Lifetime of the first 2^+ excited state in ^{166}Dy

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Abstract: The neutron-rich rare-earth isotopes in the $N = 98 - 100$ region are well known for their strange behaviour in terms of their $E(2^+)$ values, deviating from the smooth decrease expected by collective models. At the moment, there is no satisfactory theoretical explanation for the observed decrease (increase) in $E(2^+)$ energy of the $N = 98$ ($N = 100$) isotopes. Therefore, we propose an experiment with the ROSPHERE array to measure the $B(\mathrm{E2} : 2 \rightarrow 0)$ value in ^{166}Dy, which will provide important information for solving this puzzle.

I. MOTIVATION

The basis of our understanding of nuclear structure is the existence of closed neutron and proton shells. Nuclei around these shells can be well described as single particles outside an inert core. Further away from closed shells, however, the atomic nuclei starts to behave more as a collective of nucleons rather than as single particles outside a core. Several observables are related to the amount of collectivity in the nucleus, some of the most well known being decreasing energy, $E(2^+)$, and increasing reduced transition probability, $B(\mathrm{E2} : 2^+ \rightarrow 0^+)$, of the first 2^+ state, as well as increasing energy ratio $R(4/2) = E(4^+)/E(2^+)$. In the rare-earth region, the collectivity is expected to increase smoothly until it reaches a maximum at the mid-shell nucleus ^{170}Dy [1].

However, these smooth systematics are not completely realized in nature. At the $Z = 66$ nuclei (and below) the $E(2^+)$ are decreasing as expected, with a larger decrease at the $N = 98$ isotope ^{164}Dy and an increase at the $N = 100$ isotope ^{166}Dy. For ^{168}Dy the decrease continues and, even if the $E(2^+)$ in ^{170}Dy is not known, a tentative measurement of the $E(4^+)$ state suggests that this decrease continues as expected [2]. The systematics of the dysprosium isotopes are shown in Fig. 1. This suggests that there is a increase in collectivity at ^{164}Dy, followed by a decrease in collectivity at ^{166}Dy. The $R(4/2)$ systematics has a much smoother behaviour, suggesting a constant increase in collectivity when approaching mid-shell. However, there is a subtle slowing down of this increase at ^{164}Dy, followed by a faster increase at ^{166}Dy. Thus, the systematics of the $E(2^+)$ and the $R(4/2)$ systematics in this region are contradictory to each other. The first is suggesting a large increase followed by a decrease in collectivity, where the second is suggesting a small increase followed by a large increase. This strange behaviour around $N = 98, 100$ can be seen in other observables as well, like the $S_{2\mathrm{n}}$ systematics of ^{164}Dy [3] and as a shallow minimum of the g factor systematics at ^{168}Hf [4]. At the moment, there is no satisfactory explanation for the observed behaviour of the $N = 98, 100$ isotopes. One theoretical prediction in particular suggests the appearence of a new magic number at $N = 100$ [5], which would be directly reflected in the $B(\mathrm{E2} : 2 \rightarrow 0)$. Therefore, we propose a measurement of the life time of the first excited 2^+ state, directly related to the $B(\mathrm{E2} : 2 \rightarrow 0)$, in the $N = 100$ nucleus ^{166}Dy. This measurement can provide an answer to the question if the irregular behaviour of the $E(2^+)$ and $R(4/2)$ systematics is due to a change in collectivity or single particle effects in this region.

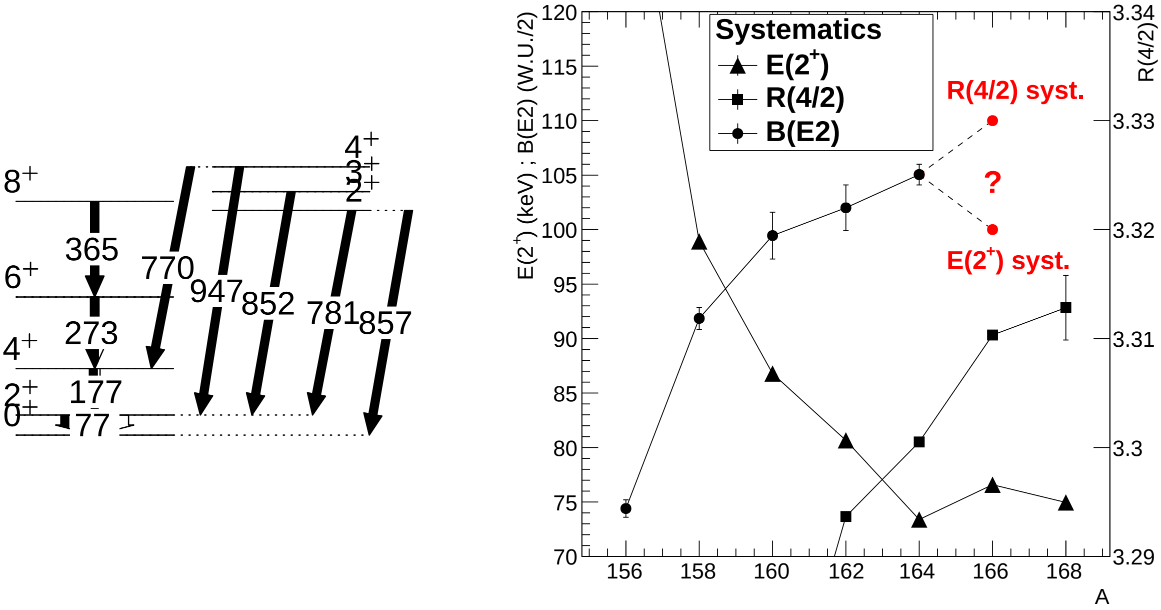

FIG. 1: Low-energy level scheme in ^{166}Dy, relevant for this proposal (left). Systematics of $E(2^+)$, $R(4/2)$ and $B(\mathrm{E2} : 2^+ \rightarrow 0^+)$ for dysprosium isotopes with $156 \leq A \leq 168$ (right). Red circles shows two possible extrapolations of known $B(\mathrm{E2} : 2^+ \rightarrow 0^+)$ values based on the $E(2^+)$ and $R(4/2)$ systematics, respectively.

Furthermore, the evolution of collectivity for the rare-earth isotopes has been suggested to have a significant influence on the astrophysical r-process, especially the formation of the $A = 160$ abundance peak at late times during freeze-out [6, 7]. In the r-process calculations a smooth increase in collectivity up to the maximum at $N = 104$ is assumed through the entire $50 \leq Z \leq 66$ region. However, a deviation from this assumption could explain some discrepancies in the calculated and experimental r-process abundances [8]. Therefore, measurement of the evolution of deformations, even if far away from the r-process path, will be of value for our understanding of the formation of the elements.

II. EXPERIMENTAL DETAILS

We propose to populate ^{166}Dy using the ^{164}Dy(^{7}Li, αp)^{166}Dy reaction at the ROSPHERE array. The reaction process is thought to be a mixture of incomplete fusion and low-energy transfer. A similar experiment was previously been used at Bucharest and were shown to populate the two-neutron transfer channel [9]. In that experiment, a ^{186}W target was used and the reaction populated states in ^{188}W with an estimated cross-section of 1–2 mb. We expect a similar cross-section for the population of ^{166}Dy in our reaction. Figure 2 shows the time spectrum from the $^{186}\mathrm{W}(^{7}\mathrm{Li}, \alpha\mathrm{p})^{188}\mathrm{W}$ with a sum of Ge gates and the $E(2^{+}) = 143$ keV as a clean $\mathrm{LaBr_3}$ stop gate.

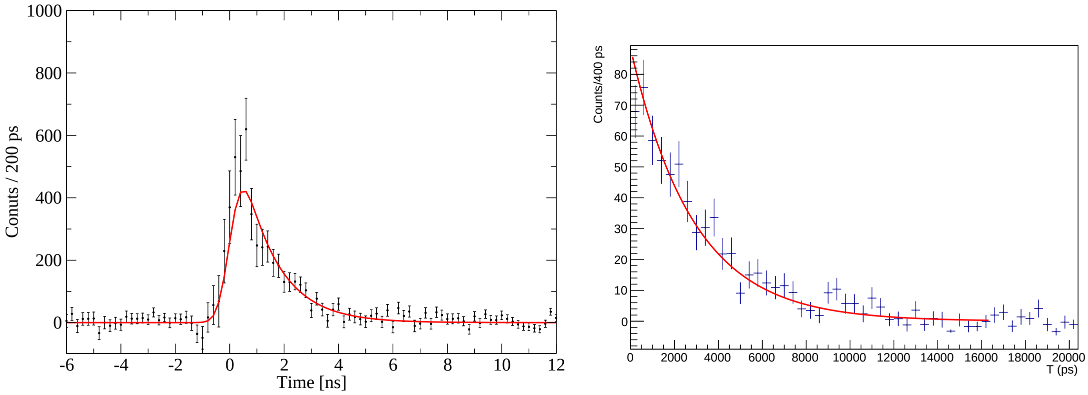

FIG. 2: Preliminary results from the $^{186}\mathrm{W}(^{7}\mathrm{Li}, \alpha\mathrm{p})^{188}\mathrm{W}$ experiment (left). Simulations of the statistics in the proposed experiment (right).

We intend to measure the lifetime of the 2^{+} state in ^{166}Dy by taking the time difference between the $4^{+}_{1} \rightarrow 2^{+}_{1}$ (177 keV), $6^{+}_{1} \rightarrow 4^{+}_{1}$ (273 keV) transitions and the $2^{+}_{1} \rightarrow 0^{+}_{1}$ (76.6 keV) transition detected in the Bucharest $\mathrm{LaBr_3}$(Ce) detectors. The $\mathrm{LaBr_3}$-$\mathrm{LaBr_3}$ matrices will be created by gating on higher-lying ^{166}Dy transitions, primarily the $4^{+}_{1} \rightarrow 2^{+}_{1}$ (177 keV) and $6^{+}_{1} \rightarrow 4^{+}_{1}$ (273 keV) transtions in the HPGe detectors. A partial level scheme for ^{166}Dy is shown in Fig. 1. The lifetime of the 2^{+} state in ^{166}Dy is expected to be in the 2.0–2.4 ns range.

III. RATE ESTIMATES AND BEAM-TIME REQUESTS

In the $^{186}\mathrm{W}(^{7}\mathrm{Li}, \alpha\mathrm{p})^{188}\mathrm{W}$ reaction, a beam energy of 31 MeV was used, which is within 2 MeV of the Coulomb barrier. In that case, it would not possible to go higher due to energy coincidences with competeing reaction channels. For ^{166}Dy this is not a problem, so we expect that a beam energy of 33 MeV, the maxium energy available from the Bucharest tandem, will provide a better population of the 6^{+} state, and also an increase of the total reaction cross-section with ~ 25 %. This increase in beam energy will increase the background from fusion reaction channels. However, it will also decrease the background from one-proton transfer channels with approximately the same amount. Therefore, the total background is expected to be unchanged.

As stated above, the cross-section for this reaction is estimated to be 1.5 mb. If we use a 5 mg/cm^2 ^{164}Dy target with a minimum beam current of 4 pnA, we will create 690 ^{166}Dy ions per second. Using an estimated HPGe efficiency of 3.5 % at 300 keV and an average $LaBr_3$ efficiency of 1.1 % for the $4^+ \rightarrow 2^+$ and $2^+ \rightarrow 0^+$ transitions, we expect 2.5 HPGe-$LaBr_3$-$LaBr_3$ coincidences per hour or 60 coincidences per day. With 12 days of beam time, we will obtain $\sim$ 720 HPGe-$LaBr_3$-$LaBr_3$ coincidences. A simulated time spectrum with this statistics and a background estimated from the ^{188}W experiment is illustrated in Fig. 2. In total, we request 12 days of beam time to measure the half-life of the first 2^+ state in ^{166}Dy with the optimum experimental conditions.

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