C-8 IONIZATION LOSS AT RELATIVISTIC VELOCITIES IN NUCLEAR EMULSIONS

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INTRODUCTION

Last year, in studying the rate of ionization loss, I, of very fast charged particles in nuclear emulsions, (M. Shapiro and B. Stiller, Phys. Rev. 87, 682 (1952).) we found a relativistic rise of 12^{+4}_{-3} % above the ionization minimum to the Fermi "plateau". This result was obtained by comparing the grain densities g of two groups of tracks P of high energy stars with associated shower multiplicities $n_s \geq 5$.

The S group is due primarily to pions, and from their known energy spectrum their grain-density histogram was expected to have a peak at g_{min}. Similarly, the P group is attributable mainly to protons so energetic that their histogram should display a peak at or near the plateau value g_{pl}. As shown in Figure C-8, 1, the theoretically expected peaks were observed, and an experimental value of the ratio I_{pl}/I_{min} for AgBr was deduced therefrom. Also, preliminary investigation of energetic electrons (with total energy $\gamma > 300$ rest masses, as determined from their scattering) indicated that the plateau for electrons lies 16 ± 3 per cent above g_{min} for mesons.

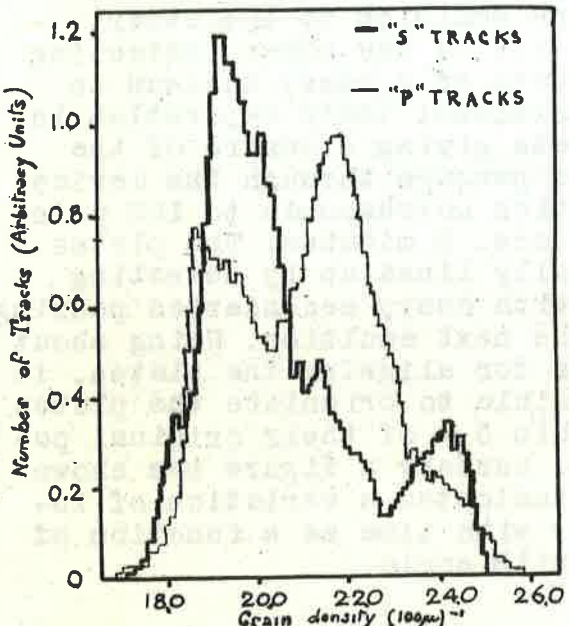

Figure C-8, 1

We have improved and extended our previous work in the following ways:

1) Measurements of multiple Coulomb scattering have been made on long tracks of many particles with velocities in the region of minimum and plateau ionization. These measurements were especially desirable in view of the uncertainty in the estimates of the energies of the shower-producing primaries from their associated multiplicities.

2) Measurements have also been made on tracks of particles with intermediate relativistic velocities in the region where the ionization increases appreciably with energy. It is important to provide experimental evidence on the variation of grain density in this region, in order to show whether any ionization theory correctly describes this variation in nuclear emulsions. It is also essential for mass estimation (and hence identification) of particles in the energy interval $5 < \gamma < 100$.

3) An experimental comparison between electrons and heavier particles as regards their "restricted ionization loss" in AgBr grains at energies $y > 15$ rest masses, is possible from our new data. Contrary to the difference in total ionization between electrons on the one hand and mesons or protons on the other, there is no reason to expect a difference between the grain densities of these two groups of particles as a function of velocity.

4) The tracks in our earlier study had been located on several plates of the same batch, exposed and processed together. Even under these conditions we found variations of a few per cent in g_{min} among the several plates. Therefore, we made the control more rigorous by gathering most of the data from a single plate 6 x 3 inches. The G.5 emulsion, 400 microns thick, had been exposed in the stratosphere for $\sim$ 8 hours at an atmospheric depth of 11 g/cm^2. We looked for differences in g_{min} between various parts of this plate, and found them to be well within ewperimental error. The plates selected had low background, high uniformity of grain density with depth, and low distortion

5) Grain densities were replaced by "blob" densities, since we find that experienced observers agree within statistical error in their blob counts, although not necessarily in their grain counts.

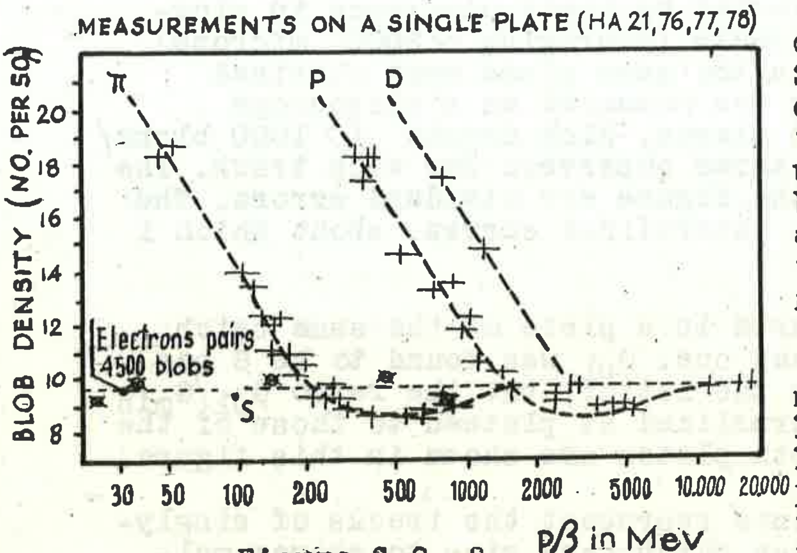

Figure C-8, 2

Figure C-8, 2 shows the blob density G as a function of y. Since the abcissa is a function of velocity only, one can plot together the various particles of unit charge.* At energies $y > 100$,** both electron and meson tracks appear. Finally, at lower velocities, mesons and protons, but no electrons, are represented.

Ideally, one would prefer to measure the rate of ionization loss over the whole range of velocities for a single type of particle. This procedure proves very difficult because of the precision required in this experiment, where the variation with which we are dealing is so small. Electrons near the minimum have energies < 3 Mev and scattering angles > $7°/(100\ \mu)^{1/2}$. Their strong scattering imposes obstacles to accurate determinations of grain or blob densities; therefore measurements of G on electron tracks have been made with adequate precision only at energies $y > 10$.

Conversely, if one wants energy determinations from scattering at energies $y > 70$ rest masses one must perforce use electrons. In fact, investigations of electron tracks in emulsions were used to establish the existence of an ionization plateau at high energies. This was done by Corson and Keck, by Mc Diarmid, and by Morrish. Because their investigations were confined to electrons, their measurements were not extended down to the minimum of ionization, and hence could not yield the ratio

*Insert ** only electron data appear. In the interval* $10 < y < 100$,

** Insert : Fig. C-8, 3*

I_{pl}/I_{min}. More recently, Violet of Berkeley, has tackled this problem with electrons alone.

The reason why $\mathcal{E}'_s$ must be used at high energies if one relies on scattering is that protons of $\gamma > 10$ have mean angles of multiple scattering which are very small, and hence too close to the noise level to permit useful measurements. For pions the corresponding limit is about $\gamma \sim 70$, whereas electron tracks lend themselves to reliable determinations of $\bar{\alpha}$ and G at energies up to several thousand rest masses. On the other hand, in the vicinity of the minimum, both $\bar{\alpha}$ and G can be measured for protons, and especially well for pions.

In the intermediate region $10 < \gamma < 40$, $\bar{\alpha}$ and G can be determined for both electrons and mesons. Thus a direct comparison can be made between the two groups, and a useful link is provided between the regions of G_{pl} and G_{min} where we have employed only $\mathcal{E}'_s$ or heavier particles respectively. Moreover, for both electrons and mesons, the rate of variation of I can be compared with theory in this intermediate region where experimental delineation of the ionization curve is particularly important.

The electron tracks were selected by their occurence in electron pairs or in tridents. Long tracks (averaging $\sim$ 80000 microns) of mesons and protons occurring in the same plate were obtained from shower stars. The scattering was measured on a microscope stage which has a "noise" < 0.15 micron. Blob counts ($>$ 1000 blobs/track) were repeated by at least three observers for each track. The errors in both G and γ shown in the figure are standard errors. The curves shown in these figures are theoretical curves, about which I will say more in a moment.

Additional tracks were measured in a plate of the same batch having the same history as the last one. G_{pl} was found to be 8 per cent higher in the former than in the latter, but the ratio G_{pl}/G_{min} was unchanged. These data were normalized at plateau to those of the last plate and the results for both plates are shown in this figure. (Fig. C-8, 3)

The three diamond-shaped points represent the tracks of singly-charged shower-generating particles which gave rise to shower multiplicities $n_s \geqslant 5$. We call these p-tracks, where p denotes "primary", although it seems safe to assume that all or most of these are protons. These three points differ from the others in that each represents several tracks rather than only one, and no $\bar{\alpha}$ measurement could be made on these, in view of their small $\bar{\alpha}$, as I explained.

In order to see how closely G for protons agrees with G for electrons at or near the plateau, we have estimated the energy of the P-particles in each multiplicity, (n_s)-group. This leads to a very rough estimate of the energy as indicated by the very wide limits of error we have assigned to these three points. Thus, for the point at $\gamma = 200$, the limits are $100 < \gamma < 500$. Fortunately, the variation of I at these high velocities is so insensitive a function of the energy that it is useful to include these points despite the large uncertainty in energy. It will be seen that the p-track data agree satisfactorily with the electron and meson data.

The multiplicity of points and the overlapping of error lines in this figure make it difficult to use in comparing theory with experiment. We have therefore constructed the next figure (C-8, 5) in which the same data are grouped into energy intervals, each containing about the same number of tracks. Two types of standard error are shown for each point in this figure; the solid error line is based on the number of blobs contributing to the point (this was about 10,000 per point); the dotted one represents the standard deviation of the tracks in a group from their mean. The theoretical curve shown here is the same as the solid curve in the last figure, i.e., it was calculated for a max. transfer of 2 Kev.

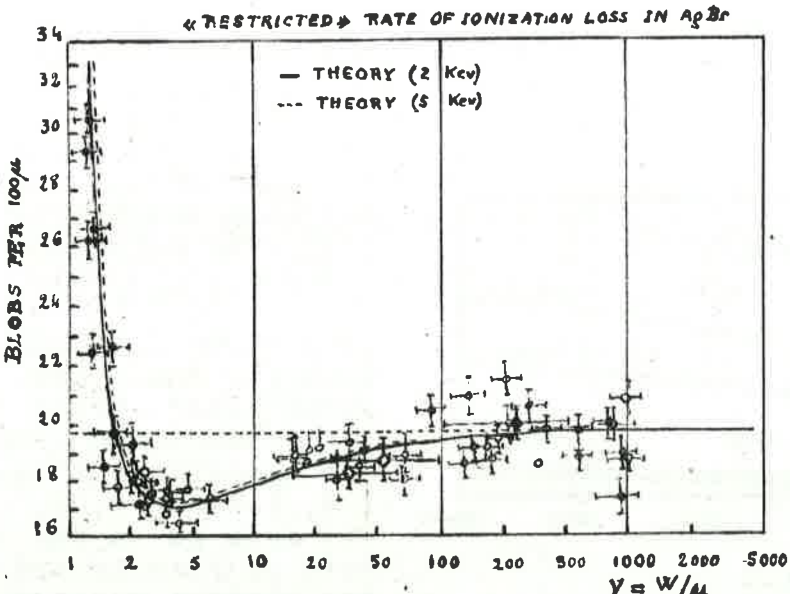

Figure C-8, 3

The tracks with $y <$ 2 are omitted from this figure.

Our evaluation of G_{pl}/G_{min} from these data yields :

$$G_{pl}/G_{min} = 1.143 \pm 0.03$$

Since there is evidence that G is proportional to I at low grain densities this value may be considered to apply also to the ratio I_{pl}/I_{min} in AgBr.

Comparison with Ionization Theory.- The ionization theory of Bethe-Bloch-Williams, which predicted an indefinitely continued relativistic increase in I with velocity, was modified by Fermi to take account of the polarization of the medium. He showed that the rate of ionization loss should saturate at sufficiently high velocities. Fermi's treatment, which employed a single dispersion frequency for the electrons in the medium, was in turn modified by Wick, Halpern and Hall, A. Bohr, Sternheimer, and Schönberg who showed that it is necessary to construct a multi-frequency theory. These authors differ as to the magnitude of the relativistic rise, the differences arising largely from the various values of the ionization potential which they used.

We have calculated theoretical ionization curves for AgBr according to the theories of Halpern and Hall and Sternheimer, using the ionization potentials of Bakker and Segre. For comparison with our experiment it is necessary to calculate not the total rate of loss usually discussed in the theories, but the limited rate of loss along a track, measured by its Ag grain density, which arises only from energy transfers to electrons up to a few Kev. Larger transfers give rise to delta-rays consisting of 2 or more Ag grains, and the grains lying off the track are ignored in ordinary grain counting. Accordingly, we computed the restricted rate of loss I as a function of , using 2 Kev for the "limiting effective energy transfer T_o" to the electrons of the medium. We have also computed I for another value of T_o", 5 Kev. The result of this calculation was shown in the dashed curve which was slightly above the solid line in Figure C-8, 4.

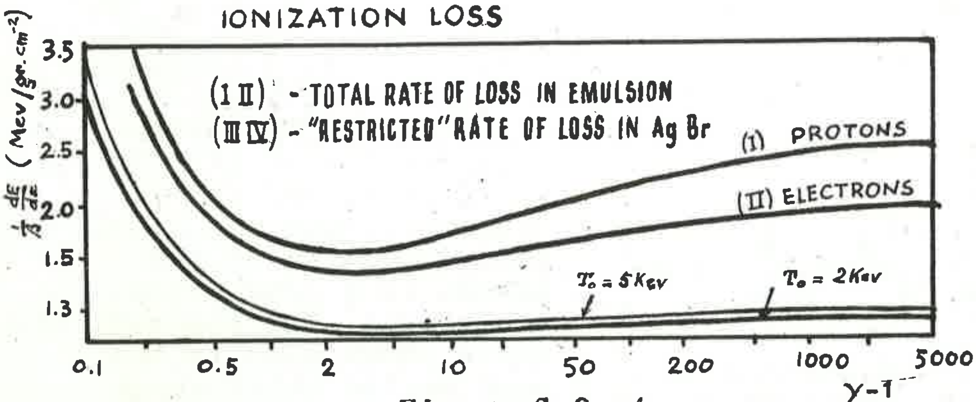

Figure C-8, 4

Either this theoretical curve or the one for 5 Kev fits our data satisfactorily. The calculated ratio I_{pl}/I_{min} for this curve is 1.152, that for the 5 Kev curve 1.137. These may be compared with our experimental value, 1.143 ± 0.03. Our data as to the rate of rise toward the plateau supports the theoretical prediction of a slow rise followed by saturation in the region beyond $\gamma \sim 100$. (Figure C-8, 5)

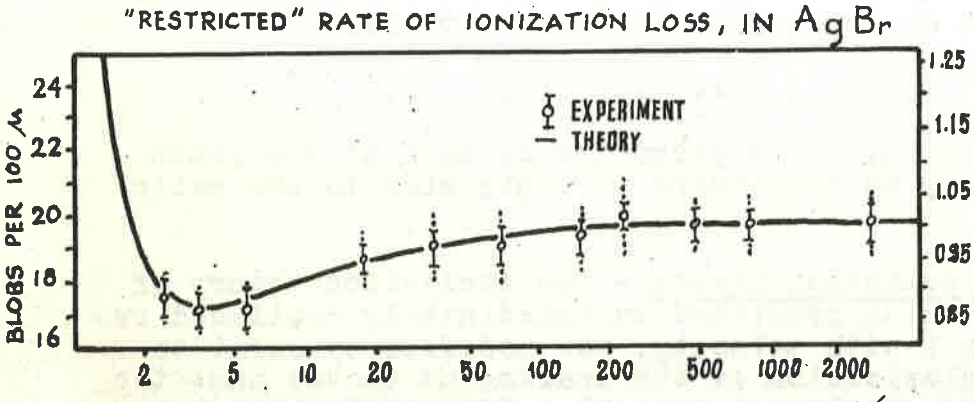

Figure C-8, 5

While our results show excellent agreement with theories of Sternheimer and of Halpern and Hall, they conflict with the new theory of Huybrechts and Schönberg, which departs more radically from Fermi's treatment. These authors predict an increase in I from minimum to plateau in AgBr of 3.8 per cent, and they suggest a method whereby this theoretical value could be pushed up to 6 per cent. Neither value seems capable of accounting for our results.

As we have seen, our values of blob density show no significant differences between electrons and heavier particles. This is just what should be expected of the restricted ionization loss with which we are concerned. The predicted difference in total rate of ionization loss between the two groups of particles arises from the different upper limits to the possible energy transfers between the moving particle and the electrons of the surrounding medium. If one applies an upper limit of a few kilovolts in order to compute the restricted energy transfer to silver bromide grains along the track, then the difference vanishes. Our results bear this out in the plateau region, as well as in the interval $10 < y < 100$.

Comparison with other experiments.- In 1949, the Brussels group found no evidence in emulsions for a relativistic rise in g exceeding their experimental error. In 1950, similar results appeared in publication from Bristol and Rochester. During the same year Pickup and Voyvodic reported preliminary indications based on a few tracks, of a relativistic increase of about 10 per cent to a plateau starting at $y \sim 20$. Voyvodic subsequently extended this work and found a rise of 8 or 9 per cent. Our present value of 14 ± 3 per cent appears to be significantly higher. (However I might remark that in Washington 2 months ago, Voyvodic said that he would now be inclined to quote his result as 10 ± 5 per cent).

As to the rate of rise of g toward saturation, various observers have found indications that saturation is completed more quickly than for the ionization loss. Our data, on the other hand, are altogether consistent with the slow rate of rise calculated according to the Halpern-Hall theory, and suggest that the polarization plateau is reached at values of $y > 100$ as predicted by this theory.

We draw the following conclusions about the restricted rate of ionization loss I in Ag Br of singly charged particles moving at relativistic velocities;

1.- As the velocity increases, I passes through a minimum at $y \sim 4$ and then rises to a limiting value I_{pl} which lies 14 ± 3 per cent above I_{min}.

2.- At velocities corresponding to the interval $10 < y < 100$, our data are consistent with the slow rate of rise predicted by the theory mentioned before.

3.- I saturates at values of $y > 100$, and maintains this value at least as far as $y = 3400$ rest masses.

4.- Electrons, mesons, and protons show the same variation in grain density.

In all these respects our results are in agreement with the theoretical curves we computed according to Sternheimer. We believe that these curves can be used, e.g, for velocity determinations based on G, and for mass determinations based on G and α. It should be emphasized, however that in this region of extremely high velocities, such determinations are still subject to considerable errors because of the inherent insensitivity of G to the velocity.
