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The Radioactive Decay of the Neutron

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The protons from the radioactive decay of the neutron have been identified by measuring their charge to mass ratio with an electrostatic field and magnetic lens spectrometer. Coincidences have been obtained between these protons and the corresponding beta-particles from the neutron decay using a second magnetic lens spectrometer to measure the energies of the beta-particles. In this manner the beta-spectrum of the neutron has been measured over the region from 300 kev to the end point and has been found to be consistent with the energy distribution expected for an allowed transition. The end point of the spectrum is 782 kev with a probable error of ±13 kev. The half-life of the neutron is 12.8 minutes with a probable error of ±2.5 minutes.

I. INTRODUCTION

CHADWICK and Goldhaber,[1] when they first obtained an accurate value for the mass of the neutron, observed that it should decay radioactively into a proton, a beta-particle, and a neutrino. Experimental confirmation of this was first reported by Snell and Miller,[2] who obtained evidence for the production of low energy positively charged particles by neutrons decaying in a beam from the Oak Ridge pile. Subsequently, Snell, Pleasonton, and McCord[3] obtained coincidences between beta-particles and low energy positive particles of approximately the proton mass resulting from the neutron decay, and the present author identified the decay product as a proton by a spectrometer method.[4] In this paper an experiment is described in which coincidences have been obtained between the beta-particles and the protons in an arrangement which has permitted the energy distribution of these beta-particles to be obtained. The experiment is an extension of that mentioned above,[4] and it used as a source of neutrons a beam from the Chalk River pile. Preliminary results were first reported at the Kingston meeting of the Royal Society of Canada in June, 1950.

The main experimental difficulty in detecting the beta-particles resulting from neutrons decaying in a beam obtained directly from a pile is the large background of electrons and gamma-rays which are always present in the vicinity of such a beam. One possible method of avoiding this background is to reflect the thermal neutrons out of the pile beam by means of a neutron mirror,[5] and a second method would be to filter out the gamma-rays by absorbers and remove the electrons by a strong magnetic field. Both these methods, however, involve loss of thermal neutron intensity if they are to be effective. In this experiment a high neutron intensity was an important consideration and, apart from a bismuth plug placed at the reacting-core end of the collimator to reduce the direct pile gamma-rays, no absorbers were placed in the beam. The beam therefore contained, in addition to thermal neutrons, a high intensity of fast neutrons, gamma-rays from neutrons captured in the collimator, and electrons. The beta-particles resulting from the neutron decay were identified from this background by obtaining their coincidences with the protons also resulting from the decay.

II. EXPERIMENTAL ARRANGEMENT

A. Apparatus at the Pile Face

Figure 1 shows a plan view of the apparatus mounted outside the main shield of the pile. A collimated beam from which the pile gamma-rays had been filtered by a five-inch thick bismuth plug at the reacting-core end of the collimator entered an aluminum vacuum tank through a 0.005-in. aluminum window and emerged through a 0.018-in. window into a beam catcher. The beam was approximately 1.2 inches in diameter as it entered the vacuum chamber and contained approximately 1.5×10^{10} thermal neutrons per second at the pile power used during this experiment. A 0.1-in. thick shutter of boron carbide powder held between two

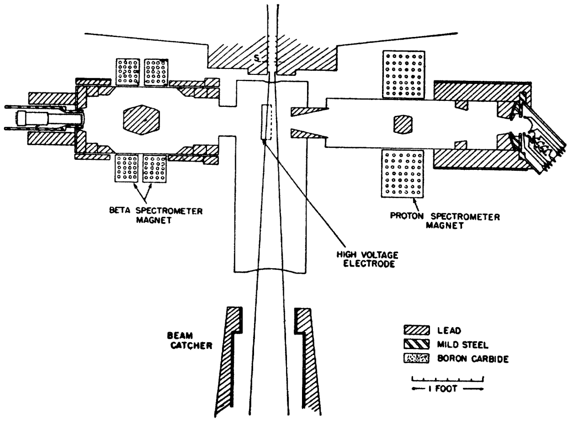

FIG. 1. Plan view of the apparatus mounted outside the main shield of the pile.

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[1] J. Chadwick and M. Goldhaber, Proc. Roy. Soc. (London) **A151**, 479 (1935).

[2] A. H. Snell and L. C. Miller, Phys. Rev. **74**, 1217A (1948).

[3] Snell, Pleasonton, and McCord, Phys. Rev. **78**, 310 (1950).

[4] J. M. Robson, Phys. Rev. **78**, 311 (1950).

[5] Thorndike, Wotring, Shutt, and Borst, BNL-39 (unpublished) and private communication to the author.

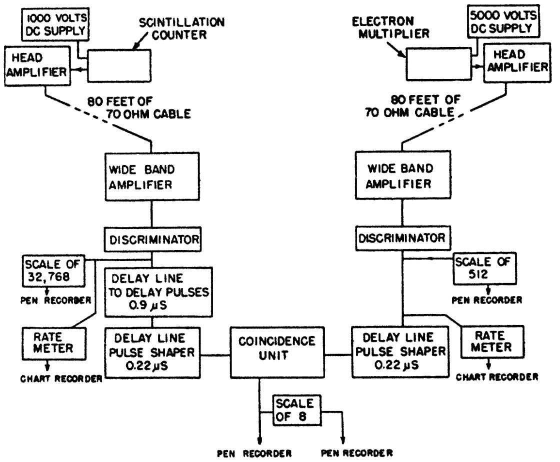

FIG. 2. Block schematic diagram of the electronic apparatus.

0.005-in. aluminum foils could be inserted in the beam at *S* in the pile shield to shut off the thermal neutrons without appreciably scattering the fast neutrons or capture gamma-rays which were also present in the beam.

Some of the protons resulting from the neutrons radioactively decaying in the beam were collected and identified by means of an electrostatic collecting system and magnetic lens spectrometer. The electrostatic field was formed by a 0.0003-in. aluminum high voltage electrode in the form of a hollow half-cylinder which was held at 13 kv positive with respect to ground, so that low energy positively charged particles such as protons from the neutron decay were deflected out of the beam through the entrance aperture into the magnetic lens spectrometer on the right of the beam. The counter at the end of this spectrometer was an electron multiplier whose first electrode covered the 4-cm diameter exit hole of the spectrometer. The first electrode of this electron multiplier was held near ground potential and the final anode at 5 kv positive with respect to ground. The multiplier was shielded from the spectrometer magnetic field by mild steel shaped to deflect this field away from the 13 beryllium copper multiplying electrodes. The central stop of the spectrometer and the defining rings were made of lead, and the end of the spectrometer was sourrounded by lead and boron carbide to reduce the background counting rate.

The spectrometer on the left of the beam was a magnetic lens beta spectrometer with a mosaic of 0.5-mm anthracene crystals covering an area of 1.5-in. diameter as detector. The light flashes from the anthracene were piped down a 6-in. length of Lucite rod to an RCA 5819 photomultiplier which was shielded from the field of the beta-spectrometer magnet by a long mild steel pipe. This beta-particle detector will hereafter be referred to as the scintillation counter to distinguish it from the electron multiplier already described as the proton detector. The beta-spectrometer was set up to have a magnification of 0.5 and a resolution of 9 percent in momentum expressed as total line width at half-maximum. It was calibrated in energy by mounting various sources in such a manner that their beta-rays had to pass through the 0.0003-in. aluminum high voltage electrode in a similar manner to the beta-particles from the neutron disintegration. The sources were electrically connected to the high voltage electrode so that the field between the high voltage electrode and the beta spectrometer was present during the calibration. Throughout the calibration the proton spectrometer magnet was set at the field required to focus protons from the neutron decay. It was first established that the current required to focus a line source of electrons (using a Cs^{137} source) was to the accuracy of the neutron decay experiment independent of the position of the source throughout the region of the neutron beam from which coincidences were to be obtained. The calibration was then made using sources mounted on the axis of the spectrometer at its intercept with the axis of the neutron beam. Three calibration points were used, namely, the *K* internal conversion line of the 411-kev gamma-ray from Au^{198} (328 kev), the end point of Au^{198} obtained by a Fermi extrapolation (957 kev),[6] and the end point of Tl^{204} (762 kev).[7] Because of the small electrostatic field between the sources and the spectrometer, and the presence of the small constant field from the proton spectrometer magnet, the current-momentum relationship for the beta-spectrometer was not exactly the same as would be expected for a normal magnetic lens beta-spectrometer. The difference was small, however, and the calibration differed from a linear calibration based on the end point of Au^{198} by only about 1.5 percent at 300 kev and 0.5 percent at 600 kev.

The two spectrometers, the electron multiplier housing, and the aluminum tank through which the beam passed formed one vacuum system which was continuously pumped by liquid nitrogen trapped oil diffusion pumps. Throughout the experiment the pressure in this vacuum system was less than 10^{-6} mm of mercury measured with a DPI ionization gauge.

B. Associated Electronic Equipment

Figure 2 shows a block schematic diagram of the electronic circuits. Two identical pulse amplifiers were used to amplify the pulses from the electron multiplier and the scintillation counter and the amplified pulses were fed to two identical discriminators. The output of the scintillation counter discriminator was fed into a forty section delay line on which taps were provided to enable any delay between 0 and 1 microsecond to

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[6] L. G. Elliott, in a private communication to the author, gave 957±3 kev as the Fermi extrapolation to the end point of Au^{198} relative to the 411-kev gamma-ray.

[7] J. L. Wolfson, in a private communication to the author, gave 762±7 kev as the Fermi extrapolation to the end point of Tl^{204} relative to the 411-kev gamma-ray of Au^{198}.

be selected. The delayed pulses were then fed to a pulse shaping unit which produced by means of a twenty-section short-circuited delay line pulses of rise time 0.01 microsecond and of duration variable up to 0.4 microsecond. The output of the electron multiplier discriminator was fed to a similar pulse shaping unit. These shaped pulses were then fed to a low impedance coincidence circuit working on the Rossi principle. The rise time of the pulses from the pulse amplifiers was such that the total time jitter of the pulses fed to the coincidence circuit at the discriminator settings used was about 0.07 microsecond because of the wide distribution in pulse sizes from the counters. Throughout the experiment the delay lines in the pulse shapers were set to produce pulses of 0.22 microsecond duration. Scalers were provided to enable the number of coincidences and also the number of pulses from the electron multiplier and from the scintillation counter to be individually recorded on a 10-pen recorder. Continuous records were also made as a check on the scalers by means of counting rate meters and chart recorders.

Using the focused electrons from the gold calibrating source, bias curves were obtained for the scintillation counter at various electron energies. From these curves the bias settings on the scintillation counter discriminator were obtained which enabled a definite fraction (87 percent) of the counts at zero bias to be recorded. These bias settings varied slightly with energy, and the appropriate settings were used in the coincidence experiment on the neutron decay to be described later in this paper. Figure 3 shows the distribution in amplitude of the pulses from the scintillation counter when electrons of 300 kev were focused on the mosaic of anthracene crystals. This curve was obtained by differentiating the bias curve obtained at this energy.

The currents through the two spectrometer magnets were electronically regulated to better than one part in a thousand by a continuous comparison of the voltages developed across standard resistances with those from standard cells. The comparisons were made by 400-cycle choppers whose outputs were amplified and arranged to control the currents through the magnets.

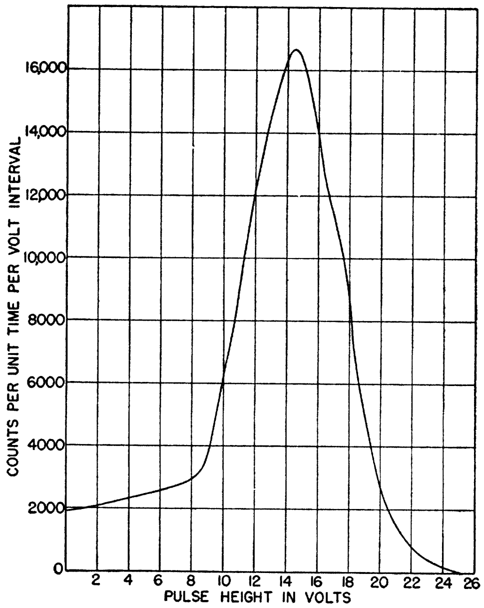

FIG. 3. Pulse amplitude distribution from scintillation counter when 300-kev electrons are focused on the mosaic of anthracene crystals.

III. EXPERIMENTAL RESULTS

A. Protons from the Neutron Decay

Figure 4 shows the counting rate obtained from the electron multiplier at different values of the proton spectrometer magnetic field with a voltage of +13 kv on the high voltage electrode. Two curves are shown, the solid line with the boron shutter "out" allowing the thermal neutrons to pass through the apparatus and the dotted line with the boron shutter "in" so that thermal neutrons were no longer present in the beam. A background which amounted to about 100 counts per minute at the peak on the "out" curve and which was due to other experimental apparatus not connected with this experiment has been subtracted from both curves. This background was obtained by closing a large iron gate, 12 inches thick, which was located about half-way along the collimator and which reduced the intensity of the beam by a factor of over 1000. This background was, of course, present in the coincidence experiments to be described later in this

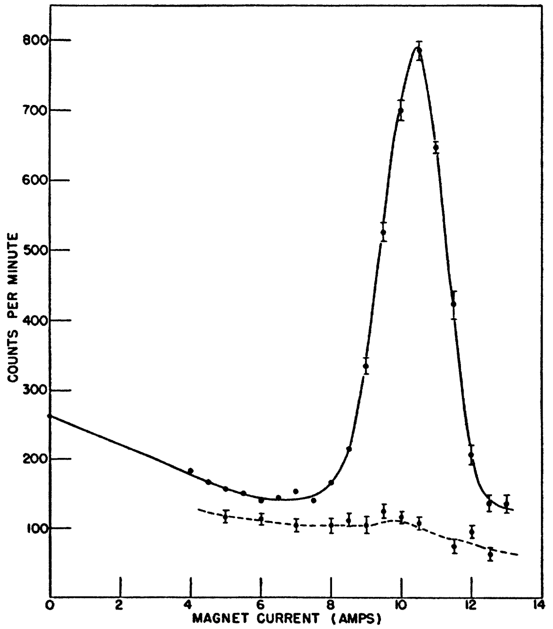

FIG. 4. Counting rate of the electron multiplier plotted against current through the proton spectrometer magnet.

paper. It can be seen that there is a large peak on the "out" curve centered at 10.5 amp which is not present on the "in" curve. This peak occurs at the correct magnetic field to focus protons of the energy received from the electrostatic field and is believed to represent protons resulting from the neutrons radioactively decaying in the beam. The pressure in the vacuum tank was varied to see if any of these protons arose from spurious effects in the residual gas, but no significant effect was observed with air or oil vapor between pressures of 7×10^{-7} mm and 5×10^{-6} mm of mercury. As a further check that the peak was not due to ionization effects, runs were made with lower voltages on the high voltage electrode. At accelerating potentials under 10 kv it would have been possible with the magnetic field available to observe the peak corresponding to singly ionized molecular hydrogen. No significant peaks other than that corresponding to protons were observed at any potential. The difference in counting rates between the "out" and the "in" conditions below 8 amp and above 12 amp is probably due to gamma-rays from the capture of thermal neutrons scattered by the vacuum chamber windows and by the air between the vacuum chamber and the beam catcher.

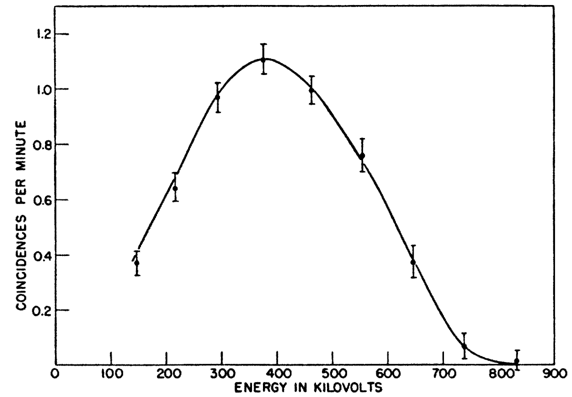

FIG. 5. Coincidence rate between beta-particles and protons resulting from the neutron decay plotted against beta-particle energy.

B. Coincidences between the Protons and the Beta-Particles

The proton spectrometer magnet current was set at 10.5 amp to correspond to the peak on the boron "out" curve, and coincidences were sought between the pulses from the electron multiplier and from the scintillation counter at various settings of the beta-spectrometer magnet current. To allow for the transit time of the protons through the proton spectrometer a delay of 0.9 microsecond was introduced into the scintillation counter channel by means of the delay line mentioned in Sec. II of this paper. The calculated transit times for the protons lie between a minimum of 0.8 microsecond and a maximum of 1.0 microsecond, depending on their paths; and a preliminary experiment indicated that the coincidence rate was a maximum with 0.9 microsecond delay introduced in the beta-counting channel. An accurate knowledge of the resolving time of the coincidence system was an essential requirement of the experimental procedure, since, owing to the high background of beta-particles recorded by the scintillation counter, the random coincidences were comparable to the expected coincidence rate from the neutron decay. The resolving time was therefore measured once every 10 hours throughout the experiment by measurement of the random coincidences when two separate radioactive sources were placed near the two counters. The resolving time was found to be 0.227 microsecond and remained constant to within ±1 percent throughout the experiment. Figure 5 shows the coincidence rate obtained with the random coincidences subtracted. The random coincidences were calculated from the individual rates and the resolving time and amounted to about 0.75 coincidences per minute. Each point on Fig. 5 represents about 24 hours of pile operation time.

To check that the genuine coincidences shown in Fig. 5 were due to the neutron decay, several check runs were made with the beta-spectrometer set at 377 kev. These are listed in Table I.

It can be seen from Table I that genuine coincidences only appear under the following conditions:

(1) thermal neutrons present in the beam,
(2) proton spectrometer set to focus protons of the energy received from the electrostatic field,
(3) the correct delay introduced in the beta-channel to allow for the transit time of the protons through the proton spectrometer.

If any one of these conditions is not satisfied, the genuine coincidences vanish. If this evidence is combined with that obtained from the proton spectrometer and with the fact that the upper limit of the energy at which genuine coincidences appear is of the correct order for the upper limit of the energy of the beta-particles to be expected from the neutron decay, it seems very probable that these coincidences are due to decaying neutrons.

The points below 300 kev are unreliable because of the absorption of low energy beta-particles by a 5-mg/cm^2 Duralumin window which separates the mosaic of anthracene crystals from the beta-spectrometer vacuum. These points are also unreliable for a reason connected with the proton collection system and discussed in the following section.

IV. PROTON RECOIL MOMENTUM AND DIRECTION

The variation with the beta-spectrometer focusing current of the coincidence rate between the beta-particles and protons will only represent the beta-spectrum of the neutron provided that the electrostatic collection system and the proton spectrometer are uniformly sensitive to protons of all momenta and directions consistent with the beta-decay process. In the ideal arrangement the efficiency of the proton system should be independent of the momentum and direction of the proton recoil; or, expressed in other words, the volume of the neutron beam from which protons can be accelerated out of the beam and focused by the proton magnetic spectrometer onto the first electrode of the electron multiplier should be independent of the magnitude of the proton recoil momentum and its initial recoil direction relative to the axis of the spectrometer. Since this ideal state cannot be attained, it is essential that an estimate should be made of the variation in this collecting volume.

To investigate this, a mechanical model was constructed of the electrostatic collecting system in which a cross section of the electrode potentials in a plane perpendicular to the neutron beam was represented by the height of a rubber sheet in a rubber model analog.[8] In such a model the paths of small spherical balls agrees closely with the paths of charged particles in the corresponding electrostatic field. By giving a ball a small initial velocity corresponding in magnitude and direction to a proton recoiling from a neutron disintegration its path through the system could be examined in one plane. Observations were made with different initial velocities covering the range of momentum and angles of interest; and in each case the point of entry through the entrance aperture of the proton spectrometer and the direction inside the spectrometer, in a region where the electrostatic field had essentially vanished, was recorded. These sets of observations were made for a series of small elements of area covering the cross section of the neutron beam. From the point of entry in the entrance aperture and the direction inside the proton spectrometer, the length of beam corresponding to each element of area, from which protons could enter the spectrometer and be focused, was calculated for various values of the component of the recoil momentum along the beam direction and therefore at right angles to the plane of the model. By summing the results for all the elements of area and making a correction for the neutron flux distribution across the beam, we obtained a set of graphs of sensitive volumes plotted against total recoil momentum for different initial recoil directions relative to the spectrometer axis.

By averaging the results over small ranges of initial recoil direction a table was prepared which gave the volume $v(p', \phi)$ of the neutron beam from which recoils of definite momentum p' and of direction lying in the small range ϕ to $\phi+d\phi$ could be collected and focused onto the first surface of the electron multiplier. This showed that the proton collection system was uniform only over a region of the recoil momentum space where the angle ϕ between the recoil direction and the proton spectrometer axis was less than 60° and that above 60° the volume from which collection was possible dropped off rapidly with increase of angle and with increase of recoil momentum. At 90° the volume $v(p', \phi)$ was almost zero, and from 90° to 140° it again increased, remaining reasonably uniform above 140°.

To assess the effect of this on the shape of the beta-spectrum, the possible recoil directions and momenta were calculated for various beta-particle energies on the assumption that momentum is conserved between the recoil proton, the beta-particle, and one zero rest mass neutrino. For beta-particle energies greater than about 350 kev, this assumption, applied in this particular experimental arrangement, implies that when coincidences are obtained, the only protons involved will be those whose angle of recoil ϕ is less than 60° and thus those which are in the region where $v(p', \phi)$ is reasonably uniform. It is only for beta-particle energies below 300 kev that an appreciable fraction of the recoils will have an angle ϕ greater than 60°. To obtain the quantitative effect of this, the individual volumes $v(p', \phi)$ were averaged over the regions of possible recoil momentum and direction predicted by the conservation of momentum and weighted by various correlations between the beta-particle and neutrino direction. In this manner mean volumes V_c from which coincidences could be obtained were calculated at given beta-particle energies for the various forms of correlation. The results are shown in Fig. 6 for three correlation factors: (a) $1+(p/E)\cos\theta$, (b) 1, and (c) $1-(p/E)\cos\theta$, where p and E are the momentum and total energy of the beta-particle and θ is the angle between the electron and the neutrino. It can be seen that above 300 kev the volume V_c is about 8.8 cc and is constant to within ±5 percent for each of the three cases. The other correlation factors $1+\frac{1}{3}(p/E)\cos\theta$ and $1-\frac{1}{3}(p/E)\cos\theta$ lie between these cases and, to avoid confusion, are not shown on Fig. 6. The volume is again constant to better than ±5 percent.

TABLE I. Check runs to show that the genuine coincidences were due to neutrons decaying.

Boron shutter	Delay introduced in beta-channel (microseconds)	Voltage on the high voltage electrode	Proton magnet current (amp)	Genuine coincidences per minute
out	0.9	13 kv	10.5	1.108 ± 0.055
out	0.5	13 kv	10.5	0.050 ± 0.04
out	0.9	0	10.5	-0.010 ± 0.035
out	0.9	13 kv	6.5	0.011 ± 0.028
in	0.9	15 kv	10.5	0.04 ± 0.03

If one assumes a multiplicity of neutrinos with randomness in their relative directions, their momenta will partially cancel each other and the proton recoils will tend to be more nearly opposite in direction to the beta particle direction. Under these circumstances the volume will become more constant than in the one-neutrino case.

If one assumes that momentum is not conserved in the process except that the maximum value of the

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[8] V. K. Zworykin and J. A. Rajchman, Proc. Inst. Radio Engrs. **27**, 558 (1939).

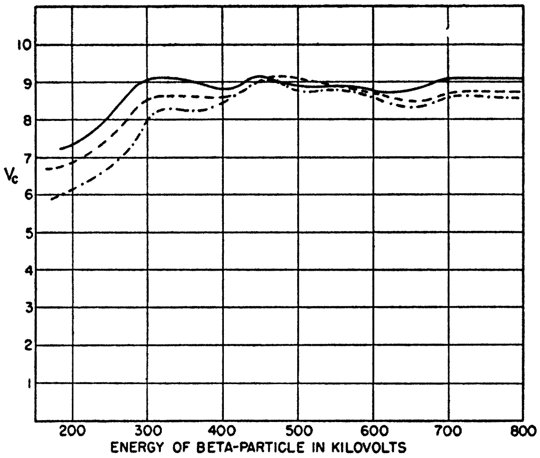

FIG. 6. Volume of neutron beam from which recoil protons corresponding to the beta-particle energies are collected and focused onto the first surface of the proton counter. Conservation of momentum has been assumed between the beta-particle, the proton, and one zero rest mass neutrino. The solid line represents the case of a $1+(p/E)\cos\theta$ correlation between the beta-particle and neutrino, the dashed line a correlation 1 and the dot and dashed line a correlation $1-(p/E)\cos\theta$.

proton recoil momentum cannot exceed the momentum corresponding to a beta-particle at the upper limit of the beta-spectrum, then all recoil directions and momenta used in the rubber model tests may be possible, and the effect on the beta-spectrum will depend on the amount of correlation between the beta-particle and the recoil proton. In the extreme case of complete correlation between a definite beta-particle energy and a definite recoil momentum and definite recoil direction, the coincidence spectrum would bear little resemblance to the actual beta-spectrum. However, an experimental check is available which can give information as to whether the proton recoils are or are not restricted to the region predicted by the conservation of momentum. This check is available in the following manner.

The number of neutrons decaying per cc of neutron beam can be obtained from the total number of proton counts and from the volume of beam V_p from which protons are collected and focused onto the first surface of the electron multiplier. This mean volume of beam, V_p, has to be obtained by averaging the individual volumes $v(p', \phi)$ over all recoil momenta p' weighted by the recoil momentum spectrum and over all recoil directions ϕ weighted by their corresponding solid angle. In this case the protons alone are concerned and the beta-particles are of no significance, so that there will be no restrictions on the angle ϕ of the proton recoil. Consequently, $v(p', \phi)$ has to be averaged over all values of ϕ from 0° to 180°, and V_p will therefore be smaller than the value obtained for V_c on the assumption of momentum conservation. From this number of neutrons decaying per cc of neutron beam and from the resolution and solid angle of the beta-spectrometer it is possible to calculate from the coincidence rate the volume of beam from which coincidences are obtained. If this volume is found to be about 8.8 cc, it will be some evidence that the recoils lie in the region predicted by the conservation of momentum. If, however, the volume is found to be appreciably less than 8.8 cc, the recoils must lie outside the restricted region predicted by conservation of momentum, and the coincidence spectrum would not necessarily represent the beta-spectrum. As will be shown in Sec. VI.A, the experimental results are in agreement with the prediction of the conservation of momentum. It is therefore assumed that the coincidence spectrum shown in Fig. 5 represents the beta-spectrum to within ±5 percent for beta-particle energies above 300 kev. Table II summarizes the results of the mechanical model tests.

V. THE END POINT OF THE BETA-SPECTRUM

Figure 7 shows the momentum spectrum of the beta-particles from the radioactive decay of the neutron. The line connecting the experimental points has been drawn as a broken line below 2000 gauss-cm to emphasize that in this region there are known instrumental defects which make the observed points inaccurate in their representation of the true momentum spectrum. These known defects are

(a) absorption of the focused beta-particles by the 5-mg/cm^2. Duralumin vacuum window in front of the scintillation counter;

(b) non-uniformity of the electrostatic collection system for the proton recoils corresponding to beta-

TABLE II. Uniformity of the volume of neutron beam, V_c, from which coincidences can be obtained as the beta-particle energy varies from 300 kev to the end point. The uniformity of volume represents the peak-to-peak error of the coincidence spectrum from the true beta-spectrum.

	Condition	V_c in cc	Uniformity of volume, in percent
1	Momentum conserved between beta-particle, proton and one neutrino. Correlation factor $1+(p/E)\cos\theta$.	8.9	±3
2	As case 1 but correlation factor $1+\frac{1}{3}(p/E)\cos\theta$.	8.9	±4
3	As case 1 but correlation factor 1.	8.8	±4
4	As case 1 but correlation factor $1-\frac{1}{3}(p/E)\cos\theta$.	8.7	±4
5	As case 1 but correlation factor $1-(p/E)\cos\theta$.	8.6	±5
6	Momentum conserved between beta-particle, proton, and multiple neutrinos. Neutrinos randomly oriented.	9	±5
7	Momentum not conserved in process. Randomness in orientation and recoil momentum of proton.	5	completely uniform
8	Momentum not conserved in process. Complete correlation between beta-particle energy and recoil proton momentum; randomness of recoil direction.	5	±30
9	Momentum not conserved in process. Complete correlation between beta-particle energy and recoil proton direction; randomness of recoil momentum.	5	±30

particles with momentum less than about 2000 gauss-cm.

The known inaccuracies in the points above 2000 gauss-cm are all less than the standard deviations of the coincidence rates which have been indicated by the vertical bars through the experimental points. The experimental data has therefore not been corrected for these known inaccuracies, which are

(a) variations of the mean volume of neutron beam from which coincidences can be obtained, as discussed in Sec. IV of this paper;

(b) effect of the finite resolution of the beta-spectrometer. This was calculated by the method of Owen and Primakoff[9] using the experimentally determined resolution curve of the spectrometer on a conversion line. The source used for this investigation (Cs^{137}) was mounted at various positions throughout the region of the neutron beam from which coincidences could be obtained, and an effective resolution curve was thereby obtained for a source of the same size as the neutron source. This resolution curve was of the form $I(p) = I(p_0) \exp[-(p-p_0)^2/2a^2]$ with $a=0.035p_0$. The effect of this resolution was found to be small compared with the standard deviations of the coincidence rates and was therefore neglected. The only points significantly affected by the resolution correction were the two at largest momentum and even for these two points the correction was less than the standard deviation.

Figure 8 shows the spectrum plotted as a Fermi plot. The F function corresponding to the effect of the coulomb field has been set equal to one at all energies, since its variation for $Z=1$ over the region from 300 kev to 800 kev is quite negligible in comparison with the standard deviations of the coincidence rates. It can be seen that above 300 kev the points lie on a straight line indicating that above this energy the energy distribution of the beta-particles is consistent with the distribution to be expected for an allowed transition.

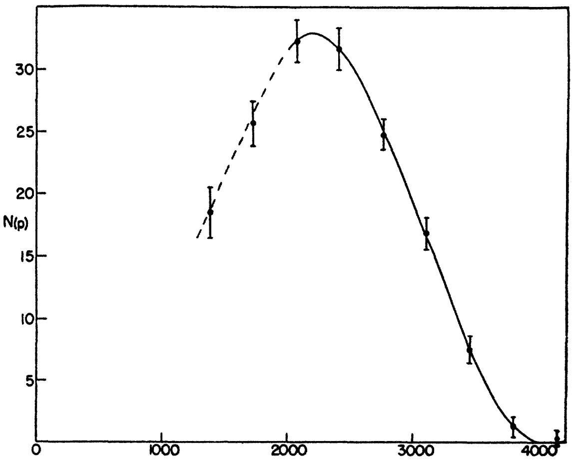

FIG. 7. Momentum spectrum of the beta-particles from the neutron decay. Below $H\rho=2000$ gauss-cm the curve is unreliable because of instrumental effects discussed in the text.

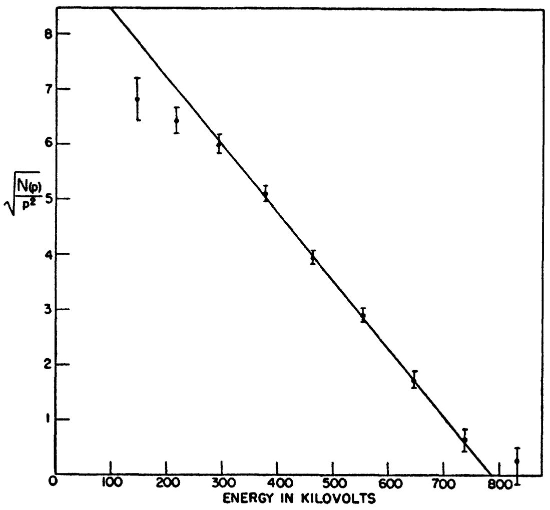

FIG. 8. The beta-spectrum of the neutron plotted as a Fermi plot. $N(p)$ is the number of coincidences per unit momentum interval.

The end point of the beta-spectrum as obtained from an extrapolation of the Fermi plot is 785 kev. A correction of 3 kev must be subtracted from this observed value of the neutron spectrum end point to allow for the energy received by the beta-particles from the electrostatic field for the proton collection. This is necessary because the calibrating sources were electrically connected to the high voltage electrode and were thus at a potential of 13 kv, while the mean potential at the position of the neutron beam was about 10 kv. Taking into account the errors due to (a) uncertainty in the actual end point of Au^{198} and of Tl^{204} relative to the 411-kev gamma-ray of Au^{198}, (b) calibration error of the beta-spectrometer, and (c) error in the extrapolation of the Fermi plot of the spectrum of the neutron decay, the value for the end point of the beta-spectrum of the neutron from this experiment is 782 kev with a probable error of ±13 kev.

VI. HALF-LIFE OF THE NEUTRON

A. Number of Neutrons Decaying per Unit Volume of Neutron Beam

The number of neutrons decaying per unit volume of the neutron beam can be estimated from the number of protons striking the first electrode of the electron multiplier and the volume of beam V_p from which it can obtain protons. The mean volume of beam from which protons can be collected and focused onto the electron multiplier was obtained by averaging over all momenta and angles of recoil the volumes $v(p', \phi)$ obtained from the mechanical model in the manner discussed in Sec. IV. In this averaging the solid angles subtended by the small angle intervals associated with each observation made on the mechanical model was

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[9] G. E. Owen and H. Primakoff, Phys. Rev. 74, 1406 (1948).

taken into account; and the distribution of recoil momenta used was that predicted by conservation of momentum between the beta-particle, recoil proton, and one zero rest mass neutrino for a mixture of the two cases of interaction with invariance properties of a tensor and of an axial vector. The value obtained in this manner for the mean volume of the beam V_p was 4.7 cc.

The number of protons which strike the first surface of the electron multiplier is the counting rate divided by the efficiency of the electron multiplier. It is a characteristic of electron multipliers that the average amplitude of the pulses obtained when counting protons is considerably larger than the average amplitude obtained when counting gamma-rays or beta-particles. Thus, as the bias setting on the electron multiplier discriminator is increased, the ratio of the proton peak increases relative to the background. The actual bias setting used in the main part of the experiment was therefore chosen so that the background was reduced to a satisfactorily low value. The efficiency of the electron multiplier for protons at this bias setting was estimated by the following procedure. Curves similar to Fig. 4 were obtained at different bias settings of the discriminator used in conjunction with the electron multiplier. From these curves a bias curve was obtained for the electron mutliplier counting protons resulting from the neutron decay. From this curve an extrapolation to zero bias indicated the number of protons which would have been counted at zero bias and showed that the ratio of the counting rate at the bias setting used in the main part of the experiment to the counting rate at zero bias was 0.29. Previous experiments[10] have indicated that for an electron multiplier using beryllium copper electrodes the efficiency for 10-kev protons was 100 percent at zero bias. However, the electron multiplier used in this experiment employed a considerably larger first electrode than the one previously tested for 10-kev protons; and with such a large surface a correction will be necessary for the probable non-uniformity of the first surface. This correction was obtained by using alpha-particles from a source of Cm^{242} of known strength. The source was mounted inside the proton spectrometer in such a position that its alpha-particles could strike the first surface of the electron multiplier. The electron-multiplier entrance-aperture was covered with 0.00025-in. aluminum to stop the low-energy secondary-electrons emitted from various parts of the spectrometer and from the source. A bias curve was then taken for the electron multiplier counting the 6-Mev alpha-particles from the curium source. It was found that this bias curve was very similar in shape to that obtained when counting protons from the neutron decay and was unaffected by the application of the magnetic field necessary to focus the protons from the neutron decay. From the counting rate at zero bias and from the solid angle presented by the electron multiplier entrance aperture to the curium source the correction to be applied due to non-uniformity of the first surface of the electron multiplier was estimated as 0.82. The resulting value for the efficiency of the electron multiplier was therefore 0.237 at the bias setting used in the main part of this experiment. The number of protons counted by the electron multiplier at this bias setting was 705 per minute at a certain known reference value of the pile power. Combining these values with the value obtained for V_p the number of neutrons disintegrating into protons per cubic centimeter of the beam is found to be 630 per minute. The various sources of error in this determination will now be considered.

The error will primarily be due to uncertainty in the knowledge of the mean volume, V_p, of the neutron beam from which protons can be collected. The data obtained from the mechanical model tests are obtained essentially by a series of calculations based on a set of observations made with the model. By performing the calculations in different manners the various volumes of beams discussed in Sec. IV were obtained for different assumptions as to the process of the neutron decay. In each case, however, the same data were used. Consequently, the values obtained for the various assumptions are probably self-consistent to the accuracy of the calculations. The absolute values of the volumes, however, depend on the accuracy of the data obtained from the mechanical model and on the accuracy of the mechanical model in representing the true paths of the protons in the electrostatic field. A series of tests made with the mechanical model indicated that its self-consistency for repetition of the same operation was such that the resulting probable error in the volume of the beam would be about ±6 percent due to the errors in the data from the mechanical model. The inherent error in the representation by the mechanical model of the true paths of the protons in the electrostatic field is difficult to estimate because no simple method has been devised to test experimentally the applicability of the method in this particular case. Some information, however, has been published by Zworykin and Rajchman[8] on the accuracy of a similar mechanical model in representing the paths of electrons between adjacent surfaces of an electron multiplier. They compared the landing coordinate of an electron liberated from one surface and accelerated to a second surface as obtained from the mechanical model with that obtained from a specially designed electronic tube. If the value obtained from the electronic tube is accepted as correct, it is possible to estimate from their published curve the error of the mechanical model value. This error will probably be a function of the starting position of the electron from the first surface and is more of the nature of a systematic error than a random error. A similar situation will arise in the mechanical model representation of the paths of the protons in the electrostatic field of the neutron decay experiment, namely, that the individual

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[10] J. M. Robson, Rev. Sci. Instr. 19, 865 (1948).

errors of the paths of the protons will be a systematic function of the exact path and consequently of the magnitude and direction of the initial proton recoil momentum. However, in the estimation of the volume of beam from which protons can be collected and focused onto the first surface of the electron multiplier, a large number of individual observations made with the mechanical model are combined. An estimate of the error of the volume has therefore been attempted by treating the individual errors of the model of Zworykin and Rajchman as being representative of the individual errors of the mechanical model in this experiment and by then treating these errors as if they were random so that a probable error can be derived for the error of one determination made with the mechanical model. In this manner, the portion of the probable error contributed by the mechanical model, of the volume of beam, V_p, from which protons can be collected and focused onto the first surface of the electron multiplier, was estimated to be ±9 percent. Several other errors must be combined with this to determine the error in the number of neutrons disintegrating per unit volume of beam. These are (a) the error in the method of calculating the volumes $v(p', \phi)$ from the mechanical model tests, (b) the error in the counting rate of the electron multiplier, and (c) the error in the determination of the efficiency of the electron multiplier for the protons resulting from the neutron decay.

The calculation of the volumes $v(p', \phi)$ from the individual results of the mechanical model involves a calculation of the trajectory of the protons through the magnetic field of the proton spectrometer. The error in this calculation is probably not serious in view of the long focal length of the magnet in comparison with the diameter of the entrance and exit window of the spectrometer and is arbitrarily considered as less than 5 percent. A further source of error will be considered here, namely, the error which arises from the method of averaging the volumes $v(p', \phi)$ to obtain the mean value V_p. The value of 4.7 cc quoted above for V_p refers to an average over the distribution of recoil momenta predicted by assuming conservation of momentum between the recoil proton, the beta-particle, and one zero rest mass neutrino with an equal mixture of tensor and axial vector invariance properties of the interaction between the nucleons and the light particles. The volumes V_p obtained by averaging over the momentum distributions[11] predicted by all the possible interactions are listed in Table III. Also listed in this table are the volumes obtained by merely averaging uniformly over all momenta and by averaging uniformly over all recoil energies. It can be seen that the volume V_p is not very sensitive to the form of beta-decay process which is assumed for the neutron decay. However, to allow for the variation, a probable error of 5 percent is included for the method of averaging.

The error in the counting rate of the electron multiplier is small statistically but may amount to 4 percent owing to possible differences in amplifier and electron-multiplier gain and discriminator bias settings between the actual runs with protons from the neutron decay and the runs used for estimating its efficiency. The probable error in the determination of the efficiency of the electron multiplier is estimated as 7 percent. When all these errors are combined, the number of neutrons decaying per minute per cubic centimeter of neutron beam is 630 with a probable error of 15 percent.

As was mentioned in Sec. IV this value for the number of neutrons decaying per minute per cc of neutron beam can be combined with the coincidence counting rate to determine the volume of beam from which coincidences are obtained. A comparison of the value thus found with that predicted by the conservation of momentum will give a check on the validity of the assumption that momentum is conserved in the neutron decay process. If n is the number of neutrons decaying per cc of beam, V_c the volume of beam from which coincidences can be obtained, $e(\mathrm{EM})$ the efficiency of the electron multiplier, $e(\mathrm{SC})$ the efficiency of the scintillation counter, Ω the solid angle of the beta-spectrometer expressed as a fraction of 4π, and R the resolution of the spectrometer defined as the fractional width of a square distribution whose area is the same as the area under the resolution curve of the spectrometer for a line source of electrons, then

TABLE III. Volume, V_p, from which protons can be collected and focused onto proton counter without restrictions as to direction of beta-particle. The correlations between the beta-particle and neutrino direction are expressed as $1+\alpha(p/E)\cos\theta$ with α having the values listed.

Condition	α	V_p, in cc
Vector	$+1$	4.5
Tensor	$+\frac{1}{3}$	4.6
Axial vector	$-\frac{1}{3}$	4.9
Scalar or pseudoscalar	-1	5.1
Equal mixture of tensor and axial vector		4.7
Averaging uniformly over all proton momenta		4.7
Averaging uniformly over all proton energies		4.5

$$V_c=\int_0^{p_{\max}}(N/p)dp\bigg/R\Omega e(\mathrm{EM})e(\mathrm{SC})n,$$

where N is the observed coincidence rate.

The integral was obtained graphically using the observed coincidence rates above 250 kev and using the extrapolation of the Fermi plot to give extrapolated rates below 250 kev. This was necessary because of the absorption in the Duralumin window separating the scintillation counter from the main vacuum. The integral was found to be 1.0 count per minute. R and Ω were determined by using a source of Cs^{137}. The source was about $\frac{1}{8}$ inch in diameter and was placed at various positions in the neutron beam covering the volume from which decay events could be recorded

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[11] O. Kofoed-Hansen, Phys. Rev. 74, 1785 (1948).

by the spectrometers. In this manner the effective solid angle for the neutron source was obtained relative to the solid angle for a small source centrally located on the beta-spectrometer axis. This latter solid angle was calculated geometrically and checked by the approximately known number of internal conversion electrons from the source. The product $R\Omega$ was found in this manner to be 9×10^{-4}. The efficiency of the scintillation counter $e(SC)$ was assumed to be equal to the counting rate at the bias used in the coincidence experiment divided by the counting rate at zero bias and multiplied by a factor giving the effective coverage by the mosaic of anthracene crystals. The bias correction was 0.87, and the coverage correction was estimated as 0.95, giving 0.825 for $e(SC)$. The efficiency of the electron multiplier $e(EM)$ has already been discussed and was found to be 0.237. Inserting these values in the above formula gives $V_c=8.9$ cc.

This value is in agreement with that predicted by the application of the conservation of momentum to the data from the mechanical model tests. It is considerably larger than the value obtained by not restricting the proton recoils to the region predicted by momentum conservation and thus gives some evidence that momentum is conserved in the neutron decay process.

B. The Density of Neutrons in the Beam

The density of neutrons in the beam was measured by the activation of calibrated manganese foils. Manganese foils were used because the activation cross section of manganese is inversely proportional to the neutron velocity for neutrons of energy less than 1 ev. Consequently, the activity produced in a manganese foil by neutrons of energy less than 1 ev is proportional to the neutron density and not the neutron flux. Thus, by obtaining the difference of the activities of a foil with and without a cadmium shield, we can measure the density directly without any determination of the distribution of neutron velocities. The use of a cadmium shield to eliminate effects due to neutrons of energy greater than 1 ev is justified because these neutrons will contribute negligibly to the density. The foils used were calibrated separately against standard manganese foils of the same thickness which had previously been calibrated by Fenning of this laboratory.[12] Fenning activated the standard manganese foils in a density of thermal neutrons which he measured absolutely with a small boron trifluoride chamber. The density of neutrons in the beam was measured in two separate measurements. In the first measurement the neutron density at various points across the beam was measured relative to the neutron density at the center of the beam at the point S in Fig. 1. This neutron distribution agreed closely with the distribution to be expected from the geometry of the collimator and was used to correct the measurements made at individual points across the beam in the mechanical model tests. As a consequence of this, the volumes of beam mentioned in this paper all refer to volumes having a neutron density equivalent to that at the center of the beam at the point S in Fig. 1. In the second measurement the absolute neutron density at the center of the beam at the point S was measured at the particular pile power used as a standard reference during this experiment. The manganese foil activations were all made both with and without cadmium covers, and the activities used were the difference of these two measurements. The value obtained in this manner for the density of neutrons at the center of the beam at the point S was 1.16×10^4 neutrons per cubic centimeter with an estimated probable error of 8 percent.

The half-life of the neutron is related to n the number of neutrons decaying per minute per cubic centimeter of beam and ρ the density of neutrons by the formula

$$T_{\frac{1}{2}}=(\rho/n)\times0.693.$$

Inserting the values quoted above, we find that $T_{\frac{1}{2}}=12.8$ min, with a probable error of 18 percent.

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[12] F. W. Fenning, Montreal Report MP-252, (1946), National Research Council of Canada (unpublished).