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Particle physics implications of coherent elastic neutrino-nucleus scattering

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Detection of coherent elastic neutrino nucleus-scattering (CEνNS) has been recently confirmed. The low-energy region of this process and its neutral current character, allows to explore beyond the Standard Model particle physics in complementary regions to other searches. I briefly review the current status and future perspectives of such constraints with a special focus on non-standard interactions.

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1. Introduction

Neutrino physics is entering the precision era. New experimental setups are contributing to a better knowledge of neutrino physics parameters. Among these new experiments, coherent-elastic neutrino-nucleus (CEvNS) based experiments are particularly interesting since they are based on a different interaction that was first measured four years ago [1]. Although proposed in the 1970s by Freedman [2], the CEvNS process was just detected recently by the COHERENT collaboration [1]. Other additional measurements, by the same collaboration, have confirmed the detection of this reaction [3, 4].

Currently, there are many experimental setups underway that plan to measure this interaction either at pion decay at rest neutrino (π-DAR) or reactor antineutrino sources (see Table I for an incomplete list). The current experimental results on CEνNS allow having measurements on the Standard Model (SM) parameters complementary to measurements in other energy regions. Therefore, the measurements through CEνNS are relevant to test the SM at energy windows that are unreachable with other types of experiments. Moreover, the CEνNS process also gives the chance to test for physics beyond the SM. Different models that explain the neutrino mass pattern predict deviations from the SM that can be tested at low energies. Being CEνNS experiments at very short baselines, they complement the restrictions obtained from long-baseline experiments.

Among the main advantages of the CEνNS process is that its cross-section increases as N^2, with N the number of neutrons,

$$\left(\frac{d\sigma}{dT}\right) \approx \frac{G_F^2 M}{4\pi}\left[1-\frac{MT}{2E_\nu^2}\right]\left[NF_N(q^2)+Z(1-4\sin^2\theta_W)F_Z(q^2)\right]^2.$$

Here, G_F is the Fermi constant, M is the mass of the nucleus, T is the nuclear recoil, and $F_N(q^2)$ and $F_Z(q^2)$ are the nuclear form factors. Despite the N^2 dependence, which makes the cross-section large, detecting this process represents an experimental challenge since the neutrino energy should be less than $\sqrt{MT/2}$, implying that the nuclear recoil will be very small, demanding a very low energy threshold for the detectors.

2. Standar Model tests

One of the most relevant parameters in the SM is the weak mixing angle. Its value has been measured with great precision at high energies. At low energies, the technical challenges make this measurement more complex. However, the SM predicts that the value for the wear mixing angle at low energies will be higher, making it important to have precise measurements that make possible

COHERENT	CCM	CONUS	CONNIE
LAR, Ge, NaI	LAr	HPGe	Si
[5]	[6]	[7]	[8]

Table 1: Some experimental proposals to measure CEνNS using a π-DAR or reactor neutrino source with different nuclei as a target.

an SM test at low energies. From the COHERENT liquid Argon first measurement, a value of the weak mixing angle can be extracted [9]

$$\sin^2\theta_W = 0.258^{+0.048}_{-0.050}, \tag{1}$$

while the first CsI COHERENT measurement implies

$$\sin^2\theta_W = 0.209^{+0.072}_{-0.069}. \tag{2}$$

Both measurements are in good agreement with the expected theoretical value. Future CEνNS measurements expect to have better sensitivity.

3. Beyond the Standard Model tests

Physics beyond the SM can be tested with CEνNS, with the advantage of having complementary information thanks to this low energy neutral current process. Different models that consider new physics predict deviation from the SM vector and axial couplings. These kinds of models can be parametrized by the so-called non-standard interactions (NSI) formalism. In this framework, the new interactions are parametrized $\varepsilon_{\alpha\beta}^{fP}$, where α and β refers to neutrino flavor; f to the charged fermion; and P stands for the left and right-handed couplings. The effective Lagrangian for NSI is given by

$$\mathcal{L}_{eff}^{NSI} = -\sum_{\alpha\beta f P} \varepsilon_{\alpha\beta}^{fP} 2\sqrt{2} G_F (\bar{\nu}_\alpha \gamma_\rho L \nu_\beta)(\bar{f} \gamma^\rho P f)$$

The effective parameters have been constrained using different experiments [10–12]. Although strong constraints exist on most of these parameters, there are also ambiguities on their restrictions. One of the best-known cases is the LMA-Dark solution [13] to the solar neutrino data. In the case of solar neutrino data, there is a region in the NSI parameter space where their values can be big. Moreover, in this case, there is no robustness of the LMA solution, and the standard oscillation values can be shifted to values of $\sin^2\theta_{12}$ bigger that 0.5.

Therefore, non-oscillatory experiments give unique information to constrain NSI parameters in regions that are unreachable by long-baseline experiments. In the case of CEνNS, the cross-section is modified to be [14]

$$\begin{aligned}
\frac{d\sigma}{dT}(E_\nu, T) &= \frac{G_F^2 M}{\pi}\left(1 - \frac{MT}{2E_\nu^2}\right) \times \\
&\times \left\{ \left[Z(g_V^p + 2\varepsilon_{ee}^{uV} + \varepsilon_{ee}^{dV}) + N(g_V^n + \varepsilon_{ee}^{uV} + 2\varepsilon_{ee}^{dV}) \right]^2 + \right. \\
&+ \left. \sum_{\alpha=\mu,\tau} \left[Z(2\varepsilon_{\alpha e}^{uV} + \varepsilon_{\alpha e}^{dV}) + N(\varepsilon_{\alpha e}^{uV} + 2\varepsilon_{\alpha e}^{dV}) \right]^2 \right\}.
\end{aligned} \tag{3}$$

At present, CEνNS experiments have disfavored the LMA-D solution [15], and future experiments will improve the NSI constraints beyond current knowledge. As an example, the expected sensitivity to the NSI parameter $\varepsilon_{\tau e}^{uV}$ for the future COHERENT proposals using germanium, argon, or NaI would be 0.142, 0.100, and 0.093, respectively, for a given configuration of systematic errors and efficiencies [16].

We can notice from the above formula that, despite breaking the LMA-D ambiguity, there will also be a parameter ambiguity for NSI parameters in CEνNS. However, the dependence is different from the oscillatory experiments. Besides, this degeneracy can be broken when considering CEνNS experiments with different targets, particularly targets with a different proportion of neutrons to protons [14]. The use of different nuclei in CEνNS experiments will be of great importance for precision physics. It will be possible to disentangle restrictions for nuclear physics and for physics beyond the SM. A particular interesting experimental setup could be the use of a simultaneous measure of CEνNS using different isotopes of the same nucleus, allowing to measure cross-sections with different proportions of neutrons to protons using the same neutrino beam [17]. Another possibility is the use of different neutrino sources, as discussed in Ref. [18].

Another interesting signal of physics beyond the SM would be the non-unitarity of the leptonic mixing matrix. If heavy neutral leptons exist, they could explain the origin of the neutrino mass pattern. The extra heavy states will imply that the usual 3×3 leptonic mixing matrix will not be unitary. Instead, the new 3×3 matrix be given by [19]

$$N = N^{NP}\, U^{3\times3} = \begin{pmatrix} \alpha_{11} & 0 & 0 \\ \alpha_{21} & \alpha_{22} & 0 \\ \alpha_{31} & \alpha_{32} & \alpha_{33} \end{pmatrix} U^{3\times3}, \tag{4}$$

where $U^{3\times3}$ is the standard leptonic mixing matrix. The diagonal parameters α_{ii} are real and close to one, while the off-diagonal are complex, and their magnitude is expected to be small. Future CEνNS experiments may reach a sensitivity to $|\alpha_{21}|$ that could be competitive with current constraints from short distance neutrino experiments such as NOMAD [20].

4. Perspectives and conclusions

CEνNS process has been detected and confirmed. Its measurement allows new restrictions on physics beyond the SM. In the future, it will restrict a region of parameters currently allowed by oscillaton experiments. It will also give new independent measurements on SM parameters in the low energy region, giving complementary tests to the robustness of the SM.

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