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TEST OF TIME-REVERSAL INVARIANCE IN ELASTIC ELECTRON SCATTERING FROM THE DEUTERON*

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A test of time-reversal invariance for an electromagnetic interaction at high momentum transfer has been performed by measuring the recoil-deuteron vector polarization for the elastic scattering of electrons from an unpolarized deuteron target for an incident electron energy of 1 GeV and a recoil-deuteron four-momentum of $q = 721$ MeV/c. The value obtained for the vector polarization is $|P| = 0.075 \pm 0.088$, showing no significant T nonconservation.

The observation that $K_L{}^0$ can decay into two pions has stimulated many investigations to search for apparent CP or T nonconservation in other processes or reactions. The conjecture that the electromagnetic interactions of hadrons may be C noninvariant[1] has resulted in several proposals for tests of this hypothesis and several experiments are, in fact, in progress. These tests are quite difficult to perform to a meaningful level, and theoretical estimates for these tests are generally model dependent.[2] One such test of T invariance which has received some theoretical consideration[3] is elastic electron scattering from a nucleus with spin $>\frac{1}{2}$. In these cases, unlike the case for a spin-$\frac{1}{2}$ nucleus, there are additional form factors which violate time-reversal invariance and which are not identically required to be zero due to current conservation. These additional form factors lead to possible nonzero expectation values of T-odd correlations such as a vector polarization of the recoil nucleus. We wish to report the result of such an experiment. Specifically, we have measured the vector polarization of the recoil deuterons in the elastic scattering reaction $e^- + d \to e^- + d$ with an unpolarized target for an electron energy of 1 GeV and a recoil-deuteron four-momentum of 721 MeV/c. This reaction has the attractive feature that $\Delta I = 0$ for the isospin. The importance of testing T invariance in $\Delta I = 0$ processes has been considered by several authors.[4]

For elastic scattering from a spin-1 nucleus and with P and T conservation, the photon-nucleon vertex may be described by form factors which correspond to the charge, electric quadrupole, and magnetic dipole moments. If the requirement of T conservation is dropped, the vertex is generally described by the above three form factors plus an additional term which violates T invariance.

In terms of these form factors, the cross section for elastic e-d scattering may be written, in the first Born approximation,[3]

$$\frac{d\sigma}{d\Omega} = \frac{d\sigma}{d\Omega}\bigg|_{\text{Ruth}} [A(q^2) + B(q^2)\tan^2\tfrac{1}{2}\theta],$$

where

$$A(q^2) = F_C{}^2 + (8/9)\eta^2 F_Q{}^2 + B(q^2)/2(1+\eta)$$

and

$$B(q^2) = \tfrac{4}{3}\eta(1+\eta)(F_M{}^2 + 4\eta^2 G^2)$$

and the form factors have as their nonrelativistic limits

$$F_c(0) \to 1$$

$$F_Q(0) \to M_d^2 Q_d$$

$$F_M(0) \to (M_d/M)\mu_d,$$

where Q_d = static deuteron quadrupole moment, μ_d = deuteron magnetic moment, $\eta = q^2/4M^2$, q^2 = (four-momentum transfer)^2, M_d = mass of deuteron, θ = laboratory electron scattering angle, $\epsilon = E/M_d$, E = incident laboratory electron energy, and M = nucleon mass. The additional form factor G violates time-reversal invariance.

The vector polarization of the recoil deuterons calculated in first Born approximation is given by[3]

$$P = \frac{(8/3) G F_Q \eta^2 (\eta - \epsilon) \tan\frac{1}{2}\theta}{A + B \tan^2\frac{1}{2}\theta}.$$

All four form factors are real numbers since the current operator is Hermitian and thus all phases are fixed. There can be no accidental cancellation to cause $P = 0$ if G and F_Q are different from zero. F_c and F_Q have never been separated experimentally, but since they have well-defined limits as $q^2 \to 0$, they may be numerically estimated in terms of the measured nucleon form factors. Thus a particular value of G will completely specify the polarization in first Born approximation. Limits on possible values of G may be obtained by comparing cross-section measurements with impulse-approximation predictions.

Recent e-d scattering measurements show a factor of ~2 discrepancy with the impulse-approximation calculations at $q \simeq 700$ MeV/c for the magnetic coefficient $B(q^2)$ (Rand et al.[5]). If all this difference is ascribed to the T-nonconserving form factor G, then it is possible to estimate the corresponding value of the vector polarization P. For the conditions of this experiment, this assumption gives an estimate of $P = 0.34$. T-conserving contributions to the polarization from two-photon exchange terms are expected to be negligible. This is supported by polarization measurements in e-p elastic scattering.

This experiment was performed by detecting the recoil deuterons scattered from an unpolarized liquid deuterium target and then measuring the azimuthal (left-right) asymmetry of the recoil deuterons after they scatter from a carbon target. The experimental layout is shown in Fig. 1. A 1-GeV/c electron beam from the Stanford Mark-III linear electron accelerator modulated by a 40.6-MHz rf structure passes through a 12-in.-long liquid target cell. The electron intensity is monitored by secondary emission monitors both before and after the target cell. The recoil deuterons are momentum analyzed by a 1.6-GeV/c, 100-in.-radius, 90°, $n = 0$ spectrometer set to analyze recoil deuterons with $|\vec{q}| = 735$ MeV/c at approximately 57°. The deuterons pass through a set of three defining counters and are identified by ionization, range, and time of flight with respect to the rf structure of the electron beam. The ratio of protons to deuterons at the defining counters is several hundred to one, and the above identification requirements reduce the proton contamination to essentially zero.

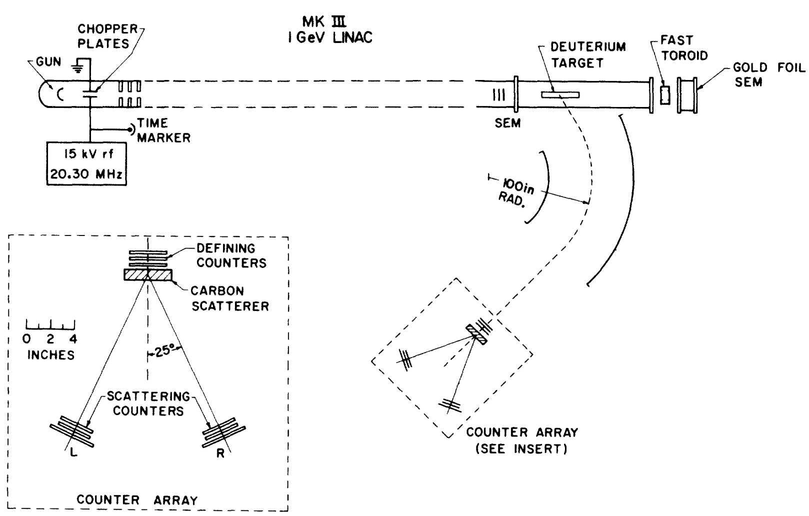

FIG. 1. Experimental layout for $e + d \to e + d$ polarization measurement.

The acceptance of the defining counters is $\Delta P/P=2.66\times10^{-2}$, $\Delta\Omega=1.0$ msr, and $\Delta\theta=0.48°$. A carbon target is placed immediately behind the defining counters and the deuterons scattered from the carbon are detected by two additional sets of counters which serve to measure the left-right asymmetry of the deuterons scattered from the carbon. The left-right convention is with respect to a normal to the plane of scattering since parity conservation restricts any polarization component to $\langle\vec{S}\cdot(\vec{k}_{in}\times\vec{k}_{out})\rangle$, where $\vec{k}_{in}\times\vec{k}_{out}$ defines the scattering plane. The left-right counters are set at ±25 deg with respect to the recoil direction and have an angular acceptance of $\Delta\theta\simeq10°$.

The analyzing properties of carbon for deuteron polarization parameters have been measured in this energy region by Baldwin et al. at the Lawrence Radiation Laboratory cyclotron.[7] These measurements cover the region from 90- to 150-MeV deuterons and the thickness of the carbon target in this experiment was chosen to accept scattered deuterons from approximately this energy interval. Specifically, for 90- to 150-MeV deuterons scattered from carbon, the vector polarization analyzing power runs from 0.25 to 0.55 for the angular acceptance of this experiment. Baldwin et al. find that the analyzing power for the tensor polarization components is zero within the statistical uncertainties. This is an important point for the present experiment as will be noted below.

The left-right asymmetry of recoil deuterons scattered from the carbon target is measured for deuteron recoil angles $+\theta$ and $-\theta$. Since a vector polarization must change sign in going from $+\theta$ to $-\theta$, this serves to eliminate systematic asymmetries due to different left-right counter efficiencies. Figure 2 shows an elastic peak taken by varying the spectrometer angle. The background underneath the elastic peak is to a good approximation an angle-independent background which is believed to be primarily due to deuterons created by pickup reactions in the deuterium target and spectrometer and target slits. The background due to deuterons from the reaction $e(\gamma)+d\rightarrow\pi^0+d$ is negligible compared with the angle-independent background. The asymmetry of the background was therefore determined by measurements beyond the elastic peak at $\theta=60°$.

The left-right asymmetry A is defined in terms of the measurements by

$$A=\frac{[R(+\theta)+L(-\theta)]-[R(-\theta)+L(+\theta)]}{[R(+\theta)+R(-\theta)+L(+\theta)+L(-\theta)]},$$

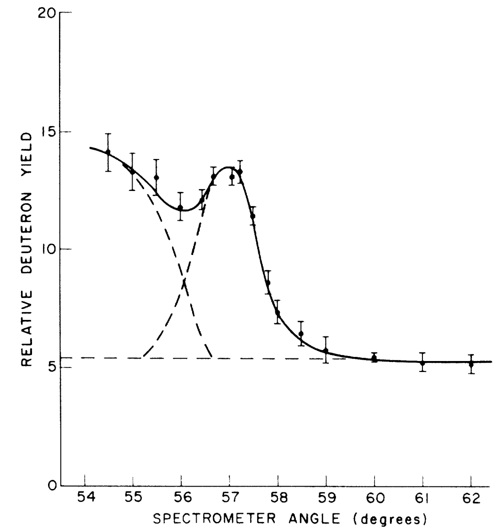

FIG. 2. Deuteron yield curve taken by varying spectrometer angle in the region of the elastic peak.

where $R(\pm\theta)$ and $L(\pm\theta)$ refer to the R-L scattering-arm rates taken at production angles $+\theta$ or $-\theta$. Measurements of A at the elastic-peak center and beyond the elastic peak were then combined to give an A for the elastic process only. The asymmetry A in terms of polarization parameters is equal to

$$A=(\sqrt{3}P\langle iT_{ll}'\rangle+\delta)/(1+\Delta),$$

where $\delta=-2\langle T_{21}\rangle\times\langle T_{21}'\rangle$ (Lakin[8]). P is the T-nonconserving vector polarization and $\langle iT_{11}'\rangle$ is the vector polarization analyzing power for d-carbon scattering. The terms δ and Δ are a consequence of T-conserving terms arising from the recoil-deuteron tensor polarization. $\langle T_{21}\rangle$ is such a deuteron tensor polarization and $\langle T_{21}'\rangle$ is the corresponding analyzing power for this term in carbon. The experiment of Baldwin et al.[7] measured the $\langle T_{2i}'\rangle$ parameters of d-carbon scattering with the exception of $\langle T_{21}'\rangle$, which was not experimentally separated from $\langle iT_{11}'\rangle$. However, the authors reason that $\langle T_{21}'\rangle$ is zero since the measured $\langle T_{2i}'\rangle$ terms are zero within the experimental accuracy. The assumption that $\langle T_{21}'\rangle\cong0$ is justified on several grounds:

(1) Optical-model calculations[9] for d-carbon scattering show that $\langle T_{2i}'\rangle$ terms are small in the region of interest and indicate that $\langle T_{21}'\rangle$ is generally less than $\frac{1}{2}$ to $\frac{1}{3}$ the size of the other $\langle T_{2i}'\rangle$ components. Since, experimentally, the $\langle T_{2i}'\rangle$ terms are measured to be zero it seems quite reasonable to assume that $\langle T_{21}'\rangle\cong0$.

(2) A strict first Born-approximation calcula-

tion of d-carbon scattering shows that $\langle T_{21}'\rangle = 0$ (Ref. 7). Thus both optical-model calculations and Born approximation suppress $\langle T_{21}'\rangle$ with respect to the other $\langle T_{2i}'\rangle$ terms.

The recoil-deuteron tensor term $\langle T_{21}\rangle$ may be estimated for the conditions of this experiment using the results of Schildknecht.[10] We thus find that $\langle T_{21}\rangle \cong 0.26$. Combining this with the experimental limits on the measured tensor analyzing power terms of Baldwin et al., we estimate that δ has an upper limit of ± 0.05. In addition, $\Delta \ll 1$. Thus, we conclude that the measured left-right asymmetry of the recoil deuterons from the elastic peak is equal to

$$A \cong \sqrt{3} P \langle iT_{11}'\rangle + \delta,$$

where P is a possible T-nonconserving vector polarization and δ is a small term arising from T-invariant effects, which we believe to be consistent with zero to an uncertainty of $\leq \pm 0.05$. This uncertainty is less than the overall precision of the experiment; and since maximal T-nonconserving effects could produce a value of P as large as ~0.40 and still be consistent with present cross-section measurements, we feel that the neglect of δ is justified. However, one should note that the contribution of T-invariant terms to the measured asymmetry A puts a natural limit on the precision of P which can be obtained with this type of experiment.

For the kinematic conditions chosen for this experiment, the elastic scattering cross section is $\sim 2\times 10^{-34}$ cm^2/sr for $q^2 = (721\ \text{MeV}/c)^2$. With an electron beam intensity of $\sim 2\times 10^{11}$ electrons/pulse and a 5-in. deuterium effective target length, the left-right arm rates at the elastic peak center are ~5 events/h. The background underneath the elastic peak is ~40% and is measured separately by measuring the quantity A beyond the kinematic limit for elastically scattered deuterons. The apparatus was also checked for systematic asymmetries by measuring A for recoil protons from e-p elastic scattering. A for this process should be zero, and the measured A was in fact zero to approximately ± 0.01 precision.

We have obtained a total of 2500 events at the elastic-peak center and 750 events taken under background conditions. These data are combined to give $A = -0.037 \pm 0.043$. In terms of a vector polarization and d-carbon analyzing power this becomes

$$P\langle iT_{11}'\rangle = -0.021 \pm 0.025.$$

The data of Ref. 7 averaged over the experimental conditions and geometry give $\langle iT_{11}'\rangle \cong 0.28$. Thus, we obtain $|P| = 0.075 \pm 0.088$ where the indicated uncertainty is statistical only. We conclude that there is no significant T nonconservation in elastic e-d scattering for $q^2 \cong (720\ \text{MeV}/c)^2$ within the limits of precision of this experiment. An interpretation of the results of this experiment, with respect to the conjectures of Ref. 1, will require estimates using specific models.

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