β-delayed neutron emissions from $N > 50$ gallium isotopes†

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β-delayed multi-neutron emission is expected to be the dominant decay mode for the nuclides far from stability, patticularly along the astrophysical r-process path. The number of neutrons emitted in decays of neutron-rich nuclei is an important input for the abundance calculations as it affects the final isobaric abundance pattern by providing neutrons for the late-time capture process and altering the decay path back to stability.[1)] Until recently, the neutron emission probabilities (P_{xn}) for the r-process abundance calculations relied on predictions[2)] based on the simplified assumption that only x-neutron emissions will occur when β-decay feeds a state above the x-neutron separation energy (S_{xn}), and the effect of less-than-x-neutron channels are negligible.

As we measured the β decays of $^{84-87}$Ga at RIBF using a high-efficiency array of ^{3}He neutron counters (BRIKEN), we have found large one-neutron emission probability (P_{1n}) values and unexpectedly small P_{2n} values, even for those Ga isotopes where the major part of the B(GT) is expected to be concentrated above S_{2n}. This was interpreted as a signature of one-neutron emission from two-neutron unbound states. This result underscores the importance of modeling the competition between multi-neutron emission channels as reported in a Rapid Communication paper.[3)] The Hauser–Feshbach statistical model[4)] was then applied to the global calculation by Möller *et al.*,[5)] which provided P_{xn} predictions based on more realistic model.

In this paper, we have performed an updated analysis of the decay of gallium isotopes. As we calculated the branching ratios using the statistical model, we found that the decay patterns were sensitive to the level densities of the daughter nuclei. In the statistical model code by Kawano *et al.*,[4)] shell and pairing energies from the mass formula by Koura *et al.*, KTUY05, were applied to the Gilbert–Cameron formula[6)] to generate phenomenological nuclear level densities.[7)]

We performed shell-model calculations using the NuShellX code with the jj45pna interaction to estimate level densities of the Ge isotopes. Owing to our computational limit, levels up to ≈7 MeV were calculated for all the spins and parities. The shell-model level densities were fitted by the constant temperature level density formula,

$$\rho = \frac{1}{T}\exp\left(\frac{E-E_0}{T}\right) \tag{1}$$

where the shell correction (δw), pairing correction (Δ), and scaling factor (f_{tweak}) in E_0 were free parameters. The shell-model level densities were consistently lower than the default ones in the statistical model code. (See original paper for details.)

Figure 1 shows the P_{2n}/P_{1n} ratios in the decays of $^{84-87}$Ga and the statistical model calculations obtained by using different level densities. The default level densities consistently predicted larger P_{2n} ratios for all four Ga isotopes. This is because a higher level density above S_{1n} in the $1n$ daughter nucleus can result in a higher probability of emitting a second neutron. The experimental ratios agree better when shell-model level densities are used, which could mean the level densities of those Ge isotopes were lower than when default parameters were used. This result reveals the need for a detailed understanding of the level densities and decay scheme, which could be studied by neutron spectroscopy.

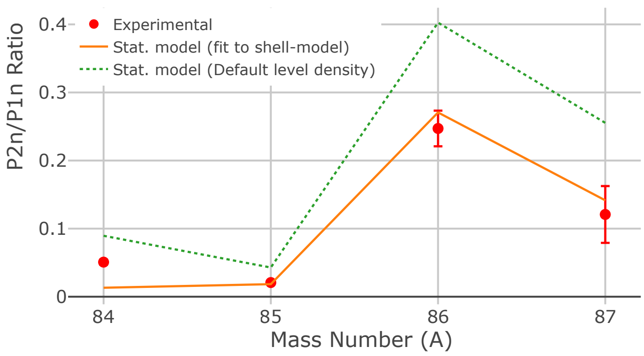

Fig. 1. P_{2n}/P_{1n} ratio in the decay of Ga isotopes. The red circle shows the experimental value, while the dashed and solid lines show the statistical model predictions obtained by using default and shell-model-based parameters for the level densities, respectively.

† Condensed from the article in Phys. Rev. C **108**, 064307 (2023)

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DOI:10.34448/RIKEN.APR.57-032