Measurements of octupole collectivity in Rn and Ra nuclei using Coulomb Excitation

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

(Following HIE-ISOLDE Letter of Intent I-091)

Measurements of octupole collectivity in Rn and Ra nuclei using Coulomb excitation

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Abstract

We propose to exploit the unique capability of HIE-ISOLDE to provide post-accelerated ^{221,222}Rn and ^{222,226,228}Ra ion beams for the study of octupole collectivity in these nuclei. We will measure E3 transition moments in ^{222}Rn and ^{222,226,228}Ra in order to fully map out the variation in E3 strength in the octupole mass region with Z~88 and N~134. This will validate model calculations that predict different behaviour as a function of N. We will also locate the position of the parity doublet partner of the ground state in ^{221}Rn, in order to test the suitability of odd-A radon isotopes for EDM searches.

Requested shifts: 29 shifts, split into 2 runs over 2 years
Beamline: MINIBALL + CD, MINIBALL + SPEDE

Introduction

For certain combinations of protons and neutrons there is a theoretical expectation that the shape of nuclei can assume octupole deformation, which would give rise to reflection asymmetry or a "pear-shape" in the intrinsic frame, either dynamically (octupole vibrations) or statically (permanent octupole deformation). Octupole forces are expected to be important when states with orbital and angular momentum differing by 3 units of $\hbar$ lie close to each other and the Fermi level. Octupole correlations should occur near the proton numbers Z= 34, 56, and 88 and the neutron numbers N= 34, 56, 88, and 134. These will be largest for the heaviest nuclei, having both Z~88 and N~134. Indeed, at these values of Z and N, nuclei exhibit phenomena associated with reflection asymmetry such as odd-even staggering of the positive- and negative-parity yrast bands in even-even nuclei and parity doublets in odd-mass nuclei and enhanced E1 moments due to a division of the centre of charge and centre of mass. A broad overview of the experimental and theoretical evidence for octupole correlations is given in reference [1].

Many theoretical approaches have been developed to describe the observed experimental features: Nilsson-Strutinsky approaches with deformed folded Yukawa and Woods-Saxon potentials, self consistent models using the Skyrme and Gogny forces, cluster models, approaches using the IBA, interpretations as rotation-induced condensation of octupole phonons and other semi-phenomenological approaches. Only the microscopic and macroscopic-microscopic models have been able to account for the behaviour of the E1 moments, but these are small ($< 10^{-2}$ single particle units) and are dominated by single-particle and cancellation effects. The only observable that should provide unambiguous and direct evidence for enhanced octupole correlations in these nuclei is the electric octupole (E3) moment, because it is generated by coherent contributions arising from the quadrupole-octupole shape and should be quite insensitive to single-particle effects. Until the measurements carried out recently by our collaboration [2], E3 moments have been determined for only one nucleus in the centre of the Z~ 88, N~134 region, ^{226}Ra [3], so that theoretical predictions have been subject to a limited scrutiny of their treatment of this quantity.

Beyond nuclear physics, atoms with octupole-deformed nuclei are very important in the search for permanent atomic electric-dipole moments (EDM). The observation of a non-zero EDM indicates T-violation beyond the Standard Model. Measurements that give a limit on the EDM provide the most important constraints on the many proposed extensions of the Standard Model [4]. Octupole-deformed nuclei will have enhanced nuclear “Schiff” moments due to the presence of nearly degenerate parity doublets (seen in odd-mass nuclei) and large collective octupole deformation e.g. [5, 6]. Since the Schiff moment induces the atomic EDM, the sensitivity over reflection-symmetric systems such as for ^{199}Hg, currently providing the most stringent limit on an EDM, can be improved by a factor of 100-1000. Essential in the interpretation of such limits in terms of new physics is a detailed understanding of the structure of these nuclei. Experimental programmes are in place to measure EDMs in both odd Rn and odd Ra octupole nuclei but so far there is little direct information on octupole correlations in these nuclei, and almost no information of the structure of the odd Rn nuclei.

Report on IS475: study of ^{220}Rn and ^{224}Ra

In our previous experiments carried out in 2010 and 2011, 3 x 10^5 and 7 x 10^5 ions/s of ^{220}Rn and ^{224}Ra ions/s respectively with energy of ~2.82 MeV.A bombarded secondary targets of ^{60}Ni, ^{114}Cd and ^{120}Sn of thickness ~ 2 mg/cm^2. We observed strong population of the ground state band of positive-parity states, excited by direct and multiple E2 Coulomb excitation, and substantial population of the octupole band of negative-parity states, excited by E3 excitation. The yields of the observed γ-ray transitions detected in MINIBALL were measured for two ranges of recoil angle for each of the three targets, and combined with existing spectroscopic data (lifetimes of low-lying states and branching ratios) to provide input to the Coulomb excitation analysis code GOSIA [7]. This code performs a least-squares fit to the matrix elements between all known states in the excitation process, which are treated as free parameters. The values of the intrinsic moments, Q_λ, determined from the experimental value of $\langle I||E\lambda||I'\rangle$, assuming the validity of the rotational model, are given in figure 1. For the E2 and E3 matrix elements the measured values are all consistent with the geometric predictions expected from a rotating, pear-shaped (static or dynamic) distribution of electric charge.

The values of Q_3, deduced from the measured B(E3; $0^+ \rightarrow 3^-$) values, are plotted in figure 2 as a function of *N*. We find that the E3 moment changes by about 50% in the entire mass region. The larger Q_3 values for ^{224}Ra and ^{226}Ra indicate an enhancement in octupole collectivity that is consistent with an onset of octupole deformation in this mass region. On the other hand ^{220}Rn has similar octupole strength to ^{230,232}Th (and to ^{208}Pb), consistent with it being an octupole vibrator as indicated by the behaviour of its energy levels [8]. If indeed this is the case then the conditions for enhancement of the Schiff moment for the odd mass system, rigid octupole shape and near-degeneracy of the parity-doubled states [9], are unlikely to be met. All experimental data are in reasonable agreement with recent theoretical calculations either using the generator-coordinate extension of the Hartree-Fock-Bogoliubov self-consistent mean field theory [10] or using a cluster model [11]. However, the trend of the experimental data is that the values of Q_3 decrease from a peak near ^{226}Ra with decreasing N (or A), which is in marked contrast to the predictions of the cluster model calculations.

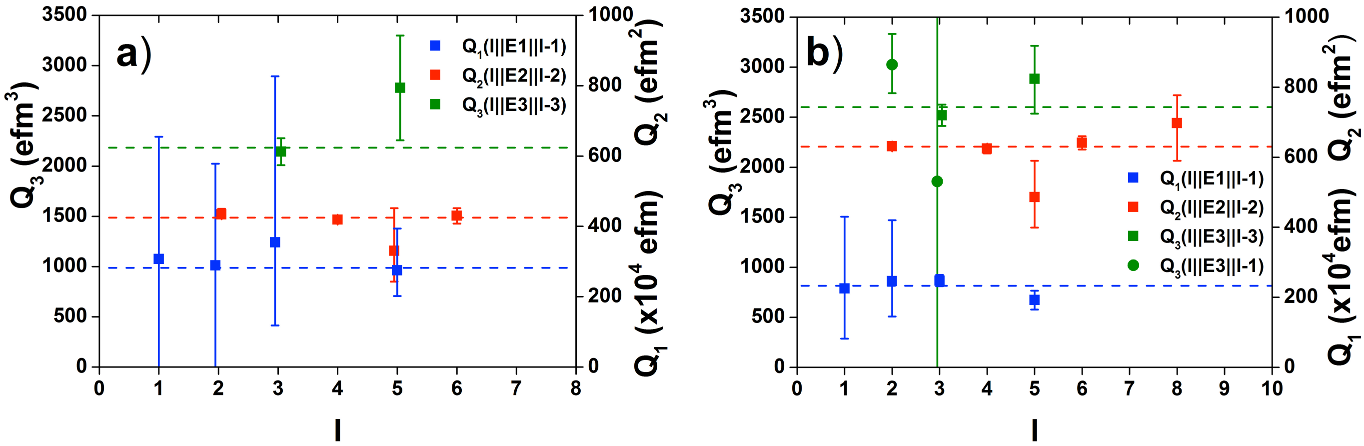

Figure 1. The values of the E1, E2 and E3 intrinsic moments Q_λ derived from the matrix elements using the relation $\langle I_i \| E_\lambda \| I_f \rangle = \sqrt{(2I_i+1}\left(I_i 0 \lambda 0 | I_f 0\right) Q_\lambda a_\lambda$ where a_λ is a constant, for (a) ^{220}Rn and (b) ^{224}Ra. The dashed lines have the value of the weighted mean for each Q_λ.

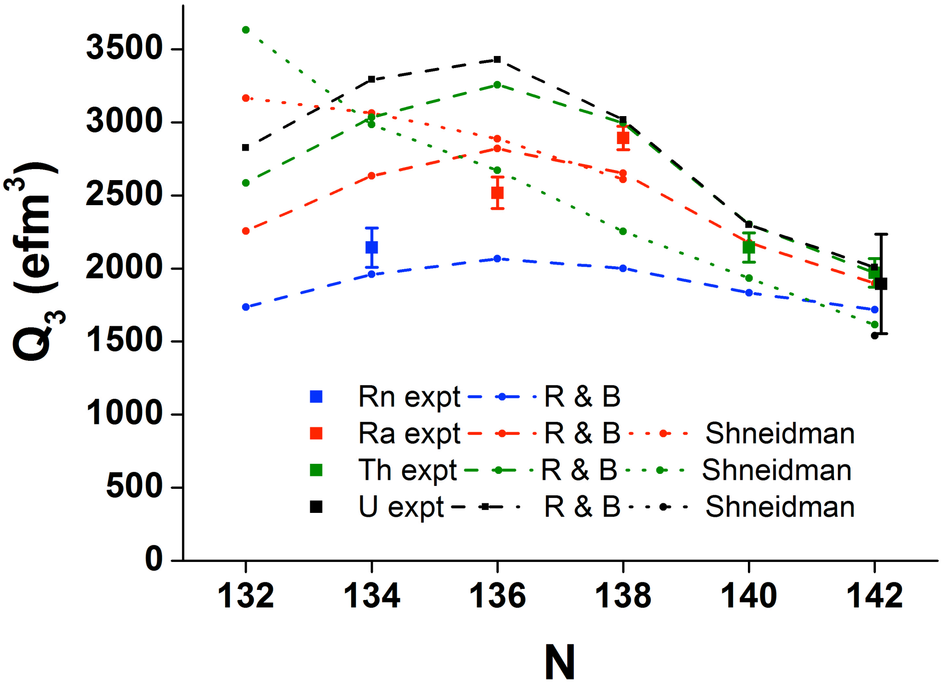

Figure 2. Measured values of Q_3 for the $0^+ \rightarrow 3^-$ transition in nuclei as a function of N. The calculated values of Robledo and Bertsch [10] and Shneidman et al [11] are given with a line joining the values to guide the eye.

Report on IS475: study of ^{221}Rn

In August/September 2012 we collected MINIBALL data following bombardment of 2mg/cm^2 ^{120}Sn with 5 x 10^3 ^{221}Rn ions/s. In this run the VADIS ion-source was not in its optimal configuration and the beam intensity was a factor of 10 lower than expected. The γ-ray spectrum accumulated after 24h is shown in figure 3.

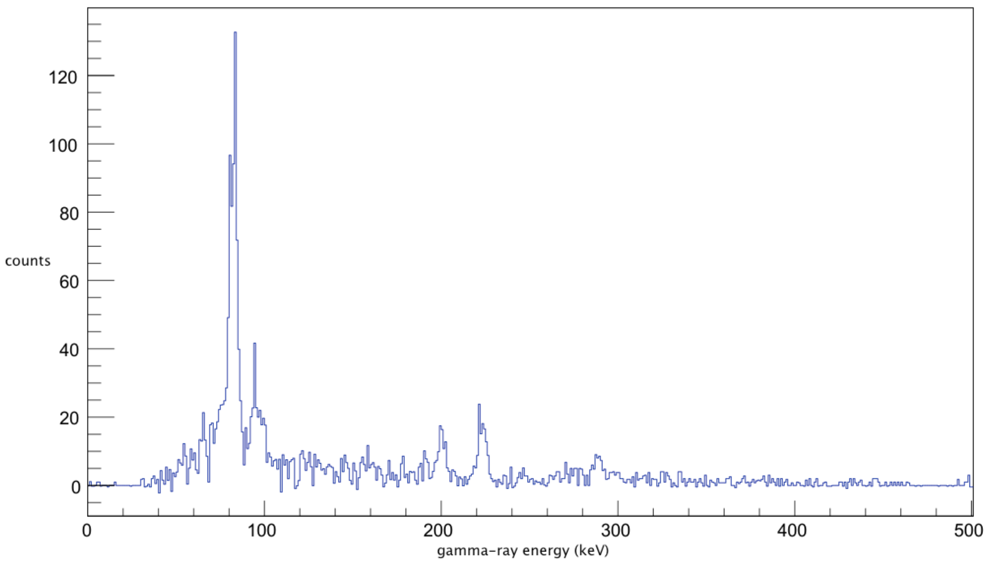

Figure 3. γ-ray spectrum following the bombardment of a ^{120}Sn target by ^{221}Rn

This spectrum is dominated by low energy transitions (presumably Rn X-rays), but 3 transitions at ~200, 225 and 290 keV can also be seen. These data are currently being analysed.

Proposal: measurement of octupole collectivity in ^{222}Rn, ^{222}Ra, ^{226,228}Ra

We propose to measure the B(E3) strength in these nuclei in order to complete the mapping of the octupole collectivity in this mass region, as well as re-measuring the B(E3; $0^+ \rightarrow 3^-$) in ^{226}Ra. This will provide a stringent test of the HFB and cluster calculations that predict the opposite behaviour in Q_3 as a function of N. These experiments will be carried out at 4 MeV.A, near the maximum "safe" Coulex energy, which will give a factor of 4 more yield in the population of the 3^- state as compared to that obtained using beams from REX-ISOLDE. A comparison of the calculated yields at the two energies (3 MeV.A and 4 MeV.A) is given in table 1. The beam intensities are for a UCx primary target and are estimated based on our experience of using the VADIS plasma ion-source (with a cooled transfer line) for ^{220}Rn and the tungsten surface ion-source for ^{224}Ra. The total beam time for each ion is given in the table; this includes the possibility for short runs on ^{60}Ni and ^{114}Cd targets within the same running period. For ^{226,228}Ra the assumption will be made that Q_3 is the same for E3 matrix elements connecting the 1^- and 3^- states, as the transitions from these states cannot be resolved.

nucleus [ions/s]	beam time [h]	transition	transition energy [keV]	counts(γ) 3 MeV.A	counts(γ) 4 MeV.A
^{222}Rn 3×10^4 *1.5×10^6*	72	$2^+ \rightarrow 0^+$	186.2	31000	30000
		$4^+ \rightarrow 2^+$	262.2	5200	13100
		$3^- \rightarrow 2^+$	449.3	100	330
		$1^- \rightarrow 0^+$	600.7	90	320
^{222}Ra 5×10^5 *2.5×10^7*	24	$2^+ \rightarrow 0^+$	111.1	66200	49000
		$4^+ \rightarrow 2^+$	190.3	72000	112500
		$3^- \rightarrow 2^+$	206.2	930	4200
		$1^- \rightarrow 0^+$	242.1	1100	1800
^{226}Ra 2×10^5 *10^7*	16	$2^+ \rightarrow 0^+$	67.7	2370	1520
		$4^+ \rightarrow 2^+$	143.9	16300	19500
		$3^- \rightarrow 2^+$	253.9	230	940
		$1^- \rightarrow 0^+$	253.7	280	360
^{228}Ra 10^5 *5×10^6*	24	$2^+ \rightarrow 0^+$	63.8	1400	900
		$4^+ \rightarrow 2^+$	140.9	13800	15600
		$3^- \rightarrow 2^+$	473.7	80	320
		$1^- \rightarrow 0^+$	474.2	90	130

Table 1: Estimated γ-ray yields (using GOSIA) following Coulomb excitation of beams on a 2 mg/cm^2 ^{120}Sn target, corrected for internal conversion. The matrix elements for ^{222}Rn, ^{222}Ra, ^{228}Ra were taken from ^{220}Rn, ^{224}Ra, ^{226}Ra respectively. The assumed beam intensity at the target and that at the entrance to REXTRAP (in italics) are in the first column.

Proposal: study of octupole band ^{221}Rn

The enhancement of the Schiff moment, important for EDM measurements, arises from the projection of nearly degenerate parity-doubled states from the same intrinsic octupole state. The primary aim of this experiment is to determine whether the ground and first excited states in odd Rn nuclei form parity doublets, as has been observed in odd-mass Ra nuclei. There is little information on the excited states in ^{221}Rn. In addition to the transitions we have seen (see figure 4), Liang et al. have observed an excited state at 30 keV populated by α-decay [12]. Estimated yields of transitions within a hypothetical, rotational-like band structure are given in table 2. These were calculated using GOSIA assuming that the intrinsic E1, E2 and E3 moments are constant and are the same as those in ^{220}Rn. The M1 matrix elements were extrapolated, using the rotational model, from the bandhead magnetic moments where measured (K= 7/2 in ^{221}Rn, assumed to have positive parity). The energies (moment of inertia) were scaled according to the relative behaviour of the even-even Rn isotopes.

The de-excitation γ-rays will be observed using the MINIBALL array, and conversion electrons will be measured using a cooled (-20C) 25-segmented Si detector, SPEDE [13], in the backward quadrant. At the low beam intensities only a small bias voltage (~ 5 kV) applied to the target is required to remove the delta-electron background; low-energy photons will be absorbed in a thin foil. Our calculations indicate that there will be an increase of yield of about 4-5 for an increase in bombarding energy from 3 to 5 MeV.A for states coupled by E3 to the ground state band, and high-lying states coupled by E2s. Therefore we expect to accumulate roughly 1-2 orders of magnitude more counts than in the pilot experiment. This should be sufficient to determine the decay scheme from γ-γ, γ-e^- and internal conversion coefficient measurements, and measurement of particle angular distribution and/or target Z dependence.

nucleus [ions/s]	**beam time** [h]	**transition**	**transition energy** [keV]	**counts (γ) 5 MeV.A**	**counts (e^-) 5 MeV.A**	**$M\lambda$, shell (e^-)**
^{221}Rn	48	$9/2^+ \rightarrow 7/2^+$	*70*	6900	38000	M1, L
1×10^5		$11/2^+ \rightarrow 7/2^+$	*140*	310	400	E2, L
5×10^6		$11/2^+ \rightarrow 9/2^+$	*70*	4300	23800	M1, L
		$13/2^+ \rightarrow 9/2^+$	*230*	520	80	E2, L
		$13/2^+ \rightarrow 11/2^+$	*160*	4900	13700	M1, K
		$15/2^+ \rightarrow 11/2^+$	*260*	660	60	E2, L
		$15/2^+ \rightarrow 13/2^+$	*100*	650	1300	M1, L
		$7/2^- \rightarrow 7/2^+$	*110*	3100	190	E1, L
		$9/2^- \rightarrow 7/2^+$	*180*	700	60	E1, K
		$9/2^- \rightarrow 7/2^-$	*70*	300	1640	M1, L

Table 2. Calculated yields (γ-ray and conversion electron) for various transitions in ^{221}Rn, following bombardment of a 2 mg/cm^2 ^{120}Sn target (for details, see text). The assumed beam intensity is given in the first column, with the intensity at the entrance to REXTRAP given in italics. The level scheme is schematic; transitions from octupole states are in bold. The last column gives the parameters for the e^- conversion line; K and L binding energies are respectively 98 and 18 keV for Rn.

Summary of request for beam-time

We request 9 shifts to measure matrix elements in ^{222}Rn, 6 shifts to study ^{221}Rn and 3 shifts to set up the beam, so that **18 shifts** are required for the Rn studies. For the study of ^{222,226,228}Ra isotopes 8 shifts are required for the measurement of the matrix elements, as well as 3 shifts for setting up. Thus **11 shifts** are required for the Ra measurements. **A total of 29 shifts are requested**.

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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
Parts 1 MINIBALL + only CD	☒ Existing	☒ To be used without any modification
		.
Part 2,3 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
	☐ 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) ^{222}Ra (2) ^{226}Ra (3) ^{228}Ra	^{222}Rn	^{221}Rn
Beam intensity	5.10^{5} ^{222}Ra 2.10^{5} ^{226}Ra 10^{5} ^{228}Ra	3.10^{4}	10^{5}
Beam energy	4 MeV.A	4 MeV.A	5 MeV.A
Cooling liquids	Liquid N_2	Liquid N_2	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]	Standard γ -ray sources for MINIBALL	Standard γ -ray sources for MINIBALL
• Isotope			
• Activity	< 10 μCi	< 10 μCi	< 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

Contamination from ^{228}Ra as discussed with RP. We have not discussed the use of ^{226}Ra

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