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RANGE MEASUREMENTS FOR MUONS IN THE GeV REGION

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RANGE MEASUREMENTS FOR MUONS IN THE GeV REGION

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The results of an experiment to measure the range of high-energy muons are reported. The reason for carrying out this experiment was the lack of data on muon ranges above a few hundred MeV. We needed this data for the design of an experiment on proton-antiproton annihilation into muon pairs. On the other hand, the results given in this paper represent the first experimental check of the validity of the range-energy relation for high values of γ^* , i.e. $\gamma = 12-25$. Measurements were made of the muon range in an absorber which consisted mainly of lead, at the following momenta:

$$P = 1.240 \pm 0.019 \text{ GeV/c}$$

$$P = 1.790 \pm 0.027 \text{ GeV/c}$$

$$P = 2.480 \pm 0.037 \text{ GeV/c}.$$

The value of the momentum was determined from the currents in the bending magnets and a calibration of beam momentum as a function of bending-magnet current. This calibration was made available by the Bubble Chamber Group, who had measured τ decays¹⁾ to obtain the K-meson momentum in the same beam. Since the range measurements and the calibration were not made simultaneously, we are obliged to quote a momentum uncertainty equal to the momentum acceptance of the beam.

The experimental set-up and the electronic block diagram are shown in Figs. 1 and 3, respectively. The apparatus consists of two main parts: the beam telescope and the range telescope.

The beam telescope

This consists of two plastic scintillators A and B, and two Vivargent-type threshold gas Čerenkov counters D_1 and D_2 ²⁾ which are filled with ethylene. A typical calibration curve of D_1 at 1.79 GeV/c

*) $\gamma = E/m$

is presented in Fig. 2, which shows the three plateaux corresponding to pions, muons and electrons. Similar calibrations were taken for both Čerenkov counters at each of the three momenta used. Two threshold Čerenkov counters are used to provide the differential velocity selection needed to detect muons with low contamination from the antiprotons, K mesons, pions and electrons. The muon electronic signature was

$$(ABD_1) \bar{D}_2,$$

with the pressures in D_1 and D_2 set in such a way as to have a very small efficiency in D_1 for detecting pions and heavier particles, and a very high efficiency in D_2 for electron detection. This method gave a muon beam with less than 5% contamination of other particles, as may be seen from the initial slope of the integral range curves.

Table 1 shows the beam composition at the three momenta, neglecting antiprotons.

Table 1

Momentum GeV/c	e^- %	μ^- %	π^- %
1.24	5.4	3.6	91.0
1.79	1.6	2.3	96.1
2.48	1.5	1.4	97.1

The range telescope

The range telescope consisted of:

- i) An eight-gap aluminium-foil spark chamber, SC, of total density 100 mg/cm² which allows a precise knowledge of the particle direction. This information was included so that we may check the multiple-scattering corrections which are necessary when incident and emergent particle directions are known. These results are not yet analysed.

- ii) A spark chamber assembly, SC_2 , consisting of a series of spark chambers of the Krienen type³). These chambers are $1 \text{ m} \times 1.5 \text{ m}$ with plates of 0.5 cm brass. After the first three plates of the chamber, there is a $1 \text{ m} \times 1.5 \text{ m} \times 2.5 \text{ cm}$ plastic scintillator V_1 . Before the last three plates of the assembly, there is a 3 cm thick iron plate which serves to increase the total surface density to 133 cm/cm^2 lead equivalent. This assembly was an insurance in case we were not able to select muons electronically with low contamination. Pions and electrons would have a high probability of interacting in this chamber and would thus allow us to interpret correctly any initial slope of the range curve. In practice, the electronic selection of muons was so good that we did not need to use the information of SC_2 .
- iii) A variable thickness of lead absorber, of cross-section $1 \text{ m} \times 1 \text{ m}$.
- iv) A $40 \text{ cm} \times 40 \text{ cm} \times 1 \text{ cm}$ plastic scintillator C. This counter was introduced to eliminate random coincidences between beam particles and intermediate energy particles which crossed the counters V outside the lead absorber. The size of this counter was chosen so that there was a negligible restriction on the multiple scattering accepted and, therefore, multiple-scattering corrections to the range could be made assuming 'infinite slice' geometry.
- v) The range chamber, SC_3 , which consisted of two assemblies, very similar to SC_2 , which were placed in series, and gave a total of 288 gm/cm^2 lead equivalent.

Experimental method

The range was measured in two ways:

- a) Electronically Coincidences $(AB D_1) \bar{D}_2 V_2 C \bar{V}_3$ and $(AB D_1) \bar{D}_2 V_2 C V_3$, for a fixed number of monitors $(AB D_1) \bar{D}_2$ and as a function of variable absorber thickness, defined the differential and integral range curves. These results are shown in Figs. 4

and 5. The effect of counter C may be seen from the measurement at 1.79 GeV, where it had not yet been included.

- b) Using SC₃ At each energy, the variable absorber thickness was chosen so as to bring the mean range to the centre of SC₃, and the coincidence (AB D₁) $\bar{D}_2$ C V₂ was used to trigger the spark-chamber system. Figure 6 shows the range curve which was determined in this way.

Calculation of the results

The two main corrections which were made to the range were the conversion of gm/cm² copper to gm/cm² lead, and the correction to the measured range for path elongation by multiple scattering. Account was also taken of the counter material in the beam and of the variation of the Čerenkov counter surface density with pressure. The lead equivalent of the chambers varies slowly with the energy. The conversion factors CX which we have used are shown as a function of material and energy in Table 2.

Table 2

Values of CX

$$[CX = (dE/dX \text{ material } X)/(dE/dX \text{ lead})]$$

Material	Energy range	
	1.0 to 2.5 GeV	10 to 100 MeV
Brass and Fe	1.24	1.40
CH ₂	1.77	2.20

The multiple-scattering corrections to the range were calculated according to the method of $\overline{\text{overas}}^4$). Account was taken of the fact that the final part of the slowing down took place in brass.

Table 3 shows the values of the ranges obtained by the three methods before and after the multiple scattering correction was applied.

Table 3

Momentum (GeV/c)	Integral range	Differential range	Spark-chamber range	
1.24	895	917	914	Before correction
1.79	1313	1288	1290	
2.48	1807	1791	1811	
1.24	910	933	930	After correction
1.79	1337	1315	1318	
2.48	1834	1821	1841	

The result is summarized in Table 4, which also shows what fraction of the total surface density was not lead. The uncertainty quoted in the range is assigned partly on the spread in values found in Table 3, and partly from an 8% uncertainty assigned to the lead equivalent of the brass in the spark chambers. Consequently, the three uncertainties are strongly correlated.

Table 4

Momentum (GeV/c)	Range	Fraction not lead
1.240 $\pm$ 0.019	925 $\pm$ 25	0.35
1.790 $\pm$ 0.027	1325 $\pm$ 25	0.25
2.480 $\pm$ 0.037	1830 $\pm$ 25	0.18

The uncorrected and corrected experimental results are shown in Fig. 7, compared with the theoretical expectations of Sternheimer⁵⁾, which include the density effect.

Table 5 shows the values of the standard deviations of the assumed Gaussian distribution of the straggling, compared with the values given by Sternheimer. The experimental values were estimated from the quartiles of the observed distributions. It may be seen that the spark-chamber values are in fair agreement with the predicted values, but the values obtained from the electronic method are consistently higher. This we attribute to the fact that, in the electronic method, the thickness of the variable lead absorber is changed during the measurement, whereas, in the spark-chamber method, it is kept fixed.

Table 5

Momentum (GeV/c)	σ electronic integral range %	σ spark chambers %	σ Sternheimer %
1.24	6.2 ± 0.8	5.2 ± 0.4	3.3
1.79	5.2 ± 0.6	3.8 ± 0.3	3.6
2.48	5.3 ± 0.4	3.4 ± 0.3	3.9

σ is given as a fraction of the mean range.

In conclusion, we may say that the experimental results agree with the Sternheimer range energy data within 2% for muons with γ of up to 23. Further, there is fair agreement between the experimental and theoretical values of the range straggling, provided that the measurement is made in fixed geometry.

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Figure Captions

Fig. 1 : Experimental set-up.

D_1, D_2 : variable pressure threshold gas Cerenkov counters.
 A, B : plastic scintillation counters 8 cm diameter, 1 cm thick
 C : plastic scintillation counter, $40 \times 40 \times 1$ cm³
 SC_1 : thin-foil 8-gap spark chamber
 SC_2 : thick-plate 14-gap spark chamber
 SC_3 : thick-plate 28-gap spark chamber
View "A" shows the arrangement of the plates and incorporated scintillation counters and iron absorber. The variable thickness of lead is always increased starting from counter C towards SC_2 .

Fig. 2 : Calibration curve of the threshold gas Cerenkov counter D_1 .
 $N(ABD_1)$ is the number of triple coincidences for fixed number of monitor (A, B) .

Fig. 3 : Electronic block diagram.

Scintillation counters V_1, V_2, V_3 are shown outside the spark chambers for clarity. They are marked P1 on Fig. 1, view "A".

Del : variable delay lines
F.D. : fast discriminators
3rd amp : fast three-stage amplifier, 2.5 nsec rise-time
scaler $ABD_1\bar{D}_2$: records the incoming muons
scaler int. : records integral range curve (coincidence unit 2)
scaler diff. : records differential range curve (coincidence unit 3)
SC trigger : trigger for spark chambers, film advancement and dead-time.

Fig. 4 : Differential range curves obtained by the electronic method.

The abscissa is the thickness of the variable absorber. To this should be added 245 gm/cm² at 1.24 GeV/c, 242 gm/cm² at 1.79 GeV/c, and 241.0 gm/cm² at 2.48 GeV/c. These values are lead equivalent, uncorrected for multiple scattering.

Fig. 5 : Integral range curves obtained by the electronic method.

The abscissa is the thickness of the variable absorber. To this should be added 327 gm/cm² at 1.24 GeV/c, 325 gm/cm² at 1.79 GeV/c, and 323 gm/cm² at 2.48 GeV/c.

Fig. 6 : Differential range curve obtained from the spark chamber measurements. Multiple scattering corrections have not been made.

Fig. 7 : Mean values obtained for the mean range as a function of momentum, before and after correcting for multiple scattering.

The solid curve shows the range-momentum calculations of Sternheimer.

50 cm

VIEW 'A' (not to scale)

Nº br = number of brass plates
 0,5cm thick
 Pl = plastic scintillator 2,5cm thick
 Fe = iron plates absorber 3cm thick

FIG.1

Particle Momentum 1.8 GeV/c

Zero pressure corresponds to atmospheric pressure

FIG. 2

FIG. 3

FIG.4

FIG.5

FIG. 6

FIG. 7