study. Another important point to be noted in this work is that electric transitions between levels of different shape such as the $6_1^+ \rightarrow 4_1^+$ transition are not extremely hindered. This gives a practical support for a treatment of Jaffrin[15] in the aligned-coupling-scheme calculation, where the mixing of prolate and oblate components is allowed.

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Time Evolution of Heavy-Ion–Induced Fission Studied by Crystal Blocking

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The shapes of crystal-blocking angular distributions have been used to study the fission decay of excited compound nuclei produced by bombardment of tungsten with ^{16}O ions. The results show that while most of the fission decays (~80%) occur with lifetimes too short to be measured by the blocking technique ($\tau \lesssim 10^{-18}$ sec), a large fraction (~20%) corresponds to lifetimes $\tau \gtrsim 10^{-16}$ sec. This indicates a significant contribution from fission after evaporation of several neutrons.

Applied to the measurement of very short nuclear lifetimes, ~10^{-15}–10^{-18} sec, the crystal-blocking technique is basically a recoil-distance method where the characteristic recoil distance $v\tau$ ranges from ~10^{-8} to 10^{-9} cm.[1,2] Extraction of a unique lifetime from the measured blocking dip requires that the compound-nucleus decay can be approximated as a simple exponential, corresponding to a well-defined lifetime. In reactions where many different levels of the compound nucleus may be formed, this requirement is not always fulfilled. We report here on a new application of the crystal-blocking technique to study the time evolution of compound nuclei which decay with a broad distribution of lifetimes. It is shown that fission decay of compound nuclei formed by oxygen-ion bombardment of tungsten contains components varying more than an order of magnitude in lifetime.

Fission induced by heavy-ion bombardment may be expected to exhibit a complex time evolution. The reasons are twofold: First, the decay width of the compound system depends on the angular momentum which can vary over a large range. Second, fission may occur not only from the initially formed state but also after evaporation of one or more neutrons. By the latter process, the nucleus is cooled and its lifetime increases rapidly as neutron evaporation proceeds.

An extensive study of heavy-ion–induced fission has been made by Karamyan and co-workers,[2,3] who used glass-plate detectors to record blocking patterns from thick crystals. By conventional analysis of the results, lifetimes were extracted which, in many cases, were larger by several orders of magnitude than those predicted from statistical models of highly excited heavy nuclei. We have studied some of these cases with an improved experimental technique. The main improvements are the use of thin targets and position-sensitive solid-state detectors.

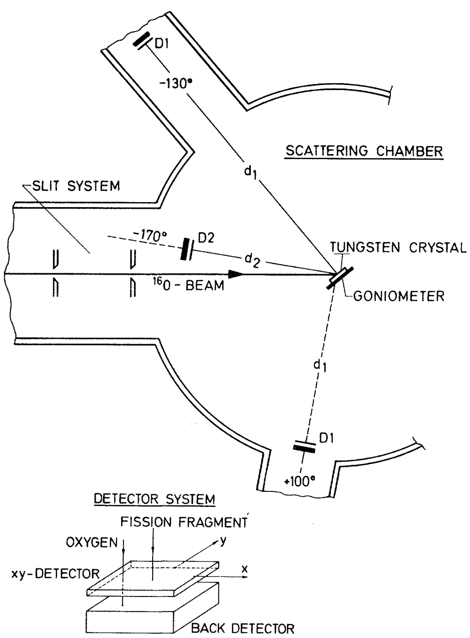

FIG. 1. Experimental arrangement. Distances of detectors from crystal are $d_1(-130°) = 232$ mm, $d_2 = 112$ mm, and $d_1(+100°) = 132$ mm. The dector assembly is illustrated separately. The orientation of the crystal corresponds to a measurement of the ⟨111⟩ dip at $-130°$.

The experimental arrangement is shown in Fig. 1. The beam from the upgraded Chalk River MP tandem accelerator was focused to a spot size of ~0.5 mm diam on a thin single crystal. Fission fragments were detected in two independent counter systems, $D1$ and $D2$. Each detection system consisted of a thin (~20 μm) two-dimensional position-sensitive ΔE silicon detector of active area 1.4 cm×1.4 cm, backed by a thicker E detector. All fission fragments were stopped in the front detector, whereas elastically scattered projectiles penetrated to the back detector and could be distinguished from fission fragments by a coincidence requirement. This method of detection allowed on-line observation of separate blocking patterns for fission fragments and for the elastically scattered beam particles.

Thin tungsten crystals grown epitaxially onto sapphire substrates were used throughout. The use of thin crystals minimizes the influence of dechanneling (or rather feeding-in), which may seriously complicate the interpretation of blocking patterns obtained with thick targets. In the measurements discussed, two different tungsten crystals were used, one having a ⟨110⟩ axis normal to the surface, the other a ⟨111⟩ axis. The ⟨110⟩ crystal was rotated to allow observation of two ⟨100⟩ axial blocking patterns simultaneously in the detector systems, $(D1, D2) = (+100°, -170°)$, as shown in Fig. 1. The ⟨111⟩ crystal was twinned, and the blocking pattern around the single perfect ⟨111⟩ axis (the surface normal) was, in turn, presented to detectors $D1$ and $D2$ located at $-130°$ and $-170°$, respectively. Figure 2 shows a pho-

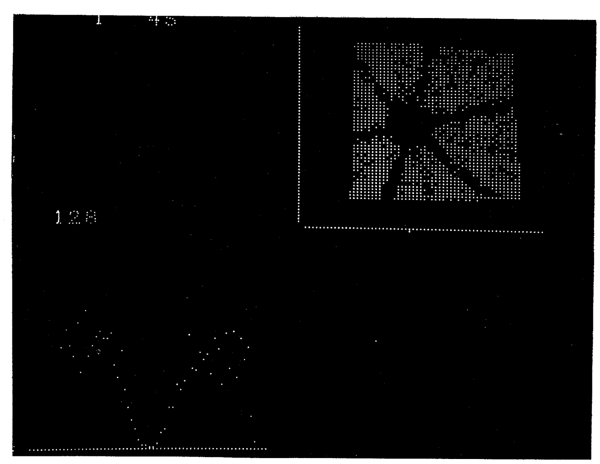

FIG. 2. Photograph of the display screen after a run for 40-MeV ^{16}O→ W ⟨111⟩. In the lower left corner, a y scan through the center of the axial dip is shown.

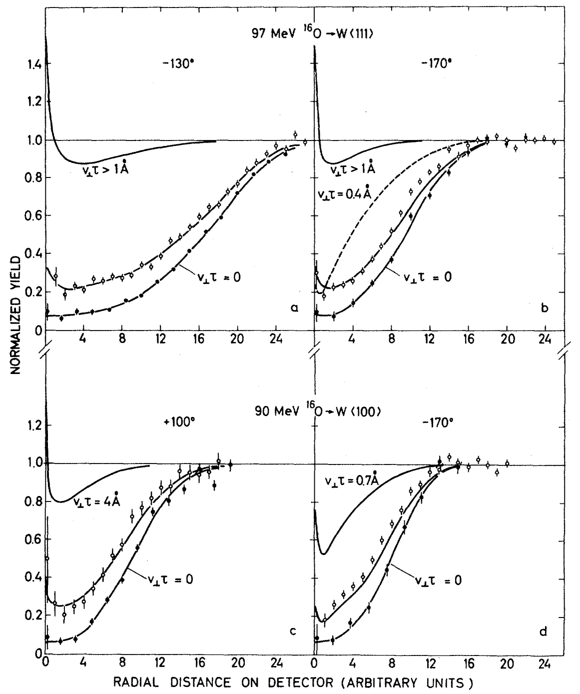

FIG. 3. Fission-fragment blocking dips for ^{16}O→ W at two bombarding energies (open circles) compared to results for prompt fission, $v_\perp\tau \simeq 0$ Å (solid circles). The latter were simulated by scaling the dips measured for elastic scattering of 40-MeV ^{16}O to the energy and nuclear charge of fission fragements, with a c.m. energy of 70 MeV. Scaling factors are 1.7, 1.9, 1.6, and 1.9 for (a), (b), (c), and (d), respectively. The uppermost curve in each subfigure was calculated for an exponential decay with $v_\perp\tau$ values as indicated. For $v_\perp\tau > 1$ Å, the result is nearly independent of the magnitude of the recoil distance.

tograph of a two-dimensional blocking pattern for 40-MeV ^{16}O elastically scattered from a tungsten crystal. The axial and planar minima for this ⟨111⟩ direction are clearly visible.

Fission induced by bombardment of tungsten and gold crystals with ^{12}C, ^{16}O, and ^{19}F ions has been investigated. Results for ^{16}O on tungsten at two bombarding energies are shown in Fig. 3 by open circles. The coordinates for the axial minimum have been determined by a computer-research routine. Circular averages around this point are plotted in Fig. 3 as a function of the radius of the circle. The results to be expected for zero-lifetime ($v_\perp\tau = 0$) fission (solid circles; the curves through the zero-lifetime data are guides only) have been generated by scaling experimental results for 40-MeV ^{16}O elastic scattering according to the well-known angular scaling of blocking patterns by $(Z/E)^{1/2}$, where Z and E are the proton number and kinetic energy of the emitted particle, respectively.

We first consider the fission data from 97-MeV ^{16}O measurements [Figs. 3(a) and 3(b)]. Because of the difference in detector distance from the crystal for the $-130°$ and $-170°$ measurements (see Fig. 1), the widths of the associated blocking patterns, in units of channels, are different. After correction for this geometrical difference and for the difference in fission-fragment lab energy in the two directions, the two distributions are indistinguishable, in contrast to the observations discussed in Ref. 2. It is, however, significant that in both cases, the minimum yields are higher than those obtained for zero-lifetime distributions (solid points). This difference is interpreted as being due to a contribution from fission decays with a very long lifetime, corresponding to a recoil distance $v\tau$ of more than ~10 Å. The fission-fragment blocking patterns expected for such a long-lived component are shown in Figs. 3(a) and 3(b) by curves labeled $v_\perp\tau \gtrsim 1$ Å. By $v_\perp\tau$ we denote the average recoil distance perpendicular to the blocking string, $v_\perp\tau = v\tau \sin\varphi$, where φ is the angle between the recoil direction (beam direction) and the blocking axis. The expected patterns have been calculated by using a continuum multistring model with statistical equilibrium.[1] For one case [$-170°$, Fig. 3(b)], the blocking pattern expected for an intermediate recoil distance (0.4 Å) has also been calculated (dashed line). This value was chosen because it gives the same minimum yield as do the measured fission distributions. It is clear that no *single* lifetime can account for the experimental distributions. Such an explanation is also ruled out by the identity of the blocking patterns measured for two different values of the angle φ. However, the superposition of a very long and a very short component can produce an acceptable fit, as shown by the curves through the data points, which were calculated from a function of the kind $(A/\tau_1) \times \exp(-t/\tau_1) + (B/\tau_2)\exp(-t/\tau_2)$, where $\tau_1 < 10^{-18}$ sec, $\tau_2 > 10^{-16}$ sec, $A = 0.82$, and $B = 0.18$.

The distribution patterns show an indication of a small increase at the center. This is just the effect to be expected from flux peaking[4,5] for the long-lived component. The recoil direction is parallel to a {112} plane, i.e., directed towards the minimum in the transverse potential. This indication is barely significant but is supported by similar observations from other runs. Such an effect has been predicted[5] but not previously observed.

The results for 90-MeV ^{16}O on tungsten are shown in the lower half of Fig. 3. The blocking distribution observed at $+100°$ is similar to those obtained for 97 MeV. The recoil direction in this case is parallel to a $\{100\}$ plane, i.e., again towards a potential minimum. At $-170°$, a shape different from the 97-MeV data is obtained near the pattern center, indicating a significant contribution from recoil distances $v_\perp\tau$ in the range 0.1–1.0 Å. A distribution calculated on the assumption of exponential decay, with an average recoil distance $\langle v_\perp\tau\rangle$ of 0.7 Å, is shown in Fig. 3, and also a fit to the measured blocking dip with 25% of this component and 75% of the zero-lifetime component. Though not perfect, the fit demonstrates that the narrow dip is obtained from an intermediate-lifefime component. For the $+100°$ distribution, the corresponding value of $v_\perp\tau$ for the long-lived component is $\sim 0.7 \sin 80°/\sin 10° = 4$ Å, and the superposition using the same relative amount (25%) of the long-lived component fits the data reasonably well.

In conclusion, these results show that the detailed shape of blocking distributions can be used to give useful information on the shape of the decay function of excited compound nuclei. In the simplest case, the consistency of an observed increase in minimum yield with an appropriate decrease in width is a crucial test of the assumption that the result can be adequately represented by a single lifetime.[6] If the width and minimum-yield changes are not consistent, a multicomponent decay function is indicated, and the present results show that three important lifetime ranges can be distinguished: short, intermediate, and long lifetimes, corresponding to $v\tau \lesssim 0.1$ Å, 0.1 Å $\lesssim v\tau \lesssim 10$ Å, and $v\tau \gtrsim 10$ Å, respectively. For both short and long lifetimes, the dip is independent of the angle φ between tne recoil direction and the blocking axis, the two dips measured for different values of φ will be identical, and only the relative magnitude of the component can be determined. For intermediate lifetimes, however, the two dips will be different and information about the magnitude of the lifetime as well as about the relative magnitude of the component may be obtained. For the present cases, $v\tau = 1$ Å corresponds to $\tau \sim 3\times10^{-17}$ sec.

Information about the magnitude of these components can be an important guide for the theoretical description of the complicated decay sequence of nuclei with high excitation energy and spin. Preliminary theoretical work[7] indicates that lifetimes $\tau \gtrsim 10^{-18}$ sec are expected for fission after evaporation of several neutrons and that the contribution of late-stage fission may be comparable to that which we have observed experimentally. A full report on the experimental results, including a more detailed comparison with calculations, is in preparation.

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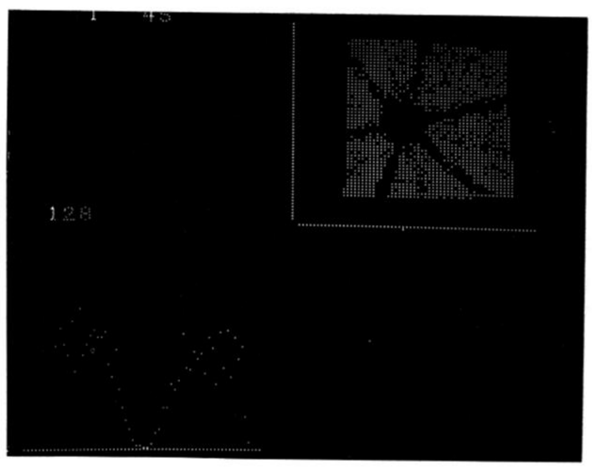

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