EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

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

Probing Shape Coexistence in neutron-deficient ^{72}Se via Low-Energy Coulomb Excitation

(October 2014)

D. T. Doherty[1], J. Ljungvall[2], M. Zielińska[1], W. Korten[1], P. Butler[3], F. Bello Garrote[4], E. Clément[5], J.P. Delaroche[6], H. De Witte[7], M. Djongolov[8], J. Eberth[9], G. de France[5], L. Gaffney[7], K. Gladnishki[8], M. Girod[6], A. Goasduff[2], A Görgen[4], K. Hadyńska-Klęk[4], M. Huyse[7], G. Jaworski[10], D. Jenkins[11], M. Klintefjord[4], M. Komorowska[12], J. Libert[4], B. Melon[13], A. Nannini[13], P. Napiorkowski[12], D. R. Napoli[10], A. Perego[13], G. Rainovski[8], E. Rapisarda[14], F. Recchia[15], P. Reiter[9], M. Rocchini[13], D. Rosiak[9], E. Sahin[4], M. Seidlitz[9], B. Siebeck[9], S. Siem[4], J. Srebrny[12], J. J. Valiente Dobon[10], P. Van Duppen[7], N. Warr[9], K. Wrzosek-Lipska[12]

[1] CEA, Saclay, France. [2] CSNSM, Orsay, France
[3] University of Liverpool, Liverpool, UK. [4] University of Oslo, Norway
[5] GANIL, Caen, France. [6] CEA/DAM, Bruyères-le-Châtel, France. [7] K.U Leuven, Belgium
[8] University of Sofia, Bulgaria. [9] IKP, University of Cologne, Germany. [10] LNL, INFN, Legnaro, Italy [11] University of York, York, UK. [12] HIL Warsaw, Poland. [13] INFN Sezione di Firenze, Italy. [14] CERN-ISOLDE, Switzerland. [15] Dipartimento di Fisica, Universita' di Padova, Padova, Italy

CERN-INTC-2014-057 / INTC-P-423
09/10/2014

Abstract

We propose to study the evolution of nuclear structure in neutron-deficient ^{72}Se by performing a low-energy Coulomb excitation measurement. Matrix elements will be determined for low-lying excited states allowing for a full comparison with theoretical predictions. Furthermore, the intrinsic shape of the ground state, and the second 0^+ state, will be investigated using the quadrupole sum rules method.

Spokesperson: D. T. Doherty (CEA, Saclay, France) [daniel.doherty@cea.fr]
Co-Spokesperson: J. Ljungvall (CSNSM, Orsay, France) [joa.ljungvall@csnsm.in2p3.fr]
Contact Person: E. Rapisarda (CERN-ISOLDE, Switzerland) [elisa.rapisarda@cern.ch]

Requested shifts: 12+3 shifts (ten shifts with a ^{208}Pb target and up to two further shifts running with a ^{196}Pt target, plus three shifts for beam tuning).
Installation: Miniball + CD

1. Introduction and Motivation

Nuclei in the mass region A ~ 70 close to the $N = Z$ line are known to exhibit a variety of nuclear shapes, which may be attributed to large shell gaps at both prolate and oblate deformation. These gaps are most pronounced for proton and neutron numbers 34 and 36 and the resulting coexistence of prolate and oblate shapes was predicted over three decades ago [1]. The nuclear shape is a very sensitive probe of the underlying nuclear structure and the effective interaction between the nucleons. Observables related to the nuclear shape, for example the electric quadrupole moment (QM), and the reduced electric quadrupole transition probability (B(E2)), are thus important benchmarks for testing nuclear structure theory.

Coulomb excitation experiments of neutron-deficient krypton (Z=36) isotopes, ^{74}Kr and ^{76}Kr [2], have enabled the intrinsic shapes for several low-lying states to be determined. These experiments have provided firm evidence for a prolate ground-state band coexisting with an excited oblate band built on the low-lying 0_2 state. However, by studying the properties of the 0_2 shape isomer [3] an inversion of the prolate and oblate configurations, and hence an oblate ground state, for the *N*=*Z* nucleus ^{72}Kr was observed. The relatively small B(E2; $0^+_2 \rightarrow 2^+_1$) value measured via intermediate-energy Coulomb excitation in ^{72}Kr [4] supports this interpretation. Many theoretical models predicted the coexistence of prolate and oblate shapes in the light Kr isotopes; the inversion of oblate and prolate configurations below A=74 is nicely reproduced by Hartree-Fock-Bogoliubov (HFB) calculations using the Gogny D1S interaction and the configuration-mixing method (GCM/GOA) [2]. Later it was shown that allowing for triaxial degrees of freedom is crucial in this mass region for properly describing the underlying nuclear structure properties [5].

For the neutron-deficient selenium (Z=34) isotopes, such as those of interest here, the shape coexistence scenario is less well established than for the krypton isotopes and, likely, even more complex. The structure of ^{72}Se has been observed to be similar to that of the *N* = 38 isotone ^{74}Kr, with an isomeric 0^+ state located just above the first 2^+ level [1]. The B(E2) strengths for yrast transitions (see Figure 1(a)) are observed to decrease towards the ground state, which is consistent with a mixed configuration. However, the actual shapes can only be inferred from the QM of the states, which are accessible in Coulomb excitation measurements. In addition, several theoretical calculations predict oblate ground states for Se isotopes with N ~ Z [6,7,8]. This is of considerable interest as oblate ground states are extremely rare, particularly in the middle of a shell, where prolate deformation usually prevails. Figure 2(a) illustrates the situation for ^{72}Se, as predicted by Adiabatic Self-consistent Coordinate (ASCC) calculations, here the ground state wave function is expected to be widely spread over the triaxial region; a maximum is expected at oblate deformation, but with the wave function extending to the prolate region [9]. The prolate character of this ground state band is then expected to develop with increasing angular momentum, as shown for both the GCM(GOA) and ASCC calculations in Figure 2(b).

Both the ASCC and GCM(GOA) calculations mentioned previously predict that the yrast 2^+, 4^+ and 6^+ have negative QMs, with the QM becoming more negative with increasing angular momentum and hence, that the states become increasing prolate as one moves up the band. This behavior is in contrast to calculations performed for more neutron deficient ^{68}Se and ^{70}Se utilising the same approach [9]. However, for the excited band, built upon the known 0^+_2 level [1], it is clear that the results of various theoretical approaches are in disagreement. ASCC calculations predict a weakly deformed, oblate excited band. Whereas, the more recent GCM(GOA) calculations predict that mixing is present for the low-lying 0^+ and 2^+ states before giving way to purer configurations at larger excitation energy. Figure 1(b) and 1(c) display the results of GCM(GOA) [8] and ASCC [7] calculations, respectively, for states at low excitation energy. When compared to the experimental results, shown in Figure 1(a), it is clear that the GCM(GOA) calculations better describe the collectivity present in this excited band built on the 0^+_2 level as well as the mixing between the excited and ground state bands. However, in both approaches the strength of the inter-band transitions is underestimated and, therefore, the mixing between these two structures is still not well understood. Testing the predictions, of both theoretical approaches, by measurement of E2 matrix elements connecting the states and of the QM of the levels is, therefore, a key goal of the present Coulomb excitation study.

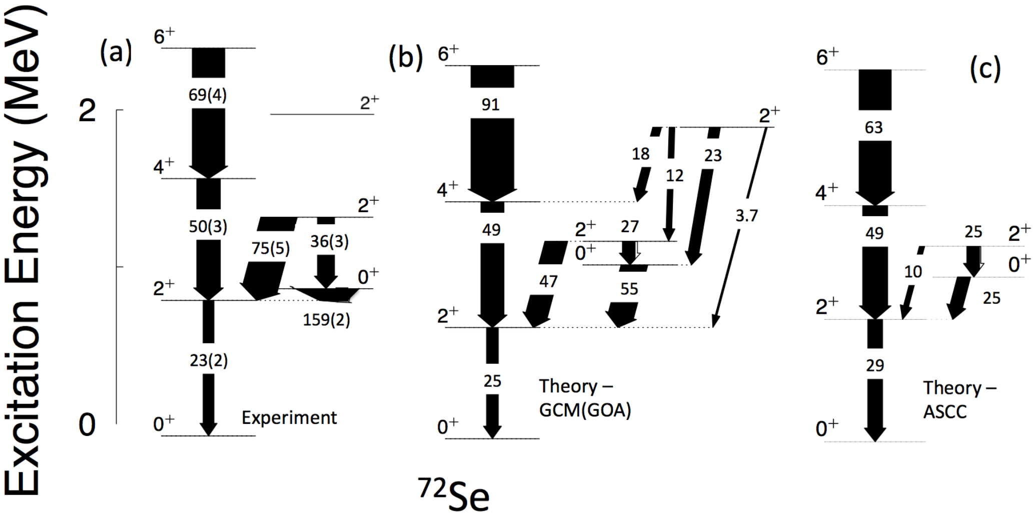

Figure 1(a): *Experimentally determined reduced transition probabilities B(E2) between low-lying states in ^{72}Se, the figure is based on Fig. 11 from Ref [10].* ***(b)*** *Comparison to a theoretical study utilising the GCM(GOA) configuration-mixing method [8].* ***(c)*** *Comparison to a theoretical study performed using Adiabatic Self-Consistent Coordinate (ASCC) method [7]. The numbers and the widths of the arrows in each of the figures represent the B(E2) values in Weisskopf units (W.u).*

At HIE-ISOLDE state-of-the-art beams of unstable ^{72}Se are now available in sufficient intensities [11] to allow for the determination of the intrinsic shape of a number of levels, including the critical 2^+_1, 2^+_2 and 4^+_1 states. For excited states with $J > 0$, an unambiguous assignment of the nuclear shape is possible by measuring the static QM via low-energy Coulomb excitation. The intrinsic shape of $J = 0$ states is not an observable in the laboratory system, however by employing the "quadrupole sum rules" method [12,13] the shape of these states may be determined from a complete set of E2 matrix elements. This approach has also been successfully employed in the analysis of Coulomb excitation experiments involving the light krypton isotopes, ^{74,76}Kr, [2] and on the even-even Hg isotopes [14].

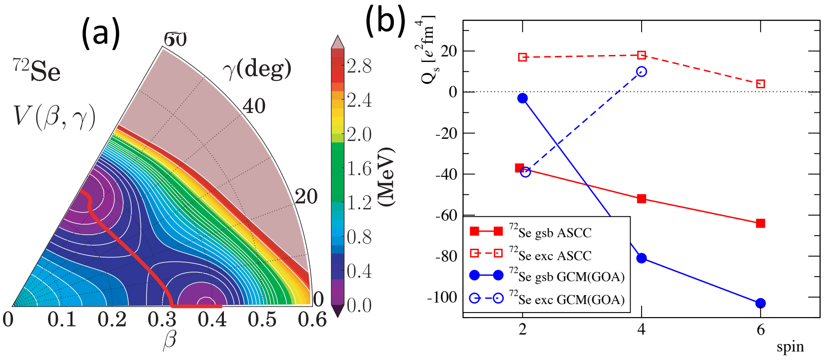

Figure 2(a): *Potential energy V(β,γ) map for ^{72}Se, plot is taken from Ref [7]. It is clear that two distinct local minima are predicted by the ASCC calculations, with the oblate minimum at γ = 60° having a slightly lower energy, of the order if a few hundred keV, than the prolate minimum (γ = 0°).* ***(b)*** *Theoretical quadrupole moments of the ground-state and excited bands* *in ^{72}Se. The GCM(GOA) calculations [8] are represented by blue circles, while ASCC calculations, represented by red squares, are from the work of Hinohara et al. [9].*

Coulomb excitation experiments are sensitive to the QM of excited states through the so-called reorientation effect, which enhances or reduces the cross section depending on the size and sign of the QM. Figure 3 shows, as an example, the calculated intensity ratio of the $6^+ \rightarrow 4^+$ and $4^+ \rightarrow 2^+$ transitions for two choices of a QM corresponding to the prolate and oblate configurations. The level scheme shown in figure 1(a) (based on the work of Ref. [10]) summarizes the available experimental data on reduced transition probabilities of low-lying states in ^{72}Se. These data strongly constrain the free parameters in the multi-dimensional least-square fit needed for the Coulomb excitation analysis of such a complex level scheme. For the analysis procedure it should, however, be noted that some older lifetime values [1] must be taken with caution. The γ–γ coincidence method used in in the work of Ljungvall *et al.* [15] eliminates the influence of side feeding, allowing more reliable lifetime measurements to be obtained. In this work, however, lifetimes were only obtained for the levels in the ground state band of ^{72}Se. In the present experiment it is, therefore, important to verify the lifetimes of the 0^+_2 and 2^+_2 states through a direct measurement of the respective B(E2) values.

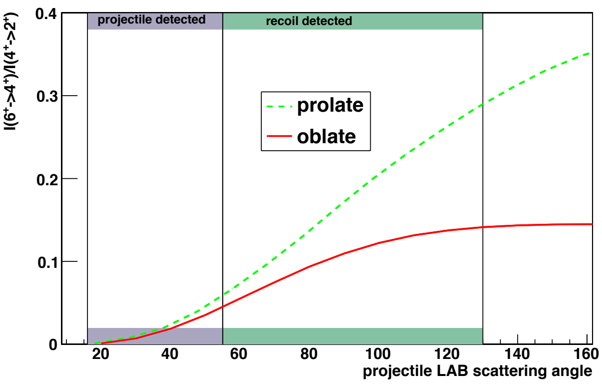

***Figure 3**. Intensity ratio of the $6^+ \rightarrow 4^+$ transition to the $4^+ \rightarrow 2^+$ transition as a function of projectile scattering angle. Calculations were performed with the GOSIA code for different extreme assumptions of the quadrupole moment of the 4^+ state (corresponding to the rotational limits). The shaded areas represent the angular coverage of the particle detector for the detection of both projectiles and recoils.*

2. Experimental Setup and Feasibility

The experiment will be performed using the Miniball/CD detector setup at the HIE-ISOLDE facility. The availability of a pure ^{72}Se beam[1] at ISOLDE removes the problems associated with other A~70 contaminants and opens up the possibility of using Coulomb excitation at so-called safe energies below the Coulomb barrier. A beam energy of 305 MeV is necessary to enhance the population of higher-lying states and enable a more precise determination of the QMs to be made via the re-orientation effect. This beam energy is only possible due to the recent HIE-ISOLDE upgrade, which allows for beams of up to 5.5 MeV/u. As in previous experiments at ISOLDE we propose to use an annular double-sided CD Si strip detector (DSSSD) placed at forward angles and covering an angular range from 16° to 53°. This allows

[1] In this instance a pure ^{72}Se beam will be achieved by extracting selenium isotopes as SeCO molecules [16] which are then broken apart in EBIS.

covering a large solid angle range in the Centre of Mass system (20° < ϑ_{cm} < 145°) by detecting *either* the scattered projectiles *or* the recoiling target nuclei. De-excitation gamma rays will be observed with the Miniball germanium detector [17] array in coincidence with the scattered particles allowing for an event-by-event Doppler correction and a significant reduction of the γ-ray background following the beta decay of the radioactive beam particles.

Transition	Multipolarity	E_γ [keV]	Predicted Yield [counts/day]	Minimum Yield [counts/day]
$2^+_1 \rightarrow 0^+_1$	E2	862	17470	
$4^+_1 \rightarrow 2^+_1$	E2	775	960	
$6^+_1 \rightarrow 4^+_1$	E2	830	75	
$8^+_1 \rightarrow 6^+_1$	E2	958	6	
$0^+_2 \rightarrow 2^+_1$	E2	75	325	135
$2^+_2 \rightarrow 2^+_1$	E2/M1 $\delta = +11^{+11}_{-4}$	455	200	160
$2^+_2 \rightarrow 0^+_2$	E2	379	35	
$2^+_2 \rightarrow 0^+_1$	E2	1317	235	
$2^+_3 \rightarrow 2^+_1$	E2/M1 $\delta = -8^{+3}_{-12}$	1137	50	25
$2^+_3 \rightarrow 0^+_2$	E2	937	25	
$3^-_1 \rightarrow 2^+_2$	E1	1117	15	

Table 1. Expected γ-ray yields per day for all observable transitions in ^{72}Se. The calculations were performed with the Coulomb excitation code GOSIA for a 305-MeV ^{72}Se beam incident on a 2 mg/cm^2 ^{208}Pb target. For key transitions which depend strongly on the relative signs of matrix elements, we also include a "worst case scenario", i.e. the minimum yield where the signs of dependent matrix elements have been varied (see Appendix A). E2/M1 mixing ratios, δ, are from Ref [10].

The expected γ-ray yields following the Coulomb excitation of a ^{72}Se beam incident on a 2 mg/cm^2 ^{208}Pb target at a "safe" energy[2] of 305 MeV have been calculated with the GOSIA code [18], as shown in Table 1. In performing these calculations we make use of all the known experimental information on excitation energies and reduced transition probabilities in ^{72}Se (see Figure 2(a)). If this information was not available we have used the most recent theoretical values from Figure 2(b). For the Miniball detector array we have assumed a γ-ray detection efficiency of 8% (with add-back applied) at 1332 keV. In calculating the γ-ray yields we have assumed an average beam intensity of 2x10^5 pps [11]. Yield calculations also indicate that with the experimental conditions listed above we would expect to observe the, previously reported, 3^- state assuming a B(E3; $0^+ \rightarrow 3^-$) strength of 10 W.u., typical for octupole excitations in this mass region. This hitherto unknown transition probability will also be measured in the present work.

In order to deduce the intrinsic shapes of the states, quadrupole moments will have to be determined. Figure 3 shows the ratio of the calculated intensity of the $6^+ \rightarrow 4^+$ transition to the $4^+ \rightarrow 2^+$ transition as a function of projectile scattering angle for two choices of QM corresponding to prolate and oblate deformation of the 4^+_1 level, respectively, demonstrating the sensitivity of the method for determining QMs. It is, however, important to note that these intensities are sensitive to the signs of other matrix elements. Hence it is important to observe all transition listed in Table 1. In

[2] The "safe" energy criterion ensures that the distance of closest approach between the nuclear surfaces is greater than ~5 fm, thus minimizing Coulomb-nuclear interference effects, *i.e.* < 0.5% of the total cross section.

particular, due to the scarce information on the 2^+_3 state (see Figure 2), sufficient statistics must be collected on decays from this level. The yields listed in Table 1 are of the same order as those obtained in a previous Coulomb excitation experiment on ^{98}Sr performed by the group, which were sufficient for QMs to be determined for the 2^+_1, 2^+_2, 4^+_1 and 6^+_1 states [19]. In an experiment running for ~2 days we expect to collect sufficient statistics to enable the precise determination of the QM of the key 2^+_1, 2^+_2 and 4^+_1 states listed in Table 1. It will also be necessary to run for up to two shifts with a ^{196}Pt target in order to collect sufficient statistics (~a few hundred counts) for the $0^+_2 \rightarrow 2^+_1$ transition. This low-energy transition (75 keV) is nearly degenerate with the Pb x-rays at 72 and 75 keV, therefore, this key transition will likely be unobservable when using the ^{208}Pb target.

Finally, as mentioned previously, we plan to extract deformation parameters $<Q^2>$ and $<Q^3\cos3\delta>$ for the first two 0^+ states by employing the quadrupole sum rules method. For the ground state $<Q^2>$ is dominated by the $<0^+_1||E2||2^+_1>$ matrix element. However, for the 0^+_2 state all $<0^+_2||E2||2^+_i>$ will enter the sum, reinforcing the need to collect sufficient statistics for these key transitions. Triaxiality parameters $<Q^3\cos3\delta>$ for these states will also be determined, for the ground state only the quadrupole moment of the first 2^+ state is required [20], together with transitional $2^+_i \rightarrow 2^+_j$ matrix elements. The triaxiality of the second 0^+ state will depend more strongly on the QM of other 2^+ states however, in the event that these 2^+ states are collective it may also be determined in the present experiment.

In conclusion, we request a total of 12 shifts of beam time with a 305-MeV ^{72}Se beam (10 on a ^{208}Pb target and up to 2 with a ^{196}Pt target) at a minimum intensity of 2 x 10^5 pps in order to perform this experiment. A further 3 shifts will be required to optimize the production and purification of the beam.

Safety Aspects

The same as for other MINIBALL at HIE-ISOLDE experiments.

References

[1] J. H. Hamilton *et al.,* Phys. Rev. Lett. **32**, 239 (1974).
[2] E. Clément *et al.*, Phys. Rev. C. **75**, 054313 (2007).
[3] E. Bouchez *et al.*, Phys. Rev. Lett. **90**, 082502 (2003).
[4] A. Gade *et al.*, Phys. Rev. Lett. **95,** 022502 (2005).
[5] M. Girod *et al.,* Phys. Lett. B. **676,** 39 (2009).
[6] W. Nazarewicz *et al.*, Nucl. Phys. A. **435**, 397 (1985).
[7] N. Hinohara *et al.* Phys. Rev. C **82**, 064313 (2010).
[8] J. P. Delaroche, Private Communication (2014).
[9] N. Hinohara *et al.* Phys. Rev. C **80**, 014305 (2009).
[10] E. A. Mc Cutchan *et al.,* Phys. Rev. C. **83,** 024310 (2011).
[11] T. Stora, Private Communication (2014).
[12] D. Cline. Ann. Rev. Nucl. Part. Sci. **36,** 683 (1986).
[13] J. Srebrny and D. Cline, Int. Journ. Mod. Phys. E **20**, 422 (2011).
[14] N. Bree *et al.* Phys. Rev. Lett. **112**, 162701 (2014).
[15] J. Ljungvall *et al.* Phys. Rev. Lett. **100**, 102502 (2008).
[16] U. Koester *et al.* Nucl. Instrum. Meth. Phys. Res. B. **204,** 303 (2003).
[17] N. Warr *et al.*, Eur. Phy. Journ A. **49**, 40 (2013).
[18] T. Czosnyka, D. Cline and C. Y. Wu, Bull Am. Phys. Soc. 28, 745 (1982) Coulomb Excitation Data Analysis Code, GOSIA: http://www.slcj.uw.edu.pl/gosia
[19] E. Clément, M. Zielińska *et al.* Publication in preparation (2014).
[20] A. Andrejtscheff *et al.* Phys. Lett. B. **1**, 329 (1994).

Appendix A.

As the signs and magnitudes of the QMs as well as several other transitional E2 matrix elements are unknown additional calculations were performed to investigate a "worst-case" scenario:

- A negative sign for the $<2^+_2 \| E2 \| 2^+_1>$ matrix element.
- A positive sign for the $<0^+_2 \| E2 \| 2^+_1>$ matrix element.
- A negative sign for diagonal matrix elements of states in the ground state band, indicating prolate deformation for all states.

In this situation the population of non-yrast states is minimal. Figure 4 shows the relative population of excited states in ^{72}Se assuming both the scenario presented in Table 1 (dotted lines) and the "worst-case" scenario (solid lines). It can be seen that in assuming this worst-case scenario the population of the 0^+_2 and 2^+_2 states may be reduced by up to 50%.

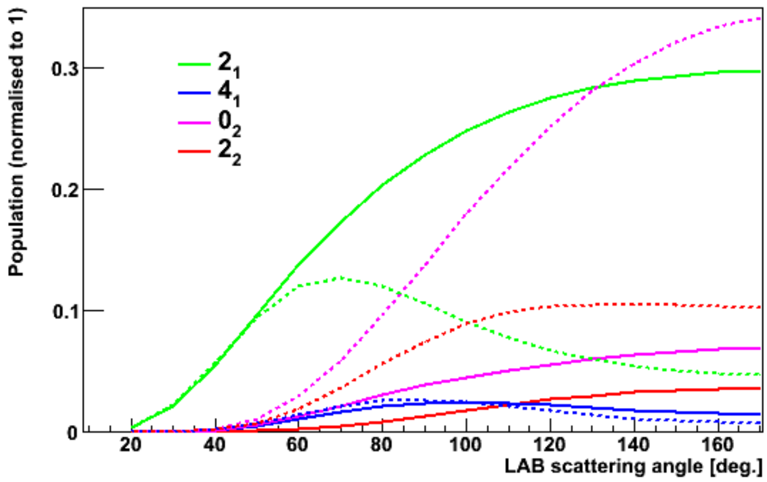

Figure 4. Relative population of excited states in ^{72}Se assuming either the matrix elements used in the calculations of Table 1 (dotted lines) or a "worst-case" scenario (solid lines).

In addition to this worst-case scenario, combinations of matrix elements also exist that would substantially increase the observed yields.

- A positive sign for the $<2^+_2 \| E2 \| 2^+_1>$ and $<2^+_3 \| E2 \| 2^+_1>$ matrix elements.
- A negative sign for the $<0^+_2 \| E2 \| 2^+_1>$ matrix element.
- Positive signs for diagonal matrix elements of states in the ground state band, indicating oblate deformation for all states.

Assuming the scenario above increases the yields (shown in Table 1) by a factor ~3 for states within the ground state band.

Finally, it is important to note that these observations also illustrate the sensitivity of the Coulomb excitation experiment to the relative signs of matrix elements. This is critical for the analysis of deformation parameters using the quadrupole sum-rule method.

Appendix

DESCRIPTION OF THE PROPOSED EXPERIMENT

The experimental setup comprises: *(Miniball + CD detector)*

Part of the Choose an item.	Availability	Design and manufacturing
MINIBALL + only CD	☒ 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 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	^{208}Pb and ^{196}Pt		
Beam particle type (e, p, ions, etc)	Ions of ^{72}Se		
Beam intensity	2 x 10^5 pps		
Beam energy	305 MeV		
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)*