Search for heavy sterile neutrinos in beta-decay of ^{144}Pr nuclei

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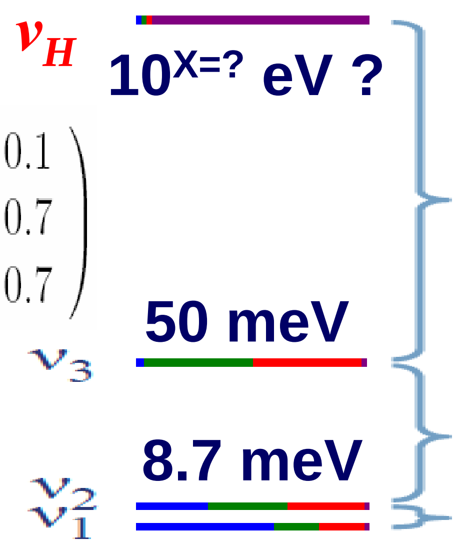
Abstract

^{144}Ce–^{144}Pr β-spectra have been measured and analyzed in order to find contribution from the heavy neutrino. New upper limits on the mixing parameter $|U_{eH}|^2 \leq (1\text{-}30)10^{-4}$ at 90% C.L. has been obtained for neutrino with the mass in the interval of 0.1-2.0 MeV, .

Neutrino mixing: PMNS matrix +mass states

$$\begin{bmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \\ \nu_s \end{bmatrix} = \begin{bmatrix} U_{e1} & U_{e2} & U_{e3} & U_{eH} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} & U_{\mu H} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} & U_{\tau H} \\ U_{s1} & U_{s2} & U_{s3} & U_{sH} \end{bmatrix} \begin{bmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \\ \nu_H \end{bmatrix}$$

$$\begin{pmatrix} 0.8 & 0.5 & 0.1 \\ 0.5 & 0.6 & 0.7 \\ 0.3 & 0.6 & 0.7 \end{pmatrix}$$



$$\nu_e = Cos\theta\,|\nu_L> + Sin\,\theta\,|\nu_H>$$

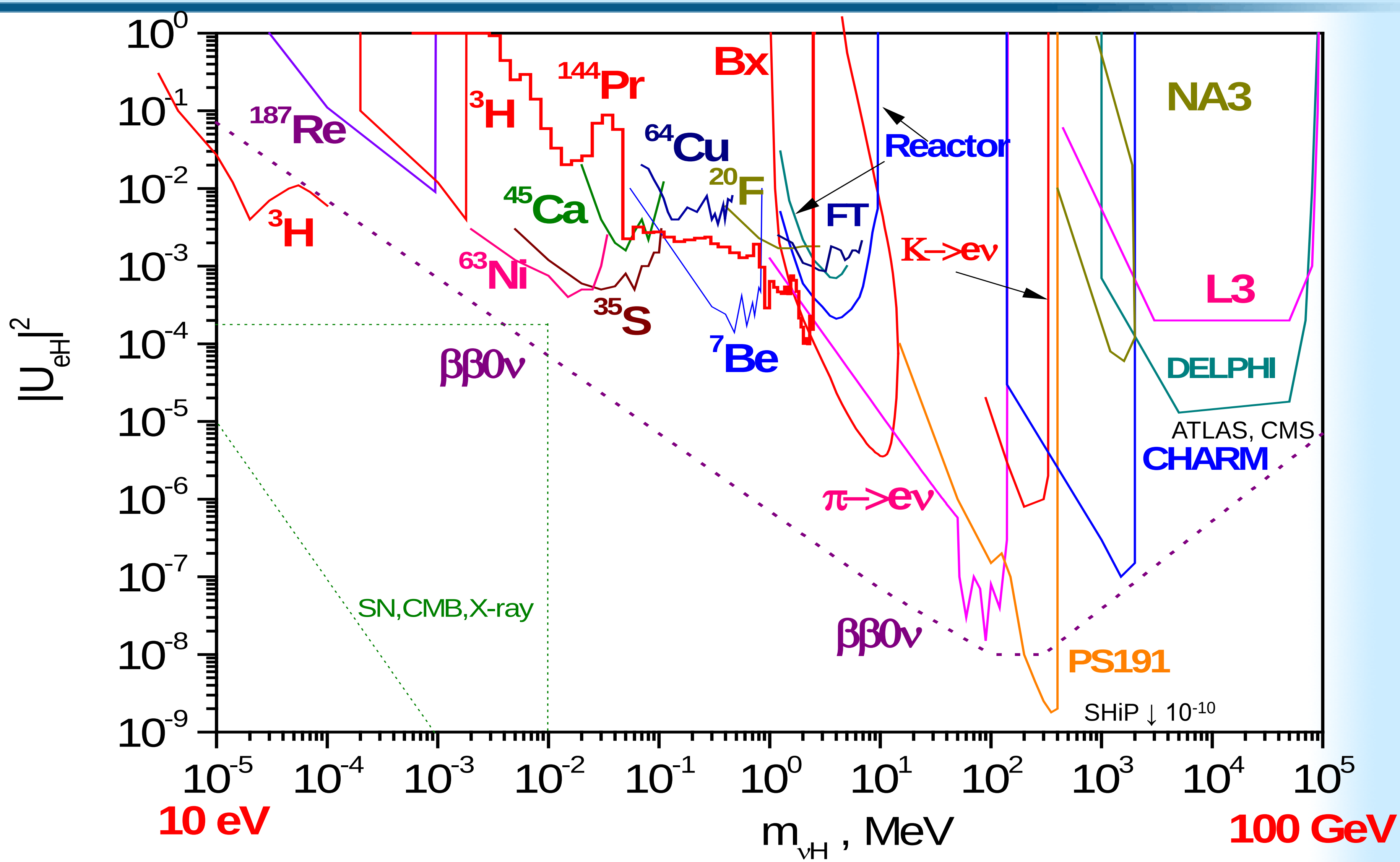
$$S_{tot} = (1-U_{eH}^2)S(m=0) + U_{eH}^2 S(m_{\nu H})$$

$$\Delta m_{12}^2 = 7.5\times10^{-5}eV^2, \Delta m_{23}^2 = 2.4\times10^{-3}eV^2$$

$$Sin^2\theta_{12} = 0.307,\ Sin^2\theta_{23} = 0.546,\ Sin^2\theta_{13} = 0.022$$

The discovery of oscillations of solar and atmospheric neutrinos means that at least 2 of 3 mass states of neutrino are nonzero. The measured parameters together with Plank telescope constraints on the sum of masses of light neutrinos impose a bound of 70 meV on the heaviest mass state $\nu_i (i = 1, 2, 3)$ *of 3 known types of neutrino. The measured width of decay of the Z boson indicates that heavier mass states of neutrino should be related to the sterile neutrino. Such neutrinos can be mixed with 3 active types of neutrino. Mixing is responsible for neutrino oscillations, can be manifested in processes of production of active neutrinos, and can lead to decays of sterile neutrinos into particles of Standard Model*

Limits on $|U_{eH}|^2$ for $m_{\nu H}$ = (10 eV -100 GeV)



The limits on the mixing parameter $|U_{eH}|^2$ (1.0 – 10^{-9}) for (10 eV-100 GeV) mass interval.

How to search for heavy neutrinos?

1. Neutrino oscillation

$L(m) = 2.5\ E(\mathrm{MeV}) / \Delta m^2(\mathrm{eV}^2)$;
$m_{\nu H} = 1$ keV => $L = 2.5\ \mu m$

2. Two-body decay

$\pi^{\pm} \to \mu^{\pm} + \nu_{\mu}$ $\quad P_{\mu}^2 = (m_{\pi}^2 + m_{\mu}^2 - m_{\nu}^2)^2 / 4m_{\pi}^2 - m_{\mu}^2$

$P_{\mu} = 29.79\ (1 - \chi(m_{\nu}^2))$ MeV

$N(A,Z) + e^- \to N(A,Z-1) + \nu_e$ $\quad T_A = (Q_{EC}^2 - m_{\nu}^2) / 2(Q_{EC}^2 + m_A^2) = 57$ eV(^{7}Be)

3. Three-body decay

β^-: $N(A,Z) \to N(A,Z+1) + e^- + \nu_e$

$S(E) = P_e W_e (E_0 - E)((E_0 - E)^2 - m_{\nu}^2)^{1/2}\ C(E) F(E,Z)$

4. Heavy neutrino decay

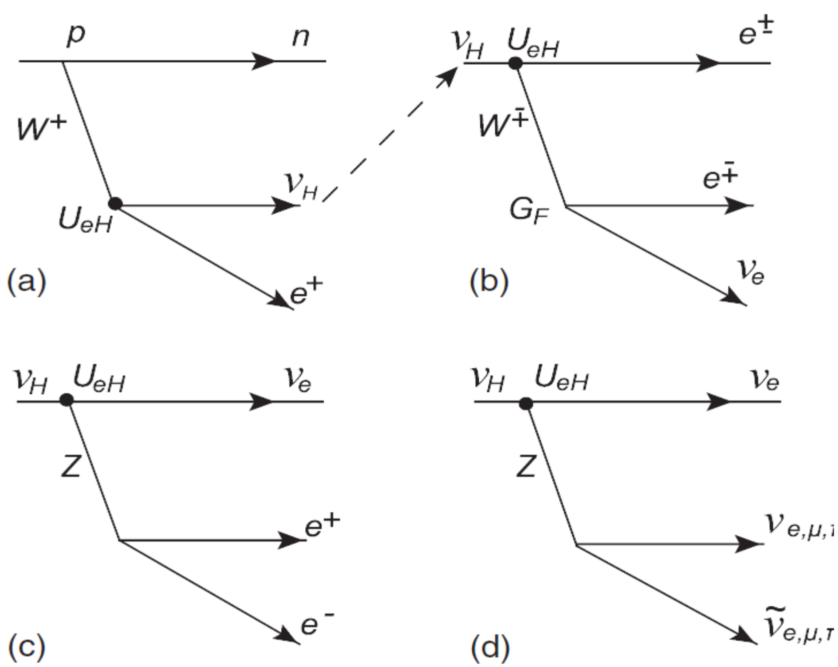
$\nu_{eH} \to \nu_L + e^+ + e^-$

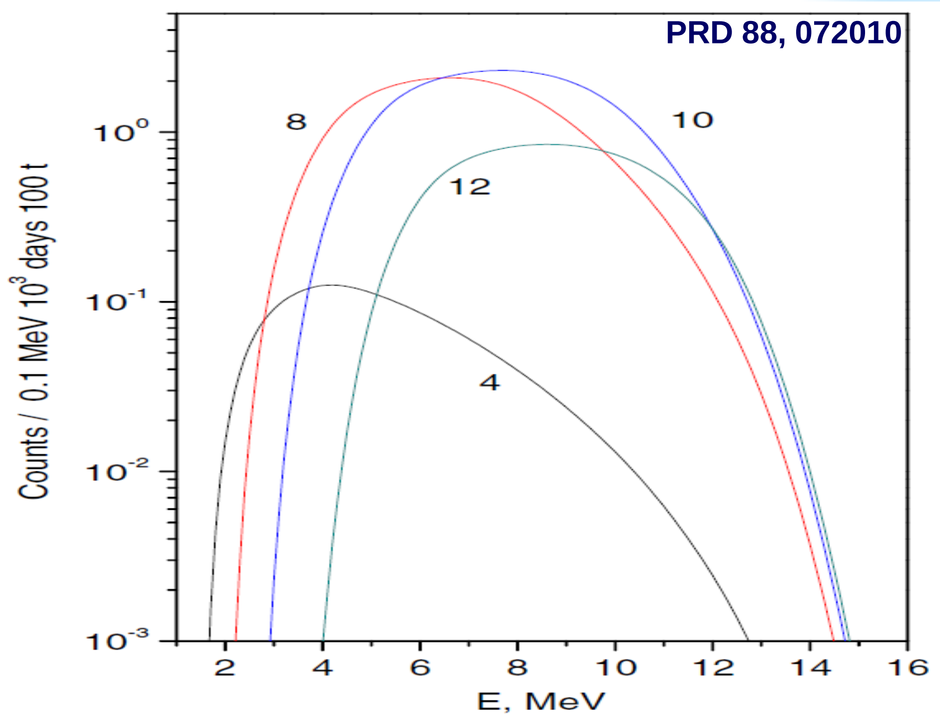
5. Neutrinoless double beta decay

$2\beta 0\nu_e$: $N(A,Z) \to N(A,Z+2) + e^- + e^-$

Heavy neutrinos can have measurable effects in nucleon and meson decays that can be explored by searching for extra peaks or kinks in the energy spectrum of their leptonic two- or three-body decays or by precisely measuring their decay branching ratios. Heavy neutrino can decay into lepton pair. If heavy neutrino states are Majorana fermions, neutrinoless double beta decay experiments may provide stringent sensitivity. Other constraints on Uℓi come from lepton universality tests, the decay width of invisible decays of Z bosons, μ and τ lepton-flavor-violating decays, and magnetic and electric dipole moments of charged leptons.

Neutrino decay: $^8B\to{}^8Be + e^+ + \nu_H \to e^+ + e^- + \nu_L$



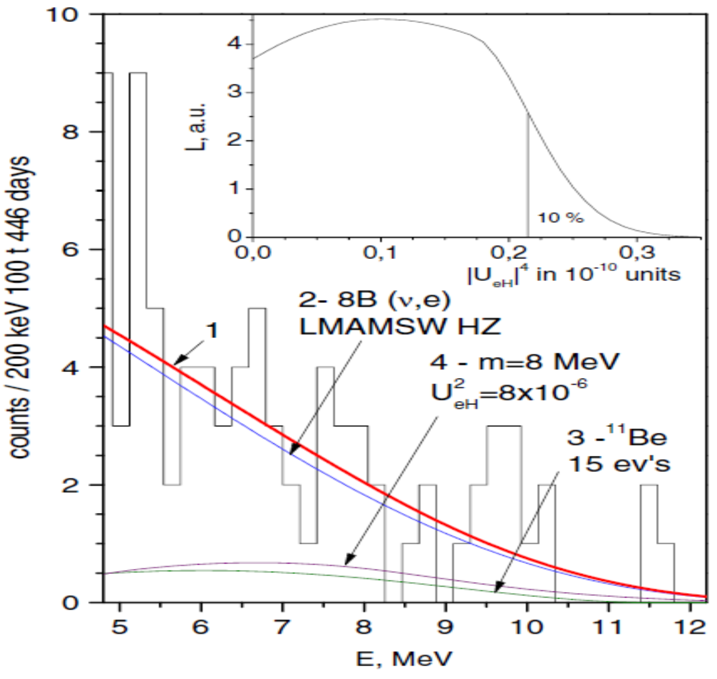


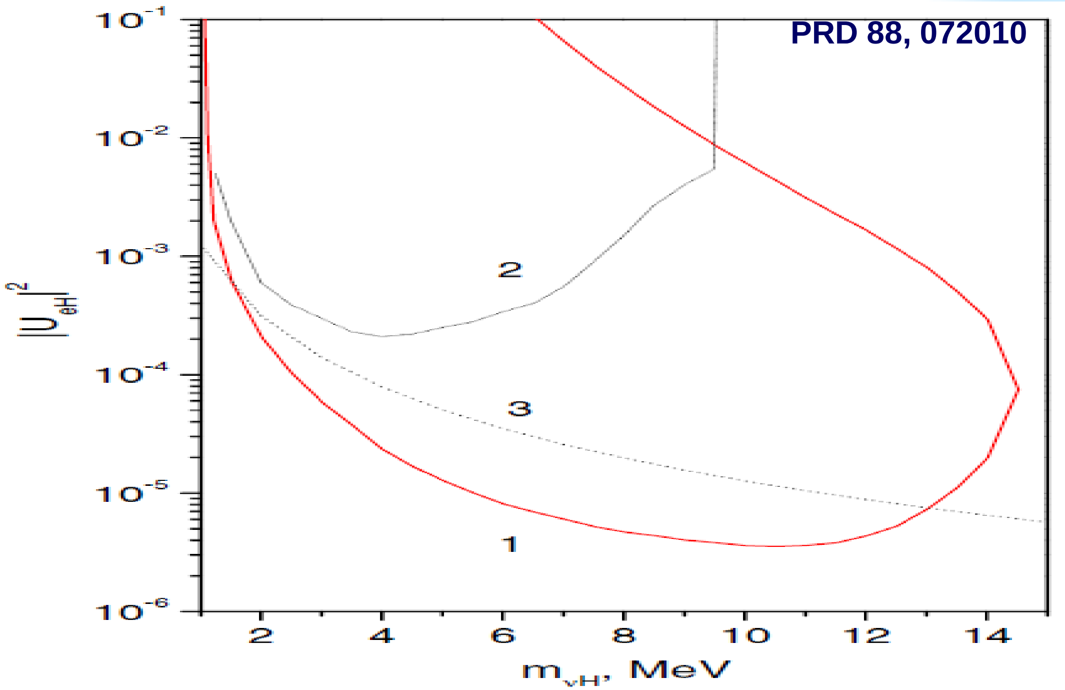
Appearance $^8B\to{}^8Be + e^+ + \nu_H$ (a) and decay of heavy neutrino. The invisible decay mode is shown also.

The expected Borexino spectra due to decay $\nu_H\to e^+ + e^- + \nu$ for different neutrino masses $m_{\nu H}$ = 4 -12 MeV and mixing parameter $|U_{eH}|^2 = 10^{-5}$.

Solar and reactor neutrino experiments are most sensitive to sterile neutrinos with masses in the range 1 MeV$<m_{\nu H}<$10 MeV. These neutrinos can decay within the detector via the channel $\nu_H\to e^+ + e^- + \nu_L$. Limits have been set by searches at the Rovno and Bugey reactors. This decay was also searched for by the Borexino experiment for neutrinos with masses up to 14MeV which can be produced in the decay of ^8B.

Neutrino decay: $^8B \rightarrow ^8Be + e^+ + \nu_H \rightarrow e^+ + e^- + \nu_L$



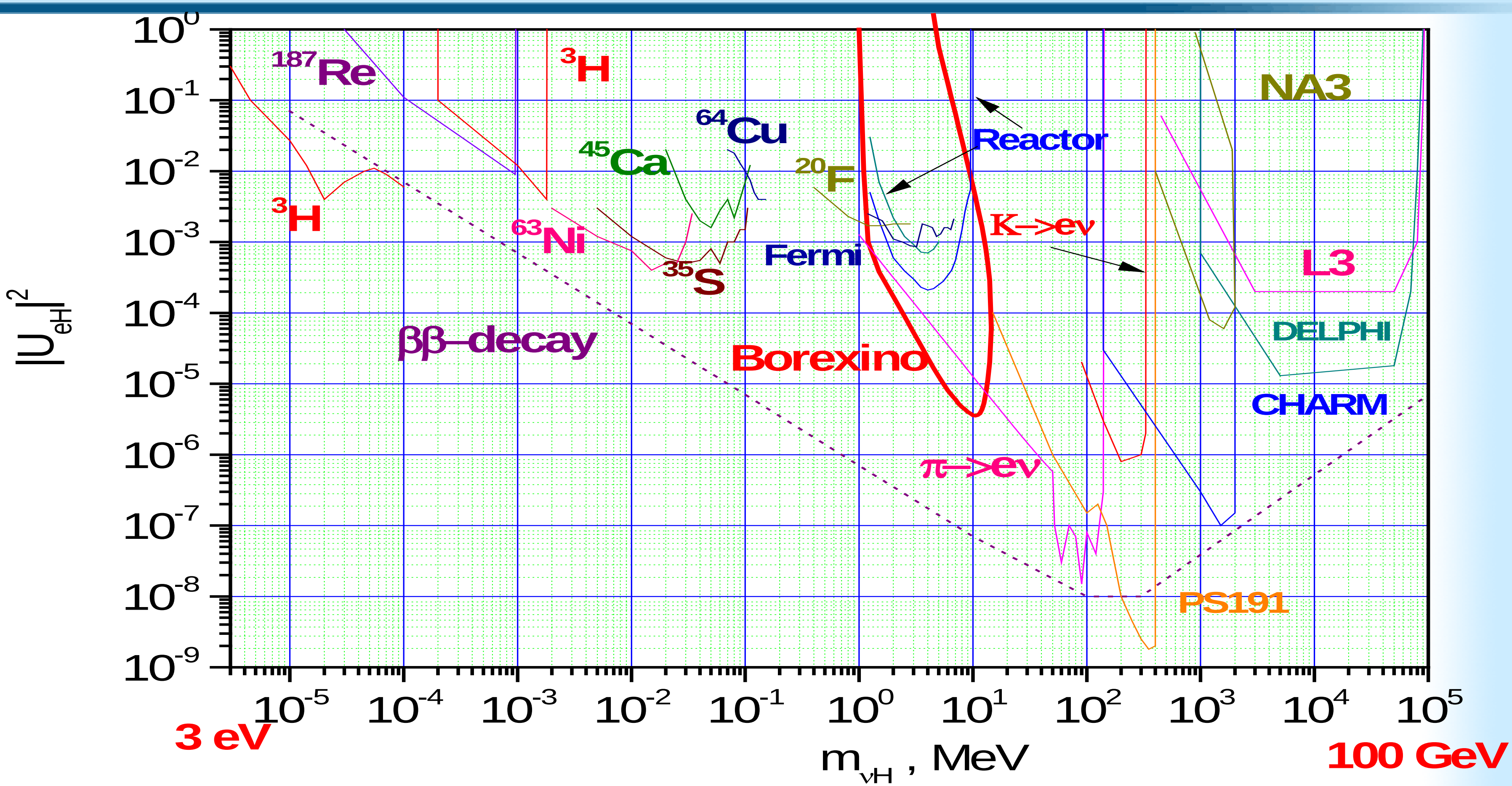


The Borexino 446 days spectrum in the (4.8–12.8)MeV range. 1- optimal fit, 2- 8B(ν,e), 3- 11Be, 4 – m=8 MeV.

Limits on $|U_{eH}|^2$ as a function of mν (90% C.L.). 1: excludes values of $|U_{eH}|^2$ and mν inside region 1. 2: Upper limits from reactor experiments 3: Upper limits from π→e+ν decay.

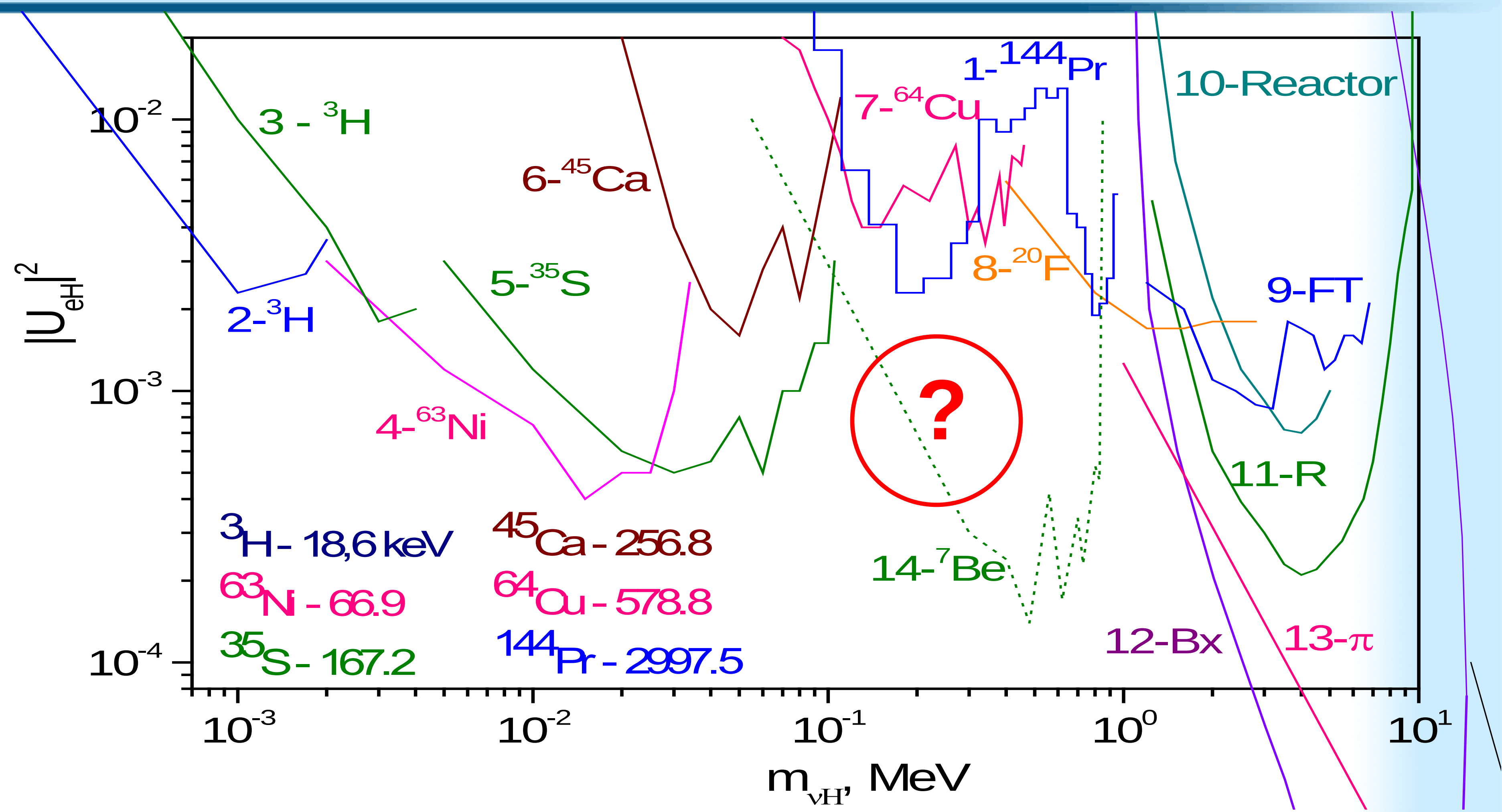
No statistically significant deviations of $|U_{eH}|^2$ from zero were observed for all tested $m_{\nu H}$. Thanks to uniquely low radioactive background and large target mass of the Borexino detector, new limits on the mixing parameter of massive neutrino in the range of mass 1.5–14 MeV to the electron neutrino have been set. These limits are 10- to 1000-fold stronger than those obtained by experiments searching for similar decays at nuclear reactors and 1.5–4 times stronger than those inferred from π-decays. Borexino has set the best limits: ***$|U_{eH}|^2 < 3\times10^{-6}$*** *for $m_{\nu H}$~10MeV.*

Limits on $|U_{eH}|^2$ for neutrino with mass (3 eV – 100 GeV)



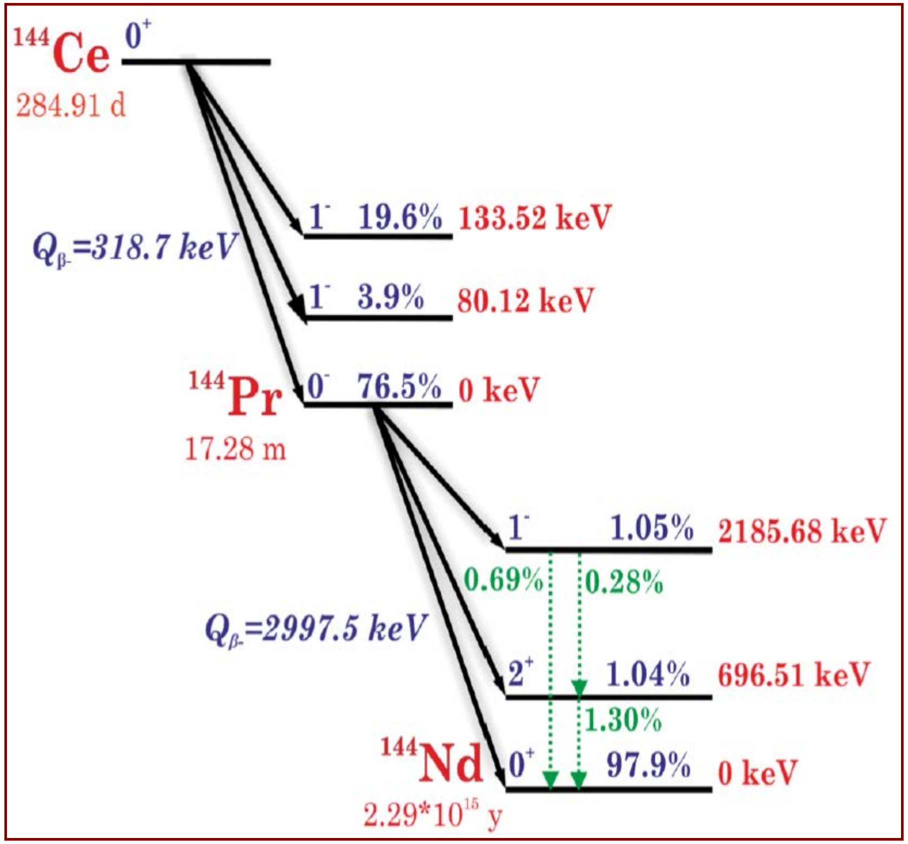
The most stringent constraints on the mixing parameter $|U_{eH}|^2$ of the heavy neutrino with the mass in the range from 10 eV to 2 MeV were obtained from the β-spectra of the ^{3}H, ^{63}Ni, ^{35}S, ^{45}Ca, and ^{64}Cu nuclei and ft values for superallowed Fermi beta transitions in ^{35}S, ^{19}F, ^{19}Ne, ^{14}O, and ^{20}F nuclei. Searches for decays of the heavy neutrino performed with reactor neutrinos and ^{8}B solar neutrinos provided the most stringent constraints on the mixing parameter for neutrinos with masses in the range of 2–10 MeV. For large masses , constraints on $|U_{eH}|^2$ were obtained from data on decays of pions and kaons

Limits on $|U_{eH}|^2$ for $m_{\nu H}$ = (1 keV -10 MeV)



Upper limits on the mixing parameter obtained from the study of the beta-spectrum shapes and solar and reactor neutrino decays. The limits on $|U_{eH}|^2$ for the mass region from 100 keV to 1 MeV are at the level of $(4\text{-}6)\times10^{-3}$, which is a few times weaker than for other regions.

^{144}Ce-^{144}Pr neutrino source



Q_β ^{144}Ce	Q_β ^{144}Pr	γ ^{144}Ce	γ ^{144}Pr
318.7 (76.5%)	2997.5 (97.9%)	133.5 (11.1%)	696.5 (1.3%)
185.2 (19.6%)	2301.0 (1.04%)	80.1 (1.36%)	2185.7 (0.69%)
238.6 (3.9%)	811.8 (1.05%)	41.0 (0.26%)	1489.1 (0.28%)

*The **^{144}Ce–^{144}Pr** source is the most promising among artificial emitters of electron antineutrinos. It was expected that this source would be used with the KamLand and Borexino detectors. One of the specific problems that must be solved in the experiment with the ^{144}Ce–^{144}Pr source is to precisely measure the β spectra of these nuclei in order to determine the intensity and shape of the antineutrino spectrum.*

*The Q energies of the β-transitions in ^{144}Ce and ^{144}Pr nuclei are 319 and 2998 keV, respectively. We analyzed spectra taking into account six most intense beta transitions to excited states of daughter nuclei. The probabilities of transitions to other excited levels of the ^{144}Pr and ^{144}Nd nuclei were no more than **0.0014%.** The ^{144}Ce undergoes 3 nonunique first-order forbidden β-transitions to ground and excited levels of the ^{144}Pr. Decays of the ^{144}Pr to the ground and first excited states of the ^{144}Nd correspond to nonunique and unique first-order forbidden transitions, respectively. Decay into the 1^- level with 2185 keV is an allowed transition.*

Shape of β-spectra

$$S(W) = P\,W\,(W_0-W)\,((W_0-W)^2-m_\nu^2)^{1/2}\;\;F(W,Z)\,C(W)$$

where P - electron momentum, E_e - electron kinetic energy,

$W = E_e + m_e$ - total electron energy, W_0 - total endpoint energy,

F(W) is Fermi function that is computed in the following parametrization:

$$F(W,Z) = F_C(Z,E_e)\,L(Z,E_e)\,C(Z,E_e)\,S(Z,E_e)\,G(Z,E_e)\,B(Z,E_e)$$

where $F_C(Z,E_e)$ is the coulomb interaction between the electron and the point-like nuclei, $L(Z,E_e)$ is the electromagnetic finite-size correction, $C(Z,E_e)$ is weak finite-size correction, $S(Z,E_e)$ is screening correction, $G(Z,E_e)$ is radiative correction and $B(Z,E_e)$ is weak magnetism correction.

C(W) - nuclear form-factor, parameterized as:

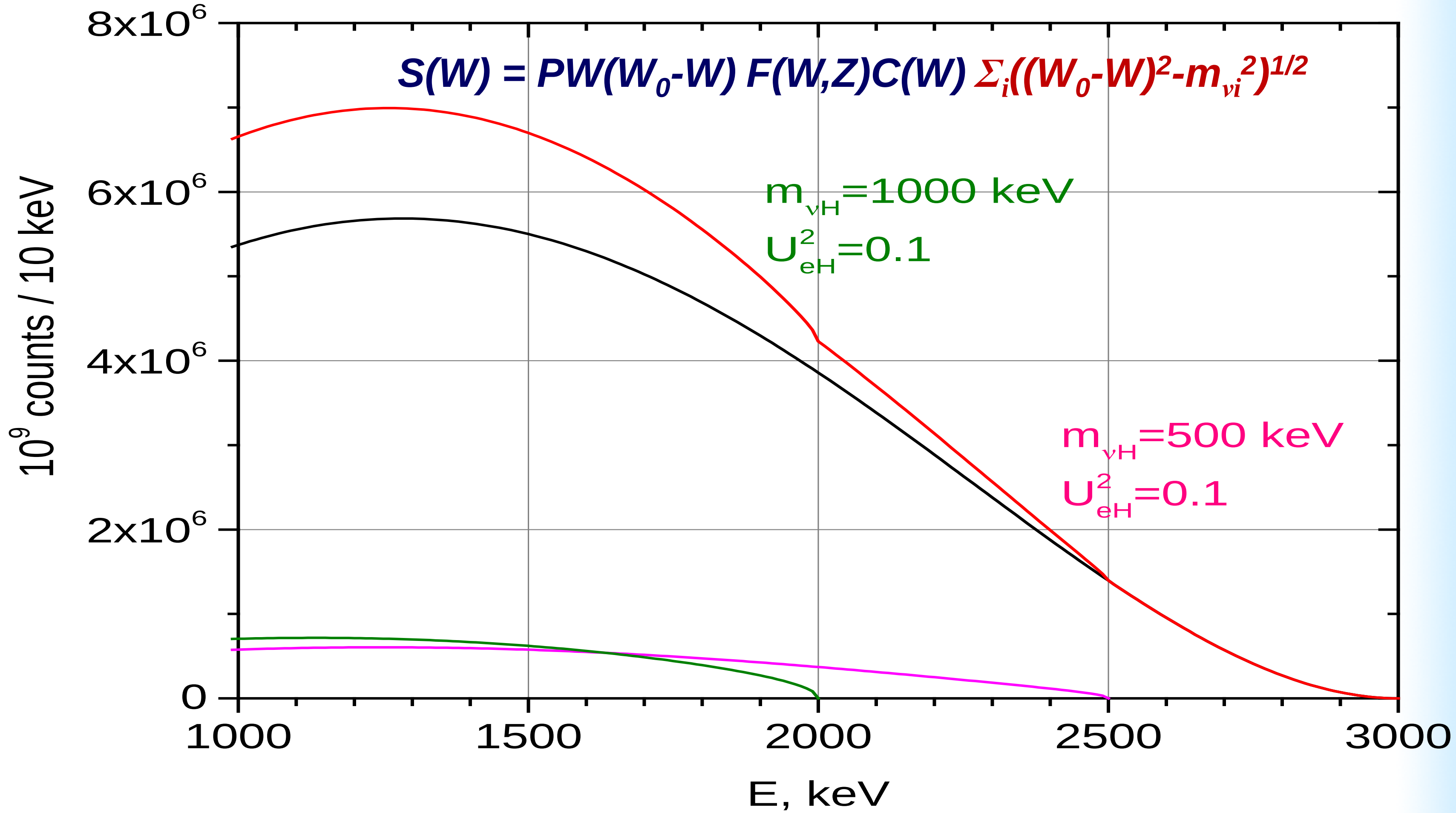
$$C(W) = 1 + C_1\,W + C_2\,W^{-1}$$

C(W) = 1 + (-0.02877 ±0.00028)W + (-0.11722 ±0.00297)W-1

In the case of the emission of heavy neutrino with the mass $m_{\nu H}$ the total spectrum is the sum of two beta spectra

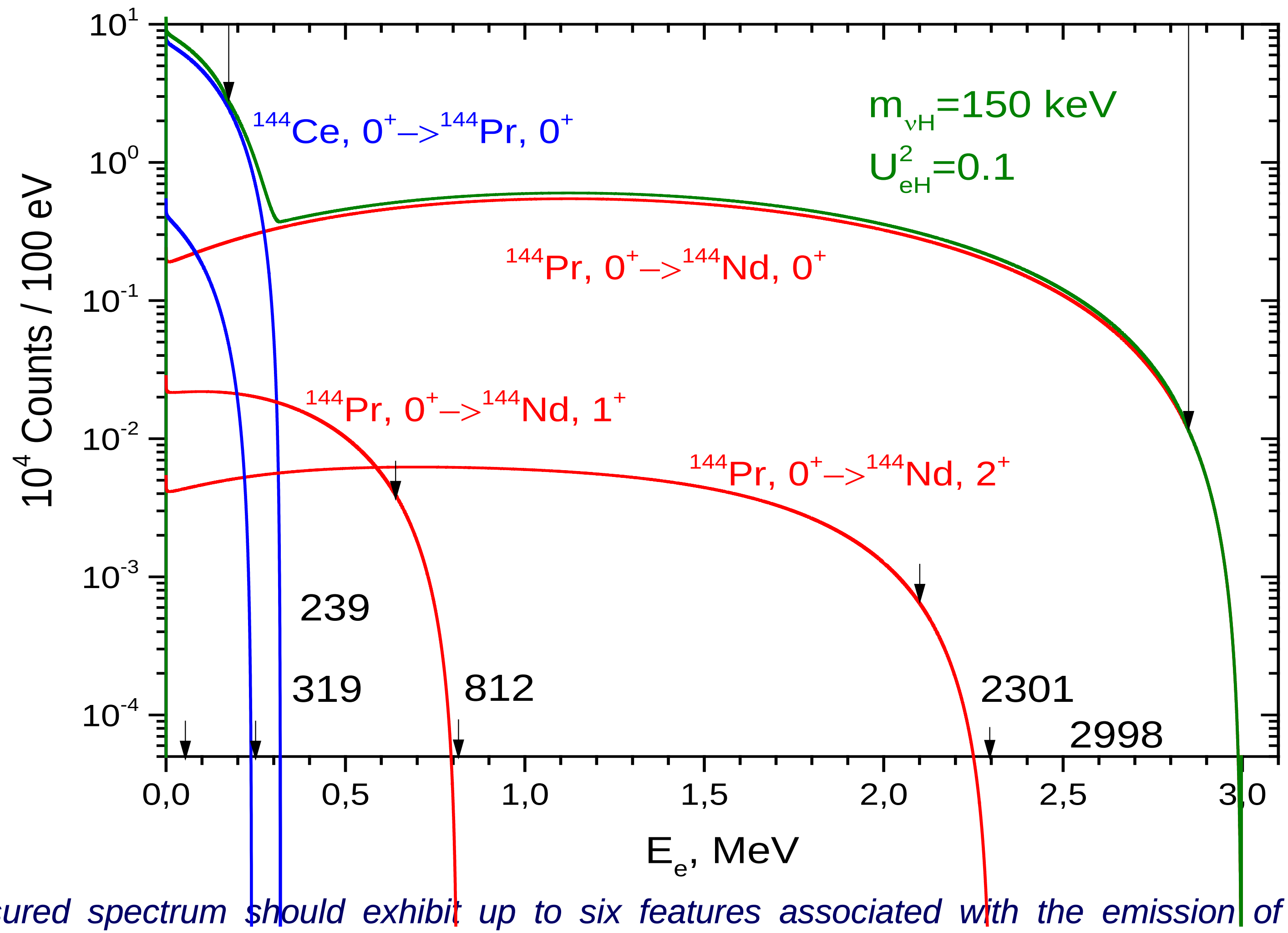
$$S_{tot}(W) = (1-U_{eH}^2)\,S(W, m=0)\;+\;U_{eH}^2\,S(W, m_{\nu H})$$

β-spectrum with massive neutrinos



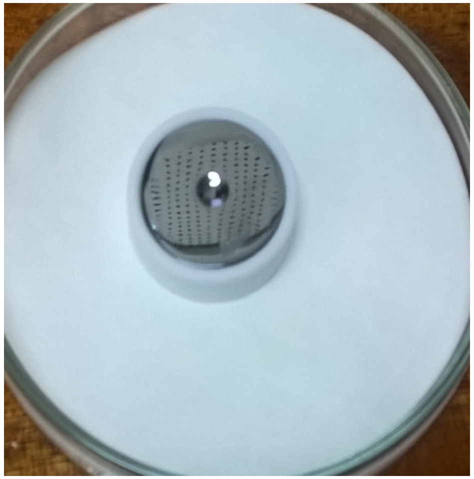
In the case of neutrino mixing, where the current state $\nu_l(l = e, \mu, \tau, s,.?)$ is the superposition of mass states $\nu_i(i = 1, 2, 3, .N)$, which is determined by the mixing matrix $|U_{li}|^2$, the spectrum of electrons from the beta decay will be the sum of N incoherent channels, each with the boundary energy and intensity.

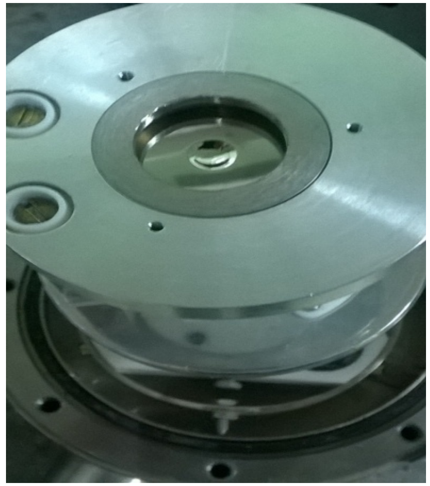
^{144}Ce-^{144}Pr β-spectra



The measured spectrum should exhibit up to six features associated with the emission of a massive neutrino depending on the value. According to the scheme of the decay, if the mass of the heavy neutrino is smaller than Q_β(^{144}Ce)–133.5=185 keV, the spectrum will have six features spaced by from the boundary energies of beta spectra. This circumstance certainly increases the sensitivity of the experiment.

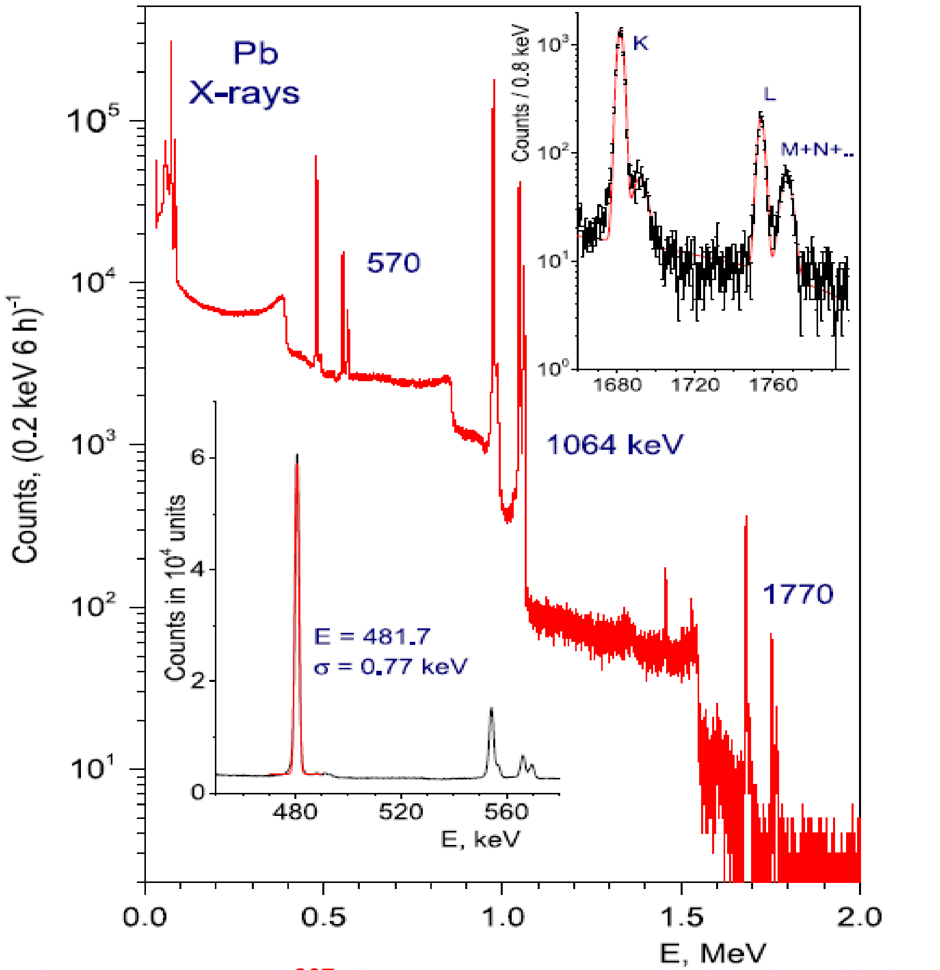
Si(Li)-detectors with 6-10 mm thick 10-30 mm in diameter



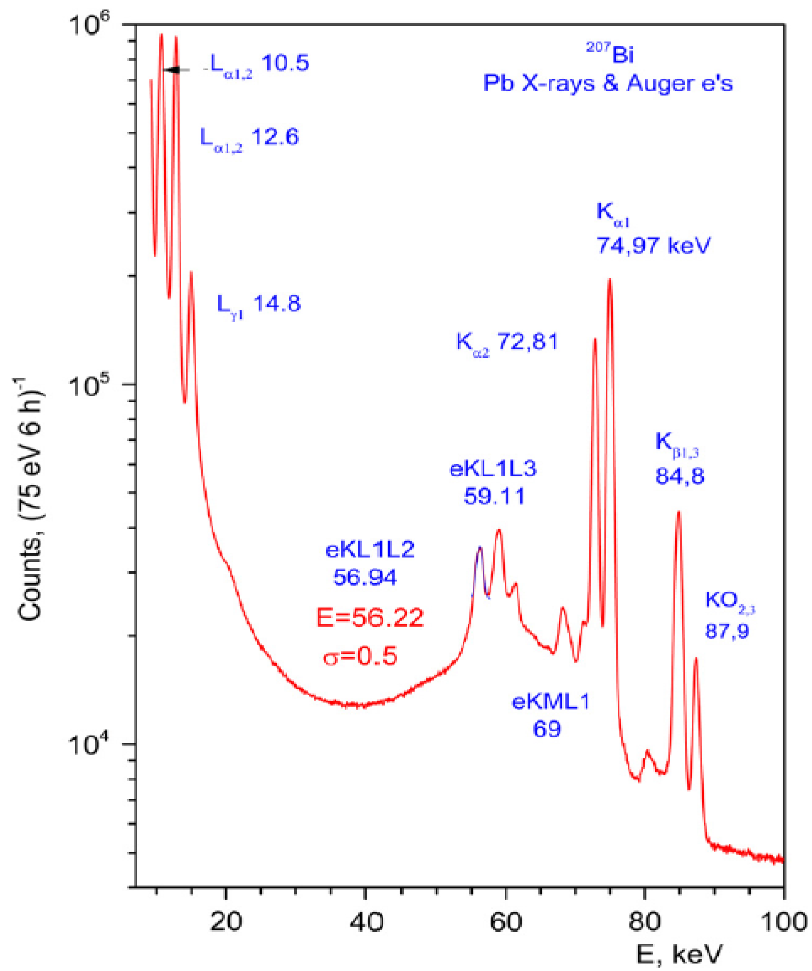


To measure the spectrum of electrons, we used a Si(Li) detectors produced at PNPI NRC KI

Parameters of Si(Li)-detectors: σ = 0.8 keV



The spectrum of ^{207}Bi source measured with the Si(Li) detector in energy range of (0.01–2.0) MeV. The inset show the electron peaks corresponding to internal conversion from *K*-, *L*-, *M*-shells of 570- and 1770 keV nuclear levels.



The spectrum of ^{207}Bi source measured with the Si(Li) detector in energy range of (5–100) keV. The spectrum contains prominent Auger peaks with energies of 57–59 keV.

Two Si(Li)- β-spectrometers

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NUCLEAR EXPERIMENTAL TECHNIQUE

A Beta Spectrometer Based on Silicon Detectors

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Beta-spectrometer with Si-detectors for the study of ^{144}Ce–^{144}Pr decays

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NUCLEAR EXPERIMENTAL TECHNIQUE

A Silicon 4π Spectrometer of β-Decay Electrons with Energies of up to 3 MeV

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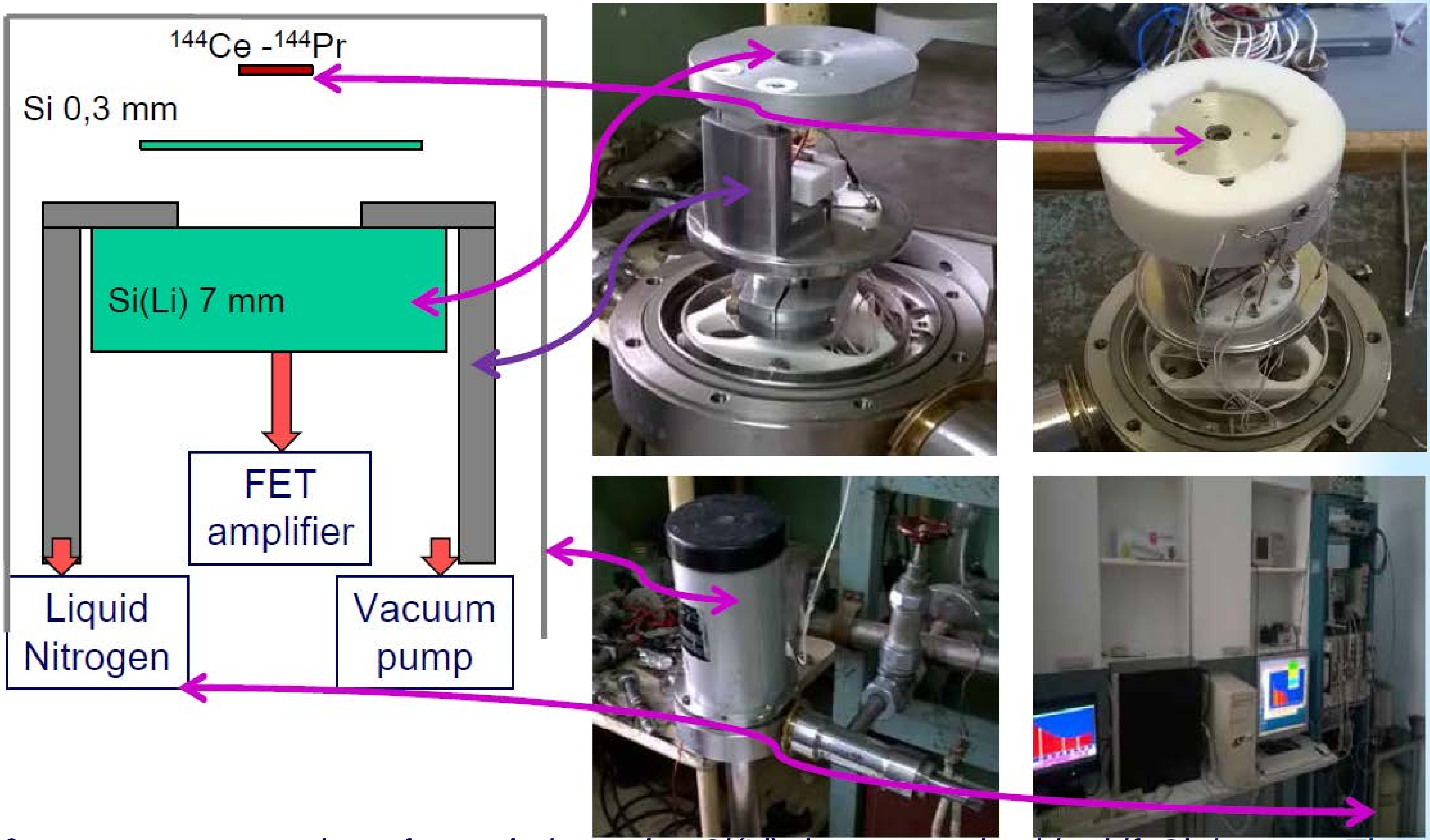
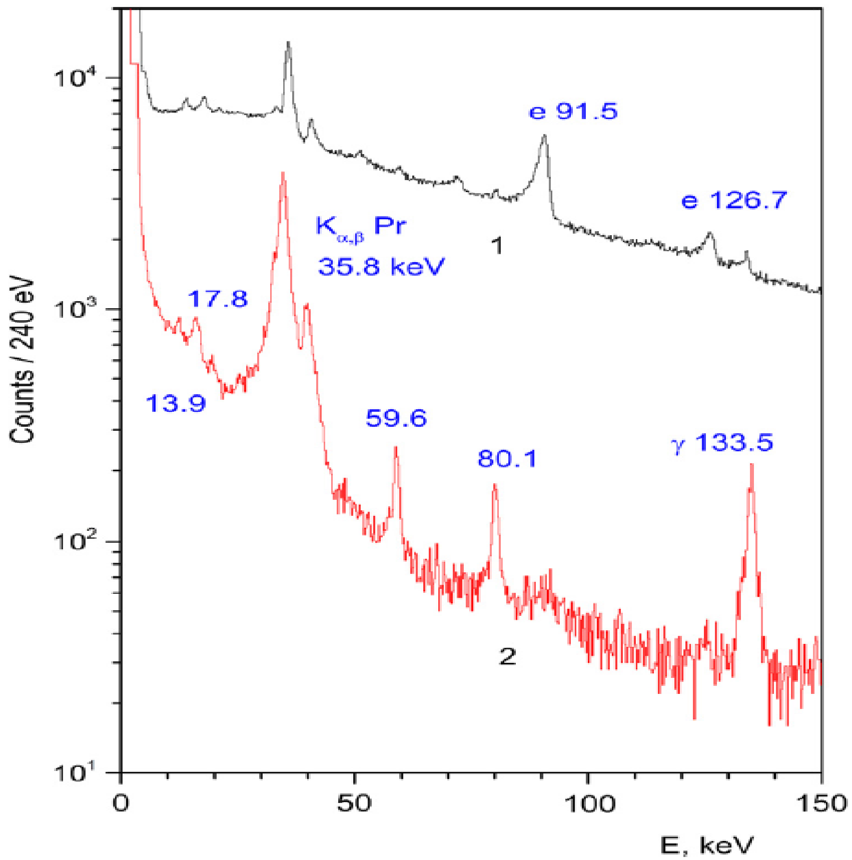
β-spectrometer with thin & thick Si-detectors

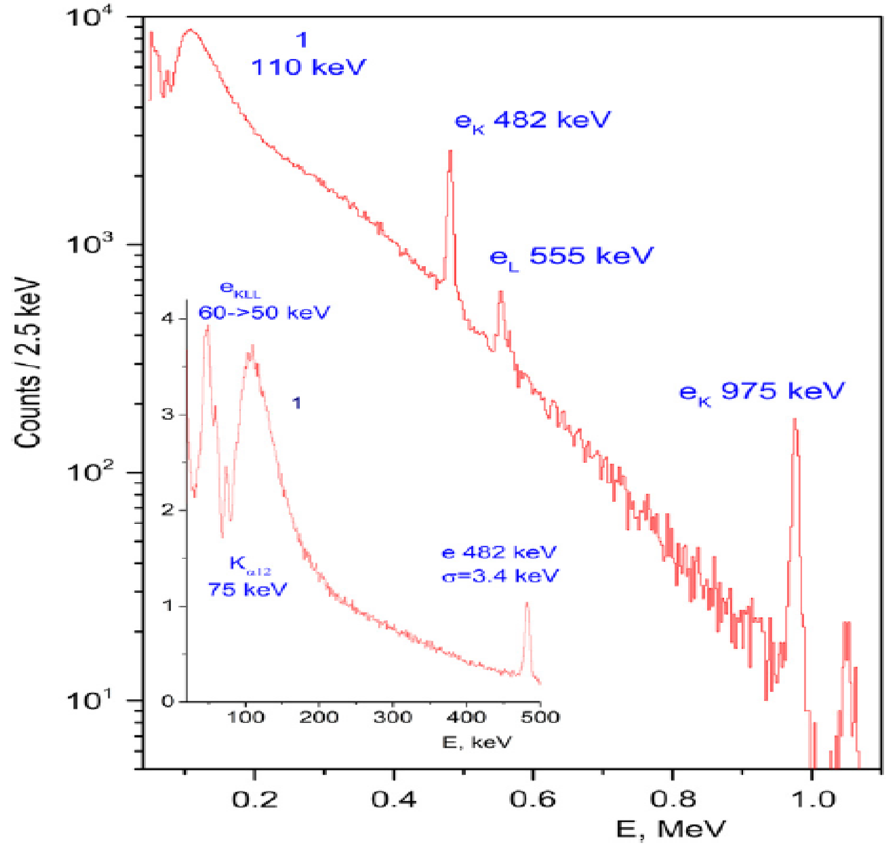


β-spectrometer consists of a total-absorption Si(Li) detector and a thin drift Si detector. The use of coincidences between the signals from the thick and thin detectors makes it possible to efficiently separate β radiation from X- and γ- rays.

Spectra of thin and thick in (anti)coincidence



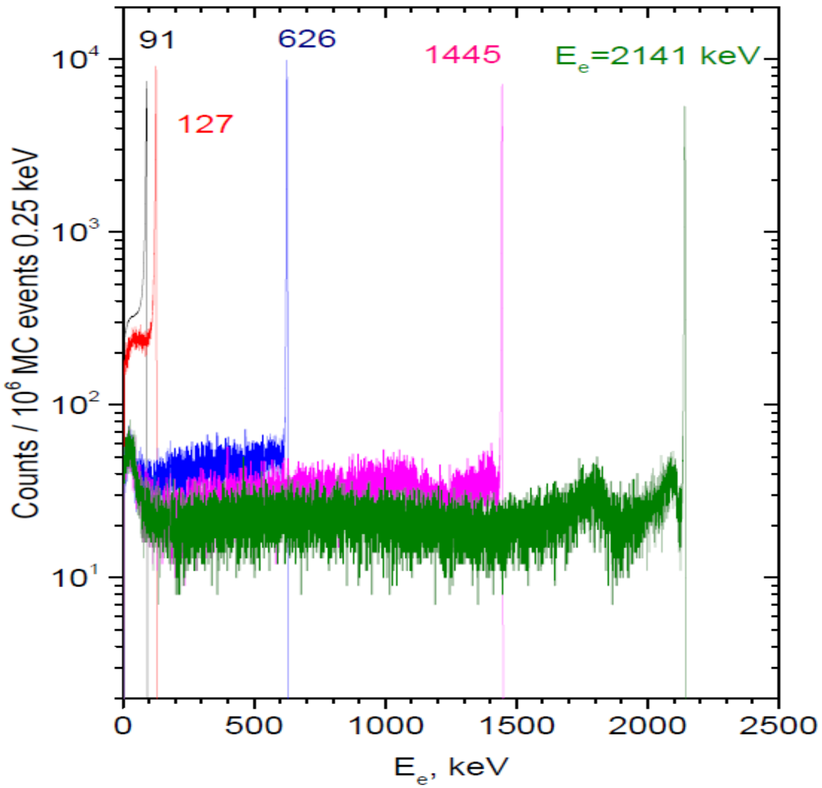
The spectrum of ^{144}Ce measured with the Si(Li) detector: 1—total spectrum, 2—in anti-coincidence with the transmission detector



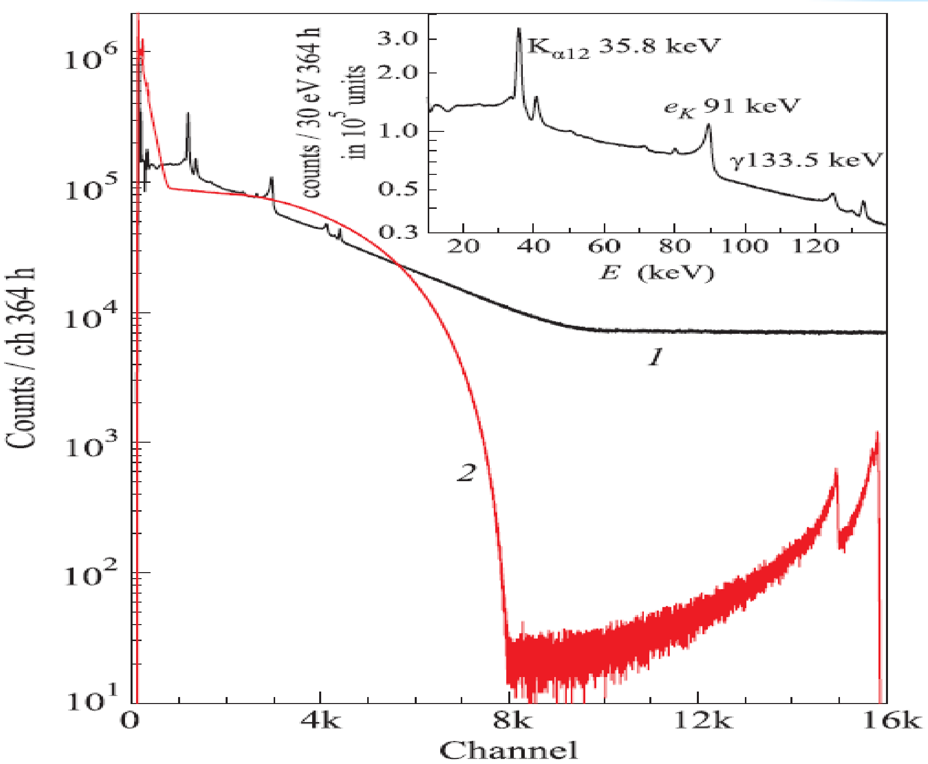
The spectrum of ^{207}Bi source measured with the 0.3 mm transmission Si detector. The inset shows the low-energy part of the spectrum, containing Auger and X-ray peaks.

This is an important part of measurement of the source radio purity since Compton scattering of uncontrolled γ-rays can mimic the contribution from a heavy neutrino.

Response function of “T-D” β-spectrometer: backscattering



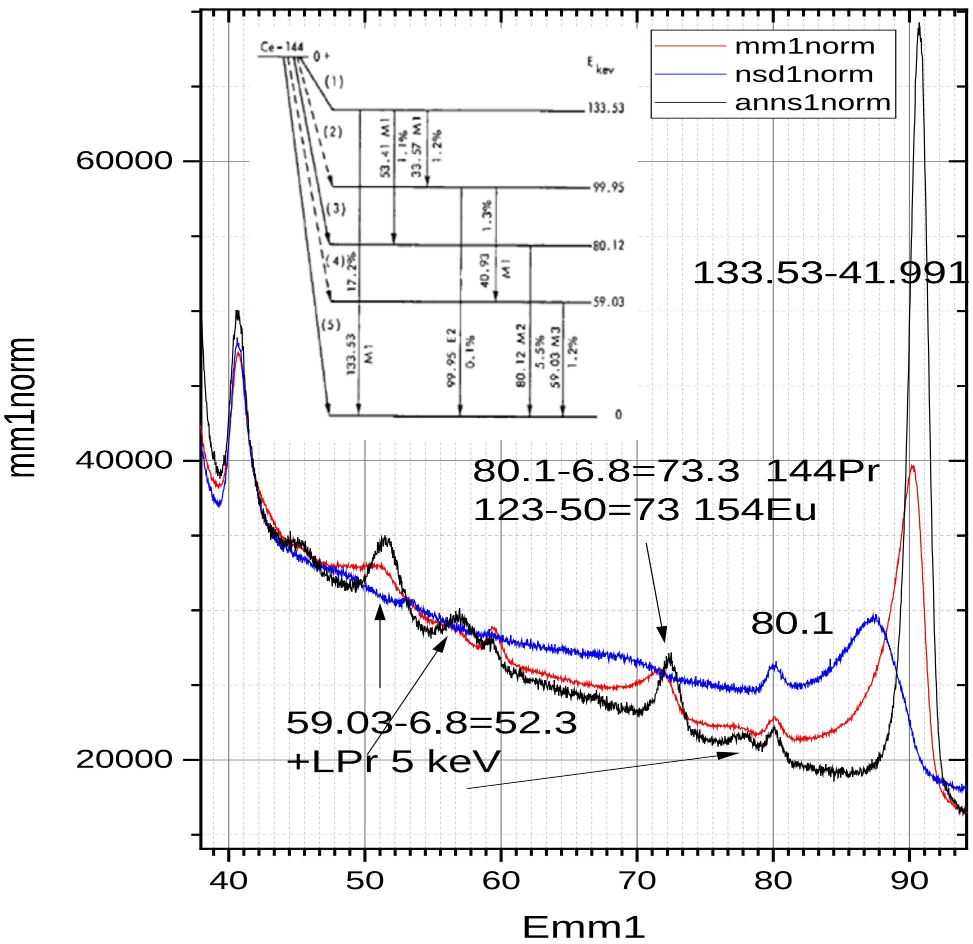
The detector response functions for ^{144}Ce–^{144}Pr conversion electrons with energies 91.5, 127, 626, 1446 and 2145 keV

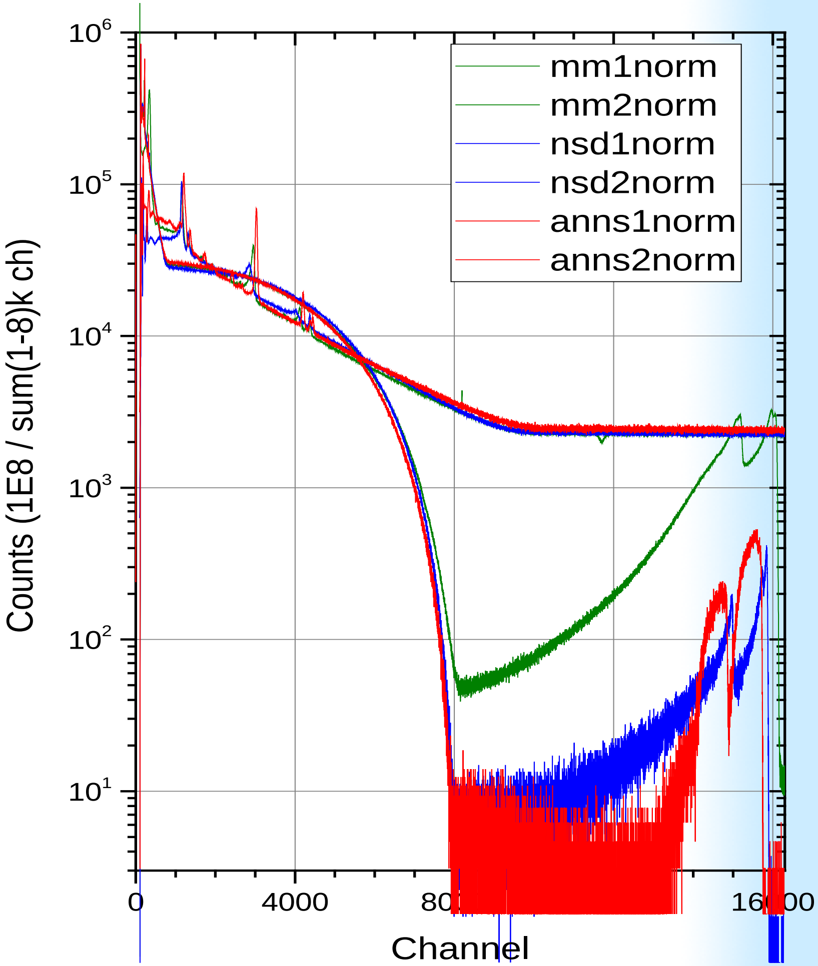


Spectra measured with the Si(Li) detector: (1) ADC1 - 0.01–0.5 MeV and (2) ADC2 - 0.05–6.0 MeV. The inset shows response function to X-rays and conversion electrons from 133.5 keV level.

The long tail of the response function due to backscattering significantly distorts the beta spectrum and makes it difficult for fitting. We used the response functions for the specific target - detector geometry simulated by the Monte Carlo method with the Geant4.

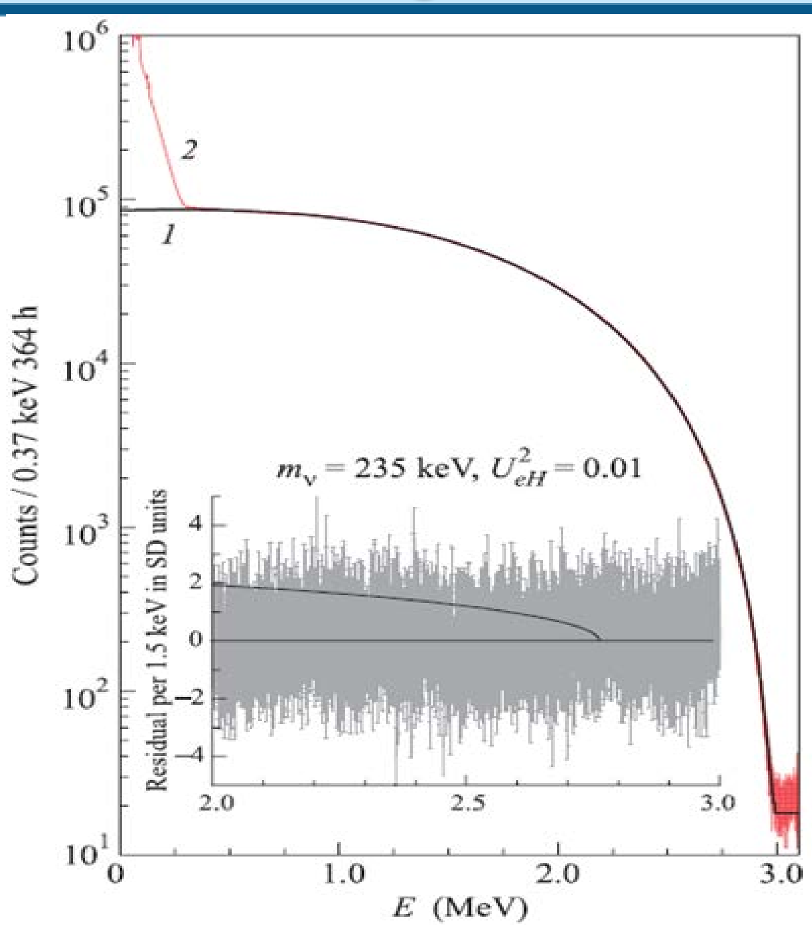
Response functions of "T-D" β-spectrometer : target

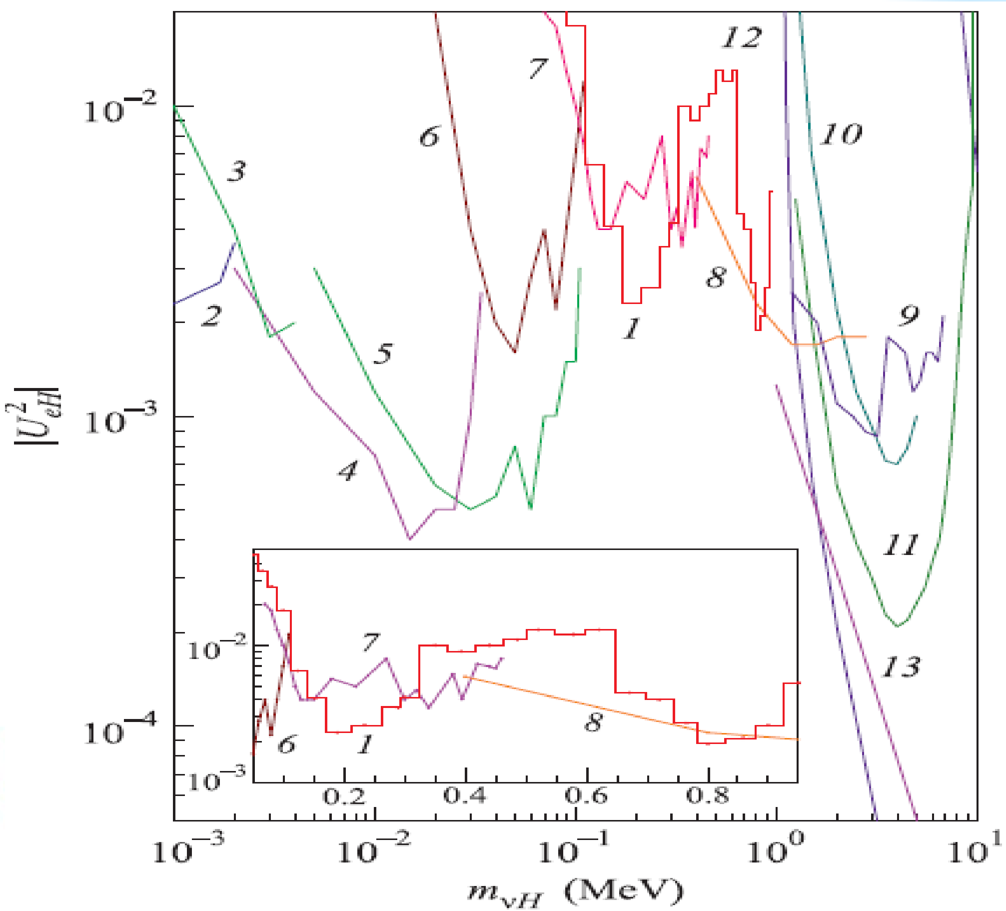




The difference in the shape of α- and electron peaks from the Gaussian is determined by probability distribution of the paths that particle travels in the target and in insensitive layer of the detector. The figure shows the response functions for three different targets with different thicknesses and different radiopurity levels.

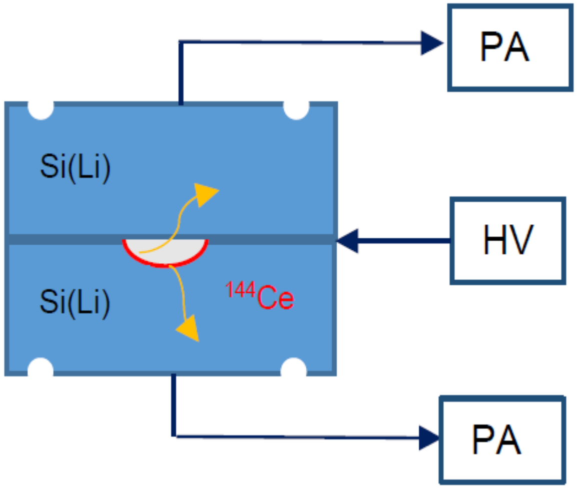
Fitting results and upper limits on $|U_{eH}|^2$





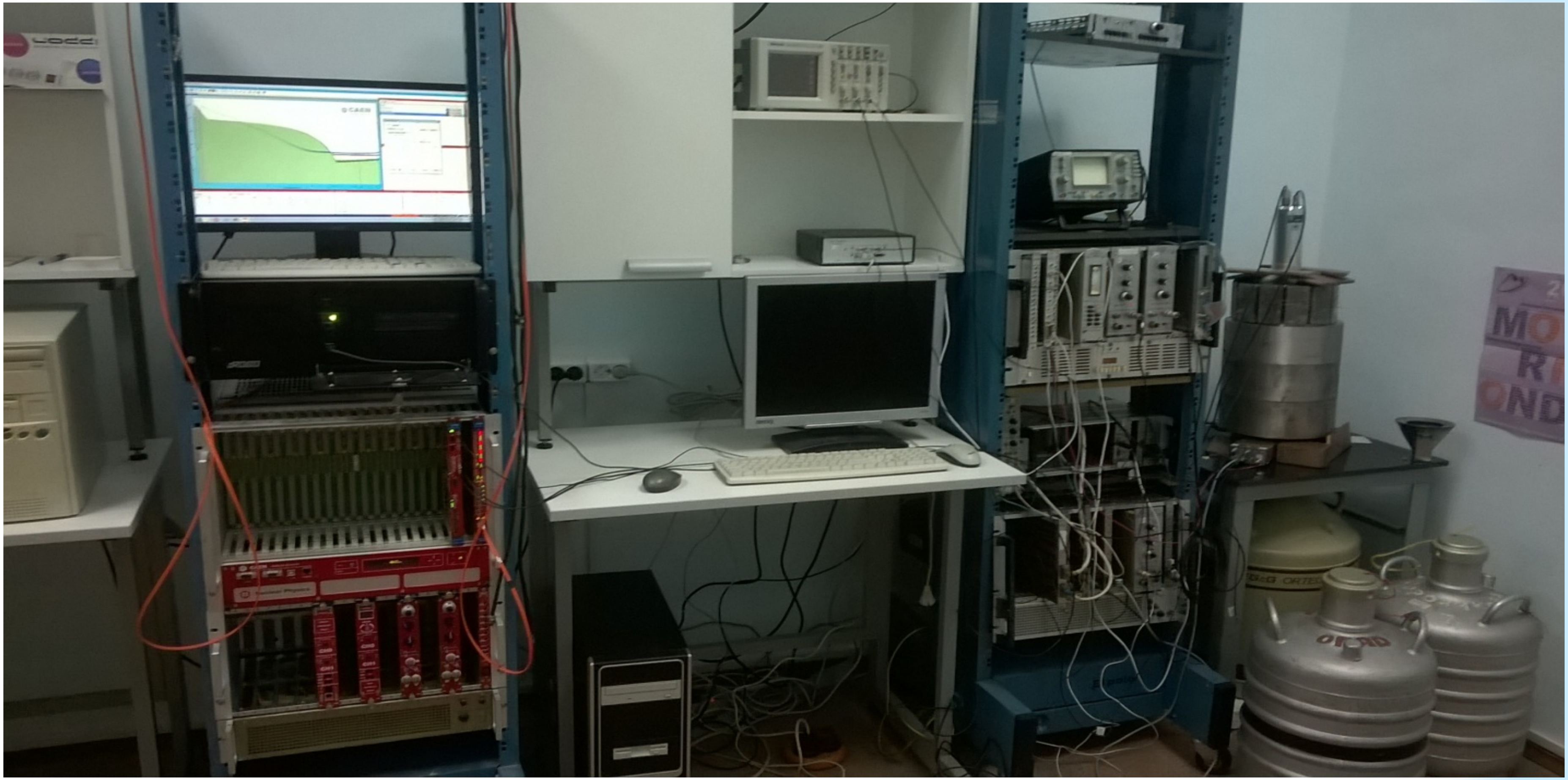
The spectrum of electrons from beta decay of ^{144}Ce-^{144}Pr nuclei have been analyzed in order to find a contribution from a heavy neutrino. New upper limits on the mixing parameter at the level уровне $|U_{eH}|^2 \leq (2-5) \times 10^{-3}$ (90% c.l.) have been found for the neutrino with the mass in the interval of 150–350 keV. Despite the sufficient statistics, the response function problems have significantly reduced the sensitivity to the heavy neutrino mixing.

4π β-spectrometer with two Si-detectors



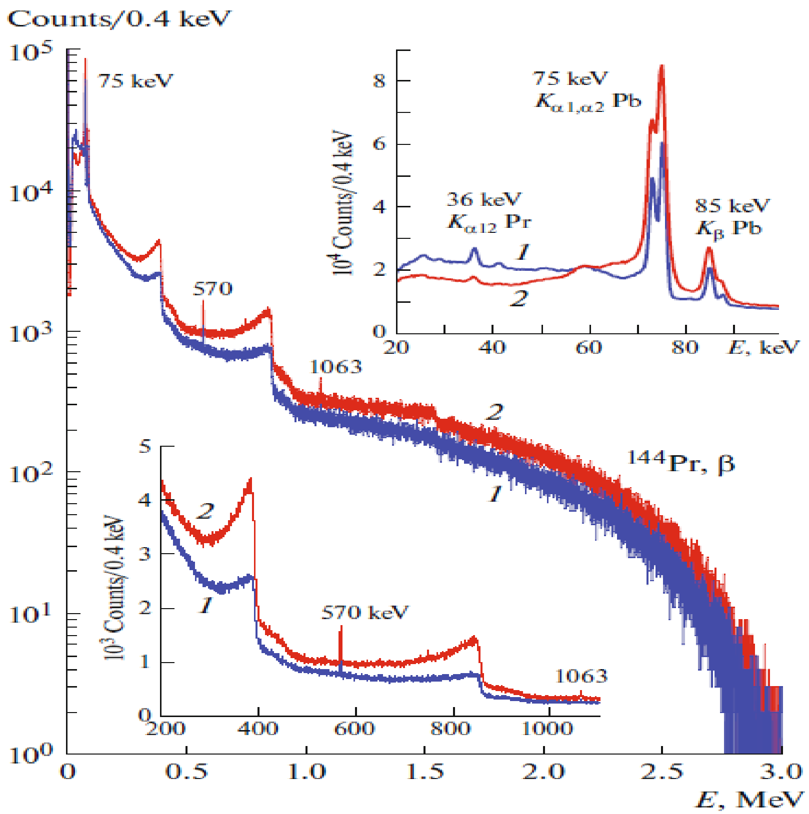
Si(Li) detectors produced in PNPI with diameter of sensitive region 16 mm, thick 9 mm, I=10 pA at 1000 V. The energy resolution measured with γ lines of ^{241}Am is FWHM= 1.1 keV. The source was deposited into a small concavity in the center of one of the detectors; the second one was attached to the top of the first one, making up a 4 geometry. A 3" BGO scintillation detector was included in the experimental setup in order to discriminate β decays of ^{144}Ce–^{144}Pr nuclei to excited levels of daughter nuclei. The BGO detector was located at a distance of 25 mm from the common surface of the Si(Li) detectors (i.e., from the measured source), thus providing a 20% geometric efficiency for emitted γ rays.

4π β-spectrometer with Si(Li)- and BGO-detectors

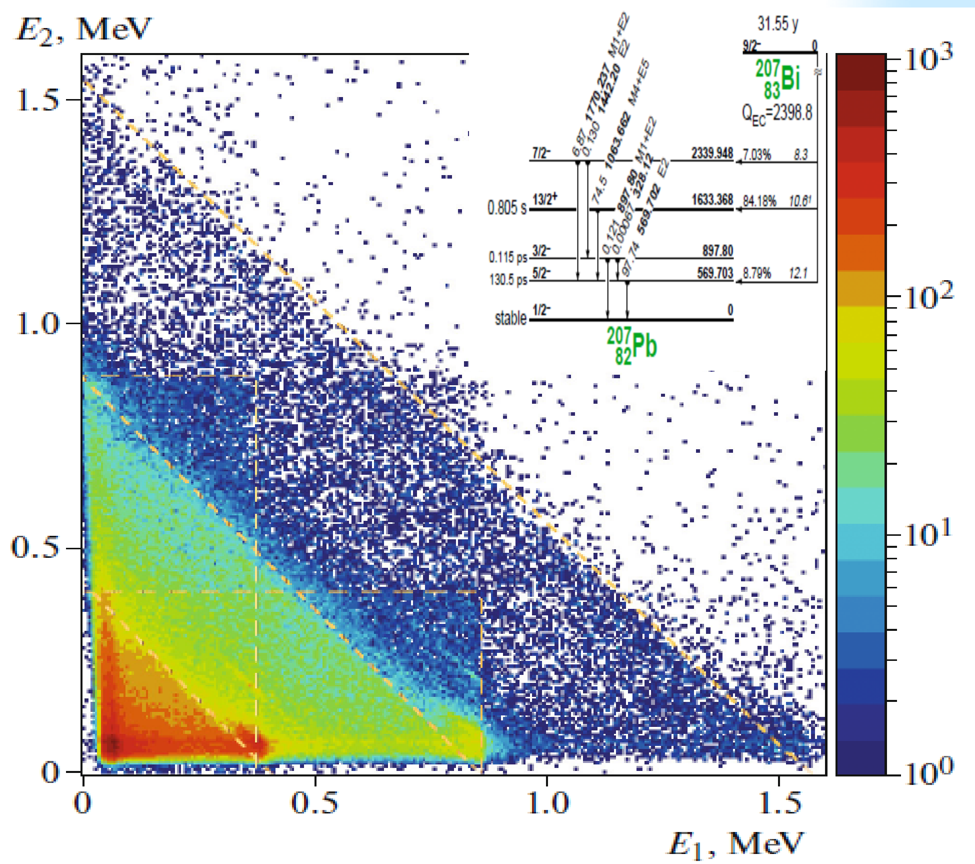


Si(Li) detectors with a sensitive region thickness of more than 8 mm provide complete absorption of electrons with an energy of 3 MeV. The selected connection of the detectors in (anti)coincidence allows direct measurement of β spectra without applying complicated additional corrections for electron backscattering from the detector surface. The entire structure was located inside a vacuum cryostat and was cooled to the liquid-nitrogen temperature.

Calibration of 4π β-spectrometer

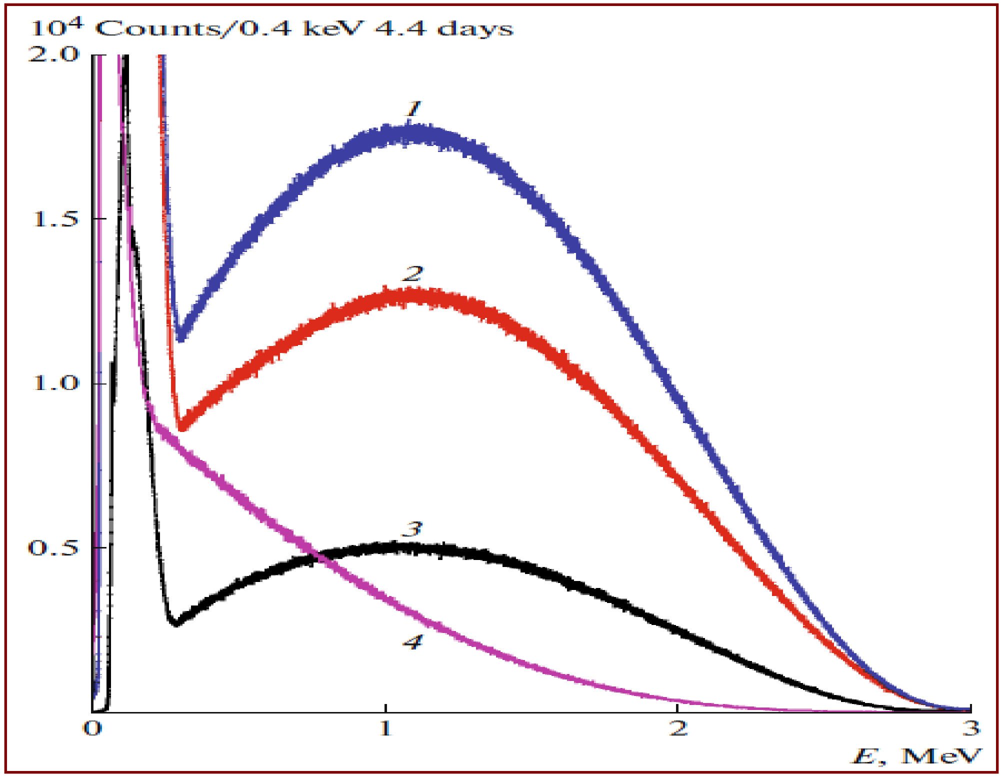


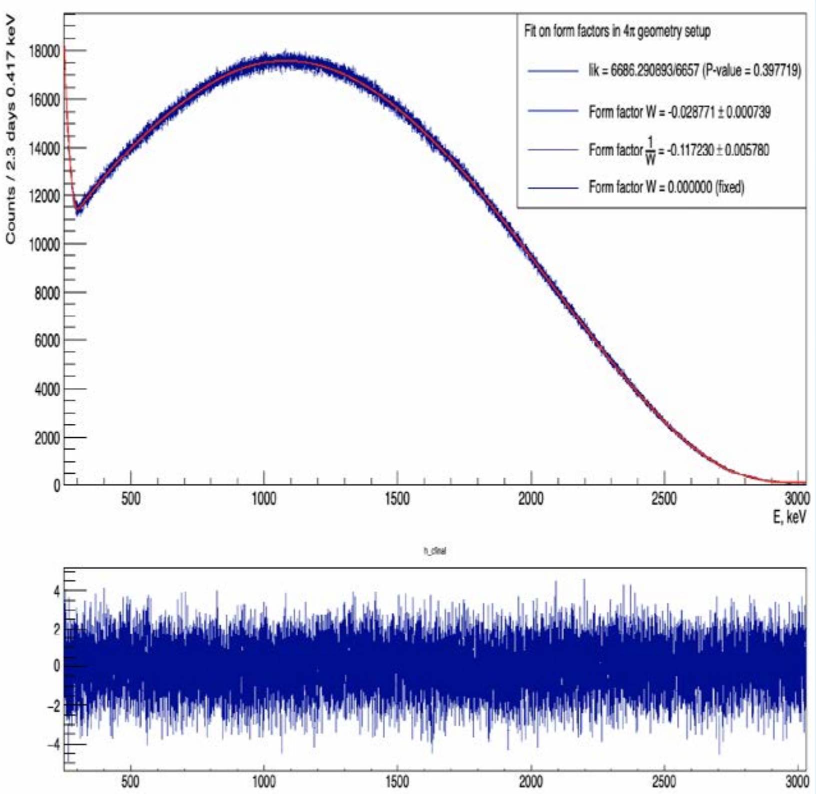
The measured calibration spectra of the pair of Si(Li) detectors with the external ^{207}Bi source, and (2) spectra of the detector with the hole. The upper inset shows the part of low-energy spectrum, and the lower inset shows the partial spectrum due to Compton scattering of γ rays with energies of 570 and 1063 keV.



The two-dimensional coincidence spectrum measured by the pair of Si(Li) detectors with the ^{207}Bi source: (E1) energy of the detector with the hole. The oblique lines correspond to backscattering of γ rays with energies of 570, 1064, and 1770 keV. The rectangles mark the events from the γ-ray cascade.

^{144}Ce–^{144}Pr spectra with 4π β-spectrometer

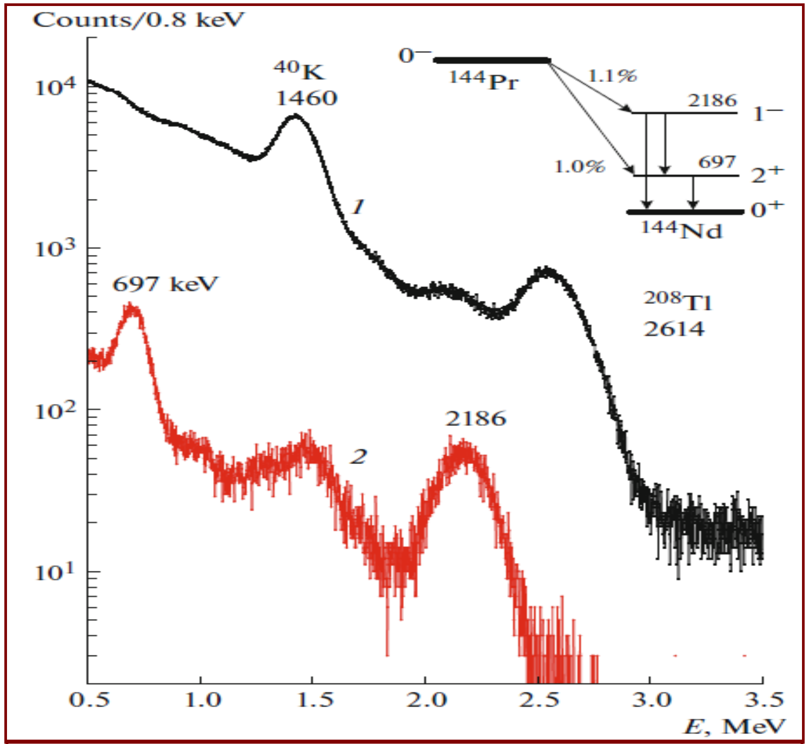




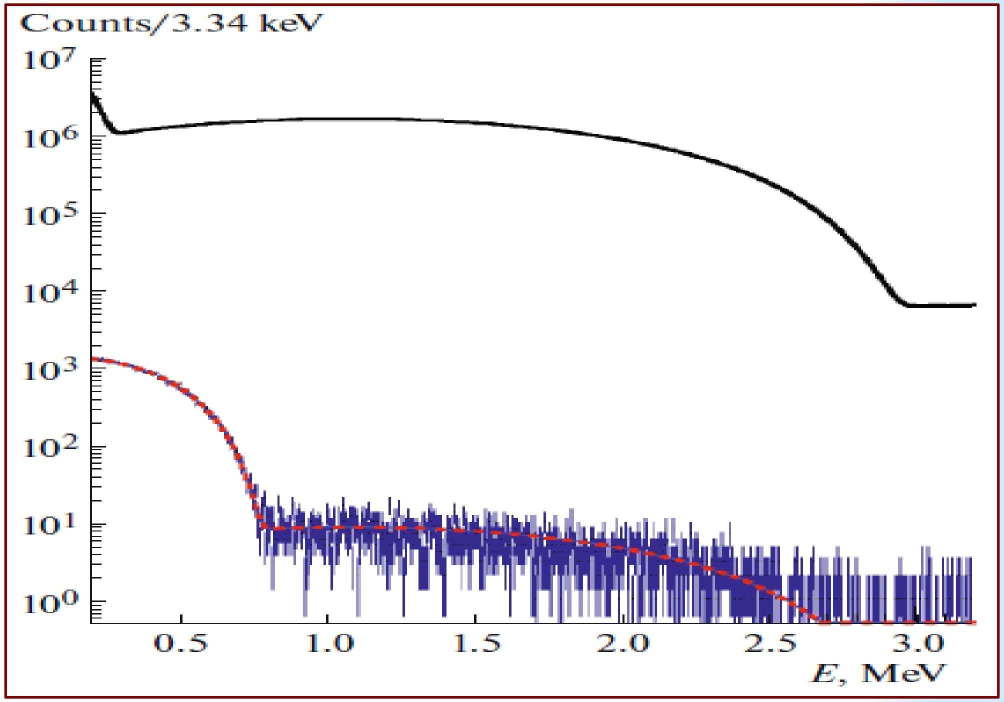
(1) spectrum of the total measured energy, (2) the spectrum of events in only one detector, (3) the spectrum of events measured by two detectors, and (4) the coincidence spectrum from one detector.

Figure shows the spectra of Si(Li) detectors recorded for single and multiple events. The full beta spectrum is the sum of these spectra, thus the problem of the detector response function associated with backscattering of electrons from the surface of the detector is solved. The created spectrometer with a response function close to Gaussian practically solves the problem of determining the spectrum of antineutrinos at energies less than 2.7 MeV. The form factor parameters for the ^{144}Pr beta spectrum are determined with an accuracy of 1%, that is sufficient to perform new experiment with a ^{144}Ce-^{144}Pr source.

Allowed β transition ^{144}Pr (0^-) → ^{144}Nd (1^-)



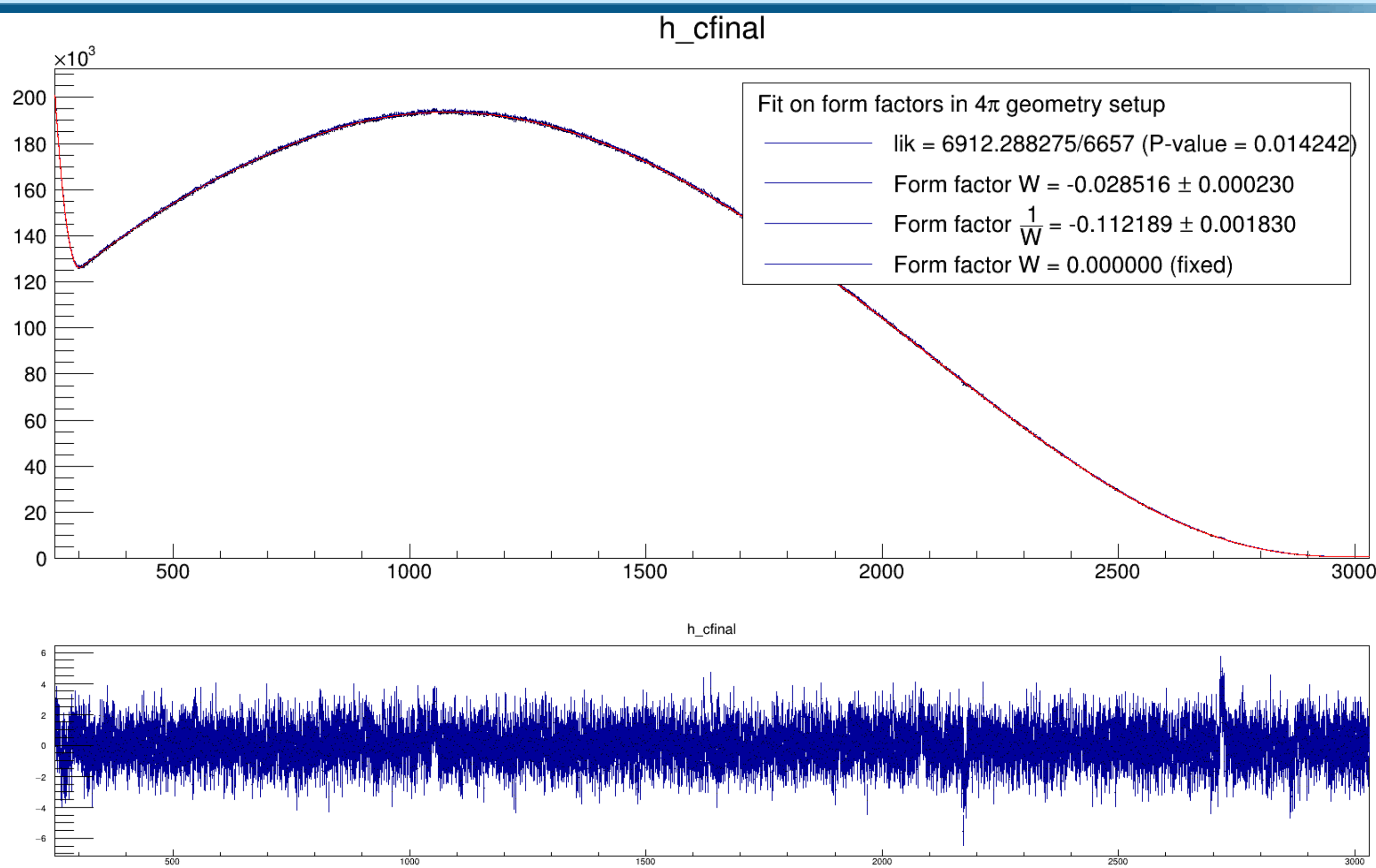
The spectra of the BGO detector: (1) background spectrum, and (2) the spectrum in coincidence with the Si(Li)-spectrometer signal.



The spectrum of the allowed β transition ^{144}Pr (0^-)→^{144}Nd (1^-) ($Q_β$ = 0.812 MeV), measured in coincidence with the BGO-detector signal (bottom), in comparison with the β spectrum for the transition to the ground state ($Q_β$ =3.0 MeV).

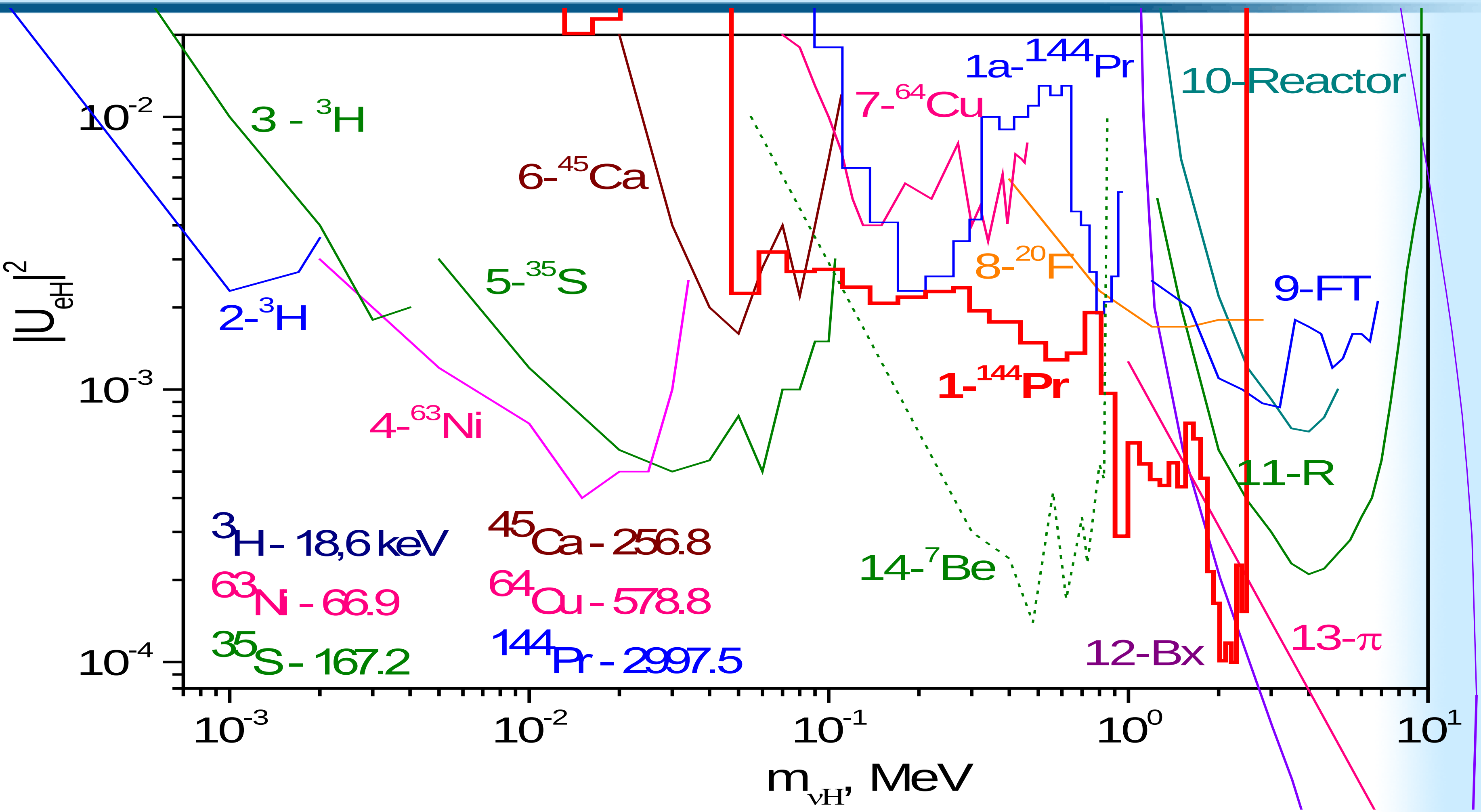
Measurements of Si(Li)-detectors spectra in coincidence with the BGO-detector allow to distinguish β-spectra corresponding to transitions to excited states of the daughter nucleus. In the case of ^{144}Pr, this is a very important part of the measurements, since the 1^- → 0^- β transition to 2186 keV ^{144}Nd level is allowed type, its shape is well defined and does not require the introduction of form factor. The correspondence of the shape of the measured spectrum to the allowed β-transition is an important criterion for the correctness of the measurements, the response function used, and the fitting procedure.

Fit of 4π β-spectrum



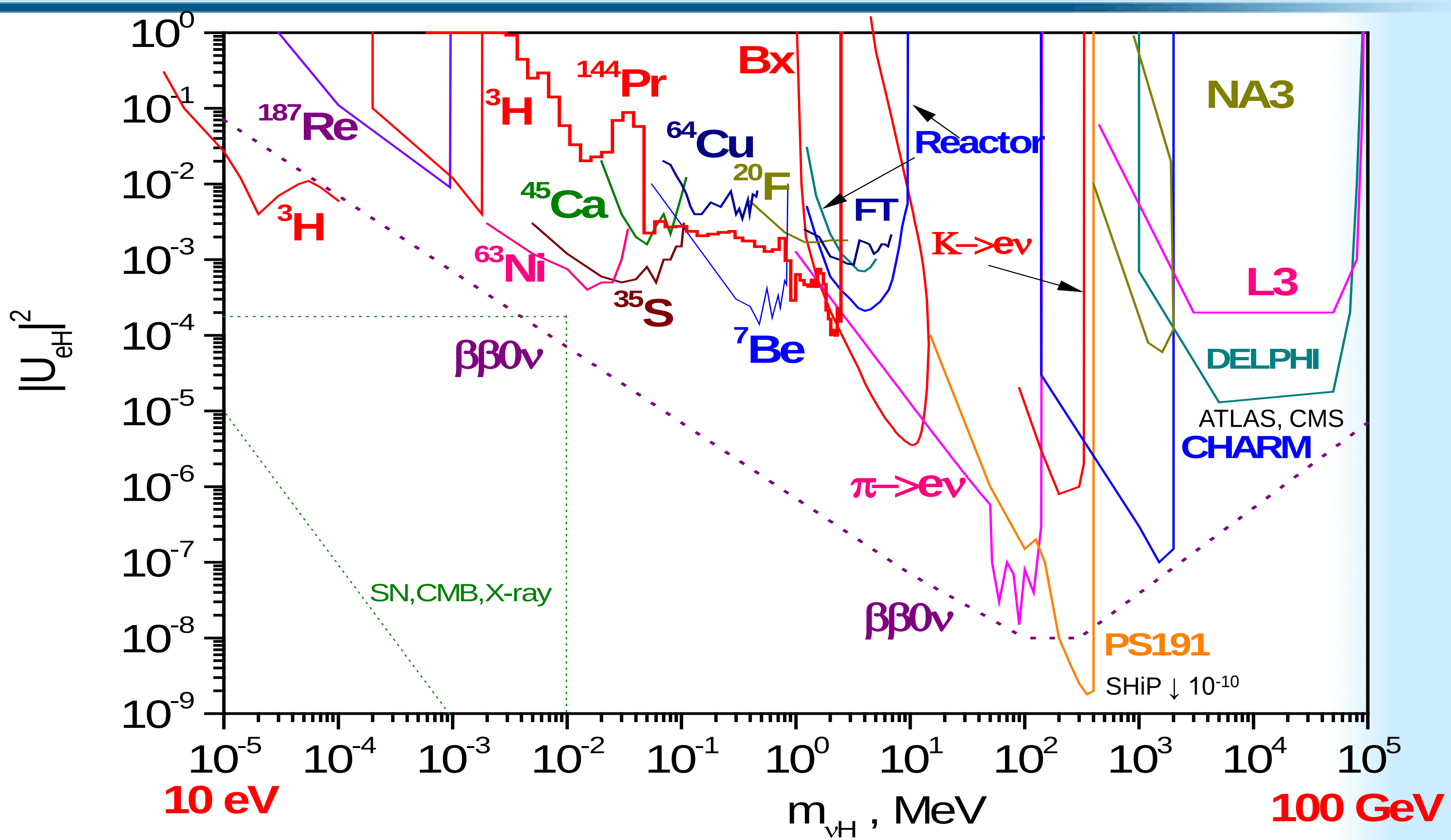
The measured spectrum, containing 1.5×10^9 events, was fitted in the energy range (250 - 3030) keV with acceptable χ^2 value 6912 / 6657 , P-value =0.014. The upper limits on the mixing parameter $|U_{eH}|^2$ were determined in a standard way from the profile of the dependence $\chi^2(|U_{eH}|^2)$ for different $m_{\nu H}$. No statistically significant deviations were observed. The obtained form-factor parameters are: $C(W) = 1 + (-0.02877 \pm 0.00028)W + (-0.11722 \pm 0.00297)W^{-1}$.

Limits on $|U_{eH}|^2$ from ^{144}Pr β-spectrum



*Spectra of electrons from ^{144}Ce–^{144}Pr decays have been measured and analyzed in order to find contribution from the heavy neutrino. For neutrino with the mass in the interval of 0.1-2.0 MeV, new upper bound **$|U_{eH}|^2 \leq (1\text{-}30)10^{-4}$** at 90% C.L. has been found for mixing parameter (red line).*

Limits on $|U_{eH}|^2$ for $m_{\nu H}$ = (10 eV -100 GeV)



The limits on the mixing parameter ***$|U_{eH}|^2$ for (10 eV-100GeV)*** *mass interval. There is something to strive for, in particular, for the beta spectrum measurement experiments.*

Thank you for the attention!