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Ionization energy loss of muons in a plastic scintillator

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Abstract. A study has been made of the ionization energy loss of cosmic-ray muons in a plastic scintillator (Ne 102a) over the momentum range 0·3–120 GeV/c.

The results have been combined with those of Crispin and Hayman for a similar material, and together give no support for the decrease expected from the radiative correction theory of Tsytovitch, the measured change in energy loss above 10 GeV/c being $+(1\cdot2 \pm 0\cdot7)\%$, compared with a predicted reduction of 4–8%.

A least-squares fit to the most probable energy loss values above 2 GeV/c gives a rate of rise of $(2\cdot7 \pm 3\cdot3)\%$, a value not inconsistent with the constancy predicted by the theory of Sternheimer.

1. Introduction

In the preceding paper by Alexander *et al.* (1968), an investigation of the Čerenkov energy loss of muons traversing a dielectric medium is reported. This work was stimulated by the papers of Tsytovitch (1962 a, b, c), who predicted the existence of a significant reduction in the Čerenkov energy loss for particles with $\gamma > 100$. This loss should also manifest itself in the measured ionization loss and, following Ashton and Simpson (1965), Crispin and Hayman (1964) estimate that the expected reduction should be in the range 4–8% for muon energies above 8 GeV (a similar reduction has been calculated by Smith and Stewart (1966)). Crispin and Hayman have, in fact, performed a cosmic-ray experiment with a virtually identical scintillator material (Ne 102: Nuclear Enterprises (G.B.) Ltd.) and the function of the present experiment is to add to the accuracy of the results for the variation of energy loss with energy for this material; such addition is clearly necessary in view of the small magnitude of the effect sought.

Smith and Stewart (1966), also using Ne 102, have measured the ionization energy loss of electrons from an electron synchrotron in a small area scintillator, and their results are compared with those of the present experiment and the results of Crispin and Hayman (1964).

Fowler and Hall (1966) have recently made a critical study of the various classical and semi-classical theories of energy loss of relativistic charged particles, mainly to clarify the ambiguity arising out of Tsytovitch's work. They predict on the basis of perturbation theory a logarithmic increase in the ionization loss similar to that predicted by Sternheimer (1953 a, b). Further, they show that higher-order corrections calculated by Tsytovitch are relevant only to the case of Čerenkov radiation in the absence of damping in the medium. In the presence of strong damping, characteristic of the ionization loss, any suppression effect is likely to be much smaller than that suggested by Tsytovitch.

Fowler and Hall also point out that the sign of any suppression-type correction would be opposite for positively and negatively charged particles. Thus measurements on cosmic-ray muons without charge separation would fail to detect this type of effect. The present experiment has been done using a magnetic spectrograph, with which it is possible to ascertain the sign of the charge of the ionizing particle.

2. Theoretical considerations

The theory of the energy loss of charged particles traversing matter due to the production of ionization and excitation is well known and will not be considered here in any detail. For the purposes of comparison with experiment the equations and theory of

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Sternheimer (1952, 1953 a, b, 1956) are taken, together with values for the constants in the equations appropriate to the plastic scintillator used (Ne 102a) given by Sternheimer (1967) and the *Nuclear Enterprises Catalogue* (1965). The theoretical variation of the most probable energy loss is shown in figure 1; in this figure the relativistic rise above the minimum is 1·3%.

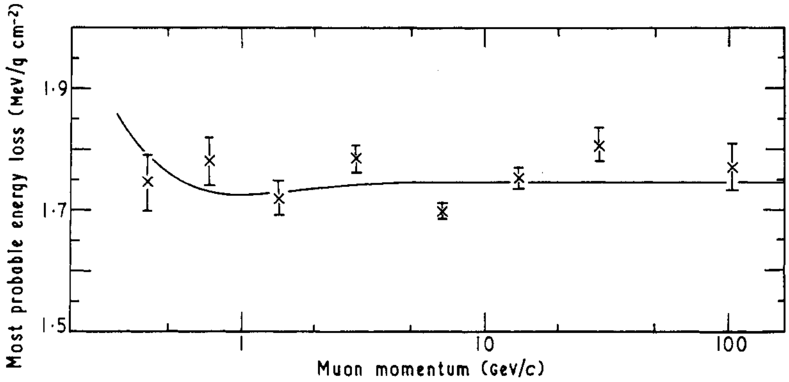

Figure 1. The combined results of Crispin and Hayman (1964) and the present work.

3. Experimental arrangement

The magnetic spectrograph utilized in the investigation described in the preceding paper was triggered using scintillation counters. The triggering pulse from one of the scintillation counters was displayed on an oscilloscope and photographed whenever the spectrograph was triggered.

The chosen scintillation counter, comprising a sheet of scintillator Ne 102a of area $43{\cdot}7 \times 37{\cdot}6$ cm^2 and thickness 2·54 cm, was of the type described by Ashton *et al.* (1965) and utilized Perspex light guides and two photomultipliers.

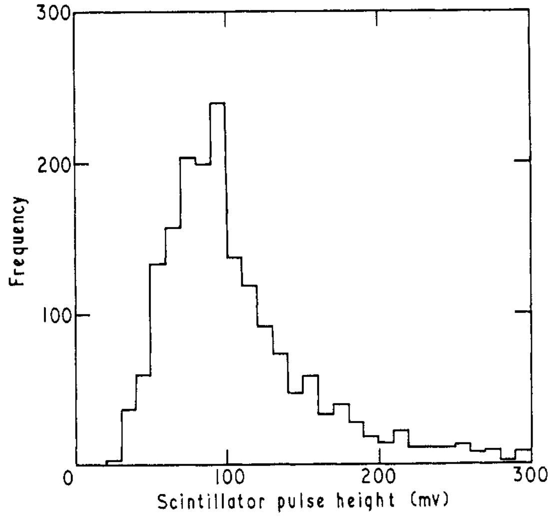

Figure 2. The distribution of pulse heights from the scintillation counter for particles of all momenta.

The pulse-height distribution of the accepted muons traversing the counter is shown in figure 2. The distribution has a width at half-height of (35 ± 3)%, which is close to the expected value of 29%. This latter value is made up from the following: Landau fluctuations in the ionization loss (19%), statistical fluctuations of the photomultiplier (20%) and non-uniformity of the counter (8%), the quantities being added in quadrature.

4. Experimental results

From the recorded events 1822 were selected as being single particles traversing the spectrograph. These particles were divided into momentum cells and the distribution of pulse heights for each momentum cell so obtained. The distributions were treated in the manner described in the preceding paper, with the result expressed in table 1.

Table 1. The distribution of the events in the momentum cells

Mean momentum of cell (GeV/c)	No. of particles	Mode of distribution (mv)
0·36	59	92·5 ± 3·4
0·72	168	90·5 ± 2·5
1·50	133	88·5 ± 2·5
2·32	166	84·5 ± 2·2
3·18	163	93·3 ± 2·1
4·56	214	86·0 ± 1·8
8·04	361	85·0 ± 1·3
15·19	301	84·5 ± 1·6
30·48	144	84·5 ± 2·2
98·60	113	81·0 ± 2·8

As a measure of the degree of flatness of the 'plateau' ionization loss, the slope of the best-fitting straight line to the values of table 1 has been calculated for the region above 2 GeV/c, i.e. for the region above the onset of the density effect. The result is a slope of $-(5·0 \pm 4·2)\%$ per decade of momentum. Such a large value and large error arise mainly from the high mode for muons of mean momentum 3·18 GeV/c. If this point is neglected, the slope of the line is reduced to $-(1·5 \pm 1·1)\%$. In neither case is the slope inconsistent with zero.

The most probable pulse heights for positive and negative muons have also been estimated separately, and the ratio is found to be $1·015 \pm 0·043$; there is thus no significant difference in the ionizing capacity of the two kinds of particle.

5. Discussion

The main aim of the present experiment was to test the Tsytovitch predictions, according to which there should be a decrease in the ionization loss at high energies ($\gamma > 100$) of some 4–8% below the Fermi plateau. As mentioned in the introduction, an improvement in the precision of the experimental result can be made by combining the present data with those of Crispin and Hayman (1964). These workers used a very similar technique and quote an increase of $(3 \pm 1)\%$ in the most probable energy loss at high momentum ($\gtrsim 100$ GeV/c). The result of combining the data is shown in figure 1. The experimental points have been normalized to the theoretical curve at a point corresponding to the mean momentum and mean value of the most probable energy loss of the recorded muons.

The value of the energy loss for muons of momentum greater than 10 GeV/c is $(1·24 \pm 0·69)\%$ above the plateau value, and a least-squares straight-line fit to the points above 2 GeV/c has a slope of $+(2·7 \pm 3·3)\%$ per decade of momentum. These two facts clearly agree with Sternheimer's expectations and lend no support to Tsytovitch's suggestion of a reduction of some 4–8%.

Turning to the energy loss for positive and negative particles separately, the present result for the ratio of the two losses, $1·015 \pm 0·043$, is consistent with that of Crispin and Hayman, $1·009 \pm 0·015$. These values support the view that there is little difference between the ionizing powers of positive and negative muons and give a resultant ratio of $1·009 \pm 0·010$.

Smith and Stewart (1966) have measured the ionization loss of electrons—also in Ne 102—in the momentum range 50–300 MeV/c. Their experimental results are shown in figure 3, where the points are normalized to the theory at a muon momentum of 14 GeV/c. (It should be noted that the theoretical curve given by these authors, which fortuitously fits their points, is incorrect.) Also plotted in figure 3 are the results of Crispin and Hayman (1964) and the results of the present investigation.

An interesting feature is that if attention is confined to the muon momentum range 5–30 GeV/c and a best line is fitted to the data, it shows an increase in the most probable energy loss of some $(9 \pm 3)\%$. The significance of this value is clearly less than that repre-

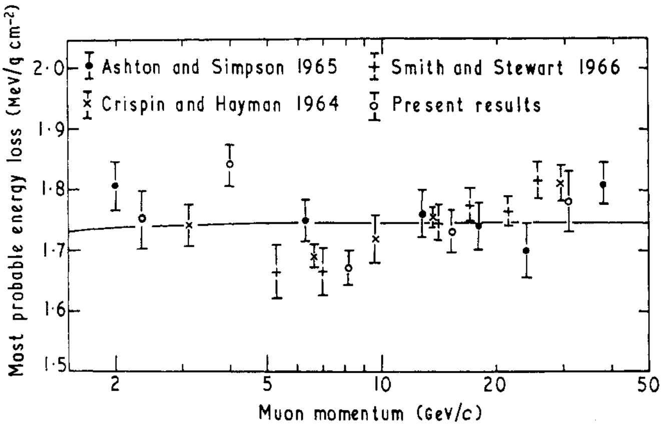

Figure 3. The results of Ashton and Simpson (1965), Crispin and Hayman (1964), Smith and Stewart (1966) and the present work, showing the consistently observed increase in energy loss over the momentum range 5–30 GeV/c.

sented by the quoted statistical error because the range of momentum has been so chosen where a lack of constancy exists. However, the fact that the three experiments taken separately show the same tendency justifies further exploration of the energy loss over this range of momentum.

The results of Ashton and Simpson (1965), also included in figure 3, obtained using a liquid scintillation counter, do not suggest an increase in the energy loss as described above, but the uncertainties of their experimental data are such that an increase cannot be ruled out. Their results do confirm the existence of the density effect in their liquid scintillator up to the highest momentum measured (250 GeV/c), and similarly there is no evidence for a decrease of energy loss as suggested by Tsytovitch.

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