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# Energy Levels in the Nucleus $\mathrm{Mn}^{56}$*

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The energy distribution of the protons emitted in the reaction $\mathrm{Mn}^{55}(d,p)\mathrm{Mn}^{56}$ has been studied by an absorption method. For excitations up to 4.38 Mev above the ground state of the $\mathrm{Mn}^{56}$ nucleus, the protons are found to fall into six distinct energy groups, corresponding to excited states at 1.07, 1.77, 2.48, 3.61, and 4.38 Mev above ground. Results are also presented which indicate that the yields of the individual proton groups vary slowly with deuteron energy, showing no sharp resonance effects. From the $Q$-value for the most energetic proton group the mass of the nucleus $\mathrm{Mn}^{55}$ has been computed to be $54.9634 \pm .0022$ mass units.

## INTRODUCTION

A NUMBER of investigators[1] have observed the energy levels in nuclei of low mass number, at excitations up to about 5 Mev, which are exhibited in the process of $(d,p)$, $(d,n)$, $(\alpha,p)$ and other particle emission reactions. The results do not appear to be in agreement with generally accepted theories,[2] which predict a greater density of levels than is observed and, also, that the level density should increase rapidly with excitation and with atomic weight. This experimental method has been applied mainly to the study of elements of low atomic weight, and the energy level spacing observed in these cases is on the average about 1 Mev or somewhat greater; moreover, no uniform trend of level spacing, either with excitation in a particular nucleus or, at a given excitation, with atomic weight, is apparent. It is of interest to extend studies of this type to elements of higher atomic weights to determine if better agreement with theory can be obtained for particle emission reactions of this type, particularly with regard to the theoretical prediction of smaller level spacings in heavier nuclei.

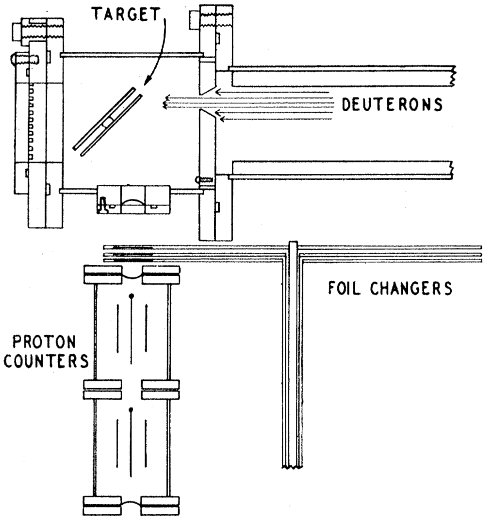

FIG. 1. Sketch of the bombardment chamber, mechanical foil changers and proton counters used in measuring the range of protons emitted in a direction perpendicular to the direction of the deuteron beam. The target is manganese metal ($\mathrm{Mn}^{55}$) evaporated on gold foil.

In the present work, the energy levels in the nucleus $\mathrm{Mn}^{56}$ have been determined by measuring the energies of the protons that are emitted when the element $\mathrm{Mn}^{55}$ is bombarded with deuterons. These nuclei contain a sufficient number of particles to make the statistical approach of theory at least reasonably valid. The assignment of levels to $\mathrm{Mn}^{56}$ is unique since manganese contains only a single isotope.

In addition to the main problem of measuring proton energies, a study has been made of the yields of the individual proton groups as a function of deuteron energy.

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[1] For example, J. D. Cockcroft and W. B. Lewis, Proc. Roy. Soc. **154**, 246 (1936); W. L. Davidson, Jr., Phys. Rev. **56**, 1062 (1939); E. B. M. Murrell and L. C. Smith, Proc. Roy. Soc. **173**, 410 (1939); Ernest Pollard and W. W. Watson, Phys. Rev. **58**, 12 (1940); T. W. Bonner, Proc. Roy. Soc. **174**, 339 (1940); M. G. Holloway and B. L. Moore, Phys. Rev. **58**, 847 (1940).

[2] H. A. Bethe and R. F. Bacher, Rev. Mod. Phys. **8**, 173 (1936); H. A. Bethe, *ibid.* **9**, 86 (1937); John Bardeen, Phys. Rev. **51**, (1937).

## EXPERIMENTAL ARRANGEMENT

The experimental arrangement used to measure proton range is shown in Fig. 1. The target is mounted in the outer bombardment chamber of the cyclotron and is inclined at an angle of 45° to both the incident beam of deuterons and to the direction of the protons that are to be counted. The geometry of the system is such that only protons emitted at angles of $90\pm4°$ to the direction of the deuteron beam will be detected.

The target material was 99.986 percent pure manganese obtained from Electro Manganese Corporation, Knoxville, Tennessee. Principal impurities were 0.012 percent sulfur as sulfide, 0.001 percent sulfur as sulfate, and less than 0.001 percent iron. Thin targets of uniform thickness were prepared by evaporating the manganese metal on gold foils. The target used to obtain most of the data to be presented here had a thickness of 1.0 cm air equivalent. A second target, having a thickness of 0.2 cm air equivalent also was used to obtain data on the high intensity groups and to study the effect of target thickness on the resolution of the method.

Various thicknesses of aluminum foils are held in position between the target and the proton counters by the mechanical foil changers, shown in Fig. 1, which are operated remotely from the cyclotron control room. Also, a considerable portion of the data was obtained using a gas absorption cell in place of the foil changers. This cell was designed so that one of its end plates could be bolted directly to the exit port of the bombardment chamber and the other end plate could be fastened directly to the face of the first counter, thus eliminating all air spaces in the path of the protons and providing a continuous control over the total absorption. A pressure line made up of one-half inch copper tubing was run from the cyclotron to the control room so that the pressure of air in the cell could be adjusted from the operator's position.

Two proton counters, operating into a coincidence circuit, are used in order to reduce the background count due to the high flux of neutrons in the vicinity of the cyclotron. The counters are operated in the proportional region, and the counting level of the second one is normally set to a comparatively high level in order to peak up the proton groups. The gas used in the counters was tank argon; counter pressures of 10, 20, 40, and 65 cm Hg were employed in the course of this work, the counting level being changed in each case to achieve the highest possible resolution.

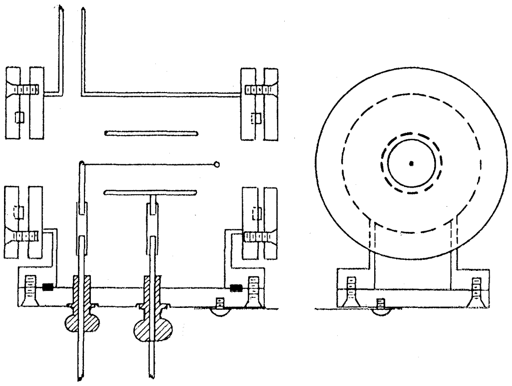

FIG. 2. Detailed drawing of the proton counter. The preamplifier unit is attached directly to the base plate of the brass cylinder enclosing the counter. Aluminum foils, held in place by rubber gasket seals, normally cover the counter ports.

A detailed drawing of the proton counter is shown in Fig. 2. The counter cylinder is of brass and is 3 cm long and 1.9 cm in diameter. The central wire is 10-mil tungsten; a small glass bead encloses the free end. High voltage is applied to the counter cylinder, and a negative pulse is taken from the central wire. A small preamplifier unit is attached to the base plate of each counter case so that the lead from the central wire to the grid of the first amplifier tube is made as short as possible, thus keeping the capacity of the wire to a minimum.

A circuit diagram of the preamplifier unit is shown in Fig. 3. This unit is essentially an impedance transformer, which takes pulses from the counter wire at a high impedance level and has a cathode follower output stage matched to a 75-ohm line. The pulses are then piped over approximately 60 feet of shielded cable to the main amplifier and the remainder of the counting system, which are located in the cyclotron control room. The feedback from the plate of the second tube, through the variable condenser, to the grid of the first, is a capacity neutralization scheme which effectively reduces the capacity of the grid input circuit, enabling a sharp pulse (about 1-microsecond half-width), with a fast rate of rise

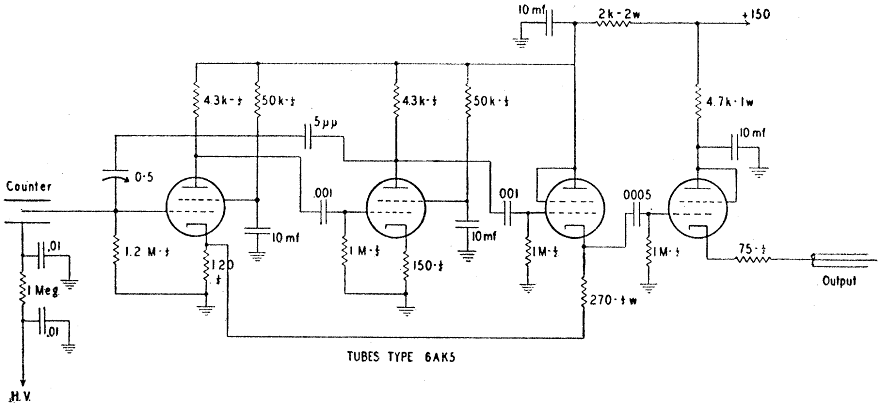

FIG. 3. Circuit diagram of the preamplifier unit. The feedback from tube 2 to tube 1 effectively reduces the capacity of the grid input circuit and sharpens the pulses from the counter. Negative feedback is employed in the cathode circuits to stabilize against voltage fluctuations and tube characteristics.

(0.1 microsecond or less), to be obtained from the counter.

The portion of the counting system at the operator's position consists of two main video amplifiers, a coincidence circuit, a slightly modified Higinbotham scale-of-64 circuit, and the usual mechanical recorders. The main amplifiers have a band pass of about 4 megacycles and a gain of 80 db. The response characteristics favor high frequencies; the low frequency response is made poor intentionally to reduce the effect of microphonics, hum, and similar sources of interference.

The coincidence circuit employs a pentode tube. The output of one of the counters is applied to the control grid of the pentode; the output of the other goes to the screen grid. Both grids are biased beyond cut-off so that the tube will conduct only when positive pulses are applied to the two grids simultaneously. The resolving time of the coincidence circuit is of the order of one to five microseconds. This figure was determined by measuring the number of random coincidences, $N_R$, occurring in the interval during which $N_1$ counts were recorded in counter 1 and $N_2$ counts registered in counter 2, the counters being activated by independent particles. The resolving time $\tau$ is then given by $N_R = 2\tau N_1 N_2$.

As mentioned above, a number of different gas pressures were used in the counters in the course of these observations, in an effort to attain higher resolution, and at each pressure it was necessary to readjust the counting level in order to obtain the best results; that is, the maximum peaking of the proton groups consistent with a reasonable counting rate. The change in counter "depth" resulting from the use of different counting levels was taken into account by a method similar to that described by Holloway and Moore.[3] A number of calibrations using ThC′ alpha-particles and an analytical study based on proton counting observations were both used to determine this correction term.

The range-energy relation for protons was taken from the curves of Livingston and Bethe.[4]

## ENERGY AND HOMOGENEITY OF THE DEUTERON BEAM

It was necessary to determine as accurately as possible the energy of the deuterons from the cyclotron, since the energy of the bombarding particle enters into the calculation of the disintegration energy (the $Q$-value) of a nuclear reaction. The homogeneity of the deuteron beam is of interest in connection with the resolution of this method of inquiry. Measurements were made on the range of the deuterons by causing the beam to pass through an absorption cell, placed at the target position, and then into a detection chamber. Two types of detectors were used in this study. One was a simple Faraday chamber, in which the amount of beam collected on an insulated probe in vacuo was measured by means

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[3] M. G. Holloway and B. L. Moore, Phys. Rev. **58**, 847 (1940).

[4] M. Stanley Livingston and H. A. Bethe, Rev. Mod. Phys. **9**, 245 (1937).

of a sensitive galvanometer. The other was a standard counter of the type shown in Fig. 2. In order to use such a counter in this application, it was necessary to reduce the beam current to a low value, employ a very small aperture (0.025-cm diameter), and measure the output of the counter by means of a counting rate meter circuit which would record up to 50,000 pulses per second. The results obtained from the use of these two detectors were in good agreement; the averaged data from six separate runs give $3.68\pm0.05$ Mev for the mean energy of the beam. When correction is made for the straggling of the deuterons resulting from their passage through the absorbing material, the half-width of the differential energy curve turns out to be $0.18\pm0.04$ Mev.

A study was made to determine the effect on beam homogeneity of varying certain of the cyclotron parameters, namely, the RF voltage, deflector voltage, gas pressure, and cross section of beam used as determined by the position and separation of the collimator jaws at the entrance to the bombardment chamber. Although a somewhat more homogeneous beam was indicated at low deflector plate voltages, no significant change in beam homogeneity was found for reasonable variations in these parameters.

The number of deuterons striking the target during each proton counting run was measured by a current integrator of the neon discharge type.[5] The unit beam which was used for each counting interval was $3\times10^{10}$ deuterons, which corresponds to a beam current of 0.25 microamperes integrated over a period of approximately 50 seconds.

### PROTON GROUPS FROM $Mn^{55}(d,p)Mn^{56}$

Figure 4 shows the results obtained over the range of proton energies from 3.0 to 9.0 Mev. The lower limit to the measurements is set by the range of the deuterons scattered from the target. The proton group ending at about 8 Mev is the end group for the reaction in question. On several occasions attempts were made to find a group of higher energy. The results were in all cases negative; it can be stated that if a group having an energy greater than 8 Mev exists, the yield is less than 5 percent of that of the end group indicated in Fig. 4.

The less prominent groups having energies greater than 4.7 Mev are shown more clearly in Fig. 5, where the scales have been expanded. A total of 21 separate runs were made over this interval of proton range, and all of these have been used for analytic purposes, although only 11 were used to obtain the averaged points shown on this graph. In Fig. 5, the number of counts taken to determine a particular point is given by the ordinate in each case.

The numerical results obtained from these data are shown in Table I. The proton range has in each case been corrected for the effects of the straggling of the protons in the absorbing material, the inhomogeneity of the deuteron energy, and the effective counter depth. The error in the measured proton range caused by finite geometry of the detection system was calculated to be 0.3 percent for the most unfavorable case. The error caused by the finite thickness of the target is also small: 0.1 cm in range for the 30-cm

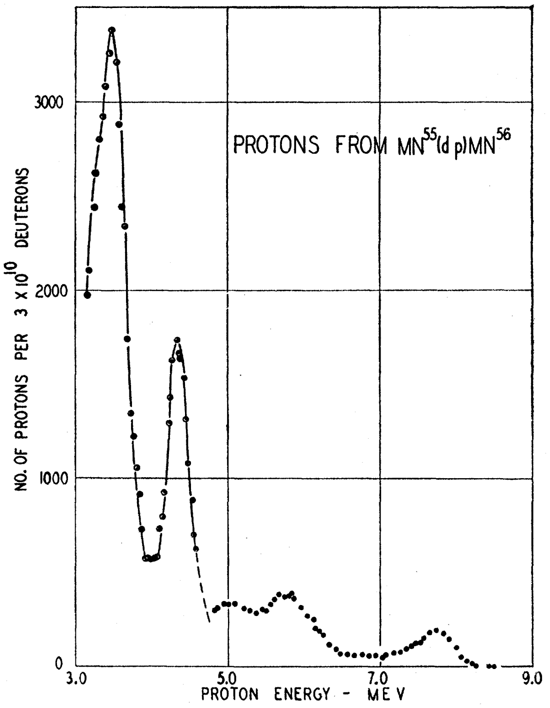

FIG. 4. The yield of protons per unit deuteron beam is plotted against proton energy. Eight runs were made over the energy range from 3.0 to 4.7 Mev; 21 runs were made over the interval from 4.7 to 8.5 Mev.

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[5] B. E. Watt, Rev. Sci. Inst. 12, 362 (1941).

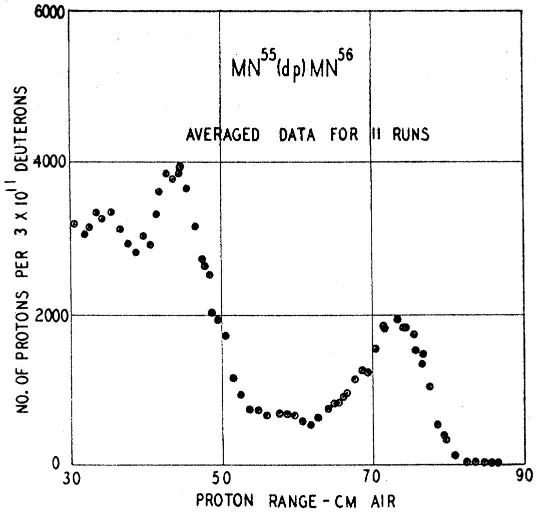

FIG. 5. A plot of the proton yield as a function of proton range, showing the less prominent groups having energies greater than 4.7 Mev. The number of counts taken to determine a particular point is given by the ordinate in each case.

proton group, for example. These last two sources of error have been neglected in computing the disintegration energies for these reactions. The reproducibility of the results obtained is indicated in Table II, where several values for the various disintegration energies, obtained from different runs and different sets of averaged data, are listed. An analysis of the experimental errors which enter into this method yields the figure ±0.11 Mev for the reliability of the $Q$-values obtained, and a study of the half-widths of the proton groups observed indicates that the resolution of this method was 0.30 Mev in the present case.

In Fig. 5, a number of small deviations from a smooth curve, suggesting partially resolved groups, are noticeable, for example at ranges of about 34 cm, 41 cm, 44 cm, and 70 cm. None of these small irregularities survived a statistical analysis, however. Moreover, from a series of experiments that were performed to determine the effect of small amounts of the most probable impurities that might be present in the manganese metal or deposited on the surface of the target, it was found that approximately 40 percent of the small deviations were to be associated with proton groups from $(d,p)$ reactions in sulfur and in deuterium. It is concluded, therefore, that these small irregularities are not to be taken as evidence of partially resolved groups from the reaction $\mathrm{Mn}^{55}(d,p)\mathrm{Mn}^{56}$.

TABLE I. Numerical results for the proton groups from the reaction $\mathrm{Mn}^{55}(d,p)\mathrm{Mn}^{56}$. The mean proton range, after corrections have been applied, is shown here.

| Proton range (cm air) | Proton energy (Mev) | $Q$ (Mev) | Levels (Mev) | Spacing (Mev) |
|---|---|---|---|---|
| 22.9 | 3.98 | 0.38 | 4.38 | |
| | | | | 0.77 |
| 30.8 | 4.73 | 1.15 | 3.61 | |
| | | | | 1.13 |
| 44.7 | 5.85 | 2.28 | 2.48 | |
| | | | | 0.71 |
| 54.4 | 6.55 | 2.99 | 1.77 | |
| | | | | 0.70 |
| 64.7 | 7.23 | 3.69 | 1.07 | |
| | | | | 1.07 |
| 82.3 | 8.29 | 4.76 | 0 | |
| | | | Average spacing | 0.85 |

The results of the present work are in general agreement with those of other investigators who have studied heavy particle emission reactions of this general type. The persistence of level spacings of the order of 0.85 Mev in the nucleus $\mathrm{Mn}^{56}$ supports the view that the nuclear energy levels exhibited in the process of heavy particle emission reactions are restricted by some selection principle, not yet fully understood, to a small fraction of the number that are theoretically possible. The fact that the level spacing observed for $\mathrm{Mn}^{56}$ is somewhat smaller than the spacing found in lighter elements might be regarded as at least qualitative agreement with the prediction of theory that the density of levels should increase at higher atomic weights.

## YIELD OF INDIVIDUAL GROUP AS A FUNCTION OF DEUTERON ENERGY

The energy of the deuterons striking the target was changed by introducing aluminum foils in the path of the beam at the entrance to the bombardment chamber. The deuteron energies attained in this way were 3.68 Mev, 3.33 Mev, and 3.15 Mev. Measurements were then made

TABLE II. Several values for the disintegration energies, obtained from different runs and sets of averaged data.

| Excitation | $Q$-values (Mev) | Best value |
|---|---|---|
| Ground | 4.75, 4.74, 4.78, 4.79 | 4.76 |
| First | 3.64, 3.72, 3.67, 3.74 | 3.69 |
| Second | 2.96, 2.98, 3.02, 3.03 | 2.99 |
| Third | 2.25, 2.27, 2.28, 2.32 | 2.28 |
| Fourth | 1.14, 1.15, 1.16, 1.17 | 1.15 |
| Fifth | 0.31, 0.38, 0.38, 0.43 | 0.38 |

to determine the relative yields from the four most prominent proton groups of the $\mathrm{Mn}^{56}$ spectrum, namely, the first, second, fourth, and sixth, in order of increasing proton range. Data similar to those shown in Fig. 4 were obtained at each beam energy, and care was taken to define the peak of each group as accurately as possible.

The results, shown graphically in Fig. 6, suggest that broad resonance phenomena are in operation in the case of groups *A* and *B*, the maximum yield for these groups occurring for a beam energy of about 3.4 Mev. Groups *C* and *D*, however, show no evidence of a resonance process for beam energies between 3.15 and 3.68 Mev. These results are in general agreement with the findings of Bennett, *et al*,[6] who observed that the yield of a single proton group from the reaction $\mathrm{C}^{12}(d,p)\mathrm{C}^{13}$ was a slowly varying function of the deuteron energy, with no indication of sharp resonance effects.

The dashed curves in Fig. 6 are approximately the envelopes of the proton energy distributions for the two deuteron energies indicated, and correspond to the distribution of proton energies suggested by Volkoff's[7] treatment of the Oppenheimer-Phillips process. It is of interest to note that the present results are not in accord with Volkoff's development: (1) the amplitude of the distribution falls off more rapidly than $E_p^{-\frac{1}{2}}$ for the proton energies obtained in the present work, and (2) the distribution does not exhibit a maximum in the vicinity of

$$E_p = E_D\left[\frac{1+\{1+1.3E_D(1+11.1/Z)\}^{\frac{1}{2}}}{2(1+11.1/Z)}\right]=4.9\text{ Mev.}$$

The possibility of a maximum in the distribution at a somewhat lower proton energy (<3.0 Mev) could not be investigated in the present work because it was not possible to count protons effectively in the presence of the comparatively large flux of deuterons scattered from the target.

## MASS OF THE NUCLEUS $\mathrm{Mn}^{55}$

If it is assumed that the emission of the proton group of longest range leaves the $\mathrm{Mn}^{56}$ nucleus in the ground state, a knowledge of the $Q$-value for this group enables the calculation of the mass of the nucleus $\mathrm{Mn}^{55}$.

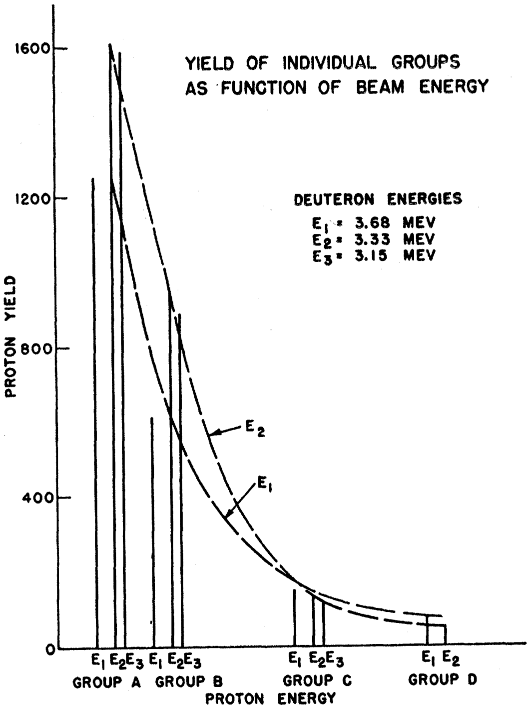

FIG. 6. The relative yields of the four most prominent proton groups from the reaction $\mathrm{Mn}^{55}(d,p)\mathrm{Mn}^{56}$ for three different deuteron energies.

From Dempster's[8] value for the packing fraction of $\mathrm{Fe}^{56}$, the data of Elliot and Deutsch[9] for the beta- and gamma-rays emitted by $\mathrm{Mn}^{56}$, and the maximum $Q$-value obtained in the present work, the mass of $\mathrm{Mn}^{55}$ is found to be 54.9634 ±.0022 mass units. This result agrees, within the limits of error, with the value found by Davidson[10] by the use of the same general method.

## ACKNOWLEDGMENTS

It is a pleasure to express appreciation to Professor Ernest Pollard for his constant interest and encouragement during this investigation, and to acknowledge with gratitude the contribution of Professor Howard Schultz, who designed the preamplifier units, main amplifiers, and coincidence circuits used in the counting system. I am also indebted to Professor R. F. Humphreys for many valuable discussions in connection with this problem.

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[6] W. E. Bennett, T. W. Bonner, H. T. Richards, and B. E. Watt, Phys. Rev. **59**, 781 (1941).

[7] G. M. Volkoff, Phys. Rev. **57**, 866 (1940).

[8] A. J. Dempster, Phys. Rev. **53**, 64 (1938).

[9] L. G. Elliot and M. Deutsch, Phys. Rev. **64**, 321 (1943).

[10] Wm. L. Davidson, Jr., Phys. Rev. **56**, 1062 (1939).