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High-resolution in-beam particle-gamma coincidence spectroscopy

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Abstract. A short summary of the present status of prompt particle decays in the mass $A \sim 60$ region is presented. It includes recent results from a GAMMASPHERE experiment, which aimed at the combined high-resolution spectroscopy of light charged particles and γ-rays to allow for more detailed studies of known decays and the identification of new cases of discrete prompt proton and α-particle emission from highly and superdeformed states.

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

During recent years, the nuclear decay mode of discrete-energy prompt proton and α-particle emission has been established in nuclei near ^{56}Ni. Different from the ground-state proton emitters, the prompt particle emission competes with γ-rays instead of β^+-radiation. This places the time scale of the decays into the 10^{-12}–10^{-15} s regime, and allows their study in "prompt" coincidence with preceding and subsequent γ-rays emitted from the parent and daughter nuclei, respectively. The prompt particle decays proceed from highly or superdeformed initial states into (near) spherical daughter states. This implies a drastic rearrangement of the nuclear mean field in the course of the decay. Hence, the decay mode may be viewed as a self-regulated two-dimensional quantum tunneling process, which is unique in Nature.

In table 1 the presently (October 2002) known cases of prompt particle emission are summarized. Following the first observation of prompt proton emission in ^{58}Cu [1], extensive subsequent spectroscopy has been performed to pin down the quantum numbers of the states involved in the decay: The spin and parity of the daughter state in ^{57}Ni was defined to $I^\pi = 9/2^+$ [2,3], individual lifetimes of the low-lying states in the band were measured [4], and the lifetime of the proton-decaying state could be limited to 0.1 ps $< \tau <$ 0.6 ps [5]. The combined statistics of several experiments suggests $I^\pi = 9^+$ for the initial state in ^{58}Cu [6]. There is no evidence for competing γ-ray transitions, and the data is consistent with a single proton line between the 8915 keV state in ^{58}Cu and the 3701 keV state in ^{57}Ni [6]. Furthermore, the configuration of the highly deformed band is unique and commonly used as reference in the mass region [12] (see also the contribution by I. Ragnarsson [13]).

Table 1. Prompt particle decays in the mass $A \sim 60$ region (October 2002). Numbers for ^{58}Ni are preliminary except for decay $\alpha 1$.

Nuclide		Particle	Q-value (MeV)	Branching (%)	Spin difference	Reference
^{56}Ni		proton	2.57	49(14)	$(7/2^+)$	[7]
^{58}Ni	$\alpha 1$	alpha	7.45	3.9(3)	(9^-)	[8,9]
	$\alpha 2$	alpha	8.23	~ 5	(9^-)	[9]
	$p1$	proton	2.26	> 80	$(9/2^+)$	[9]
	$p2$	proton	2.38	~ 100	$(9/2^+)$	[9]
	$p3$	proton	2.67	large	$(9/2^+)$	[9]
	$p4$	proton	2.66	large	$(9/2^+)$	[9]
	$p5$	proton	2.62	~ 70	$(9/2^+)$	[9]
	$p6$	proton	2.58	~ 30	$(9/2^+)$	[9]
	$p7$	proton	2.34	~ 25	$(9/2^+)$	[9]
	$p8$	proton	2.44	~ 60	$(9/2^+)$	[9]
	$p9$	proton	1.88	~ 2	$(11/2^-)$?	[9]
^{58}Cu		proton	2.34	> 97	$(9/2)^+$	[1]
^{59}Cu	$p1$	proton	1.95	2(1)	$9/2^+$	[10]
	$p2$	proton	1.92	13(2)	$9/2^+$	[10]
	$p3$	proton	1.90	9(2)	$9/2^+$	[11,10]
	$p4$	proton	2.02	8(3)	$9/2^+$	[10]
	$p5$	proton	2.48	53(8)	$9/2^+$	[11,10]

Next to the prompt proton decay in ^{58}Cu, evidence has been presented for prompt proton decays in ^{56}Ni [7] and ^{59}Cu [11] as well as the first case of prompt α-particle decay in ^{58}Ni [8].

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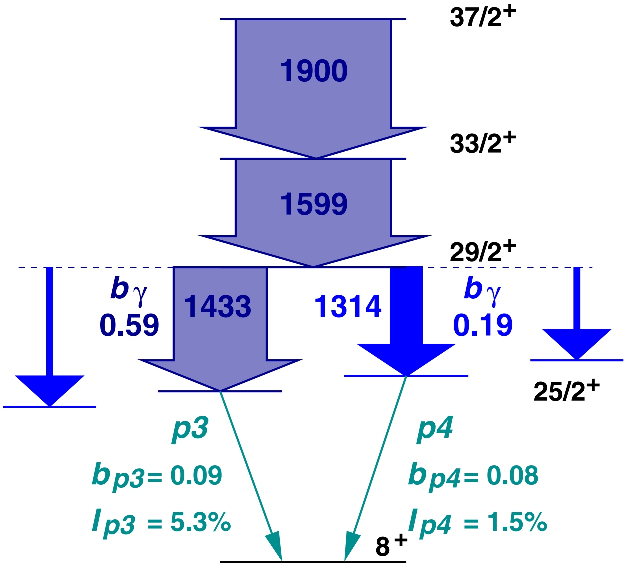

Fig. 1. Illustration of the "fine-structure" proton decay of the yrast superdeformed band in ^{59}Cu. See text and refs. [13,14,10] for details.

The unprecedented set-up, which aimed at combined high-resolution in-beam particle-$\gamma\gamma$ coincidence spectroscopy, comprised the GAMMASPHERE Ge detector array [15], parts of the charged-particle detector system MICROBALL [16], and a wall of four ΔE-E silicon-strip telescopes [17,18]. The set-up is described in ref. [6]. Additional information may also be found in several previous conference proceedings [3,19–21].

More than ten new proton decay lines and one new α-decay line have been observed in the decay-out regime of several rotational bands in ^{58}Ni and ^{59}Cu [14]. They imply the first observation of "fine structure" for the new decay mode [10] and involve states with competing α-, proton, and γ-radioactivity [9]. Note that most of the numbers with respect to ^{58}Ni in the table are preliminary.

Figure 1 shows schematically the "fine-structure" decay of the yrast superdeformed band $B5$ in ^{59}Cu [13,14, 10]. In simple semiclassical WKB calculations the higher energy of the proton branch $p4$ implies that it should have about twice the intensity of the branch $p3$. The fact that the observed ratio is $R = 1.5\%/5.3\% \sim 0.3$ indicates that different structural properties of the two initial states are of significant importance in this discrete-energy one-step particle decay-out process [10].

Given the plain number of prompt particle decays identified until now the new decay mode seems to be a common feature at least in proton-rich nuclei near ^{56}Ni. The quantitative continuation of the present studies is clearly the quest for more candidates in the vicinity of ^{56}Ni and nearby regions, *e.g.*, decays from deformed bands near ^{36}Ar and ^{40}Ca, *high*-spin states in mid-$1f7/2$ shell nuclei, or superdeformed bands in the mass $A \sim 80$–90 region. Qualitatively a high-statistics experiment shall be pursued to derive the angular distribution of the emitted particles with respect to the spin axis of the emitting nuclei. This quantity may provide access to more fundamental issues such as the wave function of a $1g_{9/2}$ proton in a deformed nuclear mean field or probing the nuclear time scale of changing the shape of the nucleus [22,23]. The latter may even be associated with the tunneling time.

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