Spatial correlations probed in direct two-nucleon removal reactions

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Abstract. Direct two-nucleon removal reactions provide an effective technique for studying both stable and highly exotic nuclides. Grazing collisions with targets of beryllium or carbon sample the projectile structure near its surface, with the geometric selectivity of the reaction favouring two-nucleon configurations exhibiting strong spatial correlations. We discuss the correlations relevant to two-nucleon removal reactions and consider knockout from $^{12}$C, which offers the opportunity to benchmark theoretical calculations and test ab-initio structure theories.

1. Correlations in two-nucleon removal reactions

Fast two-nucleon removal reactions are a key spectroscopic tool in exotic nuclei. Two well-bound nucleons are suddenly removed from an intermediate energy (secondary) beam in a collision with a target of beryllium or carbon. The technique, relying only on measurement of properties of the (heavy) projectile core or reaction residue, provides an efficient route to highly asymmetric isotopes [1]. The requirement that the projectile core interacts (at most) elastically with the target constrains the reaction to grazing collisions, probing a cylindrical volume near the projectile surface determined by the core- and nucleon-target interactions. The cross sections are calculated for transitions between the $(A+2)$-body projectile ground state $i$ and $A$-body residue final states $f$, sampling the two-nucleon overlap function defined as

$$\Psi_f^i(1,2) = \sum_{I\mu T\alpha} C^{IT}_\alpha (I_\mu J_f M_f | I J_i M_i) (T T_f \tau_f | T_\mu \tau_i) \left\{ \psi_{\beta_1}(1) \otimes \psi_{\beta_2}(2) \right\}^{T_\mu}_{I\mu}.$$

The signed two-nucleon amplitudes (TNA) $C^{IT}_\alpha$ describes the parentage of a particular residue state $f$ coupled to the two-nucleon configuration $\alpha \equiv (\beta_1, \beta_2)$ in the projectile ground state $i$. The square bracketed term in the antisymmetrized two-nucleon wave function coupled to total angular momentum $I$ and isospin $T$. Under the assumption that the residue acts as a spectator and that its state is not coupled by the eikonal reaction dynamics, the reaction samples the square modulus of $\Psi_f^i(1,2)$ projected onto the impact parameter plane. The volume sampled is determined by the core and valence nucleon S-matrices, typically calculated using density folding models [2]. Configurations $\alpha$ (or coherent mixtures thereof) that exhibit spatial correlations are thus favoured due to the geometric selectivity of the reaction. Further details of the approximations made may be found in e.g., Refs. [3, 4].

To first order the two-nucleon removal cross sections are determined by (a) the absolute magnitudes of the parentage amplitudes $C^{IT}_\alpha$ and (b) the total angular momentum $I$. $I$ is
critical in determining the spatial proximity of the two-nucleons and this sensitivity is evident in the impact parameter plane two-nucleon position probability distribution (see e.g., Figs 1 and 2 of Ref. [5]). For $I = 0$, the probability for finding the core-nucleon vectors $\vec{r}_1$ and $\vec{r}_2$ with a small angular separation $\omega$, where $\cos \omega = \vec{r}_1 \cdot \vec{r}_2$, is strongly enhanced. This has a direct impact on two-nucleon removal cross sections. Consider the example of $^{28}$Mg($-2p$), assuming a simplified $\pi[0d_{5/2}]^2$ structure with $C^{TT}_\alpha = 1$. The calculated cross sections for $I = 0, 2$ and 4 are shown in Table 1, in addition to the case where the two protons are assumed to be entirely uncorrelated save for being bound to the same core (see Ref. [1]). The $I = 0$ cross section is $\sim 40\%$ larger than the uncorrelated case, whereas for $I = 4$ there is a $\sim 20\%$ suppression. These basic spatial correlations are a crucial factor in calculating final-state exclusive cross sections and branching ratios. With full sets of shell-model TNA, coherent mixing of configurations $\alpha$ within a single major shell will further modify the spatial correlations in the overlap function [3, 5]. Beyond this, mixing of differing parity single-nucleon states, absent from most conventional shell-model model spaces, introduces interference effects that can further enhance spatial correlations [4, 6, 7].

Table 1. Stripping cross sections for $^{28}$Mg($-2p$) assuming a single configuration $\pi[0d_{5/2}]^2$ with $C^{TT}_\alpha = 1$. Model inputs (wave functions, $S$-matrices) are taken from previous work [3].

| $\sigma_{str}$ (mb) | $I = 0$ | $I = 2$ | $I = 4$ |
|-------------------|---------|---------|---------|
| Uncorrelated      | 0.27    | 0.39    | 0.27    | 0.21    |

2. Two-nucleon removal from $^{12}$C
We now discuss these aspects in the context of $^{12}$C($-2N$) where both conventional shell-model and ab-initio structure descriptions are available, allowing a first assessment of major shell mixing on two-nucleon removal. The existing 2.1 GeV/nucleon carbon on carbon data [8], though final-state inclusive, show a significant enhancement for $(T = 0, 1)$ $np$-removal ($^{10}$B residue) over $(T = 1)$ $nn$-removal ($^{10}$C residue). This enhancement is of particular interest as a potential signal and measure of strong $np$ correlations at the nuclear surface - the spatially selective nature of the reaction providing the leverage to test this. A first study [9] using conventional $0p$-shell truncated-basis shell-model TNA found reasonable agreement with experiment for $nn$-removal, but significantly underestimated the $np$-removal cross section.

Here we compare the earlier shell model results ($0p$-shell, WBP interaction) [9] to recent No-Core Shell Model (NCSM) calculations in model spaces allowing excitations up to $N_{max} = 6$ [10]. Two chiral EFT NN+3N interaction denoted NCSM1 and NCSM2 were used, softened using the similarity renormalisation group (SRG) technique. The NCSM1 NN+3N Hamiltonian used a 3N cutoff of 400 MeV with parameters fit to the $^3$H lifetime and the $^4$He binding energy, whereas for NCSM2 the 3N cutoff was 500 MeV and the parameters were fit to the lifetime and binding energy of $^3$H. Consistent with the NCSM calculations, harmonic oscillators were used for the valence nucleon radial wave functions with $\hbar \omega = 16$ MeV throughout. Further details of interactions and density-folding model $S$-matrices may be found in Refs. [9, 10].

Four $T = 0$ states ($3^{-+}_{1}, 1^{-+}_{1}, 1^{++}_{2}, 2^{++}_{2}$) in $^{10}$B and two $T = 1$ states ($0^{++}_{1}, 2^{++}_{2}$) common to both $^{10}$B and $^{10}$C are predicted to be populated. The $^{10}$B final-state inclusive cross sections $\sigma_{-np}$ are 18.36, 25.00 and 26.01 mb for the WBP, NCSM1 and NCSM2 interactions respectively, compared to the experimental cross section 35.10±3.40 mb. The respective cross sections for $^{10}$C are 5.12, 6.22 and 7.28 mb, compared to 4.11±0.22 mb. Evidently the NCSM amplitudes lead to enhanced cross sections, but the relative enhancement of the $np$ channel above the $nn$ channel is small and the significant underestimation of the $np$-channel measurement remains.
The final-state exclusive cross sections are shown in Figure 1. The three structural approaches predict measurably different patterns of final-state-exclusive cross sections. The large enhancements found for the lowest three states in the NCSM calculations are partly due to a redistribution of 0p-shell strength, but the (much) larger model space is also important. The mixing of different major shells enhances the probability for finding the two nucleons in close proximity, leading to larger cross sections. For example, the cross section for the first 1\(^+\) state in the full NCSM1 calculations is 8.52 mb; truncating these TNA to the 0p-shell gives 6.09 mb (see also Figure 7 of Ref. [10]). The associated residue momentum distributions have widths characteristic of each state, though are largely independent of the interaction.

3. Summary
Two-nucleon removal reactions are sensitive to the spatial correlations of the nucleons removed, primarily determined by their total angular momentum I. Coherent mixing of two-nucleon configurations within and between major shells can also lead to strong enhancements of spatial correlations and, consequently, cross sections. For \(^{12}\text{C}(\text{−2N})\), the extended basis NCSM calculations give larger cross sections for the low-lying states, in part due to mixing between major shells. However, the existing inclusive data suggest that the T = 0 strength is still insufficient. New final-state-exclusive measurements would offer a means to interrogate these shell-model inputs and the direct reaction mechanism predictions in detail.

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References
[1] Bazin D et al. 2003 Phys. Rev. Lett. 91 012501
[2] Al-Khalili J S and Tostevin J A 1996 Phys. Rev. Lett. 76 3903
[3] Tostevin J A and Brown B A 2006 Phys. Rev. C 74 064604
[4] Simpson E C and Tostevin J A 2010 Phys. Rev. C 82 044616
[5] Simpson E C and Tostevin J A 2012 50 Years of Nuclear BCS (Singapore: World Scientific)
[6] Catara F, Insolia A, Maglione E and Vitturi A 1984 Phys. Rev. C 29 1091;
[7] Pinkston W 1984 Phys. Rev. C 29 1123
[8] Lindstrom P J, Greiner D E, Heckman H H, Cork B, and Bieser F S 1975 LBL Report No. LBL-3650 (unpublished)
[9] Simpson E C and Tostevin J A 2011 Phys. Rev. C 83 014605
[10] Simpson E C, Navrátil P, Roth R and Tostevin J A 2012 Phys. Rev. C 86 054609