ν_e and $\bar{\nu}_e$ disappearance in Gallium and reactor experiments

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Abstract

The disappearance of electron neutrinos observed in the Gallium radioactive source experiments is analyzed in the effective framework of two-neutrino mixing. We found an indication of neutrino disappearance due to neutrino oscillations with $\sin^2 2\vartheta \gtrsim 0.03$ and $\Delta m^2 \gtrsim 0.1\,\text{eV}^2$. We studied the compatibility of this result with the data of the Bugey and Chooz reactor short-baseline antineutrino disappearance experiments. We found an indication in favor of neutrino oscillations with $0.01 \lesssim \sin^2 2\vartheta \lesssim 0.07$ and $1.8\,\text{eV}^2 \lesssim \Delta m^2 \lesssim 1.9\,\text{eV}^2$, from the Bugey data, which is compatible with the Gallium allowed region of the mixing parameters. This indication persists in the combined analyses of Gallium, Bugey, and Chooz data.

Introduction

Solar, atmospheric, reactor and accelerator neutrino experiments give very robust evidence of three-neutrino mixing [1, 2]. However, data from LSND, MiniBooNE (at low energy) ant the Gallium radioactive source experiments show some anomalies which open a window to the possible existence of exotic neutrino physics beyond three-neutrino mixing.
The Gallium radioactive source experiments (GALLEX [3] and SAGE [4, 5]) measured a lower electron neutrino flux than the expected one; this can be interpreted as an indication of the disappearance of electron neutrinos due to neutrino oscillations [6].

Gallium experiments

The Gallium radioactive source experiment consist in the detection of electron neutrinos produced by artificial ^{51}Cr and ^{37}Ar radioactive sources which decay through electron capture

$$e^- + {}^{51}\text{Cr} \to {}^{51}\text{V} + \nu_e \qquad \text{and} \qquad e^- + {}^{37}\text{Ar} \to {}^{37}\text{Cl} + \nu_e .$$

The neutrinos are detected through the reaction $\nu_e + {}^{71}\text{Ga} \to {}^{71}\text{Ge} + e^-$. We present the results of the fit of the data of Gallium radioactive source experiments in terms of effective two-neutrino oscillations. The survival probability of electron (anti)neutrinos with energy E at a distance L from the source is given by

$$P_{\overset{(-)}{\nu_e} \to \overset{(-)}{\nu_e}}(L, E) = 1 - \sin^2 2\vartheta \, \sin^2\left(\frac{\Delta m^2 L}{4E}\right) , \tag{1}$$

where ϑ is the mixing angle and Δm^2 is the squared-mass difference (see Refs. [1, 2]).

We use the theoretical value of the ratio R of the predicted ^{71}Ge production rates in each of the Gallium radioactive source experiments in the cases of presence and absence of neutrino oscillations given by

$$R = \frac{\int \mathrm{d}V\, L^{-2} \sum_i (\text{B.R.})_i\, \sigma_i\, P_{\nu_e \to \nu_e}(L, E_i)}{\sum_i (\text{B.R.})_i\, \sigma_i \int \mathrm{d}V\, L^{-2}} , \tag{2}$$

where i is the index of the ν_e lines emitted in ^{51}Cr or ^{37}Ar.
The result of the combined least-squares analysis of the four Gallium source experiments is shown in Fig. (1). One can see that there is an allowed region in the $\sin^2 2\vartheta$–Δm^2 plane at 1σ for $\Delta m^2 \gtrsim 0.6\,\text{eV}^2$ and $0.08 \lesssim \sin^2 2\vartheta \lesssim 0.4$.

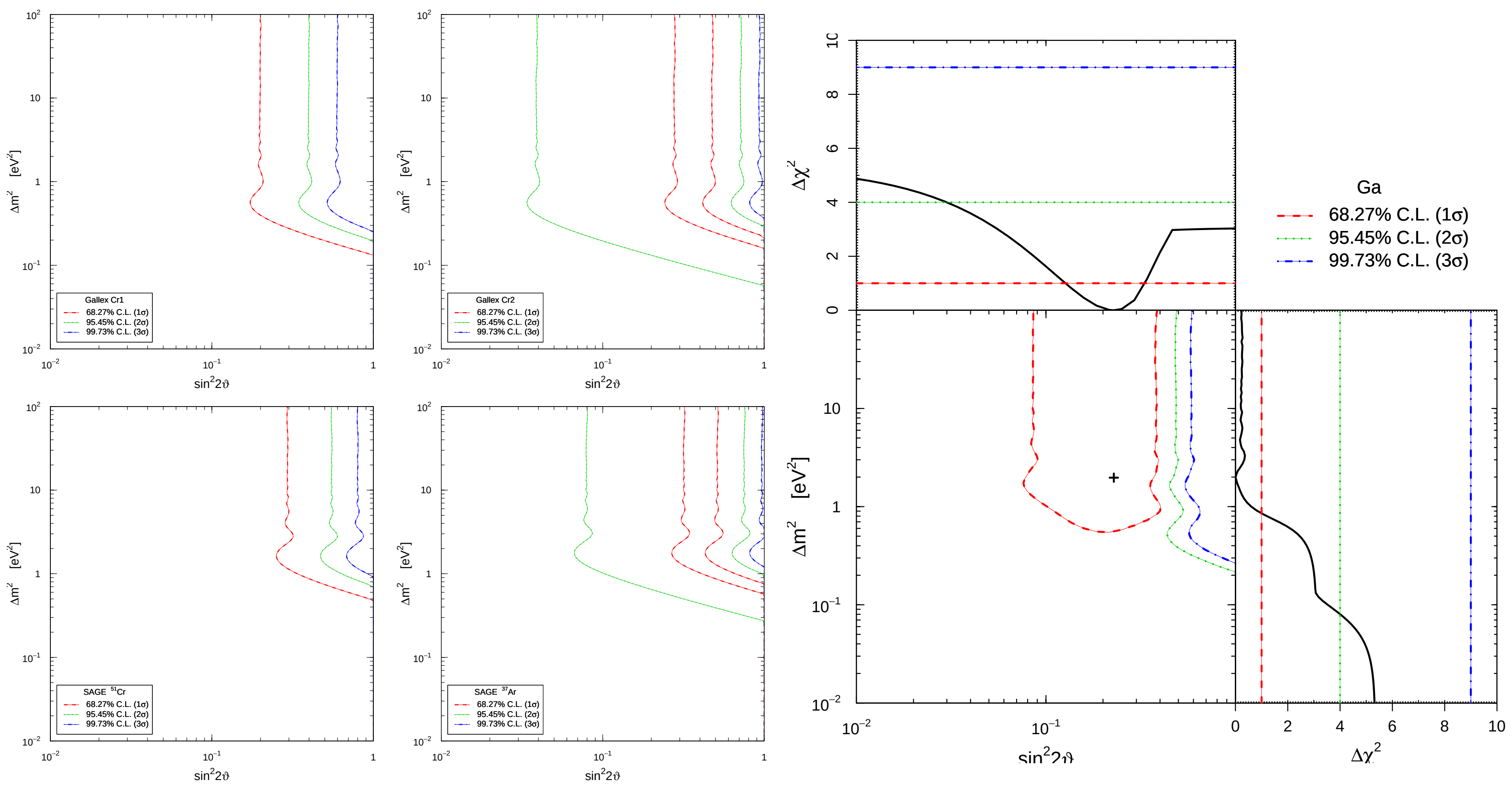

Figure 1. *(Left)* Allowed region in the oscillation parameter space for the individual Gallium radioactive source experiments. *(Right)* Allowed regions in the oscillation parameter space and marginal $\Delta\chi^2$'s for the combined fit of the results of the four radioactive source experiments.

	Ga	Bu	Ga+Bu	Bu+Ch	Ga+Ch	Ga+Bu+Ch
χ^2_{min}	2.69	46.55	52.59	47.12	6.57	53.40
NDF	2	53	57	54	3	58
GoF	0.26	0.72	0.64	0.73	0.087	0.65
$\sin^2 2\vartheta_{\text{bf}}$	0.23	0.043	0.057	0.036	0.079	0.05
Δm^2_{bf} [eV^2]	2.00	1.85	1.85	1.85	1.73	1.85

Table 1. Values of χ^2_{min}, number of degrees of freedom (NDF) and best-fit values of $\sin^2 2\vartheta$ and Δm^2 from the fit of different combinations of the results of the Gallium radioactive source experiments and the Bugey and Chooz reactor experiments.

Bugey and Chooz reactor experiments

Reactor neutrino experiments detect antineutrinos through the reaction $\bar{\nu}_{\mathbf{e}} + \mathbf{p} \to \mathbf{n} + \mathbf{e}^+$. In this process, the neutrino energy is related with the positron energy by $\mathbf{E}_\nu = \mathbf{E}_{\mathbf{e}^+} + \mathbf{1.8}$MeV. The Bugey experiment used three source-detector distances ($L_j = 15, 40, 95$ m for $j = 1, 2, 3$), while in Chooz, the distance was about 1 km.
For the Bugey experiment we use the ratio of observed and expected (in the case of no oscillation) positron spectra given in Fig. 17 of Ref. [7], in which there are $N_j = 25, 25, 10$ energy bins. We analyze the data with the following χ^2:

$$\chi^2 = \sum_{j=1}^{3} \left\{ \sum_{i=1}^{N_j} \frac{\left[\left(A a_j + b\left(E_{ji} - E_0\right)\right) R_{ji}^{\text{the}} - R_{ji}^{\text{exp}} \right]^2}{\sigma_{ji}^2} + \frac{\left(a_j - 1\right)^2}{\sigma_{a_j}^2} \right\} + \frac{(A-1)^2}{\sigma_A^2} + \frac{b^2}{\sigma_b^2} , \tag{3}$$

where E_{ji} is the central energy of the ith bin in the positron kinetic energy spectrum measured at the L_j source-detector distance; the coefficients $(A a_j + b(E_{ji} - E_0))$ are introduced to account the systematic uncertainty of the positron energy calibration [7]; R_{ji}^{exp} is the measures ratio and

$$R_{ji}^{\text{the}} = \frac{\int \mathrm{d}L\, L^{-2} \int_{E_{ji} - \Delta E_j/2}^{E_{ji} + \Delta E_j/2} \mathrm{d}E \int_{-\infty}^{+\infty} \mathrm{d}T_e\, F(E, T_e)\, P_{\bar{\nu}_e \to \bar{\nu}_e}(L, E_\nu)}{\Delta E_j \int \mathrm{d}L\, L^{-2}} ; \tag{4}$$

here $F(E, T_e)$ is the energy resolution function of the detector.
The Chooz experiment gives constrains on $\sin^2 2\vartheta$ for $\Delta m^2 \gtrsim 10^{-3}\,\text{eV}^2$. Therefore, for our purpose, the Chooz experiment is only sensitive to the average survival probability $\langle P_{\overset{(-)}{\nu_e} \to \overset{(-)}{\nu_e}} \rangle = 1 - \frac{1}{2} \sin^2 2\vartheta$. The results of our fits are shown in Fig. (2).

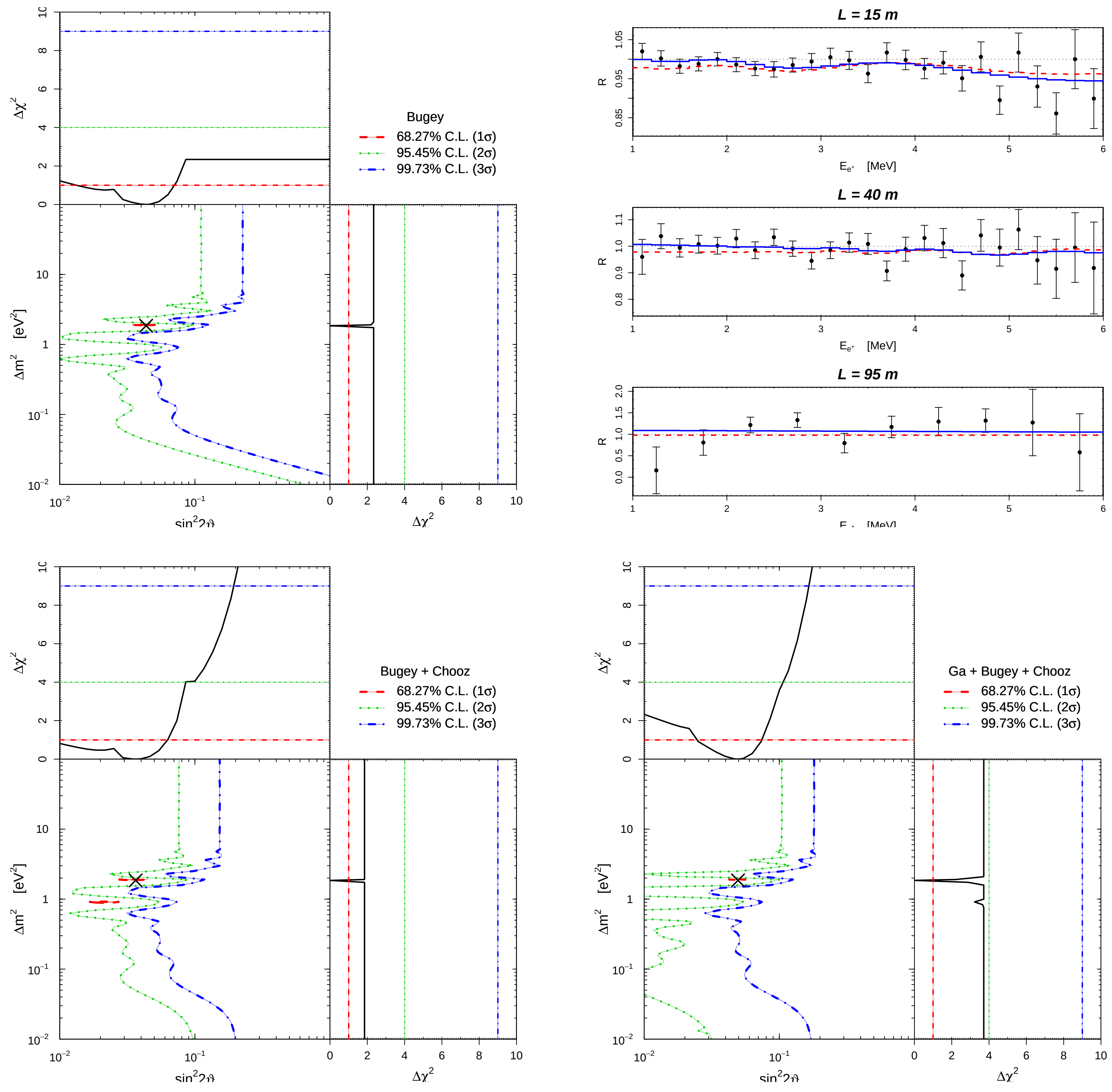

Figure 2. *(Up)* Allowed region in the oscillation parameter space and histograms with the Best Fit obtained from for the Bugey reactor experiment *(Up-Right)*. *(Down-Left)* Allowed regions in the oscillation parameter space for the combined fit of the Bugey and Chooz reactor experiments. *(Down-Right)* Allowed regions for the combined fit of the Gallium radioactive source experiments and the Bugey and Chooz reactor experiments.

Conclusions

In the framework of two-neutrino mixing, we found that, from the analysis of the Gallium radioactive source experiments, there is an indication of electron neutrino disappearance due to neutrino oscillations with $\sin^2 2\vartheta \gtrsim 0.03$ and $\Delta m^2 \gtrsim 0.1\,\text{eV}^2$. This result is compatible with the data form Bugey and Chooz reactor experiments. Besides, the Bugey data present an indication in favor of neutrino oscillations with $0.01 \lesssim \sin^2 2\vartheta \lesssim 0.07$ and $1.8\,\text{eV}^2 \Delta m^2 \simeq 1.9\,\text{eV}^2$. Such a disappearance of electron neutrinos due to $\Delta m^2 \gtrsim 0.1\,\text{eV}^2$ is an indication of the possible existence of at least one light sterile neutrino with a mass of the order about 1 eV.

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