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Lifetime in heavy ion reactions studied by crystal blocking

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Abstract : The crystal blocking technique is used for measuring compound nuclear lifetimes and reaction times in the range 10^{-15} – 10^{-19} sec., provided charge particles are emitted in the process. The lifetime is extracted from the changes in the shape of blocking dip as compared to the 'prompt'. The parameters that characterize the blocking dip, namely, the minimum yield (χ_{min}) and the dip volume (Ω) are in general a function of energy (E), atomic number (Z) and the crystal thickness. Since the products emitted in heavy ion reactions have a distribution in energy and atomic number, it is essential to investigate this dependence of blocking pattern systematically. Systematic studies of χ_{min} and the blocking dip volume (Ω) have been carried out for ions with Z = 3–14 in the energy range E = 2–5 MeV/amu in thin silicon single crystals of thicknesses 0.8–1.5 μm. It is observed that both χ_{min} and Ω follow the expected scaling behaviour.

We have used a 2-*D* position sensitive solid state detector (24 × 24 mm^2) to record the blocking patterns of elastically scattered projectiles ('promt') and various reaction products. The detector gives both X and Y position along with energy information. We have used, for the first time, a time of flight discriminator method in conjunction with blocking using the pulsed beam from the pelletron accelerator for separating the reaction products. Different mass groups are identified from energy (E) *vs* time of flight (T) spectrum and their blocking dips are then analyzed to extract the lifetime. The details of the measurements of lifetimes for the reactions $^{16}O + ^{28}Si$ and $^{12}C + ^{28}Si$ will be presented. The dependence of lifetime of the incident energy will also be discussed.

Keywords : Heavy ion reactions, life time, crystal blocking technique

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In Rutherford scattering experiments, if the target is a single crystal and a detector is placed along a crystallographic direction then scattered particles are blocked from reaching the detector. If a 2-*D* position sensitive detector (PSD) is used, one gets an image of the crystal showing various planes and the axis. Figure 1 shows < 100 > blocking pattern for elastically scattered ^{16}O (36 MeV) from < 100 > Si single crystal.

This blocking technique can be used for measuring compound nuclear life-times and reaction times in the range 10^{-15}–10^{-19} sec., provided charged particles are emitted in the

Figure 1. < 100> blocking pattern for elastically scattered ^{16}O(36 MeV) from Si crystal.

process. The lifetime is extracted from the changes in the shape of blocking dip as compared to the 'prompt'. The parameters that characterize the blocking dip, namely, the minimum yield (χ_{min}) and the dip volume (Ω), are in general a function of energy (E), atomic number (Z) and the crystal thickness. We have carried out systematic studies of χ_{min} and the blocking dip volume (Ω) for ions with Z = 3–14 in the energy range E = 2–5 MeV/amu in thin Si single crystals (0.8–1.5 μm). Both the χ_{min} and Ω were found to follow the expected scaling behaviour [1]. This result indicates that both the scaled dip volume and χ_{min} of the blocking patterns of the reaction products can be used to obtain lifetime information.

We have carried out experiments using ^{16}O (E_{inc} = 70, 84 MeV) and ^{12}C (66 MeV) beams from 14 UD BARC-TIFR pelletron accelerator at Bombay. A 1.5 μm < 100 > natural Si single crystal target was mounted on a double axes goniometer. A 2-D position sensitive semiconductor detector (active area 24 × 24 mm^2) was placed at forward angle (15° and 20°) at a distance of 56 cm from the target. The detector gives both X and Y positions along with energy. Central 10 × 10 mm^2 portion of the detector shows good linearity and gives position resolution better than 1 mm. We have used, for the first time, a time of fight (T) discriminator method in conjunction with blocking using the pulsed beam for separating the reaction products. A typical E *vs* T spectrum is shown in Figure 2. Different mass groups *viz.* elastic scattered particles, alpha particles and evaporation residues, are identified from energy (E) *vs* T spectrum. The blocking dips are constructed for different particle gropus separately and the dip volume (Ω) is calculated. Figure 3 shows the scaled blocking dip for elastically scattered particles and evaporation residues. The filling in of the dip' in case of residues is due to the lifetime effect.

The average mass $< A >$ for the evaporation residue group is found from E *vs* T spectrum and $< Z >$ is taken to be $\frac{< A >}{2}$. The average value of $\langle \frac{1}{E} \rangle^{-1}$ is calculated from

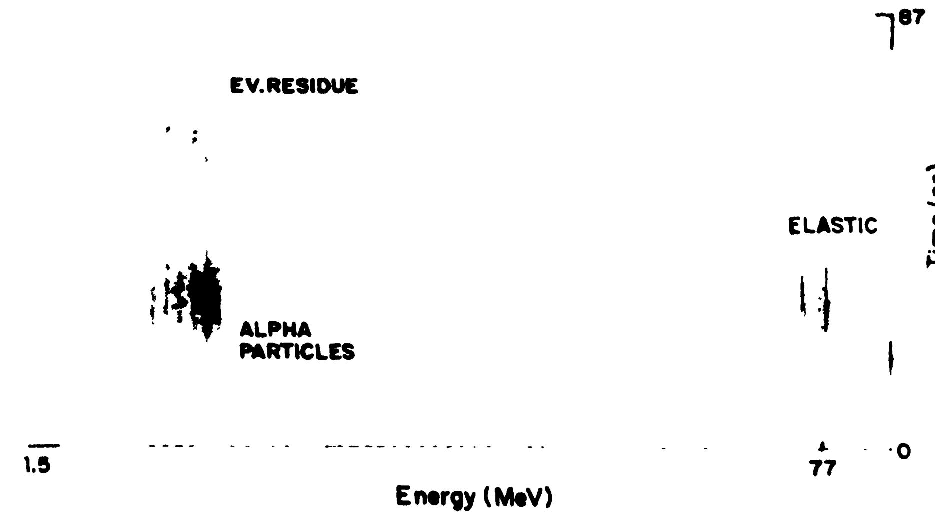

Figure 2. A typical E *vs* T spectrum for 84 MeV ^{16}O beam on Si crystal.

the energy spectrum of the products. This $\langle \frac{Z}{E} \rangle$ is then used for scaling of the dip. The experimental ratio $R = (\Omega)_{\text{products}}/(\Omega)_{\text{prompt}}$ is compared with calculated $R\ (v_{\perp}\tau)$ to

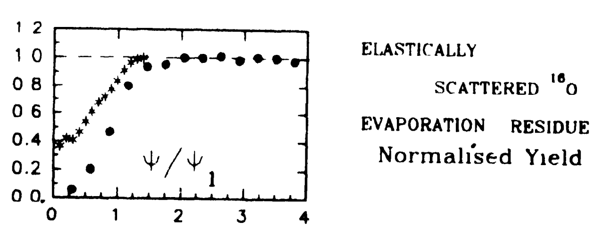

Figure 3. The noramlised yield as a function ot scaled angle from < 100 > axis of Si. ψ_1 is Lindhard's critical angle for blocking.

determine τ ($v_{\perp}$ is the recoil velocity of compound nucleus perpendicular to the row). The ratio $R(v_{\perp}\tau)$ is calculated by numerical integration using Lindhard's standard model lindl, which assumes that compound nucleus follows a simple exponential decay.

The change in the minimum yield is related to the lifetime by,

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

where C is a constant ($C \simeq$ 2–3) N is the no. of atoms per unit volume and d is the interatomic distance along the crystal axis.

Lifetime τ is calculated from both Ω and $\Delta\chi_{min}$. For inelastic products $R \simeq 1$ indicating lifetime shorter than 10^{-19} sec. The τ calculated for evaporation residues is tabulated in Table 1. Malaguti *et al* [3] have measured $\tau = 12^{+4}_{-2} \times 10^{-18}$ sec. for ^{44}Ti at excitation energy of 75 MeV. It is seen from our results (Table 1) together with their data that there is no significant change in τ of ^{44}Ti as the excitation energy varies from 56 MeV to 75 MeV.

Table 1. The compound nuclear lifetime as measured from the blocking pattern of evaporation residues.

Compound nucleus	E^* (MeV)	$<Z>$	$\langle \frac{1}{E} \rangle^{-1}$ (MeV)	R	τ (10^{-18} sec)	$\Delta\chi(\%)$	τ (10^{-18} sec)
^{44}Ti	55.8	17	16.5	0.48(0.07)	$7.7^{+2.2}_{-1.6}$	29.3	7.3(1.1)
	64.8	17	15.5	0.5(0.09)	$6.6^{+2.7}_{-1.8}$	27.8	6.4(1)
^{40}Ca	59.6	15	14.7	0.46(0.07)	$11.7^{+3.3}_{-2.6}$	25.0	9.6(1.8)

The lifetime of compound uncleus can be expressed as $\tau \sim \hbar \dfrac{\rho(E^*,J)}{N(E^*,J)}$ [4], where ρ is the level density of compound nucleus and N is the total number of decay channels to which the compound nucleus can decay. The weak dependence of τ on E^* as seen in the present case could mean that though ρ increases sharply with the excitation energy, the ratio $\dfrac{\rho(E^*,J)}{N(E^*,J)}$ does not change significantly. The explicit calculations of these numbers are not straightforward. The blocking dips for α particles show some structure which is not clearly understood. Therefore it is not easy to obtain lifetime from α dip volume.

Summary

We have measured the lifetime of compound nucleus ^{44}Ti at excitation energy of 55.8 and 64.8 MeV and of ^{40}Ca at 59.6 MeV. The τ_{CN} shows a very weak dependence on excitation energy in the case of ^{44}Ti. The energy dependence of τ_{CN} needs to be studied in more detail for other nuclei also.

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