Electromagnetic Transition Rate Measurements in the $N=80$ Isotope, $^{138}$Ce

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Abstract. A study of intrinsic state halflife measurements in the $N=80$ nucleus $^{138}$Ce has been made using the $^{130}$Te($^{12}$C,4n)$^{138}$Ce fusion evaporation reaction at beam energy of 56 MeV. The fast-timing gamma-ray coincidence method was used with a mixed LaBr$_3$(Ce)-HPGe array to establish the lifetimes of the yrast $I^\pi=6^+$ state at 2294 keV, the $I^\pi=5^-$ state at 2218 keV, the $I^\pi=11^+$ state at 3943 keV and the $14^+$ state at that at 5312 keV, all of which are in the sub nanosecond regime. Reduced transition probabilities have been calculated for the electromagnetic decays from these states.

1. Introduction
The $^{138}$Ce nucleus lies near the $N=82$ shell closure and has 8 protons above the $Z=50$ closed proton shell. Excited states in $N=80$ nuclei present an interplay of single-particle and collective degrees of freedom. Even-Z $N=80$ isotones all exhibit yrast $I^\pi=10^+$ isomeric states from $^{130}$Sn to $^{148}$Er [1-7], based, predominantly on two-neutron-hole ($\nu h_{11/2}$)$^2$ configurations.

The current work was aimed at establishing decay halflives for states in the $N=80$ isotope $^{138}$Ce to compare with the expected shell model structures expected in this nucleus.
2. Experimental Setup and Data Analysis

The nuclei of interest were populated using the $^{130}$Te($^{12}$C, 4$n$)$^{138}$Ce fusion evaporation reaction at beam energy of 56 MeV. The beam was provided by the Tandem van de Graaff accelerator at the National Institute for Physics and Nuclear Engineering, Bucharest, Romania. An isotopically enriched $^{130}$Te target of thickness 1 mg/cm$^2$ with a 20 mg/cm$^2$ $^{208}$Pb backing to stop the recoiling nuclei was used. The experiment was performed over a continuous beam time of 2.5 days, with an average on-target beam current of approximately 10 pnA. The production cross section for the $^{130}$Te($^{12}$C, 4$n$)$^{138}$Ce reaction was estimated using the ENSDF 4 code [8] and found to be 650 mb. The experimental set-up comprised of eight hyper pure germanium detectors (HPGe) and eight LaBr$_3$(Ce) scintillators arranged in a similar configuration to that described in reference [9]. Three different sizes of LaBr$_3$(Ce) crystal were used in the present work, namely those having crystal dimensions of (a) (three) $2\times2$ cylindrical; (b) (three) $1.5''\times1.5''$ cylindrical and (c) (two) $1''\times1.5''$ conical. Energy and efficiency calibrations for the response of the detectors in the array were performed using standard $^{132}$Eu, $^{137}$Cs, $^{133}$Ba and $^{60}$Co sealed, point sources placed at the target position. During the experiment data were taken with the validated master trigger conditions of either (i) Ge-Ge-Ge or (ii) LaBr$_3$(Ce)-LaBr$_3$(Ce)-Ge gamma-ray energy coincidences. A total of $\sim2\times10^8$ LaBr$_3$(Ce) $\gamma$-$\gamma$ energy coincidences were recorded during the experiment for subsequent off-line analysis.

The data were sorted off-line into a range of gamma-ray energy and time difference coincidence matrices and cubes, which were then interrogated with different, gamma-ray energy conditions and analyzed with the GASPWARE [10] and RADWARE [11] packages. The total projection spectra of the $E_2-E_\gamma$ coincidences matrices from the $^{130}$Te+$^{12}$C fusion evaporation reaction are shown in figure 1 where (a) is the total projection from HPGe detectors and (b) is the total projection spectra from the combined LaBr$_3$(Ce) detectors. The most strongly populated nuclei in the experiment were $^{138}$Ce and $^{139}$Ce arising from the 4$n$ and 3$n$ evaporation channels respectively. The instrument time response for each LaBr$_3$(Ce) detector and constant fraction discriminator (CFD) combination in the mixed array required an off-line correction for the low-energy time walk. In order to achieve this, the method described by Marginean et al., in reference [9] was used.

Figure 2 shows the partial level scheme for $^{138}$Ce relevant to the present work and based on the previous study reported in reference [12]. The yrast $6^+$ state is predicted to be based on admixtures of $(\pi g_{7/2})^2$ and $(\nu h_{11/2})^{-2}$ configurations.

For the lifetime measurements, two different techniques were used: (i) the centroid shift method in cases where the lifetime of the nuclear state was significantly shorter than the time resolution (full width at half-maximum) for the LaBr$_3$(Ce) set-up and (ii) a single decay component fitted exponential decay (with a prompt response convolution) for longer (> 1ns) decays.

Figure 3 shows the lifetime measurements obtained by gating on feeding and deexciting transitions across levels of interest on the sorted $E_{\gamma 1}-E_{\gamma 2}-\Delta T$ cubes. Additional gating conditions such as using transitions observed in the HPGe to select cascades below or above the $10^+$ isomer in $^{138}$Ce were also employed in order to obtain cleaner LaBr$_3$(Ce) coincident spectra. Figure 4 shows examples of time difference spectra which give “prompts” the time resolution of LaBr$_3$(Ce) detector: (a) 789-1038-keV with FWHM=460(9) ps (b) 390-1038-keV with FWHM=550(11) ps (c) 467-1038-keV with FWHM=540(10) ps (d) 430-980-keV with FWHM=510(10) ps.

3. Discussion and Results

The nucleus $^{138}$Ce has eight valence protons outside the closed shell $Z=50$ and two neutron holes with respect to $N=82$ [7]. Electromagnetic decays from the yrast $6^+$ state in $^{138}$Ce are predicted to be based on transitions between states built mainly from admixtures of $(\pi g_{7/2})^2$.
Figure 1. Total projection from the \( ^{130}\text{Te}(_{12}^{12}\text{C},4n)^{138}\text{Ce} \) fusion evaporation reaction at beam energy of 56 keV. Total projection spectrum measured using the (a) HPGe and (b) LaBr\(_3\)(Ce) detectors, respectively.

Figure 2. Partial level scheme of \(^{138}\text{Ce} \) relevant to the present work, taken from reference [12].

and \((\nu h_{11/2})^{-2}\) shell model configurations. Table 1 summarises the experimental state decay halflives obtained from the present work in \(^{138}\text{Ce} \). These are discussed individually below:

3.1. The \(6^+\) state
The 2294 keV level was identified in \(^{136}\text{Ba}(\alpha,4n\gamma) \) studies [13, 14] and has a well established spin/parity of \( I^\pi = 6^+ \) [15]. The state deexcites to \( I^\pi = 5^- \) state via a near pure \( E1 \) transition with an energy of 77-keV. It also decays directly to the yrast \( I^\pi = 7^- \) state via another near-pure \( E1 \) with a transition energy of 165-keV. A third decay branch from the yrast \( 6^+ \) state is observed via a 467-keV \( E2 \) transition to the yrast \( I^\pi = 4^+ \) state in \(^{138}\text{Ce} \). Figure 3 shows (a) the fitted exponential decay of the yrast \( 6^+ \) state in \(^{138}\text{Ce} \), resulting from the time differences observed between pairs of LaBr\(_3\)(Ce) detectors by gating on the gamma-ray energies of 815- and 165-keV. This time-difference spectrum was fitted with an exponential decay convoluted with a Gaussian time resolution and gives a value of the halflife of the \( I^\pi = 6^+ \) state of \( t_{1/2} = 866(15) \) ps. Figure 3 (b) shows the measured halflife of the \( 6^+ \) state to be \( t_{1/2} = 860(50) \) ps, obtained by gating on the gamma-ray energies of 815- and 467-keV gamma-ray pair.

3.2. The \(5^-\) state
Figure 3 (c) shows the time spectra associated with the decay of the yrast \( 5^- \) state in \(^{138}\text{Ce} \). An extracted experimental halflife of \( t_{1/2} = 450(14) \) ps was obtained from the centroid shift of the time difference spectra gated on \( 77^- \) and 390-keV transitions in the LaBr\(_3\)(Ce) detectors.
3.3. The $11^+$ state
A gamma-ray energy of 403 keV depopulates the yrast $11^+$ state, which has a previously reported decay half-life limit of $t_{1/2} \leq 1.5$ ns [16]. Figure 3 (d) shows the measured half-life of the $11^+$ state extracted in the current work with a value of $t_{1/2} = 107(4)$ ps obtained from the centroid shift of the time distribution associated with the 418- and 403-keV coincident transitions.

3.4. The $14^+$ state
Figure 3 (e) shows the lifetime associated with the decay of the yrast $14^+$ state. A measured half-life of $t_{1/2} = 66(3)$ ps was obtained using the centroid shift for the two difference distributions gated on the 254- and 338-keV transitions.

### Table 1. Measured transition rates from excited states in $^{138}$Ce.

| $E_{Level}$ (keV) | $J_i^\pi$ | $\rightarrow$ | $J_f^\pi$ | $E_\gamma$ (keV) | $t_{1/2}$ (ps) | $L\lambda$ | B.R. (%) | $B(\lambda L)$ (W.u.) |
|------------------|-----------|---------------|-----------|-----------------|-------------|-----------|----------|-------------------|
| 2294             | $6^+$     | $\rightarrow$ | $4^+$     | 467             | 860(50)     | $E2^+$   | 15       | 0.104 (11)        |
| 2294             | $6^+$     | $\rightarrow$ | $7^-$     | 165             | 866(15)     | $E1^*$   | 53       | $3.4(4) \times 10^{-5}$ |
| 2294             | $6^+$     | $\rightarrow$ | $5^-$     | 77              | 845(33)     | $E1^*$   | 25.6     | 0.00015 (4)       |
| 2218             | $5^-$     | $\rightarrow$ | $4^+$     | 390             | 450(14)     | $E1^*$   | 78.9     | 7.5(7) \times 10^{-6} |
| 3943             | $11^+$    | $\rightarrow$ | $10^+$    | 403             | 107(4)      | $M1^*$   | 93.8     | 0.00310 (9)       |
| 5312             | $14^+$    | $\rightarrow$ | $13^+$    | 338             | 66(3)       | $M1^\parallel$ | 25.7     | 0.0022 (13)       |

* Taken from [17].

§ Taken from [18].

**Figure 3.** Time spectra obtained in $^{138}$Ce from LaBr$_3$(Ce) $E_{\gamma 1}-E_{\gamma 2}-\Delta T$ cube with HPGe gate showing the time difference between; (a) 815- and 165-keV (b) 815- and 467-keV (c) 77- and 390-keV (d) 418- and 403-keV (e) 254- and 338-keV. The continuous lines in panels (a) and (b) are Gaussian exponential convolution fits to the spectra.
4. Conclusions
In the present work excited states in $^{138}$Ce has been populated through fusion evaporation reactions. Lifetime measurements of excited states in $^{138}$Ce have been made using the fast gamma-ray coincidence timing method with LaBr$_3$(Ce) scintillation detectors. Halflives of the yrast $6^+$, $5^-$, $11^+$ and $14^+$ states have been determined for the first time. Reduced transition probabilities have been calculated for the electromagnetic decays from these states.

5. Acknowledgements
We would like to thank the staff of the Horia Hulubei National Institute of Physics and Nuclear Engineering (IFIN-HH), R-76900 Bucharest, Romania for their excellent technical support during this experiment. This work is supported by the Science and Technology Facilities Council STFC (UK), Almajmaah University (Saudi Arabia), the DMU02/1 contact with the Bulgarian Science Fund, the Bulgarian-Romanian partnership contract number BRS-07/23 and No 460/PNII Module III, U.S. DOE under grant no. DE-FG02-91ER40609 and FPA2008-06419-C02-01. SR and RB acknowledge support from the Engineering and Physical Science Research Council (UK).

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