EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

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

Following HIE-ISOLDE Letter of Intent I-110

Coulomb excitation of $^{182-184}$Hg: Shape coexistence in the neutron-deficient lead region

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Abstract

We put forward a study of the interplay between individual nucleon behavior and collective degrees of freedom in the nucleus, as manifested in shape coexistence in the neutron-deficient lead region. As a first step of this experimental campaign, we propose to perform Coulomb excitation on light mercury isotopes to probe their excited states and determine transitional and diagonal E2 matrix elements, especially reducing the current uncertainties. The results from previous Coulomb excitation measurements in this mass region performed with 2.85 MeV/u beams from REX-ISOLDE have shown the feasibility of these experiments. Based on our past experience and the results obtained, we propose a detailed study of the $^{182-184}$Hg nuclei, that exhibit a pronounced mixing between low-lying excited states of

apparently different deformation character, using the higher energy beams from HIE-ISOLDE which are crucial to reach our goal. The higher beam energy should result in an increased sensitivity with respect to the quadrupole moment of the first and the second 2^+ states and to the overall deformation of the ground and first excited 0^+ states, including triaxiality, and will provide information on excited states (yrast and non-yrast) up to spin 8^+ from multiple-step Coulomb excitation. These observables will form stringent tests of beyond mean field and algebraic model based calculations.

Requested shifts: 30 shifts (split into 1 run over 1 year)
Beamline: MINIBALL + CD-only

1. Introduction and physics case

Shape coexistence whereby two or more shapes coexist at low excitation energy in the atomic nucleus is an intriguing phenomenon [1,2,3]. Its manifestation in the neutron-deficient nuclei in the Z=82 region has been first observed through optical spectroscopy measurements whereby a sharp transition in the mean-square-charge-radii was discovered between ^{187}Hg and ^{185}Hg [4] and since then a wide spectrum of experimental tools has been used to understand shape coexistence in this mass region (decay studies, laser spectroscopy and in-beam spectroscopy studies, and more recently Coulomb excitation experiments using post-accelerated beams from REX-ISOLDE). This resulted, amongst others, in the discovery of triple shape coexistence in ^{186}Pb [5] and an early onset of deformation in the light polonium isotopes as evidenced through laser spectroscopic studies [6]. Understanding the evolution and microscopic origin of quadrupole collectivity and shape coexistence is important as it highlights the subtle interplay between the individual nucleon behavior sharpened by the strong Z=82 shell closure and collective degrees of freedom in the atomic nucleus. These experimental observations, therefore, form ideal testing grounds of different theories. Several contemporary theoretical models have been applied to describe the structure of the nuclei around Z=82, such as phenomenological shape mixing calculations, symmetry guided models like e.g. the interacting boson model truncations [7], and beyond mean-field approaches [6,8]. These models do reproduce the global trends of the experimental findings, however important elements, especially on the subtle mixing of the different configurations, remain not understood.

In the neutron-deficient mercury isotopes with neutron number around mid-shell (N=104, ^{184}Hg) the intruding deformed states come low in excitation energy and mix with the normal more spherical states (see Fig. 1, left side). On the other hand the mixing of deformed states in the ground states of the even-even nuclei is limited as evidenced by the charge radii results that are summarized below (Fig.1, right side).

The mixing between the different states gives rise to strongly converted $2^+_2 \rightarrow 2^+_1$ transitions as recently deduced from beta-decay studies of ^{182,184}Tl performed at ISOLDE [9,10]. Moreover life times of several states have been obtained in in-beam studies (recoil distance Doppler-shift (RDDS) method [11,12,13]), these are essential to extract reliable quadrupole matrix elements from the Coulomb excitation (Coulex) analysis.

HIE-ISOLDE will provide unique, intense and pure, pencil-like beams ideally suited for Coulomb excitation in the lead region. The successful Coulomb excitation experiments using the germanium MINIBALL array to study some selected neutron-deficient, even-even mass isotopes of mercury, lead, polonium and radon have shown the potential to perform such experiments using post-accelerated ISOLDE beams and to obtain important information (transitional and diagonal matrix elements, mixing amplitudes and the population of yrast and non-yrast states) [14].

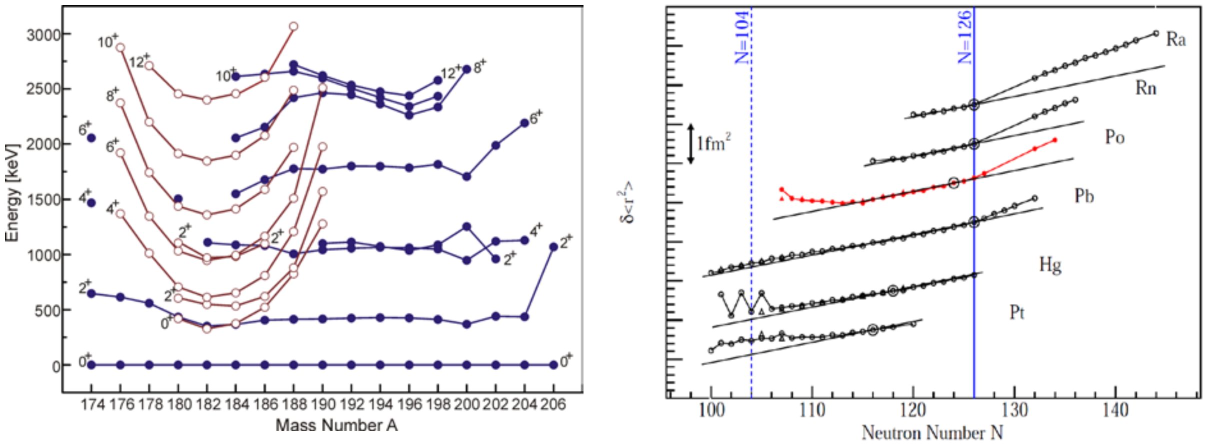

Figure 1: Left: energy level systematics of even-even Hg isotopes, taken from reference [9]. The full circles are associated with the weakly oblate band and the open circles are those related to the excited prolate band in even – even Hg isotopes.; Right: overview of the changes in the mean square charge radii for Pt, Hg, Pb, Po, Rn, Ra taken from reference [6].

However, with the low-energy of the current REX accelerator (typically 2.9 MeV/u), the population of the excited states is mainly restricted to the first 0^+, 2^+ and 4^+ states. Moreover, the sensitivity of the obtained data on the sign of the quadrupole deformation is limited. Higher beam energies and intensities, as well as improved purity and phase space conditions, will allow extracting precisely the set of reduced matrix elements that couple several excited states (including non-yrast states where currently little information is known). Combining the Coulex data with results from life-time measurements and beta-decay studies (relative gamma-ray intensities, conversion coefficients) will enable deducing the sign of the quadrupole moment of several states, particularly of the 2^+_1 and 2^+_2 states. Furthermore, using the rotational-invariant technique prescription [15,16], the overall deformation, as well as triaxiality of the 0^+ states can be deduced.

2. Results from previous experiments and comparison with theory

Using beams from REX-ISOLDE, Coulomb excitation studies have been performed on a series of even-even mercury ($^{182-188}$Hg), lead ($^{188-192}$Pb), polonium ($^{196-206}$Po) and radon ($^{208-212}$Rn, $^{220-224}$Rn) isotopes. The data analysis of the mercury data set has been finalized and the results will soon be published. The other data sets were collected more recently (lead in 2011, polonium in 2012 and radon in 2010, 2012) and are under analysis.

In the previous experiments performed at 2.85 MeV/u ^{182,184}Hg beam, gamma ray yields which depopulate the 2^+_1, 2^+_2 and 4^+_1 states were observed. Moreover an intense X-ray peak was present in the spectrum. A careful analysis of this peak and the gamma coincidence spectra learn that it stems from atomic X-rays produced when the ^{182}Hg beam passes the target, from the conversion of the observed gamma rays and the de-excitation of the 0^+_2 state [17]. From its intensity we were able to deduce the population of the 0^+_2 excited state and obtain information on all connecting matrix elements albeit with limited accuracy. Crucial for this analysis was the knowledge on the conversion coefficient of the

$2^+_2 \rightarrow 2^+_1$ transition as it contained a large E0 component (total conversion coefficient is equal to 4.2 +/- 0.8 in ^{182}Hg [10] and 23 +/- 5 in ^{184}Hg [10]). Data of similar quality were obtained for ^{184,186,188}Hg. This analysis also showed the need for "projectile particle – target particle – gamma coincidences" to obtain unambiguous data. This limits the choice of the target for the Coulex experiments in this mass region.

Table 1 shows the final results obtained for the most important matrix elements. Note the large uncertainty on the E2 diagonal matrix element of the 2^+_1 state. Only for ^{184}Hg and ^{188}Hg we can state that within one sigma, the sign of the E2 diagonal matrix element of the 2^+_1 state is positive which corresponds to an oblate shape.

Table 1. The most important E2 matrix elements obtained for ^{182}Hg and ^{184}Hg. The numbers in brackets are the extracted lower (left) and upper (right) error bars of the E2 matrix element.

ME2 [eb]	^{182}Hg	^{184}Hg
$<0^+_1\|\|E2\|\|2^+_1>$	1.29 (3; 4)	1.27 (4; 5)
$<2^+_1\|\|E2\|\|4^+_1>$	-3.71 (6)	-3.07 (6)
$<0^+_1\|\|E2\|\|2^+_2>$	0.6 (3)	0.21 (2)
$<0^+_2\|\|E2\|\|2^+_1>$	-2.65 (15)	-2.48 (138)
$<0^+_2\|\|E2\|\|2^+_2>$	1.63 (22; 19)	1.27 (23; 17)
$<2^+_1\|\|E2\|\|2^+_2>$	2.74 (23; 18)	-0.88 (7; 8)
$<2^+_1\|\|E2\|\|2^+_1>$	-0.07 (129; 117)	1.4 (12; 18)
$<2^+_2\|\|E2\|\|2^+_2>$	1.22 (71; 120)	-3.4 (19; 17)
$<2^+_1\|\|E2\|\|2^+_3>$	-	-0.96 (25)
$<0^+_2\|\|E2\|\|2^+_3>$	-	|1.15| (30)

For ^{182,186}Hg within two sigma, no conclusions can be drawn. Based on the extracted E2 matrix elements and using the quadrupole sum rule approach from the rotational invariant technique [15, 16] we obtain information on the deformation of the 0^+ ground and excited state (Fig. 3). Using this approach the ground states of the even-even mercury $^{182-188}$Hg isotopes appear to be slightly deformed with β value close to 0.15 and of oblate nature, while the excited 0^+ states are more deformed. Unfortunately, the lack of accuracy on key matrix elements prevent us from drawing firm conclusions on the nature of the deformation of the excited 0^+ state but triaxial deformation is definitely not excluded. In order to reduce the uncertainties of the extracted deformation parameters of the 0^+_1 and 0^+_2 states, more precise values on the following matrix elements are needed: $0^+_2 \rightarrow 2^+_1$, $2^+_1 \rightarrow 2^+_1$, $2^+_2 \rightarrow 2^+_2$ and any matrix element connecting to the 2^+_3 state.

Beyond mean-field calculations based on projected mean-field configurations with axial quadrupole deformations predict two 0^+ states close in energy in ^{182}Hg and ^{184}Hg. However, the ground state is dominated by prolate configurations while the first excited 0^+ is spread over a large range of deformations, in contradiction with the data. The yrast 2^+ is therefore predicted to be mainly prolate while experimentally, it seems that the prolate band becomes yrast only for $J=4^+$. Theoretically, these isotopes seem also to be very soft against triaxiality. It looks probable that inclusion of triaxiality will still alter this picture.

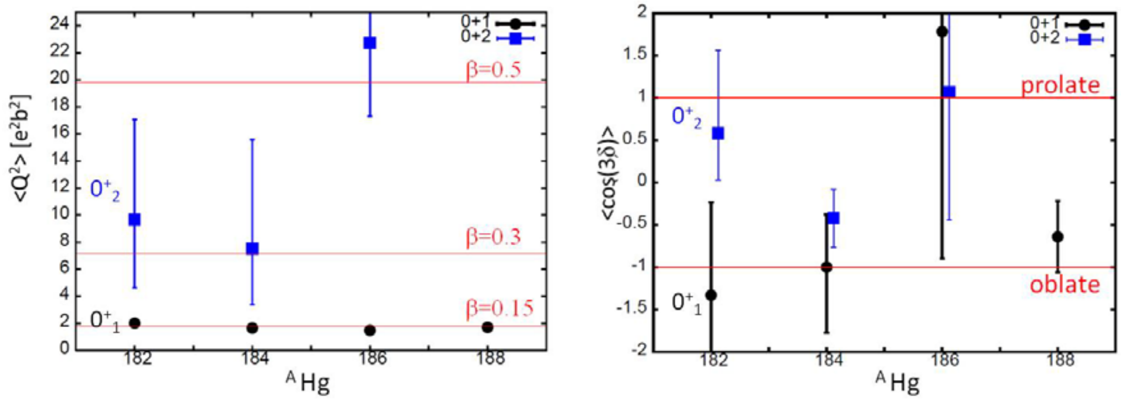

Figure 2: Experimental expectation values of <Q²> (quadrupole overall deformation parameter) and <cos(3d)> (quadrupole asymmetry parameter) for the two first 0^+ states on $^{182\text{-}188}$Hg isotopes.

This complicated theoretical situation demonstrates the interest of obtaining direct information on the geometry of the first states of these Hg isotopes. In particular, spectroscopic quadrupole moments for the 2^+ states are of prime importance [22].

3. Experimental setup and feasibility

These experiments will be performed with the MINIBALL germanium detector array, containing 8 triple clusters, equipped with a segmented silicon array. Expected count rates based on GOSIA [18] calculations for the Coulomb excitation of ^{182,184}Hg accelerated beams on a ^{120}Sn target (2 mg/cm^2) are shown in Fig. 3. The calculations were performed for ^{182,184}Hg beam intensities of 10^4 and 10^5 pps respectively and beam energy at 4 MeV/u. During the past experiments we obtained $5*10^3$ pps and 10^5 pps respectively. Both scattered ^{182,184}Hg projectiles (maximum laboratory angle ~ 41°) and ^{120}Sn target recoils will be detected using the DSSSD CD detector which subtends an angular range 15°- 50° in the laboratory frame.

The energy was chosen to be close to the safe energy calculated for the maximum scattering angle of 100° in the CM system and corresponds to 85% of the safe energy. The gamma-ray yield calculations are based on the matrix elements extracted from our previous experiments (Coulomb excitation and RDDS lifetime measurements) and include gamma-ray efficiencies of Miniball and the above mentioned beam intensities. The figure shows the expected number of counts per shift. A beam time of 4 and 24 shifts for ^{184}Hg and ^{182}Hg respectively will allow to accumulate sufficient statistics to reduce the errors on the diagonal matrix element of the 2^+ states to a level where a clear distinction between a negative, zero or positive quadrupole moment will be possible, as well as to determine the B(E2) values of transitions in the non-yrast band.

In order to determine the E0 $0^+_2 \rightarrow 0^+_1$ transition intensity we will use two alternative methods. The above mentioned technique using the X-rays will be refined using the recent measurements with lead and polonium beams to map the contribution of atomic X-rays in a systematic way. Also, a new electron spectrometer will be used in conjunction with the MINIBALL array allowing simultaneous gamma-ray – conversion electron detection. This new spectrometer, called SPEDE, will be located in the MINIBALL target chamber at backward angles without hampering the gamma-ray detection efficiency [19]. The heart of SPEDE is a segmented Si-detector allowing Doppler correction of electron energies. The overwhelming background from delta-electrons will be removed by means of high voltage and absorber foils. The expected detection efficiency at energies of interest is around 9%.

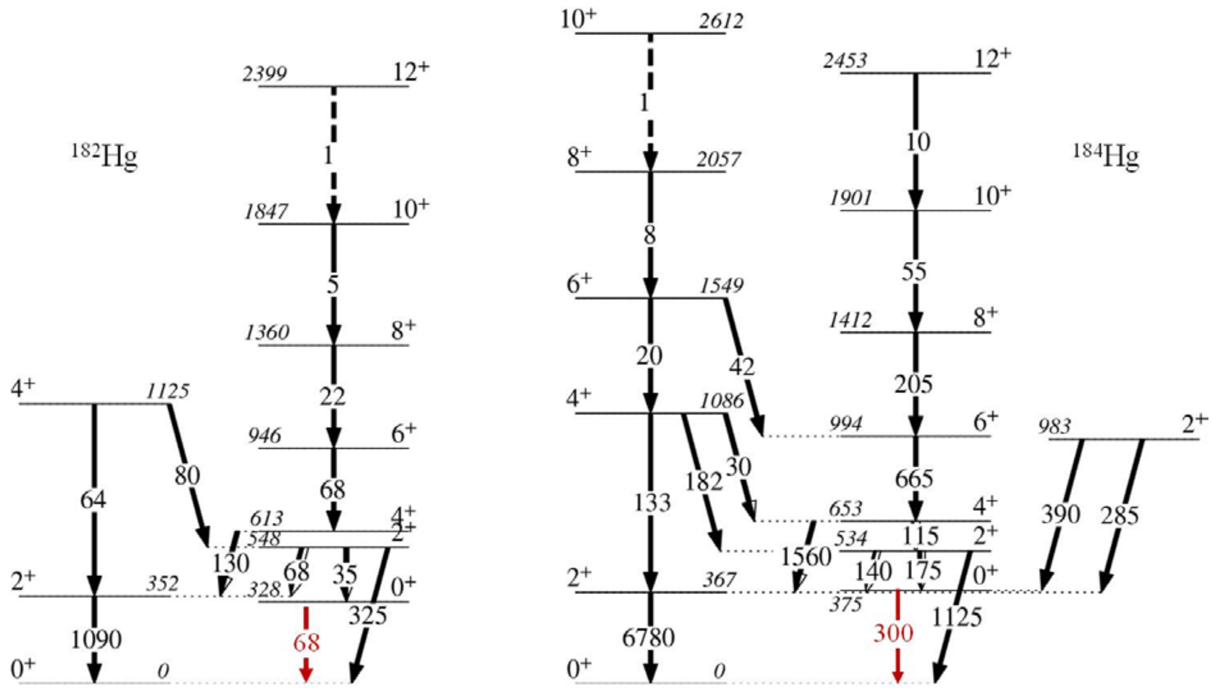

Figure 3: Expected number of counts in the photo peak per shift based on GOSIA calculations for the Coulomb excitation of ^{182,184}Hg accelerated beams on a ^{120}Sn target (2 mg/cm^2) with intensities of 10^4 and 10^5 pps respectively at 4 MeV/u. The number of estimated converted transitions, taken into account the detection efficiency of the SPEDE detector around 9%, is marked in red.

4. Outlook

As mentioned in the HIE-ISOLDE Letter of Intent [20] the proposed experiment is part of a larger campaign to probe shape coexistence in the neutron-deficient lead region studied with HIE ISOLDE beams using Coulex and transfer reaction studies. Depending on the outcome of the proposed experiment and the ongoing data analysis in the other isotopic chains, proposals will be submitted for neutron-deficient lead, polonium and radon beams including isomeric beams.

5. Beam requirements

- isotopes: **$^{182-184}$Hg** (half-life times: 10.8 s and 30.9 s respectively);
- intensity: **10^4** pps for ^{182}Hg and **10^5** pps for ^{184}Hg;
- beam energy: **4 MeV/u;**
- spatial properties of the beam: 3 mm diameter beam spot size at the target position;
- purity: >90% purity was reached in the previous experiments;
- time profile: the beam pulse from the EBIS should be as long and as homogeneous as possible (a flat profile >400 microsecond long would be ideal).

Summary of requested shifts:

We request a total number of **30 shifts** of beam time to perform this experiment: **24 shifts** for ^{182}Hg and **4 shifts** for ^{184}Hg, as well as **2 shifts** for setting–up HIE ISOLDE. According to our estimations collected statistics will allow to reduce the errors on the diagonal matrix element of the 2^+ states and to determine a sign of the quadrupole moment as well as the unknown B(E2) values between states in the non-yrast band of ^{182,184}Hg.

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Appendix

DESCRIPTION OF THE PROPOSED EXPERIMENT

The experimental setup comprises: MINIBALL + CD

Part of the Choose an item.	Availability	Design and manufacturing
[if relevant, name fixed ISOLDE installation: MINIBALL + only CD]	☒ Existing	☒ To be used without any modification
MINIBALL + only CD	☒ 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
MINIBALL + SPEDE	☐ 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 Segmented Si detector and cooling will be tested in Jyväskylä; modifications to target chamber
[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 at REX-ISOLDE.

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)	(1) ^{182}Hg ions (2) ^{184}Hg ions		

Beam intensity	10^4 ^{182}Hg 10^5 ^{184}Hg		
Beam energy	4 MeV.A		
Cooling liquids	Liquid N_2		
Gases	[gas]		
Calibration sources:	☐		
• Open source	☐		
• Sealed source	☐ [Standard γ -ray sources for MINIBALL 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