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Prompt Response Function (PRF) of Lifetime Measurement in the 2^+ State of ^{192}Os Nuclei Energy Levels from Triple-Gamma Coincidence Techniques

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Abstract

The effective prompt response function full width at half maximum, PRF FWHM of 637 ps (obtained from the prompt gamma pairs of 477 keV and 700 keV associated with the yrast 2^+ state in ^{206}Po), and 1007 ps (obtained from the Compton gamma pairs of 189 keV and 237 keV associated with the ^{192}Os(^{18}O,^{16}O)^{194}Os 2 neutron transfer reaction) were used in fitting the time difference spectra obtained from the gamma coincident pairs of 206 keV and 374 keV in a symmetrised $LaBr_3$(Ce) associated with the gamma transitions in ^{192}Os, using the Half-life program. The values of half-life measured by fitting these PRF FWHM of 637 ps and 1007 ps separately show an excellent agreement of 282(16) ps and 272(21) ps, respectively, which correspond to the global half-life value of 282(4) ps for the ^{192}Os. The mean value of 277(12) ps from these two measurements was used in calculating the B(E2; $I_L \rightarrow I_{L-2}$) of 4233(114) e^2fm^4, which is equivalent to be 81(19) W.u.

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1. Introduction

The atomic nucleus which forms the central part of the atom is made up of the protons together with the neutrons. In gen-

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eral, the atom consists of all these components together with the constant orbiting electrons. The nuclear size is estimated to be of the order of few Fermis, ranging from $\sim 1.6\,fm$ ($10^{-15}\,fm$) for light nuclei (for example Hydrogen, with only one proton) to $\sim 15\,fm$ in heaviest elements, such as Uranium [1, 2].

The nucleus of an atom is held together by the strong nuclear force, which is strong enough to overcome the proton repulsion (at short ranges of $\sim 1\,fm$). Figure 1 shows the entire nuclei chart with 283 stable or very long-lived nuclei [3] represented by the black squares. Their neutron-to-proton ratio is loosely grouped within the ranges $1.00 \rightarrow 1.40$ for $2 \leq Z \leq 50$ and $1.20 \rightarrow 1.60$ for $50 < Z \leq 94$. The addition or removal of nucleons from stable nuclei obviously will alter the N/Z ratio, resulting in the formation of radioactive, unstable, neutron-rich systems [2, 3, 4].

2. Measurement of the Nuclear Excited States Lifetimes

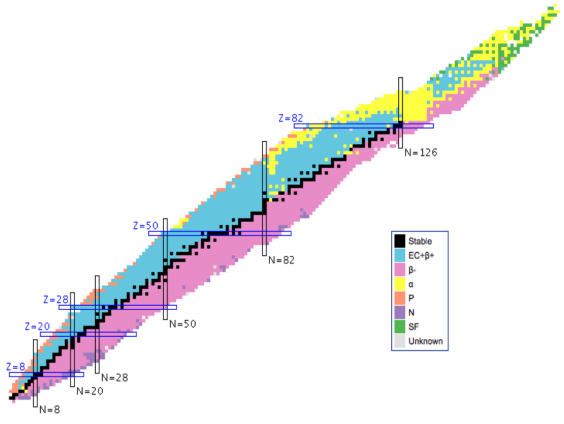

Figure 1. The chart of nuclides showing the stable nuclei in black squares with the unstable ones on either side of the band of stability. The vertical and the horizontal lines represent the magic numbers or closed shells [3].

The measurement of lifetimes of excited nuclear states can be regarded as a fundamental tool for nuclear spectroscopy [2, 5]. These play a significant role in the determination of the reduced electromagnetic transition rates which are sensitive to the intrinsic properties of the nuclear levels between which the transition proceeds [5, 6, 7]. The excited states of nuclei can be produced in many ways including light particle evaporation following a heavy-ion fusion; multi-nucleon transfer, Coulomb excitation etc. [2].

The half-lives of the excited nuclear levels can be measured using the time profile of γ rays detected with (high-resolution) gamma-ray detectors. In this article, the **Ro**manian array for γ ray **SP**ectroscopy in **HE**avy ion **RE**actions, RoSPHERE [5] was used. The lifetimes of the low-lying excited nuclear states typically range from femtoseconds to nanoseconds [7]. In this article, the convolution method was deployed for the measurement of the yrast halflife for the 2^+ state in ^{192}Os were different PRF have been used in the determination of the halflife value for the state.

However, there are several techniques by which the lifetime of the nuclear excited states can be obtained apart from the approach stated above. These techniques are broadly classified based on the range of the lifetime of the excited state [6, 7, 8], and can be subdivided into two main categories; (a) the indirect methods which measure the energy width of the state, Γ, and (b) the direct methods which measure the mean decay lifetime, τ.

3. The Concept of Convolution

Apart from the fact that these techniques are classified based on the range of lifetime information associated with the energy levels, convolution and the centroid shift methods can widely be employed in the measurement of these lifetimes of the nuclear levels [10, 11, 12, 13, 14, 15]. In these approaches, two or more γ ray transitions are used; the populating transition(s) to an energy level and the depopulating transition(s) out of the energy levels [2]; bringing about the gamma coincidence techniques.

Lifetime measurements within the picosecond to nanosecond region where the decaying γ rays are measured directly are obtained using the direct method [16]. Among these direct methods is the electronic timing technique, which in this article is based on the use of fast (time) response γ-ray detectors, made from $LaBr_3$(Ce) scintillator material [15].

For almost three decades, the electronic timing technique of $\beta - \gamma - \gamma$ coincidence method using BaF_2 crystals has been used for picosecond lifetime measurements in neutron-rich nuclei [17]. In this method, the desired decay path/cascade can be selected with the use of a high-resolution Ge detector. More recently [13, 14, 15, 18, 19], the use of triple coincidences for lifetime measurements in the picosecond region has been developed, where the time difference, ΔT, is obtained between the coincident cerium-doped $LaBr_3$ scitillators gated with a HPGe energy coincidence [20, 21]. This has led to an improvement compared to the previous BaF_2 based analysis due to the superior energy resolution and fast decay time for $LaBr_3$(Ce) detectors [22, 23].

In this article, a triple-coincidence, $\gamma_1 - \gamma_2 - \gamma_3$ technique is adopted, based on the operation of both HPGe detectors and $LaBr_3$(Ce) scintillators. The time distribution spectrum from the measured time difference between the two coincident $LaBr_3$(Ce) scintillators can be obtained either using a convolution of the prompt (Gaussian) response function and the exponential decay (see details in Figure 2) or alternatively by using the centroid shift method [24, 25, 26]. Both methods of analysis can be used when the half-life of the nuclear state is long enough to be measured by fitting the exponential nature of its decay [27] while the centroid shift method is particularly useful in cases where the half-life is of the same order or smaller than the full width at half maximum, FWHM prompt time response [27, 28, 29, 30, 31].

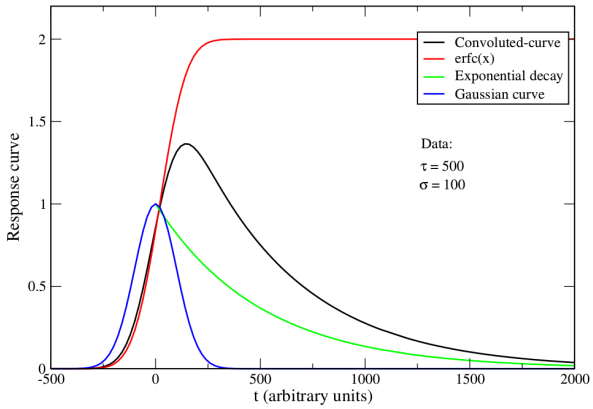

Figure 2. The convolution function with the exponential and the Gaussian prompt component as a function of t using arbitrary σ and τ, where τ is 5 times longer than σ [2].

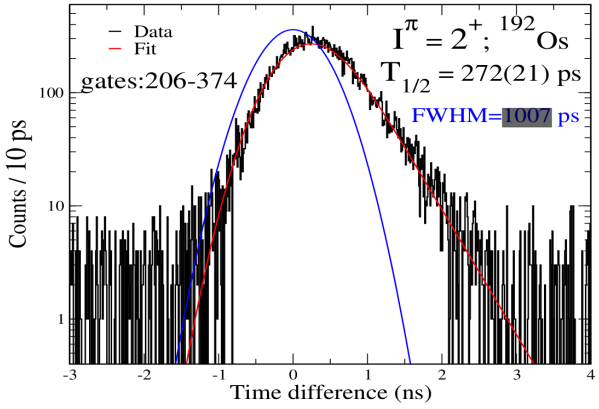

Figure 3. Background subtracted time difference spectra for the yrast $I^{\pi} = 2^{+}$ state in ^{192}Os, obtained using the deconvolution method, showing the time difference between the 206 keV and 374 keV transitions. Time difference spectra plotted with black lines are gated on ($E_{\gamma 1}$, $E_{\gamma 2}$). The continuous line is the Gaussian exponential convolution fit to the spectra.

4. Prompt Response Function (PRF) FWHM of 637 *ps* and 1000 *ps* in the $I^{\pi} = 2^{+}$ yrast state of ^{192}Os

Here, we present the lifetime measurements of the yrast state $I^{\pi} = 2^{+}$ from the ^{192}Os isotope in the ground state band obtained from the 'unsafe Coulombs Excitation' from the bombardment of the enriched (~ 99%) 20 $mgcm^{-2}$ ^{192}Os target with a 80 MeV ^{18}O beam which populates excited states associated with ^{194}Os nucleus from ground state band of 374 keV and 206 keV [2]. That is, for the time difference between the $LaBr_3$(Ce) at 374 keV (the feeding transition) of $4^{+} \rightarrow 2^{+}$ and the $LaBr_3$(Ce) at 206 keV (depopulating transition) of $2^{+} \rightarrow 0^{+}$ ground state with fixed PRF FWHM of 1007 *ps* (see Figure 4.1 for details) and 637 *ps* (see Figure 4.2) [32] using the Halflife program [33].

The choice of these PRF FWHM is necessitated from the fact that the ΔT obtained from the gamma pairs of 477 keV and 700 keV associated to ^{206}Po for the 637 *ps* [31] and 1007 *ps* as obtained from the ΔT between the Compton gamma pairs of the 189 keV and 237 keV transitions are actually very 'prompt' or

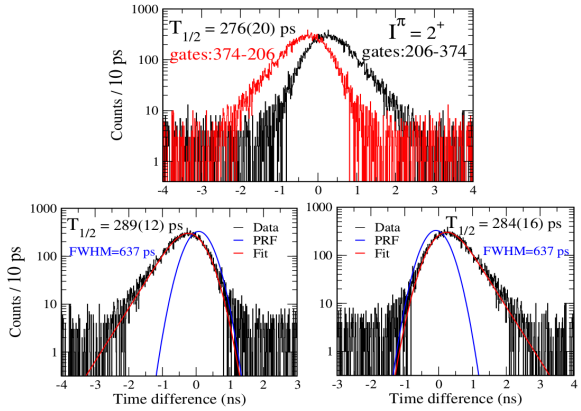

Figure 4. Time difference spectra for the yrast $I^{\pi} = 2^{+}$ state in ^{192}Os, obtained using (upper panel) the centroid shift method and (lower left and right panels) deconvolution method, showing the time difference between the gamma pairs of 206 keV and 374 keV transitions. Time difference spectra plotted with black lines are gated on ($E_{\gamma 1}$, $E_{\gamma 2}$), while the red lines show the reverse gating. The continuous lines in lower panels are the Gaussian exponential convolution fits to the spectra (the effective PRF FWHM value of 637 *ps* is taken from the ^{206}Po [31]. This Figure is taken from Ref. [33] as Figure 6 (see details in cross referencing, too).

Gaussian in nature because the time difference between them is very small as compared with a normal time difference obtained in a fit to the exponential slope. The relevance of this work here is to see whether there is a significant difference in the half-life measurement with these PRF values.

In each approach stated above, the lifetime measurements for the yrast state in ^{192}Os with fixed PRF FWHM at either 637 *ps* [32] or 1007 *ps* are in agreement with each other. This points to the fact that the time difference spectra presented in either case is prompt in which the time information from them does not contribute 'significantly' to the measured yrast state in ^{192}Os.

The weighted means of the two results obtained from fixing either PRF FWHM at 637 *ps* [32] or 1007 *ps* for the ΔT of 206 keV and 374 keV gamma pairs are presented in Figure reff5 with each result having the calculated error associated with the FWHM used and from the transitions employed here. The error bars in the stated results are mostly attributed to the fact that there is limited counts in all the measurements.

5. Discussion of Results and Conclusion

Figures 3 and 4 present the time difference spectra obtained between the gamma pairs of the 206 keV and 283 keV transitions, whose extracted half-life values are 272(21) *ps* and 282(22) *ps*, from fixing the FWHM value of 1007 *ps* and 637 *ps*, respectively, constant in the Half-life program [33]. The weighted mean of the extracted half-lives from the $LaBr_3$(Ce)- $LaBr_3$(Ce) coincidence pairs of (206, 283) keV and (206, 374) keV transitions, fixing FWHM values at either 1007 *ps* or 637 *ps*, is plotted in Figure 5. Both results agree excellently with each other approach even as the PRF FWHM was varied and within

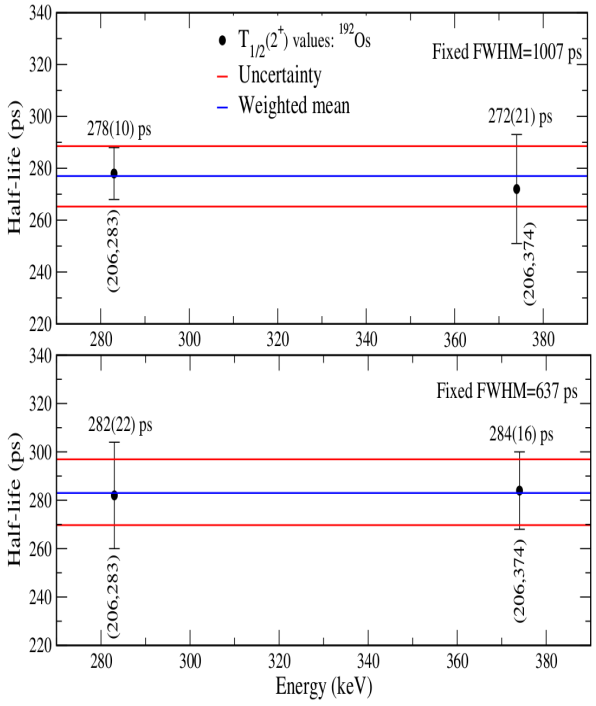

Figure 5. Plot of the measured half-life values for the $I^{\pi} = 2^+$ yrast state in ^{192}Os obtained from different approaches in the current work. The upper panel shows the weighted mean obtained from the half-life values using an effective PRF FWHM value of 1007 *ps*, while the lower panel presents the weighted mean for an effective PRF FWHM value of 637 *ps*. The horizontal solid lines indicate the weighted average of the half-life values from different decay paths, while the red lines represent the associated uncertainty in the weighted mean.

the calculated error. This result agrees with the global half-life value of 288(4) *ps* [32, 34] where other measured value for the ^{192}Os 2^+ state has been reported for the yrast state in ^{192}Os.

In conclusion, the results obtained from the PRF values of 637 *ps* and 1007 *ps* have shown a great similarity, which in turn is in agreement with the global half-life value for the 2^+ state in ^{192}Os. This is an indication that once the time difference between two gamma energies is "prompt", there is an insignificant presence of the time information (that is, in the half-life value) for such a state.

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