Measurements of subnanosecond nuclear lifetimes

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Lifetimes of some excited nuclear levels in the subnanosecond region are determined from delayed coincidence measurements. The measured values of half-life pertain to the nuclear levels: 161 keV of ^{133}Cs (180±10 psec), 343 keV of ^{175}Lu (281±10 psec), 113 keV of ^{177}Hf (583±6 psec), 896 keV of ^{168}Er (≤ 120 psec), 724 and 757 keV of ^{95}Nb (≤ 70 psec each). Measurements on the 896 (^{168}Er), 724 and 757 keV (^{95}Nb) levels have not been reported earlier. The magnetic moment of the 113 keV level of ^{177}Hf has been recalculated using the measured lifetime and a new value of $\mu(\frac{9}{2}^-)=(0.91\pm0.02)\mu_N$ is found which is in better agreement with the value predicted from theoretical considerations.

Lifetimes of excited nuclear levels are required to determine transition rates and thus to indicate whether the level is single particle or collective in nature. An accurate value of the mean life is required to determine the g factor of the excited level by the time-integral perturbed angular correlation (IPAC) method. In the present case lifetimes of some excited nuclear levels in the subnanosecond region have been measured by the slope method using an improved coincidence setup with BaF_2 and plastic scintillation detectors. The use of BaF_2 detectors in timing spectroscopy is of recent interest because of its very short scintillation decay time of 600 psec for the fast component [1]. Using this fast component it is possible to obtain subnanosecond time resolution with a BaF_2-BaF_2 and a plastic-BaF_2 coincidence setup [2].

Present measurements report on the levels of 161 keV of ^{133}Cs, 343 keV of ^{175}Lu, 113 keV of ^{177}Hf, 896 keV of ^{168}Er, and 724 and 757 keV of ^{95}Nb. (i) The half-life of the 161 keV level has been measured earlier and values from 85 to 249 psec have been reported (Table I). The accepted one is $T_{1/2}=190\pm15$ psec [3,4], measured by Välivaara *et al.* [5] by the centroid shift method. But this method of measuring lifetime is not as accurate as the slope method due to large uncertainties in the determination of centroid shifts. (ii) The measurements of half-life on the 343 keV level of ^{175}Lu have been performed by Meiling *et al.* [6] and Höjeberg *et al.* [7]. However, the values reported in Refs. [6] and [7] strongly disagree with each other (Table I). (iii) The half-life of the 113 keV level of ^{177}Hf has been measured earlier by Holmberg *et al.* [8] using a γ-γ coincidence setup with two plastic scintillators at a time resolution (1.1 nsec) much greater than the half-life measured (490±15 psec). In view of above considerations we have found it worthwhile to remeasure the lifetimes of these levels using an improved coincidence setup.

Since, to our knowledge, there are no reported measurements on the (iv) 896 (^{168}Er), (v) 724 and 757 keV (^{95}Nb) levels, attempts have also been made to find lifetimes of these levels using the present coincidence setup.

Except for ^{168}Tm, radioactive sources are obtained from BARC, Bombay, India. The ^{168}Tm source has been produced through the ^{165}Ho$(\alpha,n)^{168}$Tm reaction by using 35 MeV α beam from the Variable Energy Cyclotron, Calcutta. For the measurements a standard slow-fast coincidence setup has been used. For γ-γ and x-γ delayed coincidence experiments BaF_2 crystals chosen are any two out of the three crystals of sizes 38.1 mm diameter × 25.4 mm height, 38.1 mm diameter × 12.7 mm height, and 38.1 mm diameter × 6.3 mm height, depending on the radiation to be detected. These crystals are coupled to Phillips XP2020Q photomultiplier tubes. For β-γ delayed coincidence measurement, β particles are detected in a plastic scintillator (Pilot U) of size 25.4 mm diameter × 1.5 mm height coupled to a Phillips XP2020 photomultiplier tube. The data have been analyzed by using the well known computer program DBLCON of Warburton [9].

(i) 161 keV level of ^{133}Cs. For the measurement on this level a ^{133}Ba source is used. The delayed coincidence spectrum of the 276–161 keV cascade of ^{133}Cs shows a significant change in slope from that of the prompt curve (Fig. 1). The half-life is found to be 180±10 psec which agrees with the value measured by Välivaara *et al.* [5].

(ii) 343 keV level of ^{175}Lu. The half-life of this level is determined from x-γ (343 keV) coincidence of ^{175}Lu using a mixed source of ^{175}Hf and ^{181}Hf. The energy window setting in the BaF_2 channel for selecting the 343 keV γ ray also selects the 346 keV γ ray of ^{181}Ta. In the other BaF_2 channel the energy window is set to select x rays of ^{175}Lu and of ^{181}Ta. Therefore, coincidences will be through the 343 keV level of ^{175}Lu and also through the 482 keV level of ^{181}Ta. In this case a double-exponential curve has been observed. The decay time of the slow component found is very long compared to the fast component and it can easily be identified as showing the half-life of the 482 keV level of ^{181}Ta ($T_{1/2}=10.8$ nsec). A double-exponential fitting of the delayed curve using the

TABLE I. Results of nuclear lifetime measurements.

Isotope	Level (keV)	Method	FWHM (psec)	$T_{1/2}$ (psec)	Reference
^{133}Cs	161	e^--$e^-(t)$	910	190±15	[5]
		others		85–249	[3][a]
		γ-$\gamma(t)$	620	180±10	Present
^{175}Lu	343	x-$\gamma(t)$		≤35	[6]
		e^--$e^-(t)$		260±20	[7]
		x-$\gamma(t)$	750	281±10	Present
^{177}Hf	113	γ-$\gamma(t)$	1100	490±15	[8]
		others		320–540	[8][a]
		γ-$\gamma(t)$	620	583±6	Present
^{168}Er	896	γ-$\gamma(t)$	480	≤120	Present
^{95}Nb	724	β-$\gamma(t)$	300	≤70	Present
	757	β-$\gamma(t)$	300	≤70	Present

[a]And references given therein.

program of Warburton [9] results in a value of $T_{1/2}=281\pm10$ psec for the fast component which can also be identified as the half-life of the 343 keV level of ^{175}Lu. The half-life of the 343 keV level obtained from the present measurement disagrees strongly with the result of measurement of Meiling and Stary [6] but supports that of Höjeberg *et al.* [7] (Table I).

(iii) 113 keV level of ^{177}Hf. The half-life of the 113 keV level of ^{177}Hf has been measured from the slope of the delayed coincidence spectrum of the 208–113 keV cascade using a source of ^{177}Lu. From analysis of the coincidence spectrum we obtain $T_{1/2}=583\pm6$ psec (Fig. 2). The result disagrees with the value obtained by Holmberg *et al.* [8] and also with the values tabulated therein. The time resolution of the coincidence setup used in Ref. [8] (1.1 nsec) is much poorer than that of ours (620 psec). This fact, together with the poor energy resolution of the plastic scintillators used by Holmberg *et al.* [8] for detection of the Compton edges of the 208 and 113 keV γ rays, may be a possible cause of getting a different value. The magnetic moment of the 113 keV level of ^{177}Hf, measured previously by the IPAC method [10,11], has been recalculated since our experimental value of the half-life differs substantially from the values used by Manning *et al.* [10] and Matthias *et al.* [11] ($T_{1/2}=416$ and 520

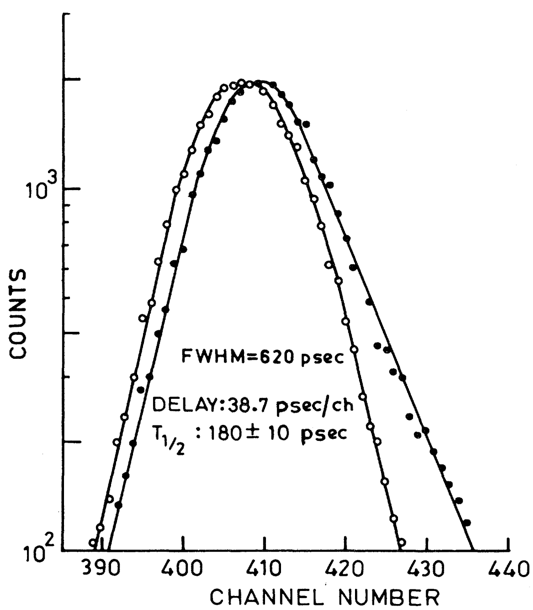

FIG. 1. γ-γ delayed coincidence spectrum of the 276–161 keV cascade of ^{133}Cs showing the lifetime of the 161 keV level and the corresponding prompt time spectrum.

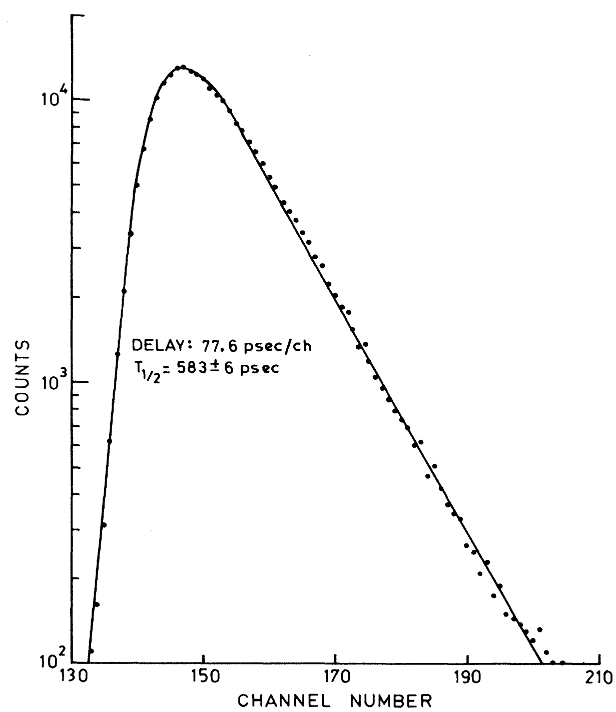

FIG. 2. γ-γ delayed coincidence spectrum of the 208–113 keV cascade of ^{177}Hf showing the lifetime of the 113 keV level.

psec, respectively). Using the value of $g\tau = 0.170 \pm 0.004$ from the report of Hübel *et al.* [12] and the meanlife $\tau = 0.841 \pm 0.008$ nsec from the present work we obtain the g factor of this level as $g = 0.202 \pm 0.005$. The revised value of the magnetic moment thus found is $\mu(\frac{9}{2}^-) = (0.91 \pm 0.02)\mu_N$ which is close to the value predicted by Matthias *et al.* [11] $[(0.82 \pm 0.15)\mu_N]$ from theoretical considerations. The magnetic moment of this level as measured by Matthias *et al.* [11] is $(1.04 \pm 0.06)\mu_N$ while Manning *et al.* [10] reports a value of $(0.99 \pm 0.27)\mu_N$.

(iv) 896 keV level of ^{168}*Er.* The half-life of this level has been measured by selecting (184+198) keV γ rays in one and (816–830) keV γ rays in the other BaF_2 detector. In this energy selection there are three cascades contributing to the coincidence spectrum. These are 198–816, 198–821, and 830–184 keV cascades. The cascade 198–821 keV passes through the 821 keV level of $T_{1/2} = 2.73$ psec [13], the 830–184 keV cascade passes through the 264 keV level of $T_{1/2} = 114$ psec [13], and the 198–816 keV cascade passes through the 896 keV level. The slope of the coincidence spectrum thus recorded is found to be equal to that of the prompt curve. With the same energies the values of FWHM and slope of the prompt curve obtained are 480 and 120 psec, respectively. From this measurement a limit of $T_{1/2} \leq 120$ psec has been set for the 896 keV level. No measurement of lifetime on the 896 keV level is reported in literature [13]. However, the measured value of $B(E2)$ [14] (0.046 ± 0.013 $e^2 b^2$) for the 816 keV transition corresponds to the half-life of 2.8 ± 0.8 psec. From the present value of the half-life the value of $B(E2)$ for this transition has been calculated to be $B(E2) \geq 0.001$ $e^2 b^2$, considering the γ transition as pure $E2$ [13].

(v) 724 and 757 keV levels of ^{95}*Nb.* Using a source of ^{95}Zr, the measurement of half-lives on these levels has been performed from β-γ coincidence by selecting (724+757) keV γ rays in the BaF_2 channel and β energy > 50 keV in the plastic channel. The energy window selection in the BaF_2 channel also includes the 766 keV γ ray of ^{95}Mo which is produced in the decay of ^{95}Nb ($T_{1/2} = 35$ d). The half-life of the 766 keV level is known to be 4.4 psec [15]. The slope of the β-γ coincidence spectrum thus recorded is found to have identical slope to that of a prompt curve measured with equal energies selected in the side channels. The slope of the prompt curve has been measured to be 70 psec. Thus it is possible from this measurement to set $T_{1/2} \leq 70$ psec for the 724 and 757 keV levels of ^{95}Nb. We have not come across any report measuring lifetimes of these two levels [15]. The values of $B(M1)$ for the 724 and 757 keV transitions are calculated from the measured lifetimes. Considering pure $M1$ type of transitions [15] these values are calculated to be $B(M1) \geq 1.46 \times 10^{-27} \mu_N^2$ and $B(M1) \geq 1.27 \times 10^{-27} \mu_N^2$ for the 724 and 757 keV transitions, respectively.

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