Shape coexistence in neutron-deficient Pb nuclei probed by quadrupole moment measurements

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INTRODUCTION

Neutron-deficient Pb isotopes are important benchmarks for investigating the phenomenon of shape coexistence in nuclei, and have recently been the subject of much experimental and theoretical interest. The information concerning the excitation spectra in these nuclei increased considerably based on detailed α- and β- decay [1] and in-beam [2, 3] studies. Calculations using a deformed mean-field approach [4] show the existence of three closely spaced minima with spherical, oblate and prolate deformations in the potential energy surfaces of the Pb isotopes around N=104. Various mean-field and beyond mean-field calculations have been recently reported, providing energy spectra and electromagnetic properties for comparison with the experimental data [5, 6]. In the shell-model picture, the coexisting structures are generated by many-particle many-hole $[mp - mh]$ proton excitations across the Z=82 shell gap. Recent detailed treatments of these excitations, including configuration mixing, were performed with the interacting boson model (IBM) [7].

An interesting feature of the Pb nuclei is the presence of many isomeric states, involving normal and intruder excitations. These isomers offer the opportunity to probe the shape coexistence through static quadrupole moment measurements. In previous studies performed at the LNL XTU-Tandem we have investigated spectroscopic quadrupole moments for three short-lived isomeric states in ^{193}Pb, one of them being the bandhead of a magnetic rotational band involving the coupling of the 11^- $\pi 3s_{1/2}^{-2} 1h_{9/2} 1i_{13/2}$ intruder excitation with a $1i_{13/2}$ quasineutron [8, 9]. In this contribution we present results of new studies, devoted to spectroscopic quadrupole moment measurements for the 11^- $\pi[2p - 2h]$ and 12^+ $\nu 1i_{13/2}^2$ isomeric states in ^{192,194}Pb.

EXPERIMENTAL PROCEDURE AND RESULTS

The isomeric states were populated and aligned in the ^{168}Er(^{28}Si,4n)^{192}Pb and ^{170}Er(^{29}Si,5n)^{194}Pb reactions at the beam energy of 143 MeV. The beams, delivered by the Legnaro XTU-Tandem accelerator, were pulsed with 2 ns pulse width and a separation of 3.2 μs for ^{192}Pb and 1.6 μs for ^{194}Pb. The method of time-differential observation of the perturbed angular distribution (TDPAD) of deexciting γ-rays has been applied. The quadrupole interaction of the isomeric states has been investigated in the electric field gradient (EFG) of the polycrystalline lattice of metallic Bi in which they were in-beam implanted. Two planar Ge detectors placed at 0° and 90°, and two Ge detectors with 20% efficiency each, placed at 27° and 90° with respect to the beam direction, were used to detect the γ rays. Illustrative TDPAD modulation spectra for the 11^- and 12^+ isomeric states in ^{194}Pb are shown in Fig. 1.

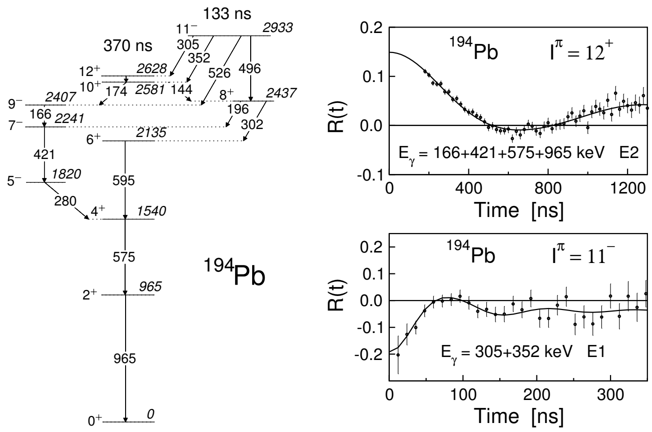

FIG. 1: *Partial level scheme of ^{194}Pb showing the decay of the 11^- and 12^+ isomeric states (from Ref. [10]) and TDPAD modulation spectra in the electric field gradient of metallic Bi.*

The deduced values for the quadrupole coupling constant $\nu_Q = Q_s V_{zz}/h$ were 96(6) and 10.6(11) MHz for the 11^- and 12^+ states in ^{192}Pb, and 120(8) and 16.2(6) MHz for the corresponding states in ^{194}Pb. Using the known quadrupole moment $|Q_s|(12^+,{}^{194}\mathrm{Pb}) = 0.48(3)$ eb [8], a reliable calibration of the electric field gradient for Pb in the Bi polycrystalline lattice, V_{zz}(PbBi) = 1.39(10)x10^{21} V/m^2, has been derived in the present experiment. With this calibration, absolute values for spectroscopic quadrupole moments Q_s were obtained as $|Q_s|(12^+,{}^{192}\mathrm{Pb}) = 0.32(4)$ eb, $|Q_s|(11^-,{}^{192}\mathrm{Pb}) = 2.9(3)$ eb and $|Q_s|(11^-,{}^{194}\mathrm{Pb}) = 3.6(4)$ eb.

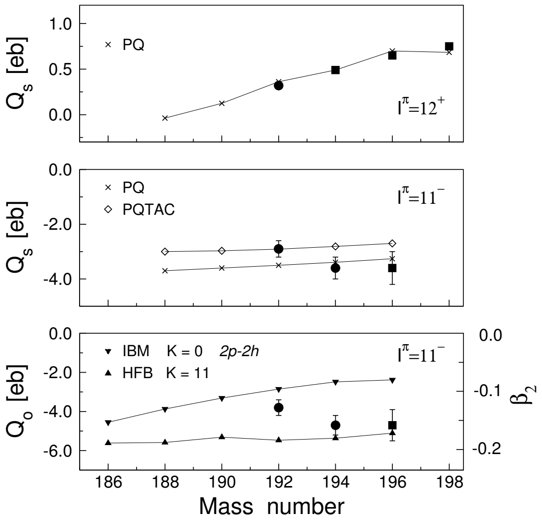

FIG. 2: *Experimental spectroscopic quadrupole moments in light lead nuclei for the 12^+ and 11^- states, from present work (full circles) and from [11, 12] (full squares), are compared in the two upper panels with the PQ and PQTAC calculations. In the lower panel, experimental intrinsic quadrupole moments for the 11^- states are compared to HFB mean-field [14] and IBM [7, 15] calculations.*

DISCUSSION

The spectroscopic quadrupole moments of the 11^- and 12^+ states in Pb nuclei, including the values determined in the present study, are compared in Fig. 2 with the calculations performed with the pairing plus quadrupole tilted axis cranking (PQTAC) model which was used to describe the observed magnetic rotational bands in light lead nuclei [13]. The calculations for the 12^+ states were performed essentially within the pairing plus quadrupole (PQ) model, as in these cases there is no tilt angle and no rotation. The experimental data are nicely reproduced by these calculations which predict a decrease of the Q_s with decreasing neutron number due to the change in the occupation number of the neutron $1i_{13/2}$ orbital. The 11^- states were calculated to be oblate deformed, with a moderate quadrupole deformation parameter varying from $\beta_2 = -\,0.13$ for ^{188}Pb to $\beta_2 = -\,0.10$ for ^{196}Pb. Calculations were performed with both the PQ and PQTAC approximations. The PQTAC values, which were obtained by treating the 11^- state as a rotational bandhead, are slightly smaller than the PQ values. As seen in Fig. 2, a good description of the experimental quadrupole moments was obtained. The Q_s values in ^{194,196}Pb are in better agreement with the PQ calculations, while the measured Q_s in ^{192}Pb is closer to the PQTAC calculation. In the lower panel of Fig. 2 are shown the experimental intrinsic quadrupole moments Q_0 of the 11^- states, obtained by assuming axial symmetry and $K{=}I$. The corresponding quadrupole deformation parameter β_2 was derived using the formula $Q_0 = \frac{3}{\sqrt{5\pi}} Z R^2 \beta_2$. Quadrupole deformation values of $-\,0.127(13)$, $-\,0.156(17)$ and $-\,0.156(26)$ were deduced for ^{192}Pb, ^{194}Pb and ^{196}Pb, respectively. They are consistent within error bars with an average deformation of $\beta_2(11^-) = -\,0.146(14)$. The experimental Q_0 are compared with theoretical values derived for the 11^- state in $^{186-196}$Pb in the framework of the Hartree-Fock-Bogoliubov (HFB) method with a Skyrme interaction and a density-dependent pairing force [14]. As seen in Fig. 2, the HFB calculations predict Q_0 values that are very slightly increasing with decreasing N, and deformation parameters varying from $-\,0.17$ to $-\,0.19$. In Fig. 2 are also given for comparison the intrinsic quadrupole moments derived in the framework of the interacting boson model for the unperturbed $[2p-2h]$ oblate band in $^{186-196}$Pb [3, 15]. The IBM values show a more pronounced dependence on the neutron number, and are somewhat smaller than the mean-field calculations. Note, however, that these Q_0 values are obtained from the calculated spectroscopic quadrupole moments in the assumption that the $[2p-2h]$ band is a pure K=0 band. The slightly smaller static quadrupole moment measured for the 11^- state in ^{192}Pb compared with the heavier nuclei ^{194,196}Pb, can be viewed as evidence for shape mixing. An increased mixing of spherical and/or prolate configurations might be present in ^{192}Pb either in the structure of the 0_2^+ oblate state on which the broken-pair proton excitation is built, or in the structure of the high K state itself. Note that a complex structure of the 11^- state, involving possible K mixing, was suggested also by the properties of the irregular band structure built above it, as discussed recently by Dracoulis et al. [2].

ACKNOWLEDGEMENTS

The authors thank the staff of the LNL XTU-Tandem for the high quality of the delivered pulsed beam and Massimo Loriggiola for preparing the delicate targets. Support through the European Community FP6 - Integrated Infrastructure Initiative - EURONS contract nr. RII3-CT-2004-506065 is acknowledged.

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