Nuclear Excitation Functions.* II. $Al^{27}(d; p, \alpha)Na^{24}$

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Hitherto unknown in light elements, a new reaction involving the emission of a proton and an alpha-particle has been observed by bombarding aluminum with 14-Mev deuterons. By an analysis of its excitation function, it is shown that the activity is not generated by the well-known (n, α) reaction, but is the result of the multiple disintegration of the compound nucleus $(Al^{27}+d)$.

INTRODUCTION

IN the course of the investigation of excitation functions of reactions induced in magnesium by deuterons, two important radioactive isotopes were produced and studied: the 3.0-year isotope Na^{22} produced from Mg^{24}, and 14.8-hour Na^{24} from Mg^{26}, both by the (d, α) reaction on these stable isotopes of magnesium. The excitation functions were found by use of the stacked foil technique[1] in which a series of aluminum foils coated with evaporated magnesium was bombarded with 14-Mev deuterons. The reaction $Mg^{24}(d, \alpha)Na^{22}$ yielded the expected curve,[2] but the curve of Na^{24} *vs.* deuteron energy was anomalous in that it showed a sudden rise at high bombarding energies. Further investigation of this excitation function showed that the increased activity at the high energy end was being generated in the aluminum foils.

The only manner in which Na^{24} has been reported produced from Al^{27} is through the (n, α) reaction, and this would not be expected to show a sharp decrease in excitation through a stack of foils only $\frac{1}{2}$ mm in thickness. The new excitation curve, therefore, was studied in some detail in an effort to ascertain the reaction actually taking place.

EXPERIMENTAL PROCEDURE

A number of aluminum foils were first stacked up and bombarded with the full deuteron beam of the M.I.T. cyclotron. Half-life measurements and a chemical analysis of the activity induced in the first few foils were carried out, the results of which confirmed the assumption that the isotope being produced from the aluminum was 14.8-hour Na^{24}. A stack of fifty foils, each 4.55 mg/cm^2 thick, was then prepared from sections of aluminum sheet of known area and weight. Variations in thickness of the foils were found by this means to be less than 1 percent. After the deuteron beam energy had been determined,[1] the stack of foils was given a deuteron exposure of 0.81 microampere hour and allowed to decay for two days to remove the shorter lived components.

Activities in the fifty foils were measured on a bell-type mica-window beta-ray counter[3] and a scale-of-128 circuit. An aluminum absorber of 80 mg/cm^2 was used to bring the counting rate to a few thousand counts per minute, and each foil was placed on the absorber to minimize changes in geometry from sample to sample; the distance between counter and absorber was increased to handle the higher intensities in the first few foils. Readings were corrected for background, about 5 percent of the lowest observation, and for decay of the Na^{24} during measurement. Finally the stack of foils as a whole was compared with a 10-microgram radium standard on a calibrated platinum screen wall gamma-ray counter,[4] and was found to contain[5] 3.30 rd of Na^{24} at the time of bombardment; this quantity was used to determine the absolute cross section of the reaction.

The activities induced in the foils were then plotted as a function of deuteron bombarding

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[1] E. T. Clarke and J. W. Irvine, Jr., Phys. Rev. 66, 231 (1944).
[2] E. T. Clarke and J. W. Irvine, Jr., Phys. Rev. 69, 680 (1946).
[3] W. Good, A. Kip, and S. Brown, Rev. Sci. Inst. 17, 262 (1946).
[4] A. Roberts, L. G. Elliott, J. R. Downing, W. C. Peacock, and M. Deutsch, Phys. Rev. 64, 268 (1943).
[5] 1 rutherford (rd) = 10^6 disintegrations per second; E. U. Condon and L. F. Curtiss, Phys. Rev. 69, 672 (1946).

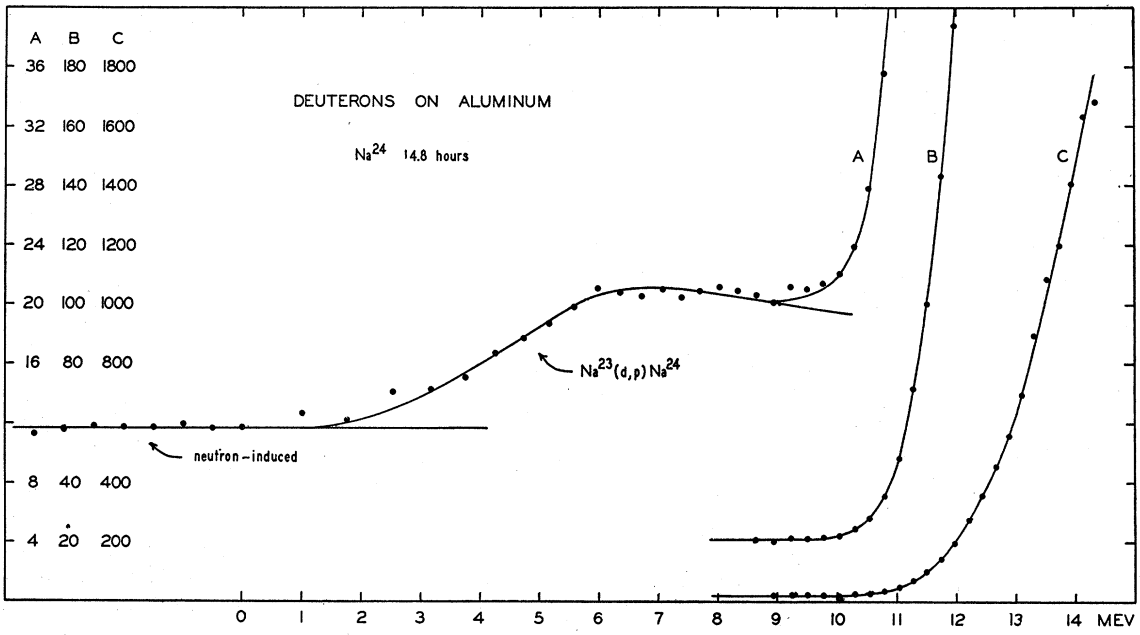

FIG. 1. Experimental excitation function of Na^{24} obtained by bombardment of aluminum foils. The ordinates, given for three ranges, are absolute, though in arbitrary units such that $1000 = 1.74 \times 10^7$ disintegrations/minute at bombardment time. Activation beyond the deuteron range is neutron induced. The $Na^{23}(d, p)Na^{24}$ activity is caused by the presence of 0.02 percent sodium contamination.

energy, the result of which is presented in Fig. 1. The curve can be divided into three distinct sections: the initial part, beyond the range of the deuterons, showing a constant excitation due to neutron activation, probably both by $Al^{27}(n, \alpha)Na^{24}$ and by $Na^{23}(n, \gamma)Na^{24}$; a region from 1 to 9 Mev in which activation first rises and then levels off with increase in bombarding energy, ascribable to sodium contamination in the aluminum metal since the curve corresponds to 0.02 percent Na producing $Na^{23}(d, p)Na^{24}$; and the interval from 9 to 14.5 Mev in which the new reaction sets in with a rapidly increasing cross section with rise in energy.

INTERPRETATION OF DATA

From the appearance of the experimental excitation function it seemed apparent that the rapid rise in production of Na^{24} with deuteron energy could not reasonably be ascribed to neutron (n, α) activation, since practically all of the product was generated in the first 0.3 mm of the aluminum target. The constant amount of Na^{24} generated in each foil beyond the range of the deuterons further bore out the hypothesis that targets of thicknesses of the order of deuteron ranges are thin for neutrons, and that no appreciable variation in neutron excitation, at least in light elements, can be expected in them.

It remained, therefore, to consider the possible deuteron reactions which might be responsible for the observed results. In disintegrating from ${}_{13}Al^{27} + {}_1H^2 \rightarrow {}_{11}Na^{24}$, 5 units of mass and 3 of charge must be emitted. Table I shows the four possible ways, together with the calculated threshold energies, in which the transition can result in emission of known elementary particles. It is evident that the only possible reaction is that of emission of a proton and an alpha-particle, all other modes requiring considerably more energy than can be imparted by 14-Mev deuterons.

Assuming that the reaction $Al^{27}(d; p, \alpha)Na^{24}$ takes place through the formation and disintegration of a compound nucleus (the Oppenheimer-Phillips mechanism has no meaning at deuteron energies high compared to that of the barrier, since in this region the deuteron break-up occurs inside the target nucleus), the shape of the excitation curve should, by analogy with

(n, p) and (n, α) excitation functions, be governed by the penetrabilities of the proton and the alpha-particle outward through the nuclear barrier. In the case of proton emission followed by loss of an alpha-particle, the total average penetrability can be expressed:

$$\bar{P}_{p,\alpha}(E_1)=\frac{1}{E_1}\int^{E_1} P_p(E_p)P_\alpha(E_\alpha)dE_p, \quad (1)$$

where E_1 represents the total available energy for the two particles, E_p and E_α the energies (including recoil), and P_p and P_α the individual penetrabilities of the proton and of the alpha-particle, respectively. The energies are related by the equation $E_1=E_p+E_\alpha$. A similar integral can be formed for the case of alpha-emission followed by proton loss; it will be slightly different because of differences in the masses and charges of the emitting nuclei.

In order to predict the absolute cross section for the $(d; p, \alpha)$ reaction, it is assumed that in the process of decay of the compound nucleus, any particle or set of particles energetically possible will emerge, and that the relative proportions of the various products are determined mainly by the probability of formation k_x of the emergent particles in the nucleus and by their penetrability P_x through the nuclear barrier. The cross section $\sigma_{d,x}$, then, may be written

$$\sigma_{d,x}=Q_c k_x P_x/\Sigma k_x P_x,$$

where Q_c is the probability of formation of a compound nucleus, and the summation extends over all possible products, including multiple disintegrations. In the assumed decay mechanism, the factor $k_x=1$ for elementary particles, less than unity for combinations such as alpha-particles.

Accordingly,

$$\sigma_{d,\alpha}=Q_c k_\alpha P_\alpha/\Sigma k_x P_x \quad (2)$$

and

$$\sigma_{d;\,p,\alpha}=Q_c k_p k_\alpha \bar{P}_{p,\alpha}/\Sigma k_x P_x;$$
$$\sigma_{d;\,\alpha,p}=Q_c k_\alpha k_p \bar{P}_{\alpha,p}/\Sigma k_x P_x. \quad (3)$$

The observed cross section should equal the sum of $\sigma_{d;p,\alpha}+\sigma_{d;\alpha,p}$. Adding Eqs. (3) and substituting $Q_c k_\alpha/\Sigma k_x P_x=\sigma_{d,\alpha}/P_\alpha$ obtained by rearrangement of Eq. (2), we find

$$\sigma_{\text{obs}}=k_p\frac{\sigma_{d,\alpha}}{P_\alpha}\bar{P}_{p,\alpha}+k_p\frac{\sigma_{d,\alpha}}{P_\alpha}\bar{P}_{\alpha,p}=\sigma_{d,\alpha}(\bar{P}_{p,\alpha}+\bar{P}_{\alpha,p}) \quad (4)$$

since $P_\alpha=1$ because the energy region in question is considerably above the barrier energy for the (d, α) reaction (6.5 Mev).

The deuteron energy E_d is corrected for recoil of the $(Al^{27}+d)$ compound nucleus and related to the total available energy E_1 by the formula

$$E_d=\frac{M+m}{M}(E_1-Q), \quad (5)$$

where M is the mass of Al^{27}, m the deuteron mass, and Q the reaction energy of the reaction $Al^{27}(d; p, \alpha)Na^{24}$.

In the determination of the quantities $\bar{P}_{p,\alpha}(E_1)$ and $P_{\alpha,p}(E_1)$, the only arbitrary factor is that of the nuclear radius. The value used here was that reported both by Grahame and Seaborg[6] and by Sherr,[7] who found $R=5.43\times10^{-13}$ cm for aluminum by measuring both elastic and inelastic scattering of fast neutrons from various targets. This radius was divided by $A^{\frac{1}{3}}=3.00$ to obtain the standard nuclear radius $r_0=1.81\times10^{-13}$ cm which was then applied to the penetrability formulae given by Bethe.[8] These penetrabilities were inserted in Eq. (1) and integrated graphically.

Since the (d, α) cross section for aluminum has not as yet been measured, the previously determined excitation function[2] for the reaction $Mg^{26}(d, \alpha)Na^{24}$ was used as an approximation. The general trend of these reactions at high energies is a decrease inversely proportional to the deuteron energy, and therefore the cross section can be expressed as a function of E_d

TABLE I. Threshold energies for possible reactions.

Particles emitted $(Al^{27}+d)-Na^{24}$	Deuteron threshold energy, Mev
$\alpha+p$	5.3
He^3+d	25.2
$2d+p$	30.8
$3p+2n$	35.5

[6] D. C. Grahame and G. T. Seaborg, Phys. Rev. **53**, 795 (1938).
[7] R. Sherr, Phys. Rev. **68**, 240 (1945).
[8] H. A. Bethe, Rev. Mod. Phys. **9**, 161 (1937).

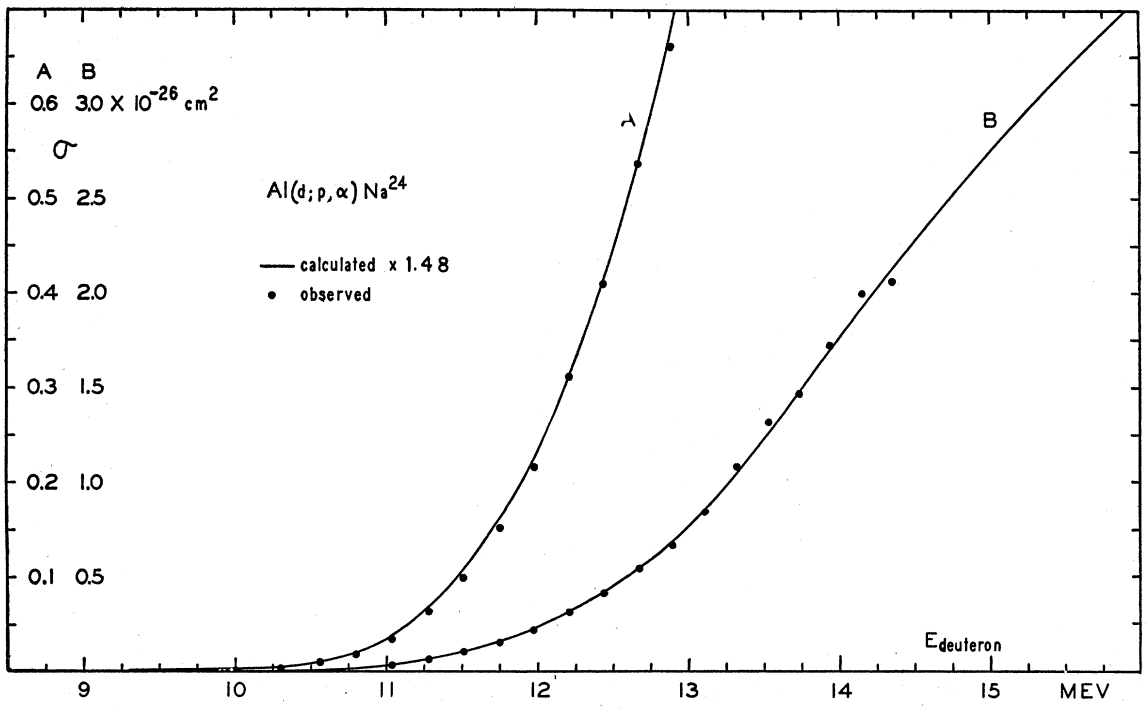

FIG. 2. Comparison of predicted excitation of $Al^{27}(d; p, \alpha)Na^{24}$ with the observed data. The calculated absolute values are within a factor of two of those found experimentally. Two ordinate scales are used to show the correspondence at lower energies.

(in Mev):

$$\sigma_{d,\alpha} = (7.0/E_d) \times 10^{-25} \text{ cm}^2. \quad (6)$$

Using Mattauch's[9] values for the neutral masses of Al^{27}(26.98980) and Na^{24}(23.99779), the reaction energy Q was found to be -4.90 ± 0.30 Mev. However, since only the difference in masses between Al^{27} and Na^{24} was needed, an independent calculation for Q was carried out, using the reaction[10] $Mg^{24} + {}_2He^4 \rightarrow Al^{27} + {}_1H^1 - 1.82$ Mev and the recently determined[11] beta-ray disintegration $Na^{24} \rightarrow Mg^{24} + 5.51$ Mev; this yielded $Q = -5.10$ Mev. An average value of $Q = -5.0$ Mev was used here since Mattauch had employed an erroneous figure (5.3 Mev) for the Na^{24} disintegration energy in checking his mass determinations.

The results of these calculations, compared with the experimental cross sections, are given in Fig. 2, where the predicted curve, multiplied by 1.48, is seen to fit the observed points. The effects of different assumed values for the quantities r_0 and Q were tested; it was found that these could be changed only by very small factors and still retain the shape of the experimental curve. With r_0 held constant, Q is determined to 0.1 Mev by this criterion, while r_0 could be varied only by about 0.1×10^{-13} cm with Q held within the limits of its probable error (0.3 Mev). The absolute cross section can be changed by about a factor of two by adjusting the variables within the limits given above, showing that the observed agreement is well within the probable error.

From the foregoing analysis there can be little doubt that the observed reaction is indeed $Al^{27}(d; p, \alpha)Na^{24}$, and that it proceeds by means of a compound nuclear mechanism. The existence of this reaction, and the success of the assumption regarding the competition for decay of the compound nucleus, also suggest an explanation for the decrease above the nuclear barrier with

[9] S. Flügge and J. Mattauch, Physik. Zeits. 44, 181 (1943).
[10] Observed by Duncanson and Miller, Proc. Roy. Soc. 146, 396 (1934); and Q values recalculated by M. S. Livingston and H. A. Bethe, Rev. Mod. Phys. 9, 300 (1937).
[11] L. G. Elliott, M. Deutsch, and A. Roberts, Phys. Rev. 63, 386 (1943).

increasing energy, observed in experimental deuteron-induced excitation curves: competition from reactions involving the emission of a second particle. The familiar $(d, 2n)$ is a special case of such reactions, in that the outgoing particles are not limited by the necessity of penetrating the Coulomb barrier and can therefore be produced with deuterons of moderate energies. The $(d; p, n)$ and $(d; n, p)$ reactions which must compete with the (d, p) and (d, n) would be difficult to observe, since they lead back to the target isotope and could be found by these techniques only where excited states of these isotopes exist. For light elements in general, where barriers are low for deuterons, the $(d; n, \alpha)$ and $(d; \alpha, n)$ reactions usually lead to stable isotopes. With the higher deuteron energies now becoming available, many more of these multiple disintegrations should be found.

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Thermal Ionization of Impurity Levels in Semi-Conductors†

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The probability of ionization of an impurity level by thermal agitation in a semi-conductor is estimated by the use of a simple Debye model. It is found that the probability of ionization by one phonon decreases exponentially with the depth of the impurity level below the conduction band, approaching zero as the energy separation becomes equal to $k\theta_D$. The probability of ionization by more than one quantum is also estimated by the use of an Einstein model. It appears that the probabilities so calculated may play an important role in determining the frequency dependence of the rectification efficiency in crystal rectifiers.

INTRODUCTION

THE electrical properties of many semi-conductors are determined primarily by the presence of impurities that introduce discrete electronic energy levels which lie between the empty conduction band of the semi-conductor and the next lowest lying filled electronic band. These discrete energy levels may act either as acceptor levels or as donator levels. In the first case, they lie near the top of the filled band, are empty at zero temperature, and can accept electrons from the filled band, thus producing "hole conduction." In the second case, the levels lie near the bottom of the empty band, are full at zero temperature, and can donate electrons to the empty band, thus augmenting the intrinsic electronic conduction. The two situations are represented schematically in Fig. 1 and Fig. 2, respectively. In the following discussion we shall consider only donator levels, which produce the so-called N-type semi-conductors, with the understanding that our conclusions are also applicable to acceptor levels forming P-type semi-conductors.

When a semi-conductor is placed in contact with a metal, a rectifying junction may be formed if the relative work functions of metal and semi-conductor are suitable. In the case of an N-type semi-conductor, the effective work function of the metal must be larger than that of the semi-conductor. Then the equilibrium situation near the junction is as represented schematically by the potential diagram of Fig. 3.[1] Practi-

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[1] F. Seitz and S. Pasternack, "The Principles of Crystal Rectifiers," NDRC Report No. 01-102, June 10, 1942.