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Unambiguously Resolving the Potential Neutrino Magnetic Moment Signal at Large Liquid Scintillator Detectors

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Non-vanishing electromagnetic properties of neutrinos have been predicted by many theories beyond the Standard Model, and an enhanced neutrino magnetic moment can have profound implications for fundamental physics. The XENON1T experiment recently detected an excess of electron recoil events in the 1–7 keV energy range, which can be compatible with solar neutrino magnetic moment interaction at a most probable value of $\mu_\nu = 2.1 \times 10^{-11}\mu_{\rm B}$. However, tritium backgrounds or solar axion interaction in this energy window are equally plausible causes. Upcoming multi-tonne noble liquid detectors will test these scenarios more in depth, but will continue to face similar ambiguity. We report a unique capability of future large liquid scintillator detectors to help resolve the potential neutrino magnetic moment scenario. With $O(100)$ kton·year exposure of liquid scintillator to solar neutrinos, a sensitivity of $\mu_\nu < 10^{-11}\mu_{\rm B}$ can be reached at an energy threshold greater than 40 keV, where no tritium or solar axion events but only neutrino magnetic moment signal is still present.

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The nonzero neutrino mass indicates that neutrinos have a tiny induced magnetic moment proportional to its mass, $\mu_\nu \approx 3.2\times10^{-19}(\frac{m_\nu}{1\,\rm eV})\mu_{\rm B}$ ($\mu_{\rm B} = \frac{e\hbar}{2m_{\rm e}}$ is the Bohr magneton), which is so small that it is out of current experimental reach.[1–3] However, many theories beyond the Standard Model (SM) predict that neutrinos can have much larger enhanced magnetic moments.[4–7] The enhanced magnetic moment allows neutrinos to interact via electromagnetic force and the effect can be large enough for it to be observed by the current and next generation of detectors, in contrast to only weak interactions of neutrinos in the SM. This has raised tremendous interest both from the theoretical and experimental particle physics community. For a mysterious particle like the neutrino, which already holds a confirmed property beyond the SM for being massive, measuring its magnetic moment is important both for further understanding the particle itself and for the search of new physics. By considering electroweak radiative corrections to neutrino mass generated by physics above the electroweak scale, it is shown in Ref. [8] that the current neutrino mass limit implies that the magnetic moment of Dirac neutrinos can not exceed $\sim10^{-14}\mu_{\rm B}$, while for Majorana neutrinos there is no such strict limit on the transition magnetic moments.[9] Therefore, if neutrinos are observed to have a magnetic moment larger than $\sim10^{-14}\mu_{\rm B}$, it will be a strong indication for Majorana particles.

Experimental search for neutrino magnetic moment (νMM) began more than 40 years ago. Measuring the energy spectrum of electron recoils induced by neutrinos from nuclear reactors or the Sun has been the most sensitive probe to νMM in laboratories on Earth.[10] The best sensitivity for reactor anti-neutrino νMM was reported by the GEMMA experiment in 2012, an upper limit of $\mu_\nu < 2.9 \times 10^{-11}\mu_{\rm B}$ (90% C.L.) was derived for electron-flavor anti-neutrino based on null results.[11] The most sensitive search for solar neutrino νMM was reported by the Borexino experiment in 2017, which yielded an upper limit of $\mu_\nu < 2.8 \times 10^{-11}\mu_{\rm B}$ (90% C.L.) for νMM of oscillation-mixed solar neutrinos, based on a null result.[12] Astrophysical analyses with stellar cooling and supernovae have derived more stringent constraints for νMM than that measured in laboratories on Earth.[13–15] These limits, however, involves complex assumptions and are heavily model-dependent. They often have to assume the existence of the yet to be confirmed right-handed neutrinos with masses in narrow ranges.[16] Therefore, direct laboratory measurement is indispensable for obtaining decisive knowledge of νMM.

In 2020, the XENON1T experiment detected an excess of low energy electron recoil events in the 1–7 keV energy range, which is consistent with a νMM of $\mu_\nu \in (1.4, 2.9) \times 10^{-11}\mu_{\rm B}$ at 90% C.L.[17] This excess, however, can also be explained by solar axions or backgrounds like tritium β-decays. While these hypotheses are equally compatible with the observed excess in the 1–7 keV energy range, the νMM scenario, if real,

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can produce signals that extend to energy regions well above 20 keV (see Fig. 1) and therefore can be cross validated unambiguously by large liquid scintillator (LS) detectors like JUNO[18] and LENA[19] with low detection thresholds. Although the upcoming multi-tonne xenon detectors, i.e., XENONnT,[20,21] LZ[22,23] and PandaX-4T,[24] will be able to investigate this low energy excess more robustly, they continue to face the difficulty of 'unexpected but possible' backgrounds of ^{3}H and ^{37}Ar in this energy window.[25] Joint analyses between the forthcoming large liquid scintillator and liquid xenon detectors will help fully elucidate the potential signal of electromagnetic interaction of the solar neutrinos.

The measurement of muon anomalous magnetic moment, $a_\mu \equiv (g_\mu - 2)/2$, by the E821 experiment in 2006 at Brookhaven National Lab and the E989 experiment in 2021 at Fermilab revealed a combined 4.2σ discrepancy between experiments and the SM theory.[26,27] Interestingly, it is suggested that new physics models which naturally generate large neutrino transition magnetic moment and small neutrino mass can also explain the muon g-2 anomaly, producing the right magnitude of signals in both XENON1T and muon g-2.[28] Direct and independent measurements of νMM thus become highly anticipated to shed light on these newly emerged puzzles.

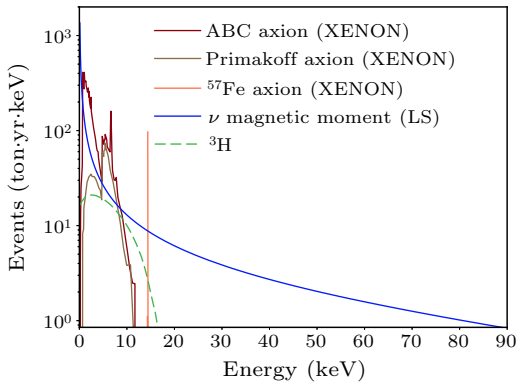

Fig. 1. Comparison on signal strengths for (1) the ABC solar axion model with a coupling constant $g_{ae} = 5\times10^{-12}$ (crimson), (2) the ^{57}Fe de-excitation axion model with a coupling constant $g_{an}^{eff} = 1\times10^{-6}$ (dirt), (3) the Primakoff axion model with a coupling constant $g_{a\gamma} = 2\times10^{-10}$ (red) in liquid xenon detectors;[29–31] (4) solar neutrino magnetic moment at a value of $\mu_\nu = 2.1\times10^{-11}\mu_B$ (blue) in liquid scintillator detectors; and (5) the β decay energy spectrum of tritium backgrounds at a level similar to the cosmogenic tritium isotope in JUNO.[18] The number of electrons per ton in liquid xenon is about 73% of that in linear alkylbenzene (LAB) based liquid scintillator.

Neutrino Magnetic Moment Signals and Relevant Backgrounds. Solar neutrinos are detected via neutrino electron elastic scattering (νeES) in LS detectors. The energy spectrum of νeES events induced by solar neutrinos can be calculated by

$$\frac{dN}{dT} = \int N_e \times \frac{d\sigma(E_\nu|T)}{dT} \times f(E_\nu)dE_\nu, \qquad (1)$$

where T is the electron recoil energy, N_e is the number of electrons in the LS target, $\frac{d\sigma(E_\nu|T)}{dT}$ is the differential cross section of νeES, and $f(E_\nu)dE_\nu$ is the solar neutrino flux in the energy interval $[E_\nu, E_\nu + dE_\nu]$.

Besides the electron density of LS, the νeES event rate is determined by the νeES cross section and the solar neutrino flux.

The νeES cross section predicted by the SM is given by

$$\frac{d\sigma^{SM}}{dT} = \frac{G_F^2 m_e}{2\pi}\Big[(g_V + g_A)^2 + (g_A^2 - g_V^2)\frac{m_e T}{E_\nu^2} + (g_V - g_A)^2\Big(1 - \frac{T}{E_\nu}\Big)^2\Big], \qquad (2)$$

where G_F is the Fermi coupling constant, m_e is the electron mass. For ν_e, $g_V = 2\sin^2\theta_W + \frac{1}{2}$, $g_A = \frac{1}{2}$; for ν_x ($x = \mu$ or τ), $g_V = 2\sin^2\theta_W - \frac{1}{2}$, $g_A = -\frac{1}{2}$.[32–35]

If neutrinos have magnetic moment, they can interact via electromagnetic force, in addition to the weak force predicted by the SM. The νeES cross section will be the sum of the SM contribution and νMM contribution:

$$\frac{d\sigma}{dT} = \frac{d\sigma^{SM}}{dT} + \frac{d\sigma^{\mu_\nu}}{dT}. \qquad (3)$$

The νMM contribution is given by

$$\frac{d\sigma^{\mu_\nu}}{dT} = \frac{\pi\alpha_{em}^2}{m_e^2}\Big(\frac{\mu_\nu}{\mu_B}\Big)^2\frac{1 - T/E_\nu}{T}. \qquad (4)$$

Here, α_{em} is the fine structure constant, μ_ν is the νMM, μ_B is the Bohr magneton.[7,36,37] It should be pointed out that adding radiative correction will result in about 2% decrease of the SM cross section $\frac{d\sigma^{SM}}{dT}$, while νMM leads to an increase of the total cross section. In this sense, adding radiative correction will not affect the significance of the search for νMM, so in the following we will just take Eq. (2) as the SM νeES cross section, for simplicity.

The solar neutrino fluxes have been measured by experiments,[38–42] and their spectra are calculated by the Standard Solar Model (SSM).[43–46] We used the solar neutrino spectra from John Bahcall's homepage[47] and the fluxes from high-metalicity SSM which is slightly favored by data.[41,42,46] Since the search for νMM is to find potential deviation of the νeES energy spectrum from that predicted by the SM, we treat the solar neutrino flux as a single spectrum that is the sum of all the components (pp, pep, hep, ^{7}Be, ^{8}B from the pp-chain, and ^{13}N, ^{15}O, ^{17}F from the CNO-cycle). The SM νeES cross sections for ν_e and ν_x ($x = \mu$ or τ) are different, so the survival probability of ν_e due to flavor oscillation of solar neutrinos is taken into account for the calculation of νeES event rate.[41]

A prominent feature of the νMM νeES signal is that it rises very fast as it goes to lower energies, due to the fact that νMM νeES cross section is inversely proportional to electron recoil energy ($\frac{d\sigma^{\mu_\nu}}{dT} \propto 1/T$) and low energy solar neutrinos have a larger flux. Therefore, great advantage for probing νMM can be gained

if the large LS detectors can lower its detection threshold.

A reasonable estimate of the detector backgrounds is essential for the evaluation of large LS detectors' potential in the search of νMM. Besides the SM νeES events, the other relevant backgrounds include internal radioactivity, external radioactivity, and cosmogenic backgrounds.

Internal radioactivity is mainly due to the isotopes: ^{14}C, ^{238}U, ^{232}Th, ^{40}K, ^{210}Pb, ^{210}Bi, ^{210}Po and ^{85}Kr.[18] The inherent ^{14}C is a major background for searching low energy signals in large LS detectors. This work assumes a ^{14}C abundance of $^{14}\mathrm{C}/^{12}\mathrm{C} = 1.0 \times 10^{-17}$; for comparison, the Borexino experiment reports an abundance of $^{14}\mathrm{C}/^{12}\mathrm{C} = 0.27 \times 10^{-17}$.[48,49] We also vary the ^{14}C abundance by 5 times smaller or 5 times larger to evaluate its effect on the sensitivity. The pile-up of ^{14}C backgrounds was taken into account in these evaluation. The rest of the radioactive isotopes are just impurities to the LS and can be reduced by purification. The contents of these impurities are referenced to Table 11–13 in Ref. [18]. Using the mature background suppression technique of pulse shape discrimination (PSD) in LS detectors, more than 99% of α backgrounds can be removed, with ∼95% efficiency of selecting β and electron recoil events.[50] Because of this, only the β and γ backgrounds from ^{238}U, ^{232}Th and ^{210}Pb decay chains are considered.

External backgrounds are γ-rays emitted by the radioactive isotopes in the ambient environment. They can be shielded by veto detectors surrounding the central detector, and can be further reduced by fiducial cut in the central detector. By doing a proper fiducial cut, the external backgrounds can be suppressed to be negligible.[51]

Cosmogenic backgrounds are induced by cosmic ray muons, they include cosmogenic neutrons and cosmogenic isotopes. Muons themselves produce events that deposit much larger energy than νMM νeES do, and they can be tagged by the veto detectors, hence they are not considered to be major backgrounds.[52] Cosmogenic neutrons will be captured by the protons in LS about 200 µs after production, releasing a 2.2 MeV γ, so they can be removed by cutting a few milliseconds data after the corresponding muon events. Cosmogenic isotopes are considered as backgrounds if they satisfy the following criteria: the decay energy of the isotopes falls into the region of the νMM νeES signals; the half-lifes of the radioactive isotopes are longer than the time of cut after muon events; the isotope production rate is larger than or comparable to the νMM νeES event rate. Cosmogenic isotopes that pass these criteria include: ^{3}H, ^{6}He, ^{7}Be, ^{11}C, and ^{12}B. The production rates of these isotopes can be referred to Tables 9–13 of Ref. [18]. If the LS detector is at deeper underground, the production rates will be smaller. For large LS detectors, usually the detection threshold is of $O(100)$ keV, higher than the ^{3}H β-decay end-point energy, so the ^{3}H backgrounds can be ignored.

The most significant electron recoil energy window for the search of νMM is in [100, 300] keV, with major contributions from ^{7}Be and pp neutrinos. The major backgrounds in this energy window are due to ^{14}C pile-up, SM νeES events, ^{210}Po, and ^{210}Bi.

Sensitivity and Discovery Potential. A toy Monte Carlo simulation has been established to study the detector response for the νMM signal and all the backgrounds in large LS detectors. For each event, the number of photo-electrons (N_{pe}) is obtained by Poisson random numbers: $N_{\mathrm{pe}} = \mathrm{Poisson}(\overline{N}_{\mathrm{pe}})$, with $\overline{N}_{\mathrm{pe}}$ representing the mean of the Poisson distribution. The mean $\overline{N}_{\mathrm{pe}}$ for an event is a product of the event energy E_{evt} and the photo-electron yield Y_{pe}. This work uses JUNO's detector design as the baseline to estimate the photo-electron yield, for it is under construction and will begin taking data soon, but the physics case sustains upon variation of detector designs for large LS detectors. The photo-electron yield is given by $Y_{\mathrm{pe}} = Y_{c1} \times f_{\mathrm{nonlin}} \times f_{\mathrm{nonuni}}$, where $Y_{c1} \approx 1300\,\mathrm{PE/MeV}$ is the photo-electron yield for 1 MeV β events at the detector center, f_{nonlin} is the nonlinear effect of the detector response for different energies, and f_{nonuni} represents the non-uniform effect of the detector response at different locations in the detector.[53] The dark noise of photo-sensors is added to each event also assuming Poisson distribution.[54]

We set up an analysis pipeline to study sensitivity and discovery potential with the toy Monte Carlo simulation data. The spectrum shape of νMM signal is highly distinguishable from that of all the backgrounds, so we can use spectrum fitting to search for the νMM signal. We use the method of χ^2 fit, with the χ^2 defined by $\chi^2 = \sum_{n=1}^{N} \frac{(D_n - M_n)^2}{D_n}$, where D represents the data and D_n is the number of events in the n^{th} bin of the spectrum, M represents the model and M_n is the expected number of events in the n^{th} bin of the model, N is the total number of bins. The best fit model is obtained by minimization of the χ^2.[55]

Since the νMM has a higher signal rate at lower energy, lowering the energy threshold of the analysis can lead to better sensitivity. The ^{3}H β-decay or potential solar axion events are below 20 keV, but by mixing with fluctuating dark noise of the photo-sensors, some of these events can get higher than 20 keV. Simulations show that, by setting the analysis threshold above 40 keV, contamination from ^{3}H β-decay or potential solar axion events can be eliminated, and the systematic uncertainty of detector response at low energy can be reduced. A large LS detector with a low-threshold trigger system (down to ∼40 keV) is ideal to provide data for the search of νMM.[56]

The νMM signals are mostly below ∼1300 keV, which divides the backgrounds into two categories: Class 1 consists of ^{14}C (and its pile-up), ^{210}Pb chain (^{210}Pb, ^{210}Bi, ^{210}Po), ^{85}Kr and ^{7}Be, which are completely within the energy range of [0, 1300] keV, where

the νMM signals reside. Class 2 consists of ^{6}He, ^{11}C, ^{12}B, ^{40}K, ^{232}Th chain and ^{238}U chain, which can have events with energy well above 1300 keV. Therefore, we can adopt a two-step fitting strategy: for the first step, fit the data above 1300 keV to constrain the backgrounds in class 2; then in the second step, fit the data below 1300 keV, with the class-2 backgrounds fixed and set free the rest. If fitting with a null model (backgrounds-only) yields χ_0^2 and fitting with an alternative model (mixture of backgrounds and νMM signals) gives χ_1^2, the detection significance can be given by $\sigma = \sqrt{\chi_0^2 - \chi_1^2}$.

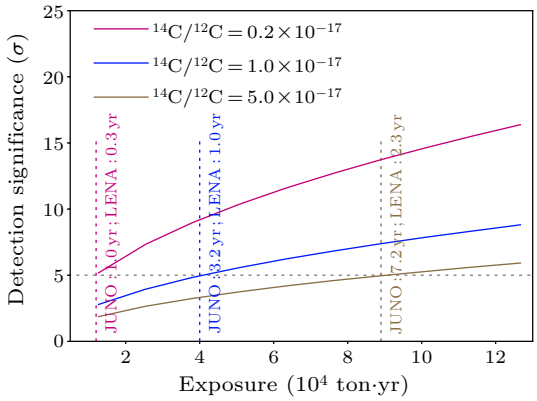

Fig. 2. The detection significance, for a potential νMM signal with a most probable value compatible with the XENON1T excess ($\mu_\nu = 2.1 \times 10^{-11}\mu_B$), as a function of exposure for liquid scintillator (LS) detectors. Future large LS detectors such as JUNO and LENA can reach these exposures. For both detectors, a fiducial cut that removes the outer layer of 2.5 m thickness is assumed to suppress the external backgrounds. For JUNO, the fiducial mass is 12.7 kton; for LENA, the fiducial mass is 39 kton. Both detectors possess the capability of unambiguously resolving the νMM scenario indicated by the XENON1T excess.

After accumulating an exposure of 127 kton·year (corresponds to $\sim$ 10 years for JUNO with $\sim$ 12.7 kton fiducial mass or $\sim$ 3.3 years for LENA with $\sim$ 39 kton fiducial mass), the LS detectors' sensitivity to νMM can reach $0.7, 0.9, 1.1 \times 10^{-11}\mu_B$ (90% C.L.) for the ^{14}C abundance of ^{14}C/^{12}C $= 0.2, 1.0, 5.0 \times 10^{-17}$, respectively. With a sensitivity better than the νMM range indicated by the XENON1T excess, future large LS detectors can resolve the νMM scenario.

The discovery potential of large LS detectors to the νMM signal strength indicated by the XENON1T excess is shown in Fig. 2 as a function of exposure. For the three values of ^{14}C abundance mentioned above, a 5-σ detection can be achieved for exposures of 12.7, 40.9, 91.2 kton·year, respectively. These exposures correspond to 1.0, 3.3, 7.2 years of JUNO livetime; and 0.3, 1.0, 2.3 years of LENA livetime. If JUNO or LENA finds no νMM signal in the corresponding livetimes, the νMM explanation for the XENON1T excess will be rejected, then other physics scenarios are needed to be investigated.

Summary and Discussion. Exploration on the electromagnetic properties of neutrinos is important to test theories beyond the SM. Neutrino magnetic moment, among other electromagnetic properties, is critical for understanding the nature of neutrinos and probing new physics. The next generation of LS detectors with extremely low threshold of $\sim$20 keV, made possible by their unprecedented large mass and modern photon detection technology, can conduct searches for neutrino magnetic moment in energy regions complementary to liquid xenon detectors. The intriguing excess of electron recoil events recently reported by XENON1T has stimulated heated debates on their origin. We have shown that large LS detectors, like the forthcoming JUNO and planned LENA, can unambiguously test the neutrino magnetic moment scenario. For an exposure of 127 kton·year, future large LS detectors' sensitivity to νMM can reach $0.9 \times 10^{-11}\mu_B$ (90% C.L.) for a ^{14}C abundance of ^{14}C/^{12}C $= 1.0 \times 10^{-17}$. With this scale of exposure, about 1.2×10^8, 2.2×10^7 and 2.3×10^5 solar neutrino events above 30, 300 and 2000 keV can be collected, which will be unprecedentedly large statistics and enable more accurate measurement of solar neutrino physics.

Uncertainties of the study include that of solar neutrino fluxes, levels of ^{14}C and other backgrounds, and the non-linearity of the detector response at low energies. The sensitivity to νMM is mainly due to ^{7}Be and pp neutrinos, which have only $\sim$0.6% uncertainty in their flux, according to the SSM, so the solar neutrino flux uncertainty is small. The spectral shape uncertainty of solar neutrinos and ^{14}C backgrounds are not severe problems. In the [100, 300] keV electron recoil energy window where νMM signal is most significant, the ratio of νMM signal to SM νeES backgrounds varies from $\sim$20% to 5%. In the same energy window, it is not single ^{14}C decay but ^{14}C pile-up that is important. One can suppress ^{14}C pile-up backgrounds using the pulse shape discrimination technique, so the ^{14}C spectral shape uncertainty has minor effect on the detection significance, but its absolute level is more important. Since the ^{14}C atoms are embedded in the LS molecular structure, they cannot be reduced by purification as performed for the other background isotopes. While LS extracted from deeper underground oil tends to contain lower ^{14}C, it is nearly impossible to control the origin of oil in the industrial production line where LS is a by-product. Therefore, ^{14}C level stays unknown till the LS detector is fully constructed and commissioned, hence it remains the largest uncertainty. As we have shown for three different levels of ^{14}C backgrounds, from ^{14}C/^{12}C $= 0.2 \times 10^{-17}$ to 5 and 25 times higher, JUNO or LENA will be able to confirm or refute the neutrino magnetic moment scenario for the XENON1T excess in 7.2 or 2.3 years even for the worst case. The LS detector response in the low energy regime could be another main source of uncertainty, but it can be controlled by calibration using low energy radioactive sources. One promising low energy calibration source

is the ^{57}Co (122 keV),[57] other sources such as the very short-lived monoenergetic $^{83\,m}$Kr (41 keV) and $^{131\,m}$Xe (164 keV) used by liquid xenon experiments could potentially be employed by LS experiments as well.[58,59] With most of these uncertainties under control and the variation of the major ^{14}C background taken into account, the capability of large LS detectors in pinpointing the possible νMM interaction in XENON1T is proven to be robust.

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