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Do nuclei go pear-shaped? Coulomb excitation of ^{220}Rn and ^{224}Ra at REX-ISOLDE (CERN)

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Abstract. The IS475 collaboration conducted Coulomb-excitation experiments with post-accelerated radioactive ^{220}Rn and ^{224}Ra beams at the REX-ISOLDE facility. The beam particles (E_{beam}: 2.83 MeV/u) were Coulomb excited using ^{60}Ni, ^{114}Cd, and ^{120}Sn scattering targets. De-excitation γ-rays were detected employing the Miniball array and scattered particles were detected in a silicon detector. Exploiting the Coulomb-excitation code GOSIA for each nucleus several matrix elements could be obtained from the measured γ-ray yields. The extracted $\langle 3^-||E3||0^+\rangle$ matrix element allows for the conclusion that, while ^{220}Rn represents an octupole vibrational system, ^{224}Ra has already substantial octupole correlations in its ground state. This finding has implications for the search of CP-violating Schiff moments in the atomic systems of the adjacent odd-mass nuclei.

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1 Introduction

There is manifold experimental evidence for nuclei within specific regions of the nuclear landscape to have strong octupole correlations [1]. Possibly, some nuclei possess these correlations even in their ground state. In a geometrical picture these correlations lead to a pear-shape distortion of the nuclear surface. The experimental evidence comprises of low-lying 3^- states in near-spherical and 1^- band heads of the K=0 octupole band in deformed nuclei, odd-even staggering of positive and negative parity yrast bands at comparably low spins, parity doublets in the neighbouring odd-mass systems and most important enhanced B(E3) strength for stretched E3 transitions.

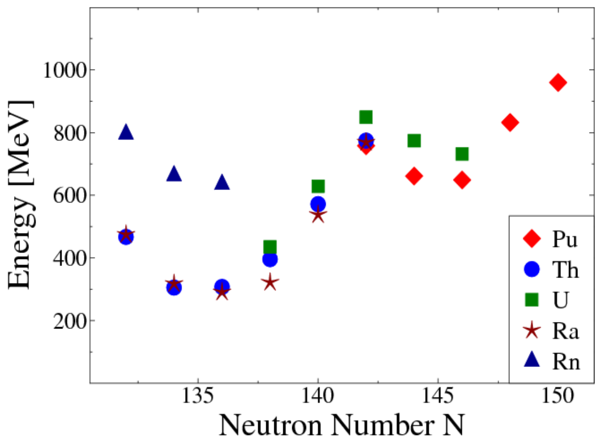

Figure 1. Excitation energy of the lowest-lying 3^- state of nuclei situated in the mass region north-east of ^{208}Pb.

Strong octupole correlations occur in nuclei for which the Fermi level for protons as well as for neutrons is situated between the unique-parity subshell and the subshell having an orbital (l) as well as total (j) angular momentum difference of $\Delta l = 3\hbar$ and $\Delta j = 3\hbar$. These particular subshell combinations are realized near the neutron (N) and proton (Z) numbers N or Z = 36, 56, 88, and 136. Supported by theoretical investigations using various approaches (e.g., see Refs. [1,2] and references therein), especially ^{224}Ra is a promising candidate for a nucleus with strong octupole correlations. Prior to this work a Coulomb excitation measurement on ^{226}Ra already exhibited strong B(E3, $J^+ \rightarrow (J+3)^-$) transition probabilities in this nucleus [3]. The reflection asymmetric pear-shape associated with strong octupole correlations leads to an asymmetric charge distribution in the nucleus. This asymmetric charge distribution would result in an enhancement of a CP-violating nuclear Schiff moment [4,5,6] in the neighbouring odd-mass nuclei, which would induce an electric-dipole moment (EDM) in the atomic system. Upper limits on EDMs have been measured to date constraining models, which propose physics beyond the standard model.

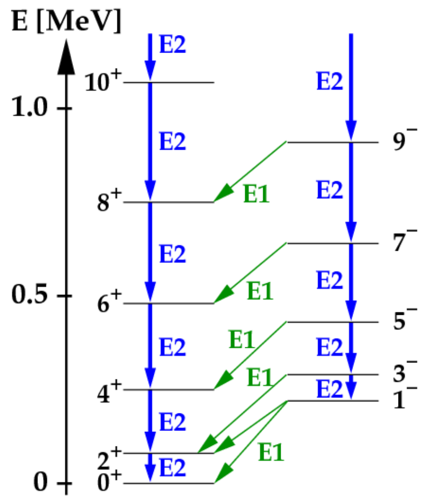

Figure 2. Low-energy level scheme of ^{224}Ra as it is relevant for sub-barrier Coulomb excitation. Data are taken from Ref. [7].

2 Experiments

The experiments were performed at ISOLDE using the Radioactive ion beam EXperiment (REX) accelerator [8]. The REX-ISOLDE facility has the world-wide unique capability to produce and post-accelerate the radon and radium nuclei of interest with a sufficient intensity and energy to perform sub-barrier Coulomb-excitation measurements. Since the latter are sensitive to E2- and E3-matrix elements they represent a tool to measure E3-transition strength which otherwise cannot be observed due the presence of competing fast E1 transitions predominantly depopulating the level of interest.
In order to produce the nuclei of interest in a spallation reaction a primary UC_x was irradiated with 1.4 GeV protons. The radioactive isotopes were mass separated, charge bred (A/q ~ 4.1), post-accelerated to 2.82 and 2.83 MeV/u, respectively, using REX and delivered to the secondary Coulomb-excitation target inside the Miniball setup [9]. The Miniball setup consists of 24 high-purity germanium (HPGe) detectors grouped into eight triple clusters for γ-ray detection and a double-sided silicon strip detector (DSSD) for particle detection and identification. The high granularity of the DSSD and the six-fold segmentation of the individual HPGe detectors guarantee a good angular resolution of the detected γ-rays and particles. Particle-γ coincidences allow for a Doppler correction and background suppression. Examples of spectra of ^{220}Rn Coulomb excited on ^{60}Ni and ^{120}Sn secondary targets are shown in Fig. 3. Additionally, ^{114}Cd was used as secondary target. The well-known Coulomb-excitation cross sections of ^{114}Cd [10] in combination with known lifetimes of ^{220}Rn and ^{224}Ra were used for the normalisation of the observed Coulomb-excitation cross sections. The use of several secondary targets with a variety of Z was necessary in order to disentangle one-step and multi-step Coulomb excitation paths.

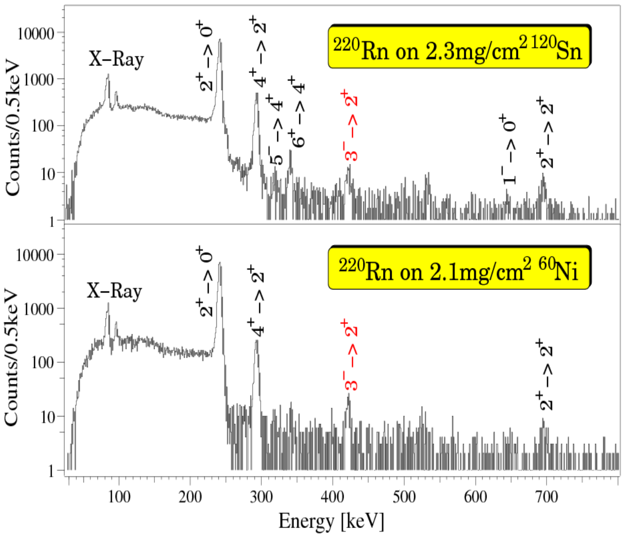

Figure 3. Particle-γ coincidence gated and Doppler-corrected γ-ray spectra of ^{220}Rn Coulomb excited using secondary ^{60}Ni (bottom) and ^{120}Sn (top) targets. Peaks are labelled corresponding to the transition they represent.

3 Results and Conclusion

The Coulomb-excitation code GOSIA was used to extract the respective matrix elements from the observed γ-ray yields. This analysis resulted amongst others in matrix elements corresponding to a B(E3, $0^+ \rightarrow 3^-$) value of 33(4) W.u. for ^{220}Rn and 42(3) W.u. for ^{224}Ra [11]. The corresponding values are shown as red points in Fig. 4. Here, it is worthwhile to point out, that the experimental trend of the two radium isotopes opposes the predictions of mean-field based calculations (e.g., see Ref. [2]) as well as cluster models [12].

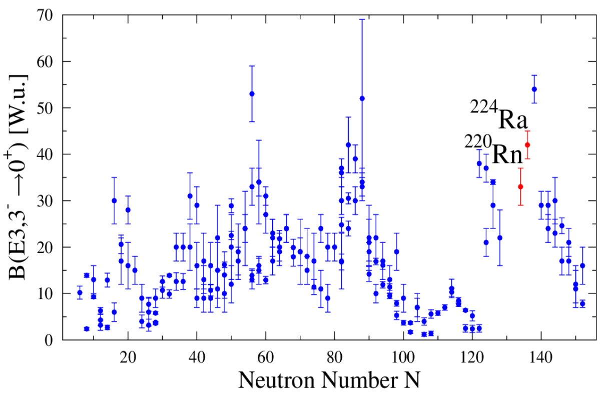

Figure 4. B(E3, $3^- \rightarrow 0^+$) strength as function of the neutron number, N. Data are taken from Refs. [11,13].

The particular behaviour of the two radium isotopes (^{224}Ra and ^{226}Ra [4]) for which the B(E3) strength is known becomes more evident when the inverse sum rule B(E3)/E_{3^-} is plotted (see Fig. 5.).

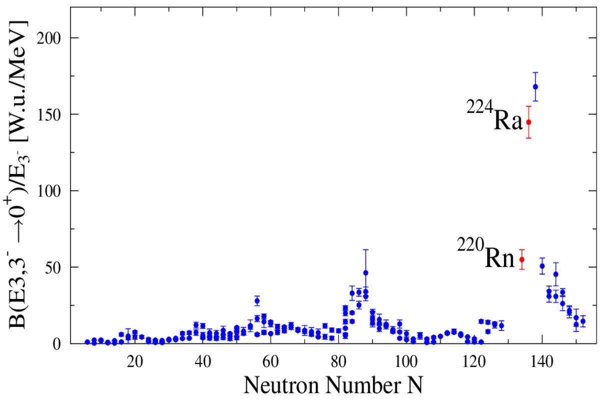

Figure 5. Inverse sum rule B(E3, $3^- \rightarrow 0^+$)/E_{3^-} as function of the neutron number, N. Data are taken from Refs. [11,13].

Assuming axial symmetry, the nuclear shape can be parameterised in terms of deformation parameters, β_λ,

$$R(\Theta) = c(\beta_\lambda)R_0\left[1 + \sum_{\lambda=2}^{\infty}\sqrt{\frac{2\lambda+1}{4\pi}}\beta_\lambda P_{\lambda 0}(\cos\theta)\right]$$

and the corresponding Legendre Polynomials, $P_{\lambda 0}(\cos\theta)$. The deformation parameters can be extracted from the measured matrix elements [10]. The shape of ^{220}Rn and ^{224}Ra as resulting from the current experiment are shown in Fig. 6. ^{224}Ra exhibits the pear-shape associated with an octupole correlated nucleus.

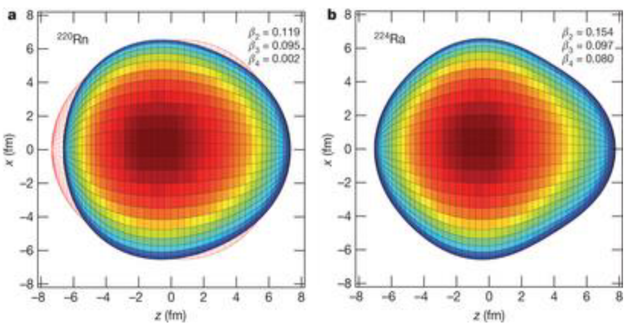

Figure 6. Surface contour plots showing ^{220}Rn (left) and ^{224}Ra (right). The deformation parameters are given in the upper right corner. Figure is taken from Ref. [11].

In conclusion the presented Coulomb-excitation experiment provided strong evidence that ^{220}Rn is rather an octupole vibrational system, while ^{224}Ra exhibits behaviour associated with an octupole deformed ground state. The associated nuclear Schiff moment [4,5,6] is predicted to result in an enhanced atomic EDM. Consequently, atoms of the odd-mass radium isotopes are favourable cases in the search for CP-violating physics. In order to answer the question, whether Rn isotopes heavier than the investigated ^{220}Rn are also favourable cases in the search for atomic EDMs more spectroscopic data are needed. The collaboration has already further approved experiments at HIE-ISOLDE, which aim to investigate even-even and odd-mass isotopes near A=224 [14] and isotopes in the octupole-soft mass region near ^{144}Ba [15].

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