Gauging Octupole Collectivity in Neutron Rich Ce Nuclei

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Abstract: The CARIBU facility at ATLAS offers new opportunities to study the nuclear structure of neutron-rich nuclei populated following the spontaneous fission of the ^{252}Cf source. The Ba-Ce nuclei around N=88 are of particular interest from a nuclear structure standpoint in that they exhibit properties associated with strong octupole collectivity. Much of the experimental information we have concerning octupole collectivity in these nuclei come from prompt gamma-ray coincidence studies using ^{252}Cf sources placed inside large gamma-ray arrays such as Gammasphere. We are proposing to enhance the knowledge of octupole collectivity in this region by obtaining spectroscopic information on the low-lying negative parity states in ^{148,150,152}Ce which are populated following the beta decay of ^{148,150,152}La. These La isotopes would be transported to the low-energy CARIBU decay station and gamma-beta coincidences measured with the X-array coupled to 2-4 LaBr(Ce) detectors. With this setup, we would not only measure excitation energies of excited states but also lifetimes, thus allowing us to determine both quadrupole and dipole moments, independently.

Octupole correlations play an important role in determining the level structure of nuclei throughout the periodic chart. Microscopically, these correlations are the result of the long-range, octupole-octupole interaction between nucleons occupying pairs of orbitals which differ by 3 units in both orbital- and total-angular momentum. Two distinct collective modes have long been identified: octupole vibration and octupole deformation. Vibrations are characterized by low-lying negative-parity states which decay to the yrast band via enhanced E1 transitions. The first excited state in ^{208}Pb is an example of an octupole vibrational state. If static octupole deformation is present, the yrast spectrum of an even-even nucleus is characterized by interweaving positive- and negative-parity states. The asymmetric shape results in a strong electric dipole moment. The enhanced electric dipole, *E1*, transitions between positive- and negative-parity states compete in deformed nuclei with electric quadrupole transitions, *E2*, which are characteristic of rotational bands. Evidence for static octupole deformation has only been found in selective areas of the nuclear chart, when orbitals which differ by Δj, Δl =3 approach the Fermi level for both protons and neutrons. Most of these examples are located in the *A*~222 and *A*~146 regions. Recently, Frauendorf has proposed an alternative explanation for the alternating parity sequences traditionally associated with static octupole deformation. Details of this description can be found in ref. [1] where the model associates alternating parity sequences with the concept of phonon condensation. Evidence for this phenomenon has recently been observed in ^{240}Pu [2].

In the A~146 region, octupole correlations are brought about by the proximity of the $h_{11/2}$ and $d_{5/2}$ orbitals on the proton side (Z~56) and $i_{13/2}$ and $f_{7/2}$ orbitals on the neutron side (N~88). Much of the evidence for strong octupole correlations in these neutron-rich nuclei in the vicinity of ^{144}Ba has come from high-spin studies where the gamma decay of excited states is measured following the spontaneous fission of a ^{252}Cf source placed at the target position of a large gamma-ray such as Gammasphere and observing strong E1 transitions connecting the yrast positive-parity even-spin sequence with the yrast negative-parity odd-spin sequence (see for example ref. [3,4]). Complementary information has been obtained in even-even ^{142,144,146}Ba isotopes following the beta decay of the corresponding odd-odd Cs isotopes [5]. In this measurement, a beta-gamma-gamma triple coincidence technique was used to obtain lifetime information on the low-spin members of the yrast positive and negative parity bands. The lifetimes of these states were measured using the timing between the de-excitation gamma ray measured in a BaF_2 detector and the beta particle measured in a plastic scintillator. Even though the BaF_2 detector has poor energy resolution, a specific beta-gamma coincidence could be selected by requiring a further coincidence with a gamma-ray measured in a Ge detector with the requirement that this gamma ray have a sub-picosecond lifetime and be in cascade with the de-excitation gamma transition of interest.

The main purpose of this proposal is to measure both excitation energies and lifetimes of the first 2^+, 1^- and 3^- states in ^{148,150,152}Ce following the decay of the corresponding La isotopes. To accomplish this, we will employ the same technique used in ref. [5], however, instead of a BaF_2 scintillators, we will employ ~4 LaBr(Ce) detectors. These scintillators will be used in conjunction with the X-array which consists of up to 5 Ge Clover detectors. The measurement will be performed at the decay station of the low-energy CARIBU beamline where the La parent nuclei will be implanted onto the moving tape system to allow the activity to be periodically removed from the focus of the detector array.

By measuring both excitation energies and lifetimes of these low-spin states, both quadrupole and dipole moments can be determined independently in order to gauge both the quadrupole and octupole collectivity at low spin for these Ce isotopes. For ^{148}La, the ground state has been assigned 2^- and strong population of the 1- and 3- states in ^{148}Ce following β decay has been observed. For ^{150,152}La, the ground state spins are unknown and no information is available for population of excited states following β decay in these nuclei. However, if the ground states remain to be 2^- or 3^- as observed in the lighter odd-odd La isotopes ($^{142-148}$La) , strong population of the low-spin negative parity states in ^{150,152}Ce is expected following the beta decay of the corresponding La isotopes.

For ^{148}Ce, the excitation energy of the low-lying 1^- (760 keV) and 3^- (841 keV) states are known. However, no information on the lifetimes of these states is available. The 2^+ energy is also known as well as its half-life (1.01ns). Interestingly, the isotone to ^{148}Ce, ^{146}Ba, has the anomalous feature that its dipole moment, D_0, is ~5 times smaller than that found for ^{144}Ba, even though, the negative parity states in ^{146}Ba are slightly lower in energy than the corresponding states in ^{144}Ba. This observation was explained in ref. [5] by noting that the dipole moment in the single-particle model is defined as follow:

$$D_0^{sp} = \frac{e}{3.6}\left[\frac{N}{A}\langle z\rangle_p - \frac{Z}{A}\langle z\rangle_n\right],$$

where <z> is the Strutinski-renormalized center of mass displacement which exhibits an oscillatory behavior as a function of shell filling. This quantity for both neutrons and protons was calculated in ref. [5] for several even-even nuclei around ^{146}Ba using deformation parameters extracted from total energy surface calculations which included a number of high-order deformation terms. It was found that for ^{146}Ba, $\langle z\rangle_p$ and $\langle z\rangle_n$ were close to zero indicating a reduced $D_{0,}$ even though, based on the excitation energies of the negative parity states, strong octupole collectivity is expected. This observation is important and shows that a small dipole moment does not necessarily correspond to weak octupole collectivity. These same calculations indicate an increase in $\langle z\rangle_p$ for Z=58 (Ce), and therefore, the expectation for ^{148}Ce is an increase in the dipole moment assuming a similar β_3 deformation parameter. Initial high-spin work using prompt-spectroscopy following spontaneous fission of a ^{252}Cf source, concluded that the octupole collectivity in ^{148}Ce was weak due to the fact that no evidence for population of the negative parity band was found [3]. A more recent measurement using Gammasphere has identified high-spin members of the negative-parity band, and the measured B(E1)/B(E2) ratios indicate enhanced octupole collectivity at moderate spin (I>10 hbar) [4]. A lifetime measurement of the 1^- and 3^- states will determine if this octupole collectivity is already present at low spin or enhanced by rotation and provide a further test of the single-particle model used to describe the reduced moment in ^{146}Ba. For reference, the half lives of the 1^- and 3^- yrast states in ^{146}Ba are 160 ps and 237 ps, respectively. It should also be noted that a detailed study of excited states populated in the beta decay of ^{148}La into ^{148}Ce may provide information relevant to other nuclear structure issues. For example, it has been suggested that heavier *N*=90 isotones exhibit X(5) symmetry. While this interpretation is not universally accepted, characterization of excited states in lighter *N*=90 nuclei such as ^{148}Ce may provide additional insight into this open nuclear structure issue.

In the case of ^{150}Ce, the yrast band has been identified up to I~20 [3]. Lifetime of the 2^+ state has been reported (~3ns), however, no negative parity states are known. While the lifetime of the parent ^{150}La is known, no gamma ray studies following beta decay have been reported. If the systematic of ground state spins for lighter odd-odd La isotopes extends to ^{150}La, the 1^- and 3^- yrast negative parity states should be strongly populated in beta decay. In the isotone, ^{148}Ba, the 1^- and 3^- states are located at 687 keV and 775 keV and based on the similarities in the excitation energies of these states in the lighter isotonic Ba and Ce isotopes, one would expect that these states in ^{150}Ce are located within 50 keV of those observed in ^{148}Ba. Based on the high spin data, the octupole collectivity is assumed to be decreased relative to the lighter Ce and Ba isotopes due to the fact that the negative parity band has not been observed in the prompt fission data. Identification of the excitation energy and lifetime of the low-spin negative parity states would quantify for the first time the strength of the octupole collectivity in ^{150}Ce.

In the case of ^{152}Ce, only the yrast band has been reported up to 16^+ from the analysis of ^{252}Cf spontaneous fission [6]. No lifetime information is available on any excited states presently identified in ^{152}Ce. The proposed beta-decay study of ^{152}La into ^{152}Ce would be the first decay study performed on ^{152}La. This study would not only provide information with regards to the excitation energy of the yrast negative parity states in the daughter nucleus ^{152}Ce, but it will also determine for the first time the ^{152}La lifetime and give constraints on its ground state spin.

Experimental Details

We propose to perform this experiment at the decay station of the low-energy CARIBU beamline. The La isotopes of interest will be implanted on to the moving tape system which sits at the target position and gamma rays following the decay of the implanted La isotopes will be measured by the Clover detectors which comprise the X-array. Since, we are also interested in measuring lifetimes of excited states, we will compliment the X-array with 2-4 LaBr(Ce) detectors and a plastic scintillator to detect β particles. Due to the timing characteristics of the LaBr(Ce) detectors and the plastic scintillator, lifetimes of states as fast as 30ps should be measurable with this system. In addition, we have already shown the power of combining Ge and LaBr(Ce) detectors to measure lifetimes of states following radioactive decay. In this case, a ^{177}Lu source was placed inside Gammasphere and two LaBr(Ce) detectors were placed close to the target position. Individual transitions could be isolated in the LaBr(Ce) spectrum by gating on coincidence transitions measured in the Ge detectors. One's abilitiy to isolate these transitions in the LaBr(Ce) detectors is aided by the fact that LaBr(Ce) offers energy resolution of 2-3% for 1 MeV gamma rays.

We have estimated the implantation rates at the target position at 156,000/sec, 8400/sec and 61/sec for ^{148,150,152}La respectively using the reported activity of current ^{252}Cf source. Based on these implantation rates, we would require 2 shifts for the ^{148}La decay, 4 shifts for the ^{150}La decay, and 7 shifts for the ^{152}La decay. Since the lifetime measurements require a 3-fold coincidence, we have estimated the triple coincidence rates assuming 0.4% efficiency for 4 LaBr(Ce) detectors, a 50% β efficiency and a 10% Ge efficiency. The Ge efficiency has been reduced to 10% due to the fact that the clover detectors will have to be pulled further away from the target position to accommodate the LaBr(Ce) detectors. For the ^{152}La case, we estimated $12x10^6$ implants in 7 shifts. Using the efficiencies quoted above, any cascade which can acquire 10% of the gamma-ray flux will yield ~250 counts in the LaBr(Ce) - plastic scintillator time spectrum which should be sufficient to give some indication of the state lifetime. It should also be noted that 2^+-0^+ transition should dominate the ^{152}Ce gamma-ray spectrum. For this case, the energy resolution of the LaBr(Ce) detector should be sufficient to allow a determination of the ^{152}Ce 2^+ lifetime by only considering LaBr(Ce) – plastic scintillator coincidences which we estimate to be ~15,000 for a 7 shift experiment.

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