STRUCTURE IN THE SUBTHRESHOLD ^{232}Th(n, f) CROSS SECTION*

J.W. BEHRENS and J.C. BROWNE
Lawrence Livermore Laboratory, University of California, Livermore, California 94550, USA

Received 19 May 1977

The fission cross section of ^{232}Th has been measured over the neutron energy range 0.1 MeV to 30 MeV at the Livermore 100 MeV electron linac. The observed structure in the cross section between 0.7 MeV and 1.4 MeV, attributed to vibrational states in the second well of the double-humped fission barrier, is clearly correlated with the angular anisotropy of fission fragments measured by others.

Structure has been observed in the subthreshold neutron-induced fission cross sections of many of the light actinides. The structure observed by Lamphere and Greene [1] in the ^{234}U(n, f) reaction was originally interpreted by Bohr [2] as representing competition between fission and inelastic neutron channels. However, a more recent analysis [3] was unable to explain similar gross structure resonances observed in the ^{230}Th(n, f), ^{232}Th(n, f) and ^{231}Pa(n, f) reactions using this interpretation. These gross structures are presently interpreted in a double-humped fission barrier model as vibrational resonances associated with the second well [3]. ^{233}Th is of particular interest because of its apparently shallow second well and the ^{232}Th fission cross section has been investigated in detail by Blons et al. [4] in the neutron energy range above 1.2 MeV where several vibrational states were observed. Between 0.6 and 3.0 MeV this cross section has been measured by Ermagambetov et al. [5] using a monoenergetic neutron source with an energy resolution of about 80 keV at 1 MeV. In addition, the angular distribution of fission fragments for ^{232}Th was measured by Ermagambetov and Smirenkin from 0.95 to 2.3 MeV [6] and by Androsenko and Smirenkin from 0.75 to 1.05 MeV [7]. These data show evidence for additional vibrational-like structure similar to that seen by Blons et al. More recently, Block et al. have observed structure in the ^{232}Th fission cross section below 100 keV [8]. In the present experiment, we have measured the ^{232}Th fission cross section relative to ^{235}U over the energy range 0.1 MeV to 30 MeV with an energy resolution of 20 keV at 1 MeV neutron energy. In this paper we discuss the structure observed in the energy region 0.7 to 1.4 MeV which correlates with previous fission fragment angular anisotropy measurements [6, 7].

The experiment was conducted at the Lawrence Livermore Laboratory (LLL) 100 MeV electron linac. The linac was operated at 1440 Hz with an electron pulse width of 10 ns to produce neutrons in a thick, water-cooled, tantalum target. The fission detectors, located at a flight path of 15.7 m from the tantulum target, were low-mass parallel-plate ionization chambers of modular design placed back-to-back in a pressure vessel, with the fission foils oriented perpendicular to the incident neutron beam. The fission chamber contained about 70 mg (150 μg/cm^2) of high purity ^{232}Th. An analysis of our ^{232}Th sample using isotope dilution mass spectrometry yielded measured impurities of one part in 10^6 ^{238}U and 3 parts in 10^9 ^{235}U. No other isotopes in the atomic mass range from 230 to 240 were observed. The time-of-flight technique was used to measure the fission cross section ratio as a function of neutron energy. The γ-ray flash from the tantalum target was the main timing reference. In separate measurements we verified the neutron energy scale derived from this timing to within ±2 ns by measuring the location of the 525 ± 2 keV resonance of lead and the 2077 ± 2 and 6293 ± 5 keV resonances of carbon [9]. The uncertainty of the energy scale is therefore ±3.5 keV at 1 MeV. The time resolution of approximately 11 ns, i.e. 0.70 ns/m, is determined by the resolution of the fission detectors (4 ns) and the neutron burst width (10 ns). This results in an energy resolution of 20 keV at 1 MeV which is a factor of

---

* Work performed under the auspices of the U.S. Energy Research and Development Administration. W-7405-Eng-48.

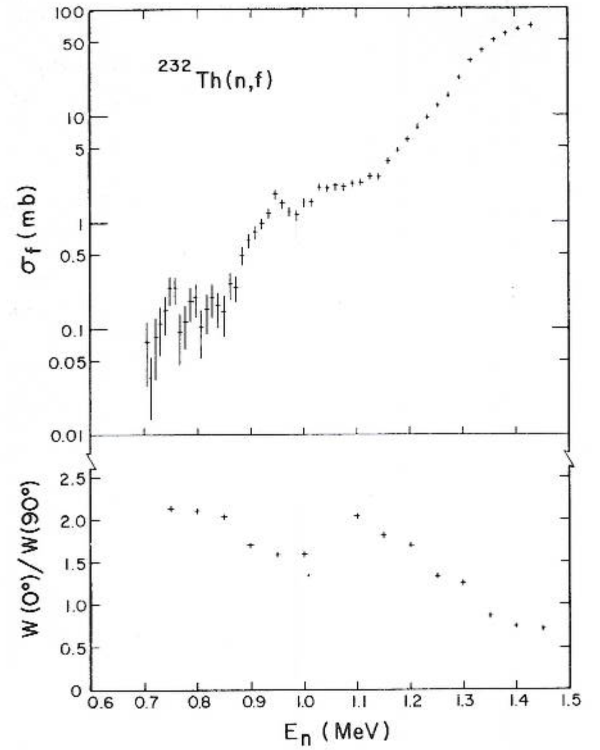

Fig. 1. Comparison of the ^{232}Th(n, f) cross section and the angular anisotropy of fission fragments in the neutron energy range 0.7 MeV to 1.45 MeV: Top – ^{232}Th(n, f) cross section. Present work is indicated by plus signs. Statistical counting uncertainties representing one standard deviation are included. Bottom – angular anisotropy $W(0°)/W(90°)$ for fission of ^{233}Th as measured by others [6, 7].

four better than the previous fission cross section measurement below 1.2 MeV [5]. Further details of the experimental method appear in ref. [10].

Fig. 1 shows the ^{232}Th fission cross section obtained in this measurement from 0.70 to 1.45 MeV along with the fission fragment angular anisotropy data, $W(0°)/W(90°)$, of Ermagambetov and Smirenkin [6] and of Androsenko and Smirenkin [7]. This ^{232}Th fission cross section was extracted using our measured ^{232}Th/^{235}U ratio and the ENDF/B-IV [11] evaluated fission cross section file for ^{235}U. Below 0.7 MeV, our sensitivity was not adequate to measure the small ^{232}Th fission cross section (<0.05 mb). A narrow resonance is observed near $E_n = 950$ keV in addition to the much wider structures near $E_n = 750$ keV and 1.1 MeV. It can be seen in fig. 1 that the $W(0°)/W(90°)$ data are clearly correlated with these gross structure resonances. The channel analysis by Ermagambetov and Smirenkin [6] indicates that the $E_n = 750$ keV and 1.1 MeV structures are associated with $K^\pi = 1/2^\pm$ where K is the projection of the angular momentum of the fissioning nucleus on the symmetry axis. Around $E_n = 950$ keV, their anisotropy data also show some contribution from a $K^\pi = 5/2^+$ or $7/2^-$ channel. This contribution most likely is due to the narrow resonance that we observe at 950 keV. The measured width of this resonance is approximately 30 keV and therefore was not observed previously due to the poorer resolution of the earlier cross section measurement [5]. If this resonance does have $K^\pi = 5/2^+$ ($7/2^-$) then we can expect it to be much narrower than the $K = 1/2$ resonances at 750 keV and 1.1 MeV because the specialization energy associated with the unpaired neutron in ^{233}Th would be different for the states with different K-values. The fission barrier would be higher for the $K^\pi = 5/2^+$ ($7/2^-$) state and hence it would be narrower.

Previous experimental results [4] indicate that the second well for ^{233}Th is shallow with the second well ground-state energy E_{II} being ≈ 4.6 MeV. Since the neutron binding energy in ^{233}Th is 4.79 MeV, a large fraction of the excited states in the second well can be examined in the ^{232}Th(n, f) reaction. The recent data of Block et al. [8] show structure in the fission cross section for ^{232}Th near the neutron binding energy. If this structure represents a vibrational state of low phonon number, then there should exist additional vibrational states below $E_n = 700$ keV. Lynn [12] has speculated that this structure may even be the zero-point vibration in the second well in which case the next vibrational state should appear around 0.5 MeV. Clearly ^{232}Th presents a unique case where one has $B_n \approx E_{II}$ and one may be able to observe all the levels in the second well. We will not be able to determine exactly how the states observed at 0.75, 0.95 and 1.1 MeV fit into this scheme until more data below 700 keV are available.

We would like to thank R.J. Dupzyk for the mass analysis of our thorium sample and J.W. Magana for his assistance in the preparation of the thorium fission foils.

References

[1] R.W. Lamphere and R.E. Greene, Phys. Rev. 100 (1955) 763.

[2] A. Bohr, Proc. United Nations International Conf. on Peaceful uses of atomic energy, Geneva 2 (1956) 220.

[3] J.E. Lynn, AERE Harwell Report AERE-R5891 (1968).

[4] J. Blons, C. Mazur and D. Paya, Phys. Rev. Lett. 35 (1975) 1749.

[5] S.B. Ermagambetov, V.F. Kuznetsov and G.N. Smirenkin, Yad. Fiz. 5 (1967) 257; Soviet J. Nucl. Phys. 5 (1967) 181.

[6] S.B. Ermagambetov and G.N. Smirenkin, Yad. Fiz. 11 (1970) 1164; Soviet J. Nucl. Phys. 11 (1970) 646.

[7] K.D. Androsenko and G.N. Smirenkin, ZHETF Pis. Red. 19 (1974) 355; JETP Lett. 19 (1974) 199.

[8] R.C. Block et al., Proc. Intern. Conf. on Interactions of neutrons with nuclei, Lowell, Mass. Vol. 2 (USERDA, Oak Ridge, 1976) p. 1400.

[9] S.F. Mughabghab and D.I. Garber, Resonance parameters, Brookhaven National Laboratory Rept. BNL-325, Vol. 1, 3rd. (1973).

[10] J.W. Behrens and G.W. Carlson, Nucl. Sci. Eng., to be published (1977).

[11] Evaluated Nuclear Data File/Format B-Version IV. This evaluation (ENDF/B-IV) originates at the Brookhaven National Laboratory, Upton, N.Y.

[12] J.E. Lynn, Proc. Intern. Conf. on Interactions of neutrons with nuclei, Lowell, Mass., Vol. 2 (USERDA, Oak Ridge, 1976) p. 828.