DECONSTRUCTING THE NUCLEUS ONE (OR TWO) NUCLEONS AT A TIME

D. BAZIN

National Superconducting Cyclotron Laboratory, Michigan State University, East Lansing, MI 48824, USA

1. Introduction

Since nuclear reactions have been used to probe the structure of nuclei, physicists have had to tackle the following conundrum: the cross section observable they measure depends on both the reaction mechanism and the structure of the states involved. To extract valuable information about the wave functions of the nuclei therefore requires a robust and trusted model of the reaction. A typical example that has been used since the early days of particle accelerators is transfer reactions, for which cross sections are calculated using optical potentials. Although this type of reaction has and continues to provide tremendous amounts of knowledge about the structure of nuclei, it has always been difficult to obtain exact agreement with experiment, in particular the absolute magnitude of the calculated cross sections are very sensitive to the parameters of the optical potentials, which are often difficult or impossible to obtain for the exit channel of the reaction.

A more promising type of reaction that has appeared since the advent of radioactive beams produced via projectile fragmentation is knockout reactions. This terminology describes a high energy peripheral reaction in which one or two nucleons are suddenly removed from a fast traveling nucleus. The assets of this type of reaction for extracting structure information, especially on rare isotopes, will be presented in this contribution.

In particular, the details of the reaction model used with this type of reaction have been probed and verified experimentally, which emphasizes the robustness of the prescriptions and approximations used, and provide a deeper understanding of the validity of the model.

At the same time, recent developments in structure theory are now focusing more and more on so-called *ab initio* models, where the structure of nuclei is calculated from first principles, much like the structure of atoms and molecules is nowadays calculated from solving the electromagnetic many-body problem.

Some of these efforts are particularly fruitful for p-shell nuclei where the computational needs are manageable. The second half of this contribution will focus on the first attempt to use of knockout reactions performed on the same p-shell nuclei, to probe the results of these new types of calculations.

2. Knockout reactions under the microscope

This type of reaction has now been used for over a decade to probe the wave functions of nuclei far from stability. Its main assets reside in the high energy regime in which they are used, providing high luminosity as well as enabling the use of sudden and eikonal approximations in the reaction model.

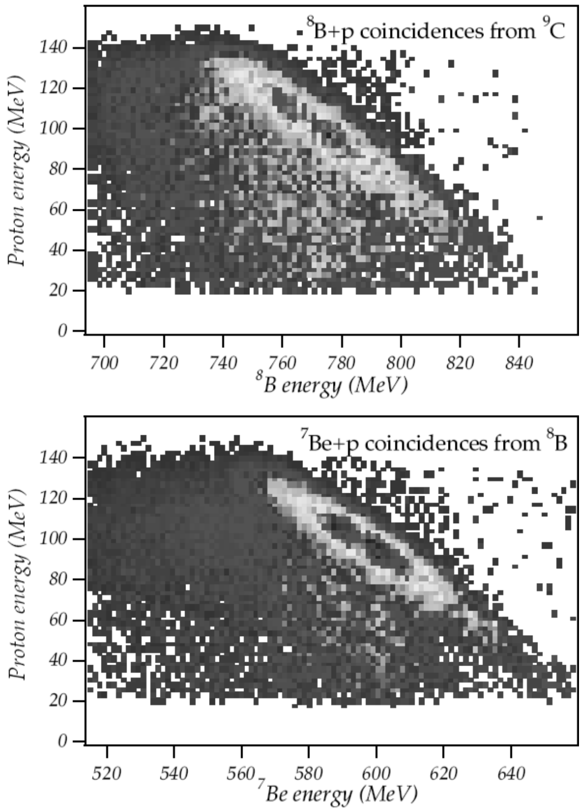

Fig. 1.1 Two dimensional spectra of the energy of protons and of the heavy residue in one-proton knockout reactions from ^{9}C (top) and ^{8}B (bottom) projectiles respectively. The narrow bands of constant energy sum correspond to elastic breakup whereas other events are associated with inelastic breakup (from [3]).

As explained elsewhere in more details [1], the kinematic characteristics and experimental method associated with this type of reaction enable very large luminosities, essential to the study of very low intensity rare isotope beams. In the case of single nucleon removal, the reaction theory models two distinct types of mechanisms in which the nucleon is removed.

The first assumes an elastic breakup scenario where the nucleon is removed via tidal forces exerted by the nuclear potential of the target, which is left in its ground state. This is usually the smallest contribution to the cross section and is also called diffraction. The second is labelled stripping or inelastic breakup because it involves a more violent interaction with the target, which ends up excited or broken up. The single-particle cross sections for these two reaction mechanisms are calculated within the eikonal model using S-matrices for the survival probabilities of the removed nucleon (S_n) and projectile residue (S_c) after the interaction [2]:

$$\sigma_{dif} = \frac{1}{2j+1} \sum_{\sigma,m} \int d\vec{k} \int d\vec{b}\, |\langle \psi_{\vec{k}\sigma} | (1 - S_n S_c) | \psi_{jm} \rangle|^2$$

and

$$\sigma_{str} = \frac{1}{2j+1} \int d\vec{b} \sum_{m} \langle \psi_{jm} | (1 - |S_n|^2) |S_c|^2 | \psi_{jm} \rangle$$

The aim of the following studies is to explore the validity of these theoretical scenarios, by experimentally probing the reaction mechanisms that take place during the reaction. To this end, an experimental setup was used in which the removed nucleon (in this case a proton) was detected in coincidence with the breakup residue. This experiment was carried out at the National Superconducting Cyclotron Laboratory (NSCL), details can be found in this publication [3]. Figure 1.1 shows the energy of the ^{8}B (^{7}Be) residue versus the energy of the detected proton in the one-proton knockout from ^{9}C (^{8}B) at 97.9 (86.7) MeV/u. The prominent feature common in these two plots are the energy-conservation bands that directly correspond to elastic breakup, where no energy is transferred to the target. Other events have a much broader distribution and correspond to inelastic breakup. This observation is a direct proof that the two reaction mechanisms envisioned in the reaction model do indeed take place experimentally. Furthermore, a quantitative study of this data reveals that the observed fractions of these two scenarios are reproduced by the eikonal calculation within error bars [3].

More recently, a similar experiment was carried out to explore reaction mechanisms that take place in two-nucleon knockout reactions. It was shown early on that whenever the two removed nucleons are taken from the lesser kind in the nucleus, this reaction proceeds in one step [4]. The eikonal reaction model was applied to this type of reaction [5]. Similarly to the one-nucleon case, three reaction scenarios were identified: i) both nucleons are removed inelastically, ii) one is removed elastically and the other inelastically, and iii) both are removed elastically.

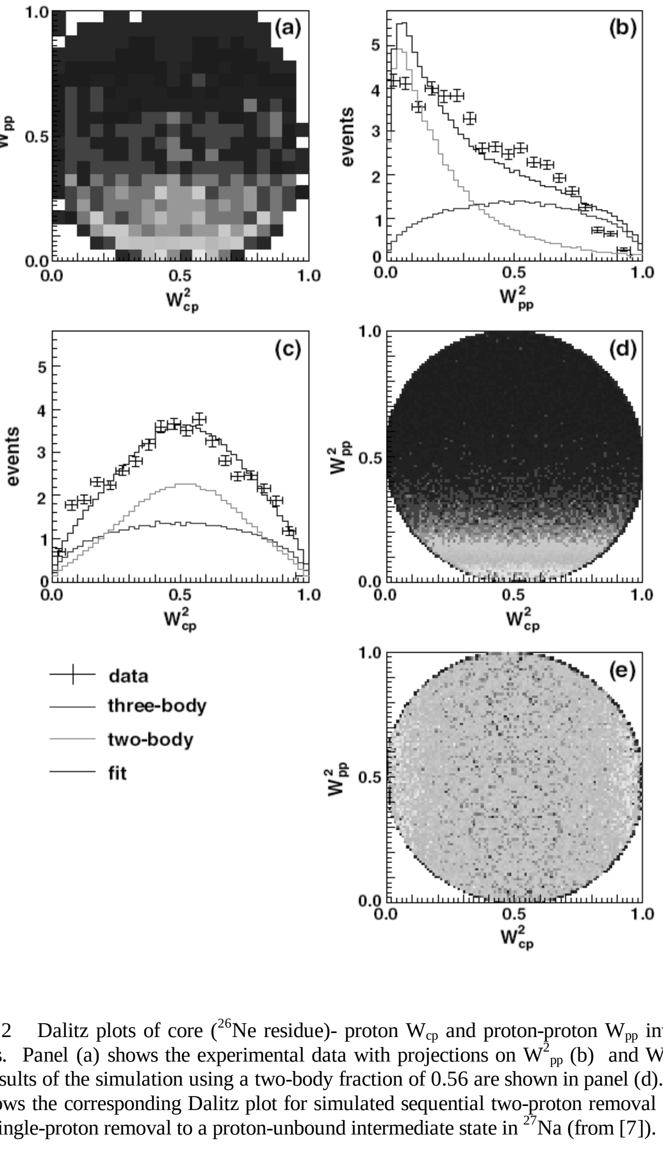

Fig. 1.2 Dalitz plots of core (^{26}Ne residue)- proton W_{cp} and proton-proton W_{pp} invariant masses. Panel (a) shows the experimental data with projections on $W^2{}_{pp}$ (b) and $W^2{}_{cp}$ (c). The results of the simulation using a two-body fraction of 0.56 are shown in panel (d). Panel (e) shows the corresponding Dalitz plot for simulated sequential two-proton removal events, via a single-proton removal to a proton-unbound intermediate state in ^{27}Na (from [7]).

The exclusive experiment performed to test these assumptions used the same setup as the previous one, on the two-proton knockout from a ^{28}Mg projectile. The observed fractions of the three scenarios for the reaction mechanism are again well reproduced by the calculation [6], further evidence that the assumptions used in the reaction model are well grounded. Going a step further in the analysis of the exclusive two-proton knock-out data, the kinematical correlations between the two removed protons were studied via Dalitz plots shown in Fig. 1.2 taken from [7]. The experimental distribution (a) and its projections (b) and (c) are compared to Monte-Carlo simulations assuming either uncorrelated (three-body) or correlated (two-body) protons during the breakup. A clear signal of a large fraction of spatially correlated protons is observed, with a fitted value of 0.56(12). This fraction is attributed to spin S=0 two-proton configurations in the ^{28}Mg wave function in the entrance channel. These results points to future studies of spin correlations of valence nucleon pairs.

3. Nuclear structure under the microscope

The possibility to solve the nuclear many-body problem using exclusively a description of the interaction between individual nucleons has arisen only recently, with techniques such as the variational and Green's function Monte-Carlo (VMC) [8], or no-core shell model (NCSM) calculations [9]. These theoretical efforts have concentrated mainly on p-shell nuclei for which the calculations are practical with to-day's computer resources. They have clearly demonstrated the importance of 3-body (3N) forces in the description of the interaction using several observables such as masses, matter radii, electromagnetic transition rates or spectroscopic factors. A remaining challenge is to be able to constrain in particular 3N forces for which only sparse data is available. It is clear that such *ab initio* models should be able to reproduce and predict the characteristics of unstable nuclei, including those located at the drip lines and beyond, precisely where data is lacking. The knockout reactions described in the previous section offer a unique opportunity to benchmark these theories on unstable nuclei, thanks to their high sensitivity and the robustness of the reaction model used to deduce spectroscopic factors. As illustrated in a recent paper [10] we have used this method on the two unstable p-shell nuclei ^{10}Be and ^{10}C by measuring absolute knockout cross sections at the level of 5% accuracy. These cross sections were then compared to calculations using nucleon densities and bound state wave function overlaps from both VMC and NCSM models. To achieve maximum consistency in the calculations of the cross sections, the theoretical densities and overlap functions were incorporated into the eikonal reaction model. An illustration of this procedure is shown in Fig. 1.3 where the VMC and NCSM bound state wave function overlaps were fitted using Wood-Saxon potentials with the addition of a spin-orbit term. The resulting Wood-Saxon parameters were subsequently used in the eikonal model to calculate the single-particle cross sections. Although their shapes differ qualitatively at large radii the majority of the overlap lies below r = 5 fm and is well described by the fit.

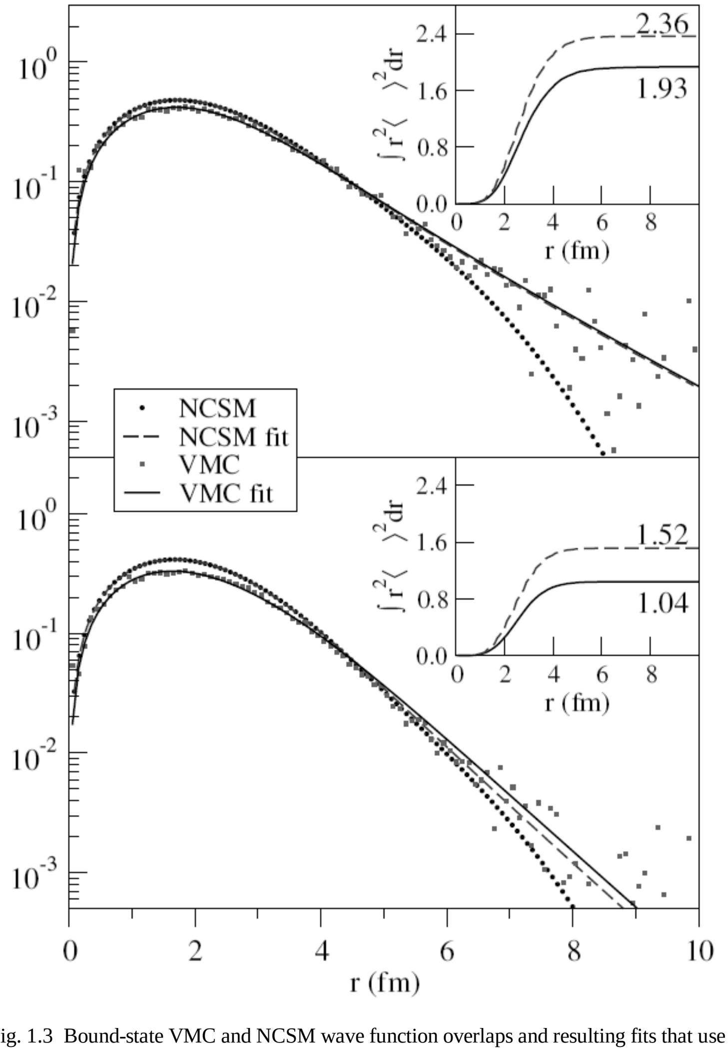

Fig. 1.3 Bound-state VMC and NCSM wave function overlaps and resulting fits that use a Woods-Saxon-plus-spin-orbit potential. (Inset) Integrals of the square overlaps that saturate at the theoretical spectroscopic factor (from [10]).

Plotting the integrated square of the overlap (insets of Fig. 1.3) highlights the dominant contribution below r = 5 fm where the VMC and NCSM also agree qualitatively on the shapes of the overlaps. The difference between them is primarily a scale factor. These two cases were chosen because both one-neutron knockout residues ^{9}Be and ^{9}C have no bound excited states, hence no γ-ray detection was required, the only possible final state of the reaction being the ground state. The comparison between the experimental and theoretical cross sections reveals a better agreement with the VMC calculations than the NCSM [10]. For the neutron knockout from ^{10}Be, the agreement is well within error bars for the VMC cross section, while the NCSM calculation is about 20% larger. The reason for this difference may lay in the influence of 3N forces, which are included in the VMC calculations only, or in differences in the description of nuclear sizes and continuum effects near the Fermi surface. In the case of the neutron knockout from ^{10}C, the NCSM cross section is nearly twice larger than the experimental one, while the VMC is closer but still about 30% too large. The larger discrepancy between the calculations and the measured cross section is likely rooted in the limitations of the eikonal model, namely the underlying assumption that the ^{9}C core is merely a spectator to the removal mechanism with such an extreme case of deeply bound valence neutron. Other cases of inclusive cross sections were also measured and are reported in [11], together with a detailed description of the experimental method. They are not as easily interpreted as the ^{10}Be and ^{10}C neutron knockout cases, because of the various final states that can be populated. They show surprising results obtained from mirror reactions that will be investigated in a follow-up experiment, which promises to provide a better understanding of the microscopic structure of p-shell nuclei.

4. Conclusion

Single and double nucleon knockout reactions offer unmatched opportunities to study the structure of rare isotopes. The high luminosity provided by this type of reaction is its greatest experimental asset, while the peripheral nature of the collision - when using a light target such as ^{9}Be or ^{12}C - enables the use of a simple eikonal model of the reaction mechanisms to calculate single-particle cross section and extract spectroscopic factors. The work presented in this contribution validates the assumptions made in the reaction model, in particular the quantitative proportions of reaction mechanisms (elastic and inelastic breakup) that occur. In addition, it demonstrates that correlations in the nucleus can be explored via two-nucleon knockout reactions, when exclusive experiments are carried out. Finally, knockout reaction inclusive cross sections have been measured on unstable p-shell nuclei to a high level of accuracy, in order to provide a test of *ab initio* structure theories. Testing these new types of theories on unstable nuclei is paramount to validating their assumptions and guiding their development.

Acknowledgments

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