see that there is a good agreement between the predictions of the pole mechanism experiment in the region q < 120 MeV/c for both distributions in Figs. 2 and 3. The results obtained for the nucleus with an average weight (Al^{27}) confirm the previous conclusions drawn from experiments on the nuclei Li^6 and C^{12}, namely that the pole diagram makes the decisive contribution at small q. With increasing q, the contributions of other diagrams become important.

Since the transition is to an excited state of Mg^{26*}, it can be assumed that the mechanism of the ($\pi^- p$) reaction does not depend on the state of the residual nucleus. The analysis of the presented distributions with respect to the polar nucleus-emission angle and the Treiman-Yang angle, and comparison with the previously obtained distributions on the nuclei C^{12} and Li^6 in the region of large q, shows that the character of the deviation from the pole approximation is also independent, in the main, of the choice of the target nucleus.

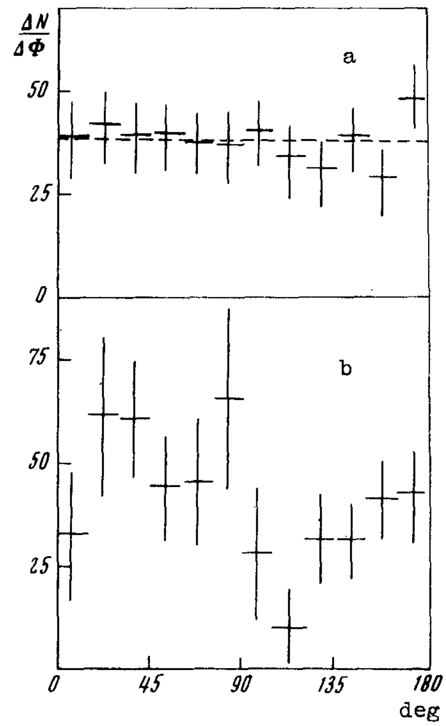

Fig. 3. Distribution with respect to the Treiman-Yang angle: a) 0 < q < 120 MeV/c, b) 120 < q < 170 MeV/c.

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ANOMALY OF THE (n, n'f) REACTION THRESHOLD

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We investigated experimentally the dependence of the fission cross sections of U^{238}, Pu^{239}, Pu^{240}, and Pu^{242} on the neutron energy E_n in the range E_n = 1.5 - 7.5 MeV, and the dependence of the angular anisotropy of the fission of Pu^{240} and Pu^{242} on E_n at E_n = 4.0 - 5.5 MeV. We have observed that the reaction (n, n'f) has a noticeable probability appreciably below the threshold energy value known from the data on the fission cross sections in the (n, f) reaction. The effect increases with increasing charge of the fissioning nucleus. The investigated "anomaly" is interpreted within the framework of the two-hump barrier model as (n, n'f) reaction with emission of neutrons in the second well.

In the neutron energy region above the barrier, owing to the approximate constancy of the cross section σ_c of the compound-nucleus formation and of the ratio of the fission and neutron widths Γ_f/Γ_n, the heavy-nucleus fission cross section $\sigma_f = \sigma_c[\Gamma_f/(\Gamma_f + \Gamma_n)]$ varies relatively little with changing energy and, as is customarily said, has a "plateau." The extent of this plateau is determined by the energy at which the probability of the (n, n'f) fission process of the target nucleus Z^A becomes appreciable after emission of a neutron by the compound nucleus Z^{A+1}. The threshold of the (n, n'f) reaction measured in the scale of the neutron energy E_n and neglecting tunneling through the fission barrier of the Z^A nucleus, is equal to the barrier height E_f. At $E_n > E_f$, the fission cross section increases until it reaches a new plateau.

In this communication we present the results of measurements of the fission cross sections of U^{238}, Pu^{239}, Pu^{240}, and Pu^{242} in the range E_n = 1.5 - 7.5 MeV. These cross sections reveal considerable deviations from the widely held but simplified notions concerning the course of $\sigma_f(E)$ and the threshold of the (n, n'f) reaction. The measurements were performed by a relative method with Van de Graaff electrostatic generators. The fission-fragment detector was a double ionization chamber. The reference element was U^{235}, the fission cross section of which was taken to be close to that recommended in [1]. The experimental data, together with the plot of the reference U^{235} fission cross section is shown in Fig. 1.

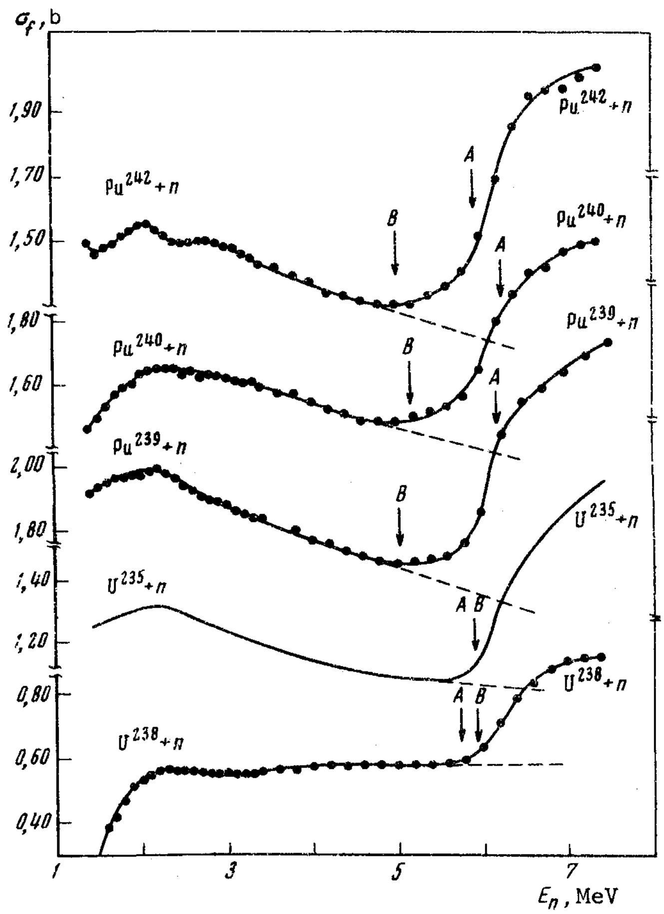

Fig. 1. Heavy-nucleus fission cross section in the vicinity of the "threshold" of the reaction (n, n'f). Dashed - extrapolation of $\sigma_f(Z^{A+1})$ above the (n, n'f) threshold.

The energy dependences of the fission cross sections of the investigated nuclei behave differently: the U^{238} cross section does indeed have a plateau (σ_f = const with accuracy ±3 - 4%), whereas the fission cross sections of the other isotopes decrease in the E_n region up to the threshold of the reaction (n, n'f). These properties, as shown in [2] are preserved in the case of U^{235}, Pu^{239}, and Pu^{241} also at higher neutron energies - between the threshold of the reaction (n, n'f), (n, 2n'f), and (n, 3n'f). They must therefore be attributed to differences in the energy dependence of Γ_f/Γ_n. The statistical description [3] predicts a correlation between the sign of $d(\Gamma_f/\Gamma_n)/dE$ and the absolute value of Γ_f/Γ_n. This correlation agrees with experiment, namely, if Γ_f/Γ_n is small, then Γ_f/Γ_n increases with energy; if $\Gamma_f/\Gamma_n \gtrsim 1$, then Γ_f/Γ_n decreases; Γ_f/Γ_n = const in the intermediate case. The latter corresponds to U^{235} (Γ_f/Γ_n = 0.2); in the case of U^{235} and the plutonium isotopes, Γ_f/Γ_n is considerably larger.

In accordance with the observed tendencies in the variation of $\sigma_f(E)$, Fig. 1 shows dashed the extrapolation of the cross section of the reaction (n, f) into the energy region where σ_f experiences the growth characteristic of the onset of the (n, n'f) reaction. From an analysis of the cross sections of the reactions (γ, f), (n, f), (d, pf), and (t, pf), it is known that the fission thresholds of the actinides amount on the average to 6 MeV and vary in a very narrow range from Th to Cf. This fact, which strongly contradicts the liquid-drop model, could be explained only after the double-hump structure of the barrier was postulated [4]. The threshold observed in the fission cross section is determined by the higher of the humps. The heights E_{fA} and E_{fB} of the inner and outer humps A and B, marked by the arrows in the figures, were taken from the systematics of [5]. It is seen from Fig. 1 that in the case of U^{235} and U^{238} the rise of σ_f occurs in the region where it is expected, whereas in the case of the plutonium isotopes this rise is shifted by approximately 1 MeV towards lower energies.

The shift of the threshold of the (n, n'f) reaction in the case of the plutonium isotopes is confirmed by the results of measurements of the angular anisotropy of the fission. This anisotropy is quite sensitive to the contribution of this process. The angular distributions of the fission fragments were measured in this study with cylindrical glass detectors. Figure 2 shows the data obtained from these measurements concerning the parameter K_0^2 -

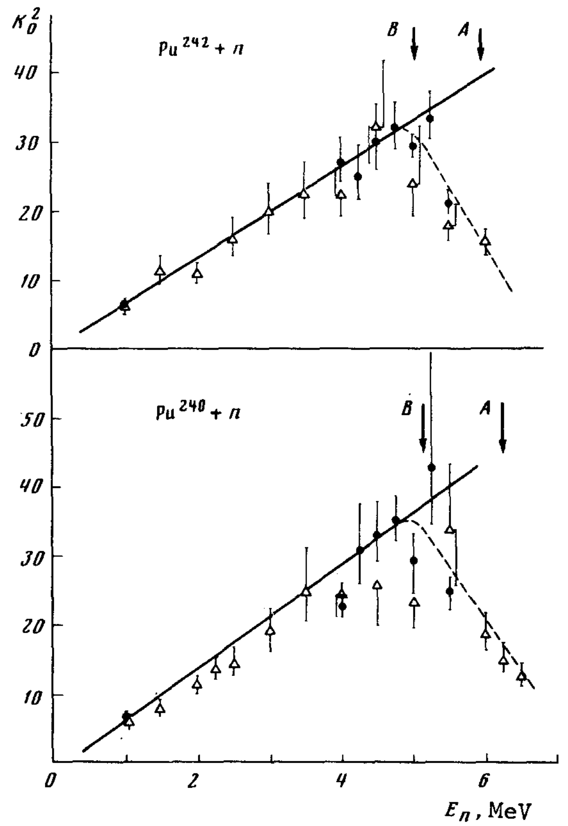

Fig. 2. Energy dependence of K_0^2 in the reactions Pu^{240}(n, f) and Pu^{242}(n, f). Solid lines - sections of linear dependence called for by the superfluid-nucleus model; dashed lines - effective value of K_0^2, distorted by the contribution of the fission of nuclei with mass number A reduced by unity after neutron emission. • - present data; Δ - data of [7].

the variance of the distribution of the projection of the angular momentum on the fissio direction. Turning on the (n, n'f) reaction should lead to a deviation of K_0^2 down from the approximately linear relation expected from the model of the superfluid nucleus [6]. This effect arises, as follows from a comparison of the data in Figs. 1 and 2, approximately where $\sigma_f(E)$ becomes non-monotonic near $E_n \approx E_{fB}$. In the case of the plutonium isotopes, the Z^A(n, n'f) process proceeds as if it were hindered not by the barrier A, as in the reaction Z^{A-1}(n, f), but by the lower barrier B.

In the model of a single-hump barrier, the observed anomalous earlier onset of the (n, n'f) reaction on the plutonium nuclei would be forbidden because the inpenetrability of the barrier, the shift of the threshold being too large in comparison with the curvature parameter $\hbar\omega/2\pi \sim 0.1$ MeV, which determines the exponential decrease of the penetrability. There is apparently only one way out - assume a noticeable probability of neutron emission already after passing through the barrier. This requires the assumption that there exists behind the barrier intermediate states in which the nucleus can live a sufficiently long time, $\hbar/\Gamma_n = 10^{-15} - 10^{-16}$ sec. In the double-hump barrier model, this phenomenon can be readily interpreted as fission after emission of a neutron in the second well (n, n'_2f), which occurs "around" the hump A.

The process (n, n'_2f) with neutron emission in the second well is more probable the deeper the well (the larger the density ρ_{II} of the excited states) and the larger the difference in the heights of the humps $\Delta_{AB} = E_{fA} - E_{fB} > 0$ (larger than the probability of not returning to the first well $P_B/(P_A + P_B + P_{\gamma 2})$). When $E_{fB} \approx E_{fA}$, and all the more if $\Delta_{AB} < 0$, the contribution of the "anomalous" process (n, n'_2f) in comparison with the ordinary (n, n'_1f) reaction (with neutron emission in the first well) is small in the ratio $(\rho_{II}/\rho_I)(P_B/P_A)$. This explains the absence of the effect in question in the case of the uranium isotopes, and also of the lighter actinides. In these nuclei we have $P_B/P_A \lesssim 1$ and $\rho_{II}/\rho_I \ll 1$, whereas for the heavy actinides the ratio of the penetrabilities of the humps P_B/P_A is large, thus compensating for the smallness of the level-density ratio ρ_{II}/ρ_I.

The de-excitation of the excited nucleus by neutron emission in the second well is the most widely used method of obtaining spontaneously-fissioning isomers. The population of the associated lowest states at the bottom of the well results from radiative transitions that dominate in the probability of the decay of the excited nucleus in the second well, when $P_{\gamma 2} \gg P_B$ and $P_{\gamma 2} \gg P_A$. To the contrary, the main contribution to the probability of the (n, n'_2f) reaction is made by higher excited states which lead mainly to passage through the barrier B. The estimates of $P_{\gamma 2}$ and P_B are in reasonable agreement with the observed cross sections for the excitation of spontaneously fissioning isomers in the (n, n_2f) reaction.

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INTERACTION OF GOLDSTONE NEUTRINO WITH ELECTROMAGNETIC FIELD

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1. Starting from the representation of the neutrino as a Goldstone particle, we have constructed in [1] a phenomenological action integral, invariant against the expanded Poincare group and containing anticommuting parameters. This integral describes the universal interaction of the neutrino with itself and with an arbitrary fermion field. The interaction of the neutrino with other fields, particularly with the electromagnetic field, is also universal and is determined by the same constant $a = \ell^4$.

The gauge-invariance requirements together with the required invariance with respect to the expanded Poincare group determine uniquely the form of this interaction. It turns out that the action integral contains only a term quadratic in the electromagnetic field, whereas terms linear in the electromagnetic field are forbidden by the considered invariance requirements. The invariant action integral, containing a minimum number of derivatives of the fields, can be written in this case in the form of the ratio

$$S = \int \frac{D(A_\mu\, dx^\mu)\, \Lambda\omega^\nu \Lambda\omega^\rho\, D(A_\alpha\, dx^\alpha)\, \Lambda\omega^{\nu'} \Lambda\omega^{\rho'}}{\epsilon_{\mu\nu\rho\lambda}\, \omega^\mu \Lambda\omega^\nu \Lambda\omega^\rho \Lambda\omega^\lambda}\, g_{\nu\nu'}\, g_{\rho\rho'}\,, \tag{1}$$

where D denotes the outer differential, Λ the outer product [2], and $A_\mu(x)$ the electromagnetic potential. The differential forms ω^μ are defined in [1].

In the more customary notation, the action integral (1) takes the form

$$S = \int \left[-\frac{1}{4} F_{\mu\nu}F^{\mu\nu} + a\, F_{\mu\nu}F^{\mu\rho}\, T^\nu_\rho + \ldots \right] d^4x, \tag{2}$$

where

$$T^\mu_\nu = \frac{i}{2}\left(\psi^* \sigma^\mu \frac{\partial\psi}{\partial x^\nu} - \frac{\partial\psi^*}{\partial x^\nu}\sigma^\mu \psi \right),$$

and the dots correspond to the omitted terms containing higher powers of the spinor fields and of the coupling constants.

It follows from (2) that the process

$$\gamma + \gamma \to \nu + \bar\nu$$

which is forbidden in the ordinary theory of weak interactions [3], is possible in the Goldstone-neutrino model. It is easy to obtain expressions for the differential and total cross sections of this process