EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

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

Search for tetrahedral states and X(5) symmetry in Yb nuclei with N~90 through Coulomb excitation using HIE-ISOLDE and Miniball

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Abstract

The ^{160}Yb nucleus (Z=70 and N=90) is double-magic with respect to the predicted Tetrahedral symmetry. Even if already studied in heavy-ion induced reactions, neutron spallation and β^+-decay, the non-yrast low-spin states and their properties are not well known. In particular it is not clear if a 3^- state exists in ^{160}Yb, which could be a tetrahedral state. We propose to study the properties of the low-spin states in the radioactive nuclei ^{160}Yb and its neighbors ^{156,158,162,164,166,168}Yb by Coulomb excitation using the HIE-ISOLDE facility and the Miniball array. The information acquired from the experiment will allow to investigate the low-spin properties of a series of nuclei in which the tetrehedral symmetry could manifest, but will also give important insights into the X(5) symmetry predicted for the N~90 nuclei, into the CBS (confined β-soft) rotor model which describes the transition between X(5) and the rigid rotor limit, and the existence of mixed symmetry states.

Requested shifts: 26 shifts
Beamline: *MINIBALL + CD-only*

1. Physics case

a) Tetrahedral symmetry

The ^{160}Yb nucleus (Z=70 and N=90) is double-magic with respect to the predicted Tetrahedral symmetry. Even if studied in heavy-ion induced reactions, neutron spallation reactions and β^{+}-decay, the properties of the low-spin states, crucial to establish the symmetry, are not yet well known. In particular, the spin and parity assignments to a low-lying 1255 keV state are contradicting: it is 3^{-} from the β^{+}-decay of ^{160}Lu and measurement of the conversion electrons [1] (see fig. 1), while it is 4^{+} from another β^{+}-decay study of ^{160}Lu [2] and from heavy-ion induced fusion-evaporation reactions [3] (see fig. 2).

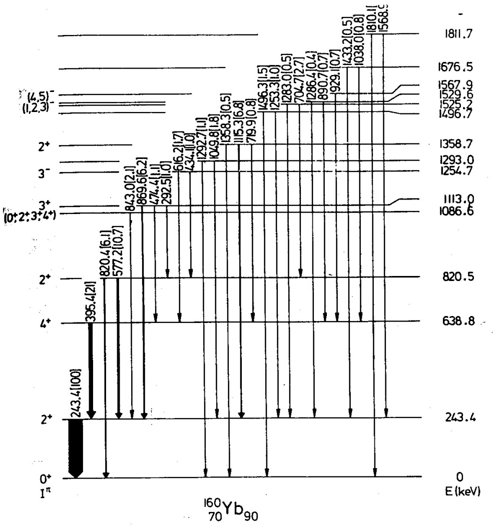

Fig.1. The level scheme of ^{160}Yb obtained from the β^{+}-decay of ^{160}Lu by Auer et al. [1].

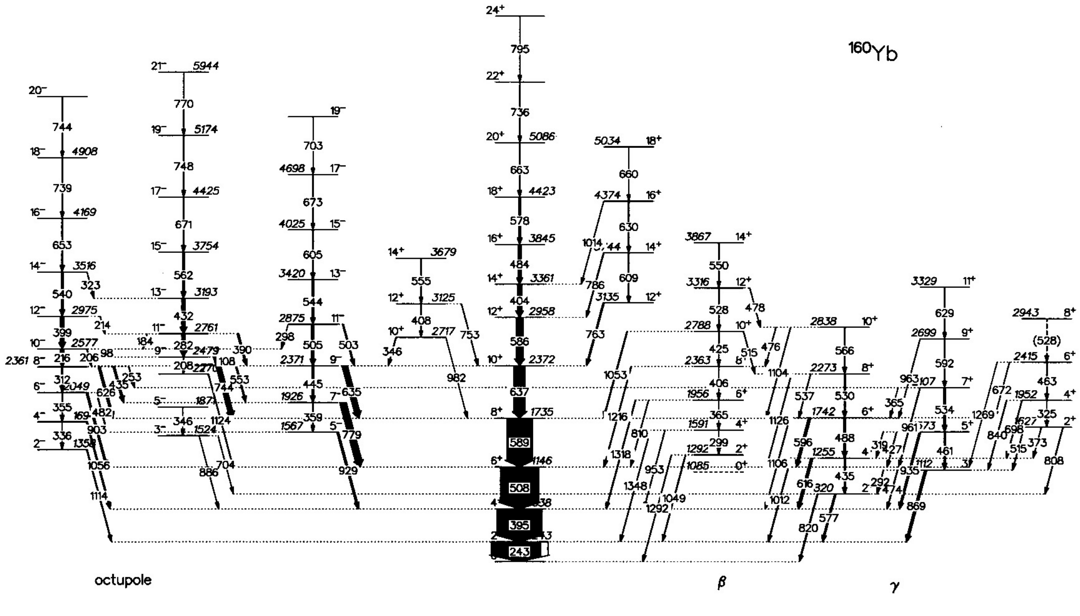

Fig.2. The level scheme of ^{160}Yb obtained from AFRODITE using the ^{147}Sm(^{16}O,3n) reaction [3].

The identification of the first 3^- and 5^- states and their decay towards the ground-state band is crucial for the discovery of the tetrahedral bands. Therefore, one would like to have another, independent mechanism to populate these states, the Coulomb excitation, which preferentially populates collective states. The 3^- states are normally non-yrast by ~1 MeV, and therefore one could question if they are efficiently populated in Coulomb excitation experiments. The answer is positive, as recently demonstrated in experiments of sub-barrier Coulomb excitation in inverse kinematics [4], in which the $3^- \rightarrow 2^+$ or the $3^- \rightarrow 4^+$ transitions of the stable Xe isotopes were seen at the level of 0.1% of the $2^+ \rightarrow 0^+$ transition.

To check if the populated negative-parity states are based on a tetrahedral shape, one should measure with good accuracy the "feeding" transition probability B(E3) up and the de-excitation transition probabilities B(E2) and B(E1) down towards states of the ground state band and other non-yrast non-collective states based on particle-hole excitations.

b) Critical point symmetry X(5)

Another good reason to study the ^{160}Yb nucleus and their neighbors is that in nuclei with N~90 the critical point symmetry, denoted by X(5) [6], is expected to be best realized. The X(5) symmetry describes the first-order shape-phase transition from a deformed axially symmetric rotor to a spherical harmonic vibrator. The energy ratio between the 4^+ and 2^+ levels of the ground state band of ^{160}Yb is 2.63, being in agreement with the X(5) prediction, but also with a shape transition from γ-soft to axially deformed [7]. One therefore needs others characteristic quantities, like the transition probabilities, to check if nuclei with good 4^+ to 2^+ energy ratio are X(5) nuclei. The lifetimes of the low-lying states in the ^{162}Yb nucleus have been recently measured [8], showing that some transitions agree with the X(5) symmetry and others are consistent with those of a deformed symmetric rotor. The measurements of the transition probabilities in a Coulomb excitation experiment will represent another independent set of data that could help to disentangle between the different theoretical descriptions. The lifetimes of the ground-state band in ^{160}Yb have been measured long time ago [9] and the results were interpreted within the cranked shell model as indication of an axially deformed nucleus.

The Coulomb excitation measurement will bring independent information on the transition probabilities not only in the ground-state band, but also in the γ-band and its connections to the ground-state band. It should be noted that the population of the non-yrast states of the γ-band is very weak, making difficult if not prohibitive to measure lifetimes using a fusion-evaporation reaction. On the contrary, the excitation of the γ-band through Coulomb excitation will selectively populate the low-spin states and will lead to much simpler spectra and implicitly to safer data. The safe Coulomb excitation data will be not affected by the unknown feeding times inherent to plunger measurements.

c) Mixed symmetry states

Another feature of the low-lying states that can be studied in Coulomb excitation is the structure of the mixed-symmetry states (MSS), which depends on the isovector quadrupole excitation in the valence shell. These nuclear structures have been modeled [10] in terms of proton-neutron MSSs in the framework of the interacting boson model (IBM-2) [11]. The IBM-2 represents an effective phenomenological model for collective excitations of the nuclear valence shell and describes the proton-neutron degree of freedom through the inclusion of N_π proton bosons and N_ν neutron bosons where N_π is taken as half the number of valence particles (or holes) of isospin *I*. The questions are at what energy do the MSSs occur in heavy nuclei and which are their properties? To answer these questions, valuable information can be obtained from a Coulomb excitation experiment using a radioactive beam of ^{160}Yb from HIE-ISOLDE.

Recently, a strong enhancement of the *F*-vector E1 transitions between octupole-phonon states and the 2^+_{ms} one-quadrupole-phonon states in four heavy nearly spherical nuclei has been found [12]. The E1 transitions to the 2^+_{ms} states are stronger than those to the 2^+_1 state by about one order of magnitude. This observation can be qualitatively interpreted as resulting from the dominantly F-vector character of the $3^- \rightarrow 2^+_{ms}$ transition, in contrast to the predominantly *F*-scalar $3^- \rightarrow 2^+_1$ transition. The inclusion of a quadrupole-octupole coupled two-body term in the effective E1 operator permits a consistent description of the quadrupole-octupole coupled E1 transition rates in nuclei. Understanding of the E1 transition matrix elements between low-energy states is necessary for the comprehension of the nuclear structure even at low excitation energies. It is therefore important to identify and investigate regular patterns that E1 transitions between low-lying nuclear states may exibit, and this can be accomplished only by using radioactive beams.

The situation is intriguing in ^{160}Yb, in which the $3^- \rightarrow 2^+_2$ transition is stronger than the $3^- \rightarrow 2^+_1$ transition [3], but in ref. [3] the 3^- state is instead assigned as the 4^+ state of the γ-band. The information concerning the 3^- state and its de-excitation is lacking completely also in the heavier ^{162}Yb and ^{164}Yb nuclei, in which no 3^- state was observed.

2. Experimental details

The nuclei of interest are studied with γ-spectroscopy following Coulomb excitation of the radioactive ions impinging on a target with similar A. Lighter targets give less excitation probability.

The set-up consists of the MINIBALL array to detect γ-rays and the CD detector in forward direction for particles. The CD detector is a double-sided segmented Si detector (DSSSD). It has four quadrants, each of them being segmented in 16 annular stripes (θ-coordinate) on the front and in 12 radial segments (φ-coordinate) on the back. The CD detector enables a determination of the reaction kinematics and an improved Doppler correction of the γ-rays. Depending on the scattering angle, either the scattered beam particle or the recoiling target nucleus is detected, but in some cases also both of them. Since they have nearly the same energies at the same angle, they cannot be distinguished by the kinematics. However, the cross section for Coulomb excitation is largest at small angles in the CM system. Therefore, the assignment of the detected nucleus or nuclei to projectile and/or target is done using the more probable alternative.

A major problem is created by isobaric contaminants in the beam. There are different methods to determine the purity of the beam, which were used in previous experiments :

- Downstream of the target the beam is stopped in the beam dump. Decays of implanted ions are detected by a Ge detector. If the lifetimes of the beam particles are smaller or comparable to the time of measurement, the contaminants can be identified by their decay (if they decay happens with emission of a gamma-ray). The longest $T_{1/2}$ of interest in this proposal is 28.58 h of ^{160}Er, all other isotopes, Tm and Ho have lifetimes below 10 min.
- A shutter in front of the laser of the RILIS, which will be used only for the Yb beam, can be closed every second supercycle of the PS Booster (“Laser ON/OFF"). Without the laser the isotope of interest is reduced in the beam and the counting rate decreases correspondingly. Additionally, the number of decays in the beam dump is reduced. The Coulomb excitation of the target is then mainly due to the contaminants in the beam which remain unaffected by the laser.

3. Proposed experiment

We propose to study the $^{156-168}$Yb nuclei, with special emphasis on ^{160}Yb predicted to be doubly magic with respect to the tetrahedral symmetry, but which also is, like other N~90 nuclei, a good candidate for the X(5) symmetry. In the same experiment it is expected to populate other non-yrast 2^+ states, which could be mixed-symmetry states. This radioactive beam with energy of around 5 MeV/u is only available at HIE-ISOLDE. If this experiment will be successful, we will be then in a position to study also other nuclei around N = 90, to investigate the variation of the properties of the non-yrast negative- and positive-parity states in the nuclei around the Yb nuclei.

4 Rate estimate and beam time request

The isotopes are produced with a standard UC_x/graphite target irradiated with the proton beam from the PS Booster. The proton beam current is assumed to be 2 μA. The yields of ^{160}Yb, the first element tested at the ISOLDE RILIS are taken from [13], which reports $2x10^7$ ions with a standard Ta foil target and W ionizer. These values will be reduced roughly by a factor of 3 for the converter target [14]. This factor is included in the rate estimate. Afterwards the ions are post-accelerated by the HIE-ISOLDE facility. The efficiency for such heavy beams should to be of the order of $5 \cdot 10^{-3}$.
The gamma yield is estimated from Coulomb excitation calculations. We included the first 2^+ and 4^+ states in the calculations. The values of the reduced transition strength B(E2) for the yrast sequences are calculated from the lifetimes available in NNDC. The B(E2) values for the side bands were calculated by assuming either that the B(E2; $2^+_2 \rightarrow 2^+_1$) is as strong as the B(E2; $2^+_1 \rightarrow 0^+_{gs}$) or that B(E2; $2^+_2 \rightarrow 0^+_{gs}$) is equal to the one measured for ^{168}Yb [14]. In addition to these assumptions the rest of the B(E2)'s for the side bands are deduced by the relative ratios given by Garrett et al. [2]. The assumptions adopted in the calculations of the positive-parity states are based on the existing experimental data on Yb isotopes, which are rather scarce:
1. there are no B(E2) values or lifetimes measured for any sideband level in ^{160}Yb nor in its close neighbors. The closest neighbor with measured values is ^{168}Yb.
2. ^{168}Yb is eight neutrons away from ^{160}Yb and thus it has a different structure (for example the first 2^+ state in ^{168}Yb is isomeric).
3. Garrett's numbers are questionable. The publication is old, the numbers are suspiciously close to his IBA-2 fit and he has assumed that all the transitions are E2.
4. Since there are no mixing ratios measured we also had to assume that all the transitions are exclusively E2's.
5. The transition strength ratio given by Garrett for the 1255 keV level of interest is even more questionable if the level is a 3^- since he has taken it as a 4^+.

For the negative-parity states the situation is also intricate. For the energy of the 3^- state we considered the 2 cases, one with 1255 keV energy and one with 1358 keV energy. For the B(E3;0->3) B(E3; $0^+ \rightarrow 3^-$) we took the values from the paper of Müller et al. [4] which describes the Coulomb excitation of the Xe isotopes. In particular, the B(E3) values for the Xe isotopes range from 2.1 to 14.3 W.u., so for each of the two energies of the 3^- state we did two calculations, one with the high B(E3) and one with the low one.

For the rest of the matrix elements we have absolute values for the yrast and relative values for the sidebands. We could not find any connection between the yrast and the sideband in order to find absolute values for the sideband, so we had to do an assumption and that was that the B(E2; $2^+_2 \rightarrow 0^+_{gs}$) is half of that of the B(E2; $2^+_1 \rightarrow 0^+_{gs}$). However since there is no connection between these sideband levels and the 3^- we don't think the cross section of the 3^- will be affected a lot.

We also did the calculation including the 5^- state at 1568 keV. For the transition $4^+ \rightarrow 5^-$ we took a value of 0.2 e*fm for the matrix element of the E1 transition, taken from the paper of Ibbotson et al. [15].

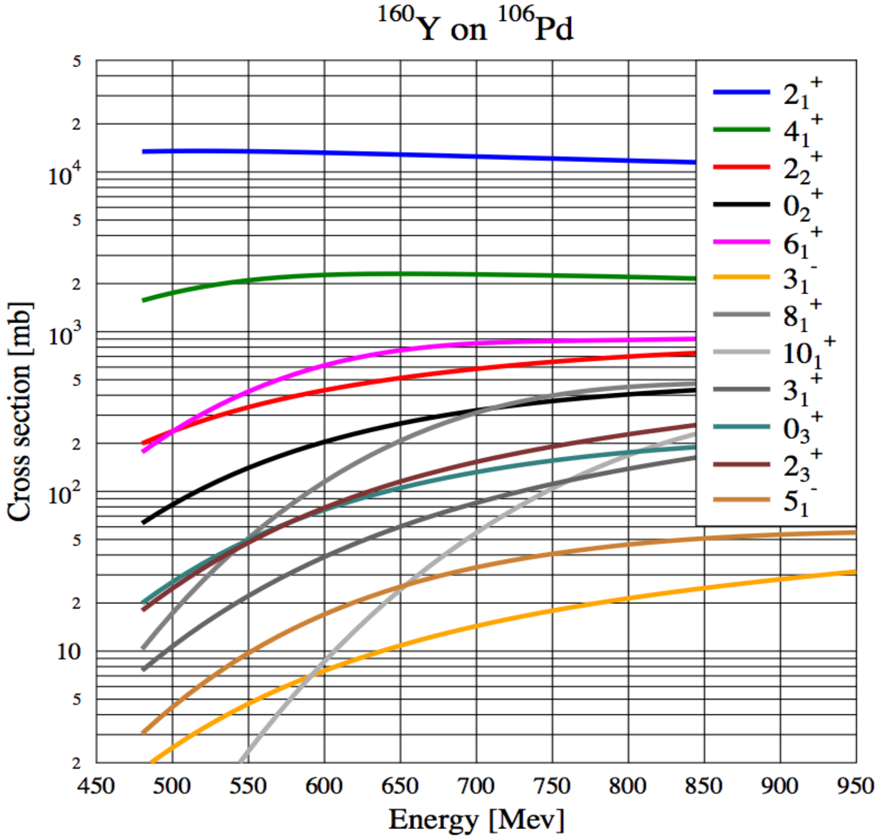

Fig.3. Coulomb excitation cross-sections calculated with GOSIA for the ^{160}Yb+^{106}Pd reaction.

As in other experiments, Pd targets of 2 mg/cm^2 thickness are assumed. The cross sections for Coulomb excitation of the 2^+ and 4^+ of ^{106}Pd are of the order of 5 b and 1 b, respectively, which will induce counting rates from the excited target nuclei in the same order of magnitude as from the beam. The appropriate Pd isotope will be chosen such that the γ-transitions from the target do not coincide with transitions from the beam. The intensity of the transitions from the target is used for normalization, since the B(E2)-values are well known. The single rate of the CD detector will be below 100 Hz in average.

As one can see in Fig. 3, a beam energy above 5 MeV/u would be desirable to get a reasonable high cross section for the population of the 3^- and 5^- states. An efficiency of 10% for MINIBALL in the range of interest and of 90% for the CD detector is assumed.

We are aiming at the determination of B(E2)-values within an error of around 10%. Therefore, we need at least 1000 counts in the γ-photopeak in coincidence with particles to have a statistical contribution to the total error of below 3%.

In the case of the IS411run the^{126}Cd nucleus, we collected approximately 100 counts within 6 hours of beam. Scaling for the^{160}Yb nucleus produced with intensity 10 times higher, we estimate around 1000 counts in 6 hours of beam.

We estimate that we need 1 day (3 shifts) to complete the investigation of this nucleus including “Laser ON/OFF" measurements.

Sufficient statistics can be obtained for the other isotopes ^{156,158,162,164,166,168}Yb with 3 shifts each, in total within 21 shifts.
Additionally, we ask for 3 shifts to prepare the beam and in total 6 shifts for changing between the seven Yb isotopes, all together 9 shifts.
We request in total 30 shifts (10 days) of beam time.

Summary of requested shifts:

Beam	Min. intensity	Target material	Ion source	Shifts
^{156}Yb	$3x10^7$	Pd	Ta	3
^{158}Yb	$9x10^8$	Pd	Ta	3
^{160}Yb	$4x10^9$	Pd	Ta	3
^{162}Yb	$6x10^9$	Pd	Ta	3
^{164}Yb	$1x10^{10}$	Pd	Ta	3
^{166}Yb	$2x10^9$	Pd	Ta	3
^{168}Yb	$2x10^9$	Pd	Ta	3

1. References

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Appendix 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
[MINIBALL + only CD, MINIBALL +T-REX]	☒Existing	☒To be used without any modification
[Part 1 of experiment/ equipment]	☐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
[Part 2 experiment/ equipment]	☐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
[insert lines if needed]		

Hazards generated by the experiment

(if using fixed installation) Hazards named in the document relevant for the fixed [MINIBALL + only CD, MINIBALL + T-REX] 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	[pressure][Bar], [volume][l]		
Vacuum			
Temperature	[temperature] [K]		
Heat transfer			
Thermal properties of materials			
Cryogenic fluid	[fluid], [pressure][Bar], [volume][l]		
Electrical and electromagnetic			
Electricity	[voltage] [V], [current][A]		
Static electricity			
Magnetic field	[magnetic field] [T]		
Batteries	☐		
Capacitors	☐		
Ionizing radiation			
Target material	Pd		
Beam particle type (e, p, ions, etc)	157-168Yb		
Beam intensity	10^7 -10^9pps		
Beam energy	5 MeV/A		
Cooling liquids	[liquid]		
Gases	[gas]		
Calibration sources:	☐		
[Open source	☐		
[Sealed source	☒[ISO standard]		

[Isotope			
[Activity			
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]		

3.1 Hazard identification

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)*

... kW