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High-spin proton and alpha-particle emission as probes for nuclear structure

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Abstract. During recent years the nuclear decay modes of discrete prompt proton and α-particle emission from (super)deformed high-spin states have been discovered in nuclei in the vicinity of ^{56}Ni. The latest news from experiments performed at EUROBALL and GAMMASPHERE regarding these decays are presented and discussed.

PACS. 23.50.+z Decay by proton emission – 23.60.+e Alpha decay – 27.40.+z $39 \leq A \leq 58$ – 27.50.+e $59 \leq A \leq 89$

This contribution presents recent advances in high-spin nuclear-structure studies in the vicinity of ^{56}Ni, focussing on the new and unique decay modes of prompt proton and α-particle emission. ^{56}Ni is generally accepted to represent a doubly magic spherical nucleus due to the shell gap at particle number 28, which separates the $1f_{7/2}$ shell from the so-called upper fp shell consisting of the $2p_{3/2}$, $1f_{5/2}$, and $2p_{1/2}$ orbits. Doubly magic nuclei are important bench marks within the nuclidic chart, because these nuclei and their closeby neighbours serve as sources and act as constraints for the shell model parameter sets, namely single-particle energies and two-body matrix elements. This implication was one of the original motivations to study this mass region in terms of high-spin spectroscopy. In addition to the comprehensive new results in the spherical minimum, the nuclear structure near ^{56}Ni exhibits a plethora of in part unprecedented phenomena, which are illustrated and summarized in fig. 1.

Next to the spherical shell gap at particle number 28 there is also a gap of similar size for a prolate deformed ($\beta_2 \sim 0.4$) ^{56}Ni nucleus [1], which is based on a 4p-4h excitation —the [303]7/2 Nilsson orbit is emptied and the [321]1/2 orbit occupied for neutrons and protons. At the same time the $\mathcal{N} = 4$ high-j low-Ω [440]1/2 intruder orbit reaches the Fermi surface. It is readily occupied in the yrast deformed and superdeformed bands in ^{58}Cu [2] and ^{60}Zn [3], which may be called the "doubly magic deformed" and "doubly magic superdeformed" nuclei of the mass region, because large and very stable shell gaps appear for $N = Z = 29$ at $\beta_2 \sim 0.4$ and $N = Z = 30$ at $\beta_2 = 0.5$ in the rotating frame.

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Most interesting is the new decay mode of prompt particle emission from states in the second minimum of the potential, which has been established in the mass $A \sim 60$ regime. It is schematically illustrated in fig. 2 for the first case observed in ^{58}Cu [2]. Excited high-spin states in ^{58}Cu are known in the spherical minimum (left-hand side of fig. 2) and in the second, deformed minimum of the nuclear potential. The latter form a nice rotational band shown in the middle of fig. 2. While the first excited state in the rotational band reveals the expected γ-decay back into the first minimum of ^{58}Cu, the lowest state observed in the second minimum ($E_x = 8915$ keV, $I = (9^+)$) emits a 2.3 MeV proton on a subnanosecond time scale. The final state of this prompt proton decay is the neutron $g_{9/2}$

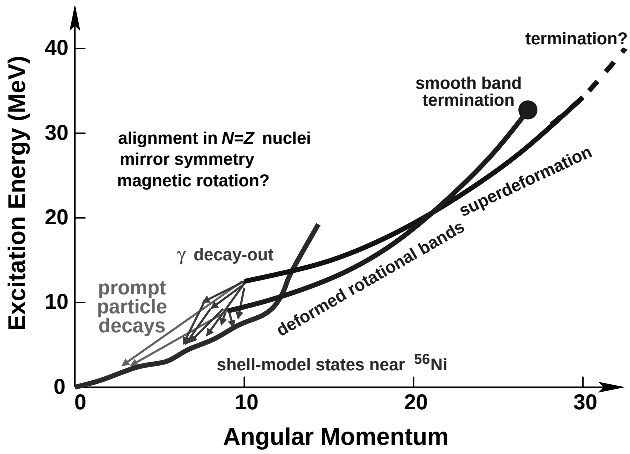

Fig. 1. Summary of high-spin nuclear-structure phenomena in the mass $A \sim 60$ region.

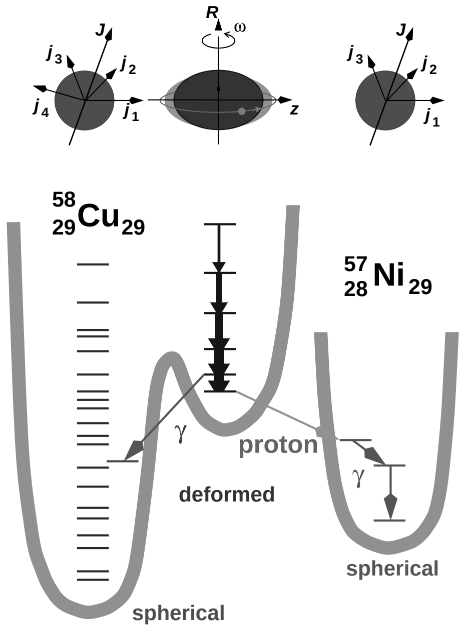

Fig. 2. Scheme of the prompt proton decay in ^{58}Cu [2].

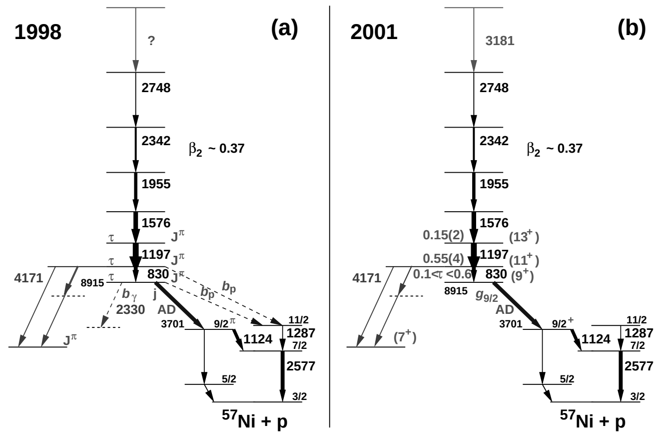

Fig. 3. Increase of experimental information concerning the prompt proton decay of ^{58}Cu between 1998 (a) [2] and 2001 (b) [4–6].

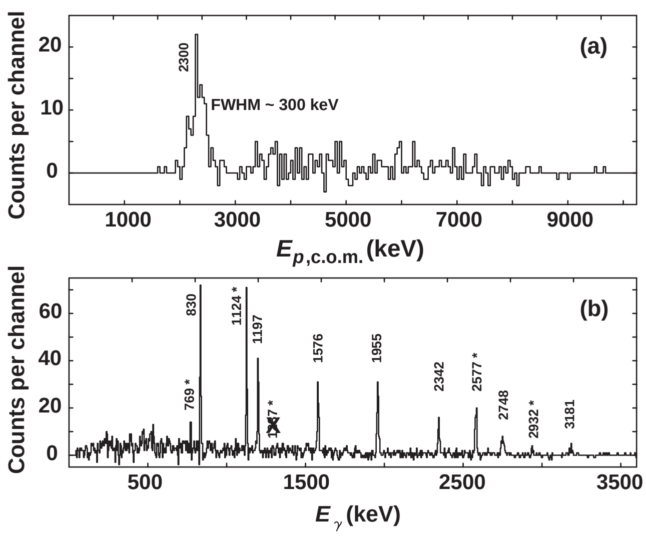

Fig. 4. Preliminary reaction channel selected proton center-of-mass (a) and γ-ray (b) spectra from experiment 3. Both spectra are gated with one of the 830, 1197, 1576, 2342, or 2748 keV lines in the ^{58}Cu band. Spectrum (a) is also in coincidence with the $9/2^+ \rightarrow 7/2^-$ 1124 keV transition in ^{57}Ni, while spectrum (b) is in additional coincidence with the 2.3 MeV proton peak. Only single proton hits in the four ΔE-E Si-strip telescopes are considered. The γ-ray peaks marked with an asterisk belong to ^{57}Ni, the others are from the band in ^{58}Cu.

spherical single-particle state in ^{57}Ni [4]. The decay mode is called "prompt", because the formation of ^{58}Cu, the γ-decay in the rotational band, the proton emission, and the γ-decay in the daughter nucleus ^{57}Ni are observed in "prompt" coincidence in thin-target in-beam high-spin experiments within a typical time window of less than three nanoseconds.

The particle decays compete with the conventional γ decay-out, and they may be viewed as self-regulated two-dimensional quantum tunneling processes. Due to the decay the remaining nuclear mean-field potential is rearranged dramatically. Quantum-mechanical tunneling is a widespread phenomenon in the natural sciences. Therefore, a full understanding of this process may be of importance far beyond nuclear physics.

Figure 3 describes the progress in terms of spectroscopic information regarding the ^{58}Cu case starting from the first observation of the new decay in 1998 [2] until early 2001. Within this period, the spin and parity of the daughter state in ^{57}Ni was determined [4], spins and parities were tentatively assigned to the band members, lifetimes of the low-lying states in the band were measured [5], and last but not least the lifetime of the proton-decaying state could be limited to 0.1 ps $< \tau <$ 0.6 ps [6].

The latter two results have been obtained from an experiment performed with EUROBALL coupled to the 4π ΔE-E Si-array ISIS [7] and the Neutron Wall [8]. The use of a backed target allows to apply the Doppler Shift Attenuation Method (DSAM) to determine lifetimes. The 830 keV line, which depopulates the 9745 keV state and feeds the proton-decaying level at 8915 keV, reveals both a stopped and a shifted component in its lineshape observed in the backward-angle CLUSTER section of EUROBALL. Therefore, energy correlations between the 830 keV γ-ray measured in the CLUSTER detectors and the 2.3 MeV proton peak in the most forward detector elements of ISIS have been studied [6].

In principle, such energy correlations allow for a DSAM lineshape analysis of the proton line. The Doppler-shift formula for γ-rays has to be replaced by the corresponding formula for particle emission. Unfortunately, this rather straightforward approach is hampered by the present experimental set-up, essentially due to a tube-shaped 12 μm aluminum absorber foil in combination with the rather large angular coverage of a single telescope in the ISIS array [7]. It turns out that only protons emitted at sufficiently large angles can penetrate the absorbers *and*

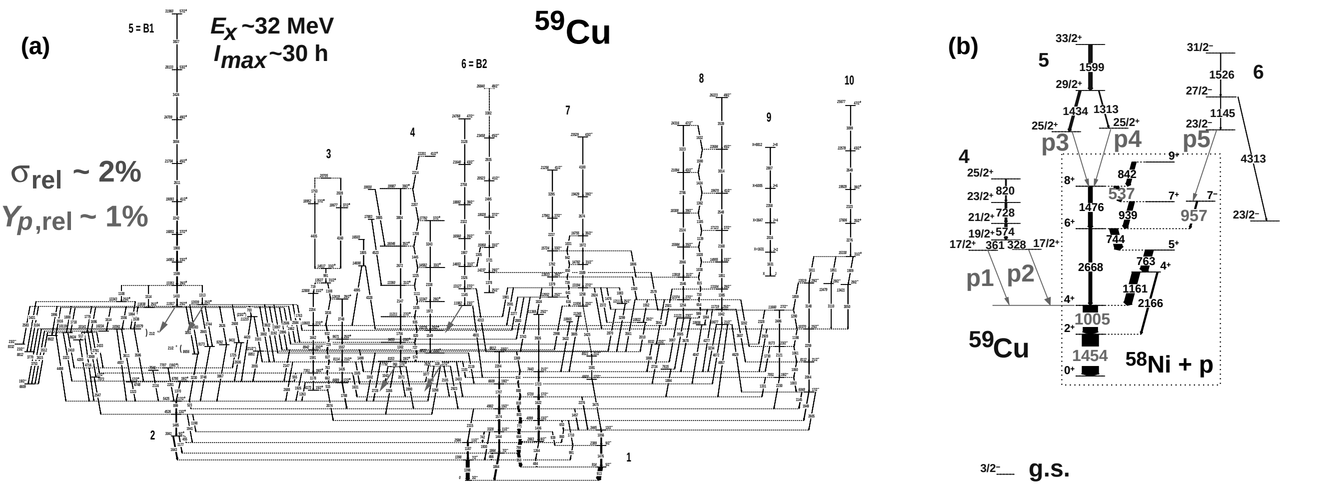

Fig. 5. Part (a) shows the high-spin excitation scheme of ^{59}Cu [13,14]. Part (b) reveals the "proton decay scheme" embedded in part (a) [15].

cross the detection threshold of the ΔE detectors of the forward telescopes. In essence, the variation of aluminum thickness leads to a considerable spread of the detected proton energy. If the protons are emitted while the recoils are still moving they have higher energies and thus can be observed more efficiently since the "visible" opening angle of the ΔE detectors increases with increasing energy. To detour this problem the following approach was pursued:

1. Simulations of proton energy spectra for different recoil velocities taking into account the full geometry of the absorbers and the most forward ring of ISIS.
2. Simulations of lineshapes for a presumed γ-ray decay from the 8915 keV level depending on the lifetime of this level and taking into account the history of the decay through the band in ^{58}Cu.
3. Comparison of experimentally observed and simulated fractions of the stopped component of the lineshape to deduce conservative lower and upper limits of the lifetime.

A detailed analysis finally yields 0.06 ps $< \tau <$ 0.58 ps for the lifetime of the proton-decaying 8915 keV state in ^{58}Cu, from which an experimental spectroscopic factor of about 10^{-3} can be estimated [6]. It awaits the predictions of detailed and profound future theoretical efforts.

The identification of prompt particle decays [1,2,9,10] has so far only been possible in GAMMASPHERE experiments, for which the Ge-array was coupled to the 4π charged-particle detector system MICROBALL [11]. However, high-resolution particle spectroscopy has been hampered by the relatively large widths of the peaks in the particle center-of-mass energy spectra. The main contribution to the widths is not the intrinsic resolution of the CsI elements of MICROBALL, but the size of the solid angle. For an element in ring 2 of MICROBALL, for example, a contribution of some 0.5 MeV to the total width of some 0.7–0.8 MeV may be attributed to the finite opening angle. To overcome this handicap the 28 most forward elements of MICROBALL were replaced with an array of four ΔE-E Si-strip telescopes providing some 800 active pixels instead (see, *e.g.*, ref. [12] for details). This reduces the geometric opening angle to $\Delta\Theta \sim 2.5°$ for a single pixel and the corresponding energy spread down to $\Delta E_{\rm CM} \sim$ 80 keV. It is not necessary to further tighten the angle coverage, because a beam spot of only 2 mm almost doubles the effective angle coverage of a pixel. It will be diffcult to maintain this geometrical contribution to the resolution below some 150 keV throughout a 7 day experiment.

The second contribution to the peak width is the target thickness. A reaction can take place anywhere in the target, and it is impossible to determine the precise spot of an individual reaction on an event-by-event basis. Therefore, the kinematic energies for recoiling nuclei are different depending on their travel paths, hence energy loss, in the target foil. The particles of interest are emitted most likely *after* having passed through the remaining path of the thin target foil. The uncertainty in the *value* of the recoil velocity (the *direction* can be rather well determined from the energies and directions of evaporated particles) does lead to a kinematical contribution to the energy resolution of 200–250 keV for a target thickness of 0.5 mg/cm^2.

Finally, the combination of intrinsic resolutions of ΔE and E strips ($\sim$ 50–60 keV each at 12 MeV) and the energy spread induced by $\sim$ 30 mg/cm^2 thick Pb absorber foils, which are necessary to protect the array from direct heavy-ion hits, yields an intrinsic contribution of about 130 keV. The sum of the three contributions amounts to an expected resolution of about 300 keV for 2.0–2.5 MeV protons, which should be compared to 700–800 keV obtained for the earlier experiments. Preliminary results are shown in fig. 4 for ^{58}Cu. They indicate a measured FWHM of some 300 keV for the proton peak, and that the suggested weak proton branches into the $11/2^-$ state in ^{57}Ni (see fig. 3) are *not* present.

An extensive new level scheme of ^{59}Cu deduced from GAMMASPHERE data is shown in fig. 5(a) [13,14]. ^{59}Cu is an immediate neighbour of ^{58}Cu, and hence a good candidate to search for prompt proton decays. In fact, two

Table 1. Prompt particle decays in the mass $A \sim 60$ region.

Nuclide		Particle	Q-value (MeV)	Branching (%)	Spin difference	Ref.
^{56}Ni		proton	2.57	49(14)	$(7/2^+)$	[1]
^{58}Ni		alpha	7.45	3.9(3)	(9^-)	[10]
^{58}Cu		proton	2.34	> 97	$(9/2)^+$	[2]
^{59}Cu	$B4$	proton	1.92	11(3)	$9/2^+$	[15]
	$B4$	proton	1.95	2(1)	$9/2^+$	[15]
	$B5$	proton	1.90	9(2)	$9/2^+$	[9, 15]
	$B5$	proton	2.02	8(3)	$9/2^+$	[15]
	$B6$	proton	2.48	53(8)	$9/2^+$	[9, 15]

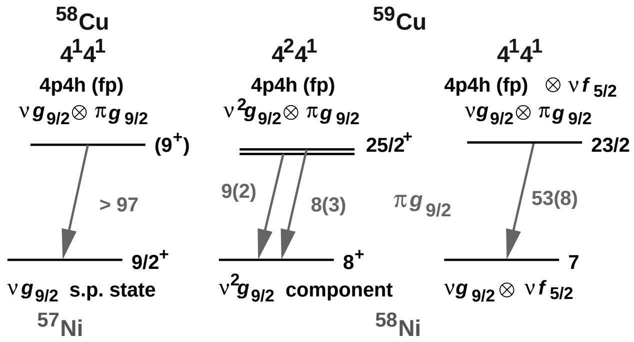

Fig. 6. Band configuration assignments in ^{58,59}Cu.

decays have already been identified [9]. The present data set employing the Si-strip detector telescopes, however, allows for detailed proton-γ coincidence spectroscopy by gating on both γ-ray and proton *lines* in E_p-E_γ-E_γ cubes. As a result, altogether five proton-decaying states have been established in ^{59}Cu, which have intensities of only $\sim 1\%$ of the strongest γ-ray lines in ^{59}Cu. The details of the "proton decay scheme" of ^{59}Cu into states of ^{58}Ni are presented in fig. 5(b) and table 1.

The two proton branches from band "5" are part of the vast single- and two-step decay-out scheme of the yrast superdeformed band in ^{59}Cu, which is visible on the left-hand side of fig. 5(a). Their very specific coupling to the daughter states in ^{58}Ni (see below), similar to ^{58}Cu, is one out of several evidences that the decay-out mechanism in the $A \sim 60$ region comprises a structure related coupling between the states in the second and the first well, in contrast to the purely statistical decay-out pattern envisaged in heavier mass regimes of the nuclidic chart.

Figure 6 sketches another nuclear-structure issue related to the particle decays, namely the band configuration assignment of band "6" in ^{59}Cu (cf. fig. 5(a)). In ^{58}Cu the configuration of the proton emitting band is $4^1 4^1$ [2]. In ^{59}Cu, band "5" has a $4^2 4^1$ configuration [13]. The spin and parity of the proton-decaying states is $I^\pi = 25/2^+$. The decays feed the 8^+ state in ^{58}Ni by emitting $g_{9/2}$ protons. In addition to seniority $v = 4$ configurations within the fp shell, the 6605 keV 8^+ state in ^{58}Ni might contain a seniority $v = 2\ \nu(g_{9/2})^2_8$ component, to which the proton decay could couple. The proton-decaying level of band "6" in ^{59}Cu has spin and parity $I^\pi = 23/2^-$. The decay proceeds into the yrast 7^- state in ^{58}Ni. Since ^{58}Ni has two neutrons outside the ^{56}Ni core, a negative-parity state needs to involve a particle or hole in a positive-parity orbit close to the orbits in the fp-shell. The simplest $v = 2$ configuration for a 7^- state is $\nu f_{5/2} \otimes \nu g_{9/2}$. The spin difference between initial and final state for the $B2$ proton decay is 9/2 and no change of parity. Thus, the decay once again involves a $g_{9/2}$ proton, which together with the $g_{9/2}$ neutron in the final-state configuration leads to a $4^1 4^1$ assignment to band "6".

To summarize, the mass $A \sim 60$ region reveals many exciting aspects of nuclear structure: i) shell model states near a doubly magic isotope; ii) deformed and superdeformed rotational bands in the second minimum; iii) issues related to the self-conjugate nature of some nuclides; iv) the unprecedented exotic decay of several of the bands through discrete prompt particle emission in competition to conventional γ decay-out mechanisms. Their present experimental status is summarized in table 1. The new experiments aiming at combined in-beam γ and particle spectroscopy are clearly challenging the present combinations of the 4π Ge-detector arrays and ancillary detector systems.

It is anticipated that with a geometrically simpler experimental set-up a DSAM proton lineshape measurement and analysis is feasible to obtain more precise lifetime values for particle-decaying states. In addition, more detailed spectroscopic information such as angular distributions or correlations shall be investigated to, *e.g.*, determine the particle angular momentum directly. Ultimately, the details of an angular distribution measured relative to the nuclear spin axis may uncover the wave function of a $g_{9/2}$ proton inside the deformed mean field of the ^{58}Cu nucleus, or reveal the time structure underlying the shape change in the course of the decay (see ref. [16] and references therein).

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