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Constraints on nonstandard interactions and the neutron radius from coherent elastic neutrino-nucleus scattering experiments

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Precise measurements of the coherent elastic neutrino-nucleus scattering may allow to test for physics beyond the Standard Model in the near future. Several new experimental setups are expected to report new and precise measurements on this process in the forthcoming years. To have robust constraints on new physics, a good knowledge of the standard physics involved in this scattering is needed. We study how different experiments can give complementary information that can be combined to have such robust constraints. We illustrate this interplay by focusing in the non-standard interactions picture in combination with a measurement of the neutron mean radius.

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After being proposed as a neutral current reaction to test the Standard Model [1], the observation of coherent elastic neutrino-nucleus scattering (CEvNS) [2] has opened the possibility to perform precision measurements in the low energy regime to test for new physics scenarios [3–7]. However, the CEvNS dependence on nuclear form factors, for neutrinos coming from a Spallation Neutron Source (SNS), introduces a source of systematic errors [8, 9] that must be under control. The situation is different for reactor neutrinos, where future CEvNS measurements will be almost free of this dependence. Future proposals in this direction are, for instance, CONUS [10] and CONNIE [11].

In this work we discuss how the correlation between different parameters (standard and non-standard) can be disentangled by using different experimental setups. We focus on combined analyses of the neutron rms radius, R_n, and the constraints to non-standard interactions (NSI) [12–14].

Within the SM, the CEvNS differential cross-section is given by [15–17]

$$\left(\frac{d\sigma}{dT}\right)^{\text{coh}}_{\text{SM}} = \frac{G_F^2 M}{\pi}\left[1 - \frac{MT}{2E_\nu^2}\right][Z g_V^p F_Z(q^2) + N g_V^n F_N(q^2)]^2, \tag{1}$$

with G_F the Fermi coupling constant, the mass of the nucleus denoted by M, the incoming neutrino energy given by E_ν, the nucleus recoil energy expressed as T, $F_{Z,N}(q^2)$ the nuclear form factors, and $g_V^{p,n}$ are the neutral current vector couplings [18]. The previous equation depends on fundamental parameters such as the weak mixing angle, $\sin\theta_W$, through the coupling constants, on nuclear physics parameters over the form factors $F_Z(q^2)$ and $F_N(q^2)$, and also on the specific detection target through the proportion of protons to neutrons Z/N.

On the other hand, we can also use CEvNS to study new physics scenarios. A common framework is that of non-standard interactions [12–14]. In this context, new terms containing non-universal and flavor changing currents are present in the associated cross section. These terms are parametrized as dimensionless coefficients $\varepsilon_{\alpha\beta}^{qV}$ (with $q = u, d, V = L, R$ and $\alpha, \beta = e, \mu, \tau$.) proportional to the Fermi constant. The parameters for which $\alpha = \beta$ refer to non-universal interactions, while those with $\alpha \neq \beta$ correspond to flavor-changing terms. By introducing these parameters, the CEvNS cross-section in the spinless limit, for $T << E_\nu$, is given by [19–21]:

$$\begin{aligned}\frac{\mathrm{d}\sigma}{\mathrm{d}T}(E_\nu, T) \simeq \frac{G_F^2 M}{\pi}\left(1 - \frac{MT}{2E_\nu^2}\right)\Bigg\{&\left[Z\left(g_V^p + 2\varepsilon_{ee}^{uV} + \varepsilon_{ee}^{dV}\right)F_Z^V(Q^2) + N\left(g_V^n + \varepsilon_{ee}^{uV} + 2\varepsilon_{ee}^{dV}\right)F_N^V(Q^2)\right]^2\\ &+ \sum_\alpha \left[Z\left(2\varepsilon_{\alpha e}^{uV} + \varepsilon_{\alpha e}^{dV}\right)F_Z^V(Q^2) + N\left(\varepsilon_{\alpha e}^{uV} + 2\varepsilon_{\alpha e}^{dV}\right)F_N^V(Q^2)\right]^2\Bigg\},\end{aligned} \tag{2}$$

where we have considered an electron antineutrino flux, which is the case of a reactor neutrino experiment. For the case of a π-DAR neutrino source, we can obtain the expression for the muon neutrino contributions by replacing the electron neutrino subindex for the corresponding incident neutrino flux.

We can use the previous information to compute the expected number of events that a detector will register as

$$N_{\text{events}} = t\phi_0 \frac{M_{\text{detector}}}{M}\int_{E_{\nu\text{min}}}^{E_{\nu\text{max}}} \lambda(E_\nu) dE_\nu \int_{T_{\text{min}}}^{T_{\text{max}}(E_\nu)} \left(\frac{d\sigma}{dT}\right)^{\text{coh}} dT. \tag{3}$$

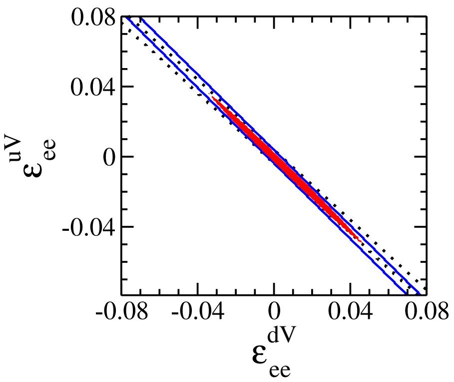

Figure 1: Expected constraints for the non-universal NSI parameters for CONNIE (dotted region) and CONUS (solid region) experiments, considering a 4 % of systematic error. The result of a combined analysis considering the correlation in the antineutrino reactor flux is also shown as a red region.

We consider one year of exposure time, t, an antineutrino flux, ϕ_0, from the reactor in either the CONNIE [11] or the CONUS [10] experimental setup with a nucleus mass, M, that corresponds to either a silicon (CONNIE) or a germanium (CONUS) target. For the antineutrino energy spectrum, $\lambda(E_\nu)$, we use the theoretical predictions discussed in Refs. [22, 23]. The different proportions of neutrons to protons in the two experiments previously mentioned will lead to complementary results, as we will see below.

Due to their low energy spectrum, for reactor antineutrinos, the momentum transfer is too small. The form factors will be close to one and can be considered constant, making these experiments almost independent of nuclear physics.

We present here the expected sensitivity to NSI parameters for these two reactor experiments. We will show the results for two nonzero NSI parameters at the same time. More details of this analysis can be found in Ref. [18]. If we combine the expected results of these two proposals, we can get more robust constraints on the NSI parameters since the well-known parameter degeneracy can be resolved [19]. We illustrate this in Figure 1, where we show the independent result of CONNIE and CONUS on the constraints for the NSI diagonal parameters ϵ_{ee}^{dV} and ϵ_{ee}^{uV} including a 4 % of systematic error. In the same figure we also show the expected result of a combined analysis of both experiments. In this last case we consider a correlated systematic error due to the reactor antineutrino flux (see Ref. [18] for details). It is clear that having two different targets will better constrain the NSI parameters, especially by using a different proportion of neutrons to protons.

At present, CEvNS has been measured only at the SNS at Oak Ridge National Laboratory (ORNL) [2, 24]. In this case, besides the sensitivity to NSI, the relatively high energy involved in the pion decay, introduces an important dependence on the form factors shown in Eq. (2). Moreover, the neutrino flux will be different in both the spectrum and the flavor content; besides electron neutrinos, there will be a contribution of muon neutrinos and antineutrinos (details of the analysis can be found in [18]).

To illustrate how a reasonable determination of the neutron distribution implies a reliable constraint on the NSI and vice versa, we show in the left panel of Fig. (2) the result of constraining the NSI parameter, ϵ_{ee}^{dV}, and the neutron charge radius, R_n, by using the data from the first measurement of

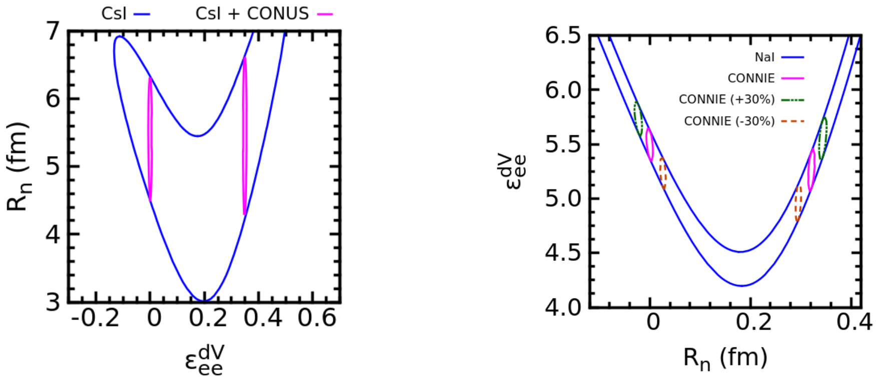

Figure 2: Left: Allowed region of the ϵ^{dV}_{ee} vs the mean neutron radius R_n at 1σ derived from the CsI measurement. The magenta regions correspond to the result for a futuristic combined measurement from COHERENT-CONUS experiments. **Right:** Expected constraints from the future experiments with a NaI detector and from CONNIE at 1σ. We also illustrate here the case of a future CONNIE measurement with a number of events in disagreement with the SM prediction. We can see that the two experiments combined can discriminate the values of both standard and non-standard parameters.

CEvNS [2] (blue region). We show in the same figure the expected allowed region from a combined analysis of the COHERENT data with the future expected constraints from the CONUS proposal (magenta region). We can notice that the two different experimental setups considered at the same time can help to improve the restrictions on both parameters.

The complete plan of COHERENT collaboration includes a NaI detector [25] to measure CEvNS. In this case we have also computed the expected sensitivity, as can be seen in the right panel of Fig. (2), where we show the expected impact on the previous results using this kind of detector [18]. In the same panel, we also show a forecast on the sensitivity when combining the analysis with the expected results for CONNIE experiment. We also display what would be the allowed region in the case that CONNIE measures a deviation from the Standard Model prediction. The different regions for a ±30% deviation in the right panel of Fig. (2) show that besides giving a signature for new physics, it would also imply a displacement in the neutron mean radius value.

The increasing activity for improved measurements of reactor and SNS CEvNS opens the door to future precise neutrino physics and physics beyond the Standard Model constraints. Future accurate constraints can be given by CEvNS experiments, especially if experimental setups using different neutrino sources are taken into consideration (reactor and SNS sources). This allows us to obtain complementary observables that could give information on standard and non-standard parameters. We have illustrated this by studying the perspectives for combined constraints on the mean neutron radius and NSI parameters.

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