Lifetimes in the decay of ^{40}Ca and ^{47}V studied by crystal blocking

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The lifetimes in the decay of compound nuclei formed in the fusion reactions $^{12}C + ^{28}Si \rightarrow ^{40}Ca$ and $^{19}F + ^{28}Si \rightarrow ^{47}V$ are measured to be (5–10)$\times 10^{-18}$ s using the blocking of evaporation residues in a Si ⟨100⟩ single crystal. Similar measurements using low-energy α particles evaporated in the decay of ^{40}Ca yield lifetimes in the same range. However, the shape of the blocking pattern for the high-energy α particles in the same decay is similar to that for the elastically scattered particles indicating a lifetime shorter than 10^{-18} s. These results, along with our earlier measurements in ^{44}Ti and those reported by others, show that the lifetimes for the later stages of the compound nuclear decay are nearly the same for nuclei in the mass range 40–160 and are relatively insensitive to the initial excitation energy.

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I. INTRODUCTION

The charged particle crystal blocking technique has been used in the past to measure compound nuclear and fission lifetimes in the range 10^{-19}–10^{-16} s [1]. This method, of late, has been applied to measure the lifetimes in heavy ion induced fusion reactions which give rise to evaporation residues [2, 3]. We have recently made such measurements in the reaction $^{16}O + ^{28}Si$ at excitation energies of 55.8 and 64.8 MeV [4] and found that the lifetimes thus measured do not show a strong dependence on the excitation energy and the angular momentum of the compound nucleus formed. In the present paper, we further extend these studies to the investigation of the time scales in the emission of the decay products in reaction $^{12}C+^{28}Si \rightarrow ^{40}Ca$ in the excitation energy range of 45–75 MeV and $^{19}F+^{28}Si \rightarrow ^{47}V$ in the 55–72 MeV range. Apart from the measurements using the evaporation residues (ER), lifetime information can be also obtained from the evaporated light particles like protons and α particles. With this intention, we have studied in the present work the blocking patterns of α particles emitted in the decay of ^{40}Ca. The results show that the lifetimes obtained from the lower-energy α particles are similar to those observed from the ERs, while the higher-energy ones yield a much smaller value. An attempt is made to understand these results in terms of the statistical model of compound nuclear decay. We have also compared our results with the recently reported lifetimes in other systems obtained using the crystal blocking method, particle-particle correlation method [5] and the atomic clock method [6].

II. EXPERIMENTAL DETAILS

The charged particle blocking measurements have been carried out using ^{12}C (E_{inc} =45, 54, 66, and 84 MeV) and ^{19}F (E_{inc}=60, 88 MeV) beams from the 14 UD BARC-TIFR pelletron accelerator at Bombay. A Si ⟨100⟩ single crystal of 0.8 μm thickness was mounted on a double-axis goniometer kept in a clean vacuum of better than 1×10^{-6} Torr. The ERs were detected in a 2-D position sensitive semiconductor detector (active area 24 $\times$ 24 mm^2) placed at a forward angle of 20° at a distance of 56 cm from the target. In order to record the blocking patterns of α particles the detector was mounted at 35° to the beam. The central 10 $\times$ 10 mm^2 portion of the detector, which shows a good linearity, is used for constructing the blocking dips [4, 7]. In this linear region the position resolution is better than 1 mm, corresponding to an angular resolution better than 0.1°. The time of flight (T) discrimination method in conjunction with charged particle blocking was employed for separating the reaction products. The preparation of thin Si single crystal target and the experimental setup are described in detail in Refs. [7, 8]. A typical E vs T spectrum for carbon beam of 84 MeV energy is shown in Fig. 1. The elastically scattered carbon ions, α particles, and residues can be seen as separate islands.

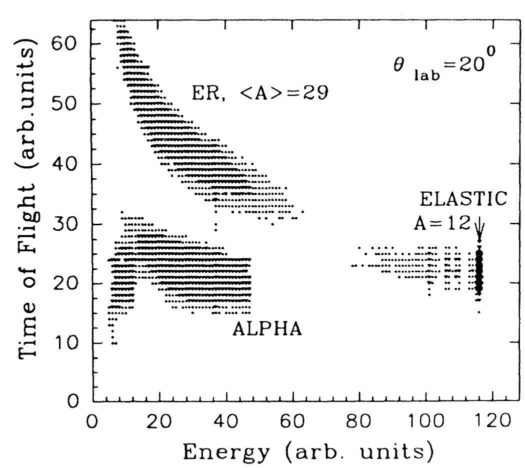

FIG. 1. A typical E vs T spectrum for $^{12}C+^{28}Si$ at E_{inc} = 84 MeV, where α particles, evaporation residues, and elastically scattered particles are seen as separate groups.

III. RESULTS AND DISCUSSION

The average mass $\langle A\rangle$ for the evaporation residue group is obtained from the E vs T spectrum. It is reasonable to assume the $\langle Z\rangle$ to be $\langle A\rangle/2$ in this mass range. The statistical model code CASCADE [9] is also used for estimating the average masses of the residues and are found to be consistent with the experimental values.

The blocking dips for different particle groups, selected by putting appropriate gates in the E-T spectrum, are constructed by circular integration around the dip minimum. The volume of blocking dip (Ω) thus obtained are scaled by $\langle E\rangle / \langle Z\rangle$ in order to get the lifetimes [3], where the average energy $\langle E^{-1}\rangle^{-1}$ is calculated from the energy spectrum of the products. In [7] we have shown that this scaling is valid over a wide range of E/Z for a variety of projectiles. We have also shown that, under similar conditions of present measurements, the multiple scattering effects are not significant even for ERs [4]. In Figs. 2(a), 2(b) the scaled blocking dips for elastically scattered particles (open circles) and evaporation residues (solid circles) obtained in the decay of ^{40}Ca at $E_{\rm inc}$ = 54 and 84 MeV respectively are shown. Similarly Fig. 3 shows the blocking dip for ERs in the decay of ^{47}V at 88 MeV incident energy. The "filling-in of the dip" indicates the presence of longer-lived components in the decaying compound nucleus. The lifetimes are calculated in a manner similar to that described in [4] using both the scaled volume and the minimum yield ($\chi_{\rm min}$) of the blocking dips. The values thus obtained from ERs are tabulated in Table I. It can be seen from this table that in ^{40}Ca and ^{47}V the measured lifetimes are not very sensitive to initial excitation energy (E^*) of the compound nucleus in the range 45–75 MeV. These values are also similar to those obtained for the decay of ^{44}Ti [3, 4] and ^{56}Ni [10].

The lifetimes in the decay of the compound nuclei can be also obtained by studying the blocking dips of the evaporated protons or α particles. Further, by comparing the observed energy spectra of these particles with the predictions of CASCADE, it is possible to separate them as coming from the early or later stages of the compound nuclear decay. Therefore, the blocking patterns of α particles were recorded in the case of decay of ^{40}Ca together with that for the evaporation residues. The relatively larger angle of detection ($\theta_{\rm lab}$ = 35°) of the α particles ensured that most of the alphas were coming from the evaporation of the compound nucleus. In Fig. 4 the energy spectrum of the α particles is shown for $E_{\rm inc}$=66 MeV. The broad spectrum was divided into two energy bins, namely 8–22 MeV and beyond 22 MeV. This energy of 22 MeV is close to the peak energy predicted by CASCADE for α decay from ^{40}Ca at $E_{\rm inc}$= 66 MeV and 84 MeV. However, for 45 MeV incident energy the lower bin was taken to be 8–15 MeV. The blocking patterns were constructed for these two regions separately and are plotted in Fig. 5. Finite lifetime effect in the blocking dip for lower-energy α particles at 66 MeV incident energy is clearly seen in Fig. 5(a). The dip for the high-energy α particles shown in Fig. 5(b) is nearly identical to the "prompt dip" indicating $\tau \leq 10^{-18}$ s. This implies that there are two different time scales involved in the evaporation of α particles. The lifetimes obtained from the blocking patterns of the α particles are tabulated in Table II. The lower-energy α particles yield a lifetime value $\sim 4\times 10^{-18}$ s, which is closer to that obtained from the ERs. Although these lifetimes are somewhat smaller than the corresponding values for the residues, they also show a similar weak dependence on the initial excitation energy. This suggests that these lower-energy α particles are predominantly coming from the later decay stages. The blocking patterns for the high-energy α particles are identical to that of elastic scattering process (prompt) indicating that $\tau < 10^{-18}$ s. As mentioned before, the contribution to high-energy α particles from direct reaction at this laboratory angle is expected to be negligible. Therefore it appears that the higher-energy α particles are emitted from the earlier decay stages which are short

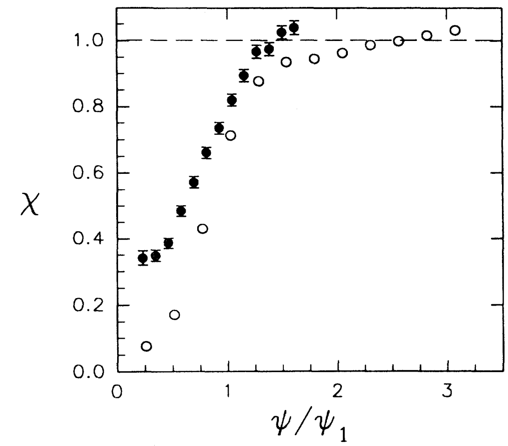

FIG. 3. Same as Fig. 2 for decay of ^{47}V at $E_{\rm inc}$ =84 MeV ($E_{\rm elastic}$=55.2 MeV, ψ_1=3.48 mrad).

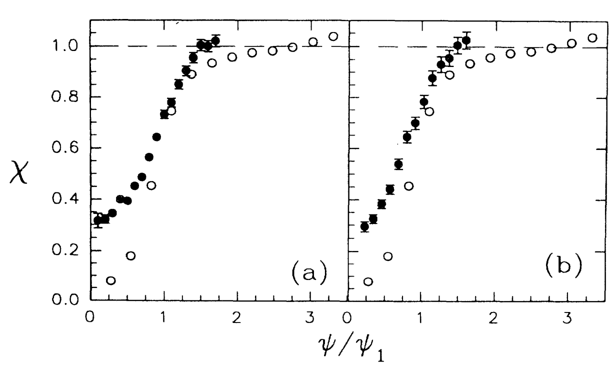

FIG. 2. Normalized blocking yield $\chi(\psi)$ as a function of scaled angle variable (ψ/ψ_1) for evaporation residues (filled circles) in the decay of ^{40}Ca (a) at $E_{\rm inc}$=54 MeV and (b) $E_{\rm inc}$ = 84 MeV. The blocking dip of the elastically scattered particles (open circles) is plotted for the reference ($E_{\rm elastic}$=42.3 MeV and Lindhard's critical angle ψ_1=3.25 mrad).

TABLE I. The compound nuclear lifetimes τ in units of 10^{-18} s, as measured from the blocking pattern of evaporation residues. The reduced volume for the elastic scattering is used as a reference and $\chi_{\rm min}^{\rm ref} = 7(1)\%$. $\Delta\chi$ is defined as $(\chi_{\rm min} - \chi_{\rm min}^{\rm ref})$. The last column $\tau_{\rm esti}$ (10^{-18} s) gives estimated values of lifetime using CASCADE.

CN	E^* (MeV)	$\langle Z \rangle$	$\langle \frac{1}{E} \rangle^{-1}$ (MeV)	ψ_1 (mrad)	R	τ	$\Delta\chi(\%)$	τ	$\tau_{\rm esti}$
^{40}Ca	44.9	15	11.8	9.7	0.50(.06)	$9.0^{+2.8}_{-1.6}$	17.0(1.7)	7.2(0.7)	0.18
	51.2	15	13.8	9.0	0.44(.05)	$13.5^{+2.2}_{-2.2}$	24.7(2.8)	10.5(1.0)	0.19
	59.6	15	15.9	8.4	0.56(.07)	$6.3^{+1.6}_{-1.5}$	27.6(2.7)	7.6(1.2)	0.18
	72.2	14	17.3	7.8	0.55(.06)	$5.7^{+1.4}_{-1.2}$	25.1(2.0)	6.4(1.0)	0.15
^{47}V	54.8	18	14.7	9.5	0.49(.05)	$7.8^{+1.6}_{-1.3}$	13.0(2)	5.0(1.0)	0.19
	71.4	18	22.3	7.7	0.50(.04)	$6.0^{+1.2}_{-0.7}$	28.0(5)	6.2(1.0)	0.17

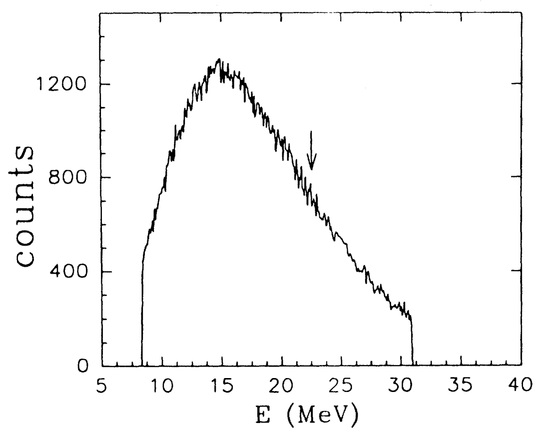

FIG. 4. Energy spectrum of α particles in the reaction ^{12}C+^{28}Si at $E_{\rm inc} = 66$ MeV. The arrow at 22 MeV indicates the position at which the spectrum is devided into low- and high-energy parts (see text).

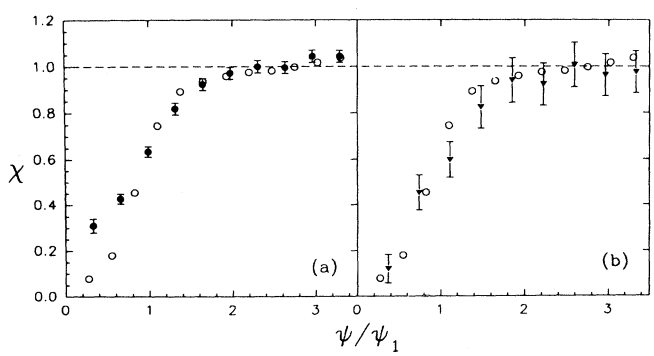

FIG. 5. Normalized blocking yield $\chi(\psi)$ as a function of scaled angle variable (ψ/ψ_1) for α particles (a) $8 < E_\alpha < 22$ MeV (filled circles) and (b) $E_\alpha > 22$ MeV (filled traingles), in the ^{12}C+^{28}Si reaction at $E_{\rm inc} = 66$ MeV. The dip for elastically scattered carbon ions (open circles) is plotted for reference ($E_{\rm elastic} = 42.3$ MeV, $\psi_1 = 3.25$ mrad).

lived. It should be mentioned here that the α particle yield in the high-energy region is very low, which gives rise to large statistical errors. In this case because of the poor statistics in the number of observed events, only dip volume is used to get τ.

The observed lifetimes are compared with the estimates made using the statistical theory as in Ref. [4]. Following Ref. [11] the lifetime of compound nucleus can be expressed as

$$\tau \sim h\frac{\rho_c(E^*, J)}{N(E^*, J)}, \tag{1}$$

where ρ_c is the level density of the compound nucleus at the excitation energy E^* and the angular momentum J, and N is the total number of decay channels to which the compound nucleus can decay. In this expression the transmission coefficients are assumed to be unity. The most probable evaporation channels considered in the present case were ^{40}Ca decaying to residue ^{31}P (at all energies studied), and ^{47}V decaying respectively to ^{38}Ar and ^{37}Ar for 60 and 88 MeV incident energies. Lifetimes have been estimated using the most probable E^* and J at various stages of evaporation of the compound nucleus as predicted by CASCADE. The fission competition is not included in the present calculation. The level density $\rho(E^*, J)$ was calculated from the relation [12]

$$\rho(E^*, J) = \frac{2J+1}{12}\sqrt{a}\left(\frac{\hbar^2}{2I}\right)^{3/2}\frac{\exp\left[2\sqrt{aE^*}\right]}{(E^*+t)^2} \times\exp\left[\frac{-[J(J+1)]}{2\sigma^2}\right]. \tag{2}$$

The level density parameter a was taken to be $A/8$. Using these relations, the earlier stages of the evaporation are found to give very short lifetimes in the range $\tau \leq 10^{-21}$ s, which will not produce any observable change in the blocking pattern. The lifetime has to be greater than $\sim 10^{-18}$ s, at the recoil velocities involved in the present measurements, for observing any perceptible modifica-

TABLE II. The lifetimes in the decay of ^{40}Ca obtained from the blocking patterns of the α particles of energy E_α. All other notations are same as in Table I.

E^* (MeV)	E_α (MeV)	$\langle \frac{1}{E} \rangle^{-1}$ (MeV)	R	τ (10^{-18} s)	$\Delta\chi(\%)$	τ (10^{-18} s)
44.9	8-15	11.8	0.56(0.06)	$4.3^{+1.1}_{-0.64}$	22.6(6)	5(1.3)
59.6	8-22	14.7	0.62(0.08)	$3.0^{+0.53}_{-0.5}$	28.0(5)	4.6(1)
72.2	8-22	15	0.61(0.08)	$2.8^{+0.75}_{-0.6}$	32.0(6)	4.3(1)
59.6	22-31	25.6	1.3 (.25)	$\leq 10^{-18}$ s	–	–
72.2	22-31	25.9	1.5 (0.4)	$\leq 10^{-18}$ s	–	–

tion of the blocking dip. This indicates that we are essentially measuring the lifetime for the later stages of the evaporation chain. We have estimated the total level width (and hence the lifetime τ_{esti}) for the last decay step taking the p, n, and α decay channels, which are listed in the last column of Table I. It can be seen that these estimates reproduce the experimentally observed trend in the lifetime as a function of initial excitation energy of the compound nucleus. We may mention here that these approximate calculations do not reproduce the observed lifetime values of $\sim 8 \times 10^{-18}$ s. As mentioned before, the τ_{esti} values listed in Table I are calculated taking the transmission coefficient $T_l \sim 1$. This is a reasonable assumption for earlier decay stages where the energy carried away by emitted particles is high compared to the separation energy. However, as the excitation energy decreases, $T_l(E)$ can become considerably smaller than unity. For example, the transmission coefficient for α particle in the decay of ^{47}V, T_α (E = 15 MeV, $l = 8\hbar$)=0.96 [13] whereas for later decay stages namely, for $^{42}\text{Ca}\rightarrow^{38}\text{Ar}$, T_α (E = 7 MeV, $l = 5\hbar$)= 0.23. The value of τ_{esti} will increase as T_l decreases. However, more rigorous calculations incorporating the appropriate transmission coefficients and the known levels at the lower excitation energies (similar to the ones given in Refs. [2, 14]) are required to make comparisons with the absolute lifetime values and to get the corresponding level density parameters.

It is seen from the data in Refs. 3, 4, and 10 and the present one that for different systems in the mass range A = 40–56 lifetimes are in the range 4–10 $\times 10^{-18}$ s. In Table III most of the available values on the nuclear lifetimes in heavy ion induced reactions are shown for comparison. With the atomic clock method [6] (where x rays from the decay products are detected) and the particle-particle correlation method [5], it is possible to estimate the lifetimes for different stages in the evaporation chain. It can be seen from the table that the lifetimes for the later stages of decay are of the order of $\sim 10^{-17}$ s for nuclei over a wide mass range A = 40–160 for similar excitation energies. Further, it is seen that the lifetimes measured using the blocking method in the

TABLE III. A summary of existing data on compound nuclear lifetimes.

Reaction	E^* (MeV)	Measurement technique	τ (10^{-18} s)	Ref.
$^{16}\text{O}+^{12}\text{C}\rightarrow^{28}\text{Si}$	66.5	Crystal blocking	2.8	2
$^{12}\text{C}+^{28}\text{Si}\rightarrow^{40}\text{Ca}$	45–75	Crystal blocking	6–9	a
$^{16}\text{O}+^{28}\text{Si}\rightarrow^{44}\text{Ti}$	55–65	Crystal blocking	6–8	4
$^{16}\text{O}+^{28}\text{Si}\rightarrow^{44}\text{Ti}$	75	Crystal blocking	12^{+4}_{-2}	3
$^{16}\text{O}+^{27}\text{Al}\rightarrow^{43}\text{Sc}$	102	particle-particle[b] correlation	3–16	5
$^{19}\text{F}+^{28}\text{Si}\rightarrow^{47}\text{V}$	55–71	Crystal blocking	6–8	a
$^{28}\text{Si}+^{28}\text{Si}\rightarrow^{56}\text{Ni}$	85	Crystal blocking	8.2±0.9	10
$^{16}\text{O}+\text{Ge}\rightarrow\text{Zr}$	100	Crystal blocking	11	15
$^{60}\text{Ni}+^{100}\text{Mo}\rightarrow^{160}\text{Yb}$	59	Atomic clock[c]	6	6

[a]Present work.

[b]The lifetime values quoted are from the model calculations with $a = A/8$ for the later stages of the decay.

[c] The lifetime for the last chance α emission, i.e., for Yb→Er.

decay of ^{44}Ti, ^{47}V, and ^{40}Ca are not very sensitive to changes in the initial excitation energy of the compound nucleus in the range investigated in the present work. It is expected that, at the initial stages of compound nuclear decay, the lifetimes are in the range 10^{-22}–10^{-20} s depending on the available excitation energy and angular momentum. This is also indicated in the model calculations of Ref. [5]. However, due to the limitations in the sensitivity of the blocking method it is not possible to observe these lifetimes in the present studies.

IV. CONCLUSION

We have measured the lifetimes in the decay of ^{40}Ca and ^{47}V at initial excitation energies of 45–75 MeV and 55–72 MeV respectively from changes in the blocking dip for evaporation residues and are found to be of the order of 10^{-17} s over the excitation energy range 45–75 MeV. Further, the low-energy α particles emitted in the compound nuclear decay indicate similar lifetimes and dependence on initial excitation energy. This weak dependence on the excitation energy suggests that the lifetimes measured in the present experiment are due to the decay of the later stages of the evaporation chain. The higher-energy α particles show lifetimes shorter than 10^{-18} s, indicating that they are most probably emitted in the early stages of the decay of the compound nucleus.

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