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The Nuclear Scattering of 1-Mev Electrons and Positrons

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The scattering of 1-Mev electrons and positrons by thin foils has been investigated from two points of view: (1) to compare the cross section for elastic nuclear scattering of positrons with that of electrons, and (2) to look for evidence of inelastically scattered electrons which have suffered large energy losses. The first experiment is of interest because theory predicts a large difference between electron and positron scattering as a result of spin-orbit coupling, and thus involves the magnetic moment of the electron. The second experiment is of importance because there have been many conflicting reports on the existence of inelastic scattering whereas theoretically one expects almost no inelastic scattering.

Electrons and positrons from artificially radioactive sources were energy selected by a solenoidal spectrometer before being scattered by various foils. After being scattered, the particles entered a second, analyzer, magnetic field and were then detected by a Geiger counter. To study inelastic scattering of electrons the analyzer field was varied. To study the e^-/e^+ scattering ratio, various scatterers could be employed without changing the equipment in any way except to replace the electron source by a positron source. Thus the e^-/e^+ scattering ratio could be measured with greater accuracy than the scattering of either particle separately.

The observed e^-/e^+ scattering ratio 2–3 is consistent with a rather rough theory which does not take into account screening. No inelastic scattering was found in foils of copper, aluminum, or platinum.

INTRODUCTION

It is perhaps surprising that there have not been any measurements of positron scattering by nuclei more precise than those of Fowler and Oppenheimer,[1] Lasich,[2] and Seliger,[3] especially since Massey[4] has predicted a large effect due to spin-orbit coupling in such a scattering experiment. There have been no other investigations of the magnetic interactions of positrons; in fact there have been surprisingly few attempts to study their behavior directly and verify the assumption that they act as Dirac particles of positive charge.

Another aspect of electron-nuclear scattering which bears further investigation is inelastic scattering. A number of experimenters[5–10] have reported the observation of much more inelastic scattering than is predicted by theory. A typical result is that of Klarmann and Bothe, who report that 48 percent of the observed scattered particles lost over 20 percent, and 21 percent had lost over 50 percent of their initial energy. All these experimenters used cloud chambers in magnetic fields measuring track curvatures to obtain energy values. Bothe,[11] using a Geiger counter with magnetic beta-ray spectrograph to measure energies of electrons, failed to observe any anomalous inelastic scattering at 210 and 370 kev.

The present work attempts to study the elastic scattering of 1-Mev positrons and electrons in copper and platinum with greater precision than that of the previous investigations. This is achieved by use of Geiger counters, rather than cloud chambers to obtain better statistics. By using the same apparatus with positron and electron sources, the ratio of electron scattering to positron scattering can be determined directly to a precision much greater than could be obtained in an absolute measure of either cross section independently, and with less possibility of errors.

The apparatus used to study elastic scattering is then also used to look for anomalous inelastic scattering in aluminum, copper, platinum, and lead.

THEORY

The scattering of charged particles by a Coulomb field is independent of the sign of the charge only in the nonrelativistic region. The relativistic corrections to the sign-independent Rutherford formula are sign-dependent and appreciable. Thus, in the 1-Mev region, the scattering at 60° of positrons by heavy nuclei differs from that of electrons by a factor of three![4]

This effect can be interpreted as a result of spin-orbit coupling and has been considered in detail by Mott,[12] using the Dirac equation. Similar qualitative results are obtained from a more naive approach, treating the Dirac electron classically as a combination point charge and magnetic dipole, giving a simple physical picture of the phenomenon.

Consider an electron passing the nucleus at a large distance, so that the deflection is small, and the undeflected path can be used to consider the effect of the magnetic interaction. The moving dipole sees the nuclear Coulomb field as a magnetic field **H** which

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[1] W. A. Fowler and J. Oppenheimer, Phys. Rev. **54**, 320 (1938).

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[3] H. H. Seliger, Phys. Rev. **78**, 491 (1950).

[4] H. W. S. Massey, Proc. Roy. Soc. (London) **A181**, 14 (1942).

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[11] W. Bothe, Z. Naturforsch. **4a**, 88 (1949).

[12] N. Mott and H. W. S. Massey, *Theory of Atomic Collisions* (Oxford University Press, Oxford, 1950), 2nd Edition, p. 74.

exerts a force

$$\mathbf{F}=(\boldsymbol{\mu}\cdot\nabla)\mathbf{H}=-(\mathbf{v}/c)\times(\boldsymbol{\mu}\cdot\nabla)\mathbf{E} \tag{1}$$

where $\boldsymbol{\mu}$ is the magnetic moment of the electron, $\mathbf{v}$ the velocity, and $\mathbf{E}$ the electric field at the position of the electron.

If the electron is polarized parallel or antiparallel to the direction of motion, the first-order effect is a force perpendicular to the plane of the motion, which reverses sign as the electron passes the nucleus, and therefore gives the electron path a small deviation but no angular deflection. The second-order effect results in an angular deflection which is always toward the nucleus and is independent of the sign of the charge or the spin direction. The second-order force can be calculated from Eq. (1) by using for $\mathbf{v}$ the transverse component of velocity given by the first-order effect. This force is found to be of order of magnitude

$$F\sim(Ze^2/r)[(Ze^2/\hbar c)(\hbar/mcr)^3]$$

where Z is the atomic number of the scattering nucleus, and r is the distance of the electron from the nucleus.

Comparing this with the Coulomb force Ze^2/r^2, it is evident that the spin-orbit force is significant for heavy nuclei where $Ze^2/\hbar c\sim 1$, and for electrons which come closer to the nucleus than the Compton wavelength $(\hbar/mc)$ of the electron.

From this naive picture, the following qualitative results are obtained which are confirmed by the rigorous calculation: (1) The scattering of negative electrons is increased, that of positrons is decreased, since the spin-orbit force is always attractive. (2) The effect is greater for nuclei of high atomic number. (3) The effect is greater for electrons than for positrons, since the former pass closer to the nucleus.

The exact quantum-mechanical calculation is laborious and complicated because of the screening of the nucleus by the atomic electrons. Barlett and Watson[13] and Massey[4] have calculated the scattering of electrons and positrons by unscreened mercury nuclei, and McKinley and Feshbach[14] give a series for light and medium nuclei. Calculations for a screened Coulomb field[15–17] have been made only for electrons, but not for positrons. These show that the effect of screening is appreciable; being 10 percent for 1-Mev electrons scattered at 60°.

For the present work, the unscreened theory is used for comparison with experiment, since there is no complete screened theory. A discrepancy between experiment and the unscreened theory of the order of 10 percent should be expected, and greater precision in the experimental result cannot be interpreted using present theory. Since such precision is easily obtainable, it is hoped that a calculation of the scattering of positrons by a screened Coulomb field will be undertaken in the near future.

For light nuclei, polystyrene and copper, the approximate formula of McKinley and Feshbach is used:

$$r=1-\beta^2\sin^2\tfrac{1}{2}\theta+\pi\alpha\beta(\sin\tfrac{1}{2}\theta)\cdot(1-\sin\tfrac{1}{2}).$$

r is the ratio of the relativistic electron scattering to Rutherford scattering, θ is the angle of scattering, α is $Ze^2/\hbar c$, and β is v/c.

The value of r for positrons is obtained by replacing α by $-\alpha$.

The validity of this approximation for light nuclei was checked by noting that the screening terms in the McKinley and Feshbach expansion had a negligible effect on the ratio of electron to positron scattering.

For platinum, the results of Bartlett and Watson and Massey were used. Although these were calculated for mercury, it is assumed that the error introduced thereby is small compared to that due to the neglect of screening.

MULTIPLE SCATTERING

Nearly all electron scattering experiments are affected to an appreciable degree by multiple scattering in the scattering medium, and many of the older experiments are seriously in error because of failure to make the proper corrections. Consequently, considerable effort has been made in the present work to reduce multiple scattering and to compute the necessary corrections. The details of the calculations are extremely laborious and are reported in the author's doctorate thesis and in an AEC technical report by Dr. T. Teichmann. I am deeply indebted to Dr. Teichmann for a very careful analysis of the problem.

A particle, emerging from a scatterer at a given angle θ with respect to the undeflected beam, may have suffered one or more collisions in passing through the scatterer. To determine the contribution of multiple scattering, it is convenient to divide it into two types: (1) scattering by an angle nearly equal to θ plus one or more small angle scatterings, (2) scattering by two or more large angles.

The first type of scattering is best calculated by an extension of the method of Butler[18] to the case of large angles (~60°). Much of the idea of this method seems to have been given first, albeit heuristically, by Chase and Cox.[19] After laborious calculations, a good deal more complicated than those given by Butler, one finds that the additional correction to the single scattering probability $P_1(\theta)$ (normalized to unity) is given by the following expression:

$$\Delta P(\theta)=t^{-2}e^{-\theta^2/4t}C(\theta,t)+tM_2(\theta)+\tfrac{1}{2}t^2M_4(\theta)+\tfrac{1}{6}t^3M_6(\theta)+\cdots$$

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where

$$t=2(\pi/0.00765)^2(e^2/mc^2)^2NsZ^{4/3}(w^2/(w^2-1))\times\int_0^{\theta_1}\sin\theta\,\sin^2\tfrac{1}{2}\theta\cdot P_1(\theta)d\theta$$

[N = number of scatterers per cm.^{3}
w = energy of electrons in units mc^2]

while $C(\theta, t)$, and $M_{2k}(\theta)$ are, respectively, rather nasty power series in θ and t, and complicated trigonometric functions of θ times derivatives of $P_1(\theta)$ up to the $2k$th. They are listed elsewhere. θ_1 is an angle rather larger than the cut-off angle (see Mott and Massey) and determined roughly so as to minimize $C(\theta, t)$ without making the remainder of ΔP (*viz.* the series in the M_k) too large.

The second type of scattering is principally double scattering, i.e., scattering by two angles greater than θ. This type of scattering can be calculated directly if the Rutherford formula is assumed for the single scattering formula. For the case where the scattered beam emerges normally from the foil, the fractional correction to single scattering due to double scattering by angles greater than θ_1 is approximately

$$\frac{\Delta P_2(\theta)}{P(\theta)}\approx\pi As\left\{\left(8+\left[\frac{1-\cos\theta}{\cos\theta}\right]^3\right)(1-\cos\theta)^{-1}\times\log\left(\frac{\csc^2\frac{1}{2}\theta_1-\csc^2\frac{1}{2}\theta}{\csc^2\frac{1}{4}\theta-\csc^2\frac{1}{2}\theta}\right)\right\}$$

where s is the foil thickness.

If this contribution of double scattering is small, that due to triple and higher order scattering involving more than two large angles can be considered to be negligible.

One particular type of double scattering of interest is the case where the first scattering is nearly in the plane of the foil.[20–22] The long path-length traversed by such a particle in the foil results in an appreciable probability for a second scattering. The energy loss due to ionization in the long-path length can be misinterpreted as inelastic scattering. For the case where the scattered beam emerges normal to the foil, the fractional contribution to the total scattering due to particles which traversed a path length in the foil between l_1 and l_2 is given by

$$\Delta P/P_1(\theta)=[2\pi P_1(\theta)(1-\cos\theta)^4/(1+\cos^2\theta)]\times[L/(L-l)+\log(l/(L-l))]_{l_1}{}^{l_2}$$

where $P_1(\theta)$ is the probability of single scattering by an angle θ, as given by the Rutherford formula, and L is the range of the particle in the scattering materials.

This effect is particularly large when the scattered beam emerges on the same side of the foil as the incident beam. For the case where both beams make equal angles with the normal,

$$\Delta P/P_1(\theta)=\{\pi P_1(\theta)[1-\cos\theta]^4[5-3\sin^2\tfrac{1}{2}\theta]\csc^6\tfrac{1}{2}\theta\}\times\{L/(L-l)+\log(l/(L-l))\}_{l_1}{}^{l_2}.$$

This may well account for the large energy losses observed by Le Prince Ringuet[9] in lead and silver foils of 0.1 mm. For 1-Mev electrons scattered by 120° in a 0.1-mm lead foil, this effect results in a large number of "inelastically" scattered particles. The probability of an energy loss between $\frac{1}{3}$ and $\frac{2}{3}$ of the original energy is twice the probability of elastic scattering!

EXPERIMENTAL PROCEDURE

A diagram of the apparatus is shown in Fig. 1. The scattering chamber is within a long solenoid, which is used to select a small energy band from the continuous spectrum of particles emitted from the source. Those which are selected by this solenoid spectrograph are incident upon the scattering foil along the elements of a cone, making an angle of 57.9°±2.7° with the axis, and have a momentum spread of ±8 percent. Those particles scattered along the axis emerge from the solenoid through the exit channel and enter the analyzer, where they are deflected by a transverse magnetic field into the thin window Geiger counter. The apparatus was evacuated to a pressure of between 10 and 50 microns, using a Cenco Hyvac pump.

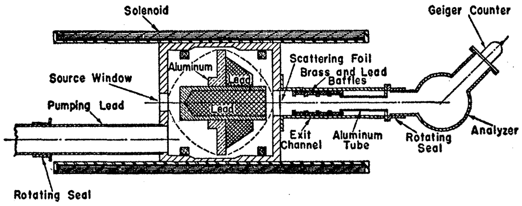

FIG. 1. Scattering apparatus.

The sources used for this experiment were Ce^{144} and Ga^{66}. A 300 millicurie source of Ce^{144} with radioactive daughter Pr^{144} was obtained from Oak Ridge and was a very satisfactory electron source, having an upper energy limit of 2.99 Mev and a half-life of 375 days. A high energy, long-lived source of positrons being unavailable, 9.4-hr Ga^{66} was used, made by α-particle bombardment of copper in the cyclotron at the Carnegie Institution of Washington.

The short half-life of the positron source and the necessity of transporting it from Washington to Princeton were the principal limitations of the elastic scattering experiment. Thus instead of studying the scattering over a wide range of angles, incident energies, and scattering materials, one angle was chosen (57.9°), three energies (0.7, 1.0, and 1.3 Mev), and three scattering materials (polystyrene, copper and plati-

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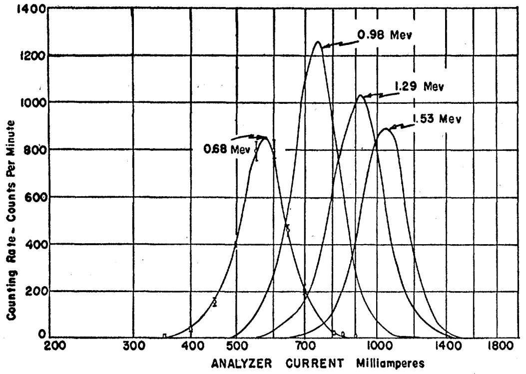

FIG. 2. Spectra of electrons scattered from 1-mil lead foil for incident energies of 0.68, 0.98, 1.29, and 1.53 Mev.

num). At these points the difference between positron and electron scattering is considerable, and the effects of spin-orbit coupling therefore quite noticeable.

Data were taken by inserting the source in the chamber and observing the counting rates of scattered particles for each energy and for each scattering material. Background counting rates, taken by removing the scattering foil, were subtracted. The complete data were taken using the electron source some time before the positron source arrived. The positron source was then continuously used until it was too weak to obtain significant data. Foils were changed at regular intervals so that the data at each point was the sum of a number of runs taken at various times during the life of the source. These data were checked for consistency with the known half-life of the source. After the positron run was completed, the electron run was repeated to reveal any possible changes in the apparatus between electron and positron runs.

The energy range of incident particles used was set by the solenoid field. The analyzer was set accordingly, and separated out the soft component of the scattered beam (inelastically scattered particles, knock-ons, etc.). Both fields were reversed in direction when changing from electrons to positrons.

The theory of McKinley and Feshbach predicts a difference of only 8 percent between the scattering of electrons and positrons from polystyrene. This value was accepted and the data from the polystyrene foil was used to normalize the electron and positron source strengths. Ratios of electron to positron scattering were then obtained for copper and platinum. The foil thicknesses used (15-mil polystyrene, 0.68-mil Cu, and 0.1- and 0.2-mil Pt), were the minimum possible to give reasonable statistics with the weak positron source used. They were still too thick to make multiple scattering as small as desired, but the corrections in most cases were of reasonable magnitude. The use of two thicknesses of platinum served as a check on the validity of the multiple scattering corrections.

The counting rates obtained with the cerium source were of the order of 300–400 counts per minute, depending on the scattering foil used, as compared with a background of 175–215 counts per minute. The gallium source gave counting rates initially of the order of 30–130 counts per minute, with a constant background of 40 counts per minute and a decaying background starting at about 60 counts per minute. Thus the data from the thinnest foils were well down in the background and long counts were required.

The investigation of inelastic scattering consisted simply of analyzing the beam of scattered particles into a momentum spectrum by varying the current in the analyzer magnet and recording the counting rate. A plot of the counting rate against the analyzer magnet current then gives a peaked curve, having a width corresponding to the energy resolution of the apparatus. Any inelastic scattering present should appear as a tail on the curve in the direction of decreasing analyzer current.

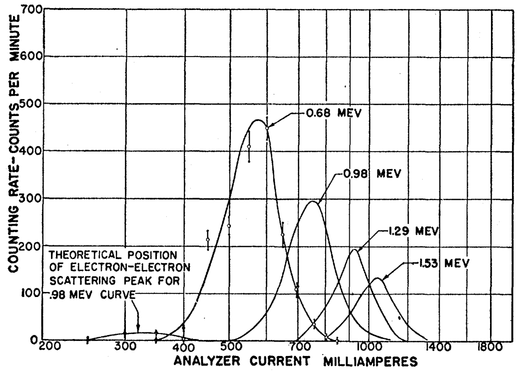

FIG. 3. Spectra of electrons scattered from 1-mil copper foil for incident energies of 0.68, 0.98, 1.29, and 1.53 Mev.

Spectra of scattered particles were taken at four incident energies from 0.68 to 1.53 Mev for foils of copper and lead. Spectra were also taken at 1 Mev for three different thicknesses of aluminum and platinum foils. These spectra represent attempts to search for inelastic scattering over a moderate energy range in representative light, medium, and heavy nuclei, and to observe, using the variation of foil thickness, any multiple effects which might otherwise be misinterpreted. Background spectra were taken with no scattering foil and subtracted from the corresponding spectra of scattered particles.

The spectra were plotted on semilogarithmic paper, as shown in Figs. 2, 3, 4, and 5. The logarithmic scale was used for analyzer current because the fractional rather than the absolute momentum resolution of the analyzer remains constant as the analyzer current is varied. On a semi-log plot, the measured counting rates can be plotted directly, with no correction factor for the resolution variation, and the area under the curve between any two abcissas is proportional to the number of scattered particles in that corresponding momentum interval.

SOURCES OF ERROR

In this experiment, the final data are counting rates in a Geiger counter. It is important to establish that these counts actually represent the phenomena to be investigated and are not due to any spurious effects. Background runs, taken with no scattering foil and subtracted, insure that the net data represent events occurring in the scattering foil. The analyzer magnet insures that all particles counted are in the desired energy range. But there are other effects, not excluded by these experimental precautions, which must be considered separately.

The principal source of error in this experiment is multiple scattering. In order to obtain reasonable counting rates with the available positron sources, foil thickness giving appreciable multiple scattering were required. Because the scattering cross section varies rapidly with energy, the amount of multiple scattering does also. Since it was not possible to change foil thicknesses for each energy measurement, a compromise value was chosen which is reasonable for mean energy. At the lower energy the multiple scattering was greater.

Calculations of multiple scattering of electrons and positrons were made using for the single scattering formulas the appropriate theoretical values of McKinley and Feshbach,[14] Mohr,[17] and Massey.[4] Table I shows the correction factors to the 4th and 6th order. It is clear from this table that the 6th-order correction to the e^-/e^+ ratio does not differ much from the 4th order except for the thickest foils of platinum at the lowest energy. In general the e^-/e^+ ratio correction factor is smaller and more constant than either of the single scattering corrections. An experimental check on the validity of the corrections is given by the comparison of two different thicknesses of platinum at the three energies used. Aside from the lowest energy, when the correction factor is large, it is gratifying that the agreement in corrected e^-/e^+ ratio is about as good as the statistical errors would allow.

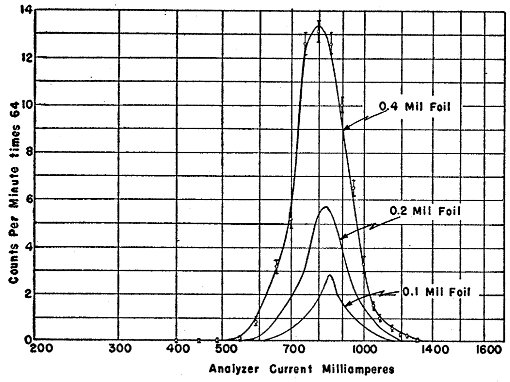

FIG. 4. Spectra of electrons scattered from platinum foils of various thicknesses. Incident energy 0.98 Mev.

Another possible source of error is scattering by the atomic electrons in the foil. Single electron scattering is easily distinguished from nuclear scattering because of the energy loss which is a unique function of the scattering angle. Multiple scattering destroys this uniqueness and results in a distribution of energy loss which can be confused with inelastic nuclear scattering. This effect is most significant in light elements, and can be eliminated by using thinner foils.

Scattering from chamber walls and gas atoms, annihilation of positrons, and the various possible interactions of the gamma-rays were all calculated roughly and found to have a negligible effect upon the results of this experiment.

RESULTS—INELASTIC SCATTERING

Figure 2 shows the spectra of scattered particles at four energies from a 1-mil lead foil. The experimental points and their standard deviations are shown for one curve, and are similar for the others.

These curves show no evidence for inelastic scattering in which the electron has lost more than 20 percent of its energy. Their breadth can be attributed completely to the energy resolution of the apparatus and to the variation of ionization energy loss due to the variable path lengths traversed in the material, as previously discussed.

It is clear from these spectra that the number of particles losing over 40 percent of their energy is extremely small, certainly less than 1 percent of the number of elastically scattered particles. There is no indication of any particles losing more than 20 percent of their energy, but these might conceivably be missed, due to the width of the spectrum. One can safely say that the total number of particles losing more than 20 percent of their energy is less than 5 percent of the total distribution.

Figure 3 shows similar results for copper, and the same conclusions can be drawn here as for the case of lead. Note that there is a subsidiary peak shown for the 0.98-Mev curve, which can be attributed to electron-electron scattering. The theoretical position of this peak is indicated on the graph and agrees very well with the curve. The magnitude of this peak is difficult

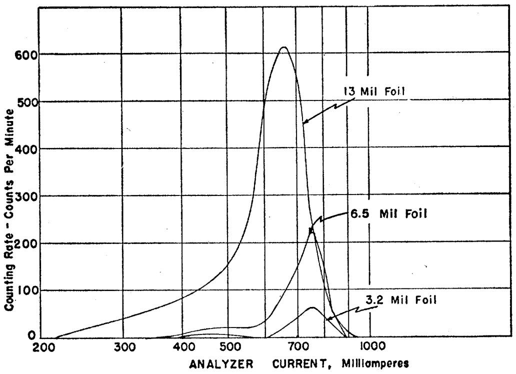

FIG. 5. Spectra of electrons scattered from aluminum foils of various thicknesses. Incident energy 0.98 Mev.

TABLE I. Summary of observed and corrected scattering of electrons and positrons by polystyrene, copper, and platinum.

Col. 1	2	3	4	5	6	7	8	9	10	11	12	13
Foil	Kinetic energy of $e\pm$	Corr. factor to single e^- scattering		Corr. factor to single e^+ scattering		Inverse Corr. factor to ratio of single e^-/e^+ scattering		Meas. value of e^-/e^+ ratio	Corrected value of e^-/e^+ ratio (Corrected to single scat.)		Theoretical value	Statistical error %
	(Mev)	4th order	6th order	4th order	6th order	4th order	6th order		4th order	6th order		
15-mil polystyrene	0.68	1.11	1.15	1.09	1.12	0.978	0.970					
	0.98	1.06	1.06	1.04	1.05	0.988	0.987					
	1.29	1.05	1.05	1.04	1.04	0.988	0.987					
0.68-mil copper	0.68[a]	1.23	1.52	1.23	1.53	0.995	1.001	1.73	1.72	1.73	1.46	4
	0.98	1.12	1.14	1.12	1.15	1.002	1.003	1.93	1.93	1.93	1.49	5
	1.29	1.06	1.07	1.06	1.07	0.997	0.997	2.07	2.06	2.06	1.51	11
0.2-mil platinum	0.68[b]	1.42	2.63	1.57	3.66	1.103	1.395	2.27	2.50	3.17	2.74	4
	0.98[a]	1.17	1.31	1.24	1.50	1.060	1.145	2.88	3.05	3.30	2.90	5
	1.29	1.18	1.21	1.43	1.49	1.211	1.228	3.00	3.63	3.68	2.98	11
0.1-mil platinum	0.68[c]	1.60	1.64	2.61	2.70	1.638	1.641	3.13	5.13	5.14	2.74	5
	0.98	1.06	1.07	1.08	1.10	1.022	1.028	3.13	3.20	3.22	2.90	4
	1.29	1.06	1.07	1.08	1.10	1.025	1.029	3.60	3.69	3.70	2.98	10

[a] In these cases the sixth-order correction is appreciable compared to the total up to the fourth order, but the relative correction for positrons and electrons remains nearly the same, and it is therefore felt that the corrections are reliable.

[b] For obvious reasons this correction cannot be regarded as reliable.

[c] The correction here could be applied in such a way that the bulk of it came from the central (Gaussian) distribution, rather than from the tail. Hence, the contributions from orders higher than the fourth could be made small, even though the correction up to the fourth order was large. It was not possible to do this for the other points with large fourth-order corrections.

to determine accurately because of the statistical error, but it is the right order of magnitude, approximately $1/Z$ times the elastic peak, the curves of other energies do not show the electron-electron peak, either because it is at too low an energy, or because its magnitude is not appreciably greater than the statistical error.

The same absence of inelastic scattering is shown on the curves for platinum at 0.98 Mev. There is no significant difference between the three foil thicknesses. The displacement of the peak toward lower energies and the broadening of the distribution with increasing foil thickness is the result of the ionization energy loss.

A definite indication of inelastic scattering appears in the spectrum of scattered particles from the 13-mil aluminum foil. A large tail is present at the low energy end of the spectrum. However, the tail is greatly diminished in the curve for the 6.5-mil foil, and it is hardly observable in the curve for the 3.2-mil foil. One concludes therefore that the tail is due to a multiple effect, probably a combination of nuclear and electron-electron scattering, which for heavy nuclei is much less probable in comparison with elastic nuclear scattering.

From the curve for the 3.2-mil aluminum foil, one can conclude that the number of particles losing more than 20 percent of their energy is certainly less than 10 percent of the total distribution.

Thus the experimental data indicate that in light nuclei electron-electron scattering in combination with multiple nuclear scattering can give rise to large numbers of electrons which have lost appreciable energy. On the other hand, there is no evidence, as claimed by previous investigators, for inelastic nuclear scattering of electrons in the 1-Mev energy region from aluminum, copper, platinum, or lead.

e^-/e^+ ELASTIC SCATTERING RATIO—DISCUSSION

Table I, columns 9, 10, 11, 12, contains the final comparison of experiment and theory on the elastic scattering of electrons and positrons by nuclei. In this table it is assumed that for a light material such as polystyrene the theory is correct and that consequently the relative electron and positron source strength can be obtained from the observed e^-/e^+ scattering ratio. The data in column 9 were obtained by multiplying the actually observed ratios by the reciprocal of the observed, corrected polystyrene e^-/e^+ ratio. Since the theory of McKinley and Feshbach predicts an e^-/e^+ ratio for polystyrene of approximately 1.08, and since the multiple scattering corrections in columns 7 and 8 are small, we have considerable confidence in this method of normalizing the radioactive source strengths.

It will be seen in columns 11 and 12 that in a rough way theory and experiment are in agreement. The discrepancy is, however, well outside our experimental error and in a direction of giving a higher e^-/e^+ ratio than expected. This may be due to the effects of screening, for the calculations of Mohr show that the effect for electrons is of comparable magnitude and is in the proper direction. However, no calculations have been made on the effect of screening on positron scattering; so no definite conclusions can be drawn until a more accurate theory is available.

Note also that if the effect of screening is appreciable, the multiple scattering corrections will be altered. The multiple scattering formula requires a knowledge of the single scattering law, and in particular of the derivatives of the angular distribution at the angle of measurement. The contribution of screening to the values of these derivatives may produce noticeable changes in the multiple scattering correction, especially if the diffraction maxima and minima discussed by Mohr are appreciable.

From these results it can be concluded that the effect predicted by theory of spin-orbit coupling on scattering of electrons and positrons is certainly present, and that the experimental data are in rough quantitative agreement with the theory which assumes that the magnetic moments of electron and positron are equal. More cannot be said at this point because of the lack of an adequate theoretical treatment of the scattering of positrons by a screened Coulomb field.

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Disintegration of the Deuteron by π^+ Mesons and the Spin of the π^+ Meson*

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The total cross section for the reaction $\pi^+ + d \rightarrow p + p$ has been measured for an average incident meson energy of 23 Mev. This corresponds to a proton energy of 340 Mev in the inverse reaction $p + p \rightarrow \pi^+ + d$, for which the total cross section has been measured by Richman, Cartwright, Peterson, and others. Comparison of these two cross sections, using the theorem of detailed balancing, leads to a determination of the statistical weight, and hence the spin, of the π^+ meson. The spin turns out to be zero.

INTRODUCTION

Of the various methods which might be used for an experimental determination of the spin of the π^+ meson, the most promising is the possibility of application of the principle of detailed balancing. This method resembles that of the measurement of the alternation of intensities in rotation-vibration spectra of homonuclear diatomic molecules, in its ability to determine unambiguously a spin of zero, and in maximum sensitivity for small values of the spin.

In order to apply the principle of detailed balancing, it is necessary to measure the ratio of the cross sections for a reaction and its inverse at the same energy in the center-of-mass system. For practical purposes one must use a reaction with only two particles participating on each side. The only nuclear reaction to which detailed balancing has been successfully applied to date is the photodisintegration of the deuteron

$$h\nu + d \rightleftarrows n + p, \tag{1}$$

and its inverse, the radiative capture of neutrons by protons. Unfortunately, the comparison has not been made at the same center-of-mass energy; the *n-p* capture cross section has been measured at low energies and the photodisintegration at energies 200 kev or more above threshold. It is therefore necessary to use the theoretical energy dependence of the cross sections. The comparison has recently been reviewed by Salpeter.[1] Agreement is obtained within the experimental error of 20 percent, if we assume the neutron spin to be $\frac{1}{2}$. This result may be taken as a more direct measurement (at least in principle) of the neutron spin than the results given by neutron scattering in *ortho-* and *para-*hydrogen; more generally it is used to verify the theoretical cross sections.

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[1] E. E. Salpeter, Phys. Rev. 82, 60 (1951).