Observation of Isovector-Isoscalar Two-Body Currents in Deuteron Knockout from ^{3}He

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The reaction $^3\mathrm{He}(e,e'd)p$ was measured at four-momentum transfer $q = 420$ MeV, for proton recoil momentum $P_r = 22$, 54, and 62 MeV/c, in parallel deuteron kinematics. Longitudinal (L) and transverse (T) response functions were obtained by means of Rosenbluth separations. The separated response functions are, respectively, found to be dominated by the contributions of isoscalar and isovector two-body currents. The L/T ratios are about 3.5. This is an order of magnitude lower than that for elastic scattering on a free deuteron, or what would be expected for a purely isoscalar transition, but approximately agrees with what is theoretically expected for isoscalar plus isovector contributions.

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For many years, starting with the formulation of the quasideuteron model, it has been understood that two-body correlations play a very important role in nuclear structure and reactions. Two-body $p + d$ breakup is a major contributor to electron scattering and photon absorption on ^{3}He below the pion production threshold. Knockout of correlated pairs dominates this reaction at high outgoing deuteron momentum [1,2], especially at kinematics close to quasielastic deuteron scattering ($x = 2$, proton recoil momentum $P_r \sim 0$). The q^2 dependence of the cross sections closely follows that of elastic scattering from free deuterons, so that one might naively expect that the dominant mechanism involves the interaction with a correlated $T = 0$ pair (quasideuteron). However, elastic scattering from a free deuteron selects isoscalar ($T = 0$) currents, whereas the two-body currents in the $^3\mathrm{He}(e,e'd)$ reaction contain isovector ($T = 1$) and as well as isoscalar components; i.e., the virtual photon may interact with a $T = 1, S = 0$ np pair, to produce a $T = 0, S = 1$ deuteron. Both $T = 0$ and $T = 1$ currents are expected to play important roles, which would be most clearly elucidated in the separate longitudinal (L) and transverse (T) contributions to the cross section, rather than in the unseparated cross section. Initial experiments in p-shell nuclei involving transitions between specific states of isospin were reported in Refs. [3] and [4].

This Letter reports the first longitudinal-transverse (L/T) separation in the reaction $^3\mathrm{He}(e,e'd)p$ near deuteron quasielastic scattering kinematics, and a comparison with theoretical analyses, which shows the importance of both isovector and isoscalar two-body correlations. We find that the L/T ratios are drastically different from those corresponding to elastic scattering from a free deuteron, and from those expected from an interaction with a $T = 0$ pair (quasideuteron) in the nucleus. This shows that the $T = 1$ correlations play a very important role.

The experiment was performed at the MIT-Bates electron accelerator, with the MEPS and OHIPS magnetic spectrometers used to detect electrons and deuterons, respectively. The accelerator was operated in pulsed mode at a duty factor near 1%, and current typically about 10 μA. The deuterons were detected parallel to the momentum transfer. The beam energies and laboratory detector angles for forward and backward kinematics were, respectively, $E_e = 382.5$, $\theta_e = 72.0°$, and $\theta_d = 48.2°$, and $E_e = 265.3$ MeV, $\theta_e = 122.2°$, and $\theta_d = 25.5°$.

The ^{3}He target consisted of a 3.2 cm diameter vertical cylinder gas cell with walls constructed of Elgalloy, of thickness 0.1 mm, through which the target gas was continuously circulated. The operating temperature was 25 K, and the pressure was 33 atm. The target cell was collimated on the electron arm side to eliminate background from the target walls. In addition, data were obtained on gaseous deuterium (D_2), and solid targets including deuterium (CD_2), carbon, and hydrogen (CH_2), which were used for acceptance, energy calibration, and normalization studies.

$\mathrm{D}(e,e'd)$ coincidence data provided a check, and gave a small empirical correction to the overall coincidence normalization. A complete description of the experiment and analysis is given in Ref. [5], and will be provided in a forthcoming longer paper.

Single arm elastic scattering data from ^{3}He were obtained concurrently in the $(e, e'd)$ running and were used for overall normalization, using a parametrization of the world's data [6]. The uncertainty in this normalization is about 3%. The corrections in q due to Coulomb distortion of the incident and scattered electrons were taken into account [7], yielding an effective momentum transfer q_{eff}.

The resulting cross sections are presented in Table I. The quoted four-momentum transfers q $(= \sqrt{-q^2})$ and proton recoil momenta P_r are Monte Carlo averages over the events obtained at the given setting, weighted by theoretically expected variations of the cross sections over the spectrometer acceptances. The forward angle data are plotted in Fig. 1, along with the results of two theoretical calculations, an effective Lagrangian diagramatic expansion calculation [2,8], and a conserved-current gauge-invariant approach [9]. The magnitudes of the cross sections resulting from both sets of calculations are dominated by the interaction with correlated pairs, whereas the contribution of one-body processes in which the virtual photon interacts with a proton and the deuteron emerges as the recoil particle, which are included in both calculations, are small.

Physics background.—The measured cross sections in the laboratory may be expressed in terms of response functions σ_i $(i = L, T, LT, TT)$ as follows:

$$d^3\sigma/dE' d\Omega_e d\Omega_d = \Gamma d\sigma/d\Omega_d \,,$$
$$d\sigma/d\Omega_d = \sigma_T + \epsilon\sigma_L + \sqrt{\epsilon(1+\epsilon)} \times \sigma_{LT}\cos\phi + \epsilon\sigma_{TT}\cos 2\phi \,, \quad (1)$$

where

$$\Gamma = \frac{\alpha}{4\pi}\frac{E'}{E}\frac{|\vec{q}|}{-q^2}\left(\frac{1}{1-\epsilon}\right)$$

is the virtual photon flux factor and

$$\epsilon = \left(1 - 2\frac{\vec{q}^{\,2}}{q^2}\tan^2\frac{\theta}{2}\right)^{-1}$$

is the polarization parameter.

TABLE I. Cross sections obtained in the present experiment. The values of proton recoil momentum P_r and the effective momentum transfer q_{eff} are data weighted averages over the experimental acceptances of the spectrometers. The cross sections are given in the laboratory. Errors are, respectively, statistical and estimated systematic errors. The quantities in parentheses are the rms experimental acceptances $\Delta P_r \equiv 2\sigma_{P_r}$.

P_r (MeV/c)	q_{eff} (MeV/c)	$d^3\sigma/dE_e d\Omega_e d\Omega_d$ (10^{33} cm^2/MeV sr^2)
23.8 (26)	421	3.49 ± 0.07 ± 0.16
42.0 (26)	415	2.20 ± 0.05 ± 0.10
61.6 (30)	411	0.85 ± 0.05 ± 0.05
21.7 (26)	423	1.15 ± 0.06 ± 0.04
48.9 (26)	409	0.54 ± 0.04 ± 0.02

In parallel kinematics only $\sigma_L \propto |\langle J_L\rangle|^2$ and $\sigma_T \propto |\langle J_T\rangle|^2$ contribute. The structure of the currents in terms of the two-body isoscalar ($\Delta T = 0$) and isovector ($\Delta T = 1$) transition components can be expressed, in the notation of Ref. [2], in the schematic form

$$J_{T=0} = (J^0_{T=0}, \vec{J}_{T=0}), \quad J_{T=1} = (0, \vec{J}_{T=1}) \,,$$

where

$$J^0_{T=0} = iF_C(q^2) \,,$$
$$\vec{J}_{T=0} = iF_C(q^2)(2\vec{p} - \vec{q})/4m - F_M^{T=0}(q^2)\frac{\mu_p + \mu_n}{2m}(\vec{\sigma}\times\vec{q}) \,,$$
$$\vec{J}_{T=1} = F_M^{T=1}(q^2)\frac{\mu_p - \mu_n}{2m}(\vec{\sigma}\times\vec{q}) \,.$$

Here $F_C(q^2)$ is the charge form factor and $F_M^{T=0(T=1)}$ are the isoscalar (isovector) magnetic form factors of the pair, $\mu_{p,n}$ are the magnetic moments of nucleons, and $\vec{p}$ and $\vec{\sigma}$ are the operators of nucleon momentum and spin.

Since $\mu_p + \mu_n \sim 0.88$ and $\mu_p - \mu_n \sim 4.71$, and $T = 1$ is statistically more probable than $T = 0$, and also taking into account that we have restricted ourselves to small virtuality (low P_r), we see that σ_L will depend only on $J^0_{T=0}$, and σ_T will be dominated by $\vec{J}_{T=1}$, that is, the magnetic and charge form factors, respectively. This is demonstrated in Fig. 2, which shows the theoretical separated response functions with both $T = 0$ and $T = 1$ contributions, and only with $T = 0$ contributions.

A Rosenbluth separation was employed to obtain the longitudinal and transverse response functions from the

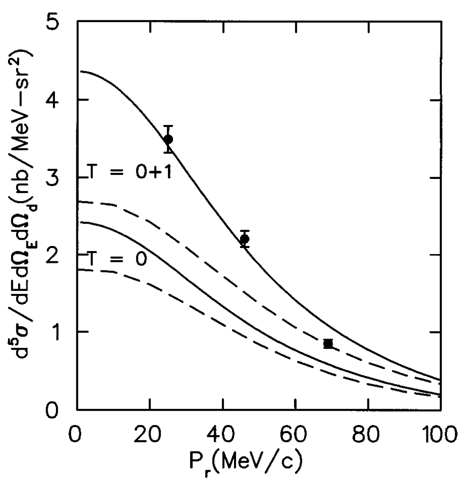

FIG. 1. The laboratory cross section for the reaction ^{3}He$(e, e'd)p$ as a function of recoil momentum P_r in parallel deuteron kinematics corresponding to forward angle electron scattering. Errors shown are statistical only. The solid curves are the results of the theoretical calculation of Refs. [2,8], and the dashed lines are the results of the calculation of Ref. [9]. The two sets of curves denoted $T = 0$ and $T = 0 + 1$ refer to isoscalar and isoscalar plus isovector contributions, respectively.

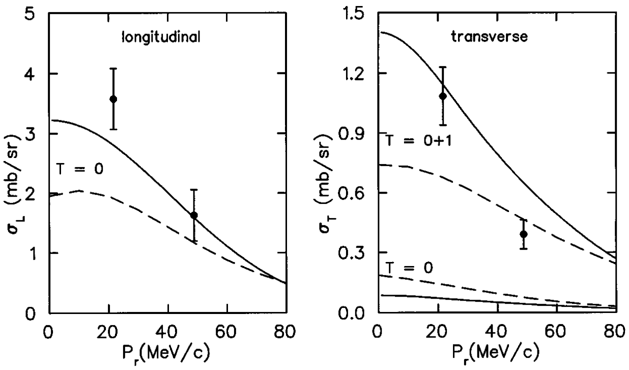

FIG. 2. The longitudinal and transverse laboratory response functions [σ_L and σ_T from Eq. (1)] vs P_r. The results of theoretical calculations with both $T = 0$ and $T = 1$ contributions and only with $T = 0$ contributions are given by solid [8] and dashed [9] curves. The data are the separated cross sections obtained in the present experiment.

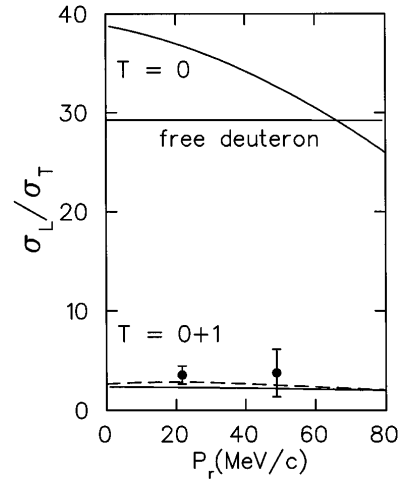

FIG. 3. The ratio σ_L/σ_T vs P_r. The curves have the same meaning as in Fig. 2. In addition, the ratio for the free deuteron is also shown.

experimental cross sections $P_r = 22$ and 54 MeV. No separation was performed for the higher recoil momentum, since cross sections were obtained only at one angle for $P_r \sim 62$ MeV. The forward and backward angle cross sections of Table I were extrapolated over small intervals to the same mean values of $q_{\rm eff}$ and P_r using the theoretically calculated q and P_r dependence of the cross section calculated as in Ref. [9]. The overall magnitudes of these corrections were smaller than about 6% of the measured cross sections. A correction of about 3% for the small contamination of σ_{LT} at $P_r = 54$ MeV$/c$, due to the finite acceptances and slight misalignment of $\vec{q}$ and $\vec{p}_d$, was made also using the theoretical calculation. The results of the separation are given in Figs. 2 and 3. The effect of adding the $T = 1$ correlations to the $T = 0$ correlations is to lower the L/T ratio by an order of magnitude. The systematic errors associated with the ratio are smaller than for the individual separated response functions, since some systematic errors for the individual response functions are correlated.

In conclusion, a L/T separation of the structure functions for deuteron knockout from ^{3}He near quasielastic kinematics ($x \sim 2$) has been performed. Compelling evidence for the important role of isovector two-body currents has been observed. As expected, the L/T ratio is much smaller than that for elastic scattering from a free deuteron, or that expected from the quasifree knockout of a $T = 0$ quasideuteron. This can be explained by the strong contribution of isovector ($T = 1$) currents which are absent in the free deuteron case. The longitudinal and transverse response functions can be roughly explained as due to isoscalar and isovector currents, respectively. However, there is disagreement among two theoretical calculations concerning the absolute values of the cross sections, with the present experimental results supporting the calculation of Refs. [2,8].

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