EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

Letter of Intent to the ISOLDE and Neutron Time-of-Flight Committee

Measurement of octupole collectivity in uranium

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Abstract

The primary goal of this experimental programme is to measure the strength of octupole correlations in neutron deficient uranium isotopes, predicted to have B(E3) values much larger than those we have previously observed in this mass region. To this end we request beam development time to optimise the yield and purity of the short-lived uranium isotopes with A=226,228,230.

Requested shifts: 4
Beamline: ISOLTRAP, MINIBALL

Physics motivation

The experiments proposed here aim to improve our understanding of the phenomenon of reflection asymmetry or 'pear shapes' that arises from octupole correlations in nuclei, in particular in isotopes of uranium. There is an abundance of experimental data and theoretical studies of octupole correlations in this mass region (for reviews see, e.g., [1, 2]) but the data for U (and Th) nuclei are incomplete and the theories give quite divergent predictions for some of the measurable observables in these nuclei. For even-even nuclei an important experimental indicator is the difference in alignment of the low-lying negative-parity states and the positive-parity states in the ground-state band. Figure 1 summarises these data for isotopes of Rn, Ra, Th and U, which suggest that for 132 < N < 140 the isotopes of Rn are octupole vibrational (difference in alignment $\Delta i_x \approx 3\hbar$) whereas the isotopes of Ra, Th and U have stable octupole deformation ($\Delta i_x \approx 0$).

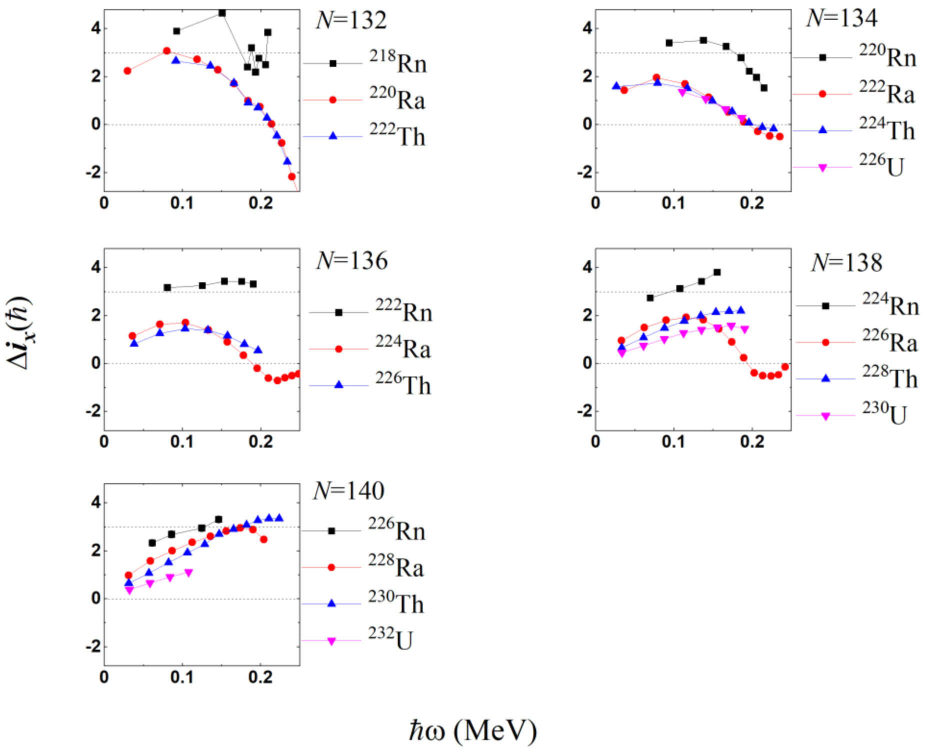

Figure 1 Plots of the difference in aligned angular momentum, Δi_x against rotational frequency ω for isotopes of Rn, Ra, Th and U. Taken from [13].

Another indication of octupole shapes is the observation of enhanced odd-Eλ moments for nuclear transitions between states of opposite parity. Large values of E1 moments have been observed for several isotopes of Ra and Th, e.g., the recent measurement in ^{228}Th [3]. However, there can be sizeable fluctuations in the E1 values because the interacting nucleons contribute both individually and collectively, giving rise to a net moment of nearly zero in some cases, as observed for ^{224}Ra [4]. On the other hand, the E3 moment is a more reliable indicator of octupole correlations as it arises from the reflection-asymmetric charge distribution throughout the nuclear volume, and largely depends on the collective behaviour of the nucleons.

For heavy nuclei where octupole correlations are expected to be strongest, measurements of $\langle I_i||\mathcal{M}(E3)||I_f\rangle$ have been reported for ^{220}Rn [5], ^{222}Rn [6], ^{222}Ra [7], ^{224}Ra [5], ^{226}Ra [8] and ^{228}Ra [7]. The trend of the values of $\langle 0^+||\mathcal{M}(E3)||3^-\rangle$ $(=\sqrt{7/16\pi}\,Q_3)$ is shown in figure 2, which suggests an enhancement of octupole correlations for even-even Ra isotopes with N < 140.

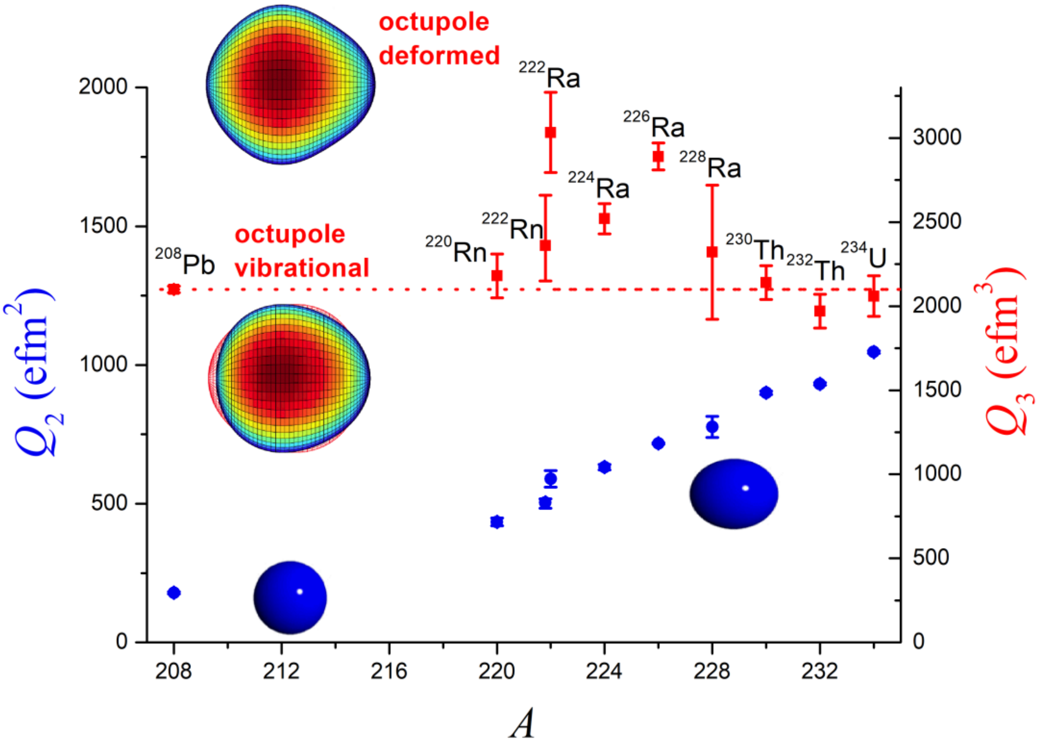

Figure 2 The systematics of measured E2 and E3 intrinsic moments Q_λ for $0^+ \rightarrow 2^+$ and $0^+ \rightarrow 3^-$ transitions, respectively, in the heavy mass region (A ≥ 208). Taken from [6, 13].

Enhanced values of E3 moments have also been observed in ^{144}Ba [9] and ^{146}Ba [10] albeit with large uncertainties; smaller values have been observed in ^{142}Ba [11] and ^{143}Ba [12].

Although theoretical calculations of the values of $\langle 0^+||\mathcal{M}(E3)||3^-\rangle$ can widely vary (see, e.g., figure 7 in Ref [13]), most agree that isotopes of U (and Th) with N ~ 132-136 should have deep minima in their potential-energy surfaces for non-zero values of octupole deformation, giving rise to large values of the E3 moment, see, e.g., Refs [14-22]. An example of one such set of calculations, taken from Ref [15], is shown in figure 3. Large values of B(E3; $0^+ \rightarrow 3^-$) (= $\langle 0^+||\mathcal{M}(E3)||3^-\rangle^2$) are predicted for ^{226,228,230}U; the 50% increase between Z=88 and Z=92 is much larger than that expected from the Z^2A^2 dependence of this quantity for identical octupole deformation.

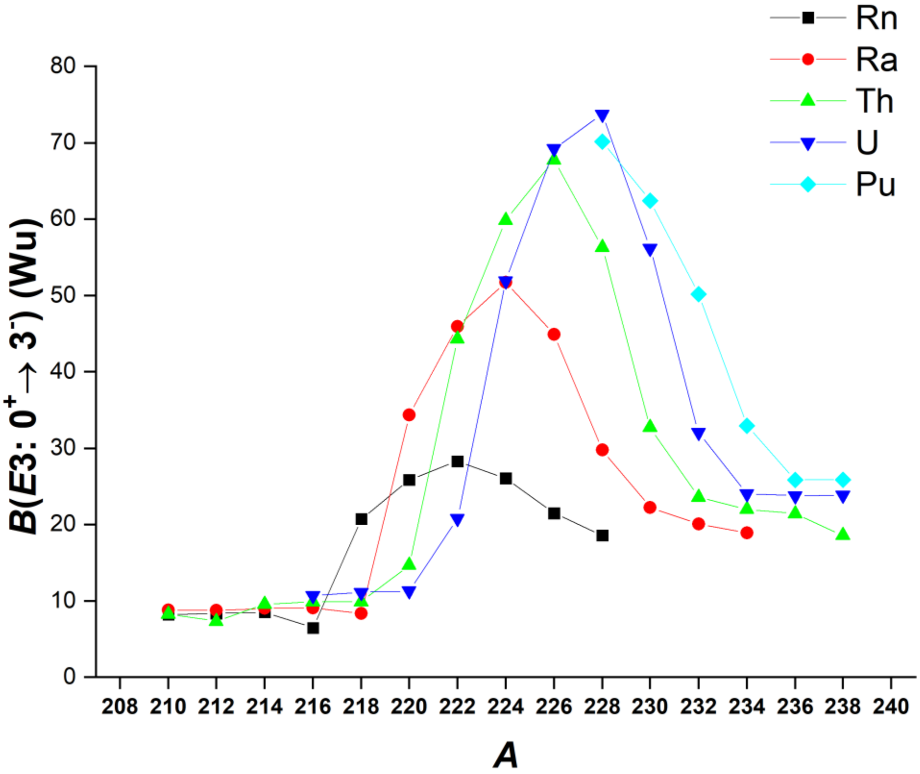

Figure 3 Theoretical values, taken from Ref [15], of B(E3; $0^+ \rightarrow 3^-$) transition strengths versus A for various isotopes of Rn, Ra, Th, U and Pu.

It is *de rigueur* to highlight the relevance of the measurements of E3 moments with on-going searches for non-zero Electric Dipole Moments (EDMs) in atoms with odd-A nuclei, whose observation would indicate CP violation much larger than that predicted by the Standard Model. Octupole-deformed nuclei will have enhanced nuclear Schiff moments that induce the atomic EDM due to the presence of nearly degenerate parity doublets and large reflection-asymmetric octupole deformations (see, e.g., Refs [23, 24]). Programmes of EDM searches using ^{225}Ra at Argonne [25], FRIB and ISOLDE [26] are underway; measurements of large E3 moments in U will infer large Schiff moments for the atomic systems [24]. Such observations could promote new candidates for EDM searches such as ^{225,227}Ac, ^{229}Th and ^{229}Pa [27] which can possibly be harvested from ISOLDE [28].

Proposed experiments

The primary goal of this experimental programme is to exploit post-accelerated beams using HIE-ISOLDE to measure the values of $\langle I_i||\mathcal{M}(E3)||I_f\rangle$ for transitions in ^{228}U, and possibly ^{226,230}U. These are considered to be refractory elements that are normally not available at ISOL facilities; however recently it has been demonstrated that certain uranium molecules are released from the primary target with measurable yields (see below). Our experience of measuring $E3$ matrix elements in ^{220,222}Rn and ^{222,224,228}Ra at ISOLDE [5-7], using the Miniball γ-ray spectrometer, suggests that the predicted re-accelerated beam intensity of $\sim 10^{4\text{-}5}$ U ions/s on the target will be sufficient to determine $\langle 0^+||\mathcal{M}(E3)||3^-\rangle$ with a precision of 10% or better. Such experiments require about 2 days of running time, bombarding two targets of different Z at energies of ~ 3MeV/u and 4MeV/u (chosen to be safe for the Coulomb excitation experiments). The analysis of the Coulomb-excitation data will be performed using the least-squares fit code GOSIA, a technique used extensively by this collaboration. It will be necessary to determine the level scheme of ^{228}U using a similar method as employed for ^{224,226}Rn [29], carried out at a bombarding energy of ~5MeV/u at ISOLDE. As demonstrated for our experiments the measurement of internal conversion coefficients is not necessary, as the members of the positive-parity band are identified by their strong population from Coulomb excitation, while knowledge of the energies of the lowest negative-parity states in ^{226}U [30] and ^{230}U [31] will help assign these states in ^{228}U. The energies of the lowest strongly-converted transitions in the ground-state band can be deduced by a Harris-type extrapolation, as applied to ^{226}U [30] and ^{254}No [32]. It may be that other methods to study ^{228}U can be employed using stable beams; however, these would use reactions with ~nb cross-sections or require radioactive targets such as ^{231}Pa, and would in many respects be more challenging than the proposed experiment using a ^{228}U beam.

Beam Request for this Letter of Intent

The ISOLDE target group have shown that volatile uranium molecules such as UO_x (produced at high source temperatures) or UF_x (produced by injection of fluorine gas) can be extracted and identified using the ISOLTRAP MR-ToF apparatus [33]. The measurements have so far been carried out for the long-lived isotopes ^{235,238}U. Here we request 4 shifts for a two-stage approach to determine the yield and purity of the short-lived uranium isotopes ^{228}U ($T_{1/2}$ 9.1m), ^{230}U (21d) and possibly ^{226}U (0.28s), following proton bombardment of the UCx target. As part of the general target and ion source development strategy at ISOLDE we will employ ISOLTRAP and a tapestation to characterise the UO_x and UF_x beams for the neutron-deficient uranium isotopes (2 shifts). If this proves successful then we will then measure the post-accelerated yields of these isotopes: the molecules will be broken up in REXTRAP, charge-bred in REXEBIS, and transported after re-acceleration in HIE-ISOLDE to the target and beam dump in Miniball (2 shifts). Here observation of γ-rays from the prompt Coulomb excitation at the secondary target and delayed γ-rays from α,β-decay at the beam dump will allow the beam composition to be assayed.

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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	☒ 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
ISOLTRAP	☒ 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] 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			
Beam particle type (e, p, ions, etc)	(1) ^{226}U (2) ^{228}U (3) ^{230}U		
Beam intensity			
Beam energy	3-5 MeV/u		
Cooling liquids	Liquid N_2		
Gases	[gas]		
Calibration	☐		

sources:			
- Open source	☐ ^{133}Ba for electron detector (contained with thin window)		
- Sealed source	☒ [Standard γ -ray sources for MINIBALL ISO standard]		
- Isotope			
- Activity	< 10 μCi		
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