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# Nanosecond lifetime measurements of $I^{\pi}=9/2^{-}$ intrinsic excited states and low-lying B(E1) strengths in $^{183}$Re using combined HPGe-$LaBr_3$ coincidence spectroscopy

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## HIGHLIGHTS

- Measurement made of EM transition probabilities from low-lying $I^{\pi}=9/2^{-}$ states in $^{183}$Re.
- ROSPHERE gamma-ray array used to isolating discrete gamma-ray cascades.
- Derived the reduced hindrances of E1 transitions in $^{183}$Re related to K-quantum number conservation.

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## ABSTRACT

This paper presents precision measurements of electromagnetic decay probabilities associated with electric dipole transitions in the prolate-deformed nucleus $^{183}$Re. The nucleus of interest was formed using the fusion evaporation reaction $^{180}$Hf($^{7}$Li,4n)$^{183}$Re at a beam energy of 30 MeV at the tandem accelerator at the HH-IFIN Institute, Bucharest Romania. Coincident decay gamma rays from near-yrast cascades were detected using the combined HPGe-$LaBr_3$ detector array ROSPHERE. The time differences between cascade gamma rays were measured using the $LaBr_3$ detectors to determine the half-lives of the two lowest lying spin-parity $9/2^{-}$ states at excitation energies of 496 and 617 keV to be 5.65(5) and 2.08(3) ns respectively. The deduced E1 transition rates from these two states are discussed in terms of the K-hindrance between the low-lying structures in this prolate-deformed nucleus.



## 1. Introduction

The decay rate of the electromagnetic transitions from excited nuclear states provide information on the underlying nuclear structure (Schwarzschild and Warburton, 1968; Perdrisat, 1966; Nolan and Sharpey-Schafer, 1979). The reduced electromagnetic transition probabilities for such transitions can be compared with predictions derived using theoretical nuclear structure models (Bohr and Mottelson, 1998; Ring and Schuck, 2004). A wide range of nuclear excited state lifetimes are possible, with direct

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measurement of values covering ranges from less than $10^{-15}$ s to greater than $10^{13}$ years (Nolan and Sharpey-Schafer, 1979; Cumming and Alburger, 1985; Walker and Dracoulis, 1999).

The Electronic Timing Technique uses scintillator-based gamma-ray detectors and enables the determination of nuclear excited state decay half lives in the time range between $10^{-12}$ and $10^{-3}$ s (Nolan and Sharpey-Schafer, 1979; Mach et al., 1989; Régis, et al., 2013). In the current work, a combined gamma-ray detection array consisting of cerium-doped, lanthanum-tribromide ($LaBr_3$: Ce) detectors and High-purity Germanium (HPGe), based at the IFIN-HH tandem accelerator, Bucharest, Romania (Mărginean et al., 2010) has been used to perform fast-timing gamma-ray spectroscopy to measure the decay half-lives of excited states with spin-parity $9/2^-$ in the nanosecond temporal regime in the prolate-deformed nucleus $^{183}$Re. With Z=75 and N=108, the nucleus $^{183}$Re lies within the deformed rare-earth region, where a number of Nilsson single-particle orbitals with large projections of angular momentum on the nuclear symmetry axis, Ω, have been identified (Löbner 1968; Bunker and Reich, 1971; Manfrass, 1974; Walker and Dracoulis, 1999; Purry et al., 2000; Kondev et al., 2015).

The two spin-parity $9/2^-$ states of focus in the current work correspond to the bandheads of two different collective band structures based on the weakly-coupled, low-Ω [541]$1/2^-$ and strongly-coupled, high-Ω [514]$9/2^-$ single quasi-proton Nilsson configurations respectively (Bunker and Riech 1971; Manfrass et al., 1974; Purry et al., 2000). Electromagnetic decay from such states to other low-lying configurations with significantly different values for the angular momentum projection on the symmetry axis are well known to be additionally hindered compared to the expected, single-particle transition rates (Löbner 1968; Walker and Dracoulis, 1999; Kondev et al., 2015). Both of these states decay into the [402]$5/2^+$ structure based on the ground state of this nucleus.

The present work addresses measurement of the half-lives of low-lying bandhead of well-defined Nilsson single-particle configurations in $^{183}$Re and investigates their relative hindrance compared to the expected K-selection rule associated with axially symmetric, prolate-deformed nuclei in the region (Löbner 1968; Bunker and Reich, 1971; Walker and Dracoulis, 1999).

## 2. Experimental details and data analysis

The nucleus of interest was formed using the fusion evaporation reaction $^{180}$Hf($^{7}$Li,4 n)$^{183}$Re at a primary beam energy of 30 MeV. An isotopically enriched metallic foil $^{180}$Hf target of thickness 12 mg/cm$^2$ was used with the beam produced by the 9 MV Tandem van de Graaff accelerator at the National Institute for Physics and Nuclear Engineering, Bucharest, Romania. The beam energy was chosen to ensure appropriate $^{183}$Re production using the PACE statistical code for fusion-evaporation reactions (Gavron, 1980). The experiment was conducted using a continuous, DC beam for 25 days of beam time, with a typical beam current of 3–4 pnA. The PACE 4 calculations predicted a production cross-section for the 4 n evaporation channel to $^{183}$Re of approximately 400 mb.

The emitted gamma rays following the decays of the characteristic rotational structures was collected using the ROSPHERE gamma-ray spectrometer array comprising 14 high- resolution HPGe detectors (used to select specific de-exciting gamma-ray cascades) and 11 $LaBr_3$(Ce) scintillation detectors to determine the decay correlation times of these cascades (Mărginean 2010; Alharbi, 2013).

The Compton suppressed HPGe detectors were placed in five angular rings with 5 detectors placed at −37°, 2 at +37°, 2 detectors each at −70° and +70° and 3 at 90° to the beam direction. The $LaBr_3$(Ce) detectors were made up from seven detector modules with cylindrical crystals of dimension of 2″ diameter x 2″ in length, and 4 modules with crystal dimensions of 1.5″ diameter and 2″ length. The $LaBr_3$(Ce) detectors were placed 2 at 90°, 3 at +70°, 3 at −70° and 3 at −37° with respect to the beam-axis.

A point source of $^{152}$Eu was placed at the target position and used for the full-energy-peak and timing response calibrations of the HPGe and $LaBr_3$(Ce) detectors. The response was used to correct for the time walk of the $LaBr_3$(Ce) detectors as a function of the energy dependence. A logical master trigger gate required that at least three individual detectors, including at least one HPGe were measured within the defined master gate range of approximately 50 ns (Alharbi et al., 2013.) Approximately $2.2 \times 10^9$ $LaBr_3$-$LaBr_3$-HPGe coincidence events were measured in the complete data set over the 25 d run time.

The data were sorted off-line into a range of coincident 2D and 3D correlation matrices defined by gated discrete gamma-ray energies on the HPGe detectors and including gamma-ray energies measured in the $LaBr_3$ detectors together with the relative time differences between coincident members of a cascade.

The time difference between the measured gamma-ray transitions resulting from the finite half-life of the intermediate excited state(s) was then determined by selecting defined gating conditions on 3 dimensional ($LaBr_3$ Energy 1, $LaBr_3$ Energy 2, Time Difference =ΔT) arrays and projecting the measured time differences between the characteristic, discrete gamma-ray energy transitions feeding into and out of the state of interest as measured by the $LaBr_3$(Ce) detectors.

The large number of discrete gamma rays measured from the decay of excited states in $^{183}$Re and other reaction channels in the current work, meant that the energy resolution of the $LaBr_3$(Ce) detectors was, in general, not sufficient to isolate the specific cascades of interest without additional channel selection. This problem was addressed by gating on the high-resolution HPGe data to select out specific decay paths and project out the coincident ($LaBr_3$. $LaBr_3$, ΔT) information. The interrogation of these coincident arrays was performed using both the GASPWARE (Bazzacco and Marginean, 1997) and RADWARE (Radford, 1995) software analysis packages.

An extensive energy level scheme for the near-yrast states in $^{183}$Re exists following the work of Purry and co-workers (Purry, 2000), which built on earlier work by Manfrass et al., (Manfrass et al., 1974). A partial level scheme of the low-lying decays associated with some of the excitations built on the low-lying 1-quasi-proton states identified by Purry et al. is presented in Fig. 1. The coincident information evaluated in the current work was consistent with the level scheme proposed by Purry et al. and no previously unreported states were identified in the current work.

## 3. Lifetime results and extracted reduced matrix elements

Figs. 2 and 3 show examples of the gated gamma-ray spectra used to isolate the time differences across the spin-parity $9/2^-$ states in $^{183}$Re at excitation energies of 496 and 617 keV respectively. The use of the HPGe gates to allow clean ($LaBr_3$, $LaBr_3$) gamma-ray coincidences to be isolated in the current work is demonstrated by these spectra.

The projected $LaBr_3$(Ce)-gated, time difference spectra for different combinations of transitions across the 496 and 617 keV levels are shown in Figs. 4 and 5 respectively. The decay half-lives for the states were extracted using two separate, but related fitting methods. The first method used a fitting procedure which incorporated the full response function of the time spectra which were assumed to be a convolution of a Gaussian prompt-response function and a single component exponential decay associated

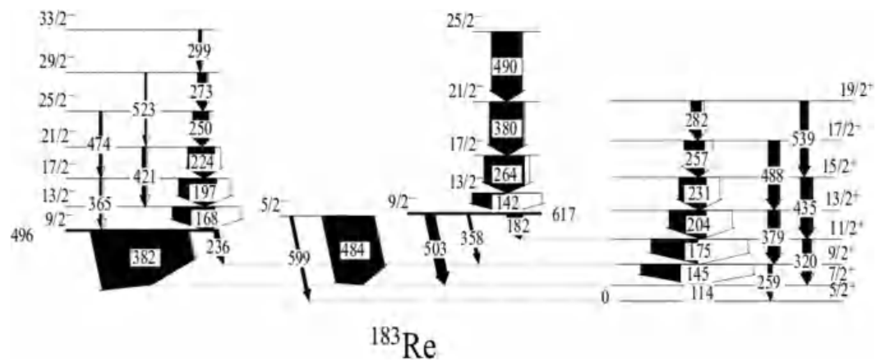


**Fig. 1.** Partial energy level scheme for $^{183}$Re based on the previous study by Purry et al. (Purry et al., 2000) showing decays observed in the current work. The Nilsson single proton configurations associated with the main states are $E_x$=0: [402]5/2$^+$; $E_x$=617 keV: [541]1/2$^-$; and $E_x$=496 keV: [514]9/2$^-$.

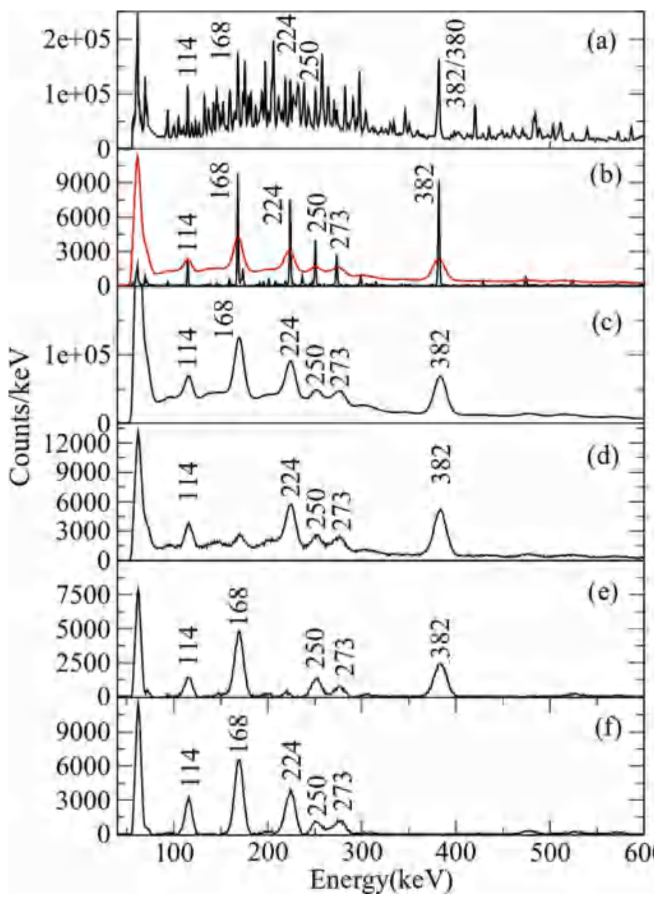


**Fig. 2.** a) Total projection spectrum for the HPGe detectors; (b) HPGe spectrum gated on197 keV in HPGe detectors; (c) $LaBr_3$ detector projections gated on 197 keV in the HPGe detectors. (d), (e) and (f) $LaBr_3$ energy spectra obtained by gating on the 197 keV transition in the HPGe detectors together with gates on 168, 224 and 382 keV transitions in $LaBr_3$ (Ce) respectively.

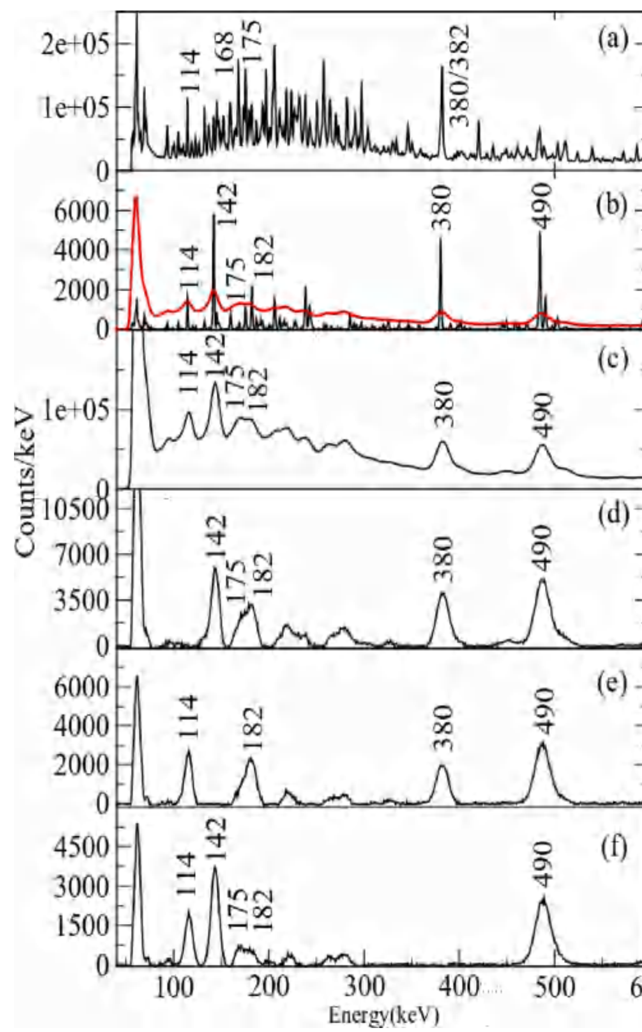


**Fig. 3.** (a) Total projection for the HPGe detectors; (b) HPGe spectrum gated on 264 keV in HPGe detectors; (c) $LaBr_3$ detector projections gated on 264 keV in the HPGe detectors. (d), (e) and (f) $LaBr_3$ energy spectra obtained by gating on the 264 keV transition in the HPGe detectors together with gates on 114, 142 and 380 keV transitions in $LaBr_3$ (Ce) respectively.

with the state lifetime (e.g. Olsen and Bostrõm 1966; Malmskog, 1966). The convolution function associated with a single exponential decay, defined by a mean-lifetime of the decay state, $\tau = T_{1/2}/\ln 2$ and a Gaussian Prompt Response Function (PRF) defined by a standard deviation from the mean $\sigma$, where $2.35\sigma$=the full width half-maximum for the Gaussian PRD, can be written as,

$$I\{t\} = A exp\left\{\frac{\sigma^2}{2\tau^2} - \frac{1}{\tau}\right\}.\left[1 - erf\left\{\frac{\sigma^2 - \tau t}{\sqrt{2}\sigma\tau}\right\}\right]$$

where erf ( ) corresponds to the error function, $A$ is an intensity normalisation constant and $t$ is the time difference since the defined time zero.

The second method fitted a single component exponential decay function to the delayed coincidence time curve but ensuring that this was fitted only for data points significantly away from the prompt time response curve (e.g., Newton, 1950; Bostrõm et al., 1966).

Fig. 4 shows the single exponential decay curve fits for transitions across the spin-parity 9/2$^-$ state at an excitation energy of

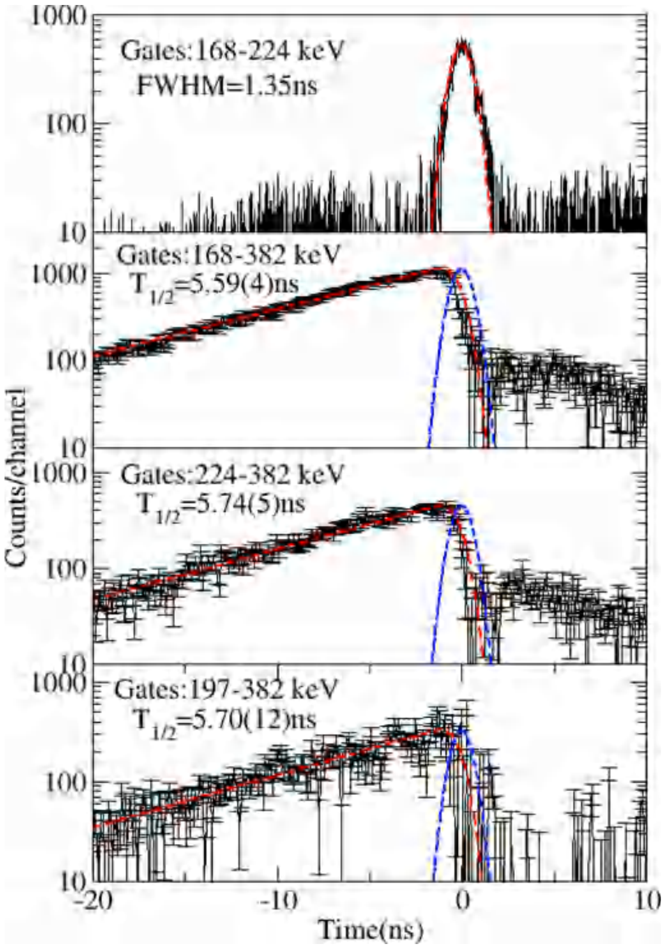


**Fig. 4.** Time difference spectra between two $LaBr_3$ (Ce) detectors with an additional HPGe gating transition to select transitions across the $K^{\pi}=9/2^{-}$ state in $^{183}Re$ at 496 keV. The upper spectrum has a HPGe gated on 197 keV and shows time measured time difference between the 168 and 382 keV transitions measured in the $LaBr_3$ (Ce) detectors. The central panel has an HPGe gate on 197 keV with LaBr3 gates on 224 and 382 keV. The lower panel has a HPGe gate on 224 keV and $LaBr_3$ (Ce) gates on 197 and 382 keV respectively. The dispersion in each of these figures is 20 ps per channel.

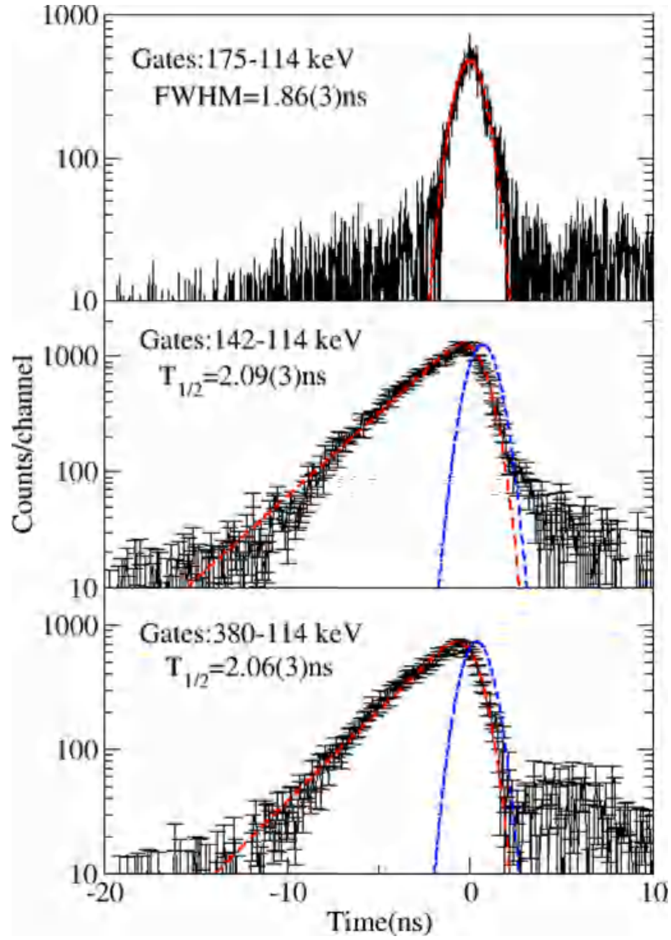


**Fig. 5.** HPGe-gated $LaBr_3$-$LaBr_3$ energy-gated time spectra showing time difference distributions for transitions across the $I^{\pi}=9/2^{-}$ state in $^{183}Re$ at 617 keV. The dispersion is 20 ps per channel.

496 keV. Fig. 5 shows the fitting of the convolution of the prompt response function and exponential decay associated with the decay of the $9/2^{-}$ state at 617 keV; the normalised prompt response function for these gamma-ray energy pairings are also shown for comparison.

The final half-life values of 5.65(5) ns and 2.08(3) ns for the $9/2^{-}$ states at 496 and 617 keV respectively, were taken from the weighted mean values of the different decay measurements across each isomeric state. This assumes that the lifetime of any intermediate state between the gating $LaBr_3$(Ce) transition and the isomeric state of interest is much shorter than the isomeric state itself. The three decay curves shown in Fig. 4 all show consistent values which suggest that the lifetimes for the intermediate states are at the picosecond timescale or faster. The previous study by Singh et al., (Singh et al., 1974) and evaluation by Firestone (Firestone, 1992) reported a half-life of 7(1) ns and 7.8(4) ns respectively for the 496 keV state. These are both longer than the value obtained in the current work of 5.65(5) ns. The evaluated data for the $5/2^{-}$ state lifetime at excitation energy 599 keV (see Fig. 1) reported a half-life for this state of 1.96(5) ns (Firestone, 1992). Our data suggests that this is in fact the half-life of the $9/2^{-}$ state at 617 keV which feeds the $5/2^{-}$ state (Purry et al. 2000).

## 4. Extracted reduced matrix elements

The measurement of these intrinsic state half-lives allows the extraction of the reduced matrix elements for the electric dipole decays between the isomeric states and the states to which they decay.

The partial half-life, $T^{A}_{1/2}$ for a discrete decay branch of the state is given by (Kondev et al., 2015)

$$T^{A}_{\frac{1}{2}} \times BR = T^{tot}_{\frac{1}{2}}$$

where *BR* is the branching ratio of that particular transition from the decaying state, where the sum of all the branching ratios is normalised to unity.

The reduced matrix element, $B(E1{:}I_i \rightarrow I_f)$ for pure electric dipole decays in units of $e^2fm^2$ for that particular gamma-ray decay, where $I_i$ is the spin of the initial decay state and $I_f$ is the spin of the state to which it decays, is related to the measured decay half-life of the decaying state by the relation (Kondev et al., 2015; Ring and Schuck, 2004; Bohr and Mottelson, 1998)

$$B(E1)e^2fm^2 = \frac{0.693}{T_{1/2}(s) \times (1+\alpha) \times 1.587 \times 10^{15} \times E_{\gamma}^{3}(MeV)}$$

where α is the total internal conversion coefficient of the decaying transition. In the current work, the value of α has been assumed to be the value for a pure E1 decay (i.e. no M2 admixture) taken from the BRICC code (Kibédi et al., 2008).

Table 1 gives a summary of the measured half-lives for the two

**Table 1**
Summary of the half-life measurements and deduced reduced matrix elements for decays from the spin-parity 9/2- states in $^{183}$Re at excitation energies of 617 and 496 keV from the current work.

| $E_\gamma$ (keV) | $E_i \to E_f$ (keV) | $I_i^\pi, K_i \to I_f^\pi, K_f$ | $T_{1/2}$ (ns) | Branching Ratio (%) | $\alpha_{tot}$ (E1) | B (E1) $e^2fm^2$ | B (E1) *Wu* |
|---|---|---|---|---|---|---|---|
| 182 | 617→435 | 9/2-, 1/2-→11/2+, 5/2+ | 2.08(3) | 52(4) | 0.082 | $3.23(6) \times 10^{-5}$ | $1.55(3) \times 10^{-5}$ |
| 358 | 617→259 | 9/2-, 1/2-→9/2+, 5/2+ | 2.08(3) | 10(2) | 0.016 | $4.52(11) \times 10^{-6}$ | $2.17(5) \times 10^{-6}$ |
| 503 | 617→114 | 9/2-, 1/2-→7/2+, 5/2+ | 2.08(3) | 38(5) | 0.007 | $1.64(3) \times 10^{-6}$ | $7.90(14) \times 10^{-7}$ |
| 382 | 496→114 | 9/2-, 9/2-→7/2+, 5/2+ | 5.65(5) | 95(4) | 0.013 | $1.37(3) \times 10^{-6}$ | $6.58(14) \times 10^{-7}$ |
| 236 | 496→260 | 9/2-, 9/2-→9/2+, 5/2+ | 5.65(5) | 5(4) | 0.042 | $5.64(15) \times 10^{-6}$ | $2.71(7) \times 10^{-6}$ |

spin-parity 9/2- states in $^{183}$Re from the current work and the associated B(E1) values for the different decay branches. The branching ratios were taken using the intensity values from Purry et al., (Purry, 2000).

These experimentally derived B(E1) values can then be compared with the expected single particle unit for electromagnetic decay rates in a nucleus using the concept of a single proton transition between idealised spherical orbits, namely the Weisskopf estimate (Weisskopf, 1951). If A is the nuclear mass number, the Weisskopf single-particle estimate can be calculated for a pure *B(E1)* in units of $e^2fm^2$, using the expression (Weisskopf, 1951; Kondev et al., 2015).

$$B_{1Wu}(E1) = 6.446 \times 10^{-2} \times A^{2/3}$$

The values for the decay branches are all in the range $10^{-8} \to 10^{-6}$ Wu which is typical for $\Delta K = 2$ hindered electric dipole transitions in this region (Perdrisat, (1966); Kondev (2015). This is consistent with the relatively small K-difference between the two proposed 9/2- states and states to which the measured transitions decay, which are based on to the [402]5/2+ ground state structure. These should all have $\Delta K = 2$ going from either $\Omega^\pi = 9/2^- \to 5/2^+$ or $\Omega^\pi = 1/2^- \to 5/2^+$ (Kondev et al.,2015).

## 5. Summary and conclusions

The coincident gamma-ray electronic fast-timing technique has been used to determine the decay half-lives of the two lowest lying spin-parity 9/2- states in the prolate-deformed nucleus $^{183}$Re. Intrinsic state half-lives of 5.65(5) ns and 2.08(3) ns have been measured for the states at excitation energies of 496 and 617 keV, which correspond to the [514]9/2- and [541]1/2- single proton Nilsson states respectively.

The deduced E1 reduced matrix elements for decays from these intrinsic states to rotational members of the [402]5/2+ ground state configuration in $^{183}$Re have been determined. While the E1 decays are significantly hindered with respect to the Weisskopf single particle estimates, they are consistent with only weakly K-forbidden decays in this deformed region. This is consistent with the Nilsson configuration assignments for the decaying states and with intermediate-Ω value configurations to which they both decay.

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