PROBING N-N CORRELATIONS WITH VIRTUAL (AND REAL) PHOTONS

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PROBING N-N CORRELATIONS WITH VIRTUAL (AND REAL) PHOTONS

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ABSTRACT
Knockout of high-momentum protons from a heavy nucleus may give information on the role of nucleon-nucleon correlations in nuclei. As meson-exchange currents may also give rise to the emission of fast protons, it is desirable to perform complementary experiments which are expected to be more sensitive to exchange-current contributions. With these aims in mind a set of (e,e'p) and (\gamma,p) experiments centered at high-recoil momenta has been performed on 208Pb. Both experiments made use of high-duty factor electron beams extracted from stretcher facilities (AmPS and the MAX-LAB, respectively). The results are compared to various distorted-wave impulse approximation (DWIA) calculations. The 208Pb(e,e'p) data at low missing energies are well described if long-range correlations are included in a quasi-particle approach, while at higher missing energies the data are well above the calculations even if short-range correlations are included. The 208Pb(\gamma,p) data cannot be understood in a direct-knockout framework. Including meson-exchange currents in the DWIA calculations through the Siegert Theorem gives a satisfactory description of the data, but this result is not corroborated by an independent RPA calculation. At higher missing energies the 208Pb(\gamma,p) data reveal enhanced strength as well, but not as much as would be expected from a quasi-deuteron estimate. Some results of related experiments are also discussed.

1. Introduction

In classical mechanics one can evaluate the momentum \( p \) of a particle with mass \( m \) bound by some potential \( U \) by equating the corresponding central force to the centripetal force:

\[
\frac{mv^2}{r} = \frac{U(r)}{r}
\]

where \( r \) represents the radial position of the particle, resulting in \( p = \sqrt{mU} \). If applied to a proton bound in a nuclear mean-field potential of about 50 - 60 MeV, we find \( p = 230 \) MeV/c, which is in good agreement with typical values of the Fermi momentum. At short inter-nucleon distances the influence of the mean field will be overwhelmed by that of the nucleon-nucleon potential, which can be as large as 500 MeV at about 1 fm. Using the aforementioned simple estimate for the corresponding proton momentum we find \( p = 680 \) MeV/c. Hence, the study of high-proton momenta in nuclei will provide information on the influence of the short- (and long-) range part of the NN-interaction on the dynamics of nucleons, i.e. on the role of NN-correlations in nuclei.

Proton momenta in nuclei can be measured by means of electromagnetically induced proton-knockout experiments, such as the reaction (e,e'p). Measurements\(^1,2,3\) of this kind have
section at photon energies around 60 MeV. An estimate of MEC-effects can be obtained by applying the Siegert theorem\textsuperscript{15,16}, which is based on current conservation. It accounts for nuclear currents not included in the direct knockout framework. The estimate is obtained by multiplying the DWIA-calculations with the ratio of PWIA cross sections with and without application of the Siegert Theorem. In this way the evaluation of MEC-effects does allow a simultaneous treatment of FSI-, LRC- and SRC-effects for both reactions.

It is also possible to compare \((e,e'p)\) and \((\gamma,p)\) data in the RPA framework\textsuperscript{17,18}, which has the advantage of enabling a consistent treatment of NN-correlations, MEC- and FSI-effects. However, as the RPA-calculations are restricted to 1p-1h configurations not all FSI-effects are included, i.e. the effect of the imaginary optical potential is not accounted for. This may hamper the comparison as the value of \(T_p\) is usually rather different in the two reactions.

3. The \(^{208}\text{Pb}(e,e'p)\) experiment

The experiment\textsuperscript{19} was carried out using the extracted electron beam from the Amsterdam Pulse Stretcher (AmPS) facility at NIKHEF\textsuperscript{20}. At an incident electron energy of 487 MeV a duty factor of about 50\% was obtained, and an average current of about 1.5 \(\mu\)A. The scattered electron and the knocked-out proton were detected in coincidence by two high-resolution magnetic spectrometers\textsuperscript{21}. The target consisted of two enriched \(^{208}\text{Pb}\) foils of 44 mg/cm\(^2\) each, separated by 5 mm and mounted in a water-cooled frame. This construction allowed to double the luminosity of the experiment while maintaining a good excitation energy-resolution, since the vertex resolution of the proton-spectrometer enabled us to identify the foil in which the event originated. Data have been obtained at fixed values of the energy and momentum transfer, which were centered at \((q,\omega) = (221 \text{ MeV/c, 110 MeV})\). A missing momentum range between 300 and 500 MeV/c was covered by rotating the proton-spectrometer. The total systematic uncertainty in the cross section amounted to 6\%. In fig. 1 three missing-energy spectra are displayed of the reduced cross section \(\sigma_{red}\) at mean values of the missing-momentum of 145, 340 and 495 MeV/c. Ex-
perimentally, $\sigma_{\text{red}}$ is determined by dividing the measured six-fold differential cross section by the off-shell electron-proton cross section $\sigma_{\text{ep}}$ due to de Forest, and by an appropriate kinematical factor. Accidental coincidences have been subtracted in the spectra, acceptance effects have been accounted for, and the spectra have been corrected for radiative processes. It is evident from fig. 1 that the relative importance of the continuum with respect to the valence transitions at $E_X < 2.5$ MeV increases with increasing momentum.

Four experimental momentum distributions, $p_x(p_m)$ have been obtained by integrating $\sigma_{\text{red}}$ over $E_X$ in the ranges $[-0.75,2.25]$, $[2.25,7.25]$, $[7.25,12.75]$ and $[12.75,18.25]$ MeV. Note that the boundary of 7.25 MeV corresponds closely to the value of the two-nucleon emission thresholds. The momentum distributions (solid circles) in each range are displayed in fig. 2 together with the data obtained by Quintero at low missing momentum.

The solid curves in fig. 2 represent a sum of mean-field momentum distributions obtained with distorted-wave impulse-approximation (DWIA) calculations that include Coulomb and proton distortions. The final-state interaction in these calculations is described by means of an optical model using the parameters from ref. 25. The employed bound-state wave functions are normalised mean-field wave functions generated in a Woods-Saxon potential.

The mean-field calculations are far below the data at high momentum for all four $E_X$ ranges. Moreover, the difference between the data and the mean-field calculations increases with increasing $E_X$. In order to investigate whether nucleon-nucleon correlations can explain this discrepancy, we also show in fig. 2 the results of CDWIA calculations employing quasi-particle wave functions, as proposed by Mahaux and Sartor using the same spectroscopic factors as in the mean-field case (dot-dashed curves).

The data for the valence transitions are well described by the calculations based on these quasi-particle wave functions, as was already observed in ref. 19, where the conclusion was drawn that at low $E_X$ the LRC contribution dominates over the SRC contribution. However, at $E_X > 2.25$ MeV the momentum distributions generated in this effective-mass approximation lie far below the data. The contribution of SRCs is possibly insufficiently accounted for in the quasi-particle approach. Hence, we examined an infinite nuclear-matter spectral function in which the high-momentum components are explicitly calculated on the basis of a realistic nucleon-nucleon interaction. Obviously, comparison of our data with the nuclear-matter momentum distribution is only meaningful above the Fermi momentum, since at low momentum the structure of the nuclear-matter spectral function cannot describe that of a finite system. The dotted curves in fig. 2 represent the nuclear-matter momentum distributions corrected for FSI- and electron-distortion effects.

The calculated short-range correlations clearly gain in importance with energy as is already seen in the left panel of fig. 2. This trend continues with increasing $E_X$ as demonstrated in the right panel of fig. 2, where the nuclear-matter momentum distributions move towards the data. In order to further investigate the importance of SRC-effects, these need to be included in a calculation for finite systems containing also LRC-effects.

Van Neck et al. have performed such a calculation by evaluating the spectral function for $^{208}$Pb within the framework of the local-density approximation (LDA), starting from the nuclear-matter spectral function at various densities. The dash-doubledotted curves in fig. 2 represent the LDA-calculations. Although the LDA-calculations include LRC-effects as prescribed by Mahaux and Sartor, they lie above the data in the first $E_X$ bin over the whole.
momentum range. This is partly due to the size of the Hartree-Fock spectroscopic factors, which results in an overestimate of the data at low momentum (< 250 MeV/c) and low $E_x < 2.25$ MeV. In the second $E_x$ bin the calculations in LDA are close to the data. This is not true any longer for the data above $E_x 2N$, where the LDA-momentum distributions are far below the data.

![Graph showing momentum distributions](image)

Fig. 2. Momentum distributions obtained for the reaction $^{208}$Pb($e,e'p$). The present data are represented by solid circles, while the plus-marks represent the data measured by Quint. The solid curves represent CDWIA calculations employing mean-field wave functions. The dot-dashed curves are the result of CDWIA calculations including correlations as proposed by Mahaux and Sartor. The dotted curves represent momentum distributions extracted from the nuclear-matter spectral function of ref. 26, modified for distortions. The CDWIA calculations employing LDA-wave functions are represented by dash-double-dotted curves.

The measured increase of high-momentum strength with energy relative to the mean-field predictions is clearly demonstrated. The SRC-effects are rapidly gaining in importance with $E_x$, but a substantial discrepancy remains between the data and all described calculations at high momenta, in particular above $E_x 2N$.

4. The $^{208}$Pb($\gamma,p$) experiment

The experiment was carried out at the photon-tagger facility of the MAX-Lab in Lund. The energy of the tagged-photon beam covered simultaneously the ranges from 41 to 48 and 51 to 57 MeV with an average total intensity of 3.7 $10^6$ photons/s. The target consisted of a self-
supporting 99% enriched $^{208}$Pb foil having an average thickness of 24.5 mg/cm$^2$. A box with mylar windows and filled with He-gas surrounded the target in order to reduce the background due to ($\gamma$,p) events on air. The energy and in-plane emission angle of the protons were measured with two solid-state detector telescopes, each of which consisted of two Silicon-Strip Detectors (SSDs) and a Hyperpure Germanium (HpGe) detector. Together the telescopes covered an angular range from 40$^0$ to 140$^0$ and subtended a solid angle of 413 msr. The total systematic uncertainty of the cross sections amounted to 9%.

In fig. 3 a typical excitation-energy spectrum of the reaction $^{208}$Pb($\gamma$,p) is displayed. The spectrum represents integrated data accumulated in a photon-energy range from 41 to 48 MeV with proton-emission angles between 40$^0$ to 94$^0$. Its shape is similar to spectra obtained with the reaction $^{208}$Pb(e,e'p). Both doublets and the transition to the 7/2$^+$ state at an excitation energy of 3.47 MeV in $^{207}$Tl are clearly excited. The first doublet comprises the transitions to the 1/2$^+$ and 3/2$^+$ states at excitation energies of 0.00 and 0.35 MeV, respectively. The second doublet has contributions from transitions to the 11/2$^-$ and 5/2$^+$ states at excitation energies of 1.35 and 1.68 MeV, respectively. The excitation-energy resolution is 470 keV.

In fig. 4 the recoil-momentum distributions for the transitions to the (1/2$^+$, 3/2$^+$) and (11/2$^-$, 5/2$^+$) doublets and the 7/2$^+$ state in $^{207}$Tl as measured in the present $^{208}$Pb($\gamma$,p) experiment (solid triangles) are compared with those obtained with the reaction $^{208}$Pb(e,e'p). The recoil-momentum distributions derived from the $^{208}$Pb($\gamma$,p) data do not coincide with those obtained from the $^{208}$Pb(e,e'p) data, i.e. no scaling of ($\gamma$,p) and (e,e'p) data is observed. The absence of scaling is in contrast to observations made on low-mass nuclei where scaling appears to occur$^{30}$. However, a recently performed comparison$^{16}$ of existing (e,e'p) and ($\gamma$,p) data on various nuclei taken at $E_\gamma = 60$ MeV also concluded that no general scaling could be observed.

Employing the quasi-particle wave functions and normalisation factors as obtained from the $^{208}$Pb(e,e'p) data, we performed ($\gamma$,p) distorted-wave impulse-approximation (DWIA) calculations$^{16,31}$ including proton distortions, which are represented by the dotted curves in fig. 4. Hence, these ($\gamma$,p) cross sections have been calculated in the same framework as was used
for the $^{208}\text{Pb}(\gamma,p')$ calculations, which is based on the direct-knockout mechanism. The optical-model parameters used in the $(\gamma,p)$ calculations have been taken from ref. 32.

The $(\gamma,p)$ DWIA-calculations are far below those of $(e,e'p)$, which is mainly due to the increase of final-state interaction effects in the $(\gamma,p)$ calculations. Whereas $T_p$ is 100 MeV in the $^{208}\text{Pb}(e,e'p)$ experiment, it is only 30 - 40 MeV at low $E_\gamma$ and 40 - 50 MeV at high $E_\gamma$ in the $^{208}\text{Pb}(\gamma,p)$ experiment. For all transitions the $(\gamma,p)$ DWIA-calculations underestimate the data by typically one order of magnitude.

![Diagram](image)

Fig. 4. Missing-momentum distributions for transitions to the $\left(1/2^+, 3/2^+\right)$ and $\left(11/2^+, 5/2^+\right)$ doublets in $^{207}\text{Tl}$. The present $^{208}\text{Pb}(\gamma,p)$ data are represented by solid triangles, the $^{208}\text{Pb}(e,e'p)$ by open circles and solid circles. The dashed curves are the result of $(e,e'p)$ CDWIA-calculations including correlations as proposed by Mahaux and Sartor. Similar DWIA-calculations for the reaction $(\gamma,p)$ with and without these correlations are represented by the dotted and dash-double-dotted curves, respectively. DWIA-calculations including an estimate of MEC-effects based on the Siegert theorem are given by the solid lines.

In previous comparisons between $(\gamma,p)$ cross sections and DWIA-calculations the effects of long-range NN-correlations were not considered, see refs. 16 and 30, for instance. While these effects are essential for a good description of the $^{208}\text{Pb}(e,e'p)$ data, the effects of long-range NN-correlations are insufficient to yield a proper description of the data in the reaction $(\gamma,p)$.

Meson-exchange currents (MEC) are possibly at the origin of the discrepancy between the DWIA-calculations and the data. An estimate of the effects of meson-exchange has been obtained by applying the Siegert theorem. As shown in fig. 4 by the solid curves, the resulting
calculations give a fair account of the data. Hence, within the limitations of the 'DWIA+Siegert' framework, MEC-effects seem to dominate the reaction $^{208}\text{Pb}(\gamma,p)$.

It is desirable to incorporate nucleonic currents, MEC-effects, NN-correlations and final-state interactions in one self-consistent framework. This has been done by Ryckebusch et al.\textsuperscript{17,18}, who have performed coupled-channel calculations in the random-phase approximation (RPA). The results of these RPA-plus-MEC calculations are represented by the solid curves in fig. 5 in which the same $^{208}\text{Pb}(\gamma,p)$ data as have already been displayed in fig. 4 are shown as angular distributions. Except for the second doublet, the RPA-plus-MEC calculations describe the data fairly well.

![Graphs showing angular distributions for transitions](image)

Fig. 5. Angular distributions for transitions to the $(1/2^+, 3/2^+)$ and $(11/2^-, 5/2^+)$ doublets in $^{207}\text{Tl}$ at average photon energies of 45 and 54 MeV. RPA calculations with and without MEC-effects are represented by the solid and dashed curves, respectively. The dotted curves are the result of DWIA-calculations including NN-correlations.

In order to investigate the relative importance of MEC-effects in the RPA-framework, calculations were performed in which the photon only couples to the nucleon current (impulse approximation). The resulting calculations (dashed curves in fig. 5) show that the exclusion of MEC-effects reduces the calculated cross sections by a factor of two on average. Hence, the effects of MEC are relatively less important in the RPA-framework as compared to the
'DWIA+Siegert' estimate. Note, that a larger contribution of MEC-effects within the RPA-framework was observed for low-mass nuclei.

For comparison, the DWIA-calculations including long-range NN-correlations, that were also shown in fig. 4, are represented by the dotted curves in fig. 5. In principle these calculations should be equivalent to the RPA-calculations without MEC-effects as both calculations include final-state interactions and long-range correlations, albeit in an entirely different framework. A discrepancy of typically one order of magnitude between both calculations is observed. This might be due to the different treatment of the final-state interaction in both frameworks. Whereas absorption processes are incompletely treated in the RPA-formalism, channel-couplings are not included in the DWIA-framework. Clearly, more theoretical effort is needed before definite conclusions can be drawn on the relative importance of final-state interactions, MEC-effects and NN-correlations in the reaction $^{208}$Pb($\gamma$,p).

As can be seen from figure 3 the high excitation-energy region of the reaction $^{208}$Pb($\gamma$,p) has also been studied. In the absence of detailed calculations for this domain, the data have been compared to the high-excitation energy $^{12}$C($\gamma$,p) data that were collected in the same kinematics for calibration purposes during the same experiment.

At missing energies beyond the two-particle emission threshold the photo-absorption process is expected to result in the emission of a p-n pair. Such a process can be described in terms of the Quasi-Deuteron Model (QDM)\textsuperscript{33}: $\sigma_{\text{abs}}^{\text{p-n}} = L(A)(N \cdot Z/A)\sigma_{\text{abs}}^{\text{deuteron}}$, where $L(A)$ represents the Levinger constant, and $\sigma_{\text{abs}}^{\text{deuteron}}$ the photo-absorption cross section on the deuteron. Using phenomenological values for $L(A)$ one would expect a $^{208}$Pb/$^{12}$C cross-section ratio of about 7.6, while the data yield 2.9 ± 0.3 more or less independent of $E_x$. It is concluded that the excitation-energy region of the reaction $^{208}$Pb($\gamma$,p) beyond $E_x$\textsuperscript{2N} is showing less strength than had been expected on the basis of the QDM.

5. Summary and outlook

The role of nucleon-nucleon correlations and meson-exchange currents has been investigated in a set of (e,e'p) and ($\gamma$,p) experiments on $^{208}$Pb at high missing momentum, i.e beyond 200 MeV/c. The data have been compared to calculations with and without inclusion of NN-correlations and MEC-effects.

Mean-field predictions significantly underestimate the $^{208}$Pb(e,e'p) data and the discrepancy increases with binding energy. For transitions leading to the discrete states at low $E_x$ values the discrepancy is removed by introducing long-range correlations. Above the two-nucleon emission threshold long-range and short-range correlations reduce the discrepancy, but are insufficient to fully account for the measured strength.

The $^{208}$Pb($\gamma$,p) data have been compared with the $^{208}$Pb(e,e'p) results obtained in the same missing-momentum range. The momentum distributions derived from the ($\gamma$,p) data do not coincide with those obtained from the (e,e'p) data. Distorted-wave impulse-approximation calculations of which the input is constrained by the (e,e'p) data underestimate the ($\gamma$,p) data by typically one order of magnitude. An estimate of meson-exchange current (MEC) effects using the Siegert theorem brings the DWIA-calculations close to the data. Random-phase approximation calculations also give a fair account of the data, but in this case MEC-effects are
predicted to be somewhat less important. Further theoretical efforts are needed to remove the apparent inconsistencies between the DWIA+Siegent framework and the RPA-calculations.

Related results have been obtained in recent (e,e'p) measurements\textsuperscript{34,35,36} on $^4$He, $^{12}$C and $^{16}$O, which have been carried out at NIKHEF. In these experiments a considerable amount of high-momentum strength was found at high missing energies up to the pion production threshold. In the case of $^{12}$C the excess strength at the largest missing momenta could be attributed to MEC-effects and intermediate $\Delta$-excitation\textsuperscript{35}.

Evidence for exchange currents at lower missing energies has been found in the excitation of the $(1/2^+, 7/2^-, 5/2^+)$ triplet at $E_X = 7$ MeV in a $^{12}$C(e,e'p)$^{11}$B experiment\textsuperscript{37} performed in the dip region. At high missing momenta the triplet is almost as strongly excited as the ground-state, which was also observed in recent $^{12}$C(γ,p) experiments\textsuperscript{38}. For a proper description of the cross sections of both reactions the inclusion of MEC-effects is essential\textsuperscript{17}.

It is concluded that exchange-current effects seem to be of increasing importance in the reaction (e,e'p) with rising missing energy and invariant mass. In order to isolate the NN-correlation effect it is mandatory to stay relatively close to the quasi-elastic peak and ultimately perform a longitudinal-transverse separation. Complementary (γ,p) data at higher photon energies should be collected in order to further constrain the exchange-current description.

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7. References


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24. E.N.M. Quint, Ph. D. Thesis, University of Amsterdam, 1988
33. J.S. Levinger, Phys. Rev. 84 (1951) 43; B. Schoch, Phys. Rev. Lett. 41 (1978) 80; and
34. 4He(e,e'p) - AmPS proposal 91-10, spokesperson J.F.J. van den Brand
36. 16O(e,e'p) - AmPS proposal 91-20, spokesperson F. Garibaldi

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