[2] R. A. Swanson *et al.*, Bull. Am. Phys. Soc. Ser. II, **2**, 205 (1957).
[3] J. M. Cassels *et al.*, University of Liverpool (to be published).
[4] J. I. Friedman and V. L. Telegdi, Phys. Rev. **106**, 1290 (1957).
[5] G. Goertzel, Phys. Rev. **70**, 897 (1946).
[6] The Columbia emulsion group, upon suggestion of Garwin, Lederman, and Sachs, has verified by direct track measurements an increase in $-a$ in an emulsion exposed in 9 kilogauss. Independently, the same effect has been observed by Barkas' group at Berkeley. We thank Dr. Barkas and Dr. Orear for preprints. [See J. Orear *et al.*, Phys. Rev. **107**, 323 (1957); W. H. Barkas *et al.*, Phys. Rev. **107**, 911 (1957).]
[7] In this case one gets for the spin expectation value

$$\langle\sigma_z\rangle=(1-x)+x[\tfrac{1}{2}(1+2\alpha^2)/(1+\alpha^2)]^n,$$

where x=fraction of μ's depolarized, α=electron cyclotron frequency/muonium hyperfine frequency, and n=number of muonium formations.
[8] The application of an external field to prevent the relaxation of polarized Li^8 nuclei has recently been made by M. T. Burgy *et al.*, Bull. Am. Phys. Soc. Ser. II, **2**, 206 (1957).

Scattering of Longitudinally Polarized Fermions with Anomalous Magnetic Moments*

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(Received July 17, 1957)

In a recent paper[1] by the author, scattering of longitudinally polarized fermions obeying Dirac's equation was described. The present note concerns itself with the generalization required if the fermions possess anomalous magnetic moments, i.e., obey the following equation

$$[\gamma_\nu(p_\nu-eA_\nu)+\tfrac{1}{2}\mu\gamma_\tau\gamma_\tau F_{\nu\tau}-im]\psi=0, \qquad (1)$$

where μ is the anomalous magnetic moment and $F_{\nu\tau}$ is the electromagnetic field intensity tensor:

$$F_{\nu\tau}=\partial A_\tau/\partial x_\nu-\partial A_\nu/\partial x_\tau. \qquad (2)$$

The matrix element M for the scattering of two such fermions is given by

$$\begin{aligned}M=&4\pi(k\cdot k)^{-1}\\&\times[\bar{u}_{\epsilon_1'}(p_1')(e_1\gamma_\nu+\tfrac{1}{2}i\mu_1\gamma_\nu k-\tfrac{1}{2}i\mu_1 k\gamma_\nu)u_{\epsilon_1}(p_1)]\\&\times[\bar{u}_{\epsilon_2'}(p_2')(e_2\gamma_\nu-\tfrac{1}{2}i\mu_2\gamma_\nu k+\tfrac{1}{2}i\mu_2 k\gamma_\nu)u_{\epsilon_2}(p_2)], \qquad (3)\\&k\equiv p_1'-p_1=-(p_2'-p_2),\end{aligned}$$

where the primed (unprimed) momenta and polarizations refer to the final (initial) state of the system and the subscripts 1 and 2 serve to distinguish the two particles.

The differential scattering cross section $\phi(\epsilon_1\epsilon_2)$ for given polarizations ϵ_1 and ϵ_2 of the initial state and summed over the polarizations ϵ_1' and ϵ_2' of the final state is

$$\begin{aligned}\phi(\epsilon_1\epsilon_2)=&E_1E_2(E_1'E_2')^{-1}(E_1+E_2)^{-2}(k\cdot k)^{-2}d\Omega\\&\times(e_1^2A_{\nu\tau}+ie_1\mu_1B_{\nu\tau}+\mu_1^2C_{\nu\tau})\\&\times(e_2^2A_{\nu\tau}'+ie_2\mu_2B_{\nu\tau}'+\mu_2^2C_{\nu\tau}'), \qquad (4)\end{aligned}$$

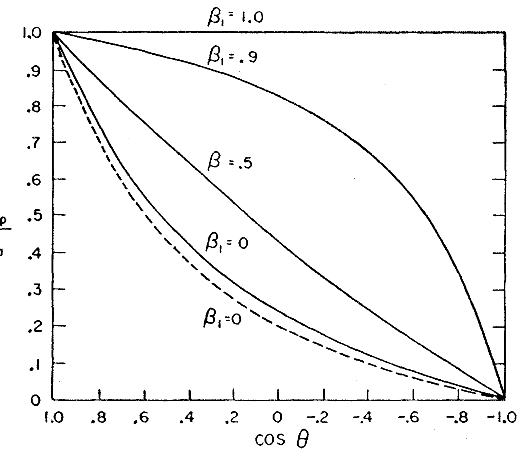

Fig. 1. The ratio ϕ_p/ϕ_a for μ-meson–neutron (solid curves) and electron-neutron (dashed curve) scattering. The neutron's velocity β_1 and the scattering angle θ are measured in the center-of-mass frame.

where

$$A_{\nu\tau}=\tfrac{1}{4}\,\mathrm{Tr}[(p_1'+im_1)\gamma_\nu(1+\epsilon_1\sigma_{p1})(p_1+im_1)\gamma_\tau], \qquad (5)$$

$$\begin{aligned}B_{\nu\tau}=\tfrac{1}{8}\,\mathrm{Tr}[&(p_1'+im_1)(\gamma_\nu k-k\gamma_\nu)(1+\epsilon_1\sigma_{p1})(p_1+im_1)\gamma_\tau\\&-(p_1'+im_1)\gamma_\nu(1+\epsilon_1\sigma_{p1})(p_1+im_1)(\gamma_\tau k-k\gamma_\tau)], \qquad (6)\end{aligned}$$

$$\begin{aligned}C_{\nu\tau}=\tfrac{1}{16}\,\mathrm{Tr}[&(p_1'+im_1)(\gamma_\nu k-k\gamma_\nu)\\&\times(1+\epsilon_1\sigma_{p1})(p_1+im_1)(\gamma_\tau k-k\gamma_\tau)], \qquad (7)\end{aligned}$$

and $A_{\nu\tau}'$, $B_{\nu\tau}'$, $C_{\nu\tau}'$ are obtained from above by replacing the subscript 1 by 2.[2] We evaluate these traces in the center-of-mass frame of reference in a coordinate system whose z axis is parallel to $\mathbf{p}_2$ and whose x-z plane coincides with the $\mathbf{p}_2-\mathbf{p}_2'$ plane

$$\begin{aligned}e_1^2A_{\nu\tau}&+ie_1\mu_1B_{\nu\tau}+\mu_1^2C_{\nu\tau}\\&=\tfrac{1}{2}e_1^2l_\rho l_\kappa\{[1-(g_1^2b)(2m_1^2)^{-1}]\delta_{\rho\nu}\delta_{\kappa\tau}\\&+i\epsilon_1(1+g_1)\delta_{\rho x}(\delta_{\kappa\nu}\delta_{y\tau}-\delta_{y\nu}\delta_{\kappa\tau})\}\\&-\tfrac{1}{2}e_1^2(1+g_1)^2(2b\delta_{\rho\kappa}+k_\rho k_\kappa)\\&\qquad\times[\delta_{\rho\nu}\delta_{\kappa\tau}+i\epsilon_1\delta_{\rho x}(\delta_{\kappa\nu}\delta_{y\tau}-\delta_{y\nu}\delta_{\kappa\tau})], \qquad (8)\end{aligned}$$

where $l\equiv p_1'+p_1$, $b\equiv p_1'\cdot p_1+m_1^2$, and g_1 is the anomalous magnetic moment in magneton units, i.e., $\mu_1\equiv e_1g_1/2m_1$.

The expression for the cross section obtained by introducing Eq. (8) (and the corresponding expression for particle "2") into Eq. (4) is too general for our purposes. We consider the following special cases:

1. Particle "1" is neutral but has an anomalous magnetic moment; particle "2" is charged but has no anomalous moment. This case describes neutron-electron and, presumably,[3] neutron-μ-meson scattering. Equation (4) becomes

$$\begin{aligned}\phi(\epsilon_1\epsilon_2)=\frac{1}{2}\left(\frac{e_2e_1g_1}{E_1+E_2}\right)^2\frac{d\Omega}{1-\cos\theta}[&r^2+2(1+\epsilon_1\epsilon_2)\\&+(\gamma_1\gamma_2r+\gamma_1^2-\tfrac{3}{2}-\epsilon_1\epsilon_2)(1+\cos\theta)]. \qquad (9)\end{aligned}$$

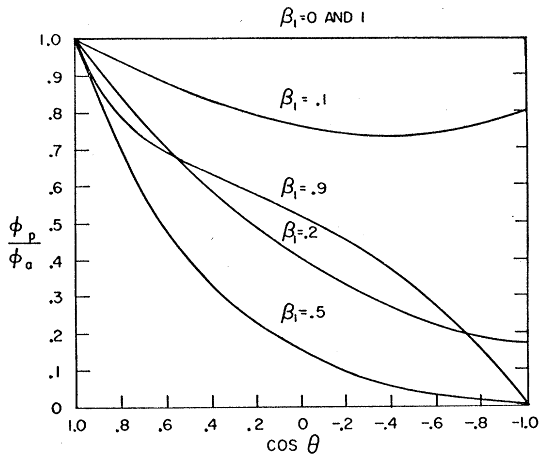

FIG. 2. The ratio ϕ_p/ϕ_a for μ-meson–proton scattering.

Here $r=m_2/m_1$, $\gamma_i=E_i/m_i$, and $\theta=$ the scattering angle. The cross section ϕ_p (ϕ_a) for spins initially parallel (antiparallel) is obtained by setting $\epsilon_1\epsilon_2=-1$ $(+1)$. In Fig. 1 the ratio ϕ_p/ϕ_a is plotted for a number of values of the neutron velocity β_1, for the neutron–μ-meson system. For the neutron-electron system the center-of-mass frame is for all practical purposes identical with the neutron's rest frame; accordingly, for this system, only the case when $\beta_1=0$ is plotted.

2. Particle "1" is charged and has an anomalous moment; particle "2" is charged but has no anomalous moment. This case describes proton-electron and proton–μ-meson scattering. Equation (4) becomes

$$\phi(\epsilon_1\epsilon_2)=\frac{1}{2}\left(\frac{e_1e_2}{E_1+E_2}\right)^2\left(\frac{d\Omega}{b^2}\right)$$
$$\times\left\{(2a^2-2ab+bm_1^2)\left(1-\frac{g_1^2b}{2m_1^2}\right)+b(b+m_2^2)(1+g_1)^2\right.$$
$$\left.+\epsilon_1\epsilon_2(1+g_1)b[b(1+g_1)+a(1+\cos\theta)]\right\},\quad(10)$$

where $a=p_1\cdot p_2=p_1'\cdot p_2'$. The ratio ϕ_p/ϕ_a obtained from Eq. (10) is plotted in Fig. 2. It is seen that ϕ_p equals ϕ_a in both the nonrelativistic and extreme relativistic limits. The energy at which ϕ_p/ϕ_a attains its minimum value depends on the scattering angle; it is approximately given by[4]

$$\gamma_1^2=1+(1/g_1).\quad(11)$$

In conclusion we note that Eq. (11) provides an estimate of center-of-mass energies required to make the scattering method work as an analyzer of polarization. Thus for the μ-meson–electron system ($g_1=0$) one needs very high energies, for the μ-meson–proton system ($g_1\simeq1.8$) one needs intermediate energies, and for the μ-meson (or electron)-neutron system ($g_1=\infty$) very low energies are sufficient.

The author wishes to thank Dr. M. Goldhaber for suggesting this calculation.

* Work performed under the auspices of the U. S. Atomic Energy Commission.

[1] A. M. Bincer, Phys. Rev. **107**, 1431 (1957). We follow here the notation and definitions of that paper.

[2] Note that this implies replacing $\boldsymbol{k}$ by $-\boldsymbol{k}$ [see Eq. (3)].

[3] Recent experiments indicate that the anomalous magnetic moment of the μ meson is, like that of the electron, negligible [T. Coffin *et al.*, Phys. Rev. **106**, 1108 (1957)].

[4] Equation (11) is exact for $\cos\theta=-1$ and it is valid for positive g_1 only. For negative g_1 the situation is more complicated; for example, $g_1=-1$ (which corresponds to a total magnetic moment zero) gives, of course, no polarization effects at any energy.

Polarization of Recoil Protons in Pion-Proton Scattering*

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(Received July 10, 1957)

TWO or more Fermi-type phase shift solutions have been found at various energies above the $T=\frac{3}{2}$ state resonance. The accidental character of this ambiguity has been discussed,[1] and its nature is reviewed briefly below in (c). If accurate charge-exchange differential cross sections become available, they may be able to discriminate between these solutions, but it is possible that the ambiguity will persist. The purpose of this note is to indicate that the ambiguity can be resolved by a feasible measurement of the recoil-proton polarization.

The proton polarization in the $T=\frac{3}{2}$ state has previously been given explicitly in terms of the phase shifts by Fermi[2] and Hayakawa *et al.*[3] They pointed out that the polarization would remove the ambiguity arising from changing the sign of all the phase shifts simultaneously, and also remove the two ambiguities indicated by Yang and Minami. There is now evidence from Coulomb interference and dispersion relations which supports only the Fermi-type phase shifts.[4,5] However, the accidental ambiguity mentioned above can also be resolved by polarization measurements.

We have analyzed the pion-nucleon scattering in the 100–300 Mev region.[1] The main conclusions are the following.

(a) The Fermi-type δ_{33} has a resonance at 187 ± 2 Mev.

(b) Below resonance $\delta_{31}\approx-5°$, $0\lesssim\delta_{13}\lesssim5°$, $-3°\lesssim\delta_{11}\lesssim0$, and both δ_1 and δ_3 are close to the straight-line extrapolation from low-energy data.

(c) Above resonance two solutions appear. This is due to the occurrence of two roots of the quartic equations which, accidentally, are approximately equal for negative and charge-exchange scattering. One solution [labeled (i) in reference 1] corresponds to $\delta_{13}\approx\delta_{31}$, but