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ABSTRACT

Measurements of grain densities of stopping π^+ and π^- mesons in emulsion show that, in the velocity interval $0.051 < \beta < 0.178$, the energy-loss rates of π^+ mesons exceed that of the π^- by amounts of 0 to 60 MeV/cm. The reported range differences between positive and negative particles are satisfactorily accounted for by the results of this experiment.

Convincing evidence that slow negative particles lose energy at lower rates than do positive particles at the same velocity has been reported by Barkas et al.[1] By measuring the ranges in nuclear emulsion of the pions and hyperons in the reactions (at rest)

$$K^- + p \rightarrow \pi^{\pm} + \Sigma^{\mp},$$

Barkas et al. found that the momentum of the low-velocity Σ^- ($\beta = 0.143$) was incorrectly given by the existing range momentum relation,[2,3] a relation that is based on positive-particle ranges. The observed range of the Σ^- produced in the above reaction was $709 \pm 1.5\ \mu$, some 25 μ greater than expected from the range-momentum relation.

Corroboration of the effect has been obtained from a measurement of range difference between positive and negative pions at $T_\pi \approx 1.6$ MeV.[4] Also, there is evidence for stopping-power differences between the positive and negative hyperons in hydrogen.[5] Too, it is highly probable that the apparent difference between the masses of the positive and negative pions[6] can be explained by this effect.

The above observations on the anomalous ranges of stopping negative particles summarize the data that indicate the rate of energy loss is dependent on the sign of the charge of the incident particle. In the experiment we are reporting here, we have examined this problem further, and have observed directly the difference in the energy-loss rate of stopping positive and negative π mesons in nuclear track emulsion. The range interval over which ionization measurements were made was $1.1 \leq R \leq 200\ \mu$, which corresponds to a velocity interval $0.035 \leq \beta \leq 0.183$ for the π^+ meson.

The data we shall discuss were obtained from a stack of 300 μ- thick

Ilford G.5 emulsions that was sequentially exposed to beams of 115-MeV/c π^+ and π^- mesons. The maximum density of pion endings of each charge was 10^4 cm^{-3}. The emulsions were isothermally developed at $5^\circ C$, by use of a reduced concentration of the developing agent (0.2 g/l Amidol). This procedure reduced the effective sensitivity of the emulsion so that the grain density at the ends of the stopping pions was unsaturated, making ionization measurements possible, yet permitted the detection of the characteristic π-μ decay signature of the π^+ meson. The π^- meson was readily identified by the highly ionizing secondary products that result from its nuclear capture at rest.

Only those pions that could be unambiguously identified as to charge were used for ionization measurements. Beginning at the stopping point of the pion, the blob density, B (in blobs per μ), and lacunarity, L (the linear fraction of a track that consists of gaps), were measured, in cells 5 to 50 μ in length, for a total range of 200 μ. B and L measurements were taken only when the dip angle of the track segment in a given cell was $\leq 15^\circ$. No dip-angle corrections were made to B and L. The grain density measurements began at the first well-defined blob of the stopping pion track that was separated from the end blob by a measurable gap. Eliminated, therefore, was the terminal blob of the track, a blob of uncertain origin in that it could be attributed to the ionization of the secondary π^- star prongs -- or, to a much less extent, to the μ-decay product of the π^+ -- as well as to the pion itself. The actual starting points of the measurements were distributed about an average 1.1 μ from the pion endings. The starting-point distributions of the samples of π^+ and π^- mesons we used to intercompare the rates of ionization were identical. Data recorded for each pion were (a) its charge, (b) the distance from track ending at which measurements began, (c) the number of blobs, B, and lacunarity, L, for the ith cell, and (d) the start and end coordinates of the ith cell, the nominal cell length being adjusted to be an integral number of blob-gap units.

Table I presents the results of the grain density measurements. Listed for each cell are the average range intervals (differences between the π^+ and π^- cells were negligible), the mean π^+ velocity, and the ratios $g+/g-$ as obtained from the ratios (a) $(B/L)_+/(B/L)_-$ and (b) $\ln L_+/\ln L_-$.[7] The data, based upon a total of 1.85×10^5 blob-gap units, are the compilation of the results of five scanners from 11 different emulsions plates.

In order to relate grain densities to rates of energy loss, we assume that the grain structure of a particle track results from energy loss in silver bromide only; i.e., energy loss in the gelatin has little effect in production of grains. This grain-producing ionization in silver bromide is called the restricted rate of energy loss. Under the assumption that δ rays with energies in excess of w tend to leave the silver bromide crystal, and therefore do not contribute to the observable primary grain density of the track, Barkas[7] has computed the restricted rate of energy loss in AgBr, ι' (in units MeV $g^{-1}cm^2$), as a function of proton energy, for w = 2 and 5 keV.

The observed grain density, g, can be related to ι' by the empirical two-parameter function $\ln\left[\frac{n}{n-g}\right] = \lambda\iota'$,[8] where λ is constant and n is the average number of silver bromide crystals penetrated by the ion. We obtain the best maximum-likelihood fit of the π^+ grain-density measurements to this function when we use ι'(2 keV), with $n = 2.20 \pm 0.05$ grains μ^{-1} and $\lambda = 38.9$ $MeV^{-1}g\ cm^{-2}$.

The reduction of the data thus entailed evaluation of the ratios ι_+'/ι_-' for each of the observed g_+/g_- ratios listed in Table I, from which the ratios and differences of the total rates of energy loss, ι(in units MeV cm^{-1}), are computed. Figure 1 presents our results on the differences between the rate of energy loss for positive and negative pions versus the pion range. The difference $\iota_+ - \iota_- = 60$ MeV/cm observed in the first cell corresponds to an ι_+ that is about 14% greater than ι_- at $\langle\beta\rangle = 0.051$. For velocities $\beta \gtrsim 0.14$, the energy-loss rates for the positive and negative pions are equal to within the 1% statistical error.

On the basis of the energy-loss data shown in Figure 1, we have computed the differences in range between the π^- and π^+ mesons, $R(\pi^-)-R(\pi^+)=\Delta R$, as a function of $R(\pi^+)$. The difference ΔR is given by

$$\Delta R = [\iota_+(R)]^{-1}\int_{1.1}^{R}(\iota_+ - \iota_-)dx.$$

The values of ΔR for pion ranges greater than 1.1 μ are given in Figure 2. The curves above and below the data illustrate how the range differences depend on possible differences in the energy loss of the pions between 0 and 1.1 μ. The top curve applies if the total energy lost by the π^+ meson in the first micron exceeds that of the π^- by $\Delta E = 15$ keV. The lower curve applies if $\Delta E = -15$ keV. The data are also compared with range difference measurements. In order of increasing range, we show the range differences obtained from (a) the Σ-hyperon data,[1] where R and ΔR are normalized by the factor m_π/m_Σ for this figure; (b) the range difference of 1.6-MeV π mesons;[4] and (c) at 725 microns range, the range difference which would account for the measured mass ratio $m_{\pi^-}/m_{\pi^+} = 0.9969 \pm 0.018$,[6] given that $m_{\pi+} \equiv m_{\pi-}$.

As demonstrated in Figure 2, the reported range differences between negative and positive particles can be fully accounted for by the results of this experiment. The sign and magnitude of the differences in energy-loss rates $\iota_+ - \iota_-$ (Figure 1) are sufficient to reproduce the range difference data. The range differences of the pions are within the statistical errors of the respective data. The diminished value of the equivalent pion range difference obtained from the Σ range data could be explained, in part, if the Σ^- possessed a large capture cross section at low velocities, thereby decreasing its range, and hence range difference. Evidence for this possibility comes from Barkas et al.,[1] who found the range straggle of the Σ^- was anomalously large -- about 50% greater than that observed for the Σ^+ and that predicted by straggling theory.

It is the unknown behavior of the energy losses for the positive and negative pions between 0 and 1.1 μ range that introduces the largest uncertainty in the estimate of the total range difference. This is illustrated in Figure 2 by the range-difference curves, which as described above, were computed under the assumption that the differences in total energy loss for the π^+ and π^- between 0 and 1.1 μ is $\Delta E = +15$ keV (upper curve) and $\Delta E = -15$ keV (lower curve). It is possibly significant that the expected range differences for the latter case agree more closely with the range-difference data. Further work on the nature of energy-loss process at velocities $\beta < 0.035$ ($\beta_{\pi+}$ at 1.1 μ range) is clearly necessary to clarify this point. Pertinent information on this topic could be obtained by undertaking measurements similar to those reported here using heavier particles, such as p and $\bar{p}$.

The results of this experiment give direct evidence for a difference in the stopping power for positive and negative particles at the same velocities, when these velocities are comparable to those of atomic electrons. Qualitatively, the effect can be described by noting that Coulomb attraction of the electrons in the stopping media by a slow positive particle will tend to increase the collision frequency with the electrons, thereby increasing the energy-loss rate of the positive particle. Conversely, slow negative particles tend to repel the electrons of the media, the electron collision and energy-loss rates are reduced, and the range is increased.

Such an effect is predicted by second-order Born approximation stopping-power theory.[9] The second-order Born approximation introduces a term in the stopping power that is proportional to z^3 of the incident particle, and hence is of the correct nature to account for the observations. However, quantitative theoretical treatments have not been successful, and a theory of this effect remains to be developed.[10]

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FOOTNOTES AND REFERENCES

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Table I. Grain density ratios.

Cell	Range (μ)	⟨β⟩	g_+/g_- (a)	g_+/g_- (b)
1	1.1 to 5.1	0.051	1.078 ± 0.022	1.070 ± 0.019
2	to 10.1	0.071	1.030 ± 0.016	1.035 ± 0.013
3	to 15.2	0.084	1.018 ± 0.015	1.018 ± 0.016
4	to 25.2	0.097	1.050 ± 0.013	1.050 ± 0.012
5	to 50.3	0.117	1.002 ± 0.009	1.020 ± 0.008
6	to 100.2	0.142	0.992 ± 0.011	0.988 ± 0.011
7	to 149.9	0.163	1.002 ± 0.014	0.996 ± 0.012
8	to 199.9	0.178	1.006 ± 0.014	1.001 ± 0.013

FIGURE CAPTIONS

Fig. 1 The difference between the total rates of energy loss for positive and negative pions, $\iota_+ - \iota_-$, vs range. The energy-loss differences evaluated from the grain density ratios given in columns (a) and (b), Table I are denoted by the symbols × and •, respectively. The hatched areas above the range scale indicate the interval of range over which the ionization measurements were made.

Fig. 2 The differences between the π^- and π^+ ranges, $\Delta R = R(\pi^-)-R(\pi^+)$ vs the pion range, as derived from the energy loss differences, Fig. 1. For ranges greater than 1.1 μ, ΔR can be represented by the function

$$\Delta R = (6\pm 0.3)\left[1 - \exp\left(- \frac{R-1.1}{45 \pm 10}\right)\right].$$

This curve is drawn through the data points. The dashed curves above and below the data illustrate how ΔR depends on the (unknown) difference in energy loss between 0 and 1.1 μ. The top curve applies if the total energy lost by the π^+ in the first micron exceeds that of the π^- by $\Delta E = 15$ keV. The lower curve applies if $\Delta E = -15$ keV. The range differences reported in References 1, 4, and 6 are also shown.

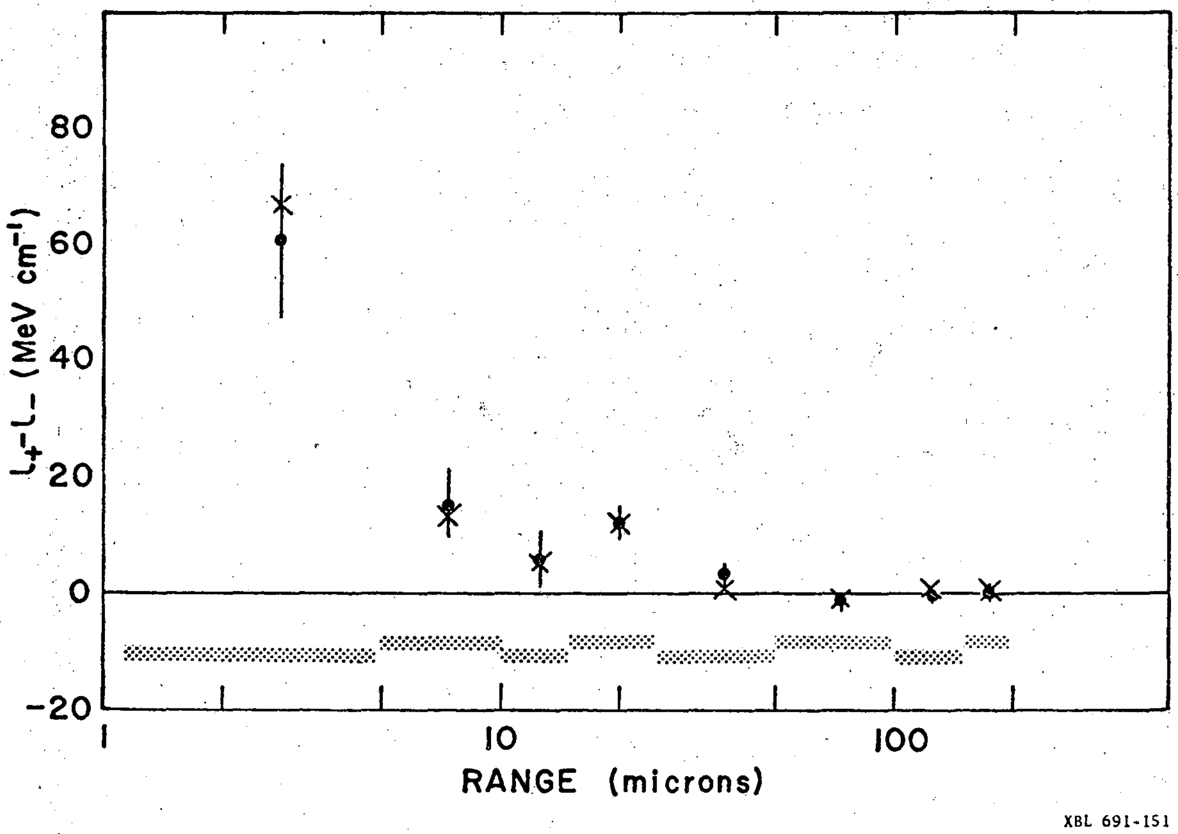
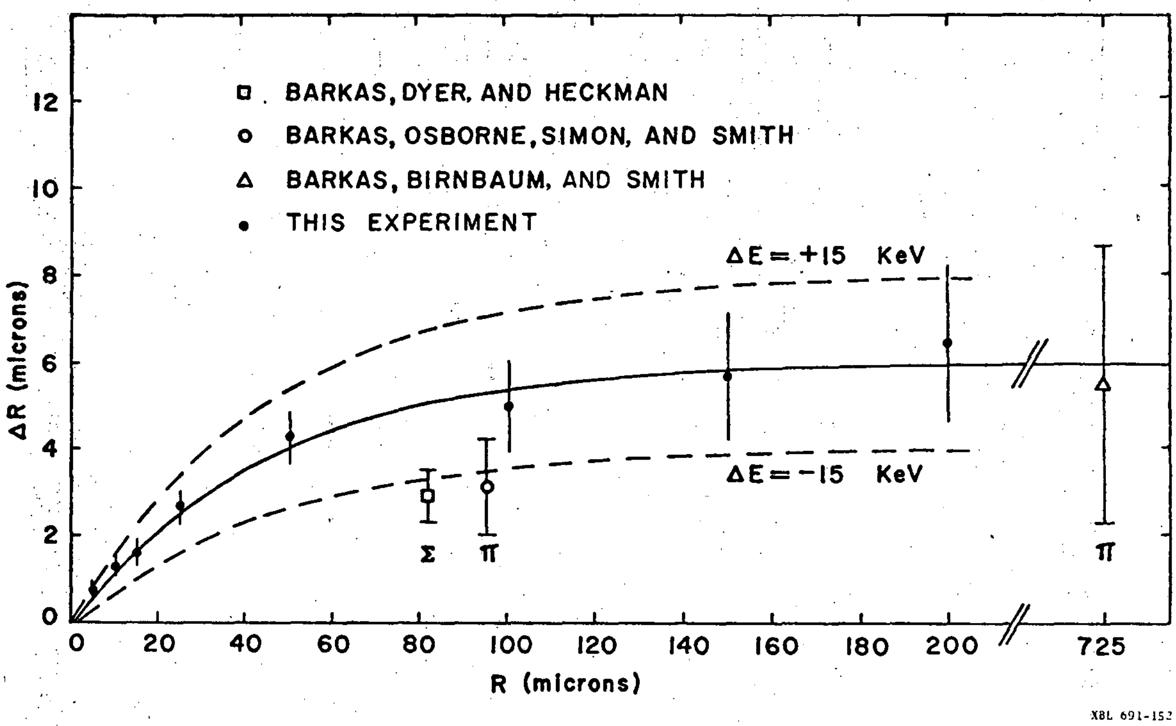


Fig. 1



BARKAS, DYER, AND HECKMAN
BARKAS, OSBORNE, SIMON, AND SMITH
BARKAS, BIRNBAUM, AND SMITH
THIS EXPERIMENT
ΔE = +15 KeV
ΔE = −15 KeV
Σ
π
π
ΔR (microns)
R (microns)
0
2
4
6
8
10
12
0
20
40
60
80
100
120
140
160
180
200
725
XBL 691-152

Fig. 2

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