Components of Antineutrino Emission in Nuclear Reactor

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Abstract

New $\bar{\nu}_e$ scattering experiments aimed for sensitive searches of the $\nu_e$ magnetic moment and projects to explore small mixing angle oscillations at reactors call for a better understanding of the reactor antineutrino spectrum. Here we consider six components, which contribute to the total $\bar{\nu}_e$ spectrum generated in nuclear reactor. They are: beta decay of the fission fragments of $^{235}\text{U}$, $^{239}\text{Pu}$, $^{238}\text{U}$ and $^{241}\text{Pu}$, decay of beta-emitters produced as a result of neutron capture in $^{238}\text{U}$ and also due to neutron capture in accumulated fission fragments which perturbs the spectrum. For antineutrino energies less than 3.5 MeV we tabulate evolution of $\bar{\nu}_e$ spectra corresponding to each of the four fissile isotopes vs fuel irradiation time and their decay after the irradiation is stopped and also estimate relevant uncertainties. Small corrections to the ILL spectra are considered.

Introduction

It has many times been underlined (see e.g. recent reviews [1, 2]) that it is important to have an exact knowledge of the reactor antineutrino ($\bar{\nu}_e$) energy spectrum for planning and for analyzing the experiments on neutrino intrinsic properties and on searches for New Physics at reactors.

In widely used Pressurized Water Reactors (PWR, VVER in Russian abbreviation) summed U and Pu isotope fission rate is $\sim 3.1 \times 10^{19}$/$s$ per 1 GW thermal power. About $N_\nu \approx 6.7$ $\bar{\nu}_e$ are emitted per one fission event. 75% of them belong to the energy range $E < 1.80$ MeV, below the threshold of the inverse beta decay reaction on proton. Quantity $N_\nu$ receives contribution from six sources:

$$N_\nu = F^F N + U^U N + \delta^F N$$

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Here $F \, N \approx 5.5 \, \bar{\nu}_e/\text{fission}$ represents summed contribution from beta decays of fission fragments of four fissile isotopes $^{235}\text{U}$, $^{239}\text{Pu}$, $^{238}\text{U}$ and $^{241}\text{Pu}$, undistorted by their interaction with reactor neutrons, $U \, N \approx 1.2 \, \bar{\nu}_e/\text{fission}$ comes from beta decay of $^{239}\text{U} \Rightarrow ^{239}\text{Np} \Rightarrow ^{239}\text{Pu}$ chain produced via neutron radiative capture in $^{238}\text{U}$ and $\delta F \, N < 0.03 \, \bar{\nu}_e/\text{fission}$ originate from neutron capture in accumulated fission fragments and give small but not negligible local distortions of the total energy spectrum of the reactor $\bar{\nu}_e$.

Plan of this report is as follows:

First, we present a short (and incomplete) overview of a half a century long history, which has led to the present understanding of the reactor antineutrinos.

Second, we give new results on the computed evolution of $\bar{\nu}_e$ energy spectra corresponding to four fissile isotopes vs fuel irradiation time and their decay after the end of the irradiation; we compare all available data and estimate relevant uncertainties.

After these data are presented on antineutrinos due to neutron radiative capture in $^{238}\text{U}$ and in accumulated fission fragments.

Finally we consider small corrections to the ILL spectra.

1 Short history

Alvarez (unpublished report, 1949 y) did historically the first estimation of the reactor $\bar{\nu}_e$ spectrum using conception of fission radiation developed by K. Way and E. Wigner [3]. The next were Perkins and King in 1958 y [4]. These studies were stimulated by B. Pontecorvo’s proposal to look for Cl $\Rightarrow$ Ar transitions near atomic reactor (1946 y) and by famous F. Reines – C. Cowan experiments. At that time and many years after it was assumed that the only source of reactor antineutrinos is the decay of $^{235}\text{U}$ fission fragments.

Kurchatov Institute’s Rovno group in 1974-77 yy noticed that in nuclear reactors fission of other heavy isotopes produces flux of comparable to that of $^{235}\text{U}$ and their energy spectra can be quite different from that of $^{235}\text{U}$, which, among other effects, would cause time variation of the neutrino induced reaction cross sections (burn up effect) [5]. Calculated energy spectrum for $\bar{\nu}_e$ emitted by $^{239}\text{Pu}$ fission fragments was first published in [6] and for each of four fissile isotopes was given in [7]. F. Avignone III et al. in 1980 y were the first to publish results on $^{238}\text{U}$ [8]. B. Davis, P. Vogel et al. in 1979 y [9] also calculated spectrum for $^{239}\text{Pu}$ and P. Vogel, G. Schenter et al. published results for four fissile isotopes in 1981 y [10]. In these publications mainly ”high” energy parts ($E > 1 – 1.5$ MeV) of the antineutrino spectra were presented.

Quoted calculations done in 1976-1981 years [6-10] have confirmed the idea that $\bar{\nu}_e$ spectra associated with fission of different isotopes considerably differ one from another. Thus, relative to $\bar{\nu}_e$ spectrum generated in the decay of $^{235}\text{U}$ fission fragments, fission of $^{238}\text{U}$ gives much harder spectrum while $^{239}\text{Pu}$ fission produces $\bar{\nu}_e$ of lower energies. The absolute values of each of the four spectra was established, however, with large uncertainties associated with poor knowledge of the decay schemes of short lived fission fragments, which significantly contribute
to the hard part of the $\bar{\nu}_e$ spectra.

Accurate knowledge of the $\bar{\nu}_e$ spectra came from experiments in which relevant beta-electron spectra were measured. Electrons and $\bar{\nu}_e$ come from the same beta decay process and are closely related. This simple idea is used in the conversion method in which $\bar{\nu}_e$ spectrum can be reconstructed (at least for not too low energies) if the spectrum of fission electrons is known. This idea was first proposed and used for $^{235}\text{U}$ by C. Muehlhause and S. Oleksa in 1957 [11] and by F. Reines group in 1959 y [12]. Later the correlation between calculated electron and $\bar{\nu}_e$ fission spectra was analyzed in 1979-1981 yy in already quoted papers [9, 10], by K. Schreckenbach et al. [13] in 1981 y and by the Rovno group in 1982 y [14]. First experiment in which $^{235}\text{U}$ and $^{239}\text{Pu}$ fission electron spectra have been measured and their considerable difference observed was performed by Rovno group in 1980-1981 yy [15]. The best $\bar{\nu}_e$ spectra for $^{235}\text{U}$, $^{239}\text{Pu}$ and $^{241}\text{Pu}$ thermal fission at the neutrino energies $E \geq 2.0$ MeV have been found by the ILL group in a number of experiments carried out in 1981-1989 yy [16]; they accurately measured relevant electron spectra and effectively modified the conversion procedure. These ILL spectra above 2 MeV are commonly used now. For $^{238}\text{U}$ is used spectrum calculated in [10].

Voloshin, Vysotskii and L. Okun’ [17], Akhmedov [18], Vogel and Engel [19] in 1986-1989 yy stimulated new efforts to search for anomalous magnetic moment of the neutrino in $\bar{\nu}_e$, e scattering experiments at reactors and further studies of the components of reactor $\bar{\nu}_e$ spectrum. The Moscow MEPhI group in 1989 y calculated time-evolution of $\bar{\nu}_e$ spectra emitted by U and Pu fission fragments [20].

The fifth component of the spectrum $^UN$, which originates from $^{238}\text{U}(n,\gamma)$ reaction, was "discovered" only in 1996 y [21]. The last component $\delta^FN$, which comes from reactor neutron capture in fission fragments was estimated in [7] and considered in [21, 22].

2 Main results

2.1 Fission antineutrinos from four fissile isotopes

For each of four fissile isotope we calculate the time evolution of the $\bar{\nu}_e$ spectrum during fuel irradiation time $t_{on}$ and its decay as a function of time $t_{off}$ after the end of irradiation. Calculations involve summation of all beta branches of 571 fission fragments. For fragments yields we use data compiled in [23]. For the decay schemes is used information accumulated in our laboratory during past 25 years. Our code evaluates the spectra in the energy range 0-10 MeV (200 points per 1 MeV) for $t_{on}$ and $t_{off}$ intervals from 0.2 hour to infinity.

Time evolution of the four spectra for $\bar{\nu}_e$ energy below 3.5 MeV is presented in Tables 1 and 2. One can see that at 3.5 MeV full saturation is achieved already in ~1 day time after the beginning of fission process, in 2-3 MeV energy range ~ 3% increase takes place at long irradiation times while low energies do not reach equilibrium even in 2 years. (In typical PWR reactors 2 year is the
average fuel irradiation time at the end of the operational run). In Table 3 one can see that at \( t_{on} = 2 \) y 50% of fission \( \bar{\nu}_e \)'s are emitted below (1.2-1.3) MeV and \( \sim 30\% \) of them have energy higher than 2.0 MeV.

Table 1: Calculated \( \bar{\nu}_e \)-spectra (1/(MeV-fission) for \( ^{235}\text{U} \) and \( ^{239}\text{Pu} \) vs irradiation time \( t_{on} \))

| Isotope | \( ^{235}\text{U} \) | | \( ^{239}\text{Pu} \) | |
|---------|----------------|---|----------------|---|
| E, MeV  | 1 d | 30 d | 100 d | 2 y | 1 d | 30 d | 100 d | 2 y |
| 0.05    | 0.102 | 0.216 | 0.300 | 0.426 | 0.165 | 0.309 | 0.397 | 0.502 |
| 0.1     | 0.226 | 0.608 | 0.897 | 1.326 | 0.229 | 0.720 | 1.019 | 1.373 |
| 0.2     | 0.718 | 1.719 | 2.007 | 2.322 | 0.722 | 2.013 | 2.402 | 2.710 |
| 0.3     | 1.129 | 2.029 | 2.316 | 2.637 | 1.043 | 1.989 | 2.217 | 2.446 |
| 0.4     | 1.587 | 2.184 | 2.353 | 2.413 | 1.475 | 2.141 | 2.284 | 2.331 |
| 0.5     | 1.866 | 2.395 | 2.496 | 2.543 | 1.753 | 2.363 | 2.442 | 2.475 |
| 0.6     | 1.740 | 2.277 | 2.366 | 2.397 | 1.739 | 2.278 | 2.343 | 2.362 |
| 0.7     | 1.847 | 2.366 | 2.459 | 2.495 | 1.854 | 2.336 | 2.398 | 2.420 |
| 0.8     | 1.868 | 2.386 | 2.486 | 2.527 | 1.886 | 2.360 | 2.426 | 2.451 |
| 0.9     | 1.873 | 2.355 | 2.450 | 2.493 | 1.885 | 2.321 | 2.382 | 2.409 |
| 1.0     | 1.812 | 2.137 | 2.203 | 2.247 | 1.798 | 2.093 | 2.132 | 2.160 |
| 1.2     | 1.702 | 1.929 | 1.988 | 2.033 | 1.580 | 1.776 | 1.809 | 1.840 |
| 1.4     | 1.541 | 1.621 | 1.661 | 1.702 | 1.399 | 1.461 | 1.482 | 1.513 |
| 1.6     | 1.472 | 1.515 | 1.522 | 1.542 | 1.316 | 1.355 | 1.362 | 1.386 |
| 1.8     | 1.378 | 1.407 | 1.412 | 1.432 | 1.215 | 1.240 | 1.245 | 1.270 |
| 2.0     | 1.241 | 1.257 | 1.262 | 1.282 | 1.082 | 1.095 | 1.101 | 1.125 |
| 2.25    | 1.054 | 1.064 | 1.068 | 1.086 | 0.909 | 0.916 | 0.921 | 0.944 |
| 2.5     | 0.887 | 0.895 | 0.898 | 0.912 | 0.754 | 0.759 | 0.763 | 0.782 |
| 2.75    | 0.768 | 0.772 | 0.775 | 0.785 | 0.647 | 0.650 | 0.653 | 0.668 |
| 3.0     | 0.650 | 0.651 | 0.651 | 0.652 | 0.538 | 0.539 | 0.540 | 0.546 |
| 3.25    | 0.553 | 0.554 | 0.554 | 0.554 | 0.445 | 0.445 | 0.446 | 0.450 |
| 3.5     | 0.452 | 0.452 | 0.452 | 0.452 | 0.355 | 0.355 | 0.356 | 0.358 |

Fuel continues to emit \( \bar{\nu}_e \) after the irradiation is stopped (Table 4). In the softest part of the spectrum (50-500 keV) the residual \( \bar{\nu}_e \) emission rate is at a level of \( \sim 50-5\% \) during the first month and does not completely vanish at \( t_{off} = 1 \) year.

To what extent are reliable calculated \( \bar{\nu}_e \) spectra in the energy range \( E < 3 \) MeV? Here, in contrast with the \( E > 3 \) MeV region, contribution of well-established beta emitters amounts to 85-90\%. We estimate that relative uncertainties here do not exceed 5-6\% (68\% C.L.). This estimate is confirmed by comparison of present results with spectra calculated earlier by Vogel and Engel [19], by MEPhI group [20] and with the ILL conversion spectra [16] (Fig.1).
Table 2: Calculated $\bar{\nu}_e$-spectra (1/(MeV-fission) for $^{238}$U and $^{241}$Pu vs irradiation time $t_{on}$

| Isotope | $^{238}$U | $^{241}$Pu |
|---------|-----------|-----------|
| E, MeV  | 1 d | 30 d | 100 d | 2 y | 1 d | 30 d | 100 d | 2 y |
| 0.05    | 0.164 | 0.302 | 0.390 | 0.503 | 0.192 | 0.328 | 0.407 | 0.502 |
| 0.1     | 0.247 | 0.715 | 1.016 | 1.397 | 0.235 | 0.695 | 0.965 | 1.286 |
| 0.2     | 0.782 | 2.008 | 2.386 | 2.723 | 0.742 | 1.956 | 2.330 | 2.643 |
| 0.3     | 1.177 | 2.089 | 2.334 | 2.596 | 1.103 | 2.008 | 2.219 | 2.448 |
| 0.4     | 1.668 | 2.298 | 2.448 | 2.499 | 1.571 | 2.216 | 2.353 | 2.397 |
| 0.5     | 1.984 | 2.558 | 2.644 | 2.681 | 1.874 | 2.473 | 2.549 | 2.580 |
| 0.6     | 1.937 | 2.471 | 2.544 | 2.567 | 1.911 | 2.435 | 2.497 | 2.516 |
| 0.7     | 2.077 | 2.578 | 2.653 | 2.680 | 2.046 | 2.536 | 2.598 | 2.620 |
| 0.8     | 2.126 | 2.621 | 2.701 | 2.732 | 2.087 | 2.568 | 2.634 | 2.659 |
| 0.9     | 2.156 | 2.608 | 2.681 | 2.714 | 2.098 | 2.537 | 2.597 | 2.624 |
| 1.0     | 2.113 | 2.420 | 2.470 | 2.504 | 2.036 | 2.331 | 2.366 | 2.395 |
| 1.2     | 1.954 | 2.162 | 2.205 | 2.242 | 1.812 | 1.998 | 2.028 | 2.061 |
| 1.4     | 1.810 | 1.880 | 1.908 | 1.943 | 1.645 | 1.701 | 1.720 | 1.754 |
| 1.6     | 1.752 | 1.793 | 1.800 | 1.821 | 1.568 | 1.603 | 1.612 | 1.642 |
| 1.8     | 1.659 | 1.686 | 1.691 | 1.713 | 1.456 | 1.479 | 1.486 | 1.517 |
| 2.0     | 1.514 | 1.528 | 1.533 | 1.555 | 1.318 | 1.330 | 1.337 | 1.368 |
| 2.25    | 1.332 | 1.341 | 1.345 | 1.365 | 1.138 | 1.145 | 1.151 | 1.179 |
| 2.5     | 1.158 | 1.164 | 1.168 | 1.184 | 0.964 | 0.969 | 0.974 | 0.998 |
| 2.75    | 1.028 | 1.032 | 1.035 | 1.047 | 0.839 | 0.842 | 0.846 | 0.865 |
| 3.0     | 0.895 | 0.896 | 0.897 | 0.900 | 0.712 | 0.713 | 0.715 | 0.724 |
| 3.25    | 0.775 | 0.776 | 0.776 | 0.779 | 0.598 | 0.599 | 0.600 | 0.606 |
| 3.5     | 0.653 | 0.654 | 0.654 | 0.655 | 0.491 | 0.491 | 0.492 | 0.495 |

2.2 Antineutrinos from neutron capture in $^{238}$U and in fission fragments

Nuclear fuel in PWR reactors contains 95-97% of $^{238}$U. $^{238}$U absorbs $\sim0.6$ neutron per fission via $(n,\gamma)$ reaction: $^{238}$U + $n$ $\rightarrow$ $^{239}$U($E_{\text{max}} = 1.26$ MeV) $\rightarrow$ $^{239}$Np($E_{\text{max}} = 0.71$ MeV) $\rightarrow$ $^{239}$Pu. This process contributes $\nu N \sim 20\%$ to the total flux. The quantity $\nu N$ is practically constant over reactor run and is known with an uncertainty of 5%. Note, that in reactors with fuel elements of natural uranium $\bar{\nu}_e$ production rate in the channel considered is $\sim1.5$ times higher.

Neutron capture in fission fragments can either increase or decrease intensity depending on energy of $\bar{\nu}_e$ (Fig. 2). The term $\delta F$ (Eq.1) is negative for energies below 0.9 MeV and positive for higher energies; it slowly changes along the reactor run and its contribution to the total flux of $\bar{\nu}_e$ does not exceed 0.3%. The negative part of $\delta F$ originates mainly from intensive absorption of neutrons in the fragment $^{135}$Xe ($T_{1/2} = 9.1$ h, $E_{\text{max}} = 0.91$ MeV), which is produced in reactor at a rate of $\sim0.07$/fission. Due to very high cross section of
Table 3: Fraction \(N(E)/N_{\text{tot}}\) of antineutrinos emitted in the energy intervals (0-\(E\)) for fuel irradiation time \(t_{\text{on}}=2\) yr

| E, MeV | \(^{235}\text{U}\) | \(^{239}\text{Pu}\) | \(^{238}\text{U}\) | \(^{241}\text{Pu}\) |
|-------|----------------|---------------|----------------|----------------|
| 0.1   | 9.94(-3)       | 1.64(-2)      | 1.10(-2)       | 1.55(-2)       |
| 0.2   | 4.73(-2)       | 6.01(-2)      | 4.48(-2)       | 5.15(-2)       |
| 0.3   | 8.84(-2)       | 0.105         | 8.04(-2)       | 9.04(-2)       |
| 0.5   | 0.179          | 0.201         | 0.158          | 0.174          |
| 0.75  | 0.290          | 0.320         | 0.257          | 0.285          |
| 1.0   | 0.399          | 0.436         | 0.357          | 0.394          |
| 1.5   | 0.570          | 0.606         | 0.517          | 0.560          |
| 2.0   | 0.700          | 0.734         | 0.646          | 0.692          |
| 2.5   | 0.798          | 0.827         | 0.749          | 0.792          |
| 3.0   | 0.869          | 0.893         | 0.827          | 0.865          |
| 4.0   | 0.951          | 0.965         | 0.926          | 0.951          |
| 5.0   | 0.983          | 0.990         | 0.971          | 0.984          |

\(N_{\text{tot}}, \bar{\nu}_e/fission\) 5.585 5.091 6.688 5.897

\footnote{Absolute values of \(N_{\text{tot}}\) for \(t_{\text{on}}=2\) years are presented in the last row}

\((n,\gamma)\) reaction (a few million barn) the majority of \(^{135}\text{Xe}\) nuclei absorb neutrons before they decay.

Neutron interactions with reactor construction materials have been found to contribute less than 0.3% to the total flux and have been neglected at this stage of study.

2.3 Small corrections to the ILL spectra

The ILL spectra have been obtained after 1-1.5 day exposure time. Their uncertainties are estimated as 2.5%. These spectra do not contain time dependent contributions due to decay of long-lived fission fragments (see Tables 1, 2) and due to additional radiation associated with neutron capture (Fig. 2), which affect part of the \(\bar{\nu}_e\) spectra above 1.80 MeV, the threshold of the inverse beta decay reaction on proton. We mention here this point because it may appear to be of some importance in searches of very small mixing angle oscillations at reactors, which have been discussed at this Conference.

Conclusions

In this report we have tried to give a short story of the long process of developments in understanding reactor antineutrino source and to outline present status of the problem. New efforts to improve the accuracy may be needed in the future. So far, however, we do not feel challenges coming from current or planned experiment, which could stimulate such efforts.
Table 4: Residual $\bar{\nu}_e$-emission: Ratios of the current $^{235}\text{U}$ and $^{239}\text{Pu}$ fission antineutrino spectra vs time after the end of fuel irradiation time $t_{off}$ to that at the end of irradiation period $t_{on} = 2$ years

| Isotope | $^{235}\text{U}$ | | | | $^{239}\text{Pu}$ | | | |
|---------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|
| E, MeV  | 1 d             | 10 d            | 30 d            | 1 y             | 1 d             | 10 d            | 30 d            | 1 y             |
| 0.05    | 0.762           | 0.592           | 0.495           | 6.2(-2)         | 0.672           | 0.487           | 0.386           | 4.4(-2)         |
| 0.1     | 0.830           | 0.651           | 0.543           | 6.6(-2)         | 0.834           | 0.606           | 0.478           | 5.1(-2)         |
| 0.2     | 0.691           | 0.395           | 0.262           | 6.2(-2)         | 0.734           | 0.403           | 0.259           | 4.2(-2)         |
| 0.3     | 0.572           | 0.358           | 0.232           | 4.5(-2)         | 0.574           | 0.315           | 0.188           | 3.4(-2)         |
| 0.4     | 0.343           | 0.180           | 9.5(-2)         | 8.3(-3)         | 0.367           | 0.163           | 8.2(-2)         | 6.6(-3)         |
| 0.5     | 0.266           | 0.120           | 5.9(-2)         | 9.2(-3)         | 0.292           | 0.104           | 4.6(-2)         | 7.4(-3)         |
| 0.75    | 0.261           | 0.113           | 5.5(-2)         | 2.9(-3)         | 0.232           | 8.4(-2)         | 3.7(-2)         | 3.1(-3)         |
| 1.0     | 0.194           | 8.1(-2)         | 4.9(-2)         | 4.2(-3)         | 0.168           | 5.6(-2)         | 3.1(-2)         | 4.7(-3)         |
| 1.25    | 0.130           | 7.5(-2)         | 5.2(-2)         | 5.9(-3)         | 0.106           | 5.4(-2)         | 3.6(-2)         | 7.4(-3)         |
| 1.5     | 6.8(-2)         | 4.1(-2)         | 3.3(-2)         | 7.6(-3)         | 6.1(-2)         | 3.6(-2)         | 2.9(-2)         | 1.0(-2)         |
| 1.75    | 3.8(-2)         | 2.0(-2)         | 1.8(-2)         | 8.4(-3)         | 4.3(-2)         | 2.6(-2)         | 2.4(-2)         | 1.2(-2)         |
| 2.0     | 3.2(-2)         | 2.2(-2)         | 2.0(-2)         | 9.2(-3)         | 3.8(-2)         | 2.9(-2)         | 2.7(-2)         | 1.3(-2)         |
| 2.25    | 3.0(-2)         | 2.2(-2)         | 2.1(-2)         | 9.6(-3)         | 3.7(-2)         | 3.1(-2)         | 3.0(-2)         | 1.5(-2)         |
| 2.5     | 2.8(-2)         | 2.1(-2)         | 2.0(-2)         | 8.8(-3)         | 3.6(-2)         | 3.1(-2)         | 2.9(-2)         | 1.4(-2)         |
| 2.75    | 2.2(-2)         | 1.8(-2)         | 1.7(-2)         | 7.5(-3)         | 3.2(-2)         | 2.8(-2)         | 2.7(-2)         | 1.3(-2)         |
| 3.0     | 2.0(-3)         | 1.1(-3)         | 1.1(-3)         | 5.8(-4)         | 1.6(-2)         | 1.5(-2)         | 1.4(-2)         | 7.5(-3)         |
| 3.25    | 1.6(-3)         | 8.7(-4)         | 8.4(-4)         | 4.5(-4)         | 1.3(-2)         | 1.2(-2)         | 1.1(-2)         | 6.0(-3)         |
| 3.5     | 1.2(-3)         | 6.0(-4)         | 5.8(-4)         | 3.1(-4)         | 8.9(-3)         | 8.2(-3)         | 7.9(-3)         | 4.2(-3)         |

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Fig. 1. Ratios of $^{235}$U and $^{239}$Pu fission antineutrino spectra found in [19, 20, 16] to the results of present work at various fuel irradiation times. 1.5 d - • [20], × [16]; 10 $^7$s - ○ [20]; 2 years - ◦ [19]
Fig. 2. Component $\delta^F N$ due to neutron capture in fission fragments. "1" - beginning, "2" - end of PWR reactor typical run.