The $Cu^{63}(n,2n)Cu^{62}$ Cross Section as a Function of Neutron Energy near the Threshold*

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Using the $D(d,n)He^3$ reaction produced by 10.5-Mev deuterons to give monoenergetic neutrons, the $Cu^{63}(n,2n)Cu^{62}$ reaction has been studied in the vicinity of the threshold. The product of the differential cross section of the former reaction and the activation cross section of the latter is obtained as a function of angle to the bombarding deuteron beam. By calibrating the Geiger counters with beta-particles from Cu^{66} produced by the thermal neutrons on Cu^{65}, the data are made absolute in terms of the known thermal capture cross section. Previous measurements of the differential cross section of the $D(d,n)He^3$ reaction allow the $Cu^{63}(n,2n)Cu^{62}$ cross section to be given as a function of energy. An extrapolation of the data gives the energy required to remove a neutron from Cu^{63} as 11.2±0.3 Mev.

I. INTRODUCTION

FOR some time it has been known that fast neutron bombardment of copper produces a beta-activity of 10-minute period. This activity has been identified as being due to the positron emitter, Cu^{62}, which is formed by the $Cu^{63}(n,2n)Cu^{62}$ reaction.[1–4] Since the energetic threshold is in the neighborhood of 12 Mev, this reaction has been used a number of times as a fast neutron detector.[5–7] Because of its convenience as such a detector, the $Cu^{63}(n,2n)Cu^{62}$ reaction has been studied with monoenergetic neutrons from the threshold up to 14 Mev.

II. EXPERIMENTAL APPARATUS

The neutrons in this experiment were produced by the $D(d,n)He^3$ reaction, where the bombarding deuterons were accelerated to 10.5 Mev by the cyclotron. The focused deuteron beam was used 15 feet away from the cyclotron with three feet of water and paraffin shielding between the cyclotron and the experimental area. The apparatus for focusing and monitoring the beam as well as for measuring the deuteron energy has been discussed previously.[8] Figure 1 is a diagram of the reaction chamber showing the arrangement of the deuteron gas target and the copper foil holder. The beam from the cyclotron was defined to ±0.6 deg. when it entered the mica window of the gas target. Rutherford scattering in this window effectively increased this spread to ±0.9 deg.[8] Both the side port for counting charged particle reaction products produced by bombarding deuterons and the exit port for the beam were also covered with mica windows. On emerging from the target the deuterons were monitored by a Faraday cage which was mounted in the center of the exit tube of the reaction chamber.

In order to mount the copper samples (5-mil foils 2.5 in.×one in.) as near to the forward direction as possible, it was found necessary to support them in holders which were placed inside the reaction chamber as shown in Fig. 1. The foils were sandwiched between $\frac{1}{16}$-in. sheets of cadmium to reduce the five-minute activity due to the $Cu^{65}(n,\gamma)Cu^{66}$ reaction which is produced mostly by thermal neutrons. The foils were mounted with their long dimension vertical and with their center in the horizontal plane which passes through the center of the gas target. The angular position of each foil in the horizontal plane and the distance of each foil from the center of the target was determined before an activation run was made. The foils subtended an angle of about ± three deg. in the horizontal plane.

III. EXPERIMENTAL PROCEDURE AND RESULTS

After a bombardment of 15 to 20 minutes, the foils were counted on thin glass-walled Geiger counters. Three such counters were used and the foils were interchanged for intercalibration purposes. The decay curves

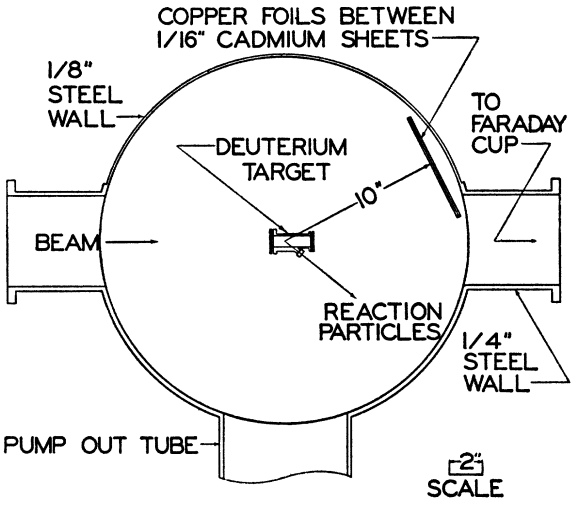

FIG. 1. Reaction chamber.

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were found to be primarily due to 10-minute activity except for foils near the $(n,2n)$ threshold, where the five minute period due to Cu^{66} produced by the (n,γ) process began to show up. It was found possible to analyze all the decay curves in terms of the 10-minute and five-minute period. In correcting the data to initial activation 10 minutes has been used as the half-life of Cu^{62}, which is the average of several determinations reported in the literature[1,2,9–12] weighted according to their quoted accuracy.

For a measurement of the 10-minute activity in the direction of the deuteron beam the beam was stopped with a gold plate and monitored by counting He^3 particles emitted through the side port of the target (Fig. 1) into a proportional counter. This determination was carried out in connection with studies of the $D(d,n)He^3$ reaction.[7]

The 10-minute activity due to background fast neutrons was determined by runs in which hydrogen was substituted for deuterium in the gas target. These background neutrons produced 10-minute activity which amounted to about five percent of the activity produced by the $D(d,n)He^3$ neutrons at 11 deg. to the direction of the beam. The background was roughly constant with angle from seven deg. to 40 deg.

A convenient calibration of the Geiger counters was possible, since the positron emitted by the Cu^{62} nucleus has an end-point energy about equal to the end-point energy of the electron emitted by Cu^{66} which is produced with thermal neutrons by the $Cu^{65}(n,\gamma)Cu^{66}$ reaction.[13] After an irradiation for a known time in a known thermal flux of the Los Alamos standard graphite pile, the copper foils were counted for several half-lives. By use of runs in which the foils were covered with cadmium a correction was obtained for the activity produced by neutrons above the thermal region (about four percent). Since the thermal capture cross section for producing Cu^{66} has been determined (0.56 ± 20 percent barn in normal copper),[14] this enables us to determine the efficiency of the Geiger counters.

The results of the experiment were calculated in terms of the product of the cross section for the $Cu^{63}(n,2n)Cu^{62}$ reaction produced by fast neutrons and the differential cross section of the $D(d,n)He^3$ reaction. It is apparent that the $(n,2n)$ cross section discussed here refers to the production of positron activity of 10-minute period. If Cu^{62} decays by other processes (K-capture for example) this will not show up in the measurements. The efficiency of the Geiger counters was included in the calculations by dividing the above product by the cross section of the $Cu^{65}(n,\gamma)Cu^{66}$ reaction for thermal neutrons in normal copper. When this ratio was plotted as a function of the angle to the direction of the deuteron beam the points obtained lay on a smooth curve within the limits expected from the counting errors and the errors involved in determining the other factors measured. The average energy of the bombarding deuterons as determined by magnetic deflection of the beam[8] was 10.5 ± 0.25 Mev.

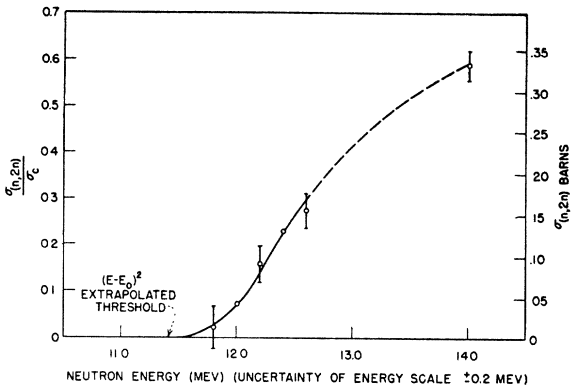

FIG. 2. Cross section of $Cu^{63}(n,2n)Cu^{62}$ reaction. For uncertainty of ordinate refer to left-hand scale which gives the ratio of the $Cu^{63}(n,2n)Cu^{62}$ cross section to the thermal capture cross section of the $Cu^{65}(n,\gamma)Cu^{66}$ reaction. Both cross sections are for activity produced in normal copper. The right-hand scale gives the $(n,2n)$ cross section directly and is based on 0.56 ± 20 percent barn (reference 14) as the thermal capture cross section.

Using data on elastic scattering of neutrons,[15–17] the results were corrected for the effect of the neutrons elastically scattered from the material of the reaction chamber behind the foils so that these neutrons pass through the foils more than once. The effect of neutrons absorbed by the material between the source and the foils was also estimated. Although these effects were small (the order of three percent) and were compensating over most of the angular region, at angles near the threshold of the $Cu^{63}(n,2n)Cu^{62}$ reaction the effect of the scattered neutrons predominated, so that the correction of about seven percent was applied to the data in this region. Over-all experimental checks of these correction factors were made which indicated the estimates were valid.

From the curves for the 10-minute activation as a function of angle and from the reported measurements of the differential cross section of the $D(d,n)He^3$ reaction,[7] the $Cu^{63}(n,2n)Cu^{62}$ cross section is plotted as a function of energy of the neutrons (Fig. 2). The uncertainty of the points as represented by the vertical lines refer to the ordinate scale on the left which gives the ratio of the $Cu^{63}(n,2n)Cu^{62}$ cross section to the $Cu^{65}(n,\gamma)Cu^{66}$ cross section. These uncertainties are estimated from the errors in the activation determina-

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tion as well as errors in the differential cross section curve for the $D(d,n)He^3$ reaction.[7] The range of the measurements given here indicated by the solid line extend only over the region in which the $D(d,n)He^3$ reaction has been studied directly by counting He^3 particles.[7] The point at 14 Mev is an independent determination by D. D. Phillips and R. W. Davis.[17] This was obtained with a known flux of 14-Mev neutrons and by use of the same method of calibration of Geiger counters as is described in this report. The dotted portion of the curve in Fig. 2 is an extrapolation between this 14-Mev point and the part of the curve obtained at lower energies. The ordinate scale on the right in Fig. 2 which gives the cross section of the $Cu^{63}(n,2n)Cu^{62}$ reaction is based on the reported value of 0.56 barn for the production of Cu^{66} in normal copper. The uncertainty of this scale is ± 20 percent and is the reported uncertainty of the capture cross section.[14]

A linear extrapolation of the points in Fig. 2 gives an apparent threshold of 11.7 ± 0.3 Mev for the $Cu^{63}(n,2n)Cu^{62}$ reaction, where the error in the energy is estimated from the uncertainty of the energy scale and the uncertainty of the extrapolation of the points. In a number of runs in which only relative values of activation were measured, independent determination of this threshold in this manner gave an average value of 11.8 ± 0.2 Mev. Within the limits of error, this is in agreement with previously reported determinations of the threshold of about 12 Mev.[1, 6, 18]

One expects the extrapolation discussed above not to be valid in the case of the $(n,2n)$ reaction. Consideration of the volumes in phase space available for the products of the $(n,2n)$ reactions suggests that the cross sections of these reactions should go to zero as $(E-E_0)^2$, where E_0 is the threshold. The curve in Fig. 2 through the lower energy points is an $(E-E_0)^2$ extrapolation, which gives a threshold of 11.4 ± 0.3 Mev. Correcting this value for the recoil energy of the compound nucleus, one obtains 11.2 ± 0.3 Mev as a neutron binding energy. This agrees within the limits of error with the threshold of the $Cu^{63}(\gamma,n)Cu^{62}$ reaction which has been determined to be 10.9 ± 0.3 Mev by betatron activation.[19]

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A Redetermination of the Relative Abundances of the Isotopes of Carbon, Nitrogen, Oxygen, Argon, and Potassium*

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Essentially pure samples of A^{36} and A^{40} have been produced by thermal diffusion and used for the preparation of synthetic argon isotope mixtures whose A^{36}/A^{40} isotope abundance ratios were very accurately determined. The mixtures were then employed for determining the mass discriminating effects in two mass spectrometers. Carbon, nitrogen, oxygen, argon, and potassium were investigated and new values given for the relative abundances of the isotopes. With atmospheric oxygen as a standard, the conversion factor between the physical and chemical atomic weight scales is 1.0002783 ± 5. The percentage abundance of K^{40} in potassium is found to be 0.0119 ± 0.0001 percent, a figure of special interest in geophysical problems, and approximately ten percent higher than the present accepted value.

THE general need for more precise information on nuclear constants suggests that a redetermination of isotope abundances in many of the elements may be of value. The existence of nearly pure samples of separated isotopes makes possible the preparation of artificial mixtures of isotopes whose relative abundances may be computed to a high degree of accuracy. The use of such standard isotopic mixtures together with mass spectrometers of modern design makes possible results in which both the accidental and systematic errors are reduced below those previously attainable. The present paper represents the beginning of a study of those elements where it appears redeterminations are of value and can profitably be made.

APPARATUS

Two mass spectrometers of the 60° type were used in the present investigation. One of these has already been described in detail.[1] During the past two years numerous minor modifications have been made in this instrument. The only one of interest here concerns the ion source. Plate J_3 has been eliminated, the space

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