COHERENT constraints on nonstandard neutrino interactions

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ABSTRACT

Coherent elastic neutrino–nucleus scattering consistent with the standard model has been observed by the COHERENT experiment. We study nonstandard neutrino interactions using the detected spectrum. For the case in which the nonstandard interactions (NSI) are induced by a vector mediator lighter than 50 MeV, we obtain constraints on the coupling of the mediator. For a heavier mediator, we find that degeneracies between the NSI parameters severely weaken the constraints. However, these degeneracies do not affect COHERENT constraints on the effective NSI parameters for matter propagation in the Earth.

1. Introduction

The COHERENT experiment has observed coherent elastic neutrino–nucleus scattering (CEνNS) [1] 43 years after its theoretical prediction in the standard model (SM) [2]. For neutrino energies below a few tens of MeV, CEνNS occurs when the momentum transfer Q is comparable to the inverse of the nuclear radius R, i.e., $QR \lesssim 1$. Compared to scattering of isolated nucleons, the cross section for coherent scattering off a nucleus is enhanced by the square of the number of neutrons in the nucleus. However, in spite of its large cross section, it is difficult to observe CEνNS because of the small momentum transfer involved.

The COHERENT experiment measures neutrinos from the Spallation Neutron Source (SNS) at Oak Ridge National Laboratory, using a sodium doped CsI scintillator that can detect nuclear recoil energies down to a few keV. They find 6.7σ CL evidence for CEνNS in good agreement with SM predictions, after fifteen months of data accumulation. The measurement of CEνNS not only completes the SM picture of neutrino interactions, but also provides a tool to study new physics beyond the SM, e.g., nonstandard neutrino interactions (NSI) [3–5], sterile neutrinos [6], neutrino magnetic moment [7], and light dark matter [8].

The total number of events has been used in Refs. [1] and [9] to constrain NSI under the contact interaction approximation. If the momentum transfer of CEνNS is comparable to the mediator mass, the shape of the spectrum is also modified. Consequently, constraints obtained using the contact approximation do not ap-

ply to the light mediator case. In this Letter, we use the spectrum of the CEνNS signal to constrain NSI including mediator effects. In Section 2, we describe our simulation of the COHERENT spectrum. In Section 3, we discuss the sensitivities to the nonstandard parameters for both the light and heavy mediators. We summarize our results in Section 4.

2. COHERENT simulation

The expected number of events for neutrino flavor α of recoil energy E_r is

$$\frac{dN_\alpha}{dE_r} = n_N \int dE_\nu \phi_\alpha(E_\nu) \frac{d\sigma_\alpha}{dE_r}(E_\nu), \tag{1}$$

where the total number of nucleons in the detector is $n_N = \frac{2m_{det}}{M_{CsI}} N_A$, with $m_{det} = 14.6$ kg being the detector mass, M_{CsI} the molar mass of CsI, and N_A the Avogadro constant. Neutrinos at the SNS consist of a prompt component of monochromatic ν_μ from the stopped pion decays, $\pi^+ \to \mu^+ + \nu_\mu$, and two delayed components of $\bar{\nu}_\mu$ and ν_e from the subsequent muon decays, $\mu^+ \to e^+ + \bar{\nu}_\mu + \nu_e$. The distribution of the total flux for each neutrino flavor is well-known and given by [5]

$$\phi_{\nu_\mu}(E_\nu) = \mathcal{N}\delta\left(E_\nu - \frac{m_\pi^2 - m_\mu^2}{2m_\pi}\right),$$

$$\phi_{\bar{\nu}_\mu}(E_\nu) = \mathcal{N}\frac{64E_\nu^2}{m_\mu^3}\left(\frac{3}{4} - \frac{E_\nu}{m_\mu}\right),$$

$$\phi_{\nu_e}(E_\nu) = \mathcal{N}\frac{192E_\nu^2}{m_\mu^3}\left(\frac{1}{2} - \frac{E_\nu}{m_\mu}\right), \tag{2}$$

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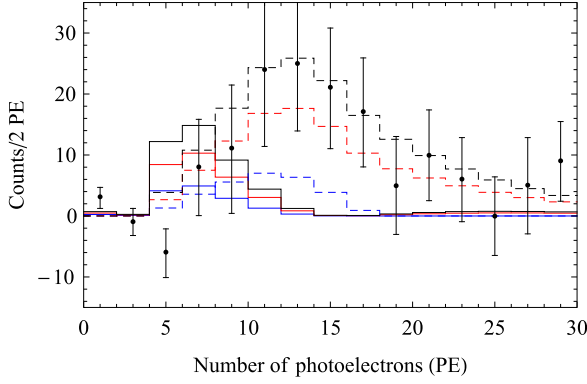
Fig. 1. The expected CEνNS events as a function of the number of photoelectrons. The dashed lines correspond to the SM, and the solid lines correspond to the NSI case with $M_{Z'} = 10$ MeV and $g = 10^{-4}$. The blue (red) [black] lines correspond to the ν_μ ($\nu_\mu + \bar{\nu}_\mu$) [$\nu_\mu + \bar{\nu}_\mu + \nu_e$] contributions. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

where the normalization factor is $\mathcal{N} = \frac{r N_{\mathrm{POT}}}{4\pi L^2}$. Here $r = 0.08$ is the number of neutrinos per flavor that are produced for each proton on target [1]. The total number of protons delivered to the mercury target is $N_{\mathrm{POT}} = 1.76 \times 10^{23}$ and the distance between the source and the CsI detector is $L = 19.3$ m [1].

The differential cross section for a given neutrino flavor ν_α in the SM is

$$\frac{d\sigma_\alpha}{dE_r} = \frac{G_F^2}{2\pi} Q_\alpha^2 F^2 (2ME_r) M \left(2 - \frac{ME_r}{E_\nu^2}\right), \qquad (3)$$

where M is the mass of the target nucleus, $F(Q^2)$ is the nuclear form factor, and the radiative corrections are neglected. We take the nuclear form factor from Ref. [10]. The effective charge in the SM is

$$Q_{\alpha,\mathrm{SM}}^2 = \left(Z g_p^V + N g_n^V\right)^2, \qquad (4)$$

where Z and N are the number of protons and neutrons in the nucleus, and $g_p^V = \frac{1}{2} - 2\sin^2\theta_W$ and $g_n^V = -\frac{1}{2}$ are the SM couplings of the Z^0 boson to the proton and neutron, with θ_W the weak mixing angle.

We ignore the contribution to the cross section from the sodium dopant because of its extremely small fractional mass (10^{-4}–10^{-5}) in the CsI detector [11]. Also, since the responses of Cs and I to a given neutrino flavor are almost identical due to very similar nuclear masses [11], we do not distinguish between Cs and I in our analysis. We adopt a simple relation between the observed number of photoelectrons (PE) and the nuclear recoil energy [1]:

$$n_{\mathrm{PE}} = 1.17 \left(\frac{E_r}{\mathrm{keV}}\right). \qquad (5)$$

After taking into account the surviving fraction of the CEνNS signals as a function of the number of photoelectrons given in Fig. S9 in Ref. [1], we show the expected CEνNS events as a function of the number of photoelectrons for the SM in Fig. 1.

3. Constraints on nonstandard neutrino interactions

We now analyze the COHERENT spectrum to constrain vector NSI parameters that lead to an effective potential for neutrino propagation in matter. In principle, COHERENT data also constrain axial-vector NSI, but because large nuclei approximately conserve parity, the constraints are weak.
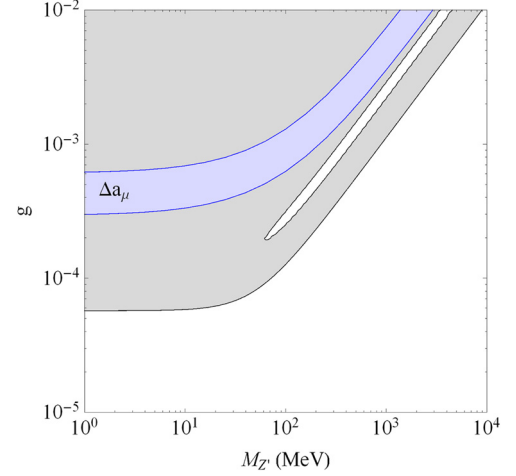
Fig. 2. The 2σ exclusion region in the ($M_{Z'}, g$) plane from the COHERENT data. The 2σ allowed region that explains the discrepancy in the anomalous magnetic moment of the muon ($\Delta a_\mu = (29 \pm 9) \times 10^{-10}$ [12]) is shown for comparison.

3.1. Light mediator

We first consider the case that NSI are induced by a light vector mediator Z' with mass $M_{Z'}$ that is comparable to the square root of the momentum transfer. For simplicity, we assume that the Z' has purely vector universal flavor-conserving couplings to neutrinos, first generation quarks and the muon. Then the effective charge in Eq. (3) can be written as

$$Q_{\alpha,\mathrm{NSI}}^2 = \left[Z \left(g_p^V + \frac{3g^2}{2\sqrt{2}G_F(Q^2 + M_{Z'}^2)}\right) \right. $$
$$\left. + N \left(g_n^V + \frac{3g^2}{2\sqrt{2}G_F(Q^2 + M_{Z'}^2)}\right) \right]^2, \qquad (6)$$

where $Q^2 = 2ME_r$ is the square of the momentum transfer.

To evaluate the statistical significance, we define

$$\chi^2 = \sum_i \left[\frac{N_{\mathrm{exp}}^i - N_{\mathrm{NSI}}^i(1+\alpha)}{\sigma_{\mathrm{stat}}^i}\right]^2 + \left(\frac{\alpha}{\sigma_\alpha}\right)^2, \qquad (7)$$

where N_{exp}^i (N_{NSI}^i) is the number of observed (predicted) events per bin, σ_{stat}^i is the statistical uncertainty, and the total normalization uncertainty is $\sigma_\alpha = 0.28$, which incorporates the neutrino flux, form factor, quenching factor and signal acceptance uncertainties [1]. We extract N_{exp}^i and σ_{stat}^i from the top right panel of Fig. 3 in Ref. [1], and consider 12 bins in the $6 \leq \mathrm{PE} < 30$ range, and ignore the small background from prompt neutrons.

We scan over possible values of the coupling g and the mediator mass $M_{Z'}$, and show the 2σ limits in the ($M_{Z'}, g$) plane in Fig. 2. The 2σ allowed region that explains the discrepancy in the anomalous magnetic moment of the muon [12] is also shown for comparison. We see that a light mediator that can explain the discrepancy in the anomalous magnetic moment of the muon is disfavored.

The shape of the limit curve in Fig. 2 can be understood from the propagator in Eq. (6), in which the NSI contribution is proportional to $\frac{g^2}{2ME_r + M_{Z'}^2}$. For a very light mediator, i.e., $M_{Z'} \ll \sqrt{2ME_r} \sim$ 50 MeV, the limit is only sensitive to the coupling g. Note that since the momentum transfer in coherent forward scattering is zero, the NSI matter effect for neutrino propagation is sensitive to $\frac{g^2}{M_{Z'}^2}$ [13], and the constraint does not apply to matter NSI induced