Properties of p resonances in the fission of ^{235}U by neutrons with energies of 1–136 eV

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The P-even front–back asymmetry in the emission of the fission fragments of ^{235}U, with respect to the direction of the neutron momentum, has been measured for the first time. Irregularities due to p resonances are observed on the energy dependence of the asymmetry coefficient α_{nf}^{fb}. The effective parameters of the strongest p resonances are determined.

1. The active research on various parity-breaking effects and discussions of possibilities for searching for T-noninvariance effects near weak neutron p resonances in complex nuclei[1–3] have recently attracted particular interest to the properties of these resonances. For heavy fissionable nuclei, however, essentially nothing is known about the parameters and decay properties of low-lying ($E_n \ll 1$ keV) neutron p resonances which are not observed in the cross section.

A new method for obtaining the corresponding information has been proposed and implemented. The idea of this method is to study the energy dependence of the p-even front–back asymmetry of the fission fragments. This asymmetry stems from an interference of s and p compound states during the capture of slow neutrons. It has a feature in the vicinity of the p resonance. According to Refs. 1 and 2, we have $W(\theta) = 1 + \alpha_{nf}^{fb}(\vec{p}_n \cdot \vec{p}_f)$, where we would have

$$\alpha_{fb}^{nf} \sim Q_{\rm sp} \cdot \sqrt{\frac{\Gamma_p^n \Gamma_p^f}{\Gamma_s^n \Gamma_s^f}} \,\mathrm{Re}\left\{ \frac{E - E_s + \frac{i\Gamma_s}{2}}{E - E_p + \frac{i\Gamma_p}{2}} \exp(i \Delta \varphi_{\rm sp}) \right\} \tag{1}$$

in the case of the simple two-level approximation. Here $\vec{p}_n$, $\vec{p}_f$ are the momenta of the neutrons and the light fragments; $Q_{\rm sp} = Q(J_s, J_p, j, K, I)/2J_s + 1$ is a spin factor;[1] $\Delta\varphi_{\rm sp}$ is a phase difference; and $\Gamma_{s,p}^{n,f}$ are the corresponding widths for the s and p interfering resonances.

2. The energy dependence of the coefficient α_{nf}^{fb} was studied in the neutron beam of the GNEĬS time-of-flight spectrometer[4] over the energy range 1–136 eV, with the help of a fast multisection ionization chamber containing ~ 2 g of ^{235}U. The experimental apparatus and the measurement procedure are described in Ref. 5.

Irregularities were observed at a level $\sim 10^{-2}$ in the energy dependence of the coefficient α_{nf}^{fb}, (Refs. 6 and 7). These irregularities correspond to the theoretical predictions for the vicinities of the strongest ($\Gamma_p^n > \overline{\Gamma_p^n}$) p-wave neutron resonances (Fig. 1). The shape of the irregularities varies from bipolar to bell-shaped. The weight-

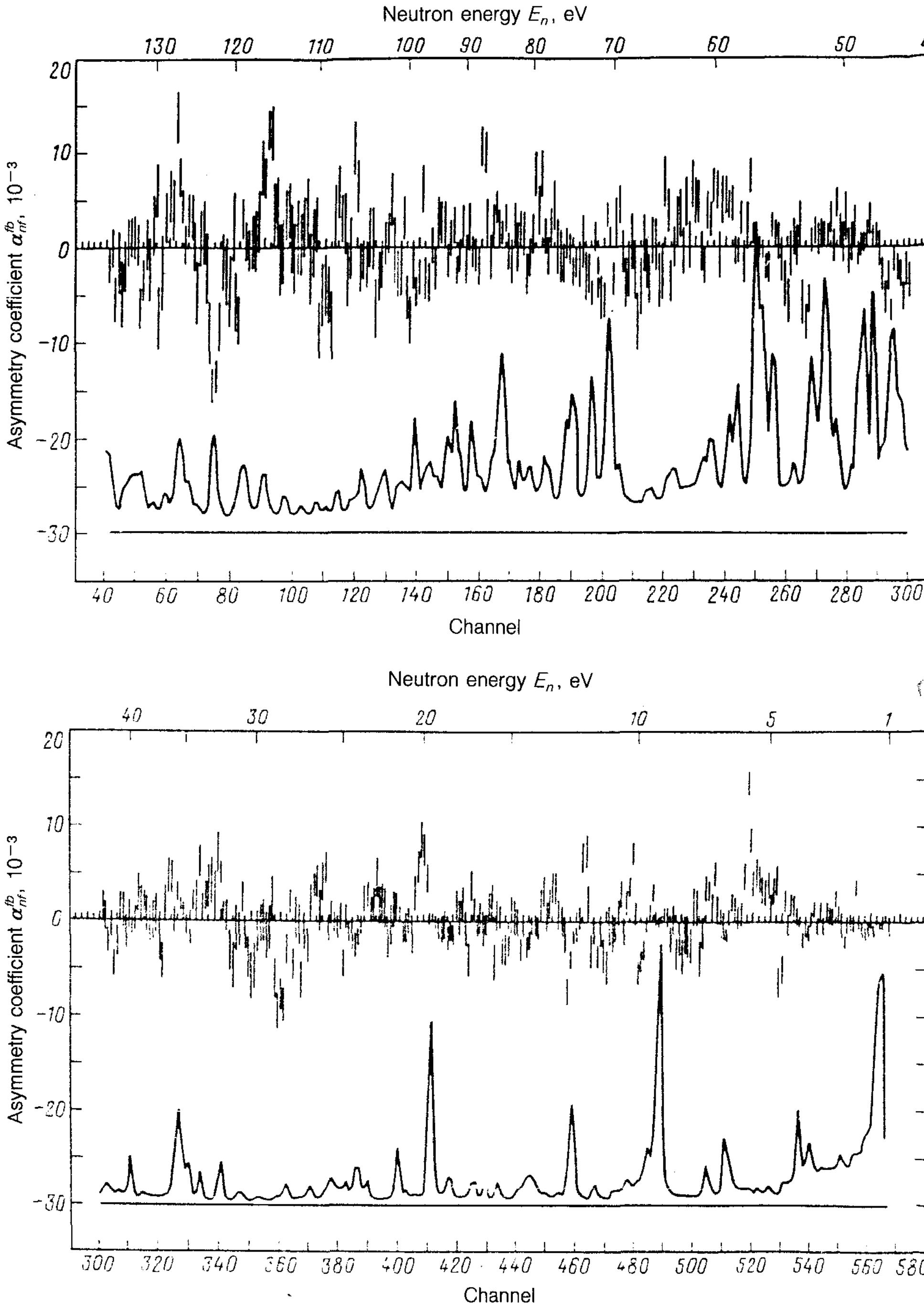

FIG. 1. Energy dependence of the front–back asymmetry coefficient $\alpha_{nf}^{fb}(E_n)$ (the experimental points), along with the ^{235}U fission cross section (the curves).

TABLE I. Effective parameters of the fit of the p resonances.

N	$Q^2_{sp}\Gamma^{n1}_p$, meV	E_p, eV	Γ_p, meV	$\Delta\varphi_s$, rad	χ^2
1	$21,7 \pm 31,9$	$1,70 \pm 0,05$	50 ± 30	$0,8 \pm 0,2$	$1,2 \pm 0,3$
2	$6,4 \pm 1,1$	$5,70 \pm 0,05$	160 ± 30	$2,9 \pm 0,1$	$1,0 \pm 0,2$
3	$1,3 \pm 0,4$	$9,90 \pm 0,05$	130 ± 50	$2,4 \pm 0,2$	$1,0 \pm 0,3$
4	$3,0 \pm 0,9$	$12,9 \pm 0,1$	240 ± 50	$1,9 \pm 0,2$	$1,1 \pm 0,4$
5	$1,2 \pm 0,5$	$20,1 \pm 0,1$	190 ± 50	$1,9 \pm 0,2$	$0,9 \pm 0,3$
6	$0,7 \pm 0,3$	$28,5 \pm 0,2$	300 ± 100	$1,4 \pm 0,4$	$1,5 \pm 0,3$
7	$17,1 \pm 6,9$	$32,05 \pm 0,05$	90 ± 30	$1,9 \pm 0,3$	$1,6 \pm 0,3$
8	$1,1 \pm 0,6$	$36,4 \pm 0,1$	180 ± 80	$2,2 \pm 0,3$	$1,5 \pm 0,3$
9	$3,2 \pm 1,3$	$45,8 \pm 0,1$	190 ± 50	$1,6 \pm 0,3$	$1,1 \pm 0,3$
10	$2,2 \pm 1,0$	$52,8 \pm 0,2$	800 ± 200	$2,3 \pm 0,3$	$0,7 \pm 0,4$
11	$7,5 \pm 3,4$	$70,75 \pm 0,15$	550 ± 150	$2,0 \pm 0,2$	$1,2 \pm 0,4$
12	$2,0 \pm 1,1$	$79,6 \pm 0,1$	200 ± 90	$0,9 \pm 0,3$	$1,1 \pm 0,3$
13	$1,8 \pm 1,3$	$87,35 \pm 0,05$	180 ± 120	$0,2 \pm 0,3$	$1,1 \pm 0,3$
14	$1,9 \pm 1,2$	$115,7 \pm 0,1$	130 ± 60	$0,2 \pm 0,5$	$0,6 \pm 0,3$
15	$5,8 \pm 4,7$	$121,8 \pm 0,1$	130 ± 30	$0,7 \pm 0,5$	$0,6 \pm 0,3$
16	$1,4 \pm 0,8$	$126,8 \pm 0,2$	260 ± 170	$0,8 \pm 0,6$	$1,0 \pm 0,3$

ed-mean integral value of the experimental effect over the entire energy range is $\overline{\alpha^{fb}_{nf}} = -(0.2 \pm 0.8) \times 10^{-4}$ (with $\chi^2 = 2.55 \pm 0.05$ per degree of freedom, indicating a physical asymmetry effect α^{fb}_{nf} in the individual energy intervals). We can thus make a first estimate of the branching ratio for direct fission.[8] Under the assumption that the amplitudes for direct fission caused by the s-wave and p-wave neutrons differ primarily by the penetrability factor of the centrifugal barrier, we find $(\sigma^{\rm direct}_f/\bar{\sigma}_f) \leqslant 5 \times 10^{-2}$ at a 95% confidence level.

3. For further analysis, we selected 16 characteristic structural features in α^{fb}_{nf} (E_n), in which the magnitude of the effect at the maxima was 3–7 standard deviations from the mean over the entire spectrum. The effective parameters of the strongest p resonances were estimated from experimental data on the basis of a least-squares fit of simplified theoretical expressions of the type in (1), constructed under the assumption of an interference of one p resonance and several nearest s resonances, with known parameters.[9] The results of this analysis of the experimental data are shown in Table I for each of the 16 features selected. The second through fifth columns of this table show the values found for the effective parameters of the fit: $Q^2_{\rm sp}\Gamma^{n1}_p$ (Γ^{n1}_p is the reduced neutron width of the p resonance), E_p, Γ_p, and $\Delta\varphi_{\rm sp}$. Since the values of J_p and K in the spin factor are not known, we assume[1] $|Q_{\rm sp}| \sim 1$ below. The last column of this table shows an estimate of the quality of the fit on the basis of the χ^2 test. The stablest parameters of the fit are E_p and Γ_p, whose values depend only weakly on the number of s resonances included in the analysis. The mean values of the effective parameters of the p resonances found for the 16 features selected are

$$\overline{(Q_{sp}^2 \Gamma_p^{n1})} = 5.0 \pm 1.5 \text{ meV};$$
$$\overline{\Gamma_p} = 240 \pm 50 \text{ meV};$$
$$\overline{\Delta \varphi_{sp}} = 1.5 \pm 0.2 \text{ rad}.$$

4. Working from the fluctuations in the fission widths Γ_p^f under the assumption $\Gamma_p^f = \Gamma_p - \Gamma_\gamma$ ($\hat{\Gamma}_\gamma = 35$ meV is the mean radiation width), we estimated the number (ν_p^f) of effective ^{235}U fission channels for p resonances with the help of the Wilets formula:[10]

$$\nu_p^f = \frac{2\overline{(\Gamma_p^f)^2}}{\overline{(\Gamma_p^f)^2} - \overline{(\Gamma_p^f)}^2} = 2.4 \pm 1.6. \tag{2}$$

An estimate of the number of degrees of freedom, ν_p^n, for the reduced neutron widths Γ_p^{n1} (under the assumption $|Q_{sp}| = 1$) yields $\nu_p^{n1} = 1.4 \pm 1.1$.

These estimates are close to the corresponding figures for known s resonances[9] in the same energy interval:

$$\nu_s^f = 2.1 \pm 0.4; \quad \nu_s^{n0} = 1.5 \pm 0.4.$$

5. The information found here is important for neutron spectroscopy of heavy nuclei and also for (in particular) fundamental research on the effects of P- and T-invariance violations, for which one would expect an enhancement near weak impurity p resonances. We note in conclusion that it would be interesting to include ^{233}U and ^{239}Pu in future research on the p-even asymmetry of the type $(\vec{p}_n \cdot \vec{p}_f)$ and thus improve the statistical accuracy of the experimental results.

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