Excitation Functions for Proton Reactions with Sodium and Magnesium*

J. W. MEADOWS AND R. B. HOLT
Nuclear Laboratory, Harvard University, Cambridge, Massachusetts
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Proton bombardment at energies up to 120 Mev have been carried out on the Harvard University cyclotron using targets of $Na^{23}NO_3$, $Mg^{25}O$, $Mg^{26}O$, and ordinary MgO. A stacked sample and absorber technique was employed, using the formation of C^{11} from interleaved polyethylene foils as a monitor. The internal scattered beam at about 180° from the scatterer and 1 inch below the median plane was employed to give better energy resolution. Absolute excitation curves have been obtained for the reactions yielding F^{18} and Na^{24} from Mg^{25} and Mg^{26}, F^{18} from Mg^{24}, and F^{18} and Na^{22} from Na^{23}.

I. INTRODUCTION

A SYSTEMATIC study of a considerable number of reactions between protons with energies up to 120 Mev and fairly light nuclei is in progress, using the Harvard University 95-in. cyclotron. Our interest in these reactions arises from the fact that the ordinary compound nucleus theory begins to fail in this energy range and in this portion of the periodic table. This paper presents results obtained to date on Na^{23}, Mg^{24}, Mg^{25}, and Mg^{26}.

II. EXPERIMENTAL METHOD

Since it has been found[1] that the energy spread in the primary beam of the Harvard cyclotron is of the order of 10 Mev, it was necessary to use an internal scattered beam (above or below the median plane) with the target to be bombarded located at approximately 180° from the scatterer in order to obtain good energy resolution. This arrangement provides focusing of particles of a given energy scattered at all small azimuthal angles, with various energies spread radially. The energy resolution is determined by the width of the target. The experimental arrangement[2] is shown in Fig. 1.

The stacked "foil" technique was used. The targets consisted of pellets of $NaNO_3$, natural MgO, and MgO enriched[3] in Mg^{25} and Mg^{26}. The pellets were $\frac{5}{16}$ in. in diameter and had a surface density of 20 to 40 mg/cm^2. These were placed in Lucite holders and stacked between $\frac{7}{16}$-in. diameter disks of copper or aluminum. A polyethylene foil of the same diameter was placed with each pellet. The $C^{12}(p, pn)C^{11}$ cross section[4] was used to monitor the beam. The excitation curve of this reaction was re-run as a check on our energy values. The samples were counted with a mica end window Geiger counter, and the decay curves were resolved to determine the amounts of the different activities present. All samples were counted, as nearly as possible, under the same geometry and mounting arrangements. Experimental corrections were made for the effect of sample thickness. The absolute values of the cross sections given are probably accurate to ±20 percent. The activities were identified by their half-lives and ranges in aluminum.

III. EXPERIMENTAL RESULTS AND CONCLUSIONS

The excitation function curves for Mg^{26} to form Na^{24} and F^{18} are shown in Fig. 2. The threshold (corrected to the laboratory system) of the $Mg^{26}(p, pd)Na^{24}$ reaction is 21.8 Mev, and that of the $Mg^{26}(p, 2pn)Na^{24}$ is 24.9 Mev. The observed threshold of approximately 20 Mev is in reasonable agreement with the first reaction shown. The curve does not show the pronounced maximum characteristic of compound nucleus formation, which indicated that other processes, such as direct knockout, etc., are probably relatively important. The large number of possible mechanisms for this reaction would lead one to expect a relatively smooth excitation function curve; our method does not provide the necessary information for deciding relative contributions of these mechanisms.

The lowest threshold energy for the formation of F^{18} from Mg^{26} is 24.6 Mev via the reaction $Mg^{26}(p, 2\alpha n)F^{18}$. The measured threshold is between 20 and 30 Mev. Other probable reactions have thresholds in excess of 40 Mev. The lack of pronounced structure of the curve

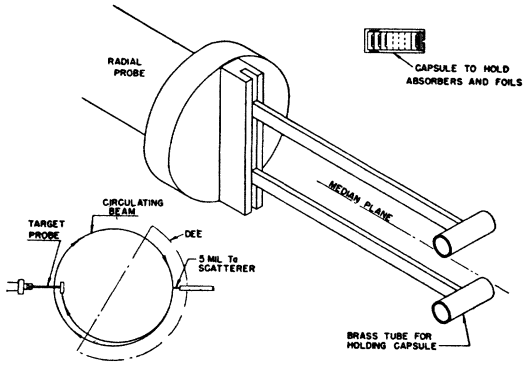

FIG. 1. Position of scatterer and target in the cyclotron tank and diagram of target holder.

* Supported by the joint program of the ONR and AEC.
[1] N. Bloembergen and P. J. Van Heerden, Phys. Rev. 82, 316A (1951).
[2] This method was developed by N. M. Hintz and N. F. Ramsey and reported in Phys. Rev. 82, 304A, 342A (1951).
[3] This material was obtained from Oak Ridge National Laboratory, Oak Ridge, Tennessee.
[4] Aamodt, Peterson, and Phillips, UCRL-526 (1949) (unpublished).

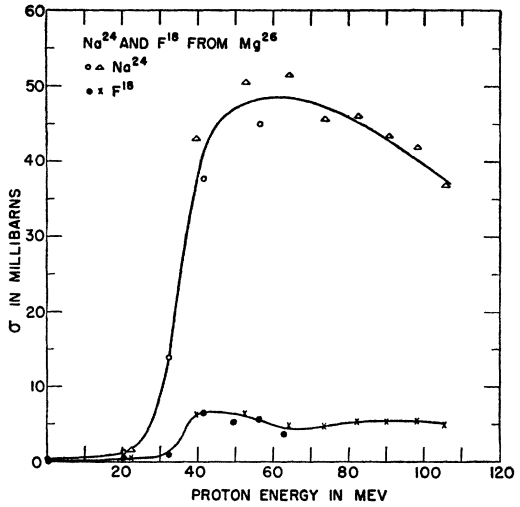

FIG. 2. Excitation functions for the formation of F^{18} and Na^{24} from Mg^{26}.

at higher energies suggests that the higher threshold reactions are relatively important.

The excitation curves for the formation of Na^{24} and F^{18} from Mg^{25} (see Fig. 3) both show pronounced maxima, indicating the importance of the formation of compound nuclei in these reactions. The $Mg^{25}(p, 2p)Na^{24}$ reaction with a threshold of 11.6 Mev is the only possible one for the formation of Na^{24}. The observed threshold is in good agreement with the above value. The three possible mechanisms (formation of compound nuclei of Mg^{26} or Al^{26} or direct knock-out) are probably all important. The general shape of this curve agrees very well with the shape calculated[5] for the $C^{12}(n, 2n)C^{11}$ reaction. The reason for the sharp peak is the low threshold for the reaction, which favors compound nucleus formation.

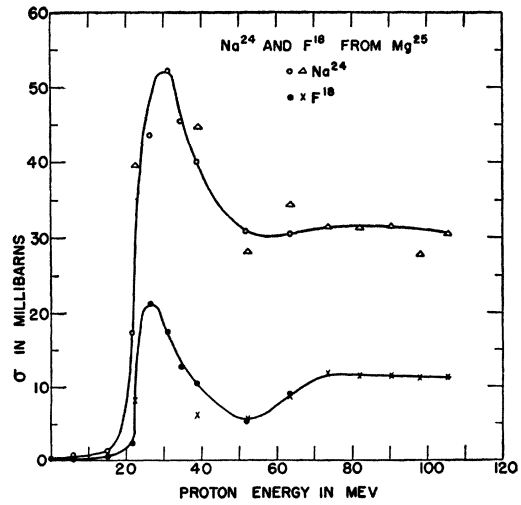

FIG. 3. Excitation functions for the formation of F^{18} and Na^{24} from Mg^{25}.

[5] W. Hecrotte and P. Wolff, Phys. Rev. 73, 265 (1948).

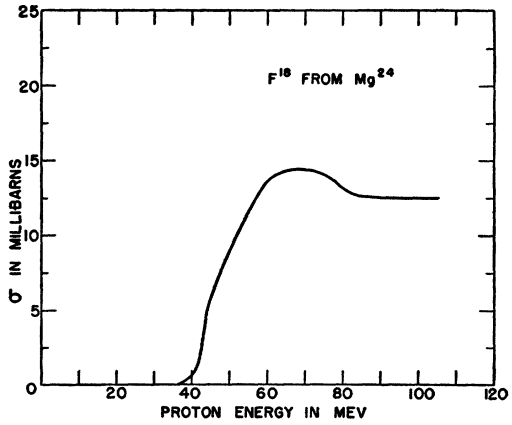

FIG. 4. Excitation function for the formation of F^{18} from Mg^{24}.

The $Mg^{25}(p, 2\alpha)F^{18}$ reaction, with a threshold of 12.0 Mev, is the lowest energetically possible reaction. The next energetically possible reaction has a threshold of about 35 Mev, which means that the reaction in the energy range between 12 and 35 Mev can proceed only by the formation of the Al^{26} compound nucleus and the "boiling off" of two α-particles. This is evident from the shape of the curve obtained in this energy range. At higher energies, the cross section again begins to rise, as reactions with higher thresholds become important.

The excitation function for the formation of F^{18} from Mg^{24} was obtained by bombarding natural MgO (78.6 percent Mg^{24}) and subtracting out the known contributions of the Mg^{25} and Mg^{26} present. The resulting curve is Fig. 4. The initial reaction (at relatively low energies) is probably $Mg^{24}(p, p\alpha d)F^{18}$ with a threshold of 32.8 Mev or $Mg^{24}(p, He^3\alpha)F^{18}$ with a threshold of 26.5 Mev.

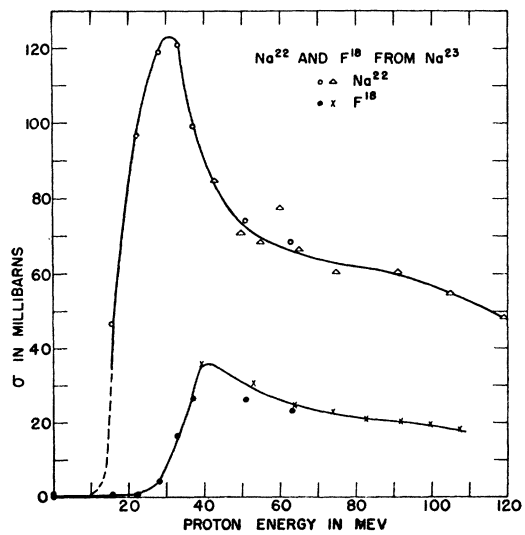

FIG. 5. Excitation functions for the formation of F^{18} and Na^{22} from Na^{23}.

The method of subtraction used makes the observed threshold somewhat inaccurate, but it is certainly less than 40 Mev.

Results obtained with Na^{23} are shown in Fig. 5. Na^{22} may be formed by the (p, d) or the (p, pn) reaction with thresholds of 11.6 and 13.8 Mev, respectively. The observed curve seems to be in agreement with the lower value. The pronounced maxima indicates the formation of a compound nucleus, and its breadth indicates that both possible modes of decay are important. At higher energies mechanisms other than the formation of the compound nucleus become important. The general shape of the curve is in fair agreement with the one calculated[6] for the $C^{12}(p, pn)C^{11}$ reaction. However, this does not account for the decline of the cross section above 100 Mev.

The $Na^{23}(p, \alpha d)F^{18}$ and $Na^{23}(p, pn\alpha)F^{18}$ with thresholds at 20.3 and 22.5 Mev, respectively, are probably the reactions by which F^{18} is formed initially. The maxima at approximately 40 Mev indicates the formation of a compound nucleus as the principal reaction at the lower energies. In the vicinity of 50 Mev other reactions such as $(p, 3p3n)$ become energetically possible and may account for the slow decline of the cross section at higher energies.

[6] W. Hecrotte and P. Wolff, Phys. Rev. **73**, 264 (1948).

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The Origin of Bombardment-Enhanced Thermionic Emission

J. B. JOHNSON
Bell Telephone Laboratories, Murray Hill, New Jersey
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Measurements on bombardment-enhanced thermionic emission from oxide cathodes show that (a) the effect is not related to normal fading and recovery of thermionic emission; (b) the emitted electrons have energies in the thermal range rather than in the secondary range. Calculations indicate that the electron bombardment releases more than enough internal secondaries to account for the effect as increased thermionic emission. A more comprehensive theory is needed for explaining why the observed effect is not even larger.

I. INTRODUCTION

A THERMIONIC emitter of (BaSr)O has its emission temporarily increased when bombarded by electrons.[1] In addition to the normal thermionic emission and to the secondary emission which normally accompanies the bombardment, there is a gradual increase of current during the first few microseconds of bombardment and a corresponding gradual decrease when the bombarding pulse is over. The persistence of the added emission after the end of the bombardment led to the belief that the emission is of thermionic rather than secondary origin. As a possible source of the bombardment-enhanced thermionic emission was suggested either a reduction of work function or an increase in the density of conduction electrons in the bombarded target. The experiments reported here deal with the energy distribution of the emitted electrons, and with the relation of the enhanced emission to the phenomenon of fading. They give further proof of the thermionic origin of the increased current, and support the view that change of electron density rather than of surface conditions is the principal cause of this current.

II. METHOD

The experiments were done with equipment similar to that described earlier. The target of activated (BaSr)O on Ni, a collector electrode and an electron gun are enclosed in a gettered and sealed-off tube. A pulsed electron beam bombards the target, with the collector negative or positive for measuring the primary or secondary current. The current of the target circuit actuates a video amplifier and is displayed on an oscilloscope. Typical results are shown in Fig. 1, which has two sets of oscillograms, (a) and (b), each of three traces, two displaced slightly from the axis which is the central trace. (The vertical strokes have been dotted in for clearness.) In the lower trace of each set the 1250-volt beam was pulsed on for 10 μsec while the collector was negative, and the trace records primary beam current. The upper trace, with the beam similarly pulsed, was made with the collector positive (with amplifier gain reduced). In Fig. 1(a) the target temperature was low and the thermionic current negligible, and the flat-topped upper trace records well-behaved secondary current. In Fig. 1(b) the thermionic current was high, but being dc it was blocked out in the coupling condensers of the circuit and does not appear in the oscillogram. The upper trace in this set shows clearly the variation of emission during and after the beam current pulse when thermionic current flows, and it is this variable emission that is under discussion.

III. EXPERIMENTS ON FADING

When temperature-limited thermionic current is drawn suddenly from an active oxide cathode there is

[1] J. B. Johnson, Phys. Rev. **73**, 1058 (1948).