Excitation Function for $Zn^{64}(n,2n)Zn^{63}$

D. R. KOEHLER AND W. L. ALFORD
Research Laboratory, Ordnance Missile Laboratories Division, Army Rocket and Guided Missile Agency, Redstone Arsenal, Alabama

(Received February 8, 1960)

The excitation function for $Zn^{64}(n,2n)Zn^{63}$ has been measured for neutron energies from 12.2 to 18.1 Mev by an activation method. An absolute cross section has been obtained by using the previously measured value of 167±11 mb at 14.4 Mev. Above threshold, the cross section is found to increase rapidly with neutron energy reaching a value of 337 mb at 18.1 Mev. A cross-section curve computed on the basis of statistical theory is shown for comparison.

INTRODUCTION

ALTHOUGH several measurements[1–6] of the $Zn^{64}(n,2n)Zn^{63}$ cross section have been made, only limited information has been obtained on the behavior of the excitation function near the 12.0 Mev[7] reaction threshold. In the present work particular attention has been given to this energy region as well as to an extension of the range of neutron energies employed by Cohen and White.[3] The relative yields of Zn^{63}, for neutrons in the energy range 12.2 to 18.1 Mev, were determined by counting the induced beta activity of 38 minute half-life.[8] The cross-section measurement of 167±11 mb by Rayburn[5] at 14.4 Mev has been used in assigning an absolute scale for the present curve.

EXPERIMENTAL PROCEDURE AND RESULTS

Using a 2-Mev Van de Graaff accelerator, a 300 $\mu g/cm^2$ tritium-zirconium target,[9] 1 cm in diameter, was bombarded by deuterons yielding neutrons through the $T(d,n)He^4$ reaction. Variation of neutron energy was achieved by selection of the deuteron energy as well as by irradiation of samples placed at various angles about the target.[10] The experimental arrangement was such that samples could be placed on a circular arc of 2-in. radius at any angle from 0° to 160° with respect to the incident deuteron beam. A neutron long counter[11] was employed for monitoring purposes; however, the differential cross-section measurements of Bame and Perry[12] were used in order to correct for variation in neutron yield with angle. Target cooling was effected by directing a jet of nitrogen gas onto the 0.25 mm platinum backing of the tritium-zirconium layer. The walls of the target extension were made of $\frac{1}{32}$-in. aluminum in order to minimize effects due to scattered neutrons.

Relative cross sections were determined by simultaneously irradiating four samples for a period of 75 minutes and subsequently measuring the induced beta activities by means of four shielded end-window (1.5–2.0 mg/cm^2) Geiger-Mueller counters. Measured activities were plotted as a function of time. An analysis of the decay curves showed the presence of activities of approximately 5 minute and 38 minute half-life after a subtraction of background counting rates. These activities were assumed to be due to the $Zn^{66}(n,p)Cu^{66}$ and $Zn^{64}(n,2n)Zn^{63}$ reactions, respectively. For each decay curve an extrapolation of the 38 minute activity to the time at which counting started gave the relative yields of Zn^{63}.

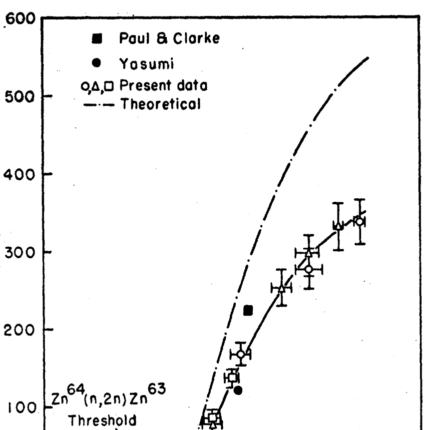

FIG. 1. The experimental $Zn^{64}(n,2n)Zn^{63}$ cross section as a function of incident neutron energy. Yasumi's result at 14.1 Mev and Paul and Clarke's value at 14.5 Mev are shown with the present data. The present data are indicated by the symbols, ○, △, □, each symbol representing the averaged results for one particular choice of four neutron energies, and corresponding to deuteron energies of 2.0, 1.5, and 0.8 Mev, respectively. The point at 12.2 Mev represents an upper limit for the cross-section value. A theoretical curve (broken line) is also given.

[1] B. L. Cohen, Phys. Rev. **81**, 184 (1951).
[2] E. B. Paul and R. L. Clarke, Can. J. Phys. **31**, 267 (1953).
[3] A. V. Cohen and P. H. White, Nuclear Phys. **1**, 73 (1956).
[4] S. Yasumi, J. Phys. Soc. (Japan) **12**, 443 (1957).
[5] L. A. Rayburn (private communication) and Atomic Energy Commission Report WASH-1018, 1959 (unpublished). The error quoted by Dr. Rayburn included the uncertainty in the $Cu^{63}(n,2n)Cu^{62}$ cross section on which his $Zn^{64}(n,2n)Zn^{63}$ measurement was based. The authors would like to thank Dr. Rayburn for this information.
[6] D. R. Koehler and W. L. Alford, Bull. Am. Phys. Soc. **4**, 405 (1959).
[7] V. J. Ashby and H. C. Catron, Atomic Energy Commission Report UCRL-5419, 1959 (unpublished).
[8] D. Strominger, J. M. Hollander, and G. T. Seaborg, Revs. Modern Phys. **30**, 636 (1958).
[9] The tritium-zirconium target was obtained from the Isotopes Division of Oak Ridge National Laboratory.
[10] J. L. Fowler and John E. Brolley, Jr., Revs. Modern Phys. **28**, 103 (1956).
[11] A. O. Hanson and J. L. McKibben, Phys. Rev. **72**, 673 (1947).
[12] S. J. Bame and J. E. Perry, Phys. Rev. **107**, 1616 (1957).

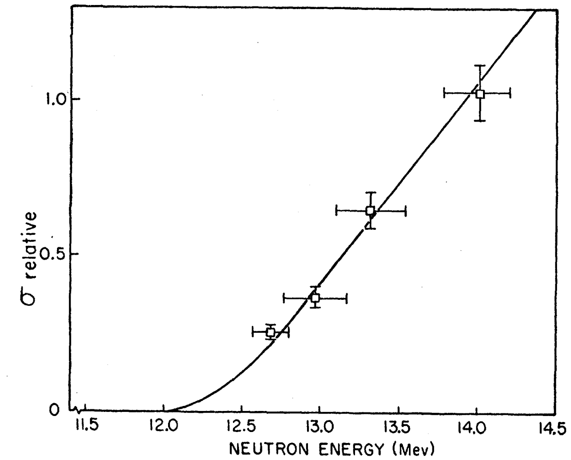

FIG. 2. Comparison of the $Zn^{64}(n,2n)Zn^{63}$ theoretical and experimental cross-section results near threshold. The solid curve represents the theoretical calculation of the relative excitation function.

The samples were made of reagent grade (99.99%) zinc metal in the form of $\frac{3}{8}$-in.$\times\frac{15}{32}$-in. rectangular sheets of thickness approximately equal to the range of the associated beta particle. Each sample consisted of two such sheets placed back to back when being irradiated and side by side when being counted. This procedure increased the number of betas counted while keeping the neutron energy spread relatively small. To reduce the errors arising from small differences in samples (less than 1% by weight) and in counter efficiencies (approximately 5% by calibration standard), the following technique was used. For a given choice of four sample positions, and the corresponding neutron energies, four runs were made. Each sample was assigned to a particular counter and during the course of the experiment was counted only by this particular counter. Sample position, however, was permuted for each run. This procedure resulted in each sample being exposed to the four neutron energies and subsequently each counter counting an activity induced by each of the four neutron energies.

Measured cross sections are shown in Figs. 1 and 2. In these figures, the neutron energy spread is shown as a horizontal bar. The main source of this spread was due to sample size (angular spread) since the thickness of the zirconium layer corresponded to only small energy decrements from 36 to 49 kev for the incident deuterons. Estimates of standard deviations, which amount to approximately $\pm 9\%$, are indicated by vertical lines, except for the 12.2-Mev point which is an upper limit for the cross section. Sources of error considered in these estimates were: (1) uncertainty in geometry and sample size; (2) contribution due to scattered and absorbed neutrons; (3) uncertainty in counting efficiencies; (4) the statistical error in counting; and (5) the error in the angular distribution of neutrons from the $T(d,n)He^4$ reaction as measured by Bame and Perry.[12] The indicated standard deviations do not include the errors due to the conversion from relative to absolute cross section.

The energy interval from 12.2 to 18.1 Mev was spanned by three sets of data, each set consisting of four neutron energies. These three sets corresponded to deuteron energies of 2.0, 1.5, and 0.8 Mev. Smooth curves were drawn through the cross-section results of each set and each curve was subsequently assigned an absolute scale by using Rayburn's value of 167 mb at 14.4 Mev.[5] A composite of the data is presented in Fig. 1. The cross sections as measured at 14.1 and 14.5 Mev by Yasumi[4] and Paul and Clarke,[2] respectively, are also indicated. A theoretical excitation function has been calculated according to statistical theory[13] and is presented as the dashed curve in Fig. 1. In the level density function $\omega(E)=C\exp(2a^{\frac{1}{2}}E^{\frac{1}{2}})$ the value $a=2.0$ was used[14] and a value of 12 was employed for the ratio of $C_{\text{odd odd}}$ to $C_{\text{even even}}$.[15] For these calculations, the cross sections for compound nucleus formation were taken from Blatt and Weisskopf,[13] assuming $r_0=1.5\times10^{-13}$ cm. Neutron and proton branching probabilities were calculated by numerical integration and other possible competing reactions were neglected. The theoretical curve is presented in Fig. 1 principally to show agreement in shape with the curve through the experimental points. The limitations[16] of the statistical theory should be recognized in attaching significance to this theoretical curve.

Figure 2 shows the cross section data near the 12.0-Mev threshold for the $Zn^{64}(n,2n)Zn^{63}$ reaction. Also shown is the relative theoretical excitation curve. For an incident neutron energy of 12.0 Mev, Zn^{64}, the intermediate nucleus in the $(n,2n)$ reaction, and Cu^{64}, the residual nucleus in the (n,p) reaction, have excitation energies up to approximately 11.8 Mev and 11.0 Mev,[7] respectively. Hence the level densities for both the even-even Zn^{64} and odd-odd Cu^{64} should be sufficiently great to meet the requirement of the statistical theory that many levels are involved in the reactions. Figure 2 is presented to show the qualitative agreement between the calculated curve and the experimental points near threshold. This figure shows on an expanded scale those points in Fig. 1 corresponding to an incident deuteron energy of 0.8 Mev.

The computations leading to the theoretical curve include a nonnegligible contribution from the $Zn^{64}(n,p)$ Cu^{64} decay channel. This results in a departure from the usual behavior of $n,2n$ cross sections where neutron emission is predominant when energetically possible. In general, the qualitative results of this experiment agree well with those of Cohen and White.[3] In the neutron energy range 13.0 to 17.5 Mev the relative cross sections found by these workers are consistent with the present results.

[13] J. M. Blatt and V. F. Weisskopf, *Theoretical Nuclear Physics* (John Wiley & Sons, Inc., New York, 1952), p. 340 ff.
[14] B. T. Feld, H. Feshbach, M. L. Goldberger, H. Goldstein, and V. F. Weisskopf, Atomic Energy Commission Report NYO-636, 1951 (unpublished).
[15] A. Poularikas and R. W. Fink, Phys. Rev. **115**, 989 (1959).
[16] R. G. Moore, Jr., Revs. Modern Phys. **32**, 101 (1960).