Many-body effects in (p,pN) reactions within a unified approach

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We set an urgently needed unified theoretical approach to interpret transfer and nucleon knockout with proton and electron probes based on an ab initio many-body description of nuclei. We aim to understand the origin of the breakdown of the Mean Field Approach (MFA) and the discrepancy of its fingerprints found in the literature. We calculate theoretical ab initio many-body Quantum Monte Carlo (QMC) and MFA wave functions for A ≤ 12. These are combined with the Faddeev/Alt-Grassberger-Sandhas (F/AGS) few-body reaction formalism to interpret the (p,pN) Quasi Free Scattering (QFS) cross sections. We obtain the first good agreement between the QMC and experimental QFS total cross sections for QFS (p,2p) from $^{12}$C. The extracted Spectroscopic Factors (SFs) from QFS agree fairly well with the QMC values and moderately with the ones deduced from transfer and electron scattering reactions. The ratio of the calculated QMC to MFA cross sections for A ≤ 12 quantify the departure of the many-body description from the MFA, and ranges from 0.6 to 1. These ratios are determined by a delicate interplay between the radii of the parent and the residual nuclei and the nucleon separation energy, and is not directly linked whether a proton or a neutron is knocked out. In addition they exhibit a different dependence on the nucleon separation energy than the one inferred from the removal analysis. Our results show a clear violation of the MFA approach, which considers that the probability of finding the (A-1)+N configuration in the A nucleus, is unit, and that a many-body approach needs to be incorporated in the reaction framework.

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The Mean Field Approach (MFA) to particle systems has played an important role in Atomic Physics for describing the periodic table of elements and in Nuclear Physics for explaining many properties of nuclei, such as the origin of the magic numbers leading to additional stability.

Many conflicting results from single nucleon knockout experiments exist with respect to the importance and nature of such MFA breakdown [1–6]. However, structure studies and reactions analyses of single nucleon knockout from a nucleus have demonstrated the need to go beyond this simplified MFA picture and to consider models comprising explicit nucleon-nucleon (NN) and three-nucleon (NNN) interactions [7, 8], NN correlations, in particular neutron-proton correlations entirely absent in the MFA [9].

The key element for the interpretation of the single nucleon knockout from an A-body nucleus is the one-nucleon spectroscopic overlap. Formally, in a many-body approach, this is defined as the inner product between the wave function (WF) of the A parent nucleus and the fully antisymmetrized A-1 residual nucleus (core, C) plus the knockout nucleon WF. Contrary, the MFA considers that the A nucleus is described only by the (A-1)+N partition, where the nucleon quantum single particle (sp) states are obtained from a simulated average interaction. Furthermore, no antisymmetrization between the nucleons inside the core and N is considered. For a given state of the residual nucleus, this overlap is a superposition of different nucleon angular momentum channels, $\ell_j$, satisfying the appropriate triangular relations [10]. The so-called SFs for a given transition are obtained from the integral of the overlap function in each angular momentum channel.

The analysis of earlier (e,e′p) experiments provides, under the assumption of the validity of the Distorted Wave Impulse Approximation (DWIA), information on the one-nucleon spectroscopic overlaps at low momentum and for low-lying energy states of the residual nucleus. The experimentally extracted SFs are reduced with respect to MFA ones [6, 11].

Nucleon knockout from a nucleus in the collision with light targets (called one-nucleon removal in the literature) has been analysed extensively [1, 2]. Deduced re-
duction factors (R_{MFA}), defined as the ratio between the inclusive experimental and the theoretical cross sections derived from sp cross sections weighted by MFA spectroscopic factors, have shown to be smaller than unit and to have a strong dependence on the nucleon separation energy S_N. Contrary to this, QFS (p,pN) [3, 4] and transfer studies [5] have revealed small and nearly constant R_{MFA} as a function of S_N. This behavior has never been clearly understood.

A consistent analysis of available experimental data together with state-of-the-art theory is currently lacking and of utmost importance for the understanding of nuclear structure along the nuclear landscape. *Ab initio* Quantum Monte Carlo (QMC) calculations [7] have been used to interpret successfully transfer reactions [12] and (e,e’p) experimental data [11]. The Faddeev/Alt-Grazberger-Sandhas (F/AGS) three-body reaction formalism provides an exact solution of the three-body scattering problem [13, 14], where all open channels are treated simultaneously. It has been recently used in several exploratory studies of (p,pN) reactions [4, 15, 16].

In this letter our goal is to set an unified theoretical approach built on the many-body one-nucleon spectroscopic overlaps deduced from the *ab initio* QMC WF, which can be used as a common input to transfer and nucleon knockout reactions such as (e,e’p) and QFS (p,pN). For reactions with nuclear probes these are incorporated in the F/AGS reaction framework. We aim to understand the failure of the MFA picture.

In our approach, one-nucleon spectroscopic overlaps are calculated from the QMC many-body WF generated using the NN and NNN forces (Argonne V18 and Urbana X potentials - AV18/UX model) [8]. We have performed a convenient parametrization of the QMC one-nucleon spectroscopic overlaps using the procedure described in [10], which incorporates the adequate asymptotic behaviour. We evaluate Variational Monte Carlo (VMC) overlaps for p- and n- knockout from 3Li, 10Be and 12C nuclei. We take the VMC and Green’s Function Monte Carlo (GFMC) overlaps for the Li parent nucleus from Ref. [10], which are able to describe the (e,e’p) reaction [11].

We also consider the MFA where the overlaps are obtained as solutions of the one-body Schroedinger equation with the Woods-Saxon interaction with standard radius and depth adjusted to the separation energy of the removed nucleon. The QMC overlaps are translationally invariant and the MFA ones need the well known center of mass (c.m.) correction [19]. The analysis of these light nuclei will contribute to construct an unified interpretation of nucleon knockout reactions along the nuclear landscape, including the QFS (p,pN) experimental data collected at the R3B-LAND setup at GSI [3, 4, 24].

The theoretical SFs for each structure model, M, (QMC and MFA) are denoted here as Z^i(M), where i identifies the energy and the angular momentum of the residual nucleus as well as the nucleon angular momentum channels, with the sum \( \Sigma(M) = \sum_i Z^i(M) \).

We use the F/AGS in a nonrelativistic form since consistent treatment of relativistic kinematics and dynamics in [17, 18] indicates only a small (few percent) relativistic effect for the total three-body breakup cross section. The reaction formalism requires three pair interactions. We take the realistic NN CD Bonn potential [20] for the proton-nucleon pair. Since the cross sections are sensitive to the parametrization of the N-C and p-C pair interactions, we take the global parametrizations that best reproduce the elastic scattering data. We consider the Koning-Delaroche (KD) optical parametrization [22] used in preliminary calculations [23] and the Cooper [21] for 12C, a global parametrization developed for medium-heavy nuclei in particular for \( A = 12 \).

The theoretical inclusive cross section \( \sigma^{th}(M, M') \) for given structure models M and M’ is obtained as the weighted sum \( \sigma_{th}(M, M') = \sum_i Z^i(M) \sigma_{sp}^i(M') \) where F/AGS single-particle cross sections \( \sigma_{sp}^i(M') \) are computed using the overlaps normalized to unit. The weights are given by the spectroscopic factors \( Z^i(M) \).

We start by benchmarking our method with the important parent nucleus 12C.

As for the nuclear structure input we consider the 12C and 11B VMC wave functions [25]. The 12C VMC WF generates a point-proton rms radius of 2.37 fm which is very close to the experimental value of 2.33 fm. The overlaps in momentum space are represented in Fig. 1. This figure shows also the difference between the 12C and 11B proton momentum distributions with a significant high-momentum tail where about 15% of the protons have momenta above 1.4 fm\(^{-1}\) which cannot be predicted by a MFA. This result is in turn consistent with electron scattering analysis [11, 26]. The dominant source of this tail is the NN tensor force, coming from the one-pion-exchange potential, with a further significant contribution from the NNN force with its two-pion-exchange terms.

The VMC proton momentum distributions have components beyond p-shell particles that may contribute to their long tails. On the other hand, the overlaps that include only p-shell particles decay more rapidly than the proton momentum distributions as a function of the nucleon momentum. This might indicate that for low momentum and energy, the \((A-1)+N\) partition of the WF of the parent nucleus with the nucleon in a p-shell is dominant.

The experimental SFs \( Z_{exp}^i \) for the parent nucleus 12C to final states of 11B are calculated dividing the experimental cross section of [24] by \( \sigma_{sp}^i(QMC) \) using the global Cooper parametrization [21] and are shown in Table I. These values agree fairly well with VMC values listed in the same Table and moderately with those extracted from electron scattering [27] and transfer [28]. We also note that the sum of the \( Z^i(MFA) \) for all final states of the residual nucleus is very close to the sum of particles in the shell (before c.m. correction), the well known sum rule. We have obtained the total theoretical cross section \( \sigma_{th}(QMC, QMC) = 21.66 \text{mb} \) close to the exper-
that we show the theoretical ratios between the II and I and to first and second excited states of 11 B. Also shown in black the difference in 12 C and 11 B proton momentum distributions multiplied by 4 (the total number of protons in a p shell in the Independent Particle Model).

The calculated VMC SFs and the MFA ones, taken from the work of Cohen and Kurath (CK) [29], together with their sums Σ are compared in Table I and II. We also show the partial sum over the final states of the residual nucleus below its breakup threshold (also called Below Particle Threshold, BPT), ΣBPT.

The GFMC spectroscopic factors for the 7 Li parent nucleus for residual 6 Li states agree fairly well with the VMC ones, validating the VMC method for the extraction of one-nucleon overlaps.

In Fig. 2 we show the theoretical ratios between the sum of spectroscopic factors obtained from QMC and MFA calculations, $R_S = \Sigma (QMC)/\Sigma (MFA)$, as a function of the nucleon separation energy $S_N$. Since 11 C and 11 B form an isospin doublet, we expect the corresponding overlaps with 12 C to be similar. This was confirmed for the overlap with the residual nucleus in the ground state. From Fig. 2 it follows that these theoretical ratios $R_S$ range from 0.6 to 0.8. This reduction is due to the fact that the MFA considers only the (A-1)+N partition for the parent nucleus wave function, therefore setting to unity the probability of finding this configuration inside the nucleus. In contrast, the QMC overlaps are calculated from fully microscopic WF for parent and residual nuclei, both normalized to unit. This means that many other partitions are present in the parent nucleus WF leading to a probability associated with (A-1)+N configuration smaller than unit.

One can also see from Fig. 2 that $R_S$ does not depend strongly on $S_N$. Instead, we have found that the overlaps, and consequently the SFs, are determined by a delicate interplay between the radii of the parent (A) and the residual (A-1) nuclei and the separation energy of the knockout nucleon, and are not directly linked whether a proton or a neutron is knocked out. This can also be seen from the ratios to the residual nuclei from knocking a proton or a neutron $\Sigma BPT(^A-1 C_{N-1})/\Sigma BPT(^A-1 C_{N-1})$ shown in Tables I and II. For example, for the parent nucleus 10 Be (6 Li) we have for the experimental nucleon separation ener-

**TABLE I: Experimental, CK and VMC spectroscopic factors $Z^I$ for parent nuclei 12 C, their sum Σ, ΣBPT (Below Particle Threshold) and ratios $R_S$. CK* include c.m. correction factors.**

| Parent nucleus | Residual nucleus |
|----------------|-----------------|
|                | N               |
| 11 B           | (3/2-) $p_{3/2}$ | 0.24(0.03) 0.377 0.108(1) |
|                | (1/2-) $p_{1/2}$ | 0.29(0.03) 0.753 0.868(4) |
|                | (3/2-) $p_{3/2}$ | 2.43(0.28) 2.850 2.357(12) |
| 12 C           | ΣBPT            | 2.96(0.28) 3.980 3.333(13) 0.768(3) |
|                | Σ              | 2.96(0.28) 3.980 3.333(13) 0.768(3) |
| 11 C           | (3/2-) $p_{3/2}$ | 2.850 2.367(12) 0.753 0.868(4) |
|                | (1/2-) $p_{1/2}$ | 3.603 3.325(13) 0.823(3) |
|                | ΣBPT           | 3.98 3.343(13) 0.770(3) |

**TABLE II: VMC and CK sum Σ, ΣBPT (Below Particle Threshold) and ratios $R_S$ for parent nuclei 7 Li, 8 Li, 9 Be. CK* include c.m. correction factors.**

| Parent nucleus | Residual nucleus | Σ(M) | CK | VMC | VMC/CK* |
|----------------|------------------|------|----|-----|--------|
| 7 Li           | BPT              | 1.016 0.874(3) 0.737(2) |
| 8 He           | BPT              | 1.999 1.606(10) 0.689(4) |
| 9 Li           | BPT              | 0.592 0.389(1) 0.563(1) |
| 9 Be           | BPT              | 0.997 0.733(3) 0.630(2) |
| 10 Be          | BPT              | 1.131 1.428(4) 0.967(3) |
| 9 Li           | BPT              | 3.859 3.597(14) 0.829(3) |
| 9 Be           | BPT              | 0.847 0.635(2) 0.666(2) |
| 10 Be          | BPT              | 1.000 0.785(3) 0.698(3) |
| ΣBPT(7 Li)     | ΣBPT(8 He)       | 2.247(9) |
| 9 Be           | BPT              | 2.556 2.174(2) 0.830(1) |
| 9 Li           | BPT              | 3.990 3.568(22) 0.805(5) |
| 10 Be          | BPT              | 1.990 1.397(5) 0.722(2) |
| ΣBPT(9 Be)     | ΣBPT(9 Li)       | 2.249(9) |
| ΣBPT(10 Be)    | ΣBPT(9 Li)       | 1.361(4) |

**FIG. 1: Overlaps in momentum space $N(k)$ calculated from the VMC overlaps for various transitions to the ground state, and to first and second excited states of 11 B.**

The theoretical value of $σ_{exp} = 19.2(18)(12)$mb, with the ratio of experimental and theoretical values being 0.886(10). This indicates a fairly good agreement between theoretical cross sections obtained using many-body VMC one-nucleon overlaps and the experimental QFS data.
er energies, $S_\Sigma = 6.81 \ (4.06)$ MeV, and $S_p = 19.64 \ (13.94)$ MeV. Defining an average nucleon radius $\bar{r} = (r_n + r_p)/2$ we have obtained $\bar{r} = \{2.56, 2.53, 2.59, 2.56, 2.99\}$ fm for $\{^{10}\text{Be}, ^9\text{Be}, ^9\text{Li}, ^8\text{Li}, ^8\text{He}\}$ respectively. Therefore, we may conclude that the overlap amplitude is larger when the radius $\bar{r}$ of the parent and residual nuclei are closer, for similar separation energies. Consequently, the corresponding SF factor is larger in these cases.

The calculated ratios resulting from a partial sum over the final states of the residual nucleus BPT, $R_\Sigma^{BPT}$, differ significantly from $R_\Sigma$, varying from 0.5 to 1. This follows naturally from the fact that the spectroscopic strength is distributed among the states differently in the VMC and MFA formalisms.

We calculate ratios of the QMC to the MFA theoretical cross sections, where in the latter the SFs were taken from [29] but where the sum is restricted to states of the residual nucleus below particle threshold, $\sigma_{th}^{BPT}(M, M')$. The $\sigma_{sp}(M)$ are evaluated using the MFA and QMC overlaps normalized to one. Since we are considering low-lying states of the residual nucleus and we found only weak dependence of the $\sigma_{sp}$ on $S_N$ [30], we expect these ratios to be nearly independent of the choice of the global parametrization and MFA details. For the case of $^{12}\text{C}$ we have similar results for the ratios using different global parametrizations [21, 22] and different MFA prescriptions [4, 29, 31].

The ratios obtained using $Z^i(QMC)$ and $Z^i(MFA)$, $R_i^{BPT} = \sigma_{th}^{BPT}(QMC, MFA)/\sigma_{th}^{BPT}(MFA, MFA)$, are represented in the upper panel of Fig. 3. We expect these ratios to be very close to $R_\Sigma^{BPT}$, which is confirmed when comparing the solid-shaded symbols in Fig. 3 to Fig. 2. Therefore they are determined by the same delicate interplay between the radii of the parent and the residual nuclei and the nucleon separation energy, and is not directly linked whether a proton or a neutron is knocked out.

The fact that the ratio $R_i^{BPT}$ is significantly below unity reveals the importance of QMC WF for the calculations of the SFs. In contrast, the effect of the microscopic treatment of the parent and residual nuclei overlaps on the calculation of the sp cross sections was found to be comparatively small. This effect is estimated from the ratio $\sigma_{th}^{BPT}(\text{QMC, QMC})/\sigma_{th}^{BPT}(\text{QMC, MFA})$ that we found ranging from 1 to 1.2. Combining these two results we conclude that the microscopic treatment of the overlaps has its bigger effect on the evaluation of the theoretical cross section through the SFs.

FIG. 2: Theoretical ratio between the sum of SFs obtained from QMC and MFA calculations, as a function of the nucleon separation energy. Solid-dark symbols correspond to the sum over all the final states of the residual nucleus, while solid-shaded symbols represent the sum restricted to final states below particle threshold of the daughter nucleus.

FIG. 3: Upper panel: ratio between the QFS partial sum of cross sections for transitions to final states of the residual nucleus below particle threshold as a function of the nucleon separation energy. The solid-shaded (open) symbols represent the ratio between total cross sections calculated with QMC weights and QMC (MFA) overlaps by those with MFA weights and overlaps. Lower panel: removal results calculated with theoretical sp removal cross sections taken from [2] are also shown for comparison.

The ratios $R_i^{BPT}$ have a small dependence on the $S_N$, which is consistent with the results for the ratio of the experimental to the theoretical cross sections within a MFA picture obtained at GSI-LAND [3, 4]. The ratio $R_i^{BPT}(II) = \sigma_{th}^{BPT}(\text{QMC, QMC})/\sigma_{th}^{BPT}(\text{MFA, MFA})$, that fully quantifies the failure of the MFA for the description of the QFS reaction is represented in Fig. 3 by the open-symbols, ranges from 0.6 to 1. We also show in the lower panel of the same figure the ratio of the theoretical cross sections for nucleon removal from $^{10}\text{Be}$ and $^9\text{Li}$ where the sp cross sections were taken from [2]. The trend of the calculated ratios for the removal reaction as a function of $S_N$ is different from that of QFS results.

In conclusion, we have set a unified theoretical approach to interpret electron scattering, transfer and QFS (p,pN) reactions, based on a common microscopic many-body description of nuclei with $A \leq 12$. We have used many-body QMC and MFA wave functions to determine one-nucleon overlaps and spectroscopic factors. For re-
actions with nuclear probes they were combined with the F/AGS reaction formalism that describes all open three-body channels simultaneously.

The theoretical ratios between QMC over MFA of the sum of SFs and of total cross sections are a very useful tool to study the departure of the many-body description of nuclei from the MFA.

The inclusion of many-body effects in the reaction mechanism allows to reproduce for the first time the experimental cross section measured in QFS (p,2p) on $^{12}$C target. The resulting experimental strength deduced from QFS for $^{12}$C to the low-lying final states of $^{11}$B, while showing a moderate agreement with the values extracted from electron scattering and transfer reaction, is in turn consistent with the predictions of VMC calculations.

Our studies carried out on light nuclei for $A \leq 12$ show that the ratio of QMC and MFA cross sections ranges from 0.6 to 1, exhibiting clearly the failure of the MFA and a weak dependence on the separation energy of the knockout nucleon. This ratio is determined by a delicate interplay between the radii of the parent and the residual nuclei and the separation energy of the knockout nucleon and it is not directly linked whether a proton or a neutron is knocked out.

In contrast, the ratio values of the experimental to the theoretical MFA cross sections extracted from the analysis of removal data [1, 2], which include stripping (not present in (p,pN)) and diffraction, range from 0.25 to 1 exhibiting a different dependence on the separation energy of the removed nucleon.

Transfer and knockout measurements for $A \leq 12$ will be very useful to get further insight on the violation of the MFA picture.

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