Direct reaction probes of single-particle states and correlations

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Abstract

The most exotic neutron-proton asymmetric nuclei are produced most efficiently in high-energy fragmentation reactions. These exotic nuclei are produced as fast secondary beams with energies of order 100 MeV per nucleon or greater, and hence $v/c > 0.3$, often with relatively low intensities. For such beams one can exploit both the detection efficiency and the cross sections for fast one- and two-nucleon removal reactions. The reaction dynamics of these channels is relatively simple due to the fast (sudden), surface grazing, and forward travelling (eikonal) nature of the reaction mechanism. More recent work now interfaces these sudden, eikonal reaction models with more microscopic nuclear structure model input. The possible roles of nucleon and pair *correlations* and their observation using such reaction data are discussed.

PACS numbers:

I. INTRODUCTION

The wave functions of nuclear many-body systems are complicated by strong two (and weaker three) nucleon forces, and the correlations they induce, that are manifest as changes to the otherwise independent single-particle motions. Mixing of the low-lying and occupied single-particle states with high-lying shells by short-range interactions and mixing with more collective configurations by longer-range terms reduces the expected *strength* associated with the simpler single-particle state description. The precise role and the importance of three-nucleon (3N) forces remains less well understood but is an increasingly important aspect of modern microscopic many-body approaches. In the absence of exact nuclear wave functions, for other than the lightest nuclei, shell-model, mean-field and beyond mean-field solutions for nuclear wave functions use modified Hamiltonians. The nucleons are then restricted to truncated model spaces where they interact through softer, more benign effective interactions, requiring necessary renormalisations of operators when calculating and comparing with experimental observables.

Very detailed studies of the nature of these effective (single-particle) states of nucleons in the stable nuclei, specifically, by knocking-out bound protons using high-energy electron beams, have revealed this interplay between the independent-particle motions and the short-, medium- and long-ranged correlations within the nuclear medium, see e.g. Ref. [1] and references therein. A firm result of these efforts was the observation that approximately 60–65% of the expected independent-particle strength is observed when one removes valence nucleons (protons) from the single-particle orbitals near the Fermi-surface of a wide range of stable nuclei.

Techniques to study the behavior of single nucleons and pairs of valence nucleons in states near the Fermi-surfaces of asymmetric nuclei include fast, direct one- and two-nucleon removal reactions. These exploit fast surface-grazing collisions of the nuclei of the beam with a light nuclear target such as beryllium or carbon. These reactions have been shown to be particularly good techniques for this purpose [2, 3]. Data and calculations for such reactions are revealing systematic behaviors and migration of valence nucleon states that suggest novel (enhanced) correlation effects in the most asymmetric nuclei. The reaction dynamics is considerably simplified when exploiting fast exotic beams, allowing use of the direct, sudden and forward focussed (eikonal) collision approximations, see e.g. Refs. [4, 5].

Recent spectroscopic applications and predictions are presented here.

Future fragmentation facilities for exotic nucleus production will bring higher intensities and also higher beam energies, typically in excess of 250 MeV per nucleon, as are already available at the RIBF at RIKEN and at GSI. At these higher energies theoretical calculations using the methods discussed will be even more reliable quantitatively.

II. NEUTRON-PROTON ASYMMETRIC NUCLEI

Access to nuclei with large $N : Z$ asymmetry allows the study of two new and generic physical features that are unique to two fermion species systems:
(i) the development (in the nucleon single-particle energy domain) of displaced neutron and proton Fermi surfaces. In e.g. neutron-rich ^{38}Si, still some distance from the neutron drip-line for $Z = 14$, the measured neutron and proton separation energies are $S_n = 5.29$ MeV and $S_p = 20.64$ MeV, and their Fermi surfaces are displaced by $\Delta S = 15.35$ MeV. This ΔS, and other macroscopic properties such as the nuclear sizes, are rather well predicted by spherical Skyrme Hartree-Fock mean field calculations.
(ii) for such a neutron-rich system, the presence (in the spatial domain) of a more extended density for the neutrons at the nuclear surface. It follows that valence protons near the nuclear surface, in orbitals at their now well-bound Fermi surface, are spatially embedded in a radial region of matter that is neutron-dominated.

These will be general features that may affect one- or two-valence-proton removal reactions from a neutron-rich system, and vice-versa. One might then expect that the wave function of these protons may be affected by and contain information due to additional and novel np-correlation effects - e.g. due to the strong short-ranged and tensor np interaction. The possible observation of such np-correlations is one motivation of the reaction studies discussed here. Evident also from the present discussion is that large neutron or proton excess will drive the Fermi surface of the excess nucleon species toward zero binding. It follows that the proximity of this threshold will result in coupling and additional effects due to the continuum. The importance of these correlations and how these are manifest in measurements is of considerable interest for validating effective and microscopic structure model predictions.

III. FAST ONE- AND TWO-NUCLEON REMOVAL REACTIONS

Details of the formalism and the approximations made in the sudden, eikonal description of fast one- and two-nucleon removal are not discussed here. These can be found in e.g. Refs. [2, 4, 5] and the references cited therein. Experimentally the reactions proceed as follows. For a given fast beam of exotic projectiles of mass number A, one observes the heavy projectile-like removal-reaction residues, of mass $(A-1)$ and/or $(A-2)$, travelling within a small angular cone about the forward (beam) direction. Measurements of the momenta of these residues and their distributions are often also made with good statistics. Two-nucleon removal reactions have recently been shown to have high spectroscopic value [6, 7]; specific recent examples of which are cited later. Exclusive yields of the different final states of the fast moving residue, but not those of the target nucleus, may be detected by Doppler-reconstructed γ-ray spectroscopy. All such removal measurements are inclusive with respect to the final states of the target and, except for a small number of precision, dedicated experiments designed to confront/validate the one-nucleon removal [8] and two-nucleon removal [9] reaction mechanism predictions, they are also inclusive with respect to the final states of the removed nucleon(s). So, the measured cross sections include nucleon removal due to both elastic and inelastic interactions of the nucleon(s) removed from the projectile and the target. These different contributions are incoherent and their theoretical values are then summed.

A. Nuclear structure and reactions interface

In the eikonal reaction treatment, the interactions of the residue (r) and the removed nucleons with the target nucleus are described by their elastic S-matrix elements, e.g. $S_r(b_r)$. These are expressed as functions of their individual impact parameters, b_i, with the target nucleus. An important feature of the high-energy ion-ion interaction (i.e. the residue-target system at energies of $\approx$100 MeV per nucleon and above) is its highly-absorptive nature, the S-matrix approximating closely to that of a diffuse surface, absorptive black disk with a radius determined by the residue and target sizes. The reactions are thus highly geometrical and constrained. It is assumed that the residue is not inelastically excited to low-lying collective and/or single-particle states in the fast, grazing collisions of importance to removal events. The absorption of the residue-target interaction at small b_r and the necessity to find and remove just one or two nucleons thus localizes the removal reactions to grazing collisions of the nuclear surfaces. Since the target is light, it will sample the wave function(s) of the removed nucleons in a relatively small cylindrical volume, with axis in the beam direction, at the surface of the projectile. It is then evident that:

(i) in two-nucleon removal, cross sections will be sensitive to the proximity (spatial correlations) of pairs of nucleons near the surface, and can therefore also provide a means to probe these spatial correlations [10],

(ii) the reaction-mechanism-sampled spatial volume invokes no spin-selection, e.g. of spin $S = 0$ over $S = 1$ pairs, and the reaction will sum these contributions,

(iii) the removal mechanism imposes no linear or angular momentum matching requirement, so the mechanism will see all nucleon configurations that have a non-vanishing probability amplitude in the sampled volume,

(iv) the reaction proceeds through the parentage/that component of the residual nucleus state present in the entrance channel, i.e. the projectile ground-state.

Regarding point (ii); if it becomes possible, through final-state phase-space detection/selection of say two protons, to identify events with correlated *di-proton-like* final state configurations, then these will most likely reflect the $S = 0$ pair content delivered to the target by the entrance channel (projectile) wave function [4]. These $S = 0$ pairs, in turn, will be present preferentially in transitions to the 0^+ states of the residue, with implications for the momentum distributions of residues in coincidence with such correlated final state events. More exclusive final state measurements will thus allow opportunities for more detailed interrogation of the reaction mechanism and of the structure amplitudes used.

In one-nucleon removal from the projectile ground-state $|^A\mathrm{Y}(J_i^\pi)\rangle$ to a given residue final state $|^{A-1}\mathrm{X}(J_f^\pi)\rangle$ one is sensitive to the nucleon radial overlap function $I_{\ell j}(r)$, whose norm is the spectroscopic factor for the transition, $S(J_i, J_f \ell j)$.

The spectroscopic factors in the following are provided by: (a) the shell-model, or (b) microscopic calculations [11]. For case (a), the shell-model, the geometry of the potentials used to generate the radial form factors is constrained using Hartree-Fock calculations; for details see Section III of [12]. As stated earlier, the Hartree-Fock predicts the nuclear size and binding systematics rather well including in the neutron-rich nuclei. In case (b), when using variational Monte Carlo (VMC) or no-core shell-model (NCSM) microscopic calculations,

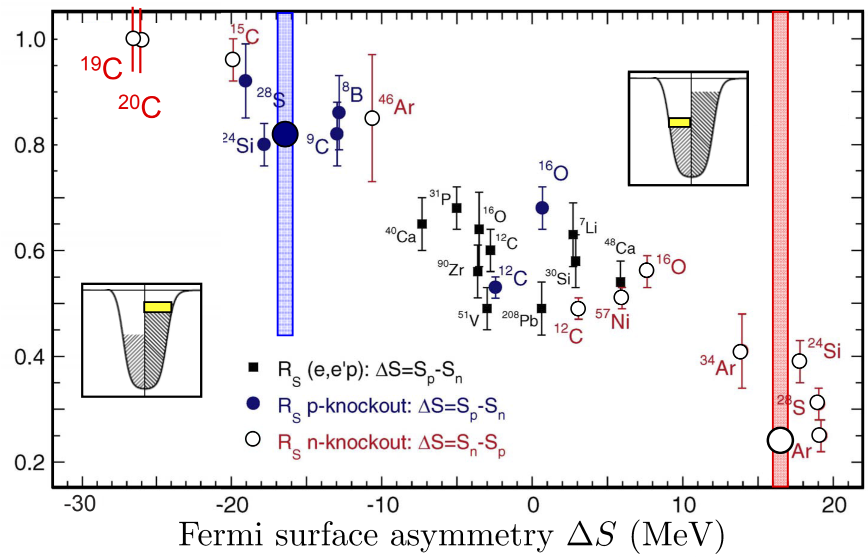

FIG. 1: Deduced ratios $R_s = \sigma_{\rm exp}/\sigma_{\rm th}$ of the measured to the theoretical, calculated one-nucleon removal cross sections as a function of the Fermi-surface asymmetry ΔS of the nuclide. As indicated by the inserts, ΔS is defined positive when a more strongly-bound nucleon is removed and negative for removal of a nucleon of the weakly-bound species. The figure is adapted from [12] and includes two new data points deduced from neutron removal measurements from the very neutron-rich carbon isotopes ^{19}C and ^{20}C, with $\Delta S < -25$ MeV, made at RIKEN at 240 MeV per nucleon [13] (extreme left). The shaded vertical bars and associate data points show the positions of additional data points for both neutron and proton removal from ^{36}Ca, with $|\Delta S| = 16.6$ MeV, made at the NSCL, also presented at this meeting [14], and which are also consistent also with the systematics shown.

both the $I_{\ell j}(r)$ and their norms are then given by the structure models.

For two-nucleon removal, no microscopic calculations of the two-nucleon overlap functions are yet available, thus the shell-model has been used.

B. One-nucleon removal: Dependence on neutron-proton asymmetry

The theoretical scheme outlined above permits systematic calculations of nucleon removal cross sections, without adjustable parameters, using shell-model structure input and with complex interactions (S-matrices) and nucleon orbital rms radii constrained by the experimental (reproduced by the Hartree-Fock) systematics. This has now been done in many cases for data sets with energies near and above 100 MeV per nucleon, including both stable [15] and very exotic nuclei. The summary of the cross section magnitudes, presented as the ratio $R_s = \sigma_{\rm exp}/\sigma_{\rm th}$ of the measured to the theoretical cross sections, is presented in Fig. 1, adapted from Gade *et al.*[12]. The figure includes two new data points deduced from loosely-bound neutron removal measurements from the very neutron-rich carbon isotopes ^{19}C and ^{20}C, having $\Delta S < -25$ MeV, made at RIKEN at 240 MeV per nucleon [13]. Additional data sets, e.g. for neutron and proton removal measurements from ^{36}Ca, having $\Delta S = \pm 16.55$ MeV, agree in their preliminary analysis [14] with these systematics. The points for stable nuclei, near $\Delta S = 0$ in the centre of the plot, are compared with the electron-induced knockout expectations with reasonable agreement. The departures of the systematics from this $R_s \approx 0.5 - 0.7$ value, and in particular the small values of R_s when removing well-bound valence nucleons with large positive ΔS, has been the subject of much interest and discussion. From a structural point of view, since these calculations use the shell-model, questions arise concerning (i) its use of a highly-truncated model space, (ii) its treatment of the continuum, and (iii) the potential role of 3N-forces, among others.

Very recent work [11] has made a first assessment of such questions by interfacing reaction measurements and calculations with microscopic nuclear structure models. Specifically, to use the one-nucleon overlap functions (and point nucleon densities for the optical interactions) from variational Monte-Carlo (VMC) and multi-shell ($12\hbar\Omega$) no-core shell-model calculations (NCSM). These overlaps, available only for light nuclei, were used to compare with measurements for the neutron removal reactions from ^{10}Be and ^{10}C, bound by 6.8 and 21.3 MeV, respectively. Both microscopic models use realistic two-nucleon (2N) forces, the Argonne v_{18} (VMC) and CDBonn (NCSM) interactions. In addition the VMC includes the Urbana IX 3N interaction. More significantly the NCSM, like the shell model, uses an oscillator basis whereas the VMC has a more flexible basis with which to incorporate continuum effects; the proton separation energy in the ^{9}C residue is only 1.3 MeV. The results show that the changes to the p-shell-model spectroscopic factors and overlap functions due to the $12\hbar\Omega$ multi-shell model space are relatively modest. The VMC calculations on the other hand lead to significantly reduced spectroscopic factors and closer agreement with experiment, with calculated [measured] cross sections of 72.8 [73(4)] mb and 30.8 [23.2(10)] mb for ^{10}Be and ^{10}C. These first results do not yet quantify the importance of 3N versus the improved treatment of near-continuum effects in the VMC approach, but are highly suggestive that oscillator-basis methods are severely challenged by the near-continuum Fermi-surface in the ^{10}C to ^{9}C neutron removal case.

Another important theoretical study generates the one-nucleon overlaps and spectroscopic factors, for $^{14-28}$O, within the coupled-cluster method [16]. The conclusion to date is that by including continuum-coupling effects, using a bound and continuum states Hartree-Fock (HF) basis from a Woods-Saxon potential, there is significant suppression of the spectroscopic factors for the removal of well-bound valence protons with increasing neutron excess; Figure 3 of Ref. [16]. Moreover, the same magnitude of effect could not be reproduced when the HF basis was built using an harmonic oscillator (HO) single-particle starting point, even when this HO basis spanned 17 major oscillator shells. These calculations suggest strongly, that the proximity of the neutron continuum in the most neutron-rich isotopes has a significant coupling (correlation effect) with the well-bound but valence proton orbitals. The spectroscopic factors are however just a part of the reaction input. The radial overlaps themselves are also available and their radial structure will be important for a full assessment of the implications for well-bound proton removal reaction studies and for understanding the small deduced R_s values for large ΔS of Fig. 1.

C. One- and two-nucleon removal: momentum distributions and spectroscopy

The spectroscopic value of residue momentum distributions following one-nucleon removal has been recognized and used for some time. The momentum distribution has a shape and a width that are characteristic of the orbital angular momentum of the orbit from which the nucleon has been removed.

γ-spectroscopy is not possible in the case of unbound final states. So, in neutron removal from neutron-rich systems leading to unbound mass $A-1$ final states, neutron detection is needed. New data on neutron removal reactions from the most neutron-rich carbon isotopes, $^{19-22}$C, taken at the RIBF at RIKEN at 240 MeV per nucleon [13], suggests such measurements would be of value for e.g. the spectroscopy of the last particle-bound (Borromean) carbon isotope and heavy halo nucleus candidate, ^{22}C. The data for ^{22}C of Ref. [13] is for inclusive neutron-removal to unbound ^{21}C with subsequent neutron decay. Measurements are therefore of the yield and the momentum distribution of the bound ^{20}C residues. The reaction analysis of these data, of removal to the predicted shell-model states of ^{21}C, and taking account of the additional broadening of the ^{20}C residue momenta in the neutron evaporation step, are in excellent agreement with the measurements. They and the shell-model suggest a large $1/2^+$ spectroscopic factor (of $\approx$1.4) for neutron removal from the ^{22}C ground state. The calculated cross section has almost equal contributions from $2s_{1/2}$ valence neutron and $1d_{5/2}$ neutron-hole configurations. This provides strong support for the halo character of the ^{22}C ground state, as suggested previously (but less quantitatively) by a large measured interaction cross section [17]. As was shown in Fig. 1, R_s values deduced using the new inclusive neutron-rich carbon data are also consistent with the systematics for other systems.

The spectroscopic significance of exclusive two-nucleon momentum distributions has been clarified only more recently [6, 7] and few exclusive data sets are available to fully validate these detailed predictions. The inclusive data sets available, and the exclusive data set for two-proton removal from ^{28}Mg, are for cases where one removes two nucleons of the minority species from already very asymmetric nuclei, which ensures that the reaction mechanism is *direct* [3, 4]. These available momentum distributions data are very well described by the eikonal model [6, 7].

A very recent study of the spectroscopy of low-lying excited states in the neutron-rich $N = 28$ nucleus ^{44}S, populated using fast two-proton removal from ^{46}Ar, has already exploited this momentum distribution sensitivity [18]. The measured exclusive momentum distributions in coincidence with decay γ-rays were able to clearly characterize populated excited states in the ^{44}S residues as having $J = 2$ and $J = 4$, and so challenge shell model expectations. Such two-nucleon removal reactions, which populate residues that are even more exotic than the projectile, thus offer a rather unique tool to probe the spatial correlations of the removed nucleons [10] as provided by nuclear structure models.

IV. FAST NUCLEON PICKUP REACTIONS

The removal reactions discussed above preferentially populate states in the residual nuclei with a strong hole-like character. Recent studies have also looked at the potential for fast nucleon *pickup* reactions to be useful for spectroscopic studies of particle-like states [19, 20]. So, the work of Refs. [19, 20] considered test case measurements and associated direct reaction model calculations for reaction events in which a single nucleon is now pickedup by a fast secondary beam. As in the removal studies, such measurements can employ thick targets and γ-ray spectroscopy of the pickup residues and thus take full advantage of the properties and detection efficiencies of fast fragmentation beams. Measurements and their analysis, for data on beryllium and carbon targets, have concluded that carbon target data are preferred, the pickup leading predominantly to bound target-like residues and hence to a simpler (two-body) direct reaction description.

It is shown that the pickup reaction on a carbon target (with four well-bound valence neutrons and protons) proceeds predominantly by a direct, single-particle pickup mechanism, with nucleons transferred between bound states in the target and the residue. The momentum mismatch implied by pick-up to a fast beam is shown to considerably enhance the cross sections for pickup to high-ℓ single-particle final states - or of fragments thereof, see in particular [20]. Future measurements of this sort are therefore very selective and should be able to identify high-ℓ neutron intruder components in the low energy spectra of the pickup residues. Such higher-ℓ intruder configurations are typically angular momentum mismatched for lower-energy light-ion transfers and so are less strongly populated.

V. SUMMARY COMMENTS

Two essential and basic requirements for nuclear reactions to be of use at rare-isotope fragmentation facilities, where the most exotic nuclei are produced as fast secondary radioactive ion beams with relatively low intensity, are (i) high detection efficiency and/or large cross sections, and (ii) realistic, practical and quantitative theoretical reaction model descriptions that are able to interface with nuclear structure models. These two criteria are well satisfied by direct one- and two-nucleon removal (and also by fast-beam nucleon-pickup) reactions, all of which have been shown to be able to be measured with suitable precision. These reaction mechanisms offer effective probes of the emerging and evolving single-particle structure of nuclei with abnormal $N : Z$ ratios. Data are contributing to (a) spectroscopic studies in some of the most exotic nuclei and (b) are asking questions on the roles of the continuum, of 3N forces, and their resulting correlations in such systems. Residue-fragment final-state-exclusive cross sections and their parallel momentum distributions can be calculated reliably theoretically after one- and two-nucleon removal. Such exclusive measurements will be used to validate/reject the correlations induced on the wave functions of single-particle states and on nucleon pairs as are calculated by theoretical structure models. The new and future facilities will bring more intense beams at higher incident energies, for which the theoretical methods and experimental techniques discussed will be more accurate. More exclusive measurements will also be possible and will bring new spectroscopic and new reaction diagnostics opportunities.

Acknowledgements

This work was supported by the UK Science and Technology Facilities Council (STFC) under Grants ST/F012012 and ST/J000051. Theoretical and experimental contributions of all collaborators are gratefully acknowledged.

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