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A MEASUREMENT OF ENERGY LOSS DISTRIBUTIONS OF ENERGETIC
MUONS IN IRON

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ABSTRACT

The energy-loss spectrum of high energy muons after traversal of a 10 meter iron degrader has been measured with an accuracy of better than 1%. Data taken at energies between 50 and 120 GeV are in agreement with predictions from a Monte Carlo program based on the most recent theoretical descriptions of all relevant processes. The stopping power calculated by this program deviates up to several percent from earlier calculations.

1. INTRODUCTION

The mathematical descriptions of processes contributing to the slowing down of relativistic muons in matter were first formulated in the 1930's, and have been steadily refined since. The tables by Richard-Serre [1], which have become the standard reference for the stopping power of fast muons, are based on the theoretical "state of art" of the 1950's. The calculations were in good agreement with cosmic ray data, though experimental accuracy was only at the level of several percent. As high energy muon beams have become available in the laboratory, improved energy loss calculations can now be compared with high precision data.

The experiment presented here has been performed in 1980 as an auxiliary measurement to the NA4 experiment [2] at the CERN SPS muon beam, which investigates deep inelastic muon scattering with a magnetized iron spectrometer and requires a precise knowledge of the energy loss. Furthermore, for the measurement of a μ^+/μ^- cross-section asymmetry [3], the difference in energy loss for positive and negative muons was of particular interest.

2. EXPERIMENTAL SET-UP

The apparatus used for this experiment was made up from several preexisting detectors, which explains some peculiarities in the set-up shown in Fig.1. Its elements performed the following functions:

- i) A vertical bending magnet of 24 mrad in the muon beam line before the experimental area served, together with a set of 4 scintillation hodoscopes (H1 to H4), as the momentum analyzer for the incoming muons; it is referred to as BMS (Beam Momentum Spectrometer) in the following.
- ii) Two mosaic-structured hodoscopes (H5 and H6) established together with a 20 cm x 10 cm scintillation counter (S1) the trigger requiring a threefold coincidence within 20 ns.
- iii) The degrader, i.e. the material in which the energy loss was to be measured, was placed between H5 and H6.
- iv) The muon momentum after the degrader was measured by the End Spectrometer (ES) which comprised a two-element horizontal bending magnet with a 40 cm wide, 14 cm high gap and a maximum bending power of 7.9 Tm. The magnet was field-mapped over its entire active volume for the five operating fields, representing a total $\int B dl$ of 4.1, 5.1, 6.3, 7.1 and 7.9 Tm. The precision achieved on the $\int B dl$ was better than 10^{-3} . The hodoscope H7, measuring the horizontal coordinate, defined in combination with H6 the track of the incoming muon. Three small (27 cm x 27 cm) and one large (200 cm x 100 cm) MWPC (C1-C4), all with 2 mm spaced vertical wires, gave the direction of the deflected muon.

3. DATA TAKING

For the bulk of the data a 930 cm long, 15 cm diameter iron cylinder ($\rho=7.84 \text{ g/cm}^3$) served as degrader; about 5% of the data were taken with two NA4 "carbon"-targets (70% C, 30% B; total length 10m) as degrader. A total of $4 \cdot 10^6$ events was recorded with both positive and negative beams of 50, 65, 110 and 120 GeV muons. The momentum spread of the incident muons was typically 10% FWHM. The intensity was kept at $2\text{-}3 \cdot 10^5$ muons per second to reduce accidental background.

To minimize the systematic errors due to chamber inefficiency and field calibrations in BMS and ES, data were collected at each beam polarity and momentum in sequences of different bending powers in the ES (four values at 50 and 65 GeV, three values at 110 and 120 GeV). For a fixed setting of the BMS three such sequences of measurements were performed, where the degrader was in the beam for the second one only. The other two, without degrader, served to intercalibrate BMS and ES and to control the stability of the measurement set up with time.

4. ANALYSIS

Cuts were applied to remove ambiguities from the reconstruction of the muon tracks. A time isolated track with a single hit in each of the hodoscopes was required before the ES; its straight line extrapolation to the fictitious center of the ES magnet had to match the outgoing track as defined by the MWPC within 2 cm. For the latter a single cluster in at least 2 of the 3 small MWPC had to fit, together with a cluster in the large MWPC, a straight line with a good χ^2 .

The momentum of the muon after the degrader was calculated using a parametrization in "principal components" [4], derived from a Monte Carlo simulation of all possible muon paths through the ES field. In a similar way the momentum of the beam muon before the degrader was determined using directly the coordinates of the elements hit in the BMS hodoscopes.

5. MONTE CARLO

Since the energy loss distribution extends all the way up to the incident energy E_μ (corresponding to zero outgoing energy), while the ES has a limited momentum acceptance, our data cannot be used to give any absolute number such as the (integral) stopping-power. They rather serve to test a representation of the energy loss, in its differential form, by a Monte Carlo (MC) simulation. The Monte Carlo program used, which will be described elsewhere [5] in detail, tracks individual muons stepwise through a given material. At each step elementary processes, with an energy transfer above a certain threshold, are randomly generated according to their probability distribution.¹ Discrete interactions of the following type are simulated above the respective "randomization" thresholds :

(i)	Delta electrons [6]	$\geq 50 \text{ MeV}$
(ii)	Bremsstrahlung photons [7]	$\geq .01 E_\mu$
(iii)	Electron pairs [8]	$\geq .005 E_\mu$
(iv)	Nuclear interaction [9]	$\geq .01 E_\mu$

¹ Differential cross-sections were taken from quoted references.

All contributions below these thresholds have been integrated, including the ionization as described by the Bethe-Bloch formula [6,10], and are applied in the form of a continuous loss per step.

To allow the direct comparison with measured spectra, the simulation includes the phase space of the beam, losses in matter other than the degrader (185 g/cm² from hodoscopes, air, etc., leading to $\approx$ 550 MeV loss in average), and the acceptance and resolution of the ES. Energy loss spectra as measured by the experiment were generated for each of the different running conditions (i.e. also with degrader "out"). The excellent agreement between measured and predicted spectra (Fig.2) allows us to use their mean values for further quantitative data-MC comparisons.

In order to avoid regions at the edge of acceptance, or with too high sensitivity to the small background from misreconstructed momenta, the mean values are calculated after imposing an upper cut on the energy loss, which is $0.5 E_{\mu}$ at $E_{\text{beam}} = 50, 65$ GeV and $0.25 E_{\mu}$ at $E_{\text{beam}} = 110, 120$ GeV. This cut rejects 5% (15%) of the theoretical energy loss distribution calculated for 100% acceptance at 50 (120) GeV.

6. RESOLUTION AND SYSTEMATIC ERRORS

The BMS provides a measurement of the individual muon momentum with $5 \cdot 10^{-3}$ (RMS) resolution. The relatively coarse determination of the incident muon angle by the ES ($\pm .14$ mrad RMS) and the multiple scattering in the ES of $.2$ ($.08$) mrad RMS at 50 (120) GeV lead to a typical momentum resolution of about 1%. The large number of recorded events allows to determine the mean values of the spectra to better than $1 \cdot 10^{-4}$ statistical error.

Care was taken when changing the excitation current of the ES magnet to move it always along a given hysteresis curve. The magnetic field, as monitored by Hall probes, proved to be reproducible and $\pm$ symmetric within $\Delta B/B = 1 \cdot 10^{-4}$. The magnet in the BMS could not be set with an equal accuracy and its Hall probes exhibit variations of up to several 10^{-3} for subsequent settings of the same nominal field. However, since the current in the BMS was never changed during a "degrader out-in-out" sequence, BMS and ES can be intercalibrated to better than $2 \cdot 10^{-4}$ using the degrader "out" data.

This is shown in Fig.3a, where the difference between measurement and prediction is plotted for all "degrader-out" runs. The values obtained for one physical setting of the BMS current are averaged to form the calibration constant (dashed line), used to correct the corresponding results with the degrader "in". Thus corrected, the latter are plotted in Fig.3b, where the dashed lines show the resulting average values for the two muon polarities as presented in table 1. The combination of the two independent data sets at +120 GeV ((2) and (8) in Fig.3b) gives an indication of the largest systematic error, which stems from spatial and temporal variations of chamber efficiencies and also causes the relatively large dispersion of individual measurement points around their respective mean values. On the basis of this and similar tests at the other energies we ascribe an error of $4 \cdot 10^{-4}$ to the momentum measured by the ES.

7. RESULTS

The relative differences of measured and calculated mean energy losses are presented in Table 1 and are to be understood as averages over the accepted beam momentum byte of $\pm 8\%$. Statistical and systematical errors were quadratically combined, where some systematic errors cancel in the μ^+/μ^- comparison. As the mean energy loss in the degrader (being roughly 18 GeV for Fe, 5 GeV for Carbon) is only a fraction of the muon energy, its relative error is correspondingly larger than the error of the measured muon momenta, quoted above. The measured values are systematically larger than the predicted ones and a growth of this difference with energy is discernible.

A small difference between μ^+ and μ^- , which could be expected due to higher order corrections from QED, can be observed but is still compatible with zero.

If one assumes the theoretical treatment used in the present MC to be the correct one, ref. [1] underestimates the muon stopping power in iron by 0.4%, 1.7% and 4.0% at 50, 120 and 300 GeV respectively. Each of the processes considered contributes to this discrepancy. For the higher energies, however, the largest contribution comes from the pair production, for which a considerably higher cross-section (up to 30%) is used in our calculation.

8. CONCLUSIONS

Distributions of muon energy loss in iron have been measured with high accuracy and are in good agreement with a new Monte Carlo simulation. The measurements show that the new calculation is accurate on the percent level, however with a tendency to underestimate the experimental data. Stopping power values as calculated by this program are, on the other hand, up to several percent higher than those from earlier calculations [1].

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FIGURE CAPTIONS

- Fig. 1 Schematic view of the experimental set-up.
 (not to scale)
- Fig. 2 Energy loss spectrum after 930 cm of iron
 for $E_{\text{beam}} = 120$ GeV.
 The data points are to be compared to the solid line,
 which represents the complete simulation of the experiment.
 The dashed curve shows the predicted spectrum without
 experimental resolution and acceptance.
- Fig. 3 Difference between measured and predicted energy loss for
 all runs taken at 120 GeV.
 The chronological order of the measurements, taken
 in sequences of different bending power values in
 the ES (I,II,III : 7.9,7.1,6.3 Tm), is indicated
 by the numbering 1 to 8.
 (a) Runs without degrader, before BMS correction.
 (b) Runs with the iron degrader, corrected for BMS calibration.

TABLE 1

Relative difference of mean measured energy loss to Monte Carlo

E_{beam} (Gev)	Fe			"Carbon"
	μ^+	μ^- (in units of 10^{-3})	$\mu^+ - \mu^-$	μ^+
50	+6.3 $\pm$ 2	+3.7 $\pm$ 2	+2.6 $\pm$ 1.7	--
65	+4.6 $\pm$ 2.5	+3.0 $\pm$ 2.5	+1.6 $\pm$ 2.3	--
110	+12.0 $\pm$ 3.5	--	--	+11 $\pm$ 12
120	+11.9 $\pm$ 3.5	+10.5 $\pm$ 3.5	+1.4 $\pm$ 3.0	+10 $\pm$ 12

FIG. 1

FIG. 2

FIG. 3