Energy loss of cosmic ray muons in the range 5-40 GeV/c

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Abstract. The new Durham Spectrograph, MARS, has been used to make a direct measurement of the mean rate of energy loss of cosmic ray muons in iron in the momentum range 5–40 GeV/*c*. Agreement is found with the predictions of Sternheimer, and Sternheimer and Peierls for ionization loss (together with values for the other losses) to within the statistical errors, which range from 2% at 6 GeV/*c* to 6% at 30 GeV/*c*.

An examination of the rate of energy loss of cosmic ray muons is of interest for two (related) reasons, namely, to search for effects which might throw some light on the reason for existence of the muon (by perhaps distinguishing it from a mere heavy electron), and to check the predictions of conventional energy loss theory. The latter is not a trivial point in view of the fact that an exact treatment of the energy-loss problem has not yet been given (see the review by Crispin and Fowler 1970), the usual approach being to take for the ionization component, which comprises the bulk of the loss at these energies, values from the extensive calculations of Sternheimer (1956) and Sternheimer and Peierls (1971) which essentially represent a best-fit classical treatment.

In the present work attention is devoted to the total energy loss of muons, this is, including bremsstrahlung, direct pair production and nuclear interaction, and there is thus even more reason for examining its magnitude. Previous determinations of the total loss have been indirect, at least for energies above a few GeV, insofar as they have involved a comparison of the sea level energy spectrum with the variation of vertical intensity with depth underground and inevitably problems have arisen over the density of the overlying strata. In the present experiment, what are effectively direct measurements have been possible using the new magnetic spectrograph (MARS) where the energy loss has been determined in the iron of the instrument itself.

The dependence of energy loss on muon sign has also been studied. Although none would be expected (at least for energy transfers distant from the maximum transferrable energy in μ–e collisions where helicity effects occur) there is interest in this study in view of the observations of Allkofer *et al.* (1971) which suggest a difference for some classes of collision.

MARS has been described by Ayre *et al.* (1969) and a detailed description will not be given here. The feature which allows an examination of the energy loss is the determination of the coordinates of the muon in five detection layers which alternate with the four magnet blocks (only three are needed to determine the mean momentum and the other two enable the energy loss to be studied).

Because of energy loss, the particle trajectories are of spiral character, and thus, for a penetrating particle passing through the magnets, the lateral displacement y is related to the vertical position x by

$$y = ax + b\left(p, \frac{\partial E}{\partial t}\right) x^2 + c\left(p, \frac{\partial E}{\partial t}\right) x^3 + \dots$$

where $a = \tan\theta$; θ is the angle of incidence, and b and c are different functions of the incident momentum p, the rate of energy loss $-\partial E/\partial t$ (t being measured in g cm^{-2}) and the geometry of the instrument.

In principle, p and the mean value of $-\partial E/\partial t$ can be determined uniquely for each particle but Coulomb scattering causes a finite uncertainty and it is necessary to take the average value for groups of particles in each momentum band.

The MARS instrument has been operated in a preliminary experiment in which the constituent flash tubes were photographed (in the eventual mode the information will be digitalized) and the films have been analysed for traversals of unambiguous muons. The selection criteria demanded that the muon track be resolved at all levels, in practice this meant that fewer than three secondary electrons accompanied it at each level. Furthermore, events with large dispersions of y values about the best-fit trajectory were rejected, although this had a negligible effect on the derived means.

The results for the mean values of $-\partial E/\partial t$ for a number of cells of momentum are shown in figure 1; in each case the momentum plotted is that corresponding to the mean, for that cell, at the centre of the spectrograph.

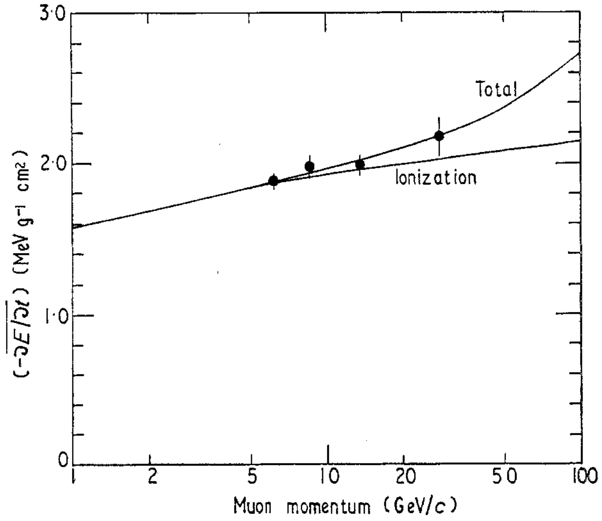

Figure 1. Mean rate of total energy loss of cosmic ray muons in iron. The experimental values are absolute.

Also shown in figure 1 is the theoretical total mean rate of energy loss of muons in iron. The contribution from ionization has been taken from the calculations of Sternheimer (1956) and Sternheimer and Peierls (1971) (the latter work gives the most recent values for the density correction). Approximate values for the other losses have been derived from the expression given by Hayman *et al.* (1963); a small downward correction, amounting to 0·7% at 40 GeV/c, has been applied to allow for those large transfers rejected because of the requirement of fewer than three accompanying electrons in the flash tube trays. (More accurate allowance for fluctuations in energy loss will be made in later work when increased experimental precision warrants it).

It is seen that there is good agreement between theory and experiment within the experimental errors, which increase from about 2% at 6 GeV/c to 6% at 30 GeV/c. With improved precision from future experiments with MARS it should be possible to determine the rate of energy loss to better than 1% and such comparisons will be extended further.

An analysis has also been made for the two signs of muons separately. The ratio of the mean rate of total energy loss for positive to that of negative muons is 1·01 ± 0·07, 1·04 ± 0·08, 0·92 ± 0·06 and 0·84 ± 0·10 at mean momenta of 6·3, 8·6, 14·4 and 27·7 GeV/*c* respectively. None is significantly different from unity.

Comparison with the results of other workers can be brief because of the paucity of direct experiments. Buhler *et al.* (1964) determined muon ranges in lead for momenta up to 2·48 GeV/*c* in an accelerator experiment and found values within 2% of the Sternheimer predictions. At a higher momentum, 8 GeV/*c*, Backenstoss *et al.* (1963) have studied the passage of negative muons through magnetized iron, with particular reference to bremsstrahlung and knock-on electron production where the energy transfer is above 1·6 GeV. Agreement with expectation was found to within approximately 3%. Our own data are not inconsistent with the results of either of these two experiments.

In conclusion, there is no marked divergence from expectation for the mean total energy loss in iron for muons in the momentum range 5–40 GeV/*c*.

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Electric monopole sum rule and helium burning

Abstract. The possibility of helium burning occurring through the reaction $^{12}C(\alpha, e^{\pm})^{16}O$ is examined for a temperature of 10^8 K. As the isoscalar electric monopole sum rule does not rule this out, the results of an electron scattering experiment are reported which demonstrate the absence of electric monopole excitations in the continuum beyond the threshold for $^{12}C + ^{4}He$.

A step in the evolution of stars (Burbidge *et al.* 1957, Salpeter 1957) leading to the build up of heavy elements, is helium burning through the reaction $^{12}C(\alpha, \gamma)^{16}O$.