Octupole correlations and ground state deformations in the neutron-deficient region of $^{116}$Ba

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INTRODUCTION

An in-beam $\gamma$-ray spectroscopy experiment was performed to identify and study excited states in the very neutron-deficient region of $^{116}$Ba. The motivation for studying these nuclei can be summarised as follows: (i) to investigate the expectation of increased octupole correlations approaching $N = Z$ due to the $h_{11/2} - d_{5/2}$ octupole coupling for both neutrons and protons; (ii) to trace the evolution of ground-state deformations from the energies of the $2^+$ states; and (iii) to investigate the behaviour of aligned angular momenta with increasing overlap of the neutron and proton wavefunctions in the same high-$j$ ($h_{11/2}$) shell. The excited states of the nuclei of interest were populated using $^{58}$Ni + $^{64}$Zn reaction and $\gamma$ rays and evaporated particles were detected with Galileo – Neutron Wall – Euclides setup. The physical motivation and experimental details are given in the sections below.

MOTIVATION

In the neutron-deficient barium isotopes the proton Fermi level lies in the low-$\Omega$ $h_{11/2}$ orbitals, which drives the nucleus towards a prolate shape. Orbitals from the positive-parity $d_{5/2}$ and $g_{7/2}$ subshells lie close to the Fermi level and also play an important role in the structure of these nuclei. At neutron mid-shell ($N = 66$) the neutron Fermi level lies in the middle of the $h_{11/2}$ subshell, but as neutron number decreases towards $N = Z = 56$, the neutrons and protons start to occupy increasingly similar orbitals which can lead to enhanced neutron-proton correlations.

An indication of the deformation of the ground-state can be obtained from the energy of the $2^+$ state, using empirical relationships, such as those of Ref. [1]. The deformation of the ground state in $^{118}$Ba appears to be smaller than that of $^{120}$Ba [2], establishing a lower limit on the trend of increasing deformation with decreasing neutron number. In the $Z = 54$ xenon isotopes, the deformation appears to increase for the lowest $N$ values [3, 4]. The recent experiment was performed, inter alia, to extract the deformation of $^{116}$Ba to compare the trend in the $Z = 56$ barium nuclei to the neighbouring $Z = 54$ xenon isotopic chain.

There is a long-standing prediction that strong octupole correlations will occur in the lightest nuclei with $52 \leq Z \leq 58$ [5, 6] due to the interaction of the $\Delta l = \Delta j = 3$ octupole-driving $h_{11/2}$ and $d_{5/2}$ orbitals. It is expected that octupole correlations will be important for both neutrons and protons within the same orbitals, which will lead to the possibility of correlations between those particles. Strutinsky-type calculations performed by Skalski [5] suggest that octupole correlations in this region is maximal for $^{112}$Ba, which has been calculated to have the deformation of $\beta_3 = 0.138$. The experimental signature of octupole correlations is the observation of low-lying negative parity states and enhanced $E1$ transitions. This type of level structure has been observed in a number of the neutron-deficient $^{52}$Te [7, 8], $^{54}$Xe [3, 9], $^{56}$Ba [2], and $^{58}$Ce [10] nuclei, and despite the observation of low-lying negative parity states and $E1$ transitions, the evidence is not yet conclusive. In order to test the predictions rigorously, we aim at investigating the isotopes that lie very close to $N = Z$.

Recently, an enhancement in collectivity has been observed in the $^{110,112}$Xe isotopes [3, 4]. $\gamma$-ray spectroscopy of these nuclei has shown a decrease in the $2^+$ and $4^+$ level energies with decreasing neutron number towards $N = 50$. For $^{110}$Xe [4] it has been suggested that the enhanced collectivity is due to the effect of the isoscalar ($T = 0$) component of the neutron-proton interaction. The issue of proton-neutron pairing can be studied by examination of the aligned angular momenta. The alignments of pairs of both $h_{11/2}$ protons and $h_{11/2}$ neutrons are expected, and these alignments have been observed [11]. For the $N = Z$ nucleus $^{108}$Xe, Caurier et al. [12] have recently used shell model calculations to predict that instead of the observations of separate $\gamma(h_{11/2})^2$ and $\nu(h_{11/2})^2$ alignments, a proton-neutron pair will align. In the neighbouring nuclei, it is expected that the rotational frequencies of the $\gamma(h_{11/2})^2$ and $\nu(h_{11/2})^2$ alignments will be delayed due to the presence of the opposite type of particles in the same subshell. We
have recently observed some evidence for this in the \( N = Z + 3 \) nucleus \(^{111}\text{Xe}\) [13, 14]. In this regard, the experiment was performed to study the lowest alignments in the most neutron-deficient barium isotopes.

**EXPERIMENTAL METHOD**

The nuclei of interest were produced via fusion-evaporation reaction between 250 MeV \( \sim 8 \) pA \(^{58}\text{Ni}\) beam and 1 mg/cm\(^2\) \(^{64}\text{Zn}\) target. Prompt \( \gamma \) rays were detected with Galileo \( \gamma \)-ray detector array [15], while the Neutron Wall [16] and Euclides [17] detectors allowed to select the reaction channels.

Galileo array in a configuration of 25 Compton suppressed HPGe detectors placed 22.5 cm from the target, at \( \theta = \{90^\circ, 119^\circ, 129^\circ, 152^\circ\} \) with respect to the beam line was used in the recent experiment. The photopeak efficiency of the Galileo array for 1.3 MeV is \( \sim 2\% \). Neutrons were identified with the Neutron Wall array, which (in the LNL setting) consists of 45 detectors filled with BC501A liquid scintillator, covering 1\( \pi \) of the solid angle in the \( \theta \leq 60^\circ \). The efficiency of detecting at least one neutron is \( \sim 25\% \). Charged particles were identified with 55 \( \Delta E - E_S \) Si telescope detectors of Euclides array. The detection efficiency is \( \sim 55\% \) and \( \sim 35\% \) for protons and \( \alpha \) particles, respectively. See also Ref. [18, 19] for details on ancillary detectors of Galileo \( \gamma \) ray spectrometer. The ancillary devices allowed a clean identification of the evaporation channels of interest and provided information for more precise event-by-event Doppler correction (see [20] for more details).

The examples of channel selection are shown on Fig. 1 and 2, where neutron (proton) gated projection of \( \gamma - \gamma \) matrix gated on \( 7/2^+ \rightarrow 5/2^+ \) 123 keV \( (2^+ \rightarrow 0^+ \) 338 keV) transition in \(^{119}\text{Ba} \) \((118\text{Xe})\) are shown.

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**CONCLUSIONS**

The experiment aiming at identification of the excited states of the very neutron-deficient nuclei in the vicinity of \(^{116}\text{Ba}\) was performed in Dec. 2015, employing Galileo – Neutron Wall – Euclides setup. The main goals of the experiment were: (i) to study trends in ground-state deformation; (ii) to look for signatures of octupole correlations; and (iii) to possibly study the effects of \( np \) interactions on rotational alignments. The ongoing analysis will allow to deepen the understanding of the evolution of structure in barium isotopes approaching \( N = Z \) line.

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