An alternative explanation of the Gallium anomaly

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We analyze the data of the Gallium experiments in terms of charged current non-standard neutrino interactions. We show that these interactions provide an alternative explanation to the Gallium anomaly. Unlike in the case of light sterile neutrinos the solution is not in tension with the measurements of other experiments.

The GALLEX \textsuperscript{13} and SAGE \textsuperscript{4,7} experiments observed solar neutrinos and measured the solar neutrino oscillation parameters. In their testing phase, intense artificial \(^{51}\text{Cr}\) and \(^{37}\text{Ar}\) radioactive sources have been placed inside of the detectors. The sources emit neutrinos through the capture of electrons, \(e^- + ^{51}\text{Cr} \rightarrow \nu_e + ^{51}\text{V}\) and \(e^- + ^{37}\text{Ar} \rightarrow \nu_e + ^{37}\text{Cl}\). The neutrinos are emitted with the energies and branching ratios summarized in Tab. I and are subsequently detected through their interactions with the Gallium nuclei in the detector, \(\nu_e + ^{71}\text{Ga} \rightarrow e^- + ^{71}\text{Ge}\).

It has been observed that the ratio of observed to expected event rates is smaller than unity. In particular, the obtained ratios are

\[ R^{G1} = 0.95 \pm 0.11, \]  
\[ R^{G2} = 0.81 \pm 0.11, \]  
\[ R^{S1} = 0.95 \pm 0.12, \]  
\[ R^{S2} = 0.790 \pm 0.095, \]

where \(G_1\) and \(G_2\) refer to the two GALLEX measurements with a Chromium source, while \(S_1\) and \(S_2\) are the SAGE measurements obtained with a Chromium and an Argon source, respectively. This deficit became known as the Gallium anomaly (see the recent reviews in Refs. \textsuperscript{8,9}). Depending on the cross section model \textsuperscript{10,11}, the statistical significance of the Gallium anomaly was between 1.9\(\sigma\) and 2.7\(\sigma\).

The results from the GALLEX and SAGE experiments have been recently confirmed by the BEST collaboration \textsuperscript{12,13}, which performed two measurements using two detector volumes. The whole detector is cylindrical, with a smaller inner spherical part surrounding the source and a larger outer part. The two measurements of the ratio of observed to expected events in the inner and outer volumes yielded

\[ R^{B1} = 0.791 \pm 0.050, \]  
\[ R^{B2} = 0.766 \pm 0.050. \]

As can be seen, the BEST results are statistically much stronger than those of GALLEX and SAGE, pushing the combined significance of the Gallium anomaly to the 5–6\(\sigma\) level, depending on the cross section model \textsuperscript{14}. The different measurements are depicted in Fig. 1. As can be seen, the average of the measurements, \(\overline{R} = 0.80 \pm 0.047\) \textsuperscript{13}, depicted by the grey band, is mostly due to the measurement of the BEST experiment.

The Gallium anomaly can be explained by short baseline neutrino oscillations induced by light sterile neutrinos. The expected ratios can be calculated via

\[ R = \frac{\int_V L^{-2} \sum_i P_{ee}(E_i, L; \vec{p}) B_i \sigma_i}{\int_V L^{-2} \sum_i B_i \sigma_i}. \]

The integral has to be performed over the detector volume. In this equation, \(L\) is the distance from the source to a point in the detector, and \(P_{ee}(E, L; \vec{p})\) is the \(\nu_e\) survival probability, which also depends on the neutrino oscillation parameters \(\vec{p}\). The sum is taken over the four (two) neutrino emission lines with energies \(E_i\) and cor-

\begin{table}[h]
\centering
\begin{tabular}{|c|c|c|c|c|}
\hline
\textbf{\(^{34}\text{Cr}\)} & \textbf{\(^{34}\text{Ar}\)}
\hline
\textbf{E [keV]} & 747 & 752 & 427 & 432 & 811 & 813
\hline
\textbf{B} & 0.8163 & 0.0849 & 0.0895 & 0.0093 & 0.902 & 0.098
\hline
\textbf{\(\sigma\) [10^{-46} cm\(^2\)]} & 60.8 & 61.5 & 26.7 & 27.1 & 70.1 & 70.3
\hline
\end{tabular}
\caption{Energies (\(E\)), branching ratios (\(B\)) and Gallium cross sections (\(\sigma\)) of the \(\nu_e\) lines emitted in \(^{51}\text{Cr}\) and \(^{37}\text{Ar}\) decays through electron capture. The cross sections are interpolated from Tab. II of Ref. \textsuperscript{15}.}
\end{table}
In a similar way, the neutrinos which are detected in the process, but instead of being pure electron neutrino states by the electron capture, are complex and modified by the non-standard interactions (NSI). These NSI can arise in many models of neutrino mass spectra \[21–23\]. They appear in form of charged current (CC-NSI) and neutral current (NC-NSI) non-standard interactions. In this work, we focus only on CC-NSI, which can have an effect in the Gallium experiments. CC-NSI modify the creation-process of neutrinos at the source and the detection-process at the detector.

In the Gallium experiments the neutrino production occurs through nuclear electron capture involving a \(u \rightarrow d\) quark transition, and the neutrino detection is done with the \(\nu + ^{71}\text{Ga} \rightarrow e^- + ^{71}\text{Ge}\) process which entails a \(d \rightarrow u\) quark transition. Hence the part of the CC-NSI Lagrangian that is relevant for the Gallium experiments can be written as

\[
\mathcal{L}_{\text{NSI}} = \frac{G_F}{\sqrt{2}} \sum_{\beta} \epsilon_\beta \left[ \bar{\nu}_\beta \gamma^\mu (1 - \gamma^5) e^- \right] \left[ \bar{e} \gamma^\mu (1 + \gamma^5) u^i \right] + \text{h.c.}, \tag{8}
\]

where \(G_F\) is the Fermi constant, \(\beta = e, \mu, \tau\), and the complex \(\epsilon_\beta\) parameters characterize the strength of the CC-NSI with respect to the Standard Model CC weak interactions. We consider for simplicity only a \(V - A\) or \(V + A\) non-standard interaction of quarks that is represented by the \(1 \pm \gamma^5\) in Eq. (8). In both cases the interaction strength is that of the Standard Model CC weak interaction suppressed by \(\epsilon_\beta\) (if \(|\epsilon_\beta| < 1\)).

In the presence of CC-NSI neutrinos are not produced as pure electron neutrino states by the electron capture process, but instead as \[24, 25\]

\[
|\nu_e \rangle = |\nu_e \rangle + \sum_{\beta = e, \mu, \tau} \epsilon_\beta |\nu_\beta \rangle. \tag{9}
\]

In a similar way, the neutrinos which are detected in the \(\nu + ^{71}\text{Ga} \rightarrow e^- + ^{71}\text{Ge}\) process are described by

\[
|\nu_d \rangle = |\nu_e \rangle + \sum_{\beta = e, \mu, \tau} \epsilon_\beta^* |\nu_\beta \rangle. \tag{10}
\]

Note that these production and detection neutrino states are not normalized, in order to describe the enhancement of neutrino production and detection in the presence of CC-NSI. For the short baselines of the Gallium experiments there are no oscillations due to the standard solar and atmospheric squared-mass differences. Therefore, the ratio of the detection rate in presence of CC-NSI and that predicted by the Standard Model is given by the zero-distance survival probability

\[
P_{ee}^\text{SBL} = \langle |\nu_d | |\nu_e \rangle \rangle^2. \tag{11}
\]

We call this quantity “survival probability” following the usual terminology, but \(P_{ee}^\text{SBL}\) is not a probability and can be larger than one. Defining \(\epsilon_\beta = |\epsilon_\beta| e^{i\phi_\beta}\), from Eqs. (9)–(11) we obtain

\[
P_{ee}^\text{SBL} = 1 + 4|\epsilon_e|^2 \cos \phi_e + 2|\epsilon_e|^2 \cos 2\phi_e + 2|\epsilon_\mu|^2 + 2|\epsilon_\tau|^2. \tag{12}
\]

We perform the analysis of the Gallium anomaly using the neutrino oscillation probability (12) and, for simplicity, we consider \(|\epsilon_\mu| = |\epsilon_\tau| = 0\). The statistical analysis is performed by calculating

\[
\chi^2 = \min_\alpha \left\{ \sum_i \left( \frac{R^i_O - (1 + \alpha) R^i_E}{\sigma^i_R} \right)^2 + \frac{\alpha^2}{\sigma^2_\alpha} \right\}, \tag{13}
\]

where \(R^i_E\) are the expected ratios obtained using Eq. (7) and Eq. (12), while \(R^i_O\) and \(\sigma^i_R\) are the observed ratios and their corresponding uncertainties, respectively. Here, \(\alpha\) is the nuisance parameter for the uncertainty in the Bahcall cross section, which we used in our analysis. For the uncertainty we have fixed \(\sigma_\alpha = 3\%\). It has been shown that using different cross section models does not significantly effect the significance of the Gallium anomaly \[14\]. We therefore consider only the Bahcall cross section in this paper. The sum is performed over the different measurements, which in our case will be the best alone, GALLEX+SAGE, and the combination of all Gallium data.

The results of our calculations are shown in Fig. 2, where we show the 90% and 99% confidence level (C.L.) contours for two degrees of freedom obtained using GALLEX+SAGE data (green lines), BEST data (black lines) and the combination of all data (grey and magenta regions). One sees that the analysis is clearly dominated by the BEST analysis, and the addition of the GALLEX and SAGE data extends the region slightly towards smaller values of \(|\epsilon_e|\). Also shown is the current 90% bound \[26\] on \(|\epsilon_e|\) obtained from CKM measurements. Note that the stronger bound obtained in Ref. \[25\] applies only if \(\phi_e = 0\). As can be seen from

\footnote{Weaker bounds have been obtained in Refs. \[27, 28\].}
Fig. 5 of this reference, the bound becomes very weak once the phase $\phi_e$ is left free in our fit.

The structure of the allowed region in Fig. 2 can be understood by considering $\phi_e = \pi$, for which $P_{ee} = 1 - 4|\epsilon_e| + 6|\epsilon_e|^2$. Then, one obtains a value of $P_{ee} \simeq 0.8$ corresponding to the gallium average ratio for $|\epsilon_e| \simeq (1 \pm \sqrt{0.7})/3 \simeq 0.054, 0.61$. One can see that these values of $|\epsilon_e|$ are allowed in Fig. 2 for $\phi_e = \pi$, with a forbidden interval in the middle, where $P_{ee} \lesssim 0.8$. Moreover, for a given value of $P_{ee} < 1$, Eq. (12) with $|\epsilon_{\mu}| = |\epsilon_{\tau}| = 0$ has a solution for $\cos \phi_e = -\sqrt{(1-P_{ee})/2P_{ee}}$. Considering $P_{ee} \simeq 0.8$, we obtain $\cos \phi_e \lesssim -\sqrt{2/16} \simeq -0.35$, which gives $0.6 \lesssim \phi_e/\pi \lesssim 1.4$. One can see that the allowed region in Fig. 2 lies in this interval.

We can perform another analysis combining the result of our calculation with the bound represented by the blue line in Fig. 3 by adding it as a prior to our analysis. The result is shown in Fig. 3 where we considered only the combined analysis of all Gallium data. In the upper panel we show the 90 and 99% C.L. contours in the $|\epsilon_e| - \phi_e$ plane before applying the prior (filled regions, these are the same as in Fig. 2) and after combining with the prior (blue lines). In the lower panel we show the marginalized $\chi^2$-profile for $|\epsilon_e|$, including (blue) and not including (red) the prior on $|\epsilon_e|$ from Ref. [26]. Our best fit point with the prior is found at $|\epsilon_e| = 0.044 \pm 0.011$, and for values of the CP phase close to $\pi$.

It should be noted that the bounds on the NSI parameters might be even overestimated, since they are usually obtained considering only one non-zero $\epsilon_{\beta}$. Allowing also for $|\epsilon_{\mu}|$ and $|\epsilon_{\tau}|$ to vary might loosen the bounds on $|\epsilon_e|$. At the same time, the effect of these parameters on the survival probability in Eq. (12) is very small and would not strongly affect our result.

In conclusion, we have shown that using CC-NSI one can fit the data of the Gallium experiments without being in strong tension with other measurements as is the case in the 3+1 analysis. This is an exciting hint in favor of the existence of neutrino CC-NSI.

This work was supported by the research grant "The Dark Universe: A Synergic Multimessenger Approach" number 2017X7X85K under the program PRIN 2017 funded by the Ministero dell’Istruzione, Università e della Ricerca (MIUR).
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