EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

Addendum (IS475) to the ISOLDE and Neutron Time-of-Flight Committee

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

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CERN-ISOLDE (J. Pakarinen, T. Stora, D. Voulot, F.Wenander)
*TU **Darmstadt*** (S. Bönig, Th. Kröll, M. Scheck)
GANIL (E. Clément)
*U **Groningen KVI*** (K. Jungmann, J. Van de Walle, L. Willmann, H.W. Wilschut)
*U **Jyväskylä*** (T. Grahn, P. T. Greenlees, R. Julin, P. Nieminen)
*U **Köln*** (A. Blazhev, N. Warr)
***Lawrence Livermore** L* (E. Kwan, M. A. Stoyer, C.-Y. Wu)
*KU **Leuven*** (M. Huyse, P. Van Duppen)
*U **Liverpool*** (P.A. Butler, L. Gaffney, R.-D. Herzberg, D.T. Joss, R.D. Page, P. Papadakis)
*U **Lund*** (J. Cederkäll)
*U **Michigan*** (T. Chupp, W. Lorenzon)
*TU **München*** (V. Bildstein, S Bönig, R. Gernhäuser, R. Krücken, D. Muecher, N. Nowak)
NSCL Michigan (K. Wimmer)
*U **Oslo*** (A.Bürger, M. Guttormsen, A.-C. Larsen, H.T.Nyhus, S. Siem, H.Toft, G. Tveten)
*U **Rochester*** (D. Cline, A.B. Hayes)
*HIL U **Warsaw*** (K. Hadynska-Klek, J. Iwanicki, P. Napiorkowski, D. Pietak, J. Srebrny, K. Wrzosek-Lipska, M. Zielinska)
*U **West Scotland*** (A. Andreyev, J.F. Smith)
*U **York*** (C. Barton, D.G. Jenkins, R. Wadsworth)

Spokespersons: P A Butler (peter.butler@liverpool.ac.uk)
DT Joss (dtj@ns.ph.liv.ac.uk)

ISOLDE contact: J Pakarinen (janne.pakarinen@cern.ch)

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Abstract

It is proposed to study octupole correlations in odd-mass Rn and Ra isotopes using Coulomb excitation at 3 MeV.A. The goals are to measure E3 matrix elements between candidate bands for parity doubling in odd-mass Ra nuclei, and to search for parity doubling in odd Rn nuclei. These data are important to test for octupole correlations in this mass region and are necessary to guide and interpret future EDM measurements designed to observe time-reversal violating interactions.

Request: The proposal requests **15 shifts** to make exploratory measurements of the odd-mass nuclei.

Preamble

We have commenced an experimental study of even-even Rn and Ra isotopes using Coulomb excitation (IS475). The first experiment, carried out in September 2010, showed that REX-ISOLDE can provide sufficient intensity of the neutron-rich heavy radioisotopes, and we have sufficient yield of the transitions of interest (measured using MINIBALL) to determine B(E3) values of low-lying transitions in ^{224}Ra. We propose here to study odd-mass Rn and Ra isotopes that could be scheduled together with the remaining time to study ^{220,222}Rn and ^{222}Ra.

Physics case

There is considerable theoretical and experimental evidence that atomic nuclei can assume reflection asymmetric shapes that arise from the octupole degree of freedom. The strongest correlations occur near the proton numbers 88 and the neutron numbers N= 134, where octupole deformation can occur in the ground state. A large number of theoretical approaches (a broad overview is given in reference [1]), such as in the Nilsson-Strutinsky approach with deformed folded Yukawa and Woods-Saxon potentials, cluster models, and self consistent models using the Skyrme and Gogny forces were developed to describe the observed experimental features. Egido and Robledo [2,3] used HFB with Gogny forces to predict ^{220,222,224}Ra to be octupole deformed and ^{218,226}Ra octupole soft. A more recent approach within the interacting boson approximation [4] predicted no octupole deformation in the ground state in these nuclei. In contrary a phenomenological model [5] based on a potential with two minima distinct by a spin dependent potential barrier, which was able to explain the observed properties of the odd-even staggering, had to assume a static octupole deformation of $\beta_3 = 0.09$ to reproduce the observed behaviour. A cluster model [6] succeeded in reproducing the available experimental values for the known electric multipole moments Q(Eλ) in various mass regions. A rather exotic approach [7] in a liquid drop like model describes the observed spin-dependent transition from an octupole vibrator to a rotational system by octupole tidal waves aligning at a critical rotational frequency. The only observable that provides unambiguous and direct evidence for enhanced octupole correlations in these nuclei is the E3 matrix element. For odd-mass nuclei, the presence of an intrinsic quadrupole and octupole deformation leads to rotational bands lying close to each other with opposite parity. Examples of bands having this behaviour have been seen in ^{223,225}Ra and ^{223,225}Th (see figure 1). However, this structure could arise by accident and only a measurement of the connecting E3 transition moments can confirm whether these are indeed parity doublets.

Beyond nuclear physics, atoms with octupole-deformed nuclei are very important in the search for permanent atomic Electric-Dipole Moments [8]. 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. 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. Since the Schiff moment induces the atomic EDM, the sensitivity over non-octupole 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. It is not known whether parity doubling occurs in the former, and in both cases there is no direct information on octupole correlations as determined from knowledge of E3 matrix elements.

We propose here to study the structure of low-lying states in odd-mass Rn and Ra isotopes with A ~ 220 by employing Coulomb excitation, thus measuring both E2 and E3 matrix elements in these nuclei. The experiments will allow us to test for octupole correlations in the established bands in odd-mass Ra nuclei and allow hitherto unobserved low-lying band structure be observed in Rn. Ideally these measurements require the higher beam energies and intensities of HIE-ISOLDE (see INTC-I-091), but the exploratory experiments proposed here can already provide some quantitative information.

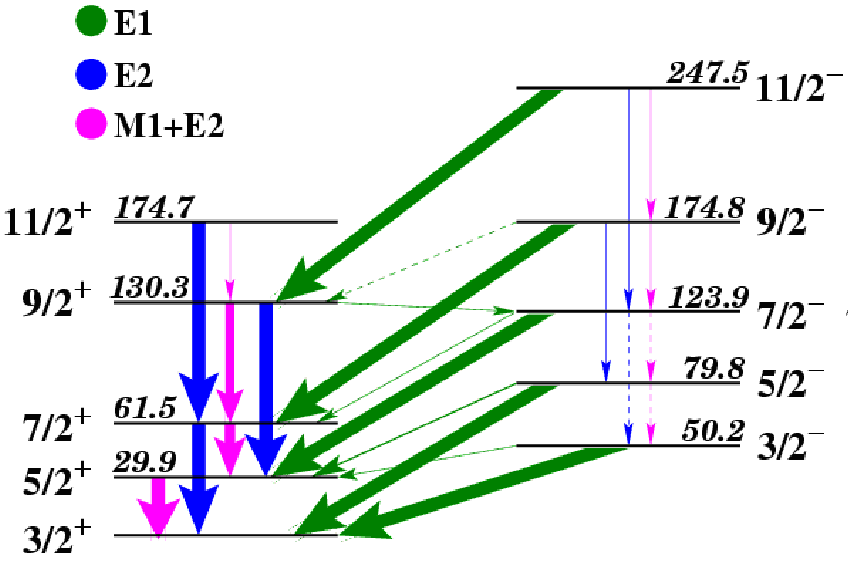

Figure 1: Level scheme of ^{223}Ra

Coulomb excitation of ^{224}Ra: results from September 2010 run

A beam of ^{224}Ra with charge states of 52^+ was accelerated with the REX-ISOLDE accelerator to an energy of 2.83 MeV/u and delivered to the MINIBALL set-up. There were three runs: one with protons on the primary UCx target and using a ^{112}Cd secondary target (11 hours) and two using an activated primary target and both ^{112}Cd and ^{120}Sn secondary targets (23 and 11 hours respectively). The average accelerated beam intensity was ~ 4 x 10^5 pps with protons and ~ 4 x 10^4 without protons, with a REX efficiency of ~1-2%.

Figure 2 shows part of the Doppler corrected gamma-ray spectrum obtained for ^{224}Ra on ^{112}Cd. Significant population of the low-lying negative-parity states is clearly observed. These data will allow B(E3) and B(E2) transition matrix elements be extracted from the measured yields for several transitions.

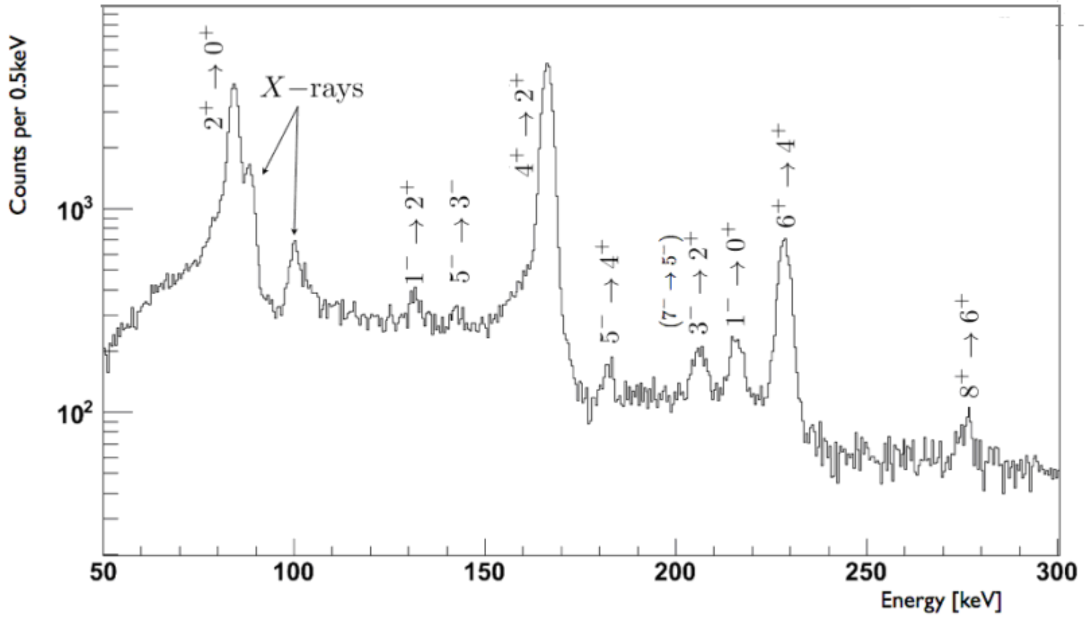

Figure 2: Spectrum of states in ^{224}Ra following Coulomb excitation a ^{112}Cd target. The irradiation time was 11 hours (with protons, 4 x 10^5 pps) and 23 hours (no protons, 4 x 10^4 pps)

Description of proposed experiment

ISOLDE is unique world-wide in having the capability of providing sufficient accelerated beam intensity of Rn and Ra isotopes for Coulomb excitation experiments. While the Rn isotopes as noble gases can be purified using a plasma cooled transfer line, we have already demonstrated that Ra beams can be extracted with sufficient post-accelerated intensity for Coulomb excitation and purity from isobaric (e.g. Fr) contamination. The primary production yields and ion yields following post-acceleration for odd-mass isotopes are given in table 1.

Nucleus	**Half-life**	**ISOLDE production yield** [Ions/μC]	**PSB or SC**	**Target Material**	**Number of ions/s at the Coulex target**
^{221}Rn	25m	1.4x10^7	SC	ThC$_X$	1.4x10^5
^{223}Rn	23m	2.5x10^6	SC	ThC$_x$	2.5x10^4
^{223}Ra	11.4d	*5x10^8*			*5 x10^5*
^{225}Ra	14.8d	2.6x10^8	SC	UC$_X$	5 x10^5

Table 1: Production yields with a given target of the isotopes of interest. For the number of ions at the Coulex target we assume 1% efficiency for REX-ISOLDE or a limit of ~5 x 10^5 ions/s. The yields for ^{223}Ra are interpolated.

The low-energy level scheme of ^{223}Ra relevant to sub-barrier Coulomb studies is shown in figure 1. The low lying states in ^{225}Ra are also known, interpreted in terms of opposite-parity bands with K=1/2, while there is no information on the excited states in ^{221,223}Rn. The low excitation energies of the first excited states in the isotopes of interest will ensure that the low-lying excited states will be favourably populated by Coulomb excitation. The primary aims of this experiment are to determine the low-lying structure of the odd-mass Rn nuclei and the E3 matrix elements connecting the lowest rotational bands in both Rn and Ra nuclei.

In the proposed experiment, the Rn and Ra beams will undergo excitation using Cd and Sn secondary targets. Both scattered projectiles (maximum laboratory angle ~ 30^o) and target recoils will be detected. The Coulex γ–ray and conversion electron yields for 3 MeV/u ^{221}Rn and ^{223}Ra beams onto a 2 mg/cm^2 ^{114}Cd target were calculated with the computer code GOSIA. The results are summarised in table 2. For the calculations a total efficiency of 10% for both γ-ray and conversion electron detection was assumed (5% for γ-ray energies < 100 keV). The transition yields assumed an integrated beam of 5 x 10^4 pps for 3 days. For all four isotopes of interest the excitation probabilities depend only upon the magnitude and sign of the E2 and E3 matrix elements. These were calculated assuming a rotational model dependence using values of the intrinsic E2 moment taken from the known $<2^+|E2|0^+>$ transition matrix element in ^{220}Rn and ^{222}Ra (for ^{221}Rn and ^{223}Ra respectively) and the E3 moment taken from $<3^-|E3|0^+>$ in ^{226}Ra (for ^{223}Ra) and assuming a B(E3; $0^+ \rightarrow 3^-$) of 30 W.u. for the even-even Rn isotopes (for ^{221}Rn). The M1 matrix elements were extrapolated, using the rotational model, from the bandhead magnetic moments where measured (K=3/2± in ^{223}Ra, 7/2 g.s. in ^{221}Rn). The E1 matrix elements were scaled using the rotational model assuming a constant intrinsic moment, measured for ^{223}Ra and taken from the adjacent even-even nuclei for ^{221}Rn. The calculated M1 and E2 matrix elements compare reasonably well with the experimental values for the few measured cases in ^{223}Ra. In the case of ^{221}Rn, where there is no knowledge of the excited states, the structure was assumed to be rotational and the energies (moment of inertia) were scaled according to the relative behaviour of the even-even Rn and Ra isotopes[1].

The de-excitation γ-rays will be observed using the MINIBALL array (the use of planar detectors will also be explored), and conversion electrons will be measured using a cooled (-20C) segmented detector in the backward quadrant. The latter will be a 25-segmented detector used in the SACRED electron spectrometer at Jyväskylä [10, 11]. At the low beam intensities only a small bias voltage (~ 5 kV) applied to the target is required to remove the delta-electron background and a magnetic field is unnecessary for transporting the electrons to the detector.

Aim of experiment and request for beam-time

We request additional beam time to IS475 in order to explore the feasibility of measuring the odd-mass Rn and Ra nuclei, choosing either ^{221}Rn or ^{223}Rn *and* ^{223}Ra or ^{225}Ra as case studies. For the Rn isotope, 6 shifts should suffice to observe ground state band transitions, and possibly observe at least one transition between the two opposite-parity bands (identified from the conversion coefficient). Allowing 3 shifts to set up the beam, **9 additional shifts are required for Rn**. For the Ra isotopes 3 shifts enable a yield measurement for the low energy $3/2^- \rightarrow 3/2^+$ transition, and electron yield measurements for transitions in the ground state band. Allowing 3 shifts to set up the beam, **6 additional shifts are required for Ra**. The ultimate goals are (1) measure whether there are parity-doublet bands in the odd-mass Rn nuclei, and estimate the average E2 and E3 intrinsic moments, and (2) measure the average E3

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[1] The observed negative ground-state electric quadrupole moment also suggests decoupling, arising from mixing of Ω=3/2, Ω=1/2 orbitals [9].

intrinsic moment in the odd-mass Ra nuclei, to test that the observed opposite-parity bands are indeed parity doublets. **A total of 15 shifts are requested**.

nucleus	**initial**	**final**	**γ energy**	**counts (γ)**	**counts (e^-)**	**Mλ, shell**
^{221}Rn	9/2+	7/2+	*70*	**1850**	**20300**	M1, L
	11/2+	9/2+	*70*	**450**	**5000**	M1, L
	13/2+	11/2+	*160*	**140**	**380**	M1, K
	7/2-	7/2+	*110*	**200**	12	E1, L
	9/2-	7/2-	*70*	10	**110**	M1, L
^{223}Ra	5/2+	3/2+	29.9	**145**	**5650**	M1, M
	7/2+	3/2+	61.5	40	**5970**	E2, L
	7/2+	5/2+	31.6	**85**	**2880**	M1,M
	9/2+	5/2+	100.4	**170**	**1170**	E2, L
	9/2+	7/2+	68.8	**125**	**1730**	M1, L
	11/2+	7/2+	113.2	**140**	**540**	E2, L
	11/2+	9/2+	44.1	12	**150**	M1,M
	3/2-	3/2+	50.2	**90**	**90**	E1, L
	7/2-	5/2+	94.0	**70**	14	E1, L
	9/2-	7/2+	113.3	**100**	6	E1,L

Table 2. Estimated counts (γ-ray and conversion electron) for various transitions in ^{221}Rn and ^{223}Ra, assuming 9 shifts with beam intensity of 5 x 10^4 pps on a 2 mg/cm^2 Cd target. The ^{221}Rn level scheme is schematic. Intensities in bold are considered significant for observation. The last column gives the parameters for the e^- conversion line; K, L, M binding energies are respectively 98, 18, 4 keV for Rn, and 104, 19, 5 keV for Ra.

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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+TREX	☒ Existing	☒ To be used with some modification
		Segmented Si detector and cooling adapted from Jyväskylä set-up; 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 [COLLAPS, CRIS, ISOLTRAP, MINIBALL + only CD, MINIBALL + T-REX, NICOLE, SSP-GLM chamber, SSP-GHM chamber, or WITCH] 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	Liquid nitrogen		
Electrical and electromagnetic			
Electricity	[voltage] [V], [current][A]		
Static electricity		5V on target	
Magnetic field	[magnetic field] [T]		
Batteries	☐		
Capacitors	☐		
Ionizing radiation			
Target material	[material]		
Beam particle type (e, p, ions, etc)	^{221}Rn or ^{,223}Rn	^{223}Ra or ^{,225}Ra	
Beam intensity	2.5x10^4 - 1.4x10^5	5 x10^5	
Beam energy	3 MeV/u	3 MeV/u	
Cooling liquids	Liquid N_2		
Gases	[gas]		
Calibration sources:			
• Open source	^{133}Ba for electron detector (contained with thin window)	^{133}Ba for electron detector (contained with thin window)	
• Sealed source	Standard γ -ray sources for MINIBALL	Standard γ -ray sources for MINIBALL	
• Isotope			
• Activity	< 10 μCi	< 10 μCi	
Use of activated material:			

• Description	☐		
• Dose rate on contact and in 10 cm distance	[dose][mSV]		
• Isotope			
• Activity			

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)*