ANOMALOUS SCATTERING OF LOW ENERGY MU-MESONS IN COPPER

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Abstract

By a special arrangement of a three-fold coincidence and anti-coincidence system a cloud chamber fitted with five ½ inch copper plates has been triggered to photograph tracks of particles stopped inside the chamber. From a total number of about 800 such pictures 250 were selected in which the ionization in the different gaps and residual range definitely identified the particles as mu-mesons. These muons had momenta varying from 100–170 Mev/c when they entered the chamber. The projected angle of scattering at each Cu-plate was measured together with the momentum of the muons from the residual range and ionization after the scattering. Altogether 446 scattering angles of muons with their momenta were analysed and a differential distribution of $p\beta\theta$ have been obtained. It has been found that the distribution agrees well with the theory of Olbert and Molière or Snyder and Scott up to $p\beta\theta = 2{\cdot}5$, and is too large by a factor of 2 to 3 for values of $p\beta\theta = 3$ to 5. The disagreement is observed to be much more prominent in the low energy region than that reported by other workers for the high energy muons.

Introduction

The scattering of mu-mesons by different nuclei has been the subject of a number of investigations during the last fifteen years. Experiments made earlier than 1953 have been summarized by Leontic and Wolfendale (1953) who have found in common with the results of previous workers a large excess of the large angle scattering distribution over the theoretical distribution expected for a 'solid' nucleus. These investigations were continued by McDiarmid (1954, 1955) whose work with the lead absorber suffered from a strong bias against recording large angle scatterings as he had a counter tray below the cloud chamber recording the scattering events. In his later work with iron absorbers he omitted this tray of counters and analysed a very large number of traversals of mu-mesons of momenta ranging from 0·3 to 4 Bev/c and concluded that there is an anomalous tail of large angles whose magnitude is roughly in agreement with Molière's theory of a 'point' nucleus. The coulomb interaction of cosmic ray mesons has also been studied by Whittemore and Shutt (1952) both at sea-level and at 3·4 km. altitude by means of a double cloud chamber with a magnetic field in between. Their results with a 5 cm. thick lead scatterer agree quite well with the distribution expected from the theory of Molière for a nucleus which scatters like a 'point' charge. Lloyd and Wolfendale (1955) and Lloyd, Rössle and Wolfendale (1957) have now made extensive measurements of the scattering of mu-mesons in the momentum range 5–150 Gev/c in a thick lead absorber by means of the Manchester cosmic ray spectrograph and a multiplate cloud chamber. Their results are again fully in agreement with Molière's point nucleus distribution. It has been pointed out by all these authors that the agreement of the distribution of the large angle scatterings with the scattering expected from a 'point' nucleus is fortuitous as similar experiments done with high energy electrons by Hofstadter *et al.* (1953, 1954) definitely indicate an equivalent spherical charge distribution of nuclei of radius equal to $1.2.A^{\frac{1}{3}}.10^{-13}$ cm., where A is the atomic mass of the nucleus. Moreover extended charge and matter distribution in nuclei is now firmly established from the experiments on mu-mesonic X-rays by Fitch and

Rainwater (1953) and medium energy cosmic ray interactions by Sinha and Das (1957). It should also be emphasized that experiments carried out by George *et al.* (1953) underground with two lead plates indicate a large angle 'tail' which is even more than that expected from a 'point' nucleus and these authors observed that the large angle scatters mainly refer to particles with energies between 100 and 300 Mev. These results therefore exhibit an increase in the anomalous scatterings for low energy mu-mesons and the experiments of Kannangara and Shrikantia (1953) with Ilford G5 plates exposed at 60 m.w.e. support this view. These authors find out a cross-section of $2{\cdot}3\times10^{-28}$ cm.^{2}/nucleon for all mu-mesons of $p\beta > 100$ Mev/c, but find a cross-section of $3{\cdot}4\times10^{-27}$ for mu-mesons of $p\beta$ in the region (100–600) Mev/c. Thus the cross-section is found to be an order of magnitude higher when the analysis is confined to muons of the low energy group. This energy dependence of anomalous scattering of muons is also clearly borne out by the experiments of Amaldi and Fidecaro (1951) who have observed with a counter hodoscope an increase in the anomalous scattering cross-section by a factor of twenty when the energy of the particle investigated was brought down to 200–300 Mev from 320 Mev to infinity. Alikhanian *et al.* (1955) have reported that the cross-section for scattering of mu-mesons in carbon plates through angles greater than 16° had been found to fall with increase in energy of the mu-mesons. They have further observed that the scattering of mu-mesons of momentum in the region 80–135 Mev/c in copper was much greater than that expected from Olbert's theoretical distribution assuming a uniform nuclear model. The results of all these experiments combined together made us believe that there is actually a progressive rise in the anomalous scattering cross-section as we go down the energy spectrum of the muons. We, therefore, thought of studying the scattering of muons of a still lower energy group (40–95) Mev corresponding to a $p\beta$ in the region of 70–150 Mev/c and of finding out whether this progressive increase is maintained down below. Although there are now sufficient data available for the scattering of the high energy groups, the scattering of the lowest energy group has not been investigated before. It has been the aim of the present experiment to collect data not only for the scattering of the lowest energy group of mu-mesons that can be possibly studied but also to determine the momentum of each scattered meson from its residual range by stopping it inside a cloud chamber. The special features of the experiment are described below.

THE EXPERIMENT

It has been the general practice of the previous workers to present data of the scattering of a group of mu-mesons of momenta varying between fairly wide limits. This is particularly unsuitable for determining accurately any energy dependence of the large angle scattering of a particular meson whose individual momentum is unknown. A meson suffering a large angle scattering may be anywhere in a momentum spectrum of considerably wide limits. A second defect, which is unavoidable in the study of the high energy group, is the presence of unwanted pions and protons in the mu-meson spectrum investigated. Although singly occurring pions and protons will be very few, particularly at sea-level and underground, yet it should be kept in mind that the large angle scatterings are also very few. Both these defects have been removed in the following experiment. It will be seen later that the momentum of a particular particle is not only known within a few Mev/c but also its identification as a mu-meson is fairly well established by its ionization and residual range.

The experimental set-up is shown in Fig. 1. A three-fold coincidence set $C_1C_2C_3$ selects the meson beam and the anti-coincidence tray A makes the whole system take photographs of particles stopped inside the chamber in any of the five half inch copper plates. This particular arrangement was utilized by the present authors (1957) to measure the mu-meson spectrum at Calcutta (geomagnetic latitude 12° N.)

at the low energy end. It is easily seen that any thickness of absorber placed above the chamber does not affect the momentum of the photographed mu-mesons at the moment they enter the cloud chamber. The momentum of a particular particle in a certain gap between the plates is determined by the amount of matter it subsequently traverses. A mu-meson after entering the cloud chamber and stopping in any one of the plates will always have its momentum between 100 and 170 Mev/c corresponding to a limit in its range from 5·5 g. cm.$^{-2}$ (mid-point of first plate) to 49·5 g. cm.$^{-2}$ (mid-point of fifth plate) of copper with an uncertainty of 5·5 g. cm.$^{-2}$ of copper equal to half the thickness of any plate. Thus, while the mu-meson spectrum was being determined at this station by interposing different thicknesses of absorber above the cloud chamber, we collected a good amount of data for the scattering of definitely established mu-mesons in the above momentum group. As the mesons were not required to pass through a counter system below the chamber as in the case of the experiments of George *et al.* (1953) or the first experiments of McDiarmid (1954), there was absolutely no bias against recording large angle scatterings. Furthermore, by reducing the thickness of each scattering plate to 11 g. cm.$^{-2}$ the effect of masking of the large angle single scattering by the mean multiple scattering is reduced. This particular experimental set-up is believed to facilitate the recording of large angle events without any bias, and a particular particle whose scattering is investigated is precisely identified as a mu-meson. The only drawback of this experiment was that the rate of useful photographs obtained was very low and a considerable time had to be devoted to collect statistically significant data.

Any particle that either stopped at minimum ionization or produced one or more secondaries was rejected as an electron. Particles whose mass values were found to be fifty per cent higher than mu-mesons from estimate of ionization and residual range were excluded. Genuine mu-mesons stopping in the first plate were also useless for scattering investigation. Altogether 250 particle tracks were selected from the photographs where distortion was minimum and visibility was good throughout the whole length of the track. The projected angle θ in the plane of illumination was measured for each scattering and the subsequent range of the particle from the mid-point of this scattering plate to the mid-point of the plate in which it stops gave the momentum of the particle. In determining the residual range after scattering, the inclination of the track to the plates was always taken into consideration. However, in most cases, the direction of the particle was almost vertical, and the momentum $p\beta$, β, k.e., and λ-values of a mu-meson at the $(n-1)$th, $(n-2)$th, $(n-3)$th, and $(n-4)$th plates when it stops in the nth plate is given in Table 1. Here n varies from 2 to 5 signifying the stoppage of a particle from the second to the fifth plate.

TABLE 1

Momenta, kinetic energies, etc. of mu-mesons scattered at the various plates inside the cloud chamber, when they stop at the n*th plate* (n = 2, 3, 4, 5)

For scattering in plate	Momentum p in Mev/c	β	$p\beta$ in Mev/c	K.E. in Mev	$\lambda = \hbar/p$ in 10^{-13} cm.
$(n-1)$th	100	0·70	70	40	1·98
$(n-2)$th	130	0·77	100	60	1·52
$(n-3)$th	150	0·86	130	78	1·32
$(n-4)$th	170	0·89	150	95	1·16

A mu-meson which stops in the fifth plate gives four measurable scattering angles, one which stops in the fourth plate, three and so on. But in all cases the momentum of the scattering mu-meson at the $(n-1)$th plate (i.e. the last but one plate) will be 100 Mev/c, at the $(n-2)$th plate 130 Mev/c and so on. It will be seen later that the quantity which is theoretically significant is the product $p\beta\theta$, and therefore this product was determined individually for 446 traversals of the half inch copper plates by mu-mesons stopping inside the cloud chamber. The values of $p\beta$ were expressed in Bev/c and the angles in degrees so that the product is represented in (Bev/c) × degrees as has been done by Whittemore and Shutt (1952). But since the absolute values of the momenta in our case are confined between 0·07 and 0·15 Bev/c, the largest individual value of $p\beta\theta$ extended only up to 6, even though the largest individual angle of scattering extended up to 60°. The distribution $F(p\beta\theta)$ of the 446 scattering events in 11 g. cm.$^{-2}$ of Cu against $p\beta\theta$ is shown in Table 2.

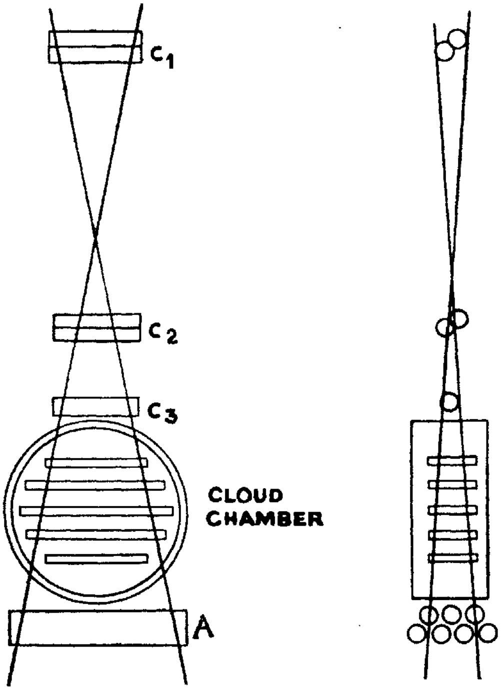

FIG. 1. The experimental arrangement of the various counter trays and the cloud chamber fitted with five ½ inch Cu-plates.

TABLE 2

The distribution of the total number of scatterings against $p\beta\theta$

$p\beta\theta$	0–1	1–2	2–3	3–6
Number	347	78	16	5

The weighted mean of the values of '$p\beta$' in our case is 89·4 Mev/c and the corresponding r.m.s. multiple scattering angle for 11 g. cm.$^{-2}$ of copper scatterer is 8·6°. We shall now try to find out the theoretical distribution expected for this scattering from the various theories put forward during recent years, using a weighted mean value of β for the spectrum investigated.

COMPARISON WITH THEORY

Calculations were first made to find out the differential distribution expected from the theories of Molière (1948) or Snyder and Scott (1949) and Olbert (1952) and then the observed distribution was compared with the theoretical distributions thus obtained. We indicate below how the theoretical distribution curves for the projected angle of scattering have been obtained.

The approximate expression for the distribution function for the scattering variable is given by Molière, for 'point' nucleus, as the following:

$$f(x) = \exp(-x^2)/\sqrt{\pi} + (1/4G)\, f^{(1)}(x;\ \propto) \quad \ldots \quad \ldots \quad \ldots \quad (1)$$

where $x = \phi/(2GQ)^{\frac{1}{2}}$

ϕ = projected angle of scattering

$$G = 5{\cdot}66 + 1{\cdot}24 \log_{10}\left[\frac{Z^{4/3}A^{-1}t}{1{\cdot}13\beta^2 + 3{\cdot}76(Z/137)^2}\right] \quad \ldots \quad \ldots \quad \ldots \quad \ldots \quad (2)$$

$$Q = 4\pi \frac{Nt}{A}\left(\frac{Ze^2}{p\beta c}\right)^2$$

$f^{(1)}(x;\ \propto)$ = the first correction function in Molière's theory.

The other terms in the above equations represent the following:

p = momentum of the scattered particle; $c\beta$ = velocity of the scattered particle; Ze = nuclear charge of the scattering material; A = atomic weight of the scattering material; N = Avogadro number; t = thickness of the scattering material in g. cm.^{2}.

For small angles the first Gaussian term in equation (1) which represents the multiple coulomb scattering is the dominant term. For large angles the second term, mainly representing large angle single scattering, becomes larger than the Gaussian term and as x approaches infinity the Molière's correction function decreases as x^{-3}. Molière assumed that the value of the single scattering angles may extend up to infinity. On the other hand, Olbert (1952) assumed that the probability of single scattering goes abruptly to zero for angles greater than ϕ_0, given below by equation (6). If the value of x for $\phi = \phi_0$ is denoted by x_0, then the distribution function of Olbert is given by

$$f(x;\ x_0) = \exp(-x^2)/\sqrt{\pi} + (1/4G)[f^{(1)}(x;\ \propto) - k(x;\ x_0)] \quad \ldots \quad \ldots \quad (4)$$

where $k(x; x_0)$ is the correction function introduced by Olbert to represent the scattering from x_0 to infinity and has to be subtracted from Molière's correction function $f^{(1)}(x; \propto)$. Condensing these two functions into one expression Olbert finally obtained the following compact form for the distribution function:

$$f(x;\ x_0) = \exp(-x^2)/\sqrt{\pi} + (1/4G)f^1(x;\ x_0) \quad \ldots \quad \ldots \quad \ldots \quad (5)$$

The function $k(x;\ x_0)$ includes the effect of the finite size of the nucleus and tends to zero as x_0 approaches infinity when Olbert's distribution (5) will become identical with Molière's distribution (1). Olbert (1952) has obtained curves for his condensed function $f^1(x;\ x_0)$ for various values of the cut-off parameter x_0 and we have made use of these values in our calculation. The cut-off parameter x_0 is given by

$$x_0 = \phi_0/(2GQ)^{\frac{1}{2}}$$

where ϕ_0 the limiting angle for single scattering is defined by the following expression:

$$\phi_0 = (a/r_n)\phi_m \quad \ldots \quad \ldots \quad \ldots \quad \ldots \quad \ldots \quad (6)$$

Here 'a' is the atomic radius as computed from the Fermi-Thomas theory and r_n is of the order of nuclear radius. The parameter ϕ_m is the so-called 'screening' angle accounting for the shielding effect of the atomic electrons. Substituting the values of all these terms we get the final value of x_0 as

$$x_0 = \frac{260}{Z}\left[\frac{A^{1/3}}{Gt}(1{\cdot}13\beta^2+3{\cdot}76(Z/137)^2)\right]^{\frac{1}{2}} \quad .. \quad .. \quad .. \quad (7)$$

In all cases the Molière and Olbert correction functions differ markedly for angles appreciably greater than the cut-off angle. Olbert's function drops to zero with increasing x much more rapidly than the Molière correction function.

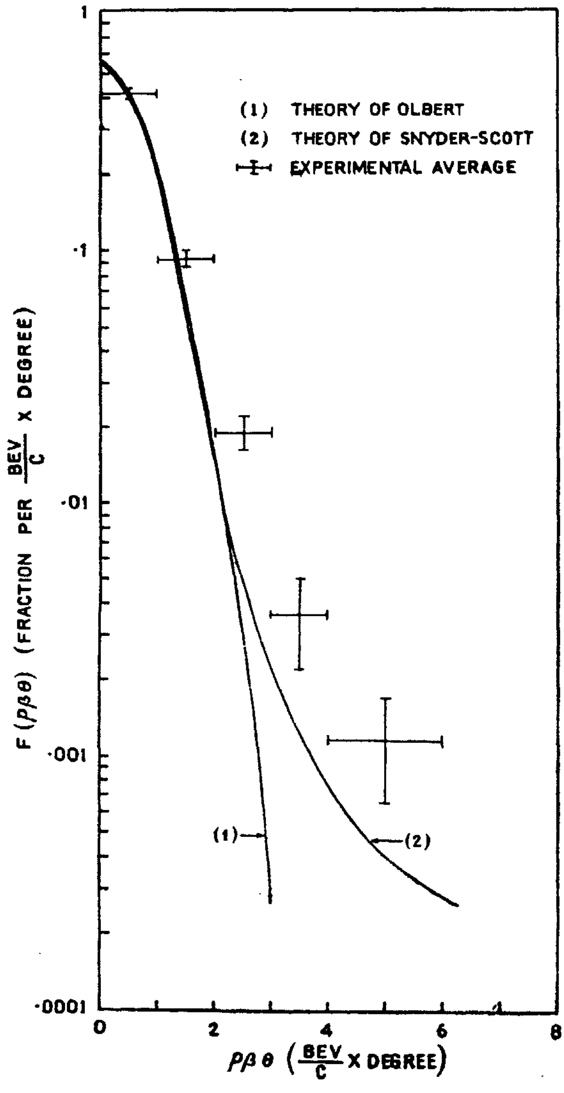

FIG. 2. The differential distribution of $F(p\beta\theta)$ by 1·25 cm. copper for mu-mesons with $0{\cdot}10 < p < 0{\cdot}17$ Bev/c.

The values of G and Q for 11 g. cm.^{2} of Cu and then the characteristic parameter $(2GQ)^{\frac{1}{2}}$ were calculated and found to be

$$Q = \frac{2{\cdot}27\times 10^{-5}}{p\beta^2}, \text{ where } p \text{ is in Bev/c.}$$

$G = 7{\cdot}18$, for $\beta = 0{\cdot}75$, the weighted mean value in our case. Hence $x = \phi/(2GQ)^{\frac{1}{2}} = 0{\cdot}967\, p\beta\theta$, where we replace ϕ by θ the more familiar symbol for the experimental projected angle of scattering. We thus find that the actual variable x of the scattering distribution is directly proportional to $p\beta\theta$.

Finally substituting values in (7) for 11 g. cm.^{2} of Cu and $\beta = 0{\cdot}75$ we get

$$x_0 = 1{\cdot}86$$

The values of $f^1(x;\, x_0)$ for $x_0 = 1{\cdot}86$ and for different values of x were obtained from Olbert's (1952) curve and values of $f(x;\, x_0)$ in equation (5) for various values of x extending from $p\beta\theta = 0$ to 6 were then calculated. The resulting distribution is plotted in curve 1 of Fig. 2 in the form $F(p\beta\theta) - p\beta\theta$, where $F(p\beta\theta) = 0{\cdot}967\, f(x;\, x_0)$ represents the fraction per (Bev/c) × degree. Exactly similar calculations were made with $x_0 = \infty$ to find out the distribution according to Molière's or Snyder and Scott's theory of 'point' nucleus and curve 2 in Fig. 2 gives the latter distribution.

Experimental values of the distribution of $p\beta\theta$ are given in Table 2. We know that the scattering distribution agrees with theory for small values of $p\beta\theta$ and hence the experimental values were normalized so that the value corresponding to $p\beta\theta = 0{\cdot}5$ (i.e. between 0 and 1) coincides with the theoretical distribution at $p\beta\theta = 0{\cdot}5$. The normalized experimental distribution has been shown along with curves 1 and 2 in Fig. 2. The agreement is quite good for the portion representing multiple coulomb scattering (up to $p\beta\theta = 2{\cdot}3$) covering angles up to three times the r.m.s. angle expected for this energy group. There are, however, points corresponding to $\theta > 3\theta$ r.m.s. which show a 'tail' in which the scattering distribution is higher than even the Molière distribution due to a 'point' nucleus by a factor of 2 to 3. Thus we find that not only does the anomalous scattering keeps on increasing with decreasing $p\beta\theta$ as found out by earlier workers but also that the magnitude of the discrepancy has increased. We shall discuss in the last section about the possible causes of this discrepancy. But before this, we shall try to find out a value of the scattering cross-section at large angles.

EXPERIMENTAL CROSS-SECTION AT LARGE ANGLES

Out of a total of 446 scattering angles observed, there were twenty cases of large angle scatterings in which the angle was greater than 25·8° which is three times the r.m.s. scattering angle (8·6°) expected for a mean $p\beta$ of 89·4 Mev/c; nine were more than 4θ r.m.s. and two greater than 5θ r.m.s. Altogether a distance of 6·21 metres of copper were traversed by the mu-mesons while these scatterings occurred and this gives the following mean free path in copper for large angle scatterings and the corresponding cross-sections.

TABLE 3

Scattering angle	Mean free path in cm. of Cu	Cross-section in 10^{-28} cm.^{2}/nucleon	Mean $p\beta$ of the particles in Mev/c
$\theta > 3\theta$ r.m.s.	$31{\cdot}10 \pm 4{\cdot}6$	$60{\cdot}6 \pm 8{\cdot}0$	90
$\theta > 4\theta$ r.m.s.	$69{\cdot}00 \pm 12{\cdot}7$	$27{\cdot}1 \pm 5{\cdot}1$	90
$\theta > 5\theta$ r.m.s.	$310{\cdot}00 \pm 155{\cdot}0$	$6{\cdot}1 \pm 3{\cdot}0$	90

In all these large angle scattering events the momentum of the individual meson could be measured by its residual range, but only after the scattering has taken place. Allowing on an average 20% loss in momentum during the scattering event, the mean $p\beta$ of the mesons scattered into angles $>3\theta$ r.m.s. is found to be 90 Mev/c with an uncertainty of 25%. Kannangara and Shrikantia (1953) have given the $p\beta$ values of the seven particles which scattered in G5 emulsion by more than 7° and this gives a cross-section of $(34 \pm 15) \times 10^{-28}$ cm.^{2}/nucleon for a mean $p\beta$ of 176 Mev/c compared to our value of $(60 \pm 8) \times 10^{-28}$ cm.^{2}/nucleon for a mean $p\beta$ of 90 Mev/c. In all other cases of scatterings so far measured, except those of Lloyd, Rössle and Wolfendale (1957) in the very high energy region, the individual momentum of the scattering particle is not known although an approximate value 40×10^{-28} cm.^{2}/nucleon has been obtained by George *et al.* (1953) for particles of $p\beta$ between 150 and 400 Mev/c. The experiment of Amaldi and Fidecaro (1951) gives a value two orders of magnitude less than these values for the same energy region. But the counter arrangement of these workers records very large angles and as such a considerable portion of moderately large angle scatterings is lost. An evaluation of the large angle cross-section by Leontic and Wolfendale (1953) gives a value of 23×10^{-28} for a momentum transfer of 85 Mev/c and the cross-section found by Whittemore and Shutt (1952) is $5{\cdot}0 \times 10^{-28}$ for mu-mesons of average momentum 1 Bev/c. The presence of a high magnetic field in between the two cloud chambers of these workers prevents low energy particles from entering the second chamber in which the scattering is observed. Recent experiments of McDiarmid (1955) with six one-inch iron plates inside a cloud chamber, operated under 26 m.w.e., show 14 cases of scattering greater than 3θ r.m.s. for (his group 2) mu-mesons of mean momentum 650 Mev/c in a total traversal of 40 metres of iron. This gives a scattering cross-section of $(13 \pm 2) \times 10^{-28}$ cm.^{2}/nucleon for a mean $p\beta$ of 650 Mev/c. McDiarmid's results also indicate greater discrepancy with Olbert's finite nuclear size theory in the lower energy group. All these experiments taken together therefore point out that the large angle scattering cross-section which cannot be explained by the coulomb scattering of a finite size nucleus increases with decrease of energy of the incident mu-mesons. In our experiment the gap existing in the data of the scattering of the low energy group of mu-mesons has been closed. It has further revealed that the large angle scattering in this region is so high that it cannot be explained even by Molière's or Snyder and Scott's theory of a 'point' nucleus. The fortuitous nature of agreement of the data on high energy mu-mesons with 'point' nucleus theory is thus clearly brought out by the present experiment.

DISCUSSION

It is difficult at the present moment to offer any plausible interpretation of this high amount of deviation from the existing theories. The uncertainty about the identification of the scattered particle as a mu-meson has been removed and so also the lack of data in the low energy region. The result is that the disagreement even with the point nucleus theory has been found to be more pronounced. There are two possible sources of these large angle scatterings: (i) A non-electrical potential between the nucleus and a mu-meson and (ii) an incoherent scattering due to the coulomb field of the nucleus. The absence of a strong interaction with nuclei of mu-mesons at rest has been amply demonstrated by the decay of the negative mu-mesons even in heavy elements. Furthermore, negative mu-mesons of Bohr-orbit (a few Mev) energies have also been found to possess negligible interaction with nuclei from the experiments of Fitch and Rainwater (1953). It will therefore be strange if they begin to interact strongly as soon as their energies reach the 100 Mev region. Even supposing that they have some kind of interaction, it will be still more difficult to explain the observed weakening of this interaction with increase of energy. The observed large angle scatterings have, therefore, to be accounted for in some other way.

The second alternative of explaining the observed results in terms of incoherent coulomb scattering has been examined by Gatto (1953) who finds that this incoherent contribution does increase with decrease of energy of the incident particle and is much larger than the coherent part at large angles. The incoherent coulomb effect therefore qualitatively explains the observed energy dependence of the anomalous scattering, but its magnitude as calculated by Gatto is only 10% of what is actually observed in heavy nuclei (Fe, Cu, Pb). It should be emphasized, however, that Gatto's calculations are valid for energies appreciably greater than 107 Mev, the rest energy of the mu-meson and the validity increases as the energy increases. The magnitude of the anomalous cross-section has been found above to be highest in the lowest energy region (40–95) Mev which is well below the rest energy of the mu-meson. Unfortunately the energy range investigated in the present experiment falls in the transition region of validity of the classical Rutherford scattering and the domain of validity of the Born approximation, with which all quantum mechanical calculations on scattering are generally made. In fact the characteristic parameter $2Zz/137\beta$ varies from 0·6 to 0·47 in our case which is neither $\gg 1$ nor $\ll 1$ and therefore none of the existing theories can be rigorously applied for this energy region. Thus the observed anomalous scattering of mu-mesons at low energies still poses a problem to the theoretical physicists.

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