pointed out[22] that inelastic neutron-gamma angular correlation experiments might assist in choosing an appropriate model, but these experiments are still quite difficult.

The technique which utilizes the detection of inelastically scattered neutrons as a tool in nuclear spectroscopy has been improved. A previously unobserved level in Pb^{206} has been found, and levels previously seen by gamma-ray detection confirmed.

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ACKNOWLEDGMENTS

The authors wish to acknowledge the assistance of Mr. W. Bornstein, who performed many of the calculations. They also wish to express their appreciation to Mr. R. L. Chase and Mr. W. A. Higinbotham for their many contributions to the design and operation of the electronic equipment. The assistance of Mr. I. Feigenbaum and Mr. K. Rosenbaum in the maintenance and operation of the cyclotron are gratefully acknowledged.

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Study of Some (p,n) Reactions by Neutron Time of Flight*

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A millimicrosecond time-of-flight technique has been applied to the study of (p,n) reactions in K, Ca^{48}, Ti, Cr, Mn, Fe, Cu, As, and Rb using the phase-focused 3-Mev proton beam from a small fixed-frequency cyclotron. The neutron spectra, resulting from these reactions, gave data from which the ground-state Q values and some of the energy levels in the residual nuclei have been determined. The reactions in K and Fe yielded only one neutron group each, which corresponded to the ground states in Ca^{41} and Co^{57}, respectively. In addition to the ground state Q values, the energies were determined for one excited state in each of the nuclei Mn^{53}, Mn^{54}, and Sr^{85}, two excited states in Zn^{65}, three excited states in Sr^{87}, and four excited states in each of the nuclei Sc^{48}, V^{49}, Fe^{55}, and Se^{75}. The angular distributions of the neutron groups were observed to be essentially isotropic in the $Ca^{48}(p,n)Sc^{48}$ and $Cu^{65}(p,n)Zn^{65}$ reactions.

INTRODUCTION

SINCE a (p,n) reaction in a stable nucleus is endoergic, a threshold energy exists below which the reaction cannot proceed. The threshold energy is expected to be large for the light nuclei but to decrease, in general, as one proceeds to heavier nuclei. With the nuclei in the medium-weight region, the threshold energies and the Coulomb barriers are not too high and relatively large neutron yields are to be expected when low-energy protons are used. Thus, (p,n) reactions in medium-weight nuclei can be used to investigate the low-lying energy level structure in these nuclei. One would expect to confirm nuclear energy levels that have been observed in β-γ decay, and to observe other states not allowed by the selection rules for β and γ decay.

Investigations of (p,n) reactions have been principally carried out with the use of photographic emulsions or BF_3 "long counters" as fast-neutron detectors. The limited resolution of the photographic technique makes it difficult to observe many low-lying nuclear states. A technique based on the use of BF_3 detectors, the so-called "counter-ratio" method of Bonner and Cook,[1] has been successful in determining the thresholds for the ground state and for excited nuclear levels in many cases.[2,3] In this method one observes the ratio of the number of counts in a BF_3 detector, which discriminates against high-energy neutrons, to the number of counts in a modified "long counter," which has a uniform sensitivity to all neutrons with energy greater than about 200 kev. By observing this ratio as a function of the incident proton energy, the thresholds for neutron production can be obtained. In this technique, however, the thresholds corresponding to close-lying energy levels can be missed because the relative counter efficiencies may not differ sufficiently for the corresponding neutron groups. This situation is particularly serious when the total neutron yield is low. Furthermore, fluctuations in the ratio curve which could be interpreted as neutron thresholds may actually correspond to the effects of compound-nucleus resonances which are observed in many (p,n) reactions. Other techniques for studying (p,n) reactions, such as the use of energy-selective neutron absorbers,[4,5] can be used successfully in only a limited number of cases.

In a study of nuclear energy levels by the use of the

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† Now at the National Bureau of Standards, Washington, D. C.

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

[2] Brugger, Bonner, and Marion, Phys. Rev. **100**, 84 (1955); Marion, Bonner, and Cook, Phys. Rev. **100**, 91 (1955).

[3] R. A. Chapman and J. C. Slattery, Phys. Rev. **105**, 633 (1957).

[4] P. H. Stelson and W. M. Preston, Phys. Rev. **83**, 469 (1951).

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(p,n) reaction, it is therefore desirable to use a technique for detecting the outgoing neutrons with sufficient energy resolution to be applicable to as large a number of different nuclei as possible. It was felt that the time-of-flight technique, used with the 18-in. cyclotron at Brookhaven to study the elastic and inelastic scattering of neutrons,[6] could be successfully employed to measure the discrete neutron energies resulting from the excitation of nuclear states in a (p,n) reaction. The time-of-flight technique has been used to study (p,n) spectra and angular distributions by a group at Argonne National Laboratory[7] utilizing a pulsed Van de Graaff generator, and by a group in the U.S.S.R.[8] using a 1.5-meter cyclotron.

The present paper describes the results obtained by utilizing the natural phase-bunching of the protons in a cyclotron and a timing technique developed at Brookhaven.[6] Using a primary proton energy of 3 Mev, neutron spectra have been observed for a number of medium weight target nuclei, namely K, Ca^{48}, Ti, Cr, Mn, Fe, Cu, As, and Rb. Q values and energy levels in the residual nuclei were obtained from these spectra.

EXPERIMENTAL CONSIDERATIONS

The experimental arrangement was basically the same as that described in the preceding paper[6] in this issue of *The Physical Review*, in which Fig. 1 shows a schematic diagram of the arrangement. The modification for the present case involved removing the neutron scatterer, and pivoting the shield and detector about a point directly beneath the target. The protons, accelerated in the cyclotron to 3 Mev, arrived at the target in pulses of about 1.5-mμsec duration, the interpulse interval being determined by the period of the rf voltage on the cyclotron dees, namely 50 mμsec in the present experiments. In all cases, the elements to be studied were in the form of thin films deposited on gold-plated copper target-holders of special design.[9] In order to eliminate any possibility of neutrons being produced in the copper of the target, the thickness of the gold plating was always sufficient to slow down the incident protons to an energy well below the threshold for the (p,n) reaction in copper. The element of interest was evaporated under high vacuum onto the gold-plated target holder and the thickness of the evaporated film was determined by weighing. Most of the targets used were less than 30 kev thick for the 3-Mev incident proton energy.

The neutrons resulting from the (p,n) reaction in the target nuclei were detected by a $1\frac{1}{2}$-in. diameter by 1-in. thick plastic scintillator mounted on an RCA 6342 photomultiplier tube. Two signals were obtained from the photomultiplier. One, a fast signal from the anode, was amplified and fed into a time-to-pulse-height converter,[10] in which the relative times of arrival of the neutrons at the detector were converted into pulse heights which were then displayed on a 100-channel quartz-line pulse-height analyzer. A second signal, taken from the last dynode in the photomultiplier, was amplified and fed into a differential pulse-height discriminator, the output of which controlled a coincidence gate between the output of the time-to-pulse-height converter and the input to the 100-channel analyzer. By adjusting the biases in the differential discriminator, it was possible to vary the detection efficiency and thus to emphasize the pulses due to high-energy neutrons relative to those due to low-energy neutrons and conversely. As can be seen in Fig. 4 of the preceding paper,[6] the detection efficiency for neutrons below 500 kev becomes very small. The neutron energies measured in these experiments varied from 2.47 Mev, corresponding to the ground state in the $Rb^{87}(p,n)Sr^{87}$ reaction, to a value of about 600 kev obtained in a number of cases.

The flight path for the neutrons from the target to the detector could be adjusted to provide the best possible resolution of the neutron groups consistent with adequate intensity above background. The length of this flight path was varied from a minimum of about 85 cm to a maximum of 425 cm in the present arrangement.

An example of the spectra obtained in these experiments is shown in Fig. 1, in which the neutron groups from the $Ca^{48}(p,n)Sc^{48}$ reaction are plotted for several different flight distances and discriminator bias settings. On these curves, time increases with decreasing channel number, with about 82 channels on the display corresponding to the 50-mμsec time interval between the proton pulses arriving at the target. The spectra are plotted with the total number of counts as ordinate and the channel number as abscissa. The relative yields of the various groups in a given spectrum were determined by using the relative detection efficiencies as a function of energy for the particular bias settings in the differential discriminator. These relative yields were varied as required to obtain statistically valid data for the various neutron groups.

Curve (a) in Fig. 1 shows the groups seen at 90° with a flight distance of 125 cm. The peak marked γ results from the γ rays which arrived at the detector about 4.2 mμsec after the protons struck the target. Slightly more than 1 rf period later, the neutrons corresponding to the groups marked 1 and 2 arrived at

[6] Landon, Elwyn, Glasoe, and Oleksa, preceding paper, [Phys. Rev. **112**, 1192 (1958)].
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[8] Bogdanov, Vlasov, Kalinin, Rybakov, and Sidorov, Proceedings of the International Conference on the Neutron Interactions with the Nucleus, U. S. Atomic Energy Commission Report TID-7547, 1957 (unpublished).
[9] Muehlhause, Bloom, Wegner, and Glasoe, Phys. Rev. **103**, 720 (1956).
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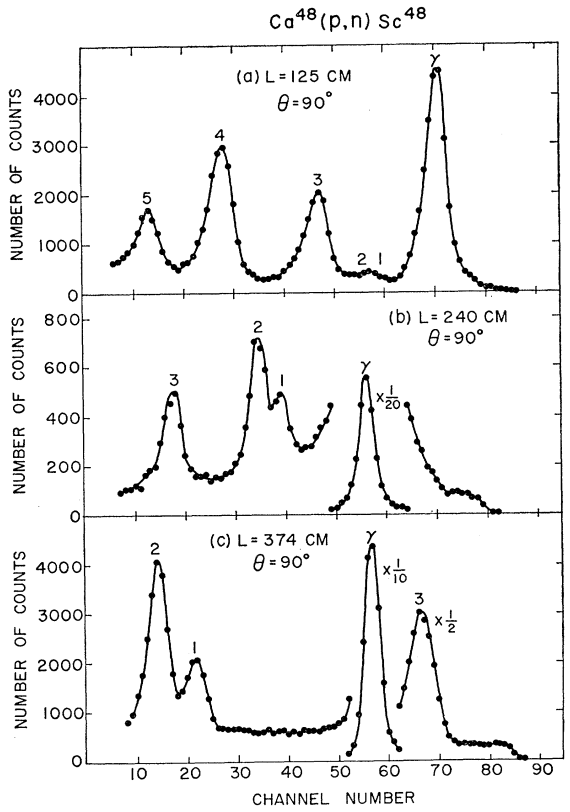

FIG. 1. The neutron groups produced in the $Ca^{48}(p,n)Sc^{48}$ reaction by 3-Mev protons. The time-of-flight for the neutrons increases with decreasing channel number; the peaks are numbered in the order of decreasing neutron energy. The γ-rays coming directly from the target appear in these plots as the peak γ. The three curves show the neutron spectra obtained at different flight distances, L, and with different detector sensitivities. The particular discriminator settings, used to obtain curves (*b*) and (*c*), enhanced the detection efficiency for the higher energy groups 1 and 2 relative to the other groups. The absolute time scale is not the same for each of these curves since the number of channels corresponding to one rf period depended on the particular adjustment of the analyzer. Also, the position of time zero on the analyzer display depended on the amount of delay in the rf signal line to the time-to-pulse-height converter. The angle between the directions of the incident protons and the outgoing neutrons is θ.

the detector. These neutrons correspond to the ground state and the first excited state in Sc^{48}. The neutron groups 3, 4, and 5, leading to excited levels of higher energy in Sc^{48}, arrived at the detector later but during the same rf period as for groups 1 and 2. These groups, 3, 4, and 5, were about 10 times as intense as groups 1 and 2. Curve (*b*) in Fig. 1 shows the same spectrum with the flight distance increased to 240 cm and with the discriminator biases set so the lower energy groups were detected very inefficiently. As can be seen, the peaks 1 and 2 are better resolved than in the case of curve (*a*). As a result of the changed bias setting in the discriminator, the neutrons in groups 1 and 2 were detected with an efficiency about 4 times greater than in the case of curve (*a*). The spectrum obtained with a flight distance of 374 cm is plotted in curve (*c*) and shows the first two groups to be quite well resolved. It can be seen from these curves that the present method can be used successfully to study neutron groups of different energies and intensities.

The neutron energies were computed by two methods. The first method consisted of observing the position of a particular neutron group on the display of the multichannel analyzer and then increasing or decreasing the flight distance by the minimum amount which again placed this neutron group at the identical position on the display. The amount by which the target-to-detector distance was changed, therefore, corresponded to the distance traveled by these particular neutrons in one rf period. The neutron velocity is then given by this change of distance divided by the rf period. The frequency of the cyclotron rf was readily measured with high accuracy by means of a crystal-controlled beat-frequency meter.

The second method for measuring the neutron energy made use of the fact that a peak appearing on each time spectrum corresponded to the γ rays coming directly from the target. The time-of-flight for the neutrons of a particular group was determined by measuring the time interval between the arrival of the neutrons and the γ rays at the detector and making use of the known γ-ray flight time (γ-ray velocity taken as 30 cm/mμsec). It was, of course, necessary to determine by an auxiliary experiment whether the neutron and the γ-ray peaks appeared during the same or different rf cycles following the arrival of the protons at the target. This method presupposes a certain prescription for relating the total number of channels involved in the multichannel display, to the rf period of the cyclotron dee voltage. This prescription was predictable from the electronics of the time-to-pulse-height converter.[10] Knowing this prescription it was possible to arrive at the flight time for the neutrons in each group, and from the flight distance the velocity, and hence the energy, could be determined. Figure 2

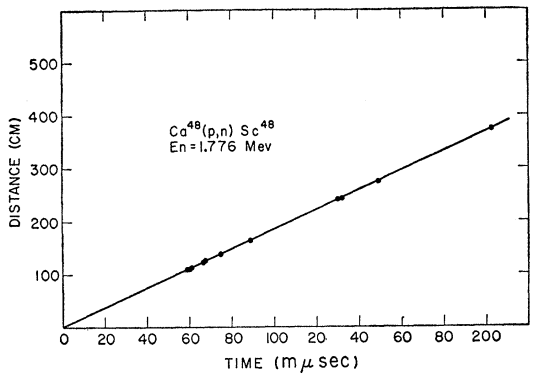

FIG. 2. A plot of distance *versus* flight time for the 1.776-Mev neutrons from the $Ca^{48}(p,n)Sc^{48}$ reaction. These neutrons appear as group No. 3 in Fig. 1. The straight line is a least squares fit to the experimental points, without including a point at zero.

is a plot of flight distance *versus* time for a particular group [marked 3 in the $Ca^{48}(p,n)Sc^{48}$ spectra, Fig. 1] with energy $E_n=1.776$ Mev. The solid line is a least-squares fit to all of the experimental points (*not* including any point at zero time). The correctness of the prescription relating total number of channels on the display to the rf period is evident, since the derived straight line goes accurately through the time zero. The two methods of energy determination gave closely the same results. A source of error in the second method might result from the fact that the pulse-height spectra are different for the neutrons and the γ rays. This would lead to differences in the centroids of the corresponding peaks. However, the use of differential biases in the discriminator minimized this source of error. It should also be pointed out that the linearity of the time-to-pulse-height converter was periodically checked by observing the spectrum of the random pulses from a radioactive source. The spectrum so obtained was linear within about 10%.

The energy of the incident proton beam was measured periodically throughout the experiment. This was accomplished by the use of a double probe inserted into the external beam pipe between the cyclotron and the target position. This probe consisted of two semicircular water-cooled aluminum plates which were spaced an amount slightly greater than the distance travelled by 3-Mev protons in one rf period. The detector was removed from the shield and placed so it was equidistant from the two aluminum probes. The time difference between the two γ-ray peaks (one from each aluminum probe) appearing on the multichannel-analyzer display, together with the known distance between the probes, gave a measure of the velocity of the protons. The energies measured in this way varied from 3.00 Mev to 3.09 Mev depending upon the particular conditions of stable cyclotron operation. The experimental results indicated that the proton energy was constant to about 0.5% over periods of several hours. It is felt that a particular proton energy was known to an accuracy of about ± 30 kev. This error determined in great part the accuracy to which Q values could be determined.

Angular distributions of the neutron groups in the $Cu^{65}(p,n)Zn^{65}$ and $Ca^{48}(p,n)Sc^{48}$ reactions were measured by pivoting the shielded detector under the target. Because of the poor resolution of the neutron groups obtained in the Cu reaction, the angular distribution shown in Fig. 8 is based on peak height rather than on peak area. For Ca^{48}, the groups were well resolved so the angular distributions of Fig. 3 are based on the areas under the peaks. In each case, a background was subtracted which corresponded to the portion of the spectrum between the peaks. The necessary corrections were applied to the data to transform them to the center-of-mass system and the angular distribution plots are in terms of center-of-mass angles. It was noticed that changes in cyclotron operating conditions produced variations in the relative peak heights of the neutron groups. Since the targets used in these experiments were thin, the spread in energy of the incident proton beam was probably not great enough to average over a statistically significant number of levels in the compound nuclei. Thus, slight changes in the incident proton energy could lead to the observed variations. The errors shown on the angular distributions are a measure of the reproducibility of the points.

RESULTS AND DISCUSSION

The results obtained from the (p,n) reactions studied in the present work are summarized in Table I. The first column lists the target element, and the second column lists the particular isotope associated with the reaction studied. Columns 3 and 4 give the ground state Q values and the energy levels of the residual nuclei deduced from the experimental data. The fifth column gives the approximate intensity, at 90°, of each neutron group relative to the highest energy group for each target element. The last column gives references to other work[4,5,11–19] leading to Q values and energy levels for the isotopes listed in column two. The Q values were calculated by using the proton and neutron energies measured during a given day's run wherever possible. All of the neutron energy measurements were made with the detector set at an angle of 90° to the incident proton beam. Errors given on the Q values are based upon estimates of the reproducibility in determining proton energies and the estimated errors in the thickness of the various targets. The errors associated with the energy level separations are estimates which are based primarily on the root-mean-square deviations from the average energy separation between the corresponding neutron groups. The energy difference between levels should not depend on the particular value of the proton energy in a given run. The relative intensities of the neutron groups at 90° were obtained by using the measured counter-sensitivity curves, and should be considered only approximate because the use of thin targets brought about changes in the relative peak heights due to changes in cyclotron operating conditions.

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[14] P. H. Stelson and W. M. Preston, Phys. Rev. **86**, 807 (1952).
[15] Lovington, McCue, and Preston, Phys. Rev. **85**, 585 (1952).
[16] P. A. Stelson and W. M. Preston, Phys. Rev. **82**, 655 (1951).
[17] J. B. Marion and R. W. Kavanagh, Phys. Rev. **104**, 107 (1956).
[18] E. M. Bernstein and H. W. Lewis, Phys. Rev. **107**, 737 (1957).
[19] J. W. Butler and C. R. Gossett, Bull. Am. Phys. Soc. Ser. II, **2**, 230 (1957).

TABLE I. Summary of the results obtained from the study of (p,n) reactions in intermediate weight nuclei using 3-Mev protons and time of flight to observe the resultant neutron spectra.

Target material	Reaction	Negative Q value for ground state (Mev)	Energy levels in residual nucleus (Mev)	Approximate relative intensity of neutron groups at 90°	References to other results
K	$K^{41}(p,n)Ca^{41}$	1.10±0.05	0.0	1	11
Ca^{48}	$Ca^{48}(p,n)Sc^{48}$	0.66±0.03	0.0	1	12
			0.112±0.005	1.7	
			0.485±0.008	7	
			0.985±0.015	9	
			1.23 ±0.02	10	
Ti	$Ti^{49}(p,n)V^{49}$	1.42±0.03	0.0	1	12
			0.086±0.01	0.9	13
			0.145±0.01	0.5	13
			0.73 ±0.02	...	
			0.97 ±0.02	...	
Cr	$Cr^{53}(p,n)Mn^{53}$	1.39±0.03	0.0	1	4,14,15
			0.368±0.007	1.2	13
	$Cr^{54}(p,n)Mn^{54}$	2.15±0.03	0.0	0.3	15
			0.061±0.01	0.4	
Mn	$Mn^{55}(p,n)Fe^{55}$	1.03±0.03	0.0	1	13
			0.399±0.012	0.8	13,16
			0.901±0.012	1	13,16
			1.270±0.010	0.5	
			1.358±0.010	0.7	
Fe	$Fe^{57}(p,n)Co^{57}$	1.67±0.03	0.0	1	
Cu	$Cu^{65}(p,n)Zn^{65}$	2.15±0.05	0.0	1	17
			0.11 ±0.01	0.9	18,5
			0.20 ±0.01	0.7	18
As	$As^{75}(p,n)Se^{75}$	1.68±0.03	0.0	1	12,19
			0.108±0.004	0.9	
			0.268±0.012	1.3	19
			0.40 ±0.02	0.7	
			0.57 ±0.02	0.7	
Rb	$Rb^{87}(p,n)Sr^{87}$	0.54±0.03	0.0	1	
			0.392±0.009	0.7	13
			0.869±0.01	0.8	13
			1.220±0.01	1.6	
	$Rb^{85}(p,n)Sr^{85}$	1.89±0.03	0.0	4	
			0.233±0.007	2.7	13

1. Potassium

A natural K target prepared by evaporation was estimated to be approximately 5 kev thick for 3-Mev protons. The predominant isotope in natural K is K^{39}(93%) but the Q value for the $K^{39}(p,n)Ca^{39}$ reaction is expected to be −7.5 Mev,[20] which is higher than the proton energy used in the present experiment. The K^{40} in the target material probably does not contribute to the reaction because of its low abundance. Thus the single neutron group observed is assigned to the $K^{41}(p,n)Ca^{41}$ reaction. The Q value determined for this group is −1.10±0.05 Mev, which is slightly higher than the value, −1.22 Mev, obtained from the threshold measurement of Richards *et al.*[11] No other neutron groups were observed, which is consistent with the fact that the first excited state in Ca^{41} is at 1.95 Mev above the ground state.[13] The Ca^{41}-K^{41} mass difference, expressed in energy units, is computed from the Q value to be 0.32±0.05 Mev. This result is somewhat less than the values, 0.44 Mev and 0.41 Mev, which are calculated from the nuclear mass data listed by Wapstra[21] and by Giese and Benson,[22] respectively.

2. Calcium[23]

A thin target of Ca, enriched to about 80% in Ca^{48}, was prepared by evaporating a film which was approximately 30 kev thick for 3-Mev protons.[24] Ca^{48} is a particularly interesting nucleus to study because of

[20] P. M. Endt and J. C. Kluyver, Revs. Modern Phys. **26**, 95 (1954).

[21] A. H. Wapstra, Physica **21**, 385 (1955).

[22] C. F. Giese and J. L. Benson, Phys. Rev. **110**, 712 (1958).

[23] Elwyn, Glasoe, Landon, and Oleksa, Bull. Am. Phys. Soc. Ser. II, **3**, 210 (1958).

[24] We acknowledge with thanks the loan of the enriched Ca^{48} from E. der Mateosian and M. Goldhaber. We thank C. Nawrocki for the preparation of the target.

the low (p,n) threshold to be expected, and because of its interest in connection with double beta decay. The neutron groups observed are shown in Fig. 1. A search was made for neutrons of higher energy than those shown in the figure and, if any others do exist, they must have an intensity which is less than 10% greater than the uncorrelated background. On the basis of this search, the peak number 1 is assumed to be the ground-state group with the result that $Q=-0.66\pm0.03$ Mev. The Ca^{48}-Sc^{48} mass difference calculated from this Q value is 0.12 ± 0.03 Mev. This value for the mass difference is comparable to that obtained from the Q value in threshold measurements, namely $Q\geq-0.64$ Mev,[12] but it is considerably lower than the value of 0.24 Mev estimated for this mass difference on the basis of mass spectroscopy and beta-decay data.[13,21,22]

The energy levels listed in Table I for Sc^{48} have not previously been reported. The low intensity of the neutron group which corresponds to the ground state in Sc^{48} is compatible with the high spin of 6 or 7, +, which is to be expected for this state on the basis of the allowed β^- decay to a 6+ level at 3.35 Mev in Ti^{48}.[13] (Shell-model calculations[25] indicate that the ground-state spin of Sc^{48} should be 6.) Furthermore, the

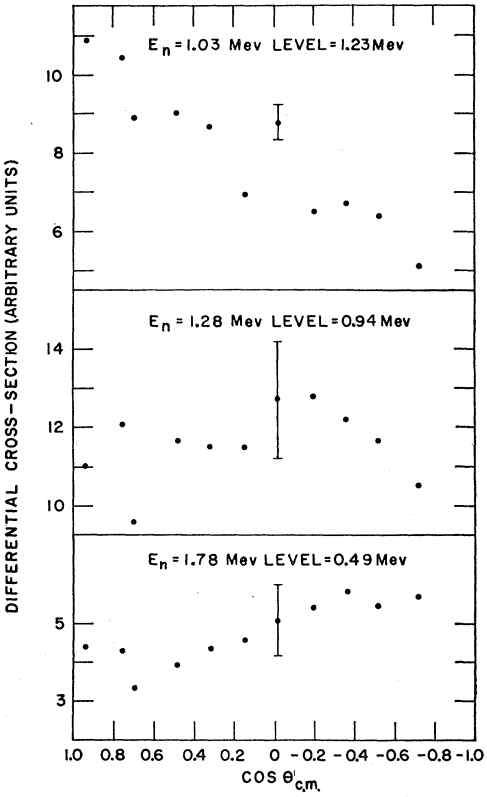

FIG. 3. The angular distributions of the three lowest energy neutron groups in the $Ca^{48}(p,n)Sc^{48}$ reaction. The errors shown on the curves indicate the approximate reproducibility of an individual point.

[25] D. Kurath, Phys. Rev. **87**, 528 (1952).

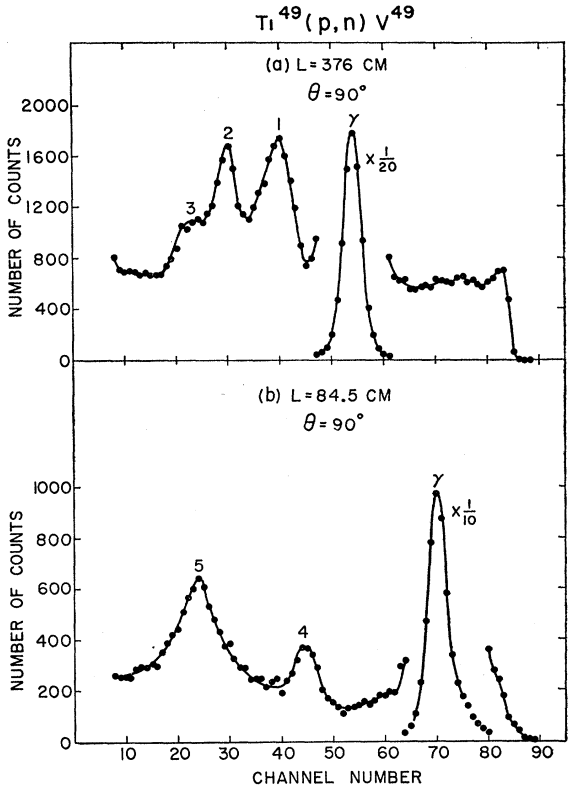

FIG. 4. Neutron groups in the $Ti^{49}(p,n)V^{49}$ reaction.

first excited state at 0.112 Mev might also be expected to have a high spin value because of the low intensity observed for the neutron group which corresponds to the excitation of this state. The low value for the (p,n) threshold energy for Ca^{48} and the large spin-change expected between Ca^{48} and Sc^{48}, are consistent with the results obtained in the search for the beta decay of Ca^{48}, namely that the half-life must be $\geq 2\times10^{14}$ years.[26]

Figure 3 shows the angular distributions of the neutron groups 3, 4, and 5 of Fig. 1. The angular distributions of the neutrons corresponding to the states at 0.485 and 0.985 Mev in Sc^{48} appear to be nearly isotropic, within the rather large error indicated. The angular distribution of the neutrons corresponding to excitation of a level at 1.23 Mev in Sc^{48} seems to be slightly peaked forward. However, as mentioned previously, not too much significance should be attached to these results because of the use of a thin target.

3. Titanium

A target of natural Ti was prepared by evaporation of a film approximately 30 kev thick. The neutron spectra obtained with this target are shown in Fig. 4.

[26] J. W. Jones and T. P. Kohman, Phys. Rev. **85**, 941 (1952); H. Selig, Atomic Energy Commission Report NYO-6626 (unpublished); J. W. Jones, Atomic Energy Commission Report NYO-6627 (unpublished).

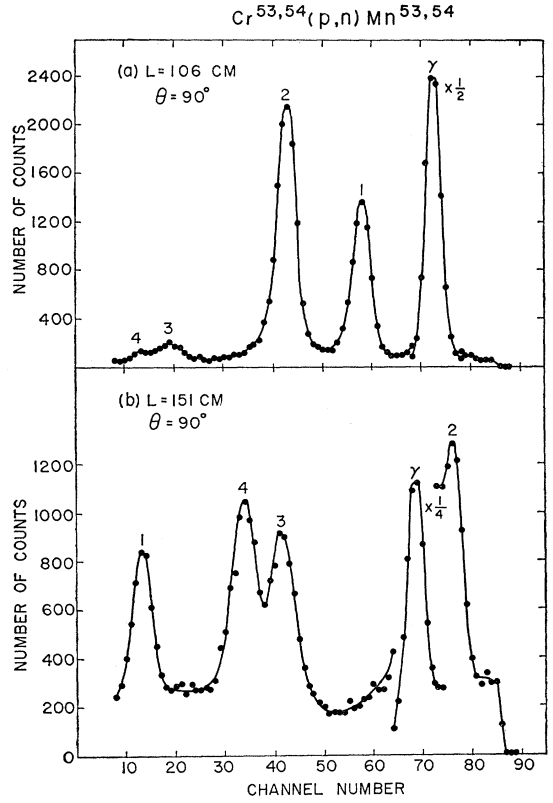

FIG. 5. Neutron groups in the $Cr^{53,54}(p,n)Mn^{53,54}$ reactions. The groups marked 1 and 2 correspond to the $Cr^{53}(p,n)Mn^{53}$ reaction. Group 3 is the ground-state group in the $Cr^{54}(p,n)Mn^{54}$ reaction, while group 4 is assigned to a level at 0.061 Mev in Mn^{54}. Curve (*b*), at a different flight distance from (*a*), shows how a variation of the counter sensitivity can be used to emphasize the low-energy neutrons relative to the higher energy neutrons. [Compare groups 3 and 4 on curves (*a*) and (*b*).]

In this figure, curve (*a*) shows the results obtained with a flight distance of 376 cm. The three neutron groups observed in this curve have been identified with the ground state and the first two excited states in V^{49}, in the $Ti^{49}(p,n)V^{49}$ reaction, even though natural Ti contains only 1.8% of Ti^{49}. The thresholds for the (p,n) reactions in the other Ti isotopes are known to be too high to be observed using 3-Mev protons.[13] Curve (*b*) shows two neutron groups of lower energy which become evident at shorter flight distances and different discrimination biases; in this case the distance was 85 cm. The 3 groups of curve (*a*) correspond to the three known levels in V^{49},[13] and the two lower energy neutron groups of curve (*b*) correspond to levels in V^{49} at 0.73 and 0.97 Mev. The level at 0.73 Mev may be the state at 0.762 Mev previously reported by Craseman and Easterday.[27] Such a state was not seen, however, by Nussbaum *et al.*[28] in a study of the decay of Cr^{49}.

The Q value determined from these results is -1.42 ± 0.03 Mev and the mass difference, V^{49}-Ti^{49}, is 0.64 ± 0.03 Mev. This Q value compares well with the previously reported value[12] of -1.392 ± 0.005 Mev. The mass difference agrees within the errors to the value 0.61 Mev which is calculated from nuclear mass data.[21,22]

4. Chromium

The neutron spectrum shown in Fig. 5 was obtained from the proton bombardment of a natural Cr target approximately 30 kev thick. These neutron groups must be due to the Cr^{53} and Cr^{54} isotopes since the thresholds for the (p,n) reactions in Cr^{50} and Cr^{52} are higher than the proton energy used in these experiments.[13] The peaks 1 and 2 correspond to the ground state and the first excited state in Mn^{53}, in the $Cr^{53}(p,n)Mn^{53}$ reaction. From these data the Q value of the ground state for Mn^{53} is determined to be -1.39 ± 0.03 Mev, which compares very favorably with the values of -1.37 Mev and -1.38 Mev previously reported by Stelson and Preston[4,14] and by Lovington *et al.*,[15] respectively. This Q value gives a Mn^{53}-Cr^{53} mass difference of 0.61 ± 0.03 Mev which is in agreement with the value of 0.60 Mev computed from mass data.[21,22] The first excited state at 0.368 Mev agrees with the level at 0.38 Mev previously reported for Mn^{53}.[13] The neutrons of group 3 in Fig. 5 probably correspond to the ground state in the $Cr^{54}(p,n)Mn^{54}$ reaction since the Q value determined from this group is -2.15 ± 0.03 Mev, which compares favorably with the value -2.16 Mev measured by Lovington *et al.* for Mn^{54}.[15] The mass difference, Mn^{54}-Cr^{54}, calculated from this Q value, is 1.37 ± 0.03 Mev which agrees with the mass difference 1.38 Mev calculated from the results of Giese and Benson,[22] but is higher than the value 1.20 Mev calculated from the data of Wapstra.[21] It is most likely that the fourth neutron group corresponds to a level in Mn^{54} at 0.061 Mev. Although the possibility exists that it might actually correspond to a level in Mn^{53} at about 0.80 Mev, no state has been previously observed at that energy while energy levels at 0.38 and 1.27 Mev have been observed.[13] (A low-energy neutron group corresponding to a level at 1.27 Mev in Mn^{53} could not be observed in this experiment due to the very low detection efficiency for such neutrons.)

It has been reported[29] that there may be an isomeric state in Mn^{54} with a half-life of 2.1 min, but recent work by McNeill *et al.*[30] has failed to confirm its existence. An attempt was made to observe such an activity in the present work by bombarding a thick target of natural Cr for a short time with 3-Mev protons. The target was then viewed with a $1\frac{1}{2}$ in. $\times$ 2 in.

[27] B. Craseman and H. T. Easterday, Phys. Rev. **90**, 1124 (1953).

[28] Nussbaum, Wapstra, Nijgh, Ornstein, and Verster, Physica **20**, 165 (1954).

[29] D. O. Caldwell and H. F. Stoddart, Phys. Rev. **81**, 660(A) (1951).

[30] McNeill, Prentice, Katz, and Link, Can. J. Phys. **35**, 753 (1957).

NaI crystal and an activity with approximately 2 minutes half-life was observed. This problem was not pursued but it is believed that the evidence for a 2-minute activity is sufficient to warrant further work in this connection.

5. Manganese

A target of natural Mn (100% Mn^{55}) was prepared by evaporating a film approximately 20 kev thick to 3-Mev protons. The neutron spectrum obtained with this target is shown in Fig. 6. Five neutron groups are observed which correspond to the ground state and the four excited states in Fe^{55} which are listed in Table I. The Q value of the ground state, determined from these data, is -1.03 ± 0.03 Mev, which falls within the range of previously measured values, namely -1.00 Mev to -1.05 Mev.[13] This Q value corresponds to a Fe^{55}-Mn^{55} mass difference of 0.25 ± 0.03 Mev, which is in approximate agreement with the value 0.23 Mev calculated from the data of Wapstra.[21]

The first two excited states in Fe^{55}, at 0.399 Mev and 0.901 Mev, are slightly lower than the results of previous investigations,[16,31] which indicate states at about 0.41 and 0.93 Mev. Stelson and Preston[16] report a level at about 1.36 Mev, which appears to be a doublet, based on the results of their study of the $Mn^{55}(p,n)Fe^{55}$ reaction, using nuclear emulsions as the neutron detector. The possibility of a doublet is also indicated by Chapman and Slattery[3] as a result of their work on (p,n) thresholds. In the present case, energy levels at 1.270 and 1.358 Mev are resolved (neutron groups 4 and 5 on Fig. 6) which seems to verify the existence of this doublet, with an energy separation of 0.088 Mev. Levels reported by Sperduto and Buechner[31] at 1.322 Mev and 1.413 Mev probably correspond to these same two states.[32]

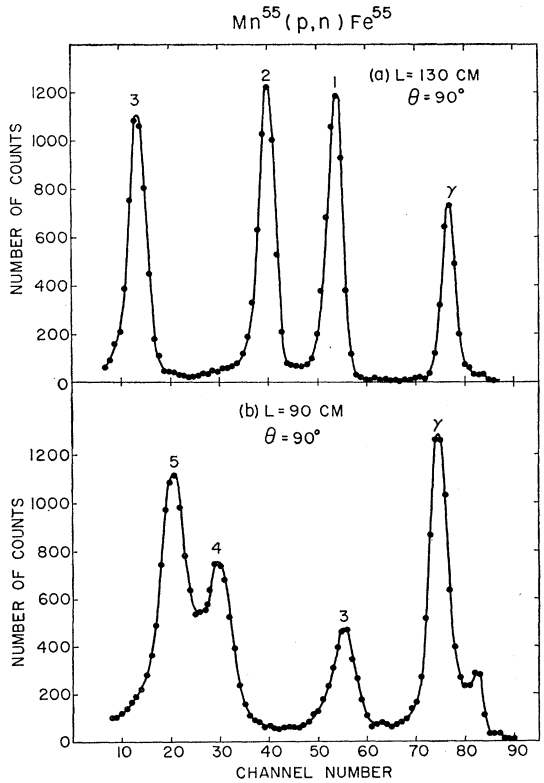

FIG. 6. Neutron groups in the $Mn^{55}(p,n)Fe^{55}$ reaction.

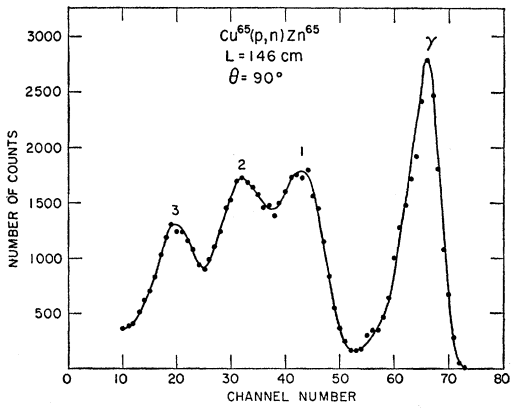

FIG. 7. Neutron groups in the $Cu^{65}(p,n)Zn^{65}$ reaction. The neutrons corresponding to excitation of a state at 0.054 Mev in Zn^{65} should appear approximately midway between groups 1 and 2 but could not be resolved in the present experiment.

6. Iron

A thin target of natural Fe (2.17% Fe^{57}) was prepared by evaporation of the metal in vacuum. The one neutron group observed corresponds to the ground state in Co^{57}. No neutron groups are expected from the other Fe isotopes since their (p,n) thresholds are all higher than 3 Mev.[13] No other energy levels are seen in Co^{57}, which is consistent with the fact that the first excited state is known to be at 1.38 Mev,[13] and is thus too high to be observed in these experiments. The one neutron group which is observed gives a Q value of -1.67 ± 0.03 Mev, from which the mass difference for Co^{57}-Fe^{57} is 0.89 ± 0.03 Mev. This result differs appreciably from the mass difference of 0.52 Mev calculated from the mass data of Wapstra.[21] A value of 0.9 Mev is predicted, however, from beta-decay systematics.[13]

7. Copper[33]

A target of natural Cu (30.9% Cu^{65}) was prepared by evaporation of the metal to a thickness of approximately 30 kev. The predominant Cu isotope, Cu^{63}, will not contribute to the (p,n) reaction at 3 Mev because

[31] A. Sperduto and W. W. Buechner, Bull. Am. Phys. Soc. Ser. II, 1, 223 (1956), and L. L. Lee, Jr. (private communication).

[32] In this connection, L. L. Lee, Jr. and F. P. Mooring (private communication) have reported levels in Fe^{55} in the $Mn^{55}(p,n)Fe^{55}$ reaction at 0.436, 0.927, 1.314, and 1.406 Mev, the latter two states probably corresponding to the doublet.

[33] Landon, Elwyn, and Glasoe, Bull. Am. Phys. Soc. Ser. II, 2, 230 (1957).

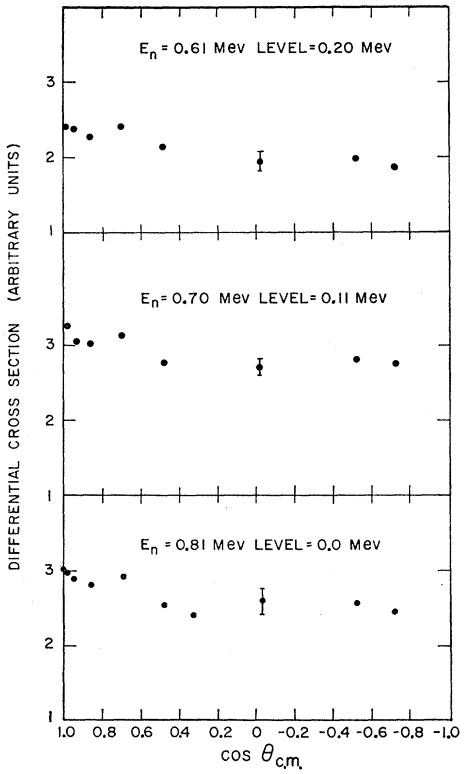

FIG. 8. Angular distributions of the neutron groups in the $Cu^{65}(p,n)Zn^{65}$ reaction. The errors shown on the curves indicate the approximate reproducibility of an individual point.

of its high threshold.[13] Figure 7 shows the neutron groups observed in the $Cu^{65}(p,n)Zn^{65}$ reaction. Three groups are observed which correspond to the ground state and excited states at 0.11 Mev and 0.20 Mev in Zn^{65}. The ground state Q value is determined to be -2.15 ± 0.05 Mev. This value compares well with the Q value of -2.1315 ± 0.0009 Mev, which is derived from a weighted mean[17] of the results in neutron threshold measurements, resonant neutron scattering measurements, and calculations based on the β decay of Zn^{65} and the n-p mass difference. The Zn^{65}-Cu^{65} mass difference is calculated to be 1.37 ± 0.05 Mev from the Q value obtained in the present experiments.

Bernstein and Lewis[18] have studied the $Cu^{65}(p,n)Zn^{65}$ reaction by observing the conversion electrons in a beta spectrometer and they have assigned energy levels at 0.054, 0.119, and 0.209 Mev to Zn^{65}. These states are consistent with observations of γ-ray transitions in Zn^{65} from the Ga^{65} β decay.[34] Marion and Chapman[5] were able to identify a state at 0.118 Mev from observations on resonant neutron scattering. The levels at 0.11 Mev and 0.20 Mev observed in this work probably correspond to the states at 0.119 and 0.209 Mev. Because of the low resolution in this particular experiment it was not possible to clearly identify a state at 0.054 Mev, but as can be seen in Fig. 7, there is definite evidence that a neutron group is present whose energy is about half-way between the ground state and the state at 0.11 Mev.

Figure 8 shows the angular distributions of the neutron groups observed in the $Cu^{65}(p,n)Zn^{65}$ reaction. The distributions appear to be essentially isotropic but there is some forward peaking. However, as mentioned previously, the use of a thin target in these experiments affects the significance of these observations.

8. Arsenic

An As target was prepared by evaporation of the natural element (100% As^{75}) to a thickness of approximately 20 kev. Figure 9 shows the neutron groups obtained in the $As^{75}(p,n)Se^{75}$ reaction. Four well-resolved neutron groups are observed. The peak labeled 5, at a neutron energy of about 775 kev, appears to correspond to more than just a single group of neutrons, but further resolution was not possible with the present equipment.

The results with the As target lead to the energy levels listed in Table I for Se^{75}. The level at 0.268 Mev probably corresponds to a state at 0.286 Mev which has been observed by looking for slow neutron thresholds in the $As^{75}(p,n)Se^{75}$ reaction.[19] The other states listed in the table have not been previously reported. The Q value of the ground state in Se^{75}, determined from these data, is -1.68 ± 0.03 Mev, which agrees

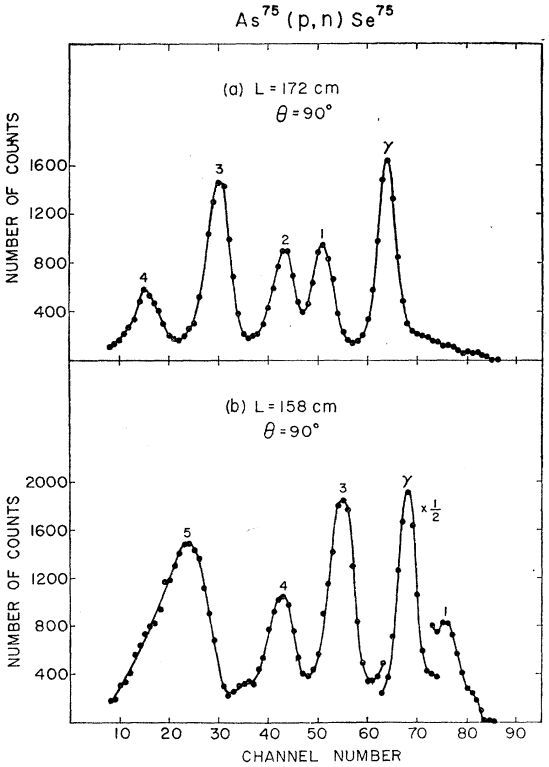

FIG. 9. Neutron groups in the $As^{75}(p,n)Sc^{75}$ reaction.

[34] B. Craseman, Phys. Rev. 93, 1034 (1954); J. F. Friichtenicht and L. A. Beach, Bull. Am. Phys. Soc. Ser. II, 3, 62 (1958).

with the values obtained from neutron threshold techniques, namely -1.652[12] and -1.648.[19] The mass difference for Se^{75}-As^{75}, computed from the Q value in this work, is 0.90 ± 0.03 Mev, which is in approximate agreement with the value 0.87 Mev calculated from the mass data of Wapstra.[21]

9. Rubidium

Figure 10 shows the neutron groups observed when a target of natural Rb (72% Rb^{85}, 28% Rb^{87}), approximately 30 kev thick, was bombarded by 3-Mev protons. The first four neutron groups correspond to the ground state and the three excited states listed in Table I for the $Rb^{87}(p,n)Sr^{87}$ reaction. The first two excited states, at 0.392 and 0.869 Mev, correspond to known levels at 0.39 and 0.87 Mev.[13] The third state at 1.220 Mev has not been previously reported. The ground-state Q value, -0.54 ± 0.03 Mev, leads to a mass difference of 0.24 ± 0.03 Mev for Rb^{87}-Sr^{87}, which is in approximate agreement with the value 0.27 calculated from the mass data of Wapstra.[21]

Group number 5 in Fig. 10 is probably the ground state in the $Rb^{85}(p,n)Sr^{85}$ reaction. The Q value determined from this group is -1.89 ± 0.03 Mev, and leads to a mass difference of 1.11 ± 0.03 Mev for Sr^{85}-Rb^{85}. This value for the mass difference agrees well with the accepted value of 1.1 Mev obtained from β-decay systematics[13] and is in approximate agreement with 1.04 Mev computed from the mass data of Wapstra.[21] It is probable that group 6 corresponds to an energy level in Sr^{85} at 0.233 Mev. A close doublet at this energy is known.[13]

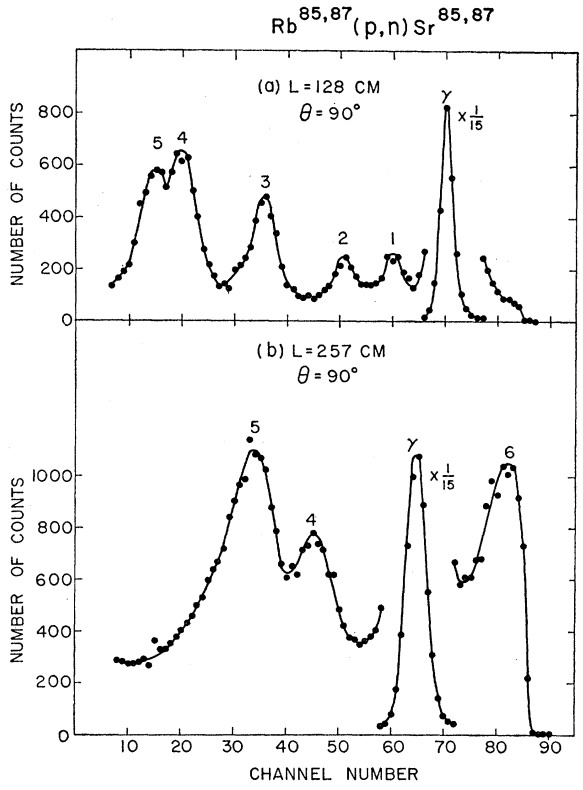

FIG. 10. Neutron groups in the $Rb^{85,87}(p,n)Sr^{85,87}$ reactions. The groups marked 1, 2, 3, and 4 correspond to the $Rb^{87}(p,n)Sr^{87}$ reaction. Groups 5 and 6 are assigned to the $Rb^{85}(p,n)Sr^{85}$ reaction.

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