^{230}Th fission cross section near 715 keV

L. R. Veeser and D. W. Muir
University of California, Los Alamos National Laboratory, Los Alamos, New Mexico 87545
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We have used neutrons from an underground nuclear explosion to measure the differential fission cross section of ^{230}Th at two angles for the resonance near 715 keV. The relative energy resolution was about 1 keV. We find evidence for fine structure within the resonance, but individual peaks are not completely resolved.

[NUCLEAR REACTIONS ^{230}Th(n,f), $E_n = 690-760$ keV; measured $\sigma(E_n, \theta_{\text{fragment}})$.]

Measurements of the neutron-induced fission cross sections for the actinide elements are a primary diagnostic for determining the shape of the potential well barrier for fission. Specifically, the cross sections for ^{230}Th and ^{232}Th show resonances near threshold, and for ^{232}Th, high-resolution measurements indicate fine structure within each of its resonances.[1] The energy level spacings and the angular distributions of the fine structure resonances have been interpreted as evidence that the barrier for the fission of ^{233}Th is triple humped.[2] The cross section for ^{230}Th has resonances which, when measured with low resolution, look quite similar to those of ^{232}Th.

We have measured the ^{230}Th fission cross section from 690 to 760 keV by observing fission fragments at 100° and 125° (relative to the direction of incident neutrons) with an energy resolution of about 1.0 keV FWHM by using an underground nuclear explosion as a pulsed neutron source. Our objective was to study the large resonance near 715 keV with high resolution to look for fine structure. Our measurements were made at two angles to give some information about the fragment angular distribution, but unfortunately we could not measure angles very far apart because of constraints on the detector geometry.

We evaporated $^{230}ThO_2$ onto a thin stainless steel backing and placed the sample at an angle of 45° relative to the incident neutrons with the thorium deposit facing toward the source and the detectors. The isotopic enrichment of the sample was 80% (^{230}Th/Th), and the thickness was 0.5 mg/cm^2. Similar samples of ^{232}Th and ^{239}Pu were stacked behind the ^{230}Th. In a measurement previously reported,[3] silicon detectors were positioned at angles of 100° and 165° to measure the thorium and ^{239}Pu cross sections between 0.1 and 3.0 MeV to determine the background and the neutron flux. The data in this paper were obtained from two additional detectors in the same experimental assembly; they viewed the ^{230}Th sample at angles of 100° and 125° and provided data with better energy resolution in a narrow energy range around the 715-keV resonance. To optimize the resolution, we connected these detectors directly (without the usual logarithmic amplification) to 50-MHz oscilloscopes (Hewlett Packard model HP180). The detectors were placed 5.1 cm from the center of the sample and subtended solid angles of about 0.07 sr.

The oscilloscopes recorded the linear detector signals over a time span of about 3.5 μs with the

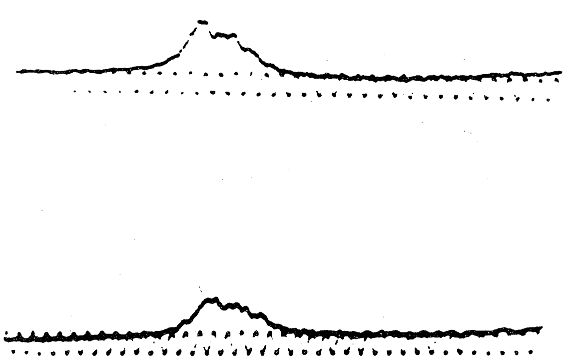

FIG. 1. The oscilloscope traces showing the fission fragment detector responses for 125° (top) and 100° (bottom). Beneath each trace is a 100-MHz sine-wave signal which provides the time calibration and baseline. Time increases from right to left.

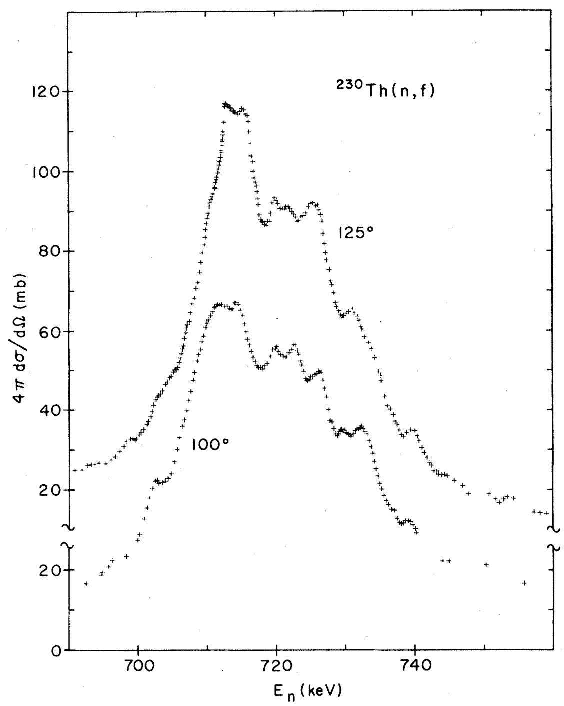

FIG. 2. Experimental results. The points were obtained by digitizing the traces of Fig. 1 and converting them to cross sections relative to the fission cross section of ^{239}Pu. The uncertainties in the cross section and in the absolute energy calibration are discussed in the text.

resonance peak roughly centered in the traces. In addition, a 100-MHz sine-wave signal was recorded to provide a baseline and a time reference. The oscilloscope traces are shown in Fig. 1. There was some interference between the data signals and the time marks in the wings of the resonance, but the two signals did not overwrite each other in the region of interest. Details of the recording procedures and equipment have been described by Hemmendinger.[4]

Figure 2 shows the results of the high-resolution measurement. The points were obtained by digitizing the oscilloscope traces and the timing signals. Since the detectors operated in the current mode, we did not count individual fission fragments. The shape of the measured curves is influenced to some extent by the response of the 500-m cables connecting the detectors to the oscilloscopes. For a square-pulse input several nanoseconds or more in length, the cable output rises to half the input value in about 10 ns, and the width of the pulse at half its height is transmitted with very little broadening, but there is a long tail on the output. We estimate that the tail can be 10% of the peak value as late as 30 ns after the end of the pulse. For the measurements shown here, there is likely to be some obscuring of any small peaks recorded shortly after a larger peak. This, or some other instrumental effect, may be responsible for the fact that there is less structure on the low-energy side of the peak than on the high-energy side.

Since we did not determine the time when the neutrons left the source, we were unable to measure the energy of the resonance absolutely. Instead we used the results of James *et al.*[5] to make an estimate. By measuring the lengths of the two detector cables, however, we were able to time the two traces relative to each other with an accuracy of about ± 0.2 keV in the relative positions of the two curves of Fig. 2. The relative detector timing from the cable length measurements also corresponds closely to the best alignment of the structure in the two measurements.

To determine statistical uncertainties from the observed signals, we calculated the number of fission fragments striking a detector per unit time. In the center of the resonance there were about 4×10^9 fragments/s striking the 125° detector. We estimate the statistical uncertainty in the height of the 5-keV-wide peak near 713 keV to be $\pm$ 5%, while in the wings of the resonance, the uncertainty in a 5-keV energy band increases to about $\pm$ 10%. Systematic uncertainties in quantities such as the

TABLE I. The parameters of Blons *et al.* (Ref. 8) for resonances with $l \leq 3$.

J^π	Energy[a] (keV)	σ_{cn}[b] (barns)
$\frac{1}{2}+$	711.5	0.38
$\frac{3}{2}+$	725.7	0.31
$\frac{5}{2}+$	722.5	0.47
$\frac{7}{2}+$		<0.01
$\frac{1}{2}-$	719.5	0.44
$\frac{3}{2}-$	714.5	0.88
$\frac{5}{2}-$	739.0	0.09
$\frac{7}{2}-$	733.0	0.12

[a]These energies were obtained from Ref. 8 by adding 6 keV to their values to make them correspond to our data peaks.
[b]Calculated compound nucleus formation cross section.

neutron flux, the ^{239}Pu reference cross section, and the detector sensitivities and solid angles can contribute a scale factor uncertainty as large as $\pm$ 20%. Usually, in measurements of this type, some of the systematic errors are reduced by measuring the flux and the cross section of interest in as similar a manner as possible,[6] but in this case, the flux was determined with a different type of recording system involving logarithmic amplifiers and much slower time resolution.[3] However, our intent here was to determine whether we could see any structure in the resonance rather than to determine its absolute cross section and energy.

Our results appear to indicate that the resonance has considerable structure, but we were unable to resolve individual line-structure peaks as well as Blons *et al.*[1] did for ^{232}Th. The uncertainties in our results prevent one from excluding the possibility that some of the smallest bumps are experimental fluctuations. However, recently Blons *et al.*[7] measured the angle-integrated fission cross section with slightly lower energy resolution but better statistical uncertainties than we obtained. Their results agree well with ours, showing roughly similar amounts of structure, but to obtain good correspondence between peaks in the two sets of measurements, it is necessary to shift our data downward in energy by 6 keV.

Blons *et al.*[7] identified eight possible resonances, suggesting that the system should be considered as two rotational bands of opposite parities superimposed upon the vibrational state. In a later paper,[8] they postulated a rearranged version of the same resonances which shows much better agreement with the angular dependence of our data. The resonance parameters are listed in Table I. (We have increased the resonance energies by 6 keV so that they can be compared with the locations of the peaks in Fig. 2.) The moment of inertia $\mathscr{I}$ for the two rotational bands is given[8] by $\hbar^2/2\mathscr{I}=(2.0\pm0.1)$ keV, and the decoupling parameters are $a(K^\pi=\frac{1}{2}^+)=1.3\pm0.2$ and $a(K^\pi=\frac{1}{2}^-)=-1.5\pm0.2$.

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