Two-Body Mechanisms in the ^{6}Li$(e,e'p)$ Reaction

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The ratio of transverse and longitudinal response functions is investigated for the quasielastic reaction ^{6}Li$(e,e'p)$. The ratio itself and its dependence on the missing energy cannot be explained in the distorted-wave impulse approximation. It is proposed that a reaction mechanism other than quasielastic one-body knockout plays a significant role.

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Quasielastic electron scattering is assumed to be dominated by processes involving the direct coupling of a virtual photon to one single nucleon inside the nucleus. Usually the *free* nucleon current is taken to describe this process. This latter assumption is often referred to as the impulse approximation. Hence it came as a surprise that the observed ratio of transverse and longitudinal (T/L) response functions in inclusive quasielastic electron-scattering data appears enhanced for various nuclei.[1] In order to explain this breakdown of the impulse approximation, among other hypotheses, exotic models were developed,[2] inspired by the idea that electromagnetic properties of a nucleon inside nuclei might be density dependent. In order to study this phenomenon in more detail, exclusive $(e,e'p)$ experiments in quasielastic kinematics on various nuclei were carried out with the aim of separating transverse and longitudinal nuclear structure functions.[3-7]

In all cases significant deviations from the ratio of free-proton response functions have been found. One of the most striking observations is the enhancement of the T/L ratio beyond the two-particle emission threshold in ^{12}C.[7,8] This enhancement has been attributed to the onset of a two-body emission process. More evidence for many-body mechanisms in $(e,e'p)$ was found at MIT-Bates in a series of ^{12}C$(e,e'p)$ experiments in the quasielastic and dip region;[9,10] a significantly enhanced continuum strength in the region corresponding to $1s$ knockout of dominantly transverse character was observed.

In this Letter we investigate the role of two-body processes in the quasielastic reaction ^{6}Li$(e,e'p)$. Since the residual nucleus ^{5}He is unbound, the two-particle emission threshold equals the separation energy of 3.7 MeV of the ^{6}Li$(e,e'p)$ reaction. Therefore effects of a two-body mechanism might already be important in the description of $1p$ proton knockout from ^{6}Li. We investigate these mechanisms in the ^{6}Li$(e,e'p)$ reaction by studying the behavior of the T/L ratio as a function of the missing energy. The experimental values of the T/L ratio have been extracted from a proton spectral function study[11,12] of ^{6}Li following the method described in Ref. 13. We will discuss this method and apply it to our ^{6}Li$(e,e'p)$ data. Results will then be compared to T/L ratios obtained with a different method[4] in an independent experiment.

In parallel kinematics, where the momentum $\mathbf{p}$ of the outgoing proton is parallel to the momentum transfer $\mathbf{q}$, only the longitudinal and transverse structure functions W_L and W_T contribute to the sixfold differential cross section for the reaction $(e,e'p)$:[14]

$$\frac{d^6\sigma}{dE_{e'}d\Omega_{e'}dE_p d\Omega_p} = pE_p\sigma_M \frac{Q^2}{\mathbf{q}^2\epsilon}[\epsilon W_L(\omega,q,p)+W_T(\omega,q,p)]\,, \quad (1)$$

where $Q^2=\mathbf{q}^2-\omega^2$ is the four-momentum transfer squared and $\epsilon=[1+(2\mathbf{q}^2/Q^2)\tan^2(\theta_{e'}/2)]^{-1}$ is the virtual-photon polarization parameter with $\theta_{e'}$ the electron-scattering angle. With a fixed incoming electron energy, the constraint of a constant $T_{\text{c.m.}}$ in parallel kinematics implies increasing values of $|\mathbf{q}|$ in going from positive to negative values of missing momentum $p_m=|\mathbf{p}|-|\mathbf{q}|$. Therefore the electron spectrometer has to be positioned at more backward angles and the polarization of the virtual photon gradually changes from longitudinal to transverse. Hence an anomalous T/L ratio will show up in $(e,e'p)$ data measured in parallel kinematics.[13]

A previous $(e,e'p)$ study of ^{6}Li was carried out in the missing-energy range $0\le E_m\le 30$ MeV and the missing-momentum range $-110\le p_m\le 200$ MeV/c.[11,12] The data were obtained in parallel kinematics keeping the relative (p-^{5}He) kinetic energy in the center-of-mass system constant at $T_{\text{c.m.}}=64.8$ MeV. Employing a three-body α-n-p calculation[15] below the $t+d$ threshold, and a $t+d+p$ cluster-model calculation[16] above, a good description of the (missing-) momentum distribution $\rho(p_m)$ above $p_m=100$ MeV/c was obtained in a

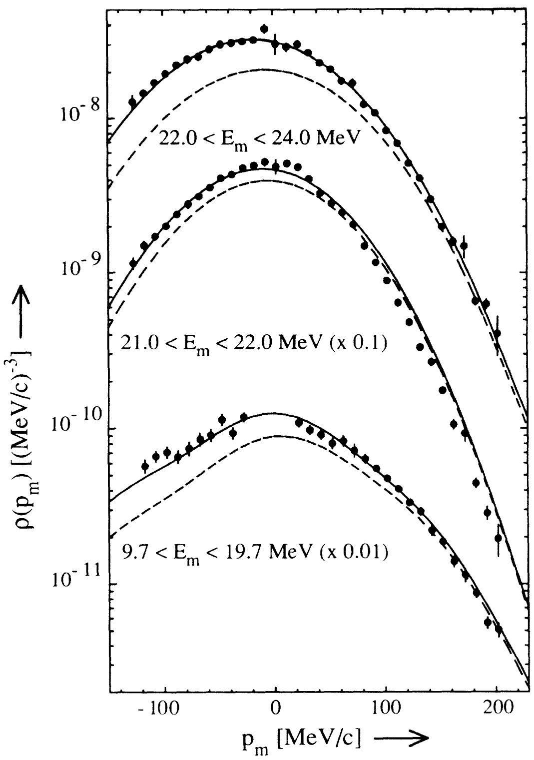

FIG. 1. Momentum distribution for the reaction ^{6}Li$(e,e'p)$ obtained by integrating the spectal function over the missing-energy ranges E_m=9.7-19.7, 21.0-22.0, and 22.0-24.0 MeV. The curves are calculated in DWIA. The solid curves include an enhanced transverse amplitude (see text).

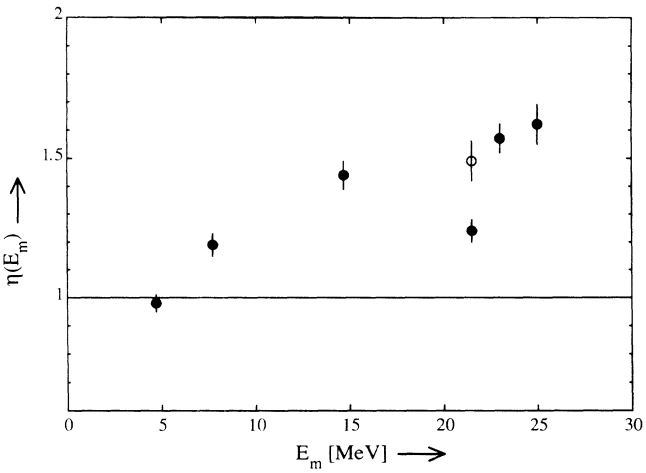

FIG. 2. Transverse-longitudinal ratio η for the quasielastic reaction ^{6}Li$(e,e'p)$ as a function of the missing energy E_m. The solid line represents the DWIA value. The values are obtained by integrating the missing-energy ranges 3.7-5.7, 5.7-9.7, 9.7-19.7, 21.0-22.0, 22.0-24.0, and 24.0-26.0 MeV. In the first three ranges, a three-body calculation has been employed (Ref. 11) while in the latter three ranges a cluster-model approach (Ref. 12) has been applied. The open circle results from rescaling the cluster-model calculations for the $t+d$ resonance by 0.8 (see text).

distorted-wave impulse-approximation (DWIA) approach,[17] with exception of a 20% overestimation in the range E_m=21.0-22.0 MeV (see Ref. 12). This range covers the $t+d$ resonance, located at 21.35 MeV. The electron distortion was taken into account in the first-order eikonal approximation.[17] The DWIA results for the energy ranges E_m=9.7-19.7, 21.0-22.0, and 22.0-24.0 MeV are shown in Fig. 1 by the dashed curves. Deviations from the DWIA are observed at missing-momentum values $p_m \leq 100$ MeV/c. Since the DWIA calculations are based on the impulse approximation (IA), the anomaly for this part of the data might be caused by a deviation of the T/L ratio of the response functions from the IA value. Since there is *no* normalization freedom in either the three-body or the cluster-model calculations, the underestimation of data below p_m=100 MeV/c has to be ascribed within these models to enhanced *transverse* strength. For that reason a parameter η, multiplying the transverse amplitude, has been introduced in the DWIA calculations. Used as a free parameter in fitting the data, a good description of the data over the full p_m range is obtained with exception of the interval E_m=21.0-22.0 MeV, as shown in Fig. 1 by the solid curves. The fitted values of η are shown in Fig. 2 as a function of the missing energy (E_m). With increasing missing energy, the enhancement η becomes larger, with a maximum value of about 1.63. The value at E_m=21.5 MeV is caused by the aforementioned 20% overestimation by the cluster-model calculation of $\rho(p_m)$ in the range E_m=21.0-22.0 MeV for $p_m \geq 100$ MeV/c. Rescaling the cluster-model calculations in this range with a factor of 0.8 and refitting η resulted in an enhancement factor $\eta=1.49\pm0.07$, depicted in Fig. 2 by the open circle.

In Ref. 4 experimental T/L ratios were extracted from an independent $(e,e'p)$ experiment on ^{6}Li. Cross sections were measured in parallel kinematics at constant values of E_m, $\mathbf{p}_m$, and $\mathbf{p}'$, the momentum of the outgoing proton, but at two different values of the photon polarization parameter ϵ. From the results of such a pair of measurements, the quantity $R_G=[(4m^2/Q^2)W_T/W_L]^{1/2}$ was calculated using Eq. (1). The results for "1p" and "1s" knockout from ^{6}Li, obtained by integrating the strength in the missing-energy ranges E_m=3.50-11.50 and 19.5-27.5 MeV, respectively, are plotted versus Q^2 in Fig. 3. A considerable deviation is observed between the data and the value of $R_G=\mu_p=2.79$ for a free proton, represented by the dashed line.

Since distortions act differently on W_L and W_T we have calculated the effects in the unfactorized DWIA framework, which was also used in the spectral function study.[11,12] This DWIA analysis differs from the one presented in Ref. 4, in that electron-distortion effects are treated in the first-order eikonal approximation.[17] The DWIA calculations are depicted in Fig. 3 by the solid

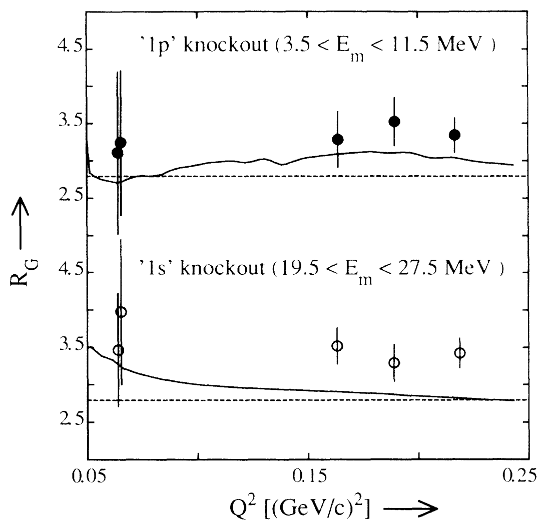

FIG. 3. R_G as a function of the four-momentum transfer for $1p$ knockout and $1s$ knockout in ^{6}Li$(e,e'p)$. The solid curves represent the results of $R_{G(\mathrm{DWIA})}$. The dashed line denotes the value $R_G = \mu_p = 2.79$. The experimental data are from Ref. 4

curves. These calculations yield a significant deviation from the free-proton ratio $\mu_p = 2.79$ in the region of interest, i.e., $0.16 < Q^2 < 0.22$, for $1p$ knockout. However, this deviation is less pronounced than the one predicted for $1p$ knockout from ^{12}C as calculated in Refs. 18–20. Whereas the latter state has a pure $l=1$ orbital momentum, the $1p$ strength in ^{6}Li is of mixed $l=0,1$ orbital momentum.[11] Since R_G is hardly affected by distortion effects for $l=0$ knockout, DWIA effects are less pronounced in the ^{6}Li $1p$ case compared to the ^{12}C $1p$ case. Note that the insensitivity of R_G to distortion effects for $l=0$ knockout was also observed by Suzuki[20] for ^{12}C$(e,e'p)$ and in the continuum Faddeev calculations for ^{3}He$(e,e'p)$ by van Meijgaard and Tjon.[21]

From the results depicted in Fig. 3, $\eta = R_{G(\mathrm{expt})}/R_{G(\mathrm{DWIA})}$ can be calculated, where $R_{G(\mathrm{DWIA})}$ denotes the DWIA value of R_G. A 1.10 ± 0.07 and 1.22 ± 0.05 enhancement is obtained for the $1p$ and $1s$ cases, respectively. The values, obtained for the energy ranges $E_m = 3.7$–19.7 and 21.0–27.5 MeV in the spectral-function study, amount to $\eta = 1.05 \pm 0.05$ and 1.32 ± 0.09, respectively. Thus the two methods of determining the experimental T/L enhancement are in fair agreement. It is noted that the T/L anomaly for $1p$ knockout mentioned in Ref. 4 is larger than the η values quoted here due to the fact that we used a more realistic approximation for the Coulomb distortions of the electron waves. This topic will be addressed in a forthcoming separate paper.[22] It is interesting, though, that a *nuclear-density* dependence of η, for which no evidence was found in Ref. 4, does seem to emerge from the present analysis of ^{6}Li data. The *missing-energy* dependence of η (see Fig. 2), however, makes the onset of another reaction mechanism component a more likely explanation. This is also supported by a similar E_m behavior observed for η in the $1s$ proton-knockout region of ^{12}C.[8] For ^{12}C a value of $\eta \sim 1.65$ was obtained at about 8 MeV above the two-particle emission threshold ($E_m = 28$ MeV).[7,8]

Since the enhancement of η both for ^{6}Li and for ^{12}C essentially starts at the two-body emission thresholds that are located at widely different values in the E_m spectra, we take this as evidence for the presence of a transverse two-body reaction component in $(e,e'p)$.

The role of multinucleon emission in the $(e,e'p)$ reaction was discussed recently by Takaki.[23] We will focus on the two-body emission as at lower missing-energy multinucleon (>2) knockout channels are still closed. Takaki discerns three important effects: initial nucleon-nucleon correlations, two-body interactions such as meson-exchange currents, and final-state interactions. The occurrence of a T/L anomaly in quasielastic inclusive (e,e') favors the first two mentioned effects as a possible cause of enhanced transverse strength since final-state interactions are less important in (e,e') than in $(e,e'p)$. In fact, Kohno[19] pointed out that the mesonic contribution could change the ratio R_G by as much as 10% for ^{12}C. Evidence for nucleon-nucleon correlations was presented in a study of the ^{3}He$(e,e'p)$ reaction.[24] Further calculations are needed to get insight into the role of these two effects for the ^{6}Li$(e,e'p)$ reaction.

But also the third effect, i.e., final-state interaction, in particular involving charge-exchange processes, may be important. From an explicit calculation of the contribution of the two-step process $(e,e'n)(n,p)$ in the quasi-elastic region,[25] a maximum enhancement of R_G of about 5% was found for ^{12}C. However, van den Brand *et al.*[26] have shown that charge-exchange processes are crucial in the explanation of a 40% breakdown of the DWIA, observed in the reaction ^{4}He$(e,e'p)$,[27] by employing a microscopic model developed by Laget.[28] These results can now be related to ^{6}Li using the following arguments. From an explicit T/L-separation experiment on ^{4}He carried out at Saclay,[6] an average $R_G = 3.6 \pm 0.3$ can be extracted, which is consistent with our $1s$ enhancement of $1.32(9)\mu_p = 3.68 \pm 0.25$. Since in Ref. 12 it is concluded for the reaction ^{6}Li$(e,e'p)$ that most strength above the $t+d$ threshold is due to proton knockout from the ^{4}He core of ^{6}Li, it is expected that at least in the region above this threshold charge exchange is very important. A complete description of the results shown in Fig. 2, however, requires an integrated approach encompassing various two-body effects.

In summary, the T/L ratios extracted from ^{6}Li$(e,e'p)$ cross sections, measured in parallel kinematics, are in agreement with those extracted from an independent experiment involving an explicit T/L separation. The calculated ratio R_G for knockout of a proton from an $l=0$ orbit appears virtually unaffected by proton and electron distortion effects, whereas it is significantly modified in the case of $l=1$ knockout. The experimentally observed *energy dependence* of η, which starts to deviate from unity at the two-body emission threshold, makes the occurrence of a two-body reaction component a more likely explanation of the observed T/L enhancement than a dependence of the electron-proton coupling on the *nuclear density*. Given the present results for ^{6}Li and the ones observed for ^{12}C, evidence is mounting that two-body reaction processes contribute to the anomalous T/L ratio observed in *inclusive* quasielastic (e,e').

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