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Nuclear spectroscopy with fast exotic beams

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Abstract. Quadrupole collectivity in the proximity of the doubly-magic shell closure at $N = Z = 28$ has been studied using intermediate-energy Coulomb excitation of ^{54,56,58}Ni and ^{52}Fe. The results will be summarized and discussed in comparison to large-scale shell model calculations.
A complementary experimental approach sensitive to the single-particle structure of exotic nuclei, one-neutron knockout at intermediate beam energies, has been applied to the proton-rich $N = 16$ isotones ^{34}Ar, ^{33}Cl and ^{32}S as well as to ^{32}Ar where the knockout residue ^{31}Ar is the last particle-bound $Z = 18$ isotope. The reduction of single-particle strength ("quenching") compared to shell-model calculations using the USD interaction is discussed in the framework of correlation effects beyond effective-interaction theory.

1. Introduction

In the nuclear shell model, the first magic number essentially created by the spin-orbit force, is 28. The nucleus ^{56}Ni with $N = Z = 28$ is the heaviest doubly-magic $N = Z$ nucleus accessible to in-beam γ-ray spectroscopy at existing radioactive-beam facilities. Projectile Coulomb excitation at intermediate beam energies is a well established experimental technique employed to probe quadrupole collectivity in even-even nuclei beyond the valley of β-stability [1, 2, 3]. Recent results of Coulomb excitation experiments in the mass region around doubly-magic ^{56}Ni will be summarized.

The shell model pictures deeply-bound orbits as fully occupied by nucleons. Configuration mixing leads to occupancies that gradually decrease to zero at and above the Fermi sea. Correlation effects [4], such as short-range, long-range, soft-core, and coupling to vibrational excitations, are beyond the effective-interaction theory employed in the shell model. The picture outlined above will be significantly 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 [5]. At rare-isotope accelerators, very deeply and loosely bound systems become accessible to experiments. One approach to assess the occupation number of single-particle states in exotic nuclei is the one-nucleon removal reaction at intermediate-energy beams [6]. Following [7], the measured spectroscopic factor C^2S relates to the occupation number of the single-particle orbit involved. Experiments probing deeply and weakly bound systems [8, 9] have been performed at the Coupled Cyclotron Facility of the National Superconducting Cyclotron Laboratory at Michigan State University and will be discussed.

Gamma-ray spectroscopy in coincidence with particle detection was used to tag the inelastic process in Coulomb excitation and to identify the final states in the knockout reactions. The highly-segmented array SeGA, equipped with 15 32-fold segmented high purity germanium detectors [10], was used in conjunction with the large-acceptance S800 spectrograph [11] to identify the γ-rays and reaction residues in coincidence. The position-sensitive focal-plane detector system [12] allowed to reconstruct the trajectories of the scattered particles on an event-by-event basis. A detailed description of the experimental setup and the reconstruction of the scattering angle using the S800 focal-plane detection system can be found in [3, 16]. Figure 1 shows a typical particle-identification spectrum for the Coulomb excitation measurement aimed to study ^{54}Ni and ^{52}Fe. The energy loss of the ions measured in the S800 ion chamber is plotted as a function of the time of flight taken between two scintillators. Figure 1 demonstrates that an unambiguous particle identification is possible even in the regime of cocktail beams.

For knockout studies, the two position-sensitive cathode readout drift counters (CRDCs) of the S800 focal-plane detector system [12] in conjunction with the known optics setting of the spectrograph serve to reconstruct the parallel momentum of the knockout residues event-by-event, providing valuable information on the l-value of the knocked-out nucleon.

2. Intermediate-energy Coulomb excitation in the neighborhood of $N = Z = 28$

The even-even chain ^{54}Ni, ^{56}Ni and ^{58}Ni of $Z = 28$ isotopes has been studied via intermediate-energy Coulomb excitation. Absolute $B(E2; 0_1^+ \to 2_1^+) = B(E2\uparrow)$ electric quadrupole excitation strengths have been determined for all three nuclei using an identical experimental approach, providing a consistent measure of quadrupole collectivity in the proximity of the much discussed doubly-magic shell closure at $N = Z = 28$ [13]. The $B(E2)$ values were deduced from the measured cross sections using Winther-Alder relativistic Coulomb excitation [14]. The results are compared to large-scale shell-model calculations.

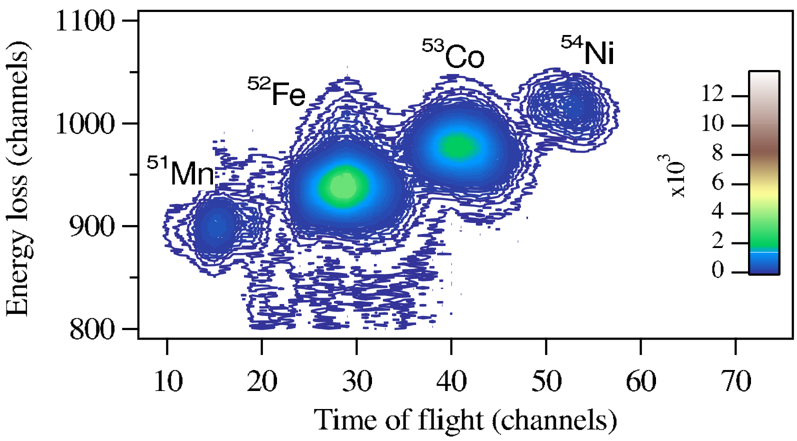

Figure 1. Typical particle identification after Coulomb excitation of a cocktail beam. Displayed is the energy loss measured with the ionization chamber of the S800 focal plane vs. time of flight taken between two scintillators.

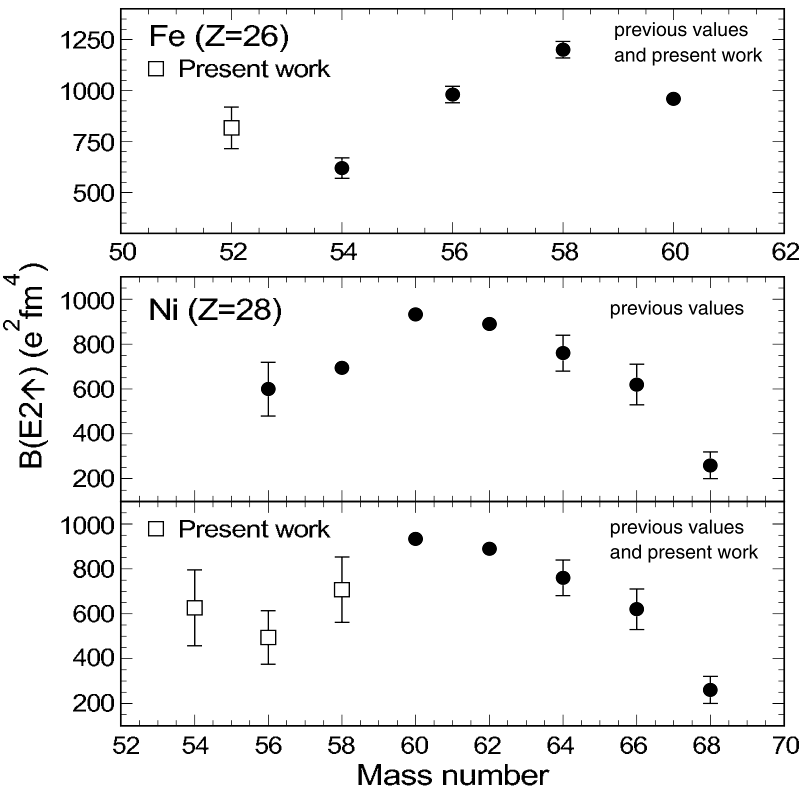

Figure 2. Reduced $B(E2; 0^+ \rightarrow 2_1^+)$ excitation strength for the even-even Fe and Ni isotopes in the vicinity of $N = Z = 28$. Open symbols indicate results from [16, 13]. For details see those references.

The characteristic rise in the excitation energy of the first 2^+ state was observed to be rather predominant at $N = 28$ while the second signature for a shell closure, the expected minimum in the systematics of the $B(E2\uparrow)$ excitation strength, is less clear (Fig. 2).

The shell–model picture suggests a rather small fraction of the total $E2$ strength to be concentrated in the 2_1^+ state in ^{54}Ni [13], driven by fragmentation, similar to the mechanism that gives rise to the low $B(E2; 0_1^+ \rightarrow 2_1^+)$ value at the much discussed nucleus ^{68}Ni with $N = 40$ [15]. There is no solid evidence, however, for a strongly excited higher–lying 2^+ state in the present experiment on ^{54}Ni [13]. The experimental $B(E2; 0_1^+ \rightarrow 2_1^+) = 626(169)\ e^2\text{fm}^4$ is close to the total $B(E2\uparrow)_{\text{tot}}$ value of 791 $e^2\text{fm}^4$ predicted within the shell-model calculation using the GXPF1 effective interaction [13].

The nucleus ^{52}Fe with $(N = Z = 26)$ has been investigated using intermediate-energy Coulomb excitation as well [16]. Much is known about excited states in ^{52}Fe [17, 18], but the important information on the $B(E2\uparrow)$ excitation strength to the first 2^+ state at 849.0(5) keV remained unavailable so far. In the projectile Coulomb excitation at a beam energy of 65.2 MeV/nucleon, a reduced transition probability of $B(E2; 0_1^+ \rightarrow 2_1^+) = 817(102)\ e^2\text{fm}^4$ [16] was deduced. The increase in excitation strength $B(E2\uparrow)$ with respect to the even-mass neighbor ^{54}Fe $[B(E2\uparrow) = 620(50)\ e^2\text{fm}^4]$ agrees with shell-model expectations as the magic number $N = 28$ is approached [16]. This measurement completes the systematics of reduced transition strengths to the first excited 2^+ state for the even-even $N = Z$ nuclei up to mass $A = 56$.

3. One-neutron knockout reactions on neutron-deficient nuclei

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+γ)X, ^{9}Be(^{33}Cl,^{32}Cl+γ)X and ^{9}Be(^{34}Ar,^{33}Ar+γ)X in inverse kinematics [19]. Coincidence experiments detecting γ-rays and knockout residues allowed for an investigation of the one–neutron removal leading to individual excited states. 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 [20]. The use of intermediate beam energies allowed a theoretical description of the reaction process within an eikonal approach in sudden approximation. The dependency of the theoretical single-particle cross sections from the Woods-Saxon parameters and the rms radius of the core was studied and, compared to weakly bound systems, found to be rather pronounced [19]. 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 [19]. Figure 3 displays the results of the aforementioned study. The lower part of the figure shows the inclusive cross section for the one-neutron removal reaction at energies above 60 MeV/nucleon. From these values and from the measured exclusive cross sections obtained from the γ rays detected following the ${}^9\mathrm{Be}({}^{33}\mathrm{Ar},{}^{33}\mathrm{Ar})X$ reaction one obtains the reduction factor R_s. It is defined as the ratio of the experimental cross section and the theoretical ones, including a structureless reaction cross section from eikonal theory and spectroscopic factors from a many-body shell-model calculation. The reduction factor for the $N = 15$ isotones is shown in the upper part of Fig. 3.

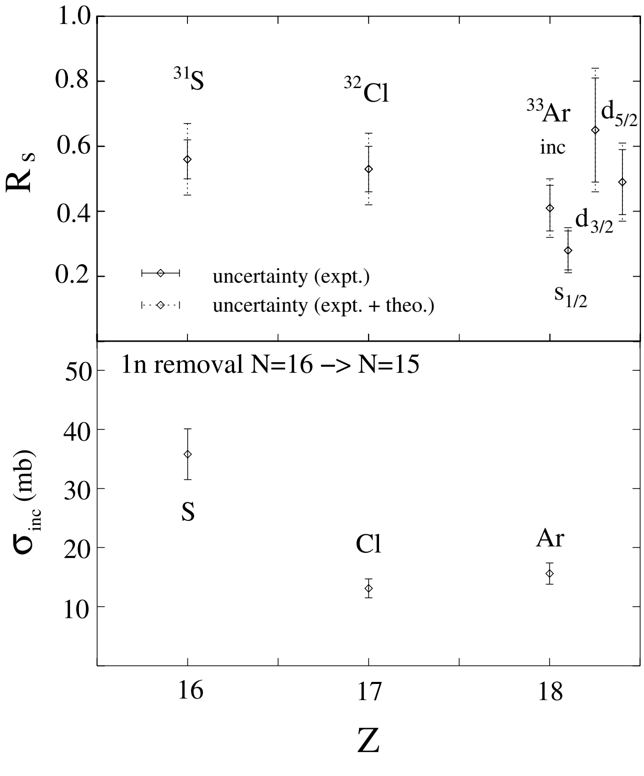

Figure 3. Reduction factors R_s and inclusive cross sections for the one-neutron knockout reactions on the neutron-deficient isotones ${}^{32}\mathrm{S}$, ${}^{33}\mathrm{Cl}$ and ${}^{34}\mathrm{Ar}$ (see Ref. [19] for details).

In the proximity of the proton drip line, the ${}^9\mathrm{Be}({}^{32}\mathrm{Ar},{}^{31}\mathrm{Ar})X$ knockout 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 [8]. This cross section to the only bound state of ${}^{31}\mathrm{Ar}$ translates into a spectroscopic factor C^2S which is only 24(3)% of that predicted by many-body shell-model theory. Refinements to the eikonal reaction theory used to extract the experimental spectroscopic factor were introduced [8] to stress that this strong reduction represents an effect of nuclear structure.

From the ${}^9\mathrm{Be}({}^{32}\mathrm{Ar},{}^{31}\mathrm{Ar})\mathrm{X}$ one-neutron removal reaction with a neutron separation energy of 22.0 MeV one extracts an emirical reduction factor R_s that is unexpectedly small. This fact may be linked to the very asymmetric nuclear matter in ^{31}Ar [8] and is visualized in Fig. 4. The left panel implies that the reduction of the occupancy with respect to the shell-model calculations might correlate with separation energy. The right panel of Fig. 4 displays the differences of radial distributions and potential depths for the isotones ^{21}O and ^{31}Ar which have the same neutron configuration.

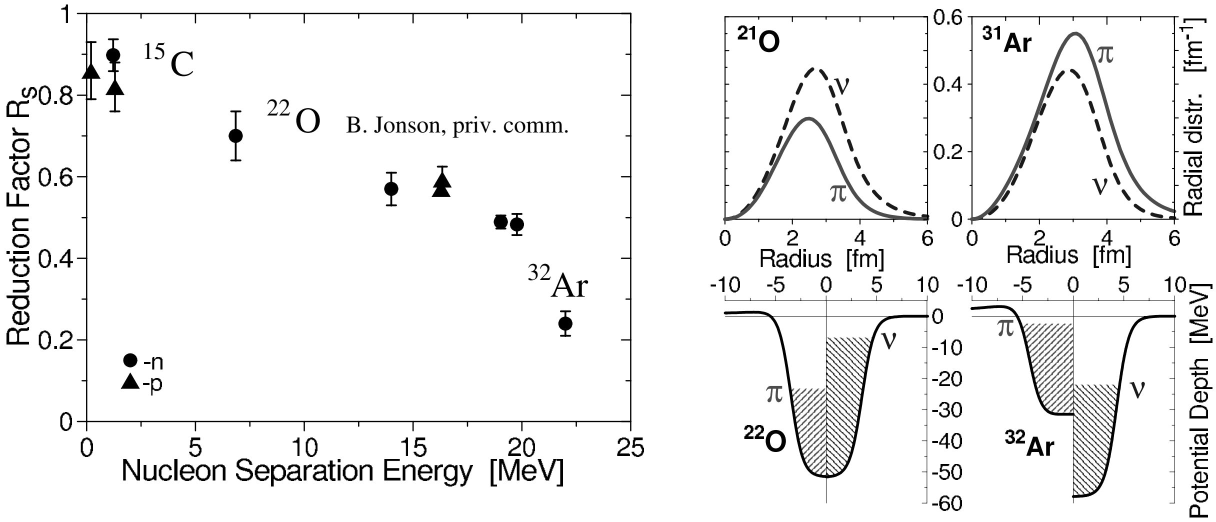

Figure 4. Reduction of the single-particle strength with respect to shell-model calculations as function of the separation energy of the removed nucleon (left) and differences in the radial distributions and potential depths for the corresponding oxygen and argon isotones (right). We note that ^{22}O and ^{32}Ar have the same neutron configuration but strikingly different reduction factors R_s. Figures taken from [8].

Acknowledgments

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