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Current Experimental Techniques of Lifetime Measurements and Their Importance for the Nuclear Structure

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Abstract. One of the most important topics in nuclear spectroscopy is measuring the lifetimes of excited states. These quantities are related to the reduced transition probabilities, which are rather sensitive to details of the intrinsic structure of the states. Therefore, such measurements represent a crucial test for various theoretical models which address different regions of the nuclear chart. Lifetimes of excited states cover many orders of magnitude, but typically they are in the range below nanosecond. Consequently, several methods allowing lifetime measurements in these regions have been developed. The ROmanian array for SPectroscopy in HEavy ion REactions (ROSPHERE) is a γ-spectrometer which was designed specifically to allow for sensitive lifetime measurements down to the picosecond range. ROSPHERE is a new 4π high-resolution γ-ray detector array which was installed at the Bucharest 9 MV tandem accelerator. The setup consists of up to 25 detectors and it is typically used in a mixed combination of high-purity Ge detectors and fast $LaBr_3$:Ce scintillation detectors. The multi-detector setup can be coupled with a state of the art plunger device allowing for lifetime measurements by employing the Recoil Distance Doppler Shift (RDDS) or in-beam Fast Electronic Scintillation Timing (FEST) technique. This work reports on two experiments performed on ^{168}Yb and ^{150}Gd illustrating the methods and how this helps our understanding of the complex nuclear phenomena including nuclear deformation.

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1 Introduction

The lifetimes of excited states have attracted a lot of interest even since the beginning of nuclear spectroscopy. They are recognized as being an essential part in determining the reduced transition probabilities which represents a crucial test for the theoretical models. In nuclear physics, the lifetimes of excited states cover a very broad range, typically from 10^{-15} to 10^{3} seconds, and therefore several methods have been developed, each covering a certain time range. The methods to extract the lifetimes are usually divided in two categories as direct and indirect methods. For the direct methods, the lifetime is determined as a result of a measurement and include among others the recoil distance Doppler shift method (RDDS), the fast timing technique (FEST), the Doppler shift attenuation method (DSAM) and the γ ray induced Doppler broadening technique (GRID). For the indirect methods, the matrix elements of the corresponding transitions are determined as result of the experiment and the lifetimes are inferred from these values. Among the most prominent examples we recall the nuclear resonance fluorescence method and the Coulomb excitation. Today, as most attractive methods are usually considered the ones determining the lifetimes directly from quantities which can be measured in experiments and do not require any nuclear model input. Two of these methods that have become a standard tool in nuclear physics are FEST [1] and RDDS [2] which will be presented in this contribution. The ROSPHERE array in Bucharest was designed from the beginning to allow for lifetime measurements using these two methods. The FEST technique is used to measure lifetimes down to the tens of picosecond range using in-beam reactions by combining two types of detectors with very good energy and timing properties, respectively. The RDDS method is suitable for lifetime measurements down to one picosecond and uses a specially constructed device that will be briefly described together with the experimental methods in section 3. In section 4, the results of two experiments using the two methods will be presented. The newly determined lifetimes allow the extraction of the reduced transition probabilities and give more insight into the systematic trends that will be presented in the last section.

2 The ROSPHERE Array

ROSPHERE is a dedicated γ-ray spectrometer designed to allow for nuclear spectroscopy studies. The array is installed at IFIN-HH in Bucharest and has 25 positions where detectors can be mounted. ROSPHERE can accommodate up to 25 HPGe detectors, and optionally, 4 planar detectors for low energy γ-ray measurements can be mounted. However, the mixed configuration is preferred with two types of detectors, high energy resolution HPGe and fast $LaBr_3$:Ce scintillators. The positions of the detectors were subject of several constraints mainly that the array is suitable for RDDS experiments (detectors placed at polar

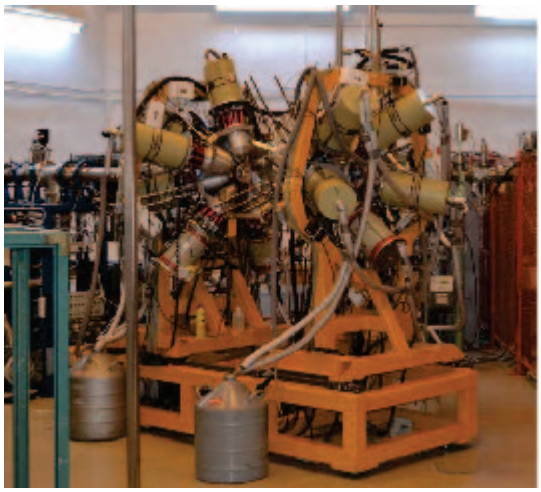

Figure 1. (Color online) The ROSPHERE array used in the mixed configuration with two types of detectors and with the plunger chamber.

angles as small as possible with respect to beam direction) and allowing good sensitivity for directional correlation orientation (DCO) ratios measurements. The best solution found was to have 5 rings of detectors, each with 5 positions situated at 37°, 70°, 90°, 110°, and 143° with respect to the beam axis. A photo of ROSPHERE is presented in Figure 1.

The HPGe detectors available at IFIN-HH have relative efficiency between 50 and 60% and typical energy resolution of about 1.9 keV at 1.33 MeV. The timing resolution is around 15 ns. When using ROSPHERE in a mixed configuration with 14 HPGe and 11 $LaBr_3$:Ce detectors, we reach an absolute efficiency of about 1.2% at 1.33 MeV for the HPGe detectors.

The fast $LaBr_3$:Ce scintillators are suited to be used for the in-beam fast-timing method. There are several types of crystals available in the lab, conical and cylindrical, having dimensions between 1.5"x1.5"x1" and 2"x2"x2". The energy resolution reaches 2-3% at 662 keV, but the superior timing properties (FWHM between 200-300 ps, depending on the size and shape of the crystal) make such detectors an ideal tool for studying lifetimes one order of magnitude below the time resolution. In the mixed configuration we use 11 $LaBr_3$:Ce detectors reaching an absolute efficiency of about 1.8% at 1.33 MeV.

3 Experimental Methods

In this section we briefly outline the main characteristics of the fast electronic scintillation timing technique and of the recoil distance Doppler shift method.

The in-beam fast-timing method was made possible by the occurrence of new $LaBr_3$:Ce detectors with very good timing properties while keeping the energy resolution at an acceptable value. When used in combination with HPGe detectors the method can be applied for in-beam fusion evaporation experiments as presented in Ref. [3]. The method requires triple γ coincidences, one γ-ray detected by HPGe detectors which allows a good selection of the γ-ray cascade, and the other two γ-rays by $LaBr_3$:Ce detectors which allows the construction of the delayed time spectrum. Such a combination of detectors can be found in ROSPHERE and has been used with success in several experiments in the last few years [4, 5]. A special attention has to be given to the timing information in order to be able to add-up the contributions from all pairs of detectors. Therefore, one needs to correct the time response of the detector for the "time walk" as a function of energy. Such a correction is applied off-line by fitting with a polynomial function the energy dependence of the detector time response. After a proper alignment of the time response of all the detectors one can properly look at time differences between all pairs of $LaBr_3$:Ce. More details about the "time walk" correction and about the method itself can be found in Ref. [3]. A typical example of such measurements will be given in the next section in the case of ^{168}Yb.

The other method discussed in the present contribution is the recoil distance Doppler shift technique which allows for lifetime measurements in the picosecond range. The excited level is populated in a nuclear reaction induced by a heavy-ion in a thin target. The momentum transferred to the residual nucleus is high enough such that the latter leaves the target and is stopped after a fixed flight distance in a stopper foil. Therefore, depending on the lifetime and on the distance, the γ rays can be emitted in flight or after the recoiling nuclei are stopped. The ones emitted in flight will be Doppler shifted depending on their energy, the recoil velocity, and on the angle of detection. Measuring for a sufficient number of target-to-stopper distances one can derive the lifetime from the evolution of the intensity ratio of the shifted and unshifted components of the γ rays. In order to overcome the problem of the level feedings, it is preferred to work in coincidence mode and apply a gate on the shifted component of the γ ray above the level of interest. In this way only the nuclei which are still in flight are selected. More information can be found in a very complete review of A. Dewald *et al.* [6]. The method requires a special device called plunger which allows parallel mounting of the target and the stopper at very short distances (on the order of 1 μm). Such precisions are obtained with dedicated piezoelectric motors. The method of controlling the plunger is described in details in Ref. [7]. A typical example of such a measurement will be given in the next section in the case of ^{150}Gd.

4 Experimental Results

4.1 Lifetime measurements using the fast-timing method in ^{168}Yb

In order to learn about the systematics of properties of quadrupole deformed nuclei we have performed an experiment to populate excited states in ^{168}Yb. The nucleus was produced in an $(\alpha, 2n\gamma)$ reaction by bombarding an ^{166}Er target with 24 MeV α particles. The detection of the γ rays was performed with a configuration of 8 HPGe and 11 $LaBr_3$:Ce detectors placed around the target chamber. The detection efficiency reached about 1% for HPGe detectors and 1% for the $LaBr_3$:Ce detectors at 1.33 MeV.

The main part of the data analysis consisted of very careful energy and time calibrations and alignments. The energy calibration was performed with a standard ^{152}Eu source. In addition, because of the instability of the photomultipliers as a function of the fluctuating rate, a run-by-run gain matching procedure was performed. As stated in the previous section, a special attention has to be given to the treatment of timing information. After the time calibration with very well known delays that covers the whole range of the Time to Amplitude Convertor (TAC) the time spectra were also corrected for the walk effect. This has been done in two steps: first, by using a standard ^{60}Co with the procedure from

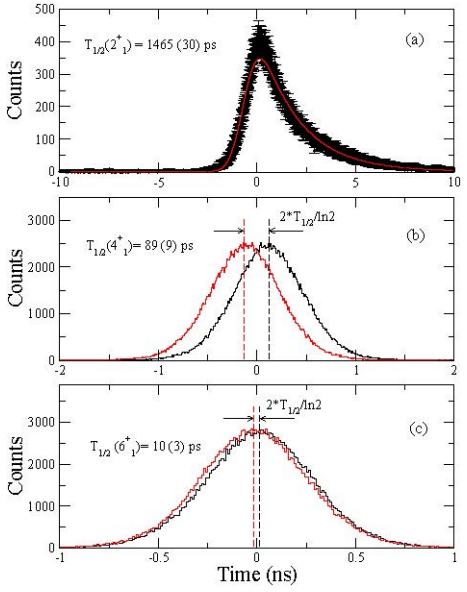

Figure 2. (Color online) Time distributions for levels in the ground-state band up to 6^+ in ^{168}Yb. The lifetime of the first 2^+ state is obtained with the deconvolution method while the other two are obtained with the centroid shift method.

Ref. [3], and second by applying an internal walk correction using the intense γ-rays in the yrast band of ^{168}Yb associated with the decay of levels with a known lifetime or with one determined in the present experiment with the deconvolution method. In the end, a proper alignment of the time spectra had to be done for all the $LaBr_3$:Ce detectors.

The usual method of extracting the lifetime is outlined in Ref. [3]. The method implies the construction of three-dimensional matrices of E_γ-E_γ-ΔT type with one or several gates applied in the HPGe detectors. By selecting the coincidence cascade in $LaBr_3$:Ce detectors and projecting on the remaining axis of the above matrix one can extract the time spectrum of the corresponding energy level. The final lifetime is obtained by the deconvolution or by the centroid shift method [3]. The time distributions obtained in this work for the yrast levels up to 6^+ in ^{168}Yb are presented in Figure 2.

4.2 Lifetime measurements using the recoil distance Doppler shift method in ^{150}Gd

The quadrupole and octupole collectivity can be inferred from reduced transition probabilities. Therefore, one needs, as a principal ingredient, the lifetime measurements of the first 2^+ and 3^- levels. In the case of ^{150}Gd a good reaction to populate the excited levels was found to be ^{140}Ce(^{13}C,3n) which populates the levels of interest with high statistics while maintaining the recoil velocity at a reasonable level (around 0.7% c). The target had a thickness of 0.5 mg/cm^2 deposited on a 3 mg/cm^2 gold foil while the recoiling nuclei were stopped by a 4 mg/cm^2 gold stopper. The ROSPHERE in the usual configuration with 14 HPGe and 11 $LaBr_3$:Ce detectors was used. In total we have measured at 11 distances between 20 μm and 500 μm. A double trigger condition was used correspond-

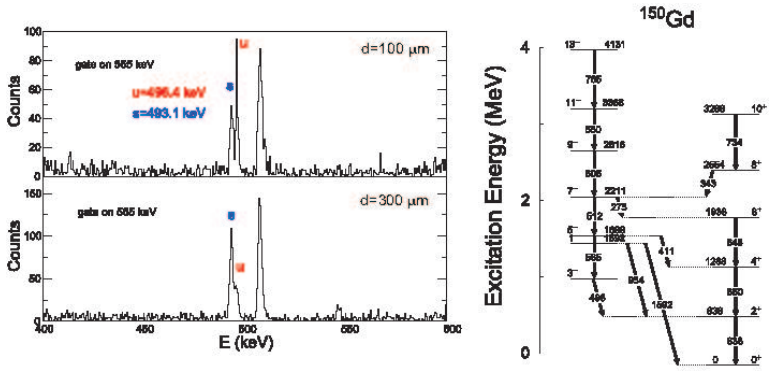

Figure 3. (Color online) Spectra of ^{150}Gd illustrating the DCCM method for two distances and a partial level scheme. The gated spectra are used to determine the lifetime of the first 3^- state.

ing to two HPGe detectors firing in coincidence or by the HPGe-$LaBr_3$-$LaBr_3$ coincidence.

With 14 HPGe available we can take advantage of the Differential Decay Curve Method (DDCM) and use the plunger method in coincidence mode. By gating on the shifted (in-flight) component of the direct feeding transition one can observe the true shifted and unshifted components of the transition depopulating the level of interest. An example of such a spectrum is shown is Figure 3 together with a partial level scheme of ^{150}Gd. The gate on the shifted component of the feeding 565.5 keV γ ray is applied in the forward direction corresponding to an angle of 37° while the shifted and unshifted components of the 496.4 keV γ ray depopulating the first 3^- states are observed at 143° backward angle for two distances.

Experimental results were obtained mainly for the first 2^+ and 3^- levels, but also for some higher-lying states. In Figure 4 we present the extracted lifetimes for the first two levels, together with the evolution of the shifted and unshifted components of the corresponding γ rays. The solid lines fitting these data are

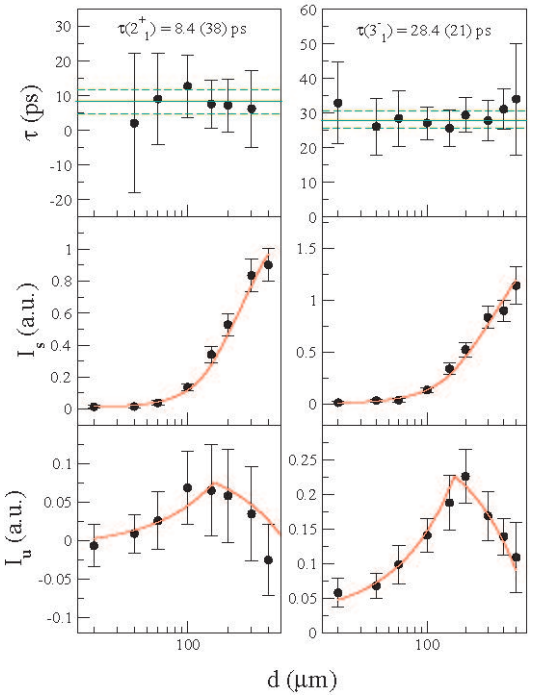

Figure 4. (Color online) Lifetimes of the first 2^+ (left) and 3^- (right) states in ^{150}Gd obtained with the RDDS method (upper panels) and the evolution of shifted (middle) and unshifted (lower panels) components as a function of distance.

evaluated according to the relation:

$$I_{uA}^{sB}(d) = \nu\tau_i \frac{d}{dt} I_{sA}^{sB}(d), \tag{1}$$

where ν is the average velocity of the recoiling nucleus, while I_{uA}^{sB} and I_{sA}^{sB} are the normalized intensities of the shifted (s) and unshifted components (u) of two transitions A and B detected in coincidence. Eq. (1) is evaluated by fitting both terms at the same time using second order polynomials. The extracted lifetimes are given in Figure 4.

4.3 Lifetime measurements using both fast-timing and RDDS methods

The fast-timing method can be applied on a very broad range, from a few tens of picoseconds up to a few nanoseconds. On the other hand the RDDS method has a range between 1 picosecond and a few hundred picoseconds, depending on the range of the micrometer. Therefore, the ranges of the two techniques overlap and can be used to test the validity of the methods in case of lifetimes in the hundreds of picosecond range. In the case of ROSPHERE array, such a test is possible by combining the two methods. The test case is the lifetime of the 11^- state at 3366 keV in ^{150}Gd for which the systematics predicts a value of the lifetime in the overlapping region allowing to test the consistency of the two methods. In Figure 5 the lifetime of the 11^- levels is presented, the RDDS method (left) gives a result of 158 (15) ps while the centroid shift method of the

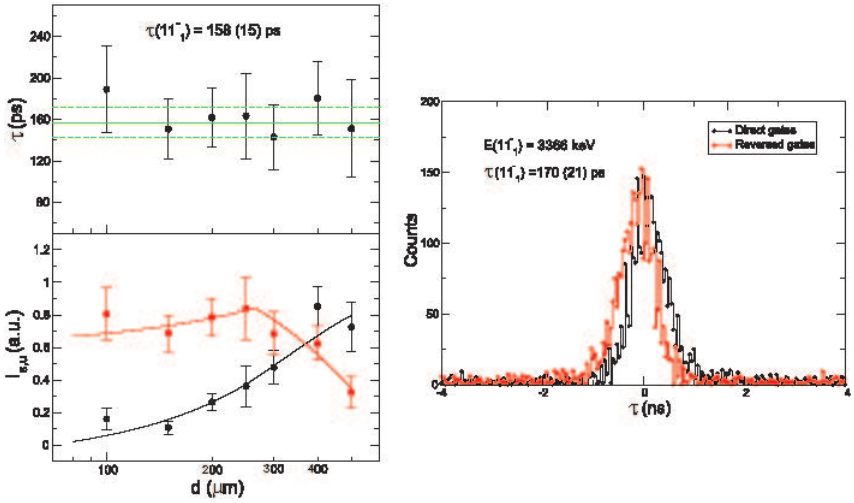

Figure 5. (Color online) Test for the consistency of the two methods for lifetime determination, RDDS and fast-timing. Left: the lifetime of the 11^- state is extracted using the RDDS method; right: the time spectrum from the fast-timing method is given.

time spectra obtained with the fast-timing technique (right) gives a value of 170 (21) ps.

5 Systematics of B(E2) and B(E3) Values and Their Importance to Nuclear Structure

Having determined the lifetimes of several states in ^{168}Yb and ^{150}Gd by using the fast-timing and RDDS methods, one can extract now the reduced transition probabilities, observables which are very sensitive to the structure of the intrinsic wavefunctions. In order to gain even more information on the structure involved it is common to look not only at one particular value, but at the systematic of transition probabilities across an entire isotopic chain. Such investigations are presented in Figure 6, both for ^{168}Yb and ^{150}Gd for B(E2) and B(E3) transition probabilities.

The extracted B(E2) values in ^{168}Yb are presented in the left panels of Figure 6 for $E2$ transitions depopulating the 2^+ and 4^+ levels in the yrast band. The points in red are the values deduced in the present experiment. The systematic presented here shows a smooth evolution of collectivity from A=158 to A=176, with a maximum around the mid-shell. In order to understand the structure of this nucleus more detailed calculations have been performed using the Interacting Boson Model (IBM) [8] and the Confined Beta Soft (CBS) [9] rotor model

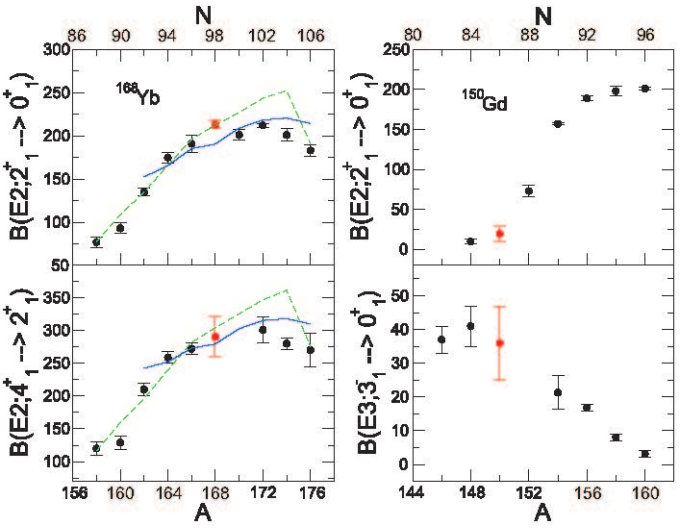

Figure 6. (Color online) Systematics of $E2$ and $E3$ transition probabilities in ^{168}Yb (left) and ^{150}Gd (right). The dashed (green) and solid (blue) lines in the left panels correspond to the IBM and CBS models, respectively.

and the results are displayed with dashed (green) and solid (blue) line, respectively. The parameters of the IBM are taken from Ref. [10]. Both models give a good description of the overall trend of transition probabilities. However, IBM gives a slight overprediction in the heavier nuclei indicating other degrees of freedom which are not taken into account in this version of the model. The CBS gives a better reproduction of the transition probabilities although the effective charge was kept constant for the entire isotopic chain. The model predictions should be tested by measuring in future experiments additional lifetimes for non-yrast states.

For ^{150}Gd we have deduced the reduced transition probabilities to the g.s for the first 2^+ and 3^- states and displayed them in Figure 6. The B(E2) value fits very well into the systematics of these observables for the entire isotopic chain. A completely different situation can be found for the B(E3) value of the first 3^- state. First of all, in order to determine this value one needs also the branching ratio to the g.s. This was determined from a β-decay experiment , but with a rather large uncertainty. The final uncertainty of the B(E3) value reflects the error bar of the branching ratio rather than that of the lifetime measurement. Nevertheless, one can compare this value with the corresponding B(E3) values in the neighboring isotopes. This picture does not fit the systematic trend usually observed for the evolution of octupole collectivity. One would expect a maximum in the B(E3) values at N=88 [11] (one of the so-called octupole driving numbers), which would correspond to ^{152}Gd. However, the trend seems to be decreasing already with ^{150}Gd, although a definite conclusion cannot be reached yet because of the large uncertainty of the value at N=86. Also, further evidence should be provided by measuring observables sensitive with respect to the octupole collectivity in ^{152}Gd.

6 Conclusions

We have presented the new ROSPHERE γ-ray spectrometer which was designed as a multi-detector setup for nuclear spectroscopy. The array consists of up to 25 detectors and is used with a mixed configuration of HPGe and $LaBr_3$:Ce detectors to allow for lifetime measurements using both the fast-timing technique and the recoil distance Doppler shift method. In this contribution we present the results obtained for lifetime measurements in ^{168}Yb with the fast-timing method and in ^{150}Gd with the RDDS technique. For the first 11^- excited level we can extract the lifetime by employing both methods and the results agree very well. We emphasized the importance of the reduced transition probabilities which can be extracted from the measured lifetimes and can be compared in a systematic way with the corresponding values in the whole isotopic chain. In this way we can learn about the quadrupole and octupole collectivity and try to understand both the smooth behavior and the irregular patterns found in atomic nuclei.

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