# Measurements of Nuclear Deexcitation Times down to $10^{-19}$ sec Using Crystal Blocking of $^{16}O$ on Diamond

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(Received 31 May 1983)

The crystal-blocking technique was used to measure the deexcitation times of the evaporation residues of 120-MeV $^{16}O$ on $^{12}C$, emerging along the ⟨110⟩ axis of a 12-$\mu$m-thick diamond crystal. The extracted times ranged from $4\times10^{-19}$ sec for Mg to $4\times10^{-18}$ sec for N, and they are consistent with statistical-model predictions.

PACS numbers: 25.70.Jj, 25.70.Gh, 27.30.+t

The crystal-blocking technique offers the unique possibility of a direct measurement of reaction times for cases where the decaying products are charged particles. This technique has been used primarily in the past to study light-ion–induced resonance reactions,[1,2] although some measurements exist for the case of heavy-ion-induced fission reactions.[3,4] A review of the technique is given by Gibson.[5] In this Letter, we have extended such measurements to heavy-ion reactions, in particular to the evaporation residues (ER) of the fusion of $^{16}O$ on $^{12}C$. In the statistical theory of decay of an equilibrated system, the ER are produced in a sequential decay of the compound nucleus by the emission of light particles where this sequence proceeds through states of well defined spins, parities, and total widths $\Gamma$. This process, if it occurs, introduces a time delay $\tau$ associated to the production of a given ER. This characteristic time is, in general, a convolution of more than one nuclear lifetime. In this Letter, we report for the first time the measurements of $\tau$ using the crystal-blocking technique, while bombarding a diamond crystal with a 120-MeV $^{16}O$ beam.

Unique features of these measurements are the achievement of high recoil velocities ($\sim 0.07c$ for the ER), the use of thin diamonds, and the use of a two-dimensional position-sensitive $E$-$\Delta E$ detector system[6] which allows us to extract the blocking pattern as a function of $Z$ and $E$ of the nuclear reaction fragment. These combined techniques gave us a lower-limit sensibility of $4\times10^{-19}$ sec.

Beams of $^{16}O$ were extracted from the tandem accelerator at the Holifield Heavy-Ion Research Facility to bombard in a random direction a 12-$\mu$m-thick diamond crystal. The thin diamond was prepared by a polishing technique[7] and was mounted in a high-precision goniometer. The ⟨110⟩ axis was found by channeling the beam and observing the typical star patterns on a phosphor screen, and then it was rotated to 16.2°, where the detector was located.

Figure 1 shows a typical two-dimensional blocking pattern obtained for the elastic scattering at a beam energy of 120 MeV; similar patterns were taken for the elastic scattering at 80-MeV bombarding energy and for nuclear reaction fragments from B to Mg for the bombardment at 120 MeV. The axial blocking dip can be seen clearly in the center of the figure, although the

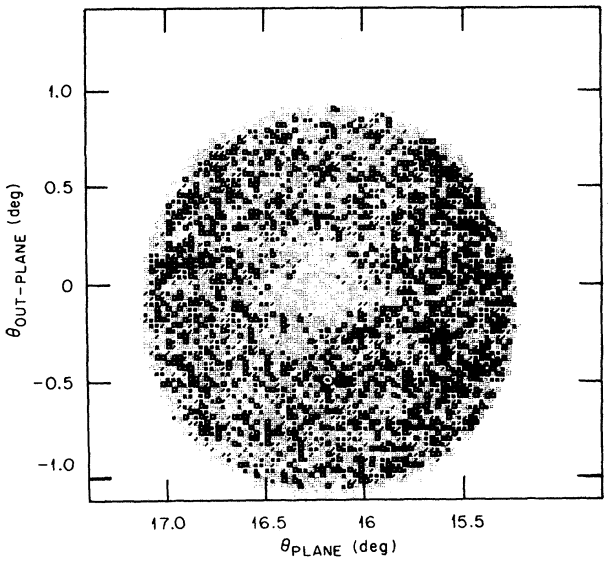


FIG. 1. Two-dimensional blocking pattern for the elastic scattering of $^{16}O$ on diamond at $E(^{16}O) = 120$ MeV. The angles are measured along the reaction plane or perpendicular to the reaction plane, and the ⟨110⟩ axis is centered at 16.2°.

typical planar blocking dips[4] are not seen because of thickness and imperfections of the crystal. After we integrate the blocking patterns over the azimuthal angle,[4] defined with respect to the ⟨110⟩ axis, and normalize to the random yield, blocking angular distributions (such as those shown in Fig. 2) are obtained and used to extract the time information. A first approach (valid for recoil distances $\lesssim 0.3$ Å) consists of extracting the time from the minimum yield $\chi$, which equals the normalized yield at the center of the blocking patterns (0 deg in Fig. 2), by means of the relation[5]

$$\chi \simeq \chi_0 + 2\pi CNd(\bar{V}_R \sin\theta_L \tau)^2, \quad (1)$$

where $\chi_0$ is the minimum yield for $\tau = 0$ and, in general, depends on the energy of the channeled particle $E$ and on its nuclear charge $Z$ because of dechanneling effects introduced by the finite thickness of the crystal. Contributions to $\chi_0$ arising from thermal vibrations (very small for the case of diamond) and mosaic spread were included. The recoil velocity $\bar{V}_R$ is usually the compound-nucleus velocity for the case of two-body final states[1,2]; however, in our case it is the average component along the beam direction of the recoiling nucleus before the last particle is emitted. This velocity is computed for Hauser-Feshbach angular distributions of the light particles with the Monte-Carlo code LILITA.[8,9] Corrections for energy loss in the crystal were included. In Eq. (1), $\theta_L$ is the scattering angle at the center of the blocking pattern (Fig. 1). The constant $C \simeq 1.3$ has been determined in an empirical way, as discussed in Ref. 5; $N$ is the atomic density, and $d$ is the atomic spacing along the row. The quantity $\chi_0$ can be determined by an adequate choice of reactions. In the experiment described here, we chose to measure the elastic scattering at two bombarding energies, 80 and 120 MeV. The 80-MeV data are shown at the top of Fig. 2 (solid points), where the minimum yield is $\chi_0 = 0.42 \pm 0.03$. The same $\chi_0$ value was found at 120 MeV, indicating that it is determined by (static) crystal imperfections. The use of Eq. (1) to extract $\tau$, although it is analytically simple and illustrates the relation between $\tau$ and the measured minimum yield, is subject to large uncertainties. Therefore, a computer code was developed to calculate the blocking angular distribution from a more accurate approach. The theoretical blocking angular distribution $Y_T(\theta)$ was calculated in the multistring statistical equilibrium approximation[4]:

$$Y_T(\theta) = \int_0^\infty Q(\vec{r}) F(\theta, \vec{r}) d^2 r, \quad (2)$$

where $Q(\vec{r})$ is the probability for the ejectile to be emitted at point $\vec{r}$, and $F(\theta, \vec{r})$ is the average probability for the ejectile emitted at point $\vec{r}$ to emerge with angle $\theta$, the averaging being along the depth of the crystal. $F(\theta, \vec{r})$ is calculated within the diffusion approximation; the interaction potential is constructed from the Hartree-Fock potential with use of the multistring continuum approximation.[4] An exponential distribution of recoil distances is used because the decay process has many lifetime components.[1] The recoil distance is given by $\bar{V}_R \sin\theta_L \tau$. The theoretical dip $Y_T(\theta)$ must then be convoluted with a Gaussian to account for static crystal imperfections (mainly mosaic spread), giving the normalized blocking angular distribution as a function of angle as

$$Y(\theta) = [(2\pi)^{1/2}\sigma]^{-1} \int_0^\infty Y_T(\theta') \exp\{-(\theta' - \theta)^2/2\sigma^2\} d\theta', \quad (3)$$

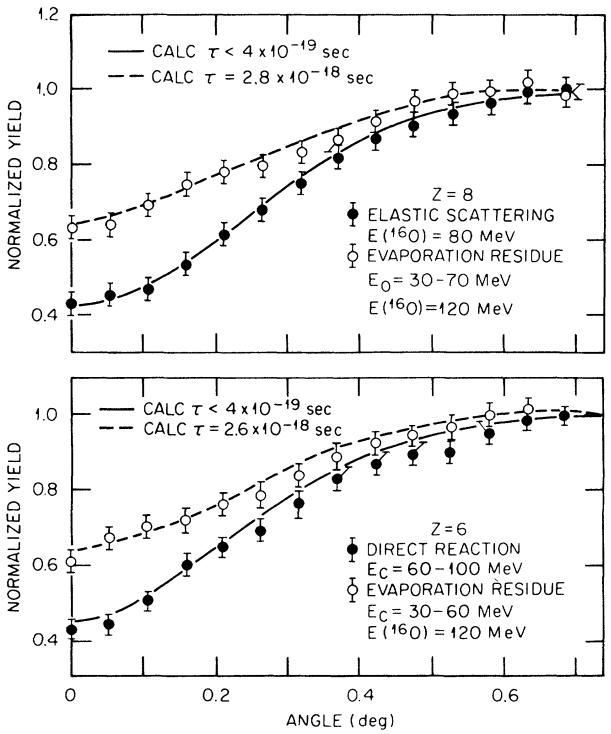


FIG. 2. Blocking angular distributions for ions of oxygen (top) and carbon (bottom). The solid points in the top part correspond to the elastic-scattering results for bombarding energy of 80 MeV and the open circles to ER for a bombarding energy of 120 MeV. The bottom part of the figure shows the blocking distributions for the ER (open circles) and direct reactions (solid circles) for $Z = 6$ at 120-MeV bombarding energy.

where the smearing width $\sigma$ contains all the contributions from static crystal imperfections.

Results of the calculations using Eqs. (2) and (3) are shown as solid and dashed curves in Fig. 2. From the analyses of the yield distributions for the elastic scattering at 80 and 120 MeV, a smearing parameter $\sigma = 0.2°$ was extracted and used for all calculations. In the $^{16}O + ^{12}C$ collision there are direct-reaction components that were also used to test the predictions of Eqs. (2) and (3). These direct-reaction components are important only for fragments of $Z \leq Z_{proj}$ and they are identified on the basis of the energy spectra which are like those shown for a similar reaction in Ref. 9. The low-energy components are characteristic of ER while the higher-energy ones are consistent with direct reactions. High-energy carbon fragments are illustrated in the lower curve at the bottom of Fig. 2 and, as can be seen, the solid line describes the data with a $\tau < 4 \times 10^{-19}$ sec, indicating a "fast" reaction. For all $\tau$ less than $4 \times 10^{-19}$ sec, all curves are indistinguishable within the experimental error bars and the sensitivity to the extraction of $\tau$ is for larger values. For example, a value of $1.3 \times 10^{-18}$ sec produces a theoretical curve that intersects the vertical axis at a value of 0.54 and is clearly distinguishable from the one for $\tau = 2.6 \times 10^{-18}$ sec (dashed curve) that best fits the data. The top part of Fig. 2 shows a comparison between the low-energy portion of the oxygen spectrum taken at $E(^{16}O) = 120$ MeV (open circles) and the results for the elastic scattering at $E(^{16}O) = 80$ MeV. The reason for this comparison is that for both data sets the oxygen average laboratory energy is approximately the same and the main difference arises from the different reaction mechanisms (ER versus elastic scattering). The extracted $\tau$ values for the cases of $Z = 8$ and $Z = 6$ are illustrated by the dashed curves in Fig. 2.

Besides the data shown in Fig. 2, other reaction fragments were analyzed. High-energy nitrogen and boron reaction products also gave $\tau < 4 \times 10^{-19}$ sec, consistent with direct reactions. The low-energy component of nitrogen and all the yields from F to Mg are consistent with the ER mechanism[9] and their extracted $\tau$ values (solid points) are given in Fig. 3(a), together with the values for carbon and oxygen. The histogram of Fig. 3(a) shows the result of Monte-Carlo Hauser-Feshbach calculations using an improved version of LILITA.[8] For these calculations, the partial decay widths $\Gamma$ used for the regions of high excitation were given by the equations of Gomez del Campo *et al.*,[10] while those for the regions of discrete levels were obtained from experimental values in the compilations of Endt and Van der Leun[11] and Ajzenberg-Selove and Lauritsen.[12] For some discrete levels where $\Gamma$ values are not known, they were assumed to be the same as for the nearby levels. From

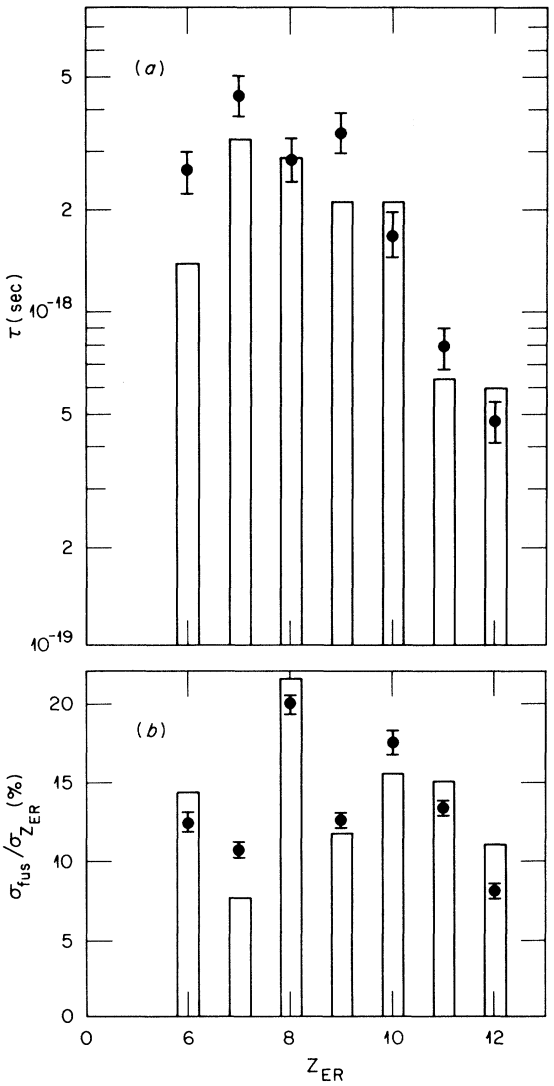


FIG. 3. (a) Comparisons of the deexcitation time $\tau$ extracted from the blocking measurements (solid points) with Monte Carlo statistical-model calculation (histogram) for the evaporation residues (ER) of the fusion of 120-MeV $^{16}O$ on $^{12}C$ (diamond). (b) Comparisons of the angle-integrated yields of evaporation residues, expressed as a percentage of $\sigma_{fus}$ for $^{16}O + ^{12}C$ (solid points), to statistical-model calculations using the code LILITA (histograms). These data were obtained with a thin carbon foil (200 $\mu g/cm^2$) at $E(^{16}O) = 117$ MeV.

many such calculations the average deexcitation time $\tau$ for a particular ER was determined. Figure 3(b) shows, for reference purposes, the results for the total integrated ER yields (solid points) for the $^{16}O + ^{12}C$ reaction at $E(^{16}O) = 117$ MeV taken with a thin (200-$\mu g/cm^2$) carbon foil. The histogram gives the results of the same calculations that predicted the $\tau$ values given in Fig. 3(a), and the figure demonstrates that the relative yields are also consistent with the calculations.

From the comparisons of Fig. 3(a), we conclude that the process of equilibrium decay has been observed through the time delay introduced by the sequential emission, and that the blocking technique can be used to yield basic information in heavy-ion reaction mechanisms down to very short times.

Two of us (J. P. F. S. and R. W. F.) would like to thank the Oak Ridge National Laboratory for hospitality. We thank the de Beers Diamond Research Laboratory for providing the raw diamond used to prepare our thin crystals, and the Oak Ridge National Laboratory and the South African Council for Scientific and Industrial Research for partial support of this work. The Oak Ridge National Laboratory is operated by Union Carbide Corporation under Contract No. W-7405-eng-26 with the U. S. Department of Energy.

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