Limits on Electron-Neutrino Oscillations from the GALLEX $^{51}$Cr Source Experiment

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Abstract

The recent result from the chromium source experiment carried out by the GALLEX collaboration implies interesting limits on the parameters $\Delta m^2$ and $\sin^2 2\theta$ describing neutrino oscillations. Values of $\Delta m^2 > 0.17$ eV$^2$ for maximal mixing and of $\sin^2 2\theta > 0.38$ for $\Delta m^2 > 1$ eV$^2$ are ruled out at 90% C.L. This result improves by more than an order of magnitude previous limits on $\Delta m^2$ derived from electron-neutrino oscillation experiments at accelerators.
The GALLEX collaboration has announced recently the first result of their experiment with an artificial neutrino source [1]. This is the first successful test of a solar neutrino experiment with an artificial radioactive source of electron neutrinos. In this note we use the fact that the $^{71}$Ge production rate reported by GALLEX is close to the expected rate to derive limits on the electron-neutrino oscillation parameters.

The GALLEX experiment is described in detail in [1,2]. The neutrinos emitted from the radioactive source, $^{51}$Cr, are monoenergetic with energies 0.746 (81%), 0.751 (9%), 0.426 (9%) and 0.431 (1%) MeV. The target solution, GaCl$_3$, fills a cylindrical container with radius 1.9 m to a height of 5 m. The source is located in a cavity, approximately 2.3 m below the surface of the GaCl$_3$.

The production rate, $Q_{Ge}$, of $^{71}$Ge atoms in the absence of oscillations is given by the following integral over the volume, $V$, of the detector:

$$Q_{Ge} = \int_V \sum_{i=1,4} \frac{\Phi_i(E_{\nu_i})}{4\pi r^2} N_{Ga} \sigma(E_{\nu_i}) dV,$$

where $\Phi_i$ is the rate of neutrino emission in each $^{51}$Cr decay mode, $r$ is the distance the neutrinos travel between production and capture, $N_{Ga}$ is the number density of $^{71}$Ga atoms, $\sigma$ is the neutrino capture cross-section, and $E_{\nu_i}$ is the neutrino energy. We have computed $Q_{Ge}$ taking into account the detailed geometry of the detector. Our result agrees with the estimate given in [1] with an accuracy of better than 1%.

The GALLEX collaboration reports a result of $1.04 \pm 0.12$ for the ratio, $R^{exp} = \frac{Q_{Ge}^{exp}}{Q_{Ge}}$, of the measured production rate of $^{71}$Ge atoms to the rate predicted using the cross-section calculated in [3]. Including the estimated theoretical error [3] of $\pm 3\%$ gives a total error of $\pm 0.13$.

If the electron neutrino produced in a $^{51}$Cr decay oscillates [4] into another neutrino type, $\nu_\mu, \nu_\tau$ or a sterile neutrino, $\nu_s$, the $^{71}$Ge production rate, $Q_{Ge}^{osc}$, in the target solution will be reduced. To calculate $Q_{Ge}^{osc}$ one must convolve the integrand in Eq. (1) with the well known
neutrino survival probability in vacuum. The estimated ratio $R^{\text{osc}} = Q^{\text{osc}}_{\text{Ge}}/Q_{\text{Ge}}$ depends on the parameters $\Delta m^2$ and $\sin^2 2\theta$ which determine the neutrino survival probability. The requirement that $R^{\text{osc}}$ does not differ significantly from $R^{\text{exp}}$ constrains the allowed region for these parameters. Since $R^{\text{exp}}$ lies slightly above the physical region for $R^{\text{osc}} (0 \leq R^{\text{osc}} \leq 1)$, we renormalize the distribution of the total error using a Bayesian approach with a flat prior distribution, as described in \[5\].

The results of our analysis are shown in Fig. 1. Values above and to the right of the full curve are ruled out at 90% C.L. In particular, values of $\Delta m^2 > 0.17 \text{ eV}^2$ for $\sin^2 2\theta = 1$ and of $\sin^2 2\theta > 0.38$ for $\Delta m^2 > 1 \text{ eV}^2$ are excluded by this analysis. For a C.L. of 95% the unacceptable range is only slightly contracted to $\Delta m^2 > 0.19 \text{ eV}^2$ for $\sin^2 2\theta = 1$ and to $\sin^2 2\theta > 0.45$ for $\Delta m^2 > 1 \text{ eV}^2$.

Our result improves by more than an order of magnitude previous limits on the maximum $\Delta m^2$ allowed by accelerator experiments. The best upper limit from electron-neutrino disappearance experiments [6,7] is $\Delta m^2 < 2.3 \text{ eV}^2$ for $\sin^2 2\theta = 1$. In the $\nu_e \rightarrow \nu_\tau$ appearance experiment [8] a weaker limit, $\Delta m^2 < 9 \text{ eV}^2$, has been obtained. The reason the GALLEX experiment implies a better limit on $\Delta m^2$, despite the small distance between source and target, is that the energy of the neutrinos from $^{51}\text{Cr}$ decay ($< 1 \text{ MeV}$) is much lower than the typical neutrino energy ($\sim 30 \text{ MeV}$ to $\sim 50 \text{ GeV}$) in accelerator experiments.

Our upper limit on the mixing angle for large $\Delta m^2$ is better than was obtained in [3] but does not improve the best existing limits from Refs. [6,8]. The most stringent limit from accelerator neutrino experiments is $\sin^2 2\theta < 7 \times 10^{-2}$ [7], which however is reached only for values of $\Delta m^2 > 100 \text{ eV}^2$.

We note in passing that the gallium solar neutrino experiments also place a strong limit on possible electron charge non-conserving interactions. Since $^{71}\text{Ga}$ is heavier than $^{71}\text{Ge}$, the decay $^{71}\text{Ga} \rightarrow ^{71}\text{Ge}$ is only forbidden by charge conservation. From the observed rate in the gallium solar neutrino experiments [1], one can conclude that the ratio of charge non-
conserving coupling constant, $\epsilon G_F$, divided by the usual weak interaction coupling constant, $G_F$, is very small

$$\epsilon < 7 \times 10^{-14},$$

if the charge non-conserving interaction is also described by a four-fermion interaction (see the second of Refs. [3], p. 359).

In conclusion, the limits on neutrino oscillations implied by the recently announced GALLEX radioactive source experiment improve thirteen-year old limits obtained in electron-neutrino oscillation experiments at accelerators.

**Acknowledgments.** We are grateful to the GALLEX collaboration for sending us a preprint of their important paper, and especially to K. Rowley for a precise sketch of the experimental geometry. J.N.B. acknowledges support from NSF grant #PHY 92-45317. The work of P.I.K. was partially supported by Dyson Visiting Professor Funds from the Institute for Advanced Study and the work of E.L. was supported by a post-doctoral INFN fellowship.
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Figure Captions

Fig. 1. Region of electron neutrino oscillation parameters ruled out at 90\% C.L. by the GALLEX $^{51}$Cr source experiment.
Fig. 1