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Energy Levels in Medium Weight Nuclei from the (p,n) Reaction

By Joseph Arthur Lovington

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ABSTRACT

The neutron yields from the reactions Cr^{53}(p,n) and Cr^{54}(p,n) were investigated using monoenergetic protons from the Rockefeller Generator. The target isotopes were obtained in enriched form from the Oak Ridge National Laboratory and evaporated onto tantalum backings to form thin targets of known thickness. Standard techniques and instruments were used in the detection and counting of the neutron yield. Plots of the neutron yield as a function of proton energy show numerous resonances which are considered to indicate the existence of energy levels in the compound nuclei Mn^{54} and Mn^{55}. The spacing of these levels is quite irregular and only average values of the spacing can be determined. The observed level spacing of the two compound nuclei is compared at equal excitation energies relative to certain characteristic levels recently described. The Mn^{55} is observed to have a level spacing slightly larger than the Mn^{54}. This difference in spacing can be qualitatively accounted for by postulating multiplet levels whose multiplicity is based on quantum mechanical combinations of orbital and intrinsic angular momentum.

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The threshold for the Cr^{53}(p,n) reaction is determined to be 1.406 ± .008 Mev and for the Cr^{54}(p,n) 2.203 ± .005 Mev. From these threshold energies and published masses of Cr^{53} and Cr^{54}, the masses of Mn^{53} and Mn^{54} are determined to be 52.95590 ± .00044 amu and 53.95574 ± .00048 amu respectively.

The threshold for the $Cr^{53}(p,n)$ reaction is determined to be 1.400 ± .009 Mev and for the $Cr^{54}(p,n)$ 2.203 ± .003 Mev. From these threshold energies and published masses of Cr^{53} and Cr^{54}, the masses of Mn^{53} and Mn^{54} are determined to be 52.95590 ± .00044 amu and 53.95574 ± .00048 amu respectively.

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CHAPTER 1

INTRODUCTION

By measuring the neutron yield from (p,n) reactions as a function of proton energy, information is obtained concerning the threshold of the reaction and the spacing and widths of the energy levels of the compound nucleus. From the threshold energy, the mass either of the target nucleus or of the residual nucleus may be computed, provided the mass of the other is known. The neutron yield shows maxima which correspond to energy levels of the compound nucleus.

Previous experiments using the Rockefeller electrostatic generator as a source included the use of vanadium and scandium as targets by Baker and Howell (B1, B2), carbon by Adamson (A1, A2) and manganese by McCue (M1). The present investigation used enriched isotopes of chromium (Cr^{53} and Cr^{54}). Experiments on other elements are in progress.

Theory predicts that the level structure of a nuclide depends upon whether the nuclide is odd or even. The two isotopes of chromium, Cr^{53} and Cr^{54} are particularly well-suited for this comparison. They are available in appreciably enriched form from the Oak Ridge National Laboratory and durable thin targets can be prepared. The threshold

energies, although not accurately known prior to this work (11), were believed to be in the working range (0.5 to 4.0 Mev) of our accelerator.

CHAPTER II

EXPERIMENTAL ARRANGEMENT

1. General.

To obtain neutron yields of sufficiently good resolution, the energy of the bombarding proton must be known rather precisely. Furthermore, this energy must be maintained constant during the period of observation.

The Rockefeller generator, of the Van de Graaff type, fulfills these requirements. The operation and use of this generator are adequately described in the literature (A1, B1, J1, [illegible]1, [illegible]1).

The analyzed beam of the generator is used to bombard the chromium targets and the neutron yields are detected and measured by standard techniques.

2. Resolution of the Generator.

A recent refinement to the resolution of the generator is the nuclear resonance method of controlling the field of the analyzing magnet. This device provides fine control and accurate measurement of the energy of the proton beam. The frequency of the proton resonance (in a cell of water) is measured and related to the energy of the protons in the beam by $E = kf^2$ (S2). By measuring the frequency of proton

resonance of a known (p,n) threshold (for Li(p,n) E_p = 1.882 ± .002 (H5)) the value of "k" is determined.

By using other known thresholds for absolute measurements and the mass 2 beam of the source for relative measurements, it has been shown that the assumption that "k" (as a function of proton energy) is constant, introduces an error of less than ± 1 Kev in proton energy over the range of energies used in this investigation. The frequency of resonance can be measured to 1 part in 100,000 which resolution is equivalent to an uncertainty in proton energy of less than ± 25 ev. The finite widths of the defining slits introduce an energy spread in the beam which Preston and Stelson (P1) have shown to be less than ± 250 ev. The history of the generator shows that variations in "k" with time may be expected. Results, based on tests conducted before and after the experimental work of this thesis indicate that this variation will cause an uncertainty of less than ± 3 Kev in the proton energy. Some examples of the reproducibility of data over periods of time are shown in Chapter IV.

In determining the absolute value of a particular proton energy the above uncertainties may be combined to give a resultant of ± 4.2 Kev. To allow for unmeasurable factors (e.g. operator judgment), a value of ± 5 Kev is

taken as the total uncertainty in proton energy. However, for relative measurements such as level spacing and level widths, the uncertainties in "k" may be neglected and relative uncertainty in proton energy may be considered to be less than ± 300 ev.

3. Instrumentation.

The neutron yield was detected by a "long counter" as described by Hanson and McKibben (H1). The pulses from the counter were fed through a Model 101 pre-amplifier and a Model 100 amplifier (E1) and counted by a commercial scaler.

The "long counter" was placed 1" from the target with its axis at right angles to the beam. This arrangement proved to be essential in the proton energy region of 1.5 Mev where the neutron yield was small, and not inconvenient in the higher energy regions where higher yields were encountered. Placing the counter at right angles to the beam instead of parallel is believed to alter the designed sensitivity but slightly.

The Rockefeller generator is equipped with a beam current integrator which measures the charge striking the target. This quantity, rather than time, was used as the basis for determining the counting rate.

CHAPTER III

TARGETS

1. Material.

The enriched chromium isotopes (Cr^{53} and Cr^{54}) were loaned by the Oak Ridge National Laboratory. They were supplied as Cr_2O_3. Table III-1 shows the spectographic analyses which accompanied the samples.

Contaminant element	Enriched Cr^{53}	Enriched Cr^{54}
Al	0.04%	0.04%*
B	0.015	-
Ca	0.08*	-
Cu	0.02	0.02*
Fe	0.04*	0.04*
Mg	0.02*	0.02
Ni	0.08*	-
Si	0.15	0.15
Na	-	0.04*
Mo	-	0.04*
Mn	-	0.04*

*Detected but less than limit of determination

Impurities other than those listed were not detected

Table III-1

None of the quantities shown is sufficient to affect the present work.

Because the isotopes were enriched rather than completely separated, their mass spectroscopic analyses are important. These were provided by ORNL and are shown in Table III-2.

Isotope	Natural abundance (81)	Enriched in Cr^{53}	Enriched in Cr^{54}
Cr^{50}	4.31%	0.193%	0.2%
Cr^{51}	unstable	-	-
Cr^{52}	83.76	9.28	7.0
Cr^{53}	9.55	90.06	3.9
Cr^{54}	2.38	0.465	89.0

Table III-2

2. Preparation.

The Cr_2O_3 was evaporated onto a tantalum backing by Baird Associates of Cambridge, Massachusetts. Their experience with other elements, particularly manganese, enabled them to provide targets of specified thickness with a very good accuracy on the first attempt. This success was fortunate because the supply of enriched material was limited. One Cr^{53} target (1.5 Kev thick) and two Cr^{54} targets (1.5 and 2.5 Kev thick) (ref. Chapter IV) were used for the de-

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Isotope	Natural abundance (%)	Enriched in Cr^{53}	Enriched in Cr^{54}
Cr^{50}	4.31	0.1975	0.06
Cr^{51}	unstable	-	-
Cr^{52}	83.76	9.30	7.0
Cr^{53}	9.55	90.30	3.9
Cr^{54}	2.38	0.445	89.0

Table III-2

2. Evaporation.

The Cr_2O_3 was evaporated onto a tantalum backing by Baird Associates of Cambridge, Massachusetts. Their experience with other elements, particularly manganese, enabled them to provide targets of specified thickness with a very good accuracy on the first attempt. This success was fortunate because the supply of enriched material was limited. One Cr^{53} target (1.5 Kev thick) and two Cr^{54} targets (1.5 and 2.5 Kev thick) (ref. Chapter IV) were used for the extailed yield curves. Thicker targets of about 20 Kev were used to determine the threshold energies.

The thin targets proved to be exceptionally stable and rugged. They were subjected to proton beams of 6-8 microamperes for periods up to 12 hours without measurable decrease in yield. The thicker targets were somewhat less rugged. In their manufacture their surfaces became crazed and under strong beams they suffered some loss of material.

The condition of the loan specifies the return of all enriched material. This required special care in the evaporating process. In order to trap any stray chromium which might otherwise be evacuated to the atmosphere, foil and glass chimneys were used to surround the target backing and the crucible.

Tantalum was used as target backing because it produces a negligible amount (if any at all) of neutrons when bombarded by protons of energies within the limits of our source. The background curves shown in the appendices were taken using clean bare tantalum as a target. The small yields observed are believed to come from reactions within the analyzing chamber of the generator. The use of a paraffin shadow cone in the line of the beam between target and counter reduced the background count by 20% indicating that most of the background neutrons are scattered from the walls and floor of the chamber room.

called yield curves. Thicker targets of about 25 kev were used to determine the threshold energies.

The thin targets proved to be exceptionally stable and rugged. They were subjected to proton beams of 4.0 microamperes for periods up to 12 hours without noticeable decrease in yield. The thicker targets were somewhat less rugged. In their manufacture their surfaces became crazed and under strong beams they suffered some loss of material.

The condition of the loan specified the return of all enriched material. This required special care in the evaporating process. In order to keep any stray molecules which might otherwise be exhausted to the atmosphere, foil and glass cylinders were used to surround the target holding and the crucible.

Tantalum was used as target backing because it produced a negligible amount (if any at all) of neutrons when bombarded by protons of energies within the limits of our source. The background curves shown in the appendices were taken using clean bare tantalum as targets. The small yields observed are believed to come from reactions within the analyzing chamber of the generator. The use of a paraffin shadow cone in the line of the beam between target and counter reduced the background count by 50% indicating that most of the background neutrons are scattered from the walls and floor of the chamber room.

CHAPTER IV

EXPERIMENTAL RESULTS

1. General.

The neutron yields from the enriched isotopes Cr^{53} and Cr^{54} in the (p,n) reaction were investigated over proton energies of 1.40 to 2.47 Mev. The plots of these yields are included as appendices A and B. For convenience the yields were originally plotted as a function of the frequency of the resonance control. Later the frequency units were converted to energy units (Chapter II). This accounts for the slight non-linearity of the energy scale. The ordinate scales are varied for clarity of presentation.

In experiments of this type it is important that the optimum energy (frequency) intervals be used. It can be readily seen that if the intervals used are not greater than the width at the half-maximum value of the observed resonance levels (a resultant of widths due to target thickness, proton energy spread, and true (p,n) resonances), in no case will more than half of the true maximum value of the level be missed. Intervals of 1/3 to 1/4 of the width at half-maximum are desirable for good detail in the curves. The width (i.e. energy spread) due to target thickness is the factor most susceptible of control. The thinner the target,

CHAPTER IV

EXPERIMENTAL RESULTS

1. General.

The neutron yields from the enriched isotopes Cr^{53} and Cr^{54} in the (p,n) reaction were investigated over proton energies of 1.40 to 4.57 Mev. The plots of these yields are included as Appendices A and B. For these cases the yields were originally plotted as a function of the frequency of the resonance control. Later the frequency units were converted to energy units (Chapter III). This accounts for the slight non-linearity of the energy scales. The ordinate scales are scaled for clarity of presentation.

In experiments of this type it is important that the optimum energy (frequency) intervals be used. It can be readily seen that if the intervals used are not greater than the width at the half-maximum point of the observed resonance levels (a resultant of widths due to target thickness, proton energy spread, and true (p,n) resonance), in no case will more than half of the true maximum value of the level be missed. Intervals of 1/3 to 1/4 of the width at half-maximum are desirable for good detail in the curves. The width (i.e. energy spread) due to target thickness is the factor most susceptible of control. The thicker the target, the better can the (p,n) resonances be resolved. Fowler et al (F1) discuss effects and measurements of the components of observed resonance widths.

2. Yields.

The enriched Cr^{54} isotope (2.5 Kev target) was investigated first. In the energy region below 2.2 Mev, the yield was quite small, although definite resonances were observed. From the measured widths of the best-defined peaks, it appeared reasonable to vary the proton energy in steps of about 1.5 Kev (5 Kc in frequency). Above 2.2 Mev of proton energy the yield increased markedly and the resonances became better defined. The yield was investigated up to 2.47 Mev.

The enriched Cr^{53} isotope (1.5 Kev target) produced about 9 times as much yield as did the Cr^{54} in the region below 2.2 Mev and the resonances were better defined. The Cr^{53} target was thinner than the first Cr^{54} target and the level widths indicated that proton energy steps of about 600 ev. (2 Kc in frequency) should be used. To obtain equivalent resolution the 1.5 Kev Cr^{54} target was prepared and the yield above 2.2 Mev investigated.

A comparison of the two yield curves below 2.2 Mev of proton energy showed that all resonant peaks which appeared in the enriched Cr^{54} were present and better resolved the better can the (p,n) resonances be resolved. Fowler et al (32) discuss effects and consequences of the experiments of observed resonance widths.

3. Yields.

The enriched Cr^{54} isotope (2.5 kev target) was investigated first. In the energy region below 2.2 mev, the yield was quite small, although definite resonances were observed. From the measured widths of the best-defined peaks, it appeared reasonable to vary the proton energy in steps of about 1.5 kev (5 cm in frequency). Above 2.2 mev of proton energy the yield increased markedly and the resonances became better defined. The yield was investigated up to 2.47 mev.

The enriched Cr^{53} isotope (1.5 kev target) produced about 5 times as much yield as did the Cr^{54} in the region below 2.2 mev and the resonances were better defined. The Cr^{53} target was thinner than the first Cr^{54} target and the level widths indicated that proton energy steps of about 600 ev. (2 cm in frequency) should be used. To obtain equivalent resolution the 1.5 kev Cr^{54} target was prepared and the yield above 2.2 mev investigated.

A comparison of the two yield curves below 2.2 mev of proton energy showed that all resonant peaks which appeared in the enriched Cr^{54} were present and better resolved in the enriched Cr^{53}. This can be accounted for by the presence (3.9%) of Cr^{53} in the enriched Cr^{54} material. Figure IV-1 is a representative sample of this comparison. A determination of the effect of this small amount of Cr^{53} in the enriched Cr^{54} was made. By assuming that the same ratio (approximately 1/9) of Cr^{53} yields existed above 2.203 Mev. as did below this energy, 1/9 of the yield of enriched Cr^{53} was subtracted from the yield of enriched Cr^{54}. No appreciable change in the characteristics (i.e. no levels were eliminated or new ones defined) of the Cr^{54} curve were noted. This correction is not included in the yield curves of appendix B.

3. Threshold Determinations.

With the considerations of section 2 above, the threshold for the $Cr^{54}(p,n)$ reaction as determined from the thin target data (appendix B) is 2.202 $\pm$ .005 Mev. A thicker target (20 Kev) was prepared in order to verify this value. Figure IV-2, a plot of the yield from this target, shows the threshold to lie at 2.204 $\pm$ .005 Mev. It is concluded that the best value of threshold energy for $Cr^{54}(p,n)$ is 2.203 $\pm$ .005 Mev.

The threshold of the $Cr^{53}(p,n)$ was less well-defined. At the lower proton energies the yield was quite low because of the coulomb barrier (6.6 Mev) and the yield of the thin

Figure IV-1

NEUTRON YIELDS FROM ENRICHED Cr^{53} and Cr^{54}

The enriched Cr^{54} curve shows a small neutron yield from the presence of Cr^{53} (3.9%) below the Cr^{54} (p,n) threshold (2.202 ± .005 Mev.)

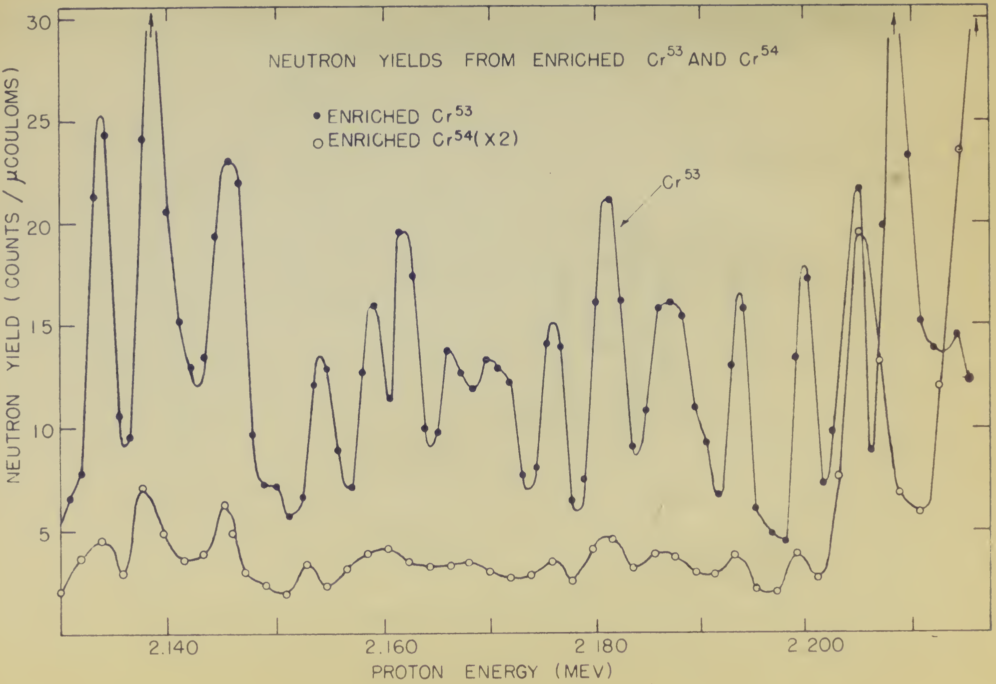

NEUTRON YIELDS FROM ENRICHED Cr53 AND Cr54
• ENRICHED Cr53
○ ENRICHED Cr54 (X2)
Cr53
NEUTRON YIELD (COUNTS / μCOULOMS)
30
25
20
15
10
5
2.140
2.160
2.180
2.200
PROTON ENERGY (MEV)

Figure IV-2

$Cr^{54}(p,n)Mn^{54}$

THRESHOLD MEASUREMENT

with

20 KEV TARGET

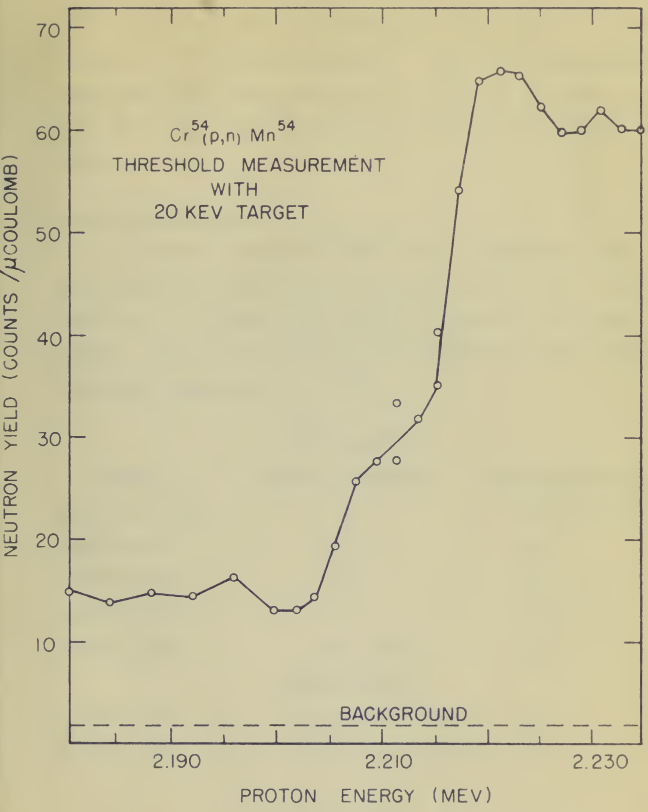
[illegible]

$^{42}Ca(d,p)^{43}Ca$

[illegible]

[illegible]

[illegible]


$Cr^{54}(p,n)\ Mn^{54}$
THRESHOLD MEASUREMENT
WITH
20 KEV TARGET
BACKGROUND
NEUTRON YIELD (COUNTS /μCOULOMB)
PROTON ENERGY (MEV)
70
60
50
40
30
20
10
2.190
2.210
2.230

Cr^{53} target was not investigated below 1.419 Mev. A thicker target of Cr^{53} was also prepared. Figure IV-3 shows the results and places the threshold for $Cr^{53}(p,n)$ at 1.406 ± .008 Mev. The larger error is assigned because of the poorer statistics.

4. Level Spacings.

As seen on the yield curves of the appendices, the distribution of the resonant peaks is not uniform. It is practical to consider only average spacing of the energy levels. Spacings as averaged over different proton energy ranges are shown in Table IV-1.

Energy	Number of Levels	Average Spacing
	$Cr^{53}(p,n)Mn^{53}$	
1.420-1.620 Mev	40	5.0 Kev/level
1.620-1.870	53	4.7
1.870-2.160	63	4.6
2.160-2.470	67	4.6
1.420-2.470	223 Total	4.7
	$Cr^{54}(p,n)Mn^{54}$	
2.202-2.470	53(1.5 Kev target)	5.1
2.202-2.470	38(2.5 Kev target)	7.0

Table IV-1

Cr^{53} target was not investigated below 1.413 Mev. A thinner target of Cr^{53} was also prepared. Figure IV-3 shows the results and places the threshold for $Cr^{53}(p,n)$ at 1.400 ± .004 Mev. The larger error is assigned because of the poorer statistics.

4. Level Spacings.

As seen on the yield curves of the appendices, the distribution of the resonance peaks is not uniform. It is unrealistic to consider only average spacing of the energy levels. Spacings as averaged over different proton energy ranges are shown in Table IV-1.

$Cr^{53}(p,n)Mn^{53}$

Energy	Number of Levels	Average Spacing
1.420-1.620 Mev	40	5.0 Kev/level
1.620-1.870	53	4.7
1.870-2.160	63	4.6
2.160-2.470	69	4.6
1.420-2.470	225 Total	4.7

$Cr^{54}(p,n)Mn^{54}$

Energy	Number of Levels	Average Spacing
2.200-2.470	53 (1.5 Kev target)	5.1
2.200-2.470	38 (4.5 Kev target)	7.0

Table IV-1

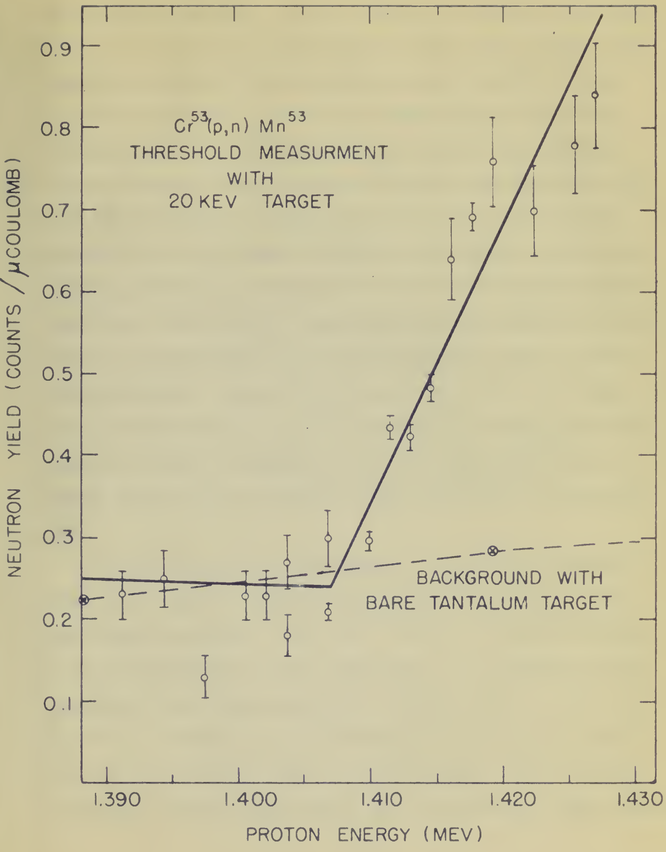
Figure IV-3

$Cr^{53}(p,n)Mn^{53}$

THRESHOLD MEASUREMENT

with

20 KEV TARGET



$Cr^{53}(p,n)\ Mn^{53}$
THRESHOLD MEASURMENT
WITH
20 KEV TARGET
BACKGROUND WITH
BARE TANTALUM TARGET
NEUTRON YIELD (COUNTS / μCOULOMB)
PROTON ENERGY (MEV)
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
1.390
1.400
1.410
1.420
1.430

Some of the levels are poorly defined and others apparently overlap so that they appear as one rather wide level. The averaging process tends to minimize these uncertainties.

The widths of the levels at 1/2 maximum are often distorted by the overlapping of the levels. To properly measure widths, isolated resonant peaks must be used. By assuming that the natural nuclear resonance can be much narrower than the target thickness, the widths of the narrowest peaks can be considered a measure of target thickness (W1). For the Cr^{53} target this was determined to be 1.5 Kev, for the Cr^{54} 1.5 and 2.5 Kev. The effect of target thickness on observed level spacing is clearly shown by the comparison of the Cr^{54} yields for the two different thickness targets (Appendix B). Resonance peaks that appeared asymmetrical or unduly thick using the 2.5 Kev target.

It may be pointed out that if a statistical distribution of levels is assumed with average spacing D, three conditions may exist: (1) $D < W$ (2) $D = W$ (3) $D > W$ where W is the resolution of the instrument. The observed level spacing for the three conditions will be (1) $\simeq W$ (2) $\simeq W$ (3) $\simeq D$. Inasmuch as D is observed to be 4-5 Kev and W is $\pm$ 300 ev (Section II-2), we may conclude that condition (3) exists and that the actual level spacing are being observed.

Some of the levels are poorly defined and others apparently overlap so that they appear as one rather wide level. The stripping process tends to minimize these uncertainties.

The widths of the levels at 1/2 maximum are often distorted by the overlapping of the levels. To properly measure widths, isolated resonant peaks must be used. By assuming that the natural nuclear resonances can be much narrower than the target thickness, the widths of the narrowest peaks can be considered a measure of target thickness (21). For the Cr^{53} target this was determined to be 1.5 kev, for the Cr^{54} 1.5 and 2.5 kev. The effect of target thickness on observed level spacing is clearly shown by the comparison of the Cr^{54} yields for the two different thickness targets (Appendix B). Resonance peaks that appeared asymmetrical or doubly when using the 2.5 kev target.

It may be pointed out that if a statistical distribution of levels is assumed with average spacing D, three conditions may exist: (1) $D < W$ (2) $D = W$ (3) $D > W$ where W is the resolution of the instrument. The observed level spacing for the three conditions will be (1) $\cong W$ (2) $\cong W$ (3) $\cong D$. Inasmuch as D is observed to be 4-5 kev and W is $\pm$ 300 ev (Section II-9), we may conclude that condition (3) exists and that the actual level spacing are being observed.

5. Reproducibility.

In this type of experiment, as in most, ability to reproduce data is an excellent check on the alignment of equipment and accuracy of data. Rechecks of prominent portions of the yield curves were made when practicable and especially after a shut-down of the generator. Figure IV-4 shows some representative checks made. The discrepancy in yield of Figure IV-4(a) is not readily explained. However, the proton energy of the resonance is the more important quantity and the displacement shown (approx. 500 ev) is within the expected uncertainty of the generator (ref. Section II-2).

Figure IV-4

REPRODUCTION OF DATA AFTER VARIOUS TIME INTERVALS

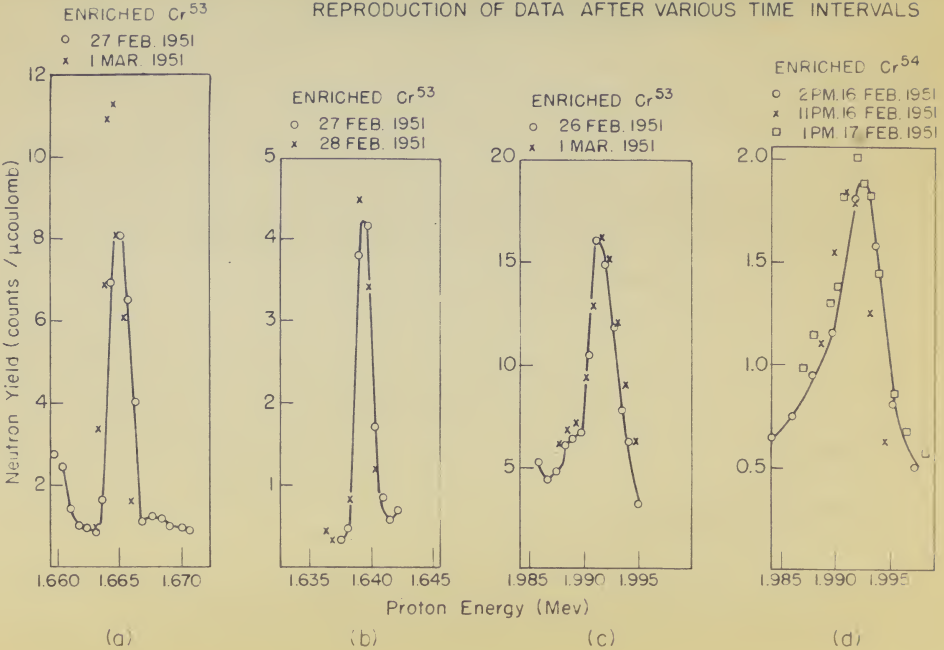
(a) Enriched Cr^{53} target

(b) Enriched Cr^{53} target

(c) Enriched Cr^{53} target

(d) Enriched Cr^{54} target. Proton energy below $Cr^{54}(p,n)$ threshold and in same region as Figure IV-4(c).

REPRODUCTION OF DATA AFTER VARIOUS TIME INTERVALS



CHAPTER V

THEORETICAL CONSIDERATIONS

1. General.

Current theories of the structure of atomic nuclei are in a continuing state of development and modification. However, the generally accepted approaches all include certain common fundamentals. Among these are:

(a) That in a nuclear reaction (e.g. (p,n)) a compound nucleus is formed whose break-up is independent of the mode of formation (B3, W4).

(b) That the energy levels that exist within a nucleus decrease (exponentially) in average spacing with increasing excitation energy (B3).

(c) That the energy level spacing also decreases (slowly) with increasing A.

Nuclear masses, binding energies and reaction threshold energies can be computed fairly accurately from the semi-empirical mass formula (F2).

2. Level Spacing.

It has been noted that the spacing of energy levels will be different for different nuclei depending on whether the number of neutrons and protons is odd or even (B2, W2). However, Hurwitz and Bethe (H4) have pointed out that these

CHAPTER V

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1. General.

Current theories of the structure of atomic nuclei are in a continuing state of development and modification. However, the generally accepted approaches all include certain common fundamentals. Among these are:

(a) That in a nuclear reaction (e.g. (p,n)) a compound nucleus is formed whose break-up is independent of the mode of formation (31, 34).

(b) That the energy levels that exist within a nucleus decrease (exponentially) in average spacing with increasing excitation energy (33).

(c) That the energy level spacing also decreases (slowly) with increasing A.

Nuclear masses, binding energies and reaction threshold energies can be computed fairly accurately from the semi-empirical mass formula (32).

2. Level Spacing.

It has been noted that the spacing of energy levels will be different for different nuclei depending on whether the number of neutrons and protons is odd or even (31, 32). However, Hurwitz and Bethe (36) have pointed out that these fluctuations are difficult to understand if one measures the level spacing at excitation energies which are based on the ground states. They have suggested instead that the excitation energy be measured from a characteristic level which depends in a smooth way on the number of protons and neutrons in the nucleus, and that such a level might be the neutron binding energy as computed from the semi-empirical mass formula without the odd-even term. Hurwitz and Bethe further indicate that the level spacing measured at equal energies relative to these levels would be expected to be the same regardless of the odd-even character of the number of neutrons.

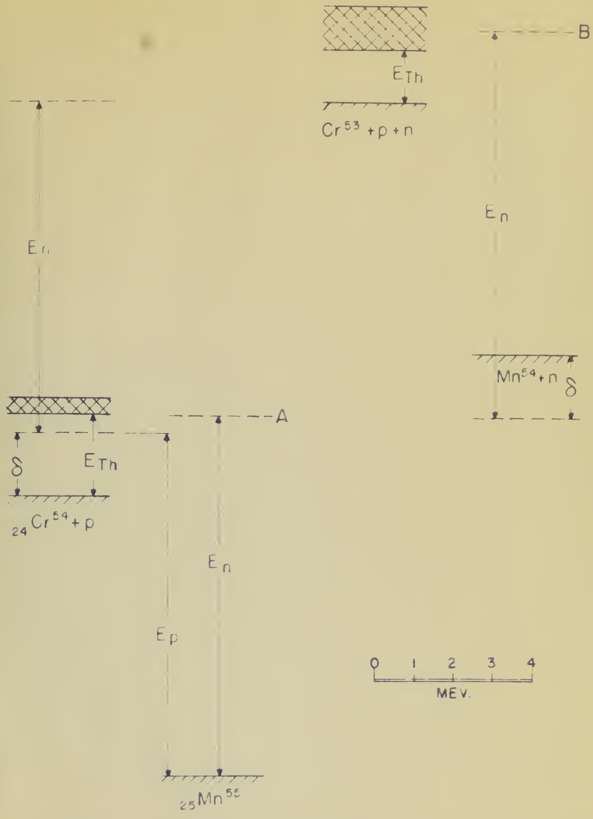
Figure V-1 is an energy level diagram showing these characteristic levels (A and B) for the compound nuclei Mn^{54} and Mn^{55}. The portions of the proton energy ranges investigated in this experiment cover the regions near these levels, hence a comparison of the level spacings would be expected to yield a ratio of unity. As seen from table IV-1 the ratio obtained is 1.1 for the 1.5 Kev target data in the vicinity of A and B, with Mn^{55} having the slightly larger spacing. The agreement of certain of the computed binding energies with experiment is given in Table V-1 fluctuations are difficult to understand if one measures the level spacing at excitation energies which are based on the ground states. They have suggested instead that the excitation energy be measured from a characteristic level which depends in a smooth way on the number of protons and neutrons in the nucleus, and that such a level might be the neutron binding energy as computed from the semi-empirical mass formula without the odd-even term. Hurwitz and Bethe further indicate that the level spacing measured at equal energies relative to these levels would be expected to be the same regardless of the odd-even character of the number of neutrons.

Figure V-1 is an energy level diagram showing these characteristic levels (a and b) for the compound nuclei Cr^{54} and Cr^{53}. The portions of the proton energy ranges investigated in this experiment cover the regions near these levels, hence a comparison of the level spacings would be expected to yield a ratio of unity. As seen from Table IV-1 the ratio obtained is 1.1 for the 1.3 Mev segment data in the vicinity of a and b, with Cr^{53} having the slightly larger spacing. The agreement of certain of the computed binding energies with experiment is given in Table V-1.

Figure V-1

ENERGY LEVEL DIAGRAM OF Cr^{53}, Cr^{54}, Mn^{54} and Mn^{55}

E_p and E_n indicate binding energy levels for last proton and neutron of indicated nucleus as computed from mass formula without odd-even term.
δ indicates elevation or depression of ground state from these levels.
E_{th} indicates (p,n) threshold as determined in this experiment.
Hatched area is proton energy range investigated.
A and B are characteristic levels discussed by Hurwitz and Bethe.



ENERGY LEVEL DIAGRAM OF Cr^{53}, Cr^{54}, Mn^{54}, AND Mn^{55}

	calculated	observed
$E_n + \delta$ for Mn^{55}	10.93 Mev	10.15 Mev (H3)
$E_n + \delta$ for Cr^{54}	10.3 Mev	9.3 Mev (G1)

Table V-1

Preston (P2) has pointed out that in observing neutron energy level spacing the existance of multiplet levels should be considered. The multiplets can be explained by the different J values which arise from the quantum mechanical combinations of the different allowed values of the orbital and intrinsic angular moments of the bombarding particle, target neucleus and emitted particle. For bombarding protons with $\ell = 0$, 1 and 2 and for an even Z-even N target isotope (Cr^{54}, I=0) the multiplet multiplicity may be as great as 5; for an even Z-odd N target (Cr^{53}, I $\geq$ 1/2) it may be 8. Hence, other things being equal, the ratio of level spacing of the former to that of the latter should be about 1.6. It appears to be possible for these multiplet levels to overlap in such a manner that each multiplet group is indistinguishable from the others. This multiplet consideration would account for the observed ratio of level spacing being greater than unity. It is difficult to be more quantitative because the intensity of the different levels of a multiplet group can be expected to very greatly, some being

	Calculated	Observed
$E_n + \delta$ for Mn^{55}	10.07 Mev	10.13 Mev (53)
$E_n + \delta$ for Cr^{54}	10.3 Mev	9.1 Mev (51)

Table V-1

Preston (72) has pointed out that in observing neutron energy level spacing the existence of multiplet levels should be considered. The multiplets can be explained by the different J values which arise from the quantum mechanical combinations of the different allowed values of the orbital and intrinsic angular momenta of the bombarding particle, target nucleus and emitted particle. For bombarding protons with $\lambda = 0$, 1 and 2 and for an even Z-even N target isotope (Cr^{54}, I=0) the multiplet multiplicity may be as great as 5; for an even Z-odd N target (Cr^{53}, $I \geq 1/2$) it may be 6. Hence, other things being equal, the ratio of level spacing of the former to that of the latter should be about 1.6. It appears to be possible for these multiplet levels to overlap in such a manner that each multiplet group is indistinguishable from the others. This multiplet consideration would account for the observed ratio of level spacing being greater than unity. It is difficult to be more quantitative because the intensity of the different levels of a multiplet group can be expected to vary greatly, some being of such low intensity that they would be lost in the background.

3. Thresholds.

Because of the mass-energy conservation in a nuclear reaction, the semi-empirical mass formula (F2) may be used to calculate the Q energy value of a reaction. The threshold energy is then readily determined from the Q energy. Table V-2 is a comparison of the computed threshold energies with those measured in this work, and provides a check on the accuracy of the mass formula.

Reaction	E_{th} (computed)	E_{th} (measured)
$Cr^{53}(p,n)$	1.82 Mev	1.406 Mev
$Cr^{54}(p,n)$	3.83	2.203

Table V-2

The widest variation occurs for $Cr^{54}(p,n)$ in which calculation the odd-even term of the mass formula occurs twice. For $Cr^{53}(p,n)$ this term is zero. However, when one considers that 1 Mev = .001074 a.m.u. this variation is not striking.

4. Masses.

If the mass of the target nucleus is known, the mass of the residual nucleus can be determined from the threshold energy of a (p,n) reaction.

of such low intensity that they would be lost in the background.

3. Thresholds.

Because of the mass-energy conservation in a nuclear reaction, the semi-empirical mass formula (??) may be used to calculate the Q energy value of a reaction. The threshold energy is then readily determined from the Q energy. Table V-2 is a comparison of the computed threshold energies with those measured in this work, and provides a check on the accuracy of the mass formula.

Reaction	E_{th} (computed)	E_{th} (measured)
$Cr^{53}(p,n)$	1.35 Mev	1.400 Mev
$Cr^{54}(p,n)$	2.47	2.203

Table V-2

The widest variation occurs for $Cr^{54}(p,n)$ in which calculation the odd-even term of the mass formula occurs twice. For $Cr^{53}(p,n)$ this term is zero. However, when one considers that 1 Mev = .00107 a.m.u., this variation is not striking.

4. Masses.

If the mass of the target nucleus is known, the mass of the residual nucleus can be determined from the threshold energy of a (p,n) reaction.

$$M_R = M_T + (M_P - M_N) - Q$$

where M_R, M_T, M_P, and M_N are the masses of the residual nucleus, target nucleus, proton and neutron respectively.

Ogata (O1) has reported the masses of the two chromium isotopes used in this work:

$$Cr^{53} = 52.95527 \pm .00044 \text{ amu}$$
$$Cr^{54} = 53.95427 \pm .00048.$$

Using

$$M_P = 1.00813 \pm .000003$$
$$M_N = 1.00898 \pm .00001$$
$$Q(53) = -1.380 \pm .008 \text{ Mev} = -.00148 \pm .00001 \text{ amu}$$
$$Q(54) = -2.165 \pm .005 \text{ Mev} = -.00232 \pm .00001 \text{ amu}$$

it is determined that

$$Mn^{53} = 52.95590 \pm .00044 \text{ amu}$$
$$Mn^{54} = 53.95574 \pm .00048 \text{ amu}.$$

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The author wishes to express his appreciation to Professor Clark Goodman who, as thesis advisor, gave invaluable guidance to this work, to Dr. J.J.G. McCue who gave so freely of his time and advice with the experimental work, to Dr. M.H. Preston for his help, especially with the related theory, and to the Rockefeller Generator crew for their aid in the conduct of the experiment.

Appendix A

NEUTRON YIELD FROM $Cr^{53}(p,n)Mn^{53}$

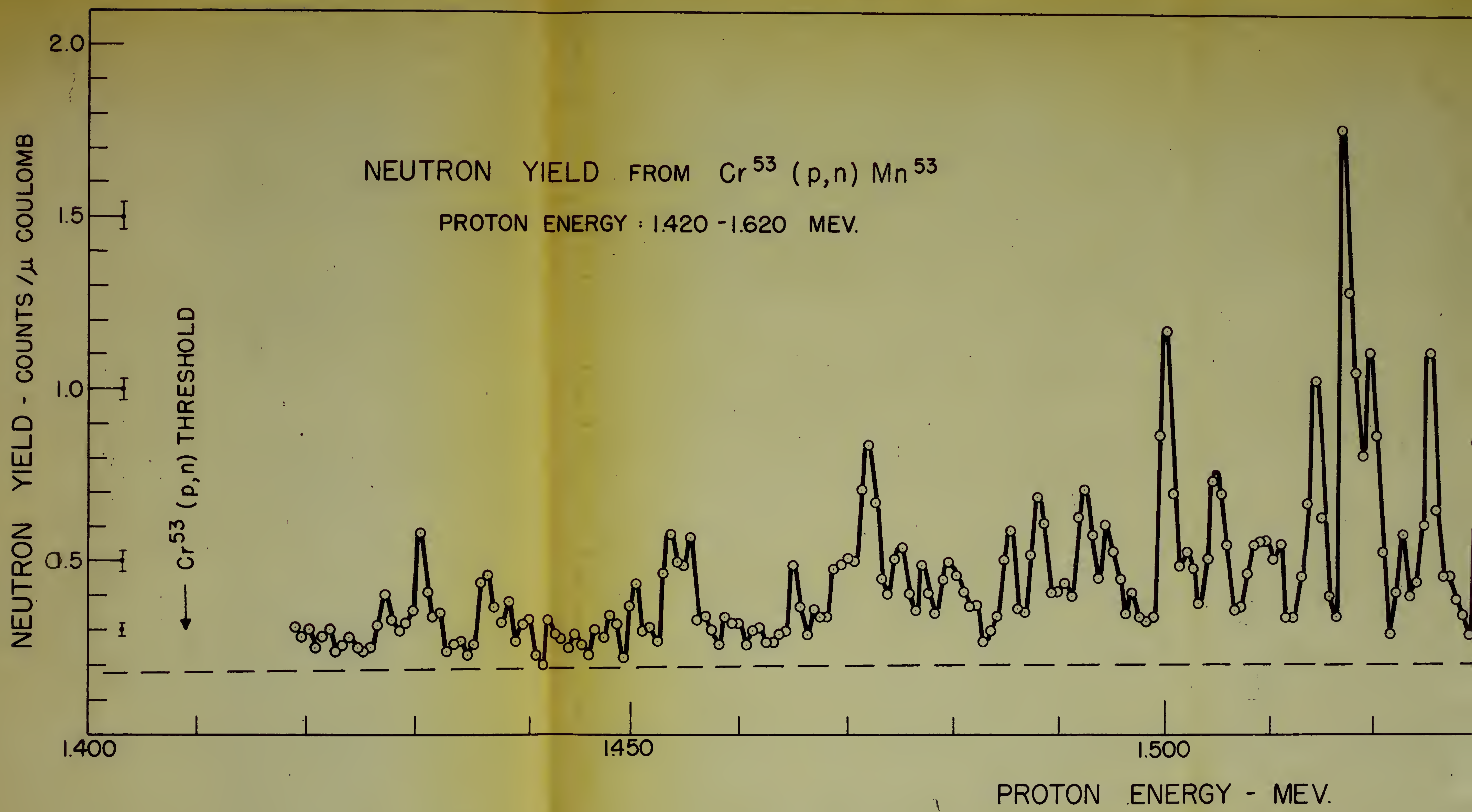
(1) Proton Energy: 1.420-1.620 Mev.

(2) Proton Energy: 1.620-1.870

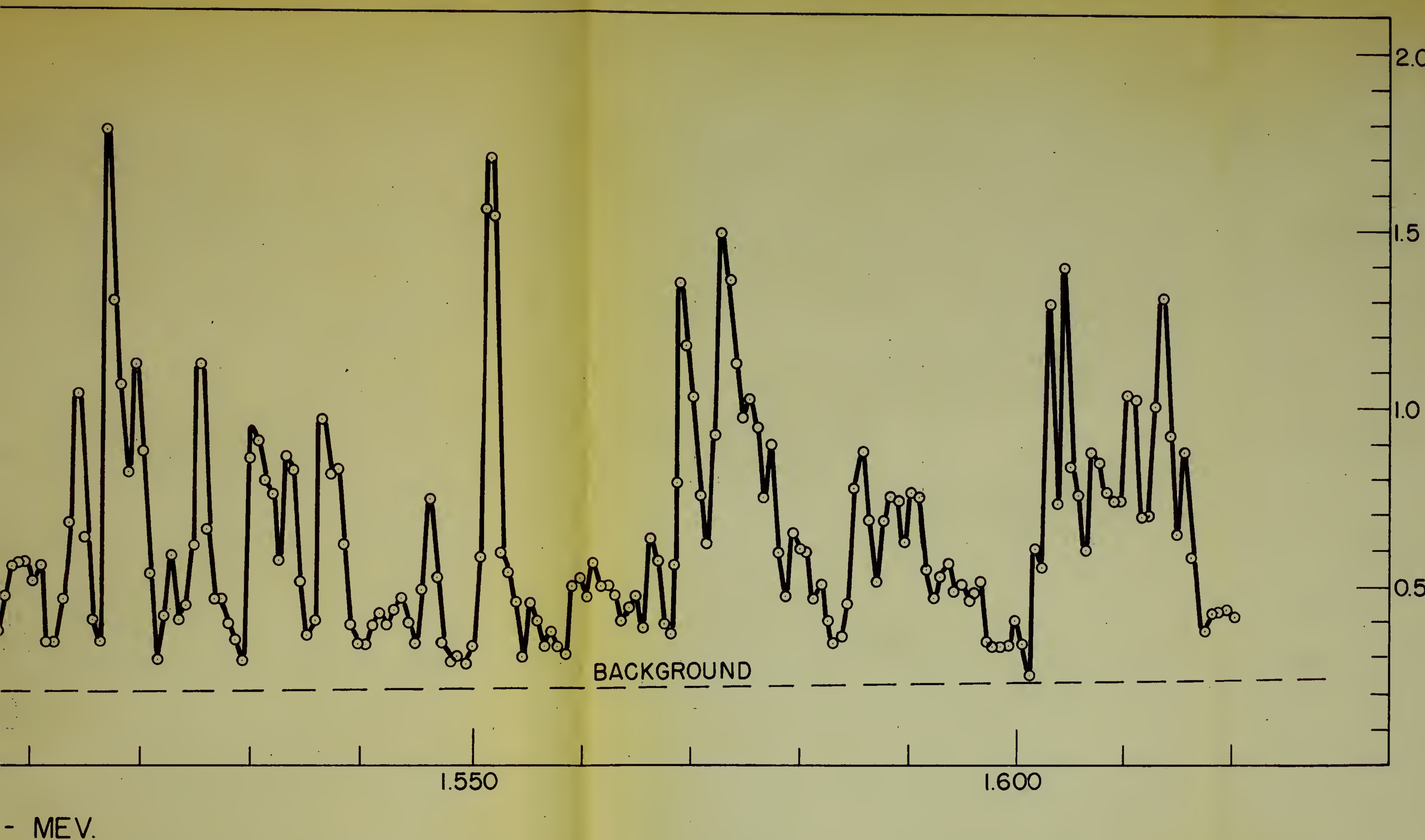
(3) Proton Energy: 1.870-2.160

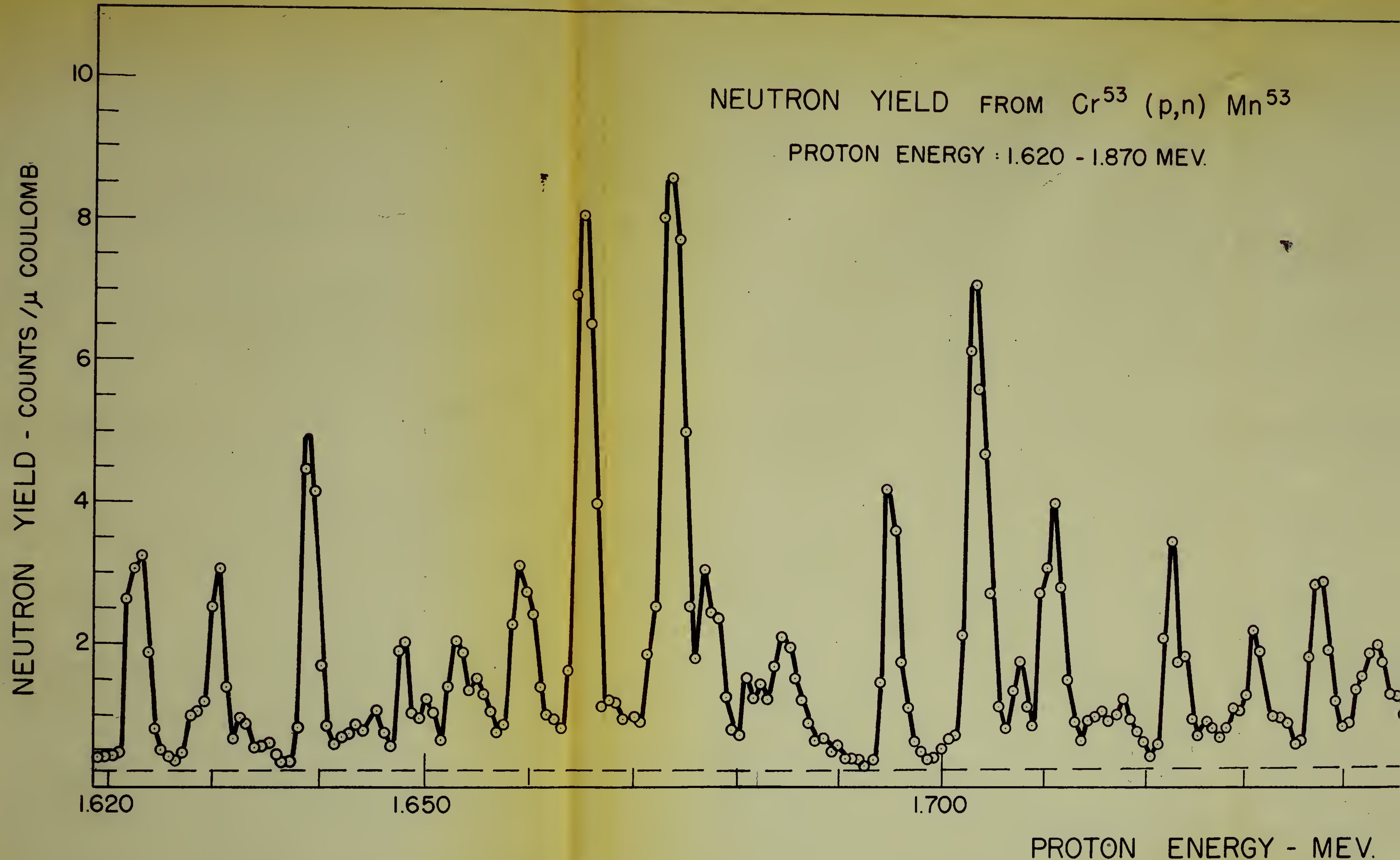
(4) Proton Energy: 2.160-2.470

Unless otherwise indicated the probable error is less than the diameter of the circles.

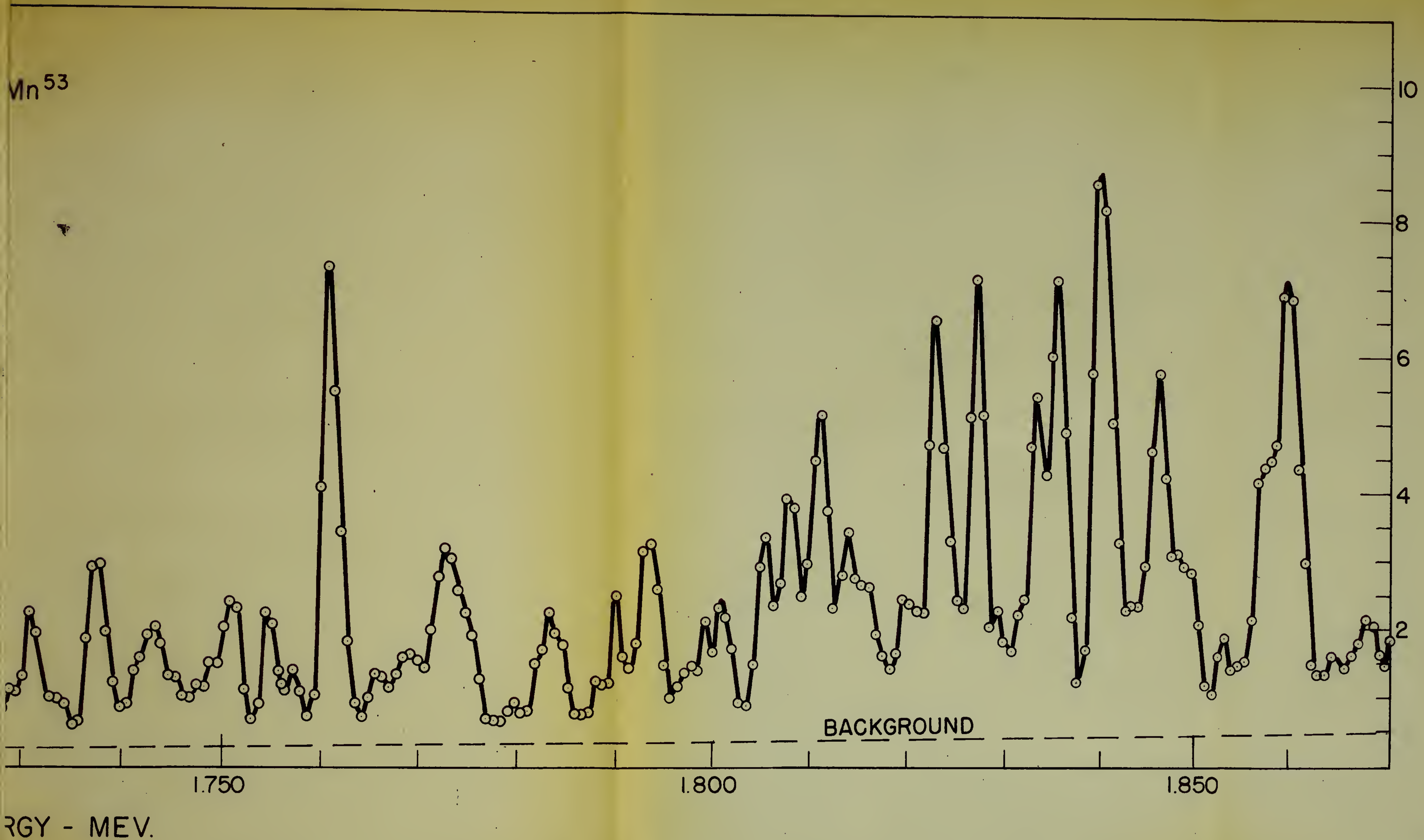


NEUTRON YIELD FROM Cr^{53} (p,n) Mn^{53}
PROTON ENERGY : 1.420 - 1.620 MEV.
NEUTRON YIELD - COUNTS / μ COULOMB
Cr^{53} (p,n) THRESHOLD
2.0
1.5
1.0
0.5
1.400
1.450
1.500
PROTON ENERGY - MEV.

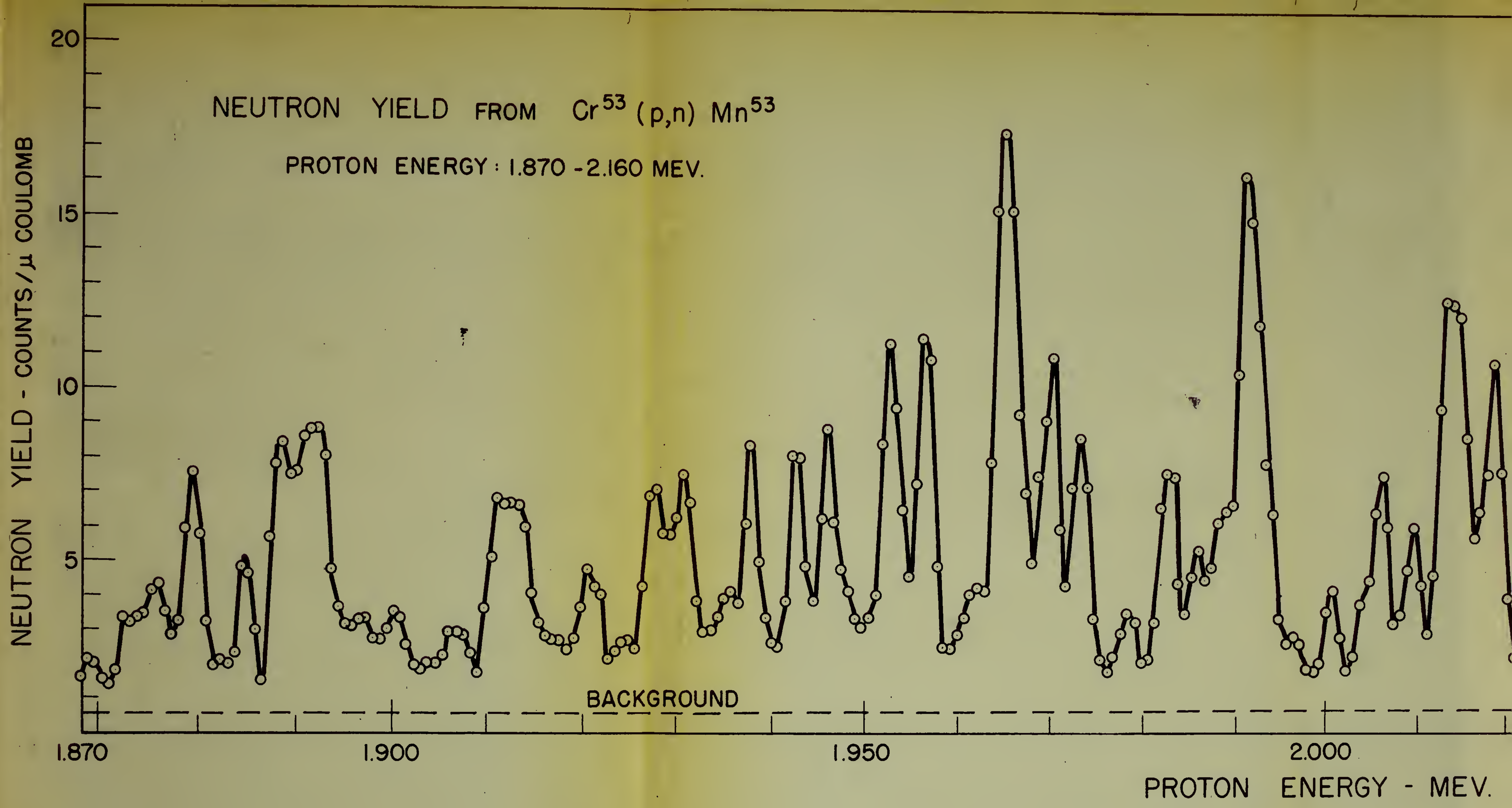

2.0
1.5
1.0
0.5
BACKGROUND
1.550
1.600
- MEV.

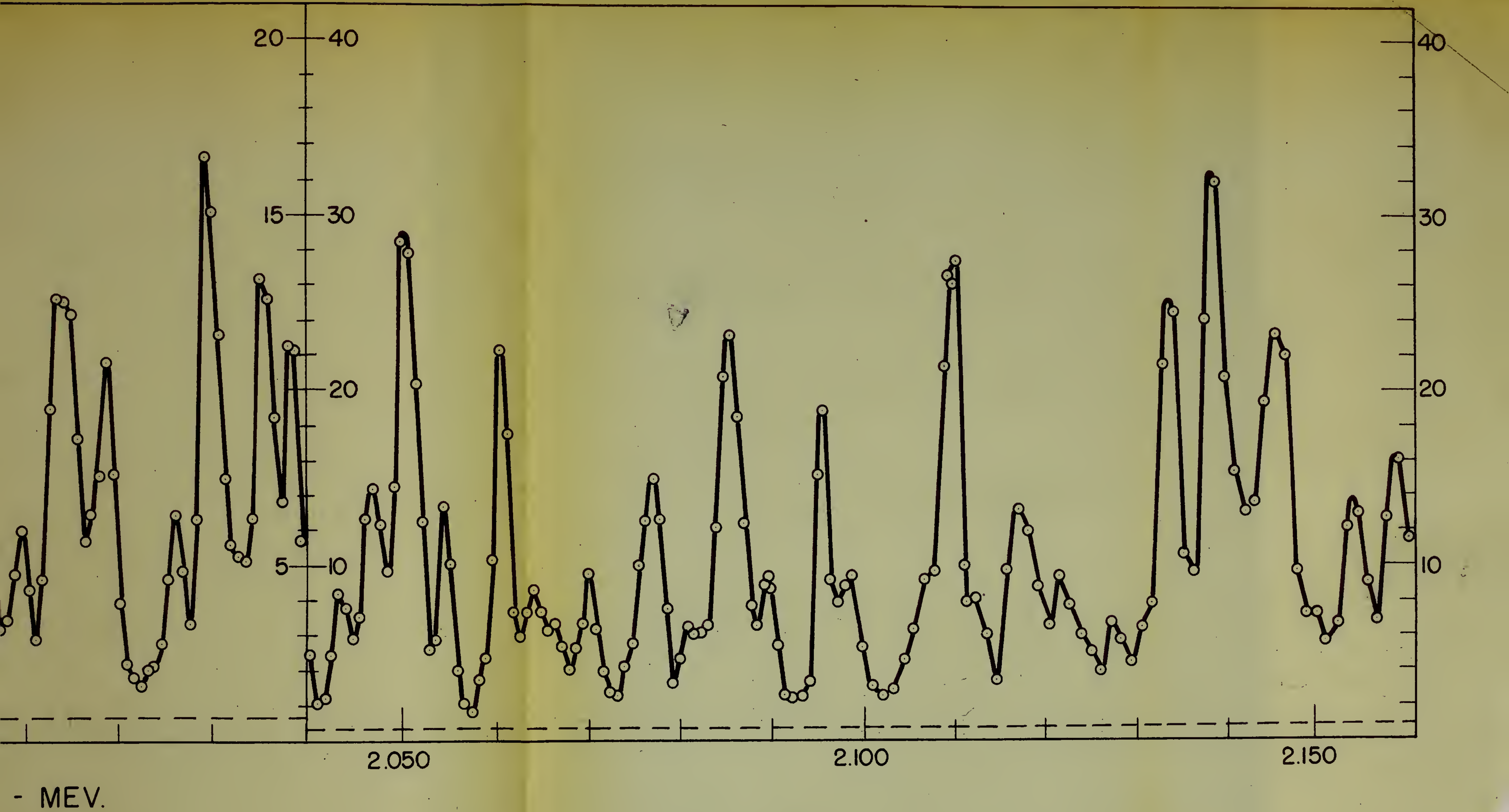


NEUTRON YIELD FROM Cr^{53} (p,n) Mn^{53}
PROTON ENERGY : 1.620 - 1.870 MEV.
NEUTRON YIELD - COUNTS / μ COULOMB
10
8
6
4
2
1.620
1.650
1.700
PROTON ENERGY - MEV.



Mn 53
BACKGROUND
10
8
6
4
2
1.750
1.800
1.850
RGY - MEV.

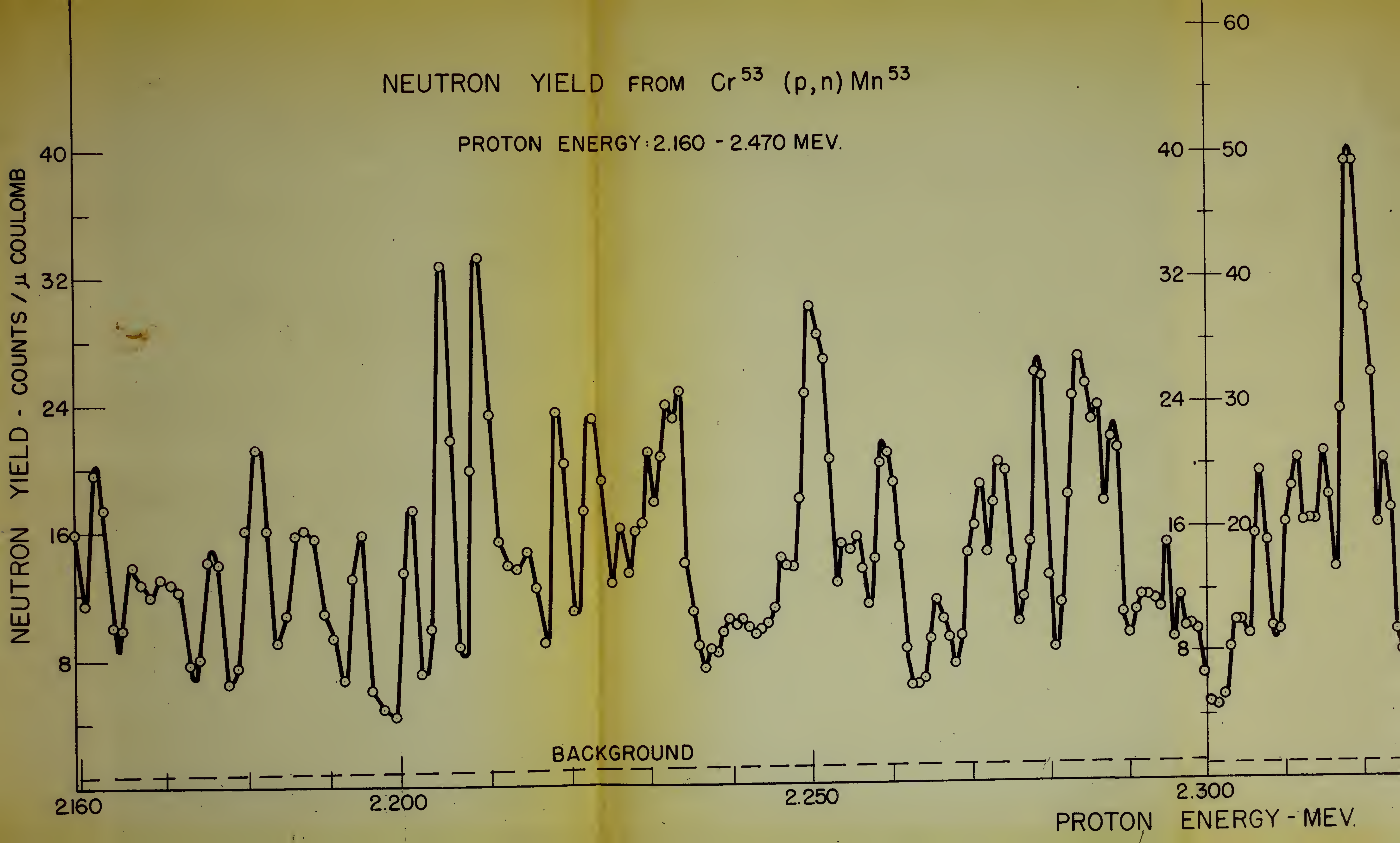

NEUTRON YIELD FROM Cr^{53} (p,n) Mn^{53}
PROTON ENERGY : 1.870 - 2.160 MEV.
NEUTRON YIELD - COUNTS / μ COULOMB
20
15
10
5
BACKGROUND
1.870
1.900
1.950
2.000
PROTON ENERGY - MEV.

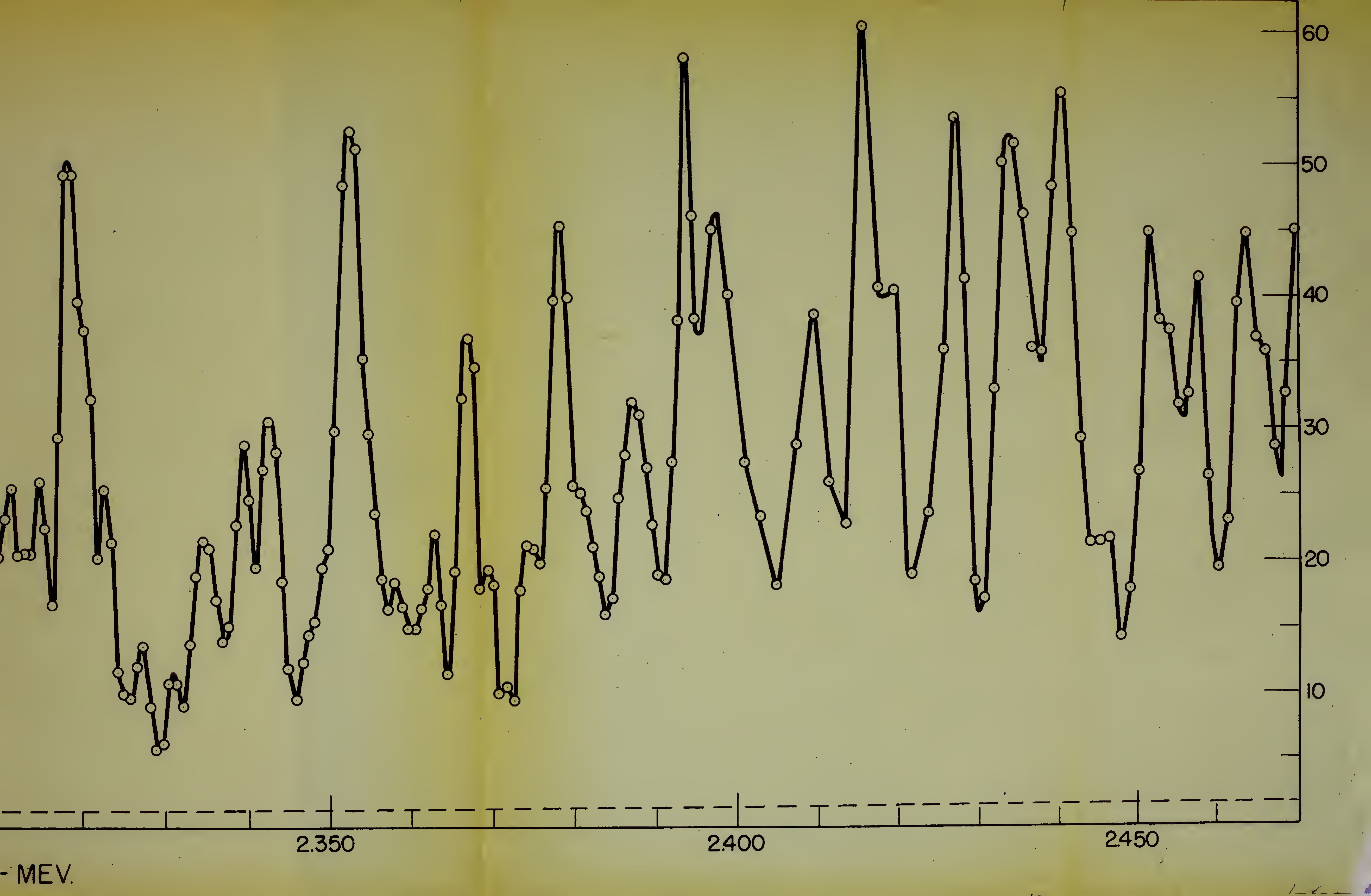


20
15
5
40
30
20
10
40
30
20
10
2.050
2.100
2.150
- MEV.

NEUTRON YIELD FROM Cr^{53} (p,n) Mn^{53}

PROTON ENERGY: 2.160 - 2.470 MEV.





60
50
40
30
20
10
2.350
2.400
2.450
- MEV.

Appendix B

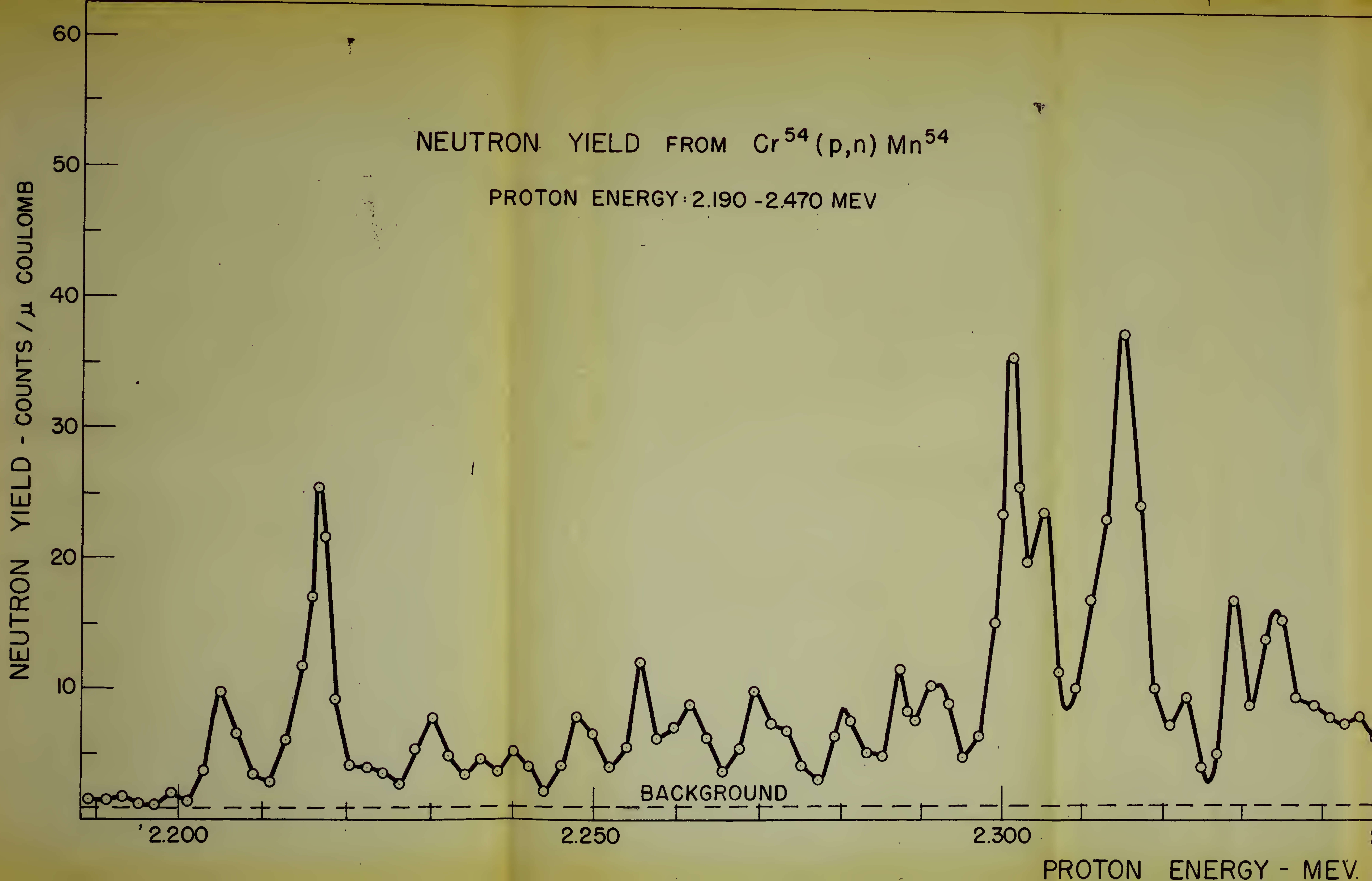
NEUTRON YIELD FROM $Cr^{54}(p,n)Mn^{54}$

Proton Energy: 2.190-2.470 Mev.

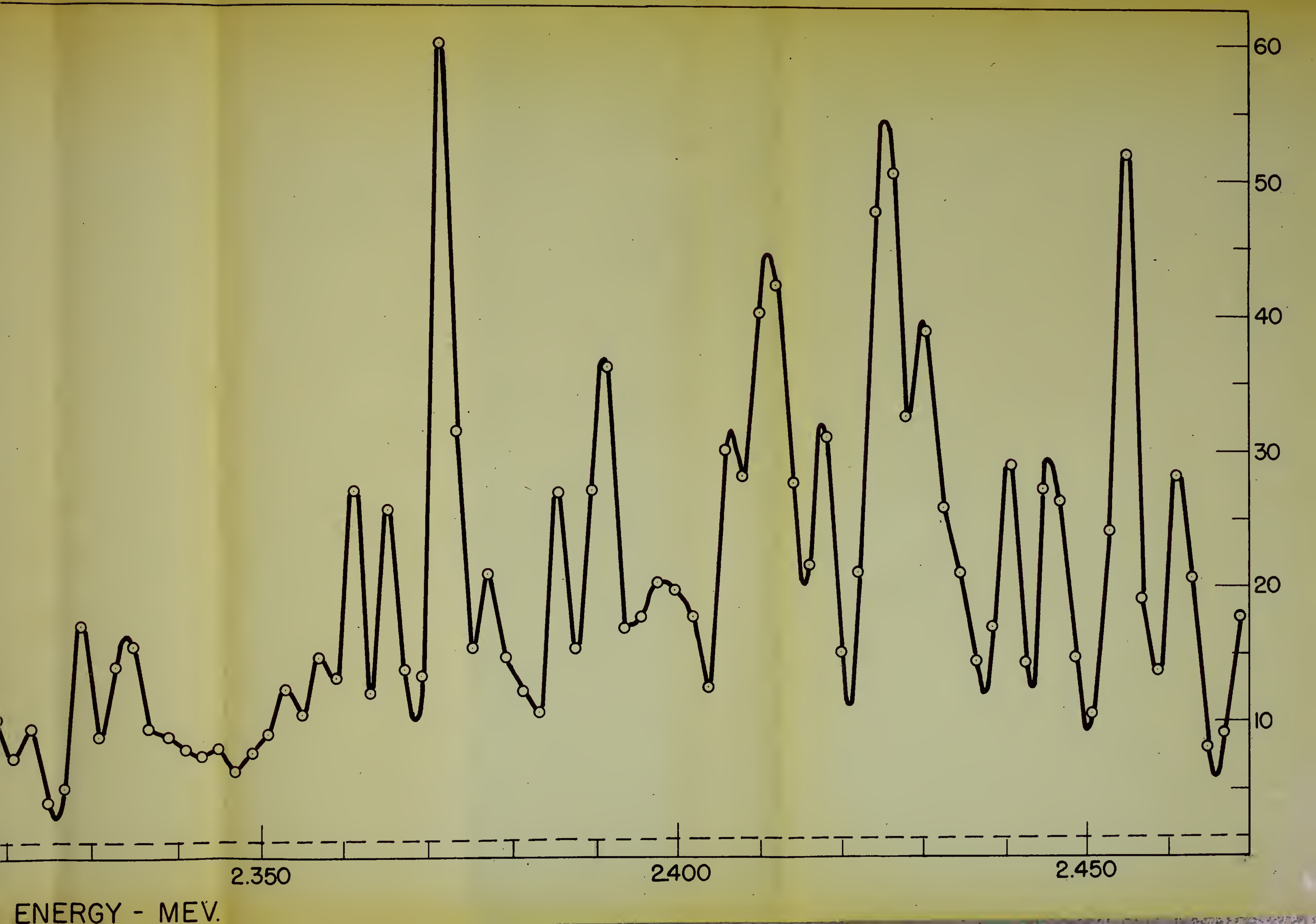
(1) 2.5 Kev target

(2) 1.5 Kev target

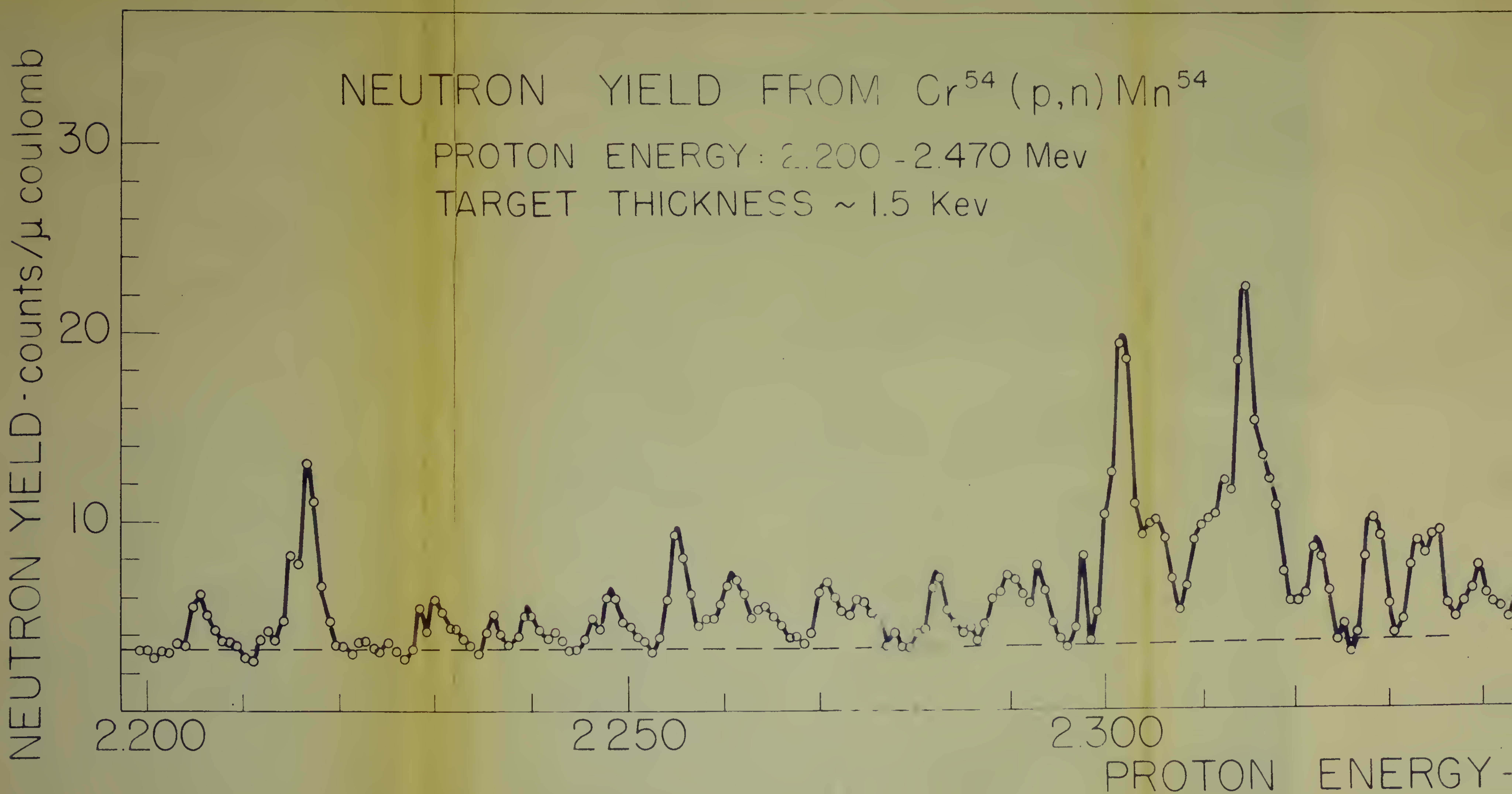
Probable error is less than diameter of circles.

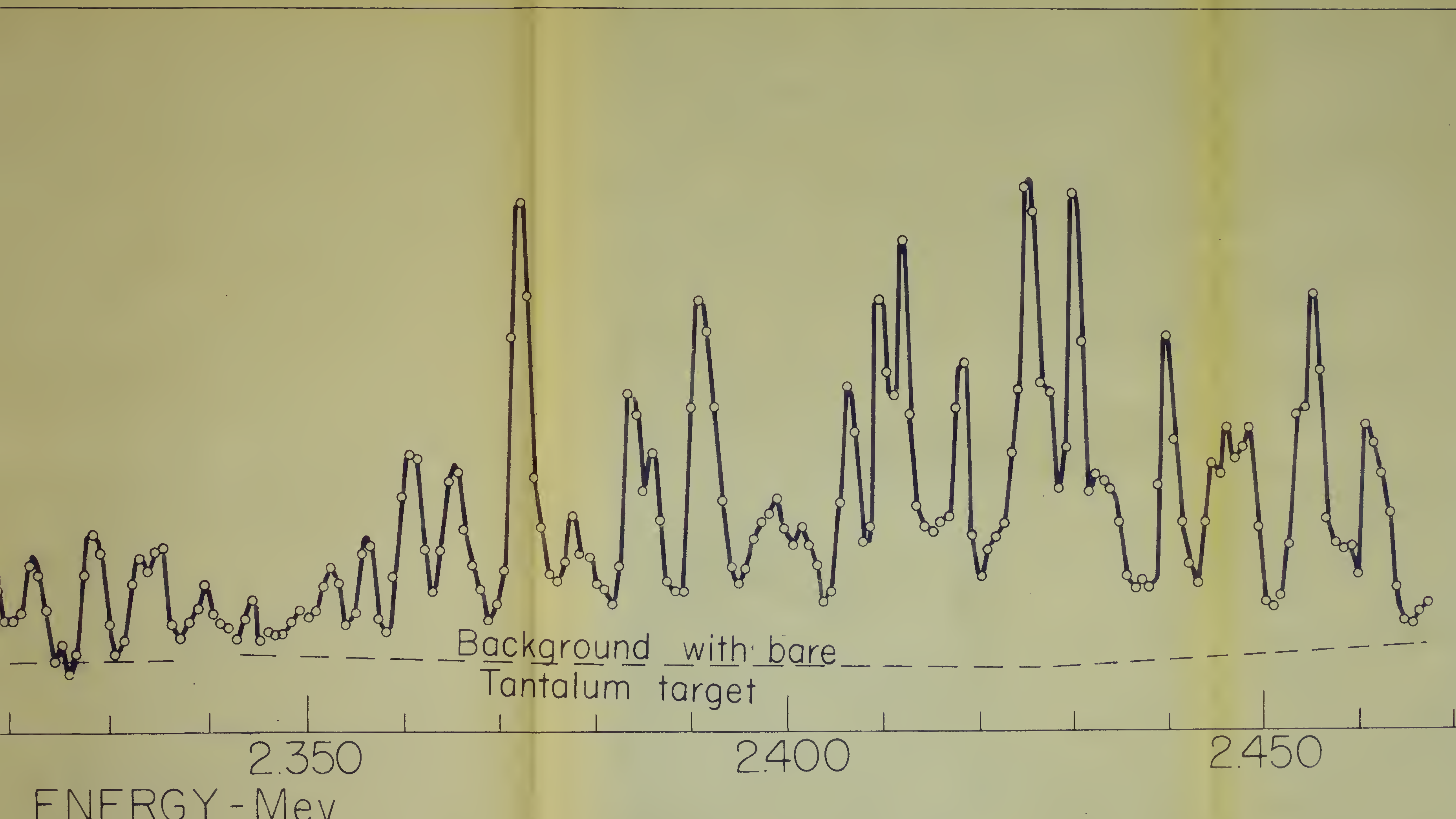


NEUTRON YIELD FROM $Cr^{54}(p,n)Mn^{54}$
PROTON ENERGY: 2.190 - 2.470 MEV
NEUTRON YIELD - COUNTS / μ COULOMB
60
50
40
30
20
10
BACKGROUND
2.200
2.250
2.300
PROTON ENERGY - MEV.



60
50
40
30
20
10
2.350
2.400
2.450
ENERGY - MEV.


NEUTRON YIELD FROM $Cr^{54}(p,n)Mn^{54}$
PROTON ENERGY: 2.200 - 2.470 Mev
TARGET THICKNESS ~ 1.5 Kev
NEUTRON YIELD - counts/μ coulomb
30
20
10
2.200
2.250
2.300
PROTON ENERGY -



Background with bare
Tantalum target
2.350
2.400
2.450
ENERGY - Mev.