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The octupole strength present in the neutron-rich, radiocative nucleus ^{146}Ba has been experimentally determined for the first time using Coulomb excitation. To achieve this, A=146 fission fragments from CARIBU were post-accelerated by the Argonne Tandem Linac Accelerator System (ATLAS) and impinged on a thin ^{208}Pb target. Using the GRETINA γ-ray spectrometer and the CHICO2 heavy-ion counter, the reduced transition probability $B(E3; 3^- \rightarrow 0^+)$ was determined as $48(^{+21}_{-29})$ W.u. The new result provides further experimental evidence for the presence of a region of octupole deformation surrounding the neutron-rich barium isotopes.

Keywords: octupole, Coulomb excitation, radioactive beam, barium

1. Introduction

The first experimental evidence indicating that the atomic nuclei of certain isotopes exhibit octupole-deformed shapes was provided several decades ago through the observations of low-lying 1^- states populated in α decay[1]. Since then, there has been a wealth of experimental and theoretical investigations attempting to understand and characterize the importance of octupole correlations in nuclei (see Ref. 2 and references therein). Indeed, there is now ample evidence to suggest that the most octupole-deformed nuclei will generally display a low-lying negative-parity band of states that interleaves with the ground-state 0^+ band with relatively fast $E1$ transitions linking the two. The strongest octupole correlations have been observed in isotopes having certain combinations of protons and neutrons, namely

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$Z,N\sim$34, 56, 88, 134,[3] which is where valence nucleons occupy pairs of single-particle orbitals near the Fermi surface that differ in orbital (ℓ) and total (j) angular momenta by 3 units of $\hbar$.[2] However, the magnitude of octupole strength present in what is expected to be the two most octupole-enhanced regions, has only recently been quantified in the neutron-deficient radium isotopes[4,5] and the neutron-rich barium isotopes[6] providing the only direct experimental evidence for octupole-deformed nuclear shapes. Such kind of measurements are difficult since they involve Coulomb excitation of radioactive beams or targets. In particular, the radioactive barium isotopes relevant for these measurements are especially difficult to measure since the lifetimes are on the order of seconds only. Those experiments have only been made possible within the past few years through the development of re-accelerated radioactive beam facilities such as CARIBU[7,8] at Argonne National Lab or REX-ISOLDE[9] at CERN. The following report highlights the newest of these studies where octupole measurements have been extended to the neutron-rich isotope ^{146}Ba with N=90.

2. Experiment

As stated above, in order to investigate the octupole strength in ^{146}Ba, a Coulomb excitation experiment was performed similar to the one done for ^{144}Ba.[6] The experimental setup was identical utilizing the CHICO2 heavy ion counter[10] and the GRETINA γ-ray tracking array[11], while the radioactive ^{146}Ba ($T_{1/2}$=2.2 sec.[12]) beam was produced by the CARIBU ^{252}Cf fission source[7,8] and accelerated through the Argonne Tandem Linac Accelerator System (ATLAS). In addition to the beam of ^{146}Ba ions, CARIBU also produced the isobaric contaminants ^{146}La and ^{146}Ce which could not be separated. The A=146 beam was injected into an electron cyclotron resonance (ECR) ion source and charge-bred to q=28$^+$. It was then accelerated through the ATLAS radio-frequency quadrupole (RFQ) and linac to 659 MeV and focused onto a 1.1 mg/cm^2 ^{208}Pb target (99.86% enriched). The average ^{146}Ba beam intensity was 3×10^3 ions per second over 12 days. There were additional stable contaminants (having the same A/q) introduced into the beam from the ECR source, including ^{94}Mo^{18+}, ^{94}Zr^{18+}, ^{120}Sn^{23+}, ^{193}Ir^{37+}, and ^{198}Hg^{38+}, however all of them were easily separated from the A=146 beam ions based on time-of-flight (TOF) and scattering angle (θ) data recorded in CHICO2 (Fig. 1). This allowed for a clean A=146 γ-ray spectrum in GRETINA recorded from the Coulomb-excited beam ions (Fig. 2).
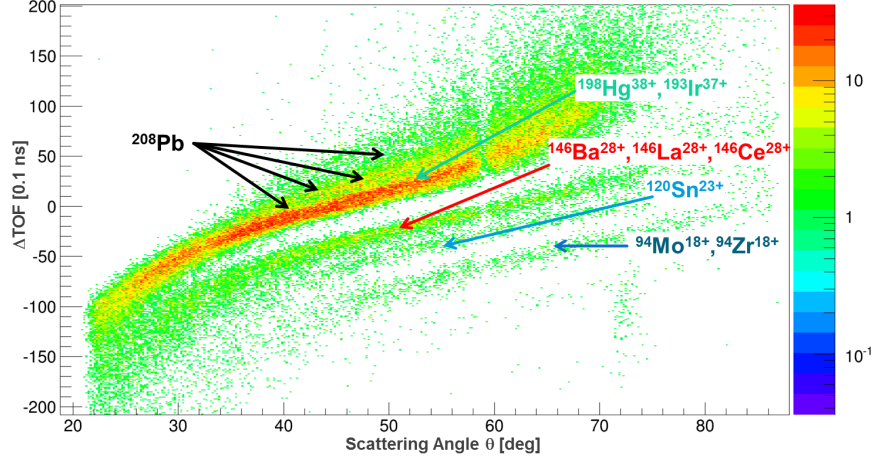
Fig. 1.   TOF vs. scattering angle recorded by CHICO2 in coincidence with a γ ray recorded in GRETINA. The A=146 group is easily distinguished from the stable beam contaminants.
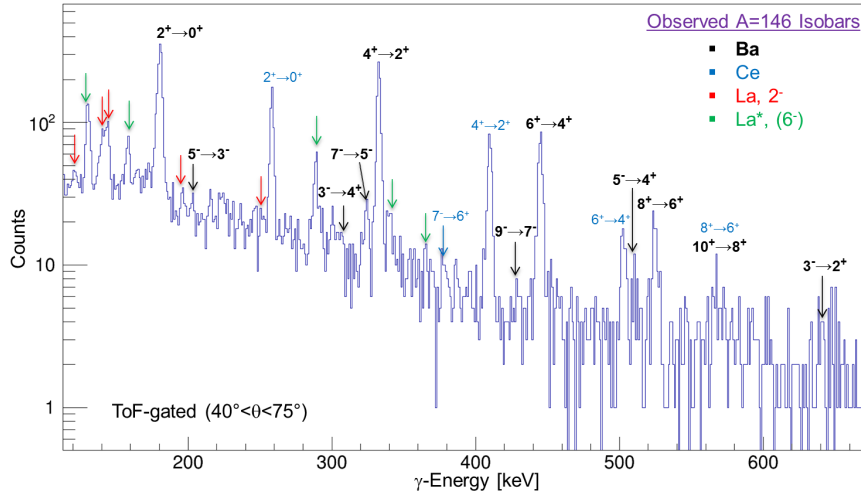

Fig. 2.   The coincident γ-ray spectrum by gating on the A=146 group in the CHICO2 TOF spectrum (Fig. 1). Many ^{146}Ba lines are seen along with lines from the radioactive isobaric contaminants that were also produced in CARIBU.

3. Analysis

In the γ-ray spectrum of Fig. 2, several peaks from ^{146}Ba are apparent, especially ones belonging to positive-parity levels in the ground-state band

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which are excited (and decay) by $E2$ transitions. The negative-parity levels are excited much less frequently, but the excitation occurs predominantly through $E3$ transitions and their decay yields provide a measurement of the corresponding $E3$ matrix elements.

The decay yields were extracted for two separate scattering angle ranges: $30°$–$40°$ and $40°$–$75°$. At lower angles, it is difficult to isolate the $A=146$ ions from the other beam contaminants in the TOF spectrum, while at higher angles there is simply not enough statistics for a useful analysis as the cross section falls off with the well-known Rutherford angular dependence $1/\sin^4(\frac{\theta}{2})$. The yields for each set of angles were analyzed using the Coulomb excitation least-squares search code, GOSIA [13,14]. Decay yields were observed for levels up to $10\hbar$ in the ground-state band and $9\hbar$ in the negative-parity band. The energies of all observed γ rays, along with several branching ratios and lifetimes, were known in advance based on previous experiments [12,15,16]. The latter information was useful for constraining the GOSIA fit. The sets of $E1$, $E2$, and $E3$ matrix elements between levels with no previously known lifetimes, however, were coupled according to the rigid-rotor prescription [17] governed by the individual intrinsic $E\lambda$ moments (see also Refs. 4,6,18). This was done to help search for the χ^2 minimum while excluding minima in unphysical regions of the parameter space which often arise from matrix elements that are relatively insensitive to the observed yields and other available experimental data (so-called nuisance parameters, see Ref. 14). Once the χ^2 minimum was found, the rigid-rotor constraint was removed to properly determine the full uncertainties, including correlations between matrix elements [19].

4. Results and Discussion

The final results from the GOSIA analysis for the $E1$ matrix elements did not display much sensitivity to the experimental data. This is not surprising since the $E1$ strength is known to be relatively weak [15] with the only observed $E1$ decays coming from the 3^- and 5^- levels. Moreover, the relative sign between the intrinsic $E1$ and $E3$ moments was found to be completely insensitive to the data. On the other hand, a number of new $E2$ and $E3$ matrix elements were well-determined from the new Coulomb excitation yields; the full set of which are reported in Ref. 19. The most significant result is the ground-state $E3$ matrix element $\langle 3_1^- \| \mathcal{M}(E3) \| 0_1^+ \rangle$ determined to be $0.65(^{+14}_{-20})$ $eb^{3/2}$ which reflects the amplitude of octupole deformation present in the ground state [2]. This corresponds to a $B(E3; 3^- \rightarrow 0^+)$

strength of $48(^{+21}_{-29})$ W.u. which is very close to the value recently reported[6] for ^{144}Ba (Fig. 3).
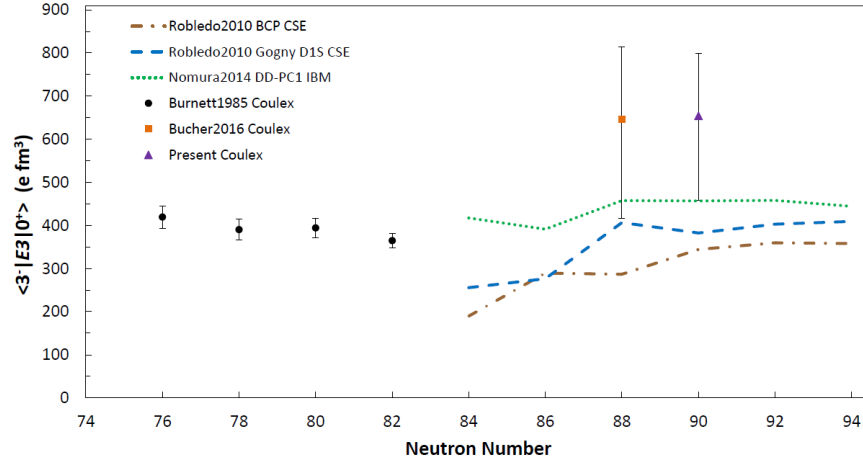

Fig. 3.   Values of the ground-state $E3$ matrix elements for neutron-rich barium (Z=56) isotopes are shown based on experimental work by Burnett *et al.*[20] and Bucher *et al.*[6] as well as theoretical work by Robledo *et al.*[21] and Nomura *et al.*[22].

The new measurement lends strong support to the idea that octupole collectivity is indeed enhanced in these barium isotopes near N=90, even exceeding the magnitude predicted in past beyond-mean-field calculations[21,22]. This is also apparent when compared to Coulomb excitation measurements performed on the stable barium isotopes[20], where no octupole enhancement is expected to come from the valence neutrons. The observed enhancement at N=90 is also consistent with the interpretation that the strong octupole correlations are driven by the presence of the high-j, unique-parity $\nu i_{13/2}$ orbital near the Fermi surface (Fig. 4) and its interaction with a nearly-filled $\nu f_{7/2}$ orbital[23]. Indeed, recent symmetry-conserving configuration-mixing (SCCM) calculations have provided quantitative support of this interpretation[19,24].

5. Conclusions

With the present measurement, the low-energy octupole strength in ^{146}Ba has been quantified. Such a measurement was only made possible by recent advances in radioactive beam acceleration (CARIBU) and state-of-
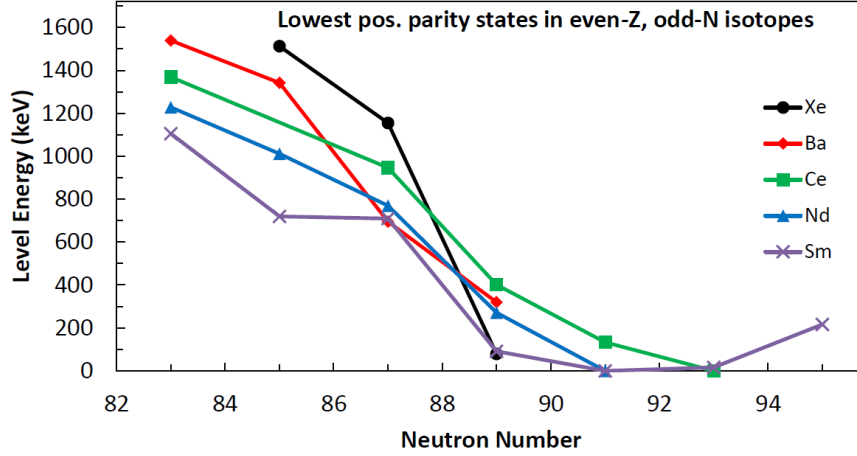
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Fig. 4. Energies of the first-excited positive-parity states in nearby even-Z, odd-N isotopes. These low-energy states must originate from the unique-parity spherical $\nu i_{13/2}$ single-particle orbitals. Clearly they approach the Fermi surface as neutrons are added towards N=90. (Data taken from the NNDC nuclear database[25].)

the-art detector arrays (GRETINA and CHICO2). The results confirm past theoretical predictions of enhanced $E3$ transitions in this nucleus and are consistent with an octupole-deformed ground state, similar to observations in neighboring ^{144}Ba. The strong octupole correlations exhibited by these neutron-rich barium isotopes can be linked to the presence of $\nu i_{13/2}$-originating orbitals near the Fermi surface at N=90 in conjuction with a nearly-full set of $f_{7/2}$ valence neutrons populated there. As a result, this region of isotopes surrounding ^{146}Ba, other than the neutron-deficient actinides around ^{226}Ra, may represent the most suitable combinations of protons and neutrons for nuclei to form stable octupole-deformed shapes.

6. Acknowledgements

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