

## On the Interaction Between Neutrons and Electrons\*

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The possible existence of a potential interaction between neutron and electron has been investigated by examining the asymmetry of thermal neutron scattering from xenon. It has been found that the scattering in the center-of-gravity system shows exceedingly little asymmetry. By assuming an interaction of a range equal to the classical electron radius, the depth of the potential well has been found to be  $300 \pm 5000$  ev. This result is compared with estimates based on the mesotron theory according to which the depth should be 12000 ev. It is concluded that the interaction is not larger than that expected from the mesotron theory; that, however, no definite contradiction of the mesotron theory can be drawn at present, partly because of the possibility that the experimental error may have been underestimated, and partly because of the indefiniteness of the theories which makes the theoretical estimate uncertain.

### INTRODUCTION

THE purpose of this paper is to investigate an interaction between neutrons and electrons due to the possible existence of a short range potential between the two particles. If such a short range force should exist, one would expect some evidence of it in the scattering of neutrons by atoms. The scattering of neutrons by an atom is mostly due to an interaction of the neutrons with the nucleus. In addition, there is a somewhat smaller interaction of neutrons and the electron system which has been observed by Bloch and his co-workers in their work on polarization of neutrons. This interaction is due to the magnetic field produced by the electronic currents within the atom acting on the magnetic moment of the neutron and will be referred to as magnetic interaction. Except for negligible higher order perturbations that will be discussed later, the magnetic interaction should not exist for atoms in which the electrons are bound in closed shells. In the present work, noble gases have been used in order to eliminate perturbations due to this magnetic interaction.

Besides the magnetic interaction, one might expect also the existence of a spin independent potential energy between neutron and electron. Such an interaction could be expected, for example, according to the current mesotron theories

of nuclear forces. According to these theories, proton and neutron are basically two states of the same particle, the nucleon. A neutron can transform into a proton according to the reaction:

$$N = P + \bar{\mu}. \quad (1)$$

( $N$  = neutron,  $P$  = proton,  $\bar{\mu}$  = negative mesotron)

Actually, a neutron will spend a fraction of its time as neutron proper (left-hand side of Eq. (1)) and a fraction of its time in a state that can be described as a proton with a negative mesotron nearby, (right-hand side of Eq. (1)). The system oscillates with extremely high frequency between these two forms and the fraction of the time spent in either of them is different depending on the specific form of mesotron theory.

According to the estimate given in Section 4, the neutron may spend 20 percent of the time as proton and negative mesotron and 80 percent of the time as neutron proper.

If these views are correct, in the immediate vicinity of a neutron one would expect an electric field of a strength equal to that produced by a charge  $0.2e$ ,  $e$  being the proton charge. Of course, this field would extend only to a very small distance, because it would be screened by the negative charge of the mesotron, which is present whenever the nucleon is in the proton form. Indeed, the range of this electric force would be of the order of magnitude of the distances of the negative mesotron from the nucleon, that is about  $10^{-13}$  cm. This force should be attractive and could be represented as a potential hole of

\* Footnote added in proof: Havens, Rabi and Rainwater (Phys. Rev. 72, 634 (1947)) have published results similar to the present ones obtained by a somewhat different method. Their results are in essential agreement with those of the present work.

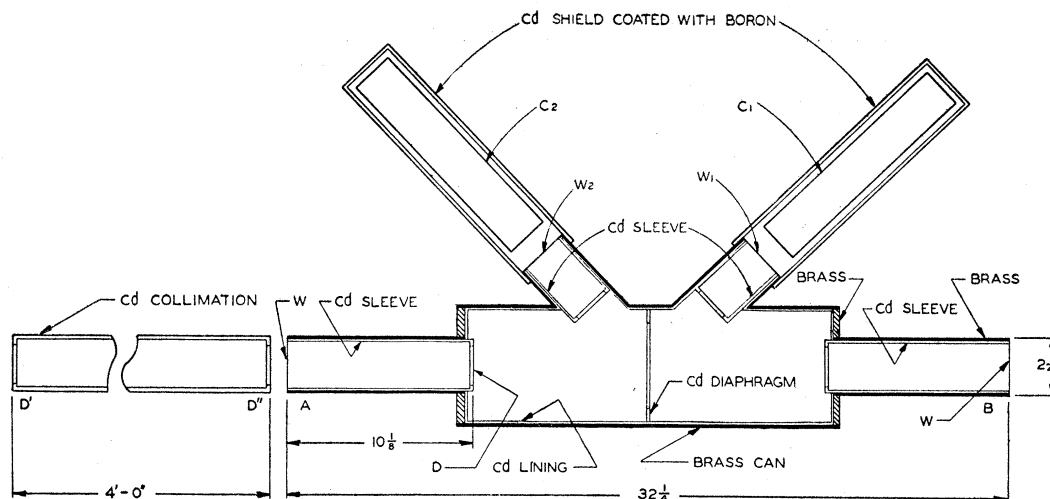


FIG. 1. Diagram of apparatus.

extremely small diameter. In the present paper, an attempt to detect an interaction of this type between neutrons and electrons is described.

If the scattering of neutrons were due only to nuclear interaction, one would expect the scattering to be spherically symmetrical in the center-of-gravity system whenever the wave-length of the neutron is large compared with nuclear dimensions. This last condition is very amply fulfilled for thermal neutrons which have a wave-length of the order of  $2 \times 10^{-8}$  cm, about 20,000 times larger than the nuclear dimensions. One would expect, therefore, that thermal neutrons should be scattered by nuclei in spherically symmetrical waves in the center-of-gravity system.

Deviations from the spherical symmetry can be due to several causes. The scattering atoms may be paramagnetic, in which case there is the magnetic interaction already discussed. A second reason for possible asymmetries in the scattering is interference of the waves scattered by different atoms. Such interference will be expected, both in solid and liquid elements and in gases with more than one atom in the molecule. Finally, asymmetric scattering could be due to a short range potential interaction whose investigation is the main object of this paper.

In order to eliminate the first two types of asymmetry, the experiments to be described were performed on xenon at pressures of the order of one atmosphere. An attempt was made to detect

deviations from the spherical symmetry in the scattering of slow neutrons by this element.

If a short range potential interaction between neutron and electron should actually exist, one would expect the scattered waves to result from the interference of a spherically symmetrical wave scattered by the nucleus and a non-symmetrical wave scattered by the electrons. This last wave is expected to be non-symmetrical because the electrons are spread through a region of dimensions of the order of  $10^{-8}$  cm, comparable to the wave-length of the neutrons. The interference of these two waves should make the intensity of the scattered beam a function of the scattering angle, as will be discussed in detail in Section 3.

#### SECTION 1. EXPERIMENTAL PROCEDURE

The apparatus used for the experiment is shown in Fig. 1. It consists of a tank of the dimensions and shape indicated in the figure, lined with cadmium as indicated, except for the four windows  $A$ ,  $B$ ,  $W_1$ ,  $W_2$ . A beam of thermal neutrons from the thermal column of the heavy water pile at the Argonne National Laboratory was allowed to pass along the axis of this tank. The beam was collimated by the cadmium diaphragms  $D$ ,  $D''$ ,  $D'$   $1\frac{1}{2}$  inches in diameter. The tank was filled with xenon at the pressure of about one atmosphere and the neutrons scattered by the gas were recorded by the 2  $\text{BF}_3$ -counters

$C_1$  and  $C_2$ . The counter  $C_1$  records the neutrons scattered at an angle of about  $45^\circ$  with the direction of the primary beam and the counter  $C_2$  records neutrons scattered at an angle of  $135^\circ$ . In order to correct unavoidable differences in sensitivity and geometry between the two counters, all the apparatus can be turned around, so that the neutrons enter through window  $B$  instead of entering through window  $A$ . Cadmium screens could be inserted in front of the windows  $W_1$  and  $W_2$ . In all measurements Cd differences were taken.

Each run of the experiment consisted of four measurements, each of which was a cadmium difference. Two of them were taken with the apparatus in the position indicated in the figure (position  $A$ ) and two with the apparatus turned around (position  $B$ ). With the apparatus in position  $A$ , one takes first the number of counts in  $C_1$  and  $C_2$  with xenon inside the tank. The counts so observed must be corrected for a background. This is obtained by taking a second series of counts while the xenon is frozen out of the tank into a liquid air trap, not shown in the figure. Let  $n_{1a}$  and  $n_{2a}$  be the net number of counts per minute in the two counters. The same two measurements are performed successively with the whole tank in position  $B$ . Let  $n_{1b}$  and  $n_{2b}$  be the net number of counts observed in the counters  $C_1$  and  $C_2$  on this second measurement. The expression

$$\rho = [(n_{1a}/n_{2a})(n_{2b}/n_{1b})]^{1/2} \quad (2)$$

gives the ratio of the scattering in the two directions at  $45^\circ$  and  $135^\circ$  corrected for the possible differences in sensitivity of the two counters.

The numbers from a typical run are given in Table I.

Two series of measurements were made, with two different pairs of counters. In each series, ten complete measurements like the one given above were taken. The consistency of the two series may be seen in Table II.

The result is

$$\rho = 1.0235 \pm 0.0085. \quad (3)$$

The errors indicated are mean square errors obtained by a statistical study of the consistency of the various runs. They are only slightly larger than the statistical errors calculated from the actual number of counts.

## SECTION 2. CORRECTIONS

Some corrections must be applied to the results (3) in order to arrive at the true ratio of the intensities scattered in the center-of-gravity system for scattering angles  $45^\circ$  and  $135^\circ$ .

Although xenon is rather heavy, one cannot altogether neglect the fact that the center of gravity of the neutron-atom system does not coincide with the center of the atom. In computing the correction due to this effect one must also take into account the fact that the scattering atoms are in thermal agitation at room temperature. There is, in addition, a geometrical correction. Although the beam going through the tank is rather well collimated, it still diverges a little while going through the tank. This introduces an asymmetry which is not eliminated by switching the tank from position  $A$  to position  $B$  and must be, therefore, corrected by calculation. Here is a brief outline of the methods used for calculating these corrections.

TABLE I. Data of a typical run.

Position	Counter	Cd	Xe	c/min	c/min cadmium difference	Net
A	$C_1$	no	yes	720	434	448 = $n_{1a}$
		yes	yes	286		
		no	no	276	-14	
		yes	no	290		
A	$C_2$	no	yes	690	429	421 = $n_{2a}$
		yes	yes	261		
		no	no	262	8	
		yes	no	254		
B	$C_1$	no	yes	726	414	406 = $n_{1b}$
		yes	yes	312		
		no	no	311	8	
		yes	no	303		
B	$C_2$	no	yes	635	400	392 = $n_{2b}$
		yes	yes	235		
		no	no	227	8	
		yes	no	219		

TABLE II. Comparison of data from two pairs of counters.

	$\frac{n_{1a}}{n_{2a}}$	$\frac{n_{2b}}{n_{1b}}$
First pair of counters	1.064	0.916
	1.064	0.975
	0.986	1.030
	1.017	0.920
	1.035	0.966
	1.104	1.019
	1.110	0.919
	1.155	1.019
	1.127	0.964
	—	0.955
Average	$1.074 \pm 0.018$	$0.968 \pm 0.014$
$\rho = \left( \frac{n_{1a}n_{2b}}{n_{2a}n_{1b}} \right)^{\frac{1}{2}} = 1.020 \pm 0.012$		
Second pair of counters	0.943	1.031
	1.000	1.091
	0.892	1.047
	1.059	1.074
	0.884	1.116
	1.035	1.109
	1.020	1.028
	0.932	1.044
	0.971	1.100
	1.005	1.183
—	1.093	
Average	$0.974 \pm 0.019$	$1.083 \pm 0.014$
$\rho = \left( \frac{n_{1a}n_{2b}}{n_{2a}n_{1b}} \right)^{\frac{1}{2}} = 1.027 \pm 0.012$		
Combined result: $\rho = 1.0235 \pm 0.0085$ .		

### a. Doppler Effect Correction

We consider an infinitely collimated beam of monochromatic neutrons being scattered by a gas, whose atoms move with a Maxwell distribution of velocity. The scattered neutrons are observed in a direction forming an angle  $\theta$  with the direction of the primary beam and are observed with a counter covering a small solid angle  $\Delta\omega$ . Two alternative assumptions are made as to the sensitivity of this counter: (1) the counter is a "thin" detector, in which case the sensitivity follows the  $1/v$ -law; (2) the counter is a "thick" detector, in which case the sensitivity is independent of the velocity of the neutron. If one assumes that the scattering of the neutrons is spherically symmetrical in the center-of-gravity system, one can calculate in a straightforward way the dependence upon  $\theta$  of the number of counts recorded. One finds that the angular dependence is represented by the following factors:

For assumption 1,

$$1 + \frac{\cos\theta}{A} \left( 1 + \frac{KT}{MV^2} \right), \quad (4)$$

and for assumption 2,

$$1 + \frac{1}{A} \left( 2 \cos\theta - 1 + \frac{KT}{MV^2} \right). \quad (5)$$

$A$  is the atomic weight of the scattering atoms,  $M$  and  $V$  are mass and velocity of the neutrons. In both formulae, terms of the order of  $1/A^2$  have been neglected.

In the actual case, the neutrons used were not monochromatic, but had approximately a Maxwellian distribution corresponding to room temperature. The correction factors (4) and (5) must, therefore, be averaged for such a distribution. The correction factors so averaged are for assumption 1,

$$1 + (2 \cos\theta/A), \quad (6)$$

and for assumption 2,

$$1 + (2 \cos\theta - \frac{1}{2})/A. \quad (7)$$

In the actual cases,  $\theta$  has the two values  $45^\circ$  and  $135^\circ$ , and we are interested in the ratio of the correction factors for these two values. Within our approximation, this ratio is the same for assumptions (1) and (2) and equal in both cases to:

$$1 + \frac{2\sqrt{2}}{A} = 1.022 \quad \text{for } \text{Xe}(A=130). \quad (8)$$

### b. Other Geometrical Corrections

The experimental results must also be corrected for another reason. The beam entering the tank is collimated by an opening of 1.5 in. diameter at  $D$  and an opening of equal diameter at  $D'$ , the distance between the two being 178 cm. The beam that passes through these two diaphragms is slightly spread and is, therefore, surrounded by a penumbra which increases with the distance from  $D$ . Consequently the two counters  $C_1$  and  $C_2$  see a beam of slightly different shape. As already pointed out, this difference between the two counters is not corrected by inversion of the tank.

In order to correct for this effect, the following procedure was adopted. An auxiliary experiment

was carried out in order to determine the sensitivity of the counters to thermal neutrons originating at different places. A counter was surrounded with cadmium, shaped as in Fig. 2, and was mounted on the tool holder of a lathe so that it was possible to move it parallel to itself into any desired position. A small source of thermal neutrons was obtained by exposing a small copper plate weighing about one gram to a beam of thermal neutrons. The neutrons scattered by this copper plate were recorded for a number of positions of the counter. In all cases the average of the readings obtained with the counter at two positions symmetrical with respect to a plane perpendicular to the neutron beam and passing through the copper scatterer was taken. This procedure corrects for the asymmetries of the source. In this way, the sensitivity of the counter surrounded by its cadmium shield was mapped as a function of the relative position of the source of scattered neutrons with respect to the counter.

The geometric corrections were calculated by dividing the volume of the beam seen by either of the counters  $C_1$  or  $C_2$  in about 200 parts. For each such section, the intensity of the radiation scattered into each counter was computed using the previously described calibration of the counter sensitivity and all the results were added. In this calculation, the Doppler correction and the correction due to the absorption of the beam were included. This rather lengthy calculation gave the following result.

If the scattering were symmetrical in the center-of-gravity system, the front counter  $C_1$  would record a slightly larger number of counts than the back counter  $C_2$ . The ratio of the number of counts would be  $\rho = 1.024$  in the case of Xe. It should be noticed that this number is quite close to the corresponding number (8) obtained by applying only the Doppler correction and assuming that otherwise the geometry is ideally well collimated. This indicates that the error due to lack of collimation is a minor one. The calculated values of  $\rho$  should be compared with the observed value (3). The difference can be attributed to a deviation of the scattering from the spherical symmetry in the center-of-gravity system.

The observed relative difference between forward and backward scattering, with all correc-

tions, is therefore

$$-0.0005 \pm 0.0085. \quad (9)$$

### SECTION 3. CALCULATION OF AN UPPER LIMIT FOR THE ELECTRON-NEUTRON INTERACTION

Both the sign and magnitude of the interaction between neutrons and electrons can be calculated from the ratio of the scattering intensities for the scattering angles  $45^\circ$  and  $135^\circ$ .

A short-range interaction between the neutron and other particles such as the nucleus or the electrons can always be represented in the Hamiltonian by terms proportional to the  $\delta$ -function of the vector leading from the other particle to the neutron. Accordingly, the interaction of the neutron with the nucleus shall be represented by:

$$a\delta(\vec{r}), \quad (10)$$

and the interaction with each electron by terms of the form,

$$b\delta(\vec{r}-\vec{r}_e), \quad (11)$$

where  $\vec{r}$  is the radius vector from the nucleus to the neutron, and  $\vec{r}_e$  is the radius vector from the nucleus to one of the electrons. The constants  $a$  and  $b$  give a measure of the interactions of the neutron with the nucleus and with one electron. They have the dimensions of energy times volume. Indeed, when the interaction is weak, as is

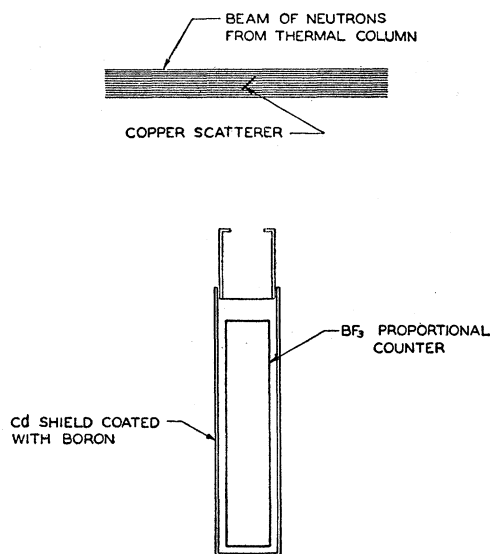


FIG. 2. Arrangement used to make geometrical corrections.

the case for the neutron-electron interaction, the coefficient  $b$  is simply equal to the volume integral of the potential energy between the two particles. If the potential energy between electron and neutron is a function  $U(r)$  of the distance  $r$  between the two particles, then

$$b = 4\pi \int_0^\infty U(r)r^2 dr. \quad (12)$$

We can now apply the Born approximation in order to find out the scattering in the various directions due to the interactions (10) and (11). A straightforward calculation, based on the Born approximation gives the following differential cross section for scattering within the element of solid angle  $d\omega$ :

$$d\sigma = \frac{M^2 d\omega}{4\pi^2 \hbar^4} (a + bZ\mathfrak{F}(\theta))^2. \quad (13)$$

$\mathfrak{F}(\theta)$  represents the form factor of the electron distribution. A simple expression for the form factor has been given by Bethe.<sup>1</sup> By means of his results, the form factors at  $45^\circ$  and  $135^\circ$  can be calculated for Xe ( $Z = 54$ ). One finds

$$\begin{aligned} \mathfrak{F}(45^\circ) &= 0.776, \\ \mathfrak{F}(135^\circ) &= 0.515. \end{aligned}$$

The difference of the form factor for the two scattering angles is responsible for the asymmetry in the scattering.

In the parenthesis of formula (13), the second term is very small compared with the first and one can neglect terms containing  $b^2$ . It follows that the ratio of the intensity scattered in two directions at  $45^\circ$  and  $135^\circ$  is given by:

$$1 + 2Z \left[ \frac{\mathfrak{F}(45^\circ) - \mathfrak{F}(135^\circ)}{a} \right] \frac{b}{a} = 1 + 28.2 \frac{b}{a}. \quad (14)$$

Comparison of these values with the experimental result (9) allows one to determine the ratio  $b/a$  between the interaction constants for neutron-electron and neutron-xenon nucleus. One finds

$$b/a = -0.00002 \pm 0.00030. \quad (15)$$

In order to obtain  $b$ , we calculate the nuclear interaction constant  $a$  from the scattering cross section.

<sup>1</sup> H. A. Bethe, Ann. d. Physik 5, 385 (1930).

The scattering cross section of xenon was determined by comparison of the scattered intensity (average of the net counts in the two counters  $C_1$  and  $C_2$ ) when the tank was filled with xenon or nitrogen. The scattering cross section of the molecule  $N_2$  was assumed to be  $20 \times 10^{-24}$ . It was found in this way that the scattering cross section of xenon is  $4.4 \times 10^{-24}$ . Disregarding the very small correction due to the electron interaction term  $b$ , it follows from (13) that the scattering cross section is given by

$$M^2 a^2 / \pi \hbar^4. \quad (16)$$

From this formula one finds

$$a = 2.46 \times 10^{-42} \text{ ergs} \times \text{cm}^3 \text{ for Xe.} \quad (17)$$

The sign of  $a$  is almost certainly positive. This choice is justified by the fact that nuclear interaction constants have been found to be positive for almost all nuclei.<sup>2</sup>

From (15) and (17) the value of  $b$  can be calculated. One finds

$$b = (-5 \pm 74) \times 10^{-47} \text{ ergs} \times \text{cm}^3. \quad (18)$$

As previously stated, the experimental error is a mean square error computed from the coherence of the various sets of measurements and it is only slightly in excess of the statistical error. In spite of that, one cannot guarantee that the actual value of  $b$  will lie within the limits as indicated in formula (18). It should be noted that the interaction constant  $b$  is found to be of the order of 10,000 times smaller than the constant of the interaction between a neutron and a proton or even smaller.

If the constant  $b$  should ultimately turn out to be negative it would mean that the potential between neutron and electron is negative (attractive force).

According to (12),  $b$  is the volume integral of the potential hole. Experiments of the type here discussed do not allow an independent determination of the depth and volume of the potential hole. If one assumes arbitrarily, that the potential hole has a volume equal to the classical volume of the electron,

$$V_{el} = (4\pi/3)(e^2/mc^2)^3 = 0.94 \times 10^{-37} \text{ cm}^3, \quad (19)$$

one finds from (18) the depth of the attractive

<sup>2</sup> E. Fermi and L. Marshall, Phys. Rev. 71, 666 (1947).

potential to be

$$\begin{aligned} \overline{U(r)} = b/V_{el} &= (-6 \pm 79) \times 10^{-10} \text{ ergs} \\ &= -300 \pm 5000 \text{ ev.} \end{aligned} \quad (20)$$

Before concluding this section, the effect of two possible perturbations should be discussed. It has been stated in the introduction that for atoms in which the electrons are bound in closed shells, no magnetic interaction between the neutron-electron system is to be expected. While this is certainly true in first approximation, one might, in reality, expect a small perturbation of this type to appear in second approximation, through the interaction of the magnetic moment of the neutron with currents in virtual excited states of the noble gas electron system. A closer discussion shows, however, that the contribution of the second order effect is quite negligible. By applying the conventional methods of quantum mechanics, one can readily estimate the interaction constant corresponding to this perturbation. This constant is found to be of the order of magnitude

$$(e\hbar/2Mc)^2 e^2 \lambda^2 / mc^2 R^3 \approx 10^{-48} \text{ ergs} \times \text{cm}^3. \quad (21)$$

In this formula  $e\hbar/(2Mc)$  is the nuclear magneton,  $\lambda$  is its wave length divided by  $2\pi$ ,  $R$  is the average radius of the electronic orbit.

It is seen that the correction (21) is entirely negligible compared with the value (18) of  $b$ .

There is a second possible interaction between neutron and atom that could lead to an asymmetric scattering. When the neutron passes by the atom and penetrates the electronic system, it is exposed to an electric field due to the unscreened part of the nuclear charge. Since the neutron is moving, this electric field in the frame of reference of the neutron gives rise to an apparent magnetic field. This last interacts with the magnetic moment of the neutron, giving rise to a mutual energy, which might be capable of contributing a scattering asymmetry. A closer discussion shows that the error introduced by neglecting this effect is negligible. The main reason is that scattering due to the interaction just mentioned is always connected with a change in the spin direction of the neutron. There can be, therefore, no strengthening of this effect by interference with the large nuclear scattering, since in the latter case, change of the spin direction of

the neutron on scattering is always coupled with a change in the spin state of the nucleus.

#### SECTION 4. COMPARISON WITH THE MESOTRON THEORY

The results (18) or (20) should be compared with the expectations of the mesotron theory.

From the qualitative discussion already given in the introduction it is clear that, according to the mesotron theory, a short-range attractive potential between neutron and electron should be expected. On the other hand, because of the indefiniteness of the mesotron theories, it is not feasible to predict in a precise way the strength of the interaction to be expected. Indeed, most mesotron theories require elimination of divergences by cutting off the field at a distance from the nucleon of the order of  $10^{-13}$  cm, which is just the expected range of the electric field surrounding the neutron.

A second point that should be mentioned in this connection is the influence on the neutron-electron interaction of the size of the electron. If we take the classical picture of the electron as a small sphere throughout whose volume negative electricity is spread, and we assume also, in a purely classical way, that the neutron is surrounded by a short range electric field, one would expect that the range of the interaction is of the order of magnitude of the largest of the two lengths, radius of the electron and range of the electric field surrounding the neutron. If the radius of the electron is larger than the range of the electric field, the interaction will extend, therefore, to a distance of the order of the electron radius. In this sense, the size of the electron influences the expected potential hole in that if the radius of the electron is taken larger, the potential hole becomes shallower and wider. Actually, one can determine on this classical model that the interaction constant, namely, the volume integral over the potential hole, is not influenced by the size of the electron. We can, therefore, in these estimates, regard the electron as a point-charge.

One possible approach to a semi-quantitative estimate of the interaction to be expected, according to the mesotron theory, is the following.

According to the most simple forms of mesotron theory, the wave function describing the

mesotrons in the vicinity of the nucleus is of the form

$$(e^{-\mu cr/\hbar})/r, \quad (22)$$

where  $\mu$  is the mesotron mass. To this wave function there corresponds a density distribution of the mesotrons proportional to the square of (22); namely, to

$$\frac{\exp[-2\mu cr/\hbar]}{r^2}. \quad (23)$$

One can then calculate in an elementary way the electric field  $E$  at a distance  $r$  from the center of the neutron,

$$E = \frac{ze}{r^2} \exp[-2\mu cr/\hbar], \quad (24)$$

where  $z$  is the fraction of the time that the neutron spends in the state represented by the right-hand side of Eq. (1) (proton and negative mesotron).

From (24) one can immediately calculate the potential energy for an electron in the electric field surrounding the neutron. One finds

$$\begin{aligned} U &= -e \int_r^\infty E dr \\ &= -ze^2 \int_r^\infty (dr/r^2) \exp[-2\mu cr/\hbar]. \end{aligned} \quad (25)$$

From (25) and (12) we obtain finally the interaction constant

$$b = -(\pi/3)(ze^2\hbar/\mu^2c^2)^2. \quad (26)$$

A simple procedure for estimating the value of  $z$  is given here. One of the objectives of the mesotron theory is to explain the neutron magnetic moment as the magnetic moment of the virtual

mesotron field surrounding the neutron. If such an interpretation is correct and if we assume further that each mesotron bears a magnetic moment equal to  $e\hbar/2\mu c$ , we are led to the estimate that the average number of mesotrons near a neutron is 0.2. Therefore, in calculating the numerical value of (26), we shall use  $z=0.2$ . Assuming a mesotron mass 200 times larger than the electron mass, we find from (26)

$$b = -1.8 \times 10^{-45}. \quad (27)$$

If we spread the interaction over the potential hole having the volume (19) we find that the depth of the potential hole is 12,000 ev.

### SECTION 5. CONCLUSIONS

The comparison of the last result with the experimentally found depth of  $-300 \pm 5000$  ev indicates an experimental value appreciably less than the theoretical estimate. This does not necessarily mean that this experiment decisively contradicts the mesotron theory. On one hand, the experimental error may be somewhat larger than has been indicated. On the other hand, the theory outlined is obviously exceedingly crude. It may very well be that some mesotron theory eventually will lead to a lower estimate of the depth of the well. It would seem that the experimental result is sufficiently conclusive to exclude the so-called strong coupling theories according to which  $z=0.5$  and the depth is therefore about 30,000 ev which appears to be well outside of our experimental error.

A final conclusion one might draw from these experiments is that no interaction of an order of magnitude larger than that predicted by the mesotron theory exists between neutron and electron.

Our thanks are due to Dr. A. Wattenberg for help in this experiment.