Merging first principle structure studies and few-body reaction formalism

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Merging first principle structure studies and few-body reaction formalism

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Abstract.

Calculations for nucleon knockout from a ^{7}Li beam due to the collision with a proton target at 400 Mev/u are shown based on *ab initio* Quantum Monte Carlo (QMC) and conventional shell-model nuclear structure approaches to describe the relative motion between the knockout particle and the heavy fragment of the projectile. Structure effects on the total cross section are shown.

1. Introduction

At the very earlier days of Nuclear Physics, nuclear experimental data have shown evidence that at the stability line, certain number of nucleons result in a greater stability, leading to the concept of magic numbers. Closely related to this idea, the independent shell model was developed, which assumes that the interactions within the many-nucleon system can be conveniently represented by a mean field potential (with a central and spin-orbit parts) for each single particle. In

the independent shell model the nucleons move independently in this potential. Shell model presupposes that residual interactions to this independent picture can be handled perturbatively.

The development of the Radioactive Ion Beam (RIB) facilities allowing the study away from the stability line unveiled the concept of shell evolution. It was verified that along the nuclear landscape some magic numbers are either disappearing or emerging. This novel behaviour has trigger numerous theoretical structure studies, that attempt to trace back shell evolution effects to the NN components of the interaction or 3-body nuclear forces. Nevertheless, despite considerable progress, a clear picture has not emerged yet.

Extracting structure information from nuclear reactions, in particular nuclear correlations or NNN force effects, faces a severe handicap. In fact, the current state-of-the-art reaction formalism relies on the fundamental assumption that essentially only a limted number of particles participate dynamically in the reaction process. Attempts have been made to incorporate the degrees of the excitation of one of the clusters into the reaction mechanisms. Clearly, *ab initio* many body structure information is required to be merged into the reaction framework.

Quantum Monte Carlo methods (QMC) allow the incorporation of sophisticated NN and NNN interactions and correlations in microscopic calculations of light nuclei bound states [1, 2]. In this work, first steps are made for merging state-of-the-art QMC wave functions into Faddeev reaction approach [3, 4]. Results of calculated total cross sections for nucleon knockout from a ^{7}Li beam due to the collision with a proton target at 400 Mev/u are shown.

2. The Faddeev/AGS multiple scattering framework

Let us consider the scattering of a many body projectile of A nucleons with a proton target. A key ingredient of standard reaction approaches to the scattering is the reduction of the overwhelming many body problem, into an effective 3-body system composed by an inert (A-1) core denoted here as C, plus a valence nucleon and a target proton. The exact dynamics of the collision in this truncated Hilber space can then be described by standard Faddeev/Alt, Grassberger and Sandhas (Faddeev/AGS) [5, 6]. This consists of a three-body non-relativistic reaction formalism treating all open channels (elastic, breakup and transfer) simultaneously.

In the assumed truncated Hilbert space $\mathcal{H}_{C+N+p}$ for $C+N+p$ free relative motion the heavy fragment can only be either in the ground state or in a low-lying excited state. Therefore, core dynamical excitations during the collision process, highly excited states above evaporation or multiple particle knockout (p,pNN' ..) are not taken into account.

In this reaction approach, the transition amplitudes leading to the observables are the on-shell matrix elements of the operators $U^{\beta\alpha}$, calculated from the solution of the three-body AGS integral equations

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

with $\alpha, \beta, \gamma = (1, 2, 3)$. Here, $\bar{\delta}_{\beta\alpha} = 1 - \delta_{\beta\alpha}$ and the two-body transition operator is

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

with the free resolvent $G_0 = (E + i0 - H_0)^{-1}$, with E the total energy of the three-particle system in the center of mass (c.m.) frame. The solution of the Faddeev/AGS equations at higher energies can be found by iteration

$$U^{\beta\alpha} \ = \ \bar{\delta}_{\beta\alpha} G_0^{-1} + \sum_\gamma \bar{\delta}_{\beta\gamma} t_\gamma \bar{\delta}_{\gamma\alpha} + \sum_\gamma \bar{\delta}_{\beta\gamma} t_\gamma \sum_\xi G_0 \bar{\delta}_{\gamma\xi} t_\xi \bar{\delta}_{\xi\alpha} + \cdots \ . \tag{3}$$

The successive terms of this series can be considered as terms of zero order (which contribute only for rearrangement transitions), first order (single scattering), second order (double scattering)

and so on in the transition operators t_γ. The $\beta = 0$ partition corresponds to three free particles in the continuum.

The breakup/nucleon knockout observables are calculated from the on-shell matrix elements of the AGS operators, as described in [7].

3. Interactions

In this work, two different structure approaches were used to obtain the projectile and residue overlap wave functions: (i) a two-body model with a Woods-saxon potential with depth constrained by the nucleon separation energy S_N, standard geometric factors (WS) and spectroscopic factors taken from [12] (ii) Quantum Monte Carlo (QMC) *ab initio* calculations based on the Argonne (AV18) NN interaction [8] with additional 3-body interactions [9]. In the work of [9] an effective interaction was found to reproduce the same overlap functions. This interaction can then be fed in the reaction formalism to calculate the Nucleon-Core ($N - C$) transition amplitude, Eq. 2.

The comparison between the effect of these two structure approaches on the calculated observables will provide insight about the importance of structure effects due to modifications of *both* geometry and spectroscopic factors.

The central effective interactions and the radial overlaps for the ^{6}Li+n and ^{6}He+p partitions are represented in Fig. 1 and Fig. 2 respectively. As shown in the figures, the *ab initio* VMC effective interactions have a larger diffuseness and a smaller depth than the WS representation.

As in earlier works, we take the realistic nucleon-nucleon CD Bonn potential [10] for the proton-nucleon particle pair. The results are essentially independent on the choice of the NN interaction. To describe the interaction between the target proton and the core (not well known) we take a phenomenological nuclear optical potential where the parameters are taken from the Koning-Delaroche (KD)[11] global optical potential parametrization evaluated at 200 MeV. In addition, we also arbitrarily take this parametrization for the knockout nucleon - Core interaction, in all the partial waves other than partial wave for the ground state of the projectile. The KD parametrization is not really designed for nuclei $A < 24$, and there is an associated uncertainty with the choice of this parametrization. Nevertheless, one might anticipate that the results presented here, with respect to the effects of the the description of the overlap functions, will be independent of this choice.

4. Results

The theoretical cross sections for the knockout of a nucleon considering a Core in its ground state, are evaluated from the transition amplitudes Eq. 3.

In the calculations, all multiple scattering terms were included to achieve convergence. In addition, all few-body kinematical contributions are evaluated accurately. For p-knockout antusymmetrization is taken into account in the multiple scattering expansion.

Taken the spectroscopic factor unity, these cross sections denoted as single particle σ_{sp} calculated with the two structure approaches and reproduced in Table 1 differ from about 10%. Upon introducing the spectroscopic factors taken from the *ab initio* [9] and the mean field Shell model framework [12], the difference between the theoretical cross sections σ_{th} remains of the same order of magnitude for the case of neutron- knockout, but increases significantly for the case of proton- knockout. This might be related to related to the fact that ^{6}He is a diffuse Core.

Our results show the same trend than those obtained from nucleon knockout due to the collision with a light target using the Glauber eikonal with the adiabatic reaction approach of [12].

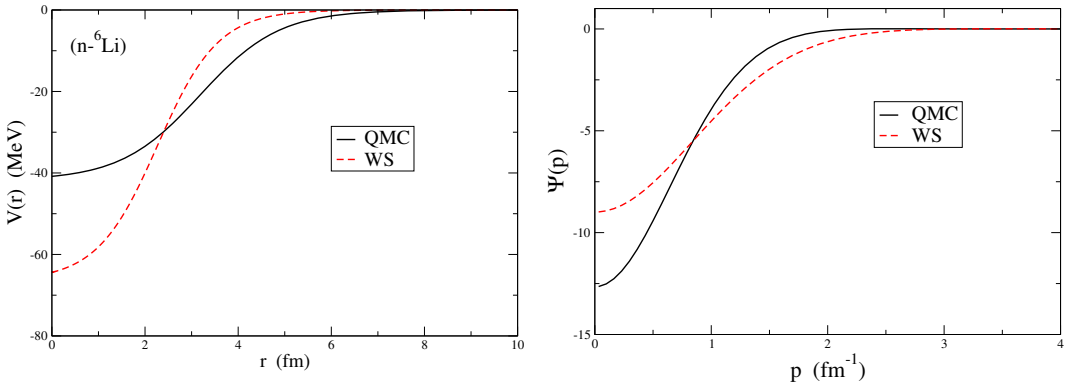

Figure 1. (Color online) Interactions and respective wave functions for describing the ^{6}Li+n

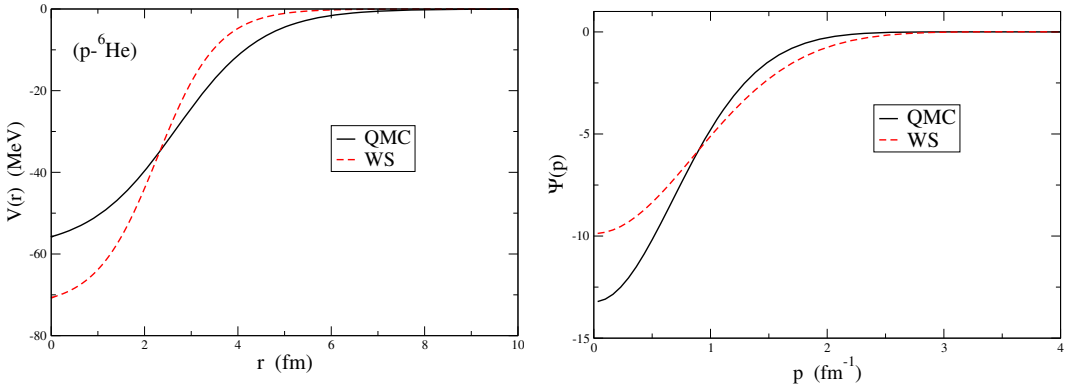

Figure 2. (Color online) Interactions and respective wave functions for describing the ^{6}He+p partition as described in the text.

Table 1. Total cross sections for N-knockout

Reaction	σ_{sp}^{QMC} (mb)	σ_{th}^{QMC} (mb)	σ_{sp}^{IPM} (mb)	σ_{th}^{IPM} (mb)	Δ_{sp}(%)	Δ_{th}(%)
^{7}Li(p,pn)^{6}Li	18.8	15.4	16.3	16.9	13	9
^{7}Li(p,2p)^{6}He	12.7	5.08	11.2	7.84	12	54

5. Conclusions and outlook

We have calculated nucleon knockout from a ^{7}Li projectile due to the collision with a proton target at 400 MeV/u. We have used the standard Faddeev/AGS few-body reaction framework considering that the heavy fragment is found in its ground state and remains inert in the collision process.

We have shown that the calculated single particle cross sections using an *ab initio* VMC approach to evaluate the radial overlaps between the projectile and the heavy fragment differ moderately of about 10% from the results obtained from a simplified Woods Saxon interaction, standard diffuseness and depth adjusted to reproduce the nucleon separation energy. On the other hand, when multiplied by the microscopic spectroscopic factors the results using the *ab initio* structure approach differ significantly from that taken form a mean field Shell model framework, for the case of proton- knockout. This might be related to related that to the fact

that a two-body model of an ^{6}He core coupled with a proton is a poor description for ^{7}Li.

Future developments to consistently include the projectile ground state and continuum from the *ab initio* structure approach into the reaction formalism will be performed.

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