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Density effects in the $(e,e'p)$ reaction

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Particle emission from different shells after electroexcitation of a nucleus is studied in the quasielastic region of the $^{12}C(e,e'p)^{11}B$ reaction. The rescattering processes and in particular the coupling between $(e,e'p)$ and $(e,e'n)$ channels show a sizable density dependence. The resulting shell dependence of the longitudinal/transverse suppression, using the free nucleon form factors, is close to the one observed in the experimental data.

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A possible medium modification of the nucleon form factor is one of the most intriguing but not yet fully understood phenomena [1]. The electromagnetic processes provide the cleanest way to verify various related theoretical concepts. Still, however, no consensus has been attained as to whether the observed peculiarities in the cross section, especially the suppression of its longitudinal against transverse component, are explainable entirely in terms of conventional nucleonic degrees of freedom or if the quarks manifest their presence as well. Certainly, in the inclusive (e,e') analysis a large fraction of the discrepancy between the data and an independent particle picture is accounted for by the higher-order configuration mixing effects [2,3]. Such effects generate a sizable broadening of the single-particle states, especially those which are located far away from the Fermi surface, and this results in a modified energy distribution of the longitudinal response function. Such broadening is simultaneously strongly reduced in the transverse response by the coherence effects [4]. This provides strong support for an important role of the conventional many-body effects. Further important ingredients include the proper treatment of the final-state interactions [5] and, to a lesser extent, the relativistic effects [5,6]. At the present stage, however, it is not possible to rule out totally a need for a modified nucleon form factor. For that purpose one would need more systematic studies from light to heavy systems where higher densities are involved and thus a medium influence on the form factor, if at all present, should be stronger.

Since exclusive $(e,e'p)$ measurements allow to determine the separate contributions to the cross section of individual nuclear shells, they are more adequate for addressing the above problem. Here, in the same experiment one selectively probes different densities. Integrating the cross section over the appropriate missing energies one obtains the total contribution coming from a given hole state. In this way the effect of broadening should be eliminated. But even in this case the NIKHEF [7] group reports the longitudinal/transverse (L/T) relative suppression for the p shell, detected in ^{12}C. This phenomenon, however, is well described by realistic final-state interactions and, in fact, is insensitive to both the relativistic and medium-modified form-factor effects [8]. Extensive discussion of those effects in $(e,e'p)$ reactions can be found in Refs. [9–11]. More intriguing is the MIT group report [12]: The observed longitudinal/transverse suppression in ^{12}C turns out to be stronger for the s shell than for the p shell. No satisfactory explanation of this fact within the nuclear many-body theory exists so far. Also, the meson exchange currents are known not to provide a significant correction for the kinematics considered [13]. If the nucleon form factor is modified in the nuclear medium a shell-dependent modification of the longitudinal and transverse structure functions is natural because the density of matter in the s shell is larger than in the p shell. However, from our recent studies of ^4He [14] one may expect the coupling between the different reaction channels (particle-hole rescattering) to play an important role in this connection. In the inclusive processes such effects suppress the longitudinal response even at comparatively high momenta ($q=500$ MeV/c) via the exchange momentum transfer [15,16]. In exclusive processes they may lead to the coupling between protons and neutrons and thus part of the longitudinal cross section escapes experimental detection in $(e,e'p)$ as compared to the pure mean-field picture [14]. Moreover, this effect may also depend on the density. Intuitively one would expect that the probability for rescattering is enhanced with increasing density. One should, however, remember that the effective interaction in the relevant $(\tau\tau')$ channel becomes weaker at higher density [17]. Which of the two effects dominates? It is a purpose of this paper to quantitatively explore the problem of stronger L/T suppression for the s shell than for the p shell.

The general coincidence cross section in the one-photon exchange approximation can be expressed as [18]

$$\frac{d^6\sigma}{dE_e' d\Omega_e' dE_p d\Omega_p} = \sigma_M p E_p (V_L R_L + V_T R_T + V_{LT} R_{LT}\cos\phi + V_{TT} R_{TT}\cos 2\phi) , \qquad (1)$$

where σ_M is the Mott cross section, the energies and solid angles of the final electron and proton are denoted as E_e',

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E_p and Ω_e', Ω_p, respectively, and ϕ is the angle between the electron-scattering plane and the one determined by the momentum transfer **q** and the proton momentum **p**. The nuclear structure functions R involve matrix elements of the corresponding current operators between the initial and final nuclear states and the coefficients V are determined by the electron variables.

In order to study the effects of the coupling between the proton and neutron emission channels we apply the recently developed method [16] to simultaneously account for the mean-field distortions and two-body rescattering processes directly in the continuum. This method allows using finite range interactions with an explicit inclusion of Pauli exchange terms and tensor correlations. The residual interaction is specified in terms of the G matrix derived [17] from the Bonn meson exchange model [19]. The G matrix has been evaluated in nuclear matter at the density corresponding to the average density in the hole-state considered. The mean-field part of the Hamiltonian is represented by a local Woods-Saxon potential which reproduces the ground-state density and separation energy [20]. The free nucleon form factor in its standard dipole parametrization is used.

Our approach allows a consistent treatment of the $(e,e'p)$ and $(e,e'n)$ channels, in particular, it allows for a microscopic treatment of the coupling between them. Since our effective interaction has been derived from the genuine nucleon-nucleon interaction it has a realistic momentum dependence in the quasielastic region, in contradistinction to many zero-range effective interactions used up to now. We stress that our mean-field distorting potential does not contain extra non-Hermitian effects. In the continuum random-phase approximation (RPA) coupled-channel method (CCM) one explicitly accounts for the couplings between all one-particle emission channels. In contrast to our model the optical-potential approach may account for absorptive effects related to reactions that go beyond one-nucleon emission. In principle, this may cause some supplementary reduction of the $(e,e'p)$ and $(e,e'n)$ strength. Intuitively, this effect should be more important for heavier nuclei. Because in the present paper we want to treat the coupling between the $(e,e'p)$ and $(e,e'n)$ on the microscopic level, we do not include an extra imaginary potential.

Figure 1 shows the separated contributions to $(e,e'p)$ and $(e,e'n)$ coincidence cross sections coming from $p_{3/2}$ and $s_{1/2}$ shells in ^{12}C at four different q values and for the energy transfer corresponding to the position of the quasielastic peak. These cross sections are plotted versus the angle between the momentum **p** of the knocked-out nucleon and the transferred momentum **q**. Thus the small angles correspond to the parallel kinematics where the interference terms [V_{LT} and V_{TT} in Eq. (1)] disappear. As is seen, the rescattering processes (the difference between CCM and pure mean-field results) sizably enhance the number of emitted neutrons at the expense of reduced proton cross section. Also, the proton angular distribution is modified due to the proton rescattering. Moreover, such effects are stronger for the $s_{1/2}$ than for the $p_{3/2}$ shell. The emission caused by the rescattering turns out to be more probable at higher densities. Consequently, by measuring

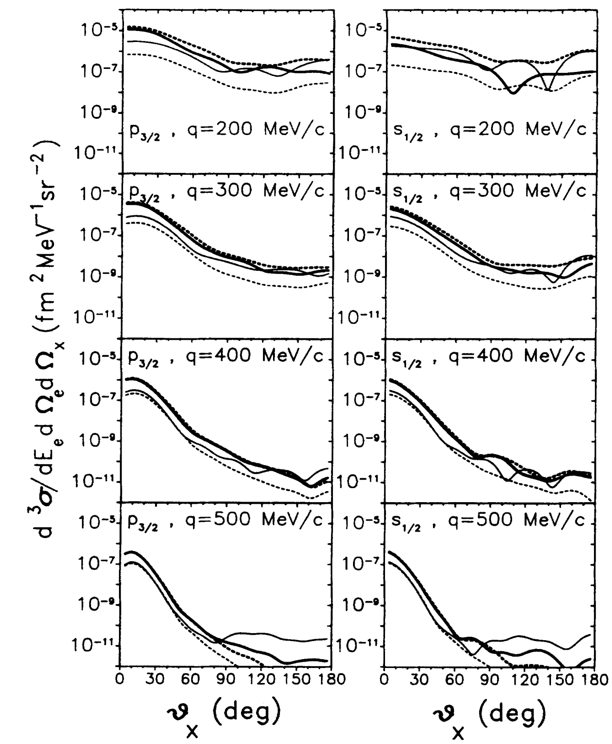

FIG. 1. The separated $p_{3/2}$ (lhs) and $s_{1/2}$ (rhs) contributions to the $(e,e'p)$ and $(e,e'n)$ cross sections (in units of fm^2 MeV^{-1}sr^{-2}) in the quasielastic peak of ^{12}C plotted as functions of the nucleon angle measured with respect to the direction of the momentum transfer **q**. The thick lines correspond to protons and the thin ones to neutrons. In each case the dashed lines describe the mean-field results and the solid lines include also the rescattering effects.

only protons in the longitudinal channel one misses part of the cross section as compared to the mean-field picture. The transverse cross section remains much less affected by such effects because in this channel the electron couples to the neutron already on the mean-field level. Of course, increasing q gets one closer to the mean-field picture because the residual interaction becomes weaker. In contrast to Ryckebusch *et al.* [21] we find that the RPA-like correlations play a crucial role in populating the $(e,e'n)$ channel. Our result is similar rather to the result of the more phenomenological, Lane formalism applied to the same reaction by the Amsterdam group [22].

For parallel kinematics the coincidence cross section [Eq. (1)] is a sum of the longitudinal and transverse components only. Their q dependence corresponding to three different calculations is illustrated in Fig. 2. Again, the p- and s-shell contributions are separated. The bigger slope of the longitudinal part reflects the fact that at higher q values the cross section is dominated by the spin-flip (transverse) processes. Since at the higher transferred momenta one penetrates the deeper regions of the nucleus, the slope is smaller for the s than for the p shell in both the longitudinal and transverse cross sections. For the s shell it even bends down in the low q region which reflects the inaccessibility of this shell. More important for the

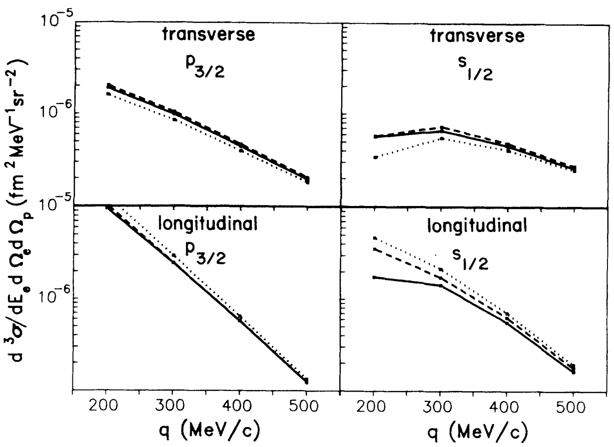

FIG. 2. The separated $p_{3/2}$ (lhs) and $s_{1/2}$ (rhs) contributions to the transverse (upper part) and longitudinal (lower part) components of the $(e,e'p)$ cross sections (in units of fm^2 MeV^{-1}sr^{-2}) in ^{12}C for parallel kinematics. The dotted lines display the mean-field results, the dashed lines the coupled-channel method with the proton-neutron coupling discarded, and the solid lines the full result.

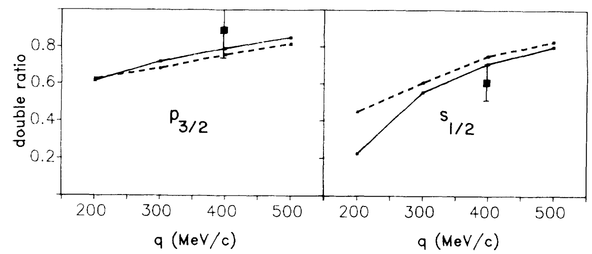

FIG. 3. The CCM longitudinal/transverse ratio divided by the same ratio calculated on the mean-field level. The dashed lines display the same quantity with the proton-neutron coupling ignored. The experimental data are those of Ref. [12].

present discussion is the difference between the results corresponding to the mean field (distorted-wave impulse approximation), CCM, and CCM with no proton-neutron coupling. As is clearly seen, the rescattering processes are more effective in the $s_{1/2}$ shell. Moreover, in the longitudinal cross section the charge-exchange effects are dominant in this respect and lead to its reduction. The transverse one, on the other hand, is even enhanced for this energy transfer [16]. This is consistent with observations made for inclusive processes and with the repulsive character of the ρ meson which generates the interaction in this channel.

The experimental data of Ref. [12] are discussed in terms of the L/T ratio divided by the same ratio for the distorted-wave impulse approximation. In such a double ratio the off-shell $p(e,e')p$ cross sections cancel out and the result is identical to the same ratio of the spectral functions. The analogous ratios extracted from our results are displayed in Fig. 3. At the momentum transfer which coincides with the measured values ($q \approx 400$ MeV/c) this corresponds to 0.79 for the p shell and 0.71 for the s shell. This is to be compared to experimental [12] $0.89 \pm 0.09 \pm 0.12$ (the same ratio extracted from the data of Ref. [7] is 0.67 ± 0.22) and $0.61 \pm 0.08 \pm 0.07$, respectively. In this kinematic region the difference of 10% in the calculation for different shells is caused entirely by the proton-neutron coupling. Without this coupling both shells give almost the same result (about 0.75).

In this context it is necessary to mention the fact that the identification of the s shell is somewhat obscured by the opening of the two-nucleon emission threshold. In Ref. [12] the effect of L/T suppression has been attributed rather to the enhancement of the transverse strength above two-particle threshold. This may suggest the importance of two-body currents in explaining the missing energy dependence. In the present paper we discuss only the integrated result, and the question of the distribution in missing energy remains to be clarified both experimentally and theoretically. We show that the coupling between the $(e,e'p)$ and $(e,e'n)$ channels is an important ingredient which must be included in order to understand the experimental result.

In conclusion, the longitudinal/transverse suppression and in particular the shell dependence of this effect does not seem to provide evidence for a medium modification of the nucleon form factor. The observed deviations from the mean-field picture arise largely from rescattering processes. Clearly, more data also are needed for the other kinematics, in order to create a more systematic picture. Certainly, studying one kinematics is not enough to draw definite conclusions especially when the error bars in the existing data are comparatively large. It would also be extremely important to obtain experimental data on the $(e,e'n)$ cross sections. The cross section for the ^{12}C $(e,e'n)$ reaction in the quasielastic region will soon be measured by the MIT group [23].

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