coefficient for internal pair conversion is being carried out at this laboratory by Mr. R. J. Mackin and Mr. C. Wong. This should provide information on the character of the gamma-ray and hence on the change of spin and parity occurring in the transition. Preliminary results indicate that the gamma-ray is magnetic dipole as is to be expected from the above considerations.

We should like to express our thanks to Professors T. Lauritsen and R. F. Christy for suggesting this problem and for several enlightening discussions on it. We are also indebted to Mr. Torben Huus for assistance in operating the electrostatic generator.

This work was supported by the joint program of the AEC and ONR.

PHYSICAL REVIEW VOLUME 85, NUMBER 4 FEBRUARY 15, 1952

The (p, n) Reaction on Separated Isotopes of Chromium*

J. A. LOVINGTON,† J. J. G. MCCUE, AND W. M. PRESTON
Laboratory for Nuclear Science and Engineering, Massachusetts Institute of Technology, Cambridge, Massachusetts
(Received November 7, 1951)

Several hundred resonances have been observed in the neutron yield from proton bombardment of the enriched isotopes Cr^{53} and Cr^{54}. No characteristic groups of resonances are observed. Upper limits to the level spacing in the compound nuclei Mn^{54} and Mn^{55} are 4 and 5 kev, respectively. The thresholds are found to be 1406±8 kev for $Cr^{53}(p,n)$ and 2202±5 kev for $Cr^{54}(p,n)$.

A. INTRODUCTION

RESONANCES in the neutron yield of the reaction $Mn^{55}(p,n)Fe^{55}$ have been studied by McCue and Preston.[1] In continuation of a program at this laboratory of investigating a number of light-intermediate weight elements with the best energy resolution practical with our equipment, we have measured the relative yield as a function of energy from the reactions $Cr^{53}+p\rightarrow Mn^{54}\rightarrow Mn^{53}+n$ and $Cr^{54}+p\rightarrow Mn^{55}\rightarrow Mn^{54}+n$. Chromium was chosen because its two heaviest stable isotopes, Cr^{53} and Cr^{54}, could be obtained from Oak Ridge enriched to a high degree and had (p,n) thresholds estimated to be conveniently low. Neutron yield resonances in these reactions correspond to excited states in the compound nuclei Mn^{54} and Mn^{55}. We wished to measure the reaction threshold energies, to search for possible regularities in the level spectra, and to compare the level spacing in two neighboring nuclei with the same number of protons, but containing, respectively, an odd and an even number of neutrons.

B. EXPERIMENTAL METHODS

The proton source was the Rockefeller electrostatic generator[2] at M.I.T. The absolute energy calibration of the machine is based on the $Li^7(p,n)Be^7$ threshold, taken as 1882.2 kev, ±0.1 percent.[3] Relative to this standard, we believe our energy measurements of sharp resonances in the present work should be accurate to ±0.1 percent, allowance being made for long-term drifts in the calibration constant, target contamination, and other sources of error. Resetting accuracy and short-term stability, as in measuring the profiles or separation of neighboring resonances, is close to 0.01 percent. Tests indicate that the effective beam energy resolution width is not over 0.08 percent when the defining slits of the magnetic analyzer are opened to 1 mm, and half as great with 0.5-mm slit openings.

Neutrons were detected by a counter consisting of a 1-inch diameter tube, filled with enriched BF_3 at a pressure of 55 cm of mercury, and embedded in an 8-inch diameter, cadmium-covered cylinder of paraffin. The counter was operated in the proportional region and the pulse-height discriminator, which followed the linear amplifier, was set at a sufficiently high level so that gamma-rays were not counted. The counter assembly was mounted with its axis perpendicular to the proton beam and its side a few centimeters from the target, at which it therefore subtended a rather large angle in the forward direction. The counter was operated in this position in order to get satisfactory counting rates despite the low reaction yields; we cannot assume that the neutron detection efficiency was inde-

TABLE I. Isotopic analysis of target materials.

Isotope	Natural abundance	Enriched Cr^{53}	Enriched Cr^{54}
Cr^{50}	4.4%	0.193%	0.2%
Cr^{52}	83.5	9.28	7.0
Cr^{53}	9.5	90.06	3.9
Cr^{54}	2.6	0.465	89.0

* This work was supported by the Bureau of Ships and the ONR.
† Lt. Commander, U.S.N. This work was done in partial fulfillment of the requirements for the degree of Master of Science in Physics at M.I.T.
[1] J. J. G. McCue and W. M. Preston, Phys. Rev. **84**, 1150 (1951).
[2] W. M. Preston and C. Goodman, Phys. Rev. **82**, 316 (A) (1951). See reference 1 for additional details.
[3] Herb, Snowdon, and Sala, Phys. Rev. **75**, 246 (1949).

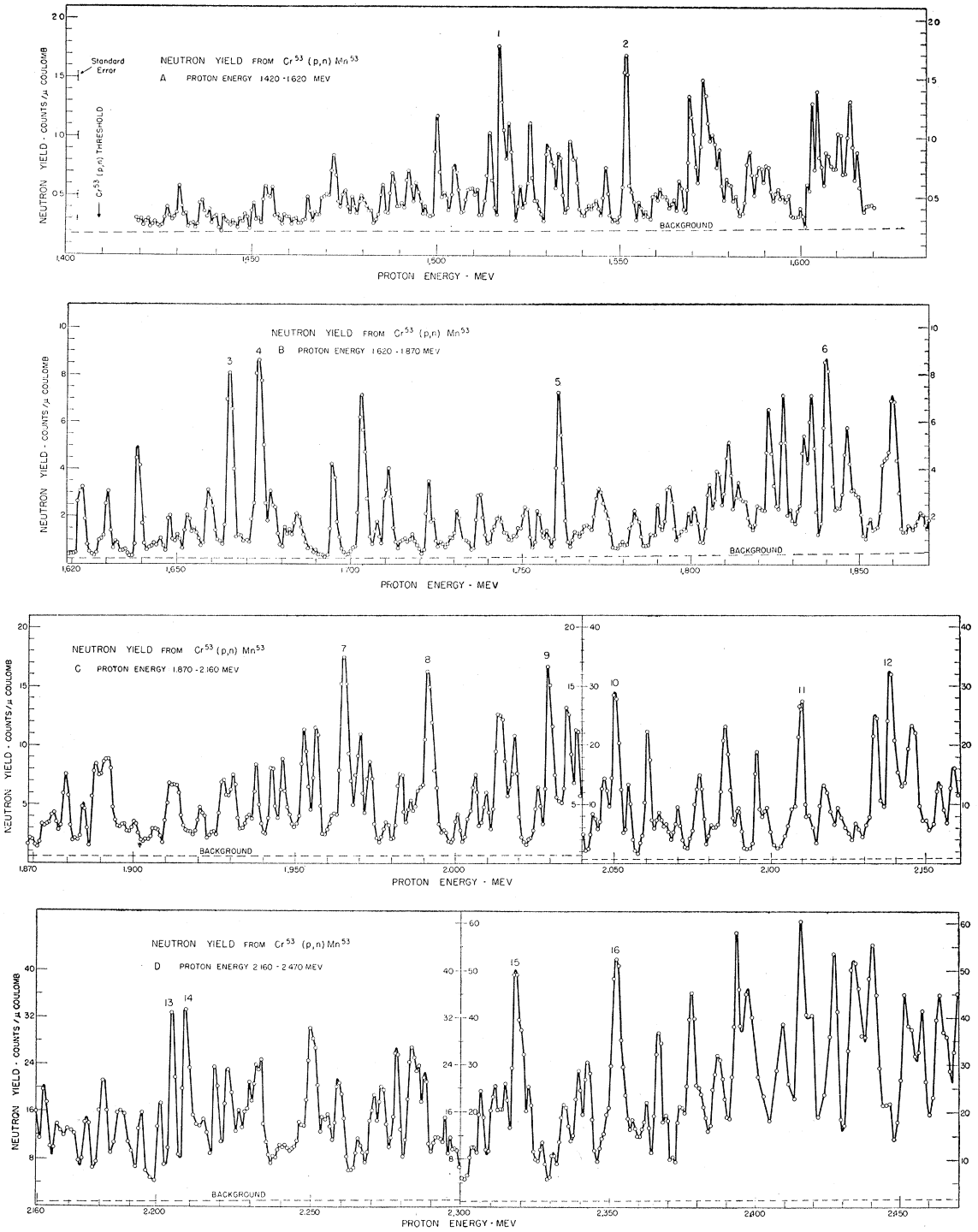

FIG. 1. Relative neutron yield from the reaction $Cr^{53}(p,n)Mn^{53}$. Note the several changes in the ordinate scale. The resolution is about 2 kev.

pendent of energy, as in the case of Hanson and McKibben's "long counter."[4]

The enriched chromium isotopes were obtained in the form of Cr_2O_3 from the Oak Ridge National Laboratory, through the courtesy of the Atomic Energy Commission. Spectroscopic analysis showed the presence of no significant chemical impurities. Table I shows the isotopic analysis furnished by Oak Ridge.

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

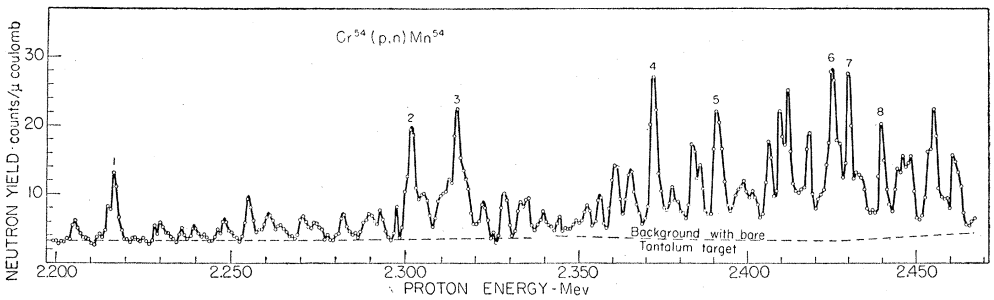

FIG. 2. Relative neutron yield from $Cr^{54}(p,n)Mn^{54}$, resolution about 2 kev.

The Cr_2O_3 was evaporated onto 10-mil tantalum target disks by Baird Associates of Cambridge, Massachusetts. The oxide decomposed on heating and thin metallic films were obtained readily. Targets of 1- to 3-kev stopping power for 2000-kev protons proved to be exceptionally stable. Using a conventional rotating target assembly, little deterioration occurred after 12 hours of operation with beam currents of 6–8 microamperes.

C. EXPERIMENTAL RESULTS

Yield Spectra

Figure 1 shows the yield spectrum of Cr^{53} up to a bombarding energy of 2470 kev. The ordinates are counts per microcoulomb proton current to the target; note that the ordinate scale changes by a factor of 25 from the low energy end to the high. Except on the first strip [Fig. 1(A)] where its magnitude is indicated near the ordinate scale, the statistical probable error is smaller in most cases than the diameter of the circles which designate experimental points. The energy scale is not linear; the kilovolts/unit length increase as $E^{\frac{1}{2}}$. The dashed curve, representing the background, was taken with a clean, bare tantalum target. This small residual yield probably comes from deuteron reactions within the analyzing chamber, as a result of the normal 0.015 percent of deuterium present in the hydrogen gas supplied to the ion source. Figure 2 shows the spectrum of enriched Cr^{54} from 2200 to 2470 kev. The background, as shown, was somewhat higher in this case.

From Table I, the Cr^{54} contamination in the enriched Cr^{53} is negligible, but there is 4 percent of Cr^{53} in the enriched Cr^{54} material. However, a careful comparison of the data of Figs. 1(D) and 2 indicates that none of the clearly defined peaks in the latter come from Cr^{53}.

Table II gives the resonance energy of a number of the stronger peaks in the spectra of $Cr^{53}(p,n)$ and $Cr^{54}(p,n)$. The peaks are identified by numbers in Figs. 1 and 2.

TABLE II. Resonance energies from the reaction $Cr(p,n)$.

$Cr^{53}(p,n)$ Ref. No. (Fig. 1)	E_R(kev)	$Cr^{53}(p,n)$ Ref. No. (Fig. 1)	E_R(kev)	$Cr^{54}(p,n)$ Ref. No. (Fig. 2)	E_R(kev)
1	1516	9	2027	1	2215
2	1552	10	2050	2	2300
3	1665	11	2108	3	2313
4	1674	12	2136	4	2370
5	1759	13	2202	5	2389
6	1838	14	2206	6	2423
7	1963	15	2316	7	2430
8	1989	16	2350	8	2437

Resolution

In the $Cr^{53}(p,n)$ spectrum of Fig. 1, we have measured the experimental width at half-maximum of a number of the stronger peaks which, from their symmetry, appear to be single resonances. The average width of the three narrowest peaks on each of the four strips, *A*, *B*, *C*, and *D* of Fig. 1, is 1.5, 1.7, 2.0, and 2.4 kev, respectively. These numbers represent upper limits to the effective resolution width in the corresponding energy ranges, due to spread in energy of the incident beam and to energy loss in the target. The broadest symmetrical peaks have observed widths of less than 3 kev. Since the average level spacing is less than 5 kev, there is a good chance that the broader peaks have unresolved components. We conclude that the natural resonance widths are not over 2 kev and that they may actually be much less. Similar remarks apply to the case of $Cr^{54}(p,n)$, Fig. 2, for which an upper limit to the resolution width is 2.2 kev.

Level Spacing

From the data of Figs. 1 and 2, there is no experimental indication that the number of resonances in a given energy range is finite. The observed widths do not differ greatly, since they are determined mainly by the experimental resolution. Under these conditions, two

TABLE III. Estimated level spacing in Mn^{54} and Mn^{55}.

Target nucleus	Compound nucleus	Energy range	No. of peaks	Average spacing, kev	
Cr^{53}	Mn^{54}	1420–1620	70	2.9	
Cr^{53}	Mn^{54}	1620–1870	64	3.9	Average
Cr^{53}	Mn^{54}	1870–2160	64	4.5	3.9
Cr^{53}	Mn^{54}	2160–2470	73	4.3	
Cr^{54}	Mn^{55}	2200–2470	56	4.8	

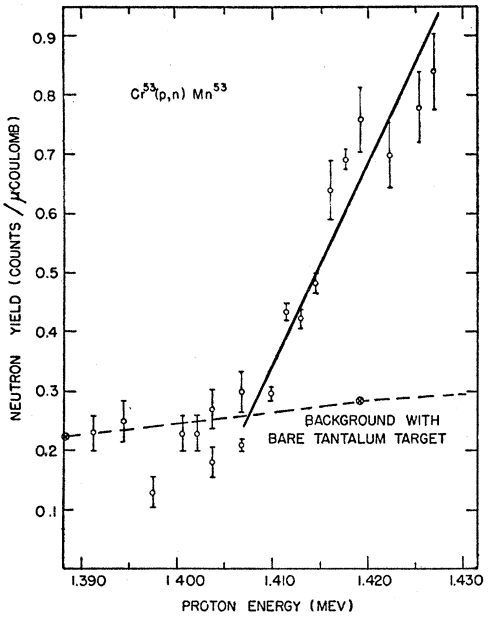

FIG. 3. Threshold measurement for $Cr^{53}(p,n)Mn^{53}$, 20-kev target.

neighboring resonances will be resolved if their separation is equal to, or greater than, their width, provided they are of comparable intensity. If their intensity ratio is as great as ten to one, their separation must be somewhat greater in order to be resolved. Below a certain minimum intensity, peaks will be lost in the background.

Table III shows the number of observed resonances in several energy intervals. The range of intensity covered is about twenty to one; that is, few peaks could be distinguished whose intensity was less than five percent of the strongest peaks in the interval. Note that the ratio of average level spacing to observed width is about two.

Thresholds

The threshold for the reaction $Cr^{53}(p,n)Mn^{53}$ was determined, using a thick target. The data are plotted in Fig. 3, which also shows the background counting rate for a pure tantalum target. The threshold is at 1406 ± 8 kev; a large error is assigned because of the poor statistical accuracy.

Figure 4 shows a similar threshold-curve for $Cr^{54}(p,n)Mn^{54}$. The threshold in this case is at 2203 ± 5 kev. The high neutron background comes from Cr^{53}, which is present to 4 percent in the enriched Cr^{54} sample (see Table I). This is further illustrated in Fig. 5, which shows the thin target data for the two isotopic samples in the region of the Cr^{54} threshold. The weak peaks in the enriched Cr^{54} curve, below 2200 kev, check well with those in the Cr^{53} curve. Their relative intensities are approximately as expected from the isotopic ratios. The peak marked (b) in the Cr^{54} curve does not coincide with that maked (a) in the Cr^{53} plot; it is therefore the first resonance of measurable intensity in the $Cr^{54}(p,n)Mn^{54}$ reaction. From these data, the threshold is at 2202 kev, with somewhat better accuracy than in the thick target determination. While the true threshold cannot be appreciably higher, it is clear that the uncertainty in its position on the low energy side is necessarily at least of the order of the average spacing between strong resonances in this region. An unequivocal threshold determination would require the measurement of the energy of the neutrons emitted.

D. DISCUSSION

The yield spectra of Cr^{53} and Cr^{54} show many resonances, but these do not fall into any obvious, repeated groups. As in the work on $Mn^{55}(p,n)$,[1] the small average level separation makes it extremely difficult to measure natural resonance widths.

Under our experimental conditions (proton energies well below the Coulomb barrier, poor resolution) the peak yield at a resonance for the p,n reaction is almost proportional to $(2J+1)\Gamma_p{}^l$, where J is the total angular momentum of a resonance formed by protons of angular momentum l, and $\Gamma_p{}^l$ is the width for proton emission.[5] The barrier penetration factors for chromium, for protons of 2.4 Mev, are roughly 21×10^{-3}, 9×10^{-3}, 2×10^{-3}, and 0.2×10^{-3} for protons of $l=0$, 1, 2, and 3, respectively. Hence the observed resonances are limited by intensity considerations to those states of the compound nucleus which can be formed by protons of $l=0$, 1, and 2, and, of these, a larger fraction of the weaker resonances will be missed because of the limited resolution. This is about as far as one can go

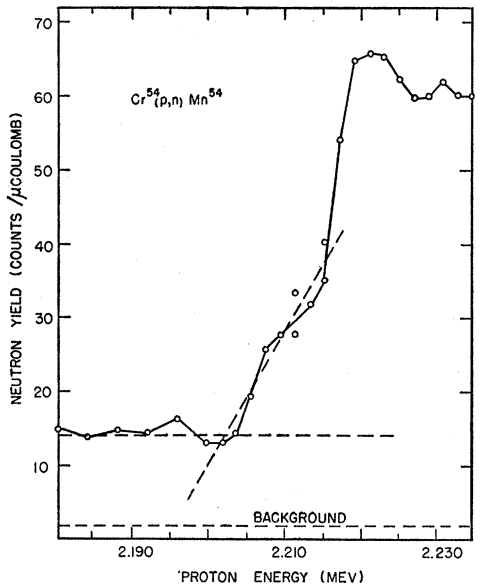

FIG. 4. Threshold measurement for $Cr^{54}(p,n)Mn^{54}$, 20-kev target. The yield below 2202 kev comes from a 4-percent impurity of Cr^{53} in this target.

[5] This is true because the proton width for $l=0$ is still considerably less than the neutron width for $l=2$, and so $\Gamma\approx\Gamma_n$.

in defining the significance of the measured level spacings listed in Table III.

From Q-values of nuclear reactions we have sufficient information to plot on an energy scale the relative positions of the ground states of the nuclei Cr^{53}, Cr^{54}, Mn^{53}, Mn^{54}, Mn^{55}, Fe^{55}, and Fe^{56}, as shown in Fig. 6. We have also indicated the excitation ranges in the compound nuclei Mn^{54}, Mn^{55}, and Fe^{56} in which the level spacing has been estimated, in the present work and in reference 1.

Nuclear theories predict a general decrease in level spacing with increase in excitation energy. One might expect that the level density in two neighboring nuclei would be approximately the same at equal excitation energies, E_x, measured from the ground state. Hurwitz and Bethe[6] suggest instead that E_x should be measured from a reference level, R, which depends in a smooth way upon the number of protons and neutrons in the nucleus as does, for example, the semi-empirical formula for the nuclear binding energy with the omission of the "odd-even" term. This is equivalent to assuming that, although the ground state is raised above the average smooth curve in odd-Z, odd-N nuclei and depressed in even-Z, even-N nuclei, the influence of the odd-even factors is negligible at high excitation energies.

In Figure 6, the reference marks A are drawn 10.3 Mev above the ground states of Mn^{55}, Fe^{56}, and Mn^{54}, while the marks B are 10.3 Mev above the reference levels R. Since Mn^{55} is odd-Z, even-N, the odd-even term δ in the mass formula is zero; R coincides with the ground state and A and B are identical. Fe^{56} is an even-Z, even-N nucleus and its ground state is below R by an amount $\delta=1.6$ Mev ($\delta=33^{-\frac{3}{4}}$ Mev). Similarly, the ground state of Mn^{54} is above R. If the level spacing is determined by the excitation energy measured from the ground state (reference arrows A in Fig. 6), we see that it should be approximately the same, in the ranges investigated, for Mn^{54} and Mn^{55}, but smaller for Fe^{56}.

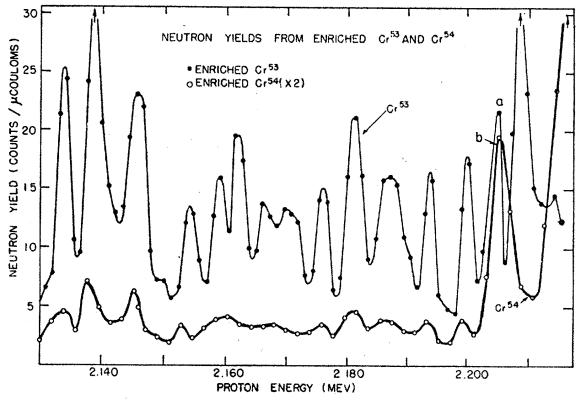

FIG. 5. Comparison of the Cr^{53} spectrum and that of Cr^{54} with a trace (4 percent) of Cr^{53}, near the threshold for the reaction $Cr^{54}(p,n)$. The peak (b), which does not coincide with (a), is the first observed Cr^{54} resonance above the threshold.

[6] H. Hurwtiz, Jr., and H. A. Bethe, Phys. Rev. **81**, 898 (1951).

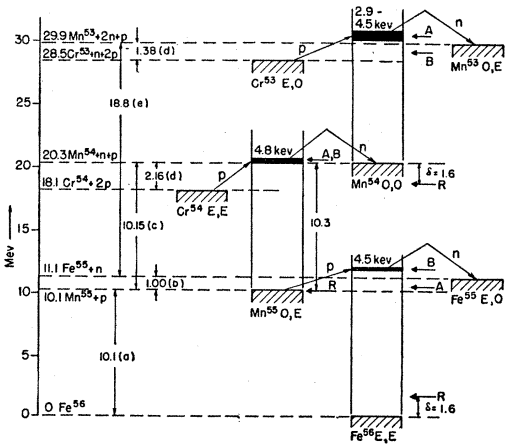

FIG. 6. Excitation energy diagram. The diagram shows the energies, relative to Fe^{56}, of the ground states of the nuclei involved in three p,n reactions: $Mn^{55}+p\rightarrow Fe^{56*}\rightarrow Fe^{55}+n$; $Cr^{54}+p$ $Mn^{55*}\rightarrow Mn^{54}+n$; and $Cr^{53}+p\rightarrow Mn^{54*}\rightarrow Mn^{53}+n$. The black bands in the high excitation regions of the compound nuclei Fe^{56}, Mn^{55}, and Mn^{54}, indicate the regions for which the average level spacing was measured in the present work, and in reference 1. The relative ground-state energies were computed from the following references:

a.	$Mn^{55}(n,\gamma)Mn^{56}$	$E_\gamma=7.25$ Mev	Kinsey, Bartholomew, and Walker, Phys. Rev. **78**, 481 (1950).
	$Mn^{56}\rightarrow Fe^{56}+\beta+\gamma$	$E_\beta+E_\gamma=3.63$ Mev	A. C. G. Mitchell, Revs. Modern Phys. **22**, 42 (1950).
b.	$Mn^{55}(p,n)Fe^{55}$	$Q=-1.00$ Mev	Reference 1.
c.	$Mn^{55}(\gamma,n)Mn^{54}$	$E_t=10.15$ Mev	A. O. Hanson, *et al.*, Phys. Rev. **76**, 578 (1949).
d.	$Cr^{54}(p,n)Mn^{54}$	$Q=-2.16$ Mev	Present paper.
	$Cr^{53}(p,n)Mn^{53}$	$Q=-1.38$ Mev	Present paper.
e.	$Fe^{54}(\gamma,n)Fe^{53}$	$E=13.8$ Mev	J. McElhinney, *et al.*, Phys. Rev. **75**, 542 (1949).
	$Fe^{53}\rightarrow Mn^{53}+\beta^+$	$E_\beta=2.5$ Mev	F. I. Boley and L. J. Laslett, Phys. Rev. **83**, 215 (1951).
	$Fe^{54}(n,\gamma)Fe^{55}$	$E_\gamma=9.28$ Mev	Kinsey, Bartholomew, and Walker, Phys. Rev. **78**, 481 (1950).

If the comparison ought to be made at the reference marks B, as suggested by the theory of Hurwitz and Bethe, Mn^{55} and Fe^{56} should have similar spacing, Mn^{54} smaller.

The experimental results show a slightly smaller average level spacing for the compound nucleus Mn^{54} than for the two others, but it cannot be stated with confidence that this difference is experimentally significant. The fraction of unresolved, and therefore undetected, resonances will increase with the ratio of average level width to level spacing. This may be the cause for the observed increase in level spacing with energy in Mn^{54}; however, some statistical fluctuation in the level density is to be expected. We must conclude that the results given in Table III represent no more than upper limits to the true average level spacing, in a region where virtually no information has been available heretofore.

We wish to express our sincere appreciation to the Rockefeller generator operating and maintenance group: Mr. Donald Thompson, Mr. I. E. Slawson, and Mr. John Adams.