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Unexpected high-energy γ emission from decaying exotic nuclei

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ABSTRACT

The $N = 52$ ^{83}Ga β decay was studied at ALTO. The radioactive ^{83}Ga beam was produced through the ISOL photofission technique and collected on a movable tape for the measurement of γ-ray emission following β decay. While β-delayed neutron emission has been measured to be 56–85% of the decay path, in this experiment an unexpected high-energy 5–9 MeV γ-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 rise to a dipolar oscillation of nuclear matter in the nucleus. This leads to large electromagnetic transition probabilities which can compete with neutron emission, thus affecting the β-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.

The description of β 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 β decay properties are driven by the strongly interacting nuclear medium [2,3]; concentrations of Gamow–Teller (GT) β 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 β decay, Q_β, 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 β-delayed neutron emission. This process is generally favored in nuclei far from stability due to the low S_n value ($\lesssim$5 MeV) [9]. It is nevertheless an open question how the transformation of a deeply bound neutron into a proton affects the nucleus as a whole. When such an abrupt change of the nuclear density of the decaying parent is induced, the rearrangement of nuclear matter could proceed through collective modes of de-excitation in the daughter isotope, involving also the most superficial nucleons. In this context, the interplay between the closed-core neutron holes after GT β decay and excess surface neutrons remains to be investigated. The presence of a neutron skin in neutron-rich systems can favor particular coherent nuclear excitation modes such as the so-called "pygmy" dipole resonance (PDR) [10]. It is an accumulation of electric dipole strength ($E1$) in the 5–10 MeV excitation-energy region. The PDR is interpreted as the result of an oscillation of the isoscalar (bal-

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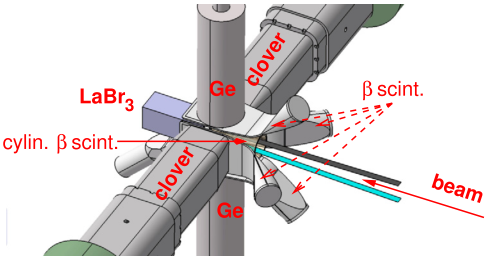

Fig. 1. A sketch of the BEDO detector arrangement.

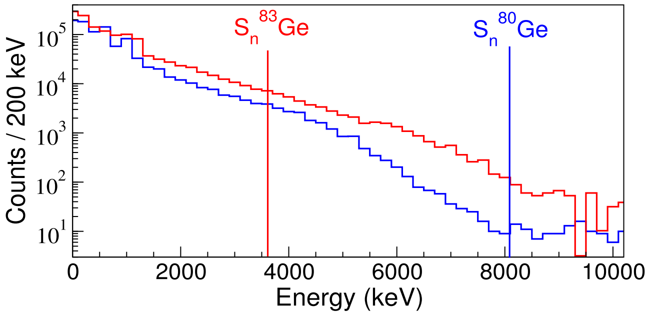

Fig. 2. The γ-ray energy spectrum as measured in coincidence with β electrons from the decay of ^{80,83}Ga. The neutron separation energies of the daughter nuclei ^{80,83}Ge are also indicated. The two spectra are normalized to the same number of β-decay events.

anced 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 ^{78}Ni, 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 ^{83,84}Ge$_{51,52}$. This is related to the shell-model space beyond the $N = 50$ shell closure, where the underlying microscopic structure involves $\nu 2d_{5/2}$ and $\nu 3s_{1/2}$ neutron orbitals. Their wave functions extend further in space than that of the last proton orbital $\pi 1f_{5/2}$, and so the neutron skin thickness is increased. In addition, the Q_β values beyond $N = 50$ for Ga isotopes decaying to Ge nuclei are above 11 MeV already in ^{83}Ga$_{52}$ [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 ^{80,83}Ge 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 ^{83}Ga, where high-energy states in the daughter ^{83}Ge are populated following GT selection rules. The energy spectra of β-delayed neutrons from ^{83,84}Ga 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 ^{83}Ga nucleus, from 5–10 MeV levels in the ^{83}Ge 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 ^{80,83}Ga ion beams, which were produced at the photofission Isotope Separation On Line (ISOL) 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 $2 \times 2 \times 4$ inch LaBr$_3$ scintillator were used for γ spectroscopy. While the Ge detectors were set with an energy range at around 2.5 MeV, the LaBr$_3$ scintillator had an 11 MeV range, matching roughly the 11.7 MeV Q-value of the ^{83}Ga β decay [9]. Germanium semiconductor detectors and the LaBr$_3$ 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 with known γ rays from ^{80}Ga radioactivity up to 5.5 MeV as well. The response function and energy linearity of the LaBr$_3$ detector were investigated up to 11 MeV using the ^{27}Al(p, γ)^{28}Si reaction at the ARAMIS accelerator operated at the CSNSM in Orsay [16]. The resolution of the scintillator is 30 keV at 1 MeV and 120 keV at 6–7 MeV.

The ^{80,83}Ga yields were measured to be $\sim 10^4$ 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 $5/2^-$ ^{83}Ga ground state, 308(1) ms [17].

Fig. 2 shows the γ spectra registered by the LaBr$_3$ detector coincident with a β particle detected in the cylindrical plastic scintillator surrounding the implantation point.

The Q$_\beta$ value of ^{80}Ga 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 (S_n) of ^{80}Ge [9]. In the case of ^{83}Ga, the decay has a slightly larger Q$_\beta$ value of 11.7 MeV [9], but the ^{83}Ge daughter has an S_n 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 ^{83}Ga β-delayed γ emission is identical to the one from ^{80}Ga 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 ^{83}Ga exceeds that from ^{80}Ga 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 ^{83}Ga half life. The ^{83}Ga 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 ^{82}Ge from ^{83}Ga 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 ^{83}Ga βn branch. Moreover, γ rays above 5 MeV from this branch would imply the population of states less than 2 MeV below the Q$_\beta$ value in ^{83}Ge. Such a process is strongly suppressed by the Fermi function. The analysis of γ–γ coincidences between the LaBr$_3$ and the Ge detectors is shown in Fig. 3. The 1238 keV line in ^{83}Ge [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 ^{83}Ga do indeed feed the previously observed lower energy levels in ^{83}Ge [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 ^{83}Ge high-energy levels populated in the ^{83}Ga β decay.

An estimate of the relative neutron and γ-ray branching 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 ^{83}Ge total γ-ray spectrum observed with the LaBr$_3$ detector was then unfolded using the simulated response function. The resulting γ-ray intensity spectrum provides an estimate of the total β feeding proceeding through γ-ray emission, $I_{\beta\gamma}$, 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 daughter ^{82}Ge, with an absolute γ intensity of 62.8(3)% [20], was taken as a reference. With the hypothesis of direct β feeding for all transitions observed, the total $I_{\beta\gamma}$ 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 ^{83}Ga [5], corresponds to an average integrated $B(GT)$ going through γ radiation 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 ^{83}Ge states.

Significant branching ratios from neutron-unbound states up to 2 MeV in less exotic nuclei have been attributed to neutron emission 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 neutron emission can come from core-neutron removal spectroscopic factors [7], but even a strong 10^6 suppression factor [7] would imply 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_n value in ^{83}Ge is all the more surprising. 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 multipolarity.

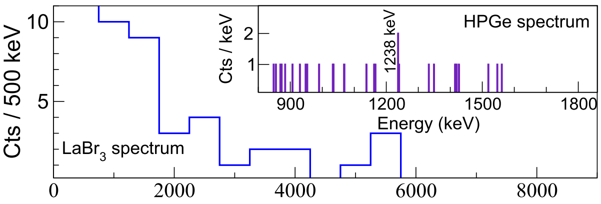

Fig. 3. γ rays registered by the LaBr$_3$ scintillator in coincidence with the ^{83}Ge 1238 keV γ ray from the Ge detectors. In the inset the inverse coincidence: the γ rays registered by the Ge detectors in coincidence with 5–6 MeV γ rays registered by the LaBr$_3$ scintillator.

Fully microscopic Quasi particle Random Phase Approximation (QRPA) calculations [23,24], with no free parameters, were performed to explore the $E1$ γ strengths of states populated by radioactivity in ^{80,83}Ge. 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 neutrons 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 ^{83}Ge the blocking procedure [28], imposing a fixed value for 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 $2qp$ proton pairs and all $2qp$ neutron pairs 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 ^{80,83}Ga to ^{80,83}Ge, the charge exchange code of Ref. [3] (pn-QRPA) provided the population 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 β-decay phonon and $E1$ phonon, for proton and neutron fluids. The ^{83}Ge

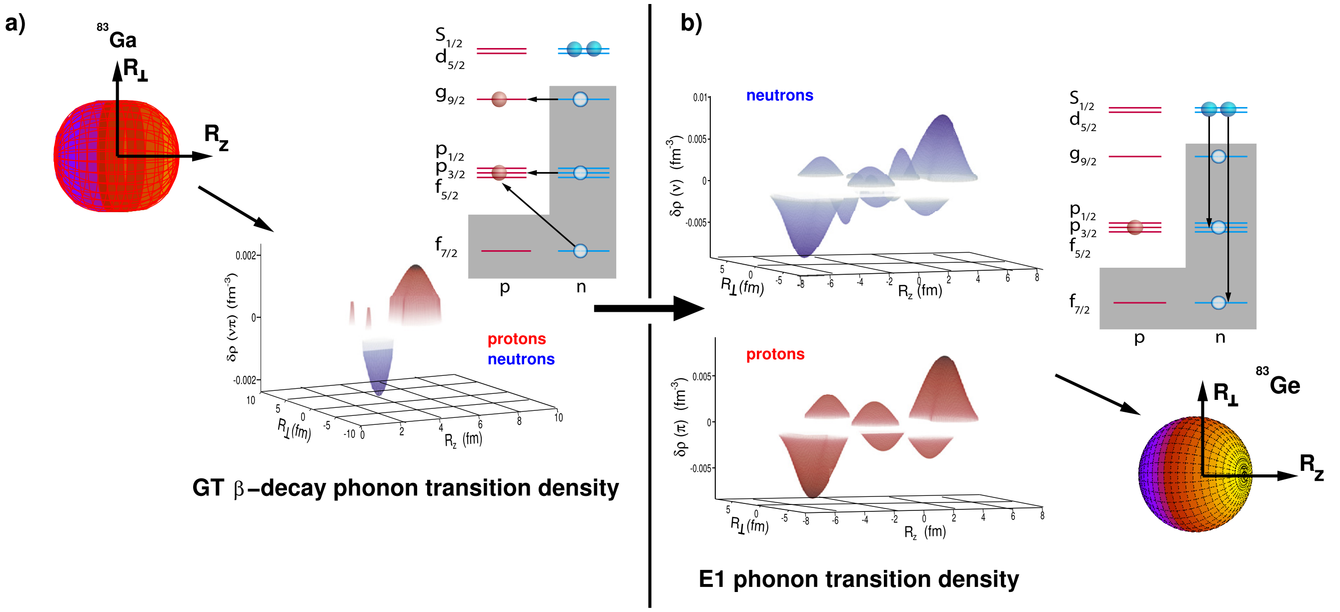

Fig. 4. The transition densities $\delta\rho$ of the GT and $E1$ phonon for the ~6 MeV states populated in the decay, in blue for neutrons, in red for protons. Panel a) Allowed β decays will mostly convert a deeply-bound neutron from the N = 50 core into a proton in the Fermi surface. Panel b) These 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 ^{83}Ge. ^{83}Ge can then de-excite via $E1$ transitions when the neutron hole in the core is filled by one of the neutrons in the $\nu 2d_{5/2}$ and $\nu 3s_{1/2}$ shells. (For interpretation of the color references in this caption, the reader is referred to the web version of this article.)

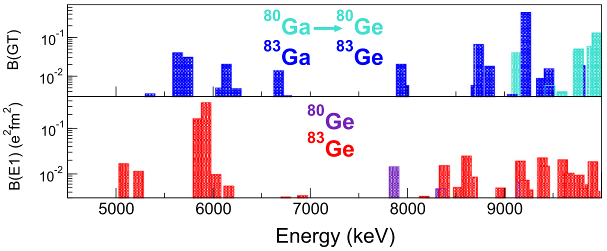

Fig. 5. GT β-decay and $E1$ strength distributions from microscopic Gogny-QRPA calculations.

mean nuclear radius is ∼5.5 fm. The β decay from the calculated deformed ^{83}Ga ground state induces a depletion in neutron density at around 3 fm and a corresponding increase in proton density at 5 fm. This peculiar variation of matter initiates a dipolar oscillation, de-exciting by an $E1$ transition to the low-energy excited states of ^{83}Ge. The displayed transition densities show that coherent excitations take place at the nuclear surface, leading to an increase of density around 6 fm. Neutrons and protons contribute jointly, nevertheless the neutron transition density is dominant and peaks more at the surface. This is indeed the expected feature of an isoscalar PDR in neutron-rich nuclei. Fig. 4 also presents a schematic view of the typical elementary spherical single-particle processes which coherently sum-up to build the QRPA GT and $E1$ strengths.

The calculated GT and $E1$ spectra are presented in Fig. 5 for the ^{80}Ge and ^{83}Ge nuclei. No quenching is included in the calculation of any of these strengths. The histograms of ^{83}Ge transition probabilities for the GT phonon, $B(GT)$, and the $E1$ phonon, $B(E1)$, show an accumulation of strength at 5–7 MeV and then again beyond 8 MeV, in good agreement with the γ-ray spectrum in Fig. 2. The $B(E1)$ strengths are as large as 0.4 $e^2\,fm^2$, or 0.2 W.u. The half-life of a 6 MeV state de-exciting by an $E1$ transition with a strength of 0.1 W.u. is $1.5 \cdot 10^{-17}$ s. This compares well with the typical neutron emission lifetimes of 10^{-16}–10^{-19} s, thus justifying the existence of a significant γ-decay branch from neutron-unbound states. Consequently, microscopic calculations confirm that the states populated by the GT decay have strong $E1$ transitions to ground (or low-excited) states. On the contrary, the ^{80}Ge isotope GT and $E1$ strengths are suppressed in the region of interest, and shifted to higher energies. The calculation thus fully reproduces the lack of β-delayed γ-ray strength in ^{80}Ge with respect to ^{83}Ge.

This result helps to open a new, broader perspective on the pivotal study by Madurga et al. [5]. Firstly, a large part of β feeding to low energy states previously attributed to FF transitions actually seems to proceed through $E1$ transitions from GT-fed high-lying levels. This dominance of GT over FF decays is in contrast with previous calculations beyond $N = 50$ and close to ^{78}Ni [29], with consequences on the r-process path. Secondly, GT decays of deeply-correlated neutrons in the closed core need the presence of coherent core-excited levels as final states in the daughter nucleus, much lower in energy than the Q_β value, to allow for a sufficient phase space. When the spin-parity combination of mother and daughter nucleus permits, the GT decay can populate collective $E1$ excitations. A significant high-energy γ-ray radiation may then occur in competition with neutron emission. Only the combination of neutron and γ radiation measurements can reveal the microscopic nature of these states, as is the case for ^{83}Ga. This mechanism must be general for neutron rich nuclei, impacting also heavier nuclei ($N = 82$, $N = 126$ shell closures).

In summary, a significant γ-ray emission was detected in the 5–9 MeV range from the decay of $N = 51$ ^{83}Ga. It originates from the decay of states neutron-unbound by several MeV, populated by the GT β decay of ^{83}Ga. State-of-the-art microscopic QRPA calculations show that the GT decay of deeply-bound neutrons 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 $N = 50$ neutron shell closure. 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 to gain a better understanding of radiative capture (n, γ) cross sections in neutron-rich matter. These are pivotal quantities for nucleosynthesis scenarii of heavy elements via the rapid neutron capture process (r-process) [8,5]. The observed high-energy γ rays feeding low-lying states also lead 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 [30–32].

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References

[1] N. Severijns, M. Beck, O. Naviliat-Cuncic, Rev. Mod. Phys. 78 (2006) 991.
[2] Y. Fujita, B. Rubio, W. Gelletly, Prog. Part. Nucl. Phys. 66 (2011) 549.
[3] M. Martini, S. Péru, S. Goriely, Phys. Rev. C 89 (2014) 044306.
[4] Y. Fujita, et al., Phys. Rev. Lett. 112 (2014) 112502.
[5] M. Madurga, et al., Phys. Rev. Lett. 117 (2016) 092502.
[6] J.L. Tain, et al., Phys. Rev. Lett. 115 (2015) 062502.
[7] A. Spyrou, et al., Phys. Rev. Lett. 117 (2016) 142701.
[8] S. Goriely, Phys. Lett. B 436 (1998) 10.
[9] M. Wang, et al., Chin. Phys. C 36 (2012) 1603.
[10] N. Paar, D. Vretenar, E. Khan, G. Colò, Rep. Prog. Phys. 70 (2007) 691.
[11] S. Ebata, T. Nakatsukasa, T. Inakura, Phys. Rev. C 90 (2013) 024303.
[12] M. Scheck, et al., Phys. Rev. Lett. 116 (2016) 132501.
[13] F. Ibrahim, et al., Nucl. Phys. A 787 (2007) 110.
[14] A. Gottardo, et al., Phys. Rev. Lett. 116 (2016) 182501.
[15] A. Etilé, et al., Phys. Rev. C 91 (2015) 064317.
[16] E. Cottereau, et al., Nucl. Instrum. Methods Phys. Res. B 45 (1990) 293.
[17] E. Mccutchan, Nucl. Data Sheets 125 (2015) 201.
[18] P. Hoff, B. Fogelberg, Nucl. Phys. A 368 (1981) 210.
[19] D. Verney, et al., Phys. Rev. C 95 (2017) 054320.
[20] J.A. Winger, et al., Phys. Rev. C 81 (2010) 044303.
[21] M.F. Alshudifat, et al., Phys. Rev. C 93 (2016) 044325.
[22] S. Agostinelli, et al., Nucl. Instrum. Methods Phys. Res., Sect. A 506 (2003) 250.
[23] S. Péru, et al., Phys. Rev. C 83 (2011) 014314.
[24] S. Péru, H. Goutte, Phys. Rev. C 77 (2008) 044313.
[25] S. Goriely, S. Hilaire, M. Girod, S. Péru, Phys. Rev. Lett. 102 (2009) 242501.
[26] M. Martini, S. Péru, S. Hilaire, S. Goriely, F. Lechaftois, Phys. Rev. C 94 (2016) 014304.
[27] S. Perez-Martin, L.M. Robledo, Phys. Rev. C 78 (2008) 014304.
[28] M. Versteegen, et al., Phys. Rev. C 94 (2016) 044325.
[29] I.N. Borzov, Phys. Rev. C 71 (2005) 065801.
[30] A. Algora, et al., Phys. Rev. Lett. 105 (2010) 202501.
[31] B.C. Rasco, et al., Phys. Rev. Lett. 117 (2016) 092501.
[32] A.-A. Zakari-Issoufou, et al., Phys. Rev. Lett. 115 (2015) 102503.