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Spectroscopic factors in exotic nuclei from nucleon-knockout reactions

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Abstract. One-neutron knockout at intermediate beam energies, an experimental approach sensitive to the single-particle structure of exotic nuclei, has been applied to the well-bound $N = 16$ isotones ^{34}Ar, ^{33}Cl and ^{32}S as well as to the $N = 14$ nucleus ^{32}Ar where the knockout residue ^{31}Ar is located at the proton drip line. The reduction of single-particle strength compared to USD shell-model calculations is discussed in the framework of correlation effects beyond the effective-interaction theory employed in the shell-model approach.

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1 Introduction

The shell model pictures deeply-bound nuclear states as fully occupied by nucleons. The mixing of configurations leads to occupancies that gradually decrease to zero in the vicinity of the Fermi energy. These correlation effects [1] —short-range, soft-core, long-range, and coupling to vibrational excitations— are beyond the effective-interaction theory employed in the shell model. The situation described above will be modified depending on the strength of these correlations. In stable nuclei, a reduction of $R_s = 0.6$–0.7 with respect to the independent-particle shell model has been established from $(e, e'p)$ data [2]. At rare-isotope accelerators, very deeply as well as weakly bound nuclear systems become accessible to experiments. One approach to assess the occupation number of single-particle orbits in exotic nuclei is the one-nucleon removal reaction at intermediate beam energies [3]. Following [4], the measured spectroscopic factor C^2S relates to the occupation number of the single-particle orbit involved. Experiments probing very deeply as well as more loosely bound nuclei [5,6] have been performed at the Coupled Cyclotron Facility of the National Superconducting Cyclotron Laboratory (NSCL) at Michigan State University (MSU) and will be discussed.

Gamma-ray spectroscopy was used to identify the final states in the knockout reactions. The array SeGA [7], consisting of fifteen 32-fold segmented high purity germanium detectors, was used in conjunction with the high-resolution S800 spectrograph [8] to identify γ-rays and reaction residues in coincidence. The two position-sensitive cathode readout drift counters of the S800 focal-plane detector system [9] in conjunction with the known optics setting of the spectrograph served to reconstruct the longitudinal momentum of the knockout residues on an event-by-event basis, providing information on the l-value of the knocked-out nucleon.

2 One-neutron knockout on well-bound N = 16 nuclei

The single-particle properties of the proton-rich $N = 15$ isotones with $Z = 16$, 17 and 18 have been studied at the Coupled Cyclotron Facility of the NSCL at MSU using the one-neutron knockout reactions ^{9}Be(^{32}S,^{31}S$+\gamma$)X, ^{9}Be(^{33}Cl,^{32}Cl$+\gamma$)X and ^{9}Be(^{34}Ar,^{33}Ar$+\gamma$)X in inverse kinematics and at intermediate beam energies [10]. Gamma-rays and knockout residues detected in coincidence tagged the one-neutron removal leading to excited

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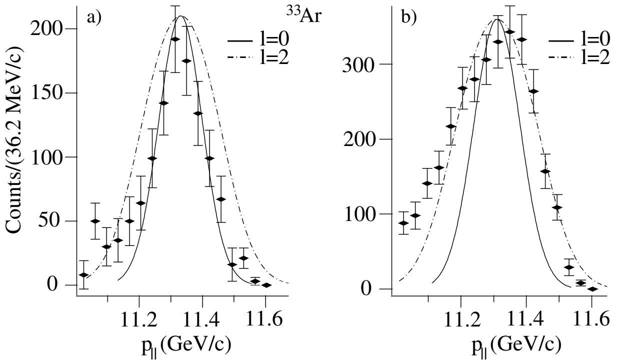

Fig. 1. Momentum distribution for the one-neutron knockout from ^{34}Ar to ^{33}Ar compared to calculated line shapes for different possible l values. (a) Momentum distribution for the knockout to the ground state of ^{33}Ar. (b) Momentum distribution for the knockout to excited states. The $s_{1/2}$ character of the ground state is indicated by the consistency of the data points with the $l = 0$ line shape while the excited states, as expected from the USD shell model, are populated by the knockout of a neutron out of $d_{5/2}$ and $d_{3/2}$ orbits ($l = 2$). For more details see [10] (figure taken from this reference).

final states in the reaction residues. The momentum distributions observed in the experiment were used to identify the angular momentum l carried by the knocked-out neutron in comparison to calculations based on a black-disk approach introduced in [11]. The momentum distributions for the knockout to the ground state of ^{33}Ar and to excited states, respectively, are shown in fig. 1.

The inclusive knockout cross section is given by the number of knockout residues per incoming projectile accounting for the number density of the Be target. From the γ-ray intensities, the knockout cross sections to individual final states can be deduced. Spectroscopic factors C^2S are then obtained by comparison to the single-particle cross sections from reaction theory [3].

The use of intermediate beam energies allowed a theoretical description of the reaction process within the sudden approximation and assuming straight-line trajectories. The dependency of the theoretical single-particle cross sections on the Woods-Saxon parameters and the *rms* radius of the core was studied and, compared to weakly bound systems, found to be rather pronounced [10].

A reduction of the experimental spectroscopic strength with respect to a USD shell-model calculation has been observed and extends the systematics established so far for stable and near-magic systems from $(e, e'p)$ and $(d, {}^3\mathrm{He})$ reactions and for deeply-bound light nuclei around carbon and oxygen from one-nucleon knockout experiments [10]. The reduction factor R_s for the knockout to the $N = 15$ isotones is shown in the upper part of fig. 2. The reduction factor is defined as the ratio of the experimental cross section and the theoretical ones, based on a structureless reaction cross section from eikonal theory and spectroscopic factors from a many-body USD shell-model calculation. The lower part of the figure shows the inclusive cross section for the one-neutron removal reactions at beam energies above 60 MeV/nucleon.

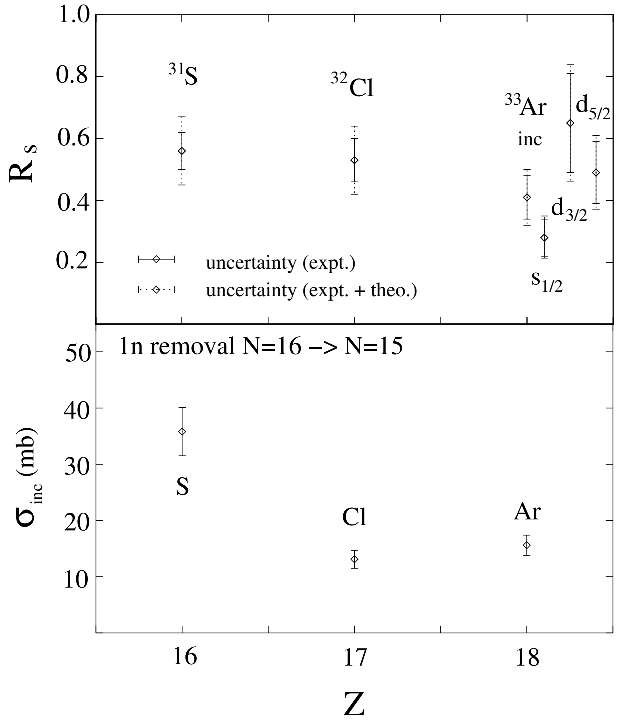

Fig. 2. Reduction factor R_s and inclusive cross section for the one-neutron knockout reactions on proton-rich $N = 16$ isotones [10] (see this reference for details).

3 One-neutron knockout to the proton-dripline nucleus ^{31}Ar —a comparison to weakly bound systems

In the proximity of the proton drip line, the ^{9}Be(^{32}Ar, ^{31}Ar)X reaction, leading to the 5/2$^+$ ground state of the most neutron deficient Ar isotope known to exist, was found to have a cross section of 10.4(13) mb at a mid-target beam energy of 65.1 MeV/nucleon [5]. This cross section to the only bound state of ^{31}Ar translates into a spectroscopic factor that is only 24(3)% of that predicted by many-body shell-model theory. Refinements to the eikonal reaction theory used to extract the spectroscopic factor were introduced to stress that this very strong reduction represents an effect of nuclear structure [5]. In summary, the ^{9}Be(^{32}Ar,^{31}Ar)X reaction with a neutron separation energy of 22.0 MeV leads to a nucleus situated at the proton drip line with only one bound state. The empirical reduction factor R_s is unexpectedly small, which may be linked to the very asymmetric nuclear matter in ^{31}Ar [5]. This is visualized in fig. 3. The left part of the figure shows that the reduction of the occupancy with respect to the USD shell-model prediction might correlate with the binding energy of the knocked-out nucleon. The right panel of fig. 3 displays the differences of radial distributions and potential depths for the isotones ^{21}O and ^{31}Ar

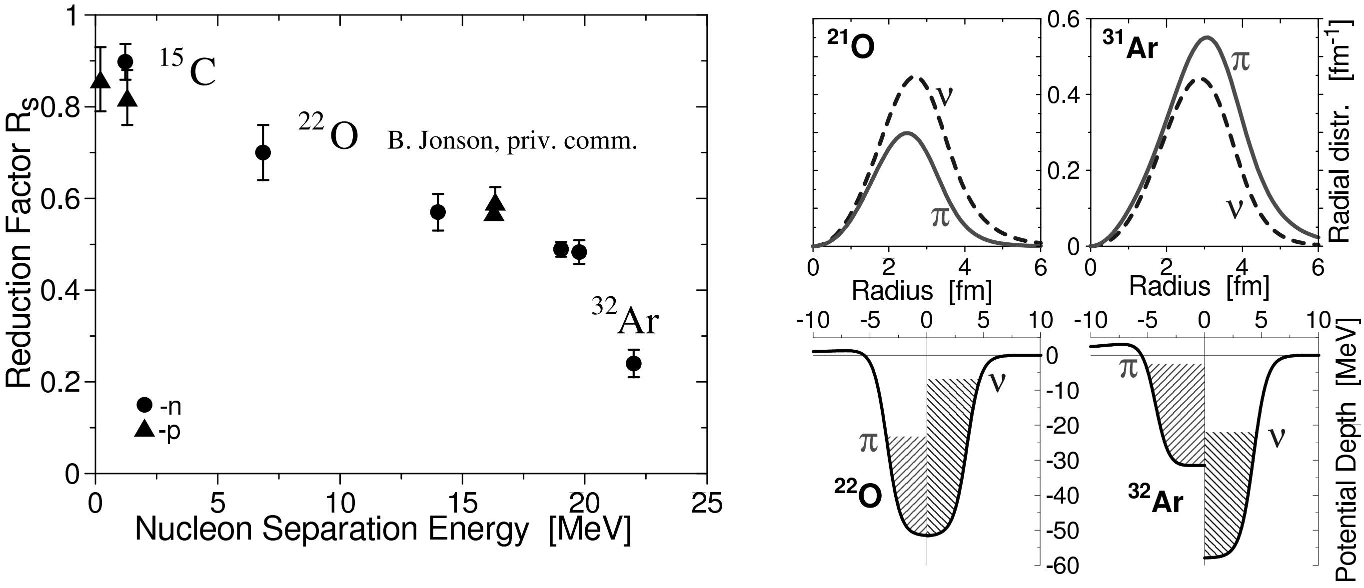

Fig. 3. Reduction in occupancy with respect to shell model predictions as a function of nucleon separation energy (left panel) and differences in the radial distributions for isotones with widely different proton numbers (right panel). We note that ^{22}O and ^{32}Ar have the same neutron configuration but strikingly different reduction factors R_s. Figures taken from [5].

to illustrate the pronounced proton-neutron asymmetry for the Ar isotopes at the proton drip line. The reduction factors for the two systems, (^{22}O,^{21}O) and (^{32}Ar,^{31}Ar), are very different.

On the contrary, there is evidence from several experiments that nucleon knockout from a halo-like state shows a reduction factor R_s closer to unity. The radioactive nuclei ^{8}B and ^{9}C [4,12] have been studied in one-proton knockout (proton separation energies of 0.14 and 1.3 MeV, respectively) giving reduction factors above 0.8 [4,12]. Recently, the one-neutron knockout from ^{15}C to the ground state of ^{14}C has been measured with high precision [6] and the reduction factor R_s is with 0.90(4)(5) close to unity and in line with the previous observations for weakly bound systems.

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