

New limits on heavy sterile neutrino mixing in ^8B decay obtained with the Borexino detector

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If heavy neutrinos with mass $m_{\nu_H} \geq 2m_e$ are produced in the Sun via the decay $^8\text{B} \rightarrow ^8\text{Be} + e^+ + \nu_H$ in a side branch of the pp chain, they would undergo the observable decay into an electron, a positron and a light neutrino $\nu_H \rightarrow \nu_L + e^+ + e^-$. In the present work Borexino data are used to set a bound on the existence of such decays. We constrain the mixing of a heavy neutrino with mass $1.5 \text{ MeV} \leq m_{\nu_H} \leq 14 \text{ MeV}$ to be $|U_{eH}|^2 \leq (10^{-3} - 4 \times 10^{-6})$, respectively. These are tighter limits on the mixing parameters than obtained in previous experiments at nuclear reactors and accelerators.

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I. INTRODUCTION

Neutrino flavor oscillations show that neutrinos are massive. In turn, heavier neutrinos can decay into lighter ones [1–6]. Within the framework of an extended standard model (SM), the simplest detectable decay modes are the radiative decay $\nu_H \rightarrow \nu_L + \gamma$ and the decay into an electron-positron pair plus a light neutrino:

$$\nu_H \rightarrow \nu_L + e^+ + e^-, \quad (1)$$

resulting from the W and Z exchange diagrams shown in Fig. 1(b) and 1(c) and possible only for $m_{\nu_H} \geq 2m_e$. The Z exchange also results in the invisible decay mode $\nu_H \rightarrow 3\nu$ [Fig. 1(d)]. Since neutrino oscillations are well described in terms of the three known light neutrinos, a heavy neutrino would necessarily need to be a nonstandard new particle.

Many extensions of the SM predict the existence of one or more sterile neutrinos, which appear as singlet fermions in νMSM neutrino in minimal standard model [6,7], mirror

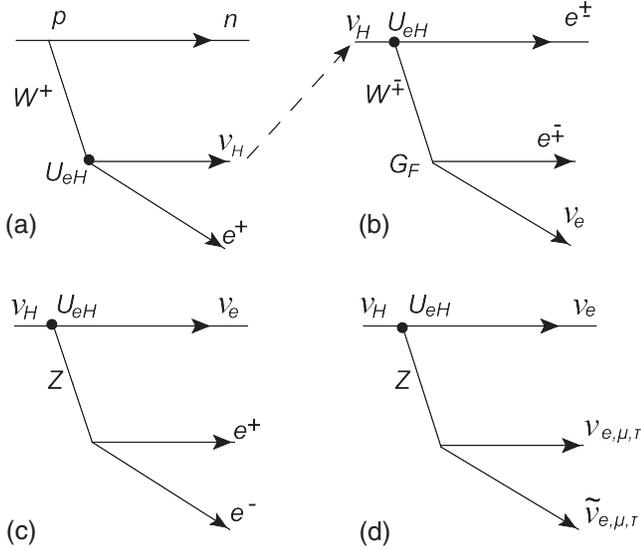


FIG. 1. Feynman graphs describing the appearance ${}^8\text{Be} \rightarrow {}^8\text{Be} + e^+ + \nu_H$ (a) and decay $\nu_H \rightarrow \nu_e + e^+ + e^-$ (b), (c) of a heavy neutrino. The invisible decay mode $\nu_H \rightarrow \nu_e \nu_i \bar{\nu}_i$ is shown also (d).

neutrinos [8], Goldstinos in supersymmetry [9], modulinos of the superstring theories [10], or bulk fermions linked to the existence of extra dimensions [11–13]. In general, massive sterile neutrinos may have arbitrary mass and mix with the active flavors.

In the heavy neutrino rest frame, the decay rate for $(\nu_H \rightarrow \nu_L e^+ e^-)$ due to W exchange was obtained in [1–3]. The total decay rate for all three modes shown in Fig. 1 including Z exchange and invisible decay $(\nu_H \rightarrow \nu_e \nu_{e,\mu,\tau} \bar{\nu}_{e,\mu,\tau})$ is [6]

$$\Gamma_{\text{c.m.}}^{\text{tot}} \cong \frac{G_F^2}{192\pi^3} m_{\nu_H}^5 |U_{eH}|^2 \left(1 + h \left[\frac{m_e^2}{m_{\nu_H}^2} \right] \right), \quad (2)$$

where U_{eH} is the mixing parameter of the heavy neutrino to the electron flavor, G_F the weak coupling constant and $h[m_e^2/m_{\nu_H}^2]$ the phase-space factor calculated in [6]. The $\nu_H \rightarrow \nu_e e^+ e^-$ decay rate $\Gamma_{\text{c.m.}}^{e^+e^-}$ due to W and Z exchange [Figs. 1(b) and 1(c)] differs from (2) by a change of bracket $(1 + h[m_e^2/m_{\nu_H}^2])$ to $h[m_e^2/m_{\nu_H}^2]$.

For ν_H , the e^+e^- decay is much faster than the radiative decay. For reference, if $m_{\nu_H} = 5$ MeV (and $|U_{eH}|^2 \sim 1$), $\tau(\nu_H \rightarrow \nu_L e^+ e^-) \approx 10$ s while $\tau(\nu_H \rightarrow \nu_L \gamma) \sim 1010$ s.

No positive evidence for heavy sterile neutrinos has so far been found in laboratory searches over a wide mass range. For masses $m_{\nu_H} < 1$ MeV the most sensitive searches have looked for kinks in the electron spectra of β decays and have constrained the sterile-electron mixing to $|U_{eH}|^2 < 10^{-2} - 10^{-3}$ [14–18]. The agreement with expectations of ft values for superallowed pure Fermi beta transitions also limits the mixing of massive neutrino and electron flavor [19–21].

The decays of massive antineutrinos from a reactor $\nu_H \rightarrow \nu_L + e^+ + e^-$ were looked for in [22–26]; the latter reference reports on the tightest limit on the mixing parameter, $|U_{eH}|^2 < (0.3-5) \times 10^{-3}$, for $m_{\nu_H} \sim (1.1-9.5)$ MeV. The limits on $|U_{eH}|^2$ were obtained in assumption that only W exchange mode occurs [Fig. 1(b)].

Heavy neutrinos with mass up to 15 MeV could be produced in ${}^8\text{B}$ decays inside the Sun and then decay in flight. Mixing parameters above $|U_{eH}|^2 < (10^{-6}-10^{-4})$ were excluded by measurements of the positron flux in interplanetary space [27].

The mixing of heavier neutrinos with both ν_e and ν_μ can be tested by looking for peaks in the leptonic decays of pions and kaons [28,29]. Alternatively one can look for the products of their decays directly [30]. The dominant decay channel for a sterile neutrino of mass 140–500 MeV is $\nu_H \rightarrow \nu + e + \pi$. For larger neutrino masses, new decay channels open up which include kaons, eta, etc. [31–35]. Accelerator experiments with beam of neutrinos from π and K decays constrain the coupling of still heavier neutrinos (see [36,37], and references therein).

Cosmological and astrophysical bounds on sterile neutrino properties are very strong but depend on the assumptions of sterile neutrino production. The most stringent bounds on $|U_{eH}|^2$ come from primordial nucleosynthesis and SN1987A data [38–42]. Sterile neutrinos can also have important cosmological implications for big bang nucleosynthesis and primordial light element abundances and could distort the spectra of both the cosmic microwave background and the diffuse extragalactic background radiation [43].

In this paper we present the results of the search for the $\nu_H \rightarrow \nu_L + e^+ + e^-$ decay inside the active volume of the Borexino detector [Figs. 1(b) and 1(c)]. For the case of the Dirac neutrinos, only diagrams with a $(\nu_H e^- W^+)$ vertex contribute to the ν_H decay. Two diagrams correspond to the decays of the Majorana neutrinos [Fig. 1(b)]. The Majorana neutrino total decay rate is given by (2) multiplied by a factor of 2, which accounts for charge-conjugated decay modes.

We have previously published a search for heavy neutrino decays using the Borexino counting test facility [44].

II. EXPERIMENTAL SETUP AND RESULTS OF MEASUREMENTS

A. Brief description of Borexino

The Borexino experiment at the underground Gran Sasso National Laboratory (LNGS) detects solar neutrinos by means of their elastic scattering on electrons in a large volume liquid scintillator detector. Thanks to its excellent radiopurity and large target mass, Borexino is ideal to answer other fundamental questions and look for exotic processes in particle physics and astrophysics.

The Borexino detector and its components have been thoroughly described in [45–57]. The central detector is

comprised of 278 tons of purified organic liquid scintillator confined to a 4.25 m radius transparent nylon vessel (IV). The IV is surrounded by a concentric spherical quenched pseudocumene buffer which shields the scintillator from γ rays and neutrinos from the periphery of the detector. The scintillator and buffer are contained in a 13.7 m diameter stainless steel sphere (SSS) on which 2212 photomultipliers (PMTs) are mounted to detect scintillation from events inside the IV. The SSS is immersed in a water-Cherenkov muon detector.

In Borexino, charged particles are detected through the scintillation light they produce in the liquid scintillator. The energy of an ionizing event occurring in the scintillator is converted to scintillation light and is quantified by the total light collected by the PMTs. To good approximation, the measured light depends linearly on the energy released in the scintillator and the energy resolution is scaled as $5\%/\sqrt{E[\text{MeV}]}$.

The detector energy and spatial resolution were studied with radioactive sources placed at different positions inside the inner vessel [57]. For energies >3 MeV of interest for this work, the energy calibration was performed with an ^{241}Am - ^9Be neutron source [49,50]. The position of an event is determined using a photon time of flight reconstruction algorithm. The position resolution, measured using the ^{214}Bi - ^{214}Po $\beta - \alpha$ decay sequence, is 13 cm [48].

B. Data selection

The measured Borexino energy spectrum in the 0–15 MeV range from 1192.0 live days of data and with different selection cuts is shown in Fig. 2. Below 3 MeV the spectrum is dominated by 2.6 MeV γ 's from β decay of trace ^{208}Tl in the PMTs and in the SSS.

The first cut on the raw data filters out events occurring within 2 ms of muons crossing the entire detector (curve 2, Fig. 2). Muons are identified by the outer detector, by the specific mean time of PMT hits when they cross the SSS and on the time corresponding to the maximum density of hit PMTs. This timing cut rejects residual muons that were not tagged by the muon detector and that interacted in the pseudocumene buffer region [53].

To remove muon-induced background due to short-lived isotopes (1.1 s ^8B , 1.2 s ^8Li , etc. [50]) and significantly reduce that from ^{11}Be ($\tau = 19.9$ s), an additional 20 s veto is applied after each muon crossing the SSS (curve 3, Fig. 2). This cut has a dead time of 745.8 days and brings the live time down to 446.2 days.

A software fiducial volume cut is needed in order to suppress external radiation background. Curve 4 of Fig. 2 shows the effect of selecting a central 100 ton fiducial volume (FV) by applying a radial cut $R \leq 3.02$ m. Finally, an $\alpha - \beta$ selection cut based on pulse shape discrimination performed with the Gatti optimal filter [58] is applied. Only events with negative Gatti variable (corresponding to γ - and β -like signals) are selected [48].

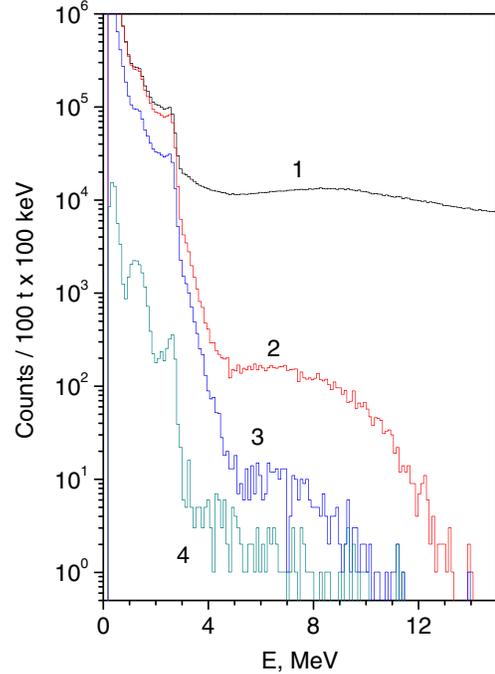


FIG. 2 (color online). Energy spectra of the events surviving incremental selection cuts. From top to bottom: (1) raw spectrum; (2) 2 ms postmuon veto cut; (3) 20 s after muons crossing the SSS cut; (4) FV cut. See text for details.

Since the energy of α particles is highly quenched in the liquid scintillator, this cut has no effect on the spectrum for energies higher than 4 MeV.

III. NEUTRINO FLUXES AND THE e^+e^- SPECTRA

Here we report on the search for heavy neutrinos produced in ^8B decays in one of the side branches of the pp fusion reaction chain in the Sun. The decay, $^8\text{B} \rightarrow ^8\text{Be} + e^+ + \nu_H$, is a variant of the standard decay with a left-handed light neutrino. In Borexino the search is performed by comparing the measured energy spectrum with that expected from ν_H decays. The latter requires the knowledge of the heavy neutrino flux $\Phi(E_\nu)$ through the detector, of the kinetic energy of the e^+e^- pairs produced [Eq. (1)], and the response function of Borexino to energy released by e^+e^- pairs in the scintillator.

The emission of a heavy neutrino in the β^+ decay of ^8B is suppressed by the mixing parameter $|U_{eH}|^2$ and a phase-space factor as

$$\Phi(E_{\nu_H}) = |U_{eH}|^2 \sqrt{1 - \left(\frac{m_{\nu_H}}{E_{\nu_H}}\right)^2} \Phi_{^8\text{B}}(E_\nu), \quad (3)$$

where E_{ν_H} is the total energy of the heavy neutrino. We use the neutrino spectrum from ^8B decay $\Phi_{^8\text{B}}(E_\nu)$ given in [59–61].

Heavy neutrinos produced in the Sun can decay on their flight to Earth. The energy spectrum of neutrinos reaching the detector is given by

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

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

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

$D = 1.5 \times 10^{13}$ cm is the average Sun-Earth distance and $\beta = p_{\nu_H}/E_{\nu_H}$.

The double differential distribution for energy ϵ and emission angle θ for the standard decay with a light neutrino ν_L for the c.m.s. is given in [1]:

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

where $f_1(\epsilon, m_{\nu_H})$ and $f_s(\epsilon, m_{\nu_H})$ are complex functions [1], $\xi = +1 (-1)$ for $\nu_H (\bar{\nu}_H)$, and $|\vec{P}| = \beta$ is the polarization of the ν_H .

The distribution (6) holds for Dirac neutrinos. The angular distribution for the decays of the Majorana neutrino is distinguishable from that of the Dirac neutrino [2]. However, the integrated decay rate remains the same in both cases [4].

The total laboratory energy of the e^+e^- pair, $E = E_{\nu_H} - E_{\nu_L}$ and ϵ relate as follows:

$$E = E_{\nu_H}(1 - (\epsilon/m_{\nu_H})(1 + \beta \cos\theta)). \quad (7)$$

In the c.m.s. the energy ϵ of the emitted neutrino is restricted according to $\epsilon \leq \epsilon_{\text{max}} = (m_{\nu_H}^2 - 4m_e^2)/2m_{\nu_H}$ that corresponds to the emission angle

$$(\cos\theta)_{\text{min}} = (1/\beta)((m_{\nu_H}/\epsilon_{\text{max}})(1 - E/E_{\nu_H}) - 1). \quad (8)$$

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):

$$\frac{dN}{dE}(E, E_{\nu_H}) = \int_{(\cos\theta)_{\text{min}}}^1 \frac{dN_{\nu_L}}{d\epsilon d\cos\theta} d\epsilon d\cos\theta. \quad (9)$$

For a given heavy neutrino energy E_{ν_H} , the energy E of the e^+e^- pair is restricted to the interval

$$E_{\nu_H} \left[1 - \frac{1 + \beta}{2} \left(1 - \frac{4m_e^2}{m_{\nu_H}^2} \right) \right] \leq E \leq E_{\nu_H}. \quad (10)$$

Integrating over the neutrino energy up to end-point energy Q_0 yields the energy spectrum of the e^+e^- pair:

$$\begin{aligned} \frac{dN}{dE}(E) &= \frac{(\Gamma_{\text{c.m.}}^{e^+e^-})^2}{\Gamma_{\text{c.m.}}^{\text{tot}}} |U_{eH}|^2 \frac{m_{\nu_H}}{c} \\ &\times \int_{2m_e}^{Q_0} \frac{dN}{dE}(E, E_\nu) \frac{\Phi(E_\nu)}{\beta E_\nu} dE_\nu. \end{aligned} \quad (11)$$

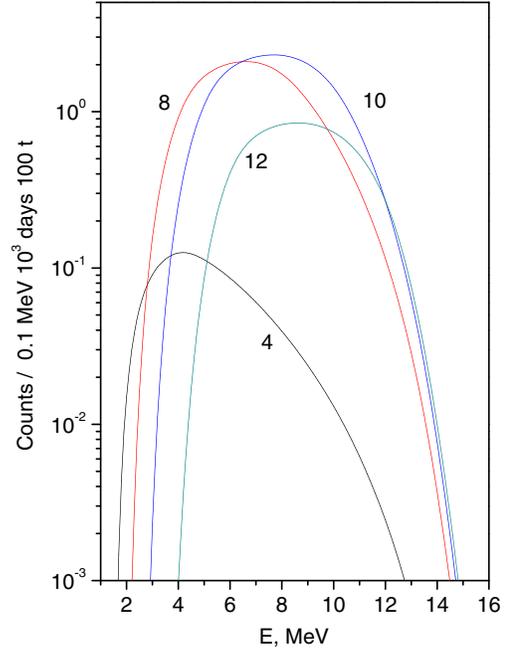


FIG. 3 (color online). The expected spectra of signals due to $\nu_H \rightarrow \nu_L + e^+ + e^-$ decay for different neutrino masses $m_{\nu_H} = 4, 8, 10, 12$ MeV and mixing parameter $|U_{eH}|^2 = 1.0 \times 10^{-5}$.

Here $\Gamma_{\text{c.m.}}^{e^+e^-}/\Gamma_{\text{c.m.}}^{\text{tot}}$ is the branching ratio for $\nu \rightarrow \nu e^+ e^-$ decay mode. Equation (11) is convolved with the response function of two e^+e^- annihilation γ rays and the energy resolution function $\sigma(E)$ to obtain the heavy neutrino energy spectrum $N^{\nu_H}(E)$. The Borexino response to e^+e^- pairs of different energies was simulated via MC using GEANT4 and taking into account the effect of ionization quenching and the nonlinear position-dependent energy response. Uniformly distributed events were simulated inside the entire inner vessel, and those reconstructed within the FV (central 100 t) were used in determining the response function and the detection efficiency. The expected spectra for different values of heavy neutrino mass m_{ν_H} and for fixed $|U_{eH}|^2 = 1 \times 10^{-5}$ are shown in Fig. 3.

IV. RESULTS AND DISCUSSIONS

A. Fitting procedure

Figure 4 shows the observed Borexino energy spectrum in the (4.8–12.8) MeV range, most sensitive to the neutrino decay signal. The spectrum includes the (ν, e) elastic scattering signal from ^8B solar neutrinos [$N^{8\text{B}}(E)$], the rate of long-lived cosmogenic ^{11}Be [$N^{11\text{Be}}(E)$] and the sought-after spectra from neutrino decays [$N^{\nu_H}(E)$]:

$$N^{\text{th}}(E) = X^{8\text{B}} N^{8\text{B}}(E) + X^{11\text{Be}} N^{11\text{Be}}(E) + X^{\nu_H} N^{\nu_H}(E), \quad (12)$$

where $X^{8\text{B}}$, $X^{11\text{Be}}$ and X^{ν_H} give the intensities of the corresponding processes.

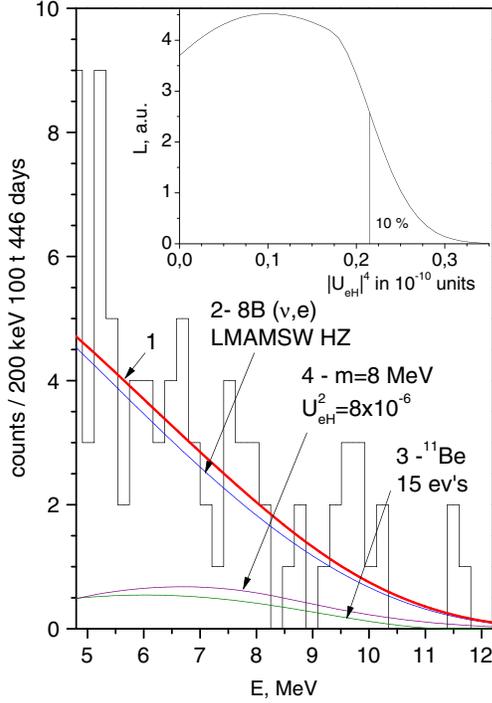


FIG. 4 (color online). The Borexino spectrum in the (4.8–12.8) MeV range. 1, optimal fit; 2, (ν, e) scattering of ${}^8\text{B}$ neutrino [LMA MSW BPS06(GS98)]; 3, ${}^{11}\text{Be}$ decays; 4, the detector response function for the decay of neutrino with $m_{\nu H} = 8$ MeV and $|U_{eH}|^2 = 8 \times 10^{-6}$. The inset shows the dependence of L on $|U_{eH}|^4$ for $m_{\nu H} = 8$ MeV.

A binned maximum likelihood fit using the expression above yields the number of $(\nu_H \rightarrow \nu_L e^+ e^-)$ events. The likelihood function assumes the form of a product of Poisson probabilities:

$$L = \prod e^{-N_i^{\text{th}}} (N_i^{\text{th}})^{N_i^{\text{exp}}} / N_i^{\text{exp}}!, \quad (13)$$

where N_i^{th} and N_i^{exp} are the expected (12) and measured number of counts in the i th bin of the spectrum, respectively. The parameter $(X^{8\text{B}})$ was constrained by the interval of standard solar model predictions for high and low solar metallicity [59–61], while $(X^{11\text{Be}})$ and $X^{\nu H}$ were left free. The fit was performed in the range of 4.8–12.8 MeV and had 76 degrees of freedom.

The maximum likelihood fit for $m_\nu = 8$ MeV is shown in Fig. 4, line 1. The best fit corresponds to the $|U_{eH}|^2 = 3.7 \times 10^{-6}$, $X^{11\text{Be}} = 0$ and $X^{8\text{B}}$ for BPSO5(GS98) model [59–61]. The modified $\chi^2 = \sum (N_i^{\text{exp}} - N_i^{\text{th}})^2 / N_i^{\text{th}}$ is 70.5/76. The low statistics dictate the use of a Monte Carlo simulation of Eq. (12) to find the probability of $\chi_p^2 \geq 70.5$. The goodness of fit ($p = 60.5\%$) shows that the function in Eq. (12) describes the spectrum well.

B. The obtained limits

No statistically significant deviations of $|U_{eH}|^2$ from zero were observed for all tested $m_{\nu H}$. The upper limit

on the number of $(\nu_H, \nu_L e^+ e^-)$ events for different $m_{\nu H}$ was found using the $L_{\text{max}}(X^{\nu H})$ profile, where $L_{\text{max}}(X^{\nu H})$ is the maximal value of L for fixed $X^{\nu H}$ when the two other parameters are left free. The $L_{\text{max}}(X^{\nu H})$ distribution obtained from MC simulations with $X^{\nu H} \geq 0$ was used to determine confidence levels in $L_{\text{max}}(X^{\nu H})$. The upper limits on the mixing parameter $|U_{eH}|^2$ were then calculated in accordance with Eq. (11).

The dependence of the number of $(\nu_H, \nu_L e^+ e^-)$ counts on $|U_{eH}|^2$ and $m_{\nu H}$ is

$$S_{\text{int}}(m_{\nu H}, |U_{eH}|) \sim m_{\nu H}^6 |U_{eH}|^4 \exp(-\text{const} \times m_{\nu H}^6 |U_{eH}|^2). \quad (14)$$

The function $S_{\text{int}}(m_{\nu H}, |U_{eH}|)$ has a maximum, for fixed $m_{\nu H}$ and E_ν , corresponding to $|U_{eH}|^2 = 2/(\text{const} \times m_{\nu H}^6) = 2(|U_{eH}|^2 \tau_{\text{c.m.}}) / \tau_f$, where $\tau_{\text{c.m.}} = 1/\Gamma_{\text{c.m.}}$ and τ_f are defined in Eqs. (2) and (5). The experiment is not sensitive to low $|U_{eH}|^2$ (due to the low probability of ν_H decay) nor to large $|U_{eH}|^2$ for which the ν_H decays occur in flight from the Sun.

The Borexino sensitivity curves for $|U_{eH}|^2$ in the $1 \leq m_{\nu H} \leq 15$ MeV range are shown in Fig. 5 together with those obtained by reactor [26] and $\pi^+ \rightarrow e^+ \nu_e$ decay experiments [28]. For the 1.5–13 MeV heavy neutrino mass region Borexino improves the limits on the mixing

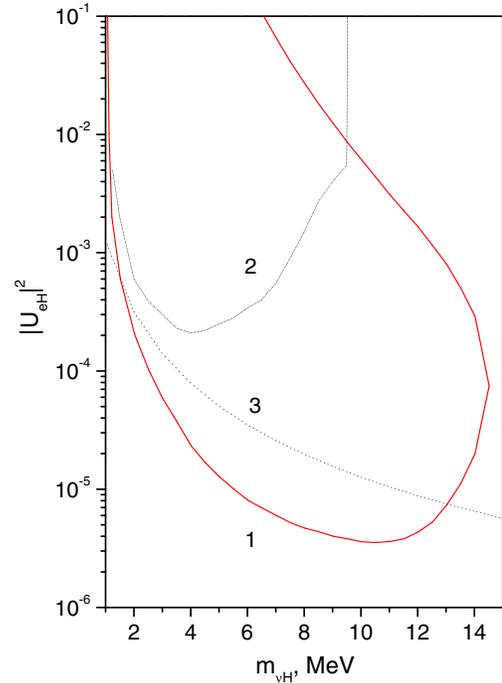


FIG. 5 (color online). Limits on the mixing parameter $|U_{eH}|^2$ as a function of neutrino mass m_ν (90% C.L.). 1: Present work excludes values of $|U_{eH}|^2$ and m_ν inside region 1. 2: Upper limits from reactor experiments on the search for $\nu_H \rightarrow \nu_L + e^+ + e^-$ decay due to W -exchange mode [26]. 3: Upper limits from $\pi \rightarrow e + \nu$ decay [28].

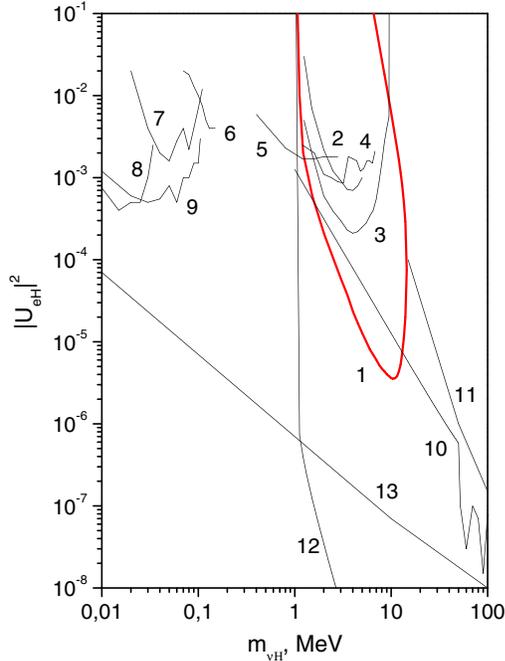


FIG. 6 (color online). The Borexino constraints (region 1) and limits on $|U_{eH}|^2$ versus $m_{\nu H}$ in the mass range (0.01–100) MeV from different experiments (see text).

parameter with respect to those obtained previously at nuclear reactors and accelerators.

The existing bounds on $|U_{eH}|^2$ in the wide mass range (0.01–100) MeV are shown in Fig. 6. Reactor experiments restrict the mixing parameter in the (1.1–9.5) MeV mass range (lines 2 [25] and 3 [26]). As noted above, these limits were obtained in assumption that only W exchange mode can occur.

For masses up to $m_{\nu H} \approx 6$ MeV, an important bound is provided by ft values for superallowed Fermi decays (line 4 [21]) and by searches of kinks in the electron spectrum of β decays of ^{20}F (line 5 [21]), ^{64}Cu (line 6 [14]), ^{45}Ca (line 7 [16]), ^{63}Ni (line 8 [18]) and ^{35}S (line 9 [18]).

For higher masses, very robust bounds can be set by looking for additional peaks in the spectrum of electrons in leptonic decays of pions and kaons (line 10 [28]). The data from the experiment PS191 sets a bound which is strongly

mass dependent, going from $|U_{eH}|^2 \leq 10^{-4}$ at $m_{\nu H} = 15$ MeV to $|U_{eH}|^2 \leq 1.5 \times 10^{-7}$ at $m_{\nu H} = 100$ MeV (line 11 [30]).

The most restrictive constraints— $|U_{eH}|^2 m_{\nu H}^4 \leq 4.8 \times 10^{-7}$ —for neutrino masses up to around 30 MeV were obtained from the absence of a γ -ray signature in conjunction with the neutrino burst from SN1987A (line 12 [38]).

For $m_{\nu H}$ in the range (100 MeV–100 GeV) the limits $|U_{eH}|^2 \leq (10^{-8}–10^{-3})$ were obtained in NA3 [32], CHARM [31], L3 [33], DELPHI [34] and Belle [35] experiments. Similar limits for sterile neutrino mixing with muon neutrino $U_{\mu H}$ can be found in [36].

Finally, if sterile neutrinos are Majorana particles, they would contribute to the mediation of neutrinoless double beta decay. The limit on the half-life time of this process can be translated into a bound on the mixing parameter $|U_{eH}|^2$, which scales as $m_{\nu H}$ for $m_{\nu H} \leq 30$ MeV and as $m_{\nu H}^{-1}$ for $m_{\nu H} \geq 400$ MeV, with $|U_{eH}|^2 \approx 10^{-8}$ at $m_{\nu H} = 100$ MeV (line 13 [62–64]).

V. CONCLUSION

Thanks to the uniquely low radioactive background and large target mass of the Borexino detector, new limits on the mixing parameter $|U_{eH}|^2$ of a hypothetical massive neutrino in the range of mass 1.5–14 MeV to the electron neutrino have been set. These limits are ten- to 1000-fold stronger than those obtained by experiments searching for $\nu_H \rightarrow \nu_L + e^+ + e^-$ decays at nuclear reactors and 1.5–4 times stronger than those inferred from $\pi \rightarrow e + \nu$ decays.

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