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# Measurements of mean reaction times for fusion-fission and fusion-evaporation processes in the $^{28}$Si + $^{28}$Si interaction

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Axial and planar blocking patterns in thin Si single crystals have been measured for the products of the reaction $^{28}$Si(150 MeV)+$^{28}$Si at $\theta_L = 15°$ and 12°. Reaction times of the order $10^{-18}$–$10^{-17}$ s have been observed for fusion-evaporation and fusion-fission processes.

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The crystal blocking technique is a very useful tool for measuring the time duration of nuclear reactions in the range $10^{-19}$–$10^{-16}$ s. In the past this technique was primarily applied to light-ion-induced reactions and, more recently, it has been successfully extended to heavy-ion-induced reactions [1-5]. In previous work [3-5] we used this method to study the time evolution for different mechanisms of the $^{16}$O+$^{28}$Si reaction. The experimental apparatus and the method of analysis are described in Refs. [3] and [4].

In the present paper we present new experimental results referring to the $^{28}$Si+$^{28}$Si reaction induced by a 150-MeV $^{28}$Si beam from the Tandem XTU facility of the Laboratori Nazionali di Legnaro. The target was a self-supporting $^{28}$Si single crystal,[1] 5000 Å thick, oriented with its ⟨110⟩ axis at $\theta_L = 15°$ (or $\theta_L = 12°$) with respect to the beam direction. The excellent quality of the crystal is shown in Fig. 1 where the bidimensional blocking pattern and the azimuthal averaged blocking dip around the ⟨110⟩ axis are reported for the elastically scattered ions. Crystal orientation is such that the composite system recoils along the {110} plane, which is horizontal in this picture. The {100} plane, referred to in Fig. 3, is vertical.

Different blocking dips for different reaction fragments and different energies were simultaneously recorded. As an example we show in Fig. 2 the energy spectrum for $Z = 15$ products and the blocking dips corresponding to three different energy regions at $\theta_L = 12°$.

As is known, a simple parameter describing the filling in of the dip is its volume $\Omega$, as defined in Refs. [4] and [5]. Although the dip volume is an integral parameter, it seems to us that it is more suitable for heavy-ion-induced reactions than the shape of the blocking dip, even if the shape contains, in principle, more information on the decay function. Indeed, in heavy-ion-induced reactions, fragments arising from energy damped mechanisms can undergo a retarded emission of gamma rays during their motion inside the crystal [6,7]. Since the effect of a retarded gamma emission is like the one of a point defect in the crystal, it should produce a change in the shape of the axial blocking dip without affecting its volume. Consequently, a change in the shape of the blocking dip with respect to the elastic one does not necessarily indicate a time delay effect.

Following Refs. [4] and [5], one can define a "reduced

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[1] This was prepared at the Physics Institute, Århus University, Denmark.

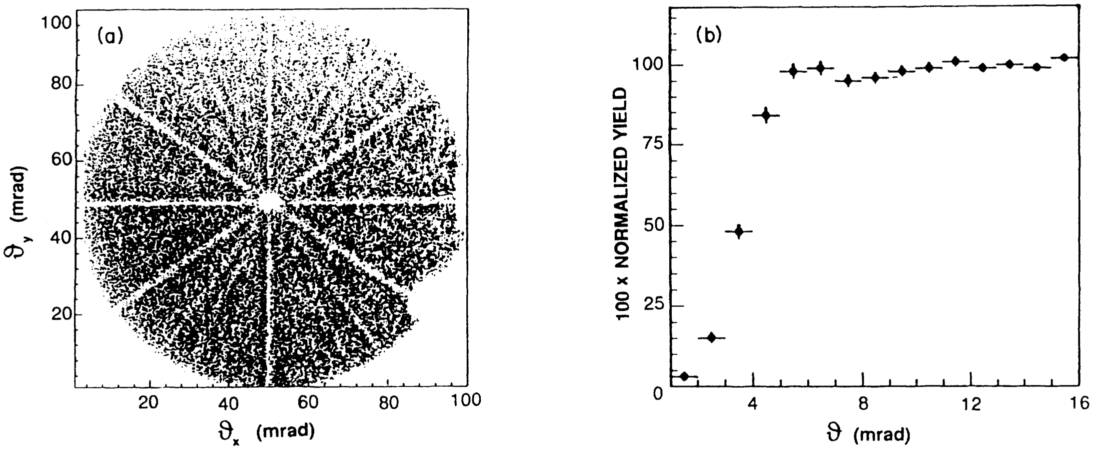

FIG. 1. Elastic patterns for $E(^{28}\mathrm{Si})=150$ MeV (a) $\theta_x$-$\theta_y$ scatter plot and (b) azimuthal averaged blocking dip around the $\langle 110\rangle$ axis.

volume" $\Omega^*=(\Omega/Z)\langle 1/E\rangle^{-1}$ which depends only on the time development of the reaction and consequently on the mean transverse displacement $v_t\tau$. Here $v_t$ is the component, orthogonal to the $\langle 110\rangle$ axis, of the velocity $v$ of the composite system formed in the reaction and $\tau$ the mean reaction time.

For the reaction products and for the elastic scattered ions, displayed in Table I, we calculated the reduced volumes $\Omega_D^*$ ($D$ denotes delayed) and $\Omega_P^*$ ($P$ denotes prompt), respectively. The experimental ratio $R_{\mathrm{exp}}=\Omega_D^*/\Omega_P^*$ can be compared with a theoretical function $R(v_t\tau)$ that is calculated in the framework of the theory of ion channeling within crystals, once the type of decay function is given.

In Fig. 3 of Ref. [4] the behavior of $R$ is shown for two different types of decay function: (a) exponential decay

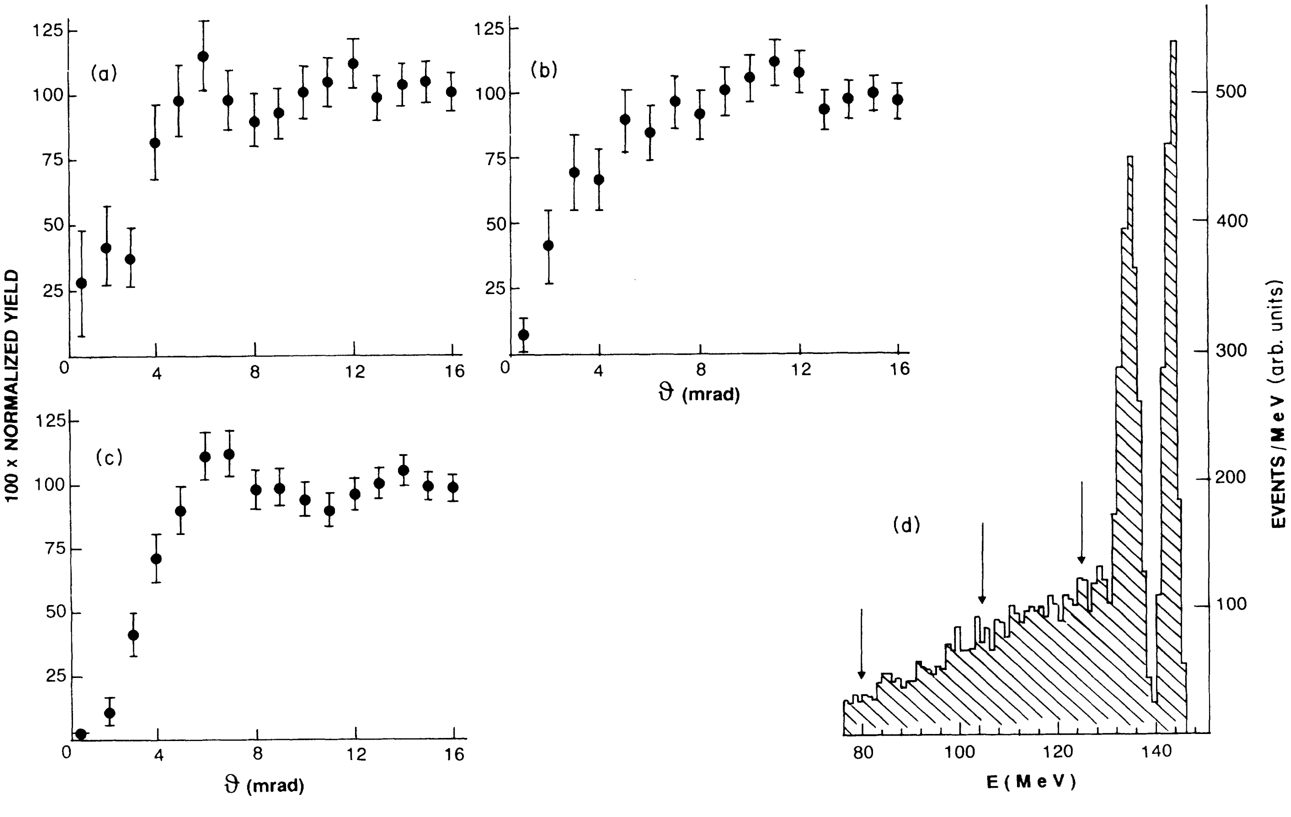

FIG. 2. Blocking dips corresponding to $Z=15$ fragments measured at $\theta_L=12°$ for (a) $80\leq E\leq 105$ MeV, (b) $105\leq E\leq 125$ MeV, and (c) $125\leq E\leq 140$ MeV, and (d) the energy spectrum of these products. Arrows in (d) separate the energy regions.

TABLE I. Summary of the experimental results collected at $\theta_L = 15°$ and 12°. $\Delta E$ is the considered energy interval of the emitted products, $\Omega^*$ is the reduced volume of the corresponding blocking dips, and $\tau$ is the mean reaction time extracted comparing the experimental ratio $R_{exp}$ with the theoretical curves of Ref. [4].

| | $\theta_L = 15°$ | | | | $\theta_L = 12°$ | | | |
|---|---|---|---|---|---|---|---|---|
| $Z$ | $\Delta E$ (MeV) | $\Omega^*$ (MeV $\mu$sr) | $R_{exp}$ | $\tau$ ($10^{-18}$ s) | $\Delta E$ (MeV) | $\Omega^*$ (MeV $\mu$sr) | $R_{exp}$ | $\tau$ ($10^{-18}$ s) |
| 14 | elastic | $230 \pm 10$ | | | elastic | $245 \pm 10$ | | |
| 15 | 70–90 | $145 \pm 81$ | $0.63 \pm 0.35$ | $4.1^{+12}_{-3.6}$ | 80–105 | $112 \pm 44$ | $0.45 \pm 0.18$ | $9.4^{+12}_{-4.2}$ |
| 15 | 90–120 | $239 \pm 77$ | $1.04 \pm 0.34$ | $\approx 0$ | 105–125 | $192 \pm 92$ | $0.78 \pm 0.37$ | $2.9^{+8.0}_{-2.9}$ |
| 15 | 120–135 | $258 \pm 69$ | $1.12 \pm 0.30$ | $\approx 0$ | 125–145 | $242 \pm 45$ | $0.99 \pm 0.19$ | $\approx 0$ |
| 16 | 70–115 | $240 \pm 41$ | $1.04 \pm 0.19$ | $\approx 0$ | 80–120 | $149 \pm 50$ | $0.61 \pm 0.20$ | $5.5^{+5.5}_{-2.9}$ |
| 16 | 115–131 | $252 \pm 92$ | $1.1 \pm 0.4$ | $\approx 0$ | 120–140 | $176 \pm 96$ | $0.72 \pm 0.40$ | $3.6^{+12}_{-3.6}$ |
| 17 | 88–116 | $194 \pm 86$ | $0.86 \pm 0.38$ | $1.4^{+5.3}_{-1.4}$ | 80–120 | $228 \pm 57$ | $0.93 \pm 0.24$ | $1.2^{+2.9}_{-1.2}$ |
| 18,19,20 | 80–110 | $127 \pm 54$ | $0.55 \pm 0.23$ | $5.6^{+7.5}_{-3.4}$ [a]<br>$4.1^{+2.7}_{-2.1}$ [b] | 70–120 | $129 \pm 17$ | $0.53 \pm 0.08$ | $7.3^{+2.4}_{-1.8}$ [a]<br>$5.5 \pm 1.1$ [b] |
| $\geq 20$ | 40–60 | $117 \pm 7$ | $0.51 \pm 0.04$ | $6.3 \pm 0.7$ [a]<br>$4.6 \pm 0.5$ [b] | 35–50 | $119 \pm 7$ | $0.49 \pm 0.04$ | $8.2 \pm 0.9$ [a]<br>$6.1 \pm 1.2$ [b] |
| $\geq 20$ | 60–80 | $160 \pm 13$ | $0.70 \pm 0.06$ | $3.1 \pm 0.5$ [a]<br>$2.9 \pm 0.5$ [b] | 50–75 | $145 \pm 11$ | $0.59 \pm 0.05$ | $5.8 \pm 0.9$ [a]<br>$4.8 \pm 0.9$ [b] |

[a] From exponential decay function.

[b] From five-step gamma-decay function.

function and (b) five step gamma-decay function. Case (b) is a schematic model for a five step evaporation chain, assuming the same lifetime for each step. In Table I experimental results are collected together with the resulting $\tau$ values obtained by comparing $R_{exp}$ with the theoretical curves.

In agreement with the results of the $^{16}O + ^{28}Si$ reaction [3,4] time durations in the $10^{-18}$–$10^{-17}$ s range were obtained for those mechanisms leading to fragments which can be considered as evaporation residues ($Z = 18$, 19, 20 and $Z \geq 20$). For these cases, the two $\tau$ values reported in Table I refer, respectively, to the purely exponential and to the "gamma" model, which correspond to two extreme cases. For lighter fragments only the exponential decay function has been used.

For the $Z = 17$ fragments we found $\tau$ values consistent with zero within the sensitivity limits of the present method ($\tau < 10^{-18}$ s). The same results were found for $Z = 16$ and 15 in the higher-energy region where fast transfer or deep inelastic processes are expected to occur. As far as the lower-energy regions are concerned, where some contribution from fissionlike processes could exist, there is weak evidence for non-negligible time effect in the case $Z = 16$ at $\theta_L = 12°$. The results for $Z = 15$ that show, both at $\theta_L = 15°$ and $\theta_L = 12°$, a time effect for the low-energy region, which disappears for higher energies, are particularly interesting.

In our experimental setup the crystal was oriented in such a way that the transverse velocity of the composite system was nearly zero with respect to the {110} plane, while $v_t$ amounts to $v \sin\theta_L$ with respect to the {100} plane [see Fig. 1(a)]. A real time effect should produce a different filling in of the two planar blocking dips if referred to the corresponding elastic ones. On the contrary, dechanneling due to either point defects or gamma-ray emission should produce the same filling in for the two planes. A simple measure of the filling in is $\Delta\chi_{min}$, which is the difference between minimum yields of the inelastic and the elastic planar dips. To test this idea we extracted from the experimental data the planar blocking dips corresponding to the events shown in Fig. 2(b), which exhibits an axial blocking with quite a different shape if compared to the elastic one, but nearly the same volume. The same procedure was applied to the data of Fig. 2(a) for which a significant volume effect was found (see Table I). The extracted planar dips are shown in Fig. 3.

Although the angular resolution of our apparatus is very poor for planar blocking, Fig. 3 clearly shows a significant difference in $\Delta\chi_{min}$ in the case of low-energy fragments [Fig. 3(c)] and no difference in the case of less damped reactions [Fig. 3(b)]. This result supports the previous observation that a time delay effect occurs for low-energy $Z = 15$ fragments.

One can observe that fragments produced through an energy-damped mechanism can also evaporate light particles, e.g., neutrons. In this case the momentum transfer to the ion traveling along the crystal will be higher than for gamma-ray emission, but the arguments previously developed with reference to planar dips will remain unchanged, and therefore the preceding conclusions are still valid.

The experimental evidence of a time delay effect for low-energy $Z = 15$ fragments indicates that they arise not from a deep inelastic collision, but from fission of the excited $^{56}Ni$ nucleus formed in the $^{28}Si + ^{28}Si$ reaction. This conclusion is at variance with simple reaction models that do not consider fusion fission in light nuclei as a relevant decay channel. Nevertheless, the experimental results of Sanders *et al.* [8] strongly indicate that $^{12}C$ fragments are produced in a binary statistical decay (fission) of the compound $^{56}Ni$ nucleus at an excitation energy slightly lower than ours.

It is interesting to compare our fusion-fission lifetimes with calculations based on the statistical model. At present, we have used the formalism of Ref. [9], that neglects angular momentum and higher-chance fission.

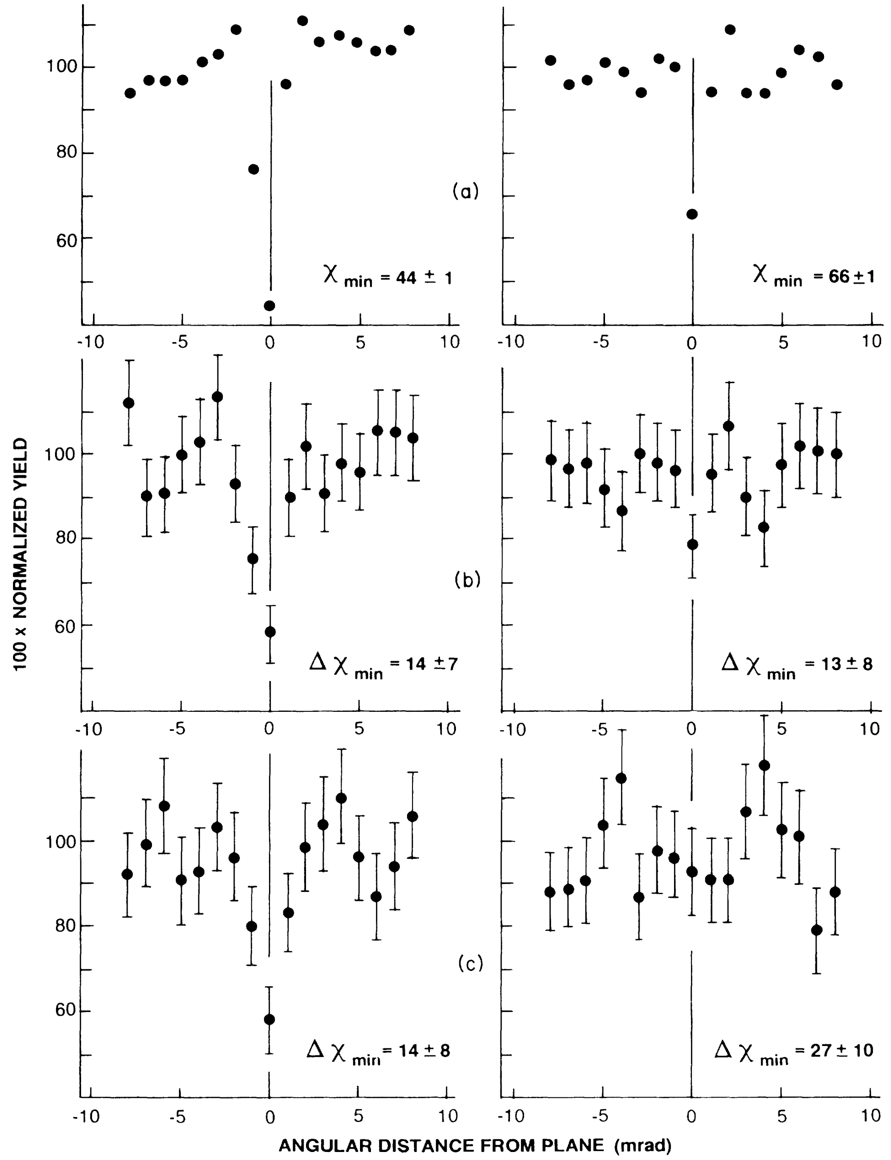

FIG. 3. Planar blocking dips with respect to the {110} plane (left side) and the {100} plane (right side) for (a) elastic events, (b) $Z=15$ and $105 \leq E \leq 125$ MeV fragments, and (c) $Z=15$ and $80 \leq E \leq 105$ MeV fragments.

Within this approximation, we calculated the mean lifetime for fission of the excited $^{56}$Ni nucleus using a fission barrier height $B_f=37.5$ MeV as calculated by Mustafa, Baisden, and Chandra [10]. At an excitation energy $E^*=86$ MeV, corresponding to the present experiment, the lifetime result for fission is $3.5\times10^{-19}$ s, clearly lower than the experimental one.

On the other hand, very long fission lifetimes have already been observed by other groups. For instance, Forster *et al.* [11] measured by blocking lifetimes of the order of $3\times10^{-17}$ s, or longer for the fission of the $^{200}$Pb compound nucleus. Detailed calculations described in their work show the need of a more refined theoretical approach that takes into account both the angular momentum distribution of the decaying nuclei and the prescission emission of light particles that strongly affects the fission mean life. Therefore there is an indication that the time delays measured for our reaction do not disagree with those calculated by a complete statistical model.

Summarizing, the mean results of the present measurements concerning the $^{28}$Si+$^{28}$Si interaction are as follows.

(i) The data referring to the $Z=15$ fragments show that the blocking method of measuring nuclear times is able to distinguish among different mechanisms on the basis of the time evolution of the reaction. In particular, for high-$Q$ values, we found events coming from a fusion-fission process having a lifetime of the order $10^{-18}$–$10^{-17}$ s, which is about a factor of 10 longer than the one predicted by simplified statistical model calculations.

(ii) The mean emission time of the ER's is in the $10^{-18}$–$10^{-17}$ s range in agreement with the results found for the reaction $^{16}$O+$^{28}$Si.

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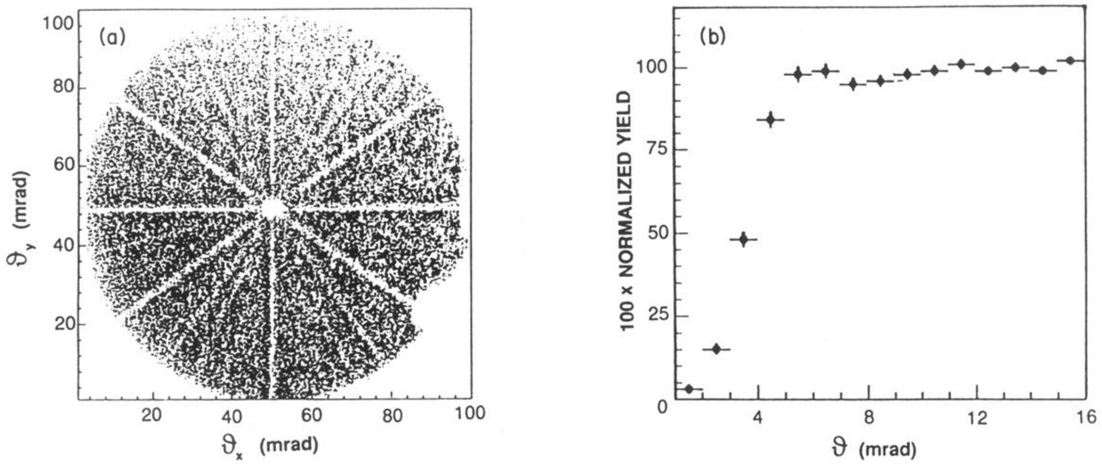

FIG. 1. Elastic patterns for $E(^{28}\mathrm{Si})=150$ MeV (a) $\theta_x$-$\theta_y$ scatter plot and (b) azimuthal averaged blocking dip around the $\langle 110\rangle$ axis.