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# Low-Energy Measurements of the Weak Mixing Angle in Coherent Elastic Neutrino-Nucleus Scattering Experiments

Mehmet Demirci[1, a)] and Onur Başlı[2, b)]

[1]*Department of Physics, Karadeniz Technical University, Trabzon TR61080, Türkiye*
[2]*Department of Physics, Bursa Uludağ University, Bursa TR16059, Türkiye*

[a)] *mehmetdemirci@ktu.edu.tr*
[b)] *onurbasli@uludag.edu.tr*

**Abstract.** The weak mixing angle is a fundamental parameter of the electroweak theory in the Standard Model (SM), and its measurement in the low energy region is still not precisely determined. Different probes, such as the atomic parity violation, coherent elastic neutrino-nucleus scattering (CE$\nu$NS), and parity-violating electron scattering on different nuclei, are sensitive to the weak mixing angle value. After the measurement of CE$\nu$NS by the COHERENT experiment, other experiments are also expected to confirm the observation. Such measurements will allow to put stronger constraints or discover new physics as well as to probe the SM by measuring its parameters. In this work, the weak mixing angle at low energies, which can be measured with increased precision in future results of CE$\nu$NS experiments is discussed. In addition to providing a comprehensive test of the electroweak theory at the quantum loop level, such measurements serve to study new physics interactions beyond the SM at the TeV scale and beyond.

## INTRODUCTION

The weak mixing angle, $\theta_W$, also known as the Weinberg angle, is one of the fundamental parameters in the theory of electroweak (EW) interactions included in the Standard Model (SM) of particle physics [1, 2]. The gauge symmetry $SU(2)_L \times U(1)_Y$ underlying the electroweak unification involves four spin-1 vector bosons, $W_\mu^+$, $W_\mu^0$, $W_\mu^-$ and $B_\mu^0$, along with two independent couplings, $g$ and $g'$. The mixing leads to a massless photon and its orthogonal massive partner, known as the $Z^0$ boson:

$$\begin{pmatrix} \gamma \\ Z^0 \end{pmatrix} = \begin{pmatrix} \cos\theta_W & \sin\theta_W \\ -\sin\theta_W & \cos\theta_W \end{pmatrix} \begin{pmatrix} B^0 \\ W^0 \end{pmatrix} \tag{1}$$

This formalism marks the birth of the weak mixing angle. Although it can be defined in terms of $tan\theta_W = g'/g$ or electromagnetic coupling $e = gg'/\sqrt{g^2 + g'^2}$, $\sin\theta_W = e/g$, in practice, the quantity $\sin^2\theta_W$ is often specified instead of the Weinberg angle itself:

$$\sin^2\theta_W = \frac{g'^2}{g^2+g'^2} \tag{2}$$

The value of $\sin^2\theta_W$ is not predicted and needs to be extracted from parity-violating neutral-current experiments. EW symmetry breaking gains masses for the Z and W bosons proportional to their gauge interactions

$$\sin^2\theta_W = 1 - \frac{m_W^2}{m_Z^2} \tag{3}$$

and the ratio of gauge boson masses gives independent precise information on $\sin^2\theta_W$. In the LEP1 and SLC collider experiments, many measurements were carried out for the Z-boson properties, and it was possible to obtain the most

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precise measurements of $\sin^2\theta_W$ in the EW interactions at high-energy regions, coherently with the SM predictions [1],

$$\sin^2\theta_W^{SM} = 0.23857(5) \tag{4}$$

motivating a further study of all the inputs into this measurement. The experimental determination of $\sin^2\theta_W$ allows the direct investigation of physical phenomena not contained in the SM, often called as new physics. In Fig. 1, the $\sin^2\theta_W$ measurements are shown as a function of the energy scale, $Q$, along with the SM predicted running of $\sin^2\theta_W$, calculated in the minimal subtraction ($\overline{MS}$) renormalization scheme [3, 4]. As shown by the red point in Fig.1, the weak mixing angle with a central value (Eq.4) is in very good agreement with the SM at low momentum transfer.

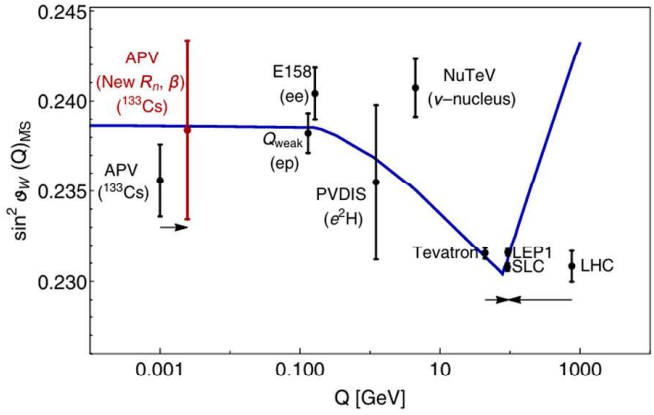


**FIGURE 1.** Variation of $\sin^2\theta_W$ with energy scale $Q$ [5]. The SM prediction is shown as the solid curve, together with experimental determinations in black at the Z pole. Abbreviation: APV, atomic parity violation; PVDIS, parity-violating deep inelastic scattering.

The coherent elastic neutrino-nucleus scattering (CE$\nu$NS) was suggested [6] soon after the discovery of the weak neutral currents [7] and recently observed by the COHERENT experiment [8]. It is well defined at low energies within the SM framework. The CE$\nu$NS process is based on the principle that neutrinos are scattered out of the nucleus as a whole via the SM neutral gauge boson $Z^0$ at low momentum transfer, giving it a small recoil energy. The differential cross-section of the neutrino scattering off the spin-0 nucleus is obtained at the tree level in the SM as

$$\left[\frac{d\sigma_{\nu_\alpha-N}}{dT_{nr}}\right]_{SM} = \frac{G_F^2 m_N}{4\pi}\left(1 - \frac{m_N T_{nr}}{2E_\nu^2}\right)[N-(1-4sin^2\theta_W)Z]^2|F(|\vec{q}|^2)|^2 \tag{5}$$

where $Z$ ($N$) is proton (neutron) number, $G_F$ is the Fermi constant, $m_N$ is the target nucleus mass, $T_{nr}$ is the nuclear recoil energy, $E_\nu$ is the energy of the incoming neutrinos, $q^2 = -Q^2 = -2m_N T_{nr}$ is the squared momentum transfer, and $F$ is the form factor of nucleus. The dependence of $\sin^2\theta_W$ of the CE$\nu$NS cross section allows the investigation of this angle at low momentum transfer, a region where an improvement in the accuracy of this parameter is greatly needed [3, 9], especially in measurements involving neutrino interactions [10].

## THE WEAK MIXING ANGLE MEASUREMENTS IN CE$\nu$NS

We can study the electromagnetic properties of neutrinos based on $\sin^2\theta_W$ measurements. As is well known, neutrinos have a zero electric charge and there are no electromagnetic interactions at tree-level in the SM. However, in many extension versions of the SM [11], neutrinos also acquire electromagnetic properties (neutrino millicharge, neutrino charge radius, neutrino magnetic moment and neutrino anapole moment) via quantum loop effects. Since the electro magnetic interaction terms of the neutrino millicharge and the neutrino charge radius are coherently added to the vector part of the weak interaction, their contributions can be calculated by using the weak mixing angle transformation.

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## Neutrino Millicharge

Neutrinos can have non-zero electric charge. This possibility may arise in theories beyond the SM and has been considered in many theoretical and experimental studies [12]. For the CE$\nu$NS process, the total differential cross section, expressed in terms of the neutrino millicharge $q_{\nu_\alpha}$ ($\alpha = e, \mu, \tau$) with flavor $\alpha$, including the electromagnetic contribution from neutrinos to the SM weak interaction together with the interference of the SM, is obtained as

$$\left[\frac{d\sigma}{dT_{nr}}\right]_{MC} = \left[\frac{d\sigma}{dT_{nr}}\right]_{SM} \left(1 - \frac{\sqrt{2}Ze}{4G_F Q_{SM}} \left(\frac{q_{\nu_\alpha}}{m_N T_{nr}}\right)\right)^2 \quad (6)$$

where $Q_{SM} = N - (1 - 4sin^2\theta_W)Z$ is the coherent weak charge that quantifies the $Z^0$-nucleus vector coupling [13]. It can be clearly seen that the dependence on the weinberg angle only arises in the proton coupling and, hence nuclei with larger proton/neutron ratio may be more sensitive to its measurements.

The contribution of the neutrino millicharge can be calculated directly by replacing

$$sin^2\theta_W \rightarrow sin^2\theta_W \left(1 - \frac{\pi\alpha_{EM}}{\sqrt{2}\, sin^2\theta_W\, G_F\, m_N\, T_{nr}}\, q_{\nu_\alpha}\right) \quad (7)$$

for the weak mixing angle in the SM CE$\nu$NS cross section (Eq.5).

## Neutrino Charge Radius

In SM, the neutrino charge radius is the only electromagnetic property of the neutrino that can have a non-zero value. For the neutrino charge radius contribution, the differential cross section including its interference with the SM CE$\nu$NS process is obtained as

$$\left[\frac{d\sigma}{dT_{nr}}\right]_{CR} = \left[\frac{d\sigma}{dT_{nr}}\right]_{SM} \left(1 + \frac{\sqrt{2}e^2\, Z}{12 G_F Q_{SM}} \left(< r_{\nu_\alpha}^2 >\right)\right)^2 \quad (8)$$

The neutrino charge radius contribution to the SM CE$\nu$NS process can also be calculated by substituting

$$sin^2\theta_W \rightarrow sin^2\theta_W \left(1 - \frac{\pi\alpha_{EM}}{3\sqrt{2}\, sin^2\theta_W\, G_F} < r_{\nu_\alpha}^2 >\right) \quad (9)$$

for the weak mixing angle in Eq.5.

## CONCLUSION

The Weinberg angle is one of the key parameters in the SM weak interactions and has been widely used in the search for new physics. There are measurements of this significant quantity at low momentum transfer. The CE$\nu$NS process that described at low energies provides a proper background for testing the Weinberg angle measurements. It is stated that the measurement of the Weinberg angle at low energies in neutrino scattering processes has much room for improvement and that CE$\nu$NS experiments have the potential to achieve competitive accuracy if systematical errors can be decreased.

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