Using isotopically enriched detectors to perform CEvNS measurements.

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Abstract. We propose the use of an array of different isotopically enriched detectors for a precise measurement of Coherent Elastic Neutrino-Nucleus Scattering (CEvNS). We show the impact that correlations between systematic uncertainties can have in different applications. Here we focus on testing the quadratic dependence in the number of neutrons of the CEvNS cross section, the determination of the neutron rms radius of target materials, and constraining Non-Standard Interactions. We exemplify our method with germanium based detectors, but the applicability can be extended to other technologies such as silicon and nickel.

1. Introduction

The process of Coherent Elastic Neutrino-Nucleus Scattering (CEvNS) is a weak neutral current process by which a neutrino interacts with a nucleus as a whole. As a result of the interaction, the nucleus acquires a kinetic recoil energy T. Theoretically, this process was proposed by Freedman in 1974 [1], but it was not until 2017 that the COHERENT collaboration reported the first experimental measurement by using a CsI detector [2]. A second measurement was reported by the same collaboration in 2020 by using a LAr detector [3]. The cross section associated to this process reads:

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

where M is the mass of the nucleus with Z (N) number of protons (neutrons), T is the nuclear recoil energy, E_ν is the incoming neutrino energy, and $F(q^2)$ are the corresponding nuclear form factors. A unique characteristic of this interaction is the quadratic dependence of the cross section in the number of neutrons of the target material, making this process dominant at low energies when compared to processes like neutrino-electron scattering and inverse beta decay. However, the low energy thresholds needed to measure the kinetic recoil energy of the nucleus make this measurement a challenging task. In addition, there are different sources of systematic uncertainties, such as those coming from nuclear form factors and quenching factors. So far, the two of the reported measurements have been done with neutrinos coming from π-DAR sources. There are still many efforts to have the first measurement for neutrinos coming from reactors, [4, 5, 6] which is more demanding because of their very low energy regime. In this work, we show how an array of different isotopically enriched detectors, taking data at the same time, can

Journal of Physics: Conference Series **2156** (2022) 012207 doi:10.1088/1742-6596/2156/1/012207

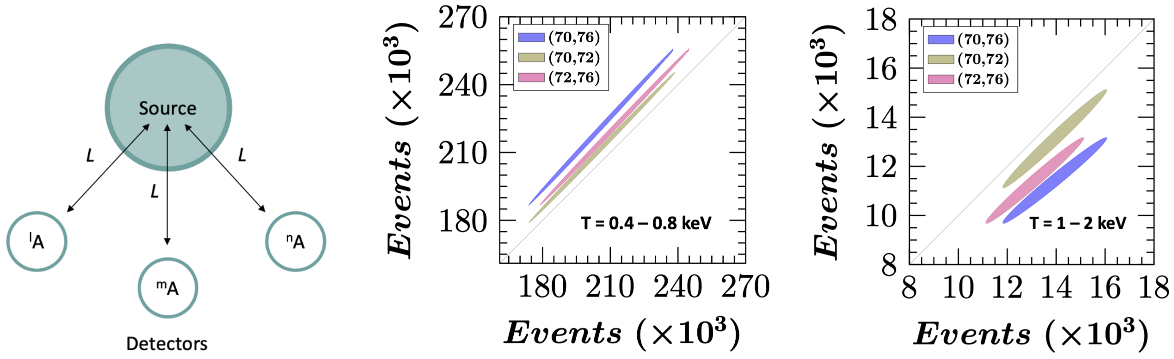

Figure 1: Left: Experimental array of three detectors, each of a different isotope with total nucleons l, m, n of the same material A. Central: Expected number of events for each isotope, comparing by pairs, consistent at a 90% C.L. with the N^2 prediction of the CEvNS cross section for $0.4 < T < 0.8$ keV. Right: Same as in central panel but for $1 < T < 2$keV.

help to mitigate the effect of systematic uncertainties for neutrinos coming from both π-DAR and reactor sources [7]. A precise measurement is of interest, since CEvNS can be used in wide applications in High Energy and Nuclear Physics.

2. The germanium approach

We consider a set of n detectors, each composed of a different isotope of the same element. The idea is to simultaneously take measurements with the n detectors located at the same distance from the neutrino source, which we consider either as π- DAR sources or reactor neutrinos. In this way, any variations in the neutrino flux will be common to all the detectors. In addition, because we consider the same element but different isotopes, there will be correlations for systematic errors coming from neutron form factors, quenching factors, and the neutrino flux itself. To illustrate the idea, we consider an array of three different germanium isotopes as shown in the left panel of Fig. 1. The election of Ge was motivated by different factors. Among them, that Ge has five stable isotopes, making it suitable to test the quadratic dependence, and that the technique of using detectors enriched in ^{76}Ge has already been used in the search of processes like neutrino-less double beta decay [8]. For a given neutrino flux, we calculate the total number of events for each of the detectors by:

$$\mathcal{N}^{theo} = N_D \int_T A(T)dT \int_{E_{min}}^{E_{Max}} dE\phi(E)\frac{\mathrm{d}\sigma}{\mathrm{d}T}, \tag{2}$$

To test a specific parameter of the theory, we perform a χ^2 analysis by minimizing the function:

$$\chi^2 = \sum_{ij}(\mathcal{N}_i^{theo} - \mathcal{N}_i^{exp})[\sigma_{ij}^2]^{-1}(\mathcal{N}_j^{theo} - \mathcal{N}_j^{exp}), \tag{3}$$

with $\mathcal{N}_i^{theo}$ the predicted number of events of the ith detector and $\mathcal{N}_i^{exp}$ the experimental measurement, which we will consider as the SM prediction. This expression considers the correlation between systematic uncertainties through the correlation matrix σ. In our analysis we will consider three detectors: ^{70}Ge, ^{72}Ge, and ^{76}Ge, and two main sources of systematic

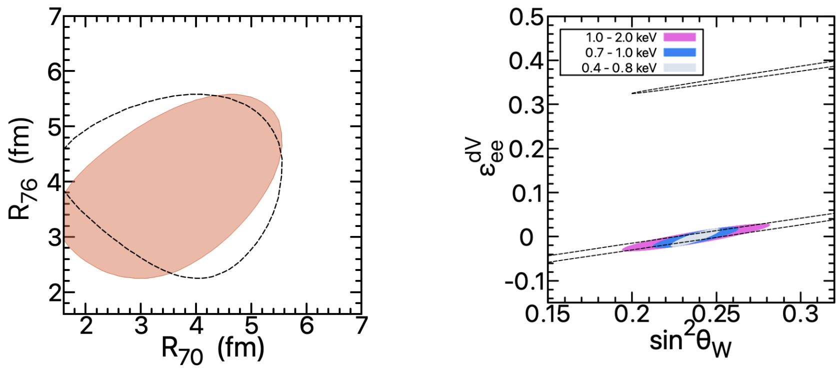

Figure 2: Left: Orange region represents the neutron rms radius at a 90% C.L. for ^{70}Ge and ^{76}Ge after marginalizing the information on ^{72}Ge. Right: Allowed region at a 90% in the parameter space of $\sin^2\theta_W$ and ε_{ee}^{dV}. Each color represents different regions of recoil energy T. In both panels the dashed line represents the uncorrelated case.

errors depending on the neutrino source, so we have:

$$\sigma^2 = \begin{pmatrix} \sigma_{70}^{stat2} + \sigma_{70}^{A\,2} + \sigma_{70}^{B\,2} & \sigma_{70}^A\sigma_{73}^A + \sigma_{70}^B\sigma_{73}^B & \sigma_{70}^A\sigma_{76}^A + \sigma_{70}^B\sigma_{76}^B \\ \sigma_{70}^A\sigma_{73}^A + \sigma_{70}^B\sigma_{73}^B & \sigma_{73}^{stat2} + \sigma_{73}^{A\,2} + \sigma_{73}^{B\,2} & \sigma_{73}^A\sigma_{76}^A + \sigma_{73}^B\sigma_{76}^B \\ \sigma_{70}^A\sigma_{76}^A + \sigma_{70}^B\sigma_{76}^B & \sigma_{73}^A\sigma_{76}^A + \sigma_{73}^B\sigma_{76}^B & \sigma_{76}^{stat2} + \sigma_{76}^{A\,2} + \sigma_{76}^{B\,2} \end{pmatrix}. \quad (4)$$

Where the upper indexes A and B refer to the most significant sources of systematic errors.

3. Probes for the SM, Nuclear Physics, and NSI

With the formalism presented in the previous section, we can study different properties of the SM and new physics. Here we discuss three main applications assuming a germanium array with 10 kg for each detector, located at 22 m from the source, during a one year data taking.

3.1. Testing the quadratic dependence on the number of neutrons

We substitute the number of neutrons N in Eq. (1) by a factor N', which will quantify a deviation from the number of neutrons in the cross section. By varying this parameter, we can use the χ^2 analysis to compare the predicted number of events with the experimental measurement. Because of its large statistics, we assume a reactor neutrino source, for which we consider that the main sources of systematic errors come from quenching factors and the neutrino flux, each contributing with a 5%. The results are shown in Fig. 1, where the central panel shows the expected number of events at a 90% C.L. when comparing the detectors by pairs in a region of recoil energy from 0.4 to 0.8 keV. The right panel shows the analogue, assuming a recoil energy range from 1 to 2 keV. By direct comparison, we can see that the order of the ellipses is inverted, since we expect a larger number of events for the lightest isotope in the high energy region, while in the low energy region we expect more events from the heaviest isotope.

3.2. Constraining the neutron rms radius

Neutrinos coming from π-DAR sources can be used to constrain the neutron rms distribution of the different isotopes. For these neutrinos, the energy regime is such that the effects of the Form Factors are relevant. We consider a Helm distribution:

$$F_N^{Helm}(q^2) = 3\frac{j_1(qR_0)}{qR_0}e^{\frac{-q^2s^2}{2}} \qquad R_n^2 = \frac{3}{5}R_0^2 + 3s^2 \quad (5)$$

where $j_1(x)$ is the spherical Bessel function of order one, R_n the neutron rms radius, and s the neutron skin. We can use CEvNS as an experimental tool to measure R_n. Again, by performing a χ^2 analysis, we can constrain its value for different germanium isotopes. Here we consider the systematic errors from quenching and form factors, each contributing with a 5%. The orange region in the left panel in Fig. 2 shows the allowed region at a 90% C.L. for the pair ^{70}Ge and ^{76}Ge when marginalizing the information of the third isotope. The dashed line represents the case for which no correlations are assumed.

3.3. Probes to the SM and NSI

As a third application, we can use the proposed array to perform SM and NSI tests. When including the effects of NSI, the CEvNS cross section reads [9]:

$$\frac{\mathrm{d}\sigma}{\mathrm{d}T} \simeq \frac{G_F^2 M}{\pi}\left(1-\frac{MT}{2E_\nu^2}\right)\left\{\left[Z\left(g_V^p+2\varepsilon_{ee}^{uV}+\varepsilon_{ee}^{dV}\right)F_Z^V(q^2)+N\left(g_V^n+\varepsilon_{ee}^{uV}+2\varepsilon_{ee}^{dV}\right)F_N^V(q^2)\right]^2 \right.$$
$$\left. + \sum_{\alpha=\mu,\tau}\left[Z\left(2\varepsilon_{\alpha e}^{uV}+\varepsilon_{\alpha e}^{dV}\right)F_Z^V(q^2)+N\left(\varepsilon_{\alpha e}^{uV}+2\varepsilon_{\alpha e}^{dV}\right)F_N^V(q^2)\right]^2\right\} \tag{6}$$

We assume a reactor source, and we perform an analysis varying the weak mixing angle, which enters through $g_V^p = 1/2 - 2\sin^2\theta_W$, and assuming only the ε_{ee}^{dV} to be different from zero. Right panel in Fig. 2 shows the results at a 90% C.L. for the three different kinetic recoil energy regions. The dashed line in the same figure shows the situation when no correlations are considered for 1 keV $< T <$ 2 keV. We can see that the effect of the correlations is to break the characteristic degeneracies that appear when introducing the effects of NSI.

4. Conclusions

The process of CEvNS has wide applicability in nuclear physics, as well as particle physics. Mitigating systematic uncertainties is of the greatest importance to enter a new era of high precision. As we have seen, the correlation between different detectors has an important impact in the comparison between the number of events expected for this process, as well as in the determination of constraints for parameters that describe SM physics and NSI.

Acknowledgments

This work was performed under the auspices of the U.S. Department of Energy by Oak Ridge National Laboratory under Contract No. DE-AC05- 00OR22725. This work has been supported by CONACyT under grant A1-S-23238.

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