PROCEEDINGS OF THE ROYAL SOCIETY A | MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

The Scattering of Mesotrons in Metal Plates

J. G. Wilson

Proc. R. Soc. Lond. A 1940 **174**, doi: 10.1098/rspa.1940.0006, published 12 January 1940

The scattering of mesotrons in metal plates

By J. G. Wilson
University of Manchester

(*Communicated by P. M. S. Blackett, F.R.S.—Received 14 August* 1939)

[Plate 1]

1. Introduction

Measurements by Blackett and Wilson (1938) showed that the scattering of cosmic-ray particles in metal plates was in approximate agreement with the simple theory then available, at least for energies less than 2×10^9 e-volts. This result provided important evidence as to the nature of the cosmic-ray particles, for it tended to confirm the view that the penetrating particles were much heavier than electrons, rather than the alternative assumption that the particles were electrons for which radiative energy losses were suppressed at high energies.

Recently, Williams (1939) has given a critical development of the theory of scattering of very energetic particles in the atomic field. This treatment leads to a more accurate value of the theoretical Coulomb scattering and shows that, for cosmic-ray scattering experiments, a fairly sharp separation in angular range is to be expected between scattering in the Coulomb field of the scattering atom and that arising from the short-range interaction between the incident particle and the separate nuclear particles. Accurate measurements of scattering therefore offer a method of estimating the magnitude of the short-range interaction of mesotrons with neutrons or protons. Williams, for example, shows that our previous measurements indicate a mesotron-proton (neutron) interaction decidedly less than that of slow neutrons with protons.

The present work incorporates the more accurate of our previous measurements and extends these to show the close agreement of mean scattering angle, and of distribution of scattering angles, with the theory of the main electrical (Coulomb) scattering. These measurements, together with a more general survey of a large number of track photographs unsuitable for accurate measurement, also lead to an estimate of the interaction cross-section of mesotrons with the constituent nuclear particles.

2. The measurement of scattering

The technique of accurate measurements of scattering of cosmic ray particles at a metal plate in an expansion chamber has been described in detail in our earlier work. The upper limit of energy has been taken at 2×10^9 e-volts and so excludes the region for which our earlier measurements indicated a possible anomaly, but for which the accuracy of experiment is low.

As far as possible electrons have been excluded from the measurements. For the tracks passing through a 2 cm. plate of gold this exclusion is complete (Wilson 1939, § 4); for other scattering plates all particles with $E_e < 2 \times 10^8$ e-volts are omitted and hence the total number of electrons remaining must be negligible. Protons cannot be similarly excluded except at low energies where they ionize heavily. However, the percentage of protons in the penetrating beam is small, probably less than 10 %, and the effect of a proton component of this order of magnitude is considered in § 7 (figure 2) and is shown to be negligible. The measurements therefore refer almost exclusively to mesotrons.

The accuracy of measurement, and hence of the comparison with theory, cannot be stated with certainty. The observations of scattering angle are made to 0·1°, and the mean value for several independent settings on the same track is probably accurate to within 0·05°. Since for the majority of the tracks used the mean scattering angle is 1–2°, this corresponds to a probable random error of measurement of less than 5 %, and leads to no appreciable systematic error in the arithmetic mean scattering. The precision of the measurements is limited by residual distortions, which are largest near the scattering plate, and by the fact that the larger clusters of ionization, which are particularly conspicuous at small magnifications, lie beside, but not necessarily exactly on, the direct trajectory of a particle. These factors make it necessary to determine the direction of the trajectory over a length for which the curvature in the magnetic field is appreciable. The individual measurements of energy are subject to considerable random errors (7 % at 10^9 e-volts), but, over the energy range used, these random errors do not lead to an appreciable systematic error in the product $\beta E_e \theta$ (see § 4).

The main source of systematic error lies probably in the value of the magnetic field. The field falls off considerably towards the edge of the chamber, and the length of track lying in this peripheral region varies according to the position of the track in the chamber. The mean effective value of the field which has been used is probably uncertain to about 3 %.

The effective magnification of the photographs also varies by 3 or 4 % between tracks at the extreme front or extreme back of the illuminated part of the chamber, but the possible variation of the adopted mean value is very much smaller than the uncertainty of field.

The measured mean scattering, $\overline{\beta E_e \theta}$, is therefore probably accurate, apart from statistical errors, to within 3 %.

3. Experimental results

The results tabulated in table 1 give measurements for four different scattering plates—1 cm. lead, 0·3 cm. lead, 2 cm. copper, and 2 cm. gold. The tracks with the gold plate are all new measurements, while most of the remainder are taken from our previous work, having been selected for the conditions given in § 2. In the second column, the number of tracks measured is shown, and in the third, the mean value of $\beta E_e \theta$, where $E_e \equiv 300 H\rho$ is measured in 10^9 e-volts and θ, the projected angle of scattering in the plane of the chamber, is measured in degrees. The theory (§ 4) shows that it is this quantity $\beta E_e \theta$, which is the measure of the multiple scattering. The value of β used corresponds to a mesotron mass $\mu = 180 m_0$. The last two columns give the direct comparison with the theoretical mean electric scattering when the finite size of the scattering nucleus is taken into account (§ 4), and for the less exact theory in which the nucleus is treated as a point charge.

Table 1. Mean angle of multiple scattering of mesotrons in metal plates

2×10^8 e-volts $< E_e < 2 \times 10^9$ e-volts

Scattering material	No. of particles	Mean scattering $\bar{\theta} = \overline{\beta E_e \theta}$ (degrees × 10^9 e-volts)	$\bar{\theta}/\bar{\theta}_{th}$ (finite nucleus)	$\bar{\theta}/\bar{\theta}_{th}$ (point nucleus)
1 cm. lead	55	0·91	1·01 ± 0·06	0·91 ± 0·06
0·3 cm. lead	15	0·48	1·00 ± 0·13	0·90 ± 0·12
2 cm. copper	25	0·73	0·98 ± 0·10	0·91 ± 0·09
2 cm. gold	90	1·75	1·06 ± 0·05	0·95 ± 0·05
Total	185	—	1·033 ± 0·035	0·931 ± 0·033
Total $\theta < 5\bar{\theta}$	184	—	1·003 ± 0·035	0·906 ± 0·033

The individual measurements of multiple scattering will be shown to agree closely with a Gaussian distribution, and the probable errors of table 1 are calculated accordingly (Brunt, 1931, p. 57). The last line of the table differs from the preceding one by the omission of one track traversing 1 cm. lead, for which $E_e = 1{\cdot}5 \times 10^9$ e-volts and $\theta = 4^\circ$. This track is considered to be a case of large-angle scattering (see § 5), and is certainly not relevant to the Gaussian scattering to which the theory is applicable (table 2). The result for all measured tracks (line 6) is in much better agreement with the finite nucleus theory given by Williams than with the point nucleus theory; however, it must be noted that since both measured and theoretical values are uncertain to 2 or 3 %, the accuracy of the comparison is rather lower than is indicated by the statistical error which is given in the table.

The distribution of scattering angles of all the measured tracks is given in table 2, and the observations are compared with the theoretical Gaussian scattering in figure 1.

TABLE 2. DISTRIBUTION OF ANGLE OF MULTIPLE SCATTERING —COMBINED RESULTS FOR ALL SCATTERING PLATES

Angular range $\theta/\bar{\theta}_{th}$	Observed number of tracks	Theoretical number of tracks (finite nucleus)
0–0·5	63	56
0·5–1·0	48	49
1·0–1·5	32	37
1·5–2·0	19	22
2·0–3·0	16	17
3·0–4·0	4	2·8
4·0–5·0	2	0·24
5·0–6·0	0	0·012
6·0–7·0	1	0·0004
> 7·0	0	0·000005

The observed distribution follows closely the theoretical scattering in the shielded field of a finite nucleus. Only one particle, to which reference has already been made, falls appreciably outside the main distribution.

4. THE SCATTERING OF FAST MESOTRONS—THEORY

The detailed general treatment of this problem is due to Williams (1939), and only the main features of the results which are applicable to cosmic-ray experiments will be given here.

The scattering is considered in terms of an effective impact parameter and two separate cases are distinguished according as the impact parameter is greater or less than a value r_0, which is approximately the nuclear radius. The main observed scattering arises from a range of impact parameters greater than r_0. This is effectively scattering in the Coulomb field of the nucleus, between extreme collision distances, the upper limit being determined by the shielding of the orbital electrons, and the lower limit (r_0) by the modification of the electrostatic field within the nucleus radius. These Coulomb collisions would normally lead to an angular distribution mainly due to multiple scattering, together with a "tail" of large-angle single scattering corresponding to close collisions which do not, on the average, occur as often as once per particle in the scattering layer. Williams shows that the effect of the lower (nuclear) limiting impact parameter is to suppress completely this "tail" of single scattering and to modify slightly

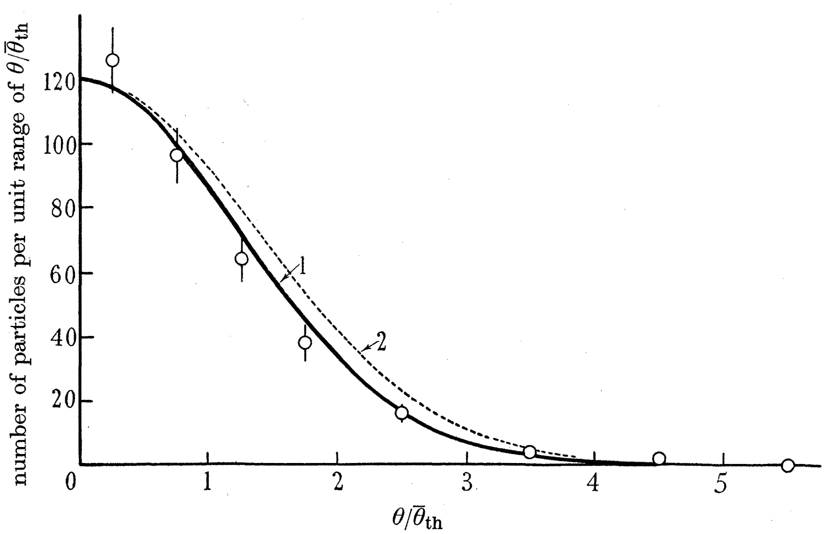


FIGURE 1. The distribution of scattering for mesotrons, $E_e < 2 \times 10^9$ e-volts. (ϕ) observed number of tracks per unit range of $\theta/\bar{\theta}_{th}$, (1) theoretical curve, finite nucleus, (2) theoretical curve, point nucleus, drawn to the same maximum as (1).

the magnitude, but not the form, of the multiple scattering distribution. Hence the scattering due to these more distant collisions is entirely multiple, and the distribution of observed scattering angles (i.e. the projection of the true scattering angles in the plane of the photograph) should be strictly Gaussian.

We may consider the closer collisions, which correspond to a distance of approach of less than r_0, in terms of scattering due to the constituent nuclear particles. It is shown by Williams that for these collisions the scattering in the Coulomb field of separate nuclear protons is negligible, and that any scattering contribution from this region is due to the short range interaction between the scattered particle and the individual neutrons and protons in the nucleus. The short-range forces produce relatively many more large-angle deflexions than arise from the multiple Coulomb scattering. The predicted absence of a single scattering "tail" to the Gaussian of electrical scattering is thus particularly favourable to the detection of scattering due to close collisions with nuclear particles.

The mean value of the multiple electrical scattering is given by

$$\bar{\theta}_{\text{th}} = (19{\cdot}5 - 3{\cdot}1 \log_{10} Z)^{\frac{1}{2}} \frac{600 Z e \sqrt{(Nt)}}{\beta E} \tag{1}$$

for scattering material of atomic number Z, thickness t and N atoms per cm.^{3}, and for a scattered particle of single charge, of electron energy $E_e \equiv 300 H\rho$ and of velocity $v = \beta c$. For 1 cm. lead, equation (1) gives the numerical value $\overline{\theta_{\text{th}} E_e \beta} = 0{\cdot}90$ degrees $\times 10^9$ e-volts. The mass of the scattered particle is effective only in so far as it determines β for a given value of E. We are not able to measure the value of β directly for the tracks used, and all of these are assumed to be mesotrons ($\mu = 180 m_0$). Protons in the energy range considered would give rise to a component of scattering of appreciably larger mean angle than that of mesotrons.

It is not possible, with the experimental data available, to discuss the *distribution* of large-angle scattering due to short range forces; in the following section an estimate of the total cross-section for this scattering is given, but the data are insufficient to give any information as to the law of force involved. These large angle collisions may conveniently be considered in terms of the energy transfer, assuming that this takes place to a single free nuclear particle.* Williams shows that for such a collision, the energy transfer ϵ is given by

$$\epsilon \sim 0{\cdot}35 \times 10^6 \, (E\phi)^2 \text{ e-volts}, \tag{2}$$

where ϕ is the deflexion at collision. The measured deflexion θ is a resultant of ϕ and the normal multiple scattering, and the most probable value of ϕ is θ.

5. Experimental evidence of short-range mesotron-neutron (proton) interaction

As already mentioned, the group of accurately measured tracks (§ 3) contains only one particle falling appreciably outside the distribution of multiple scattering. For this particle the probability of occurrence as a

* Although the mesotron collision is considered as free, the excited particle will probably lose energy to the remainder of the nucleus even if it eventually leaves the nucleus (Heitler 1938*b*).

fluctuation on the main distribution is less than 1/1000. The incident particle has an electron energy $1{\cdot}5 \times 10^9$ e-volts and the energy transfer to a particle of protonic mass corresponding to the whole observed deflexion is about 12×10^6 e-volts (equation (2)), an energy probably sufficient to cause disintegration of the nucleus, although there is no evidence that this has occurred.

Only one collision involving this large transfer of momentum has taken place for the traversal of about 4 cm. lead equivalent of scattering material. It follows, as has already been pointed out by Williams, that the mesotron interaction must be much less than that between protons and slow mesotrons.

A large number of additional photographs representing a total scattering layer of about 50 metres lead equivalent, but which are not suitable for accurate measurement, have also been inspected for the presence of mesotrons suffering large deflexions. It is unlikely that any deflexion as great as 10° would be undetected. Only one example of a large deflexion of this type was observed (photograph, plate 1). This shows a proton which has been ejected from the nucleus in the collision, and is considered in detail in § 6.1, where it is shown that the energy transfer is more than 10^8 e-volts. Although we have observed only one proton ejection of this type, Brode and Starr (1938), in a much larger number of traversals, observed three such events, which appear to represent a similar frequency of occurrence to our observations.

Table 3. Energy transfer in close nuclear collisions by mesotrons

	No. of tracks	Energy transfer (e-volts)	Equivalent thickness lead traversed (metres)	Cross-section per proton or neutron cm.^{2}
Wilson	1	$>10^7$	4	4×10^{-28}
Wilson	1	$>10^8$	50	$0{\cdot}3 \times 10^{-28}$
Brode and Starr	3*	$>10^8$	~ 200	$\sim 0{\cdot}2 \times 10^{-28}$

* Computed from observations of proton ejection; the cross-section is that per proton and *not* per proton or neutron.

We cannot exclude the possibility that some of these particles which undergo large deflexion are protons, for although protons form only a small fraction of the whole beam, the proton-proton cross-section is probably large compared with the mesotron-proton cross-section. In table 3 are given estimates of this latter cross-section on the assumption that all the incident rays are mesotron. In view of the possible presence of protons, the real mesotron-proton cross-section may be still lower than that given in the table.

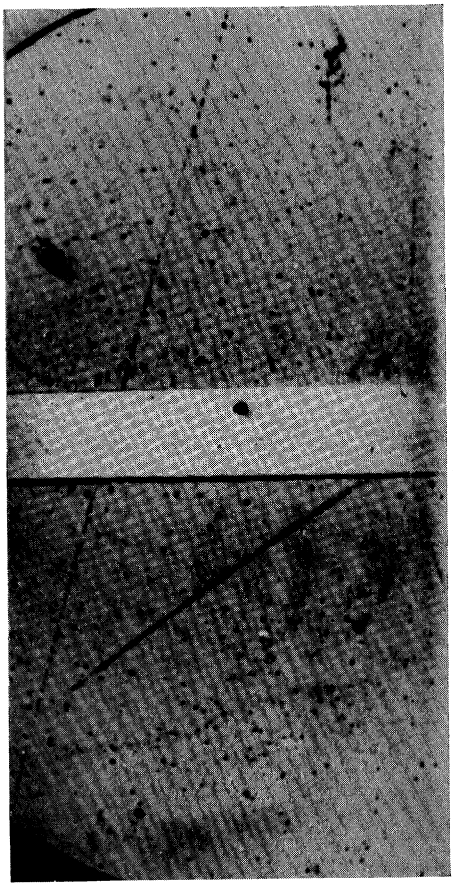
We deduce that the process of scattering of mesotrons of energy $E_e \sim 10^9$ e-volts due to short-range interaction with nuclear particles takes place with a cross-section of the order, or less than, 10^{-28} cm.^{2}. No useful estimate of the variation of this cross-section with the energy transfer is possible at present.

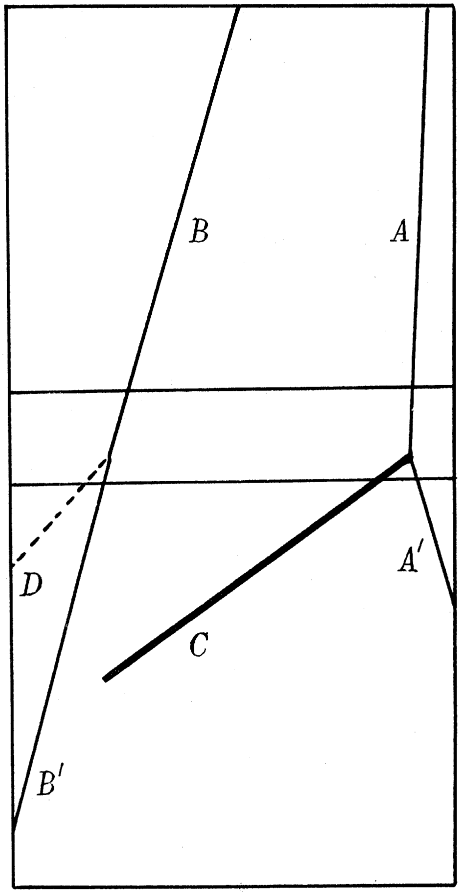
It has been pointed out elsewhere (Wilson 1939) that the scattering of a group of low energy mesotrons (included in the general results, tables 1 and 2) was completely normal and showed no cases of large-angle scattering. This group consisted of thirty-one particles, with $E_{\text{kin}}/\mu c^2 < 4{\cdot}1$, which penetrated 2 cm. gold, corresponding to the traversal of about 100 cm. lead equivalent. The mean observed scattering for these tracks was $\bar{\theta}_{\text{obs}}/\bar{\theta}_{\text{th}} = 1{\cdot}02 \pm 0{\cdot}10$, and the group contains no example of large-angle scattering. The efficiency with which large deflexions would be observed is determined by the geometry of the counters and of the scattering bar. We estimate that for the least favourable assumption as to the distribution of large-angle scattering—an isotropic distribution—the observations exclude the possibility that as many as 10 % of the particles suffer large deflexions. When predominantly forward scattering is assumed, the possible frequency of large deflexions decreases, and, for a scattering distribution corresponding to that of the Compton effect for a comparable photon energy (given by $h\nu/mc^2 \sim E$ (mesotron)$/\mu c^2$), is less than 3 %.

The range in lead for scattering due to short-range forces is thus certainly of the order of 100 cm. or more for mesotrons of a mean kinetic energy less than $4\mu c^2$. This range corresponds to a cross-section $\lesssim 10^{-27}$ cm.^{2} per proton or neutron, and hence we observe no increase of scattering at low mesotron energies as compared with that at higher energies.

6. The mesotron-proton (neutron) interaction—comparison with theory

The cross-section estimated in the previous section for this interaction ($\sim 10^{-28}$ cm.^{2}) is in agreement with that deduced by Bhabha (1938, 1939) in a *"classical" wave theory* of the mesotron. Bhabha shows that this classical treatment should describe the mesotron interaction with heavy particles up to mesotron energies of the order of the rest mass of the heavy particle, say, 10^9 e-volts. Thus our experimental energy range does not seriously exceed the valid range of the theory.





(*Facing p.* 81)

The well-known difficulties involved in the *quantum theory* of mesotrons allow a comparison of the observations with quantum theory only at the lowest energies ($E_{\text{kin}} \sim \mu c^2$). The calculated cross-section, which is of the order of $2 (\hbar/\mu c)^2 \sim 10^{-25}$ cm.^{2} (Heitler 1938*a*), seems much too large to agree with the experimental value $\lesssim 10^{-27}$ cm.^{2} (§ 5) which is obtained for kinetic energies very little greater than the mesotron rest energy.

6.1. *Discussion of plate* 1. An example of a very close collision showing some remarkable features is given in plate 1. It is unfortunate that the photograph is technically very much poorer than the average.

The incident particle, A, which is positive with an electron energy between 10^9 and 2×10^9 e-volts, is scattered through 18° to A', and a proton, C, is ejected at an angle of 53° with the direction of A. The curvature of the proton track, C, is $1{\cdot}05 \times 10^6$ g.-cm., and hence this particle leaves the plate with an energy $0{\cdot}56 \times 10^8$ e-volts: allowing for the loss of energy traversing the plate from the point of collision, we find the initial energy of the ejected proton to be $1{\cdot}7 \times 10^8$ e-volts. The energy and momentum relations for the collision indicate very little deviation from an elastic collision.

Plate 1 also shows another more energetic penetrating particle BB' which is, as far as can be judged, copunctual and contemporary with AA' (see Wilson 1939, § 6). There is some indication that BB' produces a secondary, D, which is probably electronic. A third contemporary track appears near the top right-hand corner of the photograph, but there is no indication as to its nature. The probability that the association in time of these three tracks is the result of random coincidence is negligible. Thus we have here a definite case of associated penetrating particles in a shower. It is not clear what, if any, is the relation between such phenomena and the well-known "stars" of Blau and Wambacher (1937; Schopper and Schopper 1939) which appear to consist mainly of alpha particles and protons derived from nuclear disintegration. But the proton track C would certainly be observed as a single track in a photographic emulsion.

7. The scattering distribution in the presence of protons

For the experimental energy range, protons have a velocity appreciably less than c and therefore give rise to a rather more strongly scattered component than the predominant mesotrons. In figure 2, the modification of the tail of the curve of multiple scattering is given for proton components of 20% and 40% at a mean energy of $E_e = 10^9$ e-volts. The proton component, in fact, amounts probably to only about 5% or less, and the figure shows clearly that the effect of this proportion is negligible for the number of tracks observed. The single example of large-angle scattering in the series of accurately measured photographs is also indicated in figure 2.

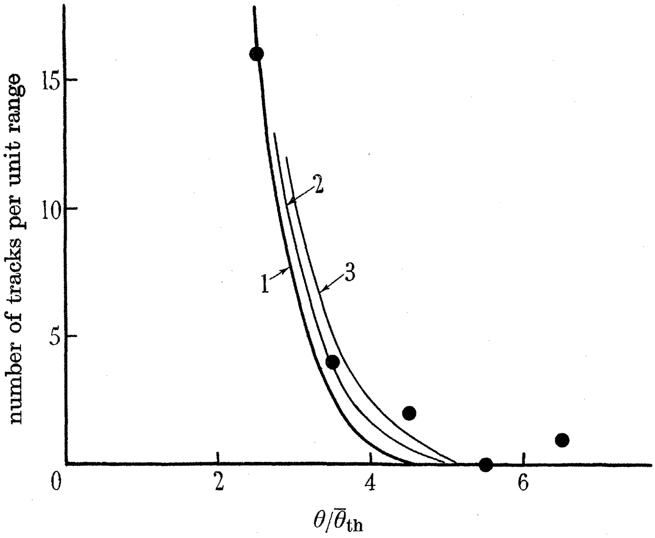


FIGURE 2. Modification of the tail of the multiple scattering curve for mesotrons in the presence of a proton component. (1) No protons, (2) 20% protons, (3) 40% protons. ● observed distribution of scattering—number of tracks per unit range of $\theta/\bar{\theta}_{th}$—(table 2).

8. Discussion and conclusion

8.1. *Scattering in the Coulomb field.* The agreement between experiment and theory for the Coulomb scattering of mesotrons is shown in § 3 to be within the probable error of the observations and of the theory.

We have found no deviation from theory for the slowest mesotrons included in our measurements (§ 5, $E_e \sim 3 \times 10^8$ e-volts), but a considerable anomaly has been reported by Fowler and Oppenheimer (1938; Fowler 1938) for 10^7 e-volt electrons scattered in thin lead foil. These workers show that while the single large-angle scattering (which is not suppressed under the conditions of their experiment) is normal, the multiple scattering is only about 40% of that predicted theoretically. This result suggests that the discrepancy is associated with the small deflexions arising from collisions near the upper shielding impact parameter. In our experiments, where a much thicker scattering plate is used, the relative importance of this region for multiple scattering is clearly much reduced. Hence the anomaly is probably determined by the thickness of the scattering layer rather than by the energy of the scattered particle.

8.2. *The interpretation of scattering due to short-range forces.** According to the present mesotron theory, the cross-section for the scattering of *charged* mesotrons by a proton or neutron is given, for energies of the order μc^2 (Heitler 1938*a*), by

$$\phi \simeq 4\pi\left(\frac{g^2}{\mu c^2}\right)^2 \simeq 10^{-25} - 10^{-26}\ \text{cm.}^2, \tag{3}$$

where g is the characteristic "charge-constant" of the mesotron theory. The cross-section increases at higher energies, but these energies ($E_{\text{kin}} > \mu c^2$) lie outside the limits of validity of the theory.

In a classical theory for *neutral* mesotrons, Bhabha (1939) finds a much smaller cross-section:

$$\phi \simeq 8\pi/3\left(\frac{g^2}{Mc^2}\right)^2 \simeq 10^{-27} - 10^{-28}\ \text{cm.}^2, \tag{4}$$

where M is the proton mass. This value, (4), is analogous to the Thomson formula for the scattering of light by electrons, and does not increase with increasing energy. The same result (4) can be derived from the quantized mesotron theory for the scattering of *neutral* mesotrons.

It should be noted that (3) is independent of the proton mass, while (4) is proportional to $1/M^2$.

The remarkable difference between (3) and (4) is due to the role which the electric charge plays in the mesotron theory, controlling to a large extent the interaction between charged mesotrons and heavy particles: a positive mesotron, for instance, can be absorbed only by a neutron and not by a proton, while no such restriction applies for neutral mesotrons. This difference of behaviour leads to the large cross-section (3).†

We have already shown (§ 6) that the experiments are not in agreement with the cross-section (3) but are consistent with (4). It might still be

* This section is based on a private communication for which I am indebted to Dr Heitler. The theoretical position outlined in this section is the result of discussions between Bhabha, Fröhlich, Heitler and Kemmer.

† If states of the heavy particle were possible with charges $+2e$, $+e$, the scattering cross-section (4) would apply also for *charged* mesotrons. This assumption, however, involves so many other difficulties that it would be premature to consider it seriously at the moment.

Heitler also points out that the cross-section for processes of the type

$$Y^\circ + N = P + Y^-$$

does not depend on the interaction assumed, but in any case is given by (4).

6-2

possible to assume that (3) is correct for energies less than μc^2 and that the cross-section decreases very rapidly (by a factor of 100!) between μc^2 and $3\mu c^2$, but this behaviour is most unlikely. It is much more probable that (4) represents the true cross-section even for *charged* mesotrons, although this result cannot be deduced from the present mesotron theory in any form.

The small experimental cross-section for charged mesotrons at low energies has therefore an important bearing on the fundamental problems of charge exchange in the interaction of charged mesotrons with heavy particles.

I am indebted to Professor P. M. S. Blackett for his constant interest and advice during this work, and to Professor E. J. Williams and Dr W. Heitler for discussions of the theory of scattering.

Summary

An extended series of accurate measurements of the scattering of mesotrons is described. These are in general agreement with our earlier measurements, and confirm within the accuracy of the experiment (about 4 %) the theoretical value given by Williams (1939) for multiple Coulomb scattering.

Theory shows that the scattering by a finite nucleus should be about 10 % less than that by a point nucleus. The experimental results, which have an accuracy of about 4 %, definitely confirm the lower value and so can be considered as supporting the correctness of the scattering theory as applied to a finite nucleus.

The evidence for the existence of large-angle scattering due to short-range forces between mesotrons and nuclear heavy particles (protons and neutrons) is discussed. The cross-section for this type of scattering is estimated to be of the order 10^{-28} cm.^{2}, and this value is in agreement with that given by Bhabha for a "classical" mesotron theory.

There is no experimental evidence for the large increase of scattering due to short-range forces at low mesotron energies given in the quantum mechanical treatment due to Heitler. For the available mesotrons of lowest energy, the cross-section is found to be less than 10^{-27} cm.^{2}. This result is not compatible with the present development of mesotron theory, and may be interpreted as indicating a failure in the treatment of the charge-exchange which leads to the interaction between charged mesotrons and heavy particles.

References

Bhabha 1938 *Nature, Lond.*, **141**, 117.
— 1939 *Proc. Roy. Soc.* A, **172**, 384.
Blackett and Wilson 1938 *Proc. Roy. Soc.* A, **165**, 209.
Blau and Wambacher 1937 *S.B. Akad. Wiss. Wien*, **146**, 623.
Brode and Starr 1938 *Phys. Rev.* **53**, 3.
Brunt 1931 *Combination of Observations*. Camb. Univ. Press.
Fowler 1938 *Phys. Rev.* **54**, 773.
Fowler and Oppenheimer 1938 *Phys. Rev.* **54**, 320.
Heitler 1938*a* *Proc. Roy. Soc.* A, **166**, 529.
— 1938*b* *Phys. Rev.* **54**, 873.
Schopper and Schopper 1938 *Phys. Z.* **40**, 22.
Williams 1939 *Proc. Roy. Soc.* A, **169**, 531.
Wilson 1939 *Proc. Roy. Soc.* A, **172**, 517.

The photodisintegration of the deuteron in the meson theory

By H. Fröhlich

H. H. Wills Physical Laboratory, University of Bristol

W. Heitler and B. Kahn

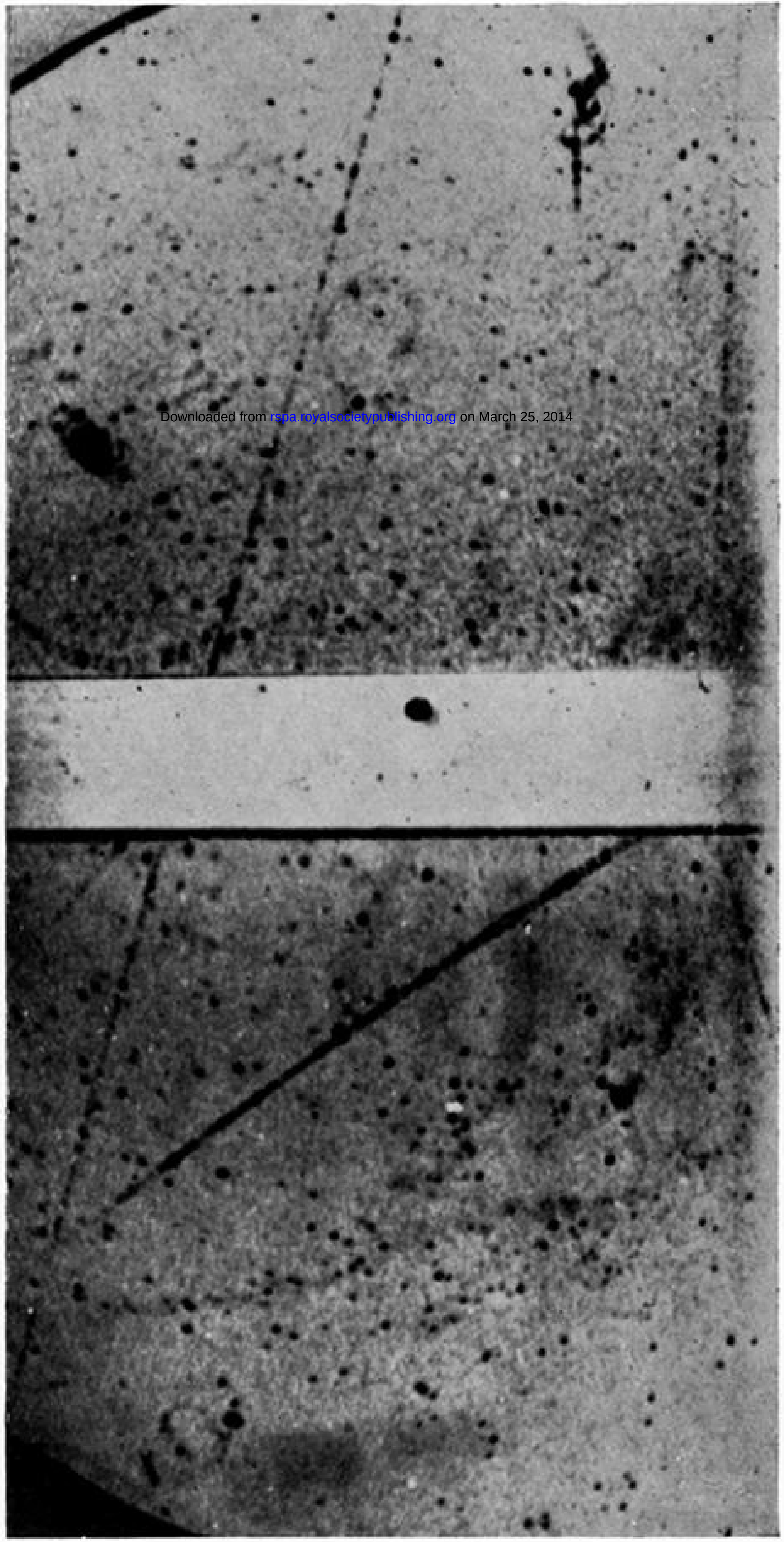
At present at Royal Society Mond Laboratory, Cambridge

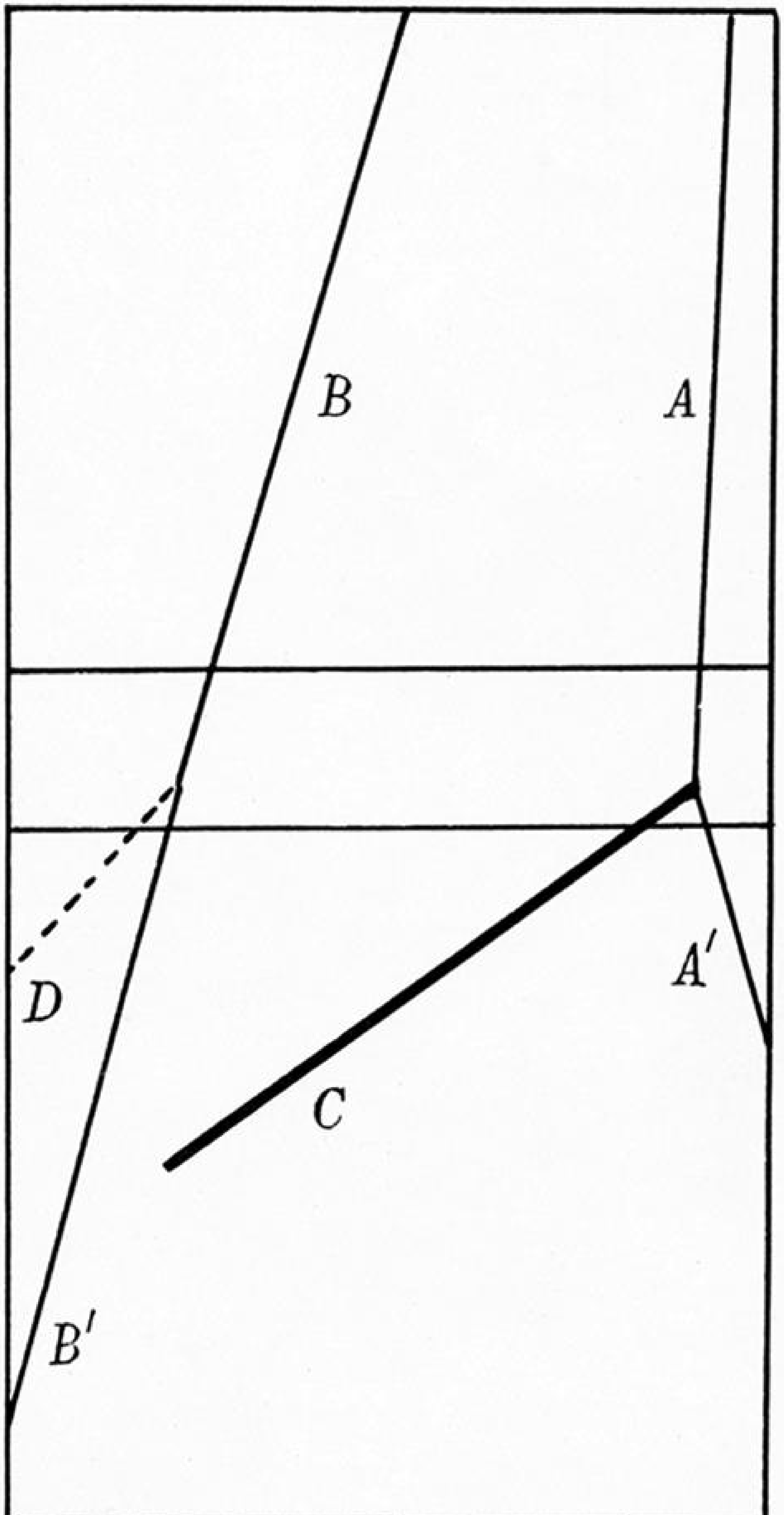
(*Communicated by J. D. Cockcroft, F.R.S.—Received* 14 *August* 1939)

1. Introduction

Bethe and Peierls (1935) have given a theory of the photoelectric effect of the deuteron which was based on the assumption that between a neutron and a proton forces of a very short range exist. This made it possible to calculate the cross-section and the angular distribution in a way which seemed to a great extent to be independent of the nature of the nuclear forces. Massey and Mohr (1935) have extended this theory. Later on Breit and Condon (1936) have taken into account the influence of exchange forces of the Majorana type.

In recent years a theory of nuclear forces has been developed, the fundamental ideas of which are due to Yukawa (1935). In this theory, the existence of free mesons (cosmic rays) is connected with the nuclear forces in a similar way as the electromagnetic forces between electrically charged




B
A
D
A′
C
B′