EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

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

Development of ^{160,162,164}Yb beams: Coulomb Excitation of Triaxial Superdeformed “β-bands” in light Yb isotopes

6 January 2021

R.A. Bark[1], C. Fransen[2], M. Beckers[2], D. Bucher[3], L. Gaffney[4], J. Gerl[5], K. Hadyńska-Klęk[6], H. Hess[2], R. Hirsch[2], E.Ince[7], J. Jolie[2], P. Jones[1], L. Kornwebel[2], T. Kröll[8], E. Lawrie[1], J.J. Lawrie[1], Z. P. Li[9], S. Majola[10], B.O. Mampaso[11], S.M. Mullins[1], C. Müller-Gatermann[12], P.J. Napiorkowski[6], S. Ntshangase[13], J. Pakarinen[14], L. Pellegri[1], P. Reiter[2], A.I. Sison[14] J. Srebrny[6], J.F. Sharpey-Schafer, F. von Spee[2], N. Warr[2], K. Wrzosek-Lipska[6], M. Wiedeking[1] and S.Q. Zhang[15]

[1] *iThemba Laboratory for Accelerator Based Sciences, Cape Town, South Africa*

[2] *Institut für Kernphysik, Universität zu Köln, Zülpicher Straße 77, D-50937 Köln, Germany*

[3] *University of the Western Cape, Cape Town, South Africa*

[4] *University of Liverpool, United Kingdom*

[5] *GSI, Helmholtzzentrum für Schwerionforschung GmbH, Darmstadt, Germany*

[6] *Heavy Ion Laboratory, University of Warsaw, Poland*

[7] *Istanbul University-Cerrahpasa Hasan Ali Yucel Education Faculty, Department of Science Education, Büyükçekmece, Istanbul, Turkey.*

[8] *Institut für Kernphysik Technische Universität Darmstadt, Germany*

[9] *School of Physical Science and Technology, Southwest University, Chongqing, 400715, China*

[10] *University of Johannesburg, Johannesburg, South Africa*

[11] *ISOLDE, CERN*

[12] *Argonne National Laboratory, 9700 S Cass Ave, Lemont, IL 60439, United States*

[13] *University of Zululand, Richards Bay, South Africa*

[14] *University of Jyväskylä, Department of Physics, Jyväskylä, Finland*

[15] *Key Laboratory of Nuclear Physics and Technology, School of Physics, Peking University, Beijing 100871, China*

Spokesperson: R.A. Bark (bark@tlabs.ac.za)
Local contacts: Bruno Mampaso (bruno.olaizola@cern.ch)
Thierry Stora (thierry.stora@cern.ch)

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 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, but Coulomb Excitation and Recoil Distance Doppler Shift techniques would give a direct measure of the deformation of these bands, including the triaxiality parameter γ. This Letter of Intent asks for the development of ^{160,162,164}Yb beams, to check the maximum achievable intensities, and beam contaminants, for Coulomb excitation and plunger measurements of the "β-bands".

Requested shifts: 6 shifts
Beamline: Beam Development for Miniball Experiment

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.

This Letter of Intent 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. The nuclide ^{162}Yb, with $R_{4/2} = 2.92$, is a candidate for X(5) symmetry, but as pointed by McCutchan *et al.* [Mc04, Mc06], the ground-band B(E2) values and the 2_2^+ to 0_2^+ level spacing deviate from X(5) predictions. However, the lack of data on the transition strengths from the 0_2^+ band precludes a clear interpretation in the framework of X(5) symmetry. 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). The heaviest Yb isotope in which the TSD β-band is predicted to occur is ^{164}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].

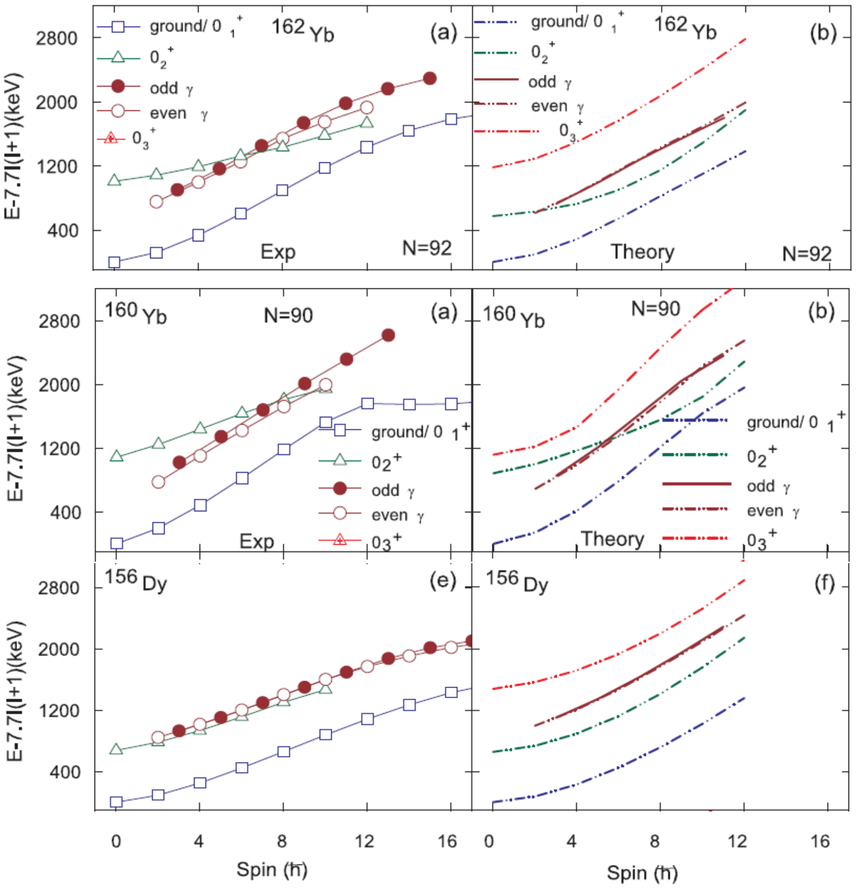

Figure. 1. *Experimental ground, β- and γ-bands (left) compared with calculation (right) [Ma19].*

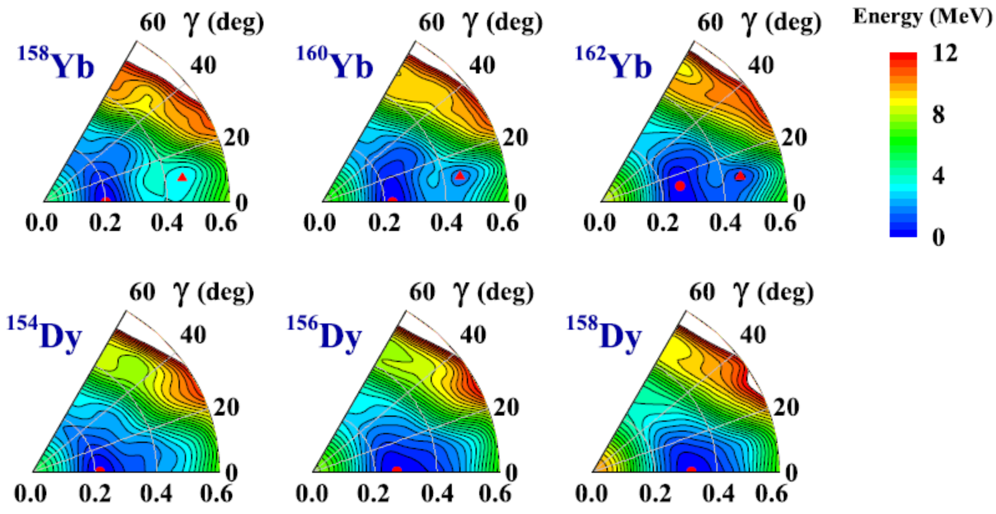

Figure. 2. *PES's of N=88, N=90 and N=92 Dy and Yb isotones in the beta-gamma β-γ-plane. Minima are marked with red symbols, circles and triangles represent the global and secondary minima, respectively. The energy spacing in the contour lines is 0.25 MeV [Ma19]. RMF PES around N=90 [Ma19].*

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 reported 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. A measurement on ^{162}Yb would simultaneously test X(5) predictions.

Therefore, in this LoI we apply for the development of the radioactive ^{160,162164}Yb beams to check (i) the maximum achievable intensity, and (ii) beam contaminants. In the following, we outline the experiments that we will propose, depending on the outcome of the beam development described in this LoI.

Experiments

A possibility to study low-spin states in the light Yb isotopes, which importantly has the advantage of measuring diagonal matrix elements and triaxiality, is Coulomb Excitation of radioactive Yb beams. Another technique, which can in principle be done simultaneously, is the Recoil Distance Doppler-Shift (RDDS) measurement of lifetimes. The latter requires a reaction in inverse kinematics. The RDDS measurement offers the advantage of an independent check on the Coulomb Excitation measurement that is insensitive to beam contamination or intensity and does not require absolute cross-sections or efficiencies. Fusion-evaporation reactions cannot be used to measure level lifetimes due to the high angular momentum transfer.

Depending on the yield, we would request time for a measurement to study the nuclear shape of one of ^{160,162,164}Yb in the Miniball array. The isotope ^{164}Yb may be expected to have the strongest RIB yield, but experimentally, little is known about the β-band above spin 2 [Si18]. More is known about the level scheme of ^{162}Yb [Mc04, Md18]; however, $4_\beta \rightarrow 2_\beta$ and $2_\beta \rightarrow 0_\beta$ γ-ray transitions have not been reported. The $2_\beta \rightarrow 0_\beta$ the γ-ray transition could be measured at the IDS (after the development of the beam). The level scheme of ^{160}Yb is the best known experimentally [Ma19]; only the $2_\beta \rightarrow 0_\beta$ γ-ray transition is yet to be observed, it could be measured either at iThemba LABS or the IDS. The level scheme of ^{160}Yb has the advantage that the crossing of the 0_β^+ band with the γ-band occurs at higher spin (~8) which reduces the complications due to mixing.

Coulomb Excitation

Transition matrix elements will be measured so that the quadrupole moment and the triaxiality parameter γ can then be deduced using Kumar-Cline sum rules [Cl86]. In Figure 3, integrated p-γ yields for the ^{92}Mo(^{160}Yb,^{160}Yb) and ^{92}Mo(^{162}Yb,^{162}Yb) reactions, as a function of spin, have been calculated using GOSIA, with the QQQ2 charged particle detector array (CD detector) subtending the forward angles between 18° and 52°, and assuming an energy-independent 7% γ-ray detection efficiency for the Miniball array. Molybdenum-92 has been chosen because it stretches well for the plunger measurement and has a first excited state at 1.5 MeV, which reduces target Coulomb Excitation. Matrix elements were derived from known lifetimes for the ground band [Mc06], and calculated [Ma19] B(E2) values for the 0_2^+ band. The calculated p-γ counts for members of the 0_2^+ band, (summed over all γ-decays per level), obtained for a beam of 10^6 pps on a 1 mg/cm^2 ^{92}Mo target, are up to 10^3 counts per level to the 6_2^+ state. The calculated and experimental branching ratios differ for decays from the β-band, so in Table 1, *experimental* branching ratios [Md18, Re07] are used to estimate p-γ yields for individual transitions depopulating the 0_2^+ band for both ^{160,162}Yb. Note that each level in the 0_2^+ band typically decays via a single strong transition, of energies around 1 MeV, where the spectra are relatively clean, having a low density of lines. Under this scenario, these would accumulate around 500 counts in 100 hrs of beam time.

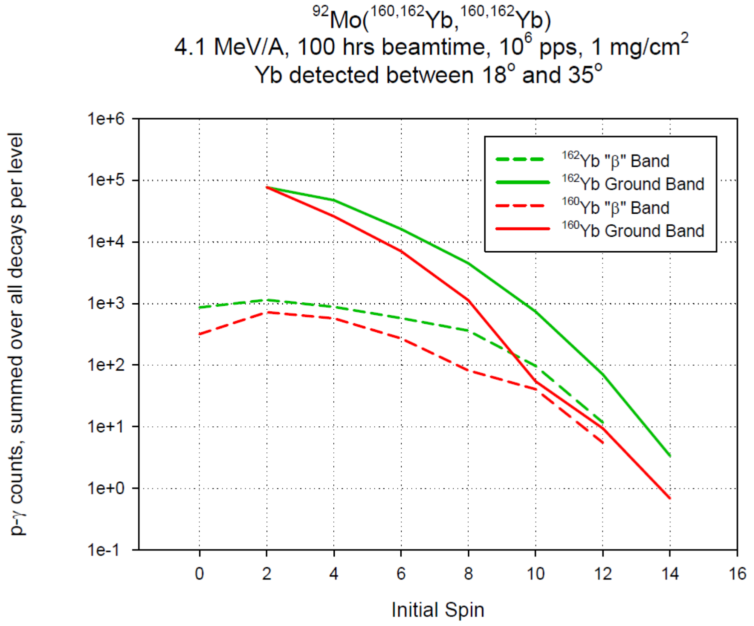

Figure. 3. *Integrated p-γ coincidence counts of a safe Coulomb Excitation measurement for the levels of the ground and 0_2^+ bands of ^{160,162}Yb. The detected particle is ^{160,162}Yb, which scatters to a maximum angle of 35°.*

Table 1. Estimated γ-ray yields, assuming constant efficiency and 100 hrs of beam time, for transitions depopulating the β-band of ^{160,162}Yb. Strongest transitions are highlighted.

		^{162}Yb			**^{160}Yb**		
Level	Transition	Eγ (keV)	Experimental γ-branching	p-γ yield 1 mg/cm^2 ^{92}Mo 1 ×10^6 pps	Eγ (keV)	Experimental γ-branching	p-γ yield 1 mg/cm^2 ^{92}Mo 1 ×10^6 pps
0_β	$0_\beta \to 2_1$	839	100	860	844	100	320
2_β	$2_\beta \to 0_1$	1130	100	510	1292	100	260
	$2_\beta \to 2_1$	963	74	380	1049	181	470
	$2_\beta \to 4_1$	643	50	260			
4_β	$4_\beta \to 2_1$	1176	100	820	1348	100	340
	$4_\beta \to 2_\beta$				298	15	50
	$4_\beta \to 4_1$	854	8	65	953	53	180
6_β	$6_\beta \to 4_1$	1160	100	345	1318	100	160
	$6_\beta \to 4_\beta$	304	68	235	365	35	55
	$6_\beta \to 6_1$				810	37	59

RDDS Measurements

As an example, we now focus on ^{162}Yb. Lifetimes of the lower states of the β-band, will be measured using RDDS, and the data will be analyzed with the differential decay curve method [De12]. We propose to employ the MINIBALL plunger device for this experiment including the CD particle detector array mounted downstream from the plunger degrader to allow for a reconstruction of the kinematics, and thus an event-by-event Doppler correction of the γ-rays of interest. The latter is crucial to achieve a good separation of the Doppler-shifted components from γ-ray emission between target and degrader, and after the degrader, respectively, in spite of the rather large scattering angle of the ^{162}Yb nuclei after the target, of up to 35°. The plunger device will be equipped with a 1.0 mg/cm^2 ^{92}Mo self-supporting, stretched target and a ^{nat}Mg degrader with a thickness of 2.5 mg/cm^2. This target - degrader combination is the best compromise to achieve a large cross section for Coulomb excitation of ^{162}Yb at the target and a predominant emission of the excited ^{162}Yb nuclei at forward angles relevant for the detection with the CD detector and the RDDS measurement. Further, the ^{nat}Mg degrader will lead to a low cross section for Coulomb excitation at the degrader (even though this contribution is not negligible and must be checked in a short target-only run). In addition, the ^{nat}Mg degrader will result in a small additional scattering of the ^{162}Yb nuclei with an average angle of about 5.8°.

We would like to stress that recoiling ^{92}Mo and ^{24}Mg nuclei can be clearly discriminated from ^{162}Yb with the CD detector. Detailed kinematics calculations yielded that for angles smaller than 33° with respect to the beam axis both energy and emission angle of ^{162}Yb and ^{92}Mo nuclei are sufficiently different to distinguish the respective events using the high granularity of the CD detector in 16 rings and 96 radial stripes.

For the minimum observation angle of the CD detector of 18° with respect to the beam axis, the ^{162}Yb nuclei have an energy after the target of $E_T = 3.00$ MeV/A and are slowed down in the degrader to $E_D = 1.61$ MeV/A. This corresponds to recoil velocities of $v_T = 24.0$ µm/ps and $v_T/c = 0.080$ after target and $v_D = 17.9$ µm/ps and $v_D/c = 0.060$ after the degrader. For the maximum usable scattering angle of ^{162}Yb of 33°, the respective energies are $E_T = 1.43$ MeV/A and $E_D = 0.31$ MeV/A corresponding to $v_T= 16.6$ µm/ps and $v_T/c = 0.0553$ after target and $v_D = 7.7$ µm/ps and $v_D/c = 0.0258$ after the degrader. As the levels of the 0_2^+ band decay mainly by transitions at energies around 1 MeV, the spectra are expected to be relatively clean. The Doppler shifts and broadenings for these γ-rays, as a function of Miniball detector/CD-detector element angles have been estimated and imply that degraded and undegraded components can be separated for about half the detector combinations.

The lifetimes of interest, in the 0_2^+ bands, are all expected to be about a picosecond, based on the calculated matrix elements [MA19]. Thus only a limited number of target - degrader distances of a few to a few tens of micrometres are needed for this measurement. The detection of about 500 counts per transition per distance should be sufficient to measure the lifetime to an accuracy of 10%.

RIB Intensities

The above discussion implies that beam intensities of several 10^6 pps of ^{160,162,164}Yb would be ideal. In consultation with Thierry Stora, initial estimates based on HRS Ta461 Ta roll, in 2011, implied a beam on target of less than 10^5 pps. It seems likely that the unit had a very low ionization efficiency from its W ionizer. Using ABRABLA to estimate in-target production, assuming RILIS to improve ionization efficiency, and the LIST trap for beam purification, the beam on target for ^{160}Yb is estimated with:

- an in-target production for 2µA, of 4.6×10^{10}pps (from ABRABLA computation)
- ×20% for diffusion limited release fraction (Beyer, NIMB 1977)
- ×10% for Laser ionization (RILIS DG)
- ×3% for losses due to LIST efficiency
- ×5% for overall HIE post acceleration efficiency

This gives 10^6pps on target, with 10^9pps rate at the low-energy side prior to purification. It is expected that isobaric impurities such as Dy will be present, as well as oxides. Since molecular beams will be produced, injection and break up should be tested in REXtrap and Rex EBIS.

Summary of requested shifts:

In summary, six shifts are requested for the development of ^{160,162,164}Yb beams. Known beam intensities will inform the development of a proposal to perform Coulomb Excitation and RDDS experiments of these isotopes.

References:

[Ag08] A. Aguillar et al., PR C **77**, 021302(R) (2008)
[Bo52] A. Bohr, Mat. Fys. Medd. Dan. Vid. Selsk. **26**, 14 (1952).
[Bo53] A. Bohr and B. R. Mottelson, Mat. Fys. Medd. Dan. Vid. Selsk. **27**, 16 (1953).
[Cl86] D. Cline Ann. Rev. Nucl. Part. Sci. **36** (1986) 683.
[De12] A. Dewald et al. Prog. Part. Nucl. Phys. **67** (2012), 786
[Fe88] M. P. Fewell et al., Phys. Rev. C **37**, 101 (1988).
[Ga01] P.E. Garrett, J. Phys. G: Nucl. Part. Phys. **27**, R1 (2001).
[He11] K. Heyde and J. L. Wood, Rev. Mod. Phys. **83**, 1467 (2011).
[Ia01] F. Iachello, Phys. Rev. Lett. **87**, 052502 (2001)
[Ma19] S. Majola et al., Physical Review C **100**, 044324 (2019)
[Mc04] E.A. McCutchan *et al.* Physical Review C **69**, 024308 (2004)
[Mc06] E.A. McCutchan *et al.* Physical Review C **73,** 034303 (2006)
[Md18] L. Mdletshe Eur. Phys. J. A (2018) **54**: 176
[Re07] C. W. Reich Nucl. Data Sheets **108**, 1807 (2007)
[Sc95] H. Schnack-Petersen et al., Nucl.Phys. A **594** (1995) 175
[Sh19] J.F. Sharpey-Schafer et al., European Physical Journal A (2019)55:15
[Si18] Balraj Singh and Jun Chen, Nucl. Data Sheets **147**, 1 (2018)
[Ød01] S. Ødegård et al., Phys. Rev. Lett. **86**, 5866 (2001).

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 + Miniball Plunger	☒ 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			
Vacuum	High Vacuum 10^{-6} mbar	High Vacuum 10^{-6} mbar	
Temperature	LN$_2$ 77 [K]	LN$_2$ 77 [K]	
Heat transfer			
Thermal properties of materials			
Cryogenic fluid	LN$_2$, 1 Bar, 10l	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)	^{160,162,164}Yb	^{160,162,164}Yb	
Beam intensity	test	> 10^{6} pps	
Beam energy		4MeV/A	

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 ^{160,162,164}Yb 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.