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EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

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

(Following HIE-ISOLDE Letter of Intent I - 102)

Solving the shape conundrum in ^{70}Se

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J.N. Orce[1], D.G. Jenkins[2], N. Erasmus[1], N.A. Khumalo[1], C. Mehl[1], S. Ngqoloda[1], B. Singh[1], S. Triambak[1], C.J. Barton[2], R. Wadsworth[2], N. Warr[3], D. Muecher[3], E. Clément[4], M. Huyse[5], R. Raabe[5], P. Van Duppen[5], A. Ekström[6], J. Cederkäll[6], J. Ljungvall[7], P. Butler[8], L. Gaffney[8], D. Joss[8], G. O'Neill[8], R. Page[8], T. Grahn[9], P.T. Greenlees[9,10], J. Pakarinen[9,10], P. Rahkila[9,10], E. Rapisarda[11], F. Wenander[11], D Voulot[11]

[1]*Department of Physics, University of the Western Cape, South Africa*
[2]*Department of Physics, University of York, York, United Kingdom*
[3]*Institut für Kernphysik, Universität zu Köln, Köln, Germany*
[4]*GANIL, Caen, France*
[5]*Instituut voor Kern- en Stralingsfysica, KU Leuven, Belgium*
[6]*Physics Department, University of Lund, Sweden*
[7]*CSNSM Orsay, France*
[8]*Department of Physics, University of Liverpool, United Kingdom*
[9]*Department of Physics, University ofJyväskylä, Finland*
[10]*Helsinki institute of Physics, Finland*
[11]*Physics Department, CERN, Switzerland*

Spokesperson: [Nico Orce] [jnorce@uwc.ac.za]
Co-Spokeperson: [David Jenkins] [david.jenkins@york.ac.uk]
Contact person: [Elisa Rapisarda] [elisa.rapisarda@cern.ch]

Abstract: We propose a multi-step Coulomb-excitation study of ^{70}Se at HIE-ISOLDE using the ^{208}Pb(^{70}Se,^{70}Se*)^{208}Pb* reaction at a safe energy of 5.0 MeV/u. We aim at a precise measurement of the $\langle 2_1^+ \mid\mid \hat{E}2 \mid\mid 2_1^+ \rangle$ diagonal matrix element as well as gaining information on additional matrix elements. Such information will shed light onto the shape conundrum of the 2_1^+ state in ^{70}Se as well as foreseeing the opportunity for a more detailed understanding of the shape-coexistence phenomenon in this region.

Requested shifts: 15+1 shifts (1 shift needed for setting up the experiment)
Installation: [MINIBALL + CD at [$57°, 77°$] forward angles]

A remarkable feature of atomic nuclei is their ability to adopt different mean field shapes for a small cost in energy compared to their total binding energy. As shown in Fig. 1, nuclei in the $A \approx 70$ region close to the $N = Z$ line are predicted to lie in a region of rapidly evolving nuclear shape because of the shell gaps at proton and neutron numbers 34 and 36. Macroscopic-microscopic models suggest a transition from gamma-soft shapes at ^{64}Ge, through oblate-prolate shape-coexistence in ^{68}Se and ^{72}Kr to some of the most prolate deformed nuclei at ^{76}Sr and ^{80}Zr. The shape coexistence in $N = Z$ nuclei, in particular, may be enhanced by the occupation of the same orbitals for protons and neutrons and the resulting neutron-proton interaction [2, 3].

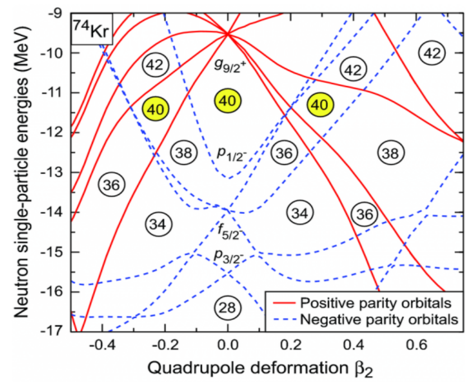

Figure 1: Deformed single-particle level energies for the orbits of interest. Figure taken from Ref. [1].

A key tool for identifying the sign of the nuclear deformation is the reorientation effect in low-energy Coulomb excitation. This effect is a second-order perturbation that generates a time-dependent hyperfine splitting of the nuclear levels and changes the population of the different magnetic substates; hence, modifying the Coulomb-excitation cross section depending on the magnitude and sign of the spectroscopic quadrupole moment, Q_S [4]. An example is the reorientation-effect measurement of ^{70}Se ($Z = 34$) at REX-ISOLDE, where the nucleus of interest was produced as an isobarically pure beam through extracting it from ISOLDE as an SeCO$^+$ molecule and breaking this molecule in the EBIS [5]. Additional accurate lifetimes measurements using the recoil-distance Doppler shift method [6], when combined with the only determination of Q_S for the 2_1^+ state [5], suggest an oblate shape for the ground state of ^{70}Se [5, 6]. Moreover, experimental and theoretical results in the light Se and Kr nuclei seems to suggest the emergence of oblate shapes as one approaches $N = Z$ [6]. However, the sudden decrease of the $B(E2; 2_1^+ \to 0_1^+)$ value from the NNDC accepted value of 44(9) W.u. [7] to the recent determination of 20.0(1.2) W.u. [6] cannot be accommodated theoretically. A large uncertainty in the $Q_S(2_1^+)$ value prevents a more detailed comparison with theory. Aided by the higher beam energies available at HIE-ISOLDE, the first goal of this proposal is the accurate determination of the $\langle 2_1^+ \,||\, \hat{E}2 \,||\, 2_1^+ \rangle$ diagonal matrix element, which currently spans from $-0.15 \leq \langle 2_1^+ \,||\, \hat{E}2 \,||\, 2_1^+ \rangle \leq +1.0$ eb.

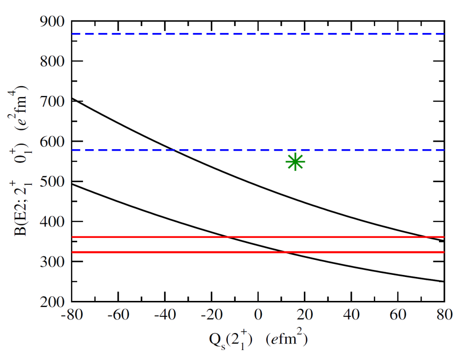

Figure 2: The $B(E2; 2_1^+ \to 0_1^+)$ value as a function of $Q_S(2_1^+)$ for the 2_1^+ state in ^{70}Se. The asterisk indicates the theoretical value. Figure taken from [6].

We propose to do a multi-step Coulomb excitation using the ^{208}Pb(^{70}Se,^{70}Se*)^{208}Pb* reaction at 5.0 MeV/u. This bombarding energy is well below the Coulomb barrier at around 427 MeV and, assuming Cline's prescribed 5.0 fm separation between nuclear surfaces for heavy-ion reactions [8], safe for laboratory scattering angles $\theta_{lab} \leq 83°$. A large Sommerfeld parameter of $\eta = 196 \gg 1$ validates the semiclassical approximation and a small adiabaticity parameter of $\xi = 0.35$ enhances the population of the 2_1^+ state in ^{70}Se. Using matrix elements extracted from Refs. [6, 7], GOSIA calculations [9] are presented in Fig. 3 for the population of the 2_1^+ state in ^{70}Se as a function of scattering angle and at different and extremely plausible $Q_s(2_1^+)$ values. Such a population strongly depends on $Q_s(2_1^+)$, being stronger as the shape becomes more oblate, and peaks at $\theta_{lab} \approx 40°$. However, the reaction-kinematics plots shown in Fig. 4 illustrate the importance of moving the CD detector closer to the target position; hence, avoiding the high-energy ^{208}Pb recoils that would badly damage the detector otherwise. The scattered ^{70}Se ions will therefore be detected with an S3 CD-type silicon detector placed covering the $[57°, 77°]$ angular range in the laboratory frame. The remaining angular coverage will be shielded from the ^{208}Pb recoils. A yield of 10^4 ions/s for the previous ^{70}Se reorientation-effect measurement at 2.94 MeV/u yielded an area of 139(13) counts for the 2_1^+ peak [5]. Comparatively, assuming the same yield and $Q_s(2_1^+) = +0.8$ eb, we could approximately achieve 650 counts/day with a 1.5-mg/cm^2 ^{208}Pb foil; 500 counts/day for $Q_s(2_1^+) = 0$ eb. Fifteen shifts will provide a measurement of $Q_s(2_1^+)$ with an approximately 10% uncertainty.

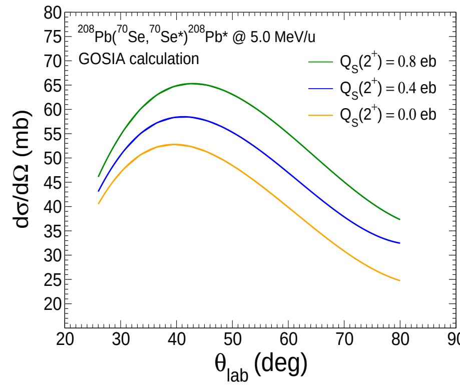

Figure 3: Calculated differential cross sections for the population of the 2_1^+ state in ^{70}Se.

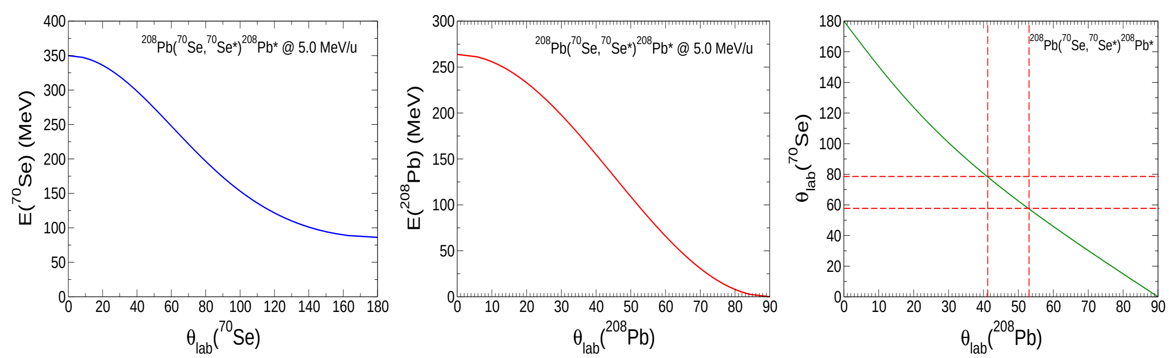

Figure 4: Reaction kinematics for the ^{70}Se ejectiles and ^{208}Pb recoils.

An additional fundamental question lies in understanding the excitation mechanism of higher-lying levels. With a total cross section of tens of mb, we expect to obtain information on transitional matrix elements relating the 2_2^+, 4_1^+, 0_2^+, 4_2^+ and 6_1^+ states. About 200 counts for the population of the 2_2^+ state will provide information on the sign of the $\langle 2_2^+ \ || \ \hat{E}2 \ || \ 2_2^+ \rangle$ matrix element, which might indicate the existence of a low-lying 0^+ excitation. In fact, low-lying excited 0^+ states have been observed in other neutron-deficient Se [10, 11, 12] and Kr [13] isotopes and associated with shape coexistence. Alternatively, with a $E(4_1^+)/E(2_1^+) = 2.16$ ratio as well as the typical sequence of 2_2^+, 4_1^+ and 0_2^+ states at almost twice the 2_1^+ excitation energy, a vibrational picture might be suggested in ^{70}Se. The breakdown of the phonon model in the Cd isotopes [14] clearly questions Bohr and Mottelson's vibrational picture and strongly encourages the search for multi-phonon excitations in other regions of the nuclear chart. J.N.O. and D.G.J. have experience performing reorientation-effect measurements at TRIUMF and iThemba LABS and REX-ISOLDE, respectively. J.N.O. has recently published a rapid communication entitled "Reorientation-effect measurement of the $\langle 2_1^+ \ || \ \hat{E}2 \ || \ 2_1^+ \rangle$ matrix element in ^{10}Be" [15].

Summary of requested shifts: 15+1 shifts (5 days) for a 10% uncertainty in $Q_S(2_1^+)$ and the determination of the sign of the $\langle 2_2^+ \ || \ \hat{E}2 \ || \ 2_2^+ \rangle$ matrix element.

References

[1] M. Bender *et al.*, Phys. Rev. C **73**, 034322 (2006).

[2] K. Heyde and J.L. Wood, Rev. Mod. Phys **83**, 1467 (2011).

[3] A. de Shalit and M. Goldhaber, Phys. Rev. **92**, 1211 (1953).

[4] O. Häusser, in Nuclear Spectroscopy and Reactions C, edited by J. Cerny (Academic, New York, 1974).

[5] A. M. Hurst *et al.*, Phys. Rev. Lett. **98**, 072501 (2007).

[6] J. Ljungvall *et al.*, Phys. Rev. Lett. **100**, 102502 (2008).

[7] http://www.nndc.bnl.gov. (*NNDC database*)

[8] Douglas Cline, Ann. Rev. Nucl. Part. Sci. **36**, 683 (1986).

[9] T. Czosnyka *et al.*, Bull. Am. Phys. Soc. **28**, 745 (1983).

[10] A. Ahmed *et al.*, Phys. Rev. C **24**, 1486 (1981).

[11] J.H. Hamilton *et al.*, Phys. Rev. Lett. **32**, 239 (1974).

[12] T. Mylaeus *et al.*, J. Phys. G**15**, L135 (1989).

[13] E. Clément *et al.*, Phys. Rev. C **75**, 054313 (2007).

[14] P. E. Garrett and J. L. Wood, J. Phys. G **37**, 064028 (2010).

[15] J. N. Orce *et al.*, Phys. Rev. C (R) (2012), in press.

Appendix

DESCRIPTION OF THE PROPOSED EXPERIMENT

We propose to use the ^{208}Pb(^{70}Se,^{70}Se*)^{208}Pb* reaction at a bombarding energy of 5.0 MeV/u. The de-excited γ-rays will be detected with the MINIBALL array and the scattered ^{70}Se ions with a forward S3 double-sided CD-type silicon detector covering $[57°, 77°]$ scattering angles in the laboratory frame. A 1.5-mg/cm^2 thick ^{208}Pb target will be required. Pure ^{70}Se beams have previously been delivered at REX-ISOLDE [5] using SeCO$^+$ molecules and breaking this molecule in the EBIS [5]. The same procedure should be available at HIE-ISOLDE.

The experimental setup comprises: (*MINIBALL + CD*)

Part of the	Availability	Design and manufacturing
(if relevant, name fixed ISOLDE installation: 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 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
[insert lines if needed]		

HAZARDS GENERATED BY THE EXPERIMENT: Hazards named in the document relevant for the fixed MINIBALL + CD installation.

Additional hazards: None.

Hazards	[Part 1 of experiment/ equipment]	[Part 2 of experiment/ equipment]	[Part 3 of 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	1 mg/cm^2 ^{208}Pb		
Beam particle type (e, p, ions, etc)	^{70}Se		
Beam intensity	10^4 ions/s		
Beam energy	5.0 MeV/u		
Cooling liquids	[liquid]		
Gases	[gas]		
Calibration sources:	☒		
• Open source	☐		
• Sealed source	☒ [ISO standard]		
• Isotope	^{152}Eu	^{60}Co	^{239}Pu, ^{241}Am, ^{244}Cm
• 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 (1-300 MHz)			
Chemical			
Toxic	[chemical agent], [quantity]		
Harmful	[chem. agent], [quant.]		
CMR (carcinogens, mutagens and substances toxic to reproduction)	[chem. agent], [quant.]		
Corrosive	[chem. agent], [quant.]		
Irritant	[chem. agent], [quant.]		

Flammable	[chem. agent], [quant.]		
Oxidizing	[chem. agent], [quant.]		
Explosiveness	[chem. agent], [quant.]		
Asphyxiant	[chem. agent], [quant.]		
Dangerous for the environment	[chem. agent], [quant.]		
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]		

Hazard identification: Hazards named in the document relevant for the fixed MINIBALL + CD installation.

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