Measurements of octupole collectivity in ^{220,222}Rn and ^{222,224}Ra using Coulomb excitation

CERN-ISOLDE (J. Cederkäll, P. Delahaye, G. Tveten, J. Van de Walle, D. Voulot, F.Wenander)
CCLRC Daresbury Laboratory (D. O'Donnell, J. Simpson)
University of Edinburgh (T. Davinson)
GANIL (E. Clément)
University of Guelph (P. Garrett, C. Sumithrarachchi, C. Svensson, S. Triambak)
University of Jyväskylä (P. T. Greenlees and R. Julin)
University of Kentucky (S.F. Ashley and S.W. Yates)
University of Köln (N. Warr)
Lawrence Livermore Laboratory (A. Hurst, M. A. Stoyer, C.-Y. Wu)
KU Leuven (A. Andreyev, B. Bastin, N. Bree, M. Huyse, O. Ivanov, and P. Van Duppen)
University of Liverpool (P.A. Butler, T. Grahn, R.-D. Herzberg, D.T. Joss, R.D. Page, J. Pakarinen, A. Petts, M. Scheck)
TU-München (V. Bildstein, R. Gernhäuser, Th. Kröll, R. Krücken, and K. Wimmer)
University of Oslo (A.Bürger, M. Guttormsen, A.-C. Larsen, H.T.Nyhus, S. Siem, N.U.H.Syed, H.Toft)
University of Rochester (D. Cline, A. Hayes)
CEA-Saclay (A. Goergen, and W. Korten)
HIL University of Warsaw (K. Hadynska, J. Iwanicki, P. Napiorkowski, D. Piętak, J. Srebrny, K. Wrzosek and M. Zielinska)
University of York (C. Barton, D.G. Jenkins and R. Wadsworth)

Spokespersons: **M.Scheck, P.A.Butler** (Liverpool)
ISOLDE contact: **J. Van de Walle**

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Abstract

We propose to exploit the unique capability of ISOLDE to provide post-accelerated ^{220,222}Rn and ^{222,224}Ra ion beams from the REX facility to enable the Coulomb excitation of the first 3^- states in these nuclei. By measuring the γ-ray yields of the E1 decays from the 3^- state using the MINIBALL array we can obtain the $\langle 3^-|E3|0^+\rangle$ transition matrix elements. This will give quantitative information about octupole correlations in these nuclei. We require **22 shifts** to fulfil the aims of the experiment.

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 [1]. From a microscopic point of view, the wave functions of low-lying 3^- octupole excitations must contain components which include the intruding unique parity state (l, j). Because of the nature of the octupole-octupole interaction in nuclei, octupole correlations arise when this intruder state comes close to the Fermi level, giving rise to [l, j; l-3, j-3] particle-hole configurations at relatively low excitation energies. The strongest correlations occur near the proton numbers Z= 34, 56, and 88 and the neutron numbers N= 34, 56, 88, and 134, where octupole deformation can occur in the ground state. 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, see e.g. [2, 3], and enhanced E1 moments due to a division of the centre of charge and centre of mass [4]. The only observable that provides unambiguous and direct evidence for enhanced octupole correlations in these nuclei is the E3 matrix element [5,6], and the measure of octupole correlations in the ground state is the B(E3, 0^+ -> 3^-). As shown in figures 1 and 2 this quantity peaks at the expected nucleon numbers, but for the mass region where octupole correlations are expected to be largest, i.e. at Z=88 ($[2f_{7/2},1i_{13/2}]_\pi$) and N=134 ($[2g_{9/2},1j_{15/2}]_\nu$) the lack of spectroscopic data is obvious. Only for ^{226}Ra with its comparatively long half life of $T_{1/2}$ = 1600y was it possible to measure the B(E3) strength using Coulomb excitation [6].

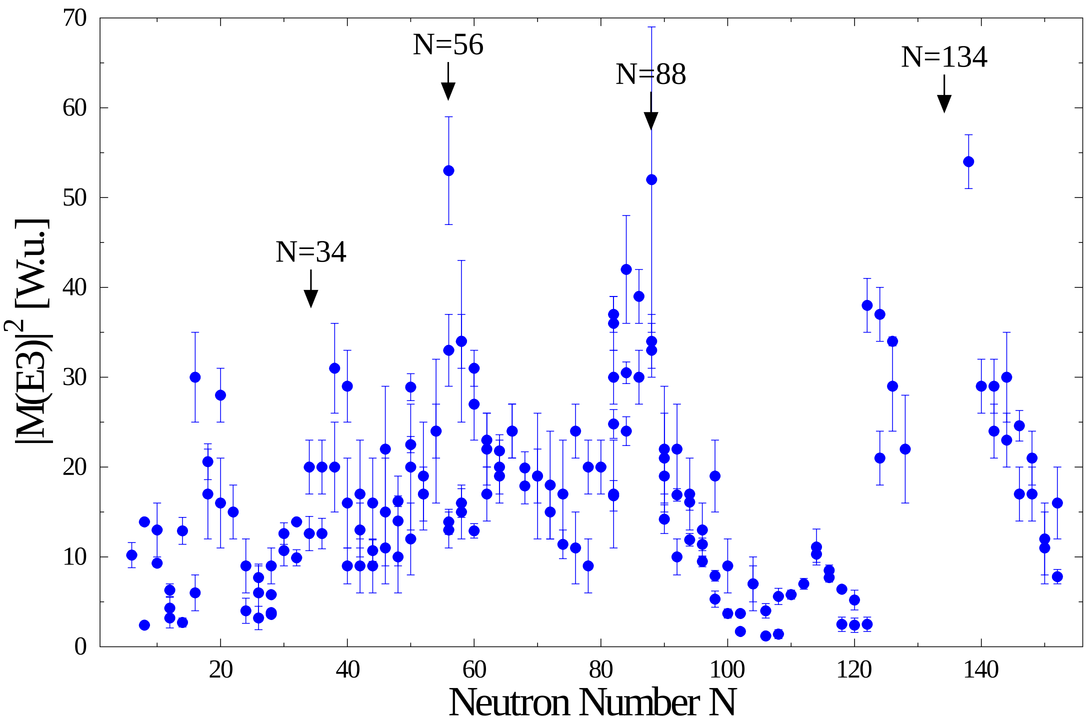

Figure 1: Plot of the E3 transition strength as a function of the neutron number N (taken from [7]).

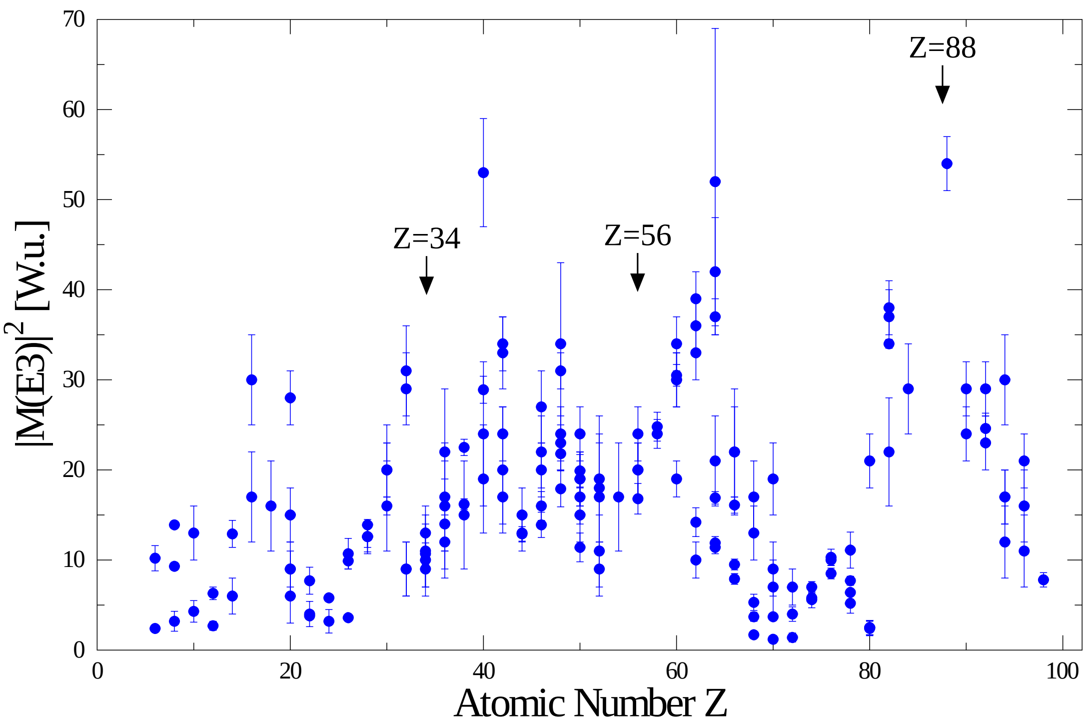

Figure 2: Plot of the E3 transition strength as a function of the proton number Z (taken from [7]).

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 [8,9] used HFB with Gogny forces to predict ^{220,222,224}Ra to be octupole deformed and ^{218,226}Ra octupole soft (see figure 3). A more recent approach within the interacting boson approximation [10] predicted no octupole deformation in the ground state in these nuclei. In contrary a phenomenological model [11] 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 β_3 = 0.09 to reproduce the observed behaviour. A cluster model [12] succeeded in reproducing the available experimental values for the known electric multipole moments Q(Eλ) in various mass regions. A rather exotic approach [13] 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.

Beyond nuclear physics, atoms with octupole-deformed nuclei like ^{225}Ra are promising candidates for the search for atomic electric-dipole moments [14]. The observation or not of a non-zero EDM arising from nuclear T-violation will place constraints on many extensions of the Standard Model. Such nuclei will have collective nuclear “Schiff” moments [15] that will become enhanced by the presence of nearly degenerate parity doublets (seen in odd mass nuclei) and large octupole deformation. Since the Schiff moment induces the atomic EDM, the sensitivity to this effect over non-octupole systems such as the classic ^{199}Hg case can be improved by a factor of 1000. The experimental studies of energy levels in the N~134 region by Cocks et al. [2] showed that Ra isotopes have the characteristics of nuclei with octupole deformation at high spin whereas the Rn isotopes are octupole vibrational. From an experimental viewpoint, the study of EDMs in odd Rn isotopes has advantages over Ra isotopes; however little is know about the octupole correlations near the ground state in these nuclei.

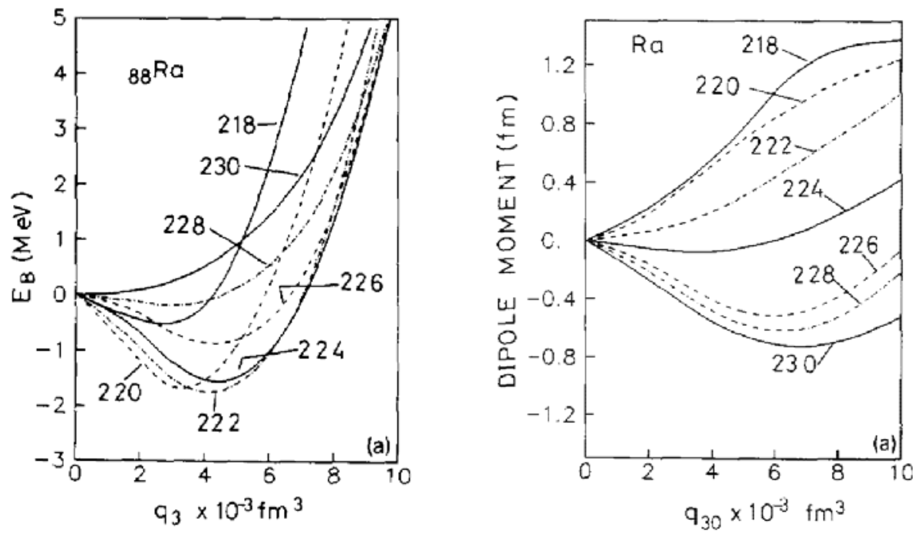

Figure 3: Octupole barrier energy ($E_B = E(\beta_3) - E(\beta_3\!=\!0)$) (left panel), and E1 moments (right panel) versus octupole moment as predicted in [8].

Until now, experiments to measure reliable B(E3) data in the actinide region were not possible because of the short half-lives of the radionuclides. The availability of heavy nuclides as radioactive beams has been demonstrated recently when for the first time Coulomb excitation experiments on several neutron deficient Hg isotopes [16] were performed at the REX-ISOLDE facility. We propose here to initiate a programme to investigate the degree of octupole deformation in the A ~ 222 mass region, in particular to make Coulex measurements of ^{220,222}Rn and ^{222,224}Ra with the proton numbers Z=86 and 88 and neutron numbers N=134 and 136, respectively. Coulomb excitation using the post-accelerated beam from REX will excite low-lying, low-spin levels of the isotopes of interest. Using the obtained γ-ray yields, we will be able to determine the value of the E3 transition matrix elements in these nuclei for the first time.

Experimental set-up and Coulex yields

ISOLDE is unique world-wide in having the capability of providing sufficient accelerated beam intensity [17] of Rn and Ra isotopes for Coulomb excitation experiments. While the Rn isotopes as noble gases can easily be purified using a plasma cooled transfer line [18], for the Ra beams CF_4 will be used with a surface ion source in order to suppress the expected Fr contamination [19]. The Coulex experiment of the Hg isotopes [16] demonstrated the ability of REX-EBIS to charge breed heavy nuclei to a charge state required for post-acceleration with an efficiency of a few per cent. To achieve a ratio A/q ~ 4.5 the Ra atoms have to be bred to an ionisation state of 50^+. Previous tests [20] have demonstrated that ^{238}U ions with a charge state of 52^+ (A/q = 4.6) were extracted from the REX mass separator with a total efficiency of 4.3%. In these tests the breeding time was 500ms, so the small repetition rate will benefit from development of slow extraction that is currently making good progress [21]. The primary production yields and ion yields following post-acceleration are given in table 1.

The low-energy level schemes of ^{220,222}Rn and ^{222,224}Ra [22] relevant to sub-barrier Coulomb studies are shown in figure 4. The lowest lying 3^- state in any nuclei is observed in ^{224}Ra. The more quadrupole and octupole vibrational character of the Rn isotopes can be seen from the higher excitation energies. The low excitation energies of the first excited states in the isotopes of interest will ensure that the first excited states will be favourably populated by Coulomb excitation. The primary aim of this experiment is to determine electric matrix elements between the ground state and the first excited 2^+ and 3^- states that will give direct information about quadrupole and octupole correlations in these nuclei. Coulomb excitation will excite in a first order process the first excited 2^+ and 3^- states via E2 and E3 transitions, respectively. Excitations via E1 transitions are usually orders of magnitude less probable. In addition, the 1^- and 3^- states will be excited by E2xE3 second order processes via the 2^+ state. The first 4^+ state will be excited in a second order process involving the first 2^+ state.

In the proposed experiment, the Rn and Ra beams will undergo excitation using ^{114}Cd and ^{120}Sn secondary targets. The de-excitation γ-rays will be observed using the MINIBALL array containing 8 triple cluster of 6-fold segmented Ge detectors [23], which has an efficiency of 7% for 1.3 MeV photons. Both scattered projectiles (maximum laboratory angle ~ 30°) and target recoils will be detected using the DSSD CD detector which subtends an angular range 16° - 53°. The Coulex γ–ray yields for 3 MeV/u ^{222}Rn and ^{224}Ra beams onto a 2 mg/cm^2 ^{114}Cd target were calculated with the computer code GOSIA [24]. The results are summarised in table 2. For the calculations a total efficiency of 10% for γ-ray detection was assumed. For all four isotopes of interest the $\langle 2^+|E2|0^+\rangle$ transition matrix element was calculated using the B(E2) value found in the NNDC data base [22]. For the Ra isotopes the values for the other transition matrix elements were assumed to be the same as those measured in ^{226}Ra [6]. For the Rn isotopes the E3 matrix elements were scaled to an assumed value of B(E3; $0^+ \rightarrow 3^-$) of 30 W.u., by comparison with the trend seen in this mass region (see figures 1 and 2).

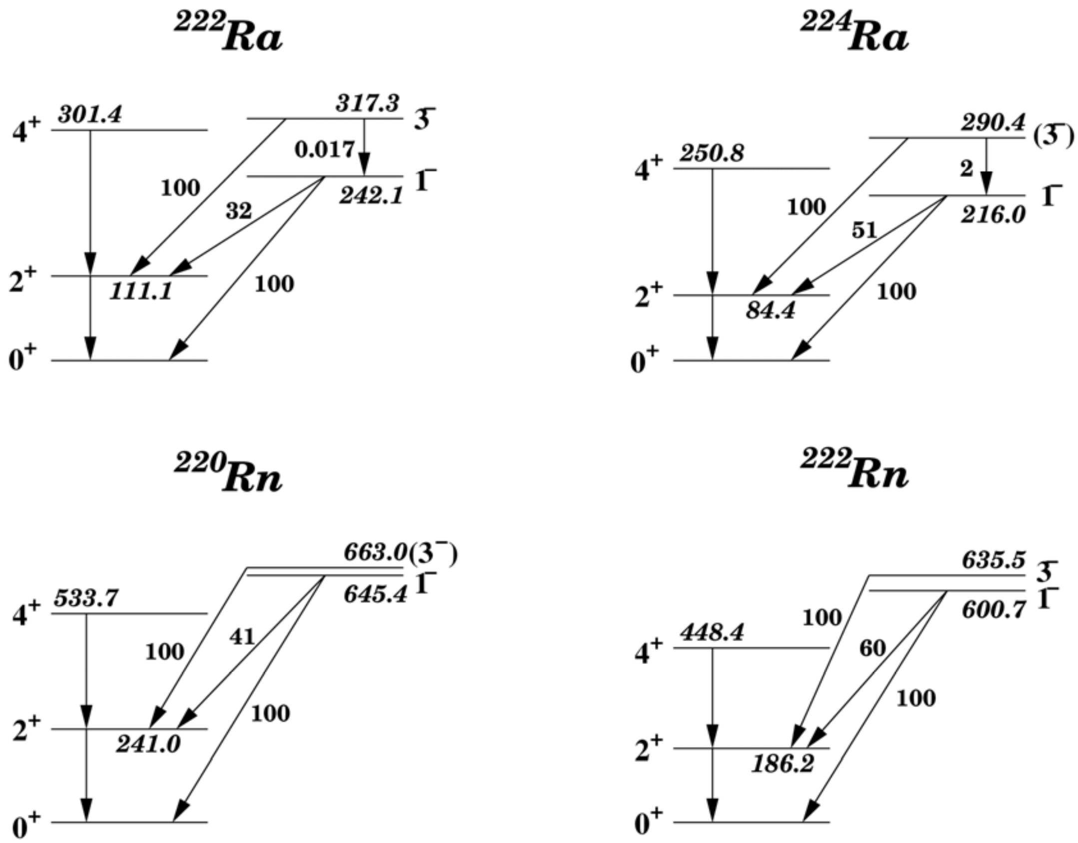

Figure 4: Low-lying, low-spin level schemes of ^{220,222}Rn and ^{222,224}Ra. Please note the different energy scales for the respective elements. The data are taken from reference [22].

Nucleus	Half-life	ISOLDE production yield [Ions/μC]	PSB or SC	Target Material	I_p [μA]	Number of ions/s at the Coulex target
^{220}Rn	56s	1.9×10^7	SC	ThC_X	1.0	1.9×10^5
^{222}Rn	3.8d	3.8×10^6	SC	ThO	1.0	3.8×10^4
^{222}Ra	38s	1.3×10^9	SC	ThC_X	0.05	6.5×10^5
^{224}Ra	3.7d	6.0×10^8	SC	UC_X	0.1	6×10^5

Table 1: Production yields with a given target of the isotopes of interest as found in reference [17]. For the number of ions at the Coulex target we assume 1% transmission efficiency through the REX-ISOLDE or a limit of ~5 x 10^5 ions/s.

Nucleus	Beam time [h]	Transition	Transition energy [keV]	γ-ray yields [Counts]
^{220}Rn	32	$2^+_1 \to 0^+_1$	241.0	10300
		$4^+_1 \to 2^+_1$	292.7	17100
		$3^-_1 \to 2^+_1$	222.0	270
		$1^-_1 \to 0^+_1$	645.4	100
^{222}Rn	80	$2^+_1 \to 0^+_1$	186.2	46100
		$4^+_1 \to 2^+_1$	262.2	10400
		$3^-_1 \to 2^+_1$	449.2	110
		$1^-_1 \to 0^+_1$	600.7	70
^{222}Ra	8	$2^+_1 \to 0^+_1$	111.1	39400
		$4^+_1 \to 2^+_1$	190.3	26600
		$3^-_1 \to 2^+_1$	216.2	570
		$1^-_1 \to 0^+_1$	242.1	390
^{224}Ra	8	$2^+_1 \to 0^+_1$	84.4	10700
		$4^+_1 \to 2^+_1$	166.4	19500
		$3^-_1 \to 2^+_1$	205.9	460
		$1^-_1 \to 0^+_1$	216.0	320

Table 2: Estimated γ-ray yields following the Coulomb excitation of 3 MeV/u ^{220,222}Rn and ^{222,224}Ra on a 2 mg/cm^2 ^{114}Cd target. The γ-ray yields are corrected for internal conversion. For further details of the calculation, see text.

Summary

We estimate that **2 shifts** will be sufficient for yield measurements of transitions in ^{222}Ra and ^{224}Ra, **4 shifts** for ^{220}Rn, **10 shifts** for ^{222}Rn, as well as **3 shifts** for setting up REX. In addition, **3 shifts** are required in a separate run to ascertain the isobaric purity of the Ra beam. As Z separation cannot be achieved using an ionisation counter, the radio-isotopic content will be assayed by measuring the γ-ray activity at the beam dump and α-activity at the CD detector. In total **22 shifts** are requested. Note that radiation protection issues [25] due to the presence of the long-living isotopes ^{210}Pb ($T_{1/2}$ = 22y) and ^{210}Po ($T_{1/2}$ = 138d) in the decay chains of ^{220}Rn and ^{222}Ra have been considered. The beam times were chosen to guarantee sufficient statistics, as well as not to exceed the limit set by radio-safety considerations of ~10^{12} nuclei of the respective isotope produced. Because of the low transition energies of the decays investigated in these studies, it is essential for this experiment that the problem of low-energy background [26] due to bremsstrahlung from the bending magnet and 9 gap resonator will be solved. As a first step additional lead shielding sheltering the Miniball array from the 9 gap resonator and the bending magnet will be installed. Further actions are currently in discussion [27].

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