Neutron Skin in CsI and Low-Energy Effective Weak Mixing Angle from COHERENT Data

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(Dated: February 26, 2019)

Both the neutron skin thickness $\Delta R_{np}$ of atomic nuclei and the low-energy neutrino-nucleon ($\nu N$) interactions are of fundamental importance in nuclear and particle physics, astrophysics as well as new physics beyond the standard model (SM) but largely uncertain currently, and the coherent elastic neutrino-nucleus scattering (CE$\nu$NS) provides a clean way to extract their information. New physics beyond the SM may cause effectively a shift of the SM weak mixing angle $\theta_W$ in low-energy $\nu N$ interactions, leading to an effective weak mixing angle $\theta_W'$. By analyzing the CE$\nu$NS data of the COHERENT experiment, we find that while a one-parameter fit to the COHERENT data by varying $\Delta R_{np}$ produces an unrealistically large central value of $\Delta R_{np}^{SM} \approx 0.68$ fm for CsI with $\sin^2 \theta_W' = 0.23857$, a two-dimensional fit by varying $\Delta R_{np}$ and $\sin^2 \theta_W'$ gives significantly smaller central values of $\Delta R_{np}^{SM} \approx 0.24$ fm and $\sin^2 \theta_W' \approx 0.21$, although their uncertainties are large. The implication of the substantial deviation of $\sin^2 \theta_W'$ from $\sin^2 \theta_W^{SM}$ on new physics beyond the SM is discussed.

Introduction.— The neutron skin thickness of atomic nuclei, defined as $\Delta R_{np} = R_n - R_p$ where $R_{n(p)} = (2 \rho_{n(p)})^{1/2}$ is the neutron (proton) rms radius of the nucleus, provides a good probe of the equation of state (EOS) for isospin asymmetric nuclear matter $^{[1,10]}$, which is critically important due to its multifaceted roles in nuclear physics and astrophysics $^{[11-14]}$ as well as some issues of new physics beyond the standard model (SM) $^{[15,19]}$. While the $R_p$ can be measured precisely from electromagnetic processes (see, e.g., Refs. $^{[20-22]}$), the $R_n$ is largely uncertain since it is usually determined from strong processes, which is generally model dependent due to the complicated nonperturbative effects. This provides a strong motivation for the Lead Radius Experiment (PREX) being performed at the Jefferson Laboratory to determine the $R_n$ of $^{208}$Pb to about 1% accuracy by measuring the parity-violating electroweak asymmetry in the elastic scattering of polarized electrons from $^{208}$Pb $^{[23]}$. The PREX Collaboration reported the first result of the neutron skin thickness of atomic nuclei for $^{208}$Pb, i.e., $\Delta R_{np}^{208}$ $\approx 0.33^{+0.16}_{-0.18}$ fm $^{[24]}$ (see, also, Ref. $^{[25]}$). The central value of 0.33 fm means a surprisingly large neutron skin thickness in $^{208}$Pb although there is no compelling reason to rule out a such large value $^{[26]}$.

Recently, the COHERENT Collaboration $^{[27]}$ reported the first observation of the coherent elastic neutrino-nucleus scattering (CE$\nu$NS) $^{[28,29]}$. In Ref. $^{[30]}$, a value of the averaged $\Delta R_{np}$ of $^{133}$Cs and $^{127}$I, i.e., $\Delta R_{np}^{\text{ave}} \approx 0.7_{-0.3}^{+0.9}$ fm, is extracted from analyzing the COHERENT data. The extracted central value of $\Delta R_{np}^{\text{ave}} \approx 0.7$ fm is unrealistically large. To the best of our knowledge, $\Delta R_{np}^{\text{ave}} \approx 0.7$ fm is actually much larger than all the predictions of current nuclear models. Moreover, since $^{208}$Pb is much more neutron-rich than $^{133}$Cs and $^{127}$I, the $\Delta R_{np}^{\text{ave}}$ is expected to be smaller than the $\Delta R_{np}^{208}$ according to the neutron skin systematics $^{[31,32]}$, and thus $\Delta R_{np}^{CS\nu NS} \approx 0.7$ fm is inconsistent with the PREX result. The inconsistency could be a hint of new physics in neutrino physics and this provides the main motivation of the present work.

We note that in Ref. $^{[30]}$, the $\Delta R_{np}^{CS\nu NS}$ is extracted from a one-parameter fit to the COHERENT data by varying $\Delta R_{np}^{CS\nu NS}$ with the low-energy weak mixing angle $\theta_W$ fixed at the SM value $\sin^2 \theta_W^{SM} = 0.23865$ obtained in the modified minimal subtraction (MS) renormalization scheme at near zero momentum transfer $Q = 0$ $^{[33]}$ (the newest value is $\sin^2 \theta_W^{SM} = 0.23857(5)$ $^{[34]}$). Experimentally, the precise determination of $\sin^2 \theta_W$ at low $Q^2$ is an ongoing issue $^{[35]}$, and the atomic parity violation (APV) experiments offer the most precise results to date. For example, by measuring the $6s1/2 - 7s1/2$ electric dipole transition in $^{133}$Cs atom, a value of $\sin^2 \theta_W = 0.2356(20)$ at $(Q) \approx 2.4$ MeV is obtained $^{[36,38]}$, which is smaller than $\sin^2 \theta_W^{SM}$ by about $1.5\sigma$. In the mid-energy regime, the Qweak Collaboration reported the recent measurement on proton’s weak charge and obtained $\sin^2 \theta_W = 0.2383(11)$ at $Q = 0.158$ GeV $^{[39]}$, agreeing well with the SM prediction. On the other hand, the low-energy neutrino-nucleon ($\nu N$) interactions could involve new physics beyond the SM $^{[35,40-46]}$, which may cause effectively a shift of the SM weak mixing angle $\theta_W$ in the $\nu N$ interactions, leading to a low-energy effective weak mixing angle $\theta_W'$. Any experimental constraints on $\theta_W'$ would provide useful information on new physics beyond the SM.

In this work, we extract the values of $\Delta R_{np}^{CS\nu NS}$ and $\sin^2 \theta_W'$ using a two-dimensional (2D) fit to the COHERENT data by varying $\Delta R_{np}^{CS\nu NS}$ and $\sin^2 \theta_W'$. Compared to the results using one-parameter fit with $\sin^2 \theta_W$ fixed at $\sin^2 \theta_W^{SM}$, we find significantly smaller central values of $\Delta R_{np}^{CS\nu NS} \approx 0.24$ fm and $\sin^2 \theta_W' \approx 0.21$ at $Q \approx 0.05$ GeV (corresponding to the energy scale of COHERENT experiment), although their uncertainties are large.

CE$\nu$NS in the COHERENT experiment.— The differential cross section for coherent elastic neutrino-nucleus scattering has a straightforward SM prediction in the case with differ-
ent proton and neutron distributions (form factors) in the nucleus. By neglecting the radiative corrections and axial contributions, the cross section can be expressed as [41, 47, 49]:

$$\frac{d\sigma}{dT}(E_\nu, T) = \frac{G_F^2 M c^2}{2\pi} G_V \left[ 1 - \frac{MT}{E_\nu} + \left( 1 - \frac{T}{E_\nu} \right)^2 \right],$$  \hspace{1cm} (1)

$$G_V = Z g_V^p F_p(q^2) + N g_V^n F_n(q^2),$$  \hspace{1cm} (2)

where $G_F$ is the Fermi coupling constant, $M$ is the nucleus mass, $E_\nu$ and $T$ are neutrino energy and nuclear recoil kinetic energy, respectively. For a given $E_\nu$, the corresponding $T$ varies from 0 to $T^{max} = 2E_\nu/(M + 2E_\nu)$. The proton and neutron neutral current vector couplings are defined, respectively, as $g_V^p = \frac{1}{2} - 2\sin^2 \theta_W$ and $g_V^n = -\frac{1}{2}$. The form factor $F_{n(p)}(q^2)$ encapsulate the neutron (proton) number density distribution in nuclei, where the momentum transfer $q$ is given by $q^2 = 2E_\nu^2 M/(E_\nu^2 - E_\nu T) \approx 2MT$ under the condition of $E_\nu \gg T$.

In the case of the COHERENT experiment, the measurement is performed using a CsI detector which is dominantly composed of $^{133}$Cs and $^{127}$I. The mass of a nucleus with $N(Z)$ neutrons (protons) is determined by its corresponding total binding energy ($E_B$) from $M = N \times m_n + Z \times m_p - E_B$ where $m_{n(p)}$ is the nucleon mass.

The binding energies per nucleon are 8.40998 MeV and 8.44549 MeV [50] for isotopes $^{133}$Cs and $^{127}$I, respectively. As for their density distributions, in order to test the model dependence, two analytic nuclear form factors are adopted, namely, the symmetrized Fermi (SF) form factor and the Helm form factor [50, 51, 52]. Both form factors are characterized by two parameters related to the nuclear radius and the surface thickness, respectively.

The SF form factor has the form [51]

$$F_{SF}(q^2) = \frac{3}{qc[(qc)^2 + (\pi qa)^2]} \left[ \frac{\pi qa}{\sinh(\pi qa)} \right] \left[ \frac{\pi qa}{\tanh(\pi qa)} \sin(qc) - qc \cos(qc) \right],$$  \hspace{1cm} (3)

and the corresponding rms radius is expressed as

$$R_{SF}^2 \equiv \langle r^2 \rangle = \frac{3}{5} c^2 + \frac{7}{5}(\pi a)^2,$$  \hspace{1cm} (4)

where $c$ is the half-density radius and $a$ quantifies the surface thickness $t = 4a \ln 3$. Experimentally, the proton distribution has been determined precisely, and we take the same parameters for proton distribution as in Ref. [50], which are obtained by fitting the proton structure data of $^{133}$Cs and $^{127}$I measured in muonic atom spectroscopy, namely, $t_p = 2.30$ fm, $c_p = 5.6710 \pm 0.0001$ fm and $c_p = 5.5931 \pm 0.0001$ fm. The corresponding proton rms radii for $^{133}$Cs and $^{127}$I are given by $R_p = 4.804$ fm and $R_p = 4.749$ fm, respectively.

The Helm form factor is expressed as [52]

$$F_{Helm}(q^2) = \frac{3j_1(qR_0)}{qR_0} e^{-qs^2/2},$$  \hspace{1cm} (5)

where $j_1(x)$ is the spherical Bessel function of order one, i.e., $j_1(x) = \sin(x)/x^2 - \cos(x)/x$. The rms radius is simply given by

$$R_{Helm}^2 \equiv \langle r^2 \rangle = \frac{3}{5} R_0^2 + 3s^2.$$  \hspace{1cm} (6)

Here, $R_0$ is the box radius and $s$ quantifies the surface thickness. Again, for the proton distributions in $^{133}$Cs and $^{127}$I, we use $s_p = 0.9$ fm following Ref. [30], which was determined for the proton form factor of similar nuclei [53], and the $R_{0,p}$ is determined by the corresponding $R_p$.

For the parameters of the neutron distributions in $^{133}$Cs and $^{127}$I, they are essentially unknown. In these neutron-rich nuclei, in principle, the neutron distributions should be different from the proton distributions because of the charge difference, which means that the neutron distributions could have different radius parameters ($c_n$ and $R_{0,n}$) and surface thickness parameters ($t_n$ and $s_n$) compared to the proton distributions. We will examine these effects in the following.

In the COHERENT experiment, the photoelectrons are counted to monitor the scattering events and extract the nuclear recoil energy, with approximately 1.17 photoelectrons expected per keV of nuclear recoil energy, denoted as $\zeta = 1.17$ keV$^{-1}$ [27]. The number of event counts in a nuclear recoil energy bin $[T_i, T_{i+1}]$ can be obtained as

$$N^t_i = N_{Csl} \sum_{\nu} \sum_{N=N_{Cs,I}} \int_{T_i}^{T_{i+1}} dT \times \frac{dN_\nu}{dE_\nu} \frac{d\sigma_{\nu-N}}{dE_\nu},$$  \hspace{1cm} (7)

where $N_{Csl}$ is the number of CsI in the detector and is given by $N_{A} m_{det}/M_{Csl}$ with $N_A$ being the Avogadro constant, $m_{det} = 14.57$ kg the detector mass and $M_{Csl} = 259.8$ g/mol the molar mass of CsI. The acceptance efficiency function $A(x)$ is described by [54]

$$A(x) = \frac{a}{1 + e^{-k(x-x_0)}} \Theta(x-5),$$  \hspace{1cm} (8)

where the parameter values are taken as $a = 0.6655 \pm 0.0212$, $k = 0.4942 \pm 0.0335$ and $x_0 = 10.8509 \pm 0.1838$, and the $\Theta(x)$ is a modified Heaviside step function defined as

$$\Theta(x-5) = \begin{cases} 
0 & x < 5, \\
0.5 & 5 \leq x < 6, \\
1 & x \geq 6.
\end{cases}$$  \hspace{1cm} (9)

The value of $E_{min}$ depends on $T$, and the $E_{max}$ is related to the neutrino source. At the Spallation Neutron Source, the neutrino flux is generated from the stopped pion decays $\pi^+ \rightarrow \mu^+ + \nu_\mu$ as well as the subsequent muon decays $\mu^+ \rightarrow e^+ + \bar{\nu}_e + \nu_\mu$. The neutrino population has the following energy
distributions \([30, 42]\)

\[
\frac{dN_{\nu_e}}{dE_{\nu_e}} = \eta \delta \left( E_{\nu_e} - \frac{m_\pi^2 - m_\mu^2}{2m_\pi} \right),
\]

\[
\frac{dN_{\nu_e}}{dE_{\nu_e}} = \eta \frac{64E_{\nu_e}^2}{m_\mu^2} \left( \frac{3}{4} - \frac{E_{\nu_e}}{m_\mu} \right),
\]

\[
\frac{dN_{\nu_e}}{dE_{\nu_e}} = \eta \frac{192E_{\nu_e}^2}{m_\mu^2} \left( \frac{1}{2} - \frac{E_{\nu_e}}{m_\mu} \right),
\]

(10)

with \(E_{\nu_e}^{\max} \leq m_\mu/2\). The normalization factor \(\eta\) is defined as \(\eta = r N_{\text{POT}}/(4\pi L^2)\), where \(r = 0.08\) is the averaged production rate of the decay-at-rest (DAR) neutrinos for each flavor per proton on target, \(N_{\text{POT}} = 1.76 \times 10^{23}\) is the total number of protons delivered to the target and \(L = 19.3\) m is the distance between the neutrino source and the CsI detector \([27]\).

To evaluate the fitting quality on the COHERENT data in Fig. 3A of Ref. \([27]\), following Ref. \([30]\), we apply the following least-squares function with only the 12 energy bins from \(i = 4\) to \(i = 15\), i.e.,

\[
\chi^2 = \sum_{i=4}^{15} \frac{\left( N_{\nu_e}^{\text{exp}} - (1 + \alpha)N_{\nu_e}^{\text{th}} - (1 + \beta)B_i \right)^2}{\sigma_i} + \left( \frac{\alpha}{\sigma_\alpha} \right)^2 + \left( \frac{\beta}{\sigma_\beta} \right)^2.
\]

(11)

Here for each energy bin, the experimental number of events, denoted as \(N_{\nu_e}^{\text{exp}}\), is generated from the C-AC differences, and \(B_i\) is the estimated beam-on background with only prompt neutrons included \([27]\). The \(\sigma_i = \sqrt{N_{\nu_e}^{\text{exp}} + 2B_i^{\text{stat}} + B_i^{\text{stat}}}\) is the statistical uncertainty where \(B_i^{\text{stat}}\) is the estimated steady-state background determined with AC data \([27]\). The \(\alpha\) and \(\beta\) are the systematic parameters corresponding to the uncertainties on the signal rate and the beam-on background rate, respectively. The fractional uncertainties corresponding to 1-\(\sigma\) variation are \(\sigma_\alpha = 0.28\) and \(\sigma_\beta = 0.25\) \([27]\). All the experimental data are taken from the COHERENT release \([34]\).

**Results and discussions.**—In the present work for CEνNS calculations, we replace the \(\theta_W\) in Eq. (1) by \(\theta_W^\nu\) to effectively consider the possible effects of new physics in \(\nu/N\) interactions. We first assume that the neutron and proton distributions have the same surface thickness parameters (i.e., \(t_n = t_p\) and \(s_n = s_p\)) and the value of \(\sin^2 \theta_W^\nu\) is fixed at the SM value of \(\sin^2 \theta_W^\text{SM} = 0.23857\), and then perform a one-parameter fit to the COHERENT data by varying \(R_n\) to extract the neutron rms radius \(R_n^{\text{CsI}}\) of CsI (\(133^{\text{Cs}}\) and \(127^{\text{I}}\) are assumed to have equal \(R_n\)). Our calculations lead to \(R_n = 5.46^{+0.91}_{-1.13}\) fm with the Helm form factor and \(R_n = 5.47^{+0.91}_{-1.13}\) fm with the SF form factor. Our results thus nicely confirm the model-independent value of \(R_n = 5.5^{+0.9}_{-1.1}\) fm extracted in Ref. \([30]\) with the same assumptions.

Furthermore, we examine the effects of the neutron surface thickness parameters. To this end, we perform a 2D fit to the COHERENT data by varying \(R_n^{\text{CsI}}\) and the surface thickness parameter while the effective weak mixing angle is fixed at \(\sin^2 \theta_W^\nu = \sin^2 \theta_W^\text{SM}\). The results indicate that a variation of \(\pm 0.02\) fm for \(\Delta R_n^{\text{CsI}}\) arises when \(s_n\) changes from 0.63 to 1.17 fm (corresponding to a variation of \(\pm 30\%\) for \(s_n = 0.9\) fm) in the Helm form factor. The same conclusion is obtained when the SF form factor is used. Therefore, compared to the obtained neutron skin thickness of \(\Delta R_n^{\text{CsI}} \simeq 0.68^{+0.91}_{-1.13}\) fm, the effects of the neutron surface thickness parameters are indeed quite small, consistent with the statement in Ref. \([30]\).

Now we turn to examining the effects of the low-energy effective weak mixing angle. The potential non-standard running of \(\sin^2 \theta_W^\nu\) in low-energy regime is expected to influence the extraction of the neutron distribution from the low-energy CEνNS experiments. The simultaneous precise determination of the neutron distribution and the low-energy \(\sin^2 \theta_W^\nu\) through CEνNS experiments can (in)validate our knowledge of nuclear physics and neutrino physics. Hence, we perform a 2D fit to the COHERENT data by varying \(R_n\) and \(\sin^2 \theta_W^\nu\) using the Helm form factor with \(s_n = s_p\). The resulting number of CEνNS event counts as a function of the number of photoelectrons is shown in Fig. 1 while the corresponding \(\chi^2\) contours are displayed in Fig. 2.

For comparison, we also include in Fig. 1 the corresponding results from the COHERENT data, the similar 2D fit by using the SF form factor with \(t_n = t_p\), and the one-parameter fit by varying \(R_n\) with fixed \(\sin^2 \theta_W^\nu = \sin^2 \theta_W^\text{SM}\) using both the Helm and SF form factors. It is seen from Fig. 1 that for both one-parameter and 2D fits, the SF and Helm form factors produce almost identical results, indicating the model independence of our results on the form of nuclear form factors. Furthermore, Fig. 1 indicates that compared to the one-parameter fit, the 2D fit predicts a fewer event counts in the region of \(7 \sim 15\) for the photoelectron number, leading to the
number of total event counts decreases by \( \sim 3.2\% \).

![FIG. 2: (Color online) The \( \chi^2 \) contours in the plane of \( R_n \) vs sin\(^2\) \( \theta_W \) obtained from a 2D fit to the COHERENT data using the Helm form factor with \( s_n = s_p \). The star marks the center values of \( R_n = 5.02 \text{ fm} \) and sin\(^2\) \( \theta_W = 0.21 \) at \( \chi^2_{\text{min}} = 2.498 \). The dashed curve corresponds to the contour at \( \chi^2 = \chi^2_{\text{min}} + 1 \).](image)

From Fig. 2, one sees that there exhibits a positive correlation between \( R_n \) and sin\(^2\) \( \theta_W \). Particularly interesting is that there exists favored center values for \( R_n \) and sin\(^2\) \( \theta_W \), i.e.,

\[
R_{n}^{\text{Helm}} = 5.02^{+2.30}_{-2.03} \text{ fm, sin}^2 \theta_W^* = 0.21^{+0.13}_{-0.10}.
\] (12)

although the uncertainty is large. We note that very similar results are obtained when the SF form factor is used. With the averaged rms radii of protons and neutrons in \(^{133}\text{Cs}\) and \(^{127}\text{I}\), we then obtain the averaged neutron skin thickness of CsI as

\[
\Delta R_{np}^{\text{CSI}} \approx 0.24^{+2.30}_{-2.03} \text{ fm}.
\] (13)

The favored central value \( \Delta R_{np}^{\text{CSI}} \approx 0.24\) fm is significantly smaller than \( \Delta R_{np}^{\text{CSI}} \approx 0.68 \) fm extracted from the one-parameter fit to the COHERENT data with fixed sin\(^2\) \( \theta_W^* = \sin^2 \theta_{W}^{\text{SM}} \), indicating the importance of the sin\(^2\) \( \theta_W^* \) in the extraction of \( \Delta R_{np}^{\text{CSI}} \) from CEνNS.

Furthermore, we examine the effects of neutron surface thickness parameters using the 2D fit to the COHERENT data by varying \( R_n \) and sin\(^2\) \( \theta_W \) with \( s_n \) and \( t_n \) fixed at various values. Our results indicate that the \( \Delta R_{np}^{\text{CSI}} \) varies by \( \pm 0.03 \) fm (the corresponding \( R_n \) varies from \( 4.99 \) fm to \( 5.05 \) fm) when the value of \( s_n \) in the Helm form factor changes from \( 0.63 \) fm to \( 1.17 \) fm (corresponding to a variation of \( \pm 30\% \) for \( s_n = 0.9 \) fm). Similarly, we find the \( \Delta R_{np}^{\text{CSI}} \) varies by \( \pm 0.04 \) fm (the corresponding \( R_n \) varies from \( 4.99 \) fm to \( 5.07 \) fm) when the value of \( t_n \) in the SF form factor changes from \( 1.61 \) fm to \( 2.99 \) fm (corresponding to a variation of \( \pm 30\% \) for \( t_n = 2.3 \) fm). The variation of \( \pm (0.03 \sim 0.04) \) fm is appreciable compared to the value of \( \Delta R_{np}^{\text{CSI}} \approx 0.24 \) fm, implying that one can extract useful information on the neutron surface thickness (diffuseness) parameters in atomic nuclei from the future precise measurements of CEνNS. Nevertheless, the extracted central value of \( \Delta R_{np}^{\text{CSI}} \approx 0.24 \) fm with an uncertainty of \( \pm (0.03 \sim 0.04) \) fm obtained in the present work is consistent with some carefully calibrated nuclear models (see, e.g., Refs. [26, 30]).

On the other hand, a substantial deviation of sin\(^2\) \( \theta_W \) from sin\(^2\) \( \theta_{W}^{\text{SM}} \), i.e., \( \Delta \sin^2 \theta_W = -0.02857 \), is obtained in the present work. This anomaly could be a hint of new physics beyond SM in neutrino physics. For example, one new physics scenario is to introduce the nonstandard interactions (NSIs) in the SM interactions, which has been widely discussed [40–43]. To make a rough estimate on the parameters in NSIs, we introduce an ad hoc nonstandard charge \( G_{\nu}^{\text{NSI}} \) to replace the \( G_{\nu} \) in Eq. (2), i.e.,

\[
G_{\nu}^{\text{NSI}} = \frac{Z_{\nu}}{A_{\nu}} \left( \sum_{V,S} \frac{1}{G_{\nu}^{V}} \rho_{V} \right) \left( \sum_{V,N} \frac{1}{G_{\nu}^{V}} \rho_{N} \right) W_{\nu}^{V},
\] (14)

where \( \delta_{\nu} = \epsilon_{\nu}^{w} \) or \( \epsilon_{\nu}^{d} \) denotes the NSI parameters. Eq. (14) can be obtained from the more general NSIs (see, e.g., Refs. [40, 41, 43]) by neglecting the flavor-changing couplings \( \epsilon_{\alpha}^{w} \) (\( \alpha \neq \beta \)) and assuming that the new flavor-preserving couplings \( \epsilon_{\alpha}^{w} \) are flavor symmetric for neutrinos and the first-generation quarks \( (u, d) \). Then one can estimate the value of \( \delta_{\nu} \) as

\[
\delta_{\nu} \approx -\frac{2Z}{3A} \Delta \sin^2 \theta_{W}^* = 0.008,
\] (15)

by assuming \( F_{\rho}(q^2) \approx F_{\nu}(q^2) \). These results indicate that the NSI contribution into the proton and neutron neutral current vector couplings is \( 3\delta_{\nu} = 0.024 \), which is even larger than the SM proton coupling \( g_{\nu}^{p} = \frac{1}{2} - 2\sin^2 \theta_{W}^{\text{SM}} = 0.02286 \).

Moreover, we would like to point out that the deviation of sin\(^2\) \( \theta_W \) from sin\(^2\) \( \theta_{W}^{\text{SM}} \) in neutrino physics can also potentially arise from the neutrino electromagnetic properties, e.g., the neutrino charge radius \( (\rho_{\nu}^{+}) \) [42, 43]. Furthermore, the deviation could be as well from the dark parity violation [5, 44]. All these scenarios beyond the SM can effectively shift down the low-energy weak mixing angle in \( \nu N \) interactions and worthy of further investigation with forthcoming more precise CEνNS data in future. It will be also very interesting to check the similar effects in other weak neutral interaction measurements, e.g., APV and PREX.

**Summary.**—We have demonstrated that the low-energy effective weak mixing angle \( \theta_{W}^* \) plays an important role in the extraction of neutron skin thickness of atomic nuclei from the CEνNS experiments. By analyzing the CEνNS data of the COHERENT experiment, we have found that while a one-parameter fit to the COHERENT data produces an unrealistically large central value of \( \Delta R_{np}^{\text{CSI}} \approx 0.68 \) fm with sin\(^2\) \( \theta_W \) fixed at sin\(^2\) \( \theta_{W}^{\text{SM}} \approx 0.23857 \), a 2D fit gives significantly smaller central values of \( \Delta R_{np}^{\text{CSI}} \approx 0.24 \) fm and sin\(^2\) \( \theta_W \) ≈ 0.21, although their uncertainties are large. While \( \Delta R_{np}^{\text{CSI}} \approx 0.24 \) seems to be reasonable, the substantial deviation of sin\(^2\) \( \theta_W \) from sin\(^2\) \( \theta_{W}^{\text{SM}} \) could give a hint on new physics beyond SM in neutrino physics.
in $\nu$-nucleon interactions. Future high precision CE$\nu$NS measurements are extremely important to put more stringent constraints on $\Delta F_{\nu N}^{\text{str}}$ and the low-energy effective $\sin^2 \theta_W$. It will be also interesting to explore the similar effects in other weak neutral interaction measurements.

Acknowledgments.— We thank Juan I. Collar for the useful communication on the quenching factor for CsI, Xiao-Gang He and Alexander I. Studenikin for useful discussions. This work was supported in part by the National Natural Science Foundation of China under Grant No. 11625521, the Program for Professor of Special Appointment (Eastern Scholar) at Shanghai Institutions of Higher Learning, Key Laboratory for Particle Physics, Astrophysics and Cosmology, Ministry of Education, China, and the Science and Technology Commission of Shanghai Municipality (11DZ2260700).

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