THE PHYSICAL REVIEW

A journal of experimental and theoretical physics established by E. L. Nichols in 1893

SECOND SERIES, VOL. 66, NOS. 1 AND 2 — JULY 1 AND 15, 1944

Deflection of Mesons in Magnetized Iron

F. RASETTI
Laval University, Quebec, Canada
(Received May 8, 1944)

The deflection of mesons in a magnetized ferromagnetic medium was investigated. A beam of mesons was made to pass through 9 cm of iron, and the resulting distribution of the beam was observed. Two arrangements were employed. In the first arrangement, the deflection due to the field caused a fraction of the mesons to hit a counter placed out of line with the others. An increase of sixty percent in the number of coincidences was recorded when the iron was magnetized. In the second arrangement, all the counters were arranged in line, and the deflection due to the field caused an eight percent decrease in the number of coincidences. These results are compared with theoretical predictions deduced from the known momentum spectrum of the mesons and from the geometry of the arrangement. The observed effects agree as well as can be expected with those calculated under the assumptions that the effective vector inside the ferromagnetic medium is the induction B, and that the number of low energy mesons is correctly given by the range-momentum relation.

INTRODUCTION

THE idea of observing the deflection of a cosmic-ray particle passing through a magnetized ferromagnetic medium was independently suggested and carried out experimentally by Rossi[1] and Mott-Smith.[2] Both these experimenters obtained negative results, which were interpreted at the time as meaning that the energy of the cosmic-ray particles was higher than expected.

These experiments provoked a discussion among theoretical physicists about the effective vector acting on a charged particle moving through a ferromagnetic medium. The classical theory gives a result that depends on the particular model chosen for the elementary magnets.[3] Moreover, one can hardly rely on the results of the classical theory since ferromagnetism is due to the electron spin and hence is a typically non-classical effect. Fortunately, a calculation based on Dirac's theory of the electron has been performed by Weizsaecker,[4] the unambiguous result being that the effective vector acting on the particle is the magnetic induction B.

Further experiments were performed by Alvarez,[5] who investigated the deflections of β-particles passing through a thin magnetized iron sheet. The observed effect was much smaller than expected, and he concluded that the effective vector is at most of the order of one-tenth of B.

Danforth and Swann[6] performed another experiment on cosmic rays. Their counters were

[1] B. Rossi, Nature **128**, 300 (1931); Lincei Rend. **2**, 478 (1930).
[2] L. M. Mott-Smith, Phys. Rev. **37**, 1001 (1931); **39**, 403 (1932).
[3] W. F. G. Swann, Phys. Rev. **49**, 574 (1936).
[4] C. F. v. Weizsaecker, Ann. d. Physik **17**, 869 (1933).
[5] L. Alvarez, Phys. Rev. **45**, 225 (1934).
[6] W. E. Danforth and W. F. G. Swann, Phys. Rev. **49**, 582 (1936).

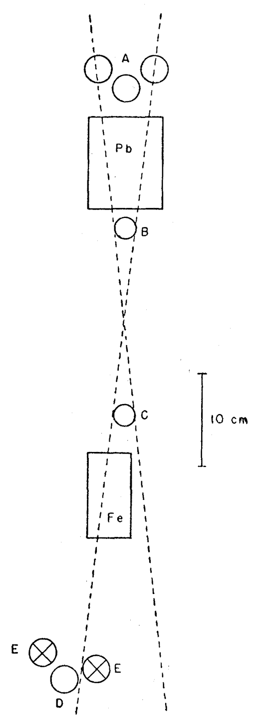

FIG. 1. Counter arrangement. Counter D is represented in the position outside of the beam defined by counters B and C. Cross-marked counters are used as anticoincidence counters.

arranged in a straight line, an iron block being placed between the two last counters. A decrease of the order of ten percent in the number of coincidences was observed when the iron was magnetized. This result was interpreted, on the basis of the then current ideas about the nature and energy distribution of the cosmic-ray particles, as meaning that the effective field was of the order of B.

The preceding summary of the results of earlier experimenters shows that it was worth while to undertake a new investigation of the problem in view of the improved technique now available. Moreover, the present knowledge of the nature of cosmic-ray particles at sea level affords an unambiguous interpretation of the results.

EXPERIMENTAL ARRANGEMENT AND RESULTS

In order to obtain results which admit of a clear interpretation, only one kind of particle must be selected. Moreover, radiation processes and the consequent cascade multiplication make the soft component wholly unfit for experiments of this sort. Therefore, one must employ a beam of mesons selected by preliminary absorption of the soft component.

The choice of the optimum thickness of magnetized iron to be employed requires some consideration. For a given thickness l, there is a minimum value of the momentum $p_{\min}$ of the mesons that are able to traverse the iron. For a given momentum p, and hence for a given radius of curvature R of the path, the deflection will be approximately proportional to l, and inversely proportional to p. Were the momentum proportional to the range, the maximum angular deflection obtainable would be independent of the thickness. However, in the low energy region the range increases rapidly with momentum, and it is only in the region of highly relativistic energies that the range-momentum relation becomes linear. Consequently, the thickness of iron must correspond to particles whose kinetic energy is at least as large as the self-energy. On the other hand, the use of an excessive thickness of iron would excessively reduce the intensity of the beam, owing to geometrical factors. When all these factors are considered, it is seen that the most favorable thickness of iron is of the order of ten cm. In the actual experiments, a thickness of 9 cm was employed, corresponding[7] to a minimum momentum of 2.1×10^8 ev/c (throughout this paper, the unit of momentum will be 10^8 ev/c).

Due allowance must be made for the scattering of mesons by the iron. Since the average angle for multiple Coulomb scattering and the magnetic deflection are, for relativistic energies, both inversely proportional to the energy, scattering will equally affect the results at all energies, provided these are sufficiently high. Hence the effect of scattering, although important, does not appreciably affect the choice of the optimum thickness.

The arrangement of the counters is shown in Fig. 1. Counters A, B, and C, with the interposed ten cm of lead, select a beam of mesons. A fourth counter D can be placed either in line with the other three, or wholly outside of the beam defined by the coincidences (BC). The iron block can be placed between the counters C and D. Two

[7] B. Rossi and K. Greisen, Rev. Mod. Phys. **13**, 240 (1941).

anticoincidence counters E are placed one on each side of the counter D, the purpose being to discriminate against showers that might give fourfold coincidences ($ABCD$) and against particles that, traversing the iron, produce secondaries. By displacing the counter D, the definition of the meson beam was tested. It was found that when the counter D was just outside of the beam, the number of fourfold coincidences dropped to about one percent of the number recorded with the four counters in line. This very low "background" is mainly responsible for the success of that part of the experiment in which the counters were placed out of line and was made possible by the use of anticoincidence counters.

With counter D out of line, the number of fourfold coincidences was almost doubled when the iron block was interposed, owing to scattering by the iron. This effect, however, did not prevent the measurement of the deflection due to the magnetic field, but made it necessary to extend the measurements over a longer period. The readings were alternately taken with and without field, and the difference was assumed to be due to the effect of the field.

The iron block, 9×4.5 cm^2 in cross section and 25 cm in length, constituted part of a closed magnetic circuit and was kept magnetized at 15,000 gauss by an electromagnet dissipating 40 watts.

Counters A, D, and E had an effective diameter of 2.9 cm and an effective length of 37 cm. Counters B and C had an effective diameter of 2.3 cm and an effective length of 22 cm. The distances between the counters are shown to scale in Fig. 1.

TABLE I. Fourfold coincidences with magnetized and unmagnetized iron. Counters out of line.

Magnetic induction B	Number of hours	Number of coincidences	Coincidences per hour
0	1200	1186	0.99 ± 0.03
+15,000	650	1073	1.65 ± 0.05
−15,000	650	1028	1.58 ± 0.05

The results obtained with the counters out of line are summarized in Table I. All the counts were taken with counter D placed 0.4 cm outside of the beam defined by the threefold coincidences (ABC). It is seen that the magnetic field increases the number of counts by about sixty percent, a far larger effect than any previous experimenter has been able to obtain. The sign of the field is indicated as positive when the positively charged particles are deflected into counter D. The difference between the numbers of positive and negative particles is within the statistical error. There is, however, a slight indication of an excess of positive mesons, as reported in the literature.[8]

TABLE II. Fourfold coincidences with magnetized and unmagnetized iron. Counters in line.

Magnetic induction B	Number of hours	Number of coincidences	Coincidences per hour	Difference per hour	Difference percent
0	450	13321	29.6 ± 0.26		
15,000	450	12368	27.5 ± 0.25	2.1 ± 0.36	7.1 ± 1.2

The experiment with the counters in line simply consisted in counting the fourfold coincidences with and without magnetic field. Obviously, in this case there is no point in reversing the field, as the arrangement is symmetrical with respect to positive and negative mesons. The decrease in the number of fourfold coincidences due to the field was of the same order of magnitude as that observed by Danforth and Swann. The results are summarized in Table II.

INTERPRETATION OF RESULTS

We shall first discuss the results obtained with the counters out of line.

In order to compare the experimental results with the theory, one must know the differential momentum spectrum of the mesons $f(p)$ and the probability $w(p)$ that a meson recorded by counters B and C will be deflected into counter D by the action of the field, assuming that the induction B is effective. Let the function $f(p)$ be normalized so that

$$\int_0^\infty f(p)dp = 1,$$

then the ratio of the number of fourfold coincidences due to the field to the number of incident mesons [coincidences (BC)] will obviously be

[8] H. Jones, Rev. Mod. Phys. 11, 235 (1939).

given by:

$$n=\int_{p_{\min}}^{\infty} w(p)f(p)dp.$$

The spectral distribution $f(p)$ can be taken from data available in the literature, and the probability $w(p)$ can be calculated from the geometry of the experiment. To perform this calculation, we shall make the following simplifications: (a) We shall assume that the meson spectrum is not appreciably affected by filtering through the roof and two floors of the building, as well as through the lead block. The distortion in the energy distribution thus introduced is certainly small, and probably within the limits of accuracy of the present knowledge of the spectrum. (b) The deflections due to scattering and to the magnetic field in the iron block are assumed to be independent of each other; that is, the effect of the field is obtained by subtracting the background observed with the unmagnetized iron. Actually, scattering will somewhat alter the intensity distribution in the undeflected beam, especially for low momentum mesons that are mainly responsible for the magnetic effect. This is believed to represent the main source of error in comparing the experimental results with the theory. (c) The radius of curvature of the meson path varies as the meson loses energy in the iron. To simplify the calculations, an average radius will be substituted.

The momentum spectrum of the mesons is wholly determined, for low energies, by the range-momentum relation. This relation, if we assume that the whole energy loss is due to collisions, is well known theoretically. The resulting momentum spectrum has been calculated and represented graphically, with an approximation sufficient for our purposes, by Euler and Heisenberg.[9] The spectrum at high energies has been deduced by several experimenters from the measurement of the curvature of tracks in the cloud chamber. A composite spectrum was obtained by joining, at $p=14$, the theoretical curve of Euler and Heisenberg with the experimental data of Jones.[8] This procedure was necessary in order to normalize the function $f(p)$ although mesons with momentum larger than 14 are ineffective in the present experiment. The differential spectrum used is shown graphically in Fig. 2.

The probability $w(p)$ for a meson recorded by counters B and C to be deflected into counter D was calculated as follows. The intensity distribution of the undeflected beam in the plane of the counter D is readily evaluated geometrically. To a first approximation, the effect of the field on the particles of one sign can be taken as a shift of the whole beam toward one side, by an amount inversely proportional to the radius of curvature and hence to the momentum. The fraction of the shifted beam that passes through counter D is calculated.

The function $w(p)$ is evaluated for p between 0 and 14 (for higher values of p the probability

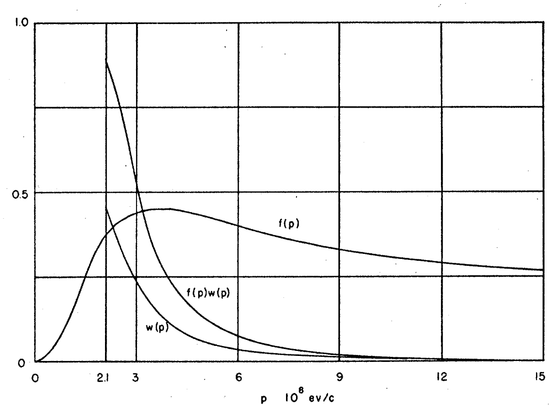

FIG. 2. $f(p)$, differential momentum spectrum; multiply ordinates by 0.1. $w(p)$, probability for a meson to be deflected into counter D. $f(p)w(p)$, product of the two functions; multiply ordinates by 0.02.

is practically zero) and is represented in Fig. 2. The figure also represents the product $f(p)w(p)$; from this latter curve it is seen that most of the contribution to the magnetic effect comes from mesons that have little more than the energy necessary to traverse the iron block.

A numerical integration gives:

$$n=\int_{2.1}^{14} w(p)f(p)dp=0.028.$$

In order to compare this figure with the experimental data, it is also necessary to know what fraction N of the beam defined by the coincidences (BC) passes through counter D when the latter is in line with the other two. This

[9] H. Euler and W. Heisenberg, Ergeb. d. exakt. Naturwiss. 17, 1 (1938).

fraction can immediately be evaluated from the geometry and is 0.49. The theoretical value of the ratio n/N is therefore:

$$(n/N)_{\mathrm{theor}} = 0.057.$$

Since only mesons of one sign can be deflected into counter D, we shall take the sum of the effects due to the positive and negative fields after subtracting the effect measured without field. This sum is 1.25 ± 0.08 coincidences per hour. The number of fourfold coincidences with the counters in line is 29.6 per hour. Hence

$$(n/N)_{\mathrm{exper}} = 1.25/29.6 = 0.042 \pm 0.003.$$

Considering the uncertain factors involved in the calculations, we may state that there is no significant discrepancy between the observed and the calculated effect.

We shall now consider the experiment with the counters in line. The calculations are similar to those discussed in the preceding case; hence the procedure followed will be briefly outlined.

In this case, the displacement of the beam due to the field gives rise to a decrease in the number of particles recorded by counter D. This decrease was calculated, from the geometry of the beam, as a function of momentum, and a numerical integral was again evaluated on the basis of the same spectral distribution as before. The theoretical result is that the field should produce a decrease of 8 percent in the number of fourfold coincidences. From Table II it is seen that the observed effect is 7.1 ± 1.2 percent. Hence, the experimental and theoretical values agree to within the statistical error.

We now wish to discuss the significance of the present experiments. The agreement between the calculated and the observed effects was obtained under two assumptions: (a) the effective vector acting on the particles inside the magnetized medium is the induction B; (b) the number of low energy mesons is correctly given by the range-momentum relation. Were the effective field considerably smaller than B, or were the number of low energy mesons smaller than assumed, then the observed effect would not have agreed with the theoretical predictions.

It would at first appear that the present experiment could not be considered as a test of both of the above-mentioned assumptions. We must consider, however, that if either of the two determining factors disagreed with the theoretical predictions, this disagreement would be only in one direction. The effective vector acting on a particle could conceivably be smaller than B (under certain classical assumptions, for example, one obtains values that are intermediate between H and B); but one could hardly imagine a reasonable hypothesis under which the effective vector could be larger than B. Regarding the number of low energy mesons, here again one may readily imagine mechanisms[10] capable of removing mesons from the beam, and hence of rendering the number of slow mesons smaller than assumed; but it would be difficult to conceive of an effect that could make the number of slow mesons higher than calculated from the range-momentum relation. We conclude that the agreement of the experimental results with the theory is a good proof, at least, of the approximate validity of both hypotheses, namely, that the effective vector is B and that the number of slow mesons is correctly given by the range-momentum relation.

[10] An interaction that might produce this effect has been discussed by J. Hamilton, W. Heitler, and H. W. Peng, Phys. Rev. **64**, 78 (1943). Their theoretical conclusions do not seem to be supported by the results of the present experiments.