In-beam $\gamma$-ray spectroscopy towards the nucleon driplines

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Abstract. The contribution of in-beam $\gamma$-ray spectroscopy to nuclear structure research in recent years will be described with the example of the experimental efforts focused on neutron-rich Cr and Fe nuclei around neutron number $N = 40$. Tremendous progress has been made at facilities around the world with complementary spectroscopic techniques, providing important benchmarks for developing shell-model effective interactions and elucidating the driving forces behind shell evolution in the exotic regime.

1. Introduction

The shell structure of the atomic nucleus is one of the cornerstones for a comprehensive understanding of this strongly correlated fermionic many-body quantum system. Large stabilizing energy gaps between groups of single-particle levels at certain, so-called "magic", fillings of the corresponding single-particle orbitals with protons and/or neutrons are part of the foundation of the nuclear shell model. Doubly-magic nuclei define the model spaces for large-scale calculations. The structure of stable nuclei is rather well described by the traditional nuclear shell model, while significant modifications have been encountered for short-lived, exotic species with unbalanced proton and neutron numbers: New shell gaps develop conventional shell closures vanish. Current theoretical and experimental efforts are focused on investigating how the shell structure changes far away from stability and how these changes relate to the isospin dependence of the $NN$ force. 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.

Major driving forces of shell evolution in neutron-rich nuclei that have been identified so far are the spin-isospin parts of the $NN$ interaction [1], in particular the monopole part of the tensor force [2]. The roles of the central part and 3N forces have been emphasized recently as well [3, 4]. Toward the driplines – in the regime of weak nucleon binding – the density dependence of the spin-orbit force and couplings to the continuum will become important [5]. Examples for the shell evolution in neutron-rich nuclei driven by the tensor force are the emergence of new shell gaps at $N = 14, 16$ and $N = 32$ in the neutron-rich $sd$ and $fp$ shell, respectively [1, 2].

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2. The experimental quest – In-beam γ-ray spectroscopy

Experimental approaches aimed to track the changes in the nuclear shell structure are manifold. They include the measurements of ground-state properties like masses, β-decay properties, and electromagnetic moments as well as the study of properties of bound and unbound excited states. One way of probing nuclear structure in quantitative ways is the application of nuclear reactions that selectively probe specific degrees of freedom. Inelastic scattering of nuclei has long been used to investigate collective degrees of freedom, involving the coherent motion of many protons and neutrons. The single-particle degree of freedom, on the other hand, is associated with the single-particle content of the many-body wave function. The single-particle properties can be studied selectively by using direct reactions that add or remove one or a few nucleons. 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.

At in-flight facilities, exotic medium-mass and light nuclei furthest away from stability can be efficiently produced by fragmentation of stable (primary) beams impinging upon stable targets at high energy. The resulting secondary beams of rare isotopes are then available for experiments at velocities exceeding 30% of c. Well-established experimental techniques used for decades to study 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 usually lower than stable beam rates by several orders of magnitude. The experimental approach of in-beam γ-ray spectroscopy compensates for the reduced intensities by employing thick reaction targets, taking advantage of the high beam velocity, and realizing experiments with luminosities comparable to stable-beam experiments but with beam rates of up to a factor of 10000 less. Reactions, for example inelastic scattering or nucleon knockout 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 scattering events [6]. Since the γ-ray emission by the reaction residue takes place in flight, the γ-ray detection systems have to be granular to allow for 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 depends on the desired reaction, secondary fragmentation and one- and two-nucleon knockout reactions [7] are typically induced by light targets, for example 9Be or 12C, while intermediate-energy Coulomb excitation [8, 9] is performed with high-Z targets like Au, Pb or Bi. The reacted beam exiting the target has to be identified with magnetic spectrographs or advanced detector systems to cleanly select the reaction channel of interest. In-beam γ-ray spectroscopy programs with fast fragmentation beams are pursued at NSCL/MSU [10] in the US, at GSI [11] in Germany, at RIBF/RIKEN [12] in Japan and at GANIL [13] in France.

![Diagram](image-url)

**Figure 1.** Schematics of in-beam γ-ray spectroscopy at fragmentation facilities.
3. A prototypical example – Shell evolution around \( N = 40 \)

Many examples of shell evolution have been identified across the nuclear chart from experimental data gathered at facilities around the world [14]. This article briefly reviews the changes of nuclear structure along the chain of \( N = 40 \) isotones, in particular at the neutron-rich end, as they are prototypical for the underlying driving mechanisms and concerted experimental and theoretical efforts. Many complementary measurements have been performed with a variety of experimental techniques at different facilities – this article will limit more detailed discussions of recent results to the most neutron-rich Fe and Cr nuclei studied with in-beam \( \gamma \)-ray spectroscopy at fragmentation facilities.

Rapid structural changes along the line of \( N = 40 \) isotones have been subject of intense experimental research and theory interest in recent years. The \( N = Z = 40 \) nucleus \(^{80}\text{Zr} \) was found to be strongly deformed [15]. \(^{68}\text{Ni} \) has a high-lying \( 2^+_1 \) state and a low \( B(E2; 0^+_1 \rightarrow 2^+_1) \) electric quadrupole excitation strength (as might be expected for a doubly-magic nucleus) [16]. Just two and four protons below \(^{68}\text{Ni} \), evidence is accumulating that \(^{66}\text{Fe} \) and \(^{64}\text{Cr} \) are collective again [17, 18, 19, 20].

The tensor force drives the shell evolution towards the neutron-rich \( N = 40 \) isotones of Fe and Cr: The attractive monopole part of the tensor force between the \( \pi f_{7/2} - \nu f_{5/2} \) orbits weakens as protons are removed from the \( \pi f_{7/2} \) orbital (moving from Ni to Ca). As a result, the \( \nu f_{5/2} \) orbit shifts up in energy and the energy gap between the \( \nu f_{5/2} \) and \( \nu g_{9/2} \) orbits is reduced, allowing for neutron occupancy of the intruder \( \nu g_{9/2} \) orbital already for nuclei with fewer than 40 neutrons.

From this picture of an energetically close neutron \( g_{9/2} \) orbital and the narrowing of the \( N = 40 \) sub-shell gap, one expects for Cr and Fe nuclei an increased importance of the \( g_{9/2} \) single-particle state for the low-lying nuclear structure as \( N = 40 \) is approached and enhanced collectivity due to neutron excitations across the \( N = 40 \) sub-shell gap. Indeed, over the last decade, evidence from experiments performed with complementary techniques at accelerator facilities around the world support this scheme of shell evolution: Low-lying \( 2^+_1 \) excited states, generally considered as one indicator of quadrupole collectivity, were identified in \( \beta \)-decay experiments at ISOLDE/CERN and GANIL for \(^{64,66}\text{Fe} \), \(^{60,62}\text{Cr} \) [17] and \(^{60,62}\text{Cr} \) [18, 19], respectively. Rotational bands built on \( 9/2^+ \) states in \(^{55,57}\text{Cr} \) [21] and a low-lying \( 9/2^+ \) isomer in \(^{59}\text{Cr} \) with possibly oblate deformation [22] were discovered in experiments using fusion-evaporation reactions at ATLAS/ANL.

The amount of deformation in neutron-rich \(^{60,62}\text{Cr} \) was first quantified at RIKEN with the determination of enhanced quadrupole deformation lengths deduced from fast-beam, inverse-kinematics, \( \gamma \)-ray tagged, inelastic proton scattering [19]. Beams of \(^{60,62}\text{Cr} \) were produced by fragmentation of a stable \(^{70}\text{Zn} \) beam at 83 MeV/u. The inelastic proton scattering was induced by a \( \text{LiH}_2 \) target [23]. The de-excitation \( \gamma \) rays were detected in the highly efficient NaI scintillator array DALI2 [24] and the scattered Cr projectiles were identified event-by-event with the time-of-flight (TOF) spectrometer TOMBEE [25, 19]. The quadrupole deformation lengths, \( \delta_{p'p} \), were deduced from angle-integrated cross sections, \( \sigma(2^+_1) \), for the excitation of the first \( 2^+ \) state in comparison to coupled-channels calculations [19]. Shell-model calculations with the GXPF1 effective interaction – not including the \( \nu g_{9/2} \) orbit – predict reduced deformation for Cr isotopes toward \( N = 40 \), while the experimental data show a significant onset of deformation [19].

A complementary approach was taken at NSCL at MSU. Two-proton knockout reaction cross sections, which probe the wave function overlaps of the projectile ground state and the final states of the knockout residue, were measured along the \( N = 40 \) isotope line: \(^9\text{Be}^{(68}\text{Ni}, {68}\text{Fe} + \gamma)X \) and \(^9\text{Be}^{(66}\text{Fe}, {64}\text{Cr})X \) [26]. In these reactions, two protons are removed from the projectile in the sudden collision with a light target (here, at bombarding energies exceeding 72 MeV/u). Two-proton knockout reactions from neutron-rich nuclei as well as two-neutron knockout reactions from neutron-deficient nuclei are well established to proceed as direct reactions [27, 28]. Results
from these two-nucleon removal reactions provide sensitive tests for two-nucleon amplitudes calculated within the shell model and probe correlation effects between like nucleons in the nuclear wave function [29, 30]. The exotic projectile beams were produced by fragmentation of a 130 MeV/u beam of $^{76}$Ge primary beam. The projectiles of interest were selected with A1900 fragment separator [31] and guided to the S800 spectrograph [32]. The two-proton knockout reactions were induced by a $^9$Be target located at the target position of the large-acceptance, high-resolution magnetic spectrograph. Gamma-ray spectroscopy was performed with the segmented Germanium Array SeGA [33]. The reaction residues were identified event-by-event with the focal-plane detection system of the spectrograph. A surprisingly small inclusive cross section for the $^9$Be($^{66}$Fe,$^{64}$Cr)X two-proton knockout reaction, $\sigma_{inc} = 0.13(5)$ mb, was measured, compared to $\sigma_{inc} = 1.42(25)$ mb for $^9$Be($^{68}$Ni,$^{66}$Fe)X. The order-of-magnitude drop in cross section for the reactions along the $N = 40$ isotope line is striking. In terms of wave function overlaps, this dramatic decrease in cross section is indicative of a significant structural change between the ground state of $^{66}$Fe and the bound final states of $^{64}$Cr, while the wave functions of the corresponding states in $^{68}$Ni and $^{66}$Fe share more overlap. This result was the first indication of yet another rapid change in nuclear structure along the $N = 40$ chain. In the same measurement, the two-proton knockout reaction $^9$Be($^{70}$Ni,$^{68}$Fe+$\gamma$)X was performed and afforded the first in-beam $\gamma$-ray spectroscopy of $^{68}$Fe. The low $2^+_1$ energy, $E(2^+_1) = 517(6)$ keV, indicated that in the chain of Fe isotopes the collectivity seems to increase beyond $N = 40$ [26].

![Figure 2](image_url)  

**Figure 2.** Order-of-magnitude drop in cross section for the two-proton knockout cross sections along the $N = 40$ isotope line indicates a structural change between $^{66}$Fe and $^{64}$Cr.

Although the experimental setup of the measurements described above allowed for $\gamma$-ray detection, the yield was too low for the spectroscopy of $^{64}$Cr$^{40}$ produced in the two-proton removal from $^{66}$Fe. $^{64}$Cr was long predicted to be the most collective $N = 40$ nucleus in this region. The first spectroscopy of its excited states was only possible recently by an inelastic scattering experiment at NSCL [34]. Level energies and excitation cross sections for $^9$Be-induced inelastic scattering of $^{62,64,66}$Fe and $^{60,62,64}$Cr were measured at intermediate beam energies with SeGA coupled to the S800 spectrograph. For the first time, the excited $2^+_1$ and $4^+_1$ states of $^{64}$Cr were reported. Information on $^{64}$Cr has remained elusive for long since the production rate of this neutron-rich nucleus is low, 2-3 $^{64}$Cr per second from fragmentation of a 30 pnA ($\approx 1.8 \times 10^{11}$ particles per second) primary beam of $^{76}$Ge. The measurement was performed at the target position of the S800 spectrograph, with SeGA surrounding a 370 mg/cm$^2$ thick $^9$Be
target to induce the inelastic excitation. Figure 3 shows the γ-ray spectrum of $^{64}\text{Cr}$. The peak at 420(7) keV corresponds to the decay of the first $2^+$ to the ground state and the second, less intense peak corresponds to the $4^+_2 \rightarrow 2^+_1$ γ-ray decay. Similarly, the $2^+_1$ and $4^+_1$ states of $^{62,64,66}\text{Fe}$ and $^{60,62}\text{Cr}$ were observed in $^9\text{Be}$-induced inelastic scattering [34]. A distinct change in the trend of the population of the excited states in the Cr isotopic chain compared to the Fe isotones was interpreted in terms of structural differences at $N = 40$, consistent with the indications from the two-proton knockout measurement. Large-scale shell model calculations including the $\nu g_{9/2}$ intruder orbital were found to reproduce the excitation spectra and trends across the isotopic chains while calculations in the $fp$-shell model space only failed to reproduce the low excitation energies indicative of enhanced quadrupole collectivity [34].

![Figure 3](image)

**Figure 3.** Event-by-even Doppler reconstructed γ-ray spectrum detected in coincidence with inelastically scattered $^{64}\text{Cr}$ identified in the S800 spectrograph.

In summary, recent measurements have confirmed (i) the onset of collectivity in neutron-rich Fe and Cr nuclei towards and at $N = 40$ and (ii) the importance of the neutron $g_{9/2}$ orbital for the description of the low-lying nuclear structure in these nuclei. This confirms the shell evolution scheme expected for this region that – driven by the tensor force – leads to a descent of the $\nu g_{9/2}$ orbit and a narrowing of the $N = 40$ sub-shell gap.

4. Summary and outlook

Nuclear structure studies are a worldwide effort with contributions coming from complementary experimental studies performed at different facilities. In-beam γ-ray spectroscopy with fast beams provides robust and sensitive approaches to study collective and single-particle degrees of freedom – measurements with a few particles per second are possible. The future of this field is bright, as new powerful heavy-ion drivers have come into operation in Japan, are under construction in Europe and are being designed in the US, new advanced tracking arrays such as GRETINA/GRETA (US) [35] and AGATA (Europe) [36] will already provide dramatically increased scientific reach in the very near future at present facilities.

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