

HIGH ENERGY MUON SCATTERING

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(presented by G. Masek)

The large angle nuclear scattering of high-energy muons has appeared, in some cosmic ray experiments, to be anomalously large, i.e., the cross section at high momentum transfers (greater than 80 MeV/c) is larger than that predicted by electromagnetic theory. However, this anomaly is *not* seen by *all* cosmic ray experiments, and hence there is considerable controversy as to its existence. We describe here an experiment which measured the large momentum transfer, single scattering cross section of a muon beam of known purity and incident energy. The energy of the muon after scattering was not measured, and hence the cross section measured was the total, elastic plus inelastic, into a given angle. We believe this experiment resolves the above question concerning the existence of the anomaly. It does not extend to sufficiently high momentum transfers to make any statements concerning the muon-proton form factor.

The experimental set-up is shown in Fig. 1. The source of muons was the 3.5 BeV/c pion beam, 7% of which decayed in the well-defined drift space

between M_2 and M_3 . The lowest energy (1.95 ± 0.04 BeV/c) muons were magnetically separated from the pion beam by the magnet M_3 , and were directed onto the scattering detector system. The primary detectors were a series of scintillation counter hodoscopes, which recorded the angles of each muon before and after traversing the target material. The muon beam in addition passed through a gas threshold Čerenkov counter and, after the hodoscope, through a 40" iron absorber. The incident muon beam contained a 3% pion contamination, but the requirements imposed by the Čerenkov counter and the absorber reduced this to an effective contamination of $\sim 3 \times 10^{-6}$, well below the point where it could contribute to the scattering distribution. The experimental parameters are summarized in Table I, and the geometrical layout of the hodoscope and the counting set-up is shown in Fig. 2.

Emulsion stacks were located before, and in the middle of, the iron absorber and were exposed to the muon beam during the entire experiment. The single

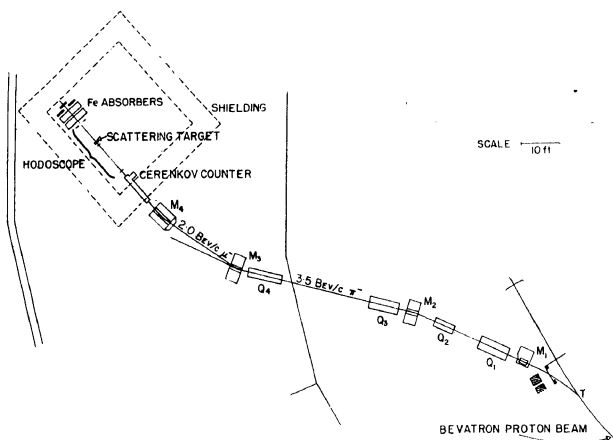


Fig. 1 Experimental layout of the pion and meson beams.

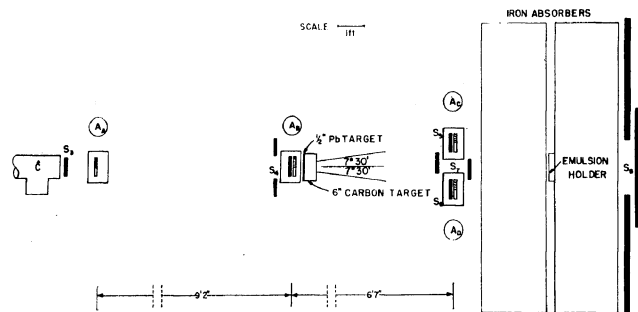


Fig. 2 Detail of the hodoscope scattering detector. The criterion for an acceptable scattering event was :

$$s_1 s_2 s_3 s_4 (s_5 \text{ OR } s_6) s_8 c \bar{s}_7 \bar{s}_9.$$

s_1 and s_2 are not shown but are beam defining counters upstream. s_9 is not labeled, but is the guard counter surrounding A_B . $\bar{s}_7 \bar{s}_9$ rejects events accompanied by knock-on electrons.

Table I. Table of Experimental Parameters

Parameter	Value
Muon beam	
Muon momentum	1.95 ± 0.04 BeV/c
Max. muon flux per burst	400
Total effective muon flux incident on carbon target	1.1×10^7
Pion beam	
Momentum	3.5 ± 0.25 BeV/c
Max. pion flux per burst	0.5×10^6
Fraction of pions decaying between M_3 and M_2	0.07
Pion contamination	
Fraction of pions in incident beam	0.03
Transmission efficiency for pions through Cerenkov counter	0.003
Transmission efficiency for pions through the Fe absorber	0.03
Total effective pion contamination	$\sim 3 \times 10^{-6}$

scattering cross section measured in the emulsion extends the experiment to lower momentum transfers and provides a good check where the two experiments overlap at about 80 MeV/c momentum transfer. (Momentum transfers given here are the "elastic" 4-momentum transfer, i.e., $|q| = 2k_0 \sin \theta/2$.)

The results of the scattering of 1.1×10^7 muons on 27 g/cm² of carbon are shown in Fig. 3. The theoretical yield was computed using the work of Drell and Schwartz¹⁾ who have applied conventional theory, including nuclear structure effects, recoil, magnetic scattering, and nucleon form factors, to precisely the problem at hand: the "low resolution" (all final energies accepted) differential cross section for scattering of a muon or electron from a light nucleus. Shell model wave functions which agree with the elastic scattering of electrons were used in these computations. The major uncertainty is the neglect of the pair correlations caused by nucleon-nucleon forces, which could represent a correction of up to 20%. The production of pions would represent a correction of $\sim 3\%$. A multiple-scattering correction which ranges from 9% to 1% has been made. In addition, an electron scattering experiment (which is now in progress in collaboration with D. Coward at Stanford) should allow a direct comparison between electrons and muons and,

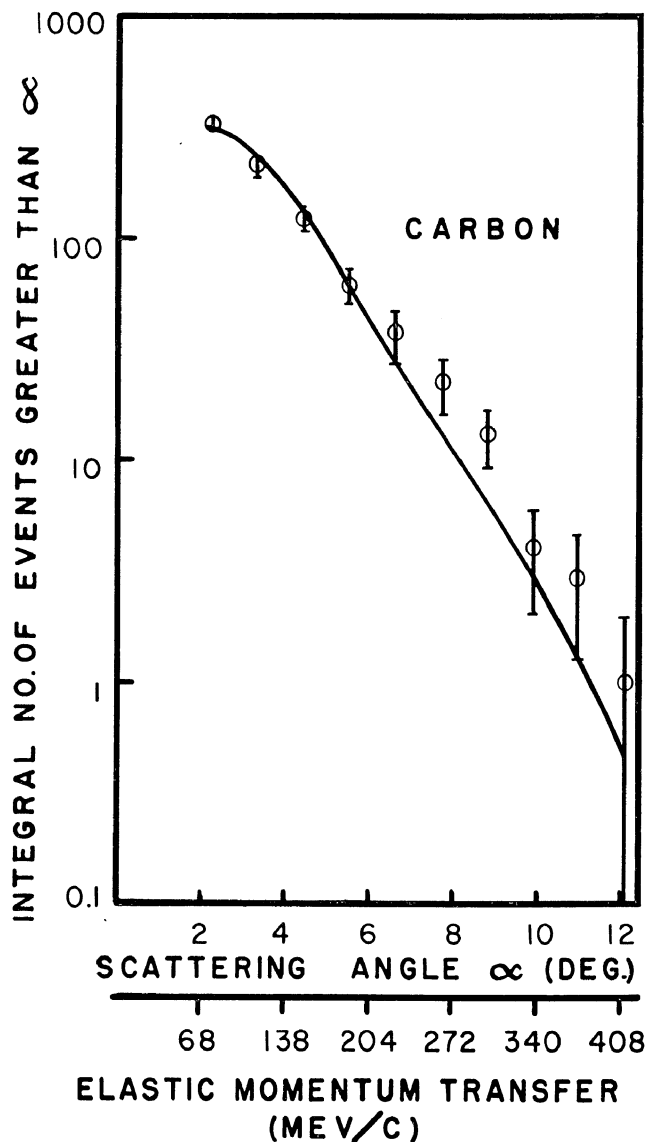


Fig. 3 Integral scattering distribution in carbon. The solid curve is the theoretical yield calculated from the work of Drell and Schwartz. The errors on the experimental points include errors due to a "target out" subtraction.

hence, remove any possible questions regarding the applicability of the above theory.

If Lloyd and Wolfendale's results²⁾ on $\sim 9,000$ muons in Pb and Fe are interpreted as an excess nuclear scattering of muons, they would require some thousands of scattered particles in the present experiment. It is clear that no such anomaly exists. Even assuming a (physically unreasonable) Z^2 dependence of the anomaly, we would still expect about ten times as many particles as we observe in the momentum transfer range above 200 MeV/c. If we make the assumption that the anomalously scattered muons have the same angular distribution as 2 BeV scattered pions (which are also directly

measured in our hodoscope), then our experimental upper limit to the anomalous cross section is

$$\left. \frac{d\sigma}{d\Omega} \right|_{\text{anom}} < 10^{-29} \text{ cm}^2 / \text{sterad per nucleon}.$$

To compare directly with the cosmic ray experiments, we have also measured the scattering distribution using a $\frac{1}{2}$ " lead target. With this, as well as the above mentioned cosmic ray experiments, multiple scattering dominates the scattering distribution, and hence in Fig. 4 our experimental results are compared with the multiple scattering predictions of Rainwater and Cooper³⁾. Also shown is the Molière scattering distribution for a *point nucleus*. The cosmic ray anomalies have been reported to agree with this distribution. Hence, once again, we feel that our results are in direct contradiction with the existence of such an anomaly. Finally, the emulsion data has been partially analyzed and it also appears to agree with the correct electromagnetic prediction for single scattering below 80 MeV/c momentum transfers. In summary, it should be restated that these experiments give *no* evidence for an anomaly in the scattering of muons, and, in fact, good agreement is found with the appropriate electromagnetic theory predictions.

We have looked into the question of extending these experiments into the physically very interesting region of higher momentum transfers where one might expect to see differences between the electron-nucleon and the muon-nucleon form factors. With substantial modification of the above set-up, we believe a 10% measurement of the cross section is possible at momentum transfers up to 700 MeV/c.

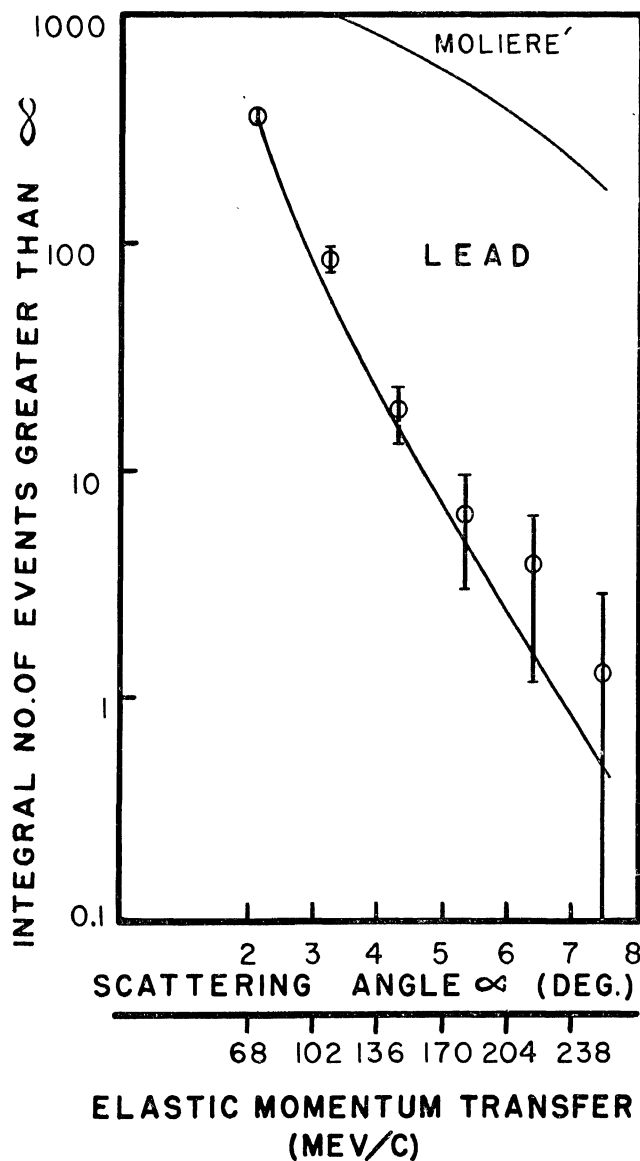


Fig. 4 Integral scattering distribution in lead. The solid curve is the theoretical yield calculated from the work of Rainwater and Cooper. The errors on the experimental points include errors due to a "target out" subtraction.

LIST OF REFERENCES AND FOOTNOTES

1. Drell, S. and Schwartz, C. Phys. Rev. **112**, p. 568 (1958).
2. Lloyd and Wolfendale. Proc. Phys. Soc. A **68**, p. 1045 (1955).
3. Cooper, L. and Rainwater, J. Phys. Rev. **97**, p. 492 (1955).

DISCUSSION

HUGHES: I would just like to remark to Masek that I believe that Ta-You Wu has found that some corrections were necessary to Molière's multiple scattering theory. I am not sure whether Wu's work is published.

MASEK: We used the Rainwater-Cooper results in evaluating the lead data. I do not think they are the same as Molière's.