# DIRECT REACTIONS WITH EXOTIC BEAMS

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A new method for studying correlations in nuclei is presented. It is based on measurements of single-nucleon knockout reactions in inverse kinematics at energies above 50 MeV/nucleon. It is a powerful spectroscopic tool for identifying single-particle structure via measured partial and differential cross sections to individual final levels. The shape of the longitudinal momentum spectra identifies the orbital angular momentum $\ell$, while the absolute cross sections determine single-nucleon spectroscopic factors. Three new aspects of this work are discussed, alignment effects, absolute spectroscopic factors as a source for information about short-range correlations, and the identification of a new direct reaction: two-proton knockout from neutron-rich nuclei.

## 1. Introduction

Correlations are central to the nuclear shell model. Although we think of this model in terms of a picture based on non-interacting nucleonic orbitals in a central field, it is, in fact, only a few nuclei near double-closed shells that are amenable to such a simple approach. The correlations arising from the long-range part of the nucleon-nucleon force usually make it necessary explicitly to take into account the mixing of many valence configurations. For heavier nuclei this often is done by using dynamical or static shape variables, while for lighter nuclei it is possible to apply more exact techniques involving the diagonalization of a large matrices representing the (effective) interactions in a restricted quantum-mechanical space.

The experiments reported here are based on the identification of the single-particle components of the nuclear wave function as observed in one-nucleon removal reactions. These provide the same type of information as the traditional single-nucleon transfer reactions at van de Graaf energies in reactions such as (p,d), (d,t) and (d,$^3$He). Our experiments have used one-nucleon removal in collisions at energies above 50 MeV/nucleon with light targets[1,2,3]. Detailed reviews of the method can be found in[4,5]. The method has an extremely high sensitivity, which has allowed experiments[3] with incident beams of less than one atom/s. Except for being in inverse kinematics, the reactions are clearly analogous to the previously studied (p,2p) and (e,e'p) "knockout" processes.

## 2. General Experimental and Theoretical Features

In the experiments at the NSCL, the momentum of the projectile residue from single-nucleon removal has been observed with the S-800 high-resolution spectrograph[6], which offers a momentum resolution of 0.025% in dispersion-matched mode. Since the experiments do not provide complete kinematics, *i.e.* the final state of the target and removed nucleon is not detected, we instead determine the final state of the projectile residue through coincidences with gamma rays. The high velocity of the projectile makes the correction of the energy for the Doppler shift absolutely esssential, and all experiments have used position-sensitive gamma detectors. All of the early work used a NaI detector array, while current work, illustrated later, is being carried out with a new array consisting of 14 32-fold segmented germanium detectors. The theoretical analysis has treated the reactions in eikonal theory and in the sudden approximation[7,2,5] while the discussions of structure has been based on large shell-model calculations with effective interactions[8,9,10].

As a specific example to clarify the ideas, consider first the reaction $^{9}$Be($^{34}$Si,$^{33}$Si,$+\gamma$)X studied by Enders *et al.*[11], which presents the simple pattern of knockout from a single closed shell with N=20. The individual final levels of the residue are identified by their gamma decay as shown in the example in Figure 1. From the coincidence rates, the shapes of the momentum distributions to the three states could be deduced, which identified the knockout to the 1.01 MeV level as $l$=0 and the other reactions as $l$=2. The coincidences also provide absolute cross sections of 67(10) mb to the $\frac{3}{2}^+$ ground state and 41(5) and 15(3) mb to the $\frac{1}{2}^+$ and $\frac{5}{2}^+$ states, respectively. The corresponding spectroscopic factors to the three states are 4.5(7), 2.0(3) and 1.3(4). The first two essentially exhaust the sum-rule values of 4 and 2 for full $0d_{5/2}$ and $1s_{1/2}$ subshells, with (more accurate) theoretical values[11] of 3.56 and 1.46. The smaller spectroscopic factor measured for the $0d_{5/2}$ state implies that the strength for this state (sum rule 6) is fragmented. (This is also the case for doubly-magic $^{40}$Ca.)

An important aspect of the reaction is that it takes place mainly at the nuclear surface, which affects the momentum distributions in a characteristic way[7]. For single-particle angular momenta $j > 1/2$, the cross sections are different for the individual $m$ sub-states, with the possibility of a result-

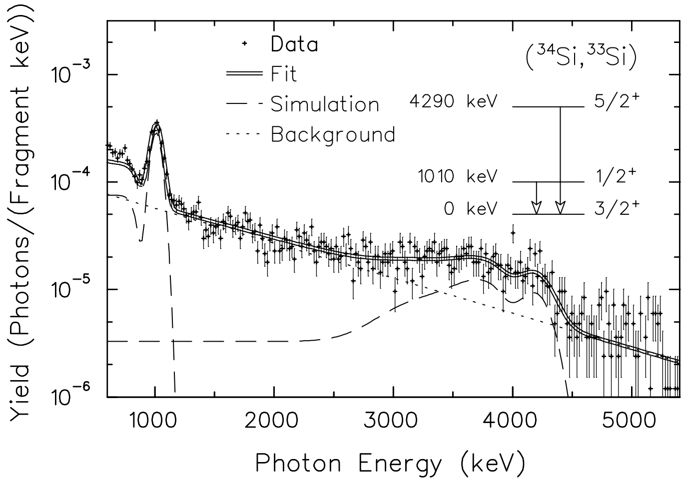


Figure 1. Spectrum of $^{33}$Si $\gamma$ rays[11] in coincidence with reaction residues after reconstruction of the center-of-mass energy. The data (points) are well described by a continuous background parameterized as a single exponential (dotted) and by line shapes deduced from a Monte-Carlo procedure (dashed), which simulates the detection process and the distortion caused by the event-by event transformation back to the center-of mass-system. Two transitions could be identified. The overall fit is shown as a double solid line. The inset shows a simplified level scheme.

ing alignment effect. This has, so far, not been observed experimentally. Theoretical estimates for a (hypothetical) example based on knockout at an energy of 400 MeV/nucleon from $^{52}$Ca to a $0f_{7/2}$ state in $^{51}$Ca are given in Fig. 2. For final states with $m$=0,1,2,3 the theoretical cross sections are, respectively, 5.3, 5.3, 6.3, and 12.8 mb. The unaligned, spin-averaged cross section is 7.7 mb. The strong preference for the highest $m$ value follows from simple geometrical considereations.

The presence of alignment in the tertiary beam will lead to a non-isotropic emission of gamma rays from the reaction residues. For the $^{52}$Ca example in the Figure, the angular distributions, shown to the right, are calculated to have an appreciable anisotropy. As can be seen from the left part of the Figure, the anisotropy can be increased further by making cuts in the particle momentum selecting the central part of the distribution, thus enhancing the proportion of $m$=$\pm$3. It is clear that the angular distributions, without any appreciable sacrifice in count rate, could be a valuable help in identifying the spins of states in residues and the associated gamma-transition multipolarities in knockout reactions.

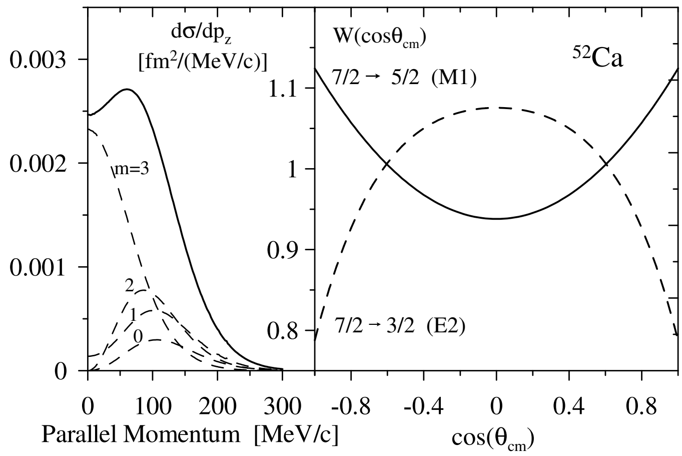


Figure 2. The left panel shows the calculated longitudinal momentum distribution for the knockout of a $0f_{7/2}$ neutron from $^{52}$Ca at 400 MeV/nucleon. The dashed lines give the contributions of the individual $m_\ell$ magnetic sub-states. The right panel shows the calculated angular distributions (in the center-of-mass system) for two possible transitions to $\frac{5}{2}^-$ and $\frac{3}{2}^-$ states in the residue as a function of the gamma-ray angle relative to the beam axis in the center-of mass frame.

## 3. Absolute spectroscopic factors and short-range correlations

The single-particle cross sections are obtained in an eikonal reaction theory that from a number of checks[2,12] appears to be very accurate on an absolute scale. As no adjustment to match theoretical and experimental spectroscopic factors has been made, it is justified to ask whether the technique provides absolute values. A first survey[4] suggests that this is the case. It was based on 27 partial cross sections measured by the $\gamma$-coincidence method for nuclei in the $p-sd$ shells, and showed very good agreement with shell-model theory based on effective interactions with a scale factor of essentially unity. A few low points corresponded to fairly deep hole states and one interpretation would be that the single-particle strength is spread differently or more than given by theory. Another likely explanation is the quenching effect discussed in the following.

Over the past two decades (e,e'p) experiments have provided accurate data for absolute occupancies of proton states in magic and nearly magic nuclei. The experiments consistently give values that are below those expected from the shell model based on effective interactions and suggest the presence of a single a general quenching factor independent of mass and of the order 0.5–0.6, see Kramer *et al.*[13]. This phenomenon is attributed to effects that go beyond the usual shell model and that arise from basic aspects of the nucleon-nucleon interaction, primarily the tensor force and the repulsive short-range part of the nucleon-nucleon force, see the review by Pandharipande *et al.*[14]. As the hard-core repulsion sets in strongly at distances below 0.4 fm, it follows that it must lead to components with high momentum in the wave function. The missing parts of the wave function are in low-energy experiments mainly conspicuous by their absence at low energies, so that the occupancies are reduced relative to shell-model calculations that do not incorporate these effects.

Recently, Brown et al.[15] and Enders *et al.*[16] examined whether the knockout reactions on nuclear targets can provide absolute spectroscopic factors. For a comparison they selected cases for which the structure is well understood, such as $^{16}$O, $^{12}$C, $^{8}$B and $^{9}$C. For some of these, data covering a wide range of beam energies were available as a check that the spectroscopic factors are extracted consistently. (The eikonal model is at its most reliable at high energies.) Starting from the assumption that the correlations arising from configuration mixing are included in the theoretical spectroscopic factors $\mathrm{S}_j^{th}$, it is convenient to define an empirical reduction factor attributed to effects not contained in the normal many-body shell model

$$R_s = \frac{\mathrm{S}_j^{exp}}{\mathrm{S}_j^{th}} , \tag{1}$$

for a partial cross section with a single $j$ value. The results of the analyses for the cases where the nucleons are strongly bound with effective separation energies covering the range 10–19 MeV gave results for protons of 0.5–0.65 in very good agreement with what is known from (e,e′p) reactions[13]. The results for neutrons, which cannnot be studied in electron scattering experiments, are very similar. The result is new but hardly surprising; it is what should be expected from isospin symmetry. The first data with radioactive beams lead to a very different result. In the cases studied, the $R_s$ parameter is much closer to unity, in the range 0.8–0.9 for the nuclei $^{8}$B, $^{9}$C, and $^{15}$C. This may reflect the lower nucleon binding energies in these cases, 0.14 to 1.3 MeV, but could also have other causes.

## 4. Two-nucleon knockout as a direct reaction

In a recent paper, Bazin *et al.*[17] show evidence that two-proton removal reactions from neutron-rich nuclei at high energy proceed as direct processes. The basic reason for this is that the asymmetry in proton and neutron separation energies suppresses the role of alternative sequential reaction paths.

As an example, in the case of the reaction on $^{28}$Mg discussed below, the alternative path, leading to $^{26}$Ne would be proton evaporation from the intermediate $^{27}$Na. However, this channel only opens up above 13.3 MeV excitation energy, where neutron evaporation offers strong competition.

The interpretation of the reaction as direct finds support in the measured inclusive cross sections, which can be calculated by a simple extension of the eikonal theory used for one-nucleon knockout. Further support comes from the measured shape of the parallel-momentum distribution of the residues, which is comparatively narrow (4% relative) and centered close to beam velocity. Qualitatively, this is in itself the signature of a direct reaction, but a more quantitative test is that the shape can be calculated precisely in a theory that assumes that the process is the knockout of two independent protons in $\ell$=2 states.

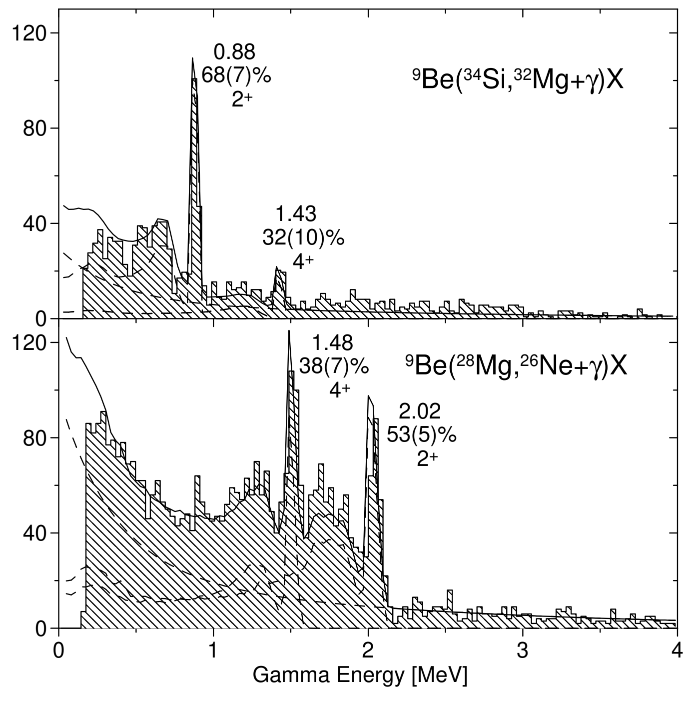


Figure 3. The gamma-ray spectra following two-proton knockout from the radioactive beams $^{28}$Mg and $^{34}$Si measured with MSU's new SeGA germanium array[18]. The main peaks are labeled by the energy in MeV, by the absolute intensity relative to the number of observed fragments, and by the spin of the initial level. The dashed peak shapes are simulated response curves normalized to match the number of counts in the full-energy peaks. The continuous distribution (dashed line) is attributed to radiation from the target.

Partial cross sections can be obtained from the coincident gamma spectra obtained in coincidence with the reaction residues, just as for one-nucleon removal reactions. Fig. 3 shows the results for the reaction $^{9}$Be($^{28}$Mg,$^{26}$Ne)X and for the corresponding reaction of $^{34}$Si. The $^{28}$Mg case is particularly transparent because the reaction connects two spherical *sd*-shell nuclei which are stabilized by the pronounced $N$=16 sub-shell closure[10]. A simple theory[17] can qualitatively account for the partial cross sections, but it also clear that coherent effects play an important role.

The importance of coherent effects is what could be expected because direct reactions involving two particles differ fundamentally from one-particle reactions. For single-nucleon knockout in the sudden approximation (and for single nucleon transfer reactions) the theoretical cross sections factorize into product of contributions reflecting reaction dynamics and nuclear structure. This very convenient feature does not generalize to reactions involving two nucleons. In two-nucleon knockout (and two-particle transfer reactions) the transition amplitudes for a given total angular-momentum transfer $J$ become a coherent superposition of many contributing pair combinations. The transition amplitudes thus mix inextricably the dynamical and structural aspects. It is clear that that a more advanced theory will be required.

The reaction and its converse, the two-neutron knockout on proton-rich nuclei, are very promising tools for spectroscopy of exotic nuclei. They lead directly toward nuclei with a yield that is extremely small in any production process, and the reactions are expected to provide specific and quantitative information on nuclear structure. Furthermore, the method appears to be be applicable to a wide range of neutron-rich nuclei extending from relatively close to stability to the drip lines. Thus the nucleus $^{28}$Mg, is considerably closer to stability ($^{31}$P) than it is to the drip line ($^{22}$C).

## 5. Concluding remarks

The experiments discussed here demonstrate that knockout reactions have considerable potential for providing decisive and quantitative structure information on rare radioactive nuclei. They also offer the high sensitivity that is a prerequisite for work with radioactive beams. In addition to this, there are now indications that the method is capable of addressing the very fundamental question of physical occupancies of the shell-model orbitals.

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