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The $Mn^{55}(p,n)Fe^{55}$ Neutron Spectrum*

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A thin (20-kev) target of manganese on a tantalum backing was bombarded by monoenergetic protons of 2.97, 3.42, and 3.77 Mev from the Rockefeller electrostatic generator. Nuclear emulsion plates (Eastman NTB, 200 microns thickness) were mounted 15 cm from the target at 0° and 90° with respect to the incident proton beam. The resulting neutron spectra, obtained from the analysis of 2400 proton recoil tracks, show well-defined groups which correspond to excited states in Fe^{55} at 0.42, 0.94, 1.36, and 2.08 Mev. The group corresponding to the level at 1.36 Mev has an unusually large width indicating that this level is complex. The Q-value for the ground-state reaction was measured to be -1.05 ± 0.05 Mev, giving the threshold for neutron production as 1.07 ± 0.05 Mev. Levels in Fe^{55} at 0.935 and 1.41 Mev have been found by Deutsch and Hedgran from a study of the decay scheme of Co^{55}. These levels correspond closely to two of the levels reported here.

I. INTRODUCTION

THE investigation of the Co^{55} decay scheme by Deutsch and Hedgran[1] indicates the existence of excited states in the Fe^{55} nucleus at 0.935 and 1.41 Mev. From a study of the neutron spectrum produced by the $Mn^{55}(p,n)Fe^{55}$ reaction at proton-bombarding energies well above the threshold (1.18 Mev;[2] 1.02 Mev[3]), information can be obtained concerning the positions of excited levels in the residual nucleus, Fe^{55}, and the relative transition probabilities from the compound nucleus to these levels. Since the selection rules for $\beta-\gamma$ decay are more stringent than those for the (p,n) process, one would expect the (p,n) investigation to confirm the levels obtained from the $\beta-\gamma$ decay and to disclose, possibly, the existence of additional levels not excited in the $\beta-\gamma$ decay. We have performed an experiment in which the neutron spectra produced by bombarding a thin manganese target with monoenergetic protons from the Rockefeller electrostatic generator were measured by means of proton recoils in photographic emulsions.

II. EXPERIMENTAL METHOD

A 20-kev manganese metal[3a] target on a tantalum backing was bombarded by 2.97-, 3.42-, and 3.77-Mev protons. Proton energies were measured by a generating voltmeter calibrated by the $Li^7(p,n)$ threshold at 1.882 Mev. Eastman NTB plates of 200 microns thickness were placed a mean distance of 15 cm from the target at 0° and 90° with respect to the incident proton beam. The processed emulsions were systematically scanned at 950× magnification (oil immersion) and proton recoil tracks within 10 degrees of the neutron direction were accepted for measurement. The range-energy relation used to convert proton recoil track lengths to neutron energy E_n was obtained by measuring the $Li^7(p,n)$ spectrum at several bombarding energies and the d–d spectrum at a single deuteron-bombarding energy.

Three corrections were applied to the data to obtain plots of relative neutron intensity *vs* neutron energy: (1) the correction for the variation of the (n,p) collision cross section with energy, (2) the correction for the different probability of leaving the emulsion for tracks of different length, and (3) the correction for the variation with neutron energy of the spacing of the experimental points. The second correction is quite small for the present investigation. The third correction was applied to make the area under a given peak represent the relative intensity of the peak.

III. DISCUSSION

The corrected data, based on about 2400 measured tracks, are given in Figs. 1 and 2 as plots of relative neutron intensity *vs* neutron energy. Figure 1 shows the neutron spectrum at 0° and 90° with respect to the incident proton beam when a bombarding energy of 3.42 Mev was employed. Figure 2 shows the spectrum at 0° with proton-bombarding energies of 2.97 and 3.77 Mev. An indication of the statistical accuracy of the data is given by the conventional symbols placed

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[1] M. Deutsch and A. Hedgran, Phys. Rev. 75, 1443 (1949).
[2] Richards, Smith, and Browne, Phys. Rev. 80, 524 (1950).
[3] J. J. G. McCue and W. M. Preston, private communication.
[3a] The manganese metal with a purity of 99.5 percent was obtained from the Fairmount Chemical Company.

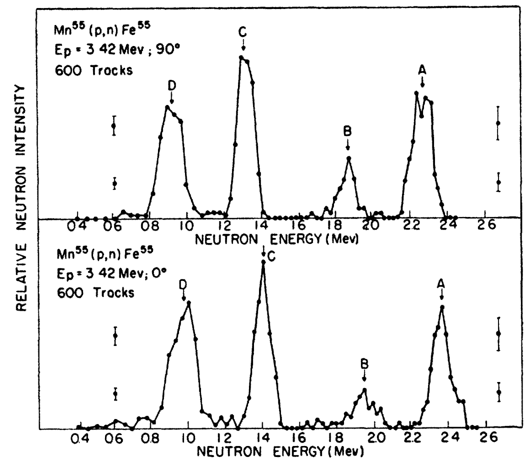

FIG. 1. Neutron spectra resulting from the bombardment of a thin manganese target with 3.42-Mev protons. The photographic plates were placed at 0° and 90° with respect to the incident proton beam.

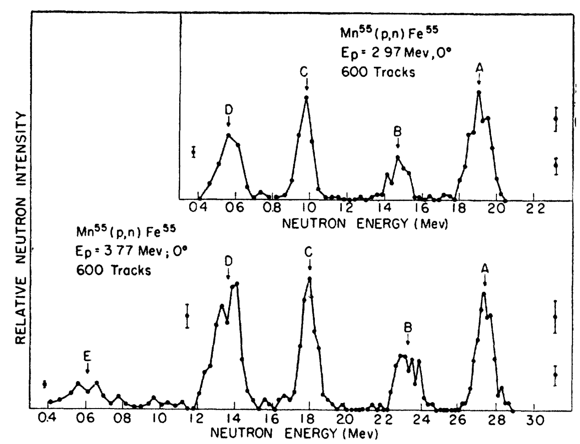

FIG. 2. Neutron spectra resulting from the bombardment of a thin manganese target with 2.97- and 3.77-Mev protons. The photographic plates were placed at 0° with respect to the incident proton beam.

in the figures. The corrections which must be applied to the data to obtain relative neutron intensity cause the statistical accuracy to decrease with increasing neutron energy.

Four groups A, B, C, and D are evident in all the spectra, while at the highest bombarding energy a fifth group E appears. The measured Q-values of these groups are given in Table I. The peaks designated by A give a Q-value for the ground-state transition of -1.05 ± 0.05 Mev and hence a threshold for the $Mn^{55}(p,n)Fe^{55}$ reaction of 1.07 ± 0.05 Mev. Richards, Smith, and Browne[2] studied the neutron yield from a thick manganese target as a function of proton bombarding energy and obtained a threshold of 1.18 ± 0.01 Mev, a value which is not in good agreement with that obtained by the method reported here. However, McCue and Preston[3] have performed an experiment similar to that of Richards, *et al.*, and find a lower value of 1.02 ± 0.02 Mev for the threshold.

The shift in energy of the neutron groups A, B, C and D at $E_p=3.42$ Mev with emergent angle $(0°\rightarrow 90°)$ is consistent with a target nucleus of $A\sim55$. A spectrum of 200 tracks (not shown) was measured at the highest proton-bombarding energy at 90° to the proton beam to establish the fact that group E also exhibited a shift in energy consistent with $A\sim55$. The observations at 0° and 90°, therefore, permit the elimination of the possibility of any of the neutron groups originating from target surface contamination by much lighter elements with larger (p,n) cross sections. However, the possibility that such contamination could produce neutron groups with sufficient intensity to be observable is unlikely. Carbon and oxygen are the two most likely contaminators and only the C^{13} and O^{18} isotopes, which have small relative abundances in the natural elements, have low enough (p,n) thresholds to produce neutrons at the proton energies employed.

The resolution of the photographic plate, proton recoil method of measuring neutron spectra increases with increasing neutron energy and therefore the half-widths of the neutron groups increase with decreasing energy. However, group D appears to have an unusually large half-width. Group C at $E_p=2.97$ and 3.42 Mev falls approximately at the same neutron energies as group D at $E_p=3.42$ and 3.77 Mev; and, hence, an effective comparison of the half-widths can be made. This indicates that group D has approximately 60 kev more width than C, suggesting that group D is complex; a level separation of 60 kev results if it is assumed that this peak is due to two levels equally strongly excited.

An energy level diagram presenting the results of the present investigation and those of Deutsch and Hedgran on the decay of Co^{55} is given in Fig. 3. It is seen that there is good correspondence between their level at 0.935 Mev and the level at 0.94 Mev. The cor-

TABLE I. Measured Q-values for the neutron groups shown in Figs. 1 and 2. The last column gives the average excitation energy above the ground state (group A) and therefore indicates the location of levels in the residual nucleus Fe^{55}.

Neutron group	Q-value (Mev) $E_p=2.97$; 0°	$E_p=3.42$; 90°	$E_p=3.42$; 0°	$E_p=3.77$; 0°	Average	Neutron group	Average excitation energy (ΔQ in Mev)
A	−1.06	−1.05	−1.05	−1.03	-1.05 ± 0.05	A	
B	−1.49	−1.45	−1.47	−1.45	-1.47 ± 0.05	B	0.42
C	−1.99	−2.01	−2.00	−1.96	-1.99 ± 0.05	C	0.94
D	−2.38	−2.42	−2.43	−2.41	-2.41 ± 0.05	D	1.36
E				−3.13	-3.13 ± 0.07	E	2.08

TABLE II. Relative transition probabilities, t, of the neutron groups shown in Figs. 1 and 2. The relative transition probability divided by the square root of the neutron energy and normalized to unity, $t/E_n^{\frac{1}{2}}$, is also given. The indicated errors are those due to statistics only; no attempt has been made to include other possible errors such as the inability to apply the selection criteria equally well to the long and short tracks.

Neutron group	Relative transition probability [t]			
	$E_p=2.97$; 0°	$E_p=3.42$; 90°	$E_p=3.42$; 0°	$E_p=3.77$; 0°
A	0.37±0.03	0.28±0.03	0.26±0.03	0.22±0.02
B	0.12±0.02	0.09±0.02	0.09±0.02	0.13±0.02
C	0.26±0.02	0.31±0.02	0.30±0.02	0.21±0.01
D	0.25±0.02	0.32±0.02	0.35±0.02	0.35±0.03
E				0.09±0.01
	$\frac{\text{Relative transition probability}}{(\text{neutron energy})^{\frac{1}{2}}}$ (normalized to unity)[$t/(E_n)^{\frac{1}{2}}$]			
A	0.28±0.02	0.22±0.02	0.21±0.02	0.17±0.02
B	0.11±0.02	0.08±0.02	0.08±0.02	0.10±0.01
C	0.27±0.02	0.32±0.02	0.30±0.02	0.20±0.02
D	0.34±0.02	0.39±0.02	0.42±0.02	0.38±0.03
E				0.15±0.02

respondence between their level at 1.41 Mev and our doublet level at 1.36 Mev is somewhat less satisfactory but is within the accuracy of the measurements involved in the two experiments.

The relative transition probabilities, t, of the different groups at the three proton-bombarding energies are listed in Table II. The quantity $t/E_n^{\frac{1}{2}}$ (normalized to unity) is also given, since, according to theory,[4] this quantity should be a measure of the "matrix element," i.e., the energy dependence of the emitted neutron has been removed. The quantities $t/E_n^{\frac{1}{2}}$ should depend on the relation of the angular momentum, I, of the target nucleus, $Mn^{55}(I=5/2)$, to the angular momenta, I', of the levels of the residual Fe^{55} nucleus. A given excited state of the residual nucleus can, in general, be reached in a number of ways, i.e., by different vectorial combinations of the angular momenta of the target nucleus, incident proton and emerging neutron. Using the theory developed by Tyson[5] for calculating the effect of the coulomb plus angular momentum barrier on the incident protons, one obtains for 3.5-Mev protons incident on manganese cross sections for the s, p, d, f, and g waves of 0.030, 0.054, 0.024, 0.005, and 0.0005 barn, respectively. The theory indicates, therefore, that there is a relatively good chance of the proton carrying in 0, 1, 2, or even 3 units of orbital angular momentum, and when this, together with the intrinsic spin of the proton, is added vectorially to the 5/2 value of the target nucleus, a large range of possible values for the angular momentum of the highly excited states of the compound nucleus is obtained. At the high excitation energy of the compound nucleus (~10–12 Mev) one would expect a small level spacing and hence many levels are available for excitation in the energy increment of 30 kev, determined largely by the target thickness. These compound states then decay to levels of Fe^{55} by the emission of a neutron which is also capable of carrying several units of angular momentum. The ratios of the cross sections for the emission of s, p, d, f, and g wave neutrons of 2.0 Mev from the Fe^{56} nucleus are calculated to be 1.0:2.5:2.1:0.6:0.1 using the formulas given by Blatt and Weisskopf.[6]

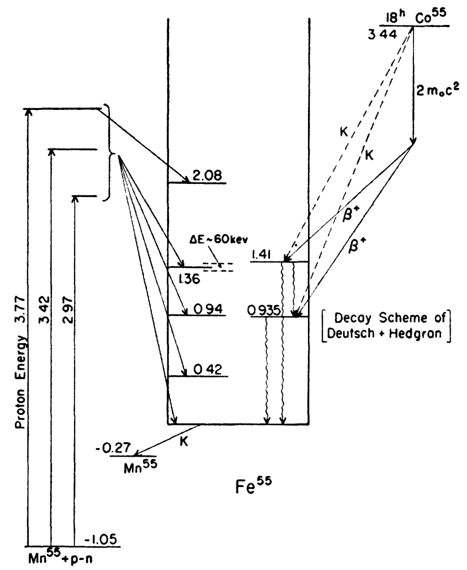

FIG. 3. Energy level diagram for the Fe^{55} nucleus.

These considerations suggest that the study of the neutron spectrum of $Mn^{55}(p,n)Fe^{55}$ induced by protons of several Mev energy should disclose the existence of levels in Fe^{55} with angular momentum values of 1/2 up to a fairly large value of perhaps 13/2 or 15/2. Levels with I' values not too different from the 5/2 value of the target nucleus should have approximately the same value of $t/E_n^{\frac{1}{2}}$. One would also expect the $t/E_n^{\frac{1}{2}}$ values to become more uniform at higher proton energies since the restrictions on the angular momenta of the incident and emerging nucleons become less severe. It is interesting to note at the highest proton bombarding energy the groups A, C, and E have about the same $t/E_n^{\frac{1}{2}}$ values and if group D is taken to be a doublet, the value of $t/E_n^{\frac{1}{2}}$ is approximately the same as for A, C, and E. However, the intensity of group B is definitely low, which suggests that the I' value for this level is quite different from 5/2 and is therefore probably quite large. This is concordant with the fact that this level is not excited in the $\beta-\gamma$ decay of Co^{55}, where more stringent selection rules are operative.

[4] Feshbach, Peaslee, and Weisskopf, Phys. Rev. **71**, 145 (1947).
[5] J. K. Tyson, Ph.D. thesis, MIT (1948).
[6] J. M. Blatt and V. F. Weisskopf, MIT Technical Report No. 42 (May, 1950).