Abstract

We investigate the origin of the strength at large missing energies in electron-induced proton knockout reactions. For that purpose the reaction $\Omega_{16}(e, e'p)$ was studied at a central value $\omega = 215$ MeV of the energy transfer, and two values of the momentum transfer: $q = 300, 400$ MeV/$c$, corresponding to the “dip region”. Differential cross sections were determined in a large range of missing energy ($E_m = 0 - 140$ MeV) and proton emission angle ($\gamma_{pq} = 0 - 110^\circ$), and compared to predictions of a model that includes nucleon-nucleon short-range correlations and two-body currents. It is observed that, in the kinematic domain covered by this experiment, the largest contribution to the cross section stems from two-body currents, while short-range correlations contribute a significant fraction.

PACS: 21.10.Pc; 24.10.-i; 25.30.Fj

Keywords: Electron-induced knockout reactions; Short-range correlations; Two-body currents
Electron-induced proton knockout \(A(e, e'p)\) reactions, at low values of missing energy \(E_m\) and missing momentum \(p_m\), are dominated by direct processes, where the detected proton is the one that was hit by the transferred virtual photon (Impulse Approximation), while the recoiling (A-1) nucleus is left in an (excited) state, of which most properties are well described by mean-field theory. At larger \(E_m\) and \(p_m\), other reaction mechanisms, as two- and multi-nucleon knockout, start to play a role. Here the undetected (A-1) system could consist of a residual nucleus and one or more nucleons that were correlated with the hit nucleon and that have been knocked out in the reaction. These mechanisms should be dominant when the values of missing energy are higher than those expected from mean-field theory for the deepest bound state and where still an appreciable strength is measured (see for example [1, 2, 3, 4] and references therein). The aim of the present paper is to examine the origin of this excess strength in terms of short-range correlations (SRC) and two-body currents. For that purpose two channels can be studied: exclusive two-nucleon knockout or semi-inclusive one-nucleon knockout.

In the two-nucleon knockout \((e, e'pN)\) reaction, SRC in nuclei are probed directly by measuring the cross section for transitions to selected states at small excitation energy in the residual nucleus [5, 6, 7, 8]. The single nucleon-knockout \((e, e'p)\) reaction can provide information on the nucleon spectral function at large energy and momentum, which is sensitive to the nucleon-nucleon interaction at short distance (cf. Ref. [9] and [10]). However, in both cases other competing processes contribute to the cross section. In particular, two-body currents, which include meson-exchange currents (MEC) and intermediate \(\Delta\)-excitation with a subsequent \(\Delta N \rightarrow NN\) interaction, are known to make a substantial contribution to both the cross section of the exclusive \((e, e'pN)\) reaction and the semi-inclusive \((e, e'p)\) reaction. Hence, for these reactions a decomposition of the cross section into contributions from one-body and two-body hadronic currents can only be made by comparing the data with calculated cross sections that include both processes.

The semi-inclusive \((e, e'p)\) data have to be compared to cross sections calculated for a large domain in missing energy \(E_m\) and missing momentum \(p_m\), because the relative contribution of either of the two processes to this reaction depends on these kinematic variables. Furthermore, in choosing the \((E_m, p_m)\) domain for which this comparison is made, one has to take into account that in the process of interest two particles are emitted and only one is detected. Thereby, \(E_m\) and \(p_m\) are largely determined by the kinetic energy and momentum of the undetected nucleon. Neglecting the momentum and intrinsic excitation of the recoiling (A-2) nucleus, the non-relativistic relation between these quantities reads:

\[
E_m = E_{thr} + \frac{A - 2}{A - 1} \frac{p_m^2}{2M},
\]

where \(M\) is the nucleon mass, the threshold energy for two-nucleon knockout \(E_{thr} = E_A - E_{(A-2)}\) is the difference between the binding energies of the A and (A-2) nucleon systems, and the factor \(\frac{p_m^2}{2M}\) in the second term is the kinetic energy of the unde-
Figure 1: Contours of the detection volumes in the \((E_m, p_m)\) phase space (top panels) and \((E_m, \gamma_{pq})\) plane (bottom panels) for the kinematics with \(q = 300\) MeV/c (left) and 400 MeV/c (right). The dashed curves show the position of the ridge according to Eq. (1).
cussed in this Letter, are about the same as those for the $^4$He experiment. This allows a comparison between both data sets, which is of interest because, in a mean-field picture, in $^4$He the nucleons are knocked out of the 1s shell, whereas in $\Omega$16 knockout of nucleons from the 1p shell is the dominant process. A detailed comparison between the data for $\Omega$16 and $^4$He will allow to study the mass dependence of short-range correlations in nuclei.

The experiment was performed in the EMIN (external target) hall of the Amsterdam Pulse Stretcher (AmPS) facility [13] at NIKHEF. Electrons extracted from AmPS had an energy of 575 MeV. The target used in this experiment was a single foil waterfall target [14]. A thin film of water was formed due to surface tension and adherence to two metal bars positioned below a thin slit, through which the water was pumped from a reservoir. The scattered electrons and emitted protons were detected in the QDQ high-resolution magnetic spectrometer and in the large-acceptance scintillator detector HADRON3 [15], respectively. The latter detector consists of two hodoscope layers (H1 and H2) and six energy determining layers (L1-L6) of plastic scintillator slabs. It features an angular acceptance of $\pm 14^\circ$ and a nominal energy acceptance of 50-225 MeV. For the present experiment the low-energy threshold was raised to 65 MeV by installation of a 5 mm thick Pb-shield in front of the detector. Thus, the detector could be placed at angles as forward as 30$^\circ$ without being swamped by low-energy protons, while simultaneously allowing the detection of protons along the momentum transfer $q$. The angular resolution was 0.52$^\circ$ both in and out of the reaction plane.

Before starting data taking the energy-response of HADRON3 was calibrated using the continuous energy-spectrum of the detected protons (singles events). The high voltages of all photo-multippliers were set such that the ADC value corresponding to the maximum energy-loss of the protons in a specific layer was about 75% of the range. The kinetic energy of the protons was determined from the amount of light measured in the layer in which the particle was stopped.

This amount of light and that measured in the preceding layer were used for particle identification [15]. The arrival time of the protons in the HADRON3 detector was extracted from the signals in the first energy-determining layer. A time resolution of 700 ps (FWHM) was achieved for coincidences between electrons and protons.

During several dedicated runs the cross-section for elastic electron scattering off $\Omega$16 was measured, using events that were recorded with the QDQ magnetic spectrometer. From these data the thickness of the waterfall target was determined using the known cross section for elastic electron scattering off $\Omega$16 [16]. The measured thickness was 173 $\pm$ 4 mg/cm$^2$. The error is completely dominated by the systematic experimental uncertainties. Throughout the experiment the target thickness was monitored by comparing the singles rates in the QDD spectrometer and HADRON3 detectors. These data indicate that over the complete experiment variations in the thickness of the water film were within a range of $\pm 3\%$. The variations are known with an accuracy of much better than 1% and accounted for in the normalization.

Data for the $\Omega$16($e, e'p$) reaction were
taken at an average transferred energy \( \omega = 210 \text{ MeV} \) and at two values of the average transferred momentum \( q \): 300 MeV/c (kinematics I) and 400 MeV/c (kinematics II). These values of \((\omega, q)\) correspond to the so-called “dip region”, the domain between the cross section maxima for quasi-elastic scattering and \( \Delta \)-production.

For each of the kinematics I and II electron-proton coincidences were measured at four angular settings \( \theta_p \) of the HADRON3 detector. They correspond to the following ranges in the proton emission-angle \( \gamma_{pq} = \theta_p - \theta_q \) with respect to the direction \( \theta_q \) of the momentum-transfer vector \( q \): \( 0^\circ \leq \gamma_{pq} \leq 102^\circ \) for kinematics I \( (q=300 \text{ MeV/c}, \theta_q=33.6^\circ) \) and \( 0^\circ \leq \gamma_{pq} \leq 85^\circ \) for kinematics II \( (q=400 \text{ MeV/c}, \theta_q=39.3^\circ) \). In the lower part of Fig. [1] the contours of the detection volumes, expressed in \( E_m \) and \( \gamma_{pq} \), are displayed for the two values of the transferred momenta. The upper part of Fig. [1] shows the corresponding phase-spaces in missing energy and missing momentum. They span the ranges \(-20 \leq E_m \leq 150 \text{ MeV} \) and \( 100 \leq p_m \leq 800 \text{ MeV/c} \), respectively.

The data were corrected for radiative effects using the formalism developed by Mo and Tsai [17]. Effects due to internal and external Bremsstrahlung as well as ionisation were taken into account. The electromagnetic character of the radiative effects allows a precise calculation of the transfer of reaction strength from small to large \( E_m \) values, while \( p_m \) can either increase or decrease. The unfolding of the radiative effects in the measured cross sections as a function of \( E_m \) and \( p_m \) was conducted as follows. Starting at the lowest \( E_m \) bin, the cross section in each \( p_m \) bin correspond-

ing to this \( E_m \) value was corrected for the loss of events. Next the radiative strength stemming from the first \( E_m \) bin was subtracted from all other bins in \( (E_m, p_m) \). This procedure was repeated for the (corrected) strength of the second \( E_m \) bin and subsequently for all other bins until the complete \( (E_m, p_m) \) spectrum was unfolded. Sizable contributions to the cross sections may stem from radiative effects originating from \( (E_m, p_m) \) regions that are not covered by the kinematic acceptance of the experiment. Especially the strength originating from the valence shells in the \( p_m \) range 50-150 MeV/c can contribute appreciably. The radiative effects associated with knockout from the \( 1p_{1/2} \) and \( 1p_{3/2} \) single-particle levels in O16 were estimated using a fit to their momentum distributions determined from high-resolution data previously measured at NIKHEF [18]. To minimize the influence of \( (E_m, p_m) \) bins with a very small number of events and consequently a small statistical accuracy, for each \( E_m \) bin fits as function of \( p_m \) were made to the data. Then, the results of the fits were used in the radiative unfolding procedure.

From the data taken at each of the two combinations of \( (\omega, q) \) the measured cross sections, differentiated with respect to the electron and proton solid angles \( (d\Omega_e, d\Omega_p) \) and to the proton kinetic energy \( (dT) \) and electron scattering energy \( (dE) \), are shown in Figs. [2] and [3]. The total systematic error in the cross section amounts to 7%. It results from the quadratic sum of 5% uncertainty in the radiative unfolding procedure including extrapolation of the continuum strength outside the measured region, and a 5% systematic experimental error. The latter results mainly from the uncertainties
in the HADRON3 detection efficiency (3%) and in the target thickness determination (2.5%).

Fig. 2 shows the cross sections measured at a momentum transfer \( q = 400 \text{ MeV/c} \). They are displayed as a function of \( E_m \) in the range 0–50 MeV, at five central values of the missing momentum. It is clear that the cross section at small \( E_m \) (10 \( \leq E_m \leq 20 \) MeV), corresponding to knockout of a proton from the 1p shell and leaving the residual nucleus in a state with small excitation energy, decreases rapidly at increasing missing momentum. This trend is characteristic for the proton momentum distribution in a nucleus as calculated in a mean field approach. A similar observation has been made for the \(^4\text{He}(e,e'p)\) reaction (cf. Ref. [2]). On the contrary, above \( E_m \approx 25 \text{ MeV} \) the \( p_m \) dependence of the cross section is softer. In this domain knockout of two or more nucleons gradually becomes the dominating reaction mechanism (see Fig. 2). According to Eq. (1), the missing energy \( E_m \) and missing momentum \( p_m \) are correlated in a two-nucleon knockout reaction in which only one nucleon is detected. Indeed, the maximum of the continuum cross section in Fig. 2 is seen to shift toward higher \( E_m \) with increasing \( p_m \).

In Fig. 3, the six-fold differential cross sections for the \( ^{16}\text{O}(e,e'p) \) reaction measured as a function of the missing energy at \( q = 300 \text{ MeV/c} \) (left) and 400 MeV/c (right), are presented for seven bins in \( \gamma_{pq} \), together with calculated cross sections. This part of the \( E_m \) spectrum contains the information on short-range correlations and other processes that contribute to two-nucleon knockout. Two domains do not contain data. They are out of the acceptance covered in the present experiment (see Fig. 1).

The theoretical cross sections for two-nucleon knockout, also shown in Fig. 3, were evaluated in an unfactorized framework based on the assumption mentioned above, i.e. that in a semi-inclusive \((e,e'p)\) reaction at large \( E_m \) two nucleons are emitted, of which one is detected [9]. They include contributions of one-body as well as two-body hadronic currents, and can be considered as an extension of the two-nucleon knockout model for transitions to the ground state and states at low excitation
Figure 3: Missing-energy spectra for the $^16\text{O} (e, e' p)$ reaction at a momentum transfer $q = 300$ MeV/c (left panel) and 400 MeV/c (right panel). The dotted curves correspond to calculated cross sections for knockout of a proton from the $s$-shell. The dashed (dot-dash) curves represent the results from calculations of two-nucleon knockout due to one-body (two-body) hadronic currents. The solid curve is the coherent sum of all contributions. The black triangles show the position where the maximum strength from correlated pairs is expected according to Eq. (1).

Figure 3: Missing-energy spectra for the $^16\text{O} (e, e' pN)$ reaction ($N$ is either a proton or a neutron) to energies beyond the nucleon separation energy [11]. In the representation of Fig. 3 the structure of the ridge stemming from two-nucleon knockout is most significant. The results obtained for the $^4\text{He} (e, e' p)$ reaction [2] were presented in the same way. Both data-sets exhibit qualitatively similar features. Note that the cross sections systematically decrease at increasing $\gamma_{pq}$ and that the values of $E_m$ at which the cross section reaches a maximum increase with increasing $\gamma_{pq}$. This is characteristic for a two-nucleon knockout reaction in which only one of the ejectiles is detected, as ex-
pressed by Eq. (1). In such a reaction the missing energy and momentum are largely accounted for by the unobserved nucleon, as indicated by the dashed curve in Fig. 1. Hence, the angles at which the cross sections reach the maximum values and the widths of the distributions are characteristic for the internal initial-state momentum of the knocked-out nucleon pair.

The various curves in Fig. 3 represent the results of unfactorized distorted-wave calculations, performed for the two values of the transferred momentum, i.e. 300 and 400 MeV/c. The dotted curve accounts for the contribution of single-proton knockout from the 1s shell. For $\gamma_{pq} \geq 25^\circ$ this cross section becomes negligibly small. The computed $(e, e'p)$ strength attributed to the SRC, i.e. central short-range and tensor correlations, are presented by the dashed curves. This strength is produced through the one-body currents and would vanish identically in a mean-field theory. The $(e, e'p)$ strength due to the genuine two-body currents, i.e. meson-exchange and isobar currents, are presented by the dot-dash curves. Finally, the solid curves represent the coherent sum of all contributions. It is observed that the cross sections stemming from the SRC (or, one-body currents) and those from meson-exchange and isobar currents (or, two-body currents) exhibit a similar dependence on $E_m$. In the considered kinematic domain the correlations (dominated by the NN tensor contribution) account for about a third of the total strength.

Comparison of the data with the calculated cross sections indicates that there is acceptable overall agreement. The calculations reasonably reproduce the dependence on $E_m$ of the cross sections at larger values of $\gamma_{pq}$. For both kinematics I and II, the experimental cross sections decrease by large factors, in the range between three to twenty, depending on the value of $\gamma_{pq}$. This reduction would be about 30% if caused only by single-proton knockout, proportional to the proton electromagnetic form factors.

In Ref. [19] the theoretical model presented here was compared to $016(e, e'p)$ JLAB data that cover a range of missing energies and momenta comparable to the present data. However, the JLAB data were obtained in quasi-elastic kinematics at considerably larger values of the energy and momentum transfer $(\omega, q) = (439 \text{ MeV}, 1000 \text{ MeV/c})$. The model could account for the transverse nature and the shape of the JLAB data, but for only half of the magnitude of the measured cross sections.

In Ref. [2] the $^4\text{He}(e, e'p)$ data taken at $\omega = 215 \text{ MeV}$ and $q = 401 \text{ MeV/c}$ are presented and compared to the results of microscopic calculations performed by Laget. The experimental and calculated cross sections presented in Fig. 3 exhibit similar features as those for the $^4\text{He}(e, e'p)$ reaction. Indeed, the effect of SRC (one-body currents) gradually decreases at increasing $\gamma_{pq}$. At $\gamma_{pq} = 80^\circ$ meson-exchange and isobar currents were found to account for about 65% of the cross section. A similar observation emerges from the $016(e, e'p)$ reaction.

In conclusion, the comparison of the present $016(e, e'p)$ data with advanced model calculations shows that, at missing energies above about 25 MeV and in the studied kinematic range of missing momentum, single-proton knockout is manifestly small. In this energy region the contributions from two-body (meson-exchange and
isobar) currents and to a lesser extent those from short-range correlations dominate the cross sections. In order to further distinguish between the latter two contributions in future experiments a longitudinal-transverse separation of the cross section is mandatory.

We would like to thank S. Colilli, R. Crateri, F. Giuliani, M. Gricia, M. Lucentini and F. Santavenere for the preparation and maintenance of the waterfall target.

This work is part of the research program of the Foundation for Fundamental Research of Matter (FOM), which is financially supported by the Netherlands’ Organisation for the Advancement of Pure Research (NWO).

References

[1] C. Marchand et al., Phys. Rev. Lett. 60 (1988) 1703; Erratum, ibid. 60 (1988) 2704.

[2] J.J. van Leeuwe et al., Phys. Lett. 523 (2001) 6.

[3] F. Benmokhtar et al., Phys. Rev. Lett. 94 (2005) 082305.

[4] K.G. Fissum et al., Phys. Rev. C70 (2004) 034606.

[5] C.J.G. Onderwater et al., Phys. Rev. Lett. 81 (1998) 2213.

[6] D.L. Groep et al., Phys. Rev. Lett. 83 (1999) 5443.

[7] R. Starink et al., Phys. Lett. B474 (2000) 33.

[8] R.A. Niyazo et al., Phys. Rev. Lett. 92 (2004) 052303.

[9] S. Janssen, J. Ryckebusch, W. Van Nespen and D. Debruyne, Nucl. Phys. A672 (2000) 285.

[10] D. Rohe et al., Phys. Rev. Lett. 93 (2004) 182501.

[11] J. Ryckebusch and W. Van Nespen, Eur. Phys. J. A20 (2004) 435.

[12] C. Ciofi degli Atti and S. Simula, Phys. Rev. C53 (1996) 1689.

[13] P.K.A. de Witt Huberts, Nucl. Phys. A553 (1993) 845c.

[14] F. Garibaldi et al., Nucl. Instr. Meth. in Phys. Res. A314 (1992) 1.

[15] A.R. Pellegrino et al., Nucl. Instr. Meth. in Phys. Res. A437 (1999) 188.

[16] H. de Vries, C.W. de Jong and C. de Vries, Atom. Nucl. Data Tables 36 (1987) 495.

[17] L.W. Mo and Y.S. Tsai, Rev. Mod. Phys. 41 (1969) 205.

[18] M. Leuschner et al., Phys. Rev. C49 (1994) 995.

[19] N. Liyanage et al., Phys. Rev. Lett. 86 (2001) 5670.