Nuclear structure studies far east and out west on the nuclear chart

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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single-particle orbitals in rare isotopes have been found: new shell gaps emerge, some conventional magic numbers are no longer valid, and theoretical models that extrapolate from stability to describe observables in exotic nuclei can fail. 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 evolution of nuclear structure around neutron number \( N = 40 \) in neutron-rich Ti isotopes and in neutron-deficient Sn nuclei approaching \(^{100}\)Sn.

1. Introduction
One important goal in nuclear physics is the development of a predictive model of the atomic nucleus. The nuclear shell model is one of the cornerstones for a comprehensive understanding of nuclei. Concerted experimental and theoretical efforts are aimed at unfolding the driving forces behind departures from the well-established, traditional shell structure, which have been observed mostly in the shortest-lived nuclei beyond the valley of stability \([1, 2, 3]\).

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 \( N = 20 \) and \( N = 28 \) as a magic number in neutron-rich nuclei in the vicinity of \(^{32}\)Mg and \(^{42}\)Si, respectively, and the emergence of new shell gaps at \( N = 32, 34 \) in the neutron-rich \( fp \) shell \([2, 3, 4, 5]\).

One important experimental task is the quantification of changes in the nuclear structure from the measurement of experimental observables that are calculable and that ultimately allow to discriminate between different theoretical approaches. The manuscript outlines how the results from in-beam \( \gamma \)-ray spectroscopy experiments performed at the National Superconducting Cyclotron Laboratory (NSCL) \([9]\) on neutron-rich Ti isotopes \([10]\) and neutron-deficient Sn nuclei informed large-scale nuclear shell-model calculations \([11]\).
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 quantitatively 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. One- and two-nucleon knockout reactions probe the single-particle degree of freedom with measured cross sections sensitive to the wavefunction overlaps between the projectile ground state and the knockout residue’s final states.

At in-flight facilities, exotic medium-mass and light nuclei away from stability can be efficiently produced by fragmentation of stable, primary beams impinging upon stable targets at high beam velocities. The resulting secondary beams of rare isotopes are then available for experiments at velocities typically exceeding 30% of the speed of light. Well-established experimental techniques used for many decades to study the structure of stable nuclei are typically not applicable at the low beam intensities encountered for the shortest-lived rare isotopes. 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 what is required for measurements with traditional 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 $\gamma$-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 factors of thousands less.

At NSCL, reactions with fast rare-isotope beams, for example intermediate-energy Coulomb excitation and nucleon knockout are induced by targets of several hundred mg/cm$^2$ thickness. The detection of $\gamma$ rays is used for the identification of the reaction residue’s final state in knockout, or to tag the inelastic process in Coulomb excitation measurements [3]. Since the $\gamma$-ray emission from the reaction residues occurs in flight, the $\gamma$-ray detection arrays have to be as granular as possible to enable an accurate angle-dependent, event-by-event reconstruction of the Doppler-shifted $\gamma$-ray transition energies into the rest frame of the emitter. The $\gamma$-ray spectroscopy of $^{60}$Ti was performed with the advanced $\gamma$-ray tracking array GRETINA [12] and the Coulomb excitation of $^{104}$Sn was executed with the high-efficiency, 192-element, CsI(Na) scintillator array CAESAR [13].

The choice of the target material is dictated by the desired reaction channel: Direct one- and two-nucleon knockout reactions [14] are typically induced by light targets, for example $^9$Be or $^{12}$C, while intermediate-energy Coulomb excitation [15, 16] requires high-$Z$ targets like gold. For the measurements described in this manuscript, the reacted beam emerging from the target was identified with the large acceptance S800 magnetic spectrograph [17] to uniquely select the reaction residue of interest in the one-proton knockout leading to $^{60}$Ti while a fixed opening-angle phoswich detector was used for particle identification in the Coulomb excitation of $^{104}$Sn.

3. Towards $^{60}$Ca – Nuclear structure of $^{60}$Ti

Data for chains of magic isotopes and regions of rapid shell evolution both offer challenging tests of nuclear models, allowing changes in nuclear structure to be tracked as a function of isospin, and providing crucial benchmarks for calculations incorporating new structural effects. The Ca isotopes and the region of neutron-rich nuclei near $N = 40$, which are subject to rapid shell and shape evolution [18, 19, 20, 21], meet at the very neutron rich $^{60}$Ca ($N = 2Z$). While even the existence of $^{60}$Ca has not been established yet, spectroscopy of $^{60}$Ti was in reach at NSCL. The measurements were enabled by the luminosity inherent to the use of fast beams from...
fragmentation [3] and the efficiency and spectral quality provided by GRETINA [12]. Figure 1 shows where $^{60}$Ti and $^{60}$Ca are located on the nuclear chart.

![Figure 1](image_url) (Color online) The region of interest on the nuclear chart.

Excited states in the neutron-rich Ti isotopes were populated in the $^{9}$Be($^{61}$V, $^{58,60}$Ti + $\gamma$)$X$ nucleon removal reactions at 90.0 MeV/u at NSCL. Typical on-target rates of 15 $^{61}$V/s were obtained following the fragmentation of a $^{82}$Se primary beam.

In the projectile-like reaction residue $^{60}$Ti, a peak at about 860 keV is observed on top of very little background. One-proton knockout is a direct reaction with sensitivity to the details of the nuclear wavefunction and it quantifies the overlap in structure between the projectile ground state and the final states populated in the knockout residue [14]. The partial cross section to an excited final state is measured from the efficiency-corrected peak area relative to the number of knockout residues. Assuming that the peak structure in $^{60}$Ti corresponds to a single transition then implies that 111(12)% of the knockout proceeds to the state depopulated by this 860-keV transition and that there is essentially no population of any other bound final state in $^{60}$Ti. For a nucleus bound by more than 5 MeV, this scenario is highly unlikely. Indeed, the asymmetric peak shape of the structure at 860 keV supports the presence of a doublet of two transitions. Analysis as a doublet implies the presence of two coincident $\gamma$ rays at 850(5) and 866(5) keV (see figure 2, inset), presumably corresponding to the $2_{1}^{+} \rightarrow 0_{1}^{+}$ and $4_{1}^{+} \rightarrow 2_{1}^{+}$ transitions in $^{60}$Ti. GRETINA’s $\gamma\gamma$ coincidence efficiency and the extremely low background in the spectra affords a $\gamma\gamma$ coincidence analysis consistent with a doublet of two coincident transitions (see [10] for details).

The partial cross sections to the $2_{1}^{+}$ and $4_{1}^{+}$ states were deduced from the feeding-corrected $\gamma$-ray intensities and the $0_{1}^{+}$ population results from subtraction. The so-determined strength constitutes 29(12)%, 30(11)%, and 40(10)% population of the $0_{1}^{+}$, $2_{1}^{+}$, $4_{1}^{+}$ states, which potentially includes unobserved feeding from higher-lying states that could not be observed due to limited statistics. The measured partial cross sections to final states in $^{60}$Ti were compared to calculations using spectroscopic factors from GXPF1A [22] and LNPS [23] shell-model effective interactions, respectively. The comparison demonstrates that the neutron $g_{9/2}$ and $d_{5/2}$ orbitals that are included in the model space of LNPS and that are absent in GXPF1A are crucial for the description of the very neutron-rich $^{61}$V ground state and $^{60}$Ti final states populated in the knockout [10].
4. Collectivity in neutron-deficient Sn isotopes

Of particular importance for the development of nuclear models is experimental data that consistently tracks structural changes as function of isospin and varied binding, for example. The chain of Sn isotopes has been an important testing ground for nuclear theory as some spectroscopic data is available from \( N = Z = 50 \) \(^{100}\)Sn \([24]\) to \(^{134}\)Sn \([25]\). In even-even nuclei, the electromagnetic \( B(E2; 0^+_1 \rightarrow 2^+_1) \) excitation strength is a measure of quadrupole collectivity, sensitive to the presence of shell gaps and nuclear deformation, among others. In the Sn isotopes, this transition strength has been reported from \(^{104}\)Sn to \(^{130}\)Sn. The trend is pronounced asymmetric with respect to mid-shell and not even the largest-scale shell-model calculations have been able to describe the evolution of transition strength across the isotopic chain without varying effective charges \([11]\).

At NSCL, the experimental study of quadrupole collectivity in the neutron-deficient nucleus \(^{104}\)Sn using intermediate-energy Coulomb excitation was possible. The \( B(E2; 0^+_1 \rightarrow 2^+_1) \) value for the excitation of the first 2\(^+\) state in \(^{104}\)Sn was measured to be 0.180(37) \( e^2 b^2 \) relative to the well-known \( B(E2) \) value of \(^{102}\)Cd. This result disagrees beyond 1-\( \sigma \) with another published measurement \([26]\). Contrary to the conclusions of \([26]\), our result indicates that the most modern many-body calculations in the shell-model framework remain unable to describe the enhanced collectivity below mid-shell in Sn approaching \( N = Z = 50 \). In this picture, we attribute the enhanced collectivity to proton particle-hole configurations beyond the necessarily limited shell-model spaces and suggest the asymmetry of the \( B(E2) \)-value trend around mid-shell to originate from enhanced proton excitations across \( Z = 50 \) as \( N = Z \) is approached \([11]\).

The measurement was performed at the NSCL at Michigan State University. The secondary projectile beam containing \(^{104}\)Sn and \(^{102}\)Cd was produced by fragmentation of a 140 MeV/u \(^{124}\)Xe stable beam on a 240 mg/cm\(^2\) \(^{9}\)Be production target and separated using a 150 mg/cm\(^2\) Al wedge degrader in the A1900 fragment separator \([27]\) and NSCL’s Radio Frequency Fragment Separator (RFFS) \([28]\).

With the known value of \( B(E2 \uparrow) = 0.28(3) \ e^2 b^2 \) for \(^{102}\)Cd \([29]\), a transition strength of \( B(E2 \uparrow) = 0.180(37) \ e^2 b^2 \) for \(^{104}\)Sn was deduced. This normalization eliminates a variety of
systematic uncertainties and absolute efficiencies in general. the result compares well with the work by Doornenbal [30] and disagrees within 1-σ with the recently published value from a relativistic Coulomb excitation measurement performed at GSI [26].

First, large-scale shell-model calculations using an inert Z = 50 core were performed to describe the data across the Sn isotopic chain. In figure 3, the results for the newly optimized NNLO interaction [41], together with those obtained with the Nth\textsuperscript{3}LO interaction [42] are presented. The latter interaction also gives the overall best reproduction of the excited states and binding energies. Thus, unless one adopts a phenomenological adjustment of the effective neutron charges, see for example Ref. [43], theory based on an inert Z = 50 core fails to describe the B(E2 ↑) strengths. If one increases the neutron effective charge to 1.0e, then the B(E2) values are increased by a factor of four and come closer to the data but do not describe the asymmetry toward neutron-deficient Sn [11]. In [34], the model space was increased to allow up to four protons to be excited from the 0g\textsubscript{9/2} orbital to 1d, 2s\textsubscript{1/2} and 0g\textsubscript{7/2}. The results from this calculation, with standard effective charges 1.5e for protons and 0.5e for neutrons, are also shown in figure 3. Overall, the data is much better described, except that the extended calculation is symmetric around the middle, whereas experiment shows an asymmetry with an enhancement at the neutron-deficient end. This indicates that proton excitations across Z = 50 are critical for the description of collectivity. It is argued, as was in [36], that the increased B(E2) strength toward the neutron-deficient nuclei is due to α correlations toward N = Z outside of the necessarily truncated shell-model spaces [11].

5. Summary
First nuclear structure information on \(^{60}\text{Ti}\) was obtained at NSCL thanks to the spectral quality of GRETINA and the \(^{61}\text{V}\) projectile beam produced by fragmentation of the unique \(^{82}\text{Se}\) primary beam. The first 2\textsuperscript{+} state of \(^{60}\text{Ti}\), at an energy of 850(5) keV, is almost twice as high as the excitation energy of the corresponding 2\textsuperscript{+} level in the N = 38 isotope \(^{52}\text{Cr}\), indicating a steep decrease in collectivity. The data on \(^{60}\text{Ti}\) are consistent with a shell-model prediction using the LNPS effective interaction which allows for the largest neutron model space yet, while they disagree with calculations restricted to the neutron fp shell. \(^{60}\text{Ti}\) represents an important benchmark, being one of the most neutron-rich systems from which to extrapolate towards \(^{60}\text{Ca}\), a nucleus with its structure closely tied to the location of the neutron drip-line in the semi-magic Ca isotopic chain [10].

On the neutron-deficient side of the nuclear chart, we have determined the \(^{104}\text{Sn} \ B(E2; 0^+ \rightarrow 2_1^+)\) strength from intermediate-energy Coulomb excitation. Unlike the conclusion of [26], the
departure from large-scale shell-model calculations persists for the neutron-deficient Sn isotopes approaching $^{100}$Sn. It is proposed that this deviation from shell model to originates from the interplay of proton particle-hole configurations beyond the necessarily limited shell-model spaces and it is argued that their effect on quadrupole collectivity is a common phenomenon along proton-magic isotope chains [11].

Acknowledgments

GRETINA was funded by the DOE, Office of Science. Operation of the array at NSCL was supported by NSF under Cooperative Agreement PHY-1102511 (NSCL) and DOE under Grant DE-AC02-05CH11231 (LBNL). Thank you, Aldo, for inspiration and your contagious passion for nuclear science.

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