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Shape transition and tilted axis rotation in ^{136}Ce

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The $\Delta I=1$ band built on the 5645 keV (14^-) level in ^{136}Ce has been extended to the 9228 keV (23^-) level using an eight CS-Clover array with 14 element NaI(Tl) multiplicity filter. The crossover $E2$ transitions have been identified for the first time. The lifetimes of the 18^- to 22^- levels have also been measured by the Doppler shift attenuation method. The observed band is reproduced well by the "tilted axis cranking"(TAC) calculations for the four quasiparticle $\nu h_{11/2}^{-2}\otimes\pi g_{7/2}h_{11/2}$ configuration having a small oblate deformation ($\epsilon_2\sim0.11$) and a tilt angle of 32°. The measured $B(M1,I\rightarrow I-1)/B(E2,I\rightarrow I-2)$ ratios as well as the $B(M1,I\rightarrow I-1)$ values for 18^- to 23^- levels show a decrease with increasing rotational frequency in agreement with these calculations, thus confirming the "magnetic rotation" (MR) nature of the band. The calculations also reveal the presence of a second minimum in energy for the four quasiparticle $\nu h_{11/2}^{-2}\otimes\pi g_{7/2}h_{11/2}$ configuration having triaxial shape with $\gamma=21°$. This minimum also supports a closely lying band with a tilt angle of 82°, implying principal axis cranking (PAC). The measured values of $B(M1,I\rightarrow I\text{-}1)/B(E2,I\rightarrow I\text{-}2)$ ratios, which are quite small at the lower spins, are also in agreement with the calculated values for the triaxial shape and a mixing with the near oblate shape. The sudden rise in the $B(M1)/B(E2)$ values at $I=18$ clearly indicates a transition from the PAC regime to magnetic rotation, which is induced by the shape change.

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Recently, a number of $\Delta I=1$ bands, named as magnetic rotation bands, arising due to shears mechanism [1] have been identified in several mass regions namely $A=190$, 135, 110, and 80 [2]. One of the most important characteristics of these bands is the decreasing $B(M1)$ values with increasing transition energies. This behavior is well explained by the application of the "tilted axis cranking"(TAC) model of Frauendorf [1]. In this model, these bands arise due to a collective motion of proton particles (holes) in low Ω orbitals coupled to a collective motion of neutron holes (particles) in high Ω orbitals or vice versa. Thus, the net proton and neutron spin vectors are aligned perpendicular to each other forming the blades of a shears. The resultant angular momentum, therefore, makes an angle with one of the principal axes. Higher angular momentum states are generated by the proton and neutron spin vectors closing on the resultant angular momentum. Such a coupling breaks the signature symmetry and gives rise to a $\Delta I=1$ sequence now termed as the magnetic rotational (MR) band. The bands in the mass 110 region arise due to one or two proton holes in high Ω $g_{9/2}$ orbitals, and two neutron particles in low Ω $g_{7/2}/d_{5/2}$ and $h_{11/2}$ neutron orbitals [3–7]. In addition to mass 110 region, the $\Delta I=1$ bands showing a decrease in $B(M1)$ values with increasing spin have been observed in $^{193-197}$Pb [8–11] isotopes also. Although $\Delta I=1$ bands have been seen in mass ~130 region but the only interpretation in terms of the shears mechanism is in ^{139}Sm [12]. The TAC calculations show a decrease in $B(M1)/B(E2)$ ratios for $\epsilon_2=0.11$, $\gamma=-15°$ in agreement with the experimental data for the $\Delta I=1$ band in ^{139}Sm; however, the data are also consistent with a nearly constant behavior of the $B(M1)/B(E2)$ ratios. The TAC calculations of Dimitrov *et al.* [13] reproduced the experimental data on $B(M1)/B(E2)$ vs I in ^{128}Ba quite well; however, the same data could also be very well understood in terms of a pure high-K band and axially symmetric rotor picture [14].

High-j bands in the mass 130 region involve low Ω protons and high Ω neutron orbitals, and constitute a good testing ground for the shears mechanism. This is also the reason for observing a coexistence of prolate and oblate shapes in this region. This encouraged us to confirm the tentative assignments and also extend to higher spins the $\Delta I=1$ band built on 5645 keV (14^-) level. Our measurements reverse the ordering of two higher lying transitions and lead to firm spin parity assignments. The crossover $E2$ transitions have been identified for the first time. Further, the lifetimes of the high spin levels with $I\geqslant18^-$ have been measured by the "Doppler shift attenuation method" (DSAM). The experimental $B(M1)/B(E2)$ ratios, as well as the $B(M1)$ and $B(E2)$ values have been obtained and compared with the predictions of the TAC model. The $B(M1)/B(E2)$ ratios for the 16^- and 17^- levels are nearly a factor of 3 smaller compared to the values for the 18^- and 19^- levels indicating a significant change in the structure at lower spins. This observation coupled with our theoretical calculations suggest a transition from a triaxial to an oblate shape in this band. Such a shape change is accompanied by the onset of magnetic rotation as evidenced in the change in coupling scheme at these angular momenta. A preliminary report of this work was presented in the DAE-BRNS Symposium on Nuclear Physics held at Kolkata, India [15].

High spin states in ^{136}Ce have been populated in the present work through the ^{124}Sn(^{16}O,4n)^{136}Ce fusion evaporation reaction by using 80 MeV ^{16}O beam from the 14-UD Pelletron at T. I. F. R, Mumbai. The target consisted of a 1.6 mg/cm^2 thick enriched ^{124}Sn foil rolled on a

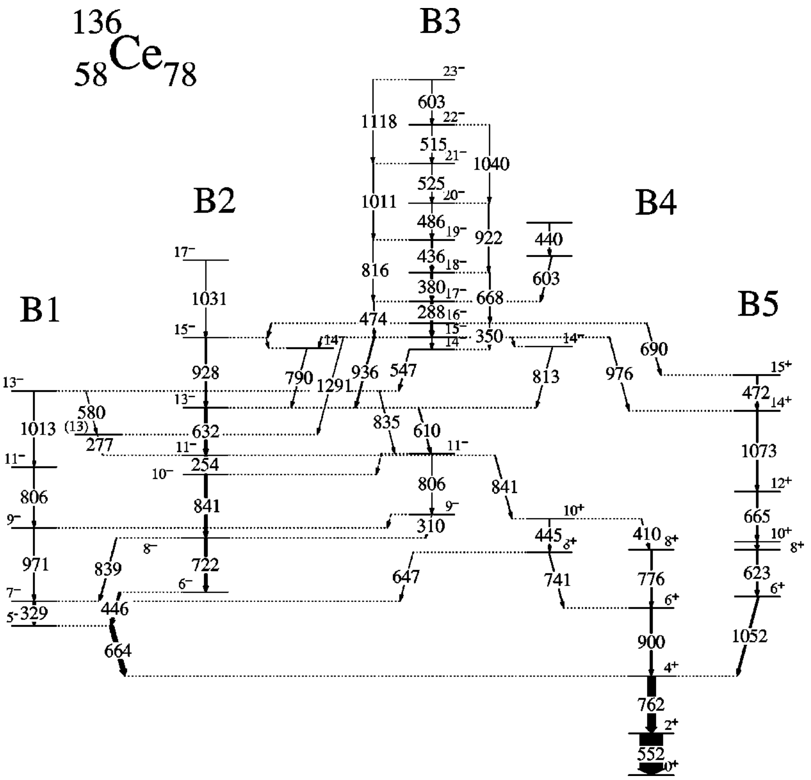

FIG. 1. Partial level scheme of ^{136}Ce.

12.8 mg/cm^2 thick gold backing. Gamma rays produced in the above reaction were detected in an array consisting of eight CS-clover detectors along with 14 element NaI(Tl) multiplicity filter. Each clover detector consists of four HPGe crystals placed in the form of a clove in a single vacuum housing [16]. The array was jointly setup by T. I. F. R., Mumbai, S. I. N. P. and IUC-DAEF, Kolkata, and N. S. C., New Delhi [17]. Each clover was treated as a single detector and data were collected in LIST mode when three or more clovers fired simultaneously along with two or more firings in NaI(Tl) multiplicity filter. These data were then sorted into two-dimensional(2D) γ-γ matrices for the study of level structure in Ce isotopes. 2D matrices were also constructed with each detector along one axis and the rest of the detectors along the other axis for the analysis of lifetimes using the Doppler shift attenuation method. The multipolarity of transitions has been determined from DCO ratios and angular distribution measurements. The partial level scheme of ^{136}Ce, obtained from the present study, is shown in Fig. 1. While several new transitions have been added to the level scheme, the main focus of the present Rapid Communication is the negative parity $B3$ band which has been extended to 9228 keV (23^-) level. The 603 keV transition was added at the top and the order of the 525 and 515 keV transitions reported in Ref. [18] has been reversed. The crossover $E2$ transitions in this band have been observed in the present work for the first time. The branching ratios for levels in the $B3$ band obtained from the intensities of gamma rays have been used to calculate the experimental $B(M1)/B(E2)$ ratios with increasing angular momentum or the energy of the $\Delta I=1$ transitions. The experimental $B(M1)/B(E2)$ ratios as a function of frequency $\hbar\omega=E_\gamma$ for $\Delta I=1$ transitions are shown with filled circles in Fig. 2(a). It is observed that the

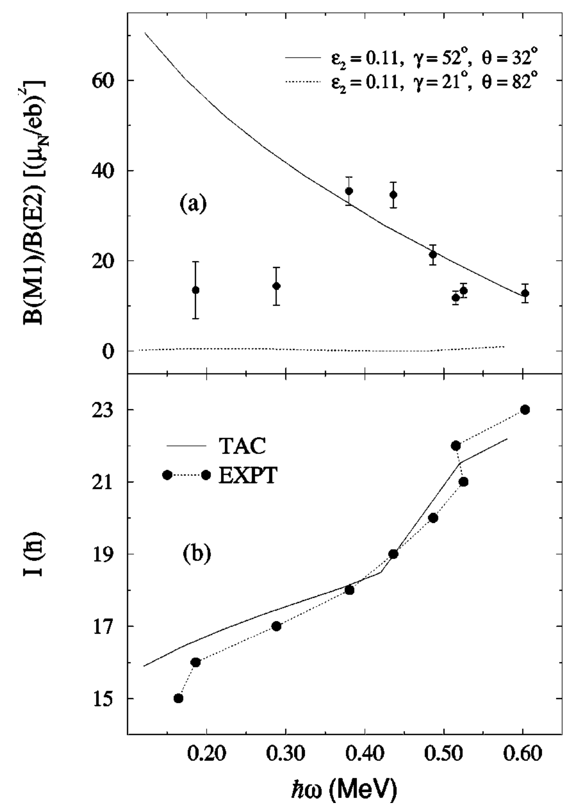

FIG. 2. (a) The experimental $B(M1)/B(E2)$ ratios vs frequency $\hbar\omega$ for transitions in the $B3$ band in ^{136}Ce. The results of TAC calculations for the shape parameters $\epsilon_2=0.11$, $\gamma=52°$ and the tilt angle $\theta=32°$ are shown with a solid line. The dotted line corresponds to $\epsilon_2=0.11$, $\gamma=21°$ and the tilt angle $\theta=82°$. (b) The experimental and calculated (TAC) angular momentum I vs frequency $\hbar\omega$.

value of $B(M1)/B(E2) \sim 10$ $(\mu_N/e\mathrm{b})^2$ for $\hbar\omega = 0.186$ and 0.288 MeV. It, however, shoots up to $B(M1)/B(E2)$ ~ 40 $(\mu_N/e\mathrm{b})^2$ for $\hbar\omega = 0.380$ MeV. Thereafter, it decreases smoothly with increasing rotational frequency. The observed decrease in the experimental $B(M1)/B(E2)$ ratios is a signature of the tilted axis rotation as also seen in the mass 190 and 110 region [3–10].

The experimental data for the $B3$ band have been compared with the calculations of the hybrid version of TAC model. It is known that ^{136}Ce is a transitional nucleus and the negative $E2/M1$ mixing ratio suggest an oblate configuration for the $B3$ band [18]. A four quasiparticle $\pi g_{7/2} h_{11/2} \otimes \nu h_{11/2}^{-2}$ configuration has been assigned to this band as also suggested earlier [18]. The pairing parameters have been chosen as 80% of the odd-even mass difference, i.e., $\Delta_p = 1.05$ MeV and $\Delta_n = 0.898$ MeV. A minimization of the total energy in the laboratory frame gives a deformation $\epsilon_2 = 0.11$, $\gamma = 52°$, which is nearly oblate. The preferred tilt angle remains near $\theta = 32°$ for most cranking frequencies. The results of our calculation for angular momentum (I) as a function of the rotational frequency, $\hbar\omega$, show a reasonably good agreement with the experimental data in Fig. 2(b). Calculations also show that the configuration chosen is indeed the lowest lying negative parity four quasiparticle configuration for the $B3$ band. The above deformation parameters $\epsilon_2 = 0.11$, $\gamma = 52°$ and the tilt angle $\theta = 32°$ were, therefore, used to calculate $B(M1)/B(E2)$ ratios and are compared with the experimental results in Fig. 2(a). The good agreement between the experimental data and the calculated curve strongly support the observation of tilted axis rotation for $\hbar\omega \geqslant 0.38$ MeV in ^{136}Ce. The $B(M1)/B(E2)$ ratios for $I = 16$ and 17 are, however, much smaller compared to those obtained by TAC calculations.

An explanation for the sharp reduction in $B(M1)/B(E2)$ values at $I = 16$ and 17 is of utmost importance to build a complete picture. Normally, this should be indicative of a band crossing at $I = 18$. For example, a similar situation is observed in ^{108}Cd [5], where the $B(M1)$ values are low near the band head and rise suddenly. The rise has been explained as arising due to $\nu h_{11/2}^2$ alignment—the band acquires a magnetic rotational character after the band crossing and the $B(M1)$ values show the characteristic decline with increasing angular momentum. Such a band crossing is invariably accompanied by a sudden change in energies (back-bending) and is seen in the case of ^{108}Cd.

The present case in ^{136}Ce, however, seems to differ from ^{108}Cd. The $B3$ band is nearly smooth except for a back bending observed at higher spins. Our calculation for the two proton $\pi g_{7/2} h_{11/2}$ configuration also fails to explain the low $B(M1)/B(E2)$ for $I = 16$ and 17. Further such a configuration does not generate enough angular momentum. A band crossing due to $\nu h_{11/2}^2$ alignment at $I = 17$ to 18 is, therefore, quite unlikely. Since ^{136}Ce is a γ soft nucleus, there is a strong possibility of a shape change with spin. We have searched for another possible minimum in energy for the $\pi g_{7/2} h_{11/2} \otimes \nu h_{11/2}^{-2}$ configuration. It is seen that another minimum does exist near $\epsilon_2 = 0.11$, $\gamma = 21°$. The TAC calculation for $\epsilon_2 = 0.11$, $\gamma = 21°$ indeed produces a band with stable tilt angle close to 82°. This band is very close to the band obtained for $\epsilon_2 = 0.11$, $\gamma = 52°$ at lower rotational frequencies. Since the tilt angle in this case is close to 82°, it almost corresponds to a principal axis cranking (PAC). This deformation leads to very low values for $B(M1)/B(E2)$ ratios ~ 0 to 0.2 $(\mu_N/e\mathrm{b})^2$ as shown in Fig. 2(a). It is, therefore proposed that the band $B3$ has $\gamma = 21°$ at lower spins and makes a transition to $\gamma = 52°$ near $I \sim 18$. But, the small $B(M1)/B(E2)$ ratios obtained for $\gamma = 21°$ require a mixing of triaxial and oblate shapes for reproducing the experimental values at lower spins. The present calculations, therefore, indicate that the sudden rise in $B(M1)$ and the transition from PAC to MR band, are the consequences of a γ-shape transition from the triaxial $\gamma = 21°$ to near oblate $\gamma = 52°$ shape. This is further confirmed by the change in the angular momentum coupling as revealed by the calculations. The composition of intrinsic angular momentum for the two minima (but same configuration) clearly reveals that the minimum at $\gamma = 21°$ supports a band which has both the neutrons and protons having large J_1 (both of the order of 8) and very small J_3 (of the order of 1). On the other hand, the minimum at $\gamma = 52°$ reveals the protons and the neutrons in near perpendicular coupling (shears mechanism); the protons have $J_1 = 6.86$, $J_3 = 5.1$ and neutrons have $J_1 = 2.3$, $J_3 = 9.9$ at a rotational frequency of 0.4 MeV. The shape change is responsible for this change in coupling. Further, the $B(M1)$ values go up at $\gamma = 52°$ because here the tilt angle is $\theta = 32°$ as compared to $\theta = 82°$ (a value close to 90 and, therefore, PAC) at $\gamma = 21°$. It is largely the protons that contribute to the $B(M1)$ values and J_3 is reasonably large for protons at $\gamma = 52°$

Although, there is a good agreement between the measured $B(M1)/B(E2)$ values and the predictions of TAC calculation for $I \geqslant 18$, it is desirable to check the predictions for $B(M1)$ and $B(E2)$ separately. Therefore, lifetimes of 18^- to 22^- states in the $B3$ band have been measured through the DSAM in the present work. Line shapes for transitions of interest were projected for clovers at $\theta = 30°$, 60°, 120°, 145° with respect to the beam axis. These spectra were gated with strong gamma rays below the transition of interest in all other clovers. The experimental line shapes were fitted with the LINESHAPE analysis code of Wells and Johnson [19] to extract lifetimes of 18^- to 22^- levels. This code was used to generate 5000 Monte Carlo simulations of the velocity history of nuclei recoiling in the target and the backing material. Electronic stopping power of Northcliffe and Schilling [20] corrected for shell effects were used for calculating the energy loss. The side feeding intensities were obtained from the intensity of the gamma rays feeding and deexciting each level. The experimental and theoretically simulated line shapes at forward 60° and backward 120° angles for 436 keV, 486 keV, and 525 keV transitions are shown in Fig. 3. The lifetimes of the 18^- to 22^- states obtained from the fits to the experimental line shapes and averaged over all the four angles mentioned above are listed in Table I. The $B(M1)$ and $B(E2)$ values obtained from the experimentally measured lifetimes and $M1/E2$ branching ratios for 18^- to 22^- levels are plotted along with the TAC calculations in Fig. 4.

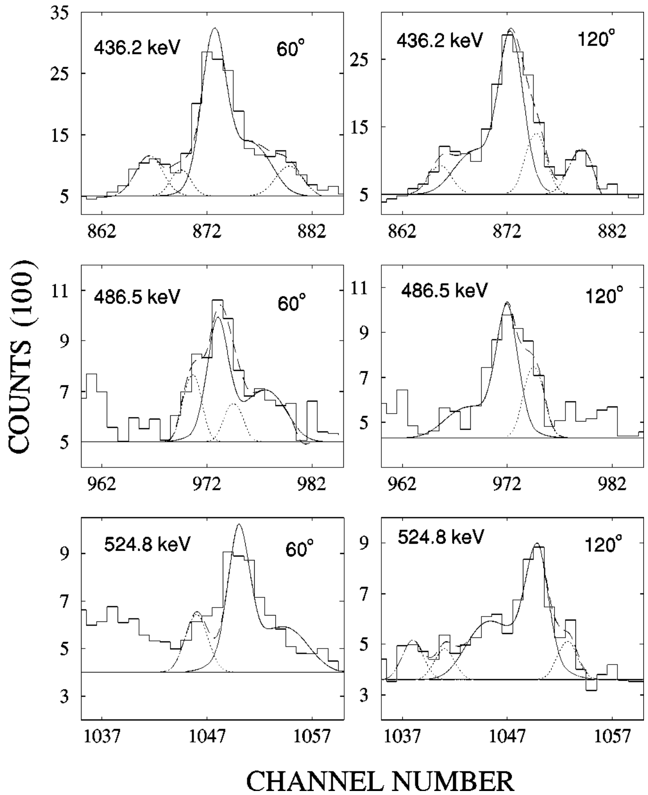

FIG. 3. Experimental and theoretical line shapes for the 436, 486, and 525 keV γ rays at the forward 60° and backward 120° angles with respect to the beam direction in the $B3$ band of ^{136}Ce. The contaminant peaks are shown in dotted lines and lineshapes for γ rays of interest are shown with solid lines.

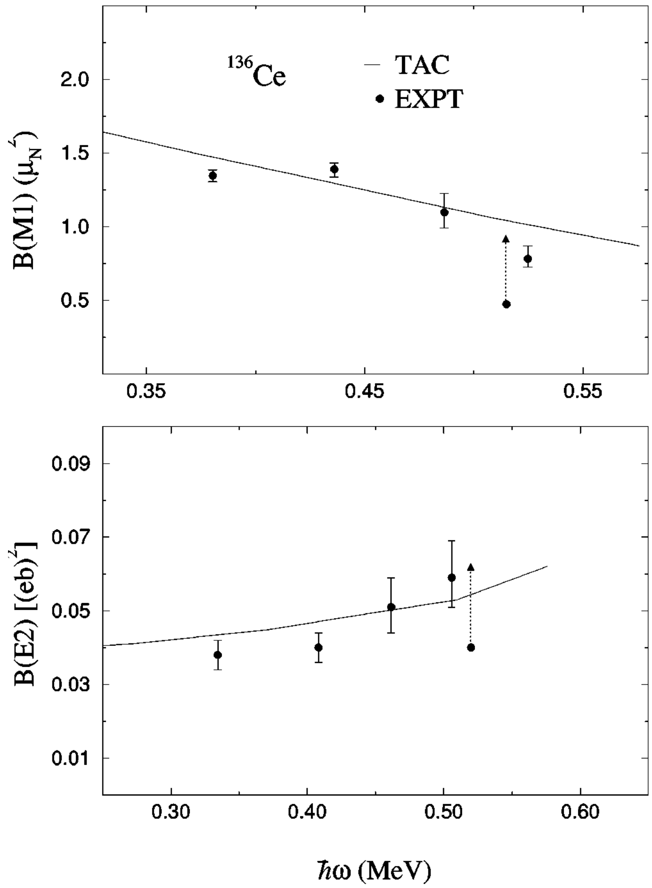

FIG. 4. $B(M1)$ and $B(E2)$ values vs $\hbar\omega$ for levels in the $B3$ band of ^{136}Ce. $\hbar\omega = E_\gamma(I\rightarrow I\text{-}1)$ for $M1$ transitions and $E_\gamma(I\rightarrow I\text{-}2)/2$ for $E2$ transitions.

It is seen that there is a good agreement between the experimental $B(M1)$ and $B(E2)$ values with those obtained from the TAC calculations. This further confirms the MR nature of the $B3$ band.

The results discussed above present the first clear evidence of "magnetic rotation" and oblate shape for $I \geqslant 18^-$ in the $B3$ band of ^{136}Ce. The small values of the measured $B(M1, I\rightarrow I\text{-}1)/B(E2, I\rightarrow I\text{-}2)$ ratios at the lower spins indicate a mixing of a triaxial shape with a near oblate shape. Also, a transition from a high-K band (PAC regime) to a magnetic rotational band (shears regime) has been witnessed; the transition is induced by a shape change. This is supported by a clear evidence of change in the angular momentum coupling. In conclusion, the present work provides the first observation of a transition from a normal principal axis rotation into a magnetic rotation band.

TABLE I. Lifetimes, $B(M1)$ and $B(E2)$ values for transitions deexciting 18^- to 22^- levels in ^{136}Ce. Errors on stopping power are not included.

E_γ (keV)	$I_i^\pi \rightarrow I_f^\pi$	τ (ps)[a]	$B(M1)$ (μ_N^2)	$B(E2)(eb)^2$
380.5	$18^- \rightarrow 17^-$	$0.734^{+0.021}_{-0.022}$	$1.346^{+0.040}_{-0.039}$	$0.038^{+0.004}_{-0.004}$
436.2	$19^- \rightarrow 18^-$	$0.454^{+0.017}_{-0.014}$	$1.391^{+0.043}_{-0.052}$	$0.040^{+0.004}_{-0.004}$
486.5	$20^- \rightarrow 19^-$	$0.379^{+0.037}_{-0.045}$	$1.097^{+0.130}_{-0.107}$	$0.051^{+0.008}_{-0.007}$
524.8	$21^- \rightarrow 20^-$	$0.365^{+0.026}_{-0.041}$	$0.782^{+0.088}_{-0.056}$	$0.059^{+0.010}_{-0.008}$
515.0	$22^- \rightarrow 21^-$	$0.577^{+0.041\text{b}}_{-0.061}$	$0.474^{+0.050}_{-0.034}$	$0.040^{+0.007}_{-0.006}$

[a]Lifetimes obtained from the weighted average of values at four angles $\theta = 30°$, 60°, 120°, and 145°.
[b]Effective lifetime.

The clover array was set up at T. I. F. R. Pelletron jointly by T. I. F. R., IUC- DAEF, Kolkata, S. I. N. P., Kolkata, and N. S. C., New Delhi. The authors would like to thank all participants of this joint national effort. Authors also would like to thank Dr. S. D. Paul, Dr. R. Palit, Dr. I. Mazumdar, and S. Nagaraj for their participation in data collection and the technical staff for smooth operation of the Pelletron. Financial support from the Department of Science and Technology (Government of India) at Roorkee, and Department of Atomic Energy (Government of India) at Amritsar is acknowledged. The partial support from the TIFR Endowment Fund, TIFR, Mumbai is acknowledged.

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