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Dominance of $^1S_0$ Proton-Pair Emission in the $^{16}O(e, e'pp)$ Reaction

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The reaction $^{16}O(e, e'pp)$ has been studied at a transferred four-momentum $(\omega, |\mathbf{q}|) = (210$ MeV, $300\,\mathrm{MeV}/c)$. Evidence has been obtained for direct knockout of proton pairs from the $1p$ shell. The excitation-energy spectrum of the residual nucleus and the missing-momentum densities indicate that knockout of a $^1S_0$ pair dominates the reaction, while there is also a noticeable contribution from knockout of ^3P pairs. [S0031-9007(97)03460-1]

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The description of short-range correlations (SRC) in complex nuclei is a long-standing problem in many-body physics. These correlations account for the effects of the nucleon-nucleon (NN) interaction at short distance and require a description of the dynamics of nucleons bound in a nuclear system that goes beyond the mean-field approach. Recently, several microscopic calculations of the momentum distribution of nucleons have been performed, both for nuclear matter [1–3] and nuclei [4,5], starting from realistic NN interactions. These calculations indicate that, due to the strong repulsive part of the NN force at short range, nucleons can scatter to energies and momenta far above the Fermi energy and momentum.

If a nucleon of a strongly correlated pair is knocked out from a nucleus, e.g., after absorption of a virtual photon, the residual $A - 1$ nucleus is likely to be left in a state with large excitation energy and momentum. As a consequence, the other nucleon may be emitted as well, which implies that information on SRC in nuclei can be obtained from studies of the semi-exclusive $(e, e'N)$ reaction at large missing energy and momentum [6,7], or from the exclusive $(e, e'NN)$ reaction. The latter reaction is expected to provide the most direct information on the effects of SRC, since in the plane wave impulse approximation (PWIA) its cross section is determined by the correlations in the relative wave function of the nucleon pair. Moreover, the identity of both emitted particles is determined, and the final state is well defined if the residual $A - 2$ nucleus is left in its ground state or a low-lying excited state.

Beyond PWIA, electromagnetically induced two-nucleon knockout may also arise from coupling to meson-exchange currents (MEC) or result from Δ-excitation with subsequent decay via a $\Delta N \rightarrow NN$ reaction. Since SRC, MEC, and Δ-excitation contribute in a different way to the $(e, e'pn)$ and $(e, e'pp)$ reactions, these reactions are expected to yield complementary information on the different processes that contribute to the cross section.

Thus far, no $(e,e'pn)$ and only two $(e,e'pp)$ studies have been published, both using ^{12}C as a target nucleus [8,9]. Although the statistical accuracy in these experiments was limited, the missing-energy spectrum displayed in Ref. [8] shows a clear signature for knockout of two protons from the 1p shell. Furthermore, these data were reasonably well described by calculations, which contained a sizable contribution of SRC in the reaction amplitude.

In this Letter we report on the results of an $(e,e'pp)$ experiment, which was performed with the double-closed shell nucleus ^{16}O as a target. Using large-solid-angle proton detectors, we could measure the angular correlation between the emitted protons with a precision that allowed us to extract information on the relative wave function of proton pairs moving in the 1p shell in ^{16}O.

The experiment was carried out with the electron beam extracted from the Amsterdam Pulse Stretcher (AmPS) at NIKHEF. The energy of the incident electrons was 584 MeV. The average beam current was 2 μA, with a duty factor of approximately 60%. A waterfall target was used, which is described in Ref. [10]. The scattered electrons were detected in a magnetic spectrometer of the QDQ type, and the knocked-out protons in two highly segmented plastic scintillator arrays, HADRON3 and HADRON4 [11]. These two detectors subtend solid angles of 225 and 550 msr and accept protons with energies from 69 to 215 MeV and from 44 to 171 MeV, respectively. The energy ranges are determined by the 5 mm lead and 2 mm steel plates, that were placed in front of the detectors to keep the counting rates of the individual scintillators below 1 MHz.

Data were taken at an energy transfer $\omega = 210$ MeV, a three-momentum transfer $|\mathbf{q}| = 300$ MeV$/c$, and emission angles of the forward proton with respect to $\mathbf{q}$ between 20° and 40°. A total of about 5000 true $(e,e'pp)$ coincidences were measured.

In analogy to the $(e,e'N)$ reaction, the missing energy and missing momentum for the $(e,e'NN)$ reaction are defined as $E_m = \omega - T_1 - T_2 - T_{A-2}$ and $\mathbf{p}_m = \mathbf{q} - \mathbf{p}_1 - \mathbf{p}_2$. The excitation energy of the $A-2$ nucleus is then given by $E_x = E_m - S_{NN}$, where S_{NN} is the two-nucleon separation energy. In Fig. 1(a), the measured excitation-energy spectrum for the reaction ^{16}O$(e,e'pp)$, obtained after subtracting accidental coincidences and after correcting for detection-volume effects, is shown. Figure 1(b) shows the missing-momentum distributions corresponding to four consecutive intervals in excitation energy. The data have not been corrected for dead times in the electronic readout system, radiative effects, and inefficiencies due to hadronic interactions of the protons in the HADRON detectors. These corrections will, however, have a small influence ($\leq$5%) on the shape of the spectrum at low-excitation energy.

For the first time, the transition to a discrete state, i.e., the ground state, can be distinguished in the excitation energy spectrum of an $(e,e'pp)$ reaction. This is due to the achieved energy resolution of about 4.5 MeV at FWHM and to the statistical accuracy of the data. In the ^{16}O(^{6}Li,^{8}B)^{14}C two-proton pickup reaction [12] and the ^{16}O$(p,t)^{14}$O two-neutron pickup reaction [13], leading to isobaric analog states, strong transitions have been observed to the ground state and two 2^+ states at excitation energies of 7.0 and 8.3 MeV. The structure of the missing-energy spectrum around 7.7 MeV is in agreement with the presence of the latter two transitions, although the peaks cannot be separated.

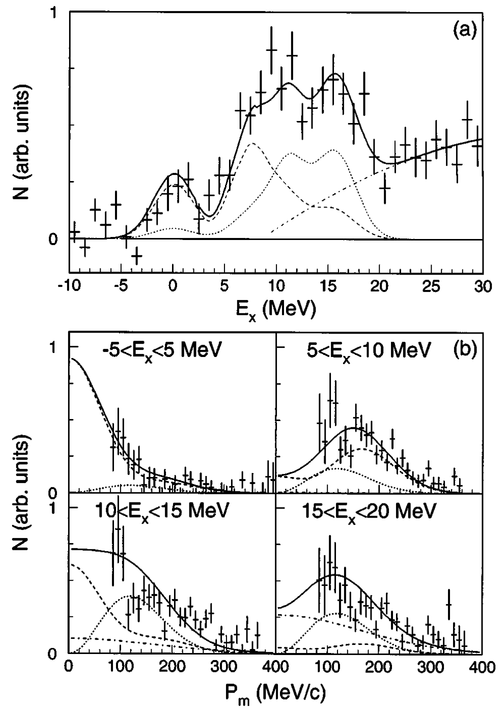

FIG. 1. Excitation-energy spectrum (a) and missing-momentum distributions (b) measured for the ^{16}O$(e,e'pp)$ reaction. The solid line is the result of a fit to the data containing three contributions: ^1S (dashed), ^3P (dotted), and continuum (dot-dashed).

The gross features of the E_x spectrum at low-excitation energy can be interpreted analogously to those of the E_m spectrum measured with the ^{12}C$(e,e'pp)$ reaction at about the same values for the energy and momentum transfer [8]. The estimated centroid energies of the cross sections for $(1p)^2$, (1p,1s), and $(1s)^2$ knockout in the ^{16}O$(e,e'pp)$ reaction are $E_x = 10$, 30, and 50 MeV, respectively. These estimates were made using the removal energies for knockout of protons from the 1p and 1s shells, extracted from ^{16}O$(e,e'p)$ data [14], taking into account the interaction energies for $(1p)^2$, (1p,1s), and $(1s)^2$ pairs. Using the estimated energies given above, the strength in the energy domain $-5 < E_x < 20$ MeV may be attributed to $(1p)^2$ knockout, and that in the domain $20 < E_x < 60$ MeV to knockout of (1p,1s) and $(1s)^2$ pairs and to the emission of more than two nucleons.

A contribution of multinucleon knockout to the E_x spectrum above 8.2 MeV, which is the neutron removal energy in ^{14}C, cannot be excluded. However, the contribution from the ^{16}O$(e,e'ppN)$ reaction to the ^{16}O$(e,e'pp)$ yield for $E_x < 20$ MeV is estimated to be suppressed by two orders of magnitude compared to that from the ^{16}O$(e,e'pp)^{14}$C reaction. This is due to the angular correlation of the $(e,e'pp)$ data, which is absent in multinucleon knockout, and the about ten times smaller detection volume for the $(e,e'ppN)$ reaction. Hence, the strength up to $E_x = 20$ MeV will predominantly stem from two-proton knockout.

In order to interpret the detailed structure of the two-dimensional (E_x, p_m) spectrum, the data have to be compared to theoretical predictions. However, calculations that fully account for the dynamics of the two protons in the initial and final state and the various contributions to the reaction amplitude, are not yet available. Therefore, we restrict ourselves to a simple factorization approximation of the cross section.

The basic ingredient in our approach is the decomposition of the initial state overlap function $\phi^*_{E\alpha}(\mathbf{p}_1,\mathbf{p}_2) = \phi_{E\alpha}(\mathbf{p}_1,\mathbf{p}_2)\sqrt{S_\alpha(E)}$ [15] in wave functions describing the relative and center-of-mass motion of the pair. The indices E and α refer to the energy and the quantum numbers of the $A - 2$ nucleus in its final state. By means of a Moshinski transformation the amplitude $\phi^*_{E\alpha}(\mathbf{p}_1,\mathbf{p}_2)$, which is directly related to the two-hole spectral function [16], can be written as

$$\phi^*_{E\alpha}(\mathbf{p}_1,\mathbf{p}_2) = \sum_{nlSjNL} \psi_{nlSj}(\mathbf{p})\Psi_{NL}(\mathbf{P})C^{NL}_{nlSj,E\alpha}\,. \quad (1)$$

Here, $\psi_{nlSj}(\mathbf{p})$ and $\Psi_{NL}(\mathbf{P})$ are the normalized wave functions for the relative and center-of-mass motion. The angular momentum coupling $\mathbf{S} + \mathbf{L} = \mathbf{J}_f$ is implicit. The expansion coefficients $C^{NL}_{nlSj,E\alpha}$ are obtained in a nuclear structure calculation [16].

Using the above expression for the spectral amplitude, one can factorize the $(e,e'pp)$ cross section if some approximations are made. In the first place, the final-state interaction of the emitted nucleons with the residual nucleus and between each other is neglected. Secondly, it is assumed that no momentum is exchanged between the two protons when the virtual photon is absorbed [17]. With these approximations the cross section can be factorized as

$$\frac{d\sigma}{d\mathcal{V}} = K \sum_{nlSj} \sigma^{nlSj}_{\rm epp}(\mathbf{p})[\Psi_{NL}(\mathbf{P})C^{NL}_{nlSj,E\alpha}]^2, \quad (2)$$

with $d\mathcal{V} = dE_{e'}d\Omega_{e'}dE_{p'_1}d\Omega_{p'_1}dE_{p'_2}d\Omega_{p'_2}$. The relative motion is now separated from the center-of-mass motion of the pair and incorporated in the cross section $\sigma^{nlSj}_{\rm epp}(\mathbf{p})$ for knockout of a (correlated) proton pair with relative momentum $\mathbf{p}$. The factor $[\Psi_{NL}(\mathbf{P})C^{NL}_{nlSj,E\alpha}]^2$ can be interpreted as the spectral function $S^{NL}_{nlSj}(E,P)$, expressing the probability of finding proton pairs with energy E and momentum P in the nucleus. An analytical form of the factorized cross section for knockout of two protons from particular shells was recently reported in Ref. [17]. However, in the latter approach an implicit summation is carried out over the quantum states of the relative and center-of-mass motion of the pair.

The factorized cross section of Eq. (2) is used to interpret the present data, with the restriction that only knockout of protons from the $1p$ shell is considered. The relative motion of the pair is then constrained to the $^1S_0$, ^3P_j (with j = 0, 1, or 2) and $^1D_2$ states. Taking into account the orthogonality of the respective wave functions and neglecting the $^1D_2$ contribution, which is justified for processes with two nucleons in close proximity, Eq. (2) can be approximated as

$$\frac{d\sigma}{d\mathcal{V}} \approx K[\sigma^{^1S}(\mathbf{p})S_{^1S}(E_x,P) + \sigma^{^3P}(\mathbf{p})S_{^3P}(E_x,P)]\,. \quad (3)$$

The cross sections $\sigma^{^1S}$ and $\sigma^{^3P}$ depend on short-range correlations and on the reaction mechanism. No distinction is made here between ^3P_j pairs with j = 0, 1, or 2. This would require a more detailed analysis of the data as well as more elaborate calculations.

If the two protons are in a ^1S initial state, two 0^+ and two 2^+ states are expected to be excited in the residual ^{14}C nucleus. The fragmentation of the lowest 2^+ state into two states is caused by multi-particle-hole excitations, which are not included in the calculations of Ref. [16]. In the following we disregard this fragmentation and consider the 2^+ states at 7.0 and 8.3 MeV as one state at the average energy of 7.7 MeV. If the pair is in a relative ^3P state, the final state can have $J^\pi = 1^+$ as well.

The angular momentum L of the center-of-mass motion of a pair with respect to the $A - 2$ nucleus is known for all transitions mentioned above. For the knockout of ^1S pairs, the angular momenta are $L = 0$ and $L = 2$ for the transitions to the 0^+ and 2^+ states, respectively. With a relative ^3P wave function of the pair, the transitions to the 0^+, 1^+, and 2^+ states are always associated with an angular momentum $L = 1$. Therefore, one may gain information as to whether the pair was in a relative ^1S or ^3P state from the distributions of the center-of-mass momenta for transitions to the various low-lying states. This can be done by comparing the calculated center-of-mass momentum distribution to the measured missing-momentum distribution, which is possible since $P = p_m$ if final-state interactions are neglected.

By combining the theoretical spectral functions $S^{NL}_{nlSj}(E)$ for knockout of ^1S and ^3P pairs from Ref. [16] with the related center-of-mass momentum distributions $F_{NL}(P)$ the energy and momentum-dependent spectral function $S_\beta(E_x,P) = \sum_n F_{NL}(P)S^{NL}_{nlSj}(E_x)$ has been obtained; β stands for either ^1S or ^3P. The distributions $F_{NL}(P)$ were calculated using harmonic oscillator wave functions. The oscillator strength was derived from a fit to the $1p$ proton momentum densities deduced from $^{16}O(e,e'p)$ data [18]. Figure 2 shows the calculated $S_\beta(E_x,P)$ spectra folded with the experimental resolution. The spectra comprise the five transitions mentioned before. The excitation energies of the 0_1^+ (g.s.), 2_1^+ (7.7 MeV), and 1^+ (11.3 MeV) states in ^{14}C were taken from experimental data [19]; the excitation energies of the 0_2^+ (12 MeV) and the 2_2^+ (16 MeV) states have been estimated on the basis of calculations [16] as no experimental data exist above 11 MeV.

The distribution $N[S_{^1S}(E_x,P) + \rho S_{^3P}(E_x,P)] + C(E_x,P)$, integrated over the momentum range that was covered by the detection volume, was fitted to the data of Fig. 1(a). Here, N is a normalization constant and $\rho = \langle\sigma_{\rm epp}^{^3P}\rangle/\langle\sigma_{\rm epp}^{^1S}\rangle$. The shape of the phenomenological continuum C was determined by a fit to the data in the region $25 < E_x < 70$ MeV and is extrapolated down to the three-nucleon knockout threshold.

The results of the fit are shown in Figs. 1(a) and 1(b). The excitation-energy spectrum is well reproduced for $\rho = 0.33 \pm 0.08^{+0.05}_{-0.04}$, indicating that within the probed kinematical range, the cross section for knockout of ^1S pairs is roughly three times as large as that for ^3P pairs. The quoted systematic errors account for the uncertainties in (i) the energy calibration; (ii) the subtraction of the accidental coincidences, caused by a nonuniform time distribution; (iii) the shape of the continuum.

According to Fig. 1(a) the 0^+ ground state and the 2^+ states around 7.7 MeV appear to be predominantly formed by the knockout of ^1S pairs. For the states above 10 MeV the ^3P knockout is most important. This interpretation is confirmed by the distributions of the missing momenta shown in Fig. 1(b), in which the curves are calculated using the parameters obtained from the fits to the missing-energy spectrum.

In a recent theoretical study it is shown that one-body hadronic currents, generated by strongly correlated $^1S_0$ proton pairs, give a significant contribution to the

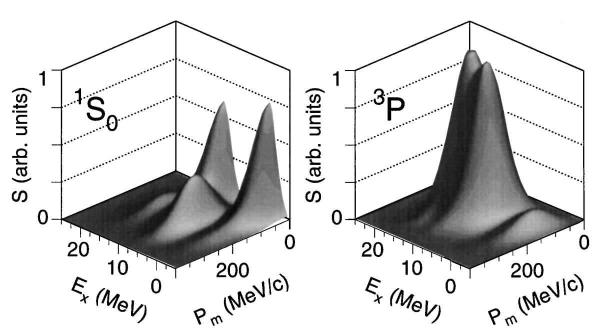

FIG. 2. Calculated spectral functions for knockout of $^1S_0$ and ^3P pp pairs from the $1p$ shell in ^{16}O, folded with an energy resolution of 4.6 MeV.

amplitude of the $^{16}O(e,e'pp)^{14}C_{g.s.}$ reaction [20]. Two-body hadronic currents are suppressed in this reaction, because only $E1$, $E2$, and $M2$ multipole transitions are allowed [21]. The transition via the $M1$ multipole, which is the dominant one for deuteron electrodisintegration and thus for knockout of $^3S_1$ pn pairs in a complex nucleus, is forbidden for knockout of pp pairs in a $^1S_0$ state. Our results can, in view of these theoretical findings, be considered as an indication of the importance of SRC. It is expected that further evidence for SRC will be obtained by comparing the experimental and theoretical cross sections for the transitions to the first 0^+ and 2^+ states. This work is in progress [20,22].

In conclusion, the $^{16}O(e,e'pp)$ reaction has been studied at an energy transfer $\omega = 210$ MeV and a three-momentum transfer $q = 300\,{\rm MeV}/c$. For the first time the excitation-energy spectrum of an $(e,e'pp)$ reaction has been measured with sufficient energy resolution and statistical accuracy to distinguish the transition to a discrete state, i.e., the ground state, in the residual nucleus. The shape of the excitation-energy spectrum up to 20 MeV and the corresponding center-of-mass momentum densities are well described by a spectral function for direct knockout of pp pairs in ^1S or ^3P states, by fitting only one parameter: the ratio $\rho = \langle\sigma_{\rm epp}^{^1S}\rangle/\langle\sigma_{\rm epp}^{^3P}\rangle$. The observation that direct knockout of ^1S pp pairs is the dominant process, opens good perspectives for extracting information on short-range correlations in nuclei from the $(e,e'pp)$ reaction.

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