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ENERGY LEVELS IN MEDIUM WEIGHT NUCLEI
from the (p,n) REACTION

—————
JOSEPH ARTHUR LOVINGTON

1951



ENERGY LEVELS IN MEDIUM WEIGHT NUCLEI

from the

(p,n) REACTION

by

JOSEPH ARTHUR LOVINGTON
" "
E.S., UNITED STATES NAVAL ACADEMY
(1942)

SUBMITTED IN PARTIAL FULFILLMENT OF THE
REQUIREMENTS FOR THE DEGREE OF
MASTER OF SCIENCE IN PHYSICS
AT THE
MASSACHUSETTS INSTITUTE OF TECHNOLOGY

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

By Joseph Arthur Lovington

Submitted for the degree of Master of Science in Physics in
the Department of Physics on May 15, 1951

ABSTRACT

The neutron yields from the reactions $\text{Cr}^{53}(p,n)$ and $\text{Cr}^{54}(p,n)$ 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.

energy levels in which spins would flip (D.A.) reaction
of these levels
indicated for the degree of order in the spin in
the experiment of Taylor on May 12, 1951

RESULTS

The neutron yields from the reactions $^{235}\text{U}(n, f)$ and
 $^{238}\text{U}(n, f)$ were investigated using an omnidirectional proton
from the Van de Graaff generator. The target isotopes were
obtained in enriched form from the Oak Ridge National Labo-
ratory and separated into fractions according to their
degrees of known isotopic enrichment. Standard techniques and instru-
ments were used in the detection and counting of the neutron
yield. Yield of the neutron yield as a function of proton
energy and neutron resonances which are considered to in-
dicate the existence of energy levels in the compound nu-
clear ^{235}U and ^{238}U . The spacing of these levels is quite
irregular and only average values of the spacing can be de-
termined. The observed level spacing of the two compounds
is compared at various energies. Theoretical values relative to
certain omnidirectional levels are also described. The ^{235}U
is observed to have a level spacing which is larger than
the ^{238}U . The differences in spacing can be qualitatively
accounted for by postulated spin levels whose mag-
nitude is based on magnetic moment calculations of the
spin and isotopic composition.

The threshold for the $\text{Cr}^{53}(\text{p},\text{n})$ reaction is determined to be $1.406 \pm .008$ Mev and for the $\text{Cr}^{54}(\text{p},\text{n})$ $2.803 \pm .005$ 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 $52.95590 \pm .00044$ amu and $53.95574 \pm .00048$ amu respectively.

The first half of the 19th century is characterized by a general decline in the number of publications. This is due to the fact that the scientific community was still in its infancy and the number of researchers was small. The second half of the century, however, saw a rapid increase in the number of publications, which was due to the fact that the scientific community had become more established and the number of researchers had increased significantly.

The third half of the century is characterized by a general decline in the number of publications. This is due to the fact that the scientific community was still in its infancy and the number of researchers was small. The fourth half of the century, however, saw a rapid increase in the number of publications, which was due to the fact that the scientific community had become more established and the number of researchers had increased significantly.

The fifth half of the century is characterized by a general decline in the number of publications. This is due to the fact that the scientific community was still in its infancy and the number of researchers was small. The sixth half of the century, however, saw a rapid increase in the number of publications, which was due to the fact that the scientific community had become more established and the number of researchers had increased significantly.

The seventh half of the century is characterized by a general decline in the number of publications. This is due to the fact that the scientific community was still in its infancy and the number of researchers was small. The eighth half of the century, however, saw a rapid increase in the number of publications, which was due to the fact that the scientific community had become more established and the number of researchers had increased significantly.

The ninth half of the century is characterized by a general decline in the number of publications. This is due to the fact that the scientific community was still in its infancy and the number of researchers was small. The tenth half of the century, however, saw a rapid increase in the number of publications, which was due to the fact that the scientific community had become more established and the number of researchers had increased significantly.

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IDENTICAL MATRICES TO ELEM

equal

- EC IDENTICAL MATRICES TO ELEM
- ED $\int_{\partial R} \mathbf{r} \cdot d\mathbf{r}$ IN A RECTANGLE - A LINEAL
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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 Hockefeller 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

ANALYSIS

INTRODUCTION

The purpose of this report is to describe the results of the study conducted to determine the effect of the use of the ...

The study was conducted over a period of six months, from the beginning of the school year to the end of the school year. The participants in the study were ...

The data collected during the study were analyzed using statistical methods. The results of the analysis show that there is a significant difference in the ...

These findings are consistent with the previous research conducted in this area. The results suggest that the use of the ...

In conclusion, the study has shown that the use of the ... is effective in ... This suggests that the use of the ... should be encouraged in ...

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.

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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 (1, 2, 3, 4, 5).

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 $E = kv^2$ (6). By measuring the frequency of proton

IT HISTORY

The history of the system is as follows: The system was developed in 1960 by the Department of Defense for the purpose of providing a secure means of communication between the Department of Defense and the Department of State. The system was designed to be used for the transmission of sensitive information and to be resistant to interception and decryption.

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DESCRIPTION OF THE SYSTEM

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resonance of a known (p,n) threshold (for $Li(p,n) \rightarrow p$ = 1.882 \pm .002 (N5)) 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 \pm 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 \pm 25 ev. The finite widths of the defining slits introduce an energy spread in the beam which Preston and Stelson (21) have shown to be less than \pm 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 \pm 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 \pm 4.2 Kev. To allow for unmeasurable factors (e.g. operator judgment), a value of \pm 5 Kev is

The first part of the paper is devoted to a study of the
 properties of the function $f(x)$ defined by the
 equation $f(x) = x + f(x^2)$. It is shown that
 $f(x)$ is a continuous function of x and that
 it satisfies the functional equation $f(x) = x + f(x^2)$.
 The second part of the paper is devoted to a study of
 the properties of the function $g(x)$ defined by the
 equation $g(x) = x + g(x^2)$. It is shown that
 $g(x)$ is a continuous function of x and that
 it satisfies the functional equation $g(x) = x + g(x^2)$.

The third part of the paper is devoted to a study of
 the properties of the function $h(x)$ defined by the
 equation $h(x) = x + h(x^2)$. It is shown that
 $h(x)$ is a continuous function of x and that
 it satisfies the functional equation $h(x) = x + h(x^2)$.

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 (21). The pulses from the counter were fed through a Model 101 pre-amplifier and a Model 100 amplifier (21) 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.

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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 spectrographic analyses which accompanied the samples.

<u>Contaminant element</u>	<u>Enriched Cr^{53}</u>	<u>Enriched Cr^{54}</u>
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*
Ko	-	0.04*
Mn	-	0.04*

*Detected but less than limit of determination

Impurities other than those listed were not detected

Table III-1

III. SUMMARY

The following table shows the results of the tests conducted on the various specimens of the material under consideration. The specimens were prepared in accordance with the requirements of the specification and were tested in accordance with the method described in the specification. The results of the tests are given in the following table.

Specimen No.	Applied Load (lb)	Displacement (in)
100.0	100.0	1.0
-	200.0	2.0
-	300.0	3.0
400.0	400.0	4.0
500.0	500.0	5.0
600.0	600.0	6.0
-	700.0	7.0
800.0	800.0	8.0
900.0	-	9.0
1000.0	-	10.0
1100.0	-	11.0

The above table shows that the material under consideration is capable of withstanding a load of 1000 lb without failure. The material is also capable of withstanding a load of 1100 lb for a short period of time.

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.

<u>Isotope</u>	<u>Natural abundance (%)</u>	<u>Enriched in Cr⁵³</u>	<u>Enriched in Cr⁵⁴</u>
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 Cr₂O₃ 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 Cr⁵³ target (1.5 Kev thick) and two Cr⁵⁴ targets (1.5 and 2.5 Kev thick) (ref. Chapter IV) were used for the de-

How it has been used in various experiments to effect the
 present work.

Because the isotopes were obtained from one
 plant source, their use spectroscopically was limited and
 isotopes were provided by GMU and are shown in
 Table III-2.

Table III-2

Isotope	Amount in GMU	Amount in GMU	Amount in GMU
^{137}Cs	4.75	0.10	0.05
^{131}I	0.05	-	-
^{132}I	11.70	0.05	1.0
^{134}Cs	0.22	0.05	1.5
^{134}Cs	5.38	0.05	0.05

Table III-2

3. Preparation

The U^{235} was separated from a natural source by
 the use of chemical methods, specifically, the
 use of other elements, particularly cesium, which
 form a stable complex of cesium chloride with a very
 good recovery on the U^{235} stage. This process was limited
 only because the supply of natural uranium was limited.
 The U^{235} source (1.5 gm total) was the U^{235} source (1.5
 and 1.5 gm total) (see Chapter IV) were used for the ex-

tailed 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.

CHAPTER IV

EXPERIMENTAL RESULTS

1. General.

The neutron yields from the enriched isotopes Cr⁵³ and Cr⁵⁴ 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,

II. STATE

EXPERIMENTAL RESULTS

The experimental results are shown in Figure 1. The data were obtained from the analysis of the spectra of the ^{22}Na source. The results are compared with the theoretical curves calculated from the theory of the β -decay of ^{22}Na . The theoretical curves are shown in Figure 2. The results are in good agreement with the theoretical curves. The results are also compared with the results of other experiments. The results are in good agreement with the results of other experiments. The results are also compared with the results of other experiments. The results are in good agreement with the results of other experiments.

the better can the (p,n) resonances be resolved. Fowler et al (Fl) discuss effects and measurements of the components of observed resonance widths.

2. Yields.

The enriched Cr⁵⁴ 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 Cr⁵³ isotope (1.5 Kev target) produced about 9 times as much yield as did the Cr⁵⁴ in the region below 2.2 Mev and the resonances were better defined. The Cr⁵³ target was thinner than the first Cr⁵⁴ 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 Cr⁵⁴ 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 Cr⁵⁴ were present and better resolved

The better has the [p,n] resonance is visible. The
of the [p,n] resonance effects the measurement of the energy
range of observed resonances which

3. Results

The energy of the [p,n] resonance (1.1 MeV) was in-
vestigated first. In the energy region below 1.1 MeV, the
yield was quite small, although definite resonances were
observed. From the measured yield of the post-defined
peak, it appeared reasonable to vary the proton energy in
steps of about 0.1 MeV in frequency. Above 1.1 MeV
of proton energy the yield increased rapidly and the two-
mass peak became better defined. The yield was investigated
up to 2.0 MeV.

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vestigated first. In the energy region below 1.1 MeV, the
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of proton energy the yield increased rapidly and the two-
mass peak became better defined. The yield was investigated
up to 2.0 MeV.

A comparison of the two yield curves below 1.1 MeV
of proton energy shows that all resonances occur with ap-
proximately the same yield. The two-
mass peak is better defined

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 $\text{Cr}^{54}(\text{p},\text{n})$ 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 $\text{Cr}^{54}(\text{p},\text{n})$ is $2.203 \pm .005$ Mev.

The threshold of the $\text{Cr}^{53}(\text{p},\text{n})$ 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

In the case of the \mathbb{R}^n space, the metric tensor is the identity matrix δ_{ij} . The Christoffel symbols are zero, and the Riemann curvature tensor is zero. The geodesic equation is $\ddot{x}^i = 0$. The geodesics are straight lines. The distance between two points is the length of the straight line segment connecting them. The volume element is $dV = dx^1 dx^2 \dots dx^n$. The Laplacian is $\Delta = \nabla_i \nabla^i = \sum_{i=1}^n \frac{\partial^2}{\partial x^i \partial x^i}$. The divergence of a vector field V^i is $\nabla_i V^i = \sum_{i=1}^n \frac{\partial V^i}{\partial x^i}$. The curl of a vector field V^i is $\epsilon^{ijk} \nabla_j V_k$. The scalar product of two vectors V^i and W^i is $V^i W_i = \sum_{i=1}^n V^i W^i$. The vector product of two vectors V^i and W^i is $\epsilon^{ijk} V_j W_k$. The cross product of two vectors V^i and W^i is $\epsilon^{ijk} V_j W_k$. The dot product of two vectors V^i and W^i is $V^i W_i = \sum_{i=1}^n V^i W^i$. The cross product of two vectors V^i and W^i is $\epsilon^{ijk} V_j W_k$.

The metric tensor is g_{ij} . The Christoffel symbols are Γ^k_{ij} . The Riemann curvature tensor is R^l_{ijk} . The geodesic equation is $\ddot{x}^i + \Gamma^i_{jk} \dot{x}^j \dot{x}^k = 0$. The geodesics are curves that parallel transport their tangent vector. The distance between two points is the length of the geodesic curve connecting them. The volume element is $dV = \sqrt{|g|} dx^1 dx^2 \dots dx^n$. The Laplacian is $\Delta = \nabla_i \nabla^i = \frac{1}{\sqrt{|g|}} \partial_i (\sqrt{|g|} g^{ij} \partial_j)$. The divergence of a vector field V^i is $\nabla_i V^i = \frac{1}{\sqrt{|g|}} \partial_i (\sqrt{|g|} V^i)$. The curl of a vector field V^i is $\epsilon^{ijk} \nabla_j V_k$. The scalar product of two vectors V^i and W^i is $V^i W_i = g_{ij} V^i W^j$. The vector product of two vectors V^i and W^i is $\epsilon^{ijk} V_j W_k$.

Appendix B

The metric tensor is g_{ij} . The Christoffel symbols are Γ^k_{ij} . The Riemann curvature tensor is R^l_{ijk} . The geodesic equation is $\ddot{x}^i + \Gamma^i_{jk} \dot{x}^j \dot{x}^k = 0$. The geodesics are curves that parallel transport their tangent vector. The distance between two points is the length of the geodesic curve connecting them. The volume element is $dV = \sqrt{|g|} dx^1 dx^2 \dots dx^n$. The Laplacian is $\Delta = \nabla_i \nabla^i = \frac{1}{\sqrt{|g|}} \partial_i (\sqrt{|g|} g^{ij} \partial_j)$. The divergence of a vector field V^i is $\nabla_i V^i = \frac{1}{\sqrt{|g|}} \partial_i (\sqrt{|g|} V^i)$. The curl of a vector field V^i is $\epsilon^{ijk} \nabla_j V_k$. The scalar product of two vectors V^i and W^i is $V^i W_i = g_{ij} V^i W^j$. The vector product of two vectors V^i and W^i is $\epsilon^{ijk} V_j W_k$.

Figure IV-1

NEUTRON YIELDS FROM ENRICHED Cr⁵³ and Cr⁵⁴

The enriched Cr⁵⁴ curve shows a small neutron yield from the presence of Cr⁵³ (3.9%) below the Cr⁵⁴ (p,n) threshold ($2.202 \pm .005$ Mev.)

The first section of the report deals with the general situation of the country at the end of 1954. It mentions that the country is still recovering from the effects of the 1953 drought and that the agricultural production is still low. It also mentions that the government is taking measures to improve the situation and that the people are working hard to rebuild the country.

1-71 2004

The second section of the report deals with the specific measures taken by the government to improve the situation. It mentions that the government has organized relief work and that it has provided food and clothing to the people. It also mentions that the government is taking measures to improve the infrastructure and that it is working to develop the economy.

It is hoped that the government will continue to take measures to improve the situation and that the people will be able to rebuild the country. The report also mentions that the government has received help from the United Nations and that it is working to improve the country's relations with other countries.

The report concludes by stating that the situation in the country is still difficult but that the government is taking measures to improve it. It also mentions that the people are working hard to rebuild the country and that the government is providing help to them. The report ends with a statement of hope for the future.

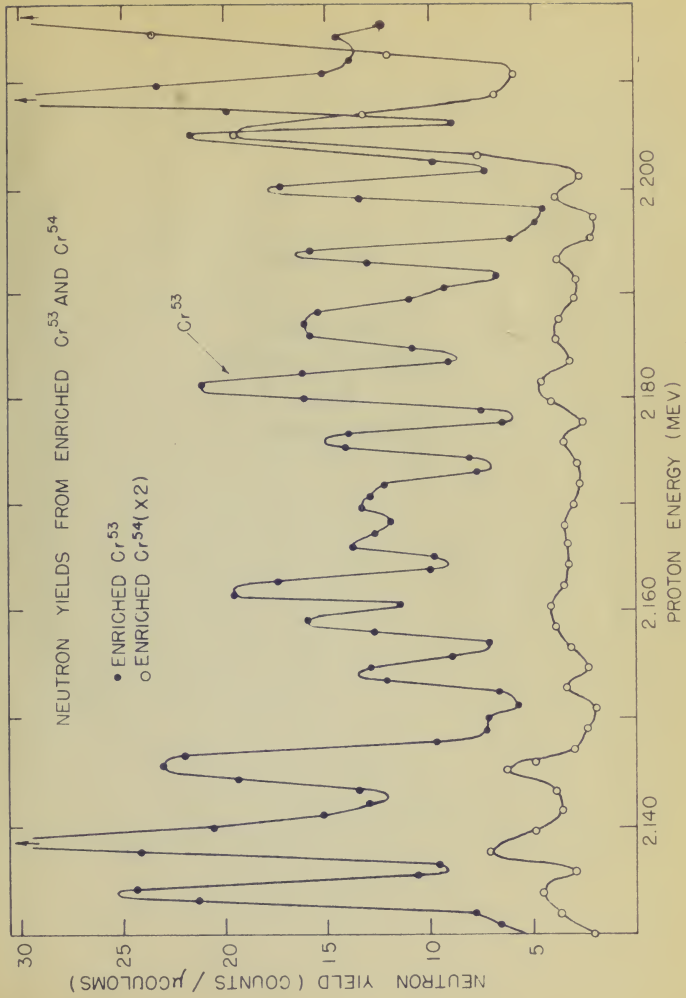


Figure IV-2

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

THRESHOLD MEASUREMENT

with

20 KEV TARGET

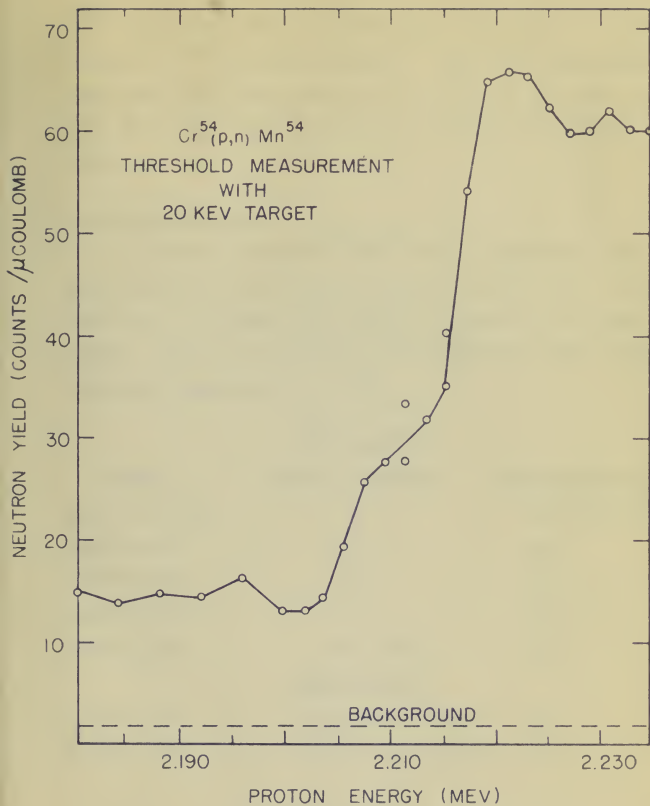
3-71 1951

$\int_{\partial D} \omega_1 \wedge \omega_2$

PROBLEMS

111

1951 111



Cr⁵³ target was not investigated below 1.419 Mev. A thicker target of Cr⁵³ was also prepared. Figure IV-3 shows the results and places the threshold for Cr⁵³(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.

<u>Cr⁵³(p,n)Mn⁵³</u>		
<u>Energy</u>	<u>Number of Levels</u>	<u>Average Spacing</u>
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
<u>Cr⁵⁴(p,n)Mn⁵⁴</u>		
2.202-2.470	59(1.5 Kev target)	5.1
2.202-2.470	38(2.5 Kev target)	7.0

Table IV-1

the latter error is reduced because of the power law
 which has been the standard for σ_{eff} of 1.000 \pm 0.005
 range of σ_{eff} was also reported. Figure 17-1 shows the re-
 sults of the investigation and the standard deviation is

Standard Deviation

As seen on the yield curve of the specimens, the
 distribution of the maximum points is not uniform. It is
 therefore to consider only those points of the energy
 levels. Specimens are averaged over different energy
 ranges are shown in Table 17-1.

<u>Average Energy</u>	<u>Number of Levels</u>	<u>Energy</u>
0.0 eV/level	50	1.000-1.000 eV
0.2	27	1.000-1.070
0.4	13	1.070-1.100
0.6	6	1.100-1.170
0.8	3	1.170-1.240
1.0	2	1.240-1.310
	<u>Total</u> 101	
		<u>Energy</u>
0.2	171.2 eV (range)	0.200-1.000 eV
0.4	181.2 eV (range)	0.400-1.000 eV

Figure IV-3



THRESHOLD MEASUREMENT

with

20 KEV TARGET

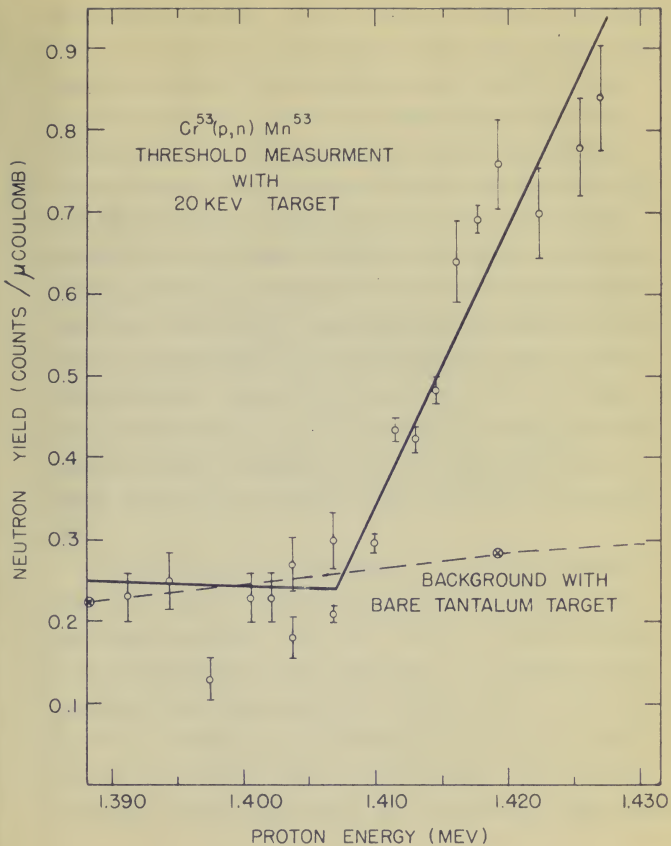
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Some of the levels are poorly defined and others apparently overlap so that they appear as one rather wide level. The averaging process tends to minimize these uncertainties.

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 (71). 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) $\approx W$ (2) $\approx W$ (3) $\approx D$. Inasmuch as D is observed to be 4-5 Kev and W is ± 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 especially
poorly so that they appear as one rather wide interval. The
averaging process tends to minimize these uncertainties.

The values of the levels at $\frac{1}{2}$ maximum are often
distorted by the overlapping of the levels. To properly
measure widths, isolated prominent peaks must be used. It

is assumed that the normal Maxwell distribution can be used
between the two energy balances, the widths of the two
lowest peaks can be considered a measure of energy balance.

The χ^2 test for this was determined to be
1.5 for the 10^4 and 2.5 for the 10^5 . The effect of the
of balance on observed level spacing is clearly shown

by the comparison of the χ^2 values for the two different
distributions between 10^4 and 10^5 . Comparison between the
peaks separated or nearly alike using the χ^2 test has

not.

It may be pointed out that if a statistical distribution
of levels is assumed with average spacing D , where
condition may exist (1) $D > D$ (2) $D = D$ (3) $D < D$ where

is the resolution of the instrument. The observed level
spacing for the three conditions will be (1) $\approx D$ (2) $\approx D$
(3) $\approx D$. Inasmuch as D is observed to be $4-5$ D and D

is ± 100 or (Section II-3), we may conclude that condition
(3) exists and that the actual level spacing may have decreased.

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 Cr⁵³ target
- (b) Enriched Cr⁵³ target
- (c) Enriched Cr⁵³ target
- (d) Enriched Cr⁵⁴ target. Proton energy below Cr⁵⁴(p,n) threshold and in same region as Figure IV-4(c).

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Figure 10-11

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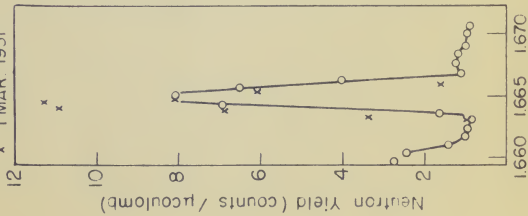
- (a)
- (b)
- (c)
- (d)

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REPRODUCTION OF DATA AFTER VARIOUS TIME INTERVALS

ENRICHED Cr⁵³

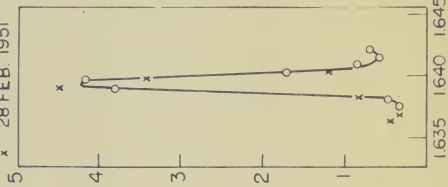
o 27 FEB. 1951
x 1 MAR. 1951



(a)

ENRICHED Cr⁵³

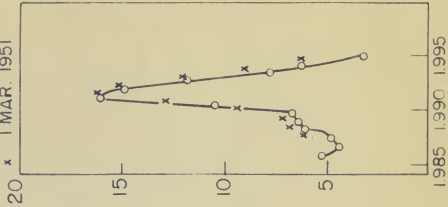
o 27 FEB. 1951
x 28 FEB. 1951



(b)

ENRICHED Cr⁵³

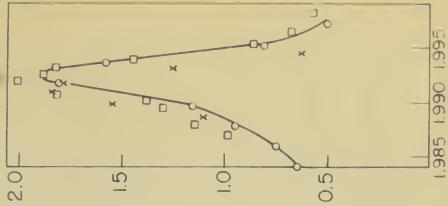
o 26 FEB. 1951
x 1 MAR. 1951



(c)

ENRICHED Cr⁵⁴

o 2 PM. 16 FEB. 1951
x 11 PM. 16 FEB. 1951
□ 1 PM. 17 FEB. 1951



(d)

Proton Energy (Mev)

Neutron Yield (counts / microcoulomb)

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, B4).

(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 E .

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, B2). However, Hurwitz and Bethe (B4) have pointed out that these

APPENDIX

EXPERIMENTAL INVESTIGATION

1. General

Current theories of the structure of atomic nuclei are in a transitional state of development and modification. However, the generally accepted viewpoint is that the nucleus consists of protons and neutrons. This is known as the liquid drop model.

(a) That in a nucleus the protons and neutrons are bound together in a liquid drop which is independent of the size of the nucleus (1, 2, 3).

(b) That the energy levels are distributed in a continuous manner (approximately) in average spacing with increasing excitation energy (4).

(c) That the energy level spacing also decreases (5) with increasing A .

Further research, including experiments on reaction rates and energy levels, has been conducted extensively since the first experimental data were obtained (6).

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 protons and neutrons is odd or even (7, 8). However, levels and spacings (9) have pointed out that there

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

The following are the results of the measurements in the various
 the level spacing at excitation energies which are shown in
 the ground state. They were suggested because they are
 excluded energy be compared from a characteristic level
 which depends in a regular way on the number of protons and
 neutrons in the nucleus, and that each level might be the
 number of levels which are expected from the semi-empirical
 model formula without the odd-even term. Further and other
 further indicate that the level spacing assumed in eq. (1)
 applies relative to these levels would be expected to be
 the same regardless of the odd-even character of the number
 of neutrons.

Figure 1-1 is an energy level diagram showing levels
 characteristic levels (a and b) for the compound nuclei
 ^{208}Po and ^{208}Pb . The positions of the levels are roughly
 indicated in this diagram over the entire range
 from levels above a separation of the level spacing
 would be expected to yield a ratio of unity. In this case
 ratio 1.1-1.2 the ratio obtained is 1.1 for the 1.1 MeV and
 the data in the vicinity of a and b, and the ratio is
 slightly lower than unity. The agreement of order of the
 observed spacing energies with the theoretical values is shown in Table
 1-1. The theoretical values are calculated from the formula
 the level spacing which is shown in eq. (1). The
 theoretical values are shown in Table 1-1.

Figure V-1

ENERGY LEVEL DIAGRAM OF Cr⁵³, Cr⁵⁴, Mn⁵⁴ and Mn⁵⁵

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.

The following are the results of the analysis of the samples taken from the various points of the river during the period of the study. The results are given in the following tables.

TABLE I

ANALYSIS OF THE SAMPLES TAKEN FROM THE RIVER AT THE POINTS INDICATED ON THE MAP.

1. The following table shows the results of the analysis of the samples taken from the river at the points indicated on the map.

2. The following table shows the results of the analysis of the samples taken from the river at the points indicated on the map.

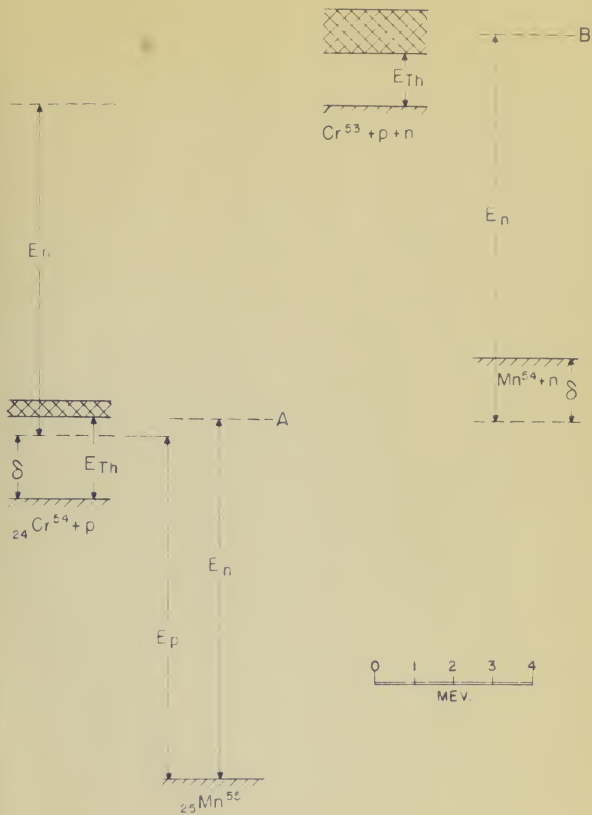
3. The following table shows the results of the analysis of the samples taken from the river at the points indicated on the map.

4. The following table shows the results of the analysis of the samples taken from the river at the points indicated on the map.

5. The following table shows the results of the analysis of the samples taken from the river at the points indicated on the map.

The following table shows the results of the analysis of the samples taken from the river at the points indicated on the map.

The following table shows the results of the analysis of the samples taken from the river at the points indicated on the map.



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

	<u>calculated</u>	<u>observed</u>
$E_n + \delta$ 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

Freston (P2) 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 moments of the bombarding particle, target nucleus and emitted particle. For bombarding protons with $l = 0, 1$ and 2 and for an even Z-even N target isotopes (Cr⁵⁴, I=0) the multiplet multiplicity may be as great as 5; for an even Z-odd N target (Cr⁵³, $I \geq 1/2$) 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 vary greatly, some being

Observed	Calculated	
10.13 (10)	10.07	$\delta = 0.06$
9.1 (9)	10.3	$\delta = 1.2$

Table V-1

The observed (9) has been calculated and is compared with the
 energy level spacing and the existence of multiplet levels known
 to be considered. The multiplets are explained by the dif-
 ferent values which arise from the various combinations of
 the different values of the orbital angular momentum, the
 intrinsic angular momentum of the nucleons, and the spin of
 the nucleons and the nucleus. The calculated results are
 $l = 0, 1$ and 2 and for an even number of nucleons
 (9), $l = 0$ and multiplets exist. For an even number of
 nucleons, $l = 1$ and 2 exist. For an even number of nucleons,
 the ratio of level spacing is $1:2:3$.
 At the present time it is difficult to explain the
 existence of the multiplets for these values of l .
 It appears to be possible for these multiplets to be
 explained in some manner that each multiplet group is in-
 dependent from the others. This multiplet description
 would account for the observed ratio of level spacing
 being 1:2:3. It is difficult to be sure that
 the observed level spacing is in fact 1:2:3. It is
 difficult to be sure that the observed level spacing is
 multiplet and can be explained in any manner, but below

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.

<u>Reaction</u>	<u>E_{th} (computed)</u>	<u>E_{th} (measured)</u>
$Cr^{53}(p,n)$	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 mass low intensity that may be lost in the beam-

spread. $\rho = 1.2 \times 10^{-12}$ g/cm³ $\lambda = 0.01$ cm

$\rho = 1.2 \times 10^{-12}$ g/cm³ $\lambda = 0.01$ cm

because of the same energy distribution in a medium

reaction, the semi-empirical mass formula (17) may be used

to calculate the energy value of a reaction. The above

value is then verified by calculation from the energy

value of the reaction of the compound nucleus with a neutron

and will be compared in this case, and verified a check

on the accuracy of the mass formula.

Table 1 shows the results of the calculations.

Reaction	Q (MeV)	Q (MeV)
$^{235}\text{U} + n \rightarrow ^{236}\text{U}^*$	7.6	7.6
$^{235}\text{U} + n \rightarrow ^{236}\text{U} + \gamma$	7.6	7.6

Table 1 -

The above reaction shows that $^{236}\text{U}^*$ is a very

excited nucleus and will undergo fission.

The $^{236}\text{U}^*$ will have a very short lifetime, and will

decay into two fission products and a neutron.

where Q is the energy of the reaction in MeV.

where Q is the energy of the reaction in MeV.

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where Q is the energy of the reaction in MeV.

where Q is the energy of the reaction in MeV.

where Q is the energy of the reaction in MeV.

where Q is the energy of the reaction in MeV.

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

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

Ogata (61) has reported the masses of the two chromium isotopes used in this work:

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

Using

$$\begin{aligned} M_T &= 1.00813 \pm .00003 \\ M_N &= 1.00866 \pm .00001 \\ Q(53) &= -1.380 \pm .008 \text{ Mev} = -.00148 \pm .00001 \text{ amu} \\ Q(54) &= -2.165 \pm .005 \text{ Mev} = -.00232 \pm .00001 \text{ amu} \end{aligned}$$

it is determined that

$$\begin{aligned} \text{Cr}^{53} &= 52.95590 \pm .00044 \text{ amu} \\ \text{Cr}^{54} &= 53.95574 \pm .00048 \text{ amu}. \end{aligned}$$

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1	1950	100	100	100
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55	2004	100	100	100
56	2005	100	100	100
57	2006	100	100	100
58	2007	100	100	100
59	2008	100	100	100
60	2009	100	100	100
61	2010	100	100	100
62	2011	100	100	100
63	2012	100	100	100
64	2013	100	100	100
65	2014	100	100	100
66	2015	100	100	100
67	2016	100	100	100
68	2017	100	100	100
69	2018	100	100	100
70	2019	100	100	100
71	2020	100	100	100
72	2021	100	100	100
73	2022	100	100	100
74	2023	100	100	100
75	2024	100	100	100
76	2025	100	100	100
77	2026	100	100	100
78	2027	100	100	100
79	2028	100	100	100
80	2029	100	100	100
81	2030	100	100	100
82	2031	100	100	100
83	2032	100	100	100
84	2033	100	100	100
85	2034	100	100	100
86	2035	100	100	100
87	2036	100	100	100
88	2037	100	100	100
89	2038	100	100	100
90	2039	100	100	100
91	2040	100	100	100
92	2041	100	100	100
93	2042	100	100	100
94	2043	100	100	100
95	2044	100	100	100
96	2045	100	100	100
97	2046	100	100	100
98	2047	100	100	100
99	2048	100	100	100
100	2049	100	100	100

ACKNOWLEDGMENTS

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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.C. McCue who gave so freely of his time and advice with the experimental work, to Dr. W.M. Preston for his help, especially with the related theory, and to the Rockefeller Generator crew for their aid in the conduct of the experiment.

MEMORANDUM

The general study of the subject was reported by
 the T. W. Havel Laboratory to include the Bureau of In-
 vestigation, Department of the Army. The work reported herein
 was conducted in accordance with the program outlined
 in the report of the Laboratory for the study of the subject
 and is a part of the project as reported by the Bureau of
 Investigation and the Office of Naval Research.

The work was done in accordance with the program
 outlined in the report of the Laboratory, and the
 results of the study are reported in this report. The
 work was done in accordance with the program outlined
 in the report of the Laboratory for the study of the
 subject and is a part of the project as reported by
 the Bureau of Investigation and the Office of Naval
 Research.

Appendix A

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

- (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}

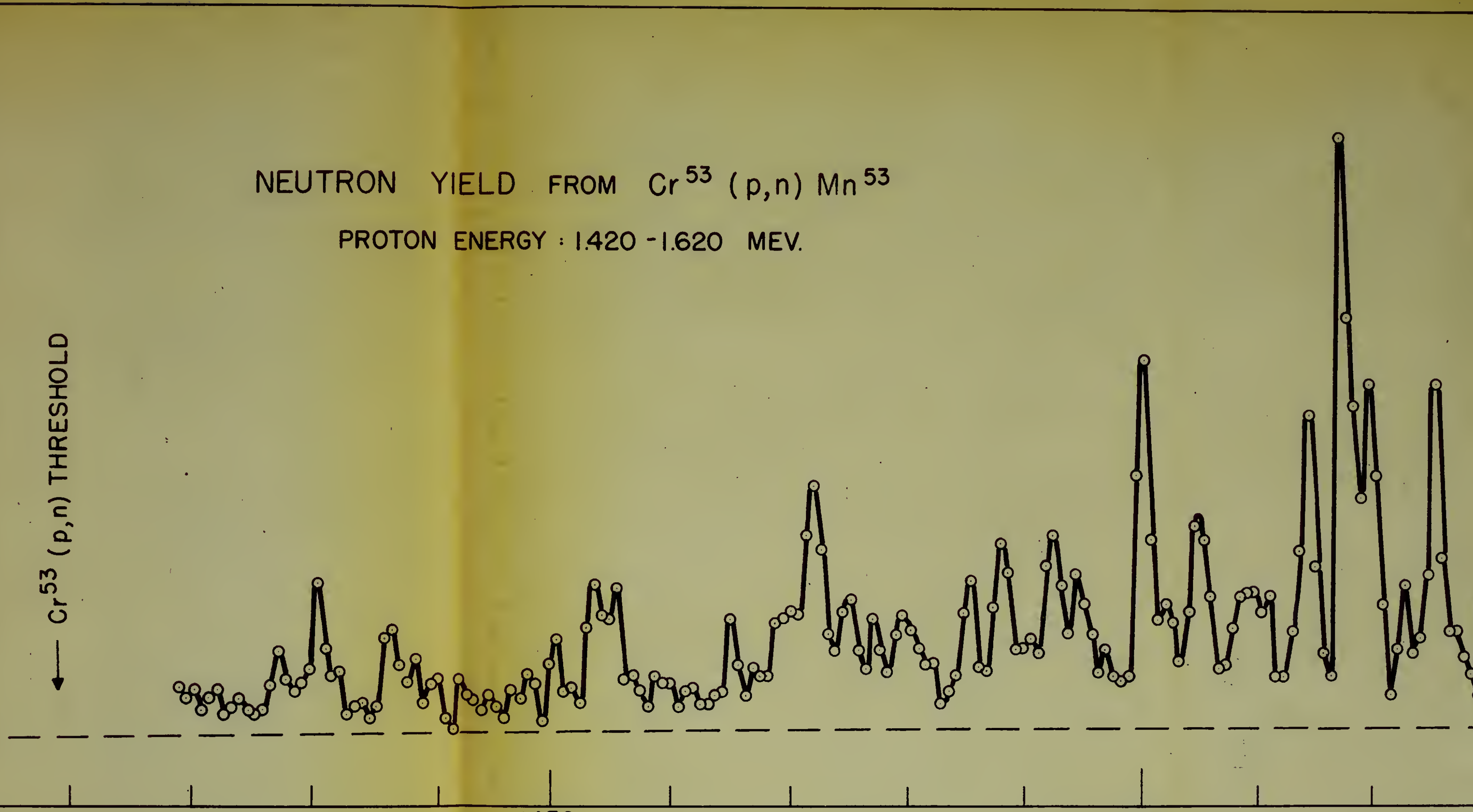
PROTON ENERGY : 1.420 - 1.620 MEV.

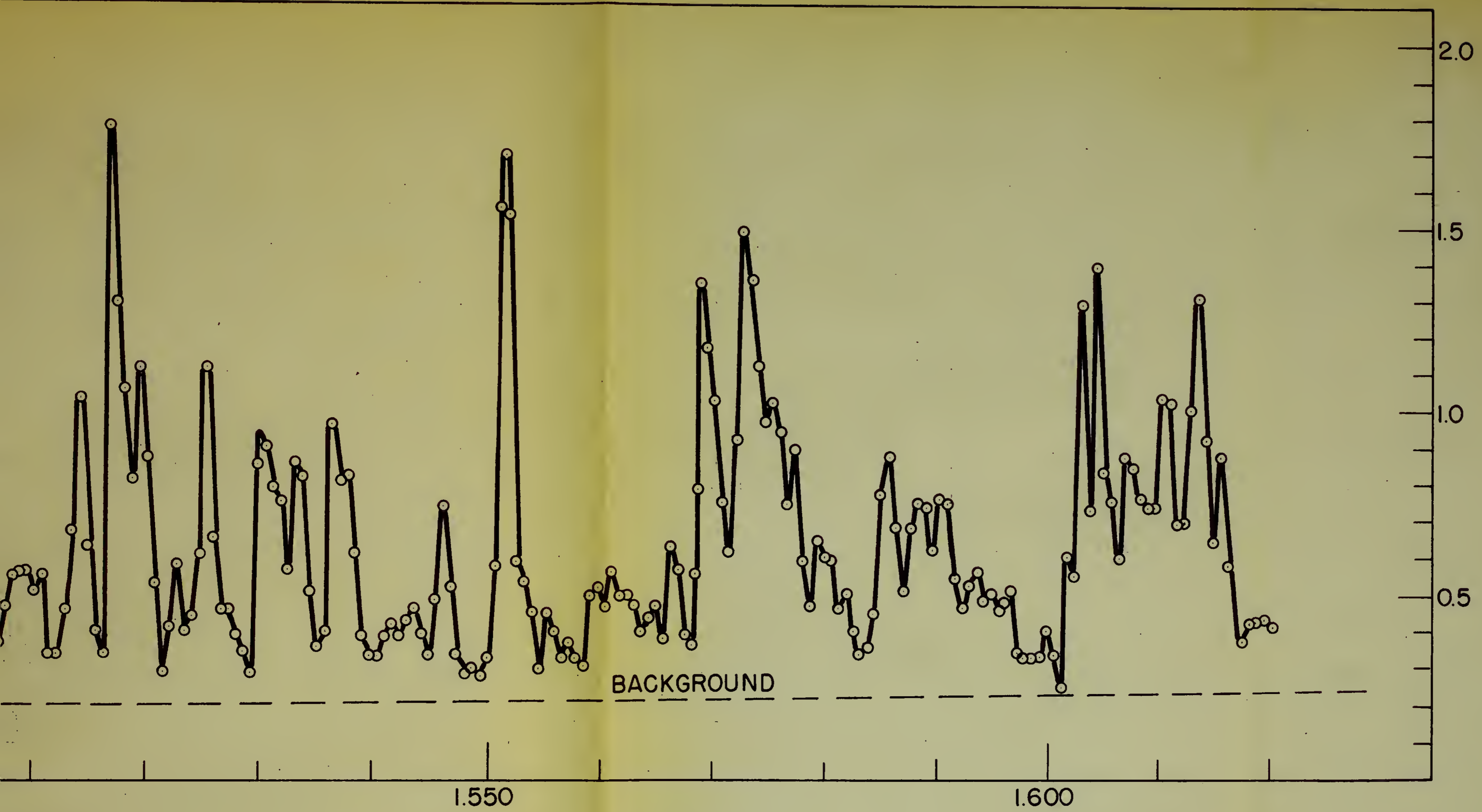
NEUTRON YIELD - COUNTS / μ COULOMB

— Cr^{53} (p,n) THRESHOLD

2.0
1.5
1.0
0.5
1.400 1.450 1.500

PROTON ENERGY - MEV.





- MEV.

BACKGROUND

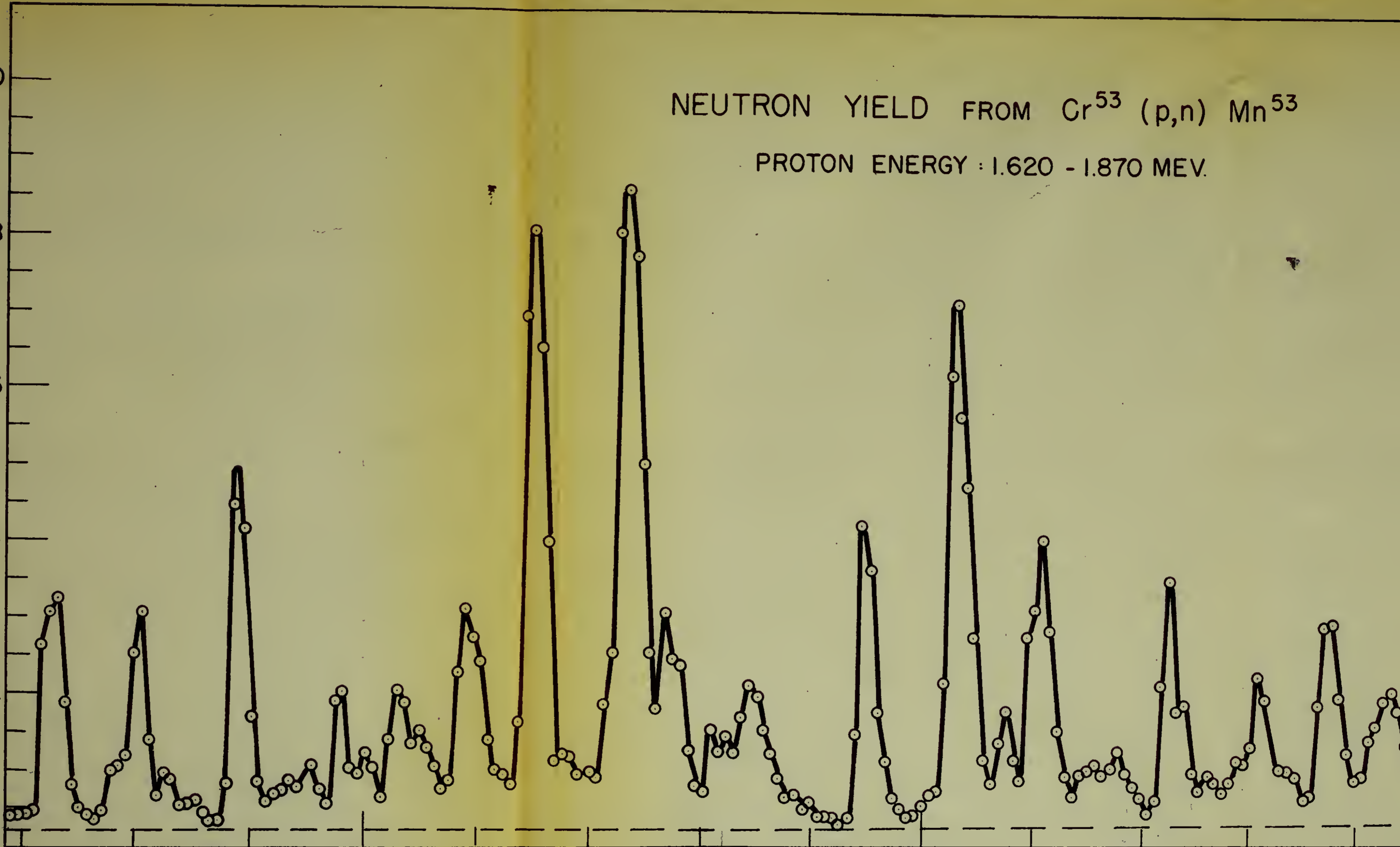
NEUTRON YIELD FROM Cr^{53} (p,n) Mn^{53}

PROTON ENERGY : 1.620 - 1.870 MEV.

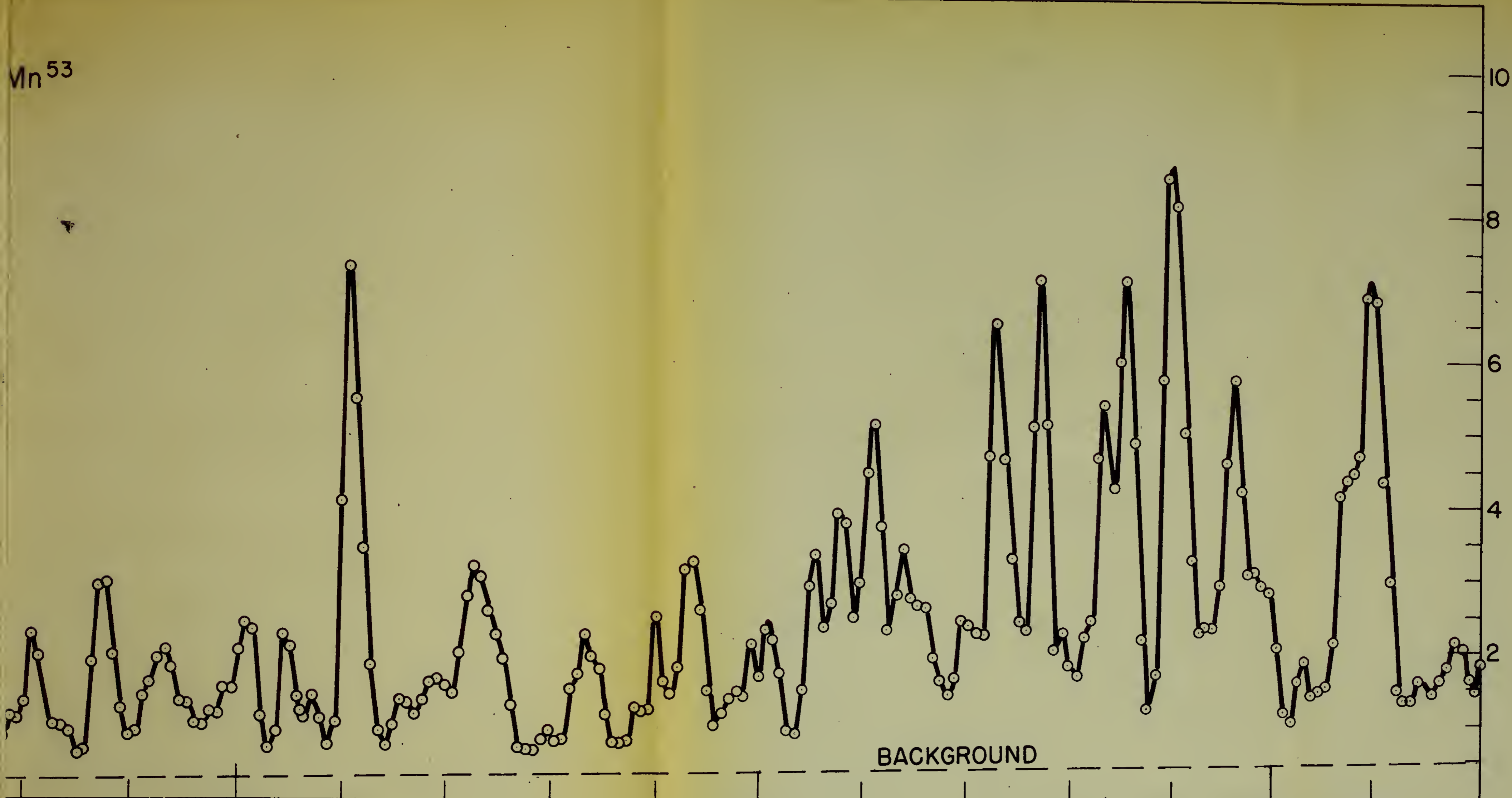
NEUTRON YIELD - COUNTS / μ COULOMB

10
8
6
4
2
1.620 1.650 1.700

PROTON ENERGY - MEV.



Mn⁵³



ENERGY - MEV.

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

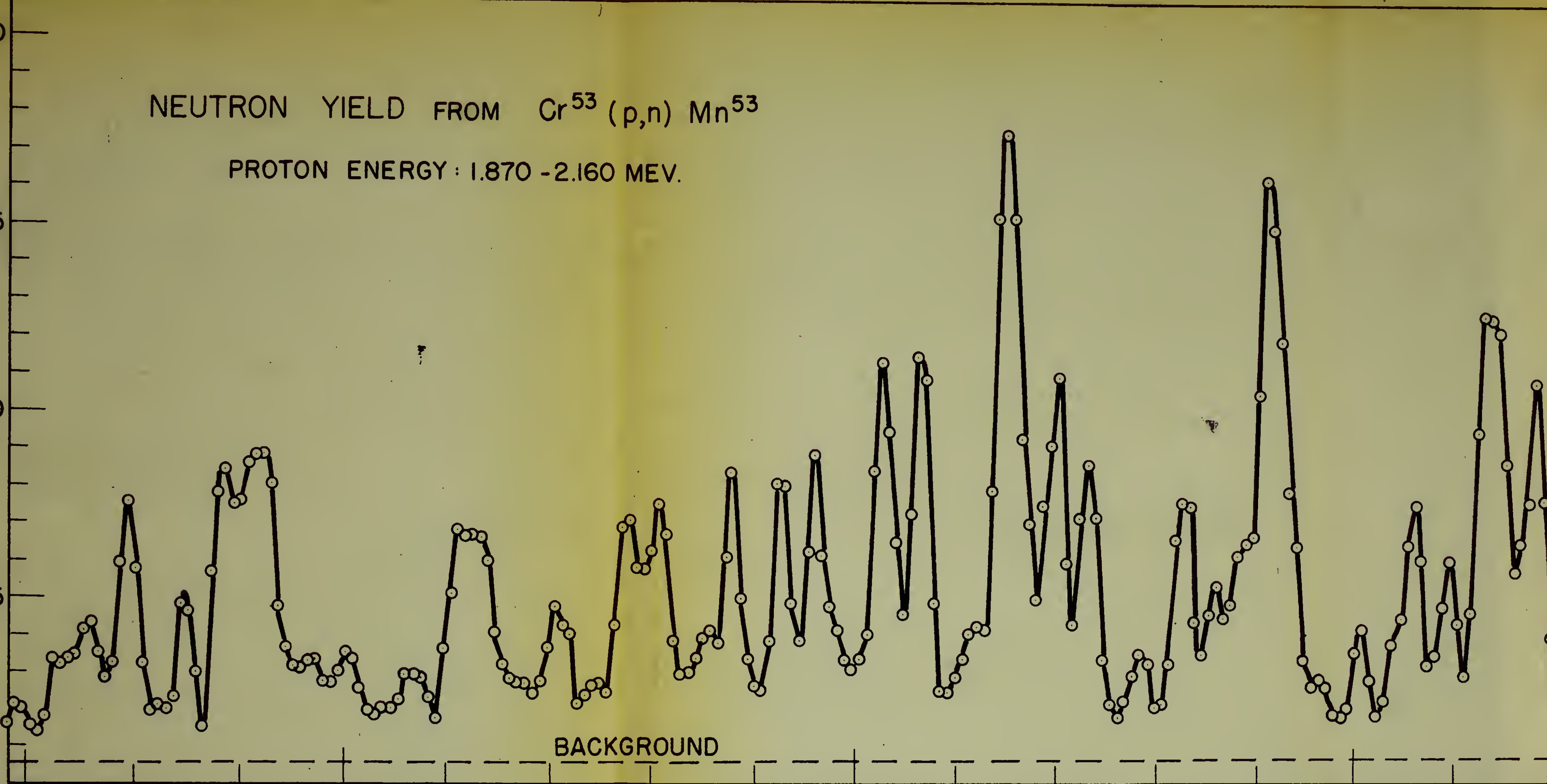
PROTON ENERGY: 1.870 - 2.160 MEV.

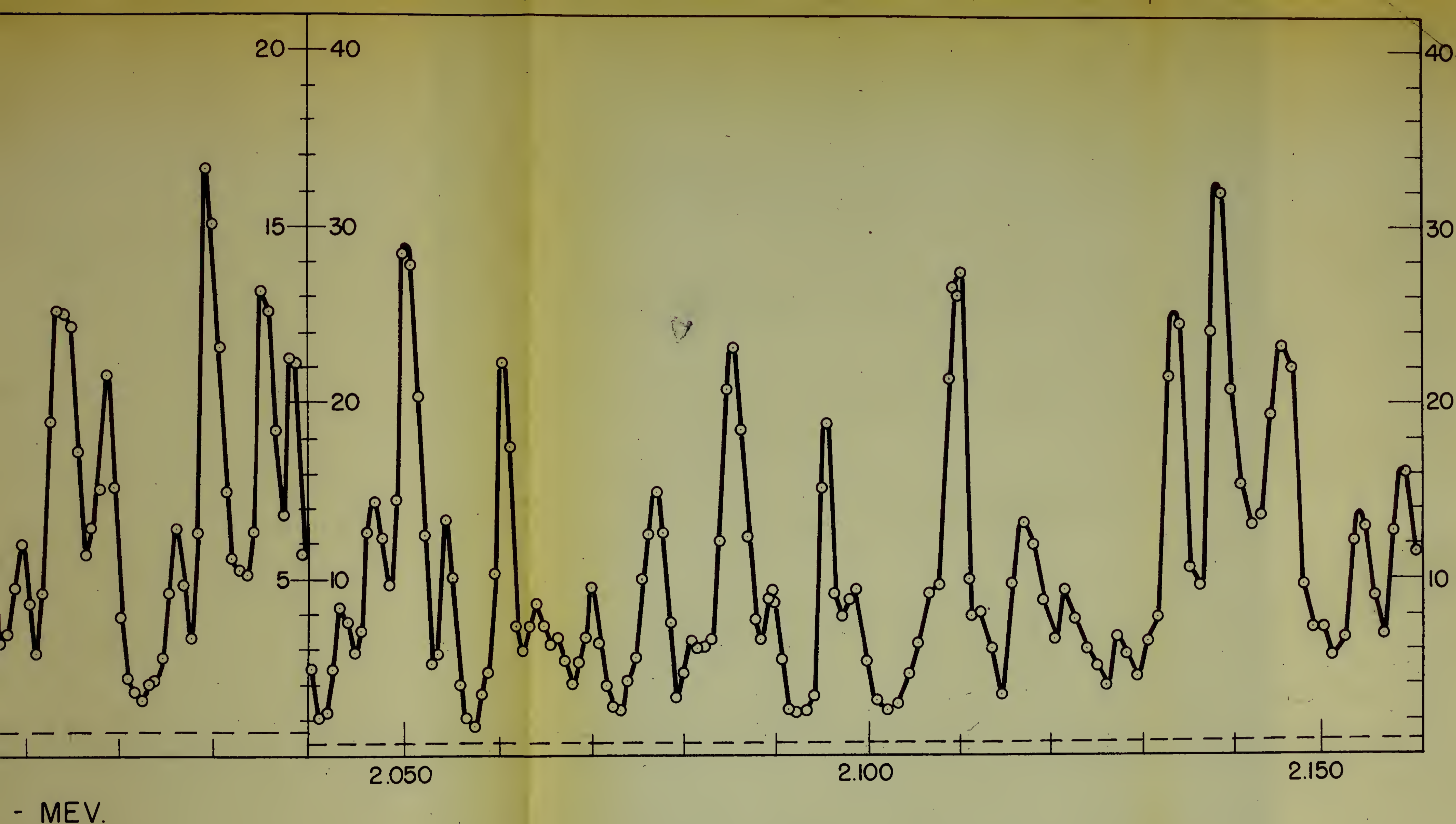
NEUTRON YIELD - COUNTS / μ COULOMB

20
15
10
5

BACKGROUND

1.870 1.900 1.950 2.000
PROTON ENERGY - MEV.





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

PROTON ENERGY: 2.160 - 2.470 MEV.

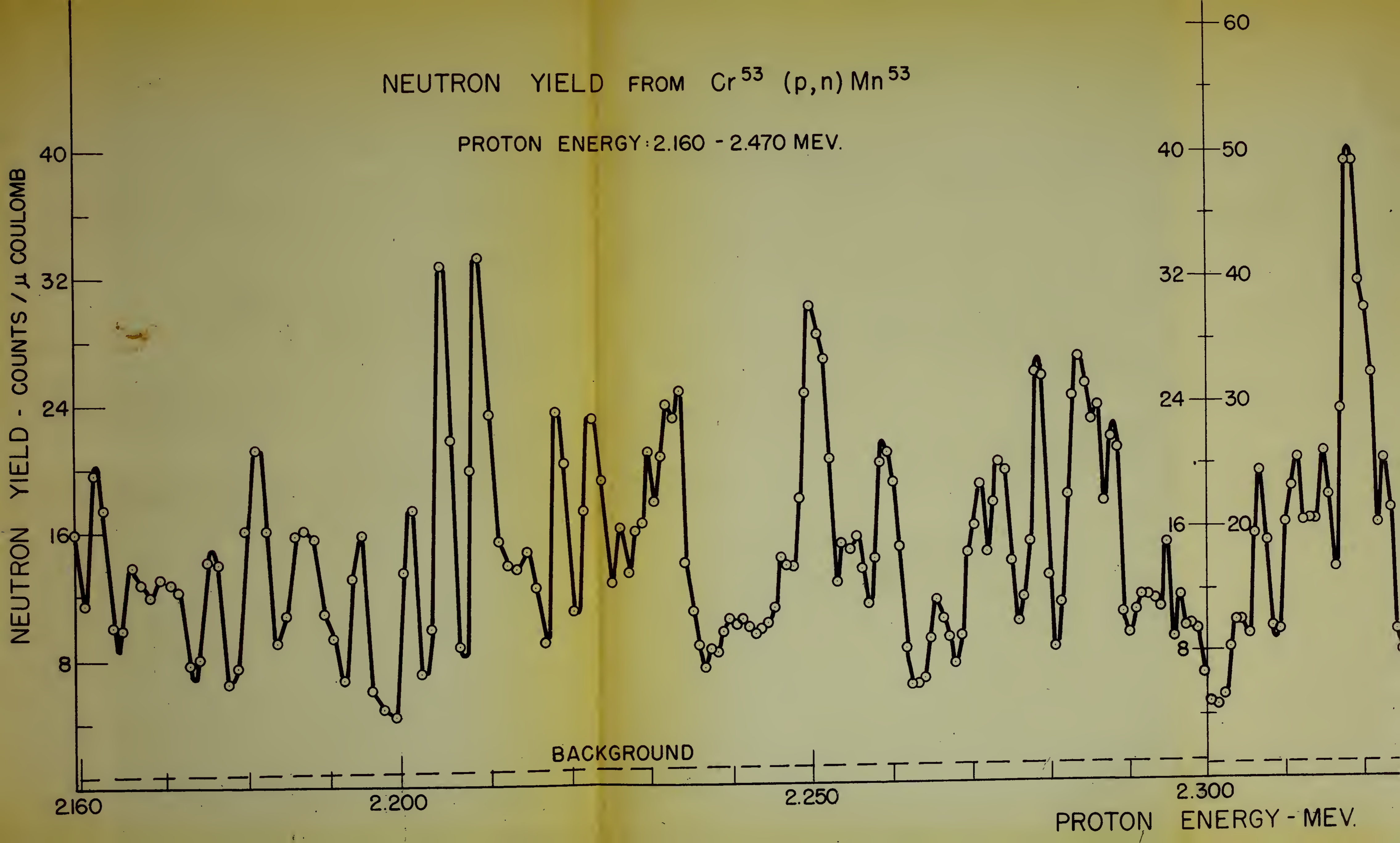
NEUTRON YIELD - COUNTS / μ COULOMB

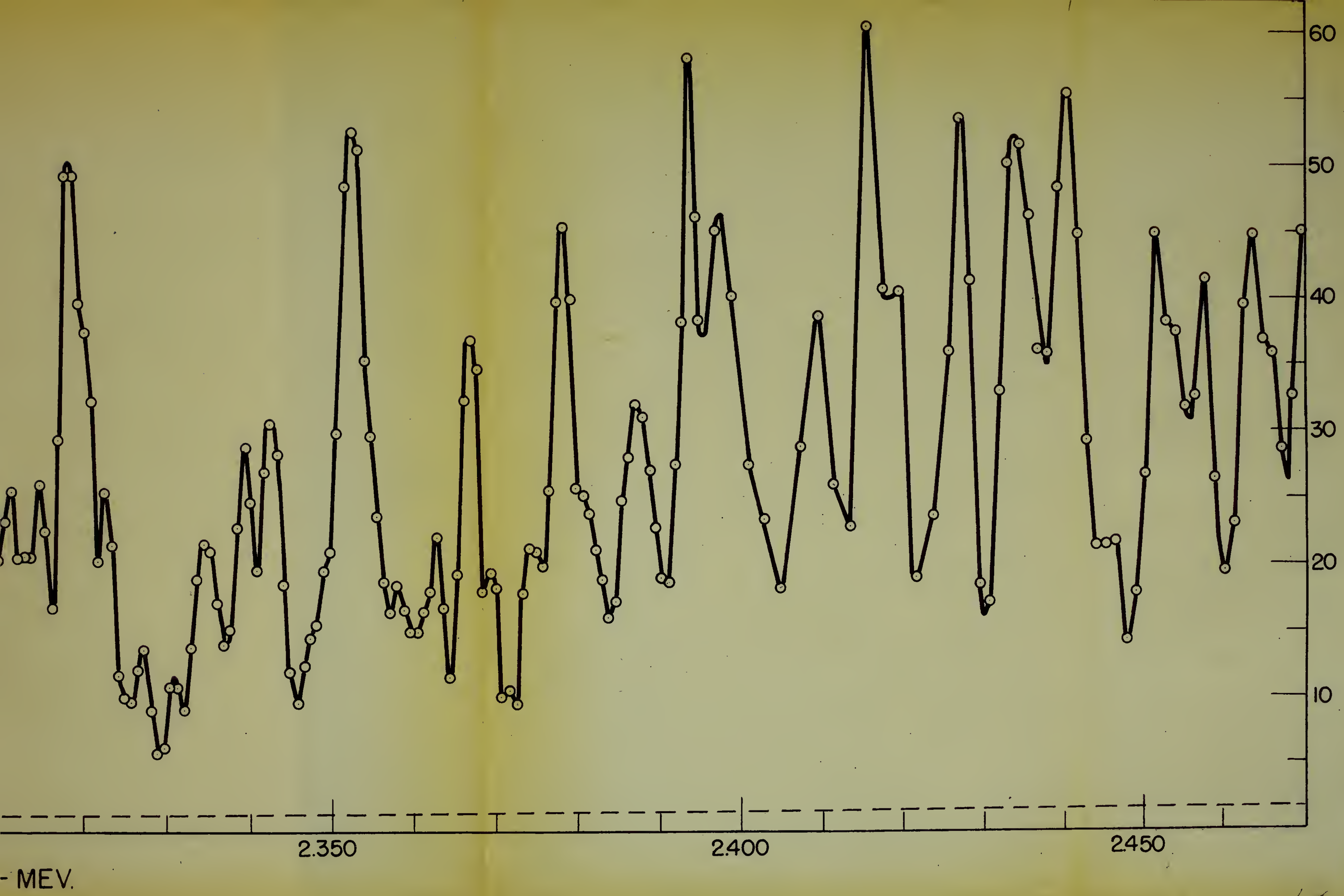
40
32
24
16
8

60
50
40
30
20
10

BACKGROUND

2160 2.200 2.250 2.300 PROTON ENERGY - MEV.





Appendix B

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

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

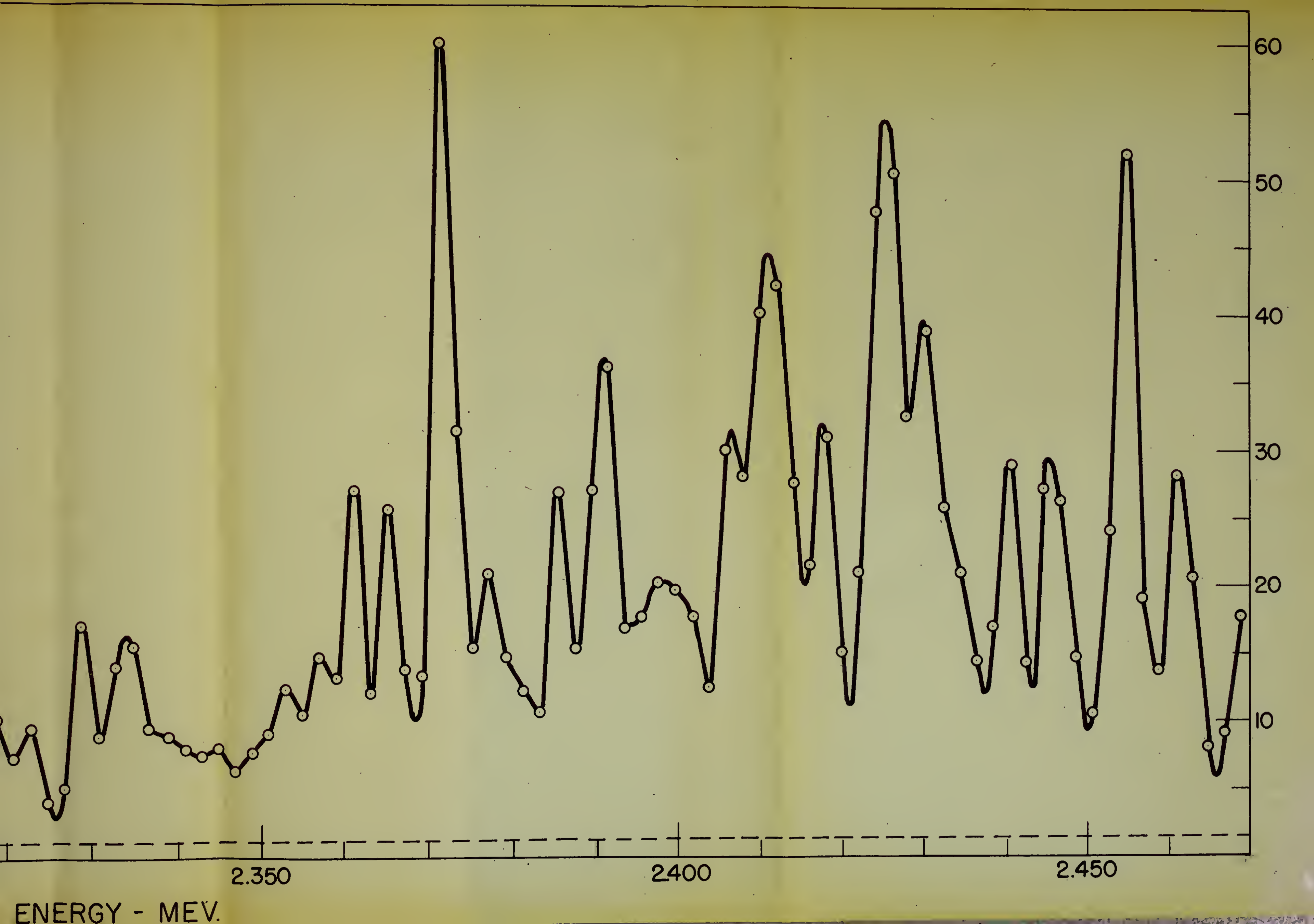
PROTON ENERGY: 2.190 - 2.470 MEV

NEUTRON YIELD - COUNTS / μ COULOMB



BACKGROUND

PROTON ENERGY - MEV.

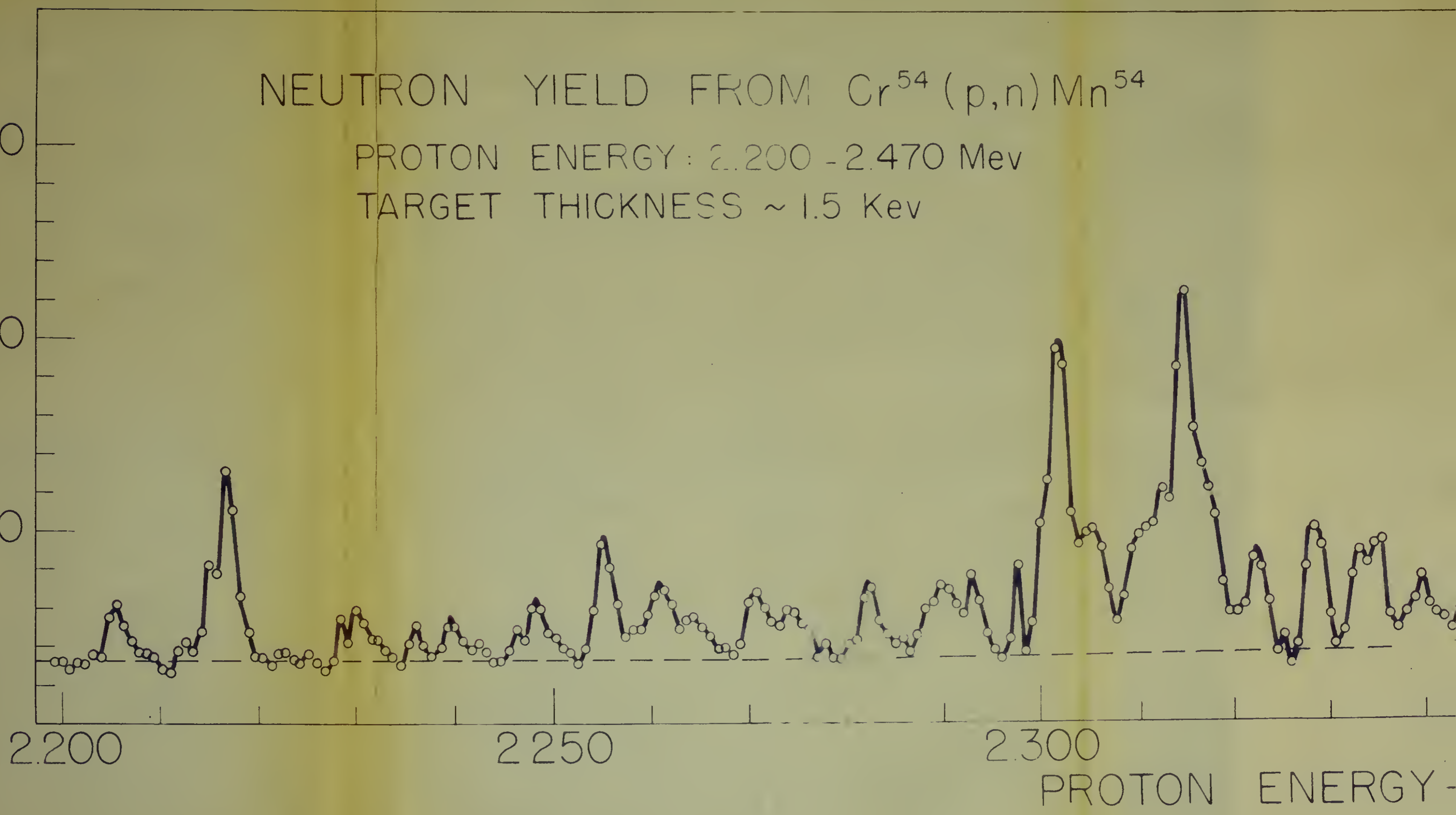


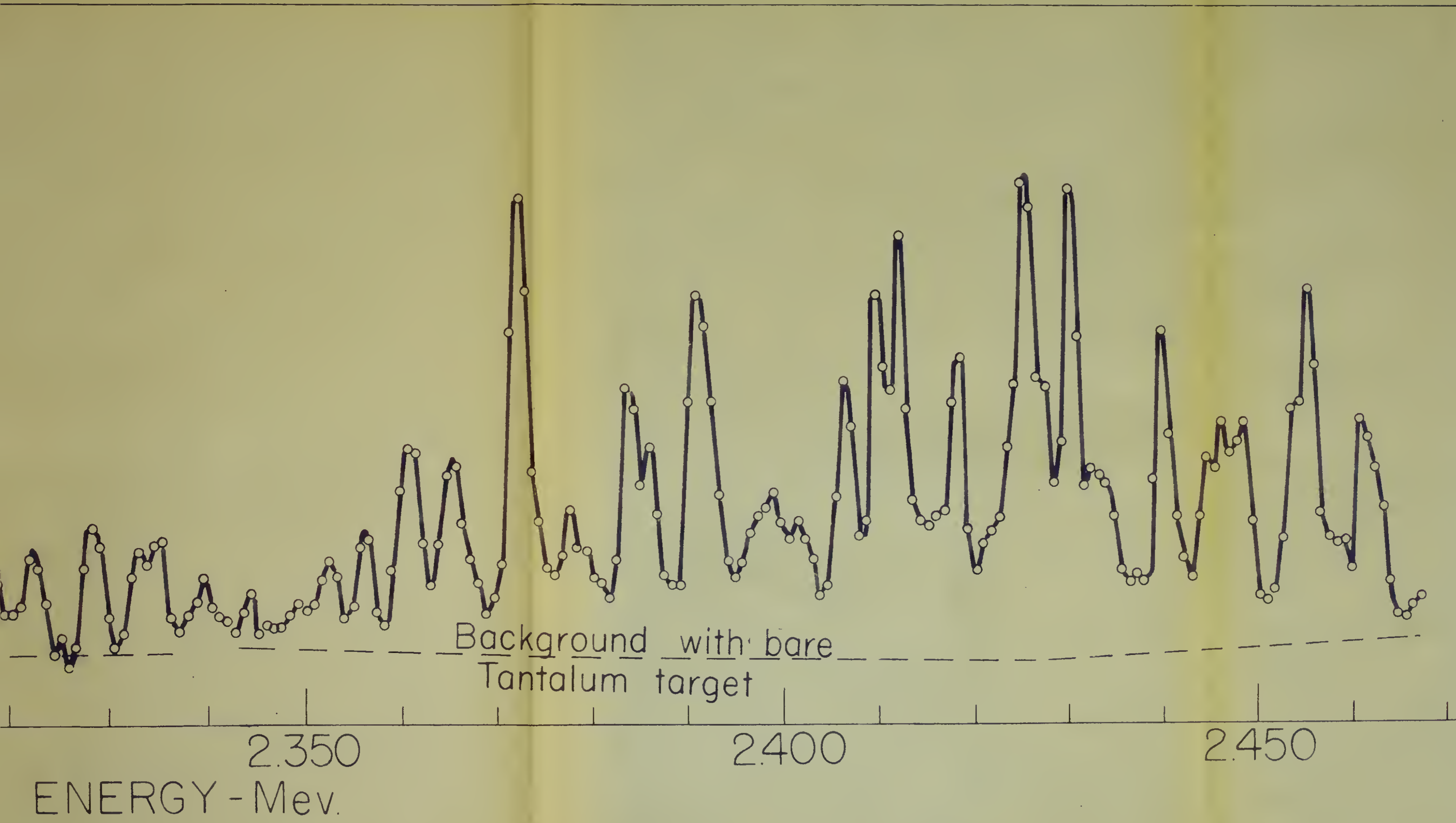
NEUTRON YIELD FROM $\text{Cr}^{54} (p,n) \text{Mn}^{54}$

PROTON ENERGY: 2.200 - 2.470 Mev

TARGET THICKNESS ~ 1.5 Kev

NEUTRON YIELD - counts/ μ coulomb









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Thesis

L853

Lovington

15640

Energy levels in medium weight
nuclei from the (p,n) reaction.

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Energy levels in medium weight nuclei fr



3 2768 002 12683 1

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