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NUCLEAR SPECTROSCOPY WITH FAST EXOTIC BEAMS*

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Results on the study of quadrupole collectivity in ^{54,56,58}Ni and ^{52}Fe using intermediate-energy Coulomb excitation are summarized and discussed in the context of the $N = Z = 28$ doubly-magic shell closure. 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 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

In the nuclear shell model, the first magic number essentially created by the inclusion of the spin–orbit force, is 28. The nucleus ^{56}Ni is with $N = Z = 28$ the heaviest doubly-magic $N = Z$ nucleus accessible to in-beam γ–ray spectroscopy at the present rare isotope facilities. Intermediate energy Coulomb excitation of the projectile is a well established experimental technique employed to probe quadrupole collectivity in even–even nuclei far from stability [1, 2]. 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 protons or neutrons. Configuration mixing leads to occupancies that gradually decrease to zero around the Fermi sea. Correlation effects [3], such as 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 [4]. At rare-isotope accelerators, very deeply as well as weakly bound systems become accessible to experimental studies. One approach to assess the occupation number of single-particle states in exotic nuclei are one-nucleon removal reactions at intermediate beam energies [5]. Following [6], the measured spectroscopic factor C^2S relates to the occupation number of the orbit involved. Experiments probing strongly and weakly bound systems [7,8] 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 was used to tag the inelastic process in Coulomb excitation and to identify the final states in the knockout reactions. The array SeGA [9], consisting of 15 32–fold segmented high purity germanium detectors, was used in conjunction with the high-resolution S800 spectrograph [10] to identify γ-rays and reaction residues in coincidence. The position-sensitive focal-plane detector system allowed to reconstruct the trajectories of the scattered particles on an event–by–event basis. A detailed description of the experimental setup and the determination of the scattering angle using the S800 focal-plane detector system can be found in [11, 12]. Figure 1 shows a typical particle-identification spectrum for the Coulomb excitation experiment. The energy loss of the ions is plotted as a function of the time of flight. As can be seen from the figure, an unambiguous identification and clear separation of the constituents of the cocktail beam is possible.

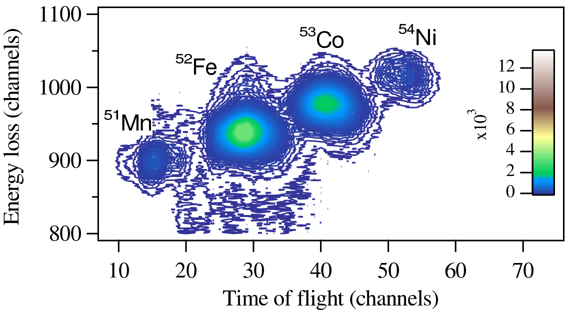

Fig. 1. Typical particle identification after Coulomb excitation of a cocktail beam (Au target). Shown is the energy loss measured with the ionization chamber of the S800 focal plane *vs.* time of flight taken between two scintillators.

For knockout experiments, the two position-sensitive cathode readout drift counters (CRDCs) of the S800 focal-plane detector system [13] 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. Intermediate-energy Coulomb excitation in the proximity 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 $B(E2; 0_1^+ \rightarrow 2_1^+)$ reduced 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 $N = Z = 28$ [18]. The results are compared to large–scale shell–model calculations.

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 [18], 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 $N = 40$ [14]. There is no solid evidence, however, for a strongly excited higher–lying 2^+ state in the present experiment on ^{54}Ni [18]. The experimental $B(E2; 0_1^+ \rightarrow 2_1^+) = 626(169)\ e^2\text{fm}^4$ is, in fact, closer 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 [18].

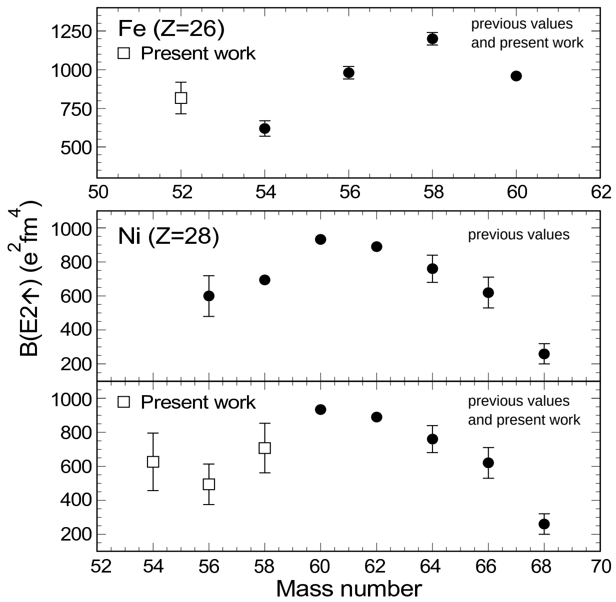

Fig. 2. Reduced $B(E2;0^+\rightarrow 2_1^+)$ excitation strength for the even–even Fe and Ni isotopes in the vicinity of $N=Z=28$. Open symbols indicate results from [12,18]. For details see those references.

The nucleus ^{52}Fe with ($N=Z=26$) has been investigated using intermediate-energy Coulomb excitation as well [12]. Much is known about excited states in ^{52}Fe [15, 16], 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^2fm^4 [12] was deduced using Winther-Alder theory of relativistic Coulomb excitation [17]. The increase in excitation strength $B(E2\uparrow)$ with respect to the even-mass neighbor ^{54}Fe ($B(E2\uparrow)=620(50)$ e^2fm^4) agrees with shell-model expectations as the magic number $N=28$ is approached [12]. 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 [20]. 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 [19]. 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 [20]. 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 [20]. Figure 3 displays the results of the aforementioned study. The lower part of the figure shows the inclusive cross section

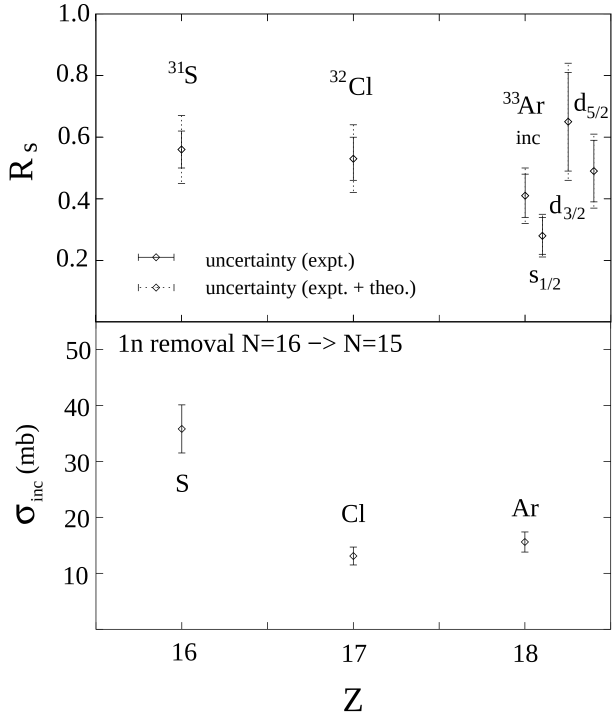

Fig. 3. Reduction factor R_S and inclusive cross section for the one-neutron knockout reactions on proton-rich $N = 16$ isotones [20] (see this reference for details).

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 gamma-rays detected in the (34Ar,33Ar) 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.

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 [7]. 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 [7]. 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 [7]. This is visualized in Fig. 4. The left part of the figure shows that the reduction of the occupancy with respect to the shell-model prediction seems to correlate with the binding energy of the nucleon. The right panel of Fig. 4 displays the differences of radial distributions and potential depths for the isotones ^{21}O and ^{31}Ar.

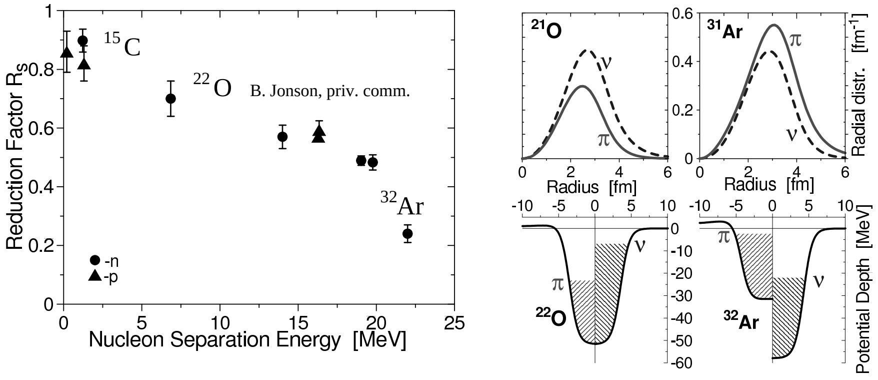

Fig. 4. Reduction in occupancy with respect to shell model as function of nucleon separation energy and (right panel) differences in the radial distributions for isotones with widely different proton numbers. We note that ^{22}O and ^{32}Ar have the same neutron configuration but strikingly different reduction factors R_s. Figures taken from [7].

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