Nuclear spectroscopy with fast exotic beams: News on $N = 28$ from recent NSCL measurements

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Abstract. The nuclear potential and resulting shell structure are well established for the valley of stability, however, dramatic modifications to the familiar ordering of single-particle orbitals in rare isotopes with a large imbalance of proton and neutron numbers have been found: new shell gaps emerge and conventional magic numbers are no longer valid. Current efforts in nuclear structure physics are aimed at unraveling the driving forces behind this structural evolution, which was found most dramatic in neutron-rich species. This manuscript will outline some of the recent efforts at NSCL aimed at shedding light on the shell evolution around neutron number $N = 28$ in neutron-rich Ar, Cl and Si isotopes.

1. Introduction
The goal of a theoretical description of the atomic nucleus with predictive power is driving experimental and theoretical research programs around the world. The nuclear shell model is one of the cornerstones for a comprehensive understanding of nuclei. Strong efforts in the field are aimed at unraveling the driving forces behind structural departures from the well-established, traditional shell model, which have been observed mostly in nuclei with a large neutron excess [1, 2, 3].

Among the robust driving forces of shell evolution identified in neutron-rich nuclei so far are the spin-isospin parts of the nucleon-nucleon $NN$ interaction [4], in particular the monopole part of the tensor force [5]. The important roles of $3N$ forces and the central part have been pointed out recently as well [6, 7]. Toward the nucleon driplines, the density dependence of the spin-orbit force and couplings to the particle continuum were shown to become important [8]. Examples for the shell evolution in neutron-rich nuclei driven by the tensor force are the breakdown of $N = 20$ as a magic number in neutron-rich nuclei in the vicinity of $^{32}\text{Mg}$ and the emergence of new shell gaps at $N = 14, 16$ in the neutron-rich $sd$ shell, respectively [4, 5].

In terms of shell evolution, the neutron magic number $N = 28$ has attracted much attention in recent years. On the neutron-rich side of the nuclear chart, below doubly magic $^{48}\text{Ca}_{28}$, the $N = 28$ shell closure was shown to disappear progressively below $Z = 20$ in $^{44}\text{S}_{28}$ [9] and $^{42}\text{Si}_{28}$ [10], however, with conflicting experimental data on $^{46}\text{Ar}_{28}$ [11, 12, 13]. Most of the initial spectroscopic information mentioned above comes from measurements of the $2^+_1$ energy, $E(2^+_1)$, and the absolute $B(E2; 0^+_1 \rightarrow 2^+_1) \equiv B(E2 \uparrow \uparrow)$ quadrupole excitation transition strength in even-even nuclei. These observables have been used extensively as indicators signaling the breakdown or persistence of a shell gap, with a high $2^+_1$ energy and low $B(E2 \uparrow \uparrow)$ excitation...
strength at a magic number (reduced collectivity) and vice versa mid-shell (collective character or deformation). The properties of odd-$A$ or odd-odd nuclei have not been exploited as extensively. The following sections will summarize recent measurements performed at NSCL [14] that used Coulomb excitation and in-beam $\gamma$-ray spectroscopy following secondary fragmentation reactions to benchmark shell-model calculations for very neutron-rich Ar, Cl and Si isotopes.

![Diagram](image)

**Figure 1.** (Color online) Rapid shell evolution has been observed along the $N = 28$ isotope line south of doubly magic $^{48}$Ca as $^{42}$Si is approached. Ar, Cl and Si isotopes recently studied at NSCL are shaded.

2. **In-beam $\gamma$-ray spectroscopy at NSCL**

Experimental approaches aimed at tracking the changes in nuclear shell structure are manifold. One way of probing nuclear structure in quantitative ways is the application of nuclear reactions that selectively probe specific degrees of freedom, e.g. single-particle or collective degrees of freedom. Coulomb excitation of nuclei has long been used to investigate collectivity. Intriguing possibilities arise along isotonic and isotopic chains of nuclei where the onset of collectivity or the migration of single-particle levels can be tracked consistently as function of the neutron number. Other less selective reactions, as for example secondary fragmentation of fast projectiles, populate the low-lying excited states of nuclei and can provide a first glimpse at the excitation level schemes of exotic nuclei [3].

At in-flight facilities, exotic medium-mass and light nuclei furthest away from stability can be efficiently produced by fragmentation of stable beams impinging upon stable targets at high energy. The resulting secondary beams of rare isotopes are then available for experiments at velocities typically exceeding $v/c = 0.3$. Well-established experimental techniques used for decades to explore the structure of stable nuclei are not applicable at the low beam rates encountered for the shortest-lived species. Powerful new experimental techniques have been developed to enable in-beam spectroscopy studies of fast rare-isotope beams with intensities several orders of magnitude less than needed for the established low-energy techniques.
The intensities of rare-isotope beams are typically lower than stable-beam rates by orders of magnitude. The experimental technique of in-beam γ-ray spectroscopy compensates for the reduced intensities by employing thick reaction targets, taking advantage of the high beam velocity, and enabling experiments at luminosities comparable to stable-beam experiments but with projectile rates of up to a factor of 10000 less. At NSCL, rare-isotope induced reactions, for example intermediate-energy Coulomb excitation, nucleon knockout or secondary fragmentation reactions, are induced by thick reaction targets (several hundred mg/cm²) and with the detection of γ rays for the identification of the reaction residue’s final state or to tag the inelastic process in Coulomb excitation measurements [3]. Contrary to barrier-energy Coulomb excitation, intermediate-energy Coulomb excitation of exotic projectile beams selectively excites the first and higher-lying 2⁺ states and possibly 3⁻ states in a single step and therefore possesses a different and unique sensitivity compared to its lower-energy counterpart.

Since the γ-ray emission from the reaction residue occurs in flight, the γ-ray detection systems have to be granular to enable an angle-dependent, event-by-event reconstruction of the Doppler-shifted γ-ray energies into the rest frame of the emitter. The choice of the target material is dictated by the desired reaction: secondary fragmentation and one- and two-nucleon knock-out reactions [15] are typically induced by light targets, for example ⁹Be or ¹²C, while intermediate-energy Coulomb excitation [16, 17] requires high-Z targets like gold, lead or bismuth. For the measurements described in this manuscript, the reacted beam emerging from the target was identified with the large acceptance S800 magnetic spectrograph [18] to uniquely select the reaction channel of interest. The γ-ray spectroscopy was performed with NSCL’s highly segmented Ge detector array SeGA [19] or the high-efficiency CsI(Na) scintillator array CAESAR [20]. Similar in-beam γ-ray spectroscopy programs with fast fragmentation beams are pursued at GSI [21] in Germany, at RIBF/RIKEN [22] in Japan and at GANIL [23] in France.

3. Coulomb excitation of the very neutron-rich ⁴⁷,⁴⁸Ar
The role of the Ar isotopes around N = 28 is of great interest. They are, with element number Z = 18, located between doubly-magic ⁴⁸Ca and the already collective S isotopes (Z = 16) on the path toward ⁴⁸Si, which has the lowest-lying 2⁺ state along the N = 28 isotonic chain. Pioneering intermediate-energy Coulomb excitation measurements [11, 9] showed that ⁴⁰,⁴²,⁴⁺S are collective with high B(E2 ↑) excitation strengths while, in two independent measurements, the B(E2 ↑) value for ⁴⁶Ar was found low as one may expect for a persistence of an shell gap [11, 12]. Shell-model calculations were unable to explain the reduced collectivity in ⁴⁶Ar [24, 25] and already predict the breakdown of N = 28 as a magic number and an onset of collectivity in the chain of Ar isotopes. A recent, low-statistics lifetime measurement for the 2⁺ state extracted a much higher B(E2 ↑) value in agreement with the shell-model description [13] but contradicts the two previous measurements.

Motivated by the pivotal location of the Ar chain, the first study of quadrupole collectivity in the N = 30, 29 isotopes ⁴⁸,⁴⁷Ar was performed at the NSCL with intermediate-energy Coulomb excitation using SeGA in conjunction with the S800 spectrograph [26]. B(E2; 0⁺₁ → 2⁺₁) and B(E2; 3/2⁺₁ → J) values were determined from Coulomb excitation cross sections and compared to state-of-the-art shell model calculations. The following paragraphs briefly summarize the findings reported in [26].

A consistent description of the collectivity at N = 28 in the isotopic chains of sulfur (Z = 16) and silicon (Z = 14) has been a challenge for large-scale shell-model calculations and was realized by Nowacki and Poves by devising two effective interactions (SDPF-U) for the sd fiss model space, one valid for Z ≤ 14 and one valid for Z > 14 [25]. In a recent shell-model work by Kaneko et al., the extended pairing plus quadrupole-quadrupole force with inclusion of a monopole interaction (EPQQM) was proposed to provide a consistent description of the breakdown of N = 28 across the Z = 20 to Z = 14 isotopic chains [27]. In Fig. 2, the shell model
$B(E2; 0_1^+ \rightarrow 2_1^+)$ values calculated with the two different effective interactions are compared to the available measured values in the chain of Ar isotopes. The two calculations describe the trend of the data on the even-even isotopes well only if one neglects the two consistent, low $B(E2 \uparrow)$ values at $N = 28$ [11, 12] and assumes that the low-statistics excited-state lifetime measurement for $^{46}$Ar stands. For $^{48}$Ar the calculation is within 2-$\sigma$ of the experimental value for the SDPF-U effective interaction. For $^{48}$Ar, the EPQQM calculation is within 1.5-$\sigma$ of the measured value. At $N = 28$, both calculations predict high $B(E2 \uparrow)$ and $E(2_1^+)\upaeth$ values, deviating from established Grodzins systematics that rather suggests their anti-correlation as observed for $^{38}$Ar. For example.

With conflicting experimental results at $^{46}$Ar and rather robust shell-model calculations at $N = 28$, it is interesting to turn to the odd-$N$ neighbor $^{47}$Ar. For $^{47}$Ar, the coupling of the odd $p_{3/2}$ proton to the $^{46}$Ar $2_1^+$ state would give rise to a quartet of states with spin values of $1/2^-$, $3/2^-$, $5/2^-$, and $7/2^-$ at about $E(2_1^+ (^{46}\text{Ar})) = 1555$ keV [12] and with a total $E2$ excitation strength of $\Sigma_J B(E2; 3/2^- \rightarrow J) = B(E2 \uparrow)^{46}A_{\text{R}}$. The extracted $B(E2; 3/2^- \rightarrow J^-)$ strength distribution for the lowest-lying excited $1/2^- - 7/2^-$ states is shown in Fig. 2. The experimental values for $J = 7/2$ and $3/2$ are upper limits as described in detail in [26]. The total $\Sigma_J B(E2; 3/2^- \rightarrow J^-)$ strength concentrated in these states is included in the $B(E2)$ systematics of Fig. 2 at $N = 29$ for experiment as well as theory. The comparison shows that both shell-model effective interactions significantly overpredict the $B(E2)$ strength concentrated in the low-lying states of $^{47}$Ar. The experimental $B(E2)$ range given in the figure indicates the possible span of the total $B(E2)$ strength ranging from the sole excitation of the $5/2^-$ states to the maximum strength observed in case the upper limits for the excitation of the $7/2^-$ and $3/2^-$ members of the quartet should be realized. This discrepancy is consistent with the situation at $N = 28$ if the measured low $B(E2 \uparrow)$ value for $^{46}$Ar should be proven correct. This result for $^{47}$Ar indicates that challenges remain for the most modern shell-model effective interactions in this area of rapid structural change and it also demonstrates the rarely exploited, unique

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**Figure 2.** (Color online) Left: $B(E2)$ values and $2^+$ excitation energies for the chain of Ar isotopes. Upper right: $\gamma$-ray spectrum of $^{47}$Ar, showing the decay from the alleged $5/2^-$ states to the $3/2^-$ ground state. Lower right: $B(E2)$ values in $^{47}$Ar. Figure adapted from [26].
benchmark posed by measurements of collectivity in odd-$A$ nuclei.

4. In-beam $\gamma$-ray spectroscopy of neutron-rich Cl isotopes
In order to inform theoretical descriptions of the region around $N = 28$ more, in-beam $\gamma$-ray spectroscopy following secondary fragmentation of a $^{48}$K beam was used to investigate the low-energy structure of $^{43-46}$Cl [28]. One new transition in $^{43}$Cl, three in $^{44}$Cl, six in $^{45}$Cl, and eight new transitions in $^{46}$Cl, for which no previous spectroscopic data exist, were observed in a spectroscopy measurement using the S800 spectrograph and SeGA. $\gamma$-$\gamma$ coincidences registered with SeGA were used to produce experimental level schemes up to 2 MeV for $^{43}$Cl and $^{45}$Cl, although no spin-parity assignments could be made based on the measured data. These level schemes were compared to large-scale shell model calculations, showing generally excellent agreement with the SDPF-U interaction. The results for $^{45}$Cl are displayed in Fig. 3 as an example. Additionally, the lifetime of the first excited state in $^{45}$Cl was obtained through a $\gamma$-ray lineshape analysis, yielding a lifetime one order of magnitude shorter than that predicted by the SDPF-U interaction, and four orders of magnitude shorter than that predicted by the EPQQM interaction. In [28], this observation is discussed in the framework of tensor corrections to the effective M1 operator for $\ell$-forbidden transitions. For the odd-odd nuclei $^{44,46}$Cl, the two shell-model effective interactions differ widely, demonstrating the power of the spectroscopy of odd-odd nuclei to benchmark shell model, however, firm spin assignments are needed and have to remain a challenge for future experimental studies.

Figure 3. Results of the in-beam $\gamma$-ray spectroscopy of $^{45}$Cl. Upper left: Example for coincidence spectra used to argue the level scheme of $^{45}$Cl. Lower left: The lineshape analysis of the 130-keV first excited state of $^{45}$Cl. Right: The proposed level scheme of $^{45}$Cl compared to calculations with the two shell-model effective interactions introduced in Section 3. Figures adapted from [28].
5. Collectivity along the chain of Si isotopes
The $B(E2; 0^+_1 \rightarrow 2^+_1)$ excitation strength for $^{34,36,40,42}$Si were measured at NSCL using the high-efficiency scintillator array CAESAR [20] in conjunction with the S800 spectrograph. Preliminary results indicate that the novel SDPF-MU effective interaction [29] that explicitly includes contributions from the tensor force describes the collectivity in the chain of Si isotopes best. The results are presently being finalized [30].

6. Summary
Neutron-rich nuclei around $N = 28$ have provided an exceptional insight into the phenomenon of shell evolution. Complementary experimental methods are employed around the world to probe various aspects of nuclear structure and serve as valuable benchmarks for nuclear theory. At NSCL, neutron-rich Ar [26], Cl [28] and Si [30] isotopes were studied experimentally and confronted with large-scale shell model calculations using two recent effective interactions. The important and under-utilized role of the spectroscopy of odd-odd, odd-$A$, and in particular the measurement of quadrupole collectivity in odd-$A$ nuclei was shown to pose sensitive benchmarks for state-of-the-art shell models.

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