USE OF BLOCKING IN CRYSTALS TO STUDY THE LIFETIME FOR FISSION OF ^{238}U BY 12-MeV PROTONS

F. Brown, D. A. Marsden, and R. D. Werner
Research Chemistry Branch, Chalk River Nuclear Laboratories, Chalk River, Ontario, Canada

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Plastic detectors were used to observe angular distributions of fission fragments emerging from a UO_2 single crystal. In fission induced by thermal neutrons and by 12-MeV protons, characteristic blocking patterns were observed, showing strong attenuations along major crystal axes. This shows that fission occurred while the nuclei were within 0.1 Å of a lattice site and indicates that the total lifetime in 12-MeV proton fission is less than 2×10^{-17} sec.

There have been few attempts to measure the lifetime of the compound nucleus in fission.[1-4] Upper limits of $<6\times10^{-14}$ sec and $<4\times10^{-14}$ sec for the reaction of fission spectrum neutrons with ^{238}U and ^{237}Np, respectively,[4] are the best estimates to date. At excitation to levels near threshold, estimates from level widths give a τ_f of $\sim10^{-14}$ sec.[5]

The present experiment is designed to measure the lifetime of compound nuclei formed in 12-MeV proton-induced fission of ^{238}U by making use of the "blocking" phenomenon that occurs in single crystals of UO_2 and by using plastic detectors sensitive to fission fragments.[6]

Briefly, blocking occurs when a charged particle originating on a lattice site is prohibited from leaving the crystal exactly along the crystal axes and, to a lesser extent, along the crystal planes. The angular distribution of such particles shows a characteristic pattern of "dips" (attenuations) corresponding to the major crystal axes and planes. On the other hand, if the charged particle originates at a point removed from the lattice site by a distance greater than the Thomas-Fermi screening distance (≈0.1 Å), the blocking will be eliminated and no characteristic pattern should be detected. This phenomenon has been observed previously for α particles,[7] protons,[8-10] and positrons,[11] but not for fission fragments. The theory of blocking and of the related phenomenon of channeling has been developed by Lindhard.[12] The possibility of measuring extremely short lifetimes in nuclear reactions by making use of the "blocking" effect in single crystals has been suggested by Tulinov,[13] Gemmell and Holland,[10] and Dabbs.[14]

We first wished to confirm that the blocking pattern for fission fragments could be observed under experimental conditions involving a thick source and possible interference from radiation damage to the crystal by the fission fragments. To do this it was necessary to measure angular distributions in a situation where the fissioning nucleus is on a lattice site. This is the case for thermal-neutron-induced fission (of ^{235}U) in a single crystal. A single crystal of natural UO_2 was irradiated in the thermal neutron beam from the $N1$ hole in the NRU reactor. A Lexan plastic detector[15,16] was placed, in vacuum, at a distance of 50 cm from the crystal, so as to detect fragments emerging along and around the $\langle111\rangle$ axis. A mask over the crystal with a 1.0-mm-diam aperture defined the angular resolution at the detector as 0.1°.

After etching, the tracks in unit areas of 1 mm^2 were counted and a scan made in a random direction passing through the $\langle111\rangle$ axis. A second scan was made in a direction perpendicular to the first, and the two scans averaged to give the results shown in Fig. 1. A dip characteristic of blocking is seen at the axis, having an attenuation of about a factor of 5. The full width at half-maximum of the dip is ≈0.9° which is of the expected magnitude.[11]

To carry out observations where the fissioning nucleus is recoiling, fission was induced (in ^{238}U) by 12-MeV protons from the High Voltage Engineering Corporation Model MP tandem Van de Graaff accelerator. The crystal was aligned using Rutherford scattering techniques and transferred to a goniometer box on the accelerator. It was tilted until a $\langle110\rangle$ axis was 2° away from the proton beam direction; and then rotated 2° away from the plane. This ensures that the beam does not enter along either a major axis or a major plane. A Lexan detector was placed at 90° to the beam, 50 cm away, to observe fission fragments emerging around one of the other $\langle110\rangle$ axes. An aperture of 1 mm defined the beam. The crystal was irradiated with ~7 nA of 12-MeV protons for ~1 h.

A track count of the detector again revealed the characteristic blocking pattern. In this case, since the statistics were better, only a single

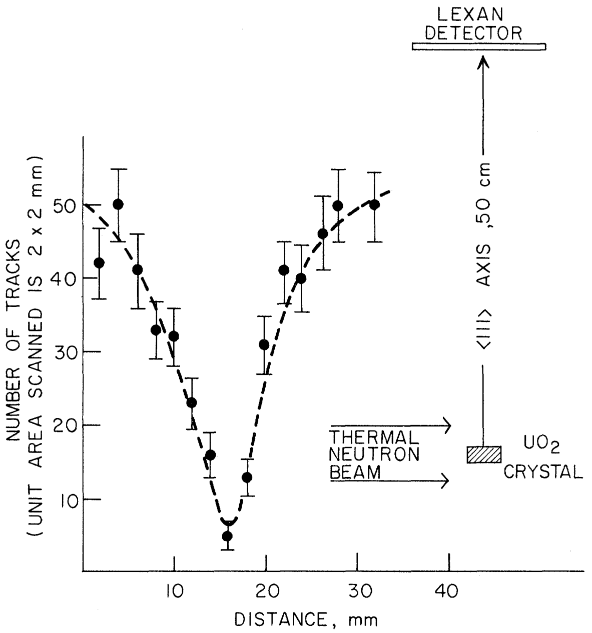

FIG. 1. Fission-fragment angular distribution around the ⟨111⟩ axis for thermal-neutron fission in a single crystal of UO_2. A distance of 1 mm at the detector subtends an angle of 0.1° at the crystal. The data are an average of two mutually perpendicular scans across the detector.

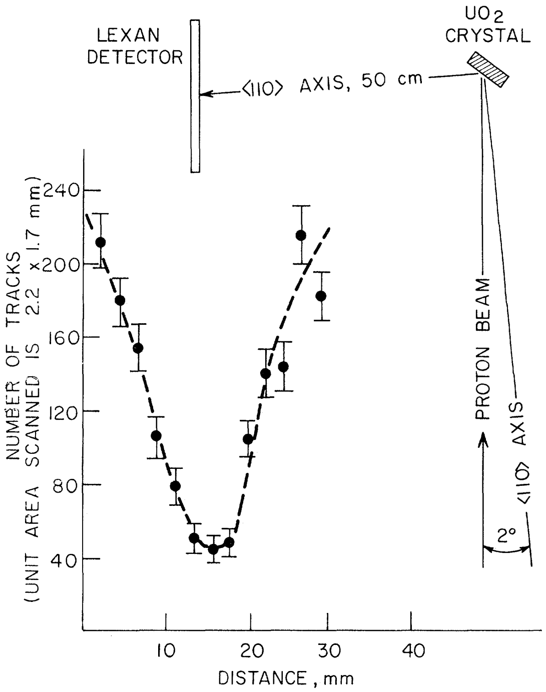

FIG. 2. Fission-fragment angular distribution around the ⟨110⟩ axis for 12-MeV proton-induced fission in a single crystal of UO_2. A distance of 1 mm at the detector subtends an angle of 0.1° at the crystal.

scan has been used to construct Fig. 2. The attenuation along the ⟨110⟩ axis was at least a factor of 7 and the full width at half-maximum was ≈1.3°. As a check on the ability of the detectors to distinguish fission fragments from scattered protons, we scattered a 12-MeV proton beam from a gold target into a Lexan detector; no tracks could be developed.

Each of the above experiments was performed three times. All results were essentially the same, although one run had very poor statistics.

In principle the attenuation should be larger. Using the reversibility principle[9] and data for channeling of He^+ ions in UO_2,[17,18] one might ideally expect a factor of about 40. The filling of the dip could be due to one or both of two causes. First, experimental deficiences such as depth effects may contribute. Second, for the proton fissions, some fraction of the nuclei may in fact have moved outside the screening distance; from the observed attenuation of 7 this fraction cannot be more than about 1 in 7.

The recoil velocity of the ^{239}Np compound nucleus for this experiment is 2×10^7 cm/sec and the time to travel outside the screening distance is therefore 5×10^{-17} sec. If no more than one-seventh of the nuclei survive for this time, the half-life must be less than about 2×10^{-17} sec.

This limit is considerably shorter than the lifetime expected for slow-neutron fission,[19] but could be quite appropriate for fission by 12-MeV protons. The lifetime measured by this type of experiment is of course the total lifetime, which in this case includes decay by neutron emission; the fission and neutron widths are probably comparable.[20]

The experimental results are also consistent with a lifetime so long that the recoiling nuclei have time to stop and diffuse back to a lattice site. Since this requires at least 10^{-12} sec, it is quite inconsistent with any estimates of fission lifetimes.

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MUON DECAY DEEP UNDERGROUND*

W. R. Kropp, Jr., and F. Reines
University of California, Irvine, California

and

R. M. Woods, Jr.
Case Western Reserve University, Cleveland, Ohio

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A measurement of delayed coincidences characteristic of muon decay has been made at a depth of 1440-hg/cm^2 standard rock with a 200-liter liquid scintillation detector. These results are consistent with the decay rate predicted from the depth-intensity curve for the penetrating component of the cosmic rays, providing independent evidence that this component is energetic muons.

It is generally accepted that cosmic rays observed deep underground are muons plus an accompanying soft secondary component. The identification is based mainly on two types of information: the interactions of the observed particles,[1] and the consistency between the sea-level muon spectrum and the depth-intensity curve.[2] Since accurate measurement of the sea-level spectrum is available to only a few hundred GeV,[3] this form of evidence is of limited usefulness at higher energies.

In this Letter we point out an additional and somewhat more direct test of the muon as the penetrating component: an observation of muon decay underground as compared with the rate expected from the depth-intensity curve. Such an observation is most persuasive because the decay of the muon with a 2.21-μsec mean life into an electron having a known energy spectrum uniquely characterizes the particle. An experiment of this type, employing a liquid scintillation detector at a depth of 1440-hg/cm^2 standard rock, is in the final stages of preparation.[4] The average energy loss for a cosmic ray arriving at this detector from the vertical direction will be about 400 GeV.[5] Particles arriving at other zenith angles will have correspondingly higher minimum energies.

Preliminary information is available from an experiment done, in the same location, in another context.[6] The relevant portion of that experimental system was a 200-liter liquid scintillator. Particles depositing more than 10 MeV in the detector triggered the electronics, and oscilloscope traces of the pulses were photographed. Delayed coincidences in the interval 1.5-5.0 μsec were observable, corresponding to an efficiency of 40% for decays with the muon mean life. Losses due to edge effects were about 8%.

In 1942 h of operation, 13 events were observed with the appropriate decay signature. The time interval and energy distributions shown in Table