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Short-Range Nucleon-Nucleon Correlations Investigated with the Reaction $^{12}\mathrm{C}(e, e'pp)$

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The reaction $^{12}\mathrm{C}(e, e'pp)$ has been studied at an energy transfer $\omega = 212$ MeV and a three-momentum transfer $|\boldsymbol{q}| = 70$ MeV/c. The measured missing-energy spectrum shows a signature for knockout of proton pairs from $(1p)^2$, $(1p, 1s)$, and $(1s)^2$ states. A comparison of the data with a calculation, in which different processes leading to two-nucleon knockout are accounted for, shows that the measured cross section for the knockout of a $(1p)^2$ pair can largely be attributed to short-range nucleon-nucleon correlations.

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Recent quasielastic electron scattering $(e, e'p)$ experiments have shown that mean-field theories can only partly describe the properties of nucleons bound in a nuclear system. The depletion of the occupancy of various shells [1], observed throughout the periodic table, suggests that a considerable fraction of the spectroscopic strength is located at large missing energy, which according to the results of many-body calculations is caused by short-range nucleon-nucleon correlations (SRC) [2,3].

A direct way to investigate SRC in nuclei is offered by the two-nucleon knockout reaction $(e, e'NN)$. In such a reaction the virtual photon may be absorbed by a correlated nucleon pair, in which the photon momentum is transferred to either of the two nucleons involved and the transferred energy is shared by both nucleons.

Meson exchange currents (MEC) and intermediate Δ excitation followed by a $\Delta N \rightarrow NN$ reaction can also lead to the emission of two nucleons in an electron scattering process. Although the dynamical aspects of MEC and Δ excitation differ from those of the absorption of a virtual photon by a correlated nucleon pair, these processes cannot be distinguished kinematically. The contributions of SRC, MEC, and Δ excitation to the experimental two-nucleon knockout cross section can therefore only be determined by comparing the data with theoretical calculations, in which these three processes are accounted for.

A study of SRC by means of two-nucleon knockout experiments can be best performed in the "dip" region, i.e., the domain between the broad peaks in the scattered electron energy spectrum corresponding to quasielastic scattering and Δ excitation. In the first place, it is expected that in this region two-nucleon knockout accounts for a sizable fraction of the inclusive (e, e') cross section. Theoretical calculations for quasielastic scattering including MEC and pion production underestimate, for example, systematically the (e, e') cross section in the dip region [4]. Secondly, the contribution of isobar currents to the cross section is relatively small compared to the Δ region.

Evidence for two-nucleon knockout in electron scattering off a complex nucleus has been obtained in semiexclusive $^{12}\mathrm{C}(e, e'p)$ experiments [5,6]. In this reaction only one of the two emitted nucleons is detected and the fact that a second nucleon is emitted is deduced from the relationship between the missing energy and the missing momentum. It is furthermore shown in Ref. [5] that a part of the measured $^{12}\mathrm{C}(e, e'p)$ cross section can be attributed to short-range correlations.

In this Letter we report on the first study of the exclusive $(e, e'pp)$ reaction in the dip region. The data will be compared with the results of a theoretical calculation, in which contributions of SRC, MEC, and Δ excitation are taken into account. Preliminary accounts of this study have been given in Ref. [7].

The experiment was performed with the linear electron accelerator MEA at NIKHEF-K at an energy of 475 MeV. The average current of the electron beam and the duty factor were 1.5 μA and 1%, respectively. The target had a thickness of 21 mg/cm^2. To maximize the coincidence count rate, the quadrupole-dipole-quadrupole electron spectrometer ($\Omega = 15$ msr, $\Delta p/p = 10\%$) was positioned at its most forward angle, i.e., $-27°$. The transferred four-momentum was $(\omega, |\boldsymbol{q}|) =$ (212 MeV, 270 MeV/c). The protons were detected with two highly segmented plastic scintillator arrays. They consist each of about 50 scintillator elements, subtend solid angles of 39 msr, and cover an energy range from 37 to 198 MeV (proton detector P_1) and from 25 to 158 MeV (proton detector P_2) [8].

During the angular correlation measurements the position of P_1 was fixed at the central angle $\theta_{p_1} = 53°$. This

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angle corresponds to $\gamma_{p_1q}^{\text{c.m.}} = 35°$, where $\gamma_{pq}^{\text{c.m.}}$ is defined as the angle between the ejected proton and q in the center-of-mass frame of the virtual photon and the two protons. The angle $\theta_p = 53°$ was the smallest angle at which data could be taken with the proton detector in view of the instantaneous singles count rate, which increases exponentially with decreasing angle. To keep this count rate in the individual detector elements below 1 MHz and the dead time below 10%, a 3 mm Pb absorber was placed in front of P_1, which changed the energy acceptance of P_1 to 58–203 MeV. The angular correlation between the two emitted protons was measured by varying the position of the P_2 detector around the angle $\theta_{p_2} = -104°$, which corresponds to $\gamma_{p_1q}^{\text{c.m.}} - \gamma_{p_2q}^{\text{c.m.}} = 180°$ and to which we therefore will refer as the conjugate angle of $\theta_{p_1} = 53°$.

The proton detectors were calibrated by using protons from the reaction $^1\text{H}(e,e'p)$ and from the inclusive reaction $^{12}\text{C}(e,p)$. From the latter reaction the correlations between the energy losses of protons in the various layers were used. Shifts in the photomultiplier gain and in the baseline of the analog pulses, caused by variations in the high instantaneous count rates, were monitored by a laser system. This system was also used to determine the electronic dead time for the individual scintillator channels. The corrections for these inefficiencies and for those due to hadronic interactions and multiple scattering of the protons were determined by simulating the response of the proton detectors in a Monte Carlo procedure using the code GEANT [9]. The energy resolution in the two proton detectors is 2.5%, and the resulting resolution in the missing energy for two-proton knockout is 6 MeV.

The total systematic error in the measured $^{12}\text{C}(e,e'pp)$ cross section is 5%, which is small compared to the statistical errors. The largest contribution to the systematic error stems from the target thickness, which was determined by measuring the cross section for elastic electron scattering off ^{12}C. This error amounts to 3%.

The statistical errors in the $(e,e'pp)$ cross sections are determined by the sum of the real triple coincidence events and the four types of accidental coincidence events. The ratio between the various contributions to the triple coincidence peak is $N_{(e'p_1p_2)}/N_{(e'p_1)p_2}/N_{(e'p_2)p_1}/N_{(p_1p_2)e'}/N_{e'p_1p_2} = 50\%/20\%/5\%/17\%/8\%$, where the particles between brackets are coincident in time.

In the upper panel of Fig. 1 the number of true triple coincidences measured at $\gamma_{p_1q}^{\text{c.m.}} = 35°$ is displayed as a function of the double missing energy $E_{2m} \equiv E_e - E_{e'} - T_{p_1} - T_{p_2} - T_{\text{recoil}}$. The ninefold differential cross section presented in the lower panel of Fig. 1 is obtained by normalizing the number of true triple coincidence events, after corrections for inefficiencies and radiative effects, to the total luminosity and the experimental phase space.

A thorough treatment of the radiative corrections, which is extremely complicated for $(e,e'NN)$ reactions, is not needed. This can be understood from the following. If the electron loses an amount of energy ϵ_γ before or after scattering takes place, the actual energy transfer is lowered by ϵ_γ, while $|\boldsymbol{q}|$ is reduced to first order by $\approx (w/|\boldsymbol{q}|)\epsilon_\gamma$ and $\cos\theta_q$ is increased by $\approx \epsilon_\gamma/|\boldsymbol{q}|(1 - \omega/|\boldsymbol{q}|)$. This implies that the detected protons are emitted at a somewhat lower $\gamma_{p_1q}^{\text{c.m.}}$, for which, however, the detectors are still centered around the conjugate angles. For example, at $\omega = 212$ MeV and $|\boldsymbol{q}| = 270$ MeV/c and with $\gamma_{p_1q}^{\text{c.m.}} = 35°$ the change in $\gamma_{p_1q}^{\text{c.m.}}$ is -0.15 deg/MeV. Taking into account that the relevant part of the missing-energy spectrum covers a range of 50 MeV, one obtains $\Delta\gamma_{p_1q}^{\text{c.m.}} \leq 8°$. Assuming, furthermore, that the $(e,e'pp)$ cross section depends only weakly on ω and $\gamma_{p_1q}^{\text{c.m.}}$, the radiative corrections will only slightly change the measured integrated cross sections. This assumption is confirmed by the calculations discussed later and by the results of a $^{12}\text{C}(e,e'pp)$ measurement at $\omega = 263$ MeV, $|\boldsymbol{q}| = 303$ MeV/c, and $\gamma_{p_1q}^{\text{c.m.}} = 50°$. The experimental cross section integrated over the range $E_{2m} = 25$–75 MeV is $(46 \pm 33) \times 10^{-12}$ fm^2/MeV^2 sr^3 [10], which is somewhat lower than the corresponding values in the dip region given in Table I. The radiative corrections, however, affect the E_{2m} spectrum. This correction can be calculated in a way similar to that for the $(e,e'p)$ data [11], taking the dependence of the cross section on E_{2m} into account. The result is an increase of the cross section in the regions $E_{2m} = 25$–30 and 50–75 MeV with 24% and 12%, respectively.

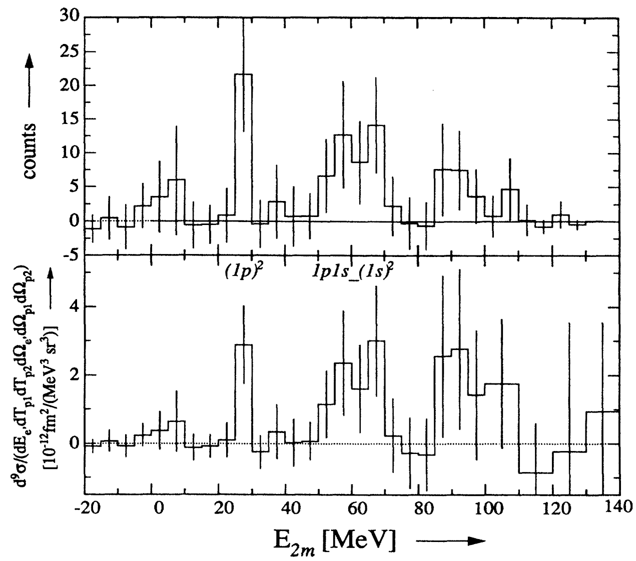

FIG. 1. In the upper panel the total number of triple coincidences, measured for $\theta_{p_1} = 53°$ ($\gamma_{p_1q}^{\text{c.m.}} = 35°$) and $\theta_{p_2} = -90°$, $-104°$, and $-118°$, is displayed as a function of the double missing energy E_{2m}. The data have been corrected for inefficiencies and accidental coincidences. In the lower panel the cross sections obtained from these data are presented. They are corrected for radiative effects.

In Fig. 1 the data measured at three positions of detector P_2, i.e., $\theta_{p_2} = -90°$, $-104°$, and $-118°$, are summed to increase the statistical accuracy of the data. Although the statistical errors are still large, one can clearly distinguish a narrow peak at $25 < E_{2m} < 30$ MeV and a broad structure at $50 < E_{2m} < 75$ MeV. The narrow peak can be identified well with a transition to the ground state of ^{10}Be, since the separation energy of two protons in ^{12}C is 27.2 MeV. Because of the modest energy resolution of 6 MeV in E_{2m}, contributions of transitions to low lying excited states in ^{10}Be cannot be separated from the ground state transition. The cross section measured in the region $E_{2m} = 50-75$ MeV can be partly attributed to knockout of a $(1p, 1s)$ pair and partly to knockout of a $(1s)^2$ pair. The average removal energies for such pairs have been calculated from the separation energies of $1p$ and $1s$ protons in ^{12}C taking into account the interaction energies of the $(1p)^2$, $(1p, 1s)$, and $(1s)^2$ proton pairs. The separation energy of a $1p$ proton in ^{12}C is 16.0 MeV. The longitudinal response for removal of a $1s$ proton from ^{12}C, determined via a separation of the longitudinal and transverse structure functions in the quasifree ^{12}C$(e, e'p)$ reaction, indicates that the $1s$ spectroscopic strength is located in the region $25 < E_m < 60$ MeV and that the centroid of this energy distribution is at 38 MeV [12]. For the interaction energies of the respective proton pairs, G-matrix elements were taken. They were increased by ≈20% to account for the induced interaction [13]. The values are $E_{\text{int}}(1p)^2 = -4.5$ MeV, $E_{\text{int}}(1p, 1s) = -2$ MeV, and $E_{\text{int}}(1s)^2 = -8.5$ MeV, thus obtaining for the two-proton removal energies $E_r(1p)^2 = 27.5$ MeV, in good agreement with the two-proton separation energy in ^{12}C, $E_r(1p, 1s) = 52$ MeV and $E_r(1s)^2 = 67.5$ MeV.

The calculated removal energies for $(1p, 1s)$ and $(1s)^2$ pairs are in the region $50 < E_{2m} < 75$ MeV, where the broad structure is located. This structure can thus be associated with the knockout of such proton pairs. The small yield in the region between the first two peaks is an indication that the cross section up to 75 MeV is dominated by two-proton knockout. At $E_{2m} = 34$ MeV two additional channels open, i.e., the ^{12}C$(e, e'ppn)^9$Be channel and the ^{12}C$(e, e'ppnn)^4$He^{4}He channel. Since no strength is observed in the region $E_{2m} = 30-50$ MeV, the contributions of these reactions to the measured cross section are small. The cross section measured for $E_{2m} >$ 85 MeV may be due to knockout out of more than two particles.

The cross sections measured at $\gamma_{p_1 q}^{\text{c.m.}} = 35°$ are presented in Table I. The data are integrated over the E_{2m} intervals 25−30, 50−75, and 25−75 MeV. In Table I ^{12}C$(e, e'pp)$ cross sections averaged over the experimental phase space are given. The calculation was performed in an unfactorized form including one-body and two-body hadronic currents, which account for the knockout of a correlated nucleon pair and MEC and Δ currents, respectively. The initial state overlap wave function for a correlated pair is approximated by the expression

$$\langle \Phi_{A-2} | \Psi_i \rangle \approx S^{1/2} f(|\boldsymbol{r}_1 - \boldsymbol{r}_2|) \phi_{n_1 l_1}(\boldsymbol{r}_1) \phi_{n_2 l_2}(\boldsymbol{r}_2) , \tag{1}$$

where $f(|\boldsymbol{r}_1 - \boldsymbol{r}_2|)$ is a two-nucleon correlation function and $\phi_{n_1 l_1}(\boldsymbol{r}_1)$ and $\phi_{n_2 l_2}(\boldsymbol{r}_2)$ are independent-particle shell-model (IPSM) wave functions. For $f(|\boldsymbol{r}_1 - \boldsymbol{r}_2|)$ a central correlation function, extracted by Gearhart and Dickhoff from a microscopic calculation of the two-nucleon density matrix in nuclear matter, has been adopted [14]. For the normalization factor S the number of $(1p)^2$, $(1p, 1s)$, or $(1s)^2$ pairs in the IPSM has been taken. The applied two-body current operators were derived from the chirally invariant effective Lagrangian with pseudovector coupling. They were calculated by means of a nonrelativistic reduction of the lowest order Feynman diagrams. Therefore, the contribution of MEC vanishes in the $(e, e'pp)$ amplitude. The contribution for the intermediate Δ currents was calculated with an energy dependent Δ propagator. The final state interaction of the two outgoing protons with the residual nucleus was described by means of an optical potential. More details of the calculations are given in Ref. [15].

Because the calculated cross section for the $(e, e'pn)$ reaction is much larger than that for the $(e, e'pp)$ reaction, a two-step process $(e, e'pn)(n, p)$ could give a sizable contribution to the $(e, e'pp)$ cross section. The contribution of this two-step process has been incorporated in the treatment of the final state interaction by using the Lane model [16,17]. The Lane model explicitly accounts for the charge exchange between analog states, which are in this case the $T = 1$ states in ^{10}B and ^{10}Be. The transition amplitude can be calculated by applying an isospin dependent optical potential. The results of the calculations indicate that a two-step $(e, e'pn)(n, p)$ process via a transition between

TABLE I. The ^{12}C$(e, e'pp)$ cross sections measured at $\theta_{p_1} = 53°$. Presented are the cross sections integrated over the E_{2m} region 25−30 and 50−75 MeV corresponding to $(1p)^2$ and $(1s, 1p) + (1s)^2$ knockout, respectively, and the cross section integrated over the region $E_{2m} = 25-75$ MeV. Also given are the cross sections calculated with a correlation function deduced from recent many-body calculations in nuclear matter (see text).

	$\frac{d^8\sigma}{dE_{e'}\, dT_{p_2}\, d\Omega_{e'}\, d\Omega_{p_1}\, d\Omega_{p_2}}$ $[10^{-12}$ fm$^2/($MeV^2 sr$^3)]$						
θ_{p_2}	Expt (25−30 MeV)	Theory $(1p)^2$	Expt (50−75 MeV)	Theory $(1p, 1s)$	Theory $(1s)^2$	Expt (25−75 MeV)	Theory all
−90°	9(8)	11	42(28)	8	1	49(31)	20
−104°	13(8)	13	40(21)	7	1	59(25)	21
−118°	21(12)	10	35(23)	6	1	52(27)	17
Average	14(5)	11	39(14)	7	1	54(16)	19

the isobaric analog $T = 1$ states in ^{10}B and ^{10}Be can be neglected [18]. It is technically more complicated to calculate the amplitude for a two-step reaction including transitions between nonanalog $T = 0$ states in ^{10}B and $T = 1$ states in ^{10}Be. However, it can be argued that this contribution to the $(e, e'pp)$ cross section is not large either. The amplitude of the first step of such a reaction, i.e., the knockout of a pn pair with isospin $T = 0$, is assumed to be substantially larger than that for a $T = 1$ pair. On the other hand, the amplitude of the subsequent Gamow-Teller charge exchange reaction is much lower than that for a Fermi transition between isobaric analog states. For example, the ratio between the cross section for the Fermi and Gamow-Teller transitions in the ^{9}Be(^{3}He, ^{3}H)^{9}B reaction is about 3 [19].

The agreement between the data and the results of the calculations in Table I is satisfactory for the $(1p)^2$ knockout. At higher excitation energies, the calculated cross sections are systematically below the experimental data, but the low number of triple coincidences does not allow a more detailed comparison for $(1p, 1s)$ and $(1s)^2$ knockout. Note that the calculations have been performed without any adjustable parameter and that the results are very sensitive to the adopted correlation function (see Ref. [15]). To investigate the relative importance of the one-body and two-body currents, calculations were performed in which only the one-body part of the hadronic current was taken into account. The cross section thus calculated amounts to about 90% of the cross section resulting from the full calculation. This indicates the dominance of the amplitude due to the one-body current, which is in two-nucleon knockout reactions determined by SRC. It is of interest to note that, in this case, the momenta of the protons in the initial state are in the range 300–550 MeV/c.

The cross sections measured at the three values of θ_{p_2} do not show a measurable angular correlation effect. This is partly due to the integration over the opening angle ($\theta = 14°$) of the proton detectors and partly to a lack of statistical accuracy in the data. However, an additional measurement at the angular combination $\theta_{p_1} = 101°$ and $\theta_{p_2} = -135°$, corresponding to $\gamma_{p_1q}^{\text{c.m.}} - \gamma_{p_2q}^{\text{c.m.}} = 260°$ which is far from the conjugate angle, provides further evidence for the dominance of two-nucleon knockout in the measured $(e, e'pp)$ yield. The integrated experimental cross section over the E_{2m} domain 25–75 MeV for this angle combination is $(11 \pm 12) \times 10^{-12}$ fm^2/MeV^2 sr^3 [10] and thus consistent with zero.

In conclusion, the double missing-energy spectrum measured for the reaction ^{12}C$(e, e'pp)$ in the dip region indicates knockout of $(1p)^2$, $(1p, 1s)$, and $(1s)^2$ proton pairs. The results of theoretical calculations, in which short-range correlations, MEC, and Δ excitation were taken into account, are in satisfactory agreement with the experimental cross sections for $(1p)^2$ knockout. The calculations, performed with a central correlation function derived from recent many-body calculations, indicate that short-range correlations drive the dominant contribution to the measured $(e, e'pp)$ cross sections.

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[1] L. Lapikás, Nucl. Phys. **A553**, 297c (1993).

[2] O. Benhar *et al.*, Nucl. Phys. **A505**, 267 (1989).

[3] W. H. Dickhoff and H. Müther, Rep. Prog. Phys. **55**, 1947 (1992); H. Müther and W. H. Dickhoff, Phys. Rev. C **49**, R17 (1994).

[4] J. W. van Orden and T. W. Donnelly, Ann. Phys. **131**, 451(1981).

[5] L. J. H. M. Kester *et al.*, Phys. Lett. B **344**, 79 (1995).

[6] R. W. Lourie *et al.*, Phys. Rev. Lett. **56**, 2364 (1986).

[7] L. J. H. M. Kester *et al.*, Nucl. Phys. **A553**, 709c (1993); in *Proceedings of 8th Amsterdam Miniconference on Correlations in Hadronic Systems,* edited by E. Jans, L. Lapikás, P. J. Mulders, and J. Oberski (NIKHEF, Amsterdam, 1993), p. 58.

[8] A. Zondervan *et al.*, Nucl. Instrum. Methods Phys. Res., Sect. A **342**, 436 (1994).

[9] R. Brun *et al.*, GEANT Manual, CERN Data Handling Division.

[10] L. J. H. M. Kester, Ph.D. thesis, Free University Amsterdam, 1993 (unpublished).

[11] J. W. A. den Herder *et al.*, Nucl. Phys. **A490**, 507 (1988).

[12] P. E. Ulmer *et al.*, Phys. Rev. Lett. **59**, 2259 (1987).

[13] M. G. E. Brand *et al.*, Nucl. Phys. **A531**, 253 (1991).

[14] C. C. Gearhart and W. H. Dickhoff (private communication).

[15] C. Giusti and F. D. Pacati, Nucl. Phys. **A535**, 573 (1991); C. Giusti *et al.*, Nucl. Phys. **A546**, 607 (1992).

[16] P. E. Hodgson, *Nuclear Reactions and Nuclear Structure* (Clarendon, Oxford, 1971).

[17] S. Boffi *et al.*, Nucl. Phys. **A436**, 438 (1985).

[18] C. Giusti and F. D. Pacati (to be published).

[19] H. Akimune *et al.*, Nucl. Phys. **A569**, 245c (1994).