Knockout Reactions

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Overview—New Challenges Need New Tools

It is now fifty years since Mayer and Jensen proposed a *shell-model* description of atomic nuclei [1], for which they shared the 1963 Nobel Prize for Physics. In their simple independent-particle picture, each nucleon (neutron or proton) feels an average potential due to all the others (the mean-field) and occupies and moves independently in a bound quantum mechanical orbital in this potential. These ideas have been immensely powerful in describing both systematic and more detailed features of the structure of nuclei, metal clusters, and related systems. In particular, they predict that nuclei are more stable when they have the right number of neutrons (N) or protons (Z) to just fill given orbitals, because there is then a natural gap in energy to the next available level; the magic neutron and proton numbers, 2, 8, 20, 28, 50, 82, and 126 that drive many systematic properties of the stable nuclei.

Today, we are able to produce very exotic nuclei, with abnormal neutron and proton combinations using dedicated accelerators. The properties of these exotic nuclei, produced in relatively small numbers in earth-based laboratories, dictate the synthesis of the heavier elements in the Universe, and so are of considerable importance to nuclear astrophysics. Modern *shell-model* calculations also include the effects of residual interactions between (otherwise independent) nucleons, using forces that reproduce the measured masses, charge radii and low-lying excited states of a large number of nuclei based on the underlying single-nucleon orbital structure. For very exotic nuclei the small additional stability that comes with the occupation of particular orbitals can have profound effects on their structure, lifetimes, and their existence as bound systems [2]. Verifications of the ordering, spacing, and the occupancy of orbitals are thus essential to assessing exotic nuclei and our ability to understand these theoretically.

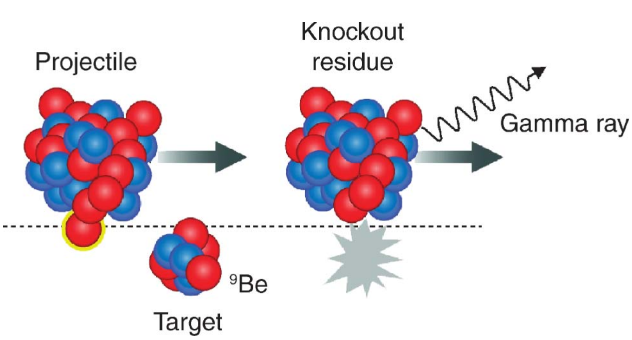

Figure 1. *Schematic of a one-nucleon knockout reaction. A single nucleon is removed from a fast-moving projectile in a grazing collision with the light target nucleus.*

This interrogation (spectroscopy) of the states of individual nucleons in short-lived nuclei uses direct nuclear reactions. New tools for this purpose are one- and two-nucleon knockout reactions involving beams of fast exotic nuclei with energies of 100 MeV per nucleon or more. Theoretically, the fast nature of the collisions allows the use of both sudden and eikonal (forward scattering) approximations, which combine to make the connection between experimental measurements, the reaction dynamics, and the nuclear structure particularly transparent, and allowing severe tests of the predictive power of state-of-the-art many-body structure calculations.

Introduction—Direct Nuclear Reactions

Direct nuclear reactions continue to provide many important and versatile tools for studies of the structure of the atomic nucleus, enabling the selective excitation of single-nucleon or collective degrees of freedom. For decades, reactions induced by stable ion beams impinging on stable target nuclei have provided a wealth of information on

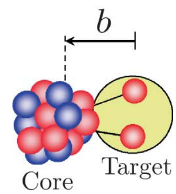

Figure 2. *Schematic showing the cylindrical volume drilled by the light target nucleus through the projectile surface within which the wave function of two nucleons is sampled, at a grazing impact parameter b. The volume extends in the beam direction, into the page.*

bulk and microscopic nuclear properties, ranging from the excitation energies of nuclear levels to the occupancies of single-particle orbits. Typically, the target-like reaction residues were the nuclei of interest. More recently, the often surprising and evolving structure of short-lived "exotic" nuclei has become a focus of experimental and theoretical research worldwide. Both very neutron-rich and neutron-deficient nuclei are produced efficiently by fragmenting stable nuclei accelerated to energies in excess of 100 MeV/u, that is 100 MeV per nucleon. The resulting exotic nuclei are then available for experiments as energetic, secondary ion beams and novel experimental techniques have been developed to exploit these beams to study the properties of rare isotopes.

Dependent on the collision energy and impact parameters there are a variety of possible outcomes when two nuclei collide. Direct nuclear reactions are characterized as involving surface-grazing collisions of the two nuclei, thus probing the shape of the nuclear surface and the states of individual nucleons in a near-surface layer. Crucial for the study of nucleonic properties is that the projectile (or target) suffers minimal rearrangement of its nucleons, ideally the reaction affecting just a single nucleon or a pair. So-called nucleon knockout reactions belong to this class of direct reactions (Figure 1). The term knockout was originally coined to describe the quasi-free proton-and electron-induced nucleon removal reactions on stable nuclei, of the (p,2p) and (e,e′p) type. Single proton or neutron knockout reactions from fast exotic ion beams were pioneered using ^{9}Be and ^{12}C targets [3]. In such a high energy, heavy-ion induced inverse-kinematics nucleon removal, a nucleon is removed suddenly from a projectile, having mass A and a known momentum, in a grazing collision with the light target. Being extremely fast, compared, for example, to the timescale of a compound nucleus reaction, there is minimal sharing of energy with the remaining protons and neutrons of the projectile during the removal event, this core of nucleons being a mere spectator and left undisturbed. This core or residue of the projectile then travels forward with a velocity close to that of the projectile beam.

The momenta and the number of these forward-travelling projectile-like residues are two key observables that carry structure information; the yield, for example, scales with the number of nucleons available to be removed from a given orbital. It follows that direct one-nucleon knockout reactions will probe the wave functions of the initial and final nuclei that differ by one nucleon. Quantities that can be deduced are the orbital angular momentum *l* of the removed nucleon and its spectroscopic factor; a measure of the strength and the extent of occupation of a given single-particle orbit. Key to interpreting the experimental data is that, due to the sudden nucleon removal, the momentum *p* of the removed nucleon within the projectile can be probed by measuring precisely the laboratory momenta of both the projectile and its reaction residue [3]. It is these measured *p*-distributions that identify the *l*-value of the orbital from which a nucleon was removed and, for a given nucleon separation energy, they have a width characteristic of the l-value. Such experiments were pioneered in the study of

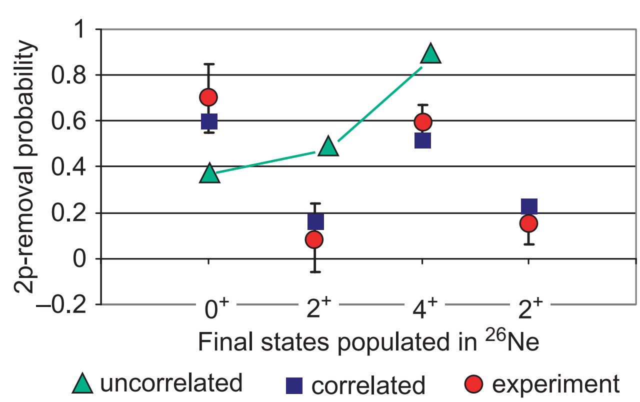

Figure 3. *The two-proton removal probabilities from neutron-rich ^{28}Mg to different final states of ^{26}Ne. The probability of each transition shows large sensitivity to the correlated motions and the total angular momentum of the two removed nucleons. This sensitivity is very accurately described by the reaction theory.*

halo nuclei–light nuclei with one or two very weakly bound nucleons, with small l, that form an extended, diffuse density or halo beyond the core of nucleons. In a knockout reaction such a halo is identified by observing a p-distribution that is very narrow, a direct consequence of the Heisenberg position-momentum uncertainty relation applied to the spatially extended halo nucleon wave function.

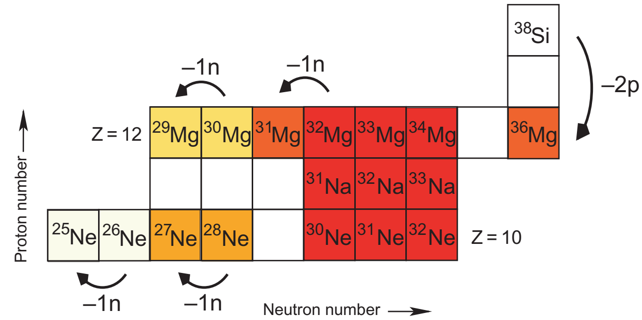

Figure 5. *One-neutron and two-proton knockout analyses were performed in the vicinity of the Island of Inversion. The measurements showed no evidence for negative-parity states in ^{25}Ne, no evidence for intruder configurations in ^{26}Ne, but an increasing intruder fp shell occupancy in the ground states of ^{28}Ne and ^{30,32}Mg, as N = 20 is approached. The reduced cross-section measured for the ^{9}Be(^{38}Si,^{36}Mg)X reaction indicated very different neutron structures in ^{38}Si and ^{36}Mg, with intruder-dominated low-lying states in ^{36}Mg (yellow to red color indicates increasing intruder content).*

Probing the Nuclear Wave Function

As will already be clear, one- and two-nucleon removal reactions will remove nucleons from all occupied orbitals in proportion to the overall probability of finding a nucleon with given quantum numbers near the projectile surface, and will populate both bound and unbound hole-like states of the residue. Also clear is that the cross-section to a given physical final state will depend on the many-body overlap of the initial and final state wave functions. If, having suddenly removed two nucleons, the produced (projectile with two holes) residue has a poor overlap with a given physical final state, then this transition will be suppressed; as might arise if there was a rapid structural change between the mass A and A – 2 nuclei. These overlaps enter the reaction calculations via the spectroscopic factors for one-nucleon removal and via the two-nucleon amplitudes for two-nucleon removal [4] and are computed from the shell-model many-body overlaps.

Fundamentally, calculations of these removal reaction yields are very robust because the reactions are highly geometrically constrained. Because the knockout reactions require that one or two nucleons undergo a violent or absorptive

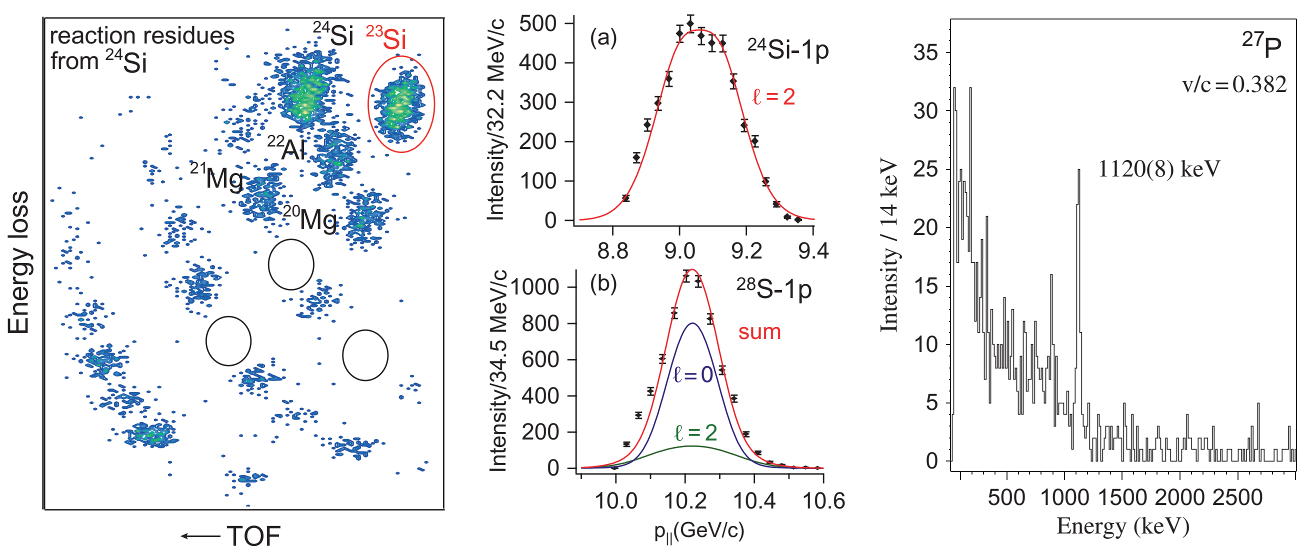

Figure 4. *Left: A typical particle-identification spectrum, here for the one-neutron knockout reaction ^{9}Be(^{24}Si, ^{23}Si + γ)X; Middle: Sensitivity of the parallel momentum distribution to the orbital angular momentum of the removed nucleon; Right: Event-by-event Doppler-reconstructed γ-ray spectrum in coincidence with ^{27}P after one-proton removal from ^{28}S. All figures are adapted from Ref. [9].*

interaction with the target, but that the residue of nucleons does not, the result is a very strong near-surface localization. The resulting sampling of the nucleon wave functions is represented in Figure 2. So, the measured one- or two-nucleon removal yields and longitudinal momentum distributions are determined by the part of the wave function inside a cylindrical volume drilled through the surface of the projectile by the passing target. In the case of the longitudinal momentum distribution, one is sensitive to the Fourier transform of the wave function (in the beam direction) throughout this probed volume. Also evident is that two-nucleon knockout cross-sections will be sensitive to the spatial correlations of nucleon pairs through the joint position probability for finding two nucleons with positions inside the sampled volume. Figure 3, for the case of two-proton removal from neutron-rich ^{28}Mg leading to different final states of ^{26}Ne, illustrates this sensitivity to the proton correlations. While beyond the space limitations of this feature article, we note that direct two-nucleon knockout residue momentum distributions also provide a clear signature of the total angular momentum carried by the two removed nucleons [5].

The validity of the sudden approximation allows these essential geometric considerations to be included reliably in an eikonal dynamical description. The inputs to the model calculations are then (a) the nucleon's and the residue's interactions with the target, that determine their amplitudes for transmission and absorption as they pass the target with a given impact parameter; that is their S-matrices for scattering with the target [1], and (b) the wave functions of the projectile ground state and the low-lying states of the projectile-like residue. These are taken consistently from, and thus test, shell-model calculations for each projectile. The robustness of the reaction calculations stem from three points: (i) For a series of experiments with very similar projectile energy, details of the nucleon's interactions with the target are the same across all analyses. (ii) The strong surface localization is encoded through the sizes of the target and projectile nuclei. Again, the target can be made common to all reactions, while the projectile and residue sizes are given quite accurately by theory, as has been confirmed experimentally. (iii) The high-energy interaction of the core of nucleons with the target can be calculated within a consistent framework, consistent with the nuclear densities, for all the reaction analyses.

In the following these considerations are used to shed light on details of the structure of exotic nuclei in volatile regions of the nuclear chart, where nuclei can change their structure profoundly if only one or two nucleons are added or removed. Direct one- and two-nucleon knockout reactions are particularly well suited for exploring such structural changes. The conditions under which the two-nucleon knockout reaction is guaranteed to be direct are more restrictive than for reactions involving one nucleon. Directness is certainly a feature of reactions that remove two nucleons of the minority species, such as two proton removals from an already neutron-rich projectile [6]. The two-nucleon knockout reactions discussed in the following fall into this latter category (i.e., the reactions drive one toward the most exotic nuclei).

Experiments—Revealing Changes in Shell Structure

The fragmentation of beams of stable nuclei at energies exceeding 100 MeV/u is a powerful method to efficiently produce fast beams (v/c > 0.3) of neutron-rich and neutron-deficient isotopes of elements lighter than uranium. Rare-isotope beams produced in this way are available at GANIL (France), RIKEN/RIBF (Japan), GSI (Germany), and NSCL/MSU (USA). Intermediate-energy and relativistic beams allow the use of thick reaction targets (thicknesses of hundreds of mg/cm^2 to several g/cm^2) and thus provide high luminosity. In reactions using the very rarest nuclei, experiments with less than 1 projectile nucleus per second have been successful.

Typically, the measurements made are inclusive in the sense that the final states of the removed nucleon and the target nucleus are not detected. The experimental task is then (i) to disentangle the nucleon knockout residues of interest from the zoo of competing reaction products emerging from the target, (ii) to identify the final state of these projectile-like residues after the reaction, and (iii) to measure the longitudinal or transverse momentum distribution of these heavy residues. The reaction residues are typically separated with magnetic spectrometers and identified via their energy loss (Z identification) and their flight time (mass resolution) (Figure 4). In the regime of thick reaction targets, the final state populations of the residues have to be tagged using in-beam γ-ray spectroscopy, using, for example, scintillator-based detection systems or high-purity germanium detector arrays. The γ-ray transitions corresponding to the decay of bound excited states are emitted by the reaction residues in flight and so are detected Doppler-shifted in the laboratory reference frame. Segmented germanium detectors, for example, are employed to Doppler-reconstruct the γ-rays emitted from the reaction residues moving at more than 30% of the speed of light event-by-event (Figure 4). With the 32-fold segmented germanium array SeGA at the NSCL, the photon emission angle is determined from the location of the segment that registered the largest energy hit. The residue momentum distributions are typically reconstructed with magnetic spectrographs. At the NSCL, the known magnetic field setting of the dipole magnets of the S800 magnetic spectrograph together with the position measurement of each reaction residue in the dispersive direction are used to reconstruct the longitudinal momentum distribution of the knockout reaction residues (Figure 4). Transverse momentum distributions have also been shown to be sensitive to the orbital angular momentum of the removed nucleon but require very accurate angle measurements as Coulomb deflection effects, for example, complicate the contribution from the knockout process to the transverse momentum. Heavy-ion induced nucleon knockout experiments have been pioneered and developed into a spectroscopic tool at the NSCL in the framework of a research program [7,8]. Numerous knockout experiments have also been performed at GANIL [9] and the GSI [10]. At RIKEN, the potential of nucleon removal reactions on a proton target have also been investigated recently [11].

Proton and neutron single-particle motion is one of the fundamental concepts used to describe the nuclear many-body problem. The nuclear potential experienced by nucleons and its resulting shell structure are well established for most stable nuclei. The single-particle energy levels are bunched, with gaps, forming the shell structure of the atomic nucleus. The large, stabilizing energy gaps between groups of single-particle states then occur at certain fillings of the orbits with a "magic number" of protons and neutrons [12,13]. However, for nuclei far from the valley of β stability, large neutron excess and reduced binding toward the neutron drip-line, for example, can lead to dramatic changes in the nuclear structure: new magic numbers develop and the conventional gaps between shells break down [14,15]. Extensive experimental [16] and theoretical efforts [17] are aimed at probing the driving forces behind these structural changes, which are most pronounced in the most neutron-rich nuclei.

A formidable testing ground for theoretical approaches that model the driving forces behind the structural changes in exotic nuclei is the so-called Island of Inversion in the vicinity of the neutron-rich nucleus ^{31}Na [18]. Measurements of the masses of neutron-rich sodium isotopes revealed that they are more tightly bound than expected if one assumes the validity of the conventional shell closure at neutron number N = 20 [19]. Evidence for an onset of deformation in this region mounted from other experimental observables. Shell-model calculations that allow for neutron particle-hole excitations across the N = 20 shell gap reproduced the experimentally observed onset of deformation in this region and predict that particle-hole "intruder" configurations are energetically favored and dominate the ground states of nuclei in this region. Due to their sensitivity to the orbital angular momentum and the occupancy of single-particle orbits, nucleon knockout reactions have been ideal to track this breakdown of the N = 20 magic number in the chains of neon and magnesium isotopes. Intruder configurations in this region involve orbital angular momenta l = 3 and/or l = 1, corresponding to neutrons occupying the $f_{7/2}$, $p_{3/2}$ or $p_{1/2}$ orbits above the sd shell. One-neutron knockout reactions from ^{28,26}Ne and ^{32,30}Mg projectiles were performed at beam energies exceeding 75 MeV/u at the NSCL [20,21]. From the direct population of negative-parity states in the knockout residues ^{25,27}Ne and ^{29,31}Mg and the shapes of their associated longitudinal momentum distributions, first direct and quantitative evidence for the gradual onset of intruder states in the chain of neon and magnesium isotopes was established (Figure 5).

At the neutron-rich exit of the N = 20 Island of Inversion, the two-proton knockout reaction ^{9}Be(^{38}Si,^{36}Mg)X was used to probe whether ^{36}Mg is part of the "Island" or not. This reaction was of particular interest because it connects the non-intruder ground state of ^{38}Si to ^{36}Mg, which, according to the best large-scale shell-model predictions, exhibits significant intruder configurations in its ground and low-lying exited states [22]. Clearly, direct, two-proton removal from the non-intruder ground state of ^{38}Si one can only connect to non-intruder configurations in the ^{36}Mg final-state. In the experiment, a very small two-proton removal cross-section was encountered, reflecting the fact that the residue produced following two-proton removal from the "normal" nucleus ^{38}Si has a very different neutron wave function and hence a reduced overlap with the low-lying eigenstates of the—now proven to be intruder-dominated—nucleus ^{36}Mg. Comparisons with the results of the reaction calculations, with shell-model inputs, determine the probability of these non-intruder components in the ground and first excited 2^+ state wave functions of ^{36}Mg to be less than 40%, indicating that the remainder is of intruder nature [22]. This firm conclusion, of intruder dominance in the low-lying level scheme of ^{36}Mg, registers this very neutron-rich nucleus as firmly inside of the "Island of Inversion" [22].

Evidence is also mounting for a region of deformation around the N = 40 isotones ^{62}Ti and ^{64}Cr where the lowering of the neutron $g_{9/2}$ orbit across the N = 40 harmonic oscillator shell closure may lead to a second "Island of

Inversion." One such piece of evidence stems from the surprisingly small, $\sigma = 0.13(5)$ mb, two-proton knockout cross-section measured at the NSCL for $^{9}Be(^{66}Fe,^{64}Cr)X$ [23]. This cross-section is a factor of 10 smaller than for the $^{9}Be(^{68}Ni,^{66}Fe)X$ reaction, which also connects two N = 40 isotones. Similar to the two-proton knockout from ^{38}Si to ^{36}Mg, such suppression is thought to signal a dramatic structural change between the ground state configurations of ^{66}Fe and the bound states of ^{64}Cr, driven by a reduced overlap between the neutron wave functions in the initial and final states.

These high sensitivities of direct one- and two-nucleon knockout reactions to details of the wave functions of some of the most rare atomic nuclei are being used in many other regions of the nuclear chart, helping to track the evolution of the fundamental nucleon shell structure and benchmark many-body and effective interaction theories. The experimental and theoretical techniques have now been developed significantly, tested in many contexts, and are well placed to provide spectroscopic opportunities at upcoming rare-isotope facilities employing fast-beam capabilities.

Acknowledgments

The work presented was supported by the National Science Foundation, under Grant No. PHY-0606007, and by the United Kingdom Science and Technology Facilities Council, under Grants Nos. EP/D003628 and ST/F012012. A.G. is supported by the Alfred P. Sloan Foundation.

Dedication

We dedicate this feature article to the memory of Professor P. Gregers Hansen whose exceptional enthusiasm and original insights into the potential for development of these spectroscopic tools have proved to be well founded.

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