On the Electrical and Anomalous Scattering of Mesotrons

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Photographs obtained without a magnetic field in a large counter-controlled cloud chamber containing lead plates of two different thicknesses have been analyzed in regard to the scattering of the mesotrons in lead. The theory of scattering developed by E. J. Williams has been used. The mathematical form of this theory makes it possible to eliminate the energy distribution of the mesotrons in comparing the observed scattering intensity in two lead thicknesses. The scattering in a 5-cm lead plate into angles greater than 4°, when compared to that in a 1-cm lead plate, is more than would have been expected on the basis of Williams' theory. The average cross section calculated for this anomalous large angle scattering agrees with the results obtained by Code but it is somewhat larger than that previously reported by Wilson. It is also noted that this cross section is in agreement with the interaction between mesotrons and nuclei computed by Marshak and Weisskopf when a spin of $\frac{1}{2}$ for the mesotrons and an energy distribution such as that computed by Hartree are assumed. Although these experiments are perhaps not yet able to distinguish between the scatterings to be expected from a mesotron spin of $\frac{1}{2}$ and that from a spin of 0, a spin of 1 seems to be definitely excluded since for this value of the spin the theory indicates a cross section of about 1000 times more than that found. It is noted that a possibility for an explanation of the observed anomaly still might be found in electromagnetic effects such as those leading to burst production by mesotrons or in attributing the anomaly to nuclear scattering of the proton component instead of mesotrons.

INTRODUCTION

THE scattering of mesotrons by matter is of interest because of its dependence on the forces between mesotrons and nuclear particles. Williams[1] has developed a theory for the scattering of cosmic-ray particles by the atomic electric fields and some experimental studies of the scattering of mesotrons in various thicknesses of different materials have been made by Vargus,[2] by Wilson,[3] and by Code.[4] Although the results of these investigations are still meager, all have found angular distributions in approximate agreement with Williams' theory in the case of mesotrons scattered up to $\sim 5°$ in thicknesses to an equivalent of ~ 6 cm of lead; but a few improbable cases in which high energy particles are scattered into angles greater than $\sim 5°$ have also been found, and these indicate the possible existence of another type of scattering force.

Williams has shown that the electrical scattering in lead is always multiple if the scattering plate is more than 1 cm thick and if the velocity of the scattered particle is not very much less than that of light, a condition which may be considered fulfilled for mesotron energies as low as 20 Mev.

[1] E. J. Williams, Proc. Roy. Soc. **A169**, 531 (1939).
[2] J. A. Vargus, Jr., Phys. Rev. **56**, 480 (1939).
[3] J. G. Wilson, Proc. Roy. Soc. **A174**, 73 (1940).
[4] F. L. Code, Phys. Rev. **59**, 229 (1941).

Suppose $P(\alpha, t, E_k)d\alpha$ is the probability that a particle of kinetic energy E_k is scattered into an angular range $d\alpha$ at the angle α while traversing a plate of thickness t. Then Williams shows that

$$P(\alpha, t, E_k)d\alpha = \frac{2}{\pi\bar{\alpha}} \exp\left(-\frac{\alpha^2}{\pi\bar{\alpha}^2}\right)d\alpha \qquad (1)$$

with

$$\bar{\alpha} = (19.5 - 3.1 \log_{10} Z)^{\frac{1}{2}} \frac{600 Ze(Nt)^{\frac{1}{2}}}{\beta^2 E}, \qquad (2a)$$

where $\bar{\alpha}$ is the arithmetic mean of the angles of the multiple scatterings in a material of N atoms of atomic number Z per cm³, when the particles have charge e, mass m, velocity βc, kinetic energy E_k and total energy $E = E_k + mc^2$. The approximations involved are good up to scattering angles of about 25°. The expression (2a) takes into account the relativistic effect, the Coulomb shielding of the nucleus by the atomic electrons, and the finite size of the nucleus, the latter of which prevents single electrical scattering into large angles. For lead (2a) reduces to

$$\bar{\alpha} = 0.90 \times 10^9 \times t^{\frac{1}{2}} / \beta^2 E, \qquad (2b)$$

where t is measured in cm and E in electron volts. Williams has shown that the effect of a mesotron spin of $\frac{1}{2}$ on the electrical scattering would be completely negligible for the energy and angular ranges with which we are here concerned. Although this theory does not consider the possibility of spin 1 for the mesotron, the good agreement between experiment and theory shows that whatever the spin of the mesotron its contribution to the small angle electrical scattering must be very small.

For very close collisions we have to assume that forces other than those of the electrical type prevail, and here the effect of the spin may be all important. Theories for the scattering of mesotrons by the non-electric short range nuclear forces have been developed by several authors. All of those theories based upon a mesotron spin of 1 predict a nuclear scattering cross section per neutron or proton between 10^{-25} and 10^{-26} cm^2, values 100–1000 times too large to agree with the experiments, and of such a magnitude that in a lead plate of thickness between 0.3 and 3 cm the nuclear scattering of a beam of mesotrons of spin 1 would be complete. As Williams and others have shown, because of their intensity and short range, the nuclear forces must scatter into large angles considerably wider than those given by the electrical theory, and this type of scattering would, therefore, be easily recognized. For mesotrons of spin 0 Bhabha[5] has shown that the non-electric scattering cross section is almost of the right order of magnitude to agree with the experiments although it is perhaps somewhat too small, and he predicts a decreasing cross section for higher energies. Assuming a spin $\frac{1}{2}$ for the mesotron, Marshak and Weisskopf[6] have given a theory which agrees with the results of scattering experiments, but quite recently Weinberg[7] has given a new theory for the nuclear scattering of mesotrons of spin $\frac{1}{2}$ which yields a cross section about 100 times too large. Weinberg's treatment, however, has the satisfactory feature, in common with the theory of Bhabha, but in contrast with that of Marshak and Weisskopf, of predicting a decreasing cross section after reaching a maximum as the energy increases, a feature in harmony with the known hardening of cosmic rays as the depth increases.

Table I. Experimental results.

Projected angle α	Upper plate $t=1$ cm	Center plate $t=5$ cm	Lower plate $t=1$ cm	Upper and lower plates $t=1$ cm
	Number of scattered particles observed			
0°– 2°	5380	3783	3057	8437
2°– 4°	138	462	144	282
4°– 6°	77	188	47	124
6°– 8°	48	119	18	66
8°–10°	7	53	3	10
10°–12°	15	34	6	21
12°–14°	8	27	2	10
14°–16°	3	13	2	5
16°–18°	7	10	2	9
18°–20°	3	6	0	3
20°–22°	3	8	0	3
22°–24°	2	5	1	3
24°–26°	0	3	4	4
26°–28°	3	5	0	3
28°–30°	0	1	0	0
>30°	9	4	0	9
0°–90°	5703	4721	3286	8989
4°–90°	185	476	85	270

[5] H. J. Bhabha, Phys. Rev. **59**, 100 (1941).

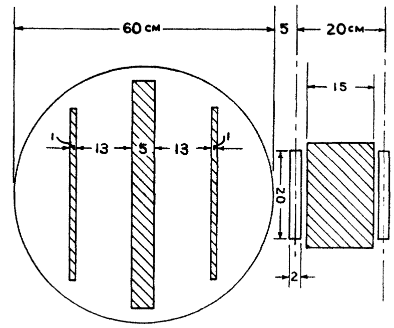

Fig. 1. Cloud chamber containing 3 lead plates, 1, 5, and 1 cm thick, respectively. Control by two counters above the chamber with 15 cm of interposed lead.

EXPERIMENTS

In view of the conflicting theories it seemed important to make more extensive studies of the scattering of mesotrons in matter. The large Wilson cloud chamber used in these experiments was 60 cm in diameter, 8 cm illuminated depth, and it contained three lead plates having thicknesses of 1 cm, 5 cm and 1 cm, respectively, spaced at distances of 13 cm from each other. Expansions were controlled by two counters in coincidence, both of which were above the chamber with 15 cm of lead interposed between them, as shown in Fig. 1. The chamber was located in a basement room with concrete equivalent of about 10 cm of lead above it. A short description of this chamber has already been given[8] and more details will be published elsewhere. The chamber was filled with 1.3 atmos. of

[6] R. E. Marshak and V. K. Weisskopf, Phys. Rev. **59**, 130 (1941).
[7] J. W. Weinberg, Phys. Rev. **59**, 776 (1941).
[8] T. H. Johnson, J. G. Barry, and R. P. Shutt, Phys. Rev. **59**, 470 (1941).

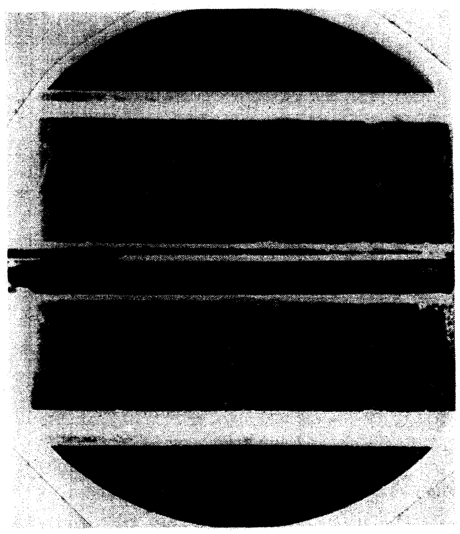

FIG. 2. Track of a mesotron scattered in lead. The difference of the density in the two upper compartments from that in the two lower ones is due to technical circumstances and not to a difference in ionization.

argon, saturated with a mixture of water and n-propyl alcohol vapors; the resulting volume expansion ratio was 1.07. Although magnetic field coils have recently been added, these were not used in the present experiments.

The present report covers the analysis of 8345 pictures, 7537 of which were stereoscopic. In all 5703 traversals through the upper 1-cm lead plate, 4721 through the 5-cm lead plate and 3286 through the lower 1-cm lead plate were observed. For each traversal the projection on the central plane of the chamber of the scattering angle of the particles traversing the lead plates was measured. In order to exclude from the analysis the electrons and penetrating rays incident obliquely, only rays which could have passed through the counters and the interposed lead were taken into consideration. Rays which appeared heavily ionizing after emerging from the lead were also excluded. The number of particles scattered by the lead plates into various angles α is given in Table I. The angles were measured with an accuracy of $\pm 0.5°$. A typical example of a track of a scattered mesotron is shown in Fig. 2.

DEDUCTION OF AVERAGE NUCLEAR SCATTERING CROSS SECTION

The observed scattering, recorded in Table I, is assumed to have resulted from two effects, the electrical scattering and the scattering due to nuclear forces. If we knew the energy distribution of the incident mesotrons, it would be possible to calculate from Williams' theory the scattering due to electrical forces and then to subtract this from the total to find the nuclear scattering, but the energy distribution in our chamber is affected by the distribution of absorbing material above the chamber and is not precisely known. It is therefore necessary to resort to an indirect method which makes use of the scattering observed in the two thicknesses of lead.

The cross section for the nuclear scattering, as mentioned above, must be small compared with that for the electrical scattering. Consequently the nuclear scattering in our lead plates will be single, and the number of particles scattered by the nuclear forces into a given angular range must be proportional to the first power of the thickness of the material. If we assume that the large angle scattering is nuclear, our 5-cm plate should show five times as much large angle scattering as that occurring in the 1-cm plate. On the other hand, the dependence of the multiple scattering on the thickness is different from that of the single scattering because the former obeys a law involving the thickness in a different and a comparatively complicated way. Suppose $I(\alpha, t)d\alpha$ represents the multiple scattering intensity. Its theoretical value may be represented by

$$I(\alpha, t)d\alpha = \int_{E_k=\bar{E}_{k0}}^{\infty} i(E_k)P(\alpha, t, E_k)dE_k d\alpha, \quad (3)$$

where $P(\alpha, t, E_k)d\alpha$ is the scattering probability given by (1), $i(E_k)dE_k$ is the number of rays in the energy range from E_k to E_k+dE_k, and $\bar{E}_{k0}$ is a certain average lower limit of the kinetic energy E_k determined by the experimental conditions.

The special mathematical form of (1) enables us to apply a direct method for the determination of the electrically scattered intensity without bringing the energy distribution into the calculation, for if instead of calculating the distribution with respect to α we transform to a new variable $u = \alpha t^{-\frac{1}{2}}$ the distribution with respect to u will be given by

$$f(u) = I(\alpha, t)(\partial\alpha/\partial u) = I(\alpha, t)t^{\frac{1}{2}}, \quad (4)$$

where $f(u)du$ is the number of particles in the range u to $u+du$, and using (1), (2b) and (3) we find

$$f(u)=\frac{2}{\sqrt{\pi}}\int_{\bar{E}_{k0}}^{\infty} i(E_k)z\exp(-z^2u^2)dE_k, \quad (5)$$

where $z=\beta^2E/k$ and $k=1.59\times10^9$ ev. The important feature of this transformation is that the distribution in u is independent of t so that if the scattering is entirely electrical the function $f(u)$ should be the same for all thicknesses of scattering material, and the product $I(\alpha, t)t^{\frac{1}{2}}$ plotted as a function of u must lie on one uniform curve independent of t. If the functions $f(u)$ obtained from the observations with different thicknesses of scattering material are not equal, the difference must be due to a disturbance by a nuclear force whose variation with distance from the center is different from and not proportional to the Coulomb force.[9] Actually $\bar{E}_{k0}$ depends upon t so that these last statements are not completely accurate, but in the range of α and E_k with which we are concerned this effect is only one of a second order correction.

Columns 1 and 2 of Table II show the experimental results for the two thicknesses of lead expressed in percent of the total number of traversals observed in each, and in Table III these values have been reduced to $f(u)$.

If the scattering were produced by Coulomb forces alone the $f(u)$ values in columns 1 and 2 of Table III would be identical except for statistical fluctuations resulting from the finite number of tracks observed. In making this comparison the sums of the $f(u)$ numbers in the range of u from 2 to 12 have been used in place of the individual values because of their greater statistical weights; but, instead of an equality, we find a value for the 5-cm thickness greater than that for the 1-cm thickness by

$$\delta=9.04-5.64=3.40. \quad (6)$$

The corresponding difference in the number of particles scattered in the 5-cm thickness over that of the particles scattered in the 1 cm of lead is

$$\Delta_1=\delta/\sqrt{t}=3.4/\sqrt{5}=(1.5\pm0.5)\text{ percent} \quad (7)$$

of the total intensity, or (15±5) percent of the number of scattered rays. This represents the excess of rays scattered in the 5-cm block into angles between 4.5° and 26°, or between $u=2$ and 12, over those we should have expected to be scattered there on the basis of the theory of electrical scattering, taking into account the number actually observed to have been scattered in the 1-cm block. The standard error of Δ_1 indicated above was found by first determining the standard errors for each of the two thicknesses, considering all particles between $u=2$ and 12 and then adding these two errors geometrically. In this calculation the standard error is taken as the square root of the number of particles scattered.

In order to find a cross section for this anomalous large angle scattering we have to apply some corrections to the above result. First, our observations concern the projections into the cloud-chamber plane of the actual angles in three dimensions. These are the angles dealt with in the Williams theory; but in the case of nuclear scattering this fact must also be taken into

TABLE II. Relative intensities of the total scattering for different thicknesses of lead.

	$I(\alpha, t)$, experimental results				$I(\alpha, t)$ computed from Hartree's energy distribution at sea level	
	1		2		3	4
α	$t=1$ cm %	Stand. error ±%	$t=5$ cm %	Stand. error ±%	$t=1$ cm %	$t=5$ cm %
0°–2°	93.80	1.02	80.10	1.30	92.30	81.30
2°–4°	3.16	0.19	9.79	0.46	4.77	9.95
4°–6°	1.39	0.12	3.98	0.29	1.50	3.79
6°–8°	0.74	0.09	2.52	0.23	0.65	1.89
8°–10°	0.11	0.04	1.12	0.15	0.32	1.08
10°–12°	0.24	0.05	0.72	0.12	0.18	0.65
12°–14°	0.11	0.04	0.57	0.11	0.13	0.45
14°–16°	0.06	0.02	0.28	0.08	0.08	0.30
16°–18°	0.10	0.03	0.21	0.07	0.04	0.22
18°–20°	0.03	0.02	0.13	0.05	0.03	0.16
20°–22°	0.03	0.02	0.17	0.06	0.03	0.12
22°–24°	0.03	0.02	0.11	0.05	0.02	0.10
24°–26°	0.04	0.02	0.06	0.04	0.02	0.08
26°–28°	0.03	0.02	0.11	0.05	0.02	0.06
28°–30°	0.00	—	0.02	0.02		0.05
>30°	0.11	0.04	0.08	0.04		0.10
4°–90°	3.02	0.19	10.08	0.47	2.95	9.05

[9] The electrical single scattering, $I_{se}(\alpha, t)$, although of negligible magnitude, is proportional to t/α^3 at not too large angles, see reference 1, and $I_{se}(\alpha, t)t^{\frac{1}{2}}$ is proportional to $1/u^3$. Hence the combined multiple and single electrical scattering can also be transformed to a function of u alone

$$[I(\alpha, t)+I_{se}(\alpha, t)]t^{\frac{1}{2}}=f_1(u).$$

consideration. For this reason it is estimated that a correction of 30 percent should be added to Δ_1. Secondly, since Δ_1 is the *difference* between the nuclear scattering in 5 cm and that in 1 cm of lead, the total nuclear scattering in the 5-cm plate is $\sim$25 percent greater than Δ_1. Taking both corrections into account we have an excess

$$\Delta = 2.3 \pm 0.8 \text{ percent} \quad (8)$$

of the total number of traversals to be accounted for by nuclear scattering. A further small correction might be made in consideration of the fact that the effective thickness of a plate for the scattering is somewhat larger than the geometrical thickness t, but an estimate of this effect gives a correction which is wholly negligible in view of the other rather large experimental uncertainties.

If we attribute this anomaly to non-electric nuclear forces, we can now determine an average cross section σ per neutron or proton for the non-electric nuclear scattering. This cross section may be defined by

$$\sigma = \Delta / tN, \quad (9)$$

where N is the number of neutrons and protons in 1 cm^3, t is the thickness of the lead, and Δ, as already noted, is the fraction of the rays scattered by other than electrical forces. Inserting values in (9) we find

$$\sigma = 6.5 \times 10^{-28} \text{ cm}^2 \pm 35 \text{ percent per neutron or proton.} \quad (10)$$

In the above calculation the energy distribution has not been used explicitly and it has only been necessary to assume that the distribution is the same for the particles incident upon the lead plates of both thicknesses.

Although the energy distribution is affected by the absorbing matter above our chamber, and is therefore not necessarily the same as that for cosmic rays in the free atmosphere at sea level, it is perhaps of interest to calculate the scattering to be expected in our lead plates with a normal sea-level energy distribution. For the purpose of such a calculation we have chosen the distribution cited by Rossi[10] as having been computed by Hartree on the basis of the Bethe-Bloch ionization energy losses by taking into account the radioactive decay of the mesotrons during their passage through the atmosphere. This distribution has been used in Eq. (3) together with the scattering probability function given by Eq. (1) and a lower energy limit $\bar{E}_{k0}$ determined in the following way. As mentioned, rays which appeared to ionize heavily have been excluded in our statistics. We define the energy loss by ionization of a ray which begins to ionize heavily as twice the energy loss at high energy and with this assumption we can calculate from the Bethe-Bloch formula a corresponding kinetic energy $E_{k01} = 16$ Mev; (we assume $m = 200$). $\bar{E}_{k0}$ lies between E_{k01} and the sum, E_{k02}, of E_{k01} plus the total energy loss in t. Actually the final result is not sensitive to the choice of $\bar{E}_{k0}$ and the approximation $\bar{E}_{k0} = (E_{k01}E_{k02})^{\frac{1}{2}}$ should be satisfactory as this gives more weight to E_{k01} in accordance with the large weight low energies have for large angles in regard to the expression (3). We find for $t = 1$ cm, $E_{k02} = 40$ Mev and $\bar{E}_{k0} = (16 \times 40)^{\frac{1}{2}} = 25$ Mev, and for $t = 5$ cm, $E_{k02} = 99$ Mev and $\bar{E}_{k0} = (16 \times 99)^{\frac{1}{2}} = 40$ Mev. With this limit the integration of Eq. (3) has been made graphically, and the scattering distribution computed in this way for the two thicknesses of our lead plates is shown in columns 3 and 4 in Table II. In comparing the calculated percentage scattered into angles greater than 4° with that observed, we find only an indication of a discrepancy in the case of the 5-cm plate and a satisfactory agreement in the case of the 1-cm plate. Thus there is little explicit evidence here to indicate the presence of non-electric nuclear scattering, although the Hartree distribution probably contains a larger percentage of low energy particles than were present in our chamber, and therefore predictions based upon it should lead to a broader

TABLE III. Values of Table II reduced to $f(u)$.

$u = \alpha/t^{\frac{1}{2}}$	$I(\alpha, t)t^{\frac{1}{2}} = f(u)$	
	1 $t = 1$ cm	2 $t = 5$ cm
Degrees $\times$ cm$^{-\frac{1}{2}}$	% $\times$ cm$^{\frac{1}{2}}$	% $\times$ cm$^{\frac{1}{2}}$
2–4	3.16	6.20
4–6	1.39	1.67
6–8	0.74	0.64
8–10	0.11	0.33
10–12	0.24	0.20
2–12	5.64	9.04

[10] B. Rossi, Rev. Mod. Phys. **11**, 296 (1939).

scattering pattern than would result from the actual energy distribution. If the figures are taken as they stand, the actual scattering into angles of more than 4° exceeds the electrical scattering predicted from the Hartree distribution by

$$\Delta_2 = (10.08 - 9.05) \text{ percent} \pm 0.5 \text{ percent} = (1.0 \pm 0.5) \text{ percent} \quad (11)$$

of the total intensity. Putting this value into expression (9) and correcting, we find a cross section per neutron or proton for the electrical nuclear scattering of

$$\sigma = 4.5 \times 10^{-28} \text{ cm}^2 \pm 50 \text{ percent.} \quad (12)$$

However it must be pointed out that this expression involves the uncertainties connected with the energy distribution in addition to our experimental errors, a fact which makes it less reliable than the expression (10).

DISCUSSION AND CONCLUSION

Other experiments with which our results may be compared include those of Code, Vargus, and Wilson. From an analysis of 451 tracks of measured energy traversing 3.8 cm of tungsten, Code[4] found a Gaussian distribution with respect to the product $\bar{E}\alpha$, where $\bar{E}$ is the average energy of a ray while traversing the scattering metal plate, in the range up to 8×10^9 ev$\times$degrees. The average value of $\bar{E}\alpha$ was in close agreement with that predicted by Williams; but Code found 10 rays having a value $\bar{E}\alpha$ greater than 8×10^9 ev$\times$degrees whereas only 1.5 were expected. If this excess of large angle scattering is attributed to non-electric nuclear scattering, the estimated cross section per neutron or proton is

$$\sigma = 5.7 \times 10^{-28} \text{ cm}^2 \pm 35 \text{ percent.} \quad (13)$$

In Wilson's experiments[3] 185 rays of measured energy were scattered in plates of lead, copper, or gold. Out of a total path of these rays, equivalent to 4 meters of lead there was only one indication of a nuclear collision, and from this Wilson infers that the cross section per neutron or proton is of the order of

$$\sigma = 4.0 \times 10^{-28} \text{ cm}^2. \quad (14)$$

Out of a larger number of traversals for which the total path was of the order of 50 meters of lead equivalent, there occurred only one collision resulting in a *nuclear disintegration.* Wilson estimated the cross section per neutron or proton for events of this type to be of the order of

$$\sigma = 0.3 \times 10^{-28} \text{ cm}^2. \quad (15)$$

From an analysis of 55 tracks of measured energy and 670 tracks of energies too high for measurements traversing one cm of platinum in the chamber of Anderson and Neddermeyer, and by using Anderson and Neddermeyer's and Blackett's energy distributions for the 670 tracks of high energy, Vargus[2] found that the scattering was in accord with the theory of Williams and no evidence could be obtained from the scattering alone of forces other than that of the Coulomb field, although, of course, Anderson and Neddermeyer have observed a number of examples of nuclear disintegrations induced by cosmic rays. Perhaps the most extensive analysis of such nuclear disintegrations resulting from cosmic-ray impacts is that of Brode and Starr[11] from which Wilson[3] has estimated a cross section per neutron or proton of

$$\sigma = 0.1 \times 10^{-28} \text{ cm}^2 \pm 60 \text{ percent.} \quad (16)$$

Comparing Code's result, (13), with ours, (10), we find good agreement considering the rather large experimental errors. This agreement is significant because of the difference of the two methods, Code's energies having been determined by the magnetic method while our method compares the scattering in two different thicknesses of material. Comparison with the cross section given by Wilson, (14), shows agreement at least in the order of magnitude. Wilson points out that the number of large angle scatterings observed depends partially on the geometry of the apparatus. It seems that the arrangements of Code and ourselves are more alike and suitable for detecting large angle scattering since both arrangements have all coincidence counters either above or inside the chamber.

As a final comparison we can average the theoretical expression for σ as function of E given by Marshak and Weisskopf over Hartree's energy distribution. The resulting theoretical *average* cross section per neutron or proton in a

[11] R. B. Brode and M. A. Starr, Phys. Rev. 53, 3 (1938).

nucleus is

$$\bar{\sigma}_{th}=3.8\times10^{-28}\text{ cm}^2. \quad (17)$$

To give an angular distribution of the anomalous scattering which could be compared with theory is not possible with the experimental data obtained thus far.

Comparing the theoretical average cross section with the experimental values we find agreement at least within the order of magnitude. Since $\bar{\sigma}_{th}$ for mesotrons of spin 0 would be about 10–20 times smaller than that for spin $\frac{1}{2}$ (Bhabha)[5] our experiments and those of Code would indicate a spin of $\frac{1}{2}$, assuming that the theory of Marshak and Weisskopf is correct, while Wilson's estimates from nuclear disintegration tend to show a spin of 0.

It has to be mentioned that by attributing a magnetic moment to the mesotron in addition to the spin some authors[12–13] have calculated the probability of burst production by mesotrons in a Coulomb field. The theoretical result when spin 0 or $\frac{1}{2}$ is assumed is of the order of that observed whereas theories based upon spin 1 seem to be definitely excluded. The scattering cross section for mesotrons has not yet been calculated under these new assumptions, and thus it is not impossible that the anomaly found experimentally can still be explained by some kind of electromagnetic interaction.

In the foregoing discussion it has been assumed that all of the rays involved in the experiments were mesotrons. Other types of rays, especially electrons and protons, are also present in the cosmic radiation at sea level, and we should estimate to what extent these might have affected our results. Considering first the electrons, there are three types which might have been included in our statistics. Electrons normally present at sea level with sufficient energy to pass through the 25-cm lead shield above the chamber would have multiplied and given rise to a cascade shower in the chamber so that these electrons would not have been counted. Knock-on electrons produced by the penetrating component would in general have been accompanied by the primary mesotron and would thus have been identified as electrons and would not have been included in the count. Finally electrons created by mesotron decay in the gas or in the lead plates of the chamber might have been present, and these might be expected to show some rather large changes in direction from that of the primary mesotron. An upper limit for the number of mesotrons decaying in the gas can be estimated by assuming a lifetime of $\tau_0=2.7\times10^{-6}$ sec. and a lower limit of $\beta=\frac{1}{2}$ for the mesotrons. The latter value of β we assume because particles slower than that ionize heavily and thus are excluded. The probability p for a mesotron decay within the range of height of about $H=60$ cm included in the cloud chamber will be

$$p=H(1-\beta^2)^{\frac{1}{2}}/\tau_0\beta c=1.3\times10^{-3}\approx0.1\text{ percent.}$$

Mesotrons which enter the lead plates with $\beta c\geqq\frac{1}{2}c$ but are slowed down to velocities $\beta c<\frac{1}{2}c$ would have an increased probability of a decay, and some of the resulting electrons might emerge from the lead at almost any angle with respect to the direction of the primary mesotron. This would contribute to the large angle scatterings included in the count but the number of such events would be negligibly small. From the energy distribution we expect about 1 or 2 percent of the total intensity to be stopped in our lead thicknesses. This estimate agrees well with the number of particles actually observed in these experiments as having been stopped. It is also noted that Rasetti[14] has found a mesotron decay in iron, and from his results we should expect about 0.1–0.2 percent of the total intensity of mesotrons to be decay electrons emerging from a 10-cm iron plate, and a somewhat smaller percentage under lead. We can thus consider the 0.2 percent as an upper limit for this effect, and adding the two effects inside the cloud chamber we find an upper limit of 0.3 percent for the number of decay electrons. As we see, this value constitutes the total number of electrons which could not easily be identified as such and might have been included in our counts. The number lies well within our statistical error and need not be further considered.

The percentage of protons in the cosmic radia-

[12] H. C. Corben and J. Schwinger, Phys. Rev. **58**, 953 (1940).

[13] R. F. Christy and S. Kusaka, Phys. Rev. **59**, 414 (1941).

[14] F. Rasetti, Phys. Rev. **59**, 706 (1941).

tion is not well known. From the number of slow protons which can be identified as such and with reasonable assumptions as to the proton energy distribution it has been estimated[15] that the total number of protons is of the order of 2 percent of the total penetrating component. As Wilson[3] has shown, a component of this order would not be evident as regards its effect upon the multiple electrical scattering. *However the possibility cannot be excluded that a great fraction or even the total of the anomalous large angle scattering observed is associated with the proton component and not with the mesotron component.* The observed number of tracks scattered in an anomalous way amounts to about 2 percent and is of the same order as the estimates of the proton component. If the cross sections for the proton-proton and proton-neutron scattering at cosmic-ray energies were about 100 times larger ($\sim 10^{-26}$ cm^2) than that calculated here for mesotrons, we could attribute the whole effect to the proton component. A further indication that we might have to seek for an explanation of the anomalous scattering in the proton component rather than in the mesotron component is the abnormally high energy loss of protons in lead reported by Wilson.[16]

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Scattering of Protons by Deuterium

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The scattering of protons by deuterium has been studied in the energy interval between 200 kev and 300 kev and as a function of angle between 20° and 90°. The ratio of observed scattering to that expected on the basis of Rutherford's formula is found to differ appreciably from unity and increase, both with increasing energy and angle.

THE work of Tuve, Heydenburg and Hafstad[1] has shown that at proton energies near 800 kev the scattering of protons from deuterium does not obey Rutherford's formula. They find a slow increase in the ratio of observed to Rutherford scattering between the angles 20° and 75°. Beyond 75° the ratio increases extremely rapidly. Primakoff[2] and Ochiai[3] have investigated proton-deuteron scattering theoretically, making use of calculated neutron-deuteron cross sections but find difficulty in fitting the observed data at large angles. It is useful to determine the energy and angular dependence of the protons scattered from deuterium since it may lead to information about the proton-proton and proton-neutron interactions.

The scattering of protons from deuterium has been observed in the energy interval between 200 kev and 300 kev, from the scattering chamber-proportional counter system described in a previous article.[4] The source of high potential[5] and the differential pumping system[6] have also been previously described. The collision products were detected by three proportional counters,

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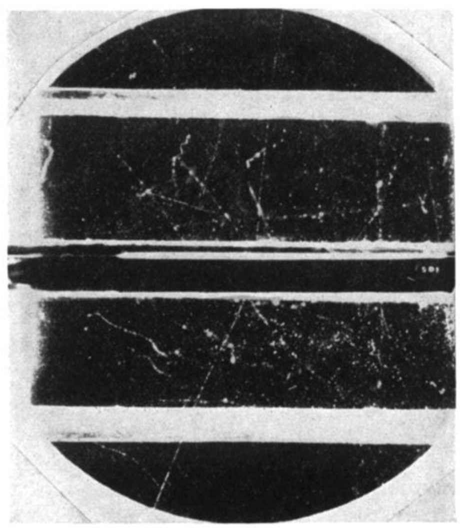

FIG. 2. Track of a mesotron scattered in lead. The difference of the density in the two upper compartments from that in the two lower ones is due to technical circumstances and not to a difference in ionization.