Gallium experiments with artificial neutrino sources as a tool for investigation of transition to sterile states

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20 July 2010

We propose to place a very intense source of $^{51}$Cr at the center of a 50-tonne target of gallium metal that is divided into two concentric spherical zones and to measure the neutrino capture rate in each zone. This experiment can set limits on transitions from active to sterile neutrinos with $\Delta m^2 \approx 1 \text{ eV}^2$ with a sensitivity to disappearance of electron neutrinos of a few percent.

Analysis of neutrino experiments has given convincing evidence of transitions between flavors, i.e., neutrino oscillations. These neutrino transitions are well described in the framework of three neutrino generations with masses $m_1, m_2,$ and $m_3$ whose mass-squared differences are $\Delta m^2_{12} \approx 8 \times 10^{-5} \text{ eV}^2$ ("solar") and $\Delta m^2_{23} \approx 2 \times 10^{-3} \text{ eV}^2$ ("atmospheric"). Almost all neutrino experiments can be explained by assuming that there are only these three neutrino generations.

The existence of three dominant neutrino generations has been further proven by experiments at LEP on the decay of the $Z^0$ boson. The LEP experiment, however, does not rule out the possibility that there may be additional sub-dominant neutrino species and there are some indications that the number of neutrino generations may be more than three. First and foremost is the accelerator experiment LSND whose results can be explained if there are neutrino transitions as then the maximal value is $\Delta m^2 \approx \Delta m^2_{23} \approx 2 \times 10^{-3} \text{ eV}^2$. To comply with the results of LEP experiments one must assume that the hypothesized fourth state of neutrino flavor has an interaction cross section with matter that is much less than the other three neutrino species, i.e., it must be “sterile”.

The idea of the sterile neutrino was first proposed by B. Pontecorvo [1] and has been used repeatedly to explain a variety of different neutrino observations [2]. For example, to explain the slowly-rising spectra of recoil electrons from $^8$B solar neutrinos in the region below 6–8 MeV in the experiments SuperK and SNO, Smirnov and Holanda [3] considered transitions to sterile states with $\Delta m^2 \approx 10^{-5} \text{ eV}^2$. Proposals for several new experiments to search for sterile neutrinos are in Ref. [4].

Another set of experiments that can be interpreted in terms of neutrino oscillations is the capture rate measurements in the Ga detectors SAGE [5, 6] and GALLEX [7]. These four experiments used very-intense reactor-produced $^{51}$Cr or $^{37}$Ar neutrino sources and their weighted-average value, expressed as the ratio $R$ of the measured production rate to the expected production rate based on the measured source strength, is $0.87 \pm 0.05$, considerably less than the expected value of unity. All possible explanations for this unexpectedly low result are discussed in detail in Ref. [8]. Foremost among these is overestimation of the cross section for neutrino capture to the lowest two excited states in $^{71}$Ge, which could yield a value of $R$ as small as 0.95. Other explanations might be a statistical fluctuation or a real physical effect of unknown origin, such as a transition to sterile neutrinos or quantum decoherence in neutrino oscillations [9].

The interpretation of the Ga source experiments in terms of oscillations to a sterile neutrino with $\Delta m^2 \approx 1 \text{ eV}^2$, as well as the agreement of these results with the reactor experiments Bugey, Chooz, and Gösgen and the accelerator experiments LSND and MiniBooNE is considered in detail in Ref. [10]. If transitions to a sterile neutrino are occurring, the region of allowed oscillation parameters inferred from the four Ga source experiments is shown in Fig. 1.

We believe that new experiments are necessary to understand the low result of the Ga source measurements. One such experiment is now in progress at the RCNP cyclotron that should provide information to better determine the cross section for neutrino capture at low energy [11]. Another experiment, which we intend to pursue, is an improved version of the Ga source measurements. Our plan, as schematically pictured in Fig. 2, is to place a source of $^{51}$Cr with initial activity of 2 MCi at the center of a 50-tonne target of liquid Ga metal that is divided into two concentric spherical zones, an inner 8-tonne zone and an outer 42-tonne zone. If the neutrino capture cross section is that calculated by Bahcall [12] and oscillations to sterile neutrinos do not occur, then at the

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At the beginning of irradiation there is a mean of 43 atoms of $^{71}$Ge produced by the source per day in each zone. After an exposure period of a few days, the Ga in each zone is transferred to reaction vessels and the $^{71}$Ge atoms produced by neutrino capture are extracted. These atoms are placed in proportional counters and their number determined by counting the Auger capture are extracted. These atoms are placed in proportional counters and their number determined by counting the Auger electrons released in the transition back to $^{71}$Ga, which occurs with a half life of 11.4 days. A series of exposures is made, each of a few days duration, with the $^{71}$Ge atoms from each zone measured in individual counters. These procedures are all well understood and were used in the prior source experiments [5, 6]. A Monte Carlo simulation based on a reasonable time sequence of extractions and using typical values of extraction efficiency, counter efficiency, and background rates indicates that the rate in each zone can be measured with a total uncertainty, statistical plus systematic, of ~5%.

If oscillations to a sterile neutrino are occurring with mass-squared difference of $\Delta m^2$ and mixing parameter $\sin^2 2\theta$ then the rates in the outer and inner zones of gallium will be different and their ratio, for the specific case of $\sin^2 2\theta = 0.3$, will be as shown in Fig. 3. To see how this new 2-zone experiment will aid in the interpretation of the Ga source measurements and may shed light on transitions to sterile neutrinos, let us consider several possible outcomes and the inferences therefrom:

- If the ratio of rates $R$ in the two zones are statistically incompatible, such as $R_1 = 1.00 \pm 0.05$ in the inner zone and $R_2 = 0.80 \pm 0.04$ in the outer zone, or vice versa, then it is likely that transitions to sterile neutrinos are occurring. We show in the upper panels of Fig. 4 the inferences that can be drawn regarding the neutrino mixing parameters for these two possible outcomes of the experiment.
- If the ratio of rates $R$ in both zones are statistically compatible, then the inferences will depend on what the average value may be. For example, if the average value is $0.95 \pm 0.034$ then it is most likely that there is an error in the neutrino capture cross section to low-energy states. This inference is not clear-cut, however, as average results in this range can also occur due to transitions to sterile neutrinos. In contrast, average values of $R$ much below 0.92 can only be due to transitions to sterile neutrinos. As an example, the bottom right panel of Fig. 4 illustrates what can be learned regarding neutrino oscillation parameters if the experimental result is $(R_1, R_2) = (0.90, 0.90)$.

As is evident, it is only with certain specific outcomes that a two-zone Ga experiment will unambiguously differentiate between an oscillation interpretation or other possible interpretations of the Ga source anomaly.

Nonetheless, our proposed Ga experiment has several significant advantages over other methods of investigation of oscillations with parameters $\Delta m^2 \approx 1 \text{eV}^2$:

- 90% of the decays of the $^{51}$Cr source give a neutrino with energy 750 keV and 10% an energy of 430 keV. This nearly-monochromatic energy is important for oscillation experiments because the energy occurs in the denominator of the transition probability $P$ in the form

$$P(\nu_e \rightarrow \nu_x) = 1 - \sin^2(2\theta) \sin^2[(1.27 \Delta m^2 \text{eV}^2) \frac{L}{E_x}]$$

where $\theta$ is the mixing angle, $L$ is the distance in m from the point in the source where neutrino emission occurs to the point in the target where this neutrino is captured, and $E_x$ is the neutrino energy in MeV. In the two-zone experiment the source is very compact, with typical linear dimension of 10–15 cm, and $L$ is only about 1 m. As a result the ripples of oscillation are strongly manifested and are not averaged out when $\Delta m^2 \approx 1 \text{eV}^2$.

- The density of gallium at its melting temperature of 29.8°C is 6.095 g/cm³ and the cross section for neutrino capture on $^{71}$Ga is $5.5 \times 10^{-45}$ cm². These factors ensure that the neutrino capture rate will be very high and can be measured with good statistical accuracy.
The activity of the neutrino source can be measured in several ways leading to a total uncertainty on the source emission rate as low as 0.5% (see, e.g., Ref. [6]).

In contrast, experiments with reactor and accelerator neutrinos suffer from several disadvantages. The neutrino energy $E_{\nu}$ is distributed over a wide spectrum and the dimensions $L$ of the sources and detectors are on the scale of several meters. Other disadvantages of a reactor or accelerator experiment are that the knowledge of the neutrino flux incident on the target is usually significantly worse than with a neutrino source and that, with some targets, there are appreciable uncertainties in the cross section for neutrino interaction.

To summarize, we propose a new experiment in which a very-intense $^{51}$Cr source irradiates a target of Ga metal that is divided into two zones and the neutrino capture rate in each zone is independently measured. If there is either a significant difference between the capture rates in the two zones, or the average rate in both zones is considerably below the expected rate, then there is evidence of nonstandard neutrino properties. In the former case this inference is independent of the nuclear physics uncertainty in the detection cross section, but in the latter case it is important that the cross section be known to within 5%.

The proposed experiment has the potential to test neutrino oscillation transitions with mass-squared difference $\Delta m^2 > 0.5$ eV$^2$. This capability exists because the experiment uses a compact nearly-monochromatic neutrino source with well-known activity, the dense target of Ga metal provides a high interaction rate, and the special target geometry makes it possible to study the dependence of the rate on the distance to the source.

Finally, we should point out that there are cosmological arguments that preclude the existence of transitions to a sterile neutrino in the mass-mixing angle region to which our experiment is sensitive [13] [2]. These arguments are, however, not model independent and, in common with many others [4], we believe that direct measurements that fully cover this region of parameter space are essential.

ACKNOWLEDGMENTS

We are grateful to W. Haxton, H. Ejiri, M. Libanov, V. Matveev, V. Rubakov, and A. Smirnov for fruitful discussions.
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