Nuclear decay times of evaporation residues of ^{44}Ti by crystal blocking method

Vandana Nanal, M. B. Kurup, and K. G. Prasad
Tata Institute of Fundamental Research, Bombay 400 005, India
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We have measured the lifetime for evaporation residues in the decay of ^{44}Ti at initial excitation energies of 55.8 and 64.8 MeV from changes in the blocking dip. The lifetime information was obtained from both minimum yield and dip volume and they give consistent results. The lifetime for evaporation residues is found to be $\sim (6-8) \times 10^{-18}$ s and shows a very weak dependence on initial excitation energy.

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I. INTRODUCTION

The phenomenon of blocking in light ion induced reactions in single crystals has been used in the past to measure the compound nuclear lifetimes. Recently the application of this technique has been extended to measure lifetimes in heavy ion induced reactions [1,2]. Using this technique it may be possible to study the time evolution in such heavy ion induced fusion reactions, which can provide a test for the statistical model of decay of compound nucleus. In Refs. [1,2] the compound nuclear lifetime values for low mass nuclei (^{16}O $+^{12}$C and ^{16}O $+^{28}$Si, respectively) at high excitation energies have been reported. In order to investigate the dependence of lifetime on the excitation energy of the compound nucleus, we have measured the lifetime in the reaction ^{16}O $+^{28}$Si at excitation energies of 55.8 and 64.8 MeV using the blocking method. In the present measurements we have used, for the first time, the "time of flight" discrimination technique in conjunction with blocking to separate the light particles emitted from the compound nucleus and the evaporation residues. The lifetime information is obtained from the changes in the blocking patterns of the evaporation residues. Malaguti *et al.* [2] have measured the lifetime in the ^{16}O $+^{28}$Si reaction at 100 MeV incident energy from the change in the scaled blocking dip volume. We have shown recently [3] that both the dip volume and the minimum yield can be used for getting lifetimes from the observed blocking dips using appropriate scaling. In the present studies both the above mentioned parameters are used to obtain the lifetime information and are seen to yield consistent results.

II. EXPERIMENTAL DETAILS

Heavy ion blocking measurements have been carried out using an ^{16}O ($E_{\rm inc}$ =70, 84 MeV) beam from the 14 UD BARC-TIFR pelletron accelerator at Bombay. The divergence of the incident beam was restricted to less than 1 mrad using a collimation system consisting of two adjustable apertures separated by a distance of 1 m. A 1.5 μm $\langle 100 \rangle$ natural Si single crystal target was mounted on a double axis goniometer kept in high vacuum (better than 1×10^{-6} torr). The pumping was done using a cryopump to obtain a clean vacuum, thereby minimizing the surface contamination of the target crystal during data collection as long exposure to the beam was necessary. A two-dimensional (2D) position sensitive semiconductor detector (active area 24×24 mm^2) was placed at a forward angle of 20° at a distance of 56 cm from the target to detect the emitted charged particles and evaporation residues. The detector gives both X and Y position information along with the total energy (E) of these particles. Even though the peripheral region of the detector shows pin-cushion distortion, the central 10×10 mm^2 portion of the detector shows good linearity and gives position resolution better than 1 mm [3]. This central region of the detector has been used for the present studies. The corresponding angular resolution of the detector is of the order of 0.1°. The details of the preparation of the thin Si single crystal target and the experimental setup are described in [3,4]. We have used the time of flight (T) discrimination method in conjunction with charged particle blocking using a pulsed beam for separating the reaction products. The fast pulse from the position sensitive detector was used as the start pulse for the time-to-amplitude converter (TAC) and the stop pulse was derived from a double drift rf buncher. The data (XE, YE, E, and T) were recorded in list mode on an event by event basis. X and Y positions were later generated using a computer program. The beam current used was less than 1 electrical nA to minimize any crystal damage. The $\langle 100 \rangle$ axis of the crystal was aligned with respect to the detector normal by monitoring the blocking pattern of elastically scattered oxygen ions. Figure 1 shows a $\langle 100 \rangle$ blocking pattern of the thin silicon crystal obtained with the 2D detector. The $\langle 100 \rangle$ axis is clearly seen as the intersection of various crystal planes. The quality of the crystal was monitored during the experiment by observing the blocking pattern for the elastic scattering of the oxygen ions.

A separate experiment was carried out using an E-ΔE telescope for the same target-projectile combination to identify the atomic number (Z) of the reaction products. A 12 μm silicon surface barrier detector was used as the ΔE detector and the position sensitive detector acted as the E detector. The E-ΔE telescope was kept at a 20° laboratory angle which is close to the grazing angle (namely, $\theta_{\rm gr}$ = 19° for 70 MeV and 15.2° for 84 MeV).

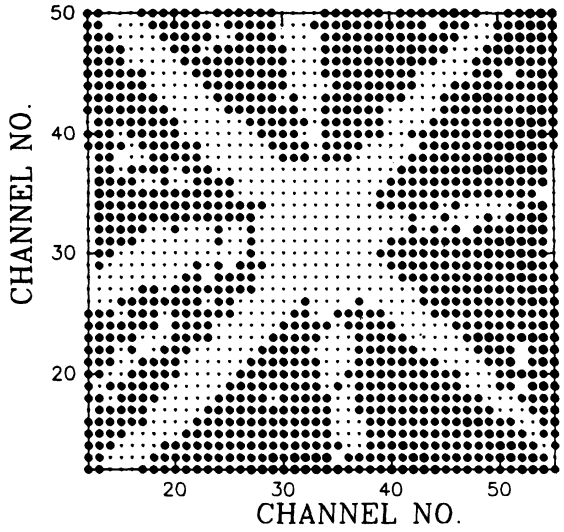

FIG. 1. A ⟨100⟩ blocking pattern obtained with a 2D position sensitive detector for elastically scattered ^{16}O of 33.6 MeV. Various crystal planes and the axis are clearly visible. The pattern shown is in the linear region of the detector and corresponds to an angular coverage of ~27 mrad in either direction.

III. DATA ANALYSIS AND RESULTS

A. *E-T* spectrum

A typical E-T spectrum is shown in Fig. 2. Different mass groups, that is, elastically scattered particles, reaction products, alpha particles, and evaporation residues, are identified.

The average mass $\langle A \rangle$ for the evaporation residue group is obtained from the E vs T spectrum and is found to be 34(±2) for both incident energies. The $\langle Z \rangle$ is assumed to be $\frac{\langle A \rangle}{2}$. The average value of $\left\langle \frac{1}{E} \right\rangle^{-1}$ is calculated from the energy spectrum of the products. This $\left\langle \frac{Z}{E} \right\rangle$ is then used to calculate the scaled dip volume. We have also used the statistical model code CASCADE [5] for calculating the average masses of the residues, which are found to be consistent with the experimental values.

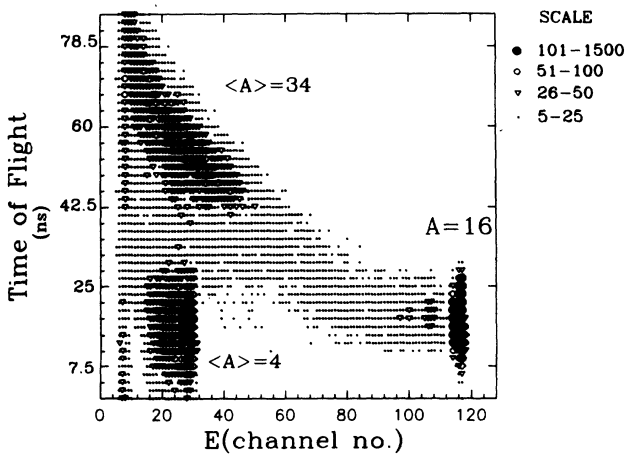

FIG. 2. A typical E vs T spectrum for E_{inc} = 84 MeV, where alpha particles, evaporation residues, and elastically scattered particles are seen as separate groups.

B. *E*-Δ*E* spectrum

In Fig. 2, it can be seen that the inelastically scattered particles in the intermediate range, i.e., products with energies higher than the residue group, have contributions from various Z, A fragments which are not resolved in the E vs T spectrum. The distribution in Z for these reaction products were estimated from E-ΔE spectra. A typical spectrum of the products for E_{inc} = 84 MeV is shown in Fig. 3 where the separate bands for α, carbon (Z=6), nitrogen (Z=7), etc., are clearly seen. The average value of Z was determined from this spectrum for the scaling of the blocking dip. For inelastically scattered particles blocking patterns were constructed from the E-T spectrum for the energy range 46–55 MeV and 60–68 MeV for 70 MeV and 84 MeV incident energies, respectively. In this energy range the contribution from $Z \geq 11$ fragments arising from the fissionlike process was negligible. The average value of $\langle Z \rangle$ was found to be 7.25 for 70 MeV and 7.4 for 84 MeV. The evaporation residues were stopped in the 12 μm ΔE detector.

C. Blocking dips

The blocking dips are constructed for different particle groups separately by circular integration around the dip minimum. These particle groups were selected by putting appropriate gates in the E-T spectrum. From the blocking dips thus obtained, the dip volumes (Ω) are determined. These dip volumes are scaled by E/Z in order to get the lifetime [2]. In Ref. [3] we have shown that scaling is valid over a wide range of E/Z for a variety of projec-

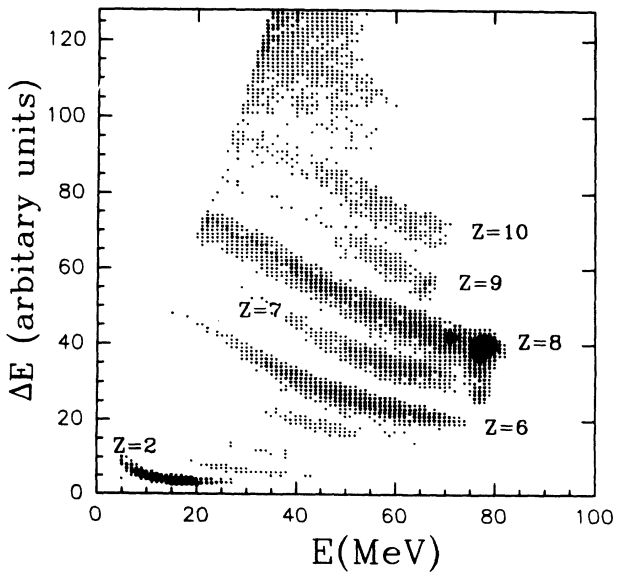

FIG. 3. A E vs ΔE spectrum obtained with a 12 μm silicon ΔE detector and 2D position sensitive detector as E detector for 84 MeV ^{16}O beam.

tiles. We have also seen that the blocking pattern for the evaporation residues ($E \sim 1$ MeV/Z) does not show any difference with target crystal thickness ranging from 0.7 to 1.5 μm, which indeed shows that multiple scattering effects do not pose a serious problem in the present measurements. Figure 4(a) shows the scaled blocking dip for elastically scattered particles (open circles) and evaporation residues (solid triangles) for the energy interval 12–30 MeV obtained at 84 MeV incident energy. The "filling in of the dip" in the case of residues is due to the lifetime effect. In Fig. 4(b) the blocking dip for inelastically scattered particles (solid circles) ($\langle Z \rangle$=7.4) is also shown. The scaled dip volume for the inelastic products is nearly same as that for the elastically scattered particles, indicating that the lifetime for these processes is shorter than 10^{-18} s.

The experimental ratio $R = (\Omega)_{\text{products}}/(\Omega)_{\text{prompt}}$ is compared with the calculated $R(v_\perp \tau)$ to determine τ ($v_\perp$ is the recoil velocity of the compound nucleus perpendicular to the atomic row and is calculated from the kinematics of the reaction assuming complete fusion). The ratio $R(v_\perp \tau)$ is calculated by numerical integration using Lindhard's standard model [6], which assumes that the compound nucleus follows a simple exponential decay.

The change in the minimum yield is related to the lifetime by [7]

$$\Delta\chi_{\min} = 2CN\pi d v_\perp^2 \tau^2, \tag{1}$$

where C is a constant ($C \simeq 2$–3), N is the atomic density of the target, and d is the interatomic distance along the crystal axis. We have used $C = 2.5$ [8]. The lifetime τ is calculated from both Ω and $\Delta\chi_{\min}$. The lifetimes obtained using both the above mentioned parameters of the blocking dip of evaporation residues are tabulated in Table I and are seen to be in good agreement. We have also compared the numerically calculated dip volume ratio R with the vectorized multistring Monte Carlo calculation [2] and they seem to agree well.

From Table I it can be seen that $\tau \sim 7 \times 10^{-18}$ s is nearly same for both 55.8 and 64.8 MeV excitation energy. Malaguti *et al.* [2] have reported $\tau = 12^{+4}_{-2} \times 10^{-18}$ s for an excitation energy of 75 MeV. This indicates that the values of τ are comparable within the uncertainties of the measurement as the excitation energy of ^{44}Ti is varied from 56 MeV to 75 MeV.

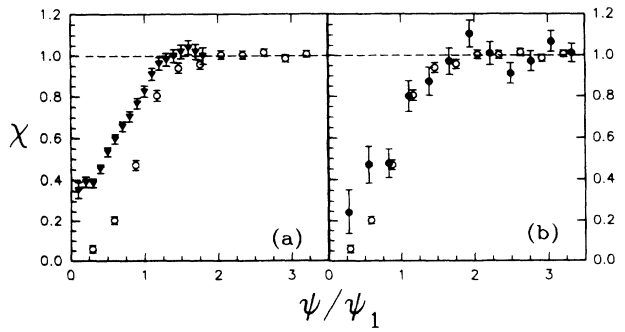

FIG. 4. Normalized blocking yield $\chi(\psi)$ as a function of scaled angle variable (ψ/ψ_1) for (a) evaporation residues (solid triangles) and (b) inelastically scattered particles (solid circles) in the energy range 60–68 MeV, at E_{inc}= 84 MeV. The dip for elastically scattered oxygen ions (open circles) is plotted for reference (E_{elastic} = 77.2 MeV, ψ_1 = 2.78 mrad). ψ_1 is the critical angle for channeling as given by Lindhard [6].

We have tried to understand this weak dependence of the observed lifetime on the excitation energy in the framework of the statistical model. In the statistical theory, the lifetime of the compound nucleus can be expressed as [9]

$$\tau \sim h \frac{\rho_c(E^*, J)}{N(E^*, J)}, \tag{2}$$

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. Using the statistical model code CASCADE we have estimated the most probable E^* and J at various stages of evaporation of the compound nucleus ^{44}Ti formed in the reaction ^{16}O + ^{28}Si at the excitation energies mentioned above. The input parameters for calculations were fixed by comparing the evaporation residue yields obtained from CASCADE with those given by Pühlhofer [5] for the ^{16}O+^{27}Al reaction. In these calculations we have observed that E^* or J of decaying nuclei in the intermediate stages are not very sensitive to gamma decay parameters. We have not included fission competition in the present calculation. As mentioned before the average mass was found to be 34(±2) from the E-T spectra. Therefore, we have chosen the most probable evaporation channel of ^{44}Ti leading to the residue ^{35}Cl for the excitation energies 55.8 and 64.8 MeV to obtain the most probable E^* and J of the residue. In order to estimate the lifetime, the level densities $\rho(E^*, J)$ were calculated using the relation [10]

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

where we have used $A/8$ for the level density parameter a. From these relations it is seen that earlier stages of the evaporation are very short lived, $\tau \sim 10^{-22} - 10^{-21}$ s, which should not show any change in the observed blocking pattern. In fact, for any observable change in the blocking pattern the recoil distance has to be greater than 0.106 Å (two-dimensional mean-square thermal vibration amplitude). In other words the lifetime has to be greater than $\sim 10^{-18}$ s at these recoil velocities. Therefore it appears that we are essentially measuring the lifetime for the later stages of the evaporation chain. We have estimated the total level width for ^{39}K taking the p, n, and α decay channels. In the case of $E^* = 55.8$ MeV for ^{44}Ti, the most probable values of E^* and J for ^{39}K were found to be 20 MeV and 12$\hbar$, respectively, and Γ = 5.1 keV. The corresponding values for 64.8 MeV excitation energy are 27 MeV and 13$\hbar$, giving a total width Γ= 5.6 keV. This shows that the estimates based on the statistical model for the decay of the later stages of the evaporation chain reproduce the experimentally

TABLE I. The compound nuclear lifetime as measured from the blocking pattern of evaporation residues [$\chi_{\min}^{\text{ref}} = 7(1.5)\%$].

E^* (MeV)	$\langle Z \rangle$	$\left\langle \frac{1}{E} \right\rangle^{-1}$ (MeV)	ψ_1 (mrad)	R	τ (10^{-18} s)	$\Delta\chi(\%)$	τ (10^{-18} s)
55.8	17	15.4	9.1	0.47(0.06)	$8.17^{+1.8}_{-1.6}$	28.5(4.0)	7.2(1.8)
64.8	17	17.4	8.5	0.495(0.06)	$6.6^{+1.6}_{-1.2}$	27.5(3.6)	6.4(1.5)

observed trend in the lifetime as a function of the initial excitation energy of the compound nucleus. In the case of 100 MeV incident energy the present estimation indicates that the width at the final decay stage of the most probable evaporation channel is smaller than that for the other two energies. We may mention here that these approximate calculations do not reproduce the observed lifetime values of $\sim 8 \times 10^{-18}$ s and more rigorous calculations similar to the ones given in Refs. [1] and [11] are required to compare the absolute lifetime values. In a recent study, DeYoung *et al.* [12] have measured the lifetime using a particle-particle correlation for $^{16}O + ^{27}Al$ to be $\sim 10^{-17}$ s for the later stages of the decay. The present measurements are consistent with this result.

IV. CONCLUSIONS

We have measured the lifetime for evaporation residues in the decay of ^{44}Ti at initial excitation energies of 55.8 and 64.8 MeV from changes in the blocking dip. Both minimum yield and the dip volume are used to get lifetime information and they give consistent results. The lifetimes for inelastic processes like one or more nucleon transfer are shorter than 10^{-18} s as expected, whereas for the evaporation residues it is of the order of 10^{-17} s and is nearly constant over the excitation energy range of 56–75 MeV. This weak dependence on the excitation energy indicates that the lifetimes measured in the present experiment are due to the decay of the later stages of the evaporation chain.

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[1] J. Gomez del Campo, D. Shapira, J.A. Biggerstaff, C.D. Moak, P.D. Miller, N. Neskovic, R.W. Fearick, and J.P.F. Sellschop, Phys. Rev. Lett. **51**, 451 (1983).

[2] F. Malaguti, S. Ostuni, E. Verondini, E. Fuschini, G. Vannini, I. Iori, A. Bracco, A. Moroni, E. Fioretto, R.A. Ricci, P. Boccaccio, and L. Vannucci, Europhys. Lett. **12**, 313 (1990).

[3] V. Nanal, P.R. Apte, M.B. Kurup, and K.G. Prasad, Nucl. Instrum. Methods B **82**, 404 (1993).

[4] V. Nanal, W.A. Fernandes, M.B. Kurup, and K.G. Prasad, Nucl. Instrum. Methods B **73**, 101 (1993).

[5] F. Pühlhofer, Nucl. Phys. **A280**, 267 (1977).

[6] J. Lindhard, Mat. Fys. Medd. Dan. Vid. Selsk. **34**, No. 14 (1965); R. B. Alexander, J.U. Andersen, and K.G. Prasad, Nucl. Phys. **A279**, 278 (1977).

[7] W.M. Gibson and K.O. Nielsen, Phys. Rev. Lett. **24**, 114 (1970).

[8] R.P. Sharma, J.U. Anderson, and K.O. Nielsen, Nucl. Phys. **A204**, 371 (1973).

[9] R. Bass, in *Nuclear Reactions with Heavy Ions*, edited by W. Beiglböck, M. Goldhaber, E. H. Lieb, and W. Thirring (Springer-Verlag, Berlin, 1980).

[10] R.G. Stokstad, in *Treatise on Heavy Ion Science*, edited by D. Allan Bromley (Plenum, New York, 1985), Vol. 3, pp. 104–105.

[11] J. Gomez del Campo, J. Barrette, R.A. Dayras, J.P. Wieleczko, E.C. Pollacco, F. Saint-Laurent, M. Toulemonde, N. Neskovic, and R. Ostojic, Phys. Rev. C **41**, 139 (1990).

[12] P.A. DeYoung, C.J. Gelderloos, D. Kortering, J. Sarafa, K. Zienert, M.S. Gordon, B.J. Fineman, G.P. Gilfoyle, X. Lu, R.L. McGrath, D.M. de Castro Rizzo, J.M. Alexander, G. Auger, S. Kox, L.C. Vaz, C. Beck, D.J. Henderson, D.G. Kovar, and M.F. Vineyard, Phys. Rev. C **41**, 1885 (1990).