SEARCH FOR THE NEUTRINO MAGNETIC MOMENT IN THE NON-EQUILIBRIUM REACTOR ANTI-NEUTRINO ENERGY SPECTRUM

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We study the time evolution of the typical nuclear reactor antineutrino energy spectrum during reactor ON period and the decay of the residual antineutrino spectrum after reactor is stopped. We find that relevant variations of the soft recoil electron spectra produced via weak and magnetic $\bar{\nu}_e, e$ scattering process can play a significant role in the current and planned searches for the neutrino magnetic moment at reactors.

1 Introduction

Efforts are currently being done to observe the neutrino magnetic moment below the limit $\mu_\nu < 2 \cdot 10^{-10} \mu_B$ that was found in previous $\bar{\nu}_e, e$ scattering experiments at SAVANNAH RIVER, KRASNOYARSK and ROVNO reactors [1]. The KURCHATOV-PNPI collaboration is planning for KRASNOYARSK new studies of low kinetic energy recoil electrons in $\bar{\nu}_e, e$ experiment with a Si semiconductor multi detector. The MUNU collaboration experiment at BUGEY with a gas TPC chamber is in the final state of preparation [2].

The dominant contribution to the soft recoil electron produced in the $\bar{\nu}_e, e$ scattering comes from the low energy part of the reactor $\bar{\nu}_e$ energy spectrum. This part of the spectrum is strongly time dependent: it never comes to saturation during the reactor operating run and does not vanish after the reactor is shut down, the time when the background is usually measured.
Here we consider the time evolution of the typical reactor $\bar{\nu}_e$ energy spectrum and discuss relevant variations of the $\bar{\nu}_e, e$ scattering recoil electron spectra.

2 TIME VARIATION OF THE REACTOR ANTINEUTRINO SPECTRUM

1. Three components contribute the reactor $\bar{\nu}_e$ energy spectrum $\rho(E)/\text{fiss} \cdot \text{MeV}$:

$$\rho(E) = F \rho(E) + U \rho(E) + \Delta \rho(E).$$  \hspace{1cm} (1)

Here, the term $F \rho(E)$ represents the radiation of the $^{235}U$, $^{239}Pu$, $^{238}U$ and $^{241}Pu$ fission fragments. The second term stems from the chain of the $\beta$-decays which follow neutron radiative capture in $^{238}U$:

$$^{238}U(n, \gamma)^{239}U \frac{\beta}{23.5 \text{min}} \rightarrow^{239}Np \frac{\beta}{2.36 \text{days}} \rightarrow^{239}Pu$$ \hspace{1cm} (2)

The last term in Eq. (1) accounts for the antineutrinos (and neutrinos) induced by the neutron interactions with other materials in the reactor core. As discussed in Ref.[3] this term adds no more than 1% to the total reactor $\bar{\nu}_e$ flux and is disregarded here.

Till recently the term $F \rho$ has traditionally been identified with the reactor $\bar{\nu}_e$ spectrum. The contribution of the chain (2) antineutrinos is however quite sizable for all reactors where neutrino experiments are running or planned. In the ROVNO, BUGEY and CHOOZ PWR-type reactors about 1.2 $\bar{\nu}_e$ per fission come from this source.

2. For each of the four isotopes $^{235}U$, $^{239}Pu$, $^{238}U$ and $^{241}Pu$ the evolution of the neutrino spectra $\rho(E, t)$ have been calculated vs time since the beginning of the fission process. The subsequent decay of the spectra during reactor OFF period have been followed.

The base used for these calculations involves data on 571 fission fragments, data on nuclear isomers and delayed neutron emission.

3. Calculations show that in PWR reactors about 2/3 of all antineutrinos belong typically to the energy range below $E = 1.5$ MeV. This part of the $\bar{\nu}_e, e$ spectrum $\rho(E, 330)$ and it’s component due to fission
fragments $\rho(E, 330)$ at the end of the reactor 330 day ON period are presented in Fig.1.

The evolution of the $\tilde{\nu}_e, e$ spectrum during PWR reactor ON period and its decay after the reactor is shut down is illustrated in Fig.2a,b.

3 RECOIL ELECTRON ENERGY SPECTRA

1. The recoil-electron spectra $S^W(T)$ and $S^M(T)$ in $cm^2/MeV \cdot fiss.$ units, ($T$ is the recoil-electron kinetic energy) for weak (W) and magnetic (M) scattering of reactor antineutrinos are found by convolution the $\tilde{\nu}_e, e$ spectra $\rho(E)$ with the differential cross sections for monoenergy antineutrino:

$$
\frac{d\sigma^W}{dT} = g_F^2 \frac{m}{2\pi} \cdot \left[4x^4 + (1 + 2x^2)(1 - \frac{T}{E})^2 - 2x^2(1 + 2x^2)\frac{mT}{E^2}\right] 
$$

$$
\frac{d\sigma^M}{dT} = \pi r_0^2 \frac{m}{\mu_B^2} \left(\frac{1}{T} - \frac{1}{E}\right),
$$

where $m$ is the electron mass, $g_F^2 \frac{m}{2\pi} = 4.31 \cdot 10^{-45} cm^2/MeV$, $x = \sin^2\theta_W = 0.232$ is the Weinberg parameter, $\pi r_0^2 = 2.495 \cdot 10^{-25} cm^2$.

2. Calculated recoil-electron spectra $S^W(T,330)$ and $S^M(T,330)$ at the end of the reactor ON period are shown in Fig.3. In searches for the neutrino magnetic moment, weak $\tilde{\nu}_e, e$ scattering plays the role of the reactor-correlated background. We note, that in order to keep this background at sufficiently low level one should try to study recoil electrons at not too high energies. As an example, the recoil electron energies $T > 100$ keV seem to be "high" to search for $\mu_\nu = 2 \cdot 10^{-11} \mu_B$ while the range $T < 700$ keV is tolerably low for $\mu_\nu = 5 \cdot 10^{-11} \mu_B$.

Calculated time variations of the recoil-electron spectra during PWR reactor ON and OFF periods for weak and magnetic scattering are presented in Fig.4a,b.

4 DISCUSSION AND CONCLUSIONS

In practice the situation is not as simple as presented above. There occur deviations from the standard operating schedule: reactor can be
stopped for a few days, or it can operate at a reduced level of power etc. For each particular experiment a comprehensive analysis of the reactor operation data should be carried out including all details.

The main result of this study is that effects due to neutrino relaxation play not negligible role in sensitive searches for the neutrino magnetic moment at reactors.

Acknowledgments

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References

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Fig. 1. Soft part of the PWR reactor typical $\bar{\nu}_e$ energy spectrum at the end of 330-day run, the dashed line - fission $\nu_e$ only.
Fig. 2. Ratios of the current $\bar{\nu}_e$ spectra to that at the end of the 330-day run for reactor ON (a) and OFF (b) periods. The numbers indicate days since the beginning of the period (a) and days after reactor shut down (b).
Fig. 3. Recoil electron kinetic energy spectra for weak and magnetic $\bar{\nu}_e$ scattering in reactor antineutrino spectrum at the end of a 330-day run. The numbers on the curves indicate the values of the moment in $10^{-11} \mu_B$. 
Fig. 4. Ratios $S^W(t)/S^W(330)$ and $S^M(t)/S^M(330)$ of the current recoil electron spectra $S^W$ and $S^M$ to the spectra $S^W(330)$ and $S^M(330)$ at the end of the 330-day run for reactor ON (a) and OFF (b) periods. The numbers on the curves indicate days since the beginning of the period (a) and days after the reactor shut down (b). Dashed lines represent magnetic scattering.