Recoil-deuteron vector polarization in elastic electron-deuteron scattering

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The vector polarization of the recoil deuteron in the elastic scattering of electrons on deuterons is calculated in the presence of weak-neutral-current couplings and is shown to be as large as other parity-violating effects in electron-nucleon scattering. Attempts should be made to detect experimentally this polarization which lies in the reaction plane.

Serious attempts[1] are being made to experimentally detect the presence of parity-violating weak-neutral-current couplings in electron-nucleon interaction as predicted by spontaneously broken gauge theories of weak and electromagnetic interactions.[2] While these experiments have concentrated on observing the parity-violating effects mainly in atomic transitions, there have been suggestions to look for such effects in electron-nucleon scattering at high energies where the parity-violating left-right asymmetries of the longitudinally polarized electrons and nucleons are shown to be of the order of $10^{-4}\ q^2/M^2$.[3] However, at high momentum transfers the net effects become small due to the rapid falloff of the weak and electromagnetic form factors of the nucleons. These form factors nevertheless enter in such a way that the parity-violating effects are an order of magnitude larger for neutron targets than for proton targets. It has been therefore suggested to perform the experiments with the deuteron target in order to look for the above enhanced effect.[4] Unfortunately, it is not easy to extract information on the electron-nucleon scattering from the electron-deuteron scattering data.

We therefore suggest in this paper that experimental attempts should be made to look for another observable in the elastic electron-deuteron scattering, i.e., the vector polarization of the deuteron which depends upon the presence of weak-neutral current in the electron-nucleon interaction; this polarization is zero in the one-photon-exchange approximation, and is shown to be as large as $10^{-4}q^2/M^2$ or even larger in certain models which contain an isoscalar axial-vector piece in the hadronic neutral weak current. Experimental observation of such an effect would establish the existence of parity-violating neutral weak currents in the electron-nucleon interactions.

By expressing the scattering amplitude A for the elastic electron-deuteron scattering written in impulse approximation as

$$A=\sum_j e^{i\vec{q}\cdot\vec{r}_j}(i\vec{\sigma}_j\cdot\vec{K}+L)\,, \tag{1}$$

where $\vec{\sigma}_j$ is the Pauli spin operator for the jth nucleon, $\vec{r}_j$ is the position operator of the jth nucleon, $\vec{q}$ is the momentum transfer given to the deuteron, and $\vec{K}$ and L are the isoscalar interaction amplitudes, it can be shown that the vector polarization of the recoil deuteron is given by[5,6]

$$\vec{P}=\frac{iB(L\vec{K}^*-L^*\vec{K})+iC\vec{K}\times\vec{K}^*}{\alpha LL^*+\beta\vec{K}\cdot\vec{K}^*+\gamma\,|\vec{K}\cdot\hat{q}\,|^2}\,, \tag{2}$$

where B, C, α, β, and γ are various linear combinations of the radial integrals involving S- and D-wave wave functions of the deuteron for which the explicit expression can be found in Ref. 6. The $\vec{K}$ and L amplitudes can be calculated by performing a nonrelativistic reduction of the total convariant nucleon matrix elements including γ and z exchanges. The matrix element for the one-photon-exchange diagram is taken to be of the standard form, i.e.,

$$\mathfrak{M}^{\gamma}\sim e^2\bar{u}(k')\gamma_\mu u(k)\,\frac{1}{q^2}\,\bar{u}(p')[F_1(q^2)\gamma^\mu+iF_2(q^2)\sigma^{\mu\nu}q_\nu/2\mu]u(p)\,, \tag{3}$$

while the most general form is taken for the Z-exchange diagram to be[7]

$$\mathfrak{M}^{z}\sim\frac{G}{\sqrt{2}}\,\bar{u}(k')\gamma_\mu(a-b\gamma_5)u(k)\bar{u}(p')\{g_{Vj}[F_1^{(j)}(q^2)\gamma^\mu+i\,F_2^{(j)}(q^2)\sigma^{\mu\nu}q_\nu/2M]$$
$$+g_{Aj}[g_A^{(j)}(q^2)\gamma^\mu\gamma_5+h_A^{(j)}(q^2)q^\mu\gamma_5]\}\,t_j u(p)\,, \tag{4}$$

where the t_j are the SU(3) matrices given by $t_0=\frac{1}{2}(\frac{2}{3})^{1/2}$, $t_3=\frac{1}{2}\tau_3$, and $t_8=\frac{1}{2}(\frac{1}{3})^{1/2}$. The expressions for $\vec{K}$

and L are derived using standard methods[8] neglecting the nucleon momentum inside the deuteron, and the result is

$$\vec{K}=\frac{eG_{MS}(q^2)}{q^2}\frac{\vec{q}\times\vec{l}^{\,e.m.}}{2M}+\frac{G}{\sqrt{2}}\left[F_{MS}(q^2)\frac{\vec{q}_1\times\vec{l}^{\,W}}{2M}+iF_{AS}(q^2)\left(\vec{l}^{\,W}+\frac{\vec{q}}{2M}\,l_0^W\right)\right], \tag{5}$$

$$L=\frac{eG_{ES}(q^2)}{q^2}\left(l_0^{e.m.}+\frac{\vec{q}\cdot\vec{l}^{\,e.m.}}{2M}\right)+\frac{GF_{ES}(q^2)}{\sqrt{2}}\left(l_0^W+\frac{\vec{q}\cdot\vec{l}^{\,W}}{2M}\right), \tag{6}$$

where $G_{ES}(q^2)$ and $G_{MS}(q^2)$ are the usual isoscalar electric and magnetic form factors of the nucleons, and

$$\begin{aligned}
&F_{AS}(q^2)=g_{A0}g_A^{(0)}(q^2)+(\tfrac{1}{3})^{1/2}g_{A8}\,g_A^{(8)}(q^2)\,,\\
&F_{MS}(q^2)=(\tfrac{2}{3})^{1/2}g_{V0}[F_1^{(0)}(q^2)+F_2^{(0)}(q^2)]+(\tfrac{1}{3})^{1/2}g_{V8}[F_1^{(8)}(q^2)+F_2^{(8)}(q^2)]\,,\\
&F_{ES}(q^2)=[(\tfrac{2}{3})^{1/2}g_{V0}F_1^{(0)}(q^2)+(\tfrac{1}{3})^{1/2}g_{V8}F_1^{(8)}(q^2)]+\frac{q^2}{4M^2}\,[(\tfrac{2}{3})^{1/2}g_{V0}F_2^{(0)}(q^2)+(\tfrac{1}{3})^{1/2}g_{V8}F_2^{(8)}(q^2)]\,,
\end{aligned} \tag{7}$$

with $(l_0^W,\vec{l}^{\,W})=l_\mu^W=\bar{u}(k')\gamma_\mu(a-b\gamma_0)u(k)$ and $l_\mu^{e.m.}=l_\mu^W(a=1,\ b=0)$. The vector polarization of the recoil deuteron is obtained by calculating the terms $i(L\vec{K}^*-L^*\vec{K})$, $\vec{K}\times\vec{K}^*$, etc. appearing in Eq. (2) from Eqs. (6) and (7), and summing over the electron spins. The expression for the polarization is considerably simplified if we neglect the D state of the deuteron. The result up to the lowest order in q^2/M^2 is then given by[9]

$$\vec{P}=-(\tfrac{4}{3})^{1/2}\frac{GM^2}{e^2}\,a\,\frac{F_{AS}(q^2)}{G_{ES}(q^2)}\,\frac{q^2}{M^2}\,\frac{E\vec{k}'+E'\vec{k}}{EE'+\vec{k}\cdot\vec{k}'}\,. \tag{8}$$

Assuming the usual dipole form of the various form factors and some reasonable value of the isoscalar axial-vector form factors $F_A^S(0)$, (see Ref. 7), this polarization is predicted to be of the order of $10^{-3}aq^2/M^2$ in the weak-neutral-current models which have an isoscalar axial-vector piece in it. The models containing no isoscalar axial-vector piece but only the isoscalar vector piece such as the Weinberg-Salam model would predict a smaller value of this polarization given by

$$\vec{P}=(\tfrac{4}{3})^{1/2}\frac{GM^2}{e^2}\,b\,\frac{F_{ES}(q^2)G_{MS}(q^2)+F_{MS}(q^2)G_{ES}(q^2)}{G_{ES}{}^2(q^2)}\times\frac{q^2}{M^2}\,\frac{\vec{q}}{M}\times\frac{(\vec{k}\times\vec{k}')}{EE'+\vec{k}\cdot\vec{k}'}\,. \tag{9}$$

This polarization $\vec{P}$ lies in the reaction plane and does not interfere with the polarization predicted in the P-conserving, T-violating electromagnetic interaction, or the polarizations coming from the interference of one-photon and two-photon exchange diagrams (which are very small), or the polarizations arising due to a possible phase difference between the S and D waves of the deuteron wave function, as they all are in a direction perpendicular to the reaction plane.[5,10] The polarization predicted from Eq. (8) could be as large as other parity-violating effects in electron-nucleon scattering, depending upon the values of a and b in various models, and should be experimentally pursued,[11] as it does not require the use of either a polarized beam or a polarized target. These experiments would be very important in determing the space and isospin structure of the neutral weak current in electron-nucleon interactions and could prove decisive in determining the existence of some recently suggested parity-violating electromagnetic interactions[12] which would predict a larger value for this polarization; they also provide information complementary to the atomic-physics experiments,[1] as they probe (to the leading order) different pieces in the weak-neutral-current electron-nucleon interaction Hamiltonian.

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