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ABSTRACT

Subbarrier fission resonances have been found in ^{230,232}Th(t,pf) and ^{230}Th(d,pf) reactions. This is in disagreement with the fission barriers predicted by the Strutinsky theory.

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In a recent article Bolsterli et al[1] have calculated the shapes of the double-humped fission barriers throughout the actinide region. These authors used the Strutinsky procedure[2] of a smoothly varying liquid drop model with shell corrections calculated from a realistic diffuse-surface single-particle potential. The work concludes that a new island of stability in the region $Z \simeq 114$, $N \simeq 184$ probably exists. The purpose of the present study was to test the theoretical predictions for the light actinide elements, namely the Th-isotopes. The barrier shapes for the even Th-isotopes calculated by different groups[1,3,4] show a high outer peak combined with a rather shallow second minimum and a very low intermediate barrier between the first and second minimum.

Recently Lynn et al.[5] have analysed results from a ^{230}Th(n,f)-experiment and derived from these data a fission barrier which indicate roughly equal heights for the two maxima. This result does not agree with the theoretical predictions. However, since the effect of an odd particle on the fission barrier is not well understood, the present study was performed in order to search for subbarrier resonances in the even Th-isotopes and thereby remove this ambiguity in the interpretation. The present letter reports subbarrier resonance structures for the even Th-isotopes ^{234}Th and ^{232}Th which have not previously been detected.

Subbarrier resonances were sought for in the following reactions: ^{230,232}Th(t,pf)^{232,234}Th and ^{230}Th(d,pf)^{231}Th. The various beams were provided from the Los Alamos Tandem Van de Graaff Facility and a bombarding energy of 15 MeV was used in both the (d,p) and (t,p) reactions. In the experimental set-up coincidences were recorded between fission events from a surface barrier annular detector and

outgoing light particles, which were mass identified by means of a ΔE-E counter telescope situated at ≈ 90° with respect to the beam axis. The experimental set up is similar to that described in Ref. 6. The energy resolution obtained in the telescope system was ≈ 70 keV. The targets were vacuum evaporated on carbon backings and were of thickness ≈ 200 $\mu g/cm^2$. The isotopic purity of the target materials was ≈ 90% and ≈ 100% for ^{230}Th and ^{232}Th respectively.

As an example of the quality of the data, the measured fission probability for the ^{230}Th (d,pf) reaction is plotted in Fig. 1 versus excitation energy in ^{231}Th. The error bars represent statistical uncertainties and do not include systematical errors in either the fission probability or the energy calibration. The uncertainty in the absolute fission probability is estimated to be ± 20% and the excitation energy uncertainty is ± 30 keV. The data have been corrected for accidental coincidences, which are shown to scale in Fig. 1. A subbarier resonance at 5.84 MeV of a width approximately equal to the energy resolution is observed in the ^{230}Th (d,pf) data; this resonance has been reported previously in the ^{230}Th (n,f)-reaction[5,6]. A resonance in ^{233}Th has probably been identified previously in the (n,f)-reaction[7].

Figure 2 shows the (t,pf) results. The broad resonance structure at 5.50-5.85 MeV in ^{234}Th has not been reported earlier, and it also seems probable that a resonance exists near 5.3 MeV, although the statistics in this case are poor. On the basis of these data it is not possible to decide whether the sharp decrease in the fission probability which starts at ≈6.15 MeV is caused by the onset of neutron evaporation alone, (B_n = 6.179 MeV) or if it is caused by a fission resonance at ≈6.15 MeV.

A weak resonance possibly occurs at 5.50 MeV in ^{232}Th, although it is not as pronounced as in the ^{234}Th case. It is concluded that subbarrier resonances occur systematically in the Th-isotopes.

The data have been analysed using a model for calculating the fission probability which assumes a two humped fission barrier. This model is essentially the same as previously used in the analysis of (d,pf) data[8]. The best fits to the data, obtained from these calculations by varying the parameters of the double humped barrier, are shown in Fig. 2 in comparison with the data. The relative order of the opening of the fission channels has been taken from Cramer et al.[9] From the calculations it was found that the difference in height of the two peaks of the fission barrier can not exceed $\approx$ 1 MeV in the ^{232}Th and ^{234}Th cases if the resonances in these nuclei should be reproduced with the observed strength (see Table I). The theoretical calculations give barrier differences between 2.0 and 4.3 MeV. It may be noted that the ^{231}Th barrier parameters are quite similar to the even Th numbers (Table I).

Theoretical and experimental barrier parameters for the Th and Pu isotopes are shown in Table I. It is seen that the overall agreement between theory and experiment for the Pu isotopes is good, but this is not the case for the Th isotopes. The trend is that the experimental values of the height of the two peaks do not vary much when going from Pu to Th, whereas the theory predicts a strong decrease of the first peak.

It would be desirable to obtain accurate fission probabilities versus excitation energy for the heavy actinide region in order to learn whether the failure in the theoretical predictions is confined to the Th region or if it persists above Pu. Such experiments, using the (^{3}He,df) reaction are in progress in this laboratory.

We are indebted to J. R. Nix and J. Pedersen for many stimulating discussions. The barrier predictions cited in Table I for Th were kindly made by J. R. Nix and J. L. Norton.

Table I

Fission Barrier Parameters: The energies of the first maximum, the second minimum and the second maximum are labeled E_A, E_{Min} and E_B respectively. The energy of the fission isomer is E_{IS}. All energies are relative to the ground state energy. The curvatures $\hbar\omega$ are labeled accordingly.

Nucleus	Ref	E_A MeV	$\hbar\omega_A$ MeV	E_{IS} MeV	E_{Min} MeV	$\hbar\omega_{Min}$ MeV	E_B MeV	$\hbar\omega_B$ MeV	E_B-E_A MeV
Theory:									
^{232}Th	a	4.8	-	2.8	-	-	7.3	-	2.5
	b	4.3	-	1.9	1.4	-	8.6	-	4.3
	c	3.4	-	2.3	1.8	-	6.6	-	3.2
^{234}Th	a	5.4	-	2.6	-	-	7.4	-	2.0
	b	4.3	-	2.0	1.5	-	8.6	-	4.3
	c	3.8	-	2.3	1.8	-	6.4	-	2.6
Experiment:									
^{231}Th	d	6.50	0.57	4.5	-	0.6	6.15	0.90	-0.35
^{232}Th	Present	5.50	0.90	4.43	4.25	0.36	6.18	0.47	0.68
^{234}Th	Present	6.05	0.90	4.41	4.12	0.57	6.45	0.70	0.40
Theory:									
^{240}Pu	a	6.3	-	2.5	-	-	5.3	-	-1.0
	e	5.8	-	2.7	-	-	5.6	-	-0.20
	c	5.2	-	2.3	1.8	-	5.5	-	0.30
Experiment:									
^{240}Pu	f	6.05	1.00	2.95	2.35	1.20	5.55	0.70	-0.50
	g	5.50	1.25	2.30	-	-	5.35	0.60	-0.15

a. Ref. 3. Mass asymmetry at the second maximum is included. Parameters from table 2A in this reference. It is not clear what value of the zero point energies in the two minima has been used in this case.

b. Values from ref. 7 but corrected for mass asymmetry at the second peak and include hexadecapole deformation at the ground state minimum. A zero point energy of 0.5 MeV is assumed for both the ground state and the isomeric state.

c. Ref. 4. Mass asymmetry at the second maximum is included. A zero point energy of 0.5 MeV is assumed for both the ground state and the isomeric state.

d. Ref. 5. Unlike these authors we have assumed a smaller and thinner first barrier, which is a qualitative result of the theory.

e. Ref. 1. A zero point energy of 0.5 MeV is assumed for both the ground state and the isomeric state.

f. Ref. 8.

g. Parameters extracted from model calculations of the excitation function for populating the fission isomer.
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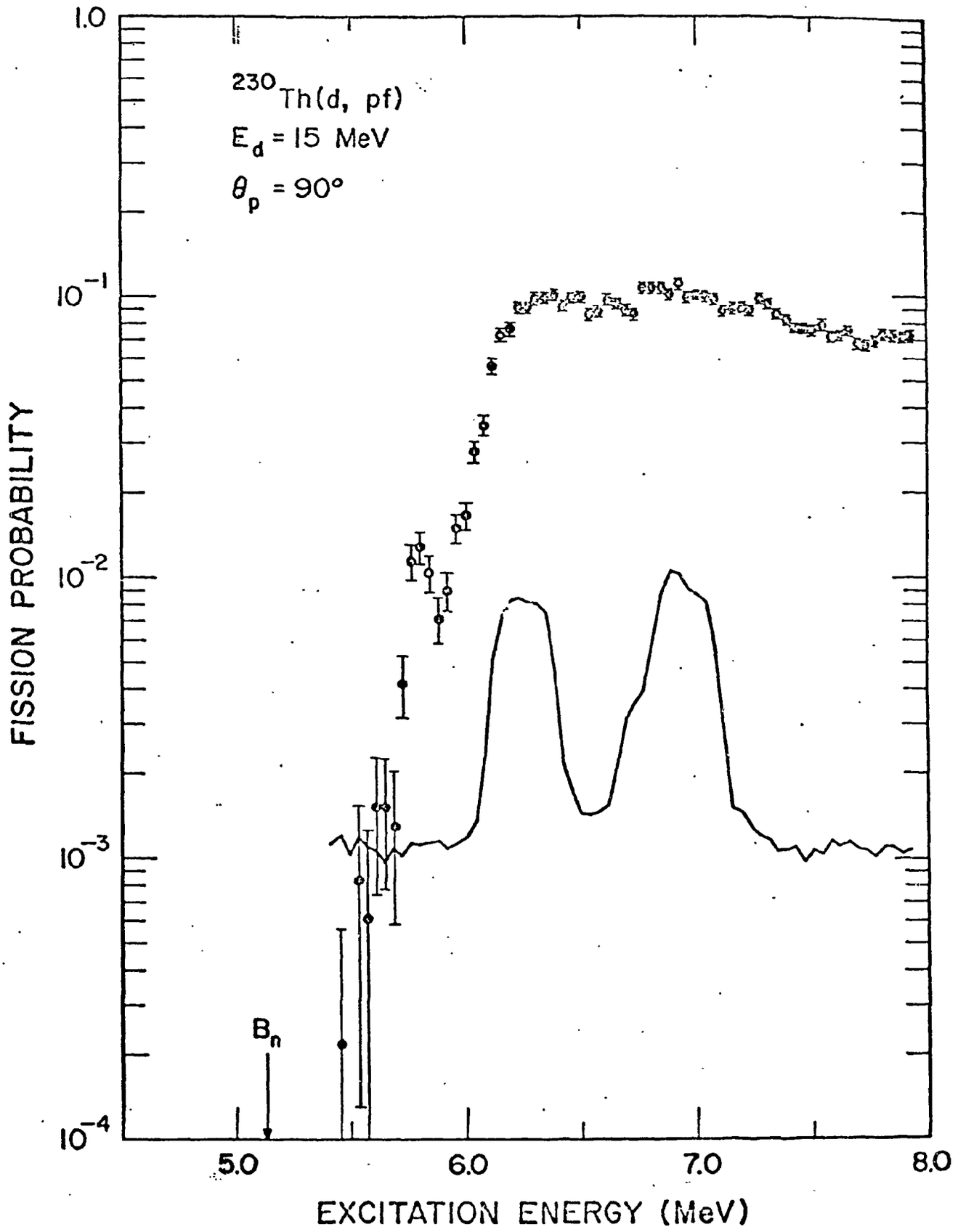
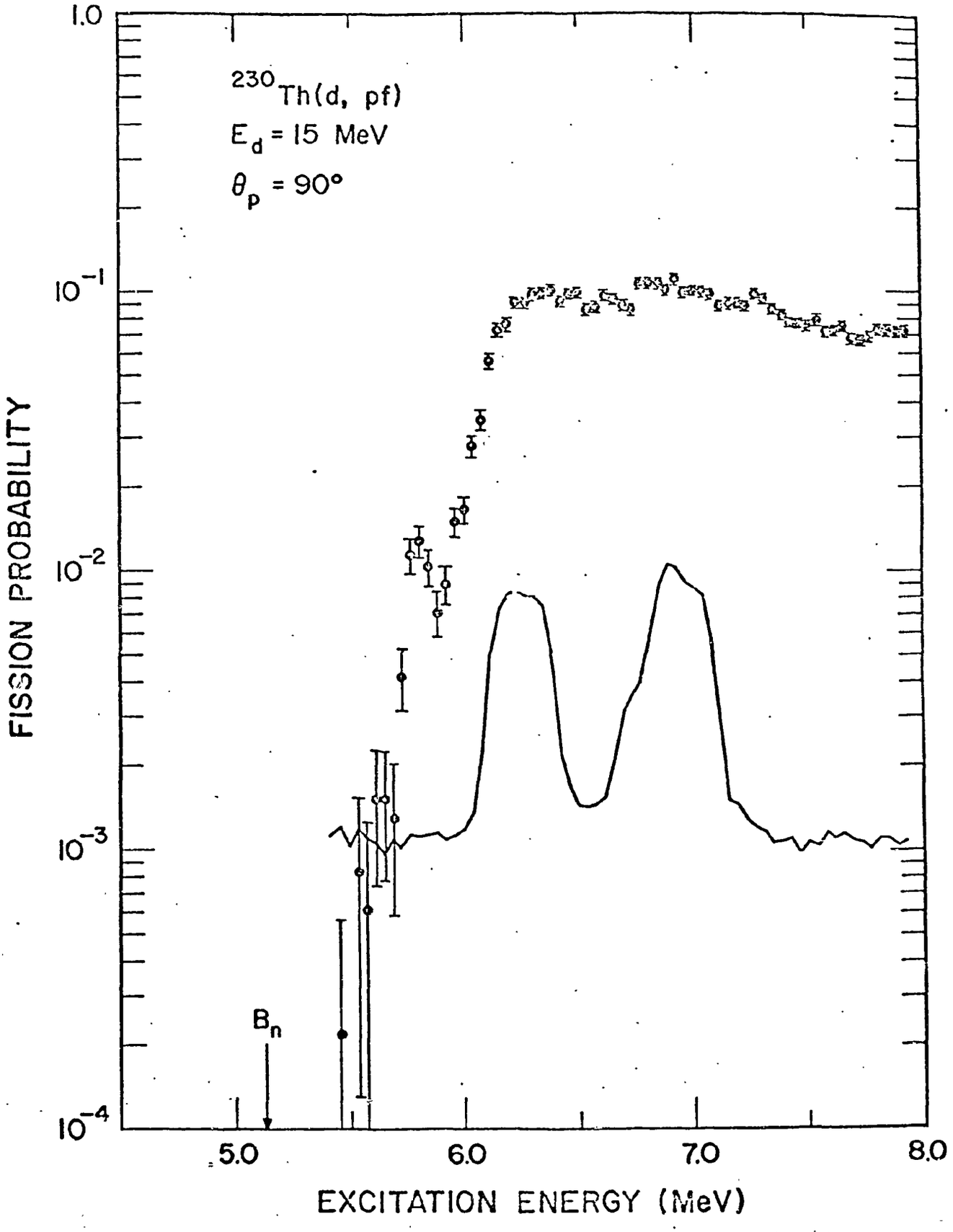
Figure Captions:

FIG. 1. Semilogarithmic plot of the measured fission probability (dots with error bars) versus excitation energy for the reaction ^{230}Th(d,pf). Accidental coincidences are represented by the solid line. The neutron binding energy is indicated by B_n.

FIG. 2. Semilogarithmic plot of the measured fission probability (dots with error bars) versus excitation energy for the reactions ^{230,232}Th(t,pf). Best fits from model calculations corresponding to parameters in Table I are represented by the solid lines. The neutron binding energies are indicated by B_n.


1.0
^{230}Th(d, pf)
E_d = 15 MeV
θ_p = 90°
10^{-1}
10^{-2}
10^{-3}
10^{-4}
FISSION PROBABILITY
B_n
5.0
6.0
7.0
8.0
EXCITATION ENERGY (MeV)


1.0
^{230}Th(d, pf)
E_d = 15 MeV
θ_p = 90°
10^{-1}
10^{-2}
10^{-3}
10^{-4}
FISSION PROBABILITY
B_n
5.0
6.0
7.0
8.0
EXCITATION ENERGY (MeV)