PHYSICAL REVIEW C **93**, 054612 (2016)

Distortion effects on the neutron knockout from exotic nuclei in the collision with a proton target

E. Cravo

Departamento de Física, Faculdade de Ciências da Universidade de Lisboa, Edifício C8, Campo Grande, 1749-016 Lisboa, Portugal and Centro de Física Nuclear da Universidade de Lisboa, Av. Prof. Gama Pinto 2, 1649-003 Lisboa, Portugal

R. Crespo*

Departamento de Física, Instituto Superior Técnico, Universidade de Lisboa, Av. Rovisco Pais 1,1049-001, Lisboa, Portugal and Centro de Ciências e Tecnologias Nucleares, Universidade de Lisboa, Estrada Nacional 10, 2695-066 Bobadela, Portugal

A. Deltuva

Institute of Theoretical Physics and Astronomy, Vilnius University, A. Goštauto St. 12, LT-01108 Vilnius, Lithuania

(Received 25 June 2015; revised manuscript received 10 March 2016; published 16 May 2016)

Background: Reaction theory plays a major role in the interpretation of experimental data and one needs to identify and include accurately all the relevant dynamical effects in order to extract reliable structure information. The knockout of a nucleon (neutron/proton) from a high energy exotic nucleus projectile colliding with a proton target allows to get insight on the structure of its valence and inner shells.

Purpose: We aim to clarify the role of the distortion on the calculated observables for nucleon knockout, in particular, the dependence of the calculated observables on the binding energy ϵ_b and angular momentum L of the knockout particle, and on the mass of the projectile core, A_c. We consider mainly the knockout of a neutron that may be either in the valence or in the inner shell of the projectile nucleus.

Method: Exact three-body Faddeev/Alt-Grassberger-Sandhas (Faddeev/AGS) calculations are performed for the nucleon knockout from stable and exotic nuclei in the collision of 420 MeV/u projectile beams with a proton target. Results are compared with plane-wave impulse approximation (PWIA) calculations.

Results: The Faddeev/AGS formalism accurately predicts: (i) a systematic nearly logarithmic dependence of the distortion parameter on the separation energy; (ii) roughly linear dependence of the ratio of the full to the PWIA cross section on the asymmetry parameter; (iii) a distinct behavior between the calculated transverse core momentum distribution from the PWIA and full Faddeev/AGS exact approach which indicates that distortion effects do not modify fully exclusive observables through a common renormalization factor.

Conclusions: To extract structure information on deeper shells one needs to include distortion effects accurately. A systematic analysis enables to estimate the total cross section for knockout of a nucleon from a given shell of nuclei at/away the stability line of the nuclear landscape. The comparison with experimental results may provide understanding on the used interaction and structure model.

DOI: 10.1103/PhysRevC.93.054612

I. INTRODUCTION

The single particle structure and its evolution along the nuclear landscape is one of the current challenges of nuclear theory. It is now well established that reaction theory plays a major role in the interpretation of the experimental data. One needs to identify and include accurately all the relevant dynamical effects in order to extract reliable structure information.

In the last decade, a large amount of experimental data and theoretical analysis has been obtained for one and two neutron knockout from a projectile beam by the collision with a light target [1–6]. In these experiments, the final state of the target nucleus is not identified. In addition, the final states of the residue are often not determined. Therefore, these analyses are often highly inclusive with respect to the target and to the projectile residue. Such inclusive studies have been widely used to determine the single-particle properties of the removed particles, measuring momentum distributions and cross sections.

A systematic analysis of the nucleon knockout from a light target (target and residue inclusive) has been carried out for a large range of symmetric and asymmetric nuclei [4] (and references therein). The systematics of [4] shows that calculated cross sections need to be reduced in order to agree with experimental data, and that this reduction is strongly isospin dependent and nearly linear in the asymmetry parameter $\Delta S = S_n - S_p$ for neutron knockout or $\Delta S = S_p - S_n$ for proton knockout, S_n (S_p) being the neutron (proton) separation energy. In particular, it was found that the experimental cross sections for the knockout of deeply bound nucleons were much smaller than the theoretical predictions. This systematics is based on the following assumptions [4]: (i) forward and adiabatic approximation in the intermediate-state propagator used by eikonal-adiabatic Glauber reaction framework; (ii) the residue-inclusive cross section is given by the sum of the single-nucleon removal cross sections (with a given angular momentum configuration) multiplied by the respective spectroscopic factors that are predicted by the independent

*raquel.crespo@tecnico.ulisboa.pt

shell model populating the residue in the ground and in all the known low-lying excited states below particle emission threshold; therefore the contribution from high excited states of the residue is neglected; (iii) when there are several residue states populated, the separation energy of the removed particle in the asymmetry parameter is replaced by their average, weighted with the respective partial cross sections.

Attempts of feeding the projectile microscopic structure description into the calculated total cross sections have been made [7,8], and have shown that the general trend of the above systematics persists.

The unravel of the origin of this strong reduction and a nearly linear dependence on the asymmetry parameter calls for a deeper understanding of both structure effects and reaction mechanisms for nucleon knockout from an exotic nucleus.

This understanding is also important for fragmentation studies, since there is a subtle interplay between direct and statistical processes contributions for the nucleon removal [9].

Single-nucleon (p,pN) knockout reactions at intermediate and high energies and in inverse kinematics are expected to be a useful tool to obtain information on single-particle occupancies of inner and outer shells. Recently, there has been a renewed interest in the study of nucleon knockout (p,pN) from stable and exotic nuclei with neutron/proton asymmetry. This may yield the possibility to extract the structure information, in particular, correlation effects [10–17]. To achieve this purpose a good understanding of the underlying reaction mechanisms is needed, in particular, the role of (i) the distortion due to high order rescattering effects; (ii) the high excited states of the fragment [13].

In the present work, we study the kinematically semi-inclusive and inclusive cross sections for the neutron knockout from a projectile in the collision with a proton target (where all fragments and final states are experimentally identified). We shall analyze the nucleon knockout from light neutron rich exotic nuclei by the collision with a proton target at high energies around 420 MeV/u, which is related to experimental measurements performed recently at GSI. The role of distortion for a p-shell proton knockout from ^{12}C at 400 MeV/u was found to be very important [13].

We assume here that the composite exotic nucleus is well described by a core and a particle occupying a single shell. The knockout of a nucleon (either in a valence or inner shell) in the collision with a target has been traditionally tackled under the assumption that the knockout particle reacts with the target (in our case a proton), while the core provides the distortion. The contribution to the calculated observables of a knockout nucleon without distortion has been standardly defined as the plane wave impulse approximation (PWIA). We aim in this manuscript to clarify the role of the distortion on the calculated observables (kinematically inclusive and semi-inclusive) for neutron knockout as a function of the binding energy and angular momentum of the knockout particle, and the mass number of the heavy fragment. We will use representative nuclear systems and compare with given examples from the nuclear landscape.

To disentangle these effects, we construct a set of composite projectile systems consisting of an inert core with given mass A_c and a neutron with a relative angular momentum L $(=0,1,2)$, and adjust the interaction to generate a bound state with a given binding energy ϵ_b. Our aim is to make a systematic analysis of the calculated observables as functions of ϵ_b, L, and A_c, by varying each parameter independently. In this systematic analysis, some of the projectile beams considered are not actual systems from the nuclear landscape. However, they constitute representative systems for the study of the knockout of valence and inner nucleons. We also consider examples from the nuclear landscape, ^{12}C and ^{17}O, chosen such that the proton-core Coulomb interaction is not significantly different from that of the present systematics.

We formulate the three-body scattering problem in the Hilbert space $\mathcal{H}_{C+n+p}$ for $C+n+p$ free relative motion where the core C can only be either in the ground state or in a low-lying excited state. In other words, core dynamical excitations during the collision process or multinucleon knockout and highly excited states above evaporation are not taken into account in this truncated Hilbert space. We shall use the standard three-body Faddeev/Alt-Grassberger-Sandhas (Faddeev/AGS) framework [11,12,18–20]. This reaction formalism exactly takes into account higher order rescattering terms [13].

II. REACTION FRAMEWORK

According to the Faddeev/AGS formalism, the transition amplitudes leading to the observables are the on-shell matrix elements of the operators $U^{\beta\alpha}$ obtained simultaneously for all open channels (elastic, breakup, and transfer) from the solution of the integral equations

$$U^{\beta\alpha} = \bar{\delta}_{\beta\alpha} G_0^{-1} + \sum_{\gamma} \bar{\delta}_{\beta\gamma} t_\gamma G_0 U^{\gamma\alpha}, \tag{1}$$

where $\bar{\delta}_{\beta\alpha} = 1 - \delta_{\beta\alpha}$, and

$$t_\gamma = v_\gamma + v_\gamma G_0 t_\gamma \tag{2}$$

is the transition operator for each interacting pair. The subscripts α,β,γ denote two-cluster configurations, i.e., the spectator particle or, equivalently, the pair in the odd-man-out notation. In Eq. (2),

$$G_0 = (E + i0 - H_0)^{-1} \tag{3}$$

is the free resolvent; E is the total energy in the three-particle center-of-mass system. The $\beta = 0$ partition corresponds to three free particles in the continuum. Equation (1) for the breakup amplitude can be viewed as a multiple scattering expansion,

$$\begin{aligned} U^{\beta\alpha} = {} & \bar{\delta}_{\beta\alpha} G_0^{-1} + \sum_{\gamma} \bar{\delta}_{\beta\gamma} t_\gamma \bar{\delta}_{\gamma\alpha} \\ & + \sum_{\gamma} \bar{\delta}_{\beta\gamma} t_\gamma \sum_{\xi} G_0 \bar{\delta}_{\gamma\xi} t_\xi \bar{\delta}_{\xi\alpha} \\ & + \sum_{\gamma} \bar{\delta}_{\beta\gamma} t_\gamma \sum_{\xi} G_0 \bar{\delta}_{\gamma\xi} t_\xi \sum_{\eta} G_0 \bar{\delta}_{\xi\eta} t_\eta \bar{\delta}_{\eta\alpha} \\ & + \cdots . \end{aligned} \tag{4}$$

The successive terms of this series can be considered as terms of zero order (which contribute only for rearrangement

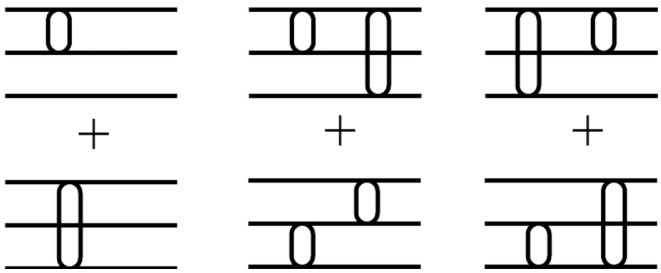

FIG. 1. Single and double scattering diagrams for breakup in the Faddeev scattering framework, as described in the text.

transitions), first order (single scattering),

$$U^{0\alpha}(\mathrm{ss}) = \sum_{\gamma} t_\gamma \bar{\delta}_{\gamma\alpha}, \tag{5}$$

second order (double scattering) in the transition operators t_γ, and so on. The breakup series up to third order is represented diagrammatically in Figs. 1 and 2 where the top line represents the proton target, while the middle and bottom lines are the knockout particle and the core, respectively.

In the Faddeev/AGS reaction framework the single scattering amplitude, represented in Fig. 1, includes the term where the proton target scatters from the knockout nucleon (p–N), represented by the top left diagram, and from the heavy fragment (p-C) represented by the bottom left diagram.

The calculated observables including only the contribution from the single scattering of the knockout nucleon by the proton target is standardly referred to as PWIA. Distortion effects with respect to PWIA result in the Faddeev/AGS reaction framework from the simultaneous combination of the p-C single scattering term and higher order multiple scattering contributions. From the multiple scattering expansion (and the respective diagrams in Figs. 1 and 2) it is clear that, formally, the distortion effects do not factorize into a renormalization factor to the PWIA term.

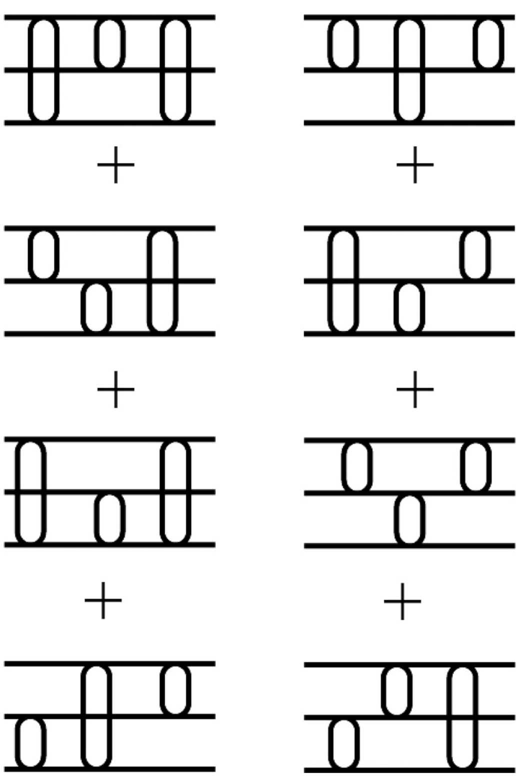

FIG. 2. Triple scattering diagrams for breakup in the Faddeev scattering framework as described in the text.

In the work of Refs. [11,13] an attempt was made to bridge the exact Faddeev/AGS reaction framework with the approximate distorted-wave impulse approximation (DWIA) and Glauber reaction formalisms. In that work it was shown that the DWIA transition amplitude can be approximately expressed in terms of a multiple scattering (MS) expansion series referred to as DWIA-MS, and shown therein to be incomplete: first, the single scattering term of this series contains only the contribution due to the scattering between the knockout particle and the target and no collision occurs between the target and the core; second, the distortion in the exit and entrance channels only partially takes into account higher order multiple scattering terms. The DWIA-MS containing multiple scattering terms up to second order, underestimate the corresponding second order Faddeev/AGS result by about 20%. A better agreement between the second order DWIA-MS results and the converged Faddeev/AGS result may be accidental [13] and more detailed insight into the linking of the two reaction approaches is necessary. In addition, current DWIA numerical implementations introduce further approximations when evaluating the scattering observables. In particular, off-shell, spin-orbit, and angle averaged approximation effects need to be investigated. In Ref. [13] it is also shown that target rescattering terms between the core and the knockout nucleon are taken into account in an approximate way in the Glauber framework.

We shall be referring to as full, the observables calculated with all multiple scattering terms needed to achieve convergence. One expects that the number of terms decreases with increasing projectile incident energy. It was shown in Ref. [13] that very subtle cancellations occur between the single scattering p-C contribution and higher order contributions, indicating that very accurate calculations of all the multiple scattering contributions need to be performed when evaluating the scattering observables.

We quantify the distortion effects as the relative difference between the calculated PWIA (σ_{PWIA}) and full (σ_{full}) total cross sections, that is

$$D = \frac{\sigma_{\mathrm{PWIA}} - \sigma_{\mathrm{full}}}{\sigma_{\mathrm{PWIA}}} = 1 - \mathcal{R}\,;\ \mathcal{R} = \frac{\sigma_{\mathrm{full}}}{\sigma_{\mathrm{PWIA}}} \tag{6}$$

with $\mathcal{R}$ as the ratio of the full to the PWIA cross section. Some relativistic corrections to these parameters can be expected.

The exact Faddeev/AGS is a convenient reaction framework to evaluate accurately the distortion D and ratio $\mathcal{R}$ parameters.

III. INTERACTIONS

Before solving the Faddeev/AGS equations we need to specify the three pair interactions. We consider in this article mainly the knockout of a neutron which can be either in a valence or inner shell. In this case, we need therefore to specify the *p-n* (proton-neutron), *n-C* (neutron-core), and *p-C* (proton-core) potentials. We take the realistic nucleon-nucleon CD-Bonn potential [21] for the proton-neutron pair. The interactions between the core and both the knockout neutron and the proton targets are not fully known.

To describe the interaction between the proton and the core we take a phenomenological nuclear optical potential with parameters from the Koning-Delaroche [22] global parametrization evaluated at 200 MeV; it contains volume (v) and surface (s) terms. The Coulomb interaction corresponds to a value of $Z = 6$.

The potential that simulates the interaction between the neutron and the core is taken here as local and L dependent. In the partial wave with the bound state the potential is real and has the form

$$V^R(r) = -V_v f(r,R_c,a_c), \tag{7}$$

where $f(r,R,a)$ is the usual Woods-Saxon form factor

$$f(r,R,a) = 1/[1 + \exp[(r - R)/a]] \tag{8}$$

and $R_i = r_i A^{\frac{1}{3}}$. In all other partial waves the potential has both real and imaginary parts taken from the Koning-Delaroche parametrization at 200 MeV due to the lack of a more enlightened choice. The optical potential parameters for the neutron- and proton-core interactions are listed in Table I.

The results presented in this article are expected to estimate the dependence of the distortion on the core mass, on the binding energy, and on the angular momentum of the knockout particle. To study this dependence we take as our reference the ^{15}C nucleus, a nuclear system assumed to be described as an S-wave neutron coupled to a ^{14}C core, with a binding energy $\epsilon_b = -1.22$ MeV. We always assume the S-wave neutron to be in the $2s_{1/2}$ state, the $1s_{1/2}$ state being Pauli forbidden.

To study the dependence of the calculated distortion on the mass of the projectile core, we construct nuclear systems with different mass numbers for the core A_c and adjust the S-wave potential parameters of Eq. (7) such that the n-core binding energy is kept at $\epsilon_b = -1.22$ MeV. The potential parameters for different A_c are listed in Table II.

To test the dependence of the calculated distortion on the binding energy of the knockout neutron, we construct several nuclear systems where the core has a constant mass number, taken to be $A_c = 14$, and the neutron is assumed to be in an S wave. The strength parameter of the S-wave interaction is adjusted in order to obtain the separation energies of some chosen nuclei, namely, $\epsilon_b = -0.50$ MeV (^{11}Be), $\epsilon_b = -1.22$ MeV (^{15}C), $\epsilon_b = -2.70$ MeV (^{23}O), $\epsilon_b = -4.50$ MeV (average of ^{17}O and ^{13}C). Note for example that in the case of the actual ^{17}O and ^{13}C nuclei the valence neutron is not in an $L = 0$ state. However, one of the aims of the present work is to study the effect of the binding between the neutron and the core on the calculated inclusive observables, keeping all other parameters unaltered. We also simulate systems with a neutron more tightly bound, with $\epsilon_b = -15.0$ MeV and -20.0 MeV. The potential parameters for a neutron in S wave with different binding energies are collected in Table III. All other potential parameters remain unaltered, with the values reported in Tables I and II.

Finally, we test the dependence of the calculated distortion on the relative orbital angular momentum of the knockout nucleon. For this we construct several nuclear systems with the same core mass number, $A_c = 14$, the same binding energies as for the S-wave bound pair, but with the neutron being in a P or D wave. The neutron-core potential parameters in these partial waves are listed in Table III.

The pair interactions in the case of real nuclear systems ^{12}C and ^{17}O are chosen in the same way.

TABLE I. Optical potential parameters for all systems and all partial waves except for the neutron-core bound state partial wave. The parameters are taken from Koning-Delaroche [22] for $Z = 6$ and $A = 14$, at 200 MeV. The depths are in MeV; the geometry parameters are in fm.

	$V^{\text{opt}}(n\text{–}C)$		$V^{\text{opt}}(p\text{–}C)$
V_v	$-16.161 - 11.044i$		$-13.121 - 13.115i$
a_v		0.676	
R_v		$1.136 \times 14^{1/3}$	
V_s	$-0.138i$		$-0.195i$
a_s	0.542		0.526
R_s		$1.304 \times 14^{1/3}$	

TABLE II. Neutron-core potential parameters for systems constructed with different core mass number A_c, a neutron with $L = 0$ angular momentum, and binding energy $\epsilon_b = -1.22$ MeV. The Woods-Saxon geometry parameters are $a_v = 0.650$ fm and $R_v = 1.250 \times 14^{1/3}$ fm; the potential depths are in MeV.

A_c	10	14	16	22
$V_v(n\text{–}C)$	−51.52	−50.29	−49.93	−49.20

IV. RESULTS

We now proceed to solve the Faddeev/AGS equations (1) and to calculate the observables for a projectile incident beam of 420 MeV/u.

TABLE III. Neutron-core potential parameters for systems constructed with the same core mass number $A_c = 14$ but different angular momenta L and binding energies ϵ_b. The Woods-Saxon geometry parameters are $a_v = 0.650$ fm and $R_v = 1.250 \times 14^{1/3}$ fm; the potential depths are in MeV.

	L		
ϵ_b (MeV)	0	1	2
−0.50	−46.82	−25.93	−53.88
−1.22	−50.29	−28.00	−55.71
−2.70	−55.49	−31.58	−59.19
−4.50	−60.57	−35.39	−63.09
−15.0	−82.91	−53.64	−82.72
−20.0	−91.89	−61.32	−91.10

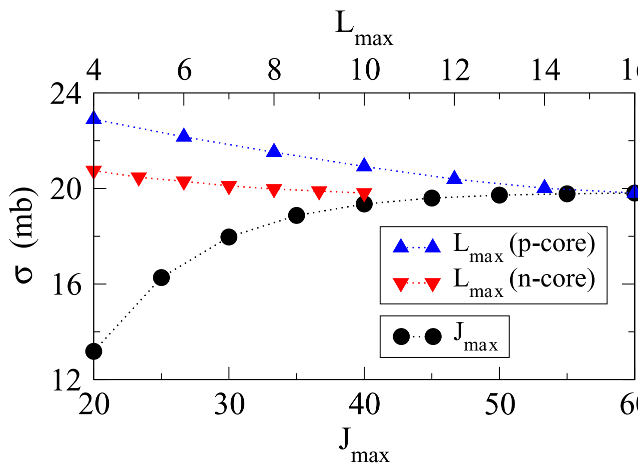

FIG. 3. Convergence of the total cross section with the valence neutron-core orbital angular momentum $L_{\max}^{n\text{-}C}$, the proton target-core orbital angular momentum $L_{\max}^{p\text{-}C}$, and the total three-particle angular momentum $J_{\max}$. The values shown correspond to the $^{14}C \otimes n(2s_{1/2})$ system with $\epsilon_b = -1.22$ MeV, but are illustrative of all systems.

In our calculations Eq. (1) is solved exactly in momentum space after partial-wave decomposition and discretization of all momentum variables. We include the nuclear interactions between all three pairs; the proton-core Coulomb interaction is taken following the technical developments implemented in Refs. [23,24].

In all the calculations the nucleons are considered as spin-1/2 particles and the nuclear cores as spin-0 particles.

In order to study the convergence of the results with respect to the partial wave decomposition, we show in Fig. 3 the calculated cross section as a function of the maximum value for the knockout neutron-core orbital angular momentum $L_{\max}^{n\text{-}C}$, the proton target-core orbital angular momentum $L_{\max}^{p\text{-}C}$, and the total three-particle angular momentum $J_{\max}$ for our representative system (that is ^{15}C). In all calculations presented in this work, we have included p-n partial waves with orbital angular momentum $L \leqslant 4$. In addition, we have used n-C partial waves with orbital angular momentum $L \leqslant 10$, p-C partial waves with $L \leqslant 16$ and the total three-particle angular momentum $J \leqslant 60$. As follows from Fig. 3 with this choice the calculated cross section is well converged.

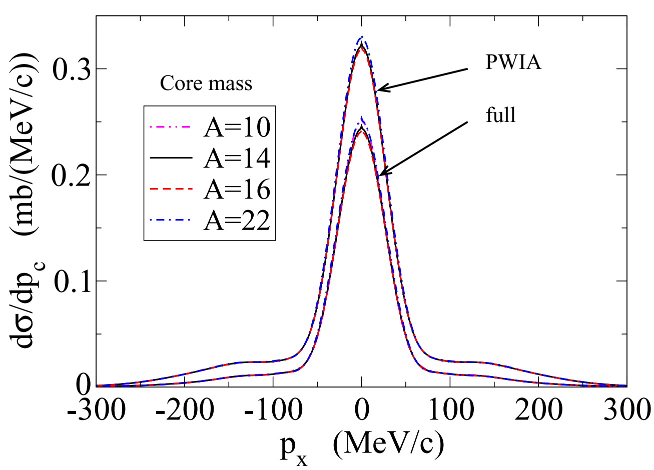

FIG. 4. Calculated fully converged and PWIA core ground state transverse momentum p_x distributions at 420 MeV/u for different values of the mass of the core.

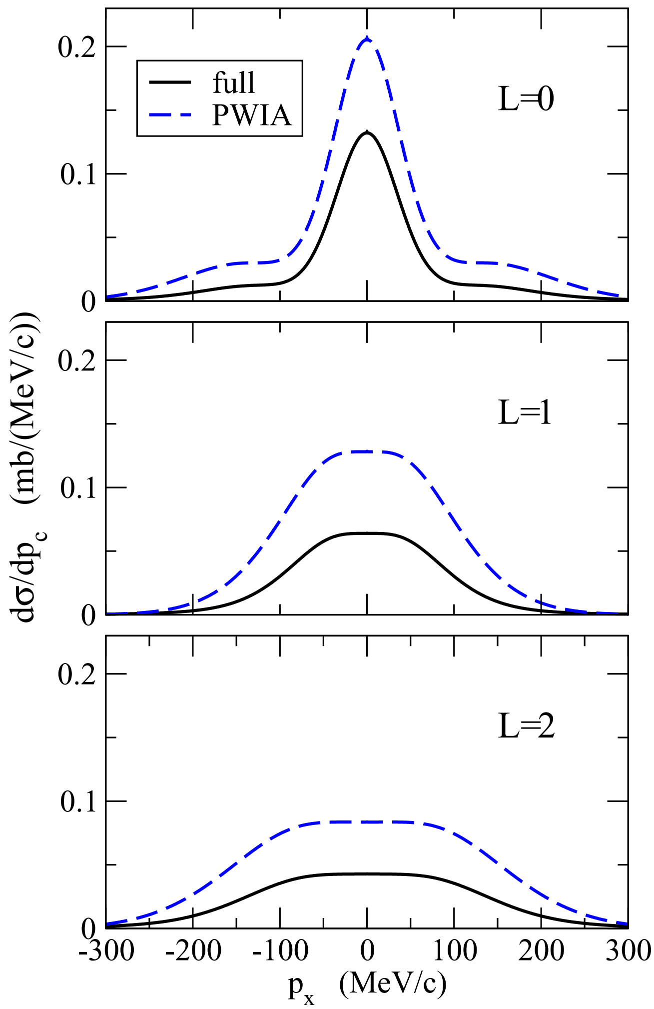

FIG. 5. Core ground state transverse momentum p_x distributions at 420 MeV/u for a system with a neutron-core binding energy $\epsilon_b = -4.50$ MeV and different angular momenta. The solid and dashed lines represent the calculated fully converged and the PWIA observables, respectively.

We have also found that the multiple scattering series is well converged with the inclusion of the fourth order scattering terms in all the cases considered here.

In order to study the dependence of the calculated total cross section upon the Woods-Saxon binding potential parameters, we varied the diffuseness and radius of the potential and adjusted the depth to give the same binding energy for our reference nucleus. We found only a weak dependence on the radius parameter. Taking $a_v = 0.65$ fm and varying the radius between $1.25 \leqslant r_v \leqslant 1.5$ (fm) the total cross section changes by 3%. Equally weak dependence on the diffuseness parameter was found. For both $r_v = 1.5$ fm and $r_v = 1.25$ we found that varying the diffuseness between $0.65 \leqslant a_v \leqslant 1.2$ (fm)

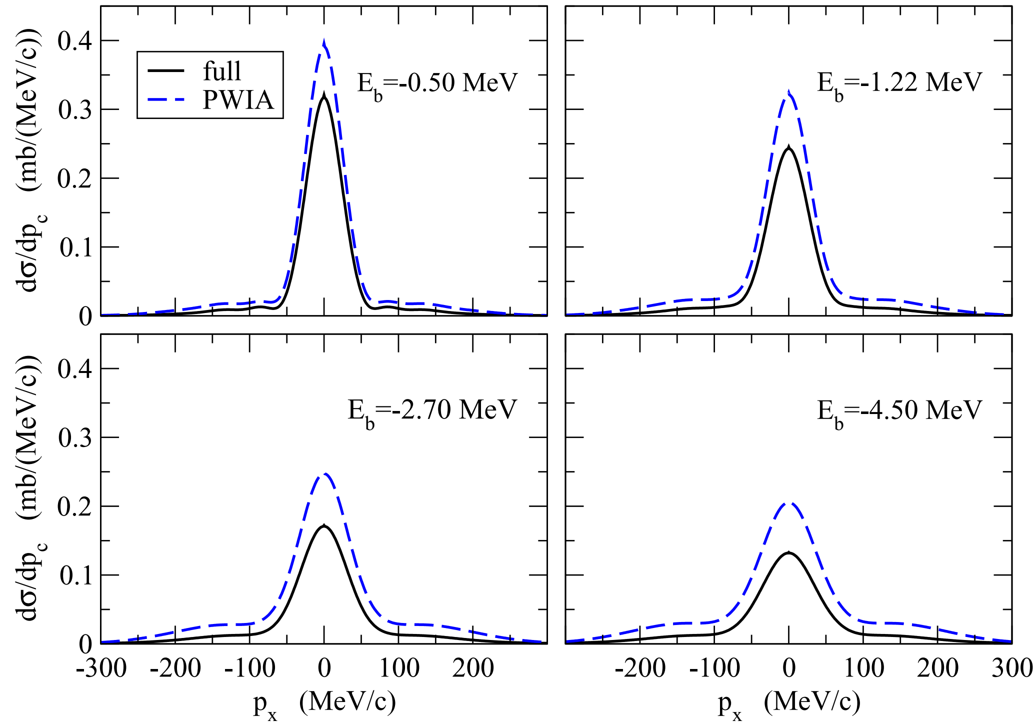

FIG. 6. Core ground state transverse momentum p_x distributions at 420 MeV/u for different values of the n-core binding energy with the angular momentum $L = 0$. The solid and dashed lines represent the calculated fully converged and PWIA scattering observables, respectively.

changes the total cross section by about 12%. We also found a comparatively weak dependence of the total cross section on the neutron-core optical potential for all partial waves other than the bound state.

Next, we compare the observables calculated with the PWIA contribution and with all multiple scattering terms necessary to achieve convergence (full).

In Figs. 4, 5, and 6 we show the calculated core ground state transverse momentum p_x distributions at 420 MeV/u for different values of the core mass, the angular momentum of the knockout particle, and the binding energy, respectively.

Figure 4 shows that the full results reduce the PWIA core momentum distribution and are essentially independent of the core mass number. The calculated distortion effect is around $D = 34\%$ in this case.

Similarly, Fig. 5 shows that the full results reduce the PWIA core momentum distribution and depend moderately on the angular momentum of the knockout particle.

On the contrary, the graphs in Fig. 6 show a large dependence of the calculated full cross section on the binding of the knockout particle. The reduction of the full cross section when compared with the PWIA increases with the binding energy of the knockout particle.

The calculated total cross sections and distortions are collected in Table IV. In Fig. 7 we represent the full and the PWIA total cross sections (top plot) and the distortion parameter (middle plot), as a function of the separation energy of the knockout nucleon in a logarithmic scale. The distortion parameter exhibits a nearly logarithmic dependence on the separation energy of the knockout particle. These results show that distortion effects are expected to be smaller for the knockout of a loosely bound particle but they are increasingly important as the separation energy of the particle increases, as for example in the case of the knockout of inner nucleons from a nucleus. There is also an effect of the angular momentum of the knockout particle, and the distortion increases if the knockout particle is in a P wave with larger separation energy.

TABLE IV. Total cross section and distortion effect to p-n single scattering as function of the neutron-core binding energy and angular momentum.

System	ϵ_b (MeV)	σ_{pn} (mb)	$\sigma_{\rm full}$ (mb)	D (%)
^{14}C $\otimes$ $n(2s_{1/2})$	− 0.50	29.3	21.5	27
	− 1.22	30.0	19.8	34
	− 2.70	29.9	17.5	42
	− 4.50	29.5	15.9	46
	− 15.0	28.0	12.7	55
	− 20.0	27.4	11.6	58
^{14}C $\otimes$ $n(1p_{1/2})$	− 0.50	30.3	18.0	41
	− 1.22	30.3	16.4	46
	− 2.70	30.1	14.7	51
	− 4.50	29.9	13.6	55
	− 15.0	28.9	11.1	62
	− 20.0	28.4	10.4	64
^{14}C $\otimes$ $n(1d_{5/2})$	− 0.50	29.7	16.1	46
	− 1.22	29.6	15.4	48
	− 2.70	29.4	14.6	50
	− 4.50	29.2	13.9	52
	− 15.0	27.9	12.1	57
	− 20.0	27.3	11.2	59

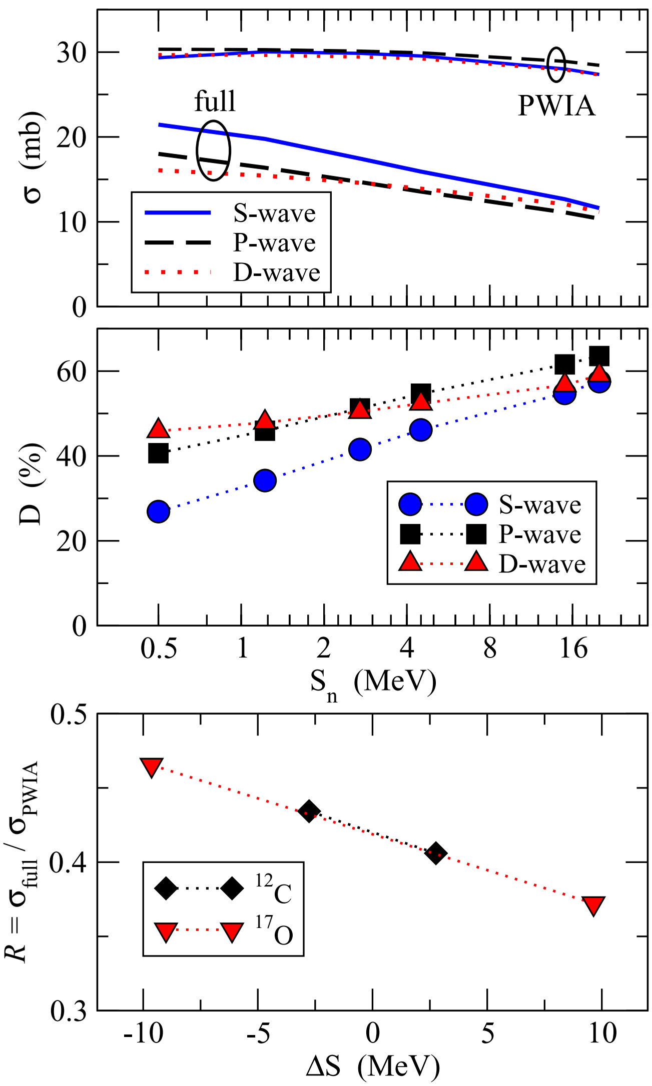

FIG. 7. Calculated total cross section, full, and p-n single scattering, as a function of the separation energy of the knockout neutron, in logarithmic scale, for different values of the angular momentum (top); the corresponding distortion parameter (middle); ratio parameter as a function of the asymmetry parameter (bottom).

Therefore it is important to evaluate accurately higher order multiple scattering terms.

The exact Faddeev/AGS formalism viewed as a multiple scattering expansion involves a sum of complex contributions to higher order terms as represented in Figs. 1 and 2. Obviously, the distorted contributions do not factorize into a renormalization factor to the proton-nucleon single scattering contribution, known as the PWIA; this complex multiple scattering expansion hinders the possibility to know beforehand an accurate analytical representation of the distortion capable of predicting the knockout of a nucleon from any shell for any nucleus along the nuclear landscape as a function of its binding and asymmetry parameter.

Nevertheless, the systematics obtained from this reaction approach shows that in this energy regime, there are subtle cancellations between the complex contributions of multiple scattering terms within all interacting pairs. The calculated distortion parameter D for a given angular momentum of the occupied shell shows nearly logarithmic dependence on the separation energy of the knockout nucleon.

We have found that the calculated distortion parameter for ^{17}O and ^{12}C differs from the interpolated values obtained from the systematic analysis by 2% and 6%, respectively. We note that there are some differences between the calculated model systematics and these real nuclei from the landscape. In the case of ^{12}C the heavy fragment has nonzero total spin which induces further angular momentum couplings. The Coulomb interaction for the proton and the heavy fragment is slightly stronger for ^{17}O.

A systematic analysis, as represented in Fig. 7, can provide a simplified estimate for the single-nucleon knockout from any given shell with angular momentum L and separation energy S_N.

In the bottom plot of Fig. 7 we also show the calculated ratio of the full and PWIA total cross section $\mathcal{R}$ defined in Eq. (6) as a function of the asymmetry parameter ΔS. This ratio makes evident a roughly linear trend when expressed as a function of the asymmetry parameter. A similar, but stronger dependence of the ratio of the theoretical to the experimental total cross section for nucleon knockout from light target (target and residue inclusive) was found in the work of Ref. [4] which might be included in distorted contributions.

In Fig. 8 we show the core transverse momentum p_x distributions at 420 MeV/u for the n-core binding energy of $\epsilon_b = -0.5$ MeV and $\epsilon_b = -15$ MeV, and angular momenta $L = 0,1,2$. The PWIA renormalized by the ratio parameter $\mathcal{R}$ (dashed line) does not follow in detail the calculated full Faddeev/AGS result (solid line), unlike the comparison between the PWIA with the DWIA approach of Ref. [14]. The results shown in Fig. 8 indicate that the distortion modifies the fully exclusive observables in a more complicated way than just a common renormalization factor.

V. CONCLUSIONS AND OUTLOOK

We used the Faddeev/AGS reaction framework assuming inert core to study the total cross section and the core transverse momentum distributions for (p,pN) reactions at 420 MeV/u as a function of the mass number of the core, the angular momentum, and the binding energy of the knockout particle.

We compared the observables using all multiple scattering terms to achieve convergence (full) with the PWIA. The Faddeev/AGS reaction formalism, when viewed in terms of a multiple scattering expansion, makes clear that the distortion effect formally does not factorize to a renormalization factor for the proton-nucleon single scattering p-N contribution, known as the PWIA. The systematics obtained from this reaction approach shows however that, in this energy regime, there are subtle cancellations between the complex contributions of multiple scattering terms from all interacting pairs. Under the assumption of an inert core we found that a distortion parameter, defined as the relative difference between the PWIA and the full Faddeev/AGS total cross section, shows nearly logarithmic dependence on the separation energy of the knockout nucleon for all considered values of the angular

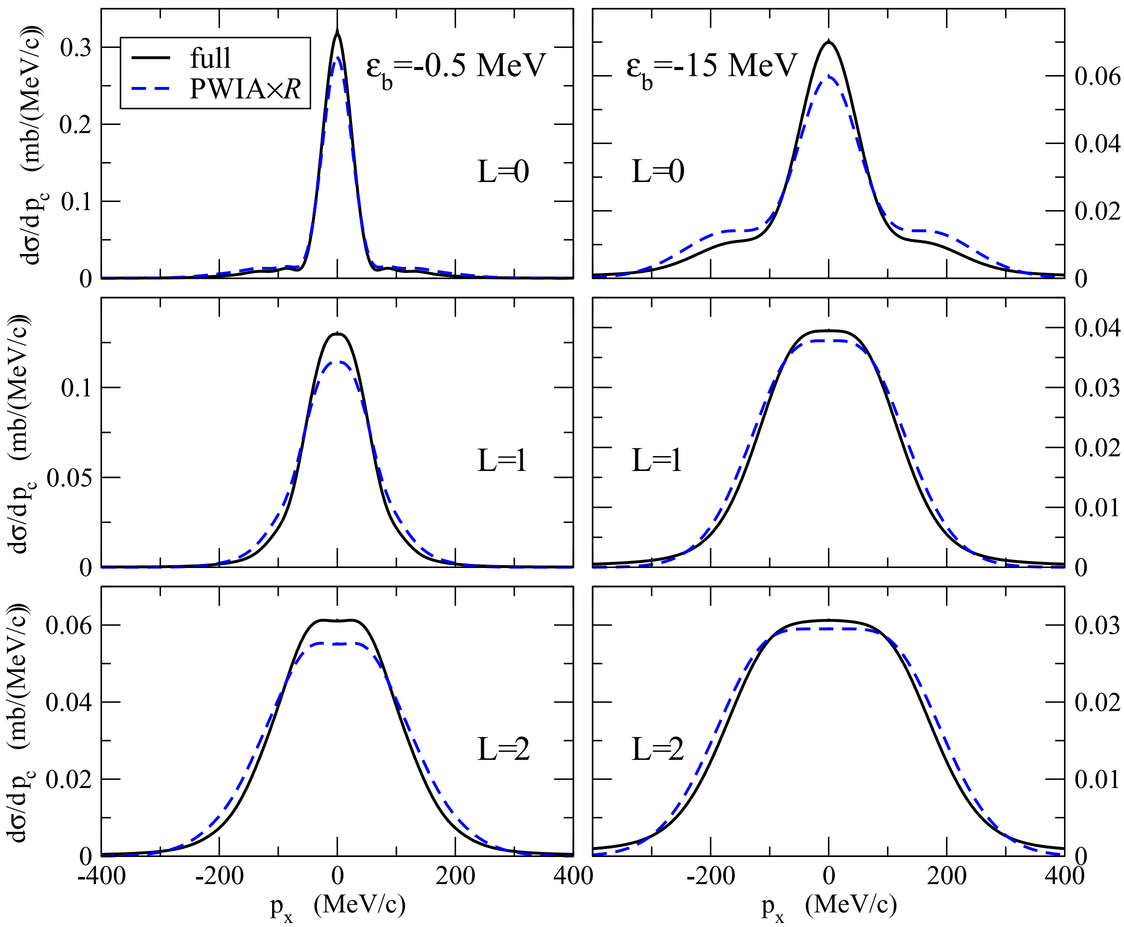

FIG. 8. Core ground state transverse momentum p_x distributions at 420 MeV/u for the n-core binding energies $\epsilon_b = -0.5$ MeV (left) and $\epsilon_b = -15$ MeV (right), and angular momenta $L = 0,1,2$. The solid and dashed lines represent the full and p–n single scattering observables renormalized by the ratio parameter between the full and the PWIA total cross section described in the text.

momentum. In particular, we expect that for (p,pN) the PWIA total cross section for the knockout of a nucleon from a inner shell leading to a high excited state of the residue will be strongly reduced by distortion higher order effects. There is also a dependence on the angular momentum of the knockout particle. Distortion effects are stronger for a knockout neutron occupying a P-wave shell with large separation energy. The dependence on the core residue mass number is negligible. This systematic analysis can provide a simple estimate of the total cross section for knockout of a nucleon from any given shell with angular momentum L and separation energy S_N from nuclei at/away the stability line of the nuclear landscape. A comparison with experimental results may provide insight on the interaction and structure model, and the contribution of multinucleon knockout and high excitation states of the core.

We found that the pure reaction theory ratio of the full to the PWIA total cross section shows a nearly linear dependence on the asymmetry parameter ΔS. The evaluation of this ratio for nucleon knockout on a proton target with identification of the final state of the heavy residue might help to clarify possible NN medium and structure effects.

The core momentum distributions calculated from PWIA and then renormalized by the ratio parameter between the full and PWIA total cross sections do not follow in detail the full result. This indicates that distortion effects do not modify the PWIA results through a common renormalization factor at these energies. The extraction of spectroscopic factors from knockout measurements relies on the validity of the factorization of distortion, and more insight on its validity is needed. A complex and detailed study of the distortion effects on kinematically exclusive observables to be measured in upcoming experiments at/away the stability line of the nuclear landscape will be carried out in the future. In particular, energy-angle or angle-angle correlations of the knockout and/or target particles available in current experiments will be analyzed. In addition, a comparison between (p,pn) and $(p,2p)$ knockout will be made.

Benchmark calculations between the Faddeev/AGS approach and other available reactions formalisms such as Glauber and DWIA, and the feeding of a microscopic description of the composite projectile will also be addressed in the future.

ACKNOWLEDGMENTS

A.D. acknowledges the support from Lietuvos Mokslo Taryba (Research Council of Lithuania) under Contract No. MIP-094/2015.

[1] P. G. Hansen and J. A. Tostevin, Annu. Rev. Nucl. Part. Sci. **53**, 219 (2003).
[2] A. Gade *et al.*, Phys. Rev. Lett. **93**, 042501 (2004).
[3] A. Gade *et al.*, Phys. Rev. C **77**, 044306 (2008).
[4] J. A. Tostevin and A. Gade, Phys. Rev. C **90**, 057602 (2014).
[5] T. Aumann *et al.*, Phys. Rev. Lett. **84**, 35 (2000).
[6] F. Flavigny, A. Obertelli, A. Bonaccorso, G. F. Grinyer, C. Louchart, L. Nalpas, and A. Signoracci, Phys. Rev. Lett. **108**, 252501 (2012).
[7] G. F. Grinyer *et al.*, Phys. Rev. Lett. **106**, 162502 (2011).
[8] O. Jensen, G. Hagen, M. Hjorth-Jensen, B. A. Brown, and A. Gade, Phys. Rev. Lett. **107**, 032501 (2011).
[9] A. Obertelli *et al.*, Phys. Rev. C **73**, 044605 (2006).
[10] L. V. Chulkov *et al.*, Nucl. Phys. A **759**, 43 (2005).
[11] R. Crespo, A. Deltuva, E. Cravo, M. Rodríguez-Gallardo, and A. C. Fonseca, Phys. Rev. C **77**, 024601 (2008).
[12] R. Crespo, A. Deltuva, M. Rodríguez-Gallardo, E. Cravo, and A. C. Fonseca, Phys. Rev. C **79**, 014609 (2009).
[13] R. Crespo, A. Deltuva, and E. Cravo, Phys. Rev. C **90**, 044606 (2014).
[14] T. Aumann, C. A. Bertulani, and J. Ryckebusch, Phys. Rev. C **88**, 064610 (2013).
[15] V. Panin *et al.*, Phys. Lett. B **753**, 204 (2016).
[16] A. M. Moro, Phys. Rev. C **92**, 044605 (2015).
[17] K. Ogata, K. Yoshida, and K. Minomo, Phys. Rev. C **92**, 034616 (2015).
[18] L. D. Faddeev, Zh. Eksp. Teor. Fiz. **39**, 1459 (1960) [Sov. Phys. JETP **12**, 1014 (1961)].
[19] E. O. Alt, P. Grassberger, and W. Sandhas, Nucl. Phys. B **2**, 167 (1967).
[20] A. Deltuva, A. M. Moro, E. Cravo, F. M. Nunes, and A. C. Fonseca, Phys. Rev. C **76**, 064602 (2007).
[21] R. Machleidt, Phys. Rev. C **63**, 024001 (2001).
[22] A. J. Koning and J. P. Delaroche, Nucl. Phys. A **713**, 231 (2003).
[23] A. Deltuva, A. C. Fonseca, and P. U. Sauer, Phys. Rev. C **71**, 054005 (2005); **72**, 054004 (2005); **73**, 057001 (2006).
[24] A. Deltuva, Phys. Rev. C **74**, 064001 (2006).