

Excited State Lifetime Measurements in Rare Earth Nuclei with Fast Electronics

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Abstract. We investigated the collectivity of the lowest excited 2^+ states of even-even rare earth nuclei. The $B(E2)$ excitation strengths of these nuclei should directly correlate to the size of the valence space, and maximize at mid-shell. The previously identified saturation of $B(E2)$ strength in well-deformed rotors at mid-shell is put to a high precision test in this series of measurements. Lifetimes of the 2_1^+ states in ^{168}Hf and ^{174}W have been measured using the newly developed LaBr_3 scintillation detectors. The excellent energy resolution in conjunction with superb time properties of the new material allows for reliable handling of background, which is a source of systematic error in such experiments. Preliminary lifetime values are obtained and discussed in the context of previous and ongoing work.

1. Introduction

The $E2$ excitation strength of the first excited 2_1^+ state in even-even nuclei is an important measure of collectivity at low energies, and therefore a benchmark for nuclear models. In general, away from closed magic shells enhanced collectivity is found, which manifests in strong axially symmetric deformations of nuclei. Such a region can be found in the mass $A \approx 170$ region of rare earth nuclei with typical β deformation values of about 0.2 - 0.3. From the geometrical relation between β deformation and $B(E2)$ strength this directly translates into large $B(E2)$ values on the order of few hundreds of Weisskopf units. Typical excitation energies of 2_1^+ states near mid-shell are about 100 keV, and typical lifetimes on the order of one or few nanoseconds.

In a simple collective picture - neglecting the evolution of nuclear orbitals as they fill with orbitals - $B(E2)$ strength should slope up approximately quadratically toward mid-shell, maximizing at mid-shell, and slope down analogously toward the next magic shell closure. This trend can, e.g. be found analytically in the $SU(3)$ limit of the Interacting Boson Model [1]. However, recently a saturation of $B(E2)$ strengths toward mid-shell has been identified from available data [2]. While $B(E2)$ strengths were observed to raise toward mid-shell, the slope of the

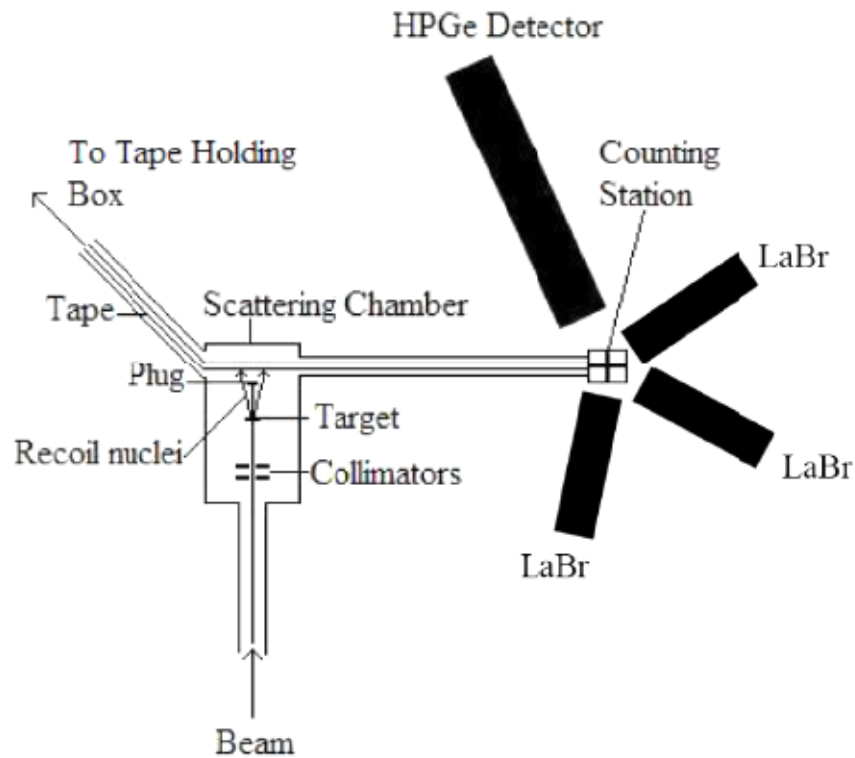


Figure 1. Schematic of the setup at the moving tape collector. Three LaBr₃ detectors were placed in close geometry around the measurement position, to which the activity was carried by the tape. An additional Ge detector was placed in order to take a high-resolution spectrum in parallel.

B(E2) strength versus neutron number in rare-earth isotopic chains decreases when approaching mid-shell (see Fig. 1 of Ref. [3]). The same (inverted) effect has been observed in g factors of the 2_1^+ states within these isotopic chains [3].

A qualitative explanation for the saturation was found [3] by the argument that neutrons are filling different angular momentum orbitals near mid-shell than protons, therefore the wavefunction overlaps and hence collectivity do not simply increase as a function of neutron number. In [3], calculations within the interacting boson model (IBM) were performed, taking into account fractional filling of the shells, therefore effectively reducing the number of active valence bosons, in order to model a reduced raise of B(E2) strengths near mid-shell. A more microscopic approach was found with in the projected shell model [4].

However, recent measurements of 2_1^+ lifetimes in the region found large discrepancies to literature values, and gave rise to the need of new, high-precision measurements of the lifetimes involved. For example, using fast timing techniques we corrected the lifetime of the 2_1^+ state in ^{172}Hf by about 15 % [5]. Within the present work, we tested the isotopes ^{168}Hf and ^{174}W . Again, fast timing techniques were applied, but using newly available LaBr₃ scintillators instead of BaF₂ scintillators. A brief overview of the techniques used, the advantages of the new material, and preliminary results are given in the following.

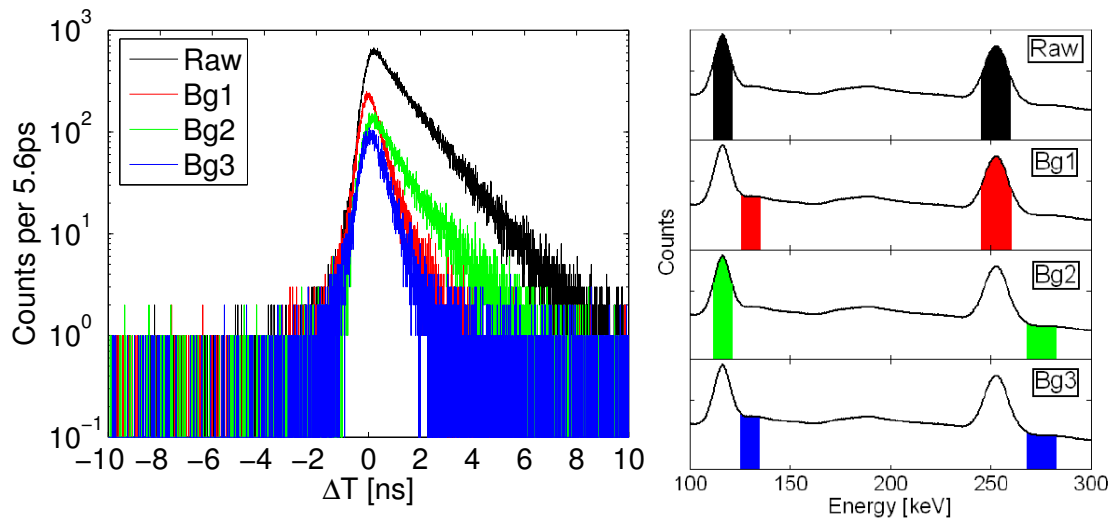


Figure 2. (Color online) The right hand side illustrates the regions where background and prompt gates were set, at the example of the spectrum taken with one of the LaBr_3 detectors. Note, that with the resolution of a BaF_2 detector (at least a factor of three larger peak widths) the identification of background would have been virtually impossible. Resulting time different spectra for each gate combination are shown on the left. The lowest (blue) spectrum corresponds to almost prompt background from higher lying states.

2. Experimental Technique

The setup for this experiment is depicted in Fig. 1. We used the moving tape collector (MTC) at the Wright Nuclear Structure Laboratory (WNSL) of Yale University. The reactions were $^{169}\text{Tm}(^{12}\text{C},7n)^{174}\text{Re}$ and $^{159}\text{Tb}(^{16}\text{O},7n)^{168}\text{Ta}$ at 115 MeV and 130 MeV beam energies, respectively, to produce the β -decay parents of ^{174}W and ^{168}Hf . The beams were delivered by the 20 MeV ESTU tandem accelerator at WNSL. Parent nuclei recoiling out of the target were implanted on a tape, whereas the beam was stopped in a gold plug arranged between the target and the tape. The tape was then periodically moved, depending on the two half-lives of the parent nuclei, so that the activation was placed in the center of the detector array. γ -rays emitted after β -decay were detected by three $1.5'' \times 1.5''$ LaBr_3 scintillators, and an additional Ge detector, in parallel to collecting the next activity spot at the well-shielded target position.

The Ge detector was placed in order to ensure that no unresolved contaminants were present at the energies of interest in the scintillator spectra. Time signals of the scintillators were fed into three time-to-analog converters (TACs), such that each detector could serve as a start or stop signal. The TAC output was then recorded in a standard analog-to-digital converter (ADC) of the WNSL data acquisition system. The very good energy resolution of the LaBr_3 scintillators (3-4 % at ^{60}Co energies compared to about 10 % for a BaF_2 crystal) allowed for a reliable subtraction of background. According to the scheme shown in Fig. 2 gates were set on the $4_1^+ \rightarrow 2_1^+$ (4-2) and $2_1^+ \rightarrow 0_1^+$ (2-0) transitions in each detector, and time differences between each pair of detectors were projected out. In addition, three sets of background gates were defined: 1) gates on (4-2) and to the right of (2-0); 2) gate to the right of (4-2) and on (2-0); and 3) gates both on the right of (4-2) and (2-0). Background gates were taken to the right only in order to avoid gating on Compton events belonging to the transitions of interest. From the resulting time difference spectra it is seen that random background was negligible.

Subtracting the projected time difference spectra from background gates 1) and 2) from the

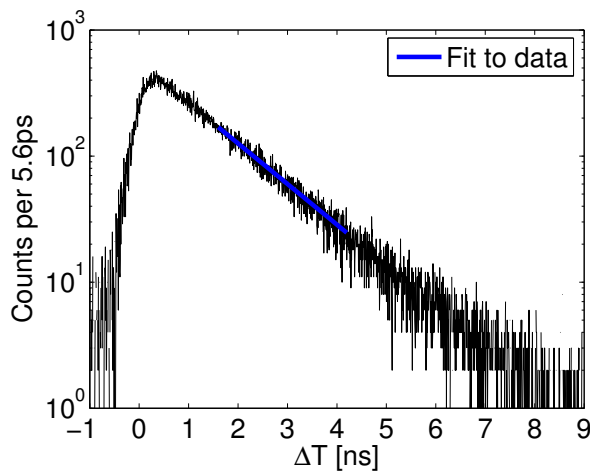


Figure 3. (Color online) Sample final time difference spectrum, with a line fitted to the linearly down-sloping part. The slope directly yields the lifetime of the state of interest.

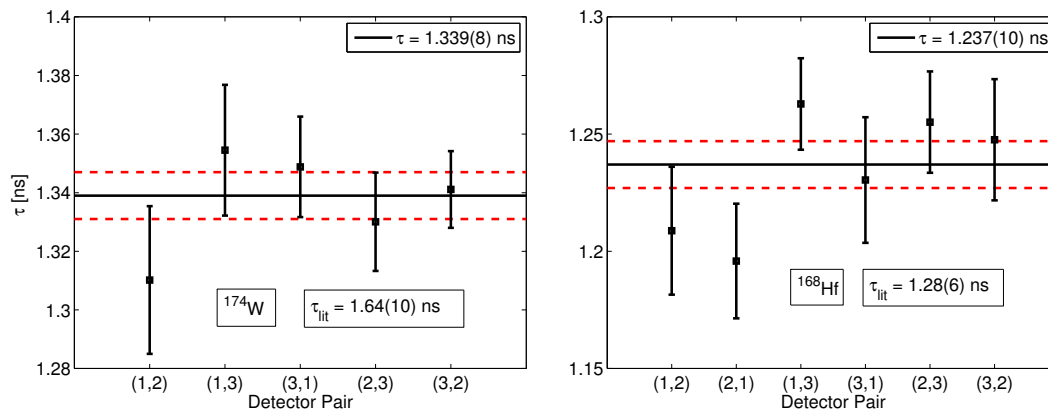


Figure 4. (Color online) Lifetimes obtained for different detector pairs for the 2_1^+ state in ^{174}W (left) and ^{168}Hf (right).

prompt time difference spectra, and adding background gate 3) back in (which has been over-subtracted in the first step) results in a proper background correction in the time difference spectra. The individual contributions are included in Fig. 2. It should be noted, that such a background treatment was only possible because of the excellent energy resolution of the LaBr_3 scintillators. A simple line-fit, as shown in a sample in Fig. 3, has then been made to each of the six resulting time difference spectra on logarithmic scale, including only the region sufficiently far away from prompt contributions. The results for the six detector pairs, shown in Fig. 4, yielded identical results within error, and the weighted average was taken. In case of the tungsten experiment, only 5 pairs of detectors could be used due to a broken channel in the electronics.

3. Results

From the technical aspect, the new LaBr_3 detectors proved to be extremely valuable because of their energy resolution, which is superior to comparable BaF_2 detectors, whereas time resolution is similar. It is only because of the energy resolution that we were able to correctly subtract background from Compton events from higher-lying states when gating on the peaks corresponding to the decays from the 2_1^+ or 4_1^+ states. Still, monitoring the spectrum with a high-resolution Ge detector is imperative in order to ensure the absence of further contaminants.

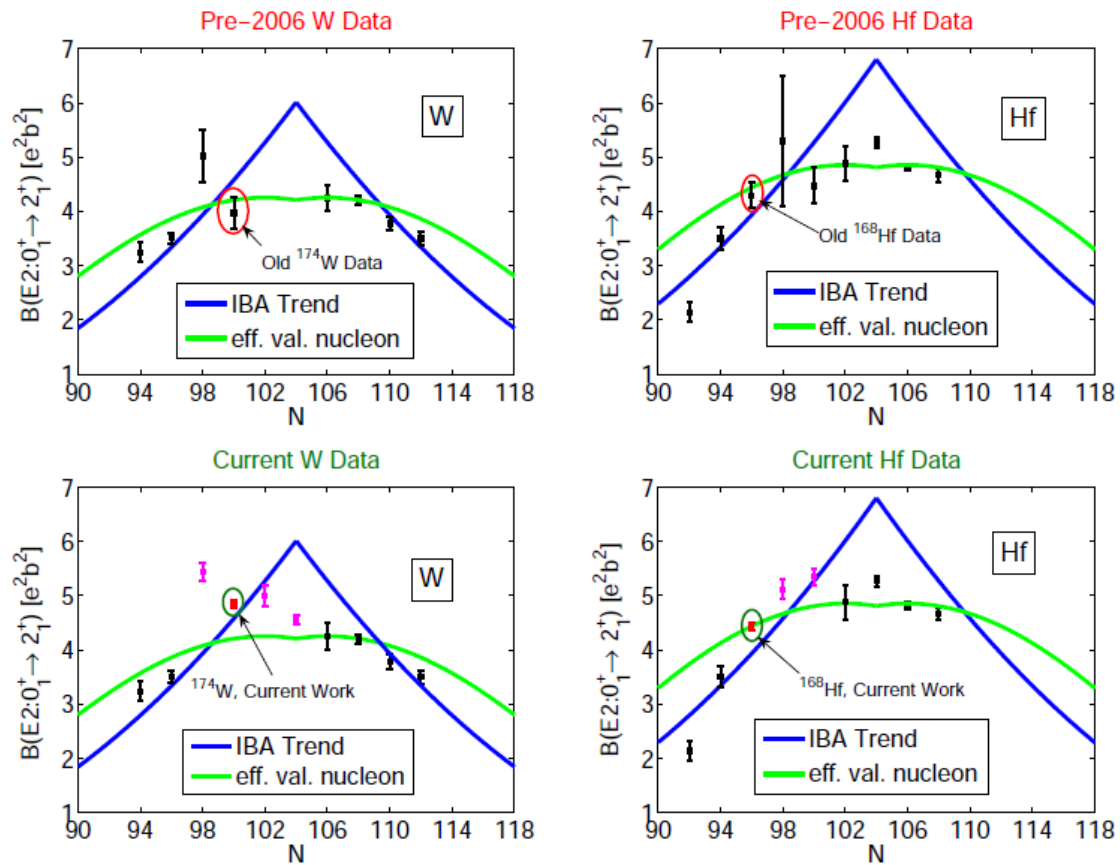


Figure 5. (Color online) Systematics of $B(E2)$ excitation strengths to the 2_1^+ state in the W and Hf isotopic chains. The top panels include data that has been listed [6, 7] prior to 2006, the bottom two panels include the newly remeasured values. Red points, marked with a circle, are the $B(E2)$ values measured within this work, magenta points are from recent data from Cologne and Stony Brook [8, 9, 10]. The curves are only given for qualitative comparison with the collective IBM; the blue curves illustrate the expected maximization of E2 strength at mid-shell, the green curves take into account fractional filling.

A multi-detector array proved to be most useful due to the large number of available detector pairs - each giving an independent time difference spectrum and, hence, an independent value for the lifetime of the state of interest.

The first analysis yields preliminary new lifetimes for the first excited 2^+ states in ^{168}Hf and ^{174}W . In both cases, the statistical errors are lowered by about an order of magnitude. For ^{168}Hf , the new result of $\tau(2_1^+; ^{168}\text{Hf}) = 1.237(10)$ ns is in agreement with the literature value [6] of 1.28(6) ns. For ^{174}W , however, the new value of $\tau(2_1^+; ^{174}\text{W}) = 1.339(8)$ ns is about 20 % lower than the literature value of 1.64(10) ns [7]. This is on the order of the deviation we found in ^{170}Hf in previous work [5]. 20 % modifications to known data should be taken serious, especially in view of the qualitative and quantitative arguments relating to a $B(E2)$ saturation near mid-shell. Figure 5 shows a comparison of data as known before 2006, with currently known data, including new values measured by the groups at the University of Cologne (Köln) [8, 9]. The new data have considerably reduced error bars and show a much more subtle change in structure than simple collective estimates (shown as blue curves) including normal numbers of valence particles (bosons), or effective numbers.

While an overall flattening trend toward mid-shell is preserved, the new data show a much more detailed sub-structure, which may be related to changes in the underlying active orbitals when crossing a major shell. Therefore, the new data will allow for much more detailed tests using more microscopic approaches like, e.g., the projected shell model. In Hf isotopes, the now available data is still consistent with a saturation of B(E2) strengths at mid-shell. In the W isotopes, however, the maximum of B(E2) strengths, and therefore the valence maximum, seems to be shifted to a considerable lower neutron number than mid-shell ($N = 104$). The new lifetime values will also be important input for a remeasurement or reevaluation of g factors in the region, which often suffered from rather large statistical errors on the 2_1^+ lifetimes.

4. Acknowledgments

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