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Large-Angle Scattering of Fast μ Mesons

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Experiments on cosmic-ray μ mesons over the past seven years have appeared to show "anomalous" scattering. This anomaly is a small excess of large-angle scattering over that expected on current nuclear models. A recent experiment by Fukui, Kitamura, and Watase has failed to show the anomaly. In the present paper the data given by Fukui *et al.* are re-examined and it is shown that their experiment is inconclusive.

INTRODUCTION

ONE of the last remaining anomalies concerning μ mesons is the excess of large-angle scattering of these particles. This anomaly has been noted by a number of workers using different types of apparatus and μ mesons derived from the cosmic radiation at sea level and below ground. The subject has been reviewed recently by Fowler and Wolfendale,[1] and the conclusion expressed there was that although there is no theoretical justification for the existence of the anomalous scattering, the anomaly had not been disproved experimentally. It was pointed out that further experiments under better controlled conditions were necessary.

An experiment has been performed recently by Fukui, Kitamura, and Watase,[2] in which the scattering of μ mesons in a multiplate chamber was studied at sea level. The selection system demanded the further penetration of an iron absorber below the chamber and subsequent decay of the particle in a thin carbon absorber. A thick iron absorber placed above ensured that the particles recorded were almost entirely μ mesons. The conclusion of the experiment appeared to be that the anomaly was disproved, at least for μ-meson energies in the region of 1 Bev. Before such a conclusion is drawn, however, there are many features of this work to which further attention should be given, the most important being the fact that the spectrum was much harder than assumed. The experimental data given by FKW permit some attempt at a re-analysis of the results and this is presented here.

Finally it will be shown that the main criticism made by FKW of the earlier experiments is incorrect.

RE-ANALYSIS OF THE EXPERIMENTAL DATA

General Comments

The analysis of these scattering experiments demands the knowledge of a number of facts which may be itemized as follows:

(1) the distribution of scattering angles of the particles—the basic data;

(2) the uncertainty in the measurements of the scattering angles—the so-called "noise-level" scattering;

(3) the momentum spectrum of the particles;

(4) the relation between the scattering distribution and the momentum of the particles for the particular scattering material used.

(1) The Basic Data

The information given by FKW enables a check to be made on all items with the exception of this one. It seems unlikely that there is any serious error in the observed scattering distribution since this is formed from direct routine measurements.

(2) The Noise-Level Scattering

It is usual, and adequate, to consider the experimental error in measuring the angle of scattering in one plate as being normally distributed and independent of errors at other plates. The error may then be determined by plotting the observed distribution in root-mean-square deflection, $\langle\phi\rangle$, and comparing this with the distributions predicted for various values of noise-level scattering, σ, (taking into account the real scattering) of fast particles with a known momentum spectrum. In this way we find that the best value for σ is 0.55°, in agreement with FKW.

(3) The Determination of the Momentum Spectrum

The derivation of the momentum spectrum of the particles is of fundamental importance. In the experiment of FKW the residual range of the μ mesons was known and their momentum in the cloud chamber was quoted as $(1.0_{-0.20}^{+0.15})$ Bev/c. The error arises from the uncertainty in position of the decay of the particle in the final absorber and the fact that the scattering takes place in a number of plates in the cloud chamber.

Various factors can give rise to appreciable errors in the momentum estimate over and above the limits quoted, and an independent check of the momentum spectrum is desirable. A check can be made from the data. In Fig. 1 is shown the experimental histogram showing the distribution in apparent momentum found

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[1] G. N. Fowler and A. W. Wolfendale, *Progress in Cosmic-Ray Physics* (North Holland Publishing Company, Amsterdam, 1958), Vol. 4, p. 105.

[2] Fukui, Kitamura, and Watase, Phys. Rev. **113**, 315 (1959), referred to as FKW.

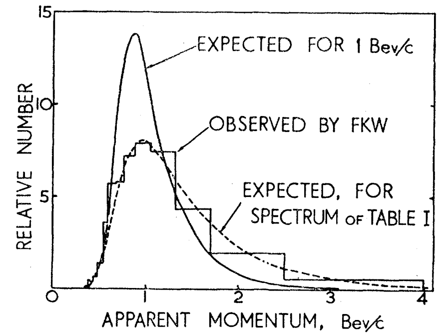

FIG. 1. The distribution in apparent momentum, $K/\langle\phi\rangle$, for the particles selected by the method of delayed coincidences.

from the distribution in rms angle of scattering; FKW assumed that this was as expected for a unique momentum of 1 Bev/c. The distribution in apparent momentum for a momentum of 1 Bev/c as calculated by us is also shown in Fig. 1, and it is clear that it is inconsistent with the experimental histogram. Details of the calculation are given in the Appendix.

We have attempted to work back from the distribution in apparent momentum and predict the actual momentum spectrum of the particles being scattered. Our best estimate gives the distribution indicated in Fig. 1. The spectrum found consisted of the cosmic-ray spectrum above 1 Bev/c together with a number of line spectra, their relative weights being given in Table I. This treatment is approximate but it is sufficiently accurate for the purpose.

(4) The Determination of the Scattering Distributions

(i) Particles selected by the delayed coincidence method.—We have calculated the expected scattering distribution for the spectrum given in Table I. The effect of noise has been included and the result is shown in Fig. 2.

The curve marked "Molière" refers to the scattering theory of Molière,[3] in which the nuclear charge is considered as concentrated at the center of the nucleus. The scattering distribution derived from the theory of Cooper and Rainwater,[4] for the conventional model of the nucleus, is also shown.

From a comparison of the expected and experimental distributions we conclude that the existence of the anomalous scattering is not definitely precluded.

(ii) Particles selected by the prompt coincidence method.—In addition to those particles undergoing what was presumed to be μ-e decay, 500 particles were selected by the method of prompt coincidences. In this case it was demanded that the particle should traverse the whole apparatus, the only information on its momentum then being a lower limit.

Some general comments can be made on the treatment of FKW. These authors found that the observed scattering was in excess of theory when the lower limit of momentum was taken as 1 Bev/c, but by taking this limit as 0.8 Bev/c near agreement with the distribution of Cooper and Rainwater was obtained. It seems to the present authors that this treatment is not allowable: a consistent value for the limiting momentum must surely be taken. If this is 1 Bev/c, then excess scattering for the particles selected by prompt coincidence results. If the value is 0.8 Bev/c, the group of faster particles, i.e., "prompt" particles, exhibit no anomaly but then there will be a considerable deficit of scattering at 0.8 Bev/c.

DISCUSSION

It seems certain that an incorrect momentum spectrum of the particles selected by delayed coincidences was used by FKW. This conclusion would be enhanced if a reason for the error could be ascertained and it seems to us that the most likely cause is selection inefficiency. It will be noted that the method of selection demanded a delay of between 1.3 and 8.6 μsec between the prompt and delayed coincidences. Now it is possible for delays in the firing of a Geiger counter to be as long as 1.3 μsec and an event where the discharge of a counter in the bottom tray of the apparatus was delayed by more than 1.3 μsec would satisfy the criteria for acceptance. Such particles would belong to the normal sea level spectrum above the momentum corresponding to the residual range in the iron absorber (i.e., >1 Bev/c). The best-fit spectrum given in Table I did in fact contain 28% of such particles, representing one spurious event for every 20 000 fast particles traversing the apparatus.

A contributory source of error might well be the production, in the absorber *beneath* the chamber, of penetrating showers by the nuclear interaction of fast μ mesons. We estimate that nearly 2000 showers occurred in the absorber in the course of the experiment, and it seems likely that in a significant fraction of these events a secondary π meson would then undergo the π-μ-e decay sequence required by the selection system.

A correction omitted by FKW is that for the effect of bias against large deflections. There will be a greater loss of the electrons from μ-e decay for those μ mesons which have scattered through a larger angle and are closer to the outside edges of the sandwich detector. This correction will, of course, depress the theoretical distributions at large angles.

TABLE I. The momentum spectrum giving the best fit to the distribution of apparent momentum found by Fukui *et al.*

	Line spectra					Continuous spectrum, normal cosmic-ray
Momentum in Bev/c	0.8	1.0	1.2	1.4	1.6	flux >1 Bev/c
Fraction of flux	11%	24%	18%	9%	10%	28%

[3] G. Molière, Z. Naturforsch. **2a**, 133 (1947); **3a**, 78 (1948).
[4] L. N. Cooper and J. Rainwater, Phys. Rev. **97**, 492 (1955).

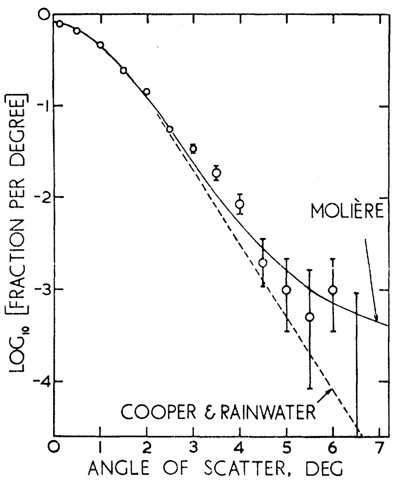

FIG. 2. The differential scattering distributions for the particles selected by the method of delayed coincidences. The experimental points of FKW are shown, together with the scattering distribution expected using the spectrum given in Table I.

Some comment must be made on the criticisms made by FKW on previous experiments on μ-meson scattering. Considerable attention is given to distortion errors in magnet cloud chambers and their effect on momentum estimates. However no experiments on μ-meson scattering have been made using magnet cloud chambers and criticism in this direction is therefore irrelevant.

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APPENDIX

The derivation of the momentum distribution from scattering measurements in multiplate chambers has been discussed by Olbert[5] and by Lloyd and Wolfendale.[6] The part relevant to the present work will now be considered.

The probability that n events, drawn from a Gaussian population with standard deviation s, will have a root-mean-square value between ϕ and $\phi+d\phi$ is

$$F(\phi;s)d\phi=f(n)\phi^{n-1}s^{-n}\exp(-n\phi^2/2s^2)d\phi.$$

For scattering in a multiplate chamber,

$$s^2=\sigma^2+(K/p_0)^2=(K/p_1)^2,$$

where p_0 is the true momentum of the particle and p_1 the momentum one would assign to the particle for $n=\infty$, if one ignored the effects of noise (assuming no change in p_0).

The apparent momentum is

$$p=K/\phi.$$

For a given p_1 (or p_0) the probability of finding p within dp is

$$N(p;p_1)dp=F(\phi;s)(d\phi/dp)dp$$
$$=f(n)(p/p_1)^{-n-1}\exp[-\tfrac{1}{2}n(p/p_1)^{-2}]d(p/p_1).$$

This curve is drawn in Fig. 1, with $p_0=1$ Bev/c. If a number of values of p_1 occur, the resultant distribution in apparent momentum is of course the sum of the elementary distributions.

[5] S. Olbert, Phys. Rev. **87**, 319 (1952).
[6] J. L. Lloyd and A. W. Wolfendale, *Report on the Conference on Recent Developments in Cloud Chamber and Associated Techniques* (University College, London, 1956), p. 51.