Quasi-free $(e, e'p)$ reactions on nuclei with neutron excess

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The understanding of the evolution of the nuclear properties with respect to the asymmetry between the number of neutrons and protons is one of the topics of major interest in modern nuclear physics. This is going to extend our knowledge about the effects of isospin asymmetry on the nuclear structure, and is also relevant for the study of the origin and the limits of stability of matter in the universe.

Nuclear reactions represent our main source of information on the properties and on the structure of atomic nuclei. Direct nuclear reactions, where the external probe interacts with only one, or few, nucleons of the target nucleus, can give deep insight on the single-particle (s.p.) properties of the many-body system. In particular, the $(e, e'p)$ reaction, where a proton is emitted with a direct knockout mechanism, represents a very clean probe to explore the proton-hole states structure of the nucleus.

We have studied the evolution of the $(e, e'p)$ cross section on nuclei with increasing asymmetry between the number of neutrons and protons. Specifically, we have investigated how the models successfully used to describe $(e, e'p)$ data in stable nuclei behave when they are used to make predictions on exotic nuclei.

Our models require the description of both ground and excited states of the nuclear system, the latter one has a particle in the continuum [1]. The calculations have been done with three different models. In a non-relativistic approach we used ground state s.p. wave functions obtained by using phenomenological Woods-Saxon (WS) wells, and also Hartree-Fock (HF) calculations with finite range D1M Gogny interactions. We also carried out calculations in a relativistic framework where the ground state wave functions have been generated by a relativistic Hartree calculation [2]. In both non relativistic (DWIA) and relativistic (RDWIA) approaches the wave function of the emitted nucleon is described by an appropriate complex optical potential containing an imaginary term which takes care of the final state interaction (FSI).

We have applied our models to a set of calcium and oxygen isotopes. We have chosen these isotopes since data taken at NIKHEF for the doubly magic nuclei ^{40}Ca, ^{48}Ca [3], and ^{16}O [4] are available. We have first tested the performances of our models in describing these data, then we have applied our models to describe some even-even isotopes of calcium and oxygen. In this report we shall show only the results regarding the calcium isotopes. Those obtained for the oxygen isotopes bring to the same conclusions.

We show in Fig. 1 the reduced cross sections of the ^{40}Ca $(e, e'p)$ reaction as a function of the missing momentum for the so-called parallel and perpendicular kinematics [1]. The DWIA calculations are carried out with the same code `DWEEPY` that was used for the analysis of the experimental data. The results obtained with phenomenological WS wave functions are compared with those obtained by solving Hartree-Fock (HF) equations with Gogny-like finite-range interactions. The RDWIA calculations are performed with the fully relativistic model developed in Ref. [2].

All the theoretical results shown in the figure provide a good description of the experimental data. As in the original data analysis [3], for the WS wave functions the radius of the potential was chosen to reproduce the width of the experimental distribution. On the other hand, no free parameters are used in the non relativistic HF and in the relativistic Dirac-Hartree wave functions, that are able to give an equivalently good description of data.

In order to reproduce the magnitude of the experimental data, a reduction factor has been applied in Fig. 1 to all the theoretical results. These factors, given in Ref. [5], have been determined by a fit of the calculated reduced cross sections to the data over the whole missing-momentum range considered in the experiment. The reduction factors applied to the DWIA-WS results are identical to those obtained in the data analysis of Ref. [3], where the same optical potential and WS wave functions were used.

The comparison with the NIKHEF data [3,

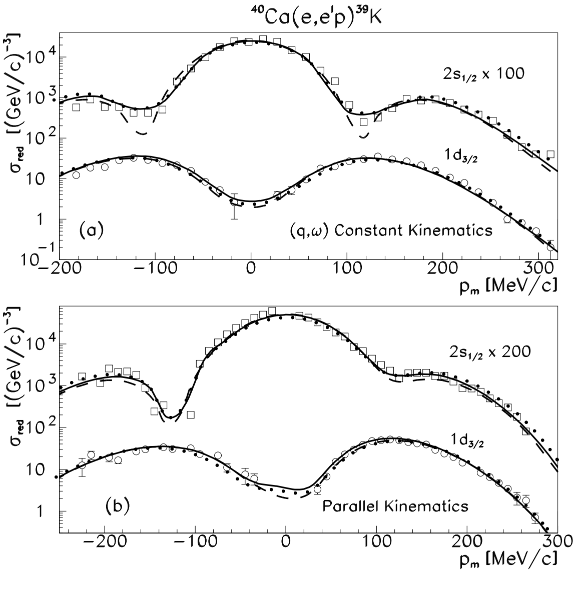

Figure 1. Reduced cross sections of the ^{40}Ca $(e,e'p)$ reaction as a function of the missing momentum $p_{\rm m}$ for the transitions to the $3/2^+$ ground state and to the $1/2^+$ excited state at 2.522 MeV of ^{39}K. In panel (a) we show the results obtained in $(\boldsymbol{q},\omega)$ constant kinematics, with incident electron energy $E_0 = 483.2$ MeV, electron scattering angle $\vartheta = 61.52°$, and $q = 450$ MeV$/c$. In panel (b) we show the results obtained in parallel kinematics, with $E_0 = 483.2$ MeV. The outgoing proton energy is $T' = 100$ MeV in both kinematics. The experimental data are taken from Ref. [3]. The solid lines give the DWIA-WS results, the dotted lines the DWIA-HF results, and the dashed lines the RDWIA results.

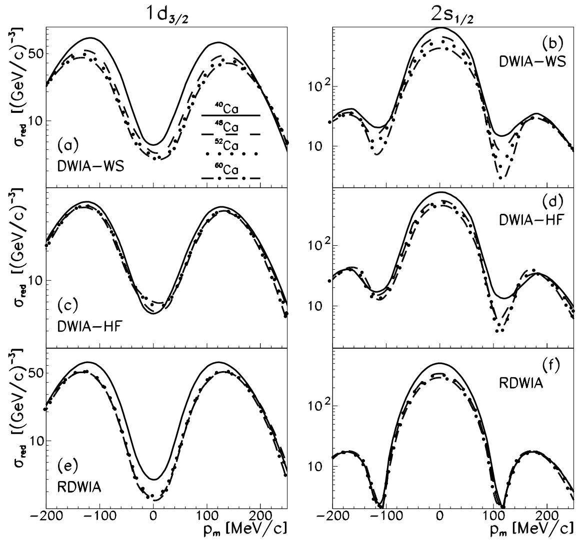

Figure 2. Reduced cross section of the $(e,e'p)$ reaction for $1d_{3/2}$ (left panels) and $2s_{1/2}$ (right panels) knockout from ^{40}Ca (solid lines), ^{48}Ca (dashed lines), ^{52}Ca (dotted lines), and ^{60}Ca (dot-dashed lines), as a function of $p_{\rm m}$. The results of the DWIA-WS calculations are presented in the panels (a) and (b), and those of the DWIA-HF calculations in the panels (c) and (d). The RDWIA results are shown in the panels (e) and (f). The calculations are done in parallel kinematics with $E_0 = 440$ MeV and $T' = 100$ MeV.

4] gave us confidence about the reliability of our three models which we have applied to ^{40,48,52,60}Ca and ^{16,22,24,28}O nuclei. In these nuclei the s.p. levels below the Fermi surface are fully occupied. This implies that these nuclei are spherical, and also that the pairing effects, when present, are negligible. As already stated before we present here only the results regarding the calcium isotopes. For all the calcium isotopes we have considered proton knock-out emission from the $1d_{3/2}$ and $2s_{1/2}$ states. Our results calculated with the same kinematic variables used in Fig. 1 are shown in Fig. 2.

The comparison between the results obtained with the three different models, DWIA-WS, DWIA-HF, and RDWIA illustrates how these models describe the effects produced by the asymmetry between the number of neutrons and protons. No reduction factors have been applied to the curves presented in these figures. It is interesting to remark that the evolution of the cross section with respect to the change of the neutron number is the same in all the panels of both figures. We observe that the ^{40}Ca lines are always above the other ones, and the size of the curves decreases with the increasing number of neutrons. This behavior is clearer in the DWIA-WS results, panels (a) and (b) of both figures, and becomes less evident in the other cases, especially in the RDWIA ones.

For a better understanding of these results it is interesting to consider the s.p. hole wave functions obtained in the three models. We show in Fig. 3 the squared moduli of the radial part of the s.p wave function for the $1d_{3/2}$ and $2s_{1/2}$ states of the various calcium isotopes. The relativistic wave functions shown in the figure are obtained by summing the squared of the radial part of the upper and lower components of the Dirac spinor. All the curves shown in the figure are normalized to one.

The behavior of the WS wave functions shown in the panels (a) and (b) can be understood by considering that the depth of the WS well becomes deeper with increasing the neutron numbers. This deepening is due to the fact that increasing the neutron number the proton experiences more binding, its separation energy increases, and the depth of the WS well, that is determined to reproduce the experimental separation energy, increases. A deeper WS well produces narrower wave functions, as the curves of the upper panels of Fig. 3 show.

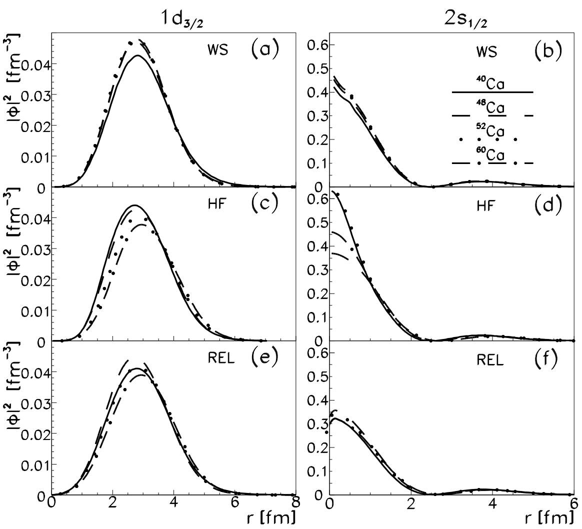

Figure 3. Squared moduli of the radial part of the $1d_{3/2}$ (left panels) and $2s_{1/2}$ (right panels) s.p. wave functions for ^{40}Ca (solid lines), ^{48}Ca (dashed lines), ^{52}Ca (dotted lines), and ^{60}Ca (dot-dashed lines). In the panels (a) and (b) we show the WS wave functions, in the panels (c) and (d) the HF wave functions, and in the panels (e) and (f) the relativistic wave functions obtained in the Dirac-Hartree approach. The normalization of the curves is $\int dr\, r^2\, |\phi|^2 = 1$.

The HF wave functions have a different behavior, as it is shown in the panels (c) and (d). In this case, the narrower wave functions are those obtained for the isotopes with smaller neutron numbers. The behavior of the relativistic wave functions is somewhat different and does not have a defined trend as in the previous cases. It is, in any case, more similar to that of the HF than to that of the WS wave functions. We point out that the values of the separation energies, and their trend as a function of the neutron number, are similar in all the three types of calculations.

The evolution of the s.p. wave functions with increasing neutron number in the three models we have adopted is different from that of the reduced cross sections. To investigate the source of this effect we have carried on $(e, e'p)$ calculations where the emitted proton wave function is treated as plane wave (PWIA). In this case, the reduced cross sections evolve exactly as the s.p. wave functions with the increase of the neutron number. This indicates that in the complete calculations the dependence of the wave functions on the proton to neutron asymmetry is responsible for a large part of the differences in the reduced cross sections, but an important and crucial contribution is given by FSI, that are described by phenomenological optical potentials. The dependence of the optical potential on the asymmetry between the number of neutrons and protons is an interesting problem that deserves careful investigation.

Measurements of the exclusive quasifree $(e, e'p)$ cross section on nuclei with neutron excess would offer a unique opportunity of studying the dependence of the properties of bound protons and of nucleon-nucleon correlations on the neutron to proton asymmetry. In this work models that have proved their reliability in the comparison with $(e, e'p)$ data on stable nuclei have been used to investigate the evolution of the $(e, e'p)$ cross sections with increasing proton-neutron asymmetry. Although the models and the theoretical ingredients adopted in the calculations contain approximations, our results can serve as a useful first reference for possible future experiments. The comparison with data can confirm or invalidate the predictions of our models and test the ability of the established nuclear theory in the domain of exotic nuclei.

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