Population of Fission Isomers in ^{236}U by the (d, p) Reaction*

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Measurements have been made of the ratio of the cross section for producing a fission isomer by the (d,p) reaction to the cross section for the (d,pf) reaction as a function of a discriminator setting on the energy of the outgoing proton. For the $^{235}U(d,p)^{236m}U$ reaction the results give isomer/prompt ratios of $(0.87 \pm 0.13) \times 10^{-4}$ for all excitation energies less than 7.5 MeV and $(2.05 \pm 0.25) \times 10^{-4}$ for excitation energies less than 6.0 MeV. The value obtained for the half-life of the ^{236m}U isomer is $T_{1/2} = 130 \pm 15$ nsec.

I. INTRODUCTION

Several groups have studied the production of fission isomers by means of direct (d,p) stripping reactions.[1-7] The population of isomers by a (d,p) reaction is believed to proceed via an excited state near the equilibrium deformation followed by penetration of the first peak in the fission barrier and subsequent γ-ray emission to reach the isomeric state in the second potential well. Thus, the mechanism for forming isomers in the (d,p) reaction is essentially the same as for the low-energy neutron-capture reactions that have also been investigated[8-12] in a variety of nuclei.

Recent measurements[7] of the relative energy spectrum of protons associated with isomer-production experiments have been analyzed in terms of a detailed model of fission through a two-peaked barrier. In this paper we report results of absolute measurements of the ratio of isomer production to fission for the $^{235}U(d,p)$ reaction as a function of excitation energy in the ^{236}U nucleus.

II. EXPERIMENTAL PROCEDURE

The equipment used 12-MeV deuterons from the Los Alamos variable-energy cyclotron in a scattering chamber and experimental area described in detail in another publication.[6]

The setup and electronics configuration are shown schematically in Fig. 1. Protons were detected at 90° to the beam in a 1-mm gold surface-barrier semiconductor detector which was covered with a 16-mil Al absorber foil. The absorber was used to shift the energy of the elastic deuterons away from the proton energies corresponding to the excitation of ^{236}U near the fission threshold. A threshold on the fast-time pickoff was used to restrict the data to events involving only protons above a fixed predetermined energy. The characteristics of the fast discriminator and the degrading foil give an effective energy resolution for the experiment of ~0.8 MeV. The energy resolution is defined as the energy difference between the proton energies where the transmission through the fast discrimination is 75 and 25%. A valid event required that the proton pulse come during the time associated with the period of the cyclotron beam pulse. When a valid event is obtained, a start pulse is provided to a time-to-amplitude converter (TAC). The TAC is stopped by a pulse from a coincidence between two fission fragments. The fission fragments are detected at 90° to the beam direction in 125-μ diffused-junction semiconductor detectors.

The output of the TAC was sorted in a multichannel analyzer and a typical output is shown in Fig. 2. The sharp accidental peaks occur at the positions of subsequent cyclotron beam pulses. The accidental contributions to the observed delayed events were determined in the following way: (1) a time spectrum of fission events was measured relative to the cyclotron oscillator signal as in previous experiments,[6] and (2) the measured time spectrum was normalized to the observed accidental peak and then subtracted from the proton-fission time spectrum (Fig. 2). The beam intensity was adjusted so that the true and accidental coincidence rates in the prompt peak were approximately equal. This resulted in a true/accidental ratio of ~2 for the delayed events.

The time spectra were corrected for accidental contributions and the number of isomeric (d,p) events was determined by fitting the delayed events to the known half-life. The total number of prompt (d,pf) events was determined from the integral of the prompt peak. Since the delayed and prompt events are measured in the same experiment, effects on the isomer/prompt ratio due to counting losses, discriminator setting, beam energy shifts, etc., tend to cancel out.

The target was a 400-$\mu g/cm^2$ UO_2 deposit evaporated on a carbon backing. The isotopic purity was 93.2% ^{235}U.

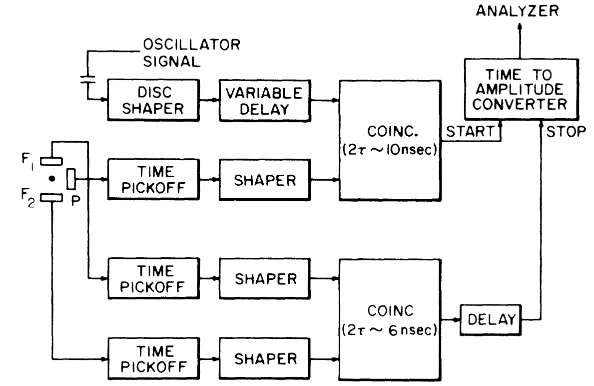

FIG. 1. Block diagram of electronics setup.

III. RESULTS

In order to get the best determination of the half-life for the ^{236m}U isomer all of the data were summed together. The sum data and the least-squares-fitted functions are shown in Fig. 3. The value $T_{1/2} = 130 \pm 15$ nsec is in good agreement with the values 130 ± 30 nsec reported by Lark *et al.*,[2] 105 ± 20 nsec reported by Wolf *et al.*,[3] and 130 ± 40 reported by Pedersen and Rasmussen.[7] Our value for the half-life is significantly longer than the value $T_{1/2} = 70 \pm 20$ nsec reported by Repnow *et al.*[4] but there is some evidence that the half-lives determined for isomers using recoil techniques may be systematically too low for (d,p) reactions.[4]

The measured isomer-to-prompt ratios are shown in Fig. 4 as a function of the maximum excitation energy for the ^{236}U nucleus. The results show that the isomer/prompt ratio decreases rapidly as the excitation of the compound nucleus is increased above the prompt-fission threshold. These results are consistent with the data report-

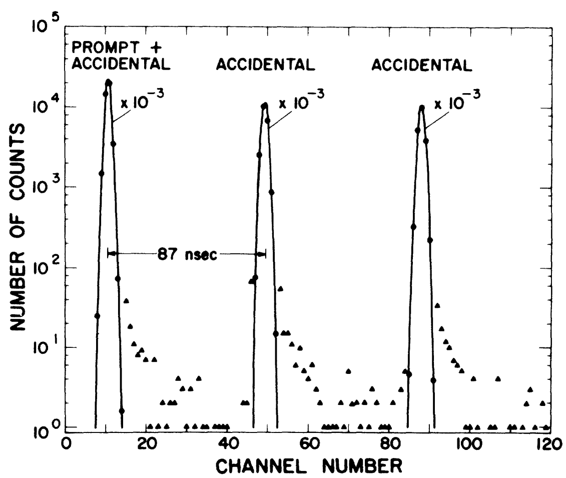

FIG. 2. Typical time spectrum for proton-fission coincidence events from the ^{235}U(d,pf) reaction.

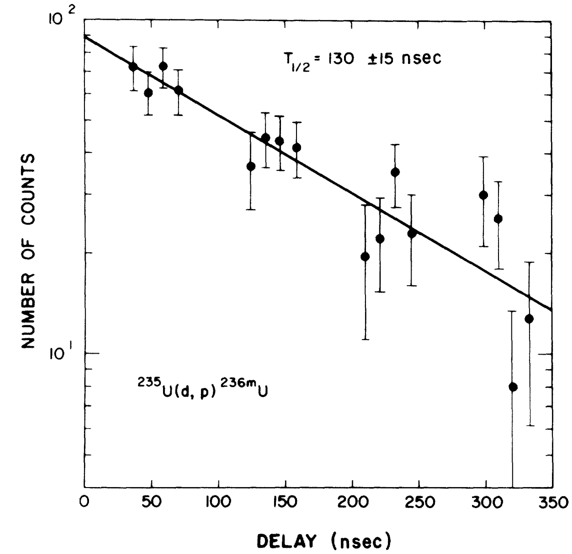

FIG. 3. Time spectrum for delayed events. Results are the sum of all runs and have been corrected for accidental contributions as described in the text. The solid line is a least-squares-fitted function with the indicated half-life.

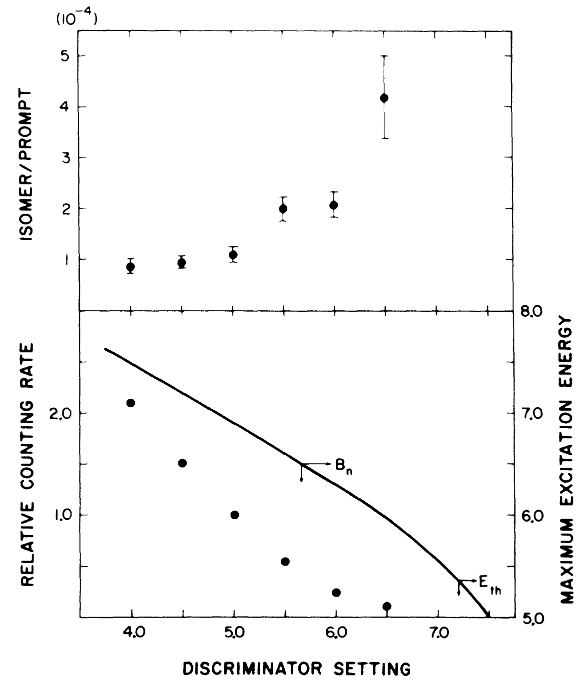

FIG. 4. Bottom half shows the relative proton counting rate as a function of the fast-discriminator setting (points) and a conversion between proton fast-discriminator setting and the maximum excitation energy in ^{236}U (solid line). Top half shows the measured ratio of isomeric prompt-fission events from the (d,p) reaction as a function of the proton fast-discriminator setting.

ed by Pedersen and Rasmussen[7] which show a peak in the isomer-production cross section for excitation energies near the fission threshold.

The dependence of the isomer/prompt ratio on excitation energy is similar to that observed for ^{242m}Am and ^{244m}Am isomers excited in (n,γ) reactions[8,9] but the absolute magnitude is about 10 times greater for the ^{236m}U case. This result is consistent with the trend that the second peak of the fission barrier decreases relative to the first peak as Z increases. The isomer/prompt ratios are not directly comparable to values obtained from (charged-particle, xn) reactions,[6] because of the differences involved in the neutron and γ-ray deexcitation processes.

Comparisons of (d,pf) and (n,f) cross-section data[13] have shown that except at low neutron energy ($E_n < 1$ MeV) the results from the two reactions are very similar. From these results we expect that the isomer/prompt ratio obtained in $(d,p\gamma)$ and (n,γ) reactions should be similar. However, neither the isomer/prompt ratio nor the measured half-life agrees very well with the results reported[11] for the $^{235}\mathrm{U}(n,\gamma)^{236m}\mathrm{U}$ reaction with 2.2-MeV neutrons. The value $T_{1/2} = 130 \pm 15$ nsec from this experiment is significantly different from the value $T_{1/2} = 66.6 \pm 8.7$ nsec reported from the (n,γ) work,[11] and the present results give an extrapolated value for the isomer/prompt ratio at $E^* = 8.7$ MeV ($E_n = 2.2$ MeV) of about $\frac{1}{4}$ the value reported from the (n,γ) experiment. Both of these discrepancies suggest that the (n,γ) results may contain a background with an apparent $T_{1/2} \sim 20-30$ nsec and an intensity roughly equal to that from the ^{236m}U isomeric decay. It seems unlikely that the (n,γ) process would excite an isomeric component that is not present in the (d,p) results, since comparisons of (d,pf) and (n,f) cross sections and angular distributions have shown that the two reactions are essentially equivalent for $E_n > 1$ MeV.[13]

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