EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

Proposal to the ISOLDE and Neutron Time-of-Flight Committee

Branching Ratios from a Triaxial Superdeformed “β-band” in ^{162}Yb

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Abstract

Relativistic Mean Field calculations predict that the 0_2^+ bands of Er and Yb isotopes around N=90 and 92 have a deformation of $\beta_2 \sim 0.45$ and $\gamma \sim 10°$. This is a rather fascinating prospect since the 0_2^+ bands, which are nominally β-vibrational bands, will have a similar deformation to bands at high-spin in this region, which have been identified as "triaxial superdeformed bands". The calculations are supported by the large observed moments-of-inertia of the "β-bands" in these nuclei. Coulomb excitation measurements combined with lifetime measurements using the Recoil Distance Doppler-Shift technique (RDDS) were proposed and approved (**INTC-P-708**) to give a measure of the deformation of these bands, including the triaxiality parameter γ. However, in order to obtain a measure of the deformation of the 4_β and 2_β levels, it is necessary to observe the $4_\beta \rightarrow 2_\beta$ and $2_\beta \rightarrow 0_\beta$ transitions and to know the relative strength of these transitions compared to the out-of-band transitions from the "β"-band to the ground band, as they will be too weak to be measured in Coulomb excitation. Here a β-decay measurement is proposed to observe the in-band transitions and give complementary information for **INTC-P-708.**

Requested shifts: 12 shifts
Beamline: IDS

Scientific Motivation

For many years, the 0_2^+ (or 0_β^+) bands of well-deformed nuclei were understood as "β-vibrations" following the seminal works of Bohr and Mottelson [Bo52, Bo53]. Nevertheless, it became clear that low-lying 0^+ bands could also arise due to other effects such as e.g. shape-coexistence [He11], and quadrupole pairing [Sh19]. Even the very existence of β-bands has been questioned some years ago [Ga01]. In nuclei with $R_{4/2} = E(4_1^+)/E(2_1^+) = 2.91$, such as those in the vicinity of N=90, there is also the opportunity to manifest the critical point symmetry X(5) [Ia01]. Here, we wish to explore the possibility that in the light Yb isotopes, in the N=90 region, the "β-band" could actually have a triaxial superdeformed (TSD) shape.

The proposal is motivated by our recent experimental results and calculations around N=90 [Ma19]. In Fig.1, the level energies of the so-called β- and γ-bands for the N=90, 92 nuclei ^{156}Dy and ^{160,162}Yb are presented, where the energies of a rigid rotor have been subtracted. The data are compared to calculations based on potential energy surfaces (PES's) calculated with the Relativistic Mean Field (RMF) and a 5-dimensional collective Hamiltonian (a modern version of the Bohr-Hamiltonian).

In both the experiment and theory, there is a striking difference in behavior of the 0_2^+ bands between ^{156}Dy and ^{160}Yb. In the former, the 0_2^+ band runs parallel to both the ground and γ-bands, while in the latter, the 0_2^+ band crosses the γ-band, as they have a larger moment-of-inertia than either the ground or γ-bands. Like ^{160}Yb, the 0_2^+ band of ^{162}Yb has a much higher moment-of-inertia than the ground band. These features can be explained by the RMF PES's (RMF+BCS with PC-PK1 density functional [Ma19]) shown in Fig. 2. In ^{156,158}Dy, a single prolate minimum is calculated near β=0.3, and as a result, two β-vibrational bands are predicted. The 0_2^+ and 0_3^+ bands are spaced equally to the spacing between ground band and 0_2^+ bands, as expected for a first and second β-vibrational band. However, in ^{160,162}Yb, a second, triaxial, highly-deformed minimum is visible in the PES at $(\beta,\gamma) \sim (0.45,10°)$ which is absent in the surfaces of the Dy isotopes. So, in the model, the 0_2^+ bands of ^{160,162}Yb are shape-coexisting TSD bands, while the 0_3^+ band is the band based on the first β-phonon. (These bands mix strongly below spin 4 in the calculations for ^{160}Yb). Interestingly, these TSD "β-bands" are predicted in a region where TSD bands have been reported at *high spin* e.g. in Lu isotopes [Sc95, Ød01] and in ^{160}Yb itself [Ag08]. Although lifetimes have been measured in the ground band in even-even nuclei in this region [e.g. Fe88, Mc06], the higher-spin members of the β- and γ-bands in the Yb isotopes have only recently been discovered, following measurements at iThemba LABS [Ma19, Md18]. No data on level lifetimes of yrare low-spin states and transition strengths from such states are known so far for the nuclei of interest, which hampers a clear interpretation of the structure of the β-bands and motivates this work.

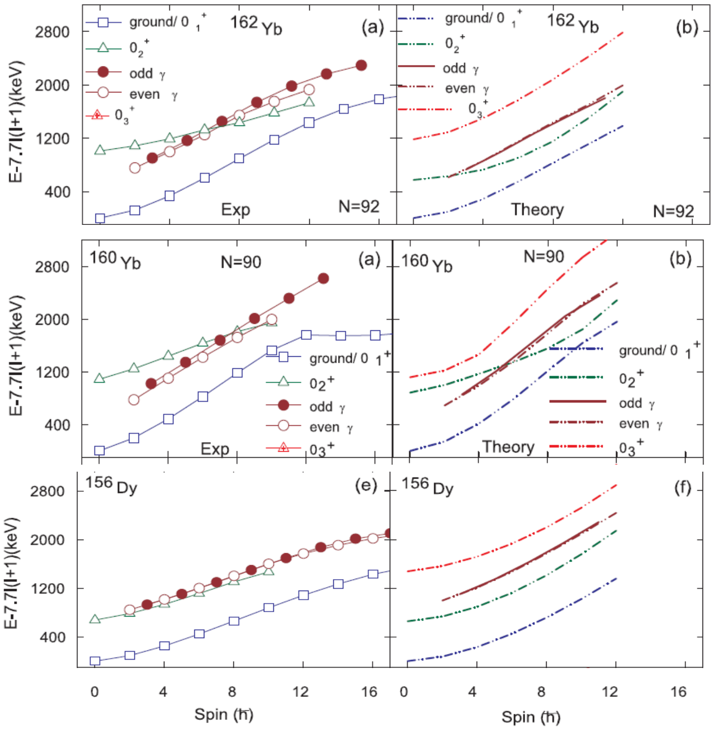

__Figure. 1__. Experimental ground, β- and γ-bands (left) compared with calculation (right) [Ma19].

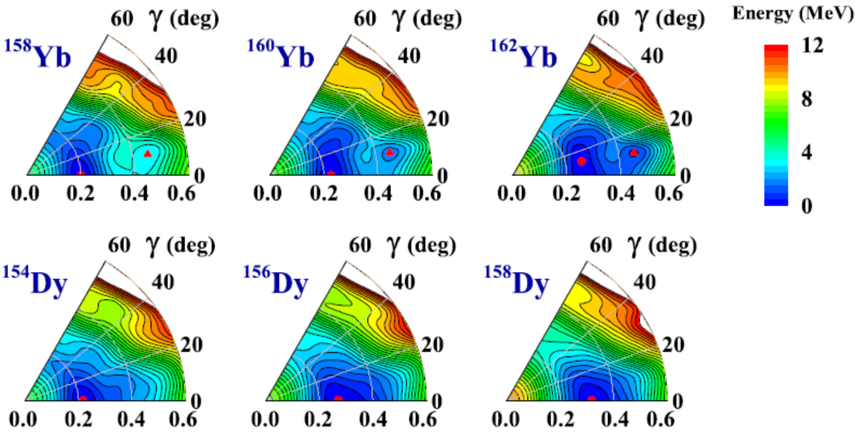

__Figure. 2.__ PES's of N=88, N=90 and N=92 Dy and Yb isotones in the β-γ-plane. Minima are marked with red symbols, circles and triangles represent the global and secondary minima, respectively. The energy spacing in the contour lines is 0.25 MeV [Ma19]. RMF PES around N=90 [Ma19].

Experiments

In **INTC-P-708**, two methods were proposed to obtain transition rates related to the "β"-band – an RDDS plunger measurement and Coulomb Excitation. Fifteen shifts of beam time were granted for these measurements. However, while much is known about the level scheme of ^{162}Yb [Mc04, Md18], the 213 keV $4_\beta \rightarrow 2_\beta$ and 124 keV $2_\beta \rightarrow 0_\beta$ γ-ray transitions, see Fig.3, have not been reported. The strength of these transitions (in the rotational model) is proportional to the square of the transition quadrupole moment, and are thus key to understanding the deformation associated with these states. These transitions are expected to be too weak to be observed in Coulomb excitation, likely due mainly to competition from the out-of-band transitions, (see Fig. 3), which are favoured by large $(E_\gamma)^5$ factors. For example, $(1130/124)^5 = 62847$. In fact, using the B(E2) values of [Ma19] one may calculate the branching ratios $P_\gamma(124)/\sum_i P_\gamma(i) = 5.3 \times 10^{-4}$ and $P_\gamma(213)/\sum_i P_\gamma(i) = 10^{-2}$, where $P_\gamma(i)$ is the transition probability of the *i*th γ-ray depopulating the 2^+ or 4^+ level. However, the B(E2) values of [Ma19] predict that the 963 keV transition be only 3% of the intensity of the 1130 keV transition, while the experimental [Mc04] ratio is 74%, see Table 1. Because of this large discrepancy between theory and experiment, it is not possible to predict the 124 keV intensity with any reliability. In order to observe these transitions, the 4_β and 2_β levels must be populated with high-statistics. Once the in-band to out-of-band branching ratios are known, the level lifetime, measured e.g. with the RDDS technique on the much stronger out-of-band transitions, will give the strength of the in-band transition.

A β-decay measurement from the decay of ^{162}Lu, which has a ground state with an 82s half-life, and isomers with 1.5 and 1.9 m half-lives, with the ISOLDE Decay Station (IDS) was also proposed to achieve the high-statistics required to observe the in-band transitions. However, the committee recommended that this part be treated as a letter of intent (LoI268), with two shifts allocated to test the yield of the ^{162}Lu beam.

With the results of one shift of LoI268 at hand, we now propose an IDS measurement.

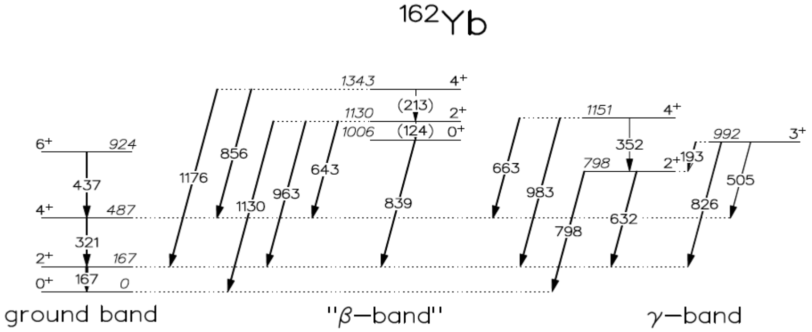

Figure. 3. *Close-up of the levels and related transitions of the ground, "β" and γ-bands of ^{162}Yb, as observed in β-decay [Mc04]. Transitions in parenthesis have not been observed.*

Table 1. Estimated γ-ray yields, assuming constant efficiency (7%) and 1 day of beam time, for transitions depopulating the β-band of ^{162}Yb. "Clean" transitions are highlighted.

Level	Transition	Eγ (keV)	Experimental γ-branching
0_β	$0_\beta \rightarrow 2_1$	839	100
2_β	$2_\beta \rightarrow 0_1$	1130	100
	$2_\beta \rightarrow 2_1$	963	74
	$2_\beta \rightarrow 4_1$	643	50
4_β	$4_\beta \rightarrow 2_1$	1176	100
	$4_\beta \rightarrow 2_\beta$		
	$4_\beta \rightarrow 4_1$	856	8

β-decay

The results of LoI 268 and LoI278

LoI268 ran together with LoI278, in which Lu and Tm yields were measured from a Ta + LIST target as a function of mass number. Tm yields were measured first, and are consistent with yields extrapolated from a 2023 measurement, see Fig. 4. Unfortunately, the tantalum target then suffered degradation, presumably due to over-heating. By the time the Lu yields were measured, the Tm yields had shown a reduction in yield by a factor of about ten. Under these conditions, the yield of ^{162}Lu was measured to be ~ 5 × 10^3/μC, implying that a yield of 5 × 10^4/μC could be possible with a fresh target. Notice that the latter value is a factor of 140 lower than the "good target" yield of ^{162}Tm, of 7 × 10^6/μC, see Fig. 4.

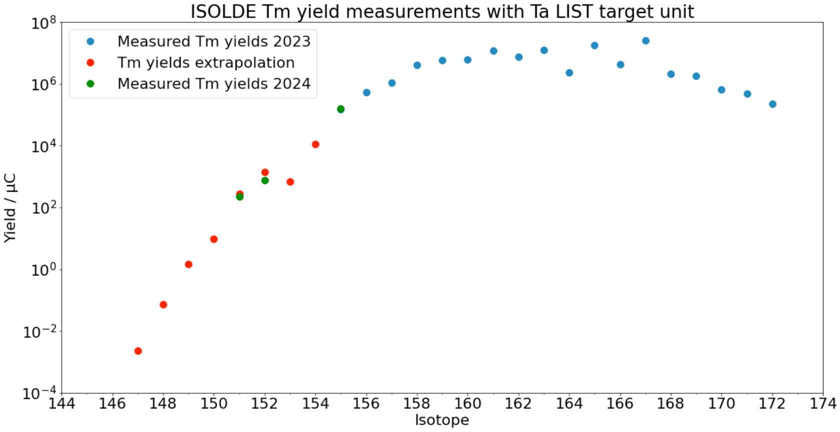

Figure. 4. *ISOLDE Tm yield measurements with Ta LIST target unit.*

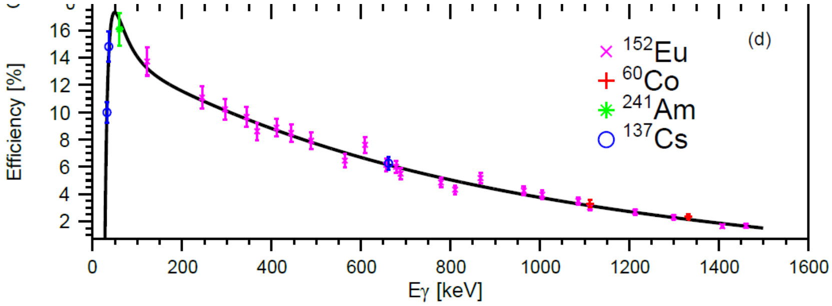

Figure. 5. *Absolute efficiency of the IDS with 3 clover detectors mounted 10cm from the implantation point on the tape, without add-back.*

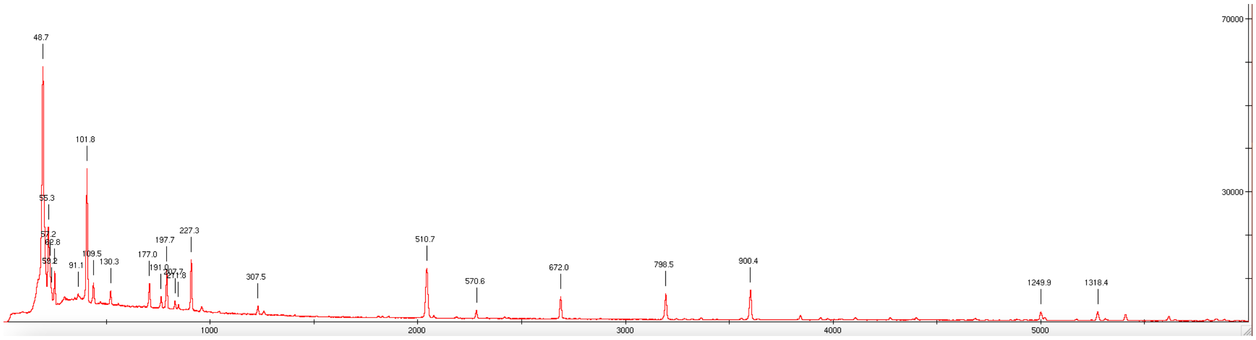

Figure. 6. *Singles spectrum of the decay of ^{162}Tm into ^{162}Er. The 102, 227, 672, 799, 900 and 1318 keV lines belong to ^{162}Er.*

Tm-162 and Lu-162 beams were then transported to the IDS, equipped at the time with 3 clover detectors and having an absolute efficiency as a function of energy as shown in Fig. 5. The γ-rays from the decay of ^{162}Tm into ^{162}Er, after 18 minutes of implantation, are shown in Fig. 6. There are already 250,000 counts in the 102 keV $2_g \rightarrow 0_g$ peak. By combining the counts in Fig. 6 with the efficiencies shown in Fig. 5, and the absolute decay intensities given in [NDS23], we conclude that the beam current entering the IDS was 5×10^3 pps/μA. For ^{162}Lu, only 4600 counts were recorded in the 166 keV $2_g \rightarrow 0_g$ peak after 37 minutes of implantation. In a previous study of the β-decay of ^{162}Lu into ^{162}Yb, [Mc04], the 1.4 x 10^{11} decays presented to the detectors of the Yale setup only produced 3.1 x 10^8 singles events. Allowing for the 1% efficiency of the Yale setup, it implies that only as much as 22% of the β-decays emitted γ-rays. With this correction, the relative intensities of [Mc04] and the absolute efficiencies shown above, we conclude that the ^{160}Lu beam current entering the IDS was about 45 pps/μA, or approximately 2 orders of magnitude less than the ^{162}Tm beam, and in line with the factor of 140 estimated above.

We conclude that a ^{162}Lu beam of 10^5 pps should be possible from a fresh Ta + LIST target with 2μA of protons.

Coincidence Measurements

The 124 and 213 keV transitions will be observed in the IDS in coincidence mode by gating on the 839 keV transition for the 124 keV transition, and the 1130, 963 and 643 lines, which can be summed, for the 213 keV transition. (The 167 gate will probably be associated with a higher background but can also be used.) If the beam is continuously implanted into the tape, eventually the decay rate will equal the implantation rate, or 10^5 Hz, when $t \gg \tau_{1/2}$. We propose to implant and count for 6 half-lives before moving the tape to limit the build-up of activity from the daughters.

We plan to populate the IDS with 12 clover detectors, at a maximum distance of 15 cm from the implantation point. We may then scale the efficiency curve shown in Fig.5 to give an efficiency of 21% at 166 keV and 9% at 1 MeV, (with a factor of 1.3 correction at 1 MeV in add-back mode). Assuming 9 shifts of beamtime at 10^5 pps, the relative intensities of [Mc04], and the branching ratios of [Ma19] we arrive at about 11000 coincidence counts for 213 keV peak and 2300 counts for the 124 keV line.

To set the condition to observe a line to e.g., 20% accuracy, we demand that the number of counts in the peak

$$N_\gamma > 5\sqrt{N_b}, \qquad (1)$$

where N_b is the number of counts in the background. The background was assessed by constructing a γ-γ matrix from the ^{162}Tm decay data recorded in LoI268. By gating on lines near 1 MeV, a backgound of ~ 2.5 counts/0.25 MeV was observed near 166 keV. With a simple scaling of statistics to 9 shifts at 10^5 pps, one finds that $5\sqrt{N_b} \sim 1200$ and that sufficient statistics should be available.

Summary of requested shifts: For the IDS measurement, we request 9 shifts of ^{162}Lu beam.

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Appendix

DESCRIPTION OF THE PROPOSED EXPERIMENT

The experimental setup comprises: *(name the fixed-ISOLDE installations, as well as flexible elements of the experiment)*

Part of the Choose an item.	Availability	Design and manufacturing
Beam Current Measurement after REX EBIS	Existing	To be used without any modification
Miniball + CD detector	Existing	To be used without any modification ☐ To be modified
	☐ New	☐ Standard equipment supplied by a manufacturer ☐ CERN/collaboration responsible for the design and/or manufacturing
IDS	X☐ Existing	X☐ To be used without any modification ☐ To be modified
	☐ New	☐ Standard equipment supplied by a manufacturer ☐ CERN/collaboration responsible for the design and/or manufacturing
[insert lines if needed]		

HAZARDS GENERATED BY THE EXPERIMENT

(if using fixed installation) Hazards named in the document relevant for the fixed [IDS] installation.

Additional hazards:

Hazards			
	[Part 1 of the experiment/equipment]	*[Part 2 of the experiment/equipment]*	*[Part 3 of the experiment/equipment]*
Thermodynamic and fluidic			
Pressure			
Vacuum	High Vacuum 10^{-6} mbar		
Temperature	LN$_2$ 77 [K]		
Heat transfer			
Thermal properties of materials			
Cryogenic fluid	LN$_2$, 1 Bar, 10l		
Electrical and electromagnetic			
Electricity	[voltage] [V], [current][A]		
Static electricity			
Magnetic field	[magnetic field] [T]		
Batteries	☐		
Capacitors	☐		
Ionizing radiation			
Target material	[material]		
Beam particle type (e, p, ions, etc)	^{162}Lu		
Beam intensity	1×10^5 pps		
Beam energy			

Cooling liquids	[liquid]		
Gases	[gas]		
Calibration sources:	☒		
- Open source	☐		
- Sealed source	☒ [ISO standard]		
- Isotope	^{152}Eu, ^{133}Ba, ^{60}Co		
- Activity	~ 10 kBq		
Use of activated material:			
- Description	☐		
- Dose rate on contact and in 10 cm distance	[dose][mSV]		
- Isotope			
- Activity			
Non-ionizing radiation			
Laser			
UV light			
Microwaves (300MHz-30 GHz)			
Radiofrequency (1-300MHz)			
Chemical			
Toxic	[chemical agent], [quantity]		
Harmful	[chemical agent], [quantity]		
CMR (carcinogens, mutagens and substances toxic to reproduction)	[chemical agent], [quantity]		
Corrosive	[chemical agent], [quantity]		
Irritant	[chemical agent], [quantity]		
Flammable	[chemical agent], [quantity]		
Oxidizing	[chemical agent], [quantity]		
Explosiveness	[chemical agent], [quantity]		
Asphyxiant	[chemical agent], [quantity]		
Dangerous for the environment	[chemical agent], [quantity]		
Mechanical			
Physical impact or mechanical energy (moving parts)	[location]		
Mechanical properties (Sharp, rough, slippery)	[location]		
Vibration	[location]		
Vehicles and Means of Transport	[location]		
Noise			
Frequency	[frequency],[Hz]		
Intensity			
Physical			
Confined spaces	[location]		
High workplaces	[location]		
Access to high workplaces	[location]		
Obstructions in passageways	[location]		
Manual handling	[location]		
Poor ergonomics	[location]		

0.1 Hazard identification

The longest lived activity from the’^{162}Lu decay chains has a half-life of approximately 1 day.

3.2 Average electrical power requirements (excluding fixed ISOLDE-installation mentioned above): *(make a rough estimate of the total power consumption of the additional equipment used in the experiment)*

None above fixed ISOLDE-installation for beam development. Plunger uses < 1kW.