The curve drawn through the experimental points in Fig. 7 has the form

$$f(\theta)=A+\sin^2\theta(1+2\beta\cos\theta),$$

with $A=0.132\pm0.041$ and $\beta=0.1$. Fitting the above parameters to the data was done in the usual manner of folding the observed angular readings about 90° as illustrated in Fig. 8, in which

$$\phi(\theta)=\tfrac{1}{2}[f(\theta)+f(180°-\theta)]=A+\sin^2\theta$$

is plotted against $\sin^2\theta$. The resulting points should fall on a straight line whose intercept with the $\sin^2\theta$ axis gives the value of A independent of the value of β. The straight line drawn through the data of the figure is determined by the method of least squares. The observed value for A is consistent, for the most part, with previous observations of less accuracy at slightly reduced energies.

Similarly, β can be determined independent of the assumed value for A by plotting $f(\theta)-f(180°-\theta)$ against $\sin^2\theta\cos\theta$. The determination of β is subject to considerably greater statistical uncertainty. Its order of magnitude does, however, agree well with what should be expected at these energies and represents an additional check on the experiment.

Integration of the angular distribution leads to a value of the total cross section,

$$\sigma=5.4\times10^{-28}\text{ cm}^2.$$

The uncertainty in the total cross section is large, and its agreement with the calculated value of Marshall and Guth for 50 percent exchange (5.5×10^{-28} cm^2) is fortuitous.

The size of the isotropic term A in the measured angular distribution can arise only from the noncentral part of the neutron-proton interaction. Austern has attempted to estimate the quantitative effects resulting from the noncentral potential on the isotropic term and has shown that the results are sensitive to both the shape and percent of exchange in the tensor term. The calculations are not of sufficient accuracy to permit further conclusions at this time.

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The Excitation Function for the $Al^{27}(d,\alpha p)Na^{24}$ Reaction*

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The absolute cross section for the $Al^{27}(d,\alpha p)Na^{24}$ ($T_{\frac{1}{2}}=15.1$ hr) reaction has been measured as a function of deuteron energy from the threshold to 190 Mev. Targets were irradiated on the Berkeley 60-inch and 184-inch cyclotrons. The observed threshold is 11.0±0.5 Mev; and the excitation function has a pronounced peak of 53 millibarns at approximately 22 Mev, falls to a broad minimum of 18 millibarns in the region of 60 Mev, and then rises slowly to 22 millibarns at 190 Mev.

INTRODUCTION

THE excitation function for the $Al^{27}(d,\alpha p)Na^{24}$ reaction has been measured as a function of deuteron energy from the threshold to 190 Mev by the stacked foil technique. The absolute cross section for the reaction as a function of energy is of particular interest since the Na^{24} induced in aluminum foils irradiated concurrently with targets in the internal circulating beam of the Berkeley 184-inch frequency-modulated cyclotron can be used to monitor the deuteron beam where direct measurement is not possible. Na^{24} has a convenient half-life (15.1 hours)[1] for counting and is the principal activity produced by high energy deuteron bombardment of aluminum. $F^{18}(T_{\frac{1}{2}}=112\text{ min})$ is the major interfering nuclide,[2] and this activity has decayed sufficiently 8 to 10 hours after bombardment that it is no longer detectable.

The excitation function has been measured previously for the energy region of interest,[3] but in these experiments no attempt was made to correct for losses of beam due to multiple Coulomb scattering and nuclear absorption, and errors due to loss of Na^{24} by recoil or Na^{24} induced by stripped and high-energy neutrons formed in the process of degrading the deuteron energy by the use of copper absorbers.

The absolute cross section of the $Al^{27}(d,\alpha p)Na^{24}$ reaction has previously been measured for 190-Mev deuterons;[4] but in view of the importance of the absolute value for the cross section, this measurement was repeated.

PROCEDURE

Irradiations

Targets for the Berkeley 184-inch cyclotron were irradiated in the internal circulating beam and in the

* This work was done under the auspices of the U. S. Atomic Energy Comission.
[1] J. H. Sreb, Phys. Rev. 81, 469 (1951).
[2] F. O. Bartell and S. Softky, Phys. Rev. 84, (1951).
[3] W. W. Meinke, Ph.D. thesis, University of California, (unpublished).
[4] H. Hubbard, Phys. Rev. 75, 1470 (1949).

internal and external electrostatically deflected beam for the energy region from threshold to 190 Mev.

The targets for the internal circulating beam were 1- and 2-mil aluminum foils about 1.5 cm long and 0.5 cm wide with 1-mil aluminum guard foils. The aluminum foils were clamped in target holders which were attached to the movable probe head of the cyclotron, and the bombarding energies were adjusted by fixing the radial distance of the target from the origin of the beam. Since degradation of the energy and intensity of the high-energy deuterons in passing through these foils is essentially negligible, the targets could be considered as thin targets. The beam intensity was approximately 1 microampere.

The targets for the internal and external electrostatically deflected beam were circular 1- and 2-mil aluminum foils of sufficient diameter that any scattered beam would be incident upon each foil. The relative cross sections for the energy region from threshold to 190 Mev were determined by interspersing the aluminum foils between copper absorbers used to degrade the energy of the incident deuterons. The aluminum target foils were placed between aluminum guard foils to protect the targets from recoils from the copper[5] and to make corrections for loss of Na^{24} due to recoils[6] unnecessary. Aluminum foils were placed beyond the range of the deuterons in order that corrections could be made for Na^{24} induced by high-energy neutrons. For the absolute cross-section measurements of the $Al^{27}(d,\alpha p)Na^{24}$ reaction at 190 Mev, the irradiations were done in the external electrostatically deflected beam. Single foils with guard foils were irradiated and the beam intensity measured by a Faraday cup arrangement as discussed in the section on beam current measurements. Collimators of $\frac{3}{4}$-inch diameter were used, and the intensities were approximately 10^{-2} and 10^{-4} microampere in the internal and external electrostatically deflected beams, respectively.

The bombardments on the 60-inch cyclotron were done in the deflected beam and a $\frac{1}{8}$-inch collimator was used. The beam intensity was approximately 1 microampere, and irradiations covered the energy region from threshold to 19 Mev.

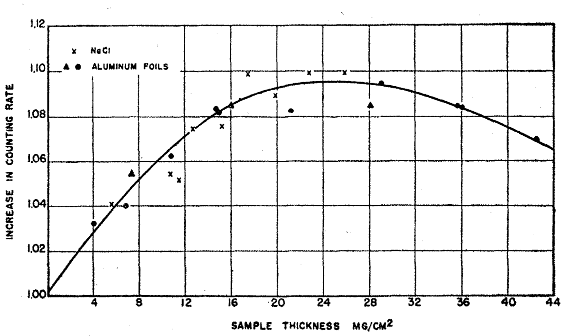

FIG. 1. Effect of sample thickness on counting rate.

Absolute Beta Counting

The foils were counted on an end-window, argon-filled, chlorine-quenched Geiger counter tube used in conjunction with a scaling circuit. All samples were counted on "infinite" aluminum backing. The counting yield of the particular working arrangement was determined relative to a 4π geometry counter.

The following procedure was used in determining the counting yield. The disintegration rate of an aliquot from a standard carrier-free solution of Na^{24} was measured in the 4π geometry proportional counter. Equal aliquots of this standard solution were placed in solutions containing varying amounts of NaCl carrier, the NaCl precipitated and placed on 1-cm^2 aluminum plates. The plates were counted in the working arrangement, and in this way the counting yield was determined as a function of sample thickness. In order to check these determinations, a stack of aluminum foils of varying thicknesses were irradiated with a well-collimated beam of 190-Mev deuterons, and the apparent specific activity measured as a function of sample thickness. The results of this determination were normalized to those from the NaCl measurements. As can be seen from the results in Fig. 2, the shape of the curve of counting rate as a function of sample thickness is the same for aluminum as it is for NaCl within experimental error. The NaCl data in Fig. 1 were normalized to a weightless aliquot of the carrier-free solution of Na^{24} counted on infinite aluminum backing.

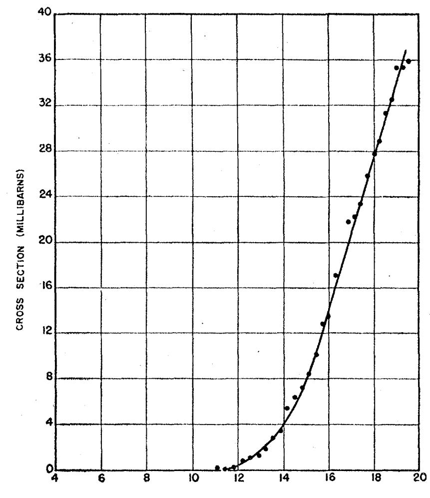

FIG. 2. Excitation function for the $Al^{27}(d,\alpha p)Na^{24}$ reaction, threshold to 19 Mev.

Beam Current Measurements

The absolute cross section measurements at 190 Mev were made in the externally deflected beam of the 184-

[5] R. E. Batzel and G. T. Seaborg, Phys. Rev. 82, 607 (1951).
[6] S. Fung and I. Perlman, Phys. Rev. 87, 623 (1952).

inch cyclotron. Aluminum foils sandwiched between guard foils were placed on the face of the Faraday cup which was used to measure the amount of beam incident upon the target. The Faraday cup and vacuum system was the same as that used by Peterson *et al.*[7] in determining the $C^{12}(p,pn)C^{11}$ cross section. The only difference in experimental arrangement was the integrating system, which in this case employed a vacuum-tube electrometer instead of a slide-back voltmeter to indicate voltage across the integrating capacitor.

Capacitors used for current integration were polystyrene dielectric units of very high leakage resistance, calibrated to better than 1 percent by both ac and dc methods. The vacuum-tube electrometers were standard Radiation Laboratory circuits of the self-balancing type, having grid currents of approximately 10^{-15} amp, whose output actuated a Leeds and Northrup "Speedomax" recorder. When the recorder pen reached full-scale deflection, a remote relay momentarily shorted the input capacitor. Thus, even on long runs the voltage across the integrating circuit was never very great. Using conventional techniques, this voltage measuring system was calibrated to better than 1 percent.

A conventional Faraday cup arrangement was used for the 19-Mev measurements on the 60-inch cyclotron. The Faraday cup was evacuated to the same pressure as the cyclotron vacuum system, approximately 2×10^{-5} mm, and the field from the cyclotron magnet at the position of the Faraday cup was about 8000 gauss, easily precluding errors due to secondary electron emission. Because of the higher beam currents available for these measurements, a simpler beam integrator was employed. This system used a biased trigger circuit to actuate the capacitor shorting relay, indicating the number of operations on an electromechanical impulse register. Although differing in some details, the system resembled the combined current indicator and integrator described by Higinbotham and Rankowitz.[8] The limit of error in beam measurements on both cyclotrons has been taken as 1 percent, although both integrators were calibrated more accurately than this figure.

RESULTS

The absolute cross section for the $Al^{27}(d,\alpha p)Na^{24}$ reaction was found to be 22 millibarns for 190-Mev deuterons and 36 millibarns for 19-Mev deuterons. The excitation function for the energy region from threshold to 19 Mev is shown in Fig. 2, and the complete excitation function curve is shown in Fig. 3.

The values of the cross section for the excitation functions were corrected for neutron background, and in the case of the 184-inch bombardments, for nuclear absorption of the deuteron beam. The degradation of the deuteron beam intensity as a function of distance traversed in the absorber stack was calculated by assuming that copper has an effective cross section of 1.6 barns for deuterons. The neutron background for the 60-inch cyclotron determinations was assumed to be constant throughout the stack and was resolved on this basis.

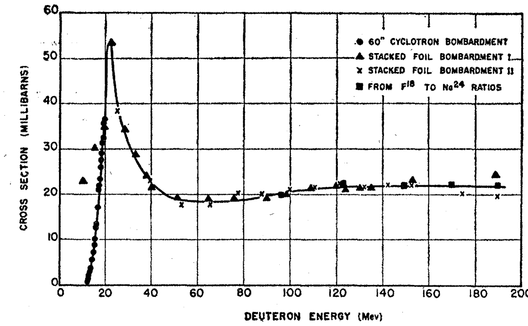

FIG. 3. Excitation function for the $Al^{27}(d,\alpha p)Na^{24}$ reaction.

For the 184-inch cyclotron measurements the contribution of the neutron induced activity was resolved by two methods. In one series of experiments the relative excitation function for the formation of F^{18} from aluminum was measured by the stacked foil technique. The neutron contribution to the formation of F^{18} was found to be negligible, undoubtedly because of its high threshold for formation (approximately 50 Mev).[2] The only assumption necessary for obtaining a good relative excitation function for the reaction was the cross section for nuclear absorption of the deuteron beam. The ratio of F^{18} to Na^{24} counts per minute formed by deuteron irradiation was then measured as a function of energy from 50 to 190 Mev by bombarding thin targets in the internal circulating beam where the neutron background is unimportant. Thus, the cross section for formation of Na^{24} was measured as a function of energy in terms of observed counts of F^{18} with no attempt being made to correct the observed F^{18} counts to number of atoms formed, and with essentially no neutron background present. The second method was the actual resolution of the neutron background from the observed activity by assuming that the activity in the aluminum foils placed beyond the range of 190-Mev deuterons was induced by stripped and knock-on neutrons with a strong forward component of momentum formed with a constant cross section and absorbed with a 1-barn cross section by the copper. As can be seen from the results in Fig. 3, the cross sections determined by the two methods checked very well.

The peak of the excitation function from 20 to 25 Mev is inherently ill-defined for two reasons; first, the distribution in energies due to straggling of the deuterons after their passage through sufficient absorber to cut the energy to 25 Mev, and secondly, the initial energy spread of the external deflected deuteron beam. For example, an initially monochromatic beam of 190-Mev deuterons would have a mean square fluctuation in energy of about 4 Mev at 20 Mev. An initial energy

[7] Aamodt, Peterson, and Phillips, Phys. Rev. **88**, 739 (1952).
[8] W. A. Higinbotham and S. Rankowitz, Rev. Sci. Instr. **22**, 688 (1951).

uncertainty of 2 Mev would lead to an energy difference of 20 Mev at an energy of 20 Mev and an energy difference of 6 Mev at 50 Mev.

As stated above, the energy scale at energies below 50 Mev, because of the uncertainty in incident deuteron energy, is subject to serious question. In order to remove the ambiguity in the deuteron beam energy, the energy scale was fixed by fitting the low-energy side of the excitation function peak to the curve resulting from the measurements on the 60-inch cyclotron. Calculations showed that an assumed incident deuteron energy of 190 Mev gave the best fit to the data in the low-energy region.

The threshold for the reaction has been measured previously[9] and is in agreement with the threshold (11.0±0.5 Mev) observed in the 60-inch cyclotron irradiation.

DISCUSSION

It is difficult to understand the large disagreement between the results of this work (22 millibarns) and the reported value (48 millibarns)[4] for the absolute cross section measurement of the $Al^{27}(d,\alpha p)Na^{24}$ reaction at 190 Mev. However, the details of the previous work were never published, and it is felt that the errors inherent in the present measurements are considerably less than ±10 percent.

Clarke[9] has shown that the shape of the $Al^{27}(d,\alpha p)Na^{24}$ excitation function in the energy region from threshold to 14 Mev is that expected by compound nucleus formation with the subsequent evaporation of the proton and alpha particle. The shape of the excitation function from 14 Mev on up to 40 Mev is still characteristic of compound nucleus formation. Undoubtedly, however, there is some contribution to the reaction in this energy region due to electrical[10] and mechanical[11] stripping of the deuteron with the neutron of the deuteron causing an $Al^{27}(n,\alpha)Na^{24}$ reaction.

Above 40 to 50 Mev, compound nucleus formation becomes relatively less important, and single nucleon-nucleon collisions (including stripping followed by emission of nucleons) become important. At 60 Mev, the proton of the deuteron has sufficient energy to produce Na^{24} by the $Al^{27}(p,3pn)Na^{24}$ reaction.[12] This is true at deuteron energies below 60 Mev but with lower probability due to the momentum of the proton within the deuteron. The increasing probability, as the energy of the deuteron increases, that either nucleon of the deuteron can leave sufficient excitation energy with the nucleus to cause Na^{24} to be formed by the emission of single nucleons from the excited nucleus, probably accounts for the rise in cross section with deuteron energy above 60 Mev.

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[9] F. T. Clarke, Phys. Rev. **71**, 187 (1947).

[10] S. M. Dancoff, Phys. Rev. **72**, 1017 (1947).

[11] R. Serber, Phys. Rev. **72**, 1008 (1947).

[12] N. M. Hintz and N. F. Ramsey, Phys. Rev. **88**, 19 (1952).