Proposal to the Bucharest TANDEM Program Advisory Committee (2012)

Lifetime Measurements of the Yrast 2_1^+, 4_1^+ and 6_1^+ states in ^{134}Ce

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Abstract

The existing experimental values of the ratios $B_{4/2}$=B(E2:$4_1^+ \rightarrow 2_1^+$) / B(E2:$2_1^+ \rightarrow 0_1^+$) and $B_{6/4}$ = B(E2:$6_1^+ \rightarrow 4_1^+$) / B(E2:$4_1^+ \rightarrow 2_1^+$) in ^{134}Ce are less than unity which is unexpected on traditional collective models and is highly anomalous. In non-magic nuclei there are only a handful of such cases, and ^{134}Ce has more valence nucleons than most of them, so it would be among the least likely to have $B_{4/2}<1$. Therefore, lifetime measurements on the yrast 2^+, 4^+ and 6^+ states in ^{134}Ce using a plunger device and the Recoil Distance Doppler-Shift (RDDS) method in coincidence mode are proposed. Excited levels of ^{134}Ce will be populated via a ^{120}Sn(^{18}O, 4n) reaction. With the new lifetime, and hence B(E2) measurements, the anomaly will either be resolved or a significant structural challenge presented.

1. Introduction and motivation

Understanding the emergence of collectivity in nuclei is one of the great challenges of modern nuclear physics. B(E2) values are among the simple spectroscopic observables we use to understand this structural evolution. Besides the B(E2) value, the first excited 2^+ state energy and the $R_{4/2}$ ratio [E(4_1^+)/E(2_1^+)] are very useful spectroscopic observables. In this proposal, we will discuss B(E2) values for low lying excited states, in particular B(E2:$4_1^+ \rightarrow 2_1^+$) and B(E2:$2_1^+ \rightarrow 0_1^+$) values. For spherical, near–magic nuclei the B(E2: $2_1^+ \rightarrow 0_1^+$) value in W.u is very low (~ a few W.u.), vibrational nuclei have on the order of 10's of W.u. while B(E2:$2_1^+ \rightarrow 0_1^+$) values are very large for well-deformed. The quantity $B_{4/2} \equiv$ B(E2:$4_1^+ \rightarrow 2_1^+$) / B(E2:$2_1^+ \rightarrow 0_1^+$) = 2 in the harmonic vibrator and 1.43 in the symmetric rotor. It is slightly smaller by taking into account finite valence spaces, as, e.g., in the IBA model. In transitional regions, descriptions such as E(5) and X(5) also give values > 1. A number of model predictions for both $B_{4/2}$ and $B_{6/2}$ are summarized in Table 1. Thus, $B_{4/2}$ is always expected to be greater than 1 except when seniority is a good quantum number which occurs at or near magic nuclei [1]. Nuclei not close to a magic number for which the $B_{4/2}$ ratio is less than 1, are considered anomalous and there is no simple model to interpret such results. It is important to experimentally verify such cases.

Table 1: Yrast B(E2) ratios for various models.

	Harm Vib.	U(5)[a)]	O(6) [a)]	Rotor	SU(3) [a)]	E(5)	X(5)
$B_{4/2}$	2	1.71	1.34	1.43	1.37	1.67	1.60
$B_{6/2}$	3	2.14	1.41	1.56	1.39	2.21	1.98

[a)] N_B = 7, corresponding to ^{134}Ce is used for these three IBA results

Reference [2] showed a survey of all even-even nuclei for 40≤Z≤80 (except N=50 and 82) with their B(E2:$2_1^+ \rightarrow 0_1^+$) and B(E2:$4_1^+ \rightarrow 2_1^+$) values and pointed out a small set of nuclei with $B_{4/2}$ < 1. Figure

1 (left) (updated from Ref. [2]) shows B(E2:4_1^+ → 2_1^+) values against B(E2:2_1^+ → 0_1^+) on equal scales so that the diagonal line defines where the B(E2: 2_1^+ → 0_1^+) and B(E2:4_1^+ → 2_1^+) values are equal, $B_{4/2}$ =1. $B_{4/2}$ <1 nuclei are seen below the diagonal line, ^{134}Ce is one of them. Figure 1 (right) shows $B_{4/2}$ as a function of the P factor ($P= N_pN_n / (N_p+N_n)$) which correlates collectivity with valence proton number (N_p) and valence neutron number (N_n). The P factor is less than ~2 for non-collective nuclei, ~ 2 - 4 for collective nuclei and larger than ~ 4 for deformed nuclei. Figure 1 includes recent B(E2) measurements of nuclei with low $B_{4/2}$ values in Ref. [2] (^{98}Ru [3], ^{180}Pt [3] and ^{144}Nd [4] where the $B_{4/2}$ values were < 1 but have moved above the $B_{4/2}$=1 line in Fig. 1(left) compared to the anomalous values given in Ref.[2]). This removes (or minimizes) some of the anomalous values noted earlier and further highlights the need to study other nuclei with anomalous $B_{4/2}$ values.

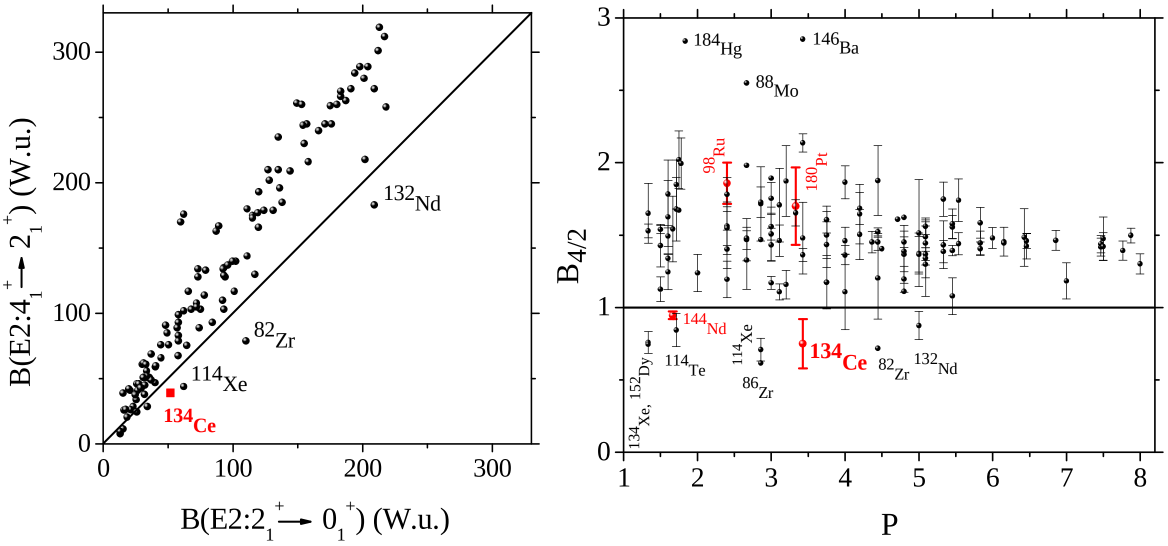

Figure 1 : Left: B(E2:4_1^+ → 2_1^+) as a function of B(E2: 2_1^+ → 0_1^+) for $40 \leq Z \leq 80$ (except magic nuclei). The diagonal line corresponds to $B_{4/2}$ = B(E2:4_1^+ → 2_1^+) / B(E2: 2_1^+ → 0_1^+) =1. Right: $B_{4/2}$ against the P factor (see text). The error bars on $B_{4/2}$ are not shown if the error is larger than 0.3. The nucleus ^{134}Ce is shown in red. In addition, the nuclei ^{98}Ru, ^{180}Pt and ^{144}Nd, which moved up in $B_{4/2}$ values with recent B(E2) measurements (see text), are denoted with red.

Figure 1 (right) shows three nuclei – ^{134}Ce, ^{82}Zr, and ^{132}Nd – characterized by $B_{4/2}$ values less than 1 and relatively large P values. That is, despite the fact that they contain a large number of valence nucleons and therefore would normally be considered to be collective nuclei with large $B_{4/2}$ values, measurements to date suggest otherwise. If these existing data are true, it is a significant structural puzzle that defies traditional models. Therefore new measurements to verify or alter these values are needed. In this proposal, our main motivation is to understand the structure of ^{134}Ce which has $B_{4/2}$ < 1 although it would otherwise be considered a collective nucleus with (E(2_1^+) = 409 keV, $R_{4/2}$ = 2.56). A part of the experimental level scheme of ^{134}Ce is shown in Fig. 2 with the literature B(E2) transitions in the yrast-band and level lifetimes [5]. In addition to the anomaly in $B_{4/2}$, B(E2:6_1^+ → 4_1^+) is also smaller than B(E2:4_1^+ → 2_1^+) and B(E2:2_1^+ → 0_1^+) which, again, is not expected for a collective nucleus. This can be easily seen in Fig. 3 (left) which shows yrast B(E2:J → J-2)/ B(E2: 2-0) ratios against J for the data for ^{134}Ce and several models. Clearly, ^{134}Ce does not behave according to any of them. Figure 3 (right) is for EGOS (E_γ over spin) as a function of spin in the yrast 2^+, 4^+, 6^+ and 8^+ states with the experimental results and some models. This (right) panel does not reveal an anomaly in the ^{134}Ce excited state energies compared to the anomaly in the B(E2) values illustrated in Fig. 3 (left).

The experiment will use a fusion evaporation reaction with an ^{18}O beam on a ^{120}Sn target to produce ^{134}Ce. Using the Bucharest plunger device at the IFIN-HH research center, we propose to measure the lifetimes of the yrast 2^+, 4^+ and 6^+ states and deduce the B(E2) values of the decays from those levels. With this experiment, either these anomalies in ^{134}Ce will be removed or the anomalies will be confirmed implying a new structure in ^{134}Ce that no model supports for collective nuclei. If ^{134}Ce has $B_{4/2}$ < 1, this nucleus will not be the only one that has < 1 property. Recent B(E2) measurements on ^{114}Xe [6] and ^{114}Te [7] show that these two nuclei have $B_{4/2}$ < 1. However, ^{114}Te is close to the Z=50 major shell closure and may only be weakly collective, whereas $R_{4/2}$ of ^{114}Xe is 2.38. While both nuclei have Np + Nn =14, as ^{134}Ce, their P factors are substantially smaller. Interestingly, another anomalous nucleus, ^{86}Zr, also has Np + Nn = 14 and is a candidate for future studies as well.

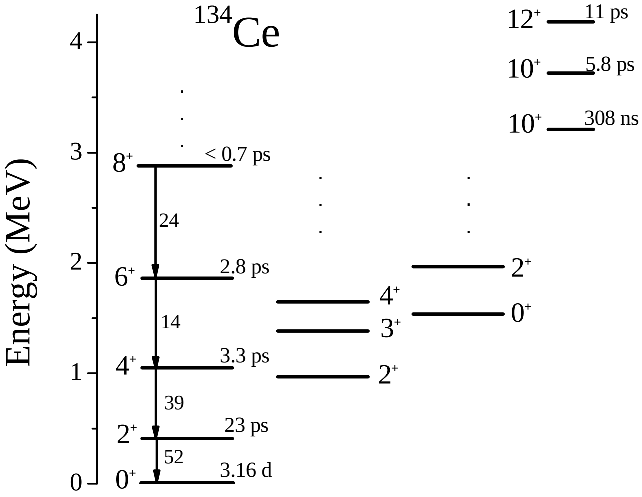

Figure 2 : First nine experimental excited levels and three additional excited states with their known lifetimes. The transitions in the yrast band are illustrated with the experimental B(E2) values in W.u.

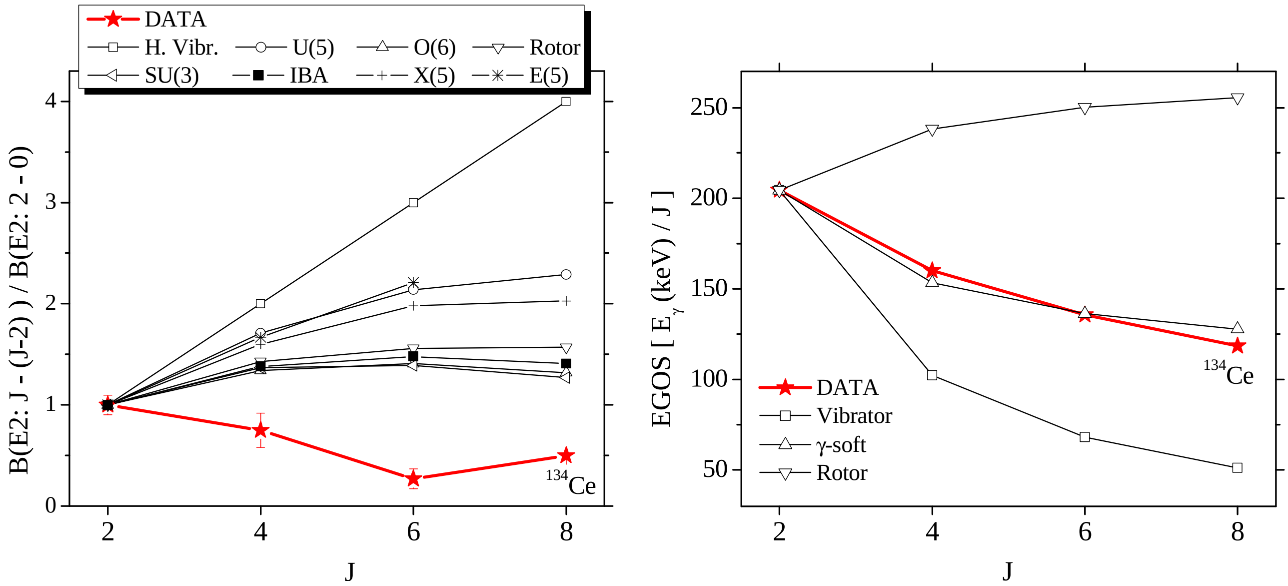

Figure 3 : (Left) The ratio between the BE2 values in yrast levels and B(E2) from the first excited 2+ to the ground state against the B(E2) values in yrast levels for some (Right) E_γ over spin (EGOS) as a function of spin . Both panels are shown with experimental results and with some models.

2. Proposed Experiment

We propose to study the lifetime values in the yrast band of ^{134}Ce by the Recoil Distance Doppler Shift method (RDDS) using the Bucharest plunger and the standard γ-ray spectroscopy setup at the IFIN-HH Tandem accelerator. We request a beam time for an experiment with an ^{18}O beam on a ^{120}Sn target. A study with the same reaction focusing on high spin states has been done in Refs. [8] and [11]. Lifetime measurements of excited states (shown some of them in Fig.2) were done in Ref. [9] where the authors noted that $B_{4/2} < 1$ and that ^{134}Ce therefore falls into a transitional region (without clarifying the meaning of this interpretation). ^{134}Ce has also been populated in (α,4n), (α,5n) and (α,6n) reactions using $^{134\text{-}136}$Ba targets and α-beams of 60, 70 and 85 MeV [10]. References [9] and [10] confirm an isomeric state at 10^+ with a lifetime of ~300ns. This should not pose a problem in the present experiments, since doppler shifts have been observed in Ref. [11], hence the isomer will be sufficiently by passed. In addition, the known ^{134}Ce yrast lifetimes were obtained by Ref. [11], in 1977, using an earlier generation plunger device and a single 10 % Ge detector. Since no coincidence analysis could be performed in Ref. [11], feeding through the long-lived isomeric state may have lead to too large lifetimes for lower-lying yrast states, leading to too low B(E2) values.

Figure 4 shows cross section results at different beam energies. These calculations are done with a ^{18}O beam and a ^{120}Sn target. Clearly, 68 MeV gives us nearly pure ^{134}Ce with 4 neutron emission. Since the energy loss of the ^{18}O beam in the Ta supporting foil is about 3.2 MeV (and a few hundred keV in the ^{120}Sn target itself), the ideal ^{18}O beam energy is about 72MeV.

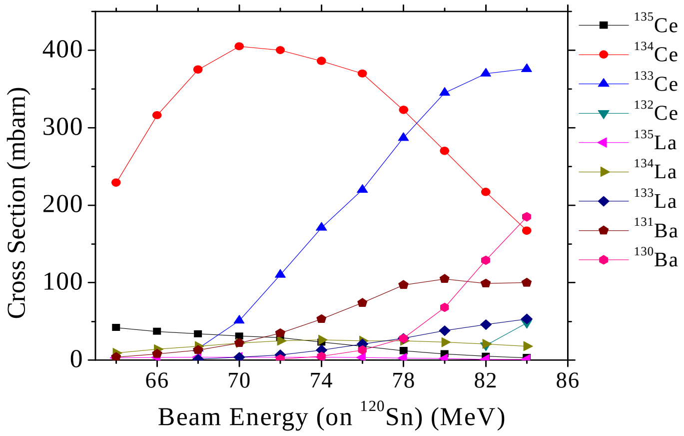

Figure 3 : Cross section results from the Cascade program [11] for an ^{18}0 beam and a ^{120}Sn target against beam energy.

2. Experimental setup

The plunger device, constructed after the Koln plunger design [12], will be used to set and maintain 6 distances (equally spaced on a logarithmic scale between 2 and 100 microns) between the 0.5 mg/cm^2 ^{120}Sn (enriched to 98.39 % in ^{120}Sn) on a 2 mg/cm^2 Ta *fronting* target have been provided by the Institut für Kernphysik, University of Cologne, and the 4 mg/cm^2 Au stopper. The γ-rays will be detected in a array of 8 HPGe detectors, each with 50% relative efficiency, placed in two rings at 143° and 35° in respect to the beam direction and 12 LaBr$_3$(Ce) detectors (used as a multiplicity filter).

3. Beam time request

To extract lifetime values from the experimental data, we plan to use the Differential Decay Curve Method [13], which implies setting gates on the shifted component of transitions populating the level of interest, thus requiring a high level of statistics for each distance. This fact puts conditions on the overall efficiency of the array, on the beam intensity and on the number of shifts/distance. Previous experiments performed with the Bucharest plunger and the standard γ-ray spectroscopy setup (in similar beam and production rates conditions) showed that to obtain a reasonably error for each distance is necessary to run at the maximum counting rate for 8 shifts (2 days). Based on the Cascade calculated cross-sections, we estimate that a beam intensity of 2pnA of ^{18}O at 72 MeV will result in a 10 kHz/HPGe counting rate. In conclusion, we ask for 12 days (36 shifts) of beam time to run at 6 target-stopper distances.

3. Conclusions

An experiment is proposed to resolve (confirm or revise) a disturbing anomaly in yrast B(E2) values in ^{134}Ce which, if true, challenges all traditional theoretical interpretations. A ^{120}Sn(^{18}O, 4n)^{134}Ce reaction will be carried out at 72 MeV beam energy and the yrast lifetimes obtained using a *Köln-type* plunger.

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