CERN-INTC-2019-025 / INTC-SR-082
24/09/2019

EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

Status Report to the ISOLDE and Neutron Time-of-Flight Committee
following HIE-ISOLDE accepted proposal INTC-P-465

Two-phonon octupole collectivity in the doubly-magic nucleus ^{146}Gd

by G. de Angelis[1] et al.
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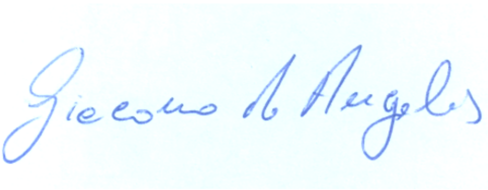
This status report refers to the accepted ISOLDE proposal INTC-P-465 (attached to this letter). **The aim of this proposed measurement is to provide the first direct determination of the double octupole E3 strength (6^+ -> 3^-) in the closed subshell nucleus ^{146}Gd via Coulomb excitation.** The knowledge of this transition rate is essential for benchmarking the many-body models used in the description of such collective states.
No beam time has been allocated up to know. Test of feasibility was performed prior to the submission of the proposal and results were already shown at the proposal presentation.(see proposal INTC-P-465).
Since ISOLDE is the only facility at the moment where this experiment can be done the proposal is fully actual (no other experiment with such secondary beam was performed elsewhere). Also the collaboration carrying the experiment is not changed.

Requested shifts: [24] shifts
Beamline: [MINIBALL + CD-only]

Best Regards



Giacomo de Angelis

CERN-INTC-2016-022 / INTC-P-465
27/05/2016

EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

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

Two-phonon octupole collectivity in the doubly-magic nucleus ^{146}Gd

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Abstract

The even-even nucleus ^{146}Gd is unusual as, together with ^{208}Pb, it has a first excited state with spin-parity 3^-. This state at an excitation energy of 1.579 MeV decays to the ground-state by a collective E3 octupole transition with a B(E3) of 37 (4) W.u.. This collectivity arises through a large number of $\Delta l=\Delta j=3$ orbital combinations around Z=64 and N=82, with the main contribution coming from particle-hole excitations in the proton $d_{5/2}$-$h_{11/2}$ orbits. Collective octupole transitions can also be found in the nearby nuclei, often built on

single/multi-particle-hole states. Although several examples of low-lying 3^- excitations which decay with large E3 strength are known, observations of multi-phonon octupole excitations are very few and firm candidates exist only for ^{208}Pb and a few nuclei in the ^{146}Gd region. In the Gd region, full characterization with transition rates was only possible for ^{147}Gd and ^{148}Gd where, due to the coupling with single-particle configurations, the two-phonon states were fortuitously yrast. In such cases the dynamical particle-phonon coupling between the octupole phonon and the correlated neutron particle pair modes produces an enhancement of octupole collectivity. Therefore the pure octupole vibrational strength has to be extracted based on particle-vibrational coupling. Although these results support octupole vibrations in these almost spherical nuclei, modern mean field calculations cannot be reconciled with available data.
The aim of this proposed measurement is to provide the first direct determination of the double octupole E3 strength (6^+ -> 3^-) in the closed subshell nucleus ^{146}Gd via Coulomb excitation. The knowledge of this transition rate is essential for benchmarking the many-body models used in the description of such collective states.

Requested shifts: [24] shifts
Beamline: [MINIBALL + CD-only]

Beam ^{146}Gd 10^6 pps from Ta target

1 Motivation

Closed shell nuclei exhibit collective excitations built from quadrupole and octupole surface vibrations. Quadrupole shape vibrations very often show large anharmonicities even in nearly spherical nuclei. Due to the smaller vibrational amplitudes and to the larger number of particles contributing, the octupole mode in doubly magic nuclei is expected to come much closer to the ideal harmonic behaviour.

A typical example is the doubly-magic nucleus ^{208}Pb, whose first excited state is a strongly collective 3^- level. ^{146}Gd is the only other known even-even nucleus with a 3^- level as the first excited state. For many years it has been recognized that ^{146}Gd displays many of the properties of a doubly magic nucleus and that Z=64 can be considered as a rather good closed subshell at N=82 [1,2,3].

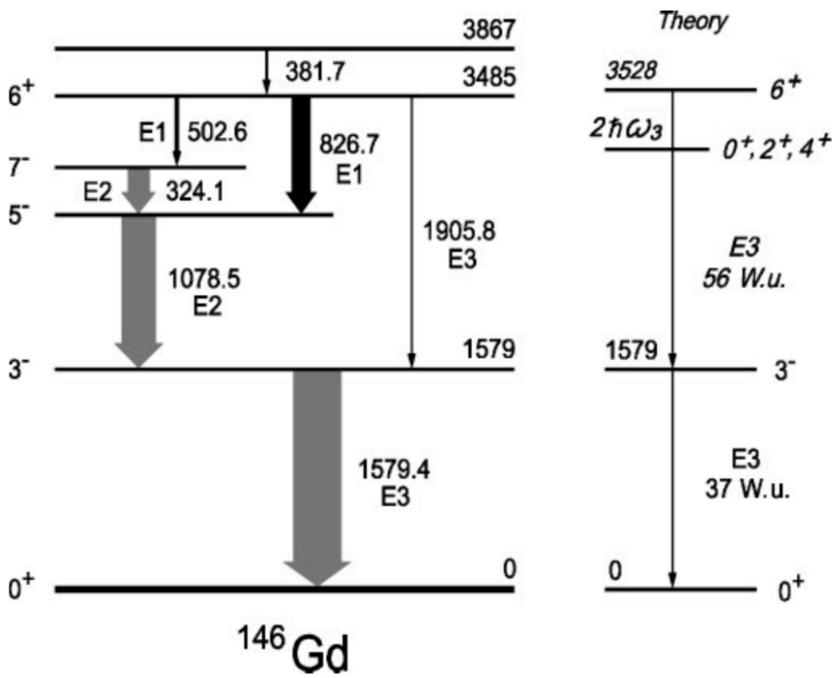

Fig.1 Octupole excitations in ^{146}Gd and predictions from theory [1].

In ^{146}Gd the first excited state, 3^-, is located at 1.579 MeV and de-excites to the ground state via a transition with a B(E3)=37(4) W.u. [1]. Due to these features the state has been interpreted as an octupole vibrational excitation [1,2,3]. Interpreting this 3^- level as an octupole boson state, it is natural to expect a "two-boson" quartet states (J= 0^+, 2^+, 4^+, 6^+) to appear. In the harmonic approximation for non-interacting phonons a degenerate two-phonon multiplet should occur at twice the energy of the one-phonon state. It is also expected to decay with an E3 transition rate which is twice that of the 3^- to 0^+ single-phonon de-excitation. A two-phonon octupole excitation built on the ground state has been identified in ^{208}Pb from a cascade of two E3 transitions from a 0^+ excited states (0^+ -> 3^- -> 0^+) [4,5]. Two phonon octupole excitations have been observed built on single-particle excitations in ^{147}Gd [1] and in the neighbouring N=84 nuclei ^{144}Nd, ^{146}Sm [5] and ^{148}Gd [2,6] and more recently in the closed-shell nucleus ^{146}Gd [7]. Only in ^{147}Gd and ^{148}Gd are the E3 rates known for the transitions connecting the double- to single-phonon excitations. In such cases anharmonicities arise from particle-phonon couplings and through the effect of the Pauli principle between the particle-hole components of the phonons. The dynamical particle-phonon coupling between the octupole phonon and the correlated neutron particle pair modes induces an enhancement of octupole collectivity with respect to the core nucleus ^{146}Gd, as observed in ^{147}Gd and ^{148}Gd and theoretically described using the Dyson boson mapping model [8]. The same description predicts that such a kinematical (Pauli principle) anharmonicity effect works as a "blocking" effect for correlated proton particle pair modes causing a reduction in collectivity in systems characterized by the coupling of the octupole phonon (with a main component of proton $d_{5/2}$-$h_{11/2}$) to proton excitations. The presence of such anharmonicities makes the extraction of the octupole collectivity quite difficult and model dependent.

Recently a 6^+ state has been identified in ^{146}Gd located at 3.485 MeV of excitation energy, almost twice the excitation energy of the one-octupole phonon excitation (1.579 MeV), decaying by an E3 gamma transition to the 3^- first excited state [7]. This decay pattern (6^+ -> 3^- -> 0^+) has been taken has an indication of the double-octupole phonon character of such excitation. However, no measurement of the B(E3) transition matrix element for such a decay (6^+ -> 3^-) has been possible up to now.

The aim of this proposal is to achieve the first direct determination of the two-octupole phonon collectivity in the doubly-magic nucleus ^{146}Gd by a Coulomb excitation measurement.

An estimate of the E3 transition matrix element from the two-octupole to one-octupole phonon states, based on the one-phonon excitation energy (1.579 MeV) and collectivity B(E3)=37(4) W.u. predicts the double-octupole state at an excitation energy of 3.528 MeV (in good agreement with the experimental finding of the state at 3.485 MeV) with a B(E3, 6^+ -> 3^-) = 56 W.u. [7]. Such an estimate includes the anharmonicities originating from the particle-hole nature of the collective vibration. Fig. 1 shows a partial level scheme of ^{146}Gd, which is relevant for this discussion, and the determined/predicted transition rates for the one- and two-phonon states

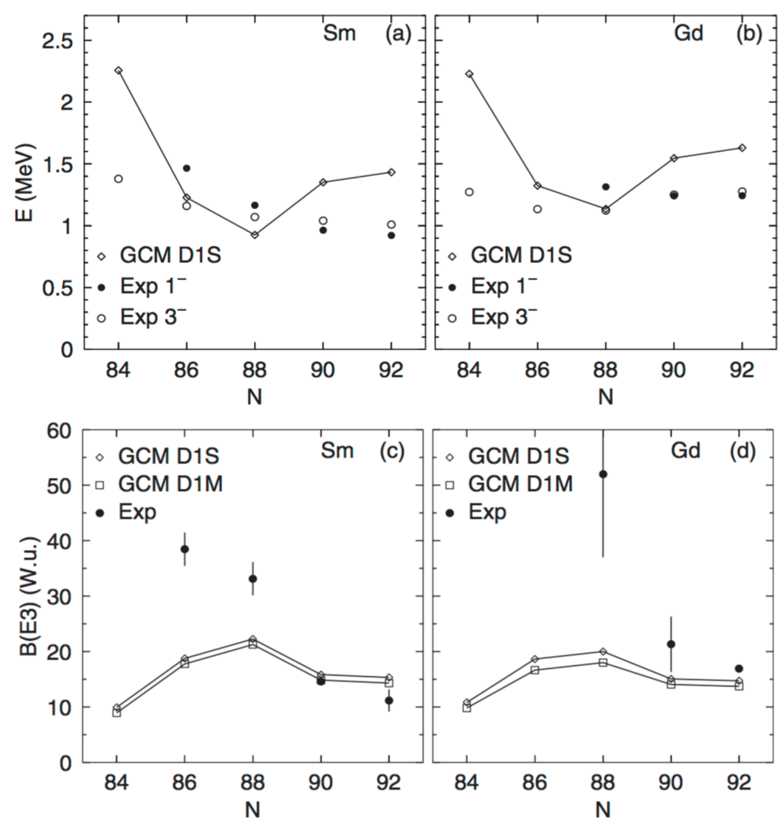

Fig. 2 Excitation energies and B(E3) transition strengths for the octupole states in the Sm and Gd nuclei. Calculations were performed with the Generator Coordinate Method (GCM) with an axial octupole moment as generating coordinate [9].

Modern mean-field calculations based on the Generator Coordinate Method and using the axial octupole moment Q_{30} as generating coordinate seem to be unable to predict the measured excitation energies and transition rates for nuclei close to shell gaps [9]. The results obtained for the octupole states in the Sm and Gd nuclei using the Gogny D1S force gives too high excitation energies for the 3^- states with discrepancies that increase approaching N=82. Correspondingly the two-phonon octupole states are expected at twice the excitation energy of the one-phonon state. B(E3) values are predicted to be rather smaller for the one-phonon de-excitation than observed experimentally [7,9]. In Fig. 2 excitation energies and transition strengths, calculated using the Generator Coordinate Method with an axial octupole moment, are reported for the octupole states in Sm and Gd. Recently those calculations have been extended to the single- and double-octupole excitations in ^{146}Gd. The results fail to reproduce the excitation energies of the octupole states, which are calculated to lie at much higher excitation energies, and predict the strengths of the transitions de-exciting the octupole states as B(E3, 3^- -> 0^+) = 24.44 and B(E3, 6^+ -> 3^-) = 54.07 W.u.[10].

To benchmark such calculations, the aim of this proposal is a direct measurement of the B(E3) transition rate for the 6^+ -> 3^- transition de-exciting the 6^+ double-octupole phonon state in ^{146}Gd. A knowledge of this B(E3) strength will fix the octupole collectivity in the Z=64, N=82 region allowing a clear treatment of the particle/hole contributions. To determine this rate we propose a Coulomb excitation measurement using a ^{146}Gd secondary beam accelerated to 5.5 MeV/u by the HIE-ISOLDE facility.

2. Experimental setup and feasibility

The experiment will be performed using the MINIBALL germanium detector array equipped with a segmented silicon array in the forward direction (CD).

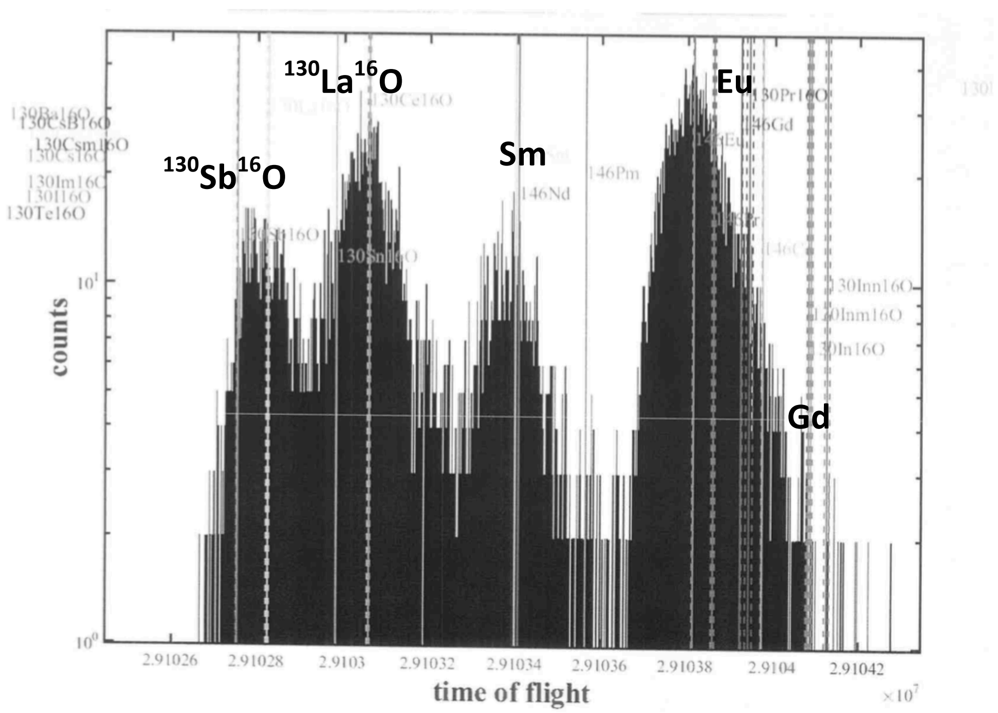

Fig.3 MR-TOF spectrum for mass A=146. Please note the strong ^{146}Eu contamination: ^{146}Gd is within the tail of the mass distribution.

For the rate estimates we have first considered the reported ISOLDE production rate (SC) at the ion-source for ^{146}Gd of 10^9 pps and an ionization and selection efficiency of 3%. To test secondary beam intensity and beam purity we have performed a beam composition measurement using the Multi-Reflection Time-of-Flight spectrometer (MR-TOF) and a Ta target (in a test performed "parasitically" to a scheduled implantation experiment).

For the Ta target a temperature of 2150^0 C was chosen as a compromise between safe operation of the source and a reasonable Gd/Eu ratio (we expect Eu to be the main contaminant due its larger volatility - the melting temperatures of Gd and Eu are 1312^0 C and 826^0 C respectively -). After extraction from the ion source the beam composition was measured using the Multi-Reflection Time-Of-flight (MR-TOF) spectrometer. The resulting A=146 mass spectrum is shown in Fig.3. As expected, the beam purity is low (about 3%) due to strong ^{146}Eu contamination with an estimated ^{146}Gd beam intensity (upper limit) of the order of 15 10^6 pps. To reach better purity we have also tested the oxide extraction (corresponding to selection in mass 146+16=162). The resulting MR-TOF spectrum is shown in Fig.4. GdO is now clearly identified and EuO is absent due to its different chemical behaviour. A purity of the order of 45% (fully compatible with the Coulex measurement since there are no overlapping gamma lines) is therefore obtained for GdO with an estimated beam intensity of 60 10^6 pps. Assuming a charge breeding and transport efficiency of 3%, we expect a secondary beam intensity of the order of 2 10^6 pps.

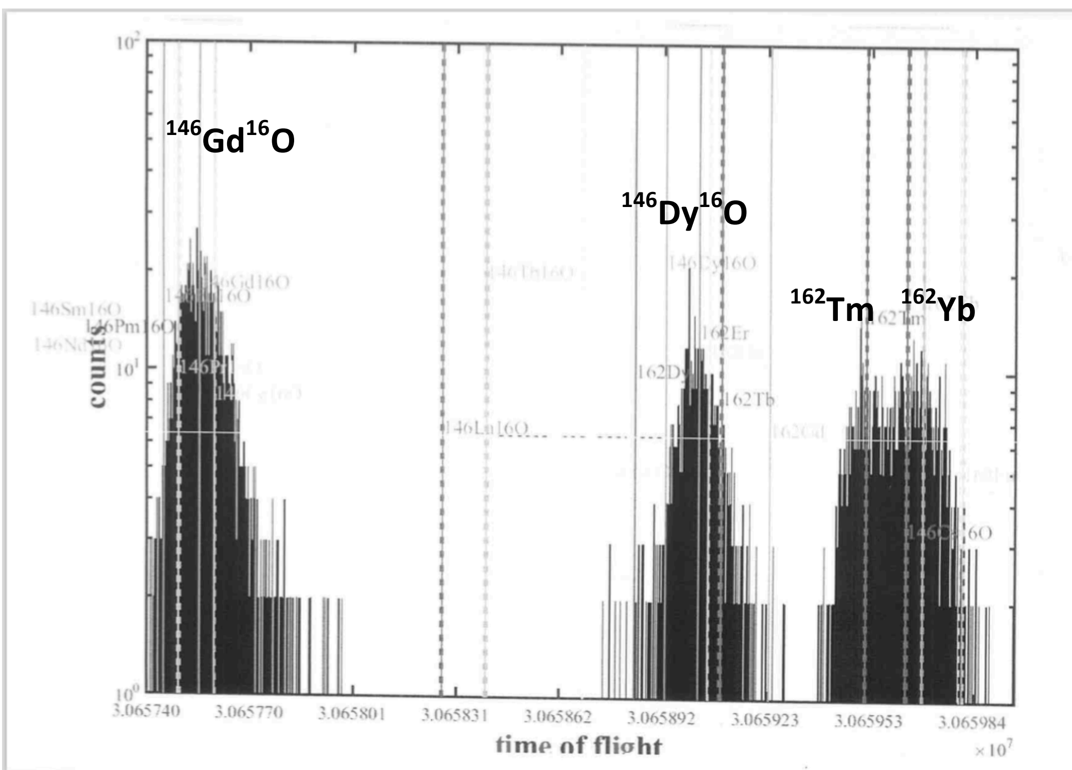

Fig.4 MR-TOF spectrum for the oxides (mass 162). Due to the absence of EuO, GdO has a purity of the order of 45%.

We plan therefore to extract the ^{146}Gd as GdO. The molecule will subsequently break up in the REX-EBIS charge breeder providing a ^{146}Gd secondary beam. For the Coulomb excitation measurement with a ^{208}Pb target, safe conditions are achieved for a beam energy of 5.5 MeV/u. The beam energy was chosen to be close to the safe energy calculated for the maximum laboratory projectile scattering angle of 53 degrees, which corresponds to 95% of the safe energy. Rate estimates have been performed with the GOSIA code using a final secondary ^{146}Gd beam intensity of 10^6 pps (the maximum count rate sustainable by the CD detector) with a total energy of 800 MeV. It should be noted that both the projectile and target are detected in the angular range covered by the segmented silicon detector (CD).

To ensure the separation of beam particles and recoils a Pb target with a thickness of 1 mg/cm2 has been chosen. Such experimental conditions favour the population of higher-lying states, particularly the population of the 6^+ level, which is the goal of this proposal.

The estimated counting rates expected in this Coulomb excitation of ^{146}Gd are given in Table 1 and correspond to the detection of the projectile and recoiling nuclei between 16 and 53 degrees in the laboratory frame. Table 1 shows the numbers of gamma rays per day for the different transitions de-exciting the 6^+ state at 3.485 MeV detected in MINIBALL in coincidence with the ^{146}Gd particles or ^{208}Pb recoils observed in the CD detector in the angular range 16-53 degrees. GOSIA calculations are done by taking into account the CD detector and the Miniball Ge array geometries and efficiencies and they include known and theoretical transitional matrix elements. Estimates, mainly based on shell model theory and on octupole vibrational coupling including anharmonicities, are used for the following matrix elements that are not experimentally available: $5^- \rightarrow 3^-$ $6^+ \rightarrow 3^-$, $6^+ \rightarrow 5^-$ and $6^+ \rightarrow 7^-$.

Table 1: Count rate estimates based on the GOSIA Coulomb excitation code for a ^{146}Gd secondary beam intensity of 10^6 pps. Transition matrix elements for the $3^-\rightarrow0^+$, $7^-\rightarrow5^-$, $6^+\rightarrow5^-$ and $6^+\rightarrow7^-$ transitions are taken from ref. [3]. B(E2) for the $5^-\rightarrow3^-$ transition is a shell model estimate [11]. For the $6^+\rightarrow3^-$ transition we have used the value estimated in Ref.[7].

I_i	I_f	**Multipolarity**	**B(Eλ; $I_i \rightarrow I_f$) [Wu]**	**Eγ [keV]**	**Counts/day**
3^-	0^+	E3	37	1579	6100
5^-	3^-	E2	0.46	1079	160
7^-	5^-	E2	0.46	324	45
6^+	3^-	E3	56	1905	4
6^+	5^-	E1	$3 * 10^{-5}$	827	100
6^+	7^-	E1	$4*10^{-5}$	503	40
2^+	0^+	E2	0.4	1972	430

Taking all this into account we expect to obtain 4 counts per day for the 1905.8 keV $6^+\rightarrow3^-$ and 100 counts per day for the 826.7 keV $6^+\rightarrow5^-$ transitions with a full statistics of 24 and 600 counts collected in 6 days (18 shifts) of beam time (needed to achieve a 20% accuracy on the B(E3)). Since the population of the 6^+ state via safe Coulomb excitation is only occurring via E3 excitation, the knowledge of the decay strength of the much stronger 826.7 keV E1 transition together with the known branching ratio will be used to extract the B(E3), $6^+ \rightarrow 3^-$ transition rate. The expected statistics should also be sufficient to search for other members of the two-octupole phonon multiplet (e.g., the 4^+ state is expected to be populated with 30% lower probability than the 6^+ state). To achieve an independent normalization for the B(E3: 3^- -> 0^+) through comparison with the target excitation we plan to use two extra days (6 shifts) for a run on a ^{94}Mo target (well known B(E2) strength and no overlapping transitions). We estimate 500 counts in two days (6 shifts) of measurement to be sufficient to obtain the B(E3, 3^- ->0^+) with an accuracy better than 20%.

Summary of requested shifts:

^{146}Gd beam 24 shifts (18 shifts on ^{208}Pb target and 6 shifts on ^{94}Mo target).

References:

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[10] J. N. Orce et al., EPJ A, to be published.

[11] G. de Angelis, priv. comm.

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	☒ 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	[material]		
Beam particle type (e, p, ions, etc)			
Beam intensity			
Beam energy			
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]		

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