DIFFERENTIAL AND INTEGRAL CHARACTERISTICS OF PROMPT FISSION NEUTRONS IN THE STATISTICAL THEORY

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Theoretical investigation of differential and integral characteristics of prompt fission neutrons (PFN) is of great interest, since the comparison of calculated characteristics with experimental data makes it possible to refine the parameters of theoretical models for PFN emission and to reveal the effect of individual fragment properties on these characteristics. One of the most current sources of experimental information about PFN characteristics of low energy fission is spontaneously fissionable ^{252}Cf, whose integral PFN-spectrum is studied the most completely and used as a neutron standard.

The investigations of PFN spectra of low energy fission of nuclei have shown that the main part of PFN is emitted by heated, fully accelerated fragments in accordance with the equilibrium statistics laws /1-8/ and that the nonequilibrium neutron emission rate seems to be less than 10 % of total number of neutrons emitted per fission event /1, 5, 6, 8/.

Numerous calculations of differential and total PFN spectra for the case of ^{252}Cf spontaneous fission have been performed by using of different theoretical models /9-18/, but in many of them a number of factors affecting the complex PFN emission process has been neglected or substantial simplifications have been used roughening the results of the calculations. It has been found at present that the use of Hauser-Feshbach statistical theory is the most consistent and promissing approach to the calculation of both spectra and PFN characteristics. On the basis of this approach a statistical model for calculation of differential PFN characteristics of low energy fission has been proposed /15,, 16/, which was systematically used to calculate the spectra and fission neutron multiplicity distributions /4, 7, 14-17/. In order to take into account the anisotropy effects arising at PFN emission from fragments the model has been improved. The improvement allowed to evaluate consistently the anisotropy of angular distributions of neutrons from individual fragments (in center-of-mass system (CMS)) of fragments and to take into account its effect on the shape of PFN spectra in laboratory system.

Model

The above mentioned statistical model used is described in detail in /15, 16/. Here we summarize briefly its basic assumptions and its main features only.

It was assumed in the model, that PFN are emitted only from fully accelerated heated fragments. This assumption corresponds to the fact, that the fragment excited state lifetime τ_c and the time of fragment acceleration τ_{acc} relate as $\tau_{acc} \ll \tau_c$ and furthermore that the condition $\tau_{diss} < \tau_{acc}$ is valid as well.

In the latter inequality τ_{diss} is the time of transformation of fragment collective excited state energy to heat energy of fragment. In the model cascade character of PFN emission from fragments is taken thoroughly into account. The fragment excitation energy distribution, fragment spin-, fragment kinetic energy distributions were taken into account as well as the fragment charge and mass distributions. The fragment shape was assumed to be spherical, the angular anisotropy of PFN emission in CMS of fragment in primary version of the model was neglegted. For the level density of excited fragment the Fermi-gas model expression /19/ is used. This expression takes into account shell structure of fragments and pair correlations in them. Neutron binding energy in a fragment was calculated according to /20/. The neutron transmission coeffecients and analogous coefficients for γ-radiation are calculated by using of optical model and of photoabsorbtion cross-sections of dipole γ-quanta respectively. The optical model parameters were taken from /21/, for photoabsorbtion cross-section the Lorenz form with parameters from /22, 23/ is used. Fragment spin distribution parameter are chosen in the same way as in /16/. The initial distribution Po(E^*, A, Z) of excitation energy E^* of the primary fragment (A, Z) is assumed to be Gaussian with parameters specified according to /16/.

As mentioned above, the hypothesis of isotropic neutron emission in CMS covers no more than 90-95 % of total number of PFN per fission. The remaining part of PFN showing itself as an increased neutron yield in the low energy region (in laboratory system of coordinates (LSC)) is considered as a non-statistical component of PFN. As it has been shown in /24/, the CMS angular distribution of particle of kinetic energy emitted from excited nucleus must be anisotropic if both the particle and the nucleus have their anqular moments different from zero. Then in the first order of approximation, as it has been shown in /24/, the angular distribution of emitted particle is proportional to $(1 + b\cos^2\theta_{CMS})$, where O_{CMS} is the particle emission angle in CMS relative to a specified direction in space, "b" is anisotropy parameter. In /24/ quasi-classical evaluation of "b" was made as well. As the calculation in /17/ has shown, the above mentioned semiempirical account of anisotropy of neutron CMS-angular distributions improves the agreement of calculated ^{252}Cf PFN integral spectrum with experimental one in the region of low energy of neutrons. Therefore the consistent account of anisotropy of CMS-angular distribution of PFN on the basis of statistical Hauser-Feshbach theory would facilitate the more precise evaluation of non-statistical component in PFN emission. For these reasons we improved the model described in /16/ by taking into consideration the angular dependence in the expression for CMS-double differential spectrum of PFN. The proper results of /25, 26/ were used. Now the expression for CMS double differential spectrum of a neutron emitted at angle θ_{CMS} to the fission axis from a fragment of mass number A, charge Z and of kinetic energy E_k with averaging over excitation energy E^* and spin of the fragment includes the expansion into Legendre polynomials $P_k(\cos\theta_{CMS})$:

$$\frac{d^2N(\varepsilon,\theta_{CMS}, A, Z, E_k)}{d \; dO_{CMS}} \propto \int dE^* \sum_J P(E^*, J,A,Z,E_k) \sum_{K'} R_{k'}(E^*, J, A, Z, \varepsilon) P_k(\cos O_{CMS}) \qquad (1)$$

where K' = 0, 2, 4,... and

$$R_{K'}(E^*, J, A, Z, \mathcal{E}) = \frac{\sum_{I',l,j} \rho(E^* - \mathcal{E} - B_n, A - 1, Z, I') \times T_{lj}(\mathcal{E}) \eta_{K'}(j, I', J)}{\Gamma_n^t(A, Z, E^*, J) + \Gamma_\gamma^t(A, Z, E^*, J)} \qquad (2)$$

Here, as in /15, 16/, $P(E^*, J, A, Z, E_k)$ is the fragment excitation energy- and spin distribution; I' is the spin of residual nucleus (A - 1, Z); $\rho(E^*, J, A, Z)$ is the level density in nucleus (A, Z) with excitation energy E^* and spin J; $T_{lj}(\mathcal{E})$ is the transmission coefficients of a neutron of CMS-energy $\mathcal{E}$, of orbital moment l and of total moment j; Γ_n^t and Γ_γ^t are the total neutron and the total radiation widths, respectively; the coefficients $\eta_{K'}(j, I', J)$ can be expressed in terms of the Clebsh-Gordan coefficients of vectorial addition of moments $\vec{j}$, $\vec{I'}$, $\vec{J}$ /27/ with $\vec{j} = \vec{l} + \vec{S}$, $\vec{J} = \vec{I'} + \vec{j}$; $\vec{S}$ is the neutron spin. The values of $P(E^*, J, A, Z)$, (E^*, J, A, Z), $T_{lj}(\mathcal{E})$, Γ_n^t and Γ_γ^t are calculated in the same manner as in the works /15, 16/, and the averaging over fragment kinetic energy E_k is performed similarly to /16/.

Results and discussion

To calculate PFN differential and integral characteristics following to the statistical model described in /15, 16/, the code "SCØFIN" /28/ was developed and adapt for BESM-6 computer. The spectra of PFN and the PFN multiplicity distributions for individual fragments of ^{252}Cf spontaneous fission were calculated. The comparison of calculated spectra of individual fragment and integral PFN spectrum with experimental ones has been performed in /3, 4, 7, 14-17/. The comparison showed, that the model reproduces adequately both the mean energies and the shape of experimental spectra. Calculated CMS spectra of neutrons averaged over E_k had close temperatures and were approximately similar, which agreed with experimental results /1/.

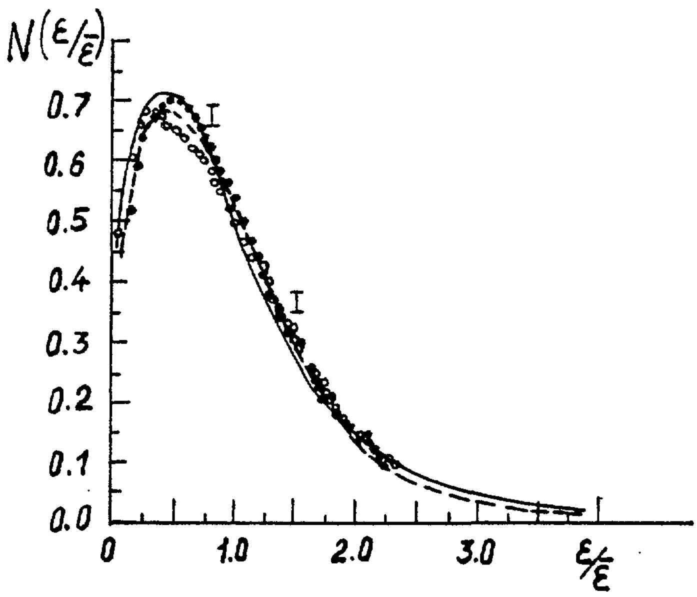

Fig. 1. Calculated and experimental spectra of PFN from ^{136}I fragment of ^{252}Cf spontaneous fission at different values of kinetic energy E_k of the pair.

• - experiment /29/, E_k = 172 MeV;
∘ - experiment /29/, E_k = 208 MeV;
——— - calculation (this work), E_k = 172 MeV;
– – – - calculation (this work), E_k = 208 MeV.

Subsequent experiments /4, 5, 29/ have shown that with the growth of difference in the value of excitation energy of fragments with a definite mass the shape of CMS spectra of these fragments deviates from "standard" one, particularly in the region of low CMS energies of neutrons $\varepsilon \lesssim \bar{\varepsilon}$. This was observed, for example, for fragments greatly differing in kinetic energy. Our more detailed calculations of CMS spectra of PFN from such fragments confirmed the above-mentioned deviation within the limits of input data uncertainty. Fig. 1 shows an example of calculated CMS spectra of neutrons from the ^{136}I fragment compared with the experimental data of /29/. The spectra are shown for two values of total kinetic energy E_k of fragments: 172 and 208 MeV. In calculations corresponding values of $\bar{E}^*$ were determined within the framework of the model /15, 16/ using the values of $\bar{\nu}$ and $\bar{\varepsilon}$ for this fragment from the work /29/. The values of dispersions $\sigma^2_{E^*}(A, E_k)$ were taken from /30/. It is seen from the Fig. 1 that in the region of neutron energies

$\varepsilon \lesssim \bar{\varepsilon}$ experimental spectra differ from one another; corresponding calculated spectra agree, in the main, with experimental ones within the limits of error. Some discrepancy between calculated and experimental spectra in the region $\varepsilon < 0.5\bar{\varepsilon}$ taking into consideration the sensitivity of calculations to the accuracy of input data /15/ seems to be connected with the uncertainty in the E^* and $\sigma^2_{E^*}$ values.

Another PFN characteristic important for understanding of the fission neutron emission mechanism is the multiplicity distribution of PFN from individual fragments. In contrast to the data on spectra the experimental data on multiplicity distributions of PFN from individual fragments of low energy fission, in particular of ^{252}Cf fission, are few in number: in this respect we can mention the well-known work /30/ and the works /31, 32/. The data of /31, 32/ give the possibility to compare the calculated multiplicity distributions of prompt neutrons from individual fragments of ^{252}Cf spontaneous fission obtained using the statistical model /15, 16/ with experimental ones. This is of particular interest considering that within the framework of most other theoretical models /11, 13/ used for calculation of fission neutron spectra consecutive calculation of multiplicity distributions of PFN from individual fragments has been unsuccessful. The experimental data presented in /31, 32/ make it possible to evaluate dispersions $\sigma^2_{E^*}(A)$ of excitation energy distributions for a number of ^{252}Cf spontaneous fission fragments and to obtain mean values of $\bar{\nu}(A)$ for these fragments. We have made calculations according to the statistical model /15, 16/ of multiplicity distributions for PFN from individual fragments using the evaluated dispersions $\sigma^2_{E^*}(A)$ and the values of $\bar{\nu}(A)$ taken from /31, 32/. Fig. 2 shows calculated multiplicity distributions $P_A(\nu)$ of prompt neutrons from several most probable fragments (^{108}Mo, ^{112}Ru, ^{144}Ba, ^{140}Xe) of ^{252}Cf spontaneous fission. For compactness of representation the distributions are given in the form of accumulated probability $F_A\ (0 \leq \nu \leq K)$; $F_A\ (0 \leq \nu \leq K) = \sum_{\nu=0}^{K} P_A(\nu)$, $K \leq \nu_{max}(A)$; $\nu_{max}(A)$ - maximum number of neutrons from the

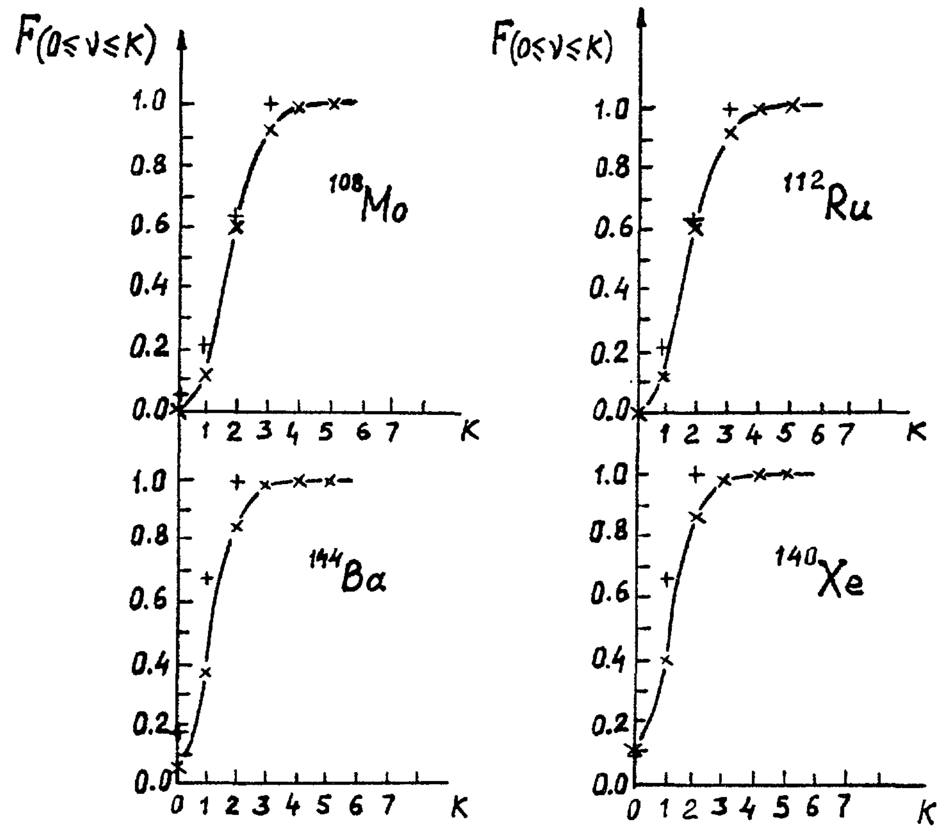

Fig. 2. Calculated multiplicity distributions of PFN from individual fragments of ^{252}Cf spontaneous fission. The distributions are given in the form of accumulated probability F_A $(0 \leq \nu \leq K)$,

$$F_A\ (0 \leqslant \nu \leqslant K) = \sum_{\nu=0}^{K} P_A(\nu).$$

x - calculation from the statistical model (this work);

\+ - binomial distribution with the parameters obtained with the values of $\bar{\nu}(A)$ and $\sigma_\nu^2(A)$ of calculated distributions.

fragment with mass number A obtained during the calculation. For comparison in the same Fig. the binomial distributions are shown with parameters derived from $\bar{\nu}_{calc.}(A)$ and $\sigma^2_{\nu_{calc.}}(A)$ of calculated $P_A(\nu)$ distributions. As it is seen from Fig. 2, calculated multiplicity distributions are not approximated by binomial ones. Fig. 3 gives the comparison of dispersions $\sigma^2_{\nu_{calc.}}(A)$ of calculated PFN

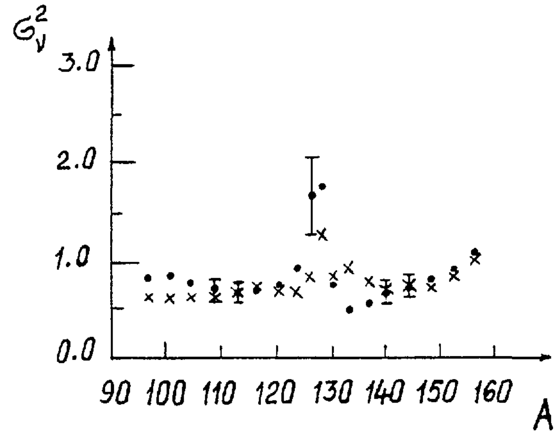

Fig. 3. Disperssion $\sigma_\nu^2(A)$ of the number of neutrons emitted from individual fragments of ^{252}Cf spontaneous fission.

• - evaluation according to the data of /31, 32/;
x - calculation from the statistical model (this work).

multiplicity distributions for a number of ^{252}Cf spontaneous fission fragments with corresponding experimental data from /31, 32/. It can be seen from Fig. 3 that the calculated values of $\sigma^2_{\nu_{calc.}}(A)$ are in good agreement with experimental ones. The values of $\bar{\nu}(A)$ taken from /31, 32/ are also well reproduced in calculations. It should be noted that CMS spectra of neutrons that we have calculated using the values of $\sigma^2_{E*}(A)$ and $\bar{\nu}(A)$ from /31, 32/ differ insignicantly from analogous spectra calculated earlier in /15/. This means that using the statistical model described in /15, 16/ one can described consistently the spectra and multiplicity distributions of PFN from individual fragments.

The problem of anisotropy value of PFN angular distributions in CMS of fragments and that of evaluation of its effect on differential and integral PFN spectra are of particular interest in studying the PFN emission mechanism. The authors calculated spectra and angular distributions of PFN from individual fragments of ^{252}Cf spontaneous fission with allowance for angular anisotropy of neutron emission in CMS of fragments using the exp essions (1) and (2). Spin values of primary fragments were taken according to the results of /33, 34/, other parameters of the model were chosen as in /15, 16/. The calculations have shown that the

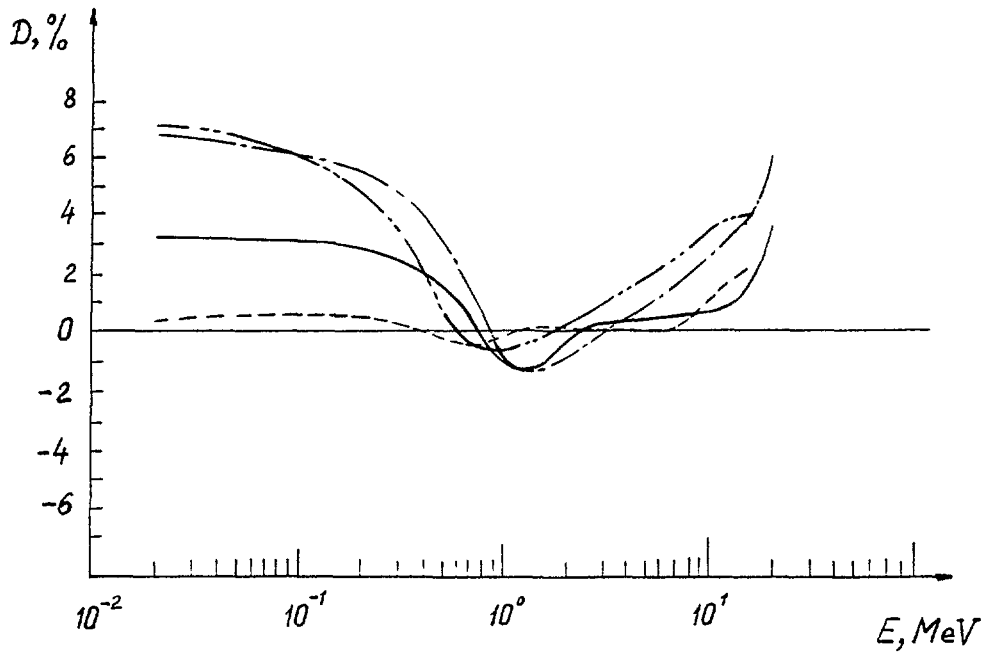

Fig. 4. Calculated LS – spectra of PFN from the fragments ^{108}Mo and ^{144}Ba of ^{252}Cf spontaneous fission obtained taking into account anisotropy of PFN emission in CMS of fragment.

The spectra are presented as a ratio to corresponding calculated LS – spectra obtained neglecting anisotropy of PFN emission in CMS of fragment.

——— ^{108}Mo } b = b(ε);
– – – – ^{144}Ba }
——·—— ^{108}Mo, b = 0.1;
——··—— ^{144}Ba, b = 0.1.

anisotropy coefficient b for PFN angular distributions in CMS of fragments depends substantially on the neutron energy and the mode of fission. Mean values $\bar{b}$ of calculated anisotropy coefficients satisfy the condition $\bar{b} \leq 0.07$ which agrees with the latest experimental evaluations /35/. Fig. 4 shows calculated LS - spectra of PFN from ^{108}Mo and ^{144}Ba fragments pertaining to the group of most probable fragments of ^{252}Cf spontaneous fission. LS - spectra are obtained from CMS - spectra calculated taking into account the angular anisotropy depending on CMS neutron energy according to (1) and (2). In Fig. 4 LS - spectra are presented as a ratio to LS - spectra obtained on the base of

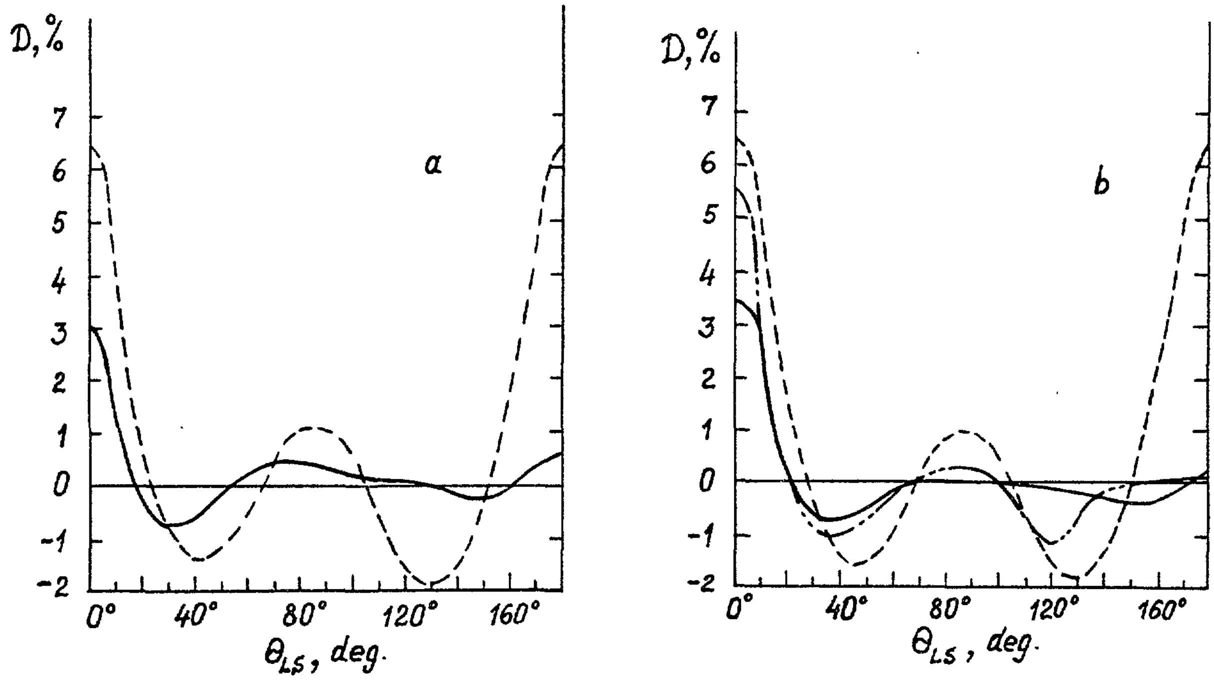

Fig. 5. a). Calculated angular LS distributions of PFN from ^{108}Mo, ^{144}Ba pair of fragments of ^{252} Cf spontaneous fission obtained taking in account PFN emission anisotropy in CMS. The angular distributions are presented in the form of ratio to corresponding angular LS distributions, isotropic in CMS of fragment.

——— - angular distribution calculated with b = b(ε);

– – – – - angular distribution calculated with b = 0.1.

b). Calculated angular LS distributions of PFN of the first cascade (ν = 1) from pairs of fragments of ^{252}Cf spontaneous fission corresponding to different mode of fission obtained taking accout of PFN emission anisotropy in CMS of fragments.

—·· — ^{96}Sr, ^{156}Nd } b = b(ε);
——— ^{108}Mo, ^{144}Ba } b = b(ε);
– – – – – ^{108}Mo, ^{144}Ba, b = 0.1

CMS spectra calculated with the statistical model /15, 16/ ignoring the anisotropy of PFN emission in CMS of fragments. The initial spin of fragments is assumed to be equal to $8\hbar$. It is seen from Fig. 4 that the effect of anisotropy on LS - spectra shows up mainly as an increase of neutron yield in the region of low ($E \lesssim 0.5$ MeV) and high ($E \gtrsim 15$ MeV) LS energies. It is also seen that the said effect is greater for a light fragment than for a heavy one. For comparison the same Fig. shows analogous calculated spectra but obtained with the use of the current phenomenological approximation of anisotropy coefficients: $b = 0.1$. From the comparison of these results it follows that the neglect of the dependence of anisotropy coefficients on neutron energy and on fragment mass leads to a overestimation of CMS anisotropy effect on the behaviour of LS - spectra in the said regions of LS energy of neutrons.

Fig. 5a depicts angular LS distributions of prompt neutrons from the same pair of fragments as in Fig. 4 calculated with (1) and (2). The form of representation of distributions is the same as in Fig. 4. As it is seen from Fig. 5a, consistent account of the anisotropy of neutron angular distributions in CMS of fragments leads to the increase of neutron yield in LS at small angles. It can be seen from Fig. 5a that these results differ somewhat from analogous ones obtained with the approximation $b = 0.1$.

Fig. 5b presents calculated angular LS distributions of the first cascade neutrons ($\nu = 1$) from the pairs of neutrons corresponding to different modes of fission. The angular distributions are calculated with account of CMS anisotropy according to the expressions (1) and (2). The calculation is performed with the same value J of initial spin of fragments ($J = 8$). One can see that the account of neutron emission anisotropy in CMS of fragments according to (1) and (2) causes the increase of neutron emission at small LS - angles with growing fission asymmetry.

Summarizing the above results one can conclude that for a more accurate statistical description of PFN spectra from fragments of low energy fission the dependence of PFN emission anisotropy in CMS on the neutron energy and fragment parameters should be taken into account during

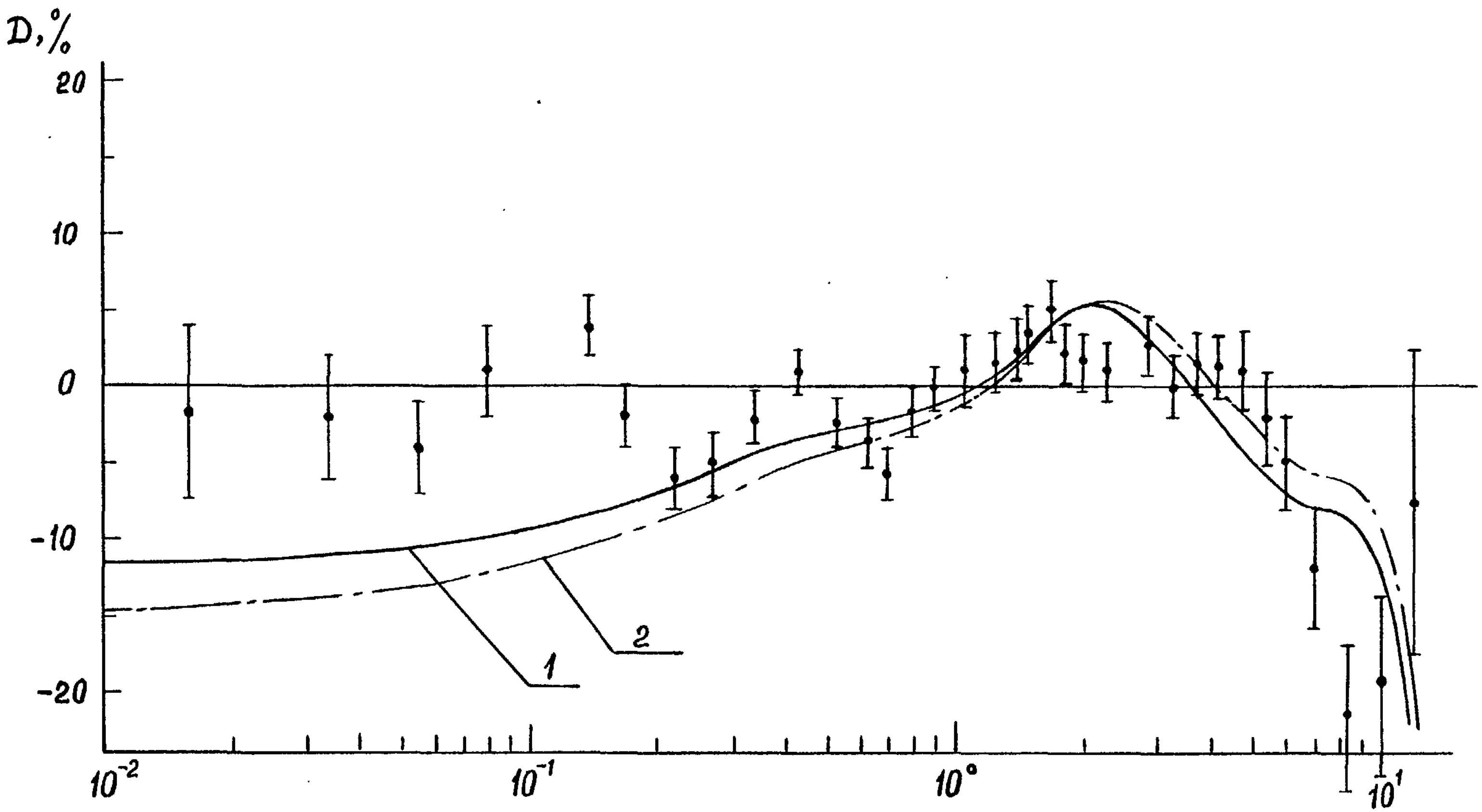

Fig. 6. Integral spectra of ^{252}Cf spontaneous fission prompt neutrons with reference to Maxwellian spectrum with T = 1.42 MeV.

1 - calculation /17/; values of $\bar{\nu}(A)$ and $\sigma^2_{E*}(A)$ were taken from /30/ and /36/ respectively (see text);

2 - calculation (this work); values of $\bar{\nu}(A)$ and $\sigma^2_{E*}(A)$ were taken from /31, 32/ (see text);

- experiment /37/.

calculations. From the results presented here it follows also that the problem of a more accurate estimation of the effect of angular CMS anisotropy of PFN emission on the results of PFN integral spectrum calculation is closely connected with that of calculated result uncertainty arising from the uncertainty in available experimental data used as input data for calculation. Fig. 6 shows two integral PFN spectra of ^{252}Cf spontaneous fission calculated using the statistical model /15, 16/ neglecting PFN emission anisotropy in CMS of fragments. The spectra are presented as a relation D to the Maxwellian spectrum with T = = 1.42 MeV. These spectra are obtained for two sets of input data differing only by the values of $\bar{\nu}(A)$ and $\sigma^2_{E*}(A)$. In Fig. 6 the spectrum denoted by 1 is calculated in /17/ using the data for $\bar{\nu}(A)$ and $\sigma^2_{E*}(A)$ taken from the works /31, 32/. As can be seen from Fig. 6, the uncertainty of calculated results in the integral spectrum low energy region of interest reaches 25 % of estimated D value. The said uncertainty gives the ideas of the order of magnitude of the deviation of calculated integral spectrum which should be caused by consideration of CMS anisotropy in this region of energies in order that this deviation could be perceptible on the background of uncertainties in the results of integral spectrum calculation.

Conclusion

The discussion of PFN differential and integral characteristics calculated with the statistical model /15, 16/ based on Hauser-Feshbach theory shows that this model provides a means for most complete and consistent account of principal features of a complex statistical process of PFN emission from fragments in low energy fission. The statistical model makes it possible to describe well enough different PFN characteristics: spectra, multiplicity distributions, angular distributions of PFN from individual fragments and integral characteristics.

The inclusion in this model of consistent calculation of PFN angular characteristic anisotropy in CMS of fragments gives the possibility to separate more completely the statistical component in PFN spectra, to determine better the relation between anisotropy and individual characteristics of fragments and to evaluate more exactly the effect of PFN emission angular anisotropy in CMS of fragments on differential and integral PFN spectra.

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