and this will not be done here. The principal difference is to multiply the breakdown field by a factor of the form $[1+(k_0T/\hbar\langle\omega\rangle_{Av})]$, where $\langle\omega\rangle_{Av}$ is a less strongly varying function of temperature than the numerator. At higher temperatures still ($T>\Theta$), the thermal release of trapped electrons, and the reduction in $\langle\beta\rangle_{Av}$ because of the higher mean energy of electrons may combine to reverse this dependence, and give "impurity breakdown," as has been observed previously.[42] Polar crystals may also be treated, and results will be tabulated in a future publication.

The writer wishes to acknowledge the advice and help of Professor Henry Primakoff, who suggested studying dielectric breakdown in nonpolar crystals, and that of Professor A. L. Hughes in discussions of experimental work. I should like to express my thanks to Dorothy Heller, who performed necessary computations, to Beatrice Broomall for typing assistance, and to the Atomic Energy Commission for a predoctoral fellowship, during the term of which the work was completed.

[42] H. Fröhlich, Proc. Roy. Soc. (London) **A188**, 521 (1947), and references to experimental work there contained.

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# The Reaction $Mn^{55}(p, n)Fe^{55}$

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The neutron spectrum from the reaction $Mn^{55}(p, n)Fe^{55}$ has been examined from the threshold to a proton bombarding energy of 2.85 Mev. The reaction threshold was found to be 1.020±0.010 Mev. Many resonances were found in the neutron yield; these correspond to excited states of $Fe^{56}$. A limited region was studied with a resolution width of about 2 kev, and an upper limit of 4.5 kev was found for the average observed level spacing.

## I. INTRODUCTION

The yield of neutrons from a $(p, n)$ reaction on a target nucleus ${}_ZX^A$, as a function of proton energy, will show maxima corresponding to excited states of the compound nucleus ${}_{(Z+1)}X^{(A+1)}$ in the range of excitation above the neutron binding energy. This same range may be investigated by measuring the total neutron cross section, as a function of neutron energy. In the latter case, the compound nucleus is ${}_ZX^{(A+1)}$. The nature of the experimental results depends very much on the energy spread, $\Delta$, in the proton (or neutron) beam owing to poor voltage control in the accelerator, finite target thickness, or other causes.

TABLE I. Previously reported work on $(p, n)$ yields.

| Target isotope | Proton energy range (Mev) | Resonances reported | Resolution | Reference |
|---|---|---|---|---|
| $T^3$ | 1.02–2.8 | 0 | good | a |
| $Li^7$ | 1.88–3.6 | 1 | good | b |
| $Be^9$ | 2.06–4.0 | 1 | good | c |
| $B^{11}$ | 3.01–4(?) | 0 | good | c |
| $C^{13}$ | 3.24–3.96 | 1 | good | d |
| $C^{14}$ | 1.00–2.6 | 9 | good | e |
| $O^{18}$ | 2.59–3.70 | 7 | good? | c |
| $K^{41}$ | 1.25–3.50 | 8 | poor? | c |
| $Sc^{45}$ | 2.9 –3.7 | 9 | poor | f |
| $V^{51}$ | 1.5 –3.8 | 22 | poor | f |

[a] Jarvis, Hemmendinger, Argo, and Taschek, Phys. Rev. **79**, 929 (1950).
[b] R. Taschek and A. Hemmendinger, Phys. Rev. **74**, 373 (1948). Hanson, Taschek, and Williams, Revs. Modern Phys. **21**, 635 (1949).
[c] Richards, Smith, and Browne, Phys. Rev. **80**, 524 (1950).
[d] Adamson, Buechner, Preston, Goodman, and Van Patter, Phys. Rev. **80**, 985 (1950).
[e] Roseborough, McCue, Preston, and Goodman, Phys. Rev. **83**, 1133 (1951).
[f] Baker, Howell, Goodman, and Preston, Phys. Rev. **81**, 48 (1951). Recent unpublished work in this laboratory (W. A. Schoenfeld and R. W. Duborg) on the reaction $Sc^{45}(p, n)$ shows at least 31 resonances between 2.91 and 3.11 Mev.

If $\Delta>D$, where $D$ is the average level spacing at a given excitation energy, the resolution is "poor." The resulting information is an average of the effects of a usually unknown number of neighboring resonances, and it is therefore difficult to interpret. We may define "intermediate resolution" as the experimental situation in which $\Gamma<\Delta<D$, where $\Gamma$ is the natural resonance width. In this case it becomes possible to estimate the level spacing, $D$, but not the amplitudes or widths of resonances, which are required before spin assignments can be made. Finally, if $\Delta<\Gamma$, the resolution is "good" and a detailed comparison can be made between experiment and the predictions of the resonance theory of nuclear reactions.

The level width $\Gamma$ increases and the spacing $D$ decreases with excitation energy, so that eventually resonances overlap. The meager information now available indicates that at least for light and intermediate weight nuclei, $\Gamma$ remains less than $D$ for the order of one million electron volts above the neutron binding energy. Both $\Gamma$ and $D$ decrease (in general) with increasing atomic weight $A$, so that even for $A=50$ the best practical resolution of electrostatic generators at the present time can barely be considered "good." Improvement in resolution is limited largely by lack of intensity, owing to the low efficiency of fast neutron

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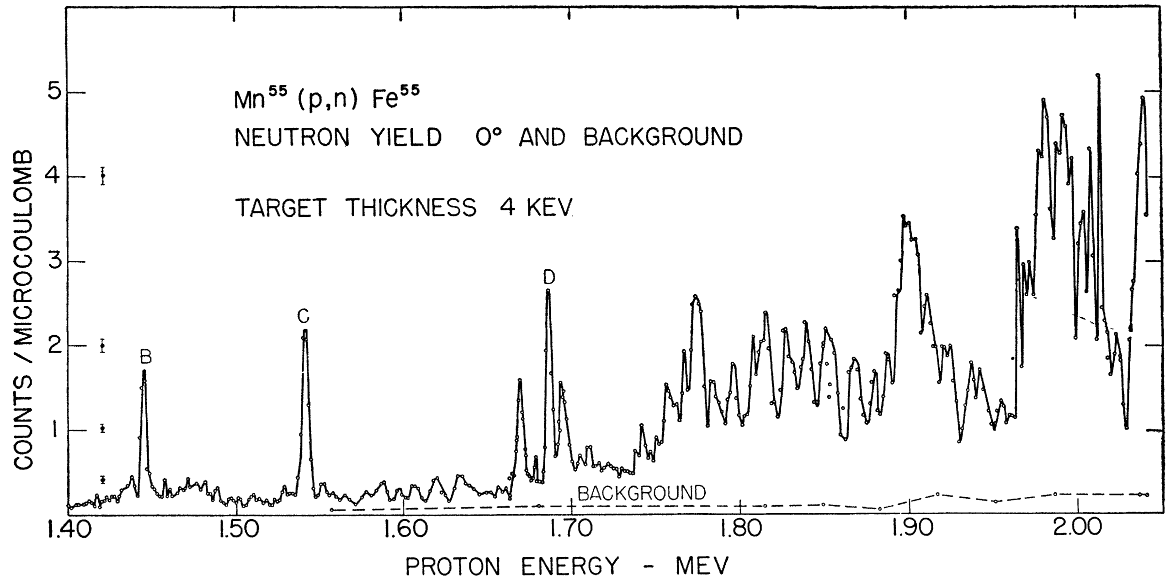


FIG. 1. Neutron yield from $Mn^{55}(p, n)Fe^{55}$; target thickness about 4 kev. Each experimental point represents 500 microcoulombs. The rms errors are shown at the left. The lower curve represents the background.

detectors. In this respect, study of $(p, n)$ reaction yields has some advantage over total cross-section measurements.[1]

A survey of total cross-section measurements is given by Adair.[2] Among the intermediate weight nuclei, only sulfur has been studied with really good resolution. Table I lists recent work on the $(p, n)$ reaction; the estimates of the degree of resolution are our own. It is doubtful that individual levels were resolved in the case of $K^{41}$ and certain that they were not with $Sc^{45}$ and $V^{51}$. We have selected $Mn^{55}$ for the work described in the present paper because it occurs naturally as a single isotope, it has a low $(p, n)$ threshold, and it may be evaporated readily to form stable targets.

## II. EXPERIMENTAL METHOD

### The Proton Beam

Protons of energy between 1.0 and 2.8 Mev were obtained from the Rockefeller electrostatic generator.[3] The beam is analyzed by 90-degree deflection in a magnetic field which is stabilized and measured by a proton magnetic moment resonance device; the generator voltage is stabilized by a corona load which is modulated by error signals obtained from that portion of the beam which hits the jaws of the object slit of the analyzer. Currents of 5 to 10 $\mu$a can be obtained with object and image slits 1 mm wide, as used throughout the present work. In this case the beam resolution function probably approximates a triangle of width 0.00075 $E_p$ at half-maximum, where $E_p$ is the proton energy.

At energies of 2 Mev, experimental points can readily be taken 0.2 kev apart and reproduced over short intervals of time. All energy measurements are made relative to the $Li^7(p, n)$ threshold, taken as a standard at 1.8822 Mev.[4] Over periods of several days, the voltage calibration has varied over an extreme range of 3 kev. Since the machine was not recalibrated for each run, our energy measurements are in general subject to this error. In addition, for most of the data we used as reference a standard frequency meter which was later found to have systematic errors between calibration points, at the maximum equivalent to 3 kev. For these reasons, we assign an uncertainty of $\pm 5$ kev to most energy measurements, relative to the $Li(p, n)$ threshold. For the threshold measurement and for the run with 2-kev resolution, we used a frequency meter with an accuracy of one part in $10^5$.

### Targets

The targets were prepared from manganese powder of high purity.[5] The manganese was heated in a tantalum boat and deposited on a clean 10-mil tantalum backing in a standard evaporating unit. The surface oxide on the manganese powder apparently decomposed during evaporation; the targets, when fresh, looked metallic. Interference colors showed that the film was deposited symmetrically about the center of the target.

[1] In the $(p, n)$ reaction we may, if we wish, measure the total neutron yield at all angles. For cross-section measurements, the detected neutrons from the source (e.g., the $Li^7(p, n)$ reaction) must be limited to a very small solid angle in order to obtain good resolution.

[2] R. K. Adair, Revs. Modern Phys. 22, 249 (1950).

[3] W. M. Preston and C. Goodman, Phys. Rev. 82, 316(A) (1951).

[4] Herb, Snowdon, and Sala, Phys. Rev. 75, 246 (1949).

[5] A spectroscopic analysis supplied by the vendors, Johnson, Matthey and Company, London, showed no lines from Al, B, Co, Cr, Cu, Fe, Mo, Ni, Pb, Si, Sn, Ti, V, W, Zn, or Zr. Lines of Mg, Ca, and Na were present, but the $(p, n)$ threshold of Mg, Na, and the abundant isotopes of Ca are higher than the proton energies used in this experiment.

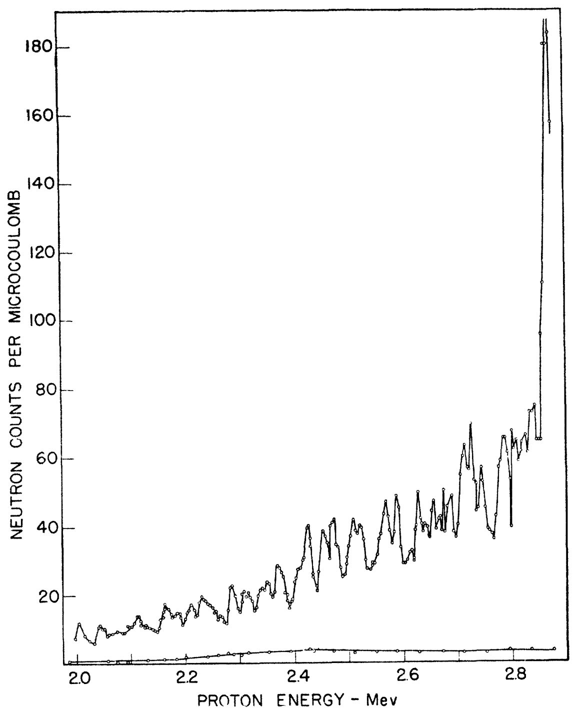


FIG. 2. Neutron yield from $Mn^{55}(p, n)Fe^{55}$; target thickness 15 kev. The rms errors are about 1 percent for all points. The lower curve represents the background.

The tantalum backing was mounted in a conventional rotating target assembly. After prolonged exposure to air, the target film tarnished and thickened. The work reported here was done with targets which had not been exposed to air for more than one hour.

The first target, used for a rough survey, had a thickness of 15 kev. The region below 2.0 Mev was examined with a target about 4 kev thick, and an interval near 1.8 Mev with one $<2$ kev thick, as estimated from the widths of resonance peaks.

### Neutron Detector

Neutrons were detected by a "long counter"[6] surrounded by a cadmium shield to eliminate response to thermal neutrons. The counter tube was 1 in. o.d. and had an active volume 12 in. long. It was filled to a pressure of 55 cm with enriched $BF_3$. A model 100 amplifier[7] was used with a commercial scaler. The discriminator was set at a level about three times higher than that at which $\gamma$-rays were counted from a radium test source. The counter sensitivity was checked periodically with a standard Ra-Be neutron source.

## III. EXPERIMENTAL RESULTS

Figure 1 shows a plot of the neutron yield from 1.40 to 2.05 Mev, with a target of about 4 kev stopping power at 1.54 Mev. The most striking features are the isolated peaks, *B* and *C*, that stand out above a background of much smaller resonances. Another strong peak, *D*, is accompanied by large satellites. At a slightly higher energy, the character of the spectrum seems to change; neighboring resonances have more nearly equal amplitudes. The dashed line represents the background counting rate with a carefully cleaned, bare tantalum target. A paraffin shadow cone placed between the latter target and the counter reduced the background by only 20 percent, showing that few, if any, of the neutrons originated in the tantalum; it is likely that

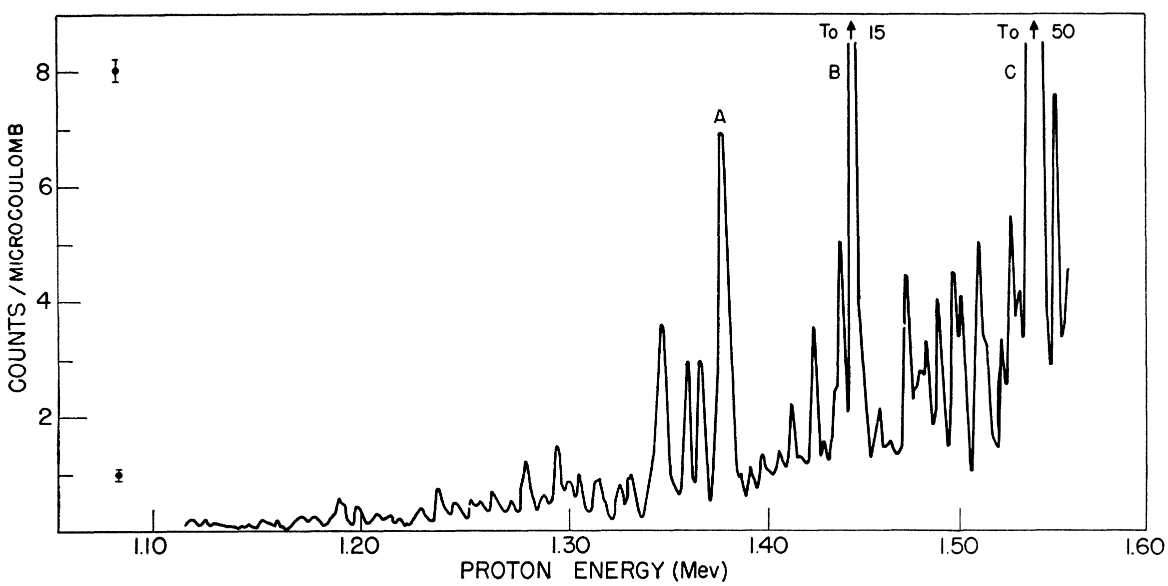


FIG. 3. Neutron yield from $Mn^{55}(p, n)Fe^{55}$; target thickness about 4 kev; long counter close to target and turned broadside to get a high counting rate. The experimental points, not shown, were 1.5 kev apart. The rms errors are shown at the left.

[6] A. O. Hanson and J. L. McKibben, Phys. Rev. **72**, 673 (1947).
[7] W. C. Elmore and M. Sands, *Electronics* (McGraw-Hill Book Company, Inc., New York, 1949).

they came from $(d, n)$ reactions in the analyzing chamber, since deuterium was present in the ion-source hydrogen supply in the normal concentration of 0.016 percent.

Each point in Fig. 1 represents 500 microcoulombs of protons. At the lowest energies, some of the peaks as drawn may be due to statistical fluctuations; above 1.6 Mev, they are certainly nearly all real.

Figure 2 shows the general course of the yield from 2.0 to 2.9 Mev, taken with a 15-kev target. In this region, the levels are so closely spaced that it did not seem worth while to attempt to resolve them. The peaks as drawn probably represent the integrated yield over an interval that includes several resonances. We did not investigate further the surprisingly large peak at 2.86 Mev, which was at the upper limit of operating voltage at that time. We have not been able to assign it to any likely contaminant in the target.

The data for Figs. 1 and 2 were obtained with the long counter 30 cm from the target, on the axis of the beam. Figure 3 shows the yield from 1.10 to 1.55 Mev, but because of the low yield in this region the counter was placed with its axis perpendicular to the beam and its side about 2 cm from the target. The counter then subtended a large angle in the forward direction, but its efficiency can no longer be assumed to be almost independent of energy. The ratio of the height of peak $C$ to that of $B$ is over 3 to 1 in this case, while in Fig. 1 it is nearly unity. This difference may be due to changing efficiency of the counter or to differing angular distributions. Below 1.2 Mev, the yield diminishes gradually towards the background level.

The resonance energies of the peaks $A$, $B$, $C$, and $D$ are $1.375\pm0.005$, $1.443\pm0.005$, $1.539\pm0.002$, and $1.684\pm0.005$ Mev, respectively, relative to a $Li(p, n)$ threshold of 1.8822 Mev. Corrections have been applied for relativity and target thickness.

The threshold for neutron production was measured with a target about 100 kev thick. Figure 4 indicates that the threshold is at 1.020 Mev, to which we assign an uncertainty of $\pm10$ kev. The corresponding $Q$-value for the $Mn^{55}(p, n)Fe^{55}$ reaction is $-1.001\pm0.010$ Mev. This $Q$-value disagrees with that found by Richards, Smith, and Browne,[8] $-1.16\pm0.01$ Mev; it agrees better with the determination of Stelson and Preston, $-1.05\pm0.05$ Mev, by a photographic method[9] and $-1.006\pm0.010$ Mev by the resonant scatterer method.[10]

Figure 5 shows two runs over the resonance $C$ at 1.539 Mev, taken with the thinnest target used, about two hours apart. The yields at resonance and the experimental half-widths $\Gamma_e$ are approximately the same, indicating negligible deterioration of the target. The experimental half-widths are 2.0 and 1.8 kev. This means that $(\Gamma^2+\Delta^2)^{\frac{1}{2}}=1.9$ kev, where $\Gamma$ is the natural resonance half-width and $\Delta$ is the resolution width,

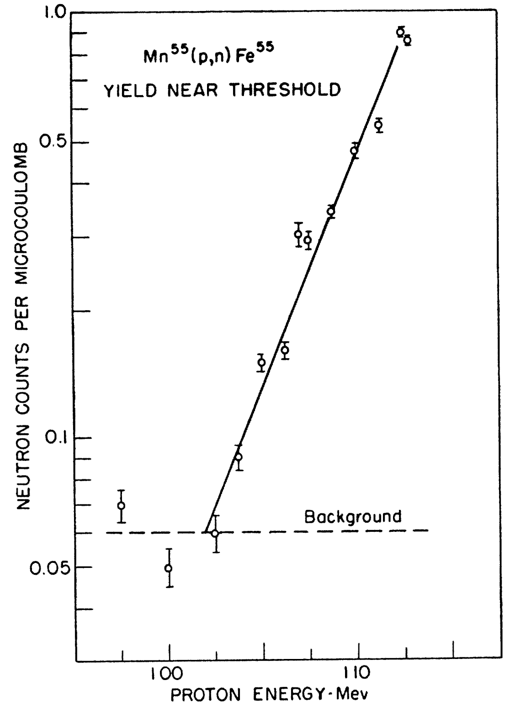


FIG. 4. Neutron yield, near threshold, from a $Mn^{55}$ target >100 kev thick.

including target thickness and spread in the energy of the proton beam. Thus both the target thickness and the natural half-width of the 1.539 resonance are less than 1.9 kev. With thicker targets, as used for Figs. 1, 2, and 3, the target thickness could be taken as equal to the measured half-width of this resonance. The shift of 1.1 kev in the position of the resonance peak may

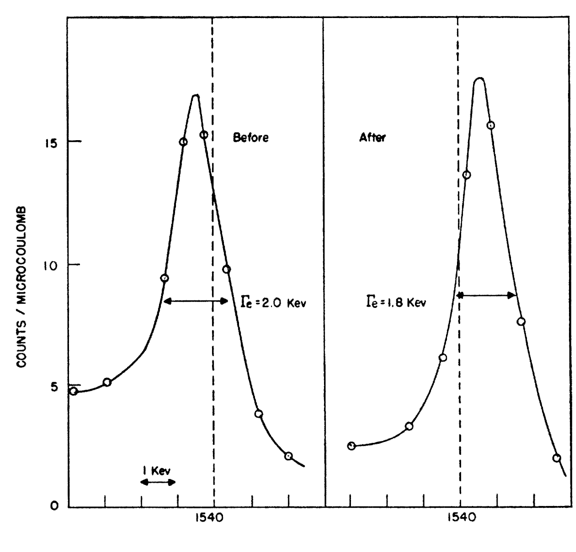


FIG. 5. The resonance at 1.539 Mev, before and after a two-hour run.

[8] Richards, Smith, and Browne, Phys. Rev. **80**, 524 (1950).
[9] P. H. Stelson and W. M. Preston, Phys, Rev. **82**, 655 (1951).
[10] P. H. Stelson and W. M. Preston, Phys. Rev. **83**, 469 (1951).

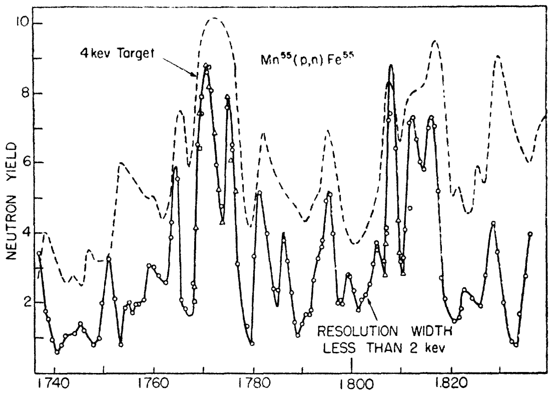


FIG. 6. Comparison of the yield curves with 4-kev and 2-kev resolution. The ordinate scales for the two curves are not the same. The counter subtended different solid angles in the two cases.

have been due to surface contamination of the target during the run or to a change in calibration.

An interval from about 1.740 to 1.835 Mev was examined with the thin target discussed above. The data are plotted in Fig. 6 (solid line) together with the same portion of the yield curve, Fig. 1, taken with 4-kev resolution (dashed line, ordinate scale arbitrary). With the improved resolution, the very broad or unsymmetrical peaks of Fig. 1 split up. The approximately symmetrical character of most of the larger resonances in Fig. 6 and the fact that several of these are appreciably wider than the 1.9-kev limit set on the resolution width indicate that we have approached "good resolution" as defined in the introduction.

It seemed possible that the large observed amplitudes of the resonances $B$ and $C$, relative to their neighbors, were due to a preferred yield in the forward direction. We accordingly made a run from 1.4 to 2.2 Mev, with a 4-kev target, taking counts simultaneously with long counters on the axis and at 90 degrees. A small Ra-Be neutron source was placed at the point of impact of the proton beam on the target, and this showed a difference in sensitivity of 1.65 between the counters which was applied as a correction to the observed counting rates. A plot of the quantity, yield at 0 degrees/yield at 90 degrees$=Y_0/Y_{90}$, showed a one-to-one correspondence with maxima in the yield at 0 degrees in nearly every case. Near 1.4 Mev, $Y_0/Y_{90}$ varied from 0.35 between resonances to about 1.0 at resonances; at higher energies, the average value of the ratio increased. We are in considerable doubt about the interpretation of these results. In particular, however, the yield at peaks $B$ and $C$ seems to be approximately equal at 0 and 90 degrees.

Stelson and Preston[9] have shown that the first two excited states of $Fe^{55}$ lie 0.42 and 0.94 Mev above the ground state. Transitions to these states can occur at proton bombarding energies above $1.45\pm0.05$ and $1.98\pm0.05$ Mev, respectively. There is no obvious change observed in the character of the spectrum near these energies.

## IV. DISCUSSION

In Fig. 6 we can detect about 21 resonances in an energy interval of 95 kev, giving an average level spacing $D=4.5$ kev. The fact that the yield curve taken with the thinnest target at places approaches the background level in this region shows that the resolution width $\Delta$, estimated to be $\leqslant 2$ kev, is considerably less than the spacing of strong levels.[11] However, two peaks will be counted as one if their separation is appreciably less than their observed width, $\Gamma_e$, and peaks of intensity less than 10 percent that of the strongest are generally indistinguishable. Thus it is not easy to define the significance of the above value for $D$ beyond stating that it represents an upper limit for the average spacing between strong levels.

From the reaction equation $Mn^{55}+H^1\rightarrow n+Fe^{55}+Q$, the mass difference $Fe^{55}-Mn^{55}=-Q-(n-H^1)$. Using our value $Q=-1.001\pm0.010$ Mev and $(n-H^1)=0.782\pm0.001$ Mev,[12] the mass difference is $0.219\pm0.010$ Mev. (We have not applied corrections for electronic shielding.)

The binding energy, $E_b$, of the last neutron in the compound nucleus $Fe^{56}$ may be computed from the following:

$$Fe^{55}+n\rightarrow Fe^{56}+E_b \quad (5a)$$

$$Mn^{55}+n\rightarrow Mn^{56}+7.25 \quad (5b)$$

$$Mn^{56}\rightarrow Fe^{56}+3.63 \quad (5c)$$

$$Fe^{55}-Mn^{55}\rightarrow 0.22. \quad (5d)$$

(The neutron binding energies in Eqs. (5b) and (5c) are taken from Kinsey *et al.*[13] and Mitchell,[14] respectively.) These relations give $E_b=11.10$ Mev, so that our value for the average observed level spacing $D=4.5$ kev refers to a region of total excitation energy of $Fe^{56}$ about $11.10+0.75=11.85$ Mev above the ground state.

[11] Compare the general rise of the yield curve in Fig. 2, where $\Delta=15$ kev.
[12] Tollestrup, Fowler, and Lauritsen, Phys. Rev. **78**, 372 (1950).
[13] Kinsey, Bartholomew, and Walker, Phys. Rev. **78**, 481 (1950).
[14] A. C. G. Mitchell, Revs. Modern Phys. **22**, 36 (1950).