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DETERMINATION OF THE FISSION THRESHOLD FROM EXPERIMENTS ON THE (d, pf) *AND* (γ, f) *REACTIONS*

L. N. USACHEV, V. A. PAVLINCHUK, and N. S. RABOTNOV

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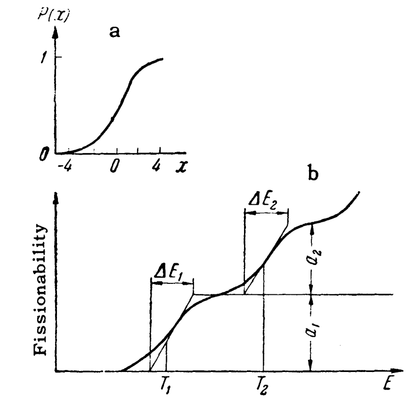
The experimental data on the energy dependence of the cross sections of the (d, pf) reactions on U^{233}, U^{235}, and Pu^{239} at excitation energies smaller than the binding energy of the neutron in the compound nucleus are interpreted under the assumption that for a completely open fission channel the fission width is much greater than the radiative width, this being consistent with the estimates made on the basis of the Bohr-Wheeler formula. It is shown that the alternative assumption ($\Gamma_f \ll \Gamma_\gamma$) which has in fact always been implied in previous analyses yields fission threshold values which are lower than the true value by several hundred keV.

STOKES, Northrop, and Boyer[1] obtained experimentally with the aid of the (d, pf) reaction the fissionability curves of the compound nuclei U^{234}, U^{236}, and Pu^{240} for excitation energies starting from $B_n - B_d$ where B_d is the deuteron binding energy and B_n is the neutron binding energy in the corresponding nucleus. The curves have a characteristic form shown in the figure. The fission thresholds were determined from these curves as those values of the energy at which the fissionability reaches half its value on the plateau. Such a determination is based on the assumption that the fissionability is proportional to the penetrability of the fission barrier which is described by the formula of Hill and Wheeler[2]

$$P(E, E_f) = \left[1 + \exp\frac{2\pi(E_f - E)}{E_{curv}}\right]^{-1}, \qquad (1)$$

where E is the excitation energy, E_f is the threshold value, and E_{curv} is the order of magnitude of the energy characterizing the curvature at the top of the barrier, and consequently its width for a given height (cf. [2]).

The penetrability of a barrier for a fixed height increases with increasing E_{curv}. However, in the general case the fissionability is equal to $\Gamma_f/(\Gamma_f + \Gamma_c)$ where Γ_c is the total width of the competing processes, and the threshold will be located at the point where the fissionability reaches half its value on the plateau only in the event when $\Gamma_f \ll \Gamma_c$ even on the plateau. This is close to being true, for instance, when the fission threshold is considerably higher than the neutron binding energy and when the chief competing process is neutron emission. However, when $E < B_n$ only



Dependence of the barrier penetrability on $x = 2\pi(E - E_f)/E_{curv}$ for $E_{curv} = 0.8$ MeV (a) and a schematic diagram of the energy dependence of the fissionability according to [1] (b). T_i – points in which the fissionability reaches half of its value on the plateau; $\Delta E_i = 2E_{curv,i}/\pi$.

gamma-quantum emission competes with the fission, i.e., $\Gamma_c = \Gamma_\gamma$. Estimates from the Bohr-Wheeler formula [3] indicate that in the region of excitation energies used in [1] with a barrier penetrability close to unity, $\Gamma_f \gg \Gamma_\gamma$, and the fissionability is 0.5 when $\Gamma_f = \Gamma_\gamma$, i.e. for a penetrability much less than unity, which corresponds to an excitation energy considerably lower than the threshold.

For quantitative estimates we make use of the Bohr-Wheeler formula:

$$\Gamma_f = \frac{D}{2\pi}\sum_{i=1}^{N} P_i(E, E_{fi}), \qquad (2)$$

where D is the distance between the levels of a compound nucleus with given spin and parity, i is the number of the fission channel, and N is the number of fission channels. From the condition $\Gamma_f = \Gamma_\gamma$ for the case of one channel, using (1) and (2), we find that the fission threshold T determined in [1] is lower than the true threshold E by the amount

Threshold shifts calculated under various assumptions on the curvature of the barrier top.

Compound nucleus	Fission thresholds assumed in [1], MeV	Fission threshold shifts ΔE_f, MeV	
		for $E_{curv} = 0.8$ MeV	for $E_{curv} = 0.4$ MeV
U^{234} ($B_n = 6.8$ MeV)	$T_1 = 5.25$	0.65	0.33
	$T_2 = 6.06$	0.41	0.2
U^{236} ($B_n = 6.4$ MeV)	$T_1 = 5.82$	0.42	0.21
Pu^{240} ($B_n = 6.4$ MeV)	$T_1 = 4.73$	0.8	0.4
	$T_2 = 5.75$	0.55	0.27

$$\Delta E_f = E_f - T = (E_{curv}/2\pi) \ln (D/2\pi\Gamma_\gamma - 1). \qquad (3)$$

To calculate the level density we used the formula of the Fermi-gas model

$$\rho(E, J) = \rho(E) \frac{2J+1}{4\sqrt{2\pi}\,\sigma^3} \exp\left\{-\frac{(J+1/2)^2}{2\sigma^2}\right\},$$
$$\rho(E) = \frac{\sqrt{\pi}}{12(6a)^{1/4}(E')^{5/4}} \exp[2(aE')^{1/2}]; \qquad (4)$$

$E' = E - \Delta$. The parameters a, Δ, and σ were chosen by A. V. Malyshev from a comparison with experimental data for $E = B_n$. As regards Γ_γ, it is known that it depends weakly on the energy, increasing by about 15 percent when the excitation energy increases by 1 MeV (see, for instance, [4]). Therefore in the calculations use was made of the average value of Γ_γ in the resonance region. It must be noted that the results obtained from the formula depend weakly on the possible errors in the determination of D and Γ_γ.

The estimates of E_{curv} available in the literature (see [1, 2, 5, 6]) vary from 0.4 to 0.8 MeV. Calculations were carried out for these two limiting cases. Inasmuch as neutrons with high orbital angular momenta take part in the formation of the compound nucleus in the (d, pf) reaction on 14-MeV deuterons, the values of ΔE_f for each threshold were calculated for J ranging from 0 to 6, the results turning out to be weakly dependent on J. The averaged values are cited in the table.

Our results indicate that for a determination of the threshold it is necessary to know as precisely as possible the energy dependence of the penetrability which may in addition be different for different thresholds. All the above considerations must necessarily also be taken into account in the determination of thresholds from the (γ, f) reaction.

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