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[3]T. Ferbel, in Meson Spectroscopy, edited by C. Baltay and A. H. Rosenfeld (W. A. Benjamin, Inc., New York, 1968). B. French, in Proceedings of the Fourteenth International Conference on High Energy Physics, Vienna, Austria, September, 1968 (CERN Scientific Information Service, Geneva, Switzerland, 1968).

[4]Events were measured on the Brookhaven National Laboratory flying-spot digitizer and Oak Ridge National Laboratory and Pennsylvania conventional measuring machines. The events had at least one uniquely identified proton and fitted the channel of interest with a fit probability greater than 10%. The resolution in the $\pi^+\pi^-\pi^0$ mass varied from ±15 MeV in the ω region to ±25 MeV in the $\varphi(1670)$ region.

[5]The smooth curve on Fig. 2(a) results from the distribution obtained when ρ^0 is selected and the $\rho^+\rho^-$ removed from the smooth background distribution used in the fit of Fig. 1(b). It was assumed that the Dalitz-plot distribution for the background was uniform. The curve drawn is approximately normalized each side of the $\varphi(1670)$; a normalization factor of 1.1 is needed showing that the assumption of a uniform background is reasonably accurate.

[6]C. Case et al., Nuovo Cimento 54A, 983 (1968); C. Baltay et al., Phys. Rev. Letters 20, 887 (1968); J. Bartsch et al., Nucl. Phys. B7, 345 (1968). Charged A_3 production in the reaction $\pi^+N \to A_3{}^+N$ similarly exhibits in this experiment a dominant π^+f^0 decay mode.

[7]A. M. Cnops et al., Phys. Rev. Letters 21, 1609 (1968), and to be published.

[8]If ρ exchange were allowed, ρ^- formation could occur and the $\pi^+\pi^-$ and $\pi^+\pi^0$ mass systems need not be identical, but the model would still be unsatisfactory since the additional diagrams would imply more ρ^0 than ρ^+ production if they are assumed to have similar phases.

[9]The calculation and experimental test were made excluding π-nucleon masses less than 1.7 GeV and the shape of the 3π distributions were assumed to be the same. This results in an over estimate of the charge-exchange Deck cross section in the A_1 region since the charge-exchange peak will be broadened due to the reduced slope of the differential cross section in charge-exchange scattering compared with elastic scattering.

[10]A further argument against a Deck-effect interpretation is that the $A_1{}^0$ region cross section has fallen by a factor 2 in going from 5.1- to 8-GeV/c incident energy. A charge-exchange Deck calculation would suggest a slower fall since the cross section depends on the allowed πN phase space.

[11]H. Harari, in Proceedings of the Fourteenth International Conference on High Energy Physics, Vienna, Austria, September, 1968 (CERN Scientific Information Service, Geneva, Switzerland, 1968). This mixture of isospin states is chosen to enhance ρ^+ and reduce the ρ^- relative to ρ^0 in the A_1 region.

HIGH-ENERGY MUON-PROTON SCATTERING: ONE-PHOTON EXCHANGE TESTS*

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Muon-proton elastic scattering has been studied in the range $0.15 < q^2 < 0.85$ (GeV/c)^2 with μ^+ and μ^- beams of 6 and 11 GeV/c and a μ^- beam of 17 GeV/c. Cross sections have been determined with uncertainties as small as 2%. Rosenbluth straight-line plots and comparisons of the μ^+ and μ^- cross sections show no deviation from the one-photon exchange approximation.

Electron-proton elastic-scattering experiments are consistent with a one-photon–exchange approximation to the electromagnetic interaction between the two particles.[1] The present experiment used muons to study this interaction with the objectives of extending the previous tests to the very high energies available at the alternating-gradient synchrotron (AGS) and of searching for deviations from the theory due to a possible μ-e universality breakdown. A detailed discussion of the μ-e comparison is presented in the next Letter.

Tests of the adequacy of this simple one-photon approach have been made in several ways.

Rosenbluth straight-line plot. —The elastic cross section is given by the Rosenbluth formula,[2]

$$\frac{d\sigma}{dq^2}=\frac{d\sigma}{dq^2}\bigg|_{NS}\frac{1}{\cot^2(\theta/2)}\left[2\tau G_M^2(q^2)+\frac{G_E^2(q^2)+\tau G_M^2(q^2)}{1+\tau}\cot^2(\theta/2)\right], \quad (1)$$

where q is the four-momentum transfer to the nucleon, θ is the lepton scattering angle, $\tau=q^2/4m_p^2$, and $d\sigma/dq^2|_{NS}$ is the cross section for scattering from a spinless point charge. The electric and magnetic form factors G_E and G_M are functions of q^2 only. The linear dependence of the quantity

$$S(q^2,\theta)\equiv\frac{d\sigma/dq^2}{(d\sigma/dq^2)_{NS}}\cot^2(\theta/2)$$

on $\cot^2(\theta/2)$ has been verified by electron-proton scattering experiments for momentum transfers as high as 4 $(\mathrm{GeV}/c)^2$.

Charge asymmetry. —In the one-photon limit, the cross sections for positive and negative lepton scattering are identical. Numerous electron experiments have found this to be true within a few percent for momentum transfers up to 5 $(\mathrm{GeV}/c)^2$.

Deviations from the Rosenbluth formula may be due to higher order processes such as two-photon exchange.[3] While these terms may be expected to contribute at the 1% level, resonance effects could enhance them considerably. One mechanism involves mediation of the two-photon exchange by a meson resonance. Such a process results in a specific modification to the angular dependence of the Rosenbluth formula. For example, exchange of two photons in a $J^P=2^+$ state adds to $S(q^2,\theta)$ a term of the form

$$\pm[C_1(q^2)\cot^2(\theta/2)+C_2(q^2)]\left[1+\frac{\cot^2(\theta/2)}{1+\tau}\right]^{1/2},$$

where the ± sign indicates that these terms, arising from the interference of the two-photon amplitude with the one-photon amplitude, change sign with the lepton charge. At low energies (large θ), the new term does not alter the linear form of S appreciably. However, at high energies, the term varies as

$$C(q^2)\cot^3(\theta/2)$$

and destroys the linearity.

We have performed a self-contained test of the presence of such terms by measuring the muon-proton elastic cross section in the range $0.15<q^2<0.85$ $(\mathrm{GeV}/c)^2$ at three incident energies (6, 11, and 17 GeV). Values of $\cot^2(\theta/2)$ as high as 6000 were obtained.

Both μ^+ and μ^- beams of 6 and 11 GeV/c were obtained from pions produced at 4.7° to the internal proton beam of the Brookhaven AGS. A 17-GeV/c μ^- beam was formed from 20-GeV/c pions produced at 0° that were subsequently deflected into the 4.7° beam by one of the AGS ring magnets. It was thus impossible to obtain a similar μ^+ beam at 17 GeV/c. While traversing the 300-ft-long flight path, a few percent of the pions decayed to muons with momenta in the desired range. Pions were attenuated by a factor of 10^6 by passing the beam through 27 ft of carbon and beryllium. The muons were then momentum analyzed to ±13% by two dipoles and collimated to an area of 3×6 in. The flux of muons at 11 GeV/c was $3.0\times10^4/(10^{12}$ protons) and higher at 6 and 17 GeV/c.

The muons were scattered in a 48-in.-long liquid-hydrogen target, as shown in Fig. 1. Trajectories of the incident muon, the scattered muon, and the recoil proton were recorded in thin-foil spark chambers. The momentum of the recoil proton was measured by stopping the particle in a 20-plate range chamber. The spark-chamber trigger was in part derived from coarse scintillation-counter hodoscopes that confined the proton recoil angle to $60°<\theta_p<90°$. Three hodoscopes in the beam required that the muon scatter by at least 15 mrad to reduce false triggers from μ-e scatterings. The scattered muon was further required to pass through 6 ft of uranium to improve the rejection of pions

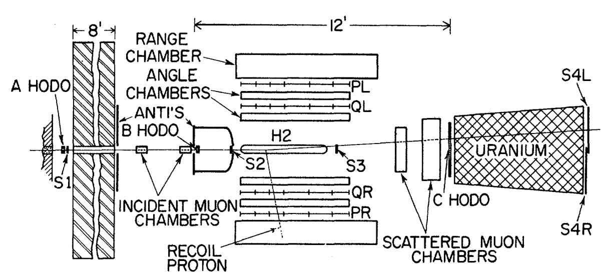

FIG. 1. Plan view of experimental setup. Muons entered the apparatus from the left and passed through the liquid-hydrogen target. Trajectories from a typical event are shown.

without further lowering the incident energy. Pions that decay to muons after interacting in the target but before striking the uranium penetrate this absorber and limit the attenuation to a factor of 150. Pion contamination in our elastic sample, measured by triggering the apparatus on beam particles that did not penetrate the uranium, was found to be 0.1%, as expected.

The spark chambers were triggered every 5-10 pulses and a total of 110 000 photographs were taken. About 40% of the events were later measured and completely reconstructed in space by an IBM 360/44 computer. Some 35% of the measured events survived reconstruction and data cuts. On extrapolation to the hydrogen target, the three-particle trajectories were found to be contained in an "interaction volume" of ~0.2 in. No events fall outside of the target boundaries. Empty-target runs showed no events originating from the target walls and accordingly no empty-target subtractions were made.

The incident momentum and the momentum transfer q are calculated by assuming an event to be an elastic μ-p scattering. A class of events was found having apparent incident momenta considerably larger than those expected from measurements of the incident spectra. These events also had calculated recoil proton momenta much larger than those momenta calculated from the proton range. These events are most likely μ-e scatterings and have been eliminated by loose cuts on the incident momentum.

The most stringent elasticity criterion is the event coplanarity. The distribution is Gaussian with a standard deviation of 1.7 mrad, which corresponds to a missing transverse momentum of 100 MeV/c for 17-GeV/c muons. Only those data with coplanarities less than 6 mrad were accepted and the small (2%) background under the elastic peak was removed by extrapolation.

The detection efficiency was determined by a Monte Carlo calculation. All data input to the calculation, such as beam spatial profiles, momentum spectra, and measuring errors, were determined independently of the main experiment. Monte Carlo distributions such as interaction volume, coplanarity, and momentum transfer agreed with the data. Recoil-proton momenta were calculated from the kinematics and also measured by range. The shape of the plot of $\Delta p/p \equiv (p_{\mathrm{calc}}-p_{\mathrm{range}})/p_{\mathrm{calc}}$ for events was found in excellent agreement with that predicted by the Monte Carlo and we therefore conclude that any inelastic contribution to our data is negligible.

Several small corrections were made to the data to arrive at final cross sections. Some good events (~1%) were vetoed by knock-on electrons produced by the incident muon. A few proton counters were found to be inefficient and events involving those counters were eliminated. The radiative corrections are at most 3% and are essentially independent of the charge and momentum of the muon.[4]

Our comparison of μ^+ and μ^- scattering is rendered particularly attractive by the fact that the incident beams for μ^+ and μ^- were found to be identical. The absolute detection efficiency is the same in both cases and does not enter here. The asymmetry for both 6- and 11-GeV/c data is shown as a function of q^2 in Fig. 2. Combining all of the data, we find the mean asymmetry to be $(-1.5 \pm 1.2)\%$. A fit to no asymmetry gives a χ^2 of 10.5 for 13 degrees of freedom. These data are clearly consistent with no asymmetry, in agreement with extensive electron data taken at lower energies in this q^2 region.

The Rosenbluth straight-line analysis is simplified by the fact that the intercept $2\tau G_M^2(q^2)$ should be totally negligible in the present experiment. Thus, the two measurements of the μ^+ cross section may also be used to test the straight-line behavior. Lines fitted to the data do indeed give intercepts consistent with zero and we constrain all lines to pass through the origin. Typical straight-line data are shown in Fig. 3. Note

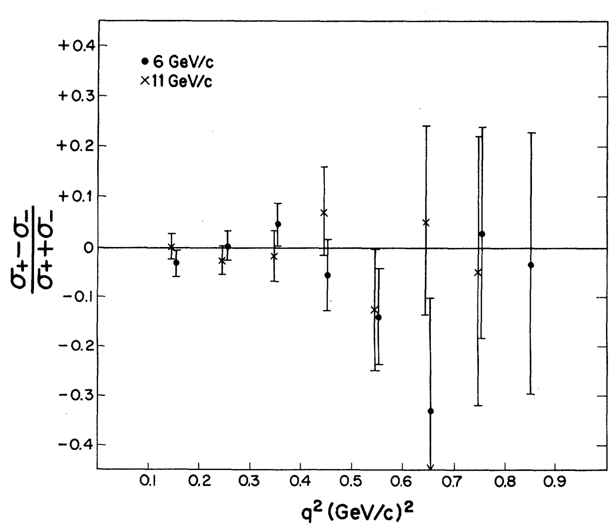

FIG. 2. Cross-section charge asymmetry $(\sigma_+ - \sigma_-)/(\sigma_+ + \sigma_-)$ vs q^2. Data at both 6 and 11 GeV/c are shown.

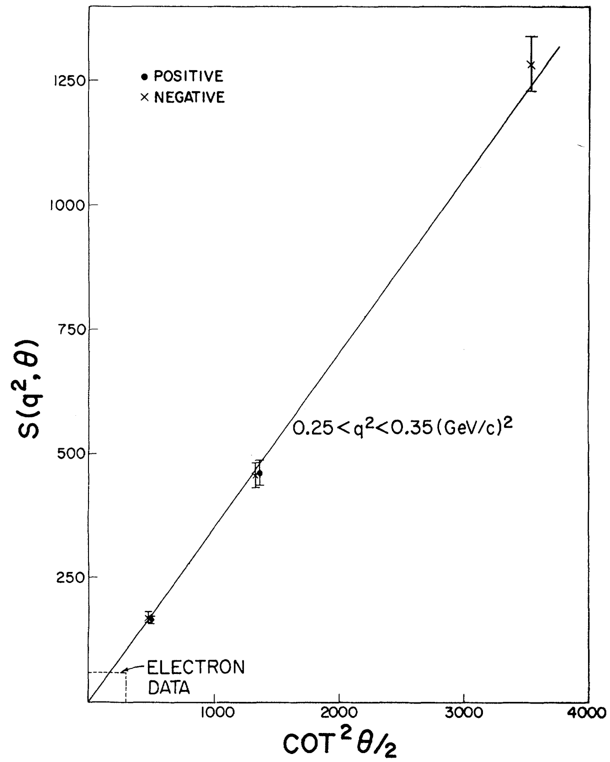

FIG. 3. A typical Rosenbluth straight-line plot of $S(q^2, \theta)$ vs $\cot^2\frac{1}{2}\theta$, showing the μ^+ and μ^- data separately. The line shown best fits the data while constrained to pass through the origin.

that any absolute normalization error does not affect the linearity of the data. The data in each q^2 interval are well fitted by a straight line and the combined χ^2 for all of the data is 17.8 for 24 degrees of freedom. A comparison of the form factors derived from this analysis with those from electron-proton scattering is presented in the following Letter.

Limits on the contribution of a 2^+ exchange process to our data were obtained by simultaneously fitting all five points at a given q^2 to Eq. (2). This method provides the most sensitive measure of any deviation as both the μ^- straight-line data and the asymmetry at 6 and 11 GeV/c are used.

We find no significant deviation of $C(q^2)$ from zero. If $C(q^2) \equiv 0$, we obtain a χ^2 of 6 when we expect 7. Assuming $C(q^2)$ constant, we find $|C| < 3\times10^{-4}$ with 95% confidence. The contribution of the two-photon amplitude is less than 4% of the one-photon amplitude at 11 GeV/c.

We have repeated this analysis for a 1^+ exchange. For small θ, the interference term is $C'(q^2)\cot(\theta/2)$. In this case, $|C'| < 0.3$, but the relative contribution of the two-photon amplitude is the same as for the 2^+ analysis.

In conclusion, we find good agreement with the one-photon-exchange approximation for q^2 up to 0.85 $(\text{GeV}/c)^2$ and incident energies up to 17 GeV.

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