KATRIN bound on 3+1 active-sterile neutrino mixing and the reactor antineutrino anomaly

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We present the bounds on 3+1 active-sterile neutrino mixing obtained from the first results of the KATRIN experiment. We show that the KATRIN data extend the Mainz and Troitsk bound to smaller values of $\Delta m^2_{41}$ for large mixing and improves the exclusion of the large-$\Delta m^2_{41}$ solution of the Huber-Muller reactor antineutrino anomaly. We also show that the combined bound of the Mainz, Troitsk, and KATRIN tritium experiments and the Bugey-3, NEOS, PROSPECT, and DANSs reactor spectral ratio measurements exclude most of the region in the $(\sin^22\theta_{ee}, \Delta m^2_{21})$ plane allowed by the Huber-Muller reactor antineutrino anomaly. Considering two new calculations of the reactor neutrino fluxes, we show that one, that predicts a lower $^{238}$U neutrino flux, is in agreement with the tritium and reactor spectral ratio measurements, whereas the other leads to a larger tension than the Huber-Muller prediction. We also show that the combined reactor spectral ratio measurements disfavor the Neutrino-4 indication of large active-sterile mixing and the $1\sigma$ allowed region around the Neutrino-4 best fit is excluded at about $2\sigma$ by the tritium bound dominated by the KATRIN data. We finally discuss the constraints on the gallium neutrino anomaly.

I. INTRODUCTION

The KATRIN collaboration presented recently [1] the first results of their high-precision measurement of the electron spectrum from $^3$H decay near the end point, where it is sensitive to neutrino masses at the eV level. They obtained an upper limit of 1.1 eV at 90% confidence level (CL) for the effective neutrino mass

$$m_\beta = \sqrt{\sum_{k=1}^{3} |U_{ek}|^2 m_k^2},$$

in the standard three-neutrino mixing framework, where $U$ is the mixing matrix and $m_k$ is the mass of the neutrino $\nu_k$, with $k = 1, 2, 3$.

The KATRIN collaboration measured the electron spectrum down to $Q = 35$ eV, where $Q \simeq 18.57$ keV is the Q-value of $^3$H, that corresponds to the end-point of the electron spectrum in the absence of neutrino mass effects. Using this spectral measurement, it is possible to constrain also the mixing with the electron neutrino of heavier non-standard neutrinos with masses smaller than about 35 eV. This is interesting in view of the indications in favor of the existence of such non-standard neutrinos given by the reactor antineutrino anomaly and the gallium neutrino anomaly (see the recent reviews in Refs. [2][4]). A possible explanation of these anomalies is short-baseline neutrino oscillations due to the existence of a non-standard neutrino with a mass of the order of 1 eV or larger. Since it is well established that there are only three active flavor neutrinos, in the flavor basis the new neutrino must be sterile. This framework is commonly called 3+1 active-sterile neutrino mixing.

In this paper, we first calculate in Section II the upper bound on $m_\beta$ in the standard framework of three-neutrino mixing, in order to test the validity of our analysis of the KATRIN data by comparing the results with those of the KATRIN collaboration. Then, in Section III we calculate the KATRIN bounds on active-sterile neutrino mixing and we show that they are more stringent than those of the Mainz [5] and Troitsk [6][7] experiments discussed in Ref. [8]. In Section IV we compare the KATRIN bounds with the results of the 3+1 analysis of the reactor antineutrino anomaly [9] assuming the standard Huber-Muller reactor neutrino flux prediction [10][11] and the two new predictions of Estienne, Fallot et al. [12] and Haven, Kostensalo, Severijns, Suhonen [13]. In Section V we discuss also the bounds of experiments that measured the reactor antineutrino spectrum at different distances. In Section VI we compare the positive results of the Neutrino-4 reactor experiment [14] with the bounds from the tritium experiments and from the other reactor spectral ratio measurements. In Section VII we discuss the constraints on the gallium neutrino anomaly. We finally summarize the results in Section VII.

II. THREE NEUTRINO MIXING

In this section we present the results of our analysis of the KATRIN data in the standard framework of three-neutrino mixing. This is useful in order to describe the method that we used in the analysis of the KATRIN data and in order to check its validity by comparing the results for $m_\beta$ with those obtained by the KATRIN collabora-
Fermi function is given by

\[ T_2 \rightarrow ^3\text{He}^T^+ + e^- + \nu_e. \]  

(2)

The differential electron spectrum is given by

\[
R_\beta(E) = \frac{G_F^2 \cos^2 \theta_C}{2\pi^3} |M|^2 F(E, Z + 1) \times (E + m_e) \sqrt{(E + m_e)^2 - m_\beta^2} \times \sum_{i,j} |U_{ei}|^2 \zeta_j \varepsilon_j \sqrt{\varepsilon_j^2 - m_\beta^2} \Theta(\varepsilon_j - m_\beta),
\]

(3)

where \( G_F \) is the Fermi constant, \( \theta_C \) is the Cabibbo angle, \( M \) is the nuclear matrix element, \( m_e \) is the electron mass, \( E \) is the kinetic energy of the outgoing electron, \( F(E, Z + 1) \) is the Fermi function describing the Coulomb effect of the electron, and \( Z = 1 \) is the atomic number of the parent nucleus. A fully relativistic description of the Fermi function is given by

\[
F(E, Z) = \frac{e^{\pi y}}{(2pR_n)^{2(1-\gamma)}} \frac{\Gamma(\gamma + iy)^2}{\Gamma(2\gamma + 1)^2},
\]

where \( y = Z\alpha E/p \) and \( \gamma = \sqrt{1 - \alpha^2 Z^2} \), with the fine-structure constant \( \alpha \) and the complex Gamma function \( \Gamma(z) \) [15]. The radius of the \(^3\text{He}^2\) nucleus is \( R_n = 2.8840 \times 10^{-3}/m_e \) [16]. In Eq. [7], \( \varepsilon_j = E_0 - E - V_j \) is the neutrino energy, with \( E_0 = M_T - M_{\text{He}} - m_e \), where \( M_T \) and \( M_{\text{He}} \) are, respectively, the mass of the initial and final nucleus. In the calculation of the \( \beta \)-decay electron spectrum \( R_\beta(E) \), we considered the excitation states of the daughter molecular system, which have excitation energies \( V_j \) and a final-state distribution with probabilities \( \zeta_j \). These quantities are calculated with the Born-Oppenheimer approximation and can be found in Refs. [17] [18].

When the experimental resolution is much larger than the values of neutrino masses, one can define the effective neutrino mass \( m_\beta \) as in Eq. [1] and approximate the differential electron spectrum as

\[
R_\beta(E) \approx \frac{G_F^2 \cos^2 \theta_C}{2\pi^3} |M|^2 F(E, Z + 1) \times (E + m_e) \sqrt{(E + m_e)^2 - m_\beta^2} \times \sum_j \zeta_j \varepsilon_j \sqrt{\varepsilon_j^2 - m_\beta^2} \Theta(\varepsilon_j - m_\beta).
\]

(5)

The KATRIN experiment combines a windowless gaseous molecular tritium source with a spectrometer based on the principle of magnetic adiabatic collimation with electrostatic filtering (MAC-E-filter) [19] [20]. This apparatus can measure the integral tritium \( \beta \)-spectrum

\[
R((qU)) = R_{bg} + A_{\text{sig}} N_T \\
\times \int_{qU} R_\beta(E) f(E - (qU)) dE,
\]

(6)

which is the convolution of the differential \( \beta \)-decay electron spectrum \( R_\beta(E) \) with the response function \( f(E - \langle qU \rangle) \). \( N_T \) denotes the effective number of tritium atoms, \( R_{bg} \) is the energy-independent background rate and \( A_{\text{sig}} \) is the signal amplitude. The response function defines the probability of passing the MAC-E-filter for an electron with the kinetic energy \( E \) at the retarding potential energy \( qU \). \( \langle qU \rangle \) is the average over different pixels and scans and serves as the working variable of the integral electron spectrum. The response function used in our analysis is taken from the red curve of the top panel of Fig. 2 in Ref. [1]. Note that an energy resolution of 2.8 eV, which is determined by the energy filter width at the minimal and maximal magnetic fields, has been included in the response function. Moreover, an additional Gaussian smearing of 0.25 eV is also included to account for the average effect of \( \langle qU \rangle \).

For the analysis of the KATRIN data, we considered the \( \chi^2 \) function

\[
\chi^2 = \sum_{i=1}^N \left( \frac{R_{\text{obs}}^i - R_{\text{pred}}^i (m_\beta^2 + \delta m_\beta^2)}{\sigma_i} \right)^2 + \left( \frac{\delta m_\beta^2}{0.32} \right)^2,
\]

(7)

where \( R_{\text{obs}}^i \) and \( \sigma_i \) are the experimental rate and its statistical uncertainty corresponding to each retarding energy value \( \langle qU \rangle_i \) in the upper panel of Fig. 3 in Ref. [1]. \( R_{\text{pred}}^i \) is the predicted rate calculated according to Eq. (6). The pull term for the variation \( \delta m_\beta^2 \) takes into account the systematic uncertainty of 0.32 eV\(^2\) on \( m_\beta^2 \) given in Table I of Ref. [1]. In the fit we considered four free parameters: \( m_\beta^2 \), the endpoint \( E_0 \), the signal amplitude \( A_{\text{sig}} \), and the background rate \( R_{bg} \). We calculated the bounds for \( m_\beta^2 \) by marginalizing over \( E_0 \), \( A_{\text{sig}} \), and \( R_{bg} \).

In Ref. [1], the KATRIN collaboration first analyzed the data allowing negative values of \( m_\beta^2 \), as discussed in Ref. [21]. With this method, they obtained \( m_\beta^2 = -1.0^{+0.9}_{-1.1} \) eV\(^2\). Under the same assumption, we obtained \( m_\beta^2 = -1.0 \pm 0.9 \) eV\(^2\), which is approximately consistent with the official KATRIN result.

In order to calculate the upper bound on the absolute scale of neutrino masses in the framework of three-neutrino mixing, we considered only physical positive values of \( m_\beta^2 \), as done by the KATRIN collaboration [1]. We obtained

\[
m_\beta < 0.8 \, (0.9) \text{ eV at } 90\% (95\%) \text{ CL},
\]

(8)

that nicely coincide with the bounds that the KATRIN collaboration obtained [1] using the Feldman-Cousins method [22].

The approximate agreement of our results for \( m_\beta \) in the standard framework of three-neutrino mixing with those of the KATRIN collaboration validates our analysis of the KATRIN data.
III. 3+1 STERILE NEUTRINO MIXING

After the successful test of our method of analysis of the KATRIN data in the case of three-neutrino mixing, we consider the extension to 3+1 active-sterile neutrino mixing with the differential electron spectrum

\[ R_\beta(E) = (1 - |U_{e4}|^2) R_\beta(E, m_\beta) + |U_{e4}|^2 R_\beta(E, m_4), \]  

(9)

where \( U \) is the 4 \times 4 unitary mixing matrix, \( R_\beta(E, m_\beta) \) is the three-neutrino differential electron spectrum in Eq. (5), and \( R_\beta(E, m_4) \) has the same expression with \( m_\beta \) replaced by \( m_4 \). We will compare the results of our analysis of the KATRIN data with the results of short-baseline (SBL) reactor neutrino oscillation experiments, that probe the effective SBL survival probability

\[ P_{\nu_e \to \nu_{\bar{e}}}^{\text{SBL}} = 1 - \sin^2 2\theta_{ee} \sin^2 \left( \frac{\Delta m_{41}^2 L}{4E} \right), \]  

(10)

where \( \Delta m_{ij}^2 = m_i^2 - m_j^2, \sin^2 2\theta_{ee} = 4|U_{e4}|^2(1 - |U_{e4}|^2) \), \( L \) is the source-detector distance, and \( E \) is the neutrino energy. Note that neutrino oscillation experiments are sensitive to the squared-mass difference \( \Delta m_{41}^2 \simeq \Delta m_{42}^2 \simeq \Delta m_{43}^2 \) whereas the KATRIN experiment is sensitive to \( m_3 \) and \( m_4 \). Therefore, in order to compare the respective results one must make some assumption on the value of one of the three light neutrino masses (\( m_1, m_2, m_3 \)), that fixes the value of \( m_\beta \) through the precise knowledge of the values of the three-neutrino mixing parameters obtained by global fits of solar, atmospheric and long-baseline neutrino oscillation data [24][27]:

\[ \Delta m_{41}^2 \simeq 7.5 \times 10^{-5} \text{eV}^2, \]  

(11)

\[ |\Delta m_{31}^2| \simeq |\Delta m_{42}^2| \simeq 2.5 \times 10^{-3} \text{eV}^2, \]  

(12)

\[ |U_{e2}|^2 \simeq 0.3, \]  

(13)

\[ |U_{e3}|^2 \simeq 0.022. \]  

(14)

It is convenient to consider as the reference mass the lightest mass, that is \( m_1 \) or \( m_3 \) in the two possible cases of Normal Ordering (NO) or Inverted Ordering (IO) of the three light neutrino masses, respectively (see the recent review in Ref. [28]). Then, we have:

NO: \[ m_3^2 = m_1^2 + |U_{e4}|^2 \Delta m_{31}^2 + |U_{e3}|^2 \Delta m_{32}^2, \]  

(15)

IO: \[ m_3^2 = m_2^2 - |U_{e4}|^2 \Delta m_{31}^2 - |U_{e3}|^2 \Delta m_{32}^2, \]  

(16)

Therefore, taking into account that the sensitivity of KATRIN to \( m_3^2 \) is at the level of the \( \text{eV}^2 \), we can neglect the small deviations of \( m_3^2 \) from \( m_1^2 \) and \( m_3^2 \) in Eqs. (15) and (16), respectively, and consider the approximate relation

\[ \Delta m_{41}^2 \simeq m_1^2 - m_3^2. \]  

(17)

We performed two analyses of the KATRIN data in the framework of 3+1 active-sterile neutrino mixing. First, we fitted the data considering \( A_{\text{sig}}, R_{bg}, E_0, m_\beta, |U_{e4}|^2, \) and \( m_4 \) as free parameters and we calculated the “free \( m_\beta \)” exclusion curves in the \( (\sin^2 2\theta_{ee}, \Delta m_{41}^2) \) plane shown in Figure 1 marginalizing the \( \chi^2 \) over \( A_{\text{sig}}, R_{bg}, E_0, \) and \( m_\beta \). This is the most general bound on 3+1 mixing given by the KATRIN data. We also calculated the exclusion curve in the case of a negligible \( m_\beta \), shown by the \( m_\beta = 0 \) line in Figure 1. This is a reasonable assumption motivated by the likeliness of a neutrino mass hierarchy, with \( m_{1,2,3} \ll m_4 \). It is also useful for the comparison in Figure 1 of the KATRIN bounds with the exclusion curves of the Mainz [5] and Troitsk [6, 7] experiments obtained in Ref. [8] under the same assumption. One can see from Figure 1 that the KATRIN bounds obtained with free \( m_\beta \) and \( m_\beta = 0 \) are slightly different only around \( \Delta m_{41}^2 \simeq 200 - 300 \text{eV}^2 \), where the Troitsk

\[ \text{KATRIN (free } m_\beta ) \]

\[ \text{KATRIN ( } m_\beta = 0 \text{)} \]

\[ \text{Combined} \]
IV. THE REACTOR ANTIENEUTRINO ANOMALY

In Figure 1, we have also drawn the regions allowed by the reactor antineutrino anomaly (HM-RAA) [9] according to the recent analysis in Ref. [23] of reactor antineutrino data compared with the Huber-Muller prediction [10, 11] (see also Ref. [29]). One can see that the constraints of tritium-decay experiments can exclude large-$\Delta m_{41}^2$ part of the RAA 99% allowed region, but it is still too weak to affect the 90% allowed region around the best-fit point. Note that this HM-RAA region is different from the original reactor antineutrino anomaly allowed region in Ref. [9] (see also Ref. [30]) mainly because it takes into account only the measured reactor neutrino rates, without the Bugey-3 [31] 14 m / 15 m spectral ratio that were included in Refs. [9, 30].

As nicely illustrated in Fig. 1 of Ref. [32], the Bugey-3 spectral ratio excludes large mixing for $\Delta m_{41}^2 \lesssim 2\text{eV}^2$, moving the best-fit region from $\Delta m_{41}^2 \approx 0.5\text{eV}^2$ to $\Delta m_{41}^2 \approx 1.8\text{eV}^2$. However, in discussing the reactor antineutrino anomaly it is better to separate the model-dependent anomaly based on the absolute neutrino rate measurements and the model-independent implications of the spectral-ratio measurements.

Recently, also the new reactor neutrino experiments DANSS [33, 34], PROSPECT [35], and STEREO [36, 37] measured the reactor antineutrino spectrum at different distances. Moreover, the NEOS [38] experiments presented the results of a measurement of the reactor antineutrino spectrum at 24 m from a reactor, relative to the spectrum measured at about 500 m by the Daya Bay near detectors [39]. These measurements provide information on short-baseline neutrino oscillations that are independent of the theoretical calculation of the reactor antineutrino flux. Therefore, they can test the model-dependent reactor antineutrino anomaly and their results can be combined with the bounds given by the tritium experiments. Here we consider the published results of the Bugey-3 [31], NEOS [38], and PROSPECT [35] experiments, together with the preliminary 2019 results of the DANSS [34] experiment, that improve significantly
the published 2018 results [34]. We cannot include in
the analysis the results of the STEREO [36, 37] experi-
ment, because there is not enough available information.
For the Bugey-3 experiment we used the same analysis
that we used in previous papers [23, 40, 41]. For the
NEOS experiment we use the $\chi^2$ table kindly provided
by the NEOS collaboration. For the PROSPECT exper-
iment we use the $\chi^2$ table published as "Supplemental
Material" of Ref. [35]. For the DANSS experiment we
performed an approximate least-square analysis of the
2019 data presented in Fig. 5 of Ref. [34] that reproduces
approximately the DANSS exclusion curves in Fig. 6 of
the same paper.

Figure 2 shows the contours of the 2σ regions in the
$(\sin^2 2\theta_{ee}, \Delta m^2_{41})$ plane obtained from the reactor
spectral ratio measurements of the Bugey-3, NEOS,
PROSPECT and DANSS experiments, and the regions
allowed at $1\sigma$, $2\sigma$, and $3\sigma$ by the combined fit. One can
see that there is an indication in favor of short-baseline
oscillations at the level of about $2\sigma$, that is due to the
coincidence of the NEOS and DANSS allowed regions at
$\Delta m^2_{41} \approx 1.3$ eV$^2$, where there is the best-fit point for
$\sin^2 2\theta_{ee} \approx 0.026$, at $\Delta m^2_{41} \approx 0.4$ eV$^2$, where there is a
$1\sigma$-allowed region, and at $\Delta m^2_{41} \approx 3$ eV$^2$, where there is
a tiny $2\sigma$-allowed region. This model-independent
indication in favor of short-baseline oscillations was dis-
cussed in Refs. [11, 32] using the 2018 [33] DANSS data and in Ref. [29]
using both the 2018 and the 2019 [34] DANSS data. Here, as explained above, we use the 2019
DANSS data, that lead to a diminished indication in favor
of short-baseline oscillations with respect to the 2018
DANSS data. Indeed, from the combined NEOS and
DANSS analyses we find only a 2.6σ indication of short-
baseline oscillations, that is smaller than the 3.7σ ob-
tained in Ref. [11]. These values agree approximately
with those found in Ref. [29].

Figure 3 shows the 99% exclusion curve in the
$(\sin^2 2\theta_{ee}, \Delta m^2_{41})$ plane obtained from the combined analy-
sis of the Bugey-3, NEOS, PROSPECT and DANSS
spectral ratios, that constrain the mixing for large values of
$\Delta m^2_{41}$, together with the combined 99% CL exclusion
curve of the Mainz, Troitsk and KATRIN tritium experi-
ments, that constrains the mixing for large values of
$\Delta m^2_{41}$. Figure 3 shows also the combined tritium and
reactor spectral-ratio 99% CL exclusion curve, that dis-
favors most of the 99% CL allowed region [23] of the
Huber-Muller reactor antineutrino anomaly. Note that
the combined tritium and reactor spectral-ratio bound
at large values of $\Delta m^2_{41}$ is much more stringent than the
tritium bound, in spite of the dominance of the tritium
bound. The reason is that the global $\chi^2$ has a minimum at
$\Delta m^2_{41} \approx 1.3$ eV$^2$ and $\sin^2 2\theta_{ee} \approx 0.025$ that cor-
responds to the reactor spectral ratio best fit in Figure 2.

Figure 3 shows that there is a tension between the
active-sterile oscillations indicated by the Huber-Muller
reactor antineutrino anomaly and the combined bound
obtained from tritium and reactor spectral-ratio mea-
surements. However, it is likely that the Huber-Muller
antineutrino flux prediction must be revised, as indicated
by the observation of a large spectral distortion at 5
MeV in the RENO [43, 44], Double Chooz [45], Daya
Bay [39], and NEOS [38] experiments (see the reviews in
Refs. [16, 17]). As already discussed in Ref. [29], there
are two recent reactor neutrino flux calculations that may
improve the Huber-Muller prediction: the calculation of
Estienne, Fallot et al. (EF) [12] that is based on the sum-
ation method, and the calculation of Hayen, Kostensalo,
Severijns, Suhonen [13] (HKSS-RAA) reactor neutrino fluxes.

![Figure 4](image_url)

**FIG. 4.** 99% CL exclusion curves in the $(\sin^2 2\theta_{ee}, \Delta m^2_{41})$ plane obtained from the combined analysis of the data of the Mainz, Troitsk and KATRIN tritium experiments and the combined analysis of the reactor spectral ratio (RSR) measurements of the Bugey-3, NEOS, PROSPECT and DANSS experiments. Also shown is the combined tritium and reactor spectral-ratio exclusion curve and the regions allowed at 90% and 99% CL by the fits of the absolute reactor rates assuming the Estienne, Fallot et al. (EF) (EF-RAA) and the Hayen, Kostensalo, Severijns, Suhonen (HKSS-RAA) (HKSS-RAA) reactor antineutrino fluxes.
actor spectral ratios with the regions allowed by the fits of the absolute reactor rates assuming the EF and HKSS fluxes. We took into account the uncertainties of the HKSS fluxes given in Ref. [13]. On the other hand, since the EF cross section per fission are given in Ref. [12] without the associated uncertainties, for them we adopted the uncertainties associated with the summation spectra estimated in Ref. [18]: 5% for $^{235}$U, $^{239}$Pu, and $^{241}$Pu, and 10% for $^{238}$U.

From Figure 4 one can see that the EF neutrino flux calculation leads only to an upper bound on the mixing at 90% CL and higher. Therefore, in this case the reactor antineutrino anomaly is not statistically significant and the EF-RAA upper bound is compatible with the upper bounds obtained from the tritium experiments and the reactor spectral ratios.

On the other hand, the HKSS fluxes lead to an increase of the reactor antineutrino anomaly with respect to the HM prediction and the corresponding HKSS-RAA allowed regions in Figure 4 are limited to larger mixing than the HM-RAA allowed regions in Figure 3. Therefore, the tension of the HKSS-RAA with the tritium and reactor spectral ratios bounds is larger than that of the HM-RAA. From Figure 4 one can see that only very small portions of the HKSS-RAA 99% allowed region are not excluded by the combined 99% bound of the tritium experiments and the reactor spectral ratios.

V. NEUTRINO-4

Let us now consider the results of the Neutrino-4 reactor experiment [14], that is another experiment that measured the ratios of the spectra at different distances from the reactor, between 6 and 12 m. We did not consider it so far because the result of this experiment is an anomalous indication of short-baseline oscillations with large mixing that is in tension with all the other experimental results. This can be seen in Figure 5 where we compare the bounds in the $(\sin^2 2\theta_{ee}, \Delta m^2_{41})$ plane obtained from the tritium experiments and the reactor spectral ratios with the allowed regions of the Neutrino-4 reactor experiment [14]. One can see that the large-mixing parts of the Neutrino-4 allowed regions are excluded by the 3\(\sigma\) combined tritium and reactor spectral-ratio exclusion curve.

At 2\(\sigma\), the combination of the reactor spectral-ratio and tritium measurements have allowed regions at $\Delta m^2_{41} \approx 1.3$ eV$^2$, where there is the best-fit point for $\sin^2 2\theta_{ee} \approx 0.025$, and at $\Delta m^2_{41} \approx 0.4$ eV$^2$, that correspond to those in Figure 2 and are due to the coincidence of the NEOS and DANSS allowed regions discussed above. Therefore, all the 3\(\sigma\) Neutrino-4 allowed regions are excluded at 2\(\sigma\) by the reactor spectral-ratio and tritium measurements.

Moreover, the 1\(\sigma\) Neutrino-4 allowed region is excluded not only by the other reactor spectral ratio measurements, but also by the tritium measurements at about 2\(\sigma\). In this region around $\Delta m^2_{41} \approx 7.5$ eV$^2$ the KATRIN bound is dominant, as one can see from Figure 4.

VI. THE GALLIUM NEUTRINO ANOMALY

Let us finally consider the gallium neutrino anomaly [50, 52, 58], that is a short-baseline disappearance of $\nu_e$'s found in the gallium radioactive source experiments GALLEX [59–61] and SAGE [53, 62–64]. There is some uncertainty on the magnitude of the gallium neutrino anomaly, that depends on the detection cross section, which must be calculated, as in Refs. [50, 52], or extrapolated from measurements of $(p, n)$ [49, 65] or $(^{3}$He, $^{3}$H) [51] charge-exchange reactions. Figure 6 shows the regions in the $(\sin^2 2\theta_{ee}, \Delta m^2_{41})$ plane allowed at 90% CL by the gallium neutrino anomaly using the detection cross sections considered recently in Ref. [52], where a new shell model calculation based on the effective Hamiltonian JUN45 was presented. The Bahcall cross section was derived in Ref. [49] from the $(p, n)$ charge-exchange measurements in Ref. [65]. The Haxton cross section was calculated in Ref. [60] using a shell model. The Frekers cross section was obtained from the $(^{3}$He, $^{3}$H) [51] charge-exchange measurements in Ref. [51].
As done in Ref. [52], we show in Figure 6 the contours of the 90% CL allowed regions that have a lower bound for the effective mixing parameter $\sin^2 2\theta_{ee}$. One can see that the relatively large Haxton cross section gives the strongest anomaly, which requires rather large active sterile mixing and is in severe tension with the tritium and reactor spectral ratio bound. Almost all the 90% CL Haxton allowed region is excluded at 99% CL by the combined tritium and reactor spectral ratio bound. The smaller Frekers and Bahcall cross sections allow smaller values of the mixing, but the corresponding 90% CL allowed regions in Figure 6 are in tension with the combined tritium and reactor spectral ratio 99% CL exclusion curve, with only some very small not-excluded areas. The JUN45 cross section is the smallest one and allows the smallest mixing, as one can see from Figure 6, where the corresponding 90% CL allowed region has several areas that are not excluded by the combined 99% CL tritium and reactor spectral ratio bound. In particular, there is a large not-exccluded area at large values of $\Delta m^2_{11}$, between about 50 and 600 eV$^2$. These comparisons indicate that the smallest JUN45 gallium detection cross section is favored with respect to the others.

### VII. CONCLUSIONS

In this paper we have discussed the implications for 3+1 active-sterile neutrino mixing of the recent KATRIN data [1] on the search for the absolute value of neutrino masses. We have first analyzed the KATRIN data in the framework of standard three-neutrino mixing, in order to check the validity of our method by comparing the resulting bound on the effective mass $m_3$ with that obtained by the KATRIN collaboration. Then, we have presented the bounds obtained from the analysis of the KATRIN data on the short-baseline oscillation parameters $\sin^2 2\theta_{ee}$ and $\Delta m^2_{41}$ in the framework of 3+1 active-sterile neutrino mixing. We have shown that the KATRIN data allow to improve the bounds of the Mainz [5] and Troitsk [6, 7] experiments discussed in Ref. [8] extending the excluded region from $\Delta m^2_{41} \approx 10 - 100$ eV$^2$ to $\Delta m^2_{41} \approx 1 - 10$ eV$^2$ for large mixing ($\sin^2 2\theta_{ee} \gtrsim 0.1$). This result allows us to extend the exclusion of the large-$\Delta m^2_{41}$ solution of the Huber-Muller reactor antineutrino anomaly to $\Delta m^2_{41} \approx 10$ eV$^2$ for $\sin^2 2\theta_{ee} \approx 0.1$ at 90% CL (see Figure 1).

We also considered the model-independent bounds of the Bugey-3 [31], NEOS [38], PROSPECT [35], and DANSS [33, 34] experiments that measured the reactor antineutrino spectrum at different distances. We have shown that there is a persistent model-independent indication [29, 41, 42] of short-baseline oscillations due to the coincidence of the NEOS and DANSS allowed regions, albeit with a smaller statistical significance passing from the 2018 [33] to the 2019 [34] DANSS data, in agreement with the discussion in Ref. [29].

The combination of the bounds of the reactor spectral ratio measurements exclude most of the low-$\Delta m^2_{41}$ solution of the Huber-Muller reactor antineutrino anomaly. Therefore, combining the tritium and reactor spectral ratio bounds, we are able to exclude most of the region in the $(\sin^2 2\theta_{ee}, \Delta m^2_{41})$ plane corresponding to the short-baseline solution of the Huber-Muller reactor antineutrino anomaly (see Figure 3).

We also discussed the implications of these bounds for the interpretations of the absolute reactor antineutrino rates assuming one of the two recent new reactor neutrino flux calculations by Estienne, Fallot et al. (EF) [12] and Hayen, Kostensalo, Severijns, Suhonen (HKSS) [13]. We have shown that the EF calculation, that predicts a $^{235}$U neutrino flux that is smaller than that of Huber-Muller, is in agreement with the bounds on 3+1 mixing obtained from the tritium and reactor spectral ratio measurements. On the other hand, since the HKSS calculation predicts reactor neutrino fluxes that are larger than those of Huber-Muller, the HKSS antineutrino anomaly region in the $(\sin^2 2\theta_{ee}, \Delta m^2_{41})$ plane is more excluded than the Huber-Muller one (see Figure 4).

We also compared the tritium and reactor spectral ratio bounds on 3+1 mixing with the indication of large mixing of the Neutrino-4 reactor experiment [14]. We have shown that most of the Neutrino-4 allowed regions

![Figure 6: Comparison of the regions in the $(\sin^2 2\theta_{ee}, \Delta m^2_{41})$ plane allowed at 90% CL by the gallium neutrino anomaly using the Bahcall [29], Haxton [50], Frekers [51], and JUN45 [52] neutrino detection cross sections discussed in Ref. [52] with the 90% CL exclusion curves obtained from the combined analysis of the data of the Mainz, Troitsk and KATRIN tritium experiments and the combined analysis of the reactor spectral ratio (RSR) measurements of the Bugey-3, NEOS, PROSPECT and DANSS experiments. Also shown is the combined tritium and reactor exclusion curve.](image-url)
in the \((\sin^2 2\theta_{\mu e}, \Delta m^2_{11})\) plane are excluded by the other reactor spectral ratio measurements, and the tritium bound, dominated by the KATRIN data, excludes the Neutrino-4 \(4\sigma\) region around the best fit at about 2\(\sigma\) (see Figure [3]).

We finally considered the gallium neutrino anomaly and we have shown that the combined bound of tritium and reactor spectral ratio measurements favor the recent JUN-45 shell model calculation of the neutrino-gallium cross section \([52]\) with respect to older estimates \([19\, 51]\).

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