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

Coulomb excitation of doubly magic ^{132}Sn with MINIBALL at HIE-ISOLDE

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Abstract

We propose to study the vibrational first 2^+ and 3^- states of the doubly magic nucleus ^{132}Sn via Coulomb excitation using the HIE-ISOLDE facility coupled with the highly efficient MINIBALL array. The intense ^{132}Sn beam at ISOLDE, the high beam energy of HIE-ISOLDE, the high energy resolution and good efficiency of the MINIBALL provide a unique combination and favourable advantages to master this demanding measurement. Reliable $B(E2,0^+ \rightarrow 2^+)$ values for neutron deficient ^{106,108,110}Sn were obtained with the MINIBALL at REX-ISOLDE. These measurements can be extended up to and beyond the shell closure at the neutron-rich side with ^{132}Sn. The results on excited collective states in ^{132}Sn will provide crucial information on 2p-2h cross shell configurations which are expected to be dominated by a strong proton contribution. Predictions are made within various large scale shell model calculations and new mean field calculations within the framework of different approaches utilising the random phase approximation and the quasi-particle random phase approximation.

Requested shifts: 18 shifts
Beamline: MINIBALL + T-REX

Motivation

The chain of Sn isotopes is currently a subject of great experimental and theoretical interest. Especially around the two doubly magic nuclei ^{100}Sn and ^{132}Sn new advanced techniques and facilities using radioactive ion beams, allow to obtain new data which offer the opportunity to test theoretical models. In particular, it is important to study doubly magic nuclei like ^{132}Sn by different approaches. New and challenging shell model calculations are performed with the largest configuration space tractable in this mass region [1]. Latest large-scale shell model calculations for the tin isotopes $^{102-130}$Sn are based on a model space for neutrons consisting of the 1d5/2, 0g7/2, 1d3/2, 2s1/2, and 0h11/2 neutrons. Core-polarization effects require to include also the proton orbits 0g9/2, 0g7/2, 1d5/2, 1d3/2, and 2s1/2. At the moment the calculations reach the computational limit at 4p-4h proton core excitations. Another very important aspect is related to the long-standing problem of how accurate a description of nuclear structure properties can be provided by realistic shell-model interactions. In this case the derivation of the shell-model two-body matrix elements is coming from a realistic nucleon-nucleon interaction. This is considered a more fundamental approach to the nuclear shell model than the traditional one based on the use of empirical effective interactions containing several adjustable parameters.

As the Z=50 gap is almost constant and large over a wide mass range, proton excitations across it require large excitation energy. The first excited 2^+ levels of Sn have excitation energies of ~1.2 MeV and vary only smoothly along are the whole Sn chain between two doubly magic Sn nuclei. These 2^+ levels are likely almost pure neutron states. The small rise and fall of the state around N = 64 is caused by the presence of a weak sub shell closure. The constancy of the 2+ energies at each side of the sub shell closure confirms that pairing correlations dilute shell occupancies and generate 2^+ states of similar configurations. The drastic increase of the 2^+ state for the ^{132}Sn nucleus arises from the fact that both neutron and proton excitations across the Z = 50 and N = 82 shell gaps require large energies. Therefore the ^{132}Sn nucleus exhibits the characteristics of a doubly magic nucleus like a high energy for the first excited states and a weak transition probability B(E2). The first 2^+ state may not be of pure neutron origin anymore, but can contain proton excitations as well. Experimental 2^+ energies and B(E2) values are shown in Fig. 1 (taken from Ref. [2]) for the Sn isotopes. The data points for unstable nuclei are obtained from Coulomb excitation using radioactive ion beams [1–7].

For N > 64 the B(E2) value follows the parabolic trend of the generalized seniority scheme with the exception of ^{132}Sn. The wave function of the 2^+_1 states of tin isotopes is dominated by neutron excitations. However, at ^{132}Sn, both proton and neutron low-energy excitations are hindered due to the presence of shell gaps. Therefore the energy of the 2^+_1 state suddenly increases and its wave function has mixed components, both from neutron and proton, causing the local increase of the B(E2) value. Beyond the N = 82 shell closure, the neutron excitations dominate again. Indications for a small B(E2) value were measured in the ^{134}Sn nucleus [7]. The local increase of B(E2) at ^{132}Sn was predicted in Ref. [8] using the quasi-particle random phase approximation (QRPA) method.

The behaviour of the B(E2) values along the isotopic chain of Sn has been analyzed up to ^{130}Sn in the framework of large-scale shell-model calculations [1]. These calculations reproduce the experimental data on the neutron-rich side, whereas they significantly underestimate the data below N = 64 when compared to the measured data points in Fig. 1.

Also 3^- states are observed at 2.5 MeV excitation energy along the Sn isotopic chain. The large B(E3) values of ~10–20 W.u. indicate that these states are collective. In ^{132}Sn the 3^- state appears to be the second excited state at 4351 keV. The configuration of the 3^- states is given in terms of neutron excitations involving the negative-parity intruder $h_{11/2}$ orbit and the positive-parity $d_{5/2}$ and $g_{7/2}$ orbits. The proximity of several neutron orbits with $\Delta l = 2$ and $\Delta l = 3$ give rise to E2 and E3 collective excitations in Sn isotopes. As these modes occur at relatively low excitation energy the single-proton states above the Z = 50 shell closure can couple to them.

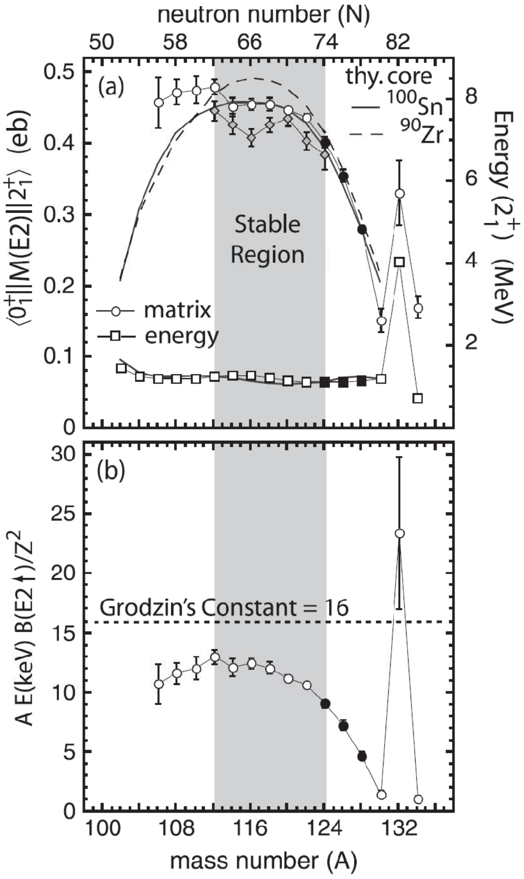

Fig. 1 *The 2^+_1 energy and E2 systematics for the Sn isotopes:*

(a) $E(2^+_1)$ and $<0^+_1 ||M(E2)|| 2^+_1>$ systematics, where the ^{100}Sn/^{90}Zr core theory curves (solid and dashed, respectively) are from recent shell-model calculations by Banu et al. [1].

(b) The Grodzins product is empirically known to be ~16 for open-shell nuclei. Black-filled points correspond to the study [2]; the white-filled (open) points are from the adopted [11] and recent literature [1-7] (i.e., weighted averages of experiments to date); the gray-filled diamonds are from a recent systematic study by Jungclaus et al. [17]. The figure is taken from Ref. [2])

Summary of theoretical investigations

First predictions for neutron-rich nuclei in the vicinity of ^{132}Sn were made employing a separable quadrupole-plus-pairing Hamiltonian and the quasi-particle random phase approximation (QRPA) [8]. Excitation energies, $B(E2,0^+_1\rightarrow2^+_1)$ strengths, and g factors for the lowest 2_1 states near ^{132}Sn (Z>50) were calculated. In this article the local maximum of the $B(E2,0^+_1\rightarrow2^+_1)$ values at N=82 and a symmetric behaviour with respect to the N=80 and N=84 neighbour was predicted. Results from this work are shown in Fig. 3.

Mean field calculations of the isovector dipole and low-lying 2^+, 3^- excitations were performed by Colo, Bortignon and co-workers [9] within the Skyrme-RPA and QRPA framework. The chain of Sn isotopes was chosen as an example among the neutron-rich nuclei of interest for present nuclear structure research. The QRPA calculations yielded the 2^+ and 3^- excitations in the Sn isotopic chain. The energy of the 2+ is reasonably well reproduced along the isotopic chain, especially the constancy between ^{120}Sn and ^{130}Sn and the changes occurring around the shell closure. However the B(E2) values are systematically underestimated in the open-shell isotopes. At the N=82 shell closure the B(E2) values are closer to the preliminary experimental results (see Fig. 3) This problem is much less severe as far as the B(E3) is concerned.

A relativistic QRPA approach has been applied for the calculation of E2 and B(E2) in spherical Sn nuclei employing a global parameter set (NL3) for the Lagrangian along with Gogny's pairing interaction (D1S) [10]. The excitation energies of the lowest 2^+ states and the B(E2) decay rates are quite well reproduced for a long isotopic chain of Sn. At A = 132 the B(E2) value shows an enhancement compared to the neighbouring isotopes. The following values are given for the $E(2^+)$ (MeV) = 1.70, 3.72, 1.03 and $B(E2)(e^2b^2)\uparrow$=0.062,0.089,0.033 for A=130,132 and 134, respectively.

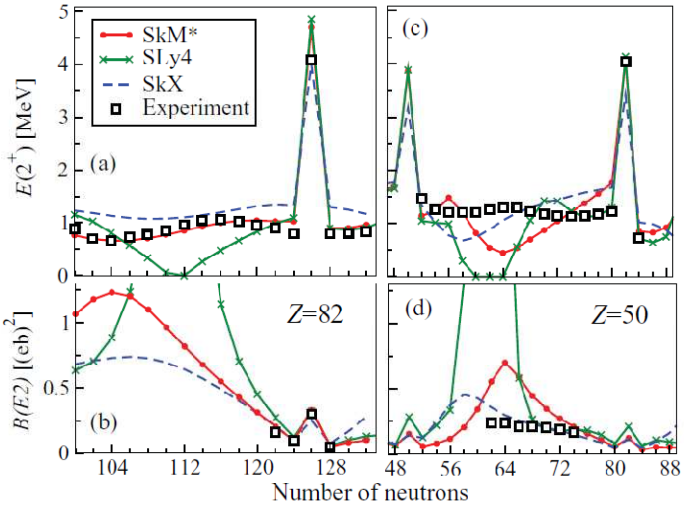

Fig. 2: *Excitation energies and reduced transition probabilities B(E2; $0^+ \rightarrow 2^+_1$) for Pb and Sn isotopes. Results are shown for three different Skyrme parameterizations. The experimental values are taken from Ref. [11]. The figure is taken from Ref. [12].*

An iterative method based on the QRPA was developed by [12] and gives substantial advantages over conventional QRPA calculations. The method is used to calculate excitation energies and decay rates of the lowest-lying 2^+ and 3^- states in Pb, Sn, Ni, and Ca isotopes using three different Skyrme interactions and a separable Gaussian pairing force. Results for the Sn chain are shown in the right-hand panels of Fig. 2. For the two doubly magic Sn isotopes, the excited states are calculated to be a roughly even mixture of proton and neutron excitations, while the excited states in the semi magic isotopes mainly involve neutron excitations. With SkX, the largest components are $\nu(d5/2)^2$ for ^{102,104}Sn, $\nu(g7/2)^2$ for $^{106,..114}$Sn Sn, and $\nu(h11/2)^2$ for $^{116,..130}$Sn.

Status of previous experiments

At the Holifield Radioactive Ion Beam Facility (HRIBF) at ORNL first measurements of the B(E2; $0^+ \rightarrow 2^+$) values for a number of nuclei in the vicinity of the N = 82 shell closures were performed [2,7,13,14,15]. An experiment was optimized to determine the transition probabilities of the first excited 2^+ state in ^{132}Sn and ^{134}Sn. The large excitation energy (4.04 MeV) of the 2^+ state in ^{132}Sn and small excitation cross-section, together with the available beam intensity made the experiment very challenging. To cope with the low γ-ray count rate an efficient BaF_2 array was employed for this measurement and not the CLARION Ge spectrometer. The results of the Coulomb excitation experiment were reported in three different conference proceedings contributions [7,14,15].

The most detailed report on the ^{132}Sn experiment is given in Ref. [15]. Only in this report a spectrum from the BaF_2 spectrometer is shown. The authors made aware that: ‘This preliminary analysis does not yet include a complete experimental calibration of the photon detector efficiency.’[15]. From this work the result for the B(E2;$0^+ \rightarrow 2^+_1$) value in ^{132}Sn is given to be 0.11±0.03 e^2b^2 (see also Fig. 3).

The ^{132}Sn experiment was performed using 470 MeV and 495 MeV ^{132}Sn ions incident on a 1.3 mg/cm^2 ^{48}Ti target. Scattered ^{132}Sn ions and target recoils were detected in a 7 cm diameter annular (CD-style) double sided Si-strip detector. Gamma rays were detected in an array of 150 BaF_2 crystals arranged in six blocks mounted in close proximity to the target. A total trigger efficiency of 55% and a full-energy efficiency of 30% were achieved for 4-MeV gamma-rays. Using the yield shown in Fig. 3, the value of B(E2;$0^+ \rightarrow 2^+_1$)=0.11(3) e^2b^2 amounts to almost 13% of the isoscalar quadrupole energy weighted sum rule. This is similar to the fraction of the quadrupole sum rule strength exhausted by the ^{208}Pb 2^+ state, which is 14%.

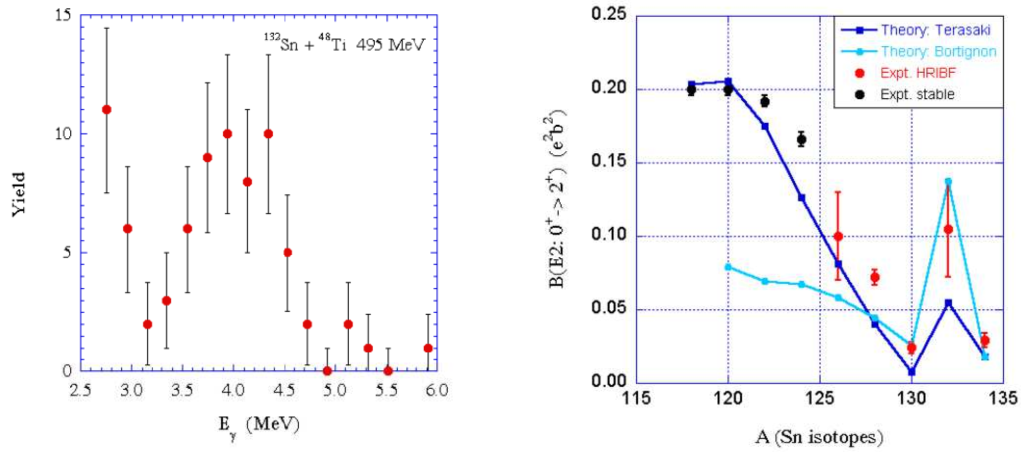

Fig. 3: *Yield of photons around 4 MeV in ^{132}Sn Coulomb excitation (left side). Dependence of B(E2; $0^+ \rightarrow 2^+_1$) on A for Sn isotopes. The dark blue curve is the calculation of Terasaki [8], the light curve is from Colo [9] (right side). The two Figures are taken from Ref. [15].*

Coulomb excitation of ^{132}Sn with MINIBALL at HIE-ISOLDE

Coulomb excitation of the first excited 2^+ and 3^- state in ^{132}Sn is proposed. High beam intensities and purities for radioactive tin ions are based on newly developed molecular SnS beams. Beam intensities of ^{132}Sn of more than 3.0E+07 ions/μC were extracted from ISOLDE targets. Beam energy of 5.5 MeV/u will be provided by the HIE-ISOLDE accelerator. This will allow employing a high Z ^{206}Pb target for Coulomb excitation and a high excitation cross section can be exploited for pure electromagnetic excitation at a distance of closest approach well above the criterion for 'safe' Coulex. The scattered ^{132}Sn can be clearly separated from the recoiling target nuclei under forward angles with position sensitive double sided Silicon detectors. The beam energy will also allow using thicker targets in order to enhance the count rates of the interesting events. The γ-rays from ^{132}Sn with transition energies of more than 4 MeV will be recorded with the MINIBALL spectrometer providing very good energy resolution of HPGe detectors. The eight MINIBALL cluster detectors each comprise three individual large volume HPGe detectors in one composite detector which is very advantageous for detection of high energetic γ–rays.

Experimental setup and count rate estimate

The high γ-ray energies of the two direct ground state transitions in ^{132}Sn of 4041keV for the $2^+_1 \rightarrow 0^+$ transition and 4352 keV for the $3^-_1 \rightarrow 0^+$ transition require a careful efficiency calibration of the MINIBALL array. This was done during the experiment IS430 where high energy γ-rays from 2124.4 keV up to 7974.7 keV from excited states in ^{11}B populated after ^{11}Be β-decay were measured with MINIBALL. The detection efficiency for the 4443.90 keV transition was reduced by a factor of 0.33 compared with the 1.3 MeV ^{60}Co line. For the count rate estimate we use 3% photo peak efficiency with add-back for energy deposition in neighboring Ge crystals.

In addition to the MINIBALL array the charged particle detectors (DSSSD) of the T-REX configuration will be employed with a CD-type detector and barrel detectors positioned under forward direction. The detector thickness of 500 μm allows stopping completely the scattered ions. The DSSSD*s* are highly segmented to allow for a kinematics reconstruction of the events and covers an angular range from 15° to 77°. Solid angle coverage of 30% is used for the count rate estimate [18].

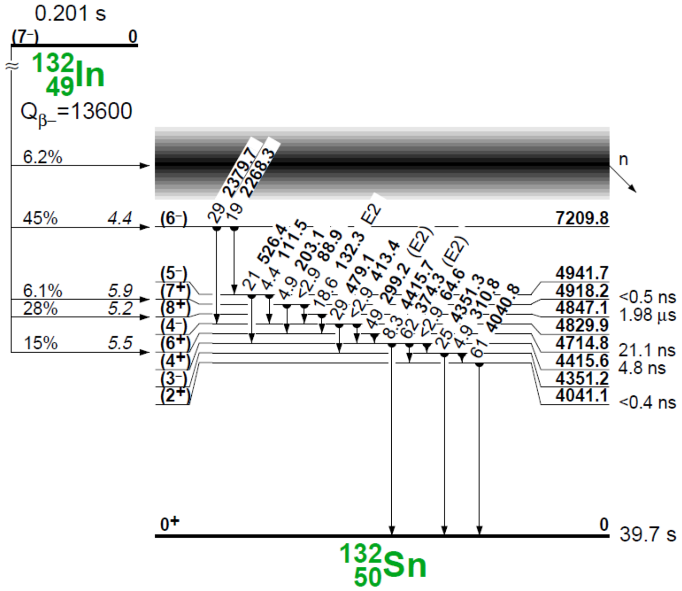

Fig. 4 *Level scheme of ^{132}Sn.*

The proposed MINIBALL experiments with an unstable beam of ^{132}Sn isotopes from HIE-ISOLDE are from the ISOLDE point of view comparable with previous successful experiments employing ^{106,108,110}Sn beams or experiments with neutron rich Cd beams. The ISOLDE yield values given for the ^{132}Sn isotopes are 3 x 10^7 ions/µC. The half live of $T_{1/2}$=39.7 s makes ^{132}Sn a favourable beam produced via a SnS^+ molecular ion (see Fig. 5 from Ref. [16]). The accelerator efficiency for the complete HIE-ISOLDE chain from REX-trap to the MININBALL target was estimated to be only 2%. A beam intensity of ^{132}Sn at the secondary target inside the MINIBALL of I(^{132}Sn)= 8.5 x 10^5 ions/s can be expected with a PSB proton beam current of 1.4 µA.

Coulomb excitation will be done at 'safe' energies of 5.5 MeV/u below the Coulomb barrier of a ^{206}Pb target. A distance of closest approach of 39.6 fm is calculated for the incoming ^{132}Sn ions hitting ^{206}Pb target nuclei with energy of 5.5 MeV/u at an angle of 77° in the laboratory. The 'safe' Coulex criterion requires distances of $d > R_p + R_t + 5$ fm = 18.8 fm.

The target thickness can be chosen very thick with 5.0 mg/cm^2 at this high beam energy. All stable Pt, Au and Pb isotopes were considered as target nuclei. Data from previous Coulomb excitation measurements with these nuclei made ^{206}Pb the most favourable choice as a target. Especially overlap with the $3_1^- \rightarrow 2_1^+$ transition at 311 keV and the $4_1^+ \rightarrow 2_1^+$ transition at 375 keV have to be avoided. Energy differences between the kinetic energy of scattered beam and target nuclei are calculated including energy losses of beam and target nuclei inside the target, the target thickness as a function of scattering angle. The centre of the projectile distribution is 540 MeV at 20° scattering angle and separated by 70 MeV from the target recoil energies at 470 MeV. At 70° detection angle with respect to the beam axis the two distributions are separated by 120 MeV.

The most relevant improvements of the proposed measurement with respect to the previous results obtained with the BaF_2 array at ORNL are: (i) the high energy resolution of the MINIBALL HPGe detectors, (ii) the large energy range for γ-ray detection, which is going down in a reliable and controlled way to a lower threshold of 50 keV and the (iii) good efficiency of the 8 triple cluster detectors of MINIBALL at 4 MeV.

Primary ISOLDE yield (ions/s) ^{132}Sn	beam intensity at MINIBALL (ions/s)	Transition/ energy	Transition/ strength	Integr. Coulex cross-section (mbarn)	Events in photo peak Count rate	
	^{132}Sn				Cts/h	Cts/120h
3×10^{7}	8×10^{5}	$0_1^+ \rightarrow 2_1^+$ 4041 keV	$B(E2,2_1^+ \rightarrow 0^+)$ 7(3) W.u. [7,15]	$\sigma(2_1^+)$ 13 mb	17	2040
3×10^{7}	8×10^{5}	$0_1^+ \rightarrow 3_1^-$ 4352 keV	$B(E3,3_1^- \rightarrow 0^+)$ >7.1 W.u. [11]	$\sigma(3_1^-)$ 1.7 mb	2	240
			$B(E1,3_1^- \rightarrow 2^+)$ >0.00017 W.u. [11]		1	120
3×10^{7}	8×10^{5}	$0_1^+ \rightarrow 4_1^+$ 4416 keV	$B(E2,4_1^+ \rightarrow 2_1^+)$ 0.4 W.u. [11]	$\sigma(4_1^+)$ 0.1 mb	0.5	60

***Table 1**: Rate estimates and beam time request.*

The cross sections for the excitation of the 2_1^+, 3_1^-, 4_1^+ states in ^{132}Sn were calculated with the Coulomb excitation code CLX. A beam energy value of 5.5 MeV/u was used. The cross section for projectile excitation was integrated for particle detection in the solid angle range in the CM system of $\Delta\theta_{CM}$=25°-115°. These angles are covered by the DSSSD detectors in the laboratory frame by $\Delta\theta_{Lab}$=15°-77°. For γ-ray detection the measured energy dependent γ-efficiency was included. Effects of the γ-ray angular distribution were neglected in the estimate. As target material ^{206}Pb was used with a thickness of 5.0 mg/cm^2.

For a reliable energy and efficiency calibration at high γ-ray energies two options are feasible at ISOLDE. Like for the experiment IS430 the β-decay of ^{11}Be ($T_{1/2}$=13.81 s) can be used for this purpose. A second option is given by a ^{66}Ga sample which can be produced with high yields (> 10^8 ions/μC) at ISOLDE directly after the production target.

Summary of requested shifts:

In conclusion, we request 5 days or 15x8 hours shifts of beam time for a Coulomb excitation measurement of the doubly magic tin isotope ^{132}Sn. The measurement has to be combined with a γ–ray calibration measurement covering the energy range up to 4.5 MeV. For the high energy γ-calibration and the HIE-ISOLDE set-up three additional shifts are needed. In total 18 shifts are requested for this proposal.

Requested shifts: 18 shifts
Beamline: MINIBALL + T-REX

References:

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Appendix

DESCRIPTION OF THE PROPOSED EXPERIMENT

The experimental setup comprises: *(MINIBALL+T-REX)*

Part of the Choose an item.	Availability	Design and manufacturing
[if relevant, name fixed ISOLDE installation: 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 + 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	[material]		
Beam particle type (e, p, ions, etc)			
Beam intensity			
Beam energy			

Cooling liquids	[liquid]		
Gases	[gas]		
Calibration sources:	☐		
• Open source	☐		
• Sealed source	x☐ [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]		

0.1 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