Final-state-interaction effects in the $(e,e'p)$ reaction

M. Buballa, S. Drożdż,* S. Krewald, and A. Szczurek*
Institut für Kernphysik, Forschungszentrum Jülich, D-5170 Jülich, Germany
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Particle emission after electroexcitation of a nucleus is studied in the quasielastic region of the ^{4}He$(e,e'p)^3$H reaction. The calculations are performed using a meson-exchange potential. The displacement observed in the experimental spectral functions appears to be due to the mean-field scattering mainly. The rescattering processes lead to the splitting between the longitudinal and transverse spectral functions in agreement with the trend of the Saclay data. The related damping of the longitudinal spectral function originates from the coupling between $(e,e'p)$ and $(e,e'n)$ channels.

The $(e,e'p)$ coincidence experiments on nuclei are particularly well suited for studying various nucleon-nucleon correlations inside a nucleus. This first originates from the well-known structure of electromagnetic interactions and, second, from the possibility of a selective analysis of various parts of the underlying phase space by proper kinematical conditions.

The coincidence cross section for the electrodisintegration of ^{4}He has been measured at NIKHEF-K [1] for two values of the momentum transfer $\mathbf{q}$ in a broad range of the missing momenta $\mathbf{p}_m=\mathbf{p}-\mathbf{q}$. The data are presented as the so-called spectral function which, under the assumption of factorization of the cross section [2,3], represents the momentum distribution of protons in the ^{4}He nucleus. The spectral functions derived from the data are found, however, to depend strongly on the kinematics chosen. Even though a sophisticated ground-state wave function was used, this fact could not be explained by a factorized distorted-wave impulse approximation (DWIA). Moreover, a recent analysis [4] of this problem using the correlated-wave-function method with the global optical-model description of the final-state-interaction effects shows sizable sensitivity of the cross section on the detailed form of the optical potential. As a consequence, the cross section and thus the spectral functions seem to reflect not only the correlations in the ground state, but also the properties of excited states and, in particular, the final-state-interaction effects. Therefore, in the following we concentrate on such effects which may partly be caused by the scattering in a mean field and partly by genuine two-nucleon rescattering processes.

The general coincidence cross section in the one-photon-exchange approximation can be expressed as [3]

$$\frac{d^6\sigma}{dE_e'd\Omega_e'dE_pd\Omega_p}=\sigma_M pE_p(V_LR_L+V_TR_T+V_{LT}R_{LT}\cos\phi+V_{TT}R_{TT}\cos2\phi)\ , \qquad (1)$$

where σ_M is the Mott cross section, the energies and solid angles of the final electron and proton are denoted as E_e', 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 $\mathbf{q}$ and the proton momentum $\mathbf{p}$. 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 entirely determined by the electron variables (for details, see Ref. [5]).

When discussing nuclear correlations, one usually refers [6] to the shell-model concept and possible correlations are also expressed in the basis generated by the underlying mean field. From this point of view, the random-phase approximation provides the most natural frame for studying $(e,e'p)$ processes. It also gives the most promising scheme concerning extensions toward the heavier systems. Therefore, for the present analysis we apply the newly developed method [7] to include two-body rescattering processes directly in the mean-field continuum. The method is based on an expansion in an energy-dependent basis of Sturmian function, which allows very efficient treatment of such effects. In particular, in this way one can make use of finite-range interactions with an explicit inclusion of exchange terms. This is important for studying higher-momentum-transfer phenomena. Only the finite-range forces provide the natural momentum cutoff for rescattering processes, and an explicit inclusion of the corresponding exchange terms appears [8] to be necessary because of a nontrivial exchange-momentum transfer dependence of the particle-hole interaction for the spin-independent modes. Here the G matrix derived [9] from meson-exchange model is used as a residual interaction. The mean-field part of the Hamiltonian is specified in terms of a local Woods-Saxon (WS) potential. Of course, the mean-field potential alone cannot reproduce the central depression in the ground-state charge-density distribution. This region carries, however, a very small fraction of nucleons which correspond to large values of the missing momenta. Much more important is the reliable description of the surface and outer parts of the wave function. Since in the mean-field approach the tail of the wave function is entirely determined by the separation energy, the depth of the WS potential is adjusted such as to reproduce also its experimental value (19.81 MeV for ^{4}He). The WS po-

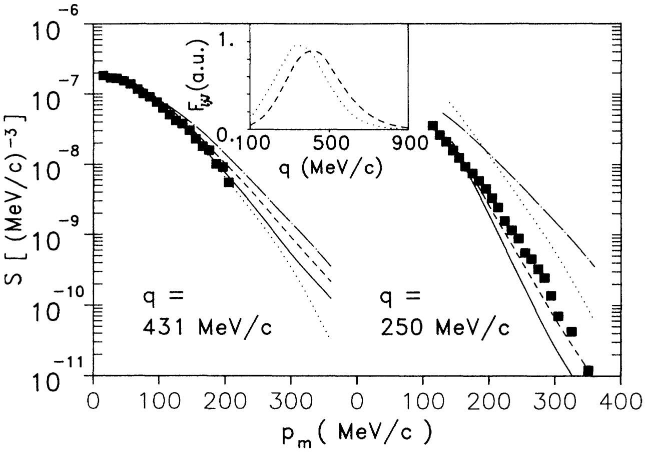

FIG. 1. Spectral function $S(p_m)$ from ^{4}He $(e,e'p)$ ^{3}H reaction for two kinematics: left-hand side $\theta_e = 70°$ ($q = 431$ MeV/c), and right-hand side, $\theta_e = 36°$ ($q = 250$ MeV/c). Both the experimental data [1] and theoretical results are presented. The dotted line represents the plane-wave approximation result with the recoil correction and dot-dashed without. Dashed line includes mean-field distortions, and the solid line includes also rescattering effects. The upper insertion illustrates the q dependence of the function defined by Eq. (4). The dotted line there discards any final-state interaction, and the dashed line includes it on the mean-field level.

tential parameters are $r_V = r_{LS} = 1.7$ fm, $a_V = a_{LS} = 0.6$ fm, $V_0 = 66.37$ MeV, and $V_{LS} = 3.2$ MeV.

The spectral function has been obtained in an analogous way as the experimental one, i.e., by dividing the general coincidence cross section by the off-shell electron-proton cross section calculated according to the current-conserving prescription [10]

$$S(p_m, E_m) = \frac{d^6\sigma}{dE_e' d\Omega_e' dE_p'} d\Omega_p \Big/ pE_p \sigma_{eN}^{\text{off-shell}} , \quad (2)$$

using the standard dipole parametrization for the nucleon form factor both when calculating the electron-nucleus and electron-nucleon cross sections.

For such a light nucleus as the alpha particle it is necessary to account for the recoil correction. The easiest way is to replace the laboratory angle by its counterpart in the recoiled system and to perform the transformation of solid angles. In this connection the ultrarelativistic kinematics for the electron and the nonrelativistic one for the hadrons has been applied.

Figure 1 shows the calculated spectral functions for both kinematics compared with the experimental data. Neglecting the recoil correction and the final-state interactions, the spectral functions are independent of the particular kinematics chosen (dash-dotted lines). The influence of mean-field distortions, measured as a difference between the dotted and dashed lines, depends on the kinematics. A major effect is found for $q = 250$ MeV/c. This can be understood in terms of the following simple arguments. The longitudinal structure function R_L can be written as

$$R_L(q) = \Big| \sum_{ljJ} A_{ljJ} F_{ljJ}(q) \Big|^2 , \quad (3)$$

with A_{ljJ} denoting a combination of Clebsch-Gordan coefficients and spherical harmonics and

$$F_{ljJ}(q) = \int r^2 dr \, j_J(qr) \Phi_f^{lj*}(r) \Phi_i^{1s1/2}(r) , \quad (4)$$

where Φ_i and Φ_f are the radial parts of the initial and final single-particle wave functions of a knocked-out nucleon. Without any final-state interaction, Φ_f is simply the Bessel function j_l. This leads to a resonant q dependence of the function F_{ljJ} with a maximum at around $q = p$. The corresponding behavior is illustrated in the inset of Fig. 1 (dotted line) for $l = 2$, $j = \frac{3}{2}$, and $J = 2$. Switching on the attractive mean field, the wavelength in the interior of the nucleus becomes shorter and the maximum of F_{ljJ} is shifted to higher q (dashed line). The cross section is thus reduced for lower and enhanced for higher q values. A similar argument applies to the transverse struction function.

The other important effect seen in Fig. 1 is due to the two-body rescattering. One observes a systematic reduction of the spectral function as compared to the mean-field result. The effect is again stronger for kinematics 2, consistent with the lower transferred momenta. One should also note a very good agreement of the theoretical results with experimental data for smaller missing momenta. Adjustment of the mean-field potential to reproduce the separation energy is of crucial importance in this connection. At larger missing momenta the calculated spectral function underestimates the data. This signals an importance of two-body correlations and meson-exchange currents, which are not included here. The room left for such effects is compatible with the results of Ref. [4].

Recently, the Saclay group has published results [11] on the separation of the ^{4}He$(e,e'p)^3$H cross section into longitudinal and transverse components. While the transverse response agrees with the theoretical predictions [12], the longitudinal one remains low with respect to the theory. The resulting splitting is particularly intriguing because essentially no missing strength in the sense of Coulomb sum rule is observed in the ^{4}He longitudinal response measured [13] in (e,e') inclusive experiments. This suggests that the suppression of the longitudinal component of the exclusive cross section cannot be linked to higher-order configuration mixing effects, as is the case in heavier nuclei [14]. In exclusive experiments one may expect some reduction of the $(e,e'p)$ cross section due to non-negligible contribution of the $(e,e'n)$ channel which couples to the first one via a charge-exchange reaction. In the inclusive (e,e') cross section, these two channels are, of course, indistinguishable and are simply summed up. That this is really an important effect is demonstrated in Fig. 2 for kinematics 1, where the nucleus is probed in a broader range of p_m. The longitudinal $S_L(p_m)$ and transverse $S_T(p_m)$ spectral functions shown in the upper part of the figure are calculated in an analogous way as $S(p_m)$ i.e., replacing the total differential cross section in Eq. (2) by its longitudinal/transverse part and similarly for $\sigma_{eN}^{\text{off-shell}}$. The reduction of the longitudinal spectral function (solid line) with respect to the mean-field result (dashed line) is almost entirely caused by the proton-neutron coupling. As displayed in the lower part of Fig. 2, this simultaneously creates the $(e,e'n)$ longitudinal cross section which is vanishing at the mean-field level. The corresponding transverse part is little influenced by such effects.

In this context it is interesting to make such a separation for kinematical configurations closer to the Saclay experiment [11]. Figure 3 shows the $|\mathbf{q}|$ dependence of the longitudinal and transverse spectral functions for two different energy transfers of 98 MeV (left-hand side) and 62 MeV (right-hand side) at a fixed missing momentum of 90 MeV/c. Since the related experimental data correspond to parallel kinematics, one pair of such points can be assigned to each of the transferred energies. The calculated longitudinal spectral function is strongly suppressed with respect to the transverse one, consistent with the tendency seen in the experimental data. This suppression originates mostly from the proton-neutron rescattering process, and because of this, it decreases with increasing $\mathbf{q}$, which is seen when looking at the ratio between the two spectral functions. The splitting, seen in Fig. 3 for higher excitation energy, already at the mean-field level, comes from the division by the off-shell electron-nucleon cross section [10] as is done in Ref. [11]. If one divides by the on-shell cross section as in Ref. [4], this splitting is much smaller. It is also interesting to note that in Ref. [4] essentially no such splitting is observed without meson-exchange current contributions.

Summarizing, it appears necessary to investigate explicitly and carefully the final-state-interaction effects in order to properly interpret the $(e,e'p)$ data. The mean-field distortions are responsible for the displacement between kienmatics 1 and 2 seen in the NIKHEF-K data. The most interesting effect of the two-body rescattering processes is a sizable suppression of the longitudinal com-

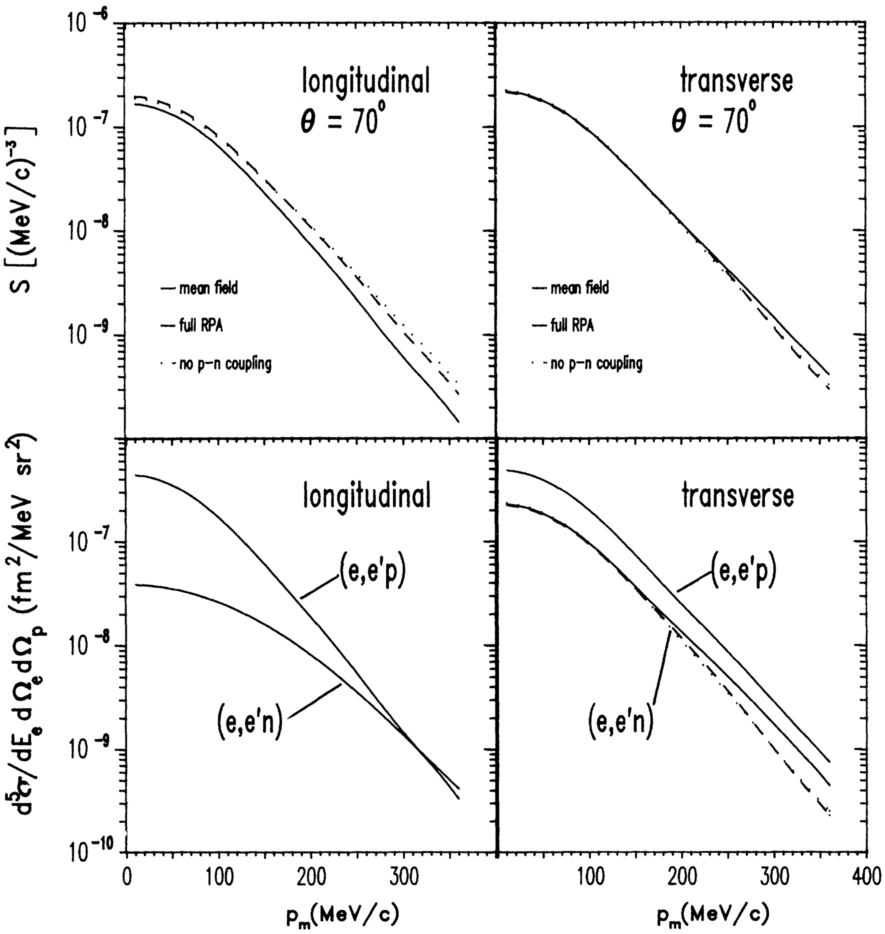

FIG. 2. Upper part: Missing momentum dependence of the longitudinal (left-hand side) and transverse (right-hand side) spectral functions for $\theta_e = 70°$. The mean-field result is represented by the dashed line, and the full RPA result by the solid line. The dotted line ignores the proton-neutron coupling in the two-body interaction. Lower part: $(e,e'n)$ vs $(e,e'p)$ cross sections for the same kinematics separated into the longitudinal and transverse parts.

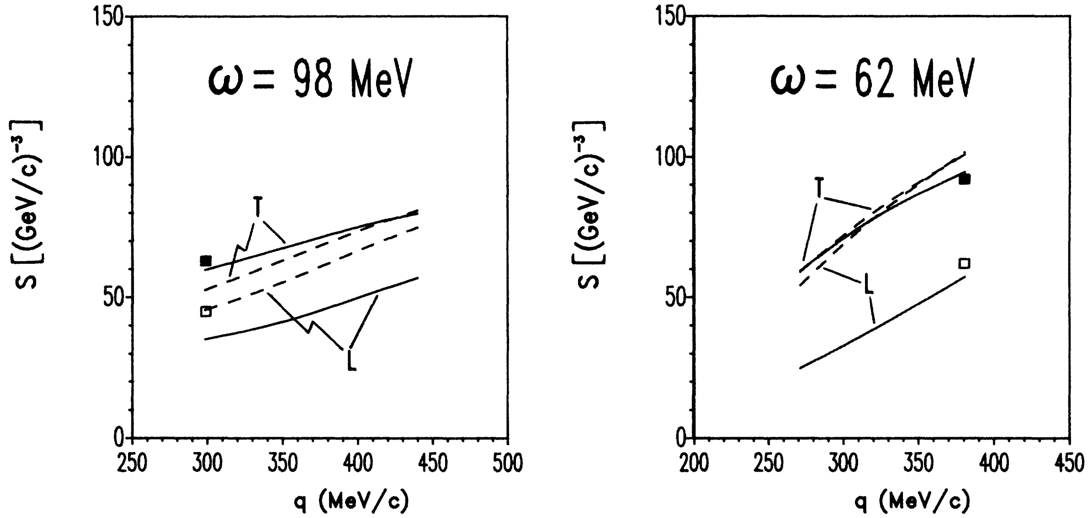

FIG. 3. Momentum-transfer dependence of the separated spectral functions for two different energy transfers ω. Dashed lines represent the mean-field result, and the solid ones include rescattering effects. The existing experimental data [11] are denoted by the open squares for the longitudinal and solid ones for the transverse spectral functions.

ponent in the $(e,e'p)$ cross section. This simultaneously gives rise to the longitudinal $(e,e'n)$ contribution. This effect, seen in experiment as a splitting between the longitudinal and transverse spectral functions, can provide valuable information about the dynamics of π and ρ mesons because these two determine the relevant part of the nucleon-nucleon interaction. It would, of course, be ideal to measure directly the longitudinal component in the $(e,e'n)$ cross section as a function of the momentum transfer.

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*Permanent address: Institute of Nuclear Physics, PL-31-342 Krakow, Poland.

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