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EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

Letter of Intent to the ISOLDE and Neutron Time-of-Flight Committee

Development of neutron-rich Tb beams for a systematic study approaching the doubly mid-shell in Rare-Earth nuclei

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Abstract: This letter of intent proposes the development of terbium beams at ISOLDE in order to perform β-decay fast-timing experiments of even-even Tb into Dy in the neutron-rich region of the nuclear chart. The final aim of this experimental campaign will be the measurement of $T_{1/2}(2_1^+)$ of the doubly mid-shell ^{170}Dy ($Z = 66$ and $N = 104$). In a simplistic interpretation of the Nuclear Shell Model, ^{170}Dy is expected to have the highest ground state deformation below ^{208}Pb due to its large proton and neutron valence space. For this purpose, yield measurements and determination of release curves for the neutron-rich terbium isotopes, in particular ^{166,168,170}Tb, are required to assess the feasibility and beam-time requirements for future experiments.

Requested shifts: 6 shifts for Tb beam development and yield measurements.

1 Introduction and physics motivation

The Nuclear Shell Model has proved to be a powerful tool to understand the single-particle properties of spherical nuclei near the shell closures defined by the nuclear magic numbers. These numbers have been firmly established using this model along the *Valley of Stability* that runs through the 2, 8, 20, 28, 50, 82 and 126 protons and neutrons numbers. In a similar way, in the regions between two magic numbers, it is expected that collectivity increases smoothly with the product of valence protons and neutrons, N_nN_p [1]. In a naive interpretation of the shell model, this effect will maximize in the regions around the doubly mid-shell nuclei, which greatly enhances the number of possible neutron and proton interactions. Assuming the standard spherical shell gaps at $N = 82 - 126$ and $Z = 50 - 82$, the maximum collectivity below ^{208}Pb can be expected in ^{170}Dy ($Z = 66$, $N = 104$). Consequently, ^{170}Dy has attracted great attention from a theoretical point of view, with several models trying to predict the deformation and collectivity of this doubly mid-shell nucleus and the evolution of the Dy isotopic chain [2–10]. The more realistic calculations actually predict that collectivity saturates near $N = 98$ and that the maximum in deformation is reached in lighter masses, ^{166}Dy or ^{168}Dy, depending on the model employed. For example, Skyrme Hartree-Fock calculations of ground-state properties of dysprosium isotopes between $A = 160$ and $A = 170$ have been performed by *Rath et al.* [4]. The unique parity high-j orbits between neutron and proton, $\pi h_{11/2}$ and $\nu i_{13/2}$, are almost half filled, ^{170}Dy and all the nuclei around it are found to be well deformed and hence rich rotational band structures are expected. This calculation also indicates that the peak of collectivity occurs for $N < 104$.

From the experimental point of view, it is possible to infer which type of collective motion dominates in the mid-shell region via the inspection of the energy systematics of the low-lying levels and the transition probability of the first excited 2^+ state to the ground state. For the first case, the excitation-energy ratio $R_{42} = E(4_1^+)/E(2_1^+)$ is evaluated for all the relevant elements in the neutron-rich region and it is presented in Fig. 1 (top). In a pure vibrational picture this ratio would be expected to be 2 while in a pure rotational one it would be $10/3 \simeq 3.33$. A value of 2.5 represents a γ-soft nucleus [Wilets-Jean (W-J) or O(6) in the interacting boson model (IBM) representation] [11], while, a value of 2.67 is associated with an asymmetric rotor (Davydov-Filippov) with $\gamma = 30°$ [12, 13]. It is clear that for all the nuclei between $Z = 60$ and $Z = 70$, the ground state band exhibits a rotational structure when the number of neutrons approaches to the mid-shell ($N = 104$). Although not obvious for the naked eye, the R_{42} value never actually reaches 3.33 for any of the isotopes plotted in Fig. 1, with the ratio saturating near 3.32. This small, but non-negligible, deviation from the pure rigid rotor has been explained by the the confined β-soft (CBS) rotor model as a centrifugal stretching; *i.e.* the quadrupole deformation of the nucleus increases with increasing angular momentum due its soft potential, as opposed to a purely rigid rotor, where it would stay constant independently of J [14, 15]. The neutron-rich Dy isotopes near $N = 104$ are among the most rigid rotors (largest R_{42}) and thus would be a great test for the centrifugal stretching, even more stringent if different B(E2) can be measured along the g.s. band (see below).

The experimental $B(E2;\, 2_1^+ \to 0_1^+)$ [or $B(E2{\downarrow})$] of the Dy isotopic chain seem to point out that the maximum collectivity happens as early as ^{164}Dy ($N = 100$) [17], similarly to Er, maybe Gd and locally Yb isotopic chains (see Fig. 1 (bottom)). However, the most exotic $B(E2{\downarrow})$ measured up to now have significant error bars that prevent a meaningful comparison. Without a complete picture of the deformation evolution up to the mid-shell, it is not possible to confirm where is the maximum of collectivity in this region in general and for the Dy isotopes in particular.

The quadrupole deformation β_2 of the ground state of an even-even nucleus can be extracted from the transition strength to the first excited 2^+ state (assuming both have the same structure, as it is the case for Dy isotopes) of its rotational band, B(E2;$2_1^+ \to 0_1^+$), through the equation:

$$\beta_2 = \left(\frac{4\pi}{3ZR_0^2}\right)\sqrt{\frac{B(E2\downarrow)}{5}} \tag{1}$$

where Z is the number of protons and $R_0 = 1.2 \cdot A^{1/3}$ the nuclear radius. B(E2), in turn, depends on the transition energy, its electron conversion coefficient α and the mean lifetime $\tau(2_1^+)$:

$$B(E2\downarrow) = \frac{E_\gamma^{-5}}{\tau(1+\alpha)\cdot 1.225 \cdot 10^{13}} \tag{2}$$

Indeed, the nuclei in the neutron-rich $N = 104$ region present B(E2 $\downarrow$) $\sim$ 200 W.u., the largest transition strengths measured below ^{208}Pb. We, thus, propose to measure

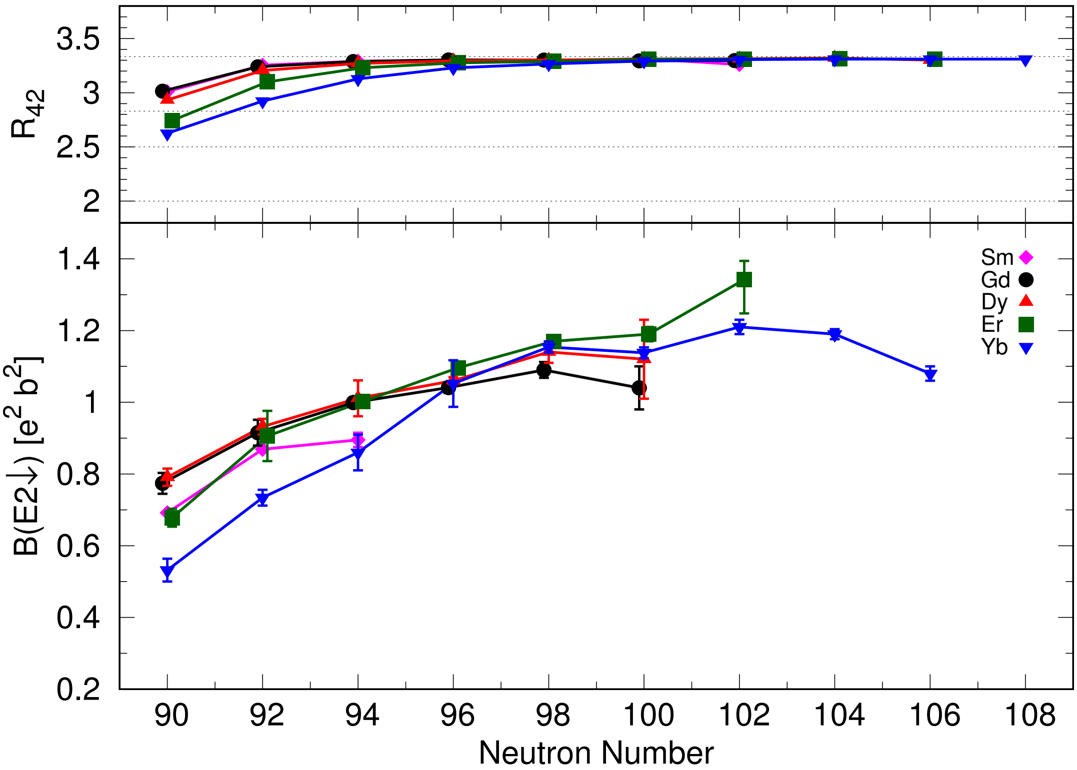

Figure 1: (Top) R_{42} and (Bottom) B(E2↓) systematics approaching the N = 104 mid-shell. Although the large error bars in B(E2↓) prevent from a rigorous comparison, the results seem to point out that the maximum collectivity is actually reached before the N = 104 mid-shell. Data points were extracted from NNDC [16] and Ref. [17] and references therein.

the lifetimes of the 2_1^+ states in the Dy isotopic chain to characterize the evolution of collectivity and deformation to clarify if its maximum appears at the $N = 104$ mid-shell or earlier.

Additionally, Casten *et al.* [18] suggested that nuclei around N = 104, specifically ^{170}Dy, are the best candidates to present pure SU(3) structures. The tentative identification of the γ-vibrational band in Ref. [19] in this nucleus, supports this theory. While measuring lifetimes in this band would be most interesting, it is uncertain if they will be in a range suitable for electronic fast timing (in the low tens of picoseconds). On the other hand, if the Tb beams are developed, additional complementary experiments can also be planned using the SPEDE detector to measure conversion electrons and $E0$ transition to firmly establish spin parity of the different states and, for example, identify the β bandhead [20]. Likewise, the IDS can be configured to perform angular correlations, one of the most powerful methods to firmly characterize nuclear structure.

2 Experimental Setup at IDS

β-decay fast-timing experiments have been performed at the ISOLDE Decay Station (IDS) employing a set-up that consists of a tape station equipped with a fast plastic scintillator close to the implantation point having almost 25% efficiency for β detection, coupled to a combination of four HPGe clover-type detectors and two $LaBr_3$ (Ce) detectors to register β-delayed γ-rays for the fast-timing measurement. This setup was successfully used in several experiments during Run2 (between 2014 and 2018) [21]. Beam transmission and beam production are the two main limitation factors for the investigation of the most exotic isotopes produced at ISOLDE. This limit for the particular case of fast-timing experiments varies between 10^2 to 1 ions/μC, depending on the amount of isobaric beam contamination. The ability of the IDS to extract physics results with very weak beams was demonstrated in a very similar experiment to what we propose here, in which lifetimes in the nanosecond range were measured with beam intensities as low as $\sim$ 1 ion/μC, see i.e. Ref. [22].

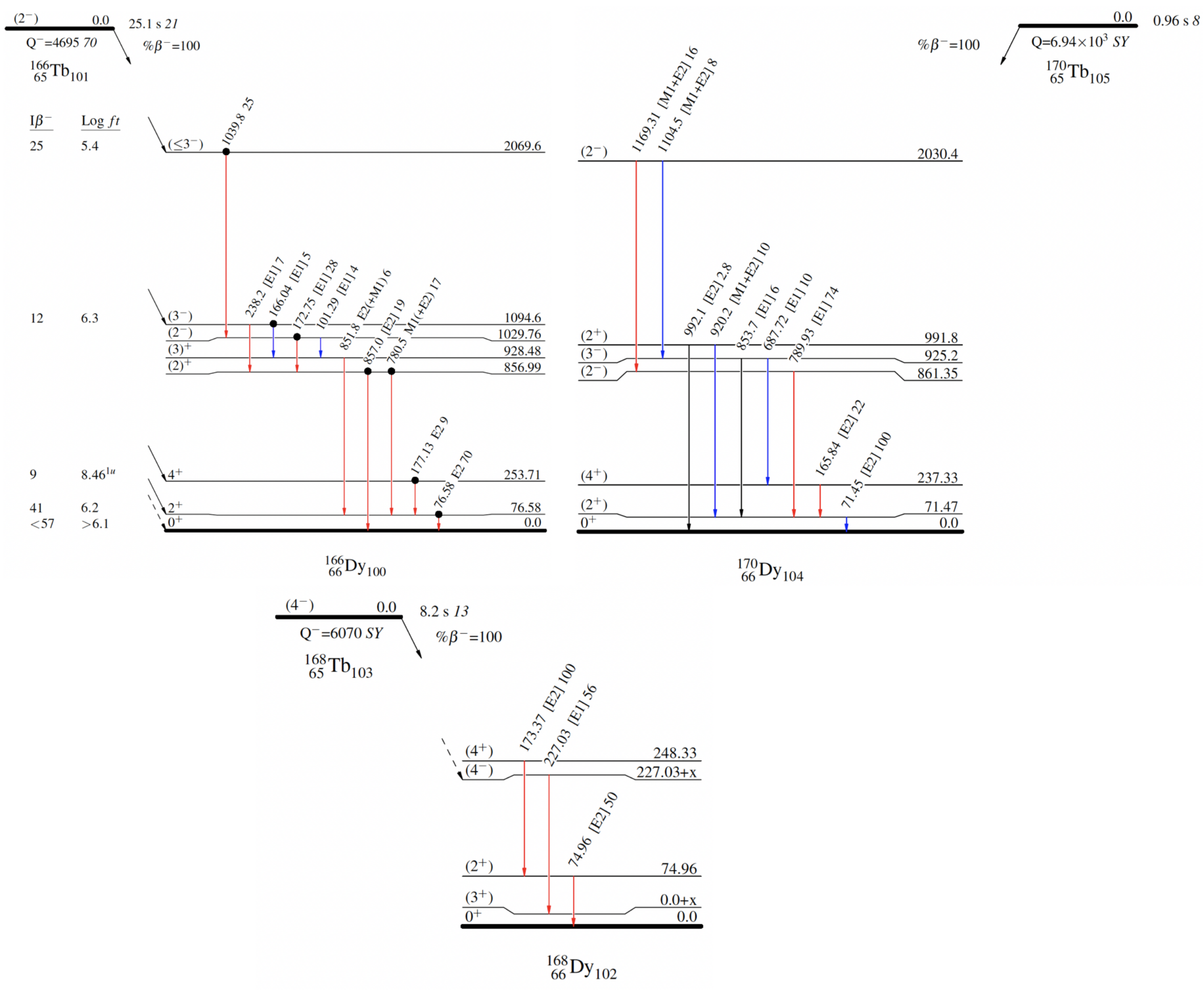

Figure 2: Level schemes of ^{166,168,170}Dy populated in β-decay. Figures taken from the NuDAT database from the NNDC [16].

For the highly converted $2_1^+ \rightarrow 0_1^+$ transition, the lifetime can be measured with different approaches. If sufficient beam intensity is achieved, the photons could be observed directly in the $LaBr_3$ crystals despite the loss of $\sim 90\%$ intensity to conversion electrons (see Ref. [19], for example). Should this not be the case, the $4_1^+ \rightarrow 2_1^+$ transition can be selected in $LaBr_3$, the conversion electron in the plastic scintillator and, optionally, the resulting x-ray in the HPGe array. Of course, a thin plastic scintillator does not have enough energy resolution to distinguish between β and conversion e^-. If the plastic is used as a START and the $2_1^+ \rightarrow 0_1^+$ transition in the $LaBr_3$ as the STOP, any long lifetime above or including the 4_1^+ state will appear as a delayed component in the timing spectrum. On the other hand, any half-life below the 4_1^+ state will show up as an antidelayed slope (the only way for this to happen is if the electron that STARTs the time difference is emitted after the $4_1^+ \rightarrow 2_1^+$ STOP transition; hence, the conversion electron from the $2_1^+ \rightarrow 0_1^+$ transition). Moreover, the expected $T_{1/2}(2_1^+)$ is in the few nanoseconds range, well above the FWHM$\sim$ 100 ps time resolution of the analog timing setup. Since no other lifetime is expected to be this long (see Fig. 2 or Ref. [17] for the specific case of ^{164}Dy) the (anti-)delayed component of the $4_1^+ \rightarrow 2_1^+$-e^- time difference can be unambiguously attributed to the 2_1^+ state.

3 Beam development

The ISOLDE online yield database mainly contains information on the neutron-deficient region of Tb isotopes produced with Ta foil targets and the SC [23]. Using these values it is possible to make a prediction for neutron-rich Tb beams with the same target, in this case around 10 ions/mu/C and 1 ion/mu/C could be expected for ^{166}Tb and ^{168}Tb, respectively [24]. Standard UC_x targets cannot be used due to Tb atoms forming carbides, which would greatly increase the release time, and therefore reduce the yield extraction. Release from oxide targets would be possible in molecular form, however this could create molecular contamination that are difficult to remove. Therefore metallic Th or U targets would be most appropriate for this region. To address the high degree of isobaric contamination expected in the region of interest, laser ionization using RILIS in combination with LIST could be used to suppress unwanted species [25]. The high temperatures required for Tb volatilization in target and transferline, however, pose a technical challenge for the LIST operation which should be addressed. A Tb laser ionization scheme is already available as indicated in the RILIS database [26] and it was recently tested at MEDICIS (ISOLDE) for the ^{155}Tb yield production [27]. The laser enhancement factor was measured for different ion-source temperatures, a laser-to-surface ratio from 15 down to 7 for the temperature range of 1400 °C to 2100 °C was obtained.

The yield measurements and determination of release curves can be done at IDS or in the ISOLDE tape station. However, the most neutron-rich Tb beams might be below the sensitivity of this kind of setups. For this reason we propose to complement this yield measurement using the MR-TOF MS at ISOLTRAP. With this device and always if the strong stable contaminants are below a 1000:1 ratio, we will be able to identify and evaluate the yields of the most exotic Tb isotopes produced at ISOLDE.

Summary of requested shifts: We request 6 shifts in total for the ^{164,166,168,170}Tb isotopes. 3 shifts to measure yields and release curves using the IDS/ISOLDE tape station and 3 shifts in order to determine the yields of the most neutron-rich Tb nuclei using MR-TOF MS.

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