Using supernova neutrinos to probe strange spin of proton with JUNO and THEIA

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(Dated: November 17, 2022)

The strange quark contribution to proton’s spin (Δs) is a fundamental quantity that is poorly determined from current experiments. Neutrino-proton elastic scattering (pES) is a promising channel to measure this quantity, and requires an intense source of low-energy neutrinos and a low-threshold detector with excellent resolution. In this paper, we propose that neutrinos from a galactic supernova and their interactions with protons in large-volume scintillation detectors can be utilized to determine Δs. The spectra of all flavors of supernova neutrinos can be independently determined using a combination of DUNE and Super-(Hyper-)Kamiokande. This allows us to predict pES event rates in JUNO and THEIA, and estimate Δs by comparing with detected events. We find that the projected sensitivity for a supernova at 1 kpc (10 kpc), is approximately ±0.01 (±0.15). Interestingly, the limits from a nearby supernova would be comparable to the results from lattice QCD, and better than polarized deep-inelastic scattering experiments. Using supernova neutrinos provides a true Q^2 \to 0 measurement, and thus an axial-mass independent determination of Δs.

I. INTRODUCTION

One of the very first measurement of the contribution of strange quarks to the spin of proton was performed by the European Muon Collaboration (EMC). The strange spin of proton (Δs) is related to the axial form-factor in the limit of vanishing momentum-transfer (Q^2). Usually, the experiments measure Δs at Q^2 \sim GeV^2, and extrapolate the results to Q^2 = 0 by assuming some parametrization for the axial form-factor. The EMC collaboration obtained,

Δs (EMC) = -0.095 ± 0.016 ± 0.023

through polarized deep-inelastic scattering (pDIS) [1]. The contribution is not only non-zero, which is in violation of the Ellis-Jaffe sum rule [2], but also negative. Subsequent measurements by COMPASS [3] and HERMES [4] have independently determined Δs, and their results are consistent with EMC. A recent global analysis can be found in Ref. [5].

On the theory front, heavy-quark contribution to the axial form-factor has been estimated in Refs. [6–8]. In recent times, precise lattice QCD calculations of the nuclear structure suggest that

Δs (Lattice) = -0.018 ± 0.006

which is closer to zero, but negative [9]. Other groups have also obtained similar estimates (see Refs. [10–12]).

Since neutrinos only interact via the weak force, neutrino proton elastic scattering (pES) is sensitive to the axial form-factor and a possible channel for measuring Δs. A clear advantage of using neutrinos is that one does not need to rely on flavor symmetries or fragmentation functions. With this motivation, the E734 experiment at Brookhaven National Lab used neutrino beams on a liquid scintillator target to determine the axial form-factor for Q^2 \in 0.45–1.05 GeV^2 [13]. Upon extrapolating their results to Q^2 = 0, they obtained

Δs (E734) = -0.15 ± 0.09

for fixed axial-mass parameter (M_A). If M_A is not fixed, then there is large uncertainty in the extracted value of Δs as they are strongly correlated at these energies. The Fermilab experiment MiniBooNE has also measured Δs through pES and obtained Δs = 0.08±0.26 by measuring the ratio of neutrino-proton and neutrino-nucleon interactions. In Ref. [14], the authors reanalyze MiniBooNE data using z-expansion parametrization of the form factors and obtain

Δs (MiniBooNE) = -0.102 ± 0.178 ± 0.080

where the uncertainty is smaller due to fixing some parameters with results from lattice QCD. For a measurement of Δs that is practically independent of M_A, one requires an intense source of low-energy neutrinos and a detector that can efficiently measure the small energies of the recoiling proton. In Ref. [15], the authors propose using neutrinos from pion decay-at-rest to measure Δs in a kton-scale scintillation detector. In this paper, we look at the possibility of measuring Δs using supernova neutrinos and large-volume scintillation detectors.

In a core collapse supernova, nearly 99% of the binding energy of the progenitor is released in the form of neutrinos. These neutrinos are emitted with energies \mathcal{O}(10) MeV, and can generate nuclear recoils with Q^2 \sim 0.01 GeV^2. The elastic scattering of these neutrinos with protons has been identified as a promising channel to study the non-electron flavors, i.e., \nu_x = \nu_{\mu}, \nu_{\mu}, \nu_{\tau}, \nu_{\tau}, using scintillation detectors [16]. Even though the scintillation from recoil proton is quenched, one can get enough statistics to reconstruct the spectrum of \nu_x [17–21]. In

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these reconstruction techniques, $\Delta s$ has been regarded as a source of uncertainty in the cross-section. In this paper, we invert the question and ask, "how well can we constrain $\Delta s$ using neutrinos from a galactic supernova?". The uncertainty in reconstruction of $\Delta s$ can be approximated by,

$$
\delta \Delta s \approx \frac{1.27}{2} \left[ \frac{1}{N} + \left( \frac{\delta \Phi}{\Phi} \right)^2 \right]^{1/2}
$$

(1)

where $N$ is the total number of events and $\delta \Phi/\Phi$ is the fractional uncertainty in the total supernova neutrino flux. A multi-kton scintillation detector would observe few thousand pES events from a supernova at 10 kpc, resulting in a small contribution from the first term. Hence, the reconstruction of $\Delta s$ mainly depends on how well we can determine the supernova neutrino spectra.

Of all currently operational neutrino telescopes, the most promising candidate to measure supernova neutrino spectra is the water Cherenkov detector Super-Kamiokande [22]. The addition of Gadolinium (Gd) salts has greatly enhanced the neutron tagging efficiency [23, 24] and allows for a clean and large-statistics measurement of $\bar{\nu}_e$ using inverse beta decay. In order to detect other flavors, one has to rely on future detectors such as DUNE [25, 26], JUNO [27–29], Hyper-Kamiokande [30], and THEIA [31]. There are other proposed detectors such as HALO [32], deuterated liquid scintillator [33], and RES-NOVA [34] that have relatively smaller volume, but will play an important role in detection of supernova neutrinos.

For our analysis, we find that DUNE is the most promising candidate for measurement of $\nu_e$ spectrum via charged-current interactions with argon [35]. The water Cherenkov detector Super-Kamiokande (SK) or its upgrade Hyper-Kamiokande (HK) (both assumed to have Gd) would measure $\nu_e$ spectrum via inverse-beta decay. The non-electron flavors, i.e., $\nu_x$ can only be detected through neutral-current interactions. In SK and HK, $\nu_x$ will be detected using elastic scattering with electrons, which also gets contribution from $\nu_\tau$ and $\bar{\nu}_e$ [36]. Thus, a combination of DUNE and SK/HK, can detect all three components of supernova neutrinos independent of $\Delta s$. The measured neutrino spectra from these detectors can be used to predict the pES event rates in scintillation detectors, and comparison with measured rates can yield limits on $\Delta s$. This possibility is explored in detail in this paper.

So far, only linear alkyl benzene (LAB) based scintillator detectors such as Borexino, KamLAND, SNO+, and JUNO have been considered as candidates to detect pES events from a galactic supernova [16–20]. In this paper, we show that the water-based liquid scintillator (WbLS) detector, THEIA, would be an excellent candidate to detect pES events. The higher light yield and smaller $^{14}$C concentration allows for a lower threshold as compared to JUNO, and larger events rates despite similar volume. Using a benchmark value for fluence parameters, and uncertainties from DUNE and SK/HK determined from Ref. [35] and [36], we determine the sensitivity to $\Delta s$ using a simple Monte Carlo simulation for uncertainty quantification. The main results of this paper are summarized in Fig. 1, where we show our projected sensitivity from a galactic supernova along with results from pDIS, beam-neutrino experiments, and lattice QCD.

\section*{II. FORECAST FOR pES IN THEIA}

THEIA is a proposed hybrid detector that uses a cocktail-like water-based liquid scintillator (WbLS) as target [31]. There are two possible configurations, THEIA25 with 25 kton WbLS (20 kton fiducial volume) and THEIA100 with 100 kton WbLS (80 kton fiducial volume). In this work, we provide estimate for THEIA25, with an understanding that the results for THEIA100 can be appropriately scaled. The unique advantage of WbLS is the ability to simultaneously detect both scintillation and Cherenkov signals of charged particles. A large-scale WbLS detector will have excellent capacity to study diffuse supernova neutrino background, reactor neutrinos, and new physics scenarios such as proton decay [31]. If operational at the time, THEIA can also detect neutrinos from the next galactic supernova through inverse beta decay, electron elastic scattering, and interactions with oxygen (similar to a Cherenkov detector like SK/HK). As THEIA can also operate as scintillation detector, it
will be sensitive to pES similar to JUNO.

To estimate the spectrum of pES events in THEIA, we follow the outline of Ref. [17]. We assume a fiducial galactic supernova that emits a total energy of \(3 \times 10^{53}\) erg over a duration of \(\sim 15\) s. The fluence of neutrinos from such a supernova is given by

\[
\frac{dE_\nu}{dE} = \frac{1}{4\pi d^2} \frac{\mathcal{E}_\nu}{\langle E_\nu \rangle} \times \frac{d\varphi_\nu}{dE}
\]  

(2)

where \(\nu = \nu_e, \bar{\nu}_e, \nu_x\) represents the neutrino flavors, \(d\) is the distance to the supernova, \(\mathcal{E}_\nu\) is the luminosity, \(\langle E_\nu \rangle\) is the average energy, and \(d\varphi_\nu/dE\) is the unit-normalized spectra which can be parameterized as,

\[
\frac{d\varphi_\nu}{dE} = \frac{(1 + \alpha_\nu)^{1+\alpha_\nu}}{\Gamma(1+\alpha_\nu)} \frac{E^{\alpha_\nu}}{\langle E_\nu \rangle^{1+\alpha_\nu}} \exp\left(-\frac{(1 + \alpha_\nu) E}{\langle E_\nu \rangle}\right)
\]  

(3)

where \(\alpha_\nu\) is called the pinching parameter [37]. For our estimates, we use \(d = 10\) kpc, \(\alpha_\nu = 3\), \(\langle E_\nu \rangle = 12\) MeV, \(\langle E_\nu \rangle = 14\) MeV, and \(\langle E_\nu \rangle = 16\) MeV. We assume equipartition of among all six flavors.

The differential cross section for pES in the Llewellyn-Smith formalism is

\[
\frac{d\sigma}{dQ^2} = \frac{G_F^2 M_p^2}{8\pi E_\nu^2} \left[ A \pm B \frac{s-u}{M_p^2} + C \frac{(s-u)^2}{M_p^4} \right]
\]  

(4)

where \(s-u = 4M_\nu E_\nu - Q^2\), \(Q^2 = 2M_p T_p\), and \(T_p\) is the kinetic energy of the recoiling proton [38]. In terms of \(\tau = Q^2/4M_p^2\),

\[
A = 4\tau \left[ (1+\tau)G_A^2 - (1-\tau)F_2^2 + \tau(1-\tau)F_1^2 + 4\tau F_1 F_2 \right],
\]

\[
B = 4\tau \left[ G_A (F_1 + F_2) \right],
\]

\[
C = \frac{1}{4} \left[ G_A^2 + F_1^2 + F_2^2 \right],
\]

where \(F_{1,2}\) are the vector form-factors\(^1\), and \(G_A\) is the axial form-factor [13]. For supernova neutrino interactions, the maximum kinetic energy of recoiling protons is only a few MeV and a simpler expression for the cross section can be derived in the limit \(Q^2 \to 0\) [16]. The axial form-factor in this limit can be written as,

\[
\lim_{Q^2 \to 0} G_A = \frac{1}{2} (g_A - \Delta s)
\]  

(5)

where \(g_A = 1.2755(11)\) [39]. We note that, for \(\Delta s \in \pm 0.15\), the total cross section can change by \(\pm 25\%\). To estimate the event rates, we use \(\Delta s = -0.018\), which is the central value reported in Ref. [9].

Only a fraction of proton’s recoil energy is converted into detectable scintillation signal, a phenomenon known as quenching. The quenched proton energy, also called the visible energy, \(E_{vis}\), is given by,

\[
E_{vis} = \int_0^{T_p} \frac{dE}{1 + k_B \langle dE/dx \rangle + C \langle dE/dx \rangle^2}.
\]  

(6)

where \(T_p\) is the kinetic energy of the recoiling proton, \(\langle dE/dx \rangle\) is the average energy loss of proton in the medium, \(k_B\) is the Birks’ constant [42], and \(C\) is the bimolecular correction [43]. The proton light-yield of WbLS (formulated from 5% LAB) has been recently measured in Ref. [41] where the quenching parameters have been determined as,

\[
k_B^{WbLS} = (1.65 \pm 0.81) \times 10^{-3} \text{ (cm/MeV)}, \tag{7}
\]

\[
C^{WbLS} = (13.30 \pm 2.70) \times 10^{-6} \text{ (cm/MeV)}^2. \tag{8}
\]

We approximate \(\langle dE/dx \rangle\) as a weighted average of H\(_2\)O and LAB using the PSTAR\(^2\) database. The dissolved scintillator concentration in THEIA would be between 0.5%–5% depending on the performance. In this paper, we only consider the benchmark value of 5% for which quenching measurements are available. For other concentrations, the results can be scaled accordingly. In Fig. 2, we show \(E_{vis}(T_p)\) for WbLS (i.e, THEIA) along with the uncertainty arising from the measured quenching parameters. We also show \(E_{vis}(T_p)\) for LAB (i.e, JUNO) based on the measurements of von Krosigk et. al. [40] where the quenching parameters have been measured with 2–3% precision. We will assume that the uncertainty in

\(^{1}\) We use \(\sin^2(\theta_W) = 0.238\), which is the appropriate low-\(Q^2\) limit, resulting in a slightly weaker dependence on vector form-factors as compared to Ref. [16].

\(^{2}\) www.physics.nist.gov/PhysRefData/Star/Text/PSTAR.html
quenching parameters of WbLS can also be significantly reduced with future measurements, and only use the central values in our Monte Carlo.

It is well understood that the pES event rate is highly sensitive to the $E_{vis}$ threshold. A natural limit for $E_{vis}$ arises from the dark noise of photo multiplies tubes (PMTs). In JUNO, this dark rate will overwhelm any signal below 0.1 MeV despite sophisticated trigger schemes [44]. THEIA plans to use a combination of ultrafast PMTs and LAPPDs (Large Area Picosecond Photo-Detectors) [31, 45], which would be different from JUNO. 

Based on the trigger schemes and dark noise of individual PMTs and LAPPDs, one can determine the low-energy threshold for THEIA. However, this is beyond the scope of this work and we adopt 0.1 MeV as our threshold, similar to JUNO.

Another major background arises from beta-decay of intrinsic $^{14}$C [16]. For JUNO, the estimate for $^{14}$C levels is around $10^{-17}$ g/g, which results in a background activity of around 42 kHz/(20 kton) [46]. The scintillation signal of these electrons cannot be distinguished from the scintillation of recoiling protons, which results in a wall-like background below 0.2 MeV [16]. As a result, the threshold for pES events in JUNO is often considered to be 0.2 MeV. Ideally, the contamination level of $^{14}$C in JUNO would be lowered to $10^{-18}$ g/g, something that is already achieved in Borexino [47]. The $^{14}$C levels in THEIA is not yet determined. To approximate the $^{14}$C background in THEIA, we will assume that the scintillator component is extremely radiopure and Borexino-like $^{14}$C levels can be achieved in WbLS. As there are no long-lived radio-isotopes of oxygen, only the scintillator component of WbLS gives rise to large low-energy backgrounds.

Given the fineness, cross section, and quenching parameters, the computation of event rates is straightforward. In Fig. 3, we show the binned pES event spectrum ($\Delta E_{bin} = 0.1$ MeV) for JUNO and THEIA. Our estimates for JUNO agree with the ones reported in Refs. [18–20, 27], barring a small enhancement due to weaker quenching. Considering smearing due to energy resolution, we estimate that only 15% of $^{14}$C beta-decays would have $E_{vis} \in 0.1–0.2$ MeV, and none above that. Over the 15 s duration of the supernova explosion and for $E_{vis} \in 0.1–0.2$ MeV, we estimate that JUNO would detect ~9450 events from $^{14}$C beta decays, and ~1400 events from pES. On the other hand, THEIA would detect only ~475 events from $^{14}$C beta decays, and ~1150 events from pES. The duration of the supernova burst could be ~10 s and the $^{14}$C backgrounds can be scaled appropriately. The improved performance of THEIA can be attributed to the fact that it has a larger proton-to-$^{14}$C ratio and weaker quenching than JUNO. Lastly, we also note that THEIA would observe ~570 events for $E_{vis} \geq 0.6$ MeV where it would be theoretically possible to distinguish between electron and proton recoils using Cherenkov to scintillation ratio.

The neutrinos from a core-collapse supernova can be temporally separated in three phases: the neutronization burst, accretion, and cooling. The neutronization burst phase is the first ~20 ms interval where a prompt burst of $\nu_e$ occurs due to electron capture by free protons in the stellar nucleus. Unlike other phases, the neutronization burst phase has a very weak dependence on the progenitor properties, and is almost a standard candle. It has been proposed that the neutronization burst can be used to determine the supernova distance [50, 51], absolute neutrino mass [52–58], neutrino mass ordering [59],
as well as new physics scenarios [60, 61]. In Tab. I, we provide our estimated event rates from pES in JUNO and THEIA for a supernova at 10 kpc. We use the time-dependent flux parameters provided in EstrellaNueva [62] which relies on the simulations of Garching group \(^3\) [63]. We choose two benchmark progenitor masses, i.e., 15 \(M_\odot\) and 27 \(M_\odot\) and provide estimates using two equation of state, i.e., LS220 [48] and Shen [49]. We find that for \(E_{vis} \gtrsim 0.2\) MeV, we get \(\sim 2\) pES events in JUNO and \(\sim 5\) pES events in THEIA. We also note that for \(E_{vis} \in 0.1-0.2\) MeV, we get \(\sim 9\) pES events in JUNO and THEIA, and the \(^{14}\)C backgrounds are \(\sim 12\) and \(\sim 5\) in JUNO and THEIA respectively. A key message from this estimate is that for the first \(~20\) ms of a supernova, the pES event rates in THEIA will overwhelm the \(^{14}\)C backgrounds, whereas for JUNO, the event rates are comparable. This would have interesting applications for supernova early warning system (SNEWS) [64] where pES events may be used as secondary trigger.

\(^3\) https://wwwmpa.mpa-garching.mpg.de/ccsnarchive/
\(^4\) assuming \(^{14}\)C concentration of \(10^{-18}\) g/g

### III. Extracting \(\Delta s\) from pES

In order to reconstruct \(\Delta s\) from pES events in JUNO and THEIA, one needs to independently determine the flux of all flavors of supernova neutrinos. As mentioned earlier, we will rely on other neutrino detectors to provide information on fluence parameters using interactions that do not depend on \(\Delta s\). It has been demonstrated in Ref. [35] that DUNE can measure \(\nu_e\) fluence parameters through charged-current interactions with argon. On the other hand, \(\bar{\nu}_e\) and \(\nu_x\) parameters can be determined using water Cherenkov detectors through inverse beta decay, elastic scattering with electrons, and interactions with oxygen [36]. It must be noted that, Gadolinium loaded Hyper-Kamiokande can attain sensitivity to \(\nu_e\) similar to DUNE, and all fluence parameters can be determined from a single experiment [65]. Similarly, in Ref. [66] it is proposed to detect \(\nu_e\) using interactions on carbon in scintillator detectors. However, both methods rely on statistical subtraction of \(\nu_x\) events that would be measured using pES in JUNO-like detectors, and hence indirectly depend on \(\Delta s\). Thus, we argue that DUNE is essential for this analysis, and assume that it would be operational before the next galactic supernova. We consider both possibilities where Super-Kamiokande (SK) may or may-not be upgraded to Hyper-Kamiokande (HK). The uncertainties in reconstruction of fluence parameters using these detectors is summarized in Tab. II. We use the DUNE sensitivity to \(\nu_e\) from Ref. [35] and SK/HK sensitivity to \(\bar{\nu}_e\) and \(\nu_x\) from Ref. [36].

We use the technique of uncertainty quantification using Monte Carlo simulations to estimate the sensitivity of pES in JUNO and THEIA to \(\Delta s\). Although we can, in principle, look at the spectrum of events, instead we only use the total number of pES events to estimate \(\Delta s\).

### TABLE I. The expected pES event rates in JUNO and THEIA from the neutronization burst phase of a supernova at 10 kpc are tabulated below. We consider two benchmark progenitor masses, i.e., 15 \(M_\odot\) and 27 \(M_\odot\). The event rates depend on the nuclear equation of state (LS220 [48] and Shen [49]). We show the pES and \(^{14}\)C event rates for \(E_{vis} \in 0.1-0.2\) MeV and \(E_{vis} > 0.2\) MeV. The \(^{14}\)C concentration is optimistically assumed to be \(10^{-18}\) g/g.

| Model        | \(E_{vis}\) [MeV] | Event   | JUNO | THEIA |
|--------------|-------------------|---------|------|-------|
| 15 \(M_\odot\) (LS220) | 0.1 – 0.2 | pES     | 9.34 | 8.84  |
|              |                   | \(^{14}\)C | 12.60 | 0.63  |
|              | > 0.2             | pES     | 4.71 | 5.96  |
|              |                   | \(^{14}\)C | –    | –     |
| 15 \(M_\odot\) (Shen)  | 0.1 – 0.2 | pES     | 9.42 | 8.90  |
|              |                   | \(^{14}\)C | 12.60 | 0.63  |
|              | > 0.2             | pES     | 4.98 | 6.24  |
|              |                   | \(^{14}\)C | –    | –     |
| 27 \(M_\odot\) (LS220) | 0.1 – 0.2 | pES     | 9.77 | 9.26  |
|              |                   | \(^{14}\)C | 12.60 | 0.63  |
|              | > 0.2             | pES     | 4.95 | 6.26  |
|              |                   | \(^{14}\)C | –    | –     |
| 27 \(M_\odot\) (Shen)  | 0.1 – 0.2 | pES     | 9.98 | 9.40  |
|              |                   | \(^{14}\)C | 12.60 | 0.63  |
|              | > 0.2             | pES     | 5.31 | 6.65  |
|              |                   | \(^{14}\)C | –    | –     |

### TABLE II. The fractional symmetric uncertainties (1\(\sigma\)) on the flux parameters for a galactic supernova at 10 kpc are tabulated below. The uncertainties in \(\nu_e\) parameters measured with DUNE are adopted from Ref. [35]. The uncertainties in \(\bar{\nu}_e\) and \(\nu_x\) parameters measured by Super-Kamiokande (SK) or Hyper-Kamiokande (HK) are taken from Ref. [36]. The second column gives the central value of these parameters.

| Parameter | Cen. | DUNE+SK | DUNE+HK |
|-----------|------|---------|---------|
| \(E_{\nu_e}\) [10^{53} \text{erg}] | 0.5 | 13\% | 13\% |
| \(E_{\bar{\nu}_e}\) [10^{53} \text{erg}] | 0.5 | 10\% | 4\% |
| \(E_{\nu_x}\) [10^{53} \text{erg}] | 0.5 | 18\% | 8\% |
| \(\langle E_{\nu_e}\rangle\) [MeV] | 12 | 7\% | 7\% |
| \(\langle E_{\bar{\nu}_e}\rangle\) [MeV] | 14 | 6\% | 3\% |
| \(\langle E_{\nu_x}\rangle\) [MeV] | 16 | 11\% | 7\% |
| \(\alpha_{\nu_e}\) | 3.0 | 18\% | 18\% |
| \(\alpha_{\bar{\nu}_e}\) | 3.0 | 20\% | 7\% |
| \(\alpha_{\nu_x}\) | 3.0 | 21\% | 17\% |
candidates within 1 kpc [70]. To approximate the reconstruction efficiency of DUNE and SK/HK for a nearby supernova, we will assume that the systematic uncertainty (mainly arising from cross-sections) is small and the errors mentioned in Tab. II are mostly statistical. For a supernova at a distance \(d\), we scale the uncertainties by a factor of \(N^{-1/2} \sim d\) to obtain our estimates. One can consider our projected sensitivity for these supernovae to be optimistic. A careful re-analysis of reconstruction for nearby supernova is required, but beyond the scope of this work. The \(\delta \Delta s\) obtained have been tabulated in Tab. III for three benchmark distances of 10, 5, and 1 kpc. We present our results for two scenarios, with and without Hyper-Kamiokande. The uncertainties reported in Tab. III for various cases are shown in Fig. 1 along with results from other experiments for comparison.

In the method described above, one is limited by the ability to properly reconstruct the fluence parameters using other detectors. A promising possibility is to exploit the neutronization burst phase of the supernova. The neutrino flux from the neutronization burst is very well predicted through simulations, and does not depend heavily on the properties of the progenitor. However, we find that there are three challenges in reconstructing \(\Delta s\) using neutronization burst. First, despite being a standard candle, there are large (5-10\%) systematic uncertainties in the flux estimates. The differences arise partly from various nuclear physics parameters, and partly from the unknown mass of the progenitor [50]. This is the source of differences in event rates given in Tab. I. Second, if the supernova is obscured by galactic dust, the distance to the supernova will be poorly known. As \(\Delta s\) and \(d\) both have similar effects on pES event rates, they are strongly correlated and the reconstructed \(\Delta s\) would have large uncertainties as well. Lastly, only a small fraction of the total luminosity is emitted during the neutronization burst. The pES event rates in JUNO and THEIA

\[
\begin{array}{|c|c|c|}
\hline
\text{Distance} & \text{Detector} & \text{DUNE+SK} \pm \text{DUNE+HK} \\
\hline
10 \text{ kpc} & \text{JUNO} & \pm 0.223 \pm 0.146 \\
 & \text{THEIA} & \pm 0.160 \pm 0.099 \\
\hline
5 \text{ kpc} & \text{JUNO} & \pm 0.117 \pm 0.078 \\
 & \text{THEIA} & \pm 0.085 \pm 0.053 \\
\hline
1 \text{ kpc} & \text{JUNO} & \pm 0.024 \pm 0.015 \\
 & \text{THEIA} & \pm 0.017 \pm 0.010 \\
\hline
\end{array}
\]

**TABLE III.** The symmetrized 1σ uncertainties on the \(\Delta s\) obtained from a fiducial galactic supernova are tabulated for three choices of distance. The \(\nu_e\) spectrum is determined from DUNE. The two columns refer to the two scenario where \(\nu_e\) and \(\nu_x\) are determined from gadolinium doped Super-Kamiokande (SK) or Hyper-Kamiokande (HK). The pES events can be measured using either JUNO or THEIA. The higher sensitivity of THEIA is due to weaker quenching and lower backgrounds than JUNO.
are small (cf. Tab. 1), and result in large statistical uncertainty. Our preliminary estimates suggest that the reconstructed $\Delta s$ is not significantly better than the one obtained by the aggregate pES events for a supernova at 10 kpc. For a nearby supernova, the uncertainty in the distance would be much smaller. A dedicated study of reconstruction of spectra of neutrinos from neutronization burst in DUNE and SK/HK would be required for a more refined estimate the $\Delta s$-sensitivity. We look forward to future work in this direction.

IV. SUMMARY

A core collapse supernova in our galaxy would provide an excellent opportunity to study low-energy physics. In this paper, we looked at the possibility whether the strange spin of proton, $\Delta s$, could be measured using neutrinos from the next galactic supernova, and the results look promising. We utilize the ability of near-future detectors DUNE and Hyper-Kamiokande to reliably estimate the spectra of all flavors of supernova neutrinos using interactions that do not depend on $\Delta s$. The reconstructed spectra can be used to estimate the pES event rate in large-volume scintillation detectors such as JUNO and/or THEIA, and compared with the measured event rates. Assuming that the variation only arises because of an unknown $\Delta s$, it is straightforward to reconstruct the allowed values of $\Delta s$.

To estimate the sensitivity of JUNO and THEIA, we perform a simple Monte Carlo simulation for uncertainty quantification. For a supernova at 10 kpc, we estimate that JUNO would be able to constrain $\Delta s$ within $\pm 0.15$ ($\pm 0.22$) using the reconstructed fluence parameters from DUNE and Hyper-(Super-)Kamiokande; whereas THEIA would be able to constrain $\Delta s$ within $\pm 0.10$ ($\pm 0.16$) using DUNE and Hyper-(Super-)Kamiokande. The better performance of THEIA is due to larger light yield of water-based liquid scintillator as compared to linear alkyl benzenes, and relatively larger proton-to-$^{14}$C ratio that allows for a lower threshold. We also provide estimates for the neutronization burst phase, and note that for the brief $\sim 20$ ms window, the pES event rates in THEIA would be larger than the $^{14}$C background. Moreover, the pES event rates from neutronization burst in JUNO are comparable to $^{14}$C background. We propose that pES events could also be used in supernova early warning systems as secondary or fail-safe triggers.

If we are lucky and the next galactic supernova is within 1 kpc, then the projected sensitivity improves to approximately $\pm 0.01$ which is comparable to results from lattice QCD, and better than polarized deep-inelastic scattering experiments. Such a nearby supernova would provide us with a once-in-a-lifetime opportunity to measure the true $Q^2 \rightarrow 0$ limit of neutrino-proton scattering, without a dedicated experiment. The rare circumstance and the reliance on multiple large-volume detectors is an attestation to the difficulty of experimental determination of $\Delta s$.

ACKNOWLEDGMENTS

The author would like to thank Ranjan Laha, Busudeb Dasgupta, Mary Hall Reno, Vedran Brdar, and Xunjie Xu for their useful comments on the manuscript. This work is supported in part by US Department of Energy grant DE-SC-0010113. The author also acknowledges the support of TIFR (India) where a part of this work was completed.
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