ and $(p,2\alpha)$ do not compete very successfully with reactions like (d,p), their cross sections are comparable to $(d,\alpha p)$ and their peaks are at approximately the same particle energy.

ACKNOWLEDGMENTS

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[7] D. C. Peaslee, Phys. Rev. 74, 1001 (1948).