PHYSICAL REVIEW D VOLUME 2, NUMBER 9 1 NOVEMBER 1970

Muon-Proton Scattering and Possible Anomalous Interaction of the Muon*

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(Received 4 June 1970)

It is argued that a possible anomalous interaction of the muon of the form $if\bar{\psi}\gamma_\lambda\psi\chi_\lambda$ can be large enough to account for the μ-p/e-p cross-section ratio and yet it is not inconsistent with the present comparison for the theoretical and experimental values of the anomalous magnetic moment of the muon.

THE similarity between the muon and the electron has been an outstanding problem in particle physics. Except for its mass, the muon behaves almost just like an electron. One interesting speculation is that a bare muon has the mass of an electron, but owing to some anomalous interaction between the muon and a hypothetical neutral vector boson χ,[1] the muon acquires its observed physical mass. With an interaction Lagrangian given by

$$\mathfrak{L}=if\bar{\psi}(x)\gamma_\lambda\psi(x)\chi_\lambda(x)\,, \tag{1}$$

where $\psi(x)$ and $\chi_\lambda(x)$ denote the muon and χ field, respectively, this anomalous interaction also contributes δa to the muon anomalous magnetic moment. In the lowest-order perturbation,

$$\delta a=\frac{f^2}{12\pi^2}\frac{m^2}{M_\chi{}^2}, \tag{2}$$

where m is the muon mass, M_χ is the χ boson mass, and $m/M_\chi \ll 1$ has been assumed in dropping higher-order terms. Using[2]

$$\delta a=a_{\rm expt}-a_{\rm theor}=(29\pm34)\times10^{-8}\,, \tag{3}$$

one gets from Eq. (2) as an upper limit for the ratio

$$f^2/M_\chi{}^2\lesssim 7\times10^{-3}/M_N{}^2\,, \tag{4}$$

where M_N is the nucleon mass.

Recently experiments on μ-p scattering at large momentum transfer (to $q^2\lesssim 1$ GeV$^2/c^2$) have become available.[3] The μ-p data appear to differ from the corresponding e-p experiment by about 8% in the cross section. It is natural to investigate whether the proposed μ-χ interaction which gives a very small δa is large enough and consistent with these μ-p results.[4]

With the inclusion of one χ boson exchange between the muon and the proton, the "effective" electric and magnetic form factors become

$$\tilde{G}_E(q^2)=[1-\delta_E(q^2)]G_E(q^2) \tag{5}$$

and

$$\tilde{G}_M(q^2)=[1-\delta_M(q^2)]G_M(q^2)\,, \tag{6}$$

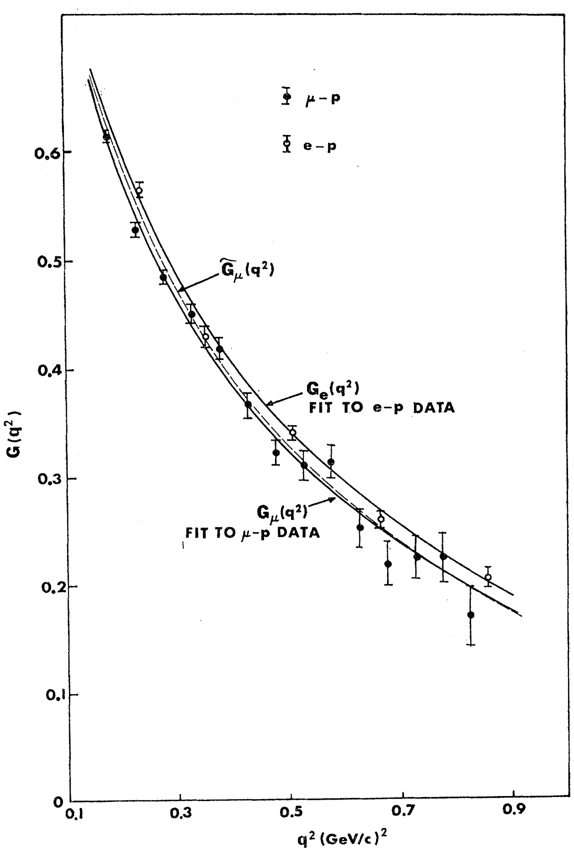

FIG. 1. Form factor calculated from Eqs. (5) and (8) versus q^2, together with μ-p and e-p experimental data taken from Ref. 3.

* Work supported in part by the National Research Council of Canada.

[1] I. Yu. Kobzarev and L. B. Okun, Zh. Eksperim. i Teor. Fiz. 41, 1205 (1961) [Soviet Phys. JETP **14**, 859 (1962)]; R. Sugano, Progr. Theoret. Phys. (Kyoto) **28**, 508 (1962); Y. Ne'eman, Phys. Rev. **134**, B1355 (1964); S. J. Brodsky and E. DeRafeal, *ibid.* **168**, 1620 (1968).

[2] The precise measurement of the anomalous magnetic moment $a_{\rm expt}$ was given by J. Bailey *et al.*, Phys. Letters **28B**, 288 (1968). $a_{\rm theor}$ is the anomalous magnetic moment calculated from quantum electrodynamics to fourth order including also an estimate of the contribution from some sixth-order diagrams and also from strong interactions. See, for example, J. Aldins, T. Kinoshita, S. J. Brodsky, and A. J. Dufner, Phys. Rev. Letters **23**, 441 (1969).

[3] L. Camilleri, J. H. Christenson, M. Kramer, L. M. Lederman, Y. Nagashima, and T. Yamanouchi, Phys. Rev. Letters **23**, 149 (1969); **23**, 153 (1969). The scaling law $G_E=G_M/\mu$ is used in the analysis of the data. Although recently this scaling law has become doubtful [see, for example, Chr. Berger *et al.*, Phys. Letters **28B**, 276 (1968); J. Litt *et al.*, *ibid.* **31B**, 40 (1970)], Camilleri *et al.* mentioned that their results would not be affected.

[4] S. A. Basri has also studied this problem [Phys. Rev. D **1**, 165 (1970)]. The value he used for f^2/M^2, however, is inconsistent with the muon anomalous magnetic moment measurement by three orders of magnitude.

where

$$\delta_E(q^2)\approx\delta_M(q^2)\simeq\frac{f^2}{e^2}\frac{q^2}{q^2+M_X{}^2}. \tag{7}$$

Here we have assumed that the $pp\chi$ vertex part has a form similar to the $pp\gamma$ vertex, and $f_{\chi pp}=f_{\chi\mu\mu}\equiv f$, $f_{\chi ee}=0$. Note that in order for Eq. (2) to be valid, M_X should be at least of the order of 1 GeV. For $M_X\gtrsim 3$ GeV,[5] we can write approximately

$$\delta_E\approx\delta_M\approx f^2q^2/e^2M_X{}^2 \tag{8}$$

for $0.15<q^2<0.9$ $(\mathrm{GeV}/c)^2$. Equation (5) with Eq. (8) is plotted in Fig. 1 together with the experimental curves taken from Ref. 3. It is seen that the proposed μ-χ interaction is not inconsistent with the μ-p data.[6]

[5] S. Hayes, R. Imlay, P. M. Joseph, A. S. Keizer, J. Knowles and P. C. Stein, Phys. Rev. Letters **24**, 1369 (1970).

[6] L. Camilleri, Ph.D. thesis, Columbia University, 1969 (unpublished), mentioned that the deviation increases with q^2, $0.03<\delta<0.06$ for $0.15<q^2<0.9$ $(\mathrm{GeV}/c)^2$. Equation (8) gives $0.01<\delta<0.07$, although clearly Eq. (8) is not accurate for large q^2 if M_X is not massive enough. We would like to thank Dr. Camilleri for sending us a copy of his thesis.

Within the rather restrictive range of momentum transfer quoted above, the deviation of the μ-p data from the e-p may also be regarded as due to systematic experimental normalization errors,[3] rather than due to any appreciable contribution from the χ boson. Two sources of systematic errors are (i) error in the absolute normalization (2%) arising from counter inefficiency, and (ii) error in the determination of q (0.5%) which yields an error of 2.5% in the cross section. In this connection it is interesting to recall that Ng and Sugano[7] recently also considered a derivative coupling between the muon and χ boson, namely,

$$\mathcal{L}=if\bar{\psi}(x)\psi(x)\partial_\lambda\chi_\lambda(x)\,, \tag{9}$$

in order to explain the possible anomalous properties of cosmic muons with $f^2/M_X{}^2\approx 5\times10^{-7}$ $(\mathrm{GeV}/c)^{-4}$. Such a coupling will have an unobservably small effect on μ-p scattering for any practical momentum transfer. Thus, an extension of the μ-p scattering to cover larger momentum transfer may help to distinguish various μ-χ couplings.

[7] S. H. Ng and R. Sugano, Progr. Theoret. Phys. (Kyoto) **43**, 1588 (1970).

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Meson-Nucleon Scattering and Asymptotic Conservation of Helicity

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(Received 17 July 1970)

We have considered the validity and consistency of the hypothesis of asymptotic conservation of s-channel helicity, and the dynamical hypothesis that the P' Regge trajectory decouples from the A amplitude in πN and KN diffraction scattering. Sum rules which follow from these hypotheses are shown to be quite consistent with the experimental data.

I. INTRODUCTION

The hypothesis that diffraction scattering of hadrons at high energies occurs with the conservation of the s-channel helicities of the particles involved has recently been proposed by Gilman, Pumplin, Schwimmer, and Stodolsky.[1] For the scattering of pseudoscalar mesons (M) from nucleons (N) this hypothesis has important implications for the invariant amplitudes $A(s,t)$ and $B(s,t)$ defined[2] in terms of the Feynman amplitude for $M(k_1)+N(p_1)\to M(k_2)+N(p_2)$ by

$$\bar{u}(p_2)Tu(p_1)$$
$$=\bar{u}(p_2)[-A(s,t)+i\tfrac{1}{2}(\boldsymbol{k}_1+\boldsymbol{k}_2)B(s,t)]u(p_1)\,. \tag{1}$$

The helicity amplitudes in the s-channel c.m. system for asymptotic energies at fixed t are given in terms of the

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‡ On leave of absence from Carnegie-Mellon University, Pittsburgh, Pa. Research sponsored by the Air Force Office of Scientific Research, Office of Aerospace Research, U. S. Air Force, under AFOSR Grant No. 70-1866.

[1] F. J. Gilman, J. Pumplin, A. Schwimmer, and L. Stodolsky, Phys. Letters **31B**, 387 (1970).

[2] We use the notations of J. Hamilton and W. S. Woolcock, Rev. Mod. Phys. **35**, 737 (1963). In particular, s, t, and u are the usual Mandelstam variables; $W(E)$ is the total (nucleon) c.m. energy.