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ABSTRACT

Cross sections for proton-induced fission of ^{238}U have been measured at seven proton energies ranging from 3.0 to 4.45 MeV using two position sensitive parallel-grid avalanche counters in a kinematic coincidence. In addition, an upper limit for the fission cross section was established a a proton energy of 2.5 MeV. The fission cross section decreases as expected at extreme sub-barrier energies down to a level of $\simeq$ 20 pb at 3 MeV. This result is in contradiction to recent findings of Ajitanand *et al.*,[1] who found that the fission excitation function exhibited a plateaux at about 1000 pb in the energy range from 1.0 to 3.5 MeV.

1. Introduction

Unexpectedly large cross sections for proton and alpha-induced fission of uranium targets have recently been reported by Ajitanand et al.[1,2]. These authors used a nuclear track detector technique for identifying fission fragments. By this method, they found that the fission cross section persists at a level of 0.1-1.0 nb down to beam energies of only a few MeV. At the lowest energy measured, the classical distance of closest approach between projectile and target exceeds by $\simeq$ 100 fm or about 10 times the proximity required for fusion. No acceptable explanation has been presented for these unique results. Consequently, we have undertaken to measure one of the reactions ($p+^{238}$U) using a different experimental technique, in which both fission fragments are detected in kinematic coincidence. Based on our measurements, we find that the fission cross section behaves as expected from simple barrier penetration and optical model calculations such as those of Ref. 1. These results are clearly at variance with the earlier measurements, which report a cross section 100 times larger at even lower proton energies.

2. Experiment

The measurement of sub-nanobarn cross sections in a reasonable amount of accelerator time requires relatively large beam currents (300-900nA) and, consequently, detectors which are almost totally insensitive to large rates ($\simeq 10^7$/sec) of elastically scattered protons. Ajitanand et al. used Lexan polycarbonate track detectors,[1] which are insensitive to protons and alpha particles to measure these small fission cross sections. These detectors do not, however, provide any timing information that would help to discriminate against background events.

The present measurements were carried out using two 20x20 cm^2 parallel-grid avalanche counters (PGAC's)[3] to detect both fission fragments in kinematic coincidence. These detectors, which were operated with 2 Torr isobutane gas, were found to be insensitive to the high rates of elastically scattered protons. The PGAC's provided timing information (the time resolution between the counters was typically 500 ps), x and y positions (with a resolution of 3 mm), and specific ionization. Binary fission events were identified by fulfilling three conditions: time coincidence, back-to-back emission of the fragments in the c.m. system, and anode signals consistent with strongly ionizing particles.

Coincident fission fragments produced by the bombardment of a 260 $\mu g/cm^2$ U_3O_8 target by a collimated beam of protons from the Argonne Physics Division's 4.5 MV Dynamitron Accelerator were detected in the two PGAC's. These were mounted at 90° to the beam direction at a distance of 11.5 cm from the target, each subtending a solid angle of 1.8 sr. A silicon monitor detector placed at an angle of 165° with respect to the beam direction was used to measure elastically scattered protons for cross section normalization. This detector subtended a solid angle of 5.4×10^{-5} sr. The beam current, which was between 300 and 900 nA in all runs, was measured in a Faraday cup located 70 cm behind the target. The duration of the runs ranged from 2 hours at 4.45 MeV to 14 hours at 3 MeV.

3. Data Analysis

One-dimensional spectra of the time difference, $\Delta t = t_2 - t_1$, between the anode signals from the counters are shown for events associated with large anode signals on the left side of Fig. 1. Events within a 25 ns window, indicated in the figure by dashed lines, are considered to be coincidences. Calculated mass distributions are shown on the right side of the figure for coincidences which satisfy the additional requirement of back-to-back emission in the c.m. system. The mass spectra all exhibit the double humped structure characteristic of actinide fission. This structure is also evident in the time spectra. The mass distributions in Fig. 1 were derived from the measured time difference $\Delta t = t_2 - t_1$ by assuming that the fission occured at rest in the lab frame and that the sum of the velocities of the fragments was a constant.

The back-to-back emission of the fragments was checked by calculating the quantities $(x_1 + x_2)/2$ and $(y_1 + y_2)/2$, where (x_1, y_1) and (x_2, y_2) refer to the points of detection in the two counters, the x direction in both being defined along the beam and the y direction along the vertical. Histograms of these average positions are

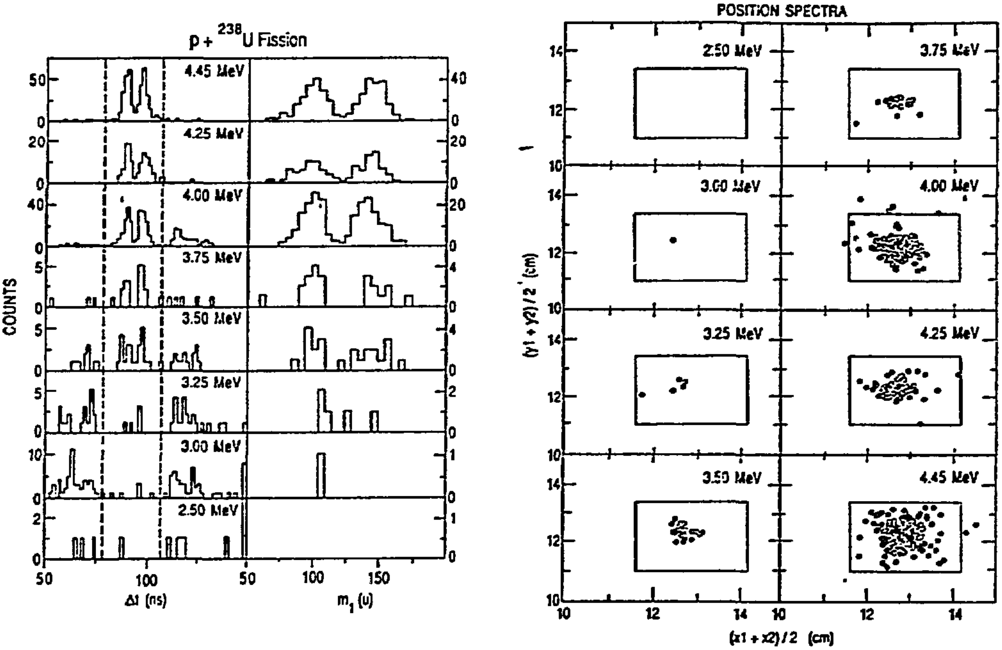

Fig. 1. Left: The measured time difference ($\Delta t = t_2 - t_1$) is shown for events associated with large anode signals. Derived fragment mass spectra for events satisfying the additional requirement of back-to-back emission is also shown. Right: Position spectra for events satisfying the requirements of time coincidence and large anode signals. Events falling within the indicated rectangular window are considered to exhibit back-to-back emission and accepted as true fission events.

shown in the right panel of Fig. 1 for events which satisfy the coincidence and anode signal requirements. For back-to-back events, one expects to see an average position corresponding to the location of the beam spot on the target with some spreading due to the combined effects of the initial momentum of the fissioning system, neutron evaporation from the fragments, multiple scattering in the target, and the position resolution of the detectors. A well defined average position is evident at the higher energies, and this allowed a window (2.6x2.4 cm^2) to be placed as illustrated to define valid fission events. The number of events satisfying all three requirements (time coincidence, back-to-back emission, and large anode signals) at each incident proton energy is listed in Table 1.

The background at long and short times in some of the runs is attributed to a known, weak contamination of ^{252}Cf on the walls of the scattering chamber. In these events, it is one fragment traversing both detectors which creates the apparent coincidence, as illustrated in the left panel of Fig. 2. This background is particularly noticeable at long times in the 4 MeV data due to the absence of an aluminum foil, thick enough to stop fission fragments, on the back of one of the detectors. In other

Table 1. Experimental fission cross sections for p + ^{238}U

E_p (MeV)	N_{fis} (counts)	σ_{fis} – (barns)
2.50	0	$< 1.2 \times 10^{-10}$
3.00	1	$(2.3^{+5.}_{-2.}) \times 10^{-11}$
3.25	5	$(1.9 \pm .9) \times 10^{-10}$
3.50	23	$(1.5 \pm .3) \times 10^{-9}$
3.75	22	$(4.1 \pm .9) \times 10^{-9}$
4.00	215	$(2.5 \pm .2) \times 10^{-8}$
4.25	108	$(6.9 \pm .7) \times 10^{-8}$
4.45	367	$(1.9 \pm .1) \times 10^{-7}$

runs the background counts correspond to fragments that passed through viewing holes in the aluminum foils behind either detector. In all cases, the ^{252}Cf events can be clearly separated from fission events in the target. As illustrated in the right panel of Fig. 2, this interpretation of the background events is consistent with the x-y distribution, since it is absent in the region, which is blocked by vertical brass tube, from which the target ladder extents.

The present setup also provided for an efficient method of measuring the background contribution from neutron-induced fission. A secondary UF$_4$ foil of thickness 350 μg/cm^2 was placed 2.5 cm above the target being bombarded by the proton beam. Neutron-induced fission events emerging from the foil would be detected in kinematic coincidence with an efficiency of $\simeq$ 80%. Only two events were observed, which may be associated with the neutron induced fission in this foil., both at 4 MeV bombarding energy. From their location, it seems more probable that these two events are actually associated with the primary target. Consequently, the neutron background was neglected in calculating the cross section for proton-induced fission.

5. Results

As indicated in Table 1, only one fission event was observed at an incident proton energy of 3.0 MeV. Because of the over-determination of the properties of the event, i.e. collinearity, time difference Δt, and energy losses in the two detectors, the confidence level for this being a true fission event is estimated to be $\geq$ 90%. This is calculated from the probability that the event in the position window is accidental.

The cross sections were calculated assuming an isotropic angular distribution of the fission fragments. This is expected to be a reasonable assumption based on the data of Boyce et al.,[5] who find an anisotropy of 5% at 10 MeV incident proton

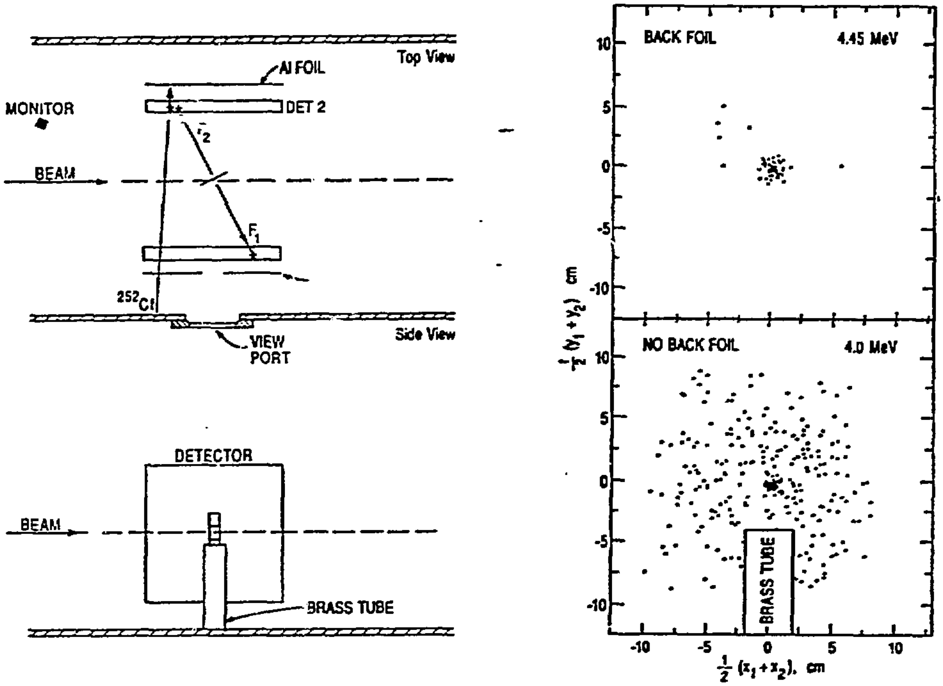

Fig. 2. *Left:* Top and side view of the experimental arrangement (not to scale). *Right:* Average position distributions for 4.0, and 4.45 MeV.

energies. The present data were also analyzed to produce angular distributions at each energy. All of these were found to be consistent with the assumption of isotropy to within statistical uncertainties. The resulting fission cross sections are listed for all incident energies in Table 1 and shown in Fig. 3 along with the data of Boyce et al.,[5] Kononov et al.,[6] and Ajitanand et al.[1] At 2.5 MeV incident energy, no valid fission events were observed and hence the listed value represents an upper limit on the cross section at this energy. The uncertainties in all cases reflect statistical uncertainties in the number of fissions observed, compounded with an estimated 3% uncertainty in the solid angle subtended by the PGAC's. The uncertainties at the lowest energies were calculated according to the prescription of Schmidt et al.[7] and represent a 68% confidence level.

The present measurements are in good agreement with all of the previous data at energies above 4 MeV, and with the data of Ajitanand et al.[1] at energies of 4 and 3.5 MeV. Below 3.5 MeV, the present measurements exhibit an exponential decline with decreasing proton energy, following the behavior expected from barrier penetration. We do not observe the enhancement seen in the data of Ref. 1. The one event seen at 3 MeV indicates a cross section several orders of magnitude below that seen in the

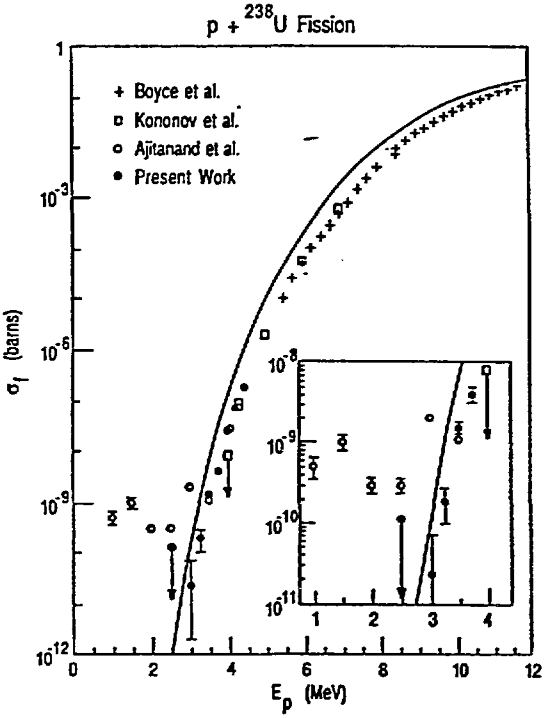

Fig. 3. The fission cross sections measured in the present work (solid circles) are compared with the results of ref. 1 (open circles), ref. 5 (crosses), and ref. 6 (open squares. The full drawn curve represents the optical model estimate published in ref. 1

previous measurement. The fact that no events were seen at 2.5 MeV indicates an upper limit on the cross section a factor of 3 lower than the previous measurement.

6. Conclusion

In conclusion, we find no evidence of an enhancement in the proton-induced fission cross section for ^{238}U at the energies measured. The data indicate an exponential decline with decreasing proton energy, in agreement with the expectation of barrier penetration and consistent with the optical model calculation of Ajitanand et al.[1]

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