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Future perspectives for a weak mixing angle measurement in coherent elastic neutrino nucleus scattering experiments

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ABSTRACT

After the first measurement of the coherent elastic neutrino nucleus scattering (CENNS) by the COHERENT Collaboration, it is expected that new experiments will confirm the observation. Such measurements will allow to put stronger constraints or discover new physics as well as to probe the Standard Model by measuring its parameters. This is the case of the weak mixing angle at low energies, which could be measured with an increased precision in future results of CENNS experiments using, for example, reactor antineutrinos. In this work we analyze the physics potential of different proposals for the improvement of our current knowledge of this observable and show that they are very promising.

1. Introduction

Neutrinos are one of the most elusive particles. With a small cross section, its detection has been always a challenge for the experimentalist. Despite this difficult task, neutrino physics is in a precision era with increasingly accurate measurements [1–4]. Among the recent progress in this field is the detection, for the first time, of the coherent elastic neutrino-nucleus scattering (CENNS). This reaction was proposed [5] just after the discovery of the weak neutral currents [6] and recently detected by the COHERENT collaboration [7]. Besides the natural interest in confirming this recent detection, there are different issues that are of current interest in nuclear and neutrino physics. Many new physics scenarios can be probed, as it has been proposed in the case of Non Standard Interactions (NSI) [8–11], a Z' gauge boson [12–15], electromagnetic neutrino properties [16,17] and even the case of an sterile neutrino [18–21]. Methods alternative to inverse beta decay (IBD) of reactor neutrino detection can also shed light in the so called reactor neutrino anomaly [22], as we have pointed out in [18].

Reactor neutrinos have a great tradition of discoveries, since the first neutrino detection [23] and in the last decades they have played an important role in establishing the three neutrino oscillation paradigm [1], IBD has been the golden channel in reactor neutrino detection. However there are other interesting neutrino reactions that can also be used to probe neutrino fluxes from reactors, as is the case of elastic neutrino-electron scattering (ENES) detected for the first time in the seventies [24] and measured with increased precision by the TEXONO [25] and MUNU [26] Collaborations; and more recently of CENNS measured at the neutron spallation source by the COHERENT Collaboration [7]. It is expected that in the near future improved measurements of ENES reaction can be provided by the GEMMA experiment [27].

The expectation for a new measurement of the weak mixing angle in CENNS has already been studied in the past, for example for the case of the TEXONO [17] and the CONUS [28] proposals. Here we focus in the case of the CONNIE [29–31], MINER [32], and RED100 [33] research programs and reanalyse the TEXONO and CONUS case studies in order to compare them on an equal footing and to contrast the importance of different characteristics of each experiment. In particular, we note here how sensitivities can depend on the experiment detection targets due to a different protons to neutrons proportion.

The dependence of CENNS cross section on the weak charge Q_W allows the study of the weak mixing angle at extremely low momentum transfer, a region where an improvement in the accuracy of this parameter is very much needed [34,35], particularly in measurements with neutrino interactions [36]. We will show that, although the sensitivity to the weak charge is relatively small in

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CENNS, it will be possible to have competitive measurements of the $\sin^2\theta_W$ in the low energy regime if the systematic uncertainties are under control. We will discuss that, besides the importance of high statistics, the proportion of protons to neutrons in a given target will also play an important role.

2. CENNS experiments with reactor antineutrinos

Several future proposals plan to measure CENNS with increased statistics, opening the possibility to test the Standard Model in the ultra-low energy regime. To study the sensitivity of these proposals to the weak mixing angle, we start by considering the CENNS cross section, given by the following expression [37]

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

Here, M is the mass of the nucleus, E_ν is the neutrino energy, and T is the nucleus recoil energy; $F_{Z,N}(q^2)$ are the nuclear form factors that are especially important at higher momentum transfer, as can be the case of neutrinos coming from spallation neutron sources, while for reactor antineutrinos, they have a minimal impact and will be considered as equal to one in this work. The neutral current vector couplings (including radiative corrections) are given by [37],

$$g_V^p = \rho_{\nu N}^{NC}\left(\frac{1}{2} - 2\hat{\kappa}_{\nu N}\hat{s}_Z^2\right) + 2\lambda^{uL} + 2\lambda^{uR} + \lambda^{dL} + \lambda^{dR}$$
$$g_V^n = -\frac{1}{2}\rho_{\nu N}^{NC} + \lambda^{uL} + \lambda^{uR} + 2\lambda^{dL} + 2\lambda^{dR} \quad (2)$$

where $\rho_{\nu N}^{NC} = 1.0082$, $\hat{s}_Z^2 = \sin^2\theta_W = 0.23129$, $\hat{\kappa}_{\nu N} = 0.9972$, $\lambda^{uL} = -0.0031$, $\lambda^{dL} = -0.0025$, and $\lambda^{dR} = 2\lambda^{uR} = 7.5 \times 10^{-5}$ [38].

From the previous expressions for the vector couplings, it is straightforward to note that the dependence on the weak mixing angle appears only on the protons coupling and, therefore, nuclei with larger protons to neutrons proportion could be more sensitive to this measurement. On the negative side, we can also notice that this contribution is small in comparison with the neutron one. Despite this, a high statistics CENNS experiment will be sensitive to this coupling and, therefore, the weak mixing angle can be measured with a precision similar to the one at current measurements in this low energy regime. Currently, most of the proposals are working with a relatively small amount of material and considering upgrades in the near future. In what follows, we will consider the optimistic case of the upgraded, high statistics, detectors that are the ones that have the possibility to make an accurate measurement.

For estimating the number of expected events (SM) in the detector, we use the expression,

$$N_{\rm events}^{\rm SM} = t\phi_0 \frac{M_{\rm detector}}{M} \int_{E_{\nu\rm min}}^{E_{\nu\rm max}} \lambda(E_\nu) dE_\nu \int_{T_{\rm min}}^{T_{\rm max}(E_\nu)} \left(\frac{d\sigma}{dT}\right)^{\rm coh}_{\rm SM} dT, \quad (3)$$

where $M_{\rm detector}$ is the mass of the detector under study, ϕ_0 is the total neutrino flux, t is the data taking time period, $\lambda(E_\nu)$ is the neutrino spectrum, E_ν is the neutrino energy, and T is the nucleus recoil energy. The maximum recoil energy is related to the neutrino energy and the nucleus mass through the relation $T_{\rm max}(E_\nu) = 2E_\nu^2/(M + 2E_\nu)$.

In our analysis, in order to forecast the sensitivity of the CENNS experiments, we will use two different approaches: we will perform a χ^2 analysis of each proposal, considering that the future experiment will measure the number of events predicted by the Standard Model. To compute this values we will use the predicted value for the weak mixing angle at zero momentum transfer ($\sin^2\theta_W = 0.2386$). With this value as the test experimental value, we will perform a fit considering different values of the systematic uncertainties, plus the extreme benchmark case of only statistical error. A second approach, also used in the present article, will be the computation of the χ^2 function considering the predicted statistical error and the systematics coming from the reactor neutrino spectrum [39], this method has been previously used for the case of ENES experiments [36]. For the reactor neutrino spectrum we will use the expansion discussed in Ref. [22], while for energies below 2 MeV the computations reported in Ref. [40] were considered. In each case we assumed as a benchmark one year of data taking.

Table 1
List of some experimental proposals to detect CENNS with reactor antineutrinos.

	T_{thres}	Baseline	Z/N	Det. Tec.	Fid. Mass
CONNIE [29,30]	28 eV	30 m	1.0	CCD (Si)	1 kg
RED100 [33]	500 eV	19 m	0.70	Lq.Xe	100 kg
MINER [32]	10 eV	1 m	0.81	^{72}Ge:^{28}Si (2:1)	30 kg
TEXONO [46]	100 eV	28 m	0.79	HPGe	1 kg
CONUS [28]	100 eV	10 m	0.79	HPGe	100 kg

As already mentioned above, in our first approach we will consider an analysis based on the function

$$\chi^2 = \frac{(N_{\rm events}^{\rm SM} - N^{th})^2}{\sigma_{stat}^2 + \sigma_{syst}^2}, \quad (4)$$

where the theoretical prediction for the number of events N^{th} will depend on the value of the weak mixing angle and we will consider different values for the future systematic error $\sigma_{syst} = pN^{th}/100$, where p will be the percentage of systematic uncertainty. For our second approach, we will consider the current level of uncertainty in the reactor antineutrino spectrum as an input.

We have computed the expected number of events taking into account the experimental details of each proposal, summarized in Table 1. For the RED100 proposal [33] we consider a 100 kg target of Xe, a material that is currently of great interest for coherent scattering [41] and that has reached a low energy threshold in different tests [42]. A 500 eV threshold is expected in the case of the RED100 experiment. New analyses in this direction are encouraging and it is expected that the detector will perform even better [43]; however, for our analysis we will restrict to this more conservative estimate. The RED100 experiment will be located at the Kalinin power plant. In the case of CONNIE, we consider the most optimistic case of a 1 kg Si detector, with a 28 eV threshold, located at 30 m from the Angra-2 reactor. As for the MINER proposal, we perform our computations considering a detector that will be made of ^{72}Ge and ^{28}Si. The proportion between these two materials is of $2:1$ and the threshold energy is expected to reach 10 eV. The antineutrino source in this case will be a non-comercial TRIGA-type pool reactor that delivers mainly ^{235}U antineutrinos [44]. We will consider an event rate of 5 kg $^{-1}$ day^{-1} [32] and, as in the case of all other proposals, one year of data taking. For the case of TEXONO, we have considered their proposed High-purity Germanium detectors as a target with the threshold energy $T_{thres} \sim 100$ eV [45,46] exposed to an antineutrino flux coming from the Kuo-Sheng nuclear power plant. Finally, in the case of the CONUS proposal we follow [28], where a detector of up to 100 kg of germanium is considered, with a recoil energy threshold as low as 100 eV.