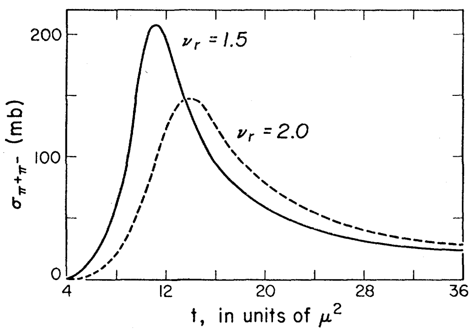

FIG. 7. The total cross section for $\pi^+-\pi^-$ scattering which would correspond to $\Gamma=0.4$ and two values of ν_r if there were no scattering in states other than $J=1$, $I=1$.

For all values of the parameters investigated, this approximation is an excellent one; i.e., for $\nu_r=1.5$ and $\Gamma=0.4$, $\nu_0=652$. The pion radius corresponding to these parameters is $\langle r_\pi{}^2\rangle=0.44$.

Since the pion form factor is closely related to the pion-pion scattering amplitude in the $J=1$, $I=1$ state [see Eqs. (10) and (11) of L], one can calculate the cross section which would be implied by the above results if there were no scattering in other states. The total cross section for $\pi^+-\pi^-$ scattering calculated under these hypotheses is shown in Fig. 7.

IV. CONCLUSIONS

We conclude that a resonance in the $J=1$, $I=1$ state of pion-pion scattering characterized by the position $\nu_r=1.5$ and the width $\Gamma=0.4$ would give complete agreement with experiment for the isotopic-vector anomalous magnetic moment and its structure, and, with some ambiguity, for the proton charge structure. The position and width of the resonance are not very precisely determined; furthermore, the contributions of higher-mass intermediate states we have neglected will certainly have some effect on the parameters. It is, however, difficult to imagine a mechanism other than the proposed resonance that would resolve the discrepancies which existed between dispersion theory and experiment.[16]

ACKNOWLEDGMENTS

We are indebted to Dr. Geoffrey F. Chew for his advice throughout this work and to Dr. Stanley Mandelstam, Dr. Sidney Drell, and Dr. Marshall Baker for helpful discussions. We also thank Mr. Michael Lourié for carrying out the numerical calculations on the IBM-650 computer.

[16] For an analysis of these discrepancies see S. D. Drell, *1958 Annual International Conference on High-Energy Physics at CERN*, edited by B. Ferretti (CERN, Geneva, 1958).

PHYSICAL REVIEW VOLUME 117, NUMBER 6 MARCH 15, 1960

Electron-Neutrino and Electron-Antineutrino Scattering

R. W. KING* AND D. C. PEASLEE†
Purdue University,‡ Lafayette, Indiana

AND

J. F. PERKINS
Lockheed Aircraft Corporation, Marietta, Georgia

(Received October 12, 1959)

Cross sections for electron-neutrino and electron-antineutrino scattering are given as a function of recoil electron energy, averaged over a reactor spectrum of antineutrinos.

If it ultimately becomes feasible to observe elastic electron-neutrino and electron-antineutrino scattering, the observation must depend on the ionization produced by the recoil electron. The following note estimates relevant cross sections and energy distributions.[1]

The conventional assumption of a universal Fermi interaction with lepton conservation and two-component neutrinos would yield a neutrino-electron interaction of the form

$$H=g\{\bar{\psi}_e\gamma_\mu(1-\gamma_5)\psi_\nu\}\{\bar{\psi}_\nu\gamma_\mu(1-\gamma_5)\psi_e\} \quad (1a)$$

$$=g\{\bar{\psi}_e\gamma_\mu(1-\gamma_5)\psi_e\}\{\bar{\psi}_\nu\gamma_\mu(1-\gamma_5)\psi_\nu\} \quad (1b)$$

$$=-g\{\bar{\psi}_e\gamma_\mu(1-\gamma_5)\psi_e\}\{\bar{\psi}_{\bar{\nu}}\gamma_\mu(1+\gamma_5)\bar{\psi}_{\bar{\nu}}\}. \quad (1c)$$

Fierz transposition leads from Eq. (1a) to (1b); and Eq. (1c) is appropriate to antineutrino-electron scattering, as would be induced by the flux from a reactor. The cross section from Eq. (1c) for an electron at rest is

$$d\sigma=(8/\pi)(\mathrm{gm})^2N^{-3}(N+1-E)(E-1)dE, \quad (2)$$

* Present address: Australian National University, Canberra, A.C.T., Australia.
† Assisted by the Air Force Office of Scientific Research.
‡ Alfred P. Sloan Research Foundation Fellow.

[1] Only elastic scattering is considered; the inelastic process $\bar{\nu}+e\rightarrow\mu+\bar{\nu}$ has a threshold of order $\mu^2/2m\approx10$ Bev, and it is difficult to imagine sources for such energetic neutrinos and antineutrinos with measurable intensity.

where N, E are the antineutrino and recoil electron energies in units of mc^2, the electron rest energy and $(8/\pi)(\mathrm{gm})^2 = 1.8\times 10^{-44}$ cm².

At a fixed recoil energy the effective partial cross section for antineutrinos from a reactor is

$$y(E)=\int_{N_0}^{\infty}\left(\frac{d\sigma}{dE}\right)P(N)dN, \qquad N_0=\tfrac{1}{2}[E-1+(E^2-1)^{\frac{1}{2}}], \tag{3}$$

where the neutrino energy distribution is $P(N)$, normalized to $P(N)dN=6.1$, the average number of neutrinos per fission in a reactor. Figure 1 shows $y(E)$ with this normalization for two extremes of reactor spectrum.[2] Mean cross sections for energy transfer to the electrons are

$$\langle\sigma E\rangle = mc^2\int_1^{\infty}(E-1)y(E)dE = 1.3\pm 0.1\times 10^{-44}\ \mathrm{cm^2\ Mev},$$
$$\langle\sigma E^2\rangle = (mc^2)^2\int_1^{\infty}(E-1)^2 y(E)dE = 2.0\pm 0.2\times 10^{-44}\ \mathrm{cm^2\ Mev^2}. \tag{4}$$

The uncertainties in Eq. (4) reflect the spread between the curves of Fig. 1.

If electron scattering could be observed from the neutrinos emitted in thermonuclear reactions, Eq. (1b) would obtain with a corresponding cross section

$$d\sigma=(8/\pi)(\mathrm{gm})^2N^{-1}(N+1-E)^{-1}(E-1)dE. \tag{5}$$

For fixed E the cross section (5) is much larger than (2) near the threshold $N=N_0$; the two become identical as $N\rightarrow\infty$.

It may be of interest to compare these conclusions with those obtainable from a generalized type of universal Fermi interaction[3] without lepton conservation

$$\begin{aligned}H=ig(&[\{\bar\psi_e\gamma_\eta(1-\gamma_5)\psi_\mu\}-\{\bar\psi_\mu\gamma_\eta(1-\gamma_5)\psi_e\}]\\&\times[j\{\bar\psi_\nu\gamma_\eta\gamma_5\psi_\nu\}-j'\{\bar\psi_\lambda\gamma_\eta\gamma_5\psi_\lambda\}]\\&+2[\{\bar\psi_\mu\gamma_\eta(1-\gamma_5)\psi_\mu\}-jj'\{\bar\psi_e\gamma_\eta(1-\gamma_5)\psi_e\}]\\&\times[\bar\psi_\lambda\gamma_\eta\psi_\nu]),\end{aligned} \tag{6}$$

where $j^2=j'^2=1$ and λ, ν are independent, Majorana neutrinos. The μ-e decay process given by the first term of Eq. (6) is indistinguishable from the conventional one by any measurement on μ or e. The e-ν scattering term looks different at first sight, but it must be remembered that the neutrinos causing the reaction are 100% polarized in a sense depending on their source (fission or fusion). Thus in Eq. (6) one must accordingly put $\psi_\nu\rightarrow\frac{1}{2}(1\pm\gamma_5)\psi_\nu$, although without implying any lepton conservation thereby. The resulting cross sections are then just (2) and (5); thus is another example of the feature remarked in reference 3 that even if lepton conservation is explicitly denied as a principle, it happens that 100% neutrino polarization makes all β-decay processes behave as if lepton conservation obtained.

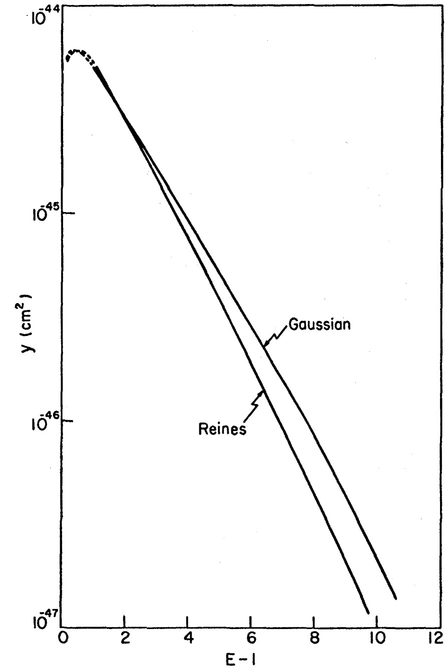

FIG. 1. Average cross section for reactor antineutrino scattering as function of recoil electron energy (Emc^2). Curves "Gaussian" and "Reines" are notation of reference 2.

The values of j and j' in Eq. (6) are not known *a priori*. In particular, it would be possible to take linear combinations involving different $j, j'=\pm 1$ in order to eliminate the e-ν scattering terms entirely while retaining those for μ-e decay. For the purposes of this scheme an experimental check on the magnitude of Eq. (2) would be of real interest.

[2] R. W. King and J. F. Perkins, Phys. Rev. **112**, 963 (1958).
[3] D. C. Peaslee, Phys. Rev. **117**, 873 (1960).