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ENERGY SPECTRUM OF REACTOR ANTINEUTRINOS AND SEARCHES FOR NEW PHYSICS (RECENT DEVELOPMENTS)

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The study of the electron neutrino properties — its mass, mixing, magnetic moment — is the main goal of the present reactor antineutrino experiments. We consider the time evolution of the reactor $\bar{\nu_e}$ spectrum during reactor ON and reactor OFF periods. An important role of the time variations of the reactor $\bar{\nu_e}$ spectrum in searches for neutrino magnetic moment is discussed. Corrections to the predicted earlier theoretical and precise measured inverse beta-decay cross sections are calculated. We found that the residual $\bar{\nu_e}$ emission during the reactor OFF period can play a non-negligible role in oscillation experiments.

Поиски и изучение новых свойств нейтрино являются главной целью ведущихся в настоящее время экспериментов с реакторными нейтрино. Нами подробно исследованы типичные изменения в спектре реакторных антинейтрино за время работы реактора и в спектре остаточной антинейтринной активности реактора после его остановки. Мы нашли, что эффекты нестационарности реакторного спектра антинейтрино могут играть значительную роль в экспериментах по поиску осцилляций и магнитного момента нейтрино. Нами вычислены поправки, обусловленные эффектами нестационарности, к прецизионно измеренному и рассчитанному сечениям поглощения антинейтрино протоном. Найдено, что остаточное антинейтринное излучение реактора после его остановки может играть заметную роль для ряда типичных в последние годы постановок экспериментов.

1. ANTINEUTRINO SOURCE

Power reactors emit large numbers of antineutrinos, about $6 \cdot 10^{20} \bar{\nu_e}$ per second, broadly distributed over energies up to about 12 MeV with a peak at 0.3 MeV. Here we consider the energy spectrum of pressurized light water reactors (PWR or VVER in Russian classification). Reactors of this type are used in the most neutrino experiments (Rovno, Gosgen, Bugey, Choos, Palo Verde). They usually operate for 11 months, followed by a shutdown of one month to allow for the replacement of one-third of the fuel elements. At the beginning of reactor ON period about $\alpha_5 = 70\,\%$ of the fissions are from ^{235}U, $\alpha_9 = 20\,\%$ from ^{239}Pu, $\alpha_8 = 7\,\%$ from ^{238}U, and $\alpha_1 = 3\,\%$ from ^{241}Pu. During operation ^{235}U burns out, and ^{239}Pu and ^{241}Pu are accumulated continuously from ^{238}U. The average contributions to the total number of fissions are $\bar{\alpha_5} = 58\,\%$, $\bar{\alpha_9} = 30\,\%$, $\bar{\alpha_8} = 7\,\%$, $\bar{\alpha_1} = 5\,\%$, practically identical for all light water reactors and are considered as reactor «standard».

2. $\bar{\nu}_e$ SPECTRUM FOR $E > 2$ MeV («STANDARD» APPROACH)

Systematic studies of the $\bar{\nu}_e$ spectrum at low energies $E < 2$ MeV (to which $\sim 70\,\%$ of all emitted $\bar{\nu}_e$ belong) have been started some years ago [1]. This part of the spectrum during ON and OFF periods is strongly time-dependent [2].

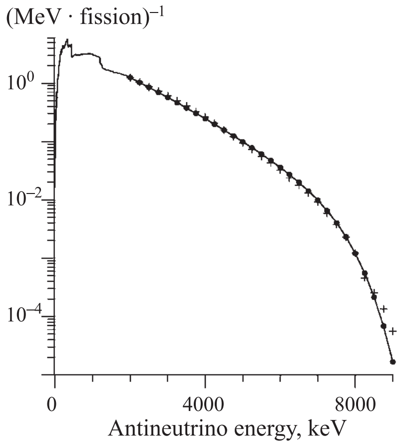


Fig. 1. Reactor antineutrino energy spectrum (contributions to the number of fissions: ^{235}U — 58 %, ^{239}Pu — 30 %, ^{238}U — 7 %, ^{241}Pu — 5%): curve ($E < 2$ MeV) — calculation [1, 2]; circles ($E > 2$ MeV) — measurement [3] at reactor (Rovno); crosses ($E > 2$ MeV) — standard $\bar{\nu}_e$ spectrum (from electron spectra [4, 5])

At energies above the threshold 1.8 MeV for inverse neutron beta decay reaction

$$\bar{\nu}_e + p \rightarrow n + e^+ \qquad (1)$$

the average spectrum for reactor ON period is known quite well [3].

The corresponding «standard» reactor antineutrino energy spectrum $\rho(E)$ at $E > 2$ MeV is a mixture of equilibrium energy spectra from the beta-decay of the fission products of ^{235}U, ^{239}Pu, ^{238}U, ^{241}Pu

$$\rho(E) = \sum \bar{\alpha}_i \rho_i(E), \qquad (2)$$

where $\sum \bar{\alpha}_i = 1$, $i = 5, 9, 8, 1$ and $\rho(E)$ is in units of $(\text{MeV} \cdot \text{fission})^{-1}$.

The «standard» $\bar{\nu}_e$ spectrum is the average spectrum for reactor ON period. The $\bar{\nu}_e$ spectra $\rho(E)$ for ^{235}U, ^{239}Pu, and ^{241}Pu are usually derived from one day exposure time experimental electron spectra [4, 5] and for ^{238}U — from calculation [6].

At the «standard» level of accuracy the reactor $\bar{\nu}_e$ spectrum is considered as saturated after the first day of reactor ON period. Furthermore, a residual $\bar{\nu}_e$ activity at $E > 2$ MeV after the first day of reactor OFF period is also considered as negligible.

The «standard» reactor $\bar{\nu}_e$ spectrum is indicated by crosses in Fig. 1. Our measurements at reactor (Rovno) above 2 MeV and our present calculations below 2 MeV are indicated by circles and curve. The «standard» and experimental spectra agree within uncertainties.

3. $\bar{\nu}_e$ SPECTRUM FOR $E = 0{-}12$ MeV (PRESENT APPROACH)

We have found that at present level of experimental and theoretical accuracy the «standard approach is not always sufficient.

The present calculations of the reactor $\bar{\nu}_e$ spectrum and residual $\bar{\nu}_e$ activity after reactor shutdown include:

a) time-dependent activity of the fission products;

b) time-dependent fission contributions $\alpha_i(t)$ of the fissionable isotopes: ^{235}U, ^{239}Pu, ^{238}U, ^{241}Pu;

c) time-dependent $\bar{\nu}_e$ activity coming from the neutron captures in $^{238}\text{U}(n,\gamma)$: $^{238}\text{U}(n,\gamma)^{239}\text{U} \rightarrow ^{239}\text{Np} \rightarrow ^{239}\text{Pu}$;

d) time-dependent $\bar{\nu}_e$ activity coming from the neutron captures in fission products;

e) time-dependent residual $\bar{\nu}_e$ activity of fission products and heavy elements produced during previous reactor ON periods.

4. RESULTS AND DISCUSSION

4.1. The evolution of the calculated $\bar{\nu}_e$ spectrum during reactor ON period is shown in Fig. 2. The differences of time-dependent spectra are small in the high-energy part of the $\bar{\nu}_e$ spectrum and become large for the low-energy part where most of all reactor antineutrinos are emitted. In experiments on $\bar{\nu}_e e^-$ scattering aimed to search for the neutrino magnetic moment a dominant contribution comes from the low-energy part of the spectrum. Therefore the time variation of reactor $\bar{\nu}_e$ spectrum plays a significant role in searches for the neutrino magnetic moment.

4.2. Nuclear reactors are intensively used in experiments searching for neutrino oscillations. Antineutrinos are detected via the inverse beta-decay reaction (1). One of the methods of searching for oscillations is to measure «visible» cross section at a great distance from reactor and compare one with the well-known cross section measured near nuclear reactor. The ratio of the measured near nuclear reactor (15 m) cross section [7] to calculated one for «standard» spectrum is

$$R_{\text{meas/calc}} = \sigma_{\text{meas}}/\sigma_{\text{calc}} = 0.987 \pm$$

$$\pm 1.4\,\%\,(\text{exp.}) \pm 2.7\,\%\,(\text{calc.}) \quad (68\,\%\,\text{C.L.}).$$

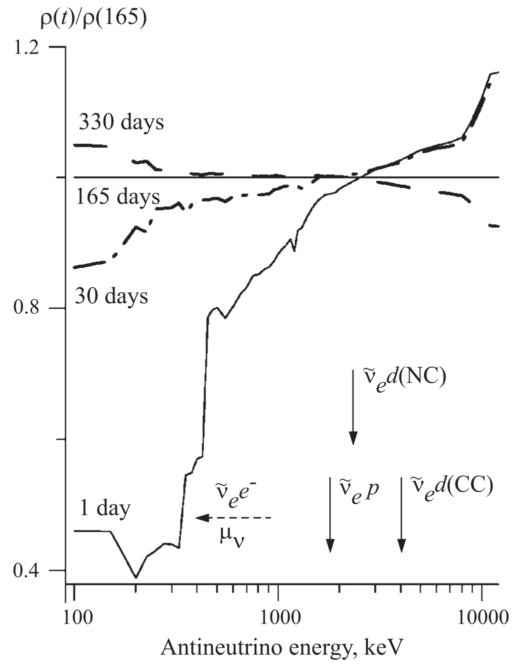


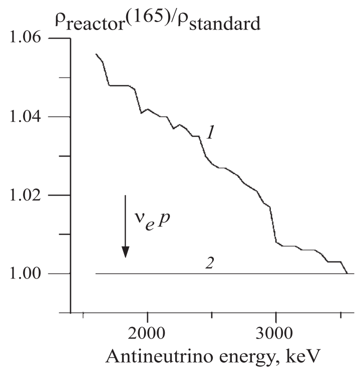
Fig. 2. Ratios of the current reactor $\bar{\nu}_e$ spectra to one at the middle of the 330-day reactor ON period. The inscriptions indicate the time sinse the beginning of reactor ON period. The thresholds of $\bar{\nu}_e$ interactions are showed by arrow below

We have obtained that σ_{calc} for the «standard» spectrum is approximately 0.6 % lower than cross section for the present $\bar{\nu}_e$ spectrum. As an illustration of this effect we show in Fig. 3 the ratio of the present reactor $\bar{\nu}_e$ spectrum to the «standard» one. At this level of accuracy the corrections to the inverse beta-decay cross section from present antineutrino pectrum calculation are becoming non-negligible.

The correction to σ_{meas} may be of the same order of magnitude. This correction is derived from non-negligible $\bar{\nu}_e$ activity during OFF period (see Fig. 4) when backgrounds are usually measured.

4.3. Corrections from $\bar{\nu}_e$ activity after the reactor shut down may be more important if, for example, a neutrino oscillation experiment is performed with one detector and two reactors: the nearest one (distance r from a reactor core) and a far one (distance R). Experiments of this type were performed at Rovno (18 m, 98 m), Bugey (15 m, 95 m) and Krasnoyarsk (three reactors — 57 m, 57 m, 234 m).

For the distance ratio $R/r \sim 6$ (Rovno, Bugey), the inverse beta decay reaction rate from $\bar{\nu}_e$ activity of the nearest reactor after its shut down may be equal to $\sim 1/4$ of the rate from the far reactor during its ON period. It is obvious that such experiments are in need of a new method of analysis.



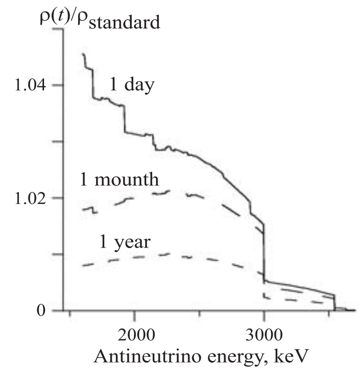


Fig. 3. Ratio of the reactor $\bar{\nu}_e$ spectrum (*1*) at the middle of 330-day reactor ON period to the standard spectrum (*2*)

Fig. 4. Ratios of the reactor $\bar{\nu}_e$ spectra for reactor OFF period to the standard one. The inscriptions indicate time after reactor shut down

CONCLUSION

Searches for phenomena beyond the Standard Model of electroweak interaction in neutrino experiments at nuclear reactors require refining our knowledge of the reactor $\bar{\nu}_e$ spectrum. In practice, at the present level of experimental and theoretical accuracy a comprehensive analysis of the $\bar{\nu}_e$ spectrum for each experiment at nuclear reactor is becoming necessary.

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