Determination of the $B(E3, 0^+ \to 3^-)$-excitation strength in octupole-correlated nuclei near $A \approx 224$ by the means of Coulomb excitation at REX-ISOLDE

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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 $\langle 3^- || \hat{E}3 || 0^+ \rangle$ 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. An observation that has implications for the search of CP-violating Schiff moments in the atomic systems of the adjacent odd-mass nuclei.

1. Introduction

There is substantial experimental evidence for nuclei within specific regions of the nuclear landscape to have strong octupole correlations. 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 consists of low-lying 3^- states (see Fig. 1) 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 (e.g., see Fig. 2), parity doublets in the neighboring odd-mass systems and, most importantly, enhanced $B(E3)$ strength for stretched E3 transitions [1].

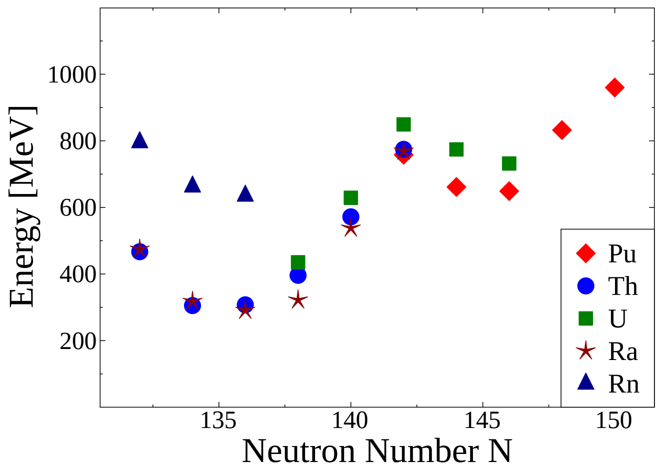

Figure 1. Excitation energy of the lowest-lying 3^- state in nuclei situated in the mass region north-east of ^{208}Pb.

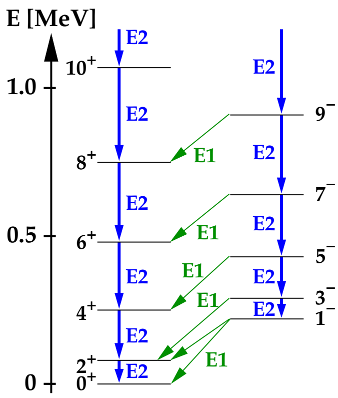

Figure 2. Low-energy level scheme of ^{224}Ra as relevant to sub-barrier Coulomb excitation. Data are taken from Ref. [2].

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 $N, Z = 36, 56, 88, 136$. Supported by theoretical investigations using various approaches (e.g. see Ref. [3] 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 [4]. Strong octupole correlations and the reflection asymmetric pear-shape associated with it

Journal of Physics: Conference Series **533** (2014) 012007 doi:10.1088/1742-6596/533/1/012007

lead to an asymmetric charge distribution in the nucleus. The latter results in an enhancement of a possible CP-violating nuclear Schiff moment [5] in the neighboring odd-mass nuclei. While it is unlikely to be measured in a nuclear system, it is predicted to be amplified in the atomic system and can at least be used for measuring upper limits for atomic electric-dipole moments and, therefore, constraining models which propose physics beyond the standard model.

2. Experiments

The experiments were performed at ISOLDE using the Radioactive ion beam EXperiment (REX) accelerator [6]. 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 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 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 target was irradiated with 1.4 GeV protons. The radioactive isotopes were mass separated, charge bred ($A/q \approx 4.1$), 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. The Miniball setup consists of 24 high-purity germanium detectors grouped into eight triple clusters for γ-ray detection and a double-sided silicon strip detector for particle detection and identification. Particle-γ coincidences allow for a Doppler correction and background suppression. Exemplary spectra of ^{220}Rn Coulomb excited on ^{60}Ni and ^{120}Sn secondary targets are shown in Fig. 3. Furthermore, ^{114}Cd was used as secondary target.

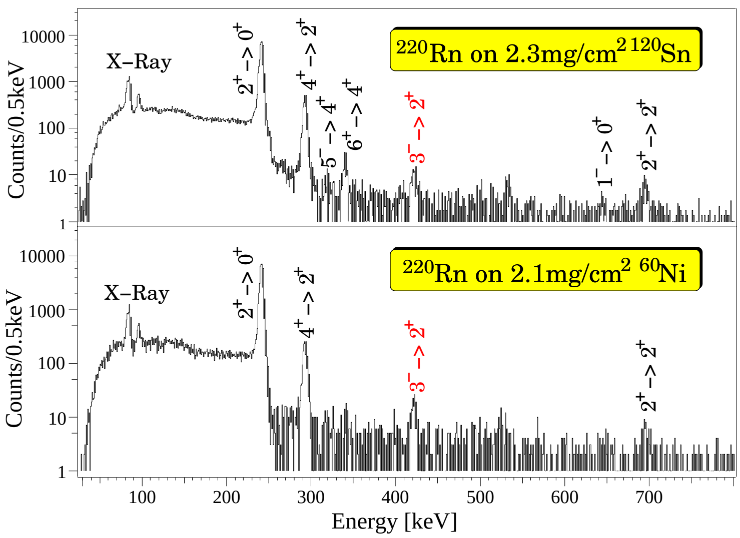

Figure 3. Particle-γ coincidence gated and Doppler-corrected γ-ray spectra of ^{220}Rn Coulomb excited using secondary ^{60}Ni (bottom) and ^{120}Sn (top) targets. Peaks are labeled corresponding to the transition they represent.

3. Results and Conclusions

The Coulomb-excitation code GOSIA was used to extract matrix elements from the observed γ-ray yields. This analysis resulted amongst others [8] in matrix elements corresponding to a $B(E3, 3^- \to 0^+)$ value of 33(4) W.u. for ^{220}Rn and 42(3) W.u. for ^{224}Ra. The corresponding values are shown in Fig. 4 as an inverse sum rule of the squared matrix element divided by the excitation energy of the corresponding 3^- level. The inverse sum rule is applied as it combines

Journal of Physics: Conference Series **533** (2014) 012007 doi:10.1088/1742-6596/533/1/012007

the two most important experimental observables and highlights the special role of the two radium isotopes (^{224}Ra and ^{226}Ra [4]) for which the B(E3) strength was measured so far. Here, it is worthwhile to point out, that the experimental trend of the two radium isotopes favours mean-field based models and opposes cluster models [8].

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

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

and the corresponding Legendre Polynomials, $P_{\lambda 0}(\cos\theta)$. The deformation parameters can be calculated using the measured matrix elements [4]. The shape of ^{220}Rn and ^{224}Ra as resulting from the current experiment are illustrated in Fig. 5. Obviously, ^{224}Ra exhibits nicely the pear-shape associated with an octupole correlated nucleus.

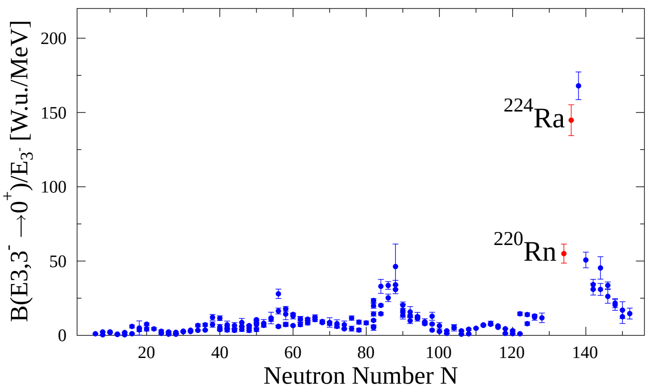

Figure 4. Inverse sum rule of the $B(E3, 3^- \rightarrow 0^+)$ strength divided by the energy of the 3_1^- level plotted over the neutron number, N.

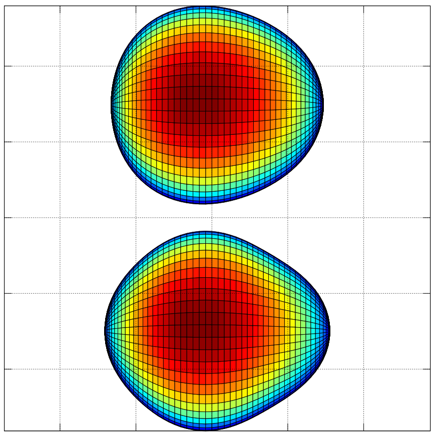

Figure 5. Surface contour plot of ^{220}Rn (top) and ^{224}Ra (bottom).

In conclusion the presented Coulomb-excitation experiment provided strong evidence that ^{220}Rn is rather an octupole vibrational system, while ^{224}Ra possesses an octupole deformed ground state. Therefore, at present, atoms of the odd-mass radium isotopes are favourable cases in the search for CP-violating physics. The collaboration has already further approved experiments at HIE-ISOLDE which aim to investigate even-even and odd-mass isotopes near $A = 224$ [9] and also the mass region near ^{144}Ba [10].

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