Cross sections were determined by calibrating the NaI crystal with radioactive sources of known strength. Attenuation of neutrons and gamma rays in the scatterer was calculated, but no multiple scattering corrections were made. The scattering rings had radial and axial thicknesses of one inch. The incident neutron flux was calculated from the known cross section for the $d-d$ reaction. Cross sections are given in barns/steradian at 90°. Knowledge of the angular distribution of the γ rays is necessary to determine the total cross sections for production of these γ rays.

The cross sections have been corrected for isotopic abundance in all cases except that of antimony. This element has two isotopes of approximately equal abundance, so that without further knowledge of the level schemes, it is not possible to assign the γ ray to one particular isotope. From the breadth of the peak, it is probable that there are two unresolved γ rays present.

In the case of gold, no peaks were detected. The large attenuation of the gold scatterer would greatly cut down the yield of any γ rays produced. The figure given in the table is an estimated upper limit on the cross section for production of a 1-Mev γ ray.

The level scheme shown for Al is taken from Endt and Kluyver.[4] The γ-ray energies shown on the spectrum are within 1 percent of the energies obtained from the known levels.

The level scheme shown for Fe is based on the assumption that all the γ rays cascade through the 850-kev level.[5] The quantum energies given are taken from the Fe spectrum in Fig. 1 and agree well with measurements on the γ rays from Mn^{56} and Co^{56}.

[4] P. M. Endt and J. C. Kluyver, Revs. Modern Phys. **26**, 95 (1954).
[5] Jennings, Weddell, Alexeff, and Hellens, Phys. Rev. **98**, 582 (1955).

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Study of the Nuclear Reactions $Sc^{45}(p,n)Ti^{45}$, $Cu^{63}(p,n)Zn^{63}$, $Cu^{65}(p,n)Zn^{65}$, and $Zn(p,n)Ga$†

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The counter ratio method has been applied to the (p,n) reactions for Sc^{45}, Cu^{63}, Cu^{65}, and Zn to determine the Q-values for the ground-state thresholds and to locate low-lying states in the residual nuclei. The thresholds for the (p,n) reactions were found to be 2.908 Mev for Sc^{45}, 4.215 Mev for Cu^{63}, 2.169 Mev for Cu^{65}, and 3.749 Mev for Zn^{68}. Other neutron thresholds were found corresponding to excited states in Ti^{45} at 0.743, 1.194, 1.347, 1.460, 1.876, 2.016, 2.430, and 2.555 Mev; in Zn^{63} at 0.191, 0.642, and 1.043 Mev; and in Zn^{65} at 0.78, 1.26, and 1.93 Mev. A threshold was found in the $Zn(p,n)Ga$ reaction which is probably due to a level in Ga^{68} at 0.170 Mev. Cross sections for the yield of neutrons in the forward direction were determined. The yields of neutrons from thin Sc^{45} and Cu^{63} targets were obtained for the proton energy region from the thresholds to 70 kev above these thresholds. McKibben nomographs are given for these two reactions.

INTRODUCTION

THE study of (p,n) reactions for medium weight elements has not been as extensive as for the light elements because of the difficulty of obtaining separated isotopes and because of the smaller cross sections near threshold. The knowledge of the levels in the residual nuclei is meager. The existence and spacing of these levels can be determined by measuring the energies of the neutron groups from the proton bombardment of the target nuclei several Mev above the threshold energy or by studying the γ rays accompanying these reactions. In some cases the levels have been determined from the beta decay of the next higher isobar.

A greater knowledge of medium-weight element (p,n) reactions as neutron sources is valuable because of the present interest in neutron scattering experiments in the 1–150 kev range. Because of the low center-of-mass velocity, the neutrons emitted near threshold from these reactions have energies of only a few kilovolts and the energy is approximately independent of angle in the forward direction. Although the yields are low, the beam currents obtainable with present-day Van de Graaff accelerators make the use of these sources possible in the kilovolt region. To obtain satisfactory resolution, thin targets and well resolved proton beams are necessary. Using these sources, experiments can be performed at zero degrees to the proton beam with neutron energies of a few kilovolts and only a small variation in energy with angle.

The counter ratio method which was first described by Bonner and Cook[1] employs two paraffin-moderated

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[1] T. W. Bonner and C. F. Cook, Phys. Rev. **96**, 122 (1954).

BF_3 counters. One counter (called the modified long counter) essentially determines the yield of neutrons of all energies from a reaction, while the second counter (called the slow counter) discriminates against fast neutrons in favor of slow neutrons. The ratio of the counting rate of the second counter to that of the first reveals not only thresholds corresponding to the ground states of the residual nuclei, but thresholds due to excited states as well. By applying this method to (p,n) reactions, the yield of neutrons in the forward direction and the existence and spacing of the low-lying states in the residual nuclei can be determined simultaneously.

Preliminary studies of the thick-target yield of neutrons from the proton bombardment of scandium by Hanson, Taschek, and Williams[2] showed that the $Sc^{45}(p,n)Ti^{45}$ reaction might be useful as a source of kilovolt neutrons, with a yield near threshold about 40 times that of the $V(p,n)$ reaction, another possible source of kev neutrons. They determined the threshold energy for the reaction to be 2.9 Mev and found that the cross section was roughly 30 millibarns near threshold. The threshold of 4.2 Mev for the $Cu^{63}(p,n)Zn^{63}$ reaction suggested that it might also give a satisfactory yield of neutrons near threshold.

The counter ratio method was also applied to the reactions: $Cu^{65}(p,n)Zn^{65}$, $Cu^{63}(p,n)Zn^{63}$, and $Zn(p,n)Ga$. Preliminary results with Cu^{65} have previously been obtained[3] with this technique. Only a rough measurement of the threshold of the $Zn^{68}(p,n)$ threshold has been reported.[4]

EXPERIMENTAL PROCEDURE

A procedure for the counter ratio method similar to that described by Marion, Brugger, and Bonner[5] was used in these experiments. This method involves the use of two BF_3 counters, one embedded in a paraffin cylinder 5 in. in diameter and 5 in. in length (modified long counter) and the second surrounded by a ring of paraffin $\frac{1}{2}$ in. thick and 2 in. in length (slow counter). Both counters were placed at 0° with respect to the direction of the proton beam and subtended approximately the same solid angle at the target. A multiple target holder was used. The geometrical arrangement is shown in Fig. 1.

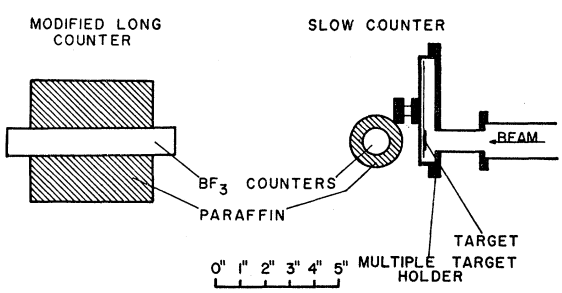

FIG. 1. Geometrical arrangement of the two counters and the target holder used in performing counter ratio experiments.

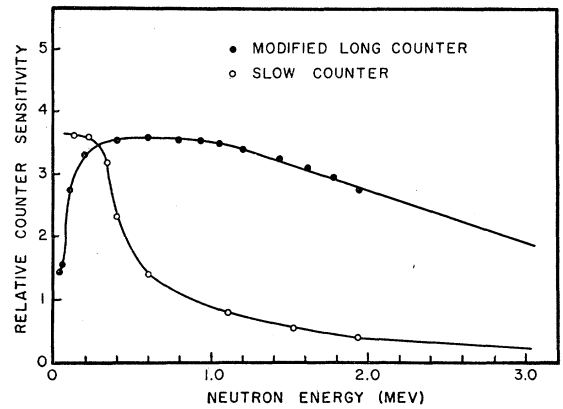

FIG. 2. Relative efficiencies as a function of the neutron energy of the slow counter and of the modified long counter in its position behind the slow counter.

The efficiency of the two counters as a function of neutron energy is given in Fig. 2. These data were determined by observing the counting rate in each of the counters as the energy of a beam of protons striking a LiF target was varied. The results were then compared to the absolute yield into the same cone determined by Taschek and Hemmendinger[6] in order to find the relative efficiency as a function of neutron energy. The efficiency of the modified long counter in its position behind the slow counter decreases rapidly for neutrons of energy less than 0.3 Mev. This is a desirable characteristic for detecting weak neutron thresholds with the counter ratio method; however, the neutron yields measured with this counter below 0.3 Mev are too small by as much as a factor of 2.5 for low-energy neutrons.

Pronounced resonances are obtained in most (p,n) reactions and the effects of these resonances are largely eliminated by using the counter ratio method.[1] However, in the case of the $Cu^{65}(p,n)$ reaction and to a smaller extent in the $Cu^{63}(p,n)$ reaction the effects of the resonances were not completely eliminated. At bombarding energies above the 2.97-Mev threshold of the first excited state of Zn^{65}, fluctuations in the counter ratio were observed that were too large to be attributed to statistics. The ratio of the number of neutrons emitted to the first excited state compared to the number emitted to the ground state would be expected to change from one resonance to another, because of the change in angular momentum and parity between successive levels of the compound nucleus. The fluctuations in the counter ratio are attributed to such changes.

[2] Hanson, Taschek, and Williams, Revs. Modern Phys. **21**, 635 (1949).
[3] C. F. Cook and T. W. Bonner, Phys. Rev. **94**, 807(A) (1954).
[4] Blaser, Boehm, Marmier, and Scherrer, Helv. Phys. Acta **24**, 441 (1951).
[5] Marion, Brugger, and Bonner, this issue [Phys. Rev. **100**, 46 (1955)].
[6] R. F. Taschek and A. Hemmendinger, Phys. Rev. **74**, 373 (1948).

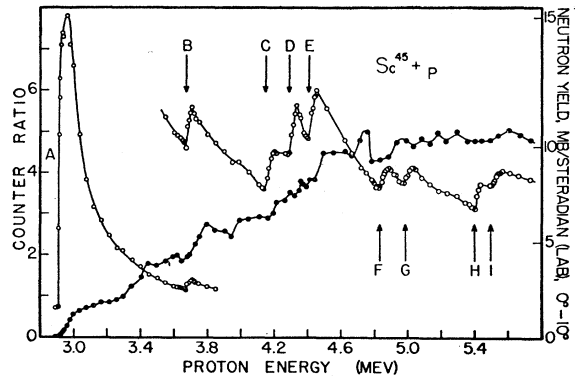

FIG. 3. The counter ratio (open circles) and the yield of neutrons in the forward direction measured by the modified long counter (solid circles) as a function of the proton energy for the $Sc^{45}(p,n)Ti^{45}$ reaction. *The counter ratios have been multiplied by 5 for proton energies above 3.6 Mev.*

Below the thresholds corresponding to the first excited states, there were no fluctuations observed that could not be attributed to statistics. To eliminate partially the fluctuations due to resonances, the data taken for Cu^{65} with a 35-kev target were averaged over 120 kev, while 120-kev targets were used for scandium and zinc. This averaging process increased the error in determining the threshold energies.

Values of the cross sections for the yield of neutrons in the forward direction in units of millibarns per steradian in the laboratory system were obtained for the proton bombardment of Sc^{45}, Cu^{63}, and Cu^{65}. A long counter similar to that described by Hanson and McKibben[7] was used to determine the cross sections. It was placed at zero degrees to the beam and 42 inches from the target and recorded the number of neutrons per microcoulomb of beam striking the targets. To eliminate variations in the efficiency of the long counter with neutron energy, weighed targets of Sc_2O_3, Cu^{63}, Cu^{65}, and LiF were bombarded at proton energies so that the emitted neutrons had an energy of about 0.60 Mev. This was not completely realized in the case of Cu^{63} because of a second group of neutrons emitted to the 0.191-Mev state of Zn^{63}. The differential cross section for the $Li^7(p,n)Be^7$ reaction which has been determined to an accuracy of about 10 percent by Taschek and Hemmendinger[6] was used as the standard to which the other reactions were compared.

For cross section determinations the target material was evaporated onto 2-mil pure aluminum backings. The amount of target material was determined by weighing the backings before and after an evaporation. A quartz spring with about 1 milligram per millimeter sensitivity, in conjunction with a telescope containing a calibrated eyepiece, was used to make the weighings. The weights of the Sc_2O_3, Cu^{63}, Cu^{65}, and LiF on the targets were 267, 323, 473, and 220 micrograms/cm^2, respectively.

[7] A. O. Hanson and J. L. McKibben, Phys. Rev. **72**, 673 (1947).

$Sc^{45}(p,n)Ti^{45}$

To study the yield of neutrons from the proton bombardment of scandium, targets were made by evaporating Sc_2O_3 from a V-shaped tungsten filament onto tungsten or weighted aluminum blanks. At temperatures close to the evaporating temperature (~1300°C) the Sc_2O_3 on the filament turned from white to black. The thickest target which was made (~120 kev thick) was dark grey in color, while the thinner targets were cream colored. Baker, Howell, Goodman, and Preston[8] reported making scandium targets by evaporating Sc_2O_3 from a carbon boat. In the process they reported that the oxide was reduced and metal targets were made. Targets that were made at the same time as the targets used in this experiment were also used to study the inelastic scattering of protons from scandium and the results[9] showed that the targets contained a considerable amount of oxygen. A scandium target evaporated onto a glass backing had a very high electrical resistance which also indicates that the oxide and not the metal was deposited.

Figure 3 shows the counter ratio and the yield of neutrons in the forward direction for scandium bombarded by protons of energies from 2.9 to 5.6 Mev. The target used was 120-kev thick to protons of 2.9 Mev and had a tungsten backing. The yield has been corrected for background obtained by bombarding a clean tungsten blank. The counter ratio shows the usual sharp rise at the ground-state threshold energy of 2.908 Mev (A) and other thresholds *B*, *C*, *D*, *E*, *F*, *G*, *H*, and *I* at higher energies due to eight excited states in Ti^{45}. Table I lists the threshold energies and the *Q*-values for the $Sc^{45}(p,n)Ti^{45}$ reaction and the excitation energies of the Ti^{45} states. The 120-kev target has essentially eliminated fluctuations due to resonances in the compound nucleus, by averaging the effects of a large number of resonances.

The ground-state threshold energy was measured to be 2.908±0.004 Mev yielding a *Q*-value for the reaction of −2.844±0.004 Mev; a mass defect of −25.87

TABLE I. Neutron thresholds in the reaction $Sc^{45}(p,n)Ti^{45}$.

Threshold	Threshold energy (Mev)	*Q*-value (Mev)	Ti^{45} (Mev)
A	2.908±0.004	−2.844±0.004	0
B	3.667±0.010	−3.587±0.010	0.743±0.011
C	4.129±0.007	−4.038±0.007	1.194±0.008
D	4.285±0 009	−4.191±0.009	1.347±0.010
E	4.400±0.010	−4.304±0.010	1.460±0.011
F	4.826±0.009	−4.720±0.009	1.876±0.010
G	4.969±0.012	−4.860±0.012	2.016±0.013
H	5.392±0.010	−5.274±0.010	2.430±0.011
I	5.520±0.007	−5.399±0.007	2.555±0.008

[8] Baker, Howell, Goodman, and Preston, Phys. Rev. **81**, 48 (1951).

[9] Gossett, Phillips, Schiffer, and Windham, this issue [Phys. Rev. **100**, 203 (1955)].

±0.56 Mev and a mass of 44.97222±0.00060 amu[10] are indicated for Ti^{45}. This threshold is in good agreement with the value of 2.9 Mev obtained by Hanson, Taschek, and Williams[2] and that estimated from the curve of Baker, Howell, Goodman, and Preston[8] as 2.87 Mev. A Q-value for the $Sc^{45}(p,n)Ti^{45}$ reaction can be calculated from the positron decay[11] of Ti^{45}. This calculation gives a Q-value of -2.822 ± 0.010 Mev, which is 0.022 Mev lower than that obtained from the threshold measurement. The higher thresholds are assigned errors depending on the estimated accuracy of extrapolating the leading edge of the threshold.

The differential cross section for the yield of neutrons in the forward direction was obtained at a proton energy of 3.53 Mev and was found to be 3.4 percent of that for the reaction $Li^7(p,n)Be^7$ at a proton energy of 2.30 Mev. The comparison was made for the same neutron energy to eliminate any energy dependence of the long counter efficiency. This gives a cross section for the $Sc^{45}(p,n)Ti^{45}$ reaction averaged over a proton energy from 3.41 to 3.53 Mev of 3.6 mb. The yield of neutrons into the forward cone of half-angle 10° is given by the right-hand ordinate of Fig. 3 in units of millibarns per steradian in the laboratory system.

The proton energy region from threshold to 0.070 Mev above threshold was investigated with a 2.7-kev target. The thickness of this target was determined by comparing the counting rate with that from a thicker weighed target. The amount of scandium oxide on the thin target was determined to be 29.5 micrograms/cm². Figure 4 shows the yield of neutrons measured by the slow counter from threshold to 0.070 Mev above threshold. The yield has been corrected for background. Since the counter sensitivity is essentially constant over this energy region, the yield has not been corrected for any variation in the counter sensitivity. The levels

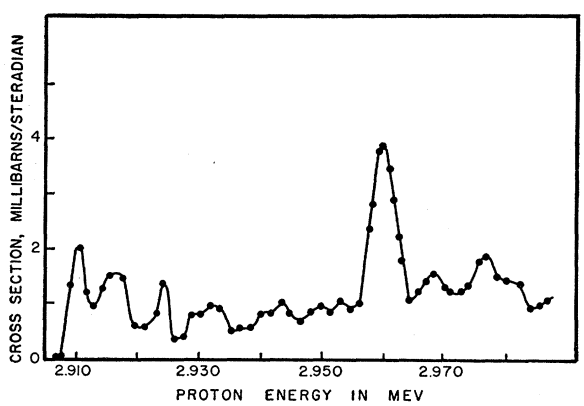

FIG. 4. The yield of neutrons in the forward direction as a function of the proton energy as measured by the slow counter for the $Sc^{45}(p,n)Ti^{45}$ reaction.

[10] Mass values of Sc^{45}, Cu^{63}, and Cu^{65} were taken from the tables of E. Segrè, *Experimental Nuclear Physics* (John Wiley and Sons, Inc., New York, 1953), Vol. 1, p. 745.

[11] Ter-Pogossian, Cook, Porter, Morganstern, and Hudis, Phys. Rev. **80**, 360 (1950).

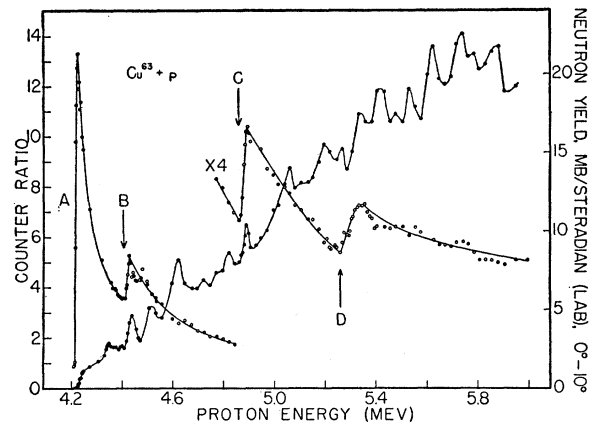

FIG. 5. The counter ratio showing thresholds at A, B, C and D and the yield of neutrons in the forward direction as a function of the proton energy as measured by the modified long counter for the $Cu^{63}(p,n)Zn^{63}$ reaction.

appear to be as wide as 6 kev and are spaced about 2–9 kev apart. The cross section near threshold was determined by comparing the counting rates to that for 3.53-Mev protons and then correcting for the change in counter sensitivity.

If the energy separation between levels is considerably greater than the level widths, the yield will become very small between resonances. In this case if the theoretical (p,n) threshold falls between two resonances, the experimental threshold would not appear until the proton energy reaches the next higher resonance, thus introducing a small error in the Q-value for the (p,n) reaction calculated from the neutron threshold.

$Cu^{63}(p,n)Zn^{63}$

The separated isotope of Cu^{63} (99.11 percent Cu^{63}) in the form of CuO was obtained from the Oak Ridge National Laboratory. The CuO was reduced to metallic copper and targets were made by evaporating the metal onto weighed aluminum blanks or onto tungsten blanks. Figure 5 shows the counter ratio and the yield of neutrons in the forward direction for a 17-kev Cu^{63} target. The yield has been corrected for background. The sharp rises at 4.215, 4.410, 4.868, and 5.265 Mev are attributed to the ground-state threshold and three excited state thresholds. The small dip and rise near 4.50 Mev is attributed to a resonance effect and not to a threshold. Table II lists the threshold energies and the Q-values for the $Cu^{63}(p,n)Zn^{63}$ reaction and the excitation energies in Zn^{63}.

The ground-state threshold energy of 4.215±0.004 Mev yields a Q-value of -4.149 ± 0.004 Mev; a mass defect of -44.48 ± 1.86 Mev and a mass of 62.95223 ±0.00200 amu[10] are indicated for Zn^{63}. A previous determination of the Q-value for this reaction by Strain[12] gave -4.04 ± 0.17 Mev, and that by Blaser, Boehm, Marmier, and Scherrer[4] gave -4.14 ± 0.1 Mev.

[12] C. V. Strain, Phys. Rev. **54**, 1021 (1938).

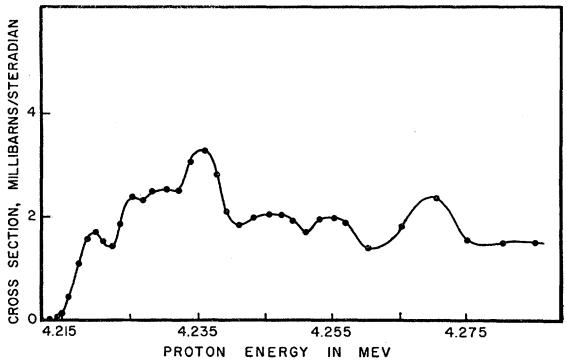

FIG. 6. The yield of neutrons in the forward direction as a function of the proton energy as measured by the slow counter for the $Cu^{63}(p,n)Zn^{63}$ reaction.

A preliminary determination by Cook and Bonner[3] gave -4.21 Mev. Recently Kington, Bair, Cohn, and Willard[13] have measured the threshold for the $Cu^{63}(p,n)Zn^{63}$ reaction to be 4.213 ± 0.008 Mev, which is in very good agreement with the present value. The Q-value calculated from the energy of the Zn^{63} positron decay of 2.36 Mev[14] gives better agreement than does that calculated with the value of 2.320 Mev.[15]

The cross section for the yield of neutrons in the forward direction was obtained by comparing the yield per nucleus of Cu^{63} bombarded by 4.74-Mev protons to that of Li^7 bombarded by 2.30-Mev protons. The cross section for neutrons emitted into the forward direction averaged over a proton energy from 4.71 to 4.74 Mev was 6.7 mb. The yield curve was normalized to this value of the cross section.

The region from threshold to 0.070 Mev above threshold was reinvestigated with a 3.6-kev target. Figure 6 shows the yield measured by the slow counter, corrected for background, but uncorrected for the small change in counter sensitivity in this energy region. The target thickness and the cross section were determined by the same methods used for the scandium reaction. The amount of Cu^{63} on the target was 85 micrograms/cm^2. The data of Fig. 6 indicates a complicated resonance structure. It is uncertain whether the observed widths of some of the resonances are level widths or are due to target thickness and to the spread in energy of the beam.

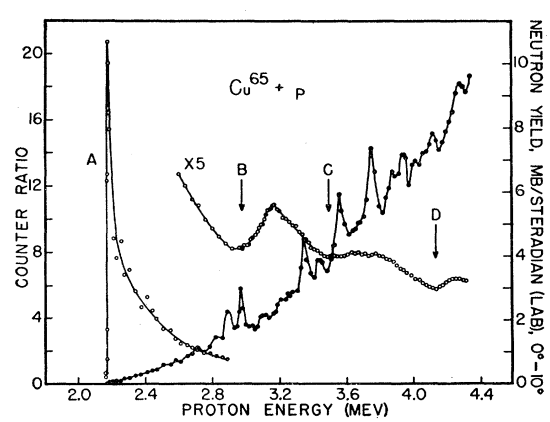

FIG. 7. The counter ratio (open circles) and the yield of neutrons in the forward direction as a function of the proton energy as measured by the modified long counter (solid circles) for the $Cu^{65}(p,n)Zn^{65}$ reaction.

$Cu^{65}(p,n)Zn^{65}$

The separated isotope of Cu^{65} (98.2 percent Cu^{65}) in the form of CuO was reduced to metallic copper and evaporated onto weighed aluminum disks. Figure 7 shows the counter ratio and the yield of neutrons in the forward direction for a Cu^{65} target bombarded with protons. The data were taken with a target with a weight of 473 micrograms/cm^2 ($\sim$35 kev thick at 2.2 Mev). Above 2.95 Mev the counter ratio has been averaged over 120 kev to smooth out the fluctuations due to the pronounced resonances. This averaging increased the error in determining the energies of the second and third thresholds. Table III lists the threshold energies and Q-values for the $Cu^{65}(p,n)Zn^{65}$ reaction.

TABLE II. Neutron thresholds in the reaction $Cu^{63}(p,n)Zn^{63}$.

Threshold	Threshold energy (Mev)	Q-value (Mev)	*Zn^{63} (Mev)
A	4.215 ± 0.004	-4.149 ± 0.004	0
B	4.410 ± 0.010	-4.340 ± 0.010	0.191 ± 0.011
C	4.868 ± 0.010	-4.791 ± 0.010	0.642 ± 0.011
D	5.265 ± 0.014	-5.182 ± 0.014	1.043 ± 0.015

TABLE III. Neutron thresholds in the reaction $Cu^{65}(p,n)Zn^{65}$.

Threshold	Threshold energy (Mev)	Q-value (Mev)	*Zn^{65} (Mev)
A	2.169 ± 0.004	-2.136 ± 0.004	0
B	$2.97\ \pm0.03$	$-2.92\ \pm0.03$	0.78 ± 0.03
C	$3.45\ \pm0.03$	$-3.40\ \pm0.03$	1.26 ± 0.03
D	$4.13\ \pm0.02$	$-4.07\ \pm0.02$	1.93 ± 0.02

The ground-state threshold energy of 2.169 ± 0.004 Mev gives a Q-value of -2.136 ± 0.004 Mev; a mass defect of -47.54 ± 1.96 Mev and a mass of 64.94895 ±0.00210 amu[10] are indicated for Zn^{65}. This Q-value is in good agreement with that obtained by Cook and Bonner[3] of -2.12 ± 0.03 Mev, but lower by 0.030 Mev than the -2.166 ± 0.010 Mev value obtained by Shoupp, Jennings, and Jones[16] when their data are corrected for the accurate $Li^7(p,n)Be^7$ threshold energy. Kington, Bair, Cohn, and Willard[13] have recently measured the disintegration Q-value to be -2.137 ±0.005 Mev. The Q-value calculated from the positron decay of Zn^{65} is -2.129 ± 0.002 Mev,[17] 0.007 Mev

[13] Kington, Bair, Cohn, and Willard, Phys. Rev. **99**, 1393 (1955).
[14] Huber, Medicus, Preiswerk, and Steffen, Helv. Phys. Acta **20**, 496 (1947).
[15] A. A. Townsend, Proc. Roy. Soc. (London) **A177**, 357 (1941).
[16] Shoupp, Jennings, and Jones, Phys. Rev. **73**, 421 (1948).
[17] R. W. King, Revs. Modern Phys. **26**, 388 (1954).

lower than that calculated from the present threshold energy.

Crasemann[18] has studied the decay of Ga^{65}. The difference in energy between the two positrons reported indicates that the decay of Ga^{65} might leave Zn^{65} in excited states at 0.78 or 1.26 Mev. Since no high-energy γ rays were reported, this assignment is indefinite. No indication of low-lying states at 0.052, 0.092, or 0.114 Mev in Zn^{65} that would correspond to the γ rays of these energies reported by Crasemann were noticed in the counter ratio. Thresholds corresponding to these levels would not have been observed unless they were rather intense, since the total yield is low and the relative counter efficiencies would not have changed sufficiently to indicate a second group of neutrons if they appeared with nearly the same energy as the first group.

The cross section was obtained by comparing the yield per nucleus from a weighed Cu^{65} target bombarded with 2.75-Mev protons to the yield per nucleus

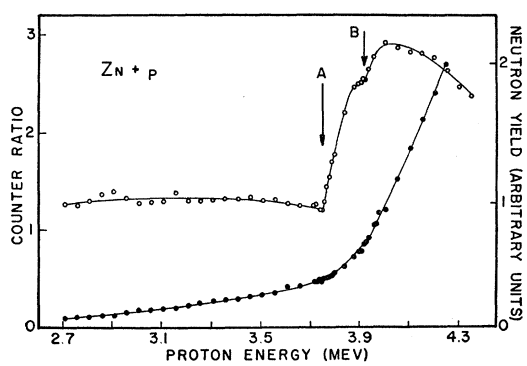

FIG. 8. The counter ratio (open circles) and the relative yield of neutrons in the forward direction as a function of the proton energy as measured by the modified long counter (solid circles) for the $Zn(p,n)Ga$ reaction.

from Li^7 bombarded with protons of 2.30-Mev energy. The cross section for the yield of neutrons in the forward direction averaged over a proton energy from 2.71 to 2.75 Mev was 1.1 mb.

$Zn(p,n)Ga$

The threshold of the $Zn^{68}(p,n)Ga^{68}$ reaction was measured to be 3.4 ± 0.3 Mev by Marmier and Scherrer[4] using a cyclotron and stacked foils. In order to obtain a more precise value for this threshold, experiments were carried out with a normal Zn target. Figure 8 shows the counter ratio and yield of neutrons in the forward direction for a 120-kev natural zinc target bombarded by protons. Neutrons emitted below a proton bombarding energy of 3.7 Mev are due to Zn^{67}, which is 4.11 percent abundant in natural zinc and has a (p,n) threshold at 1.812 Mev,[19] and due to Zn^{70} (0.62 percent abundant) with a threshold at 1.47 Mev.[19] At 3.749 Mev and again at 3.921 Mev the ratio rises sharply. The first threshold at A is attributed to the ground state of Zn^{68} (18.56 percent abundant) and the second threshold at B is attributed to an excited state in the residual nucleus Ga^{68}. These assignments to Zn^{68} and not to Zn^{67} or Zn^{70} are made on the basis of the larger isotopic concentration of Zn^{68} in the target and the agreement with the expected threshold of Zn^{68}. The ground-state threshold at 3.749 ± 0.006 Mev gives a Q-value of -3.694 ± 0.006 Mev, which is in good agreement with the Q-value of -3.68 ± 0.20 Mev calculated from the positron decay[17] of Ga^{68}. The second threshold at 3.921 ± 0.006 Mev with a Q-value of -3.864 ± 0.006 Mev indicates an excited state of Ga^{68} at 0.170 ± 0.009 Mev above the ground state.

$Sc^{45}(p,n)Ti^{45}$ and $Cu^{63}(p,n)Zn^{63}$ Reactions as Kilovolt Neutron Sources

At the present time the $Li^7(p,n)Be^7$ reaction, emitting neutrons at backward angles, is the most widely used source of kilovolt neutrons. The disadvantages of working at backward angles, using rotating targets, and the necessity of evaporating the target in the accelerator vacuum system are usually compensated by the many advantages of this reaction. The yield of neutrons even in the backward hemisphere is large and the threshold can be reached by most Van de Graaff accelerators. The energy resolution obtainable is one of the greatest advantages.

The energy of the neutrons emitted from either scandium or Cu^{63} changes rapidly the first few kilovolts above threshold. At a proton energy 4 kev above the scandium threshold, the neutron energy has reached 10 kev, and a 1-kev beam spread introduces about 2-kev spread in neutron energy. For 20-kev neutrons a proton beam spread of 1 kev introduces a spread in the neutron beam of 1 kev. For scandium, when 20-kev neutrons are emitted at 0°, 19.5-kev neutrons are emitted at 15° or only a 0.5-kev variation in neutron energy over this large angle. Thus samples subtending large angles could be used for neutron scattering or absorption without introducing a large energy spread.

Neutron sources obtained from the bombardment of heavier elements will have the advantage in experiments where background and room scattering into the detector are important. The number of neutrons emitted toward the detector as compared to the number emitted elsewhere is greatest when working at 0°. Further improvements in the energy resolution of Van de Graaff accelerators may make the doppler broadening the major limitation in resolution. Heavier nuclei such as Sc^{45} and Cu^{63} thus will be much superior to a light element such as Li^7.

The yield of neutrons in the forward direction for the scandium reaction just above threshold is about 1.5 mb per steradian. These cross sections are approximately 10 percent of the cross section per unit solid angle for

[18] B. Crasemann, Phys. Rev. **93**, 1034 (1954); **90**, 995 (1953).
[19] C. Trail and C. H. Johnson, Phys. Rev. **91**, 474(A) (1953).

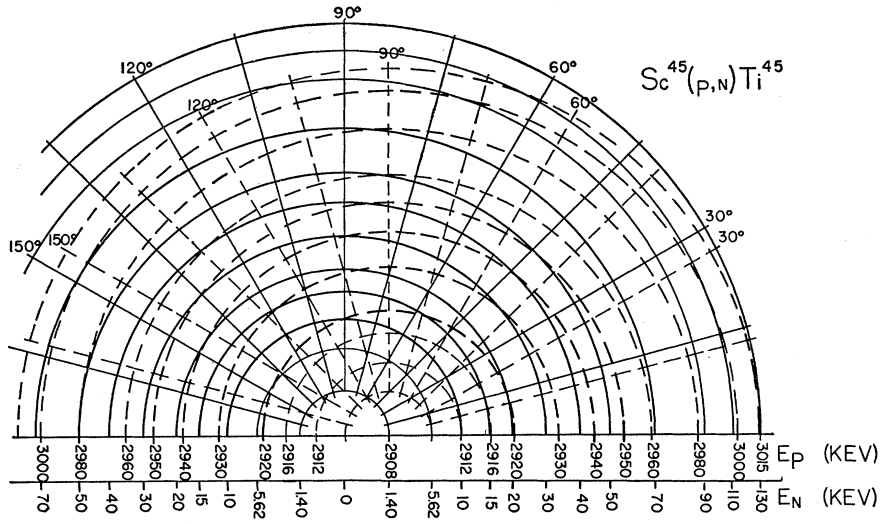

FIG. 9. A nomograph for the $Sc^{45}(p,n)Ti^{45}$ reaction. The upper energies and dotted circles are the proton energies in kilovolts. The lower energies and solid circles are the neutron energies in kilovolts. The solid radial lines are for angles in the laboratory system. The dotted radial lines are for angles in the center-of-mass system.

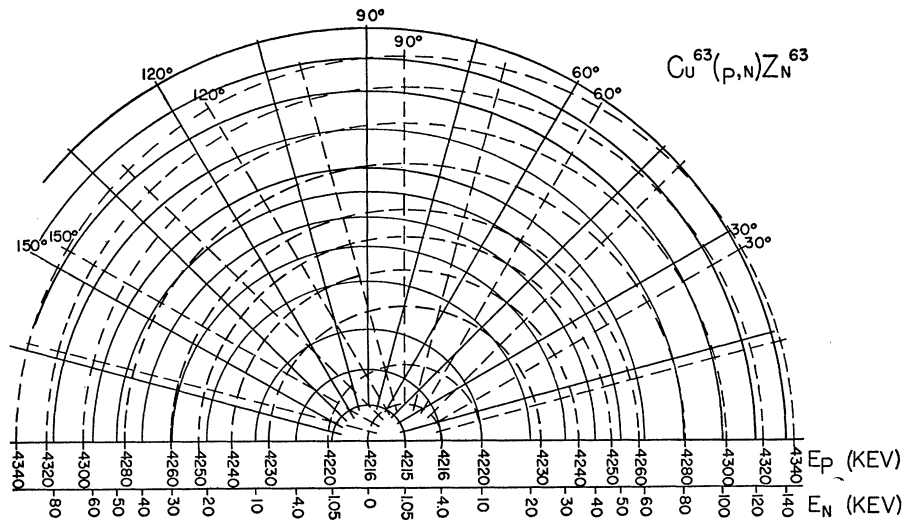

FIG. 10. A nomograph for the $Cu^{63}(p,n)Zn^{63}$ reaction. The upper energies and dotted circles are the proton energies in kilovolts. The lower energies and solid circles are the neutron energies in kilovolts. The solid radial lines are for angles in the laboratory system. The dotted radial lines are for angles in the center-of-mass system.

kev neutrons emitted at 120° from the $Li^7(p,n)Be^7$ reaction. The yields from Sc^{45} and Cu^{63} would still be adequate for neutron sources if large beam currents were used. There was no indication that target material was being lost when the targets were mounted in the poorly cooled multiple target holder and bombarded with 4 or 5 microamperes of beam. If the copper or Sc_2O_3 were evaporated onto thin backings and these were mounted flush to the thin, aircooled end of the accelerator vacuum system, the targets should be able to withstand 50 microamperes of beam.

The counter ratio for both Sc^{45} and Cu^{63} give no indication that there are low-lying states in Ti^{45} or in Zn^{63} below 190 kev. Thus the sources should be monoenergetic up to neutron energies of 200 kev. As may be seen from Fig. 4 the yield of neutrons from scandium varies rapidly with energy. However, the sharp resonances and low yields between resonances might be used to obtain a well-resolved neutron beam of discrete energy from a proton beam of 3- or 4-kev beam spread. By rotating the counter and scatterer from 0° to larger angles, neutrons could be obtained that would have energies that correspond to the gaps in the forward yield of neutrons. Thus a continuous variation in neutron energy could be obtained. Figures 9 and 10 are nomographs for these two reactions of the same type described by Hanson, Taschek, and Williams[2] for $Li^7(p,n)Be^7$.