Unexpected high-energy $\gamma$ emission from decaying exotic nuclei

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The $N=52^{82}\text{Ga}$ $\beta$ decay was studied at ALTO. The radioactive $^{82}\text{Ga}$ beam was produced through the ISOL photofission technique and collected on a movable tape for the measurement of $\gamma$-ray emission following $\beta$ decay. While $\beta$-delayed neutron emission has been measured to be 56–85% of the decay path, in this experiment an unexpected high-energy 5–9 MeV $\gamma$-ray yield of 16(4)% was observed, coming from states several MeVs above the neutron separation threshold. This result is compared with cutting-edge QRPA calculations, which show that when neutrons deeply bound in the core of the nucleus decay into protons via a Gamow–Teller transition, they give origin to a dipolar oscillation of nuclear matter into the nucleus. This leads to large electromagnetic transition probabilities which can compete with neutron emission, thus affecting the $\beta$-decay path. This process is enhanced by an excess of neutrons on the nuclear surface and may thus be a common feature for very neutron-rich isotopes, challenging the present understanding of decay properties of exotic nuclei.

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The description of $\beta$ decay as a weak interaction process has reached such a level of precision that it has become a powerful tool in the search for evidence of physics beyond the Standard Model [1]. In nuclei, global $\beta$ decay properties are driven by the strongly interacting nuclear medium [2,3]; concentrations of Gamow–Teller ($GT$) $\beta$ strength at several-MeV energies have been predicted and observed [2,4–7]. However, the understanding of the role of neutron overabundance on radioactive emission in very exotic nuclei is still in its infancy. Current scenarios in several nuclear applications and astrophysics [8] can be substantially affected.

In very neutron-rich nuclei the total energy released through $\beta$ decay, $Q_\beta$, can go beyond 10 MeV and subsequently even deeply bound neutrons can decay into protons. When the daughter nucleus is produced in a high-energy configuration above the neutron separation threshold $S_n$, it usually de-excites through $\beta$-delayed neutron emission. This process is generally favored in nuclei far from stability by the low $S_n$ value ($\lesssim 5$ MeV) [9]. It is nevertheless an open question how the transformation of a deeply bound neutron into a proton affects the nucleus as a whole. When such an abrupt change of the nuclear density of the decaying parent is induced, the rearrangement of nuclear matter could proceed through collective modes of de-excitation in the daughter isotope, involving also the most superficial nucleons. In this context, the interplay between the closed-core neutron holes after $GT$ $\beta$ decay and excess surface neutrons remains to be investigated. The presence of a neutron skin in neutron-rich systems can favor particular coherent nuclear excitation modes such as the so-called “pygmy” dipole resonance (PDR) [10]. It is an accumulation of electric dipole strength...
(E1) in the 5–10 MeV excitation-energy region. The PDR is interpreted as the result of an oscillation of the isoscalar (balanced number of protons and neutrons) inner core against the neutron skin [10].

Recent time-dependent Hartree–Fock–Bogoliubov calculations [11] point out several mass regions of the nuclide chart where these surface effects should be more manifest. Among them, a sudden increase in the neutron skin around 78N, beyond the N = 50 shell closure, has been predicted [11]. This leads to an enhancement by a factor ~3 in the E1 strength at energies between 5 and 10 MeV, exactly where the PDR is expected to occur [11]. The increase is particularly important at atomic number Z = 32, in neutron-rich Ge isotopes such as 83,84Ge21,22. This is related to the shell-model space beyond the N = 50 shell closure, where the underlying microscopic structure involves ν2d5/2 and ν3s1/2 neutron orbitals. Their wave functions extend further in space than that of the last proton orbital π1f5/2, and so the neutron skin thickness is increased. In addition, the Qβ values beyond N = 50 for Ga isotopes decaying to Ge nuclei are above 11 MeV already in 83Ga22 [9]. The phase space for the decay of neutrons belonging to the N = 50 and N = 28 shell closures is thus large, making this region pivotal for the study of the combined effects of neutron excess and decay of inner core neutrons. The present investigation of the highest-energy part of the 80,83Ge β-delayed gamma emission spectrum was further encouraged by two recent studies [12,5]. In Ref. [12] it was pointed out that, as long as the spin-parity combinations of mother–daughter nuclei permit, Fermi β decay may populate PDR states. In neutron-rich nuclei, however, GT β decay is the dominant process. Madurga et al. [5] report on the β decay of 80Ga, where high-energy states in the daughter 83Ge are populated following GT selection rules. The energy spectra of β-delayed neutrons from 83,84Ga decays are clearly constrained by the underlying nuclear structure, as opposed to a structureless level-density dependence [5].

This letter reports on the β-delayed γ emission of the 83Ga nucleus, from 5–10 MeV levels in the 83Ge daughter. These levels are neutron unbound and, contrary to expectations, a significant amount of γ radiation was observed in competition with neutron emission. Results will be compared with theoretical calculations.

The measurement was performed using the low-energy radioactive 80,83Ga ion beams, which were produced at the photofission Isotope Separation On Line (ISON) facility ALTO, operated at the IPN in Orsay [13]. The beam was then selected following a standard procedure [14] and delivered to the BEDO setup [15], consisting of a tape station dedicated to β-delayed γ-spectroscopy studies, depicted in Fig. 1. The cylindrical plastic scintillator around the implantation point is for β-electron detection, with an average efficiency of 56%. Four Ge detectors and a 2 × 2 × 4 inch LaBr3 scintillator were used for γ spectroscopy. While the Ge detectors were set with an energy range at around 2.5 MeV, the LaBr3 scintillator had an 11 MeV range, matching roughly the 11.7 MeV Q-value of the 83Ga β decay [9]. Germanium semiconductor detectors and the LaBr3 scintillator in the setup BEDO [15] were calibrated in energy and efficiency using standard γ-ray sources up to 1.5 MeV and for the scintillator also with known γ rays from 86Ga radioactivity up to 5.5 MeV. The response function and energy linearity of the LaBr3 detector were investigated up to 11 MeV with the γAl(p,γ)6Li reaction at the ARAMIS accelerator operated at CSNSM in Orsay [16]. The resolution of the scintillator is 30 keV at 1 MeV and 120 keV at 6–7 MeV.

The 80,83Ga yields were measured to be ~104 and ~10 pps, respectively. Ions were implanted on tape in 3 s spurts, followed by 2 s intervals of decay measurements. The collection time corresponds to roughly ten times the half-life of the 5/2− 83Ga ground state, 308(1) ms [17].

Fig. 2 shows the γ spectra registered by the LaBr3 detector coincident with a β particle detected in the cylindrical plastic scintillator surrounding the implantation point. The Qβ value of 80Ga decay is 10.3 MeV [9], and the γ-rays are observed to extend up to 8 MeV. This is consistent with previous findings [18] and with the 8.1 MeV neutron separation energy (Sn) of 80Ge [9]. In the case of 83Ga, the decay has a slightly larger Qβ value of 11.7 MeV [9], but the 83Ge daughter has an Sβ value of only 3.6 MeV [9]. Consequently, the γ-rays from the decay would be expected to reach up to roughly 4 MeV. Surprisingly, the energy spectrum is observed to extend all the way up to ~8–9 MeV. The slope of 83Ga β-delayed γ emission is identical to the one from 80Ga until 5 MeV, although with a larger intensity. The slope does not present any kind of change at 3.6 MeV, where the neutron separation threshold lies. After 5 MeV, a broad structure appears, the gamma-ray yield from 83Ga exceeds that of 80Ga by two orders of magnitude until about 8–9 MeV. Several observables were studied to cross-check this result. The time distribution of γ rays in the 5–9 MeV range is compatible with 83Ga half life. The 83Ga β-delayed neutron emission probability has been measured to be large, between 56(7)% and 85(6)% of the total decay strength [5,19]. Levels populated in 82Ge from 83Ga βn decay have been studied in detail in Refs. [19,20], and no γ-rays were reported above 3.4 MeV, thus excluding a contribution from 83Ga βn branch. Moreover, γ rays above 5 MeV from this branch would imply the population of states less than 2 MeV below the Qβ value in 83Ge. Such process is strongly suppressed by the Fermi function. The analysis of γ–γ coincidences between the LaBr3 and the Ge detectors is shown in Fig. 3. The 1238 keV line in 83Ge [20] is coincident with γ-rays below 4 MeV and then in the 5–5.5 MeV range, proving that the high-energy photons emitted following the decay of 83Ga do indeed feed the lower energy levels in 83Ge previously observed [21,20]. The statistical significance of the coincidence is >99%. Finally, the absence of the 1348 keV transition in the γ–γ coincidence spectrum excludes a relevant neutron contribution to the 5–9 MeV signals in the scintillator. The photons in the 5–9 MeV range must therefore have their source in the 83Ge high-energy levels populated in the 83Ga β decay.

An estimate of the relative neutron and γ-ray branchings was obtained from a simulation of the detector response function. This
was done with GEANT4 code [22] and the model was validated up
to 11 MeV using the aforementioned ARAMIS γ source [16]. The
83Ge total γ-ray spectrum observed with the LaBr3 detector was
then unfolded using the simulated response function. The result-
ing γ-ray intensity spectrum provides an estimate of the total β
feeding proceeding through γ-ray emission, I_Bγ, of states between
5 and 9 MeV relative to those of known intensity for low-energy
γ transitions. The 1348 keV line in the β-delayed neutron daugh-
ter 82Ge, with an absolute γ intensity of 62.8(3)% [20], was taken
as a reference. With the hypothesis of direct β feeding for all tran-
sitions observed, the total I_Bγ value for states in the 5 to 9 MeV
interval works out at 16(4)%. This value, when normalized to the
2.0(4) MeV−1 B(GT) deduced from neutron emission in 83Ga [5],
corresponds to an average integrated B(GT) going through γ ra-
diation of 0.4(1) MeV−1. This strength has escaped observation
in Ref. [5,21,20]. The present measurement suggests that this γ
branching of the neutron-unbound states accounts for a large part
of the β strength previously attributed to the low-lying 83Ge states.

Significant branching ratios from neutron-unbound states up to
2 MeV in less exotic nuclei have been attributed to neutron emis-
Sion hindrance due to a centrifugal barrier [6]. In the present case
the ℓ transferred by the emitted neutron can be as low as 1, so
the centrifugal barrier effects are less relevant. A hindrance of neu-
tron emission can come from core-neutron removal spectroscopic
factors [7], but even a strong 106 suppression factor [7] would im-
ply neutron emission lifetimes of the order of only 10−16−10−17 s.

The high branching ratio measured for γ-ray emission from states
up to 5 MeV above the S_p value in 83Ge is all the more surpris-
ing. Only fast, possibly collective E1 transitions can compete with
neutron emission from levels in this energy range. Other parity-
changing electromagnetic transition, like M2 or E3, are suppressed
by at least three orders of magnitude due to their higher multiplo-
arity.

Fully microscopic Quasi particle Random Phase Approximation
(QRPA) calculations [23,24], with no free parameters, were per-
formed to explore the E1 γ strengths of states populated by ra-
dioactivity in 80,83Ge. The sole input of the QRPA framework of
this work is the effective nucleon–nucleon Gogny D1M interaction [25],
effective over the whole nuclear chart [26]. The coherent QRPA
solutions are built from the quasi-particle spectrum obtained in
Hartree–Fock–Bogoliubov (HFB) calculations. Protons and the neu-
trons are described as pairs of time-reversed companions, and then
the standard equal filling approximation, discussed in Ref. [27], is
used. For the odd-mass 83Ge, the blocking procedure [28], impos-
ing a fixed value to the occupation of given single-particle orbitals,
has been used in order to obtain the quasi-particle (qp) spectrum
associated with nuclear states. Several blocked configurations of
the unpaired nucleon involving relevant single-particle orbitals
were analyzed. Subsequently, the QRPA coherent excitations are
built on the same basis as in the HFB calculations, preserving the
axial symmetry. In these in-nuclear excitations, all the 2qp neu-
tron pair and all 2qp neutron pair are considered in the coherent
summation building the phonon excitation. However, for odd-mass
nuclei, only one component of the two time-reversed components
of the blocked quasi-particle level, the “down” one, can take part
in the 2qp excitations. For the β decays of 80,83Ga to 80,83Ge, the
charge exchange code of Ref. [3] (pn-QRPA) provided the popu-
lation of states in the daughter nuclei. The pn-excitation phonon
operator results from the summation on proton–neutron 2qp.

Fig. 4 illustrates the transition densities of the GT γ-decay
phonon and E1 phonon, for proton and neutron fluids. The 83Ge
mean nuclear radius is 5.5 fm. The β decay from the calculated
deformed 83Ga ground state induces a depletion in neutron den-

![Fig. 3. γ rays registered by the LaBr3 scintillator in coincidence with the 83Ge 1238 keV γ ray from the Ge detectors. In the inset the inverse coincidence: the γ rays registered by the Ge detectors in coincidence with 5–6 MeV γ rays registered by the LaBr3 scintillator.](image)

![Fig. 4. The transition densities δρ of the GT and E1 phonon for the ~6 MeV states populated in the decay, in blue for neutrons, in red from protons. Panel a) Allowed β decays will mostly convert a deeply-bound neutron from the N = 50 core into a proton in the Fermi surface. Panel b) These excited states fed by β-decay (7/2−, 5/2−, 3/2−) correspond to particle-hole E1 excitations on the 5/2+ ground state of 83Ge. 83Ge can then de-excite via E1 transitions when the neutron hole in the core is filled by one of the neutrons in the v2d5/2 and v3s1/2 shells. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)](image)
Fig. 5. GT β-decay and E1 strength distributions from microscopic Gogny-QRPA calculations.

can trigger coherent dipolar oscillations (PDR) which in turn engender a significant emission of E1 γ radiation. The process is favored by the rapid development of a neutron skin beyond the neutron shell closure N = 50. In this regard, the observed change in radioactive emission may be a common feature of very exotic nuclei. It remains for future measurements to better quantify the phenomenon, and explore its evolution in even more neutron-rich nuclei. The low production yields of such species in present and future radioactive ion-beam facilities makes it difficult to investigate the PDR in very neutron-rich systems via the standard charge-exchange or coulomb-excitation reactions. The possibility of using β decay to at least partially study the PDR can thus help a better understanding of radiative capture (n, γ) cross sections in neutron-rich matter. These are pivotal quantities for nucleosynthesis scenarios of heavy elements via the rapid neutron capture process (r-process) [8,5]. The observed high-energy γ rays feeding low-lying states also leads to a reduction of measured first-forbidden β-decay probabilities, challenging present understanding of their role in very exotic nuclei [29]. The global properties of the β-delayed radiation emission are also relevant for reactor physics and related topics [30,31].

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