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New experimental limits on heavy neutrino mixing in ^{8}B-decay obtained with the Borexino Counting Test Facility

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If heavy neutrinos with mass $m_{\nu_H} \geq 2m_e$ are emitted in the decays of ^{8}B in the Sun, then decays $\nu_H \to \nu_L + e^+ + e^-$ should be observed. In the present work the results of background measurements with the Borexino Counting Test Facility have been used to obtain bounds on the number of these decays. As a result new limits on the coupling $|U_{eH}|^2$ of a massive neutrino in the range of 1.1 MeV to 12 MeV have been derived ($|U_{eH}|^2 \leq 10^{-3}$–10^{-5}). The obtained limits on the mixing parameter are stronger than obtained in previous experiments using nuclear reactors and accelerators.

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1. Introduction. If neutrinos have mass, then the heavier one can decay to the lighter one [1, 2]. The simplest detectable decay modes in the framework of an extended standard model (SM) are radiative decay $\nu_H \to \nu_L + \gamma$ and decay into an electron, a positron and a light neutrino:

$$\nu_H \to \nu_L + e^+ + e^-. \qquad (1)$$

The e^+e^- decay mode, which becomes possible if $m_{\nu_H} \geq \geq 2m_e$, results from a W exchange diagram, as shown in fig.1. Because atmospheric, solar and reactor neutrino oscillations have been discovered, this heavy neutrino

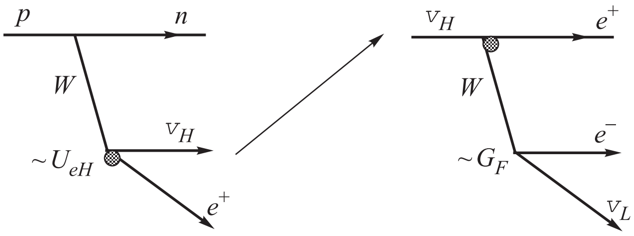

Fig.1. Feynman graphs describing the appearance ($^8\mathrm{B} \to \to {}^8\mathrm{Be} + e^+ + \nu_H$) and decay ($\nu_H \to \nu_L + e^+ + e^-$) of a heavy neutrino

cannot be connected with one of the three mass eigenstates forming three known neutrino flavors. Moreover, this fourth neutrino has to be coupled in the $(e - W)$-vertex with U_{eH} and G_F constants, but it cannot be coupled (or coupled very weakly) to the Z-boson.

Many extensions of SM predict the existence of a sterile neutrino: a singlet fermion can be a mirror neutrino, goldstino in SUSY, modulino of the superstring theories, or a bulk fermion related to the existence of extra dimensions [3]. In general, the sterile neutrino may have an arbitrary mass and can mix with all three active neutrinos.

The decay rate for this mode in the center of mass system of the decaying neutrino is [1, 2]:

$$\Gamma_{c.m.} \cong \frac{{G_F}^2}{192\pi^3} m_{\nu_H}^5 |U_{eH}|^2 |U_{eL}|^2 h[\frac{{m_e}^2}{m_{\nu_H}^2}], \qquad (2)$$

where U_{eH} is the mixing parameter of the heavy neutrino to the electron, ${G_F}^2/192\pi^3 = 3.5 \cdot 10^{-5}\,\mathrm{MeV}^{-5} \cdot \mathrm{s}^{-1}$, $h[{m_e}^2/m_{\nu_H}^2]$ is the phase-space factor calculated in [2], and one can assume $|U_{eL}|^2 \simeq 1$. In SM the probability of the e^+e^--mode is much higher than for radiative decay: e.g., for $m_{\nu_H} = 5\,\mathrm{MeV}$ (and $|U_{eH}|^2 \sim 1$) one obtains $\tau(\nu_H \to \nu_L e^+ e^-) \approx 10\,\mathrm{s}$ against $\tau(\nu_H \to \nu_L \gamma) \sim 10^{10}\,\mathrm{s}$.

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The possible decay of massive antineutrinos from a reactor $\nu_H \to \nu_L + e^+ + e^-$ has been studied in [4–8]; the latter gives the strongest restrictions on the mixing parameter ($|U_{eH}|^2 < (0.3\text{–}5) \cdot 10^{-3}$ in the mass region $m_{\nu_H} \sim 1.1\text{–}9.5\,\mathrm{MeV}$). Accelerator experiments performed in a beam of neutrinos from π- and K-decays constrain the coupling of still heavier neutrinos (see [9] and refs. therein). A heavy neutrino with mass up to 15 MeV can be produced in the Sun in the reaction $^8\mathrm{B} \to {}^8\mathrm{Be} + e^+ + \nu$, then it can decay in flight. An upper limit $|U_{eH}|^2 \sim 10^{-5}$ was obtained by considering data on the positron flux in interplanetary space [10].

More restrictive bounds were obtained from SN1987A data [11–14]. On the other hand big bang nucleosynthesis requires a fast decay branch ([11–14] and refs. therein). This fast mode could be realized by the decay of the heavy particle into a Goldstone boson and a light neutrino. Obviously, this decay mode should be slower as about 500 s, which is the time needed for the particle to reach the detector.

Borexino, a real-time liquid scintillator (LS) detector for low-energy neutrino spectroscopy, is near completion in the underground laboratory at Gran Sasso (see [15, 16] and refs. therein). The main goal of the detector is the direct measurement of the flux of ^{7}Be solar neutrinos of all flavors via neutrino-electron scattering. In this paper we present the results of the search for the $\nu_H \to \nu_L + e^+ + e^-$ decay inside the active volume of the prototype of the Borexino detector.

2. Experimental set-up and results of measurements. *2.1. Brief description of the detector.* The prototype of the Borexino detector, the Counting Test Facility (CTF), was constructed with the aim of testing the key concept of Borexino, namely the possibility to purify a large mass of liquid scintillator at the level of contamination for U and Th of a few units 10^{-16} g/g. In this simplified scaled-down version of the Borexino detector, a volume of LS is contained by a 2 m diameter transparent inner nylon vessel mounted at the center of an open structure that supports 100 phototubes (PMT) [17]. The whole system is located within a cylindrical tank (11 m diameter, 10m height) that contains 1000 tons of ultra-pure water, which provides a 4.5 m shielding against neutrons originating from the rock, and against external γ-rays from PMTs and other construction materials.

The upgrade of the CTF, refereed to as CTF-II, was equipped with a carefully designed muon veto system. It consists of 2 rings of 8 PMTs each, installed at the bottom of the tank. The radius of the rings are 2.4 and 4.8 m. Muon veto PMTs look upward and have no light concentrators. The muon veto system was optimized to have a negligible probability of registering the scintillation events in the so-called "neutrino energy window" from 250 to 800 keV. The behaviour of the muon veto at higher energies has been specially studied for the previous work [18]. The energy dependence of the probability $\eta(E)$ of identification of an event with energy E in the LS by the muon veto was also calculated by a ray-tracing Monte Carlo (M-C) method. The calculated function was adjusted to reproduce correctly the experimental measurements with the ^{226}Ra source. Detailed reports on the CTF have been published [19 – 22].

2.2. Detector calibration. The energy of an event in the CTF detector is defined using the total collected charge from all PMTs. The coefficient linking the event energy and the total collected charge is called light yield (or photoelectron yield). At low energies the phenomenon of "ionization quenching" violates the linear dependence of the light yield versus energy [23]. The deviations from the linear law can be taken into account by the ionization deficit function $f(k_B, E)$, where k_B is Birks' constant. For the calculations of the ionization quenching effect for PXE (phenylxylylethane, $C_{16}H_{18}$) scintillator we used the KB program from the CPC library [24]. The ionization quenching effect leads to a shift in the position of the peak of the energy deposit of the gammas on the energy scale calibrated using electrons. For example, the position of the 1022 keV two annihilation gamma quanta in the CTF-II corresponds to the 860 keV energy deposit of the electron. A check of the MC-simulation code was performed by modeling ^{40}K data. The detector energy and spatial resolution were studied with radioactive sources placed at different positions inside the active volume of the CTF. Typical spatial 1σ resolution is 10 cm at 1 MeV. The studies showed also that the total charge response of the CTF detector can be approximated by a Gaussian curve. For energies $E \geq 1$ MeV (which are of interest here), the relative resolution can be expressed as $\sigma_E/E = \sqrt{3.8 \cdot 10^{-3}/E + 2.3 \cdot 10^{-3}}$ (E is in MeV) [25] for events uniformly distributed over the detector's volume.

The energy dependence on the collected charge becomes non-linear for energies $E \simeq 5$ MeV because of the saturation of the ADCs used. In this region we use only the observation or non-observation of candidate events; hence the mentioned nonlinearity does not influence the result of the analysis.

2.3. Data selection. In this analysis, 29.1 days of the August-September 200 data taking period were used (fig.2). In our analysis we used 29.1 days of data from CTF-II (fig.2). The major part of the CTF background at low energies is induced by the activity of ^{14}C, ^{85}Kr and ^{39}Ar [26]. At higher energies, background is mainly induced by muons. The spectrum without any cuts (spectrum *1*) is presented on the top. The second spectrum was obtained by applying the muon cut, which suppressed the background rate by up to two orders of magnitude, mainly at high energy.

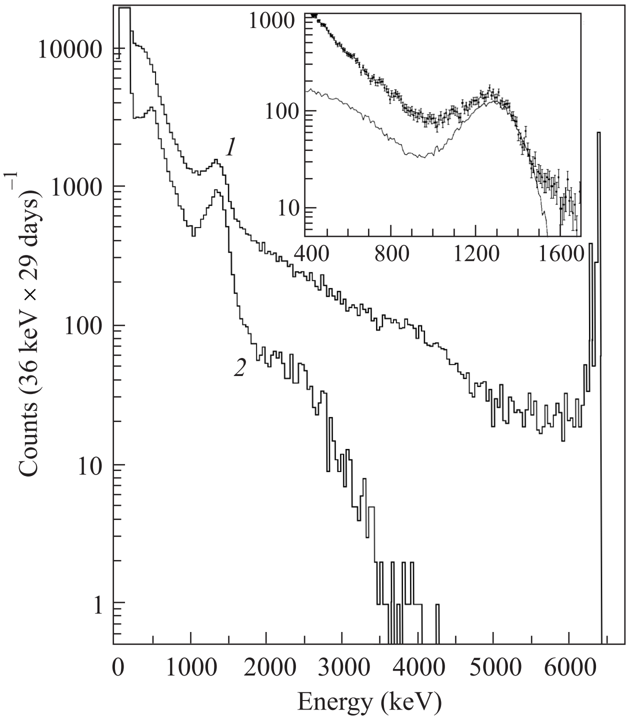

Fig.2. Background energy spectra of the 4.2 ton BOREXINO CTF-II detector measured during 29.1 days: *1* – spectrum without any cuts; *2* – with muon veto applied. In the inset, the simulated response function for external ^{40}K gammas is shown together with the experimental data

The peak at 1.36 MeV, present in both spectra, is due to ^{40}K decays outside the scintillator, mainly in the ropes supporting the nylon sphere. The peak-like structure at ~ 6.2 MeV is caused by saturation of the electronics by high-energy events. As one can see from fig.2, muon identification cuts remove most of background induced by muons in such way that there are no events with energy higher than 4.5 MeV. In our analysis we used only this fact.

3. Neutrino flux and deduced limits. In order to obtain bounds on the parameters $|U_{eH}|^2$ and m_ν, the spectrum obtained by CTF has to be compared with the energy spectrum expected for ν_H-decay. To calculate it one has to know the flux of heavy neutrinos through the detector $\Phi(E_\nu)$, kinetic energy of created e^+e^- pairs, and the response function of CTF to two-annihilation quanta.

The emission of a heavy neutrino, coupled to an electron, in the reaction of β^+-decay of ^{8}B is suppressed by the mixing parameter $|U_{eH}|^2$ and a phase-space factor:

$$\Phi_{m_\nu}(E_\nu) = |U_{eH}|^2 \sqrt{1-(\frac{m_{\nu_H}}{E_\nu})^2} \Phi_{^8B}(E_\nu) \qquad (3)$$

where E_ν is the total energy of the heavy neutrino ($\Phi_{m_\nu}(E_\nu)$=0 for $E_\nu < m_\nu$). For calculation we have used the neutrino spectrum from ^{8}B decay $\Phi_{^8B}(E_\nu)$ given in [27].

The heavy neutrino emitted in the Sun can decay on its flight to Earth. The energy spectrum of neutrinos reaching the detector is given by

$$\Phi(E_\nu) = \exp(-\tau_f/\tau_{c.m.})\Phi_{m_\nu}(E_\nu), \qquad (4)$$

where $1/\tau_{c.m.} = \Gamma_{c.m.}$ defined by (2). τ_f is the time of flight in c.m.s.:

$$\tau_f = \frac{m_{\nu_H}}{E_\nu}\frac{L}{\beta c}. \qquad (5)$$

Here $L = 1.5\cdot 10^{13}$ cm is the average distance between Sun and Earth and $\beta = \sqrt{1-(m_\nu/E_\nu)^2}$.

The double differential distribution for energy ϵ and emission angle θ of the light neutrino ν_L for the c.m.s. was obtained in [2]:

$$\frac{dN_{\nu_L}}{d\epsilon d\cos\theta} = \Gamma_{c.m.}(f_1 + \xi|\mathbf{P}|f_s\cos\theta), \qquad (6)$$

where $f_1(\epsilon, m_{\nu_H})$ and $f_s(\epsilon, m_{\nu_H})$ are complex functions defined in [2], $\xi = +1(-1)$ for ν_H ($\overline{\nu_H}$), and $|\mathbf{P}| = \beta$ is the polarization of the ν_H.

The total laboratory energy of the e^+e^--pair, $E = E_\nu - E_{\nu_L}$, is connected with ϵ as follows:

$$E = E_\nu(1-(\epsilon/m_\nu)(1+\beta\cos\theta)). \qquad (7)$$

In the c.m.s. the energy ϵ of the emitted neutrino is restricted by value $\epsilon \le \epsilon_{min} = (m^2_{\nu_H} - 4m^2_e)/2m_{\nu_H}$ that corresponds to the emission angle

$$(\cos\theta)_{min} = (1/\beta)(\epsilon_{min}(1-E/E_\nu)-1). \qquad (8)$$

The differential spectrum of the e^+e^--pair is obtained by integration of (6) over $\cos(\theta)$ (or ϵ) and taking into account eq.(7):

$$\frac{dN}{dE}(E, E_\nu) = \int\limits_{(\cos\theta)_{min}}^{1} \frac{dN_{\nu_L}}{d\epsilon d\cos\theta} d\epsilon d\cos\theta. \qquad (9)$$

For a given energy of heavy neutrino E_ν, the energy E of the e^+e^--pair is restricted to the interval

$$E_\nu[1-\frac{1+\beta}{2}(1-\frac{4m_e^2}{m^2_{\nu_H}})] \le E \le E_\nu. \qquad (10)$$

Integrating over neutrino energy up to end-point energy Q_0, one can obtain the spectrum of total e^+e^--pair energy:

$$\frac{dN}{dE}(E) = \Gamma_{c.m.}|U_{eH}|^2 \frac{m_\nu}{c} \int\limits_{2m_e}^{Q_0} \frac{dN}{dE}(E, E_\nu)\frac{\Phi(E_\nu)}{E_\nu} dE_\nu. \qquad (11)$$

The Monte-Carlo method has been used in order to simulate the CTF response $S(E)$ to two-annihilation quanta. The gamma – electron showers were followed using the EGS-4 code [28], taking into account the ionization quenching factor and the dependence of the registered charge on the distance from the detector's center. The obtained response function looks like the sum of two gaussian peaks at energies 860 and 430 keV, with dispersion $\sim$ 70 keV and relative intensities $\sim$ 3 : 1.

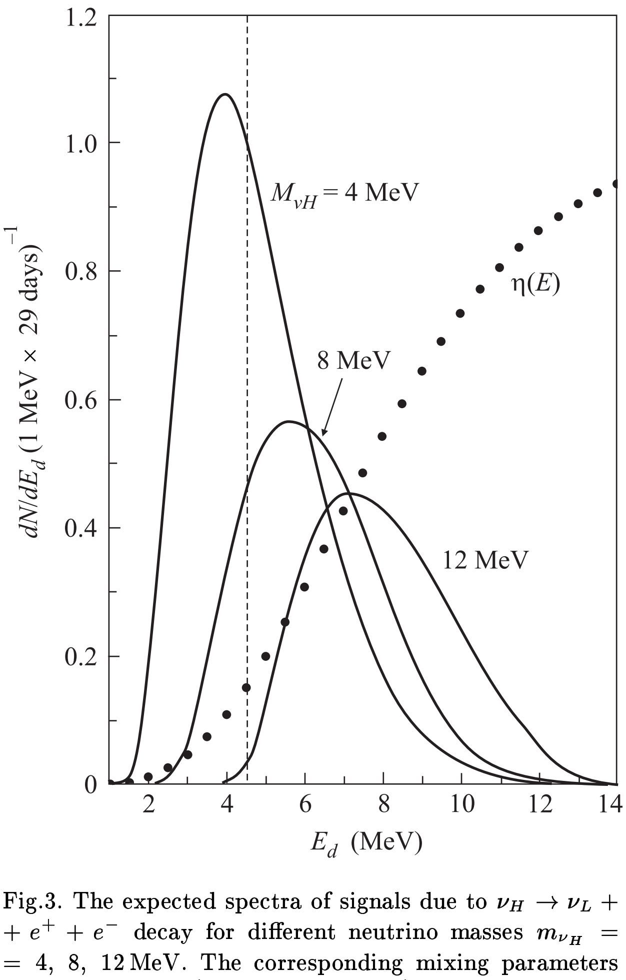

Fig.3. The expected spectra of signals due to $\nu_H \to \nu_L + e^+ + e^-$ decay for different neutrino masses m_{ν_H} = 4, 8, 12 MeV. The corresponding mixing parameters ($|U_{eH}|^2 = 1.8\cdot 10^{-4}, 3.9\cdot 10^{-5}, 1.3\cdot 10^{-4}$) lead to the CTF-II count rate 2.44/29.1 d for $E_d \ge 4.5$ MeV. The probability $\eta(E)$ of identification of an event in the LS by the muon veto is shown by point curve

Peaks have low energy tails containing $\sim$ 10% of the total intensity.

Taking into account the probability of suppression of the high energy events by the muon veto (1-$\eta(E)$) [18] and the detector response function $R(E,E')$ with σ_E defined as in section 2.2, the energy spectrum of signals in the detector is obtained by convolutions (11) over $S(E)$ and $R(E,E')$:

$$\frac{dN}{dE}(E) = VT(1-\eta(E)) \int\limits_{E-3\sigma}^{E+3\sigma} \left(\int\limits_{E_d-2m_e}^{E_d} \frac{dN}{dE'}(E') \times \right.$$
$$\left. \times\, S(E_d - E')dE' \right) R(E_d, E)dE_d. \qquad (12)$$

Here V is the volume of the detector and T is the time of measurement. The obtained spectra for various values of m_ν are shown in fig.3. The shape of (12) differs from (11) – it is shifted on about 870 keV to high energy and

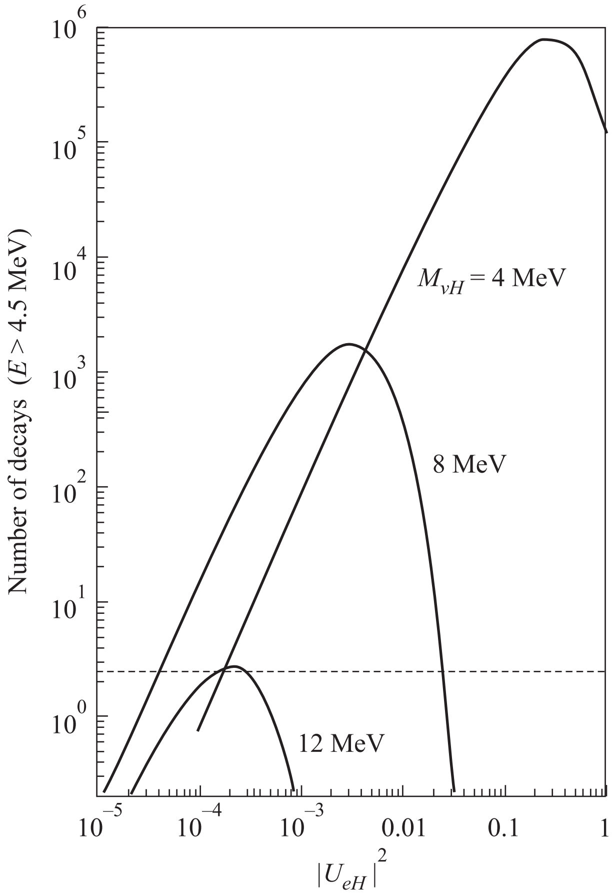

Fig.4. Counting rates of CTFII as a function of the mixing parameter $|U_{eH}|^2$ for different values of heavy neutrino mass. The level 2.44 events / 29.1 d is shown by the dotted line

it is suppressed at higher energies by muon veto (e.g. $\eta(5\,\mathrm{MeV}) = 0.2$, fig.3).

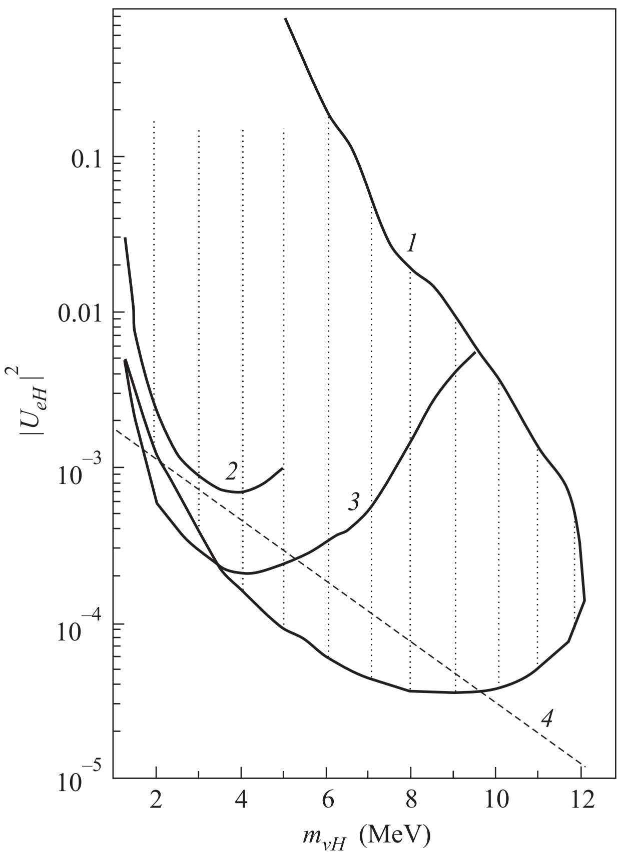

Fig.5. Limits on the mixing parameter $|U_{eH}|^2$ as a function of neutrino mass m_ν (90% c.l.). *1* – present work excludes values of $|U_{eH}|^2$ and m_ν inside dotted region; *2*, *3* – upper limits from reactor experiments on the search for $\nu_H \to \nu_L + e^+ + e^-$ decay [7, 8]; *4* – upper limits from $\pi \to e + \nu$ decay [29]

As mentioned above, we used in analysis only the fact that there are no events with $E \geq 4.5$ MeV. In accordance with the recommendation for Particle Data Group [9], the statistical maximal number of events for zero events observed is 2.44 (at 90% confidence level).

The relation

$$S_{int}(m_\nu, |U_{eH}|) = \int\limits_{4.5MeV}^{Q_0} \frac{dN}{dE_d}(E_d) \leq 2.44 \qquad (13)$$

leads to bounds on parameters $|U_{eH}|^2$ and m_ν. The dependence of the number of counts on parameters of $|U_{eH}|^2$ and m_ν is:

$$S_{\mathrm{int}}(m_\nu, |U_{eH}|) \sim m_\nu^6 |U_{eH}|^4 \exp\left(-\mathrm{const} \cdot m_\nu^6 |U_{eH}|^2\right). \qquad (14)$$

Functions $S_{int}(|U_{eH}|)$ are shown on fig.4 for different values of m_ν. The experiment is not as sensitive for low $|U_{eH}|^2$ (due to the low probability of ν_H decay) as for the high values of $|U_{eH}|^2$, because in this case ν_H decays during its flight from the Sun. The maximum $S_{int}(|U_{eH}|^2)$ for fixed m_ν and E_ν corresponds to $|U_{eH}|^2 = 2(|U_{eH}|^2\tau_{c.m.})/\tau_f$, where $\tau_{c.m.}$=$1/\Gamma_{c.m.}$ and τ_f are defined by (2) and (5).

The region of restricted values of parameters $|U_{eH}|^2$ and m_ν are shown in fig.5 in comparison with results of reactor experiments [7, 8] and the search for massive neutrinos in the decay $\pi^+ \to e^+\nu_e$ in accelerators [29]. For the neutrino mass region 4–10 MeV the obtained limits on the mixing parameter are stronger than those obtained in previous experiments using nuclear reactors and accelerators.

4. Conclusion. Using the extremely low background and large mass of the Borexino Counting Test Facility, new limits on the mixing parameter $|U_{eH}|^2$ of a massive neutrino in the range of mass 1.1 MeV to 12 MeV have been set. These limits are more than one order of magnitude stronger than these obtained in previous experiments using nuclear reactors.

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