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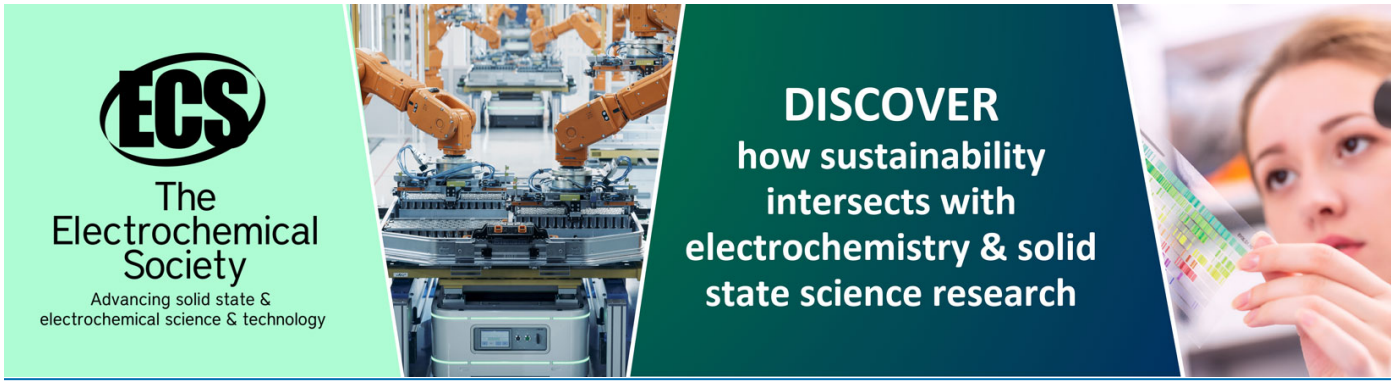

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Signatures of shell-effects in collective excitations

V. Werner[1], J. R. Terry[1], M. Bunce[1,2] and Z. Berant[1,3]

[1] Wright Nuclear Structure Laboratory, Yale University, P.O. Box 208120, New Haven, CT 06520, USA

[2] Department of Physics, University of Surrey, Guildford GU2 7XH, United Kingdom

[3] Nuclear Research Center Negev, Beer-Sheva, Israel

E-mail: volker.werner@yale.edu

Abstract. Two methods for measuring lifetimes of excited states in nuclei are discussed. One recently developed method involves a plunger device and inverse kinematics Coulomb excitation with heavy beams. The other method covers a different lifetime range and relies on electronic timing. Both methods have recently been applied at Yale University. This paper will give a brief overview of technical aspects of those measurements. A short motivation and preliminary results of the experiments are given.

1. Introduction

This lecture covered methods for lifetime measurements in the picosecond and nanosecond region, using different techniques. One is the well-known plunger technique, which we now put to novel use in inverse kinematics reactions, namely Coulomb excitation. The new technique [1] has been applied to stable beams at the Wright Nuclear Structure Laboratory (WNSL) at Yale University, and has recently also been used by the Cologne group at Jyvaskylä (see contribution by Ch. Fransen). The second technique presented in this paper is the measurement of lifetimes of excited states via fast electronic timing. This method has been known since a long time, but is one of the standard techniques for decay-spectroscopy at existing and upcoming radioactive ion beam facilities.

Both methods have recently been applied at WNSL attacking two different physics themes, which have the common ground of investigating the evolution of the B(E2) excitation strengths of the first excited 2^+ state over series of isotopes. For nuclei near closed shells those lifetimes are usually in the picosecond range, too short for fast electronics measurements, and therefore require the use of Doppler shift techniques. The plunger method that we used will be presented in Section 2. We performed a recoil distance Doppler shift (RDDS) experiment on ^{120}Te, in order to extend the $B(E2)$ excitation strength systematics within the Te isotopic chain to its lightest stable isotope.

Section 3 will address measurements of lifetimes of the first excited state in near mid-shell even-even nuclei. Such lifetimes are usually in the proximity of a nanosecond and are therefore accessible with fast electronics techniques. An experiment on the deformed nucleus ^{172}Hf will be presented. The method will be shown, and the new, preliminary result will be discussed in the framework of saturation of $B(E2)$ strengths toward mid-shell.

2. Inverse kinematics RDDS

2.1. Experimental details

For many even-even nuclei, the lifetimes of the first excited 2^+ states are known from their measured Coulomb excitation cross sections. However, in general this can result in systematic errors due to unknown quadrupole moments or non-observed feeding. The RDDS technique offers a model independent way of measuring lifetimes, independent from the excitation mechanism. Whereas, classically, RDDS measurements have been performed mostly in normal kinematics fusion evaporation or Coulomb excitation experiments, in the era of radioactive beam experiments the use of inverse kinematics is mandatory. We performed a first measurement in inverse kinematics Coulomb excitation using heavy beams.

The measurement was performed at WNSL using the New Yale Plunger Device (NYPD) and eight clover detectors in the SPEEDY array [2]. A 300-MeV beam of ^{120}Te was produced by the 20-MeV ESTU tandem van de Graaff accelerator at WNSL, and impinged on a stretched carbon target with a thickness of 400 μg/cm^2. The beam was Coulomb excited on the carbon target, and then reacted and unreacted beam were stopped in a copper target of 14 mg/cm^2 thickness. The distance between the target and stopper foils were varied over a range of 5 - 1100 μm, therefore varying the probability of in-flight decay of the Coulomb excited 2_1^+ state in ^{120}Te. The beam energy was well below (about 50% at mid-target) the Coulomb barrier, ensuring that excitations of states other than the 2_1^+ state were negligible. This simplified the analysis tremendously, since no feeding needed to be taken into account, and a simple decay function was fitted to the data.

Carbon from the target was forward scattered by the reaction and passed the stopper foil. The carbon particles were subsequently detected in a circular silicon detector, placed directly behind the target. Gamma-rays from the de-excitation of the 2_1^+ state were detected in the clover detectors, which were placed at 41.5° and 138.5° relative to the beam axis, either at Doppler shifted energies in the case of in-flight decay, or at the excitation energy of 560.4 keV of the 2_1^+ state. The trigger for the data acquisition was a particle-gamma coincidence. After random background subtraction the observed peaks appeared on almost no background, and were well separated due to the large v/c value of about 6%. Sample spectra are shown in Fig. 1.

Figure 1 also includes lines from the decays of higher-lying excited states, which are two orders of magnitude smaller than the peak of interest and can therefore be neglected. Statistics in those lines were insufficient to perform an RDDS analysis for those states, however, we were able to perform a Coulomb excitation analysis to extract their $B(E2)$ decay strengths relative to that of the 2_1^+ state.

2.2. RDDS analysis and results

In order to extract a lifetime, we define the ratio

$$P(d) = \frac{I_\gamma^{(shifted)}(d)}{I_\gamma^{(total)}(d)} \ , \tag{1}$$

of the shifted peak intensity $I_\gamma^{(shifted)}$ over the total peak intensity $I_\gamma^{(total)}$ for each distance d between the two foils. The peak intensities are corrected for detector efficiencies and the angular distribution of gamma-rays, which was obtained from the Coulomb excitation code by Winther and de Boer [3]. Neglecting feeding from higher-lying states, the P ratio should follow a simple decay law:

$$P(d) = 1 - e^{-\lambda(d-d_0)} \ , \tag{2}$$

where $\lambda = 1/(v\tau)$ contains the lifetime information. The mean velocity v is extracted directly from the mean energies of the Doppler shifted peaks at forward and backward angles. d_0 is left

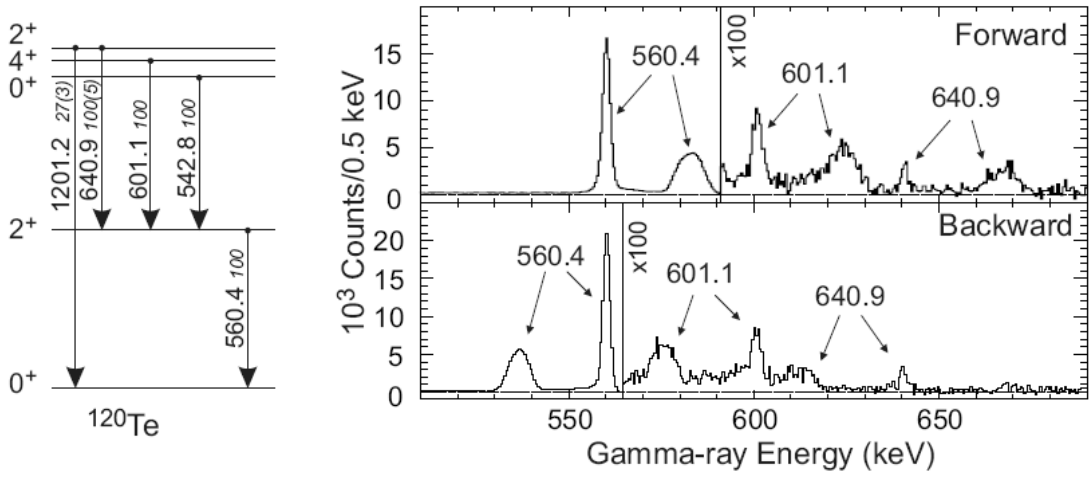

Figure 1. Particle gated and random subtracted sum spectra of ^{120}Te for all plunger distances. The left top and bottom panels show the summed spectra for the $2_1^+ \rightarrow 0_1^+$ transition at forward and backward angles, respectively. The right top and bottom panels correspondingly show other observed transitions, according to the level scheme on the left hand side.

as a free fit parameter that corresponds to the minimum achievable distance between the two foils.

At high recoil velocities, relativistic effects need to be taken into account. As such, the detector angles in the laboratory frame have to be corrected. The Lorentz transformation of the angular distribution consists of a transformation of the emission angle, as well as of a multiplicative factor J from the Jacobian transformation to the center of mass (CM) frame:

$$J = \frac{d\Omega_{CM}}{d\Omega_{lab}} = \frac{1-(v/c)^2}{(1-v/c\cdot\cos\theta_{lab})^2} \ . \tag{3}$$

While the transformation of the emission angle has a negligible effect on the angular distribution of gamma-rays, the Jacobian of the transformation leads to a significant difference between the angular distributions of gamma-rays emitted in-flight or stopped. The correction in our case is on the order of 8%.

The hyperfine interaction between the nucleus and the atomic electrons when recoiling into vacuum causes a de-orientation of the aligned nuclear state [4]. This effect is taken into account by time-dependent attenuation coefficients

$$G_k^{(stopped)}(d) = \exp\left(-\frac{|g|d}{vC_k}\right) \text{ and} \tag{4}$$

$$G_k^{(in-flight)}(d) = \frac{1}{1+\frac{|g|\tau}{C_k}} \frac{1-\exp\left(-(1+\frac{|g|\tau}{C_k})\frac{d}{v\tau}\right)}{1-\exp\left(-\frac{d}{v\tau}\right)} \ , \tag{5}$$

where $|g|$ is the absolute value of the g factor of the excited state. De-orientation due to recoil into vacuum has been extensively studied for tellurium isotopes at $v \approx 0.06c$ [5], where the parameters C_k that appear within the G_k coefficients have been fixed, and therefore could be used for the present analysis. The data points from the ^{120}Te experiment, including all corrections, and the fit to obtain the lifetime of the 2_1^+ state are shown in Fig. 2. The fit results in a mean lifetime of $\tau = 10.4(2)$ ps, which is a significant improvement compared to the currently listed value of $\tau_{lit} = 1.3(27)$ ps [6].

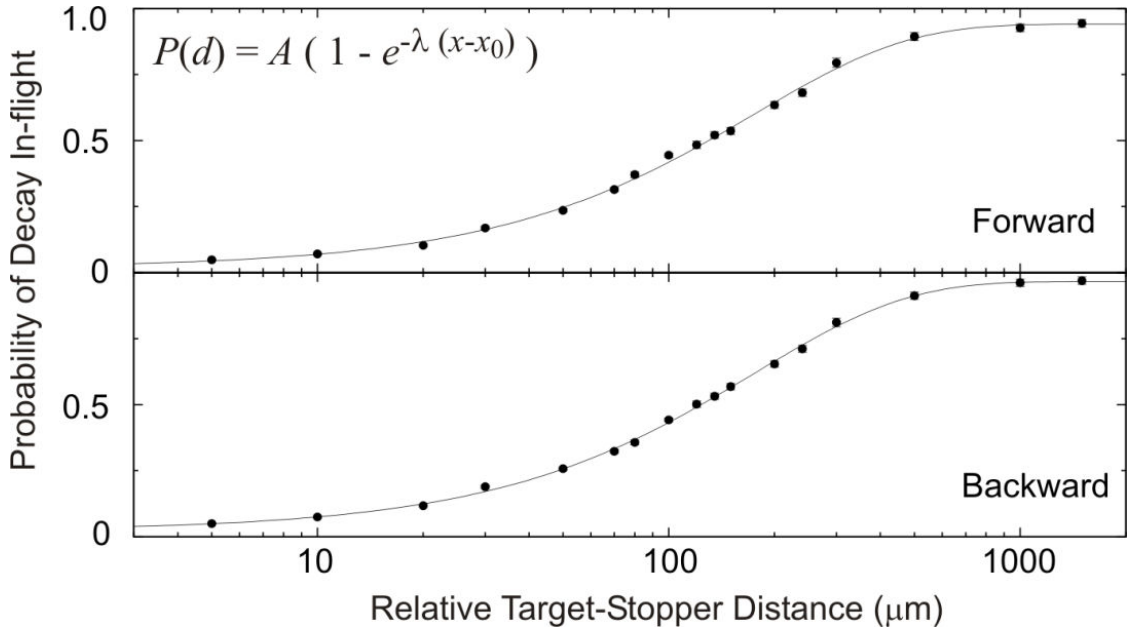

Figure 2. P ratios from eq. (1) and the fitted function from eq. (2) for the 2_1^+ state in ^{120}Te.

2.3. Future use of the plunger method

The RDDS technique as presented above is suitable for experiments with weak beams. In order to test this, only part of the present data has been sorted corresponding to a beam intensity of 10^{5-6} particles per second, which is in the range of new radioactive beam facilities. An analysis of the reduced data set yielded a lifetime result with a statistical error well below 10%. The plunger technique should also allow to measure absolute values of g factors of excited states over series of isotopes. Therefore, the de-orientation from recoil into vacuum needs to be measured by the angular distributions of gamma-rays. The hyperfine parameters in eqs. (4) and (5) need to be fixed from a measurement of a state with known g factor. Since those parameters should not vary within an isotopic chain, for neighbor isotopes the only free parameter in the de-orientation coefficients then is the g factor. This technique is currently being tested at WNSL.

3. Fast electronics lifetime measurements

3.1. Experimental details

In this section a method of measuring lifetimes using electronics is presented. In our case, we have been interested in the lifetime of the 2_1^+ state of the well-deformed rare-earth nucleus ^{172}Hf. Data on the Hf isotopes (as well as other isotopic chains) suggest that the $B(E2)$ strengths in deformed nuclei rise toward mid-shell, but show a saturation effect around mid-shell [7, 8]. Since much of the available data stems from the 1970's, and was often obtained in relatively low statistics experiments, we tested this by a new lifetime measurement.

The safest way to obtain the lifetime of a given state is to have a signal from the direct population of the state, and a signal from its decay, and measure the time difference between both. The signals in our case were given by the gamma-ray transitions $4_1^+ \rightarrow 2_1^+$ at 214.0 keV and $2_1^+ \rightarrow 0_1^+$ at 95.2 keV. The corresponding gamma-rays were detected by four BaF_2 scintillators surrounding the source. The beta-decay from ^{172}Ta populates mostly directly the 4_1^+ state in ^{172}Hf. The mother nuclei ^{172}Ta were produced at the moving tape collector (MTC) setup [9] at WNSL using the reaction ^{165}Ho(^{12}C,5n). Fusion evaporation residues, which were recoiling out

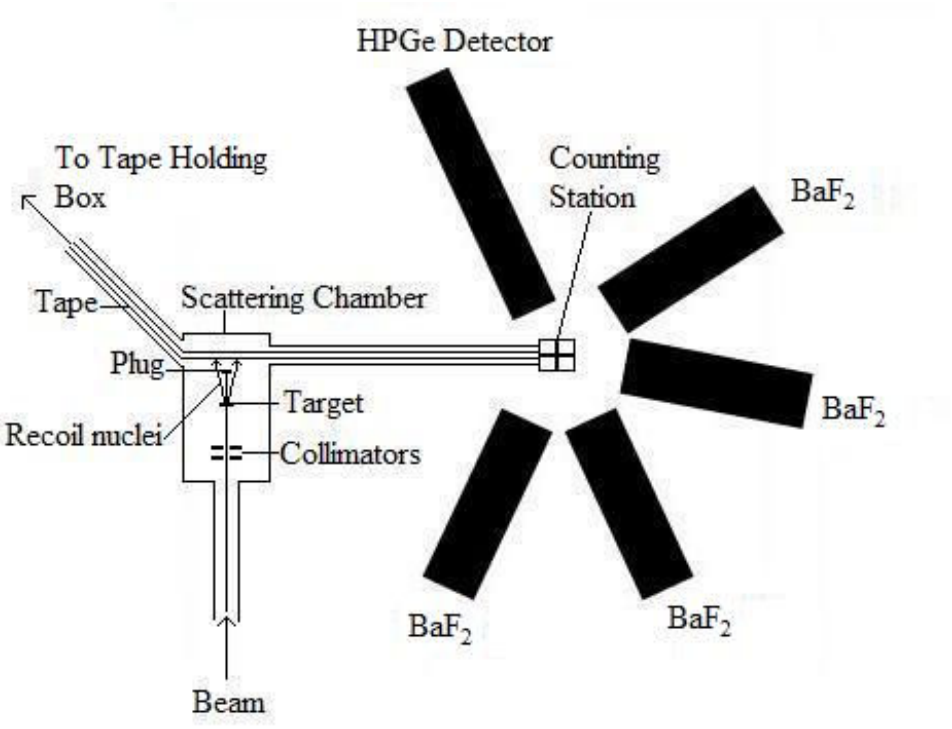

Figure 3. Schematic of the setup at the MTC. Four BaF_2 detectors were used for the lifetime measurement, in addition one Ge detector was used as a monitor.

of the 4 mg/cm^2 self-supporting foil, were implanted on a tape behind the target. The beam itself was stopped by a gold plug in between target and tape, while most recoils passed the plug at angles larger than 2°.

The halflife of ^{172}Ta is about 36 minutes, therefore a tape cycle of about 67 minutes was chosen. That means that activity was collected on tape for 67 minutes, and then moved in between the detectors, while activating the next spot on the tape in parallel to measuring gamma-rays after beta-decay at the well-shielded detector setup. After the detection period, the activated spot was carried away to a tape holding box in order to minimize unwanted background from subsequent beta-decays. A schematic of the MTC setup is shown in Fig. 3.

The array of four BaF_2 detectors allowed for a total of twelve independent detector pairs for the lifetime measurement. For each pair, an energy gate was set on the $4_1^+ \rightarrow 2_1^+$ transition in one detector, and on the $2_1^+ \rightarrow 0_1^+$ in the other detector. The constant fraction time signals from both detectors (with the condition on the energies) were fed into VME based time-to-digital converters (TDCs), and the amplified energy signals were fed into VME based analog-to-digital converters (ADCs). The TDC time resolution was set to its minimum of about 35 ps per channel.

A standard germanium detector was also added to the setup, in order to derive a high-resolution spectrum from the source, and therefore exclude the possibility of contaminants in the peaks of interest. A sample energy spectrum of a BaF_2 detector is shown in comparison to the Ge spectrum in Fig. 4. The energy resolution of the scintillator would not have allowed to exclude contaminants, but no lines other than the expected decays of interest are observed in the Ge detector. The energy gates placed on the BaF_2 spectra are indicated by "A" and "B". The corresponding times of events in regions "A" and "B" of two detectors were subtracted from each other and sorted into time-difference spectra. A sample is shown in the insert of Fig. 4.

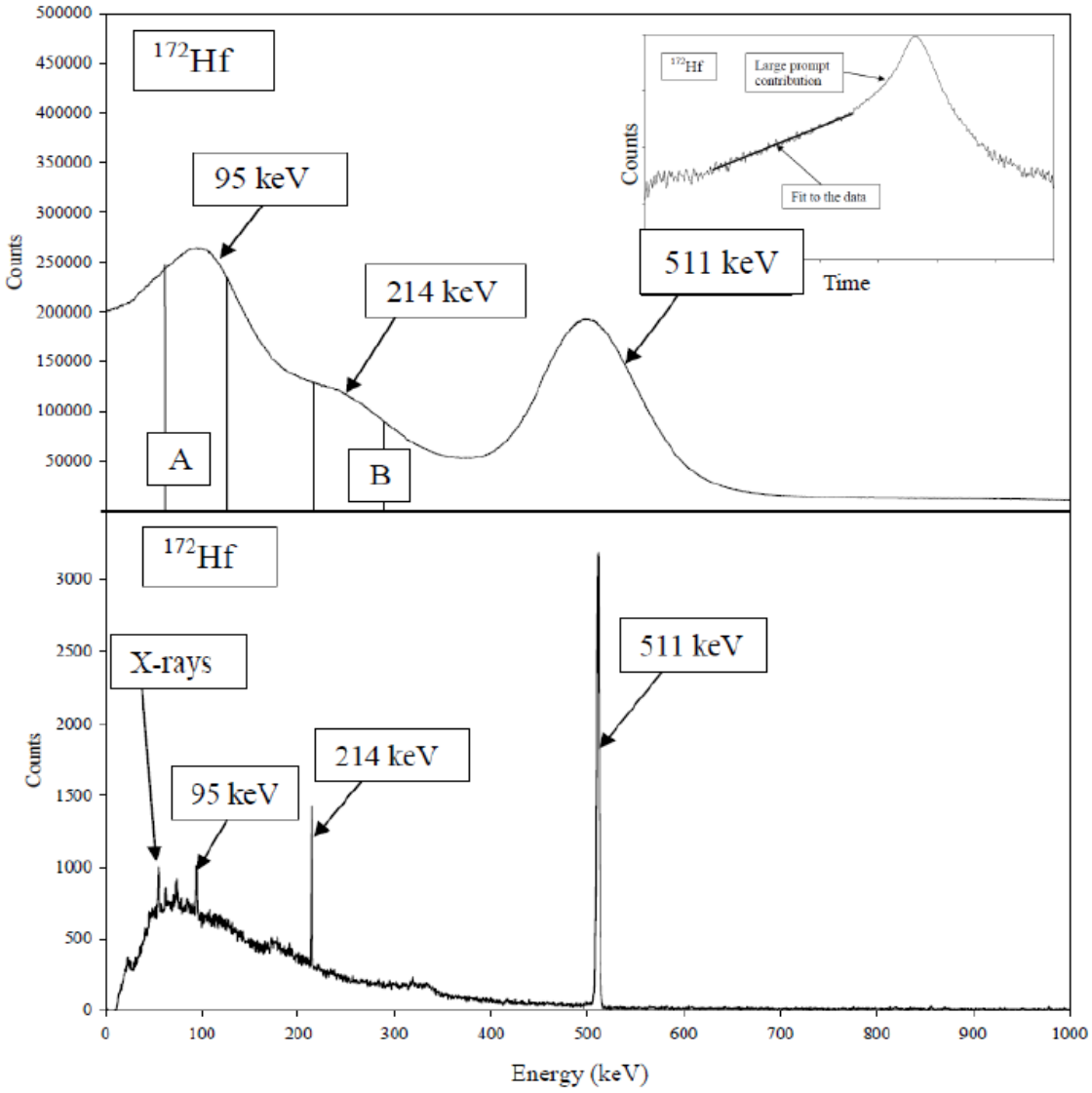

Figure 4. Energy spectrum of a BaF_2 detector (top), compared to the spectrum taken with a Ge detector (bottom). The insert in the top panel illustrates a sample time-difference spectrum (log-scale) between two BaF_2 detectors and a fitted line to the relevant portion.

3.2. Fast timing analysis and results

In order to obtain the lifetime of the 2_1^+ state, we simply fit a line to the portion of the time-difference spectrum that corresponds to the exponential decay of the state. The region in the time-difference spectrum that corresponds to the detector response, therefore the time resolution of the system (prompt peak), has been determined before the actual experiment using prompt coincidences from a ^{60}Co source. In that measurement gates were placed on the Compton background of the ^{60}Co spectra around 95 keV and 214 keV, thus the energy regions of interest. This step is important since the time resolution is a function of gamma-ray energy. The portion of the time-difference spectra which is dominated by the system response function is well excluded from the region of the lifetime fit.

For the final analysis, only 6 out of 12 detector pairs could be used due to problems with

some of the electronics branches. Still, we are left with 6 independent values for the 2_1^+ lifetime in ^{172}Hf, which we average to a mean lifetime of $\tau = 2.655(79)$ ns. This is a significant difference to the literature value of $\tau_{lit} = 2.23(14)$ ns [10], and lowers the error bar by a factor of two. Lowering the lifetime of the 2_1^+ state in ^{172}Hf leads to an increase of its $B(E2)$ value, which now does not show a drop as from listed data (*e.g.*, Fig. 1 in Ref. [7]), but rather further increases from the value in ^{170}Hf, which has recently been remeasured [11]. Therefore, it is important to check further isotopes toward mid-shell in order to see to which extent a saturation effect is actually present in the Hf isotopic chain.

3.3. Future prospects of fast lifetime measurements

The largest drawback in our measurements using BaF_2 detectors is the poor energy resolution of those detectors, which is typically in the range of 10%. In our case the obtained spectra were sufficiently clean to avoid problems that may arise from contaminant or overlapping peaks. However, in general it would be appreciable to get a better energy resolution, but a similarly good timing resolution. A scintillator material ($LaBr_3$) which has these properties has recently been developed and will be of particular interest for future studies in decay spectroscopy.

4. Acknowledgments

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