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Measurements of the Σ^+ hyperon mass which we have carried out in earlier experiments[1] led us to the conclusion that the range of the Σ^- hyperon is greater than that of a positive particle of the same mass and momentum. We had some indication also of a similar effect for negative pions. In our earlier pion work the effect was only some 3 microns in a range of 800 microns, so that extreme accuracy of measurement was required to detect it. This estimate of 3 microns also is predicted from our hyperon measurements. We are now carrying out a new experiment designed particularly to measure the range difference for pions whose energies are in the vicinity of one MeV. While this is an extremely difficult energy region in which to work, and pi mesons are far too light to make good test particles, it seemed possible nevertheless to make some measurements.

In particular we wish to study the velocity dependence of the range difference, which should start at zero and approach a plateau at some moderate velocity. Here we report a measurement for a pion range of about 100μ.

EXPERIMENTAL

If a range difference between positive and negative pions of only 3μ is to be measured, it is, of course, necessary that all systematic errors in the range difference be much smaller than this. One must treat the positive and

[1] W. H. Barkas, John N. Dyer and Harry H. Heckman, Phys. Rev. Letters 11, 554 (1963).

negative particles in as symmetric a way as possible. The design of this experiment was made with this objective in mind. The basic apparatus is shown in Fig. 1. The small copper target, seen at the right in Fig. 1, is supported by a tungsten wire. To the left of this is a neutron shield made from brass and tungsten, and farther to the left are the emulsion plates in position for exposure. This apparatus was placed in a vacuum chamber and between the pole pieces of a large magnet. The 750 MeV proton beam from the 184" cyclotron was collimated and focused on the target by a quadrupole lens. The beam entered and left the vacuum chamber through thin Al windows. A magnetic field of 7500 gauss was used. Pi mesons of both charges are produced in the target and travel in oppositely directed orbits in the magnetic field to the emulsion detectors. Ilford K.5 emulsion plates 1" $\times$ 6" $\times$ 200μ were placed back-to-back with the emulsion sides facing outward and exposed with the emulsion plane at an angle of 10° with respect to the median plane of the magnet. Thus positive and negative mesons were recorded at the same time, one by the upward facing emulsion plate, and one by the downward facing one (Fig 1).

Four runs were made for the purpose of achieving a maximum of symmetry in the treatment of the positive and negative particles. For run one, the negative pions coming forward from the target and positive pions coming backward from the target are recorded. The two plates were interchanged for run two by turning over the pair. Positive and negative particles entering each emulsion go in the same direction, and variations of the stopping power of the emulsions are thus nullified. The next two runs were similar to runs 1 and 2 except that the magnetic field was reversed so that positive particles coming forward from the target were recorded. This procedure nullified the effects of inhomogeneity of the magnetic field, and of inaccuracies in the geometry of the apparatus. The uniformity of the magnetic field was tested, nevertheless, and found to be uniform to within 0.17%

The plates were scanned for π mesons under 1000× magnification. The mesons are recognized by their large multiple scattering and their characteristic endings. One-prong π^- stars were distinguished from π^+ decays by estimating the ionization and, if possible examining the range of the secondary particle. Zero prong π^- stars were included in the analysis. These have characteristic blobs at their ending and are easily distinguished from μ mesons because μ mesons of the same Hρ have ranges nearly twice as long as the π ranges.

In order to carry out our analysis of the track ranges, three items of information are required for each track: 1) The entrance angle φ_n of each track, projected onto the plane of the emulsion, 2) the position on the emulsion plate where the track entered, and 3) the track length. The entrance angles were measured by the scanner, using an eyepiece goniometer. The ranges were measured with the use of a digitized microscope, the output from which is recorded on IBM cards. The operator records as many points along the particle track as he judges are necessary to calculate the true range of the particle accurately. The initial point recorded serves to determine the position of the track on the emulsion plate. In terms of the quantities shown in Fig. 2, the expression for the radius of curvature is

$$\rho = \frac{d}{2} \sec (\varphi_n - \theta). \tag{1}$$

The value φ_n is the projection of the measured entrance angle on the median plane of the magnet, and θ and d are easily related to the measured coordinates of the entry point of the particle.

Because the total number of meson tracks available for analysis is not large and these tracks fall in a continuum of Hρ values from 60 to 85 Kg-cm, it was necessary for us to develop a procedure that enables us to compare ranges of tracks with different energies. A simple and general way to do this is to calculate for each track the quantity $(R_e - R_t)$, where R_e is the measured track length and R_t is the length expected of a π^+ particle from magnetic analysis. In order to calculate this second quantity, we need a range-momentum relation. We found that the range table compiled by Heckman et al.[2] is represented accurately by the expression

$$\lambda = C(H\rho)^{3.377} \tag{2}$$

We adjusted the constant C so that the measured π^+ ranges were well represented by equation 2. This equation together with the relation (Eq. 1) enables us to calculate R_t.

The choice of target size represents a compromise between the undesirable extremes of a large target, which increases the uncertainty in $H\rho$, and a small target which leads to a low ratio of pions coming from the target to background particles. We chose the size of the target to be such that the straggling of ranges, owing to the uncertainty in the origin of the particle orbit, matches the natural range straggling. The relative dimensions of the target were adjusted to minimize the uncertainty in $H\rho$. The angle at which the orbit crosses the centerline of the apparatus is $\pi/2 - (\theta_m - 2\theta)$. The target dimensions chosen result in a smaller straggling when $\theta_m - 2\theta$ is near 0°. We have therefore limited our analysis to mesons having values of $\theta_m - 2\theta$ less than 15°.

It should be noted that in order to eliminate systematic errors, we do not take weighted averages of the results from different emulsion plates. Instead, we weighted each plate equally. The error in an average taken in this

[2] H. H. Heckman, B. L. Perkins, W. G. Simon, F. M. Smith, and W. H. Barkas, Phys. Rev. 117, 554 (1960).

way is $\sigma^2 = \frac{1}{n^2} \sum_{i=1}^{n} \sigma_i^2$, which is to be compared with the relation $\frac{1}{\sigma^2} = \sum_{i=1}^{n} \frac{1}{\sigma_i^2}$ for a weighted average. Of course, we attempt to obtain enough data to give nearly equal statistical weights to the plates. The data that we have taken for one point of the range difference-velocity curve are given in table I. It is clear that the precautions taken to eliminate systematic errors and asymmetries are essential.

Table I. Measured range difference between negative and positive pions with energy ≈ 1.6 MeV.

Emulsion Plate	Charge	Direction of Particles	Number of Events	$\langle R_e - R_t \rangle$ Microns	$\langle R_- - R_+ \rangle$ Microns	$\langle R \rangle$ Microns
2A	+	backward	25	2.05 ± 1.24	-.35 ± 2.21	94.86
2A	-	forward	17	1.70 ± 1.83		94.75
2B	+	backward	24	-2.32 ± 1.96	5.70 ± 2.37	97.88
2B	-	forward	23	3.38 ± 1.33		93.40
3A	+	forward	25	-2.17 ± 1.45	4.23 ± 1.99	96.88
3A	-	backward	31	+2.06 ± 1.37		99.16
3B	+	forward	17	+3.65 ± 1.65	2.83 ± 2.38	92.12
3B	-	backward	16	+5.48 ± 1.72		96.35
Average $\langle R_- - R_+ \rangle$:				3.10 ± 1.12μ for $\langle R \rangle$ = 95.7μ		

FIGURE CAPTIONS

Figure 1. Apparatus used for emulsion exposure: Positive and negative pions emerge from the target and travel in oppositely directed orbits to the upward and downward facing emulsion plates.

Figure 2. Geometry of the particle orbits.

Fig. 1

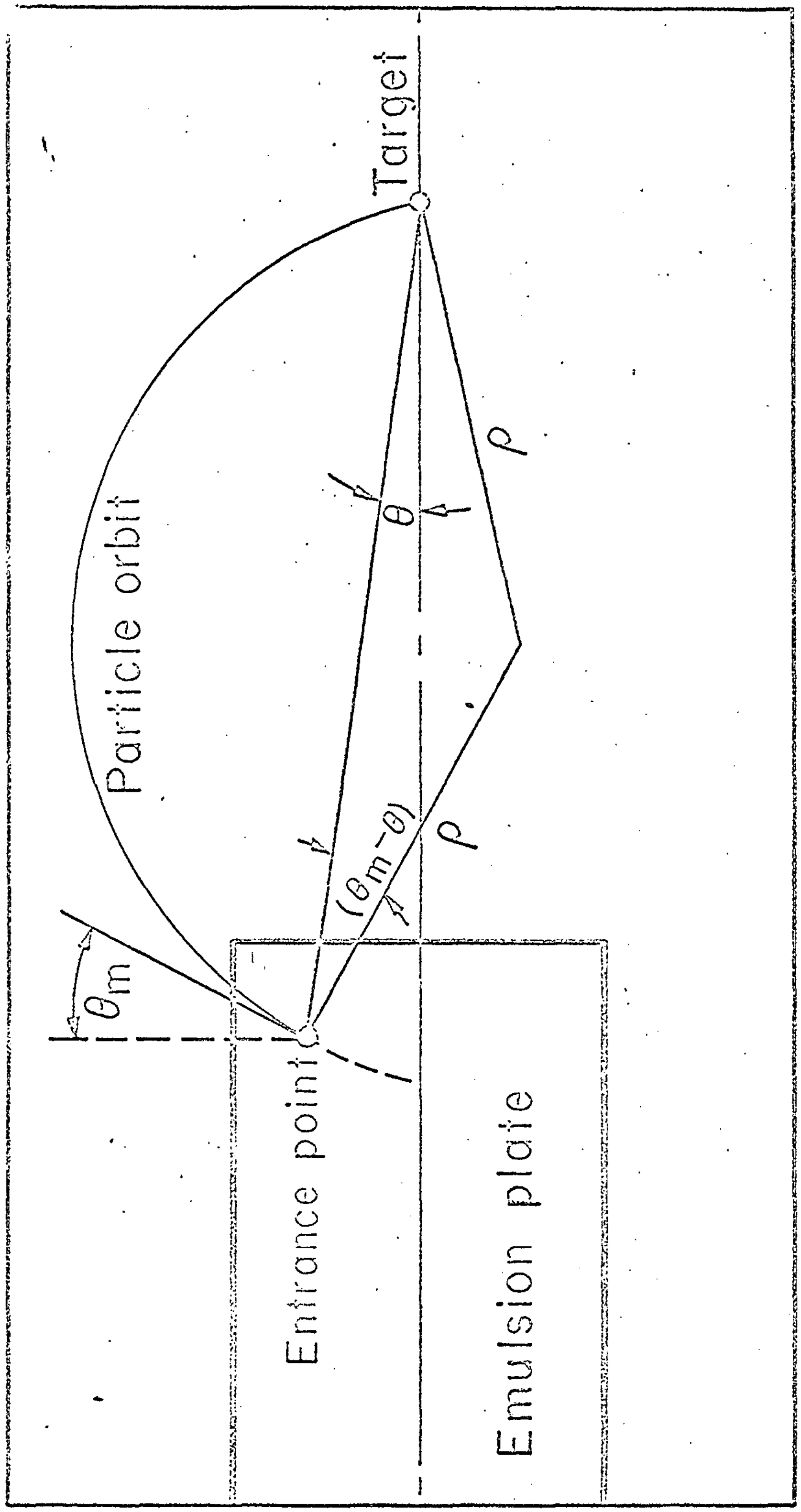

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Fig. 2