Low-Lying Level Structure of the Zn^{65} Nucleus*†

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Sulfur and beryllium samples have been used as energy-selective neutron absorbers to investigate the low-lying level structure of the Zn^{65} nucleus. The transmission through the samples of the neutrons from the $Cu^{65}(p,n)Zn^{65}$ reaction was measured as a function of the proton energy and the known resonances in the neutron total cross sections of S and Be were observed for both the neutron group leaving Zn^{65} in the ground state and for a group leaving Zn^{65} in an excited state at 118 ± 8 kev. At a proton energy of 2.9 Mev, these two groups are of approximately the same intensity. The Q-value for the $Cu^{65}(p,n)Zn^{65}$ reaction was found to be -2.141 ± 0.005 Mev. The 585-kev resonance in S was observed with neutrons from the $V^{51}(p,n)Cr^{51}$ reaction and the threshold energy of 1.566 Mev for this reaction was confirmed.

INTRODUCTION

THE low-lying level structure of the Zn^{65} nucleus has been investigated by observing[1] the decay scheme of Ga^{65} and by measurements[2] made on neutron threshold energies in the $Cu^{65}(p,n)Zn^{65}$ reaction. The threshold measurements indicated an excited state of Zn^{65} at 785 kev and some higher excited states; no lower-lying levels were observed. The small cross section at bombarding energies near the ground-state threshold energy did not permit a careful search for levels below an excitation of about 200 kev, and although no neutron thresholds were observed in this region, the absence of low-lying states could not be established.

Crasemann[1] observed γ rays of energies 52, 92, and 114 kev in the decay of Ga^{65}. The 52-kev γ ray was tentatively assigned to an isomeric state of Ga^{65}. There was the possibility, however, that all three γ rays orignated in Zn^{65}, the decay product. Neutron thresholds corresponding to excited states in Zn^{65} at these energies would not have been observed by Brugger, Bonner, and Marion[2] unless they had been very intense.

An investigation of the neutron groups from the $Cu^{65}(p,n)Zn^{65}$ reaction using photographic plates could not furnish conclusive proof concerning the existence of low-lying states in Zn^{65} because of the limited resolution of this technique. Another possibility for performing an investigation of Zn^{65} levels is to use the $Cu^{65}(p,n)Zn^{65}$ reaction as a source of neutrons and observe the transmission of these neutrons through a sample whose neutron total cross section contains pronounced, isolated resonances. The occurence of resonances other than those due to the ground-state group of neutrons indicates the presence of additional neutron groups and, therefore, excited states of the residual nucleus. Such a method has been used previously by Stelson and Preston[3] in the study of neutron spectra from (p,n) reactions on medium-weight elements.

Strong resonances are known in the neutron total cross sections of sulfur[4,5] (585 ± 3 kev, $\Gamma=1.4$ kev) and beryllium[4,6] (620 ± 10 kev, $\Gamma=30$ kev) which are sufficiently far from neighboring resonances to permit the use of these elements as energy-selective neutron absorbers. Therefore, measurements of the transmission through samples of S and Be of the neutrons from the proton bombarding of Cu^{65} permit an investigation of the low-lying level structure of the Zn^{65} nucleus by observing the bombarding energies at which these resonances occur.

EXPERIMENTAL

A. Apparatus

The transmission measurements were carried out in the geometry shown in Fig. 1. The neutron detector was a modified long counter of the type described by Marion, Brugger, and Bonner.[2,7] The face of this counter was placed at a distance of 6 inches from the target and the

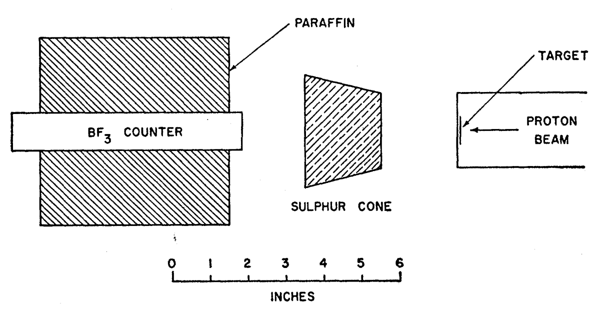

FIG. 1. Geometrical arrangement of the neutron detector and absorber sample used for making the transmission measurements.

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[1] B. Crasemann, Phys. Rev. **93**, 1034 (1954).
[2] Brugger, Bonner, and Marion, Phys. Rev. **100**, 84 (1955).
[3] P. H. Stelson and W. M. Preston, Phys. Rev. **83**, 469 (1951).
[4] D. J. Hughes and J. A. Harvey, *Neutron Cross Sections*, Brookhaven National Laboratory Report BNL-325 (Superintendent of Documents, U. S. Government Printing Office, Washington, D. C., 1955).
[5] Peterson, Barschall, and Bockelman, Phys. Rev. **79**, 593 (1950).
[6] C. K. Bockelman, Phys. Rev. **80**, 1011 (1950); Adair, Barschall, Bockelman, and Sala, Phys. Rev. **75**, 1124 (1949).
[7] Marion, Brugger, and Bonner, Phys. Rev. **100**, 46 (1955).

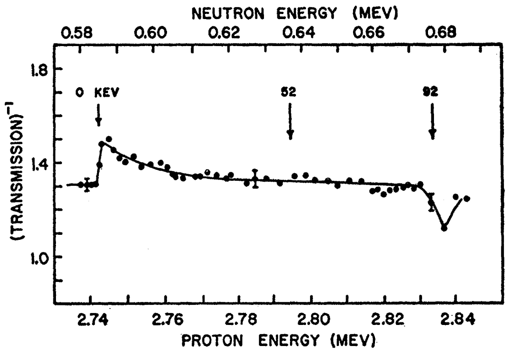

FIG. 2. Reciprocal of the transmission through a sulfur sample as a function of proton energy for neutrons from the $Cu^{65}(p,n)Zn^{65}$ reaction. The neutron energy values are for the ground-state group and are based on a Q-value of -2.131 Mev. The arrows indicate where resonances would occur for neutrons emitted to Zn^{65} states at 0, 52, and 92 kev. The indicated probable errors are typical standard deviations for a number of determinations at each energy.

absorber samples were located midway between the target and the detector. The sulfur sample was in the form of a truncated cone 2 inches in length as shown in Fig. 1, while the available beryllium samples was in the form of a cylinder 1.5 inches in diameter and 1.5 inches in length. The preparation of the targets of Cu^{65} used in this experiment has been described previously.[2] The separated isotope was obtained from the Stable Isotopes Division of the Oak Ridge National Laboratory.

Protons were accelerated in the Rice Institute 6-Mev Van de Graaff generator. The bombarding energy was determined by measuring the field strength in the 90° magnetic analyzer with a proton moment magnetometer.[7] The primary energy standard was the threshold for the $Li^7(p,n)$ reaction.[8]

B. 585-kev Resonance in Sulfur

The transmission measurements made with the sulfur cone absorber are shown in Fig. 2. The Cu^{65} target used was about 20 kev thick at a proton energy of 2.7 Mev and was rather nonuniform. The effect of the nonuniformity is evident in the shape of the 585-kev resonance which occurs at a proton energy of 2.742 Mev. The arrows in Fig. 2 indicate the points at which the 585-kev resonance would be expected for neutrons from the $Cu^{65}(p,n)Zn^{65}$ reaction leaving Zn^{65} in excited states at 52 and 92 kev. There is no evidence for the emission of neutrons to a state at 52 kev at a proton energy of 2.8 Mev with an intensity greater than about 0.4 of the ground-state group. No definite conclusions can be reached concerning the 92-kev state through the use of the sulfur absorber, since any effect would be masked by the next higher resonance in S for the ground-state group which begins with a dip at a neutron energy of 0.68 Mev. This effect is evident in Fig. 2.

Since the width of the 585-kev resonance in S (1.4 kev) is much less than the target thickness, the resonance energy is determined by the mid point of the observed rise. This occurs at a bombarding energy of 2.742 ± 0.004 Mev. In order to make this bombarding energy correspond to a neutron energy of 585 ± 3 kev at the mean angle of observation, the Q-value for the $Cu^{65}(p,n)Zn^{65}$ reaction must be taken to be -2.131 ± 0.005 Mev. This value is 5 kev less than that obtained from a measurement of the neutron threshold energy, -2.136 ± 0.004 Mev.[2] Although the agreement of the two Q-values is within the experimental error of the two measurements, since the proton energy determinations were made with the same equipment and using the same technique, this small energy difference may be significant. It is possible that a neutron threshold measurement may give too high a threshold energy if the theoretical threshold occurs between two compound nucleus resonances. In this case, there will be no appreciable neutron emission until the next resonance is reached and the apparent threshold will be too high.

In order to determine if the difference in Q-values observed in the two experiments could be due to a faulty energy calibration or to the geometrical arrangement employed in the transmission measurements, a similar transmission experiment was performed with neutrons from the $V^{51}(p,n)Cr^{51}$ reaction. The results are presented in Fig. 3. The neutron energy at the resonance (indicated by the arrow in Fig. 3) was calculated to be 586 kev at the mean angle of observation, by using the threshold energy of 1.5656 ± 0.0015 Mev, obtained by Gibbons, Macklin, and Schmitt.[9] Therefore, in the case of the $V^{51}(p,n)Cr^{51}$ reaction, there is no disagreement on the Q-value between the sulfur resonance experiment and the threshold determination.

C. 620-kev Resonance in Beryllium

The beryllium sample was substituted for the sulfur cone and the transmission experiment with $Cu^{65}(p,n)$ neutrons was repeated so that a further investigation of

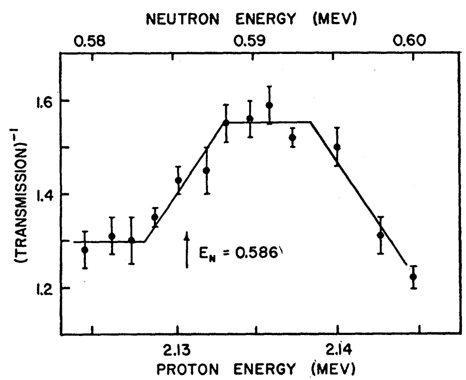

FIG. 3. Reciprocal of the transmission through a sulfur sample as a function of proton energy for neutrons from the $V^{51}(p,n)Cr^{51}$ reaction. The indicated probable errors are the standard deviations for a number of determinations at each energy.

[8] Jones, Douglas, McEllistrem, and Richards, Phys. Rev. **94**, 947 (1954).

[9] Gibbons, Macklin, and Schmitt, Phys. Rev. **100**, 167 (1955).

the possibility of a 92-kev state in Zn^{65} could be carried out and to extend the sulfur data to the region in which the effect of a 114-kev level could be observed. These data are presented in Fig. 4. A uniform, 30-kev Cu^{65} target was used. In addition to the 620-kev resonance due to the ground-state neutrons, there is a pronounced peak at a proton energy of 2.90 Mev. Since the ground-state neutrons have an energy of 740 kev at this proton energy and since the beryllium cross section in this energy region is nearly constant, this effect must be due to 620-kev neutrons from the $Cu^{65}(p,n)Zn^{65}$ reaction being emitted to a Zn^{65} level at 118±8 kev. Since the change in the transmission at the two observed peaks is approximately the same, the intensities of neutron emission to the Zn^{65} ground state and 118-kev state are approximately equal at a proton energy of 2.9 Mev. Again, there is no evidence for the emission of neutrons to Zn^{65} states at 52 or 92 kev at a proton energy of 2.9 Mev with an intensity greater than about 0.2 of the intensity of the ground-state and 118-kev state groups.

The calculations of the neutron energies shown in Fig. 4 were made with the Q-values of −2.131 Mev. The neutron energy at the Be resonance was then found to be 622±8 kev, in good agreement with the other determinations.[4,6]

D. Search for γ Radiation

Since the ground-state and 118-kev state neutrons from the $Cu^{65}(p,n)Zn^{65}$ reaction have approximately equal intensities at a proton energy of 2.9 Mev, it was throught that a search for the γ rays from the de-excitation of the 118-kev state, and possibly of other states, would be feasible. To minimize the γ radiation from other sources, a self-supporting normal copper foil, about 50 kev thick at a proton energy of 3 Mev, was mounted at 45° to the beam in a lead-lined tube which allowed the proton beam to be stopped about 2 feet in back of the foil. A NaI crystal, shielded from the machine background by $\frac{1}{2}$ inch of lead, was placed at 90° to the beam and 2 inches from the copper foil. A pulse-height distribution of the γ radiation from the proton bombardment of the foil was taken at 2.9 Mev. The distribution was observed from a γ-ray energy of 0 to 250 kev without the occurence of any discernible peak.

Even if the 118-kev radiation is fairly intense at this bombarding energy, the low-energy tail from the γ radiation produced by the interaction of the protons in the copper and of the neutrons in the NaI crystal would tend to obscure its presence. The present measurements are therefore inconclusive as to the presence of low-lying energy γ radiation accompanying the $Cu^{65}(p,n)Zn^{65}$ reaction.

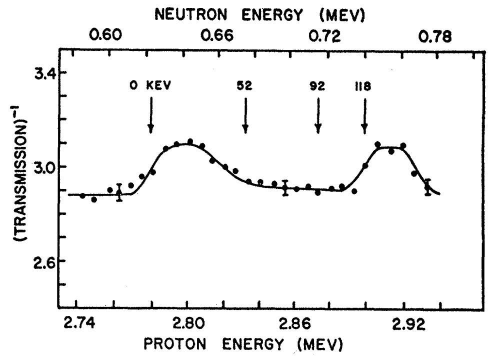

FIG. 4. Reciprocal of the transmission through a beryllium sample as a function of proton energy for neutrons from the $Cu^{65}(p,n)Zn^{65}$ reaction. The neutron energy values are for the ground-state group and are based on a Q-value of −2.131 Mev. The arrows indicate where resonances would occur for neutrons emitted at Zn^{65} states at 0, 52, 92, and 118 kev. The indicated probable errors are typical standard deviations for a number of determinations at each energy.

DISCUSSION

The present experiments have demonstrated the presence of a low-lying excited state in Zn^{65} at an energy of 118 kev. The possibility that other levels exist in this region cannot be excluded on the basis of these measurements. The energy of 118 kev agrees well with the γ-ray energy of 114 kev obtained by Crasemann[1] in a study of the decay scheme of Ga^{65}, and it seems probable that these two measurements deal with the same level. On the basis of the present work and that of Crasemann, it is still impossible to construct a consistent decay scheme for Ga^{65}, since the origin of the 52- and 92-kev γ rays is still uncertain.

The occurence of low-lying levels in Zn^{65} may be expected due to the competition between the filling of the $f_{\frac{5}{2}}$ and $p_{\frac{3}{2}}$ levels for neutron numbers near 35 (for Zn^{65}). Since these levels are quite close in energy, configurations of low excitation energy may be expected. Such an effect occurs from proton numbers 33 (As^{75}) and 35 (Br^{79}) and would therefore be expected for neutrons as well.[10] It is also possible that the pure single particle levels are more easily excited than those arising from $f_{\frac{5}{2}}-p_{\frac{3}{2}}$ competition, and that, therefore, only those states of higher excitation, which are more likely to be single particle levels, were observed in the neutron threshold measurements.[10]

Since an excited state in Zn^{65} at 118 kev has been established and since the possibility still remains that there are other states at even lower excitations, the use of the $Cu^{65}(p,n)Zn^{65}$ reaction as a source of mono-energetic, low-energy neutrons seems unadvisable above neutron energies of about 50 kev.

[10] M. Goldhaber (private communication).