ELASTIC ELECTRON-DEUTERON SCATTERING AND VIOLATION OF CP-INVARIANCE

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The cross section for elastic scattering of electrons by deuterons is derived. The contribution of the T-noninvariant form factor of the deuteron current is discussed in the light of experimental data. Polarization experiments are considered, which could detect the T-noninvariant form factor via the asymmetry of the angular distribution and the polarization of the recoil deuterons.

1. INTRODUCTION

BERNSTEIN, Feinberg, and Lee (abbreviated BFL)[1] have advanced the hypothesis of violation of C- and T-invariance of the electromagnetic interaction of hadrons. It was shown that it is possible to introduce a T-noninvariant interaction into an electromagnetic vertex containing scalar or spinor particles with different masses.

In the present paper it is shown that a T-noninvariant interaction can be introduced into the electromagnetic vertex of an arbitrary particle of spin $j \geq 1$.[2)] The general form of the contribution to elastic scattering of electrons by particles of arbitrary spin is derived in the one-photon approximation. In the simplest case of a particle of spin $j = 1$, the cross section in the presence of T-noninvariant terms is compared with the elastic scattering of electrons by deuterons. The results indicate a possibility of explaining the discrepancy between the experimental and theoretical data.

2. PARAMETRIZATION OF THE CURRENT AND T-INVARIANCE

If one foregoes T-invariance in electromagnetic interactions, there appear additional terms in the matrix elements of the current. Such additional terms appear in the one-particle matrix elements of any particle of spin $j \geq 1$. Thus one can look for T-violation not only in decay experiments (as proposed by BFL) but also in elastic scattering of particles of spin $j \geq 1$.

Indeed, the general form of the parametrized one-particle matrix element of the conserved electromagnetic current operator is defined by [3]:

$$\langle \mathbf{P}', \varkappa, j, m' | J_\mu(x) | \mathbf{P}, \varkappa, j, m\rangle = \frac{\exp\{iq_\lambda x_\lambda\}}{(2\pi)^3\sqrt{4P_0P_0'}} \sum_{m''} D^j_{m'm''}(\mathbf{P}, \mathbf{P}') \times \left\langle m'' \middle| F_1K_\mu + \frac{i}{\varkappa^2}F_2R_\mu + q^2F_3\Gamma_\mu' \middle| m \right\rangle, \tag{1}$$

$$K_\mu = P_\mu + P_\mu', \qquad q_\mu = P_\mu - P_\mu',$$

$$R_\mu = \varepsilon_{\mu\nu\lambda\sigma}P_\nu' P_\lambda \Gamma_\sigma(\mathbf{P}),$$

$$F_i = \sum_k f_{ik}(q^2)\left[\frac{iP_\lambda'\Gamma_\lambda(\mathbf{P})}{\varkappa\sqrt{1+q^2/4\varkappa^2}}\right]^k,$$

$$\mathbf{\Gamma}(\mathbf{P}) = \varkappa\mathbf{j} + \mathbf{P}\frac{(\mathbf{Pj})}{P_0+\varkappa}, \qquad \Gamma_0(\mathbf{P}) = (\mathbf{Pj}),$$

$$\Gamma_\mu' = \Gamma_\mu(\mathbf{P}) - \left[\frac{q_\mu}{q^2} + \frac{K_\mu}{K^2}\right]P_\lambda'\Gamma_\lambda(\mathbf{P}). \tag{2}$$

Here $\mathbf{P}$, $\mathbf{P}'$, m, and m′ are the momenta and spin projections on the z axis of a particle of mass κ, and $f_{ik}(q^2)$ are the relativistically invariant form factors for a particle of spin j. Equations (1) and (2) were derived from covariance considerations of the current operator only. Hermiticity of the current implies that the $f_{ik}(q^2)$ are real. P- and T-invariance of the current forbid form factors with odd indices k both in F_1 and in F_2. Therefore the sum in F_1 is over the range $2j \geq k \geq 0$, and in F_2 over the range $2j - 1 \geq k \geq 0$, even k only. In F_3, P-invariance imposes summation over odd k in the range $2j - 1 \geq k \geq 1$, and the other form factors in F_3 are T-noninvariant. They contribute T-noninvariant terms in the elastic scattering cross sections of particles with $j \geq 1$.

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2)Similar considerations have been put forward by Kobzarev et al.[2]

3. THE ONE-PHOTON APPROXIMATION AND THE CROSS SECTION FOR ed SCATTERING

It is well known (cf., e.g., [4]) that the one-photon character of the exchange implies the following angular dependence of the cross section for scattering of electrons on particles with arbitrary spin in the laboratory system:

$$\frac{d\sigma}{d\Omega} = \left(\frac{d\sigma}{d\Omega}\right)_{\text{Mott}} \left\{A(q^2) + B(q^2)\operatorname{tg}^2\frac{\theta}{2}\right\}. \qquad (3)^*$$

Under the assumption of T-invariance, expressions have been derived in [5, 6] for the functions $A(q^2)$ and $B(q^2)$ in terms of electric and magnetic form factors of the particles. In this case $B(q^2)$ involves only the magnetic form factors, whereas $A(q^2)$ involves both types. The contribution to the cross section from the T-noninvariant family of form factors $f_{3,2n+1}(q^2)$ vanishes for $j = 0, 1/2$, and for $j \geq 1$

$$\left(\frac{d\sigma}{d\Omega}\right)_T = \left(\frac{d\sigma}{d\Omega}\right)_{\text{Mott}} \frac{\xi^3}{1+\xi}\left[1 + 2(1+\xi)\operatorname{tg}^2\frac{\theta}{2}\right] \qquad (4)$$

$$\times \left\{\sum_k \Phi_{3k}(j)\,\xi^{k/2} f_{3k}(q^2)\right\}^2, \qquad \xi = \frac{q^2}{4\varkappa^2}$$

The functions $\Phi_{3k}(j)$ depends only on the values j of the spin of the particle.

Thus, in the simplest case $j = 1$ (for definiteness we call such particles deuterons) the cross section for elastic ed scattering is

$$\frac{d\sigma}{d\Omega} = \left(\frac{d\sigma}{d\Omega}\right)_{\text{Mott}} \left\{f_{10}^2(q^2) + \frac{32}{3}\xi^2 f_{12}^2(q^2)\right.$$

$$+ \frac{2}{3}\xi\left[1 + 2(1+\xi)\operatorname{tg}^2\frac{\theta}{2}\right]$$

$$\left.\times\left[f_{20}^2(q^2) + \frac{16\xi^2}{1+\xi} f_{31}^2(q^2)\right]\right\}. \qquad (5)$$

The family of form factors $f_{3,2n+1}(q^2)$ defines the so-called magnetic multipoles of the second kind.[7, 8] Thus, the value of the form factor $f_{31}(q^2)$ in (5) can be directly expressed, for $q^2 = 0$, in terms of the quadrupole magnetic moment of the second kind M_2^{II}:

$$f_{31}(0) = {}^9/_2\varkappa^2 M_2^{\text{II}}, \qquad (6)$$

where

$$\delta^3(\mathbf{q}) M_2^{\text{II}} = \langle jj|M_{zz}^{\text{II}}|jj\rangle, \quad j = 1,$$

$$\langle|M_{ik}|\rangle = \frac{1}{18}\int d^3x\,[2x_i x_k \mathbf{x}\langle|\mathbf{J}|\rangle$$

$$- \mathbf{x}^2(x_i\langle|J_k|\rangle + x_k\langle|J_i|\rangle)]. \qquad (7)$$

*tg = tan.

4. COMPARISON WITH EXPERIMENT

We try to evaluate the upper limit of the contribution which might come from the fourth form factor, making use of the latest experiments on elastic ed scattering.[9] In this experiment, the relationship (3) was tested in the momentum transfer interval $q^2 = (6.0-20.0)\ \text{F}^{-2}$ for three scattering angles and $B(q^2)$ came out significantly larger than the value calculated on the basis of the impulse approximation (the maximum deviation was by a factor of two at $q^2 = 12\,\text{F}^{-2}$). Since relativistic effects cannot be essential for the momentum transfers under consideration, Buchanan and Yearian[9] have attempted to explain the discrepancy in terms of the Adler-Drell[10] exchange currents. However doubts arise as to this interpretation, since theoretical considerations (unitary symmetry)[11] and analysis of experimental data on photoproduction[12] tend at present to a significant lowering of the photoproduction coupling constant of the ρ meson $g_{\gamma\pi\rho}$.

If the hypothesis that T-invariance is violated is true for electromagnetic interactions, one might consider the fourth term in (5) responsible for the indicated discrepancy. Then the experiments imply that the contribution from the term with $f_{31}(q^2)$ in $B(q^2)$, in the indicated q^2-interval, is of the same order as the contribution from the term with $f_{21}(q^2)$. Hence, for $q^2 \approx 12\ \text{F}^{-2}$ it follows that $f_{31} \sim 1$.

The contribution to $A(q^2)$ from both families of magnetic form factors is small compared to the electric form factors and therefore the experimental and theoretical data for $A(q^2)$ are in fair agreement. In principle one could, on the basis of more precise experimental data and a larger number of experimental points, derive the q^2 dependence of the magnetic form factor of the second kind from elastic ed-scattering experiments.

5. EXPERIMENTS WITH POLARIZED DEUTERONS

It is however clear, that an exact verification of the proposed hypothesis is possible in experiments with polarized particles. There is a possibility of singling out the contribution of the form factor $f_{31}(q^2)$ in the cross section for scattering of unpolarized electrons on polarized deuterons, in terms of the angle asymmetry:

$$\left|\left(\frac{d\sigma}{d\Omega}\right)_{\text{left}} - \left(\frac{d\sigma}{d\Omega}\right)_{\text{right}}\right| = \left(\frac{d\sigma}{d\Omega}\right)_{\text{Mott}}$$

$$\times\ 16 f_{12} f_{31}\xi^2\left(\frac{\xi}{\eta} + \xi\operatorname{tg}^2\frac{\theta}{2}\right)^{1/2} B_i, \qquad (8)$$

where B_i is the deuteron target polarization normal to the scattering plane.

The proposed polarization experiment can be inverted, i.e., one could measure the recoil deuteron polarization for scattering of an unpolarized beam on an unpolarized target. In this case the polarization vector of the deuterons will be normal to the plane of scattering and will have the value

$$\mathbf{B}_f = \frac{16}{3}\frac{(d\sigma/d\Omega)_{\text{Mott}}}{(d\sigma/d\Omega)_{\text{unpol}}}\xi^2 f_{12} f_{31}\left(\frac{\xi}{\eta}+\xi\,\mathrm{tg}^2\frac{\theta}{2}\right)^{1/2}\mathbf{N}, \qquad (9)$$

where

$$\mathbf{N} = \mathbf{p}\times\mathbf{p}'/|\mathbf{p}\times\mathbf{p}'|,$$

and $\mathbf{p}$ and $\mathbf{p}'$ are the momenta of the electrons before and after scattering. In the point approximation, if one takes into account the estimate of the upper limit for $f_{31}(q^2)$, one obtains for $q^2 \approx 12\ \mathrm{F}^{-2}$ a polarization of approximately one percent.

Both effects disappear completely if the electromagnetic interaction is T-invariant. We note that the angle dependence of the cross sections (5) and (8) are different.

The corresponding calculations show that experiments with aligned deuterons are significantly less effective than experiments with polarized deuterons, for the detection of a T-noninvariant form factor.

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21