

Using $\bar{p}p$ and e^+e^- annihilation data to refine bounds on the baryon-number-violating dinucleon decays $nn \rightarrow e^+e^-$ and $nn \rightarrow \mu^+\mu^-$

Shmuel Nussinov¹ and Robert Shrock²

¹*School of Physics and Astronomy, Tel Aviv University, 6997801 Tel Aviv, Israel*

²*C. N. Yang Institute for Theoretical Physics and Department of Physics and Astronomy, Stony Brook University, Stony Brook, New York 11794, USA*



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We use $\bar{p}p$ and e^+e^- annihilation data to further strengthen lower bounds on the partial lifetimes for the baryon-number-violating dinucleon decays $nn \rightarrow e^+e^-$ and $nn \rightarrow \mu^+\mu^-$. These bounds are of interest since baryon number violation is expected to occur in nature and is predicted in many theories beyond the Standard Model.

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I. INTRODUCTION

In Ref. [1], lower limits on the partial lifetimes $\tau/BR \equiv \Gamma^{-1}$ for a number of $\Delta B = -2$, $\Delta L = 0$ dinucleon decays were presented, including $nn \rightarrow e^+e^-$, $nn \rightarrow \mu^+\mu^-$, $nn \rightarrow \nu_\ell\bar{\nu}_\ell$, and $np \rightarrow \ell^+\nu_\ell$, where $\ell = e, \mu, \tau$. (Here, for the decay of an initial state to a given final state, Γ and BR denote the decay rate and branching ratio, and τ denotes the mean life of the initial state.) The lower bounds obtained in [1] were substantially stronger than limits from direct experimental searches. In this paper we use data on $\bar{p}p$ and e^+e^- annihilation to further improve the lower limits on the partial lifetimes for $nn \rightarrow e^+e^-$ and $nn \rightarrow \mu^+\mu^-$ decays.

The violation of baryon number, B , is expected to occur in nature, because this is one of the necessary conditions for generating the observed baryon asymmetry in the universe [2]. Baryon number violation (BNV) is, indeed, predicted in many ultraviolet extensions of the Standard Model (SM), such as grand unified theories. A number of dedicated experiments have been carried out since the early 1980s to search for proton decay (and the decay of neutrons bound in nuclei). These experiments have obtained null results and have set stringent lower limits on the partial lifetimes for such $\Delta B = -1$ baryon-number-violating nucleon decays. A particularly strong lower bound, $\tau/BR > 1.6 \times 10^{34}$ yrs, has been set by the Super-Kamiokande (SK) experiment for the decay channel $p \rightarrow e^+\pi^0$ [3], which can be clearly identified in the water Cherenkov detector of this

experiment. (This and other experimental limits are quoted at the 90% confidence level, CL.)

A different type of baryon number violation has also received attention, namely $n - \bar{n}$ oscillations, which have $|\Delta B| = 2$ [4–19]. It was observed early on that $n - \bar{n}$ oscillations might provide the source of baryon number violation necessary for baryogenesis [4]. We briefly review some background and basic notation (see also [1]). We denote the $n - \bar{n}$ transition amplitude as $\langle \bar{n} | \mathcal{H}_{\text{eff}} | n \rangle \equiv \delta m$. In (field-free) vacuum, the Hamiltonian matrix has diagonal elements $\langle n | \mathcal{H}_{\text{eff}} | n \rangle = \langle \bar{n} | \mathcal{H}_{\text{eff}} | \bar{n} \rangle = m_n - i(\lambda_n/2)$, where $\lambda_n = 1/\tau_n$ is the decay rate of a free neutron. The diagonalization of this matrix yields the mass eigenstates $|n_\pm\rangle = (|n\rangle \pm |\bar{n}\rangle)/\sqrt{2}$, with eigenvalues $m_\pm = (m_n \pm \delta m) - i\lambda_n/2$. Starting with a pure $|n\rangle$ state at $t = 0$, there is then a probability for this to be an $|\bar{n}\rangle$ at time $t > 0$ given by $|\langle \bar{n} | n(t) \rangle|^2 = [\sin^2(t/\tau_{n\bar{n}})]e^{-\lambda_n t}$, where $\tau_{n\bar{n}} = 1/|\delta m|$. An experiment at the Institut Laue-Langevin searched for $n - \bar{n}$ oscillations using a neutron beam from a reactor and obtained the lower bound $\tau_{n\bar{n}} > 0.86 \times 10^8$ sec, i.e., $|\delta m| < 0.77 \times 10^{-29}$ MeV [11].

The presence of a nonzero transition amplitude $\langle \bar{n} | \mathcal{H}_{\text{eff}} | n \rangle$ means that a physical neutron state $|n\rangle_{\text{phys}} = \cos\theta_m |n\rangle + \sin\theta_m |\bar{n}\rangle$ in a nucleus has an admixture of $|\bar{n}\rangle$. This admixture has a very small coefficient,

$$\sin\theta_m \simeq \theta_m \sim \frac{|\delta m|}{[(V_{n,R} - V_{\bar{n},R})^2 + V_{\bar{n},I}^2]^{1/2}} \lesssim 10^{-31}, \quad (1.1)$$

where $V_n = V_{n,R}$ and $V_{\bar{n}} = V_{\bar{n},R} + iV_{\bar{n},I}$ denote the potentials of the n and \bar{n} in the nucleus. As reflected by the imaginary term $iV_{\bar{n},I}$ in $V_{\bar{n}}$, the small admixture of $|\bar{n}\rangle$ in $|n\rangle_{\text{phys}}$ leads to annihilation with a neighboring neutron or proton in the nucleus, and thus to $\Delta B = -2$ dinucleon decays. Owing to the dominance of strong over

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electroweak interactions, these dinucleon decays yield mainly hadronic final states, typically comprised of multiple pions. The small coefficient θ_m is compensated by the large number $\sim 10^{33}$ of nucleons in a nucleon decay detector, so nucleon decay experiments are also sensitive to these $\Delta B = -2$ dinucleon decays (a recent review is [16]).

Because the operators that contribute to baryon-number-violating decays of individual nucleons are four-fermion operators with coefficients of mass dimension -2 , while the operators that contribute to $n - \bar{n}$ transitions and the associated dinucleon decays are six-quark operators with coefficients of mass dimension -5 , it follows that, if the physics responsible for baryon number violation were characterized by a single mass scale, M_{BNV} , then nucleon decays would be much more important than $n - \bar{n}$ oscillations as a manifestation of baryon number violation. However, there are examples of beyond-Standard-Model (BSM) physics in which (because of exact or approximate symmetries in the models) BNV nucleon decay is absent [6] or is suppressed well below observable levels [12], so that $n - \bar{n}$ oscillations and the associated $\Delta B = -2$ dinucleon decays are the main manifestation of baryon number violation and can occur at levels comparable to current bounds. Some further studies of such models include [15,20,21].

There is thus strong motivation to investigate the implications of current experimental limits on $\Delta B = -2$ dinucleon decays. Using a minimal effective field theory approach, Ref. [1] derived approximate relations between the rates for dinucleon decays to hadronic final states and to various $\Delta L = 0$ dilepton final states and combined these with experimental lower bounds on the partial lifetimes for these hadronic dinucleon decays to infer rough lower bounds on the dinucleon decays to dileptons. In the present work we shall use $\bar{p}p$ and e^+e^- annihilation data to strengthen the lower bounds obtained in Ref. [1] on the partial lifetimes for the dinucleon decays $nn \rightarrow \ell^+\ell^-$, where ℓ denotes e or μ .

II. BACKGROUND

We first recall some relevant background. In the presence of a nonzero $n - \bar{n}$ transition amplitude δm and the associated dinucleon decays, the rate for matter instability is

$$\Gamma_{m.i.} \equiv \frac{1}{\tau_{m.i.}} \simeq \frac{2(\delta m)^2 |V_{\bar{n}l}|}{(V_{nR} - V_{\bar{n}R})^2 + V_{\bar{n}l}^2}. \quad (2.1)$$

It follows that $\tau_{m.i.} \propto (\delta m)^{-2} = \tau_{n\bar{n}}^2$. Explicitly, $\tau_{m.i.} = R\tau_{n\bar{n}}^2$, where the factor $R \sim O(10^2)$ MeV $\simeq 10^{23}$ sec $^{-1}$ depends on the nucleus. The SK experiment has set the best limit on this type of matter instability [19], $\tau_{m.i.} > 1.9 \times 10^{32}$ yr. Antiproton annihilation on hydrogen yields multipion final states with average multiplicities of

~ 5 [22,23]. Monte Carlo simulations that account for the absorption of \bar{n} annihilation pions on their way out of the ^{16}O nucleus have been carried out in Ref. [19]. These simulations yield considerably lower average pion multiplicities, namely 3.5 and 2.2 for total and charged pion multiplicities resulting from an \bar{n} annihilation in an ^{16}O nucleus [19]. Consequently, there is a substantially larger probability for two-pion final states to occur in antinucleon-nucleon annihilation in the ^{16}O nuclei in the SK detector than in $\bar{p}p$ annihilation. The most restrictive lower bound on the partial lifetime of an exclusive nn dinucleon decay is for dineutrons in ^{16}O [24], namely

$$\Gamma_{nn \rightarrow 2\pi^0}^{-1} > 4.04 \times 10^{32} \text{ yr}. \quad (2.2)$$

The leading contribution to the decay $nn \rightarrow \ell^+\ell^-$ is described by a Feynman diagram in which the $|\bar{n}\rangle$ component in an initial $|n\rangle_{\text{phys}}$ annihilates with a neighboring n , producing a virtual photon γ in the s -channel, which then materializes into the final-state $\ell^+\ell^-$ pair. There is also a weak neutral-current contribution from a diagram with a virtual Z boson in the s -channel, but this is heavily suppressed by the factor $(2m_N)^2/m_Z^2 < 10^{-3}$. Let us denote the four-momentum of the virtual photon as q and the four-momenta of the ℓ^- and ℓ^+ as p_2 and p_1 , with $q = p_1 + p_2$ and $q^2 = s = (2m_N)^2$. Neglecting the heavily suppressed weak neutral-current contribution, and neglecting small effects due to Fermi motion, the amplitude for $nn \rightarrow \ell^+\ell^-$ is

$$A_{nn \rightarrow \ell^+\ell^-} = (\delta m)e^2 \langle 0 | J_{em}^\lambda | n\bar{n} \rangle \frac{1}{q^2} [\bar{u}(p_2)\gamma_\lambda v(p_1)], \quad (2.3)$$

where δm represents the initial $n - \bar{n}$ transition amplitude, and $e = \sqrt{4\pi\alpha_{em}}$ and J_{em}^λ denote the electromagnetic coupling and current.

It follows that

$$\begin{aligned} \Gamma_{nn \rightarrow \ell^+\ell^-} &\sim P e^4 \frac{R_2^{(\ell^+\ell^-)}}{R_2^{(2\pi^0)}} \Gamma_{nn \rightarrow 2\pi^0} \\ &\sim P e^4 \Gamma_{nn \rightarrow 2\pi^0}, \end{aligned} \quad (2.4)$$

where P denotes the probability that the total angular momentum of the initial nn state is greater than 0 and the initial state has the appropriate quantum numbers to produce a nonzero amplitude $A_{nn \rightarrow \ell^+\ell^-}$. Note that a $J = 0$ initial nn state yields a vanishing coupling $\propto q_\lambda [\bar{v}(p_2)\gamma^\lambda u(p_1)] = 0$ with the lepton electromagnetic current bilinear. This estimate made use of the fact that the ratio of two-body phase space factors $R_2^{(\ell^+\ell^-)}/R_2^{(2\pi^0)}$ is very close to unity for both $\ell = e$ and $\ell = \mu$. Combining (2.4) with the experimental lower limit (2.2) for a dineutron in an ^{16}O nucleus, Ref. [1] then obtained the rough estimate for

the lower bound on the partial lifetime (i.e., inverse decay rate Γ^{-1}) for $nn \rightarrow \ell^+\ell^-$ in an ^{16}O nucleus:

$$\begin{aligned} \Gamma_{nn \rightarrow \ell^+\ell^-}^{-1} &\gtrsim P^{-1}(5 \times 10^{34} \text{ yr}) \\ &\gtrsim 5 \times 10^{34} \text{ yr} \quad \text{for } \ell = e, \mu. \end{aligned} \quad (2.5)$$

III. APPLICATION OF $\bar{p}p$ AND e^+e^- ANNIHILATION DATA

We next improve the rough lower limit (2.5) in [1] by using $\bar{p}p$ and e^+e^- annihilation data. For a given reaction or decay, let s_i denote an initial state and let s_a and s_b

denote two (kinematically allowed) final states. It will be convenient to introduce the compact notation

$$R_{s_a/s_b}^{(s_i)} \equiv \frac{\Gamma_{s_i \rightarrow s_a}}{\Gamma_{s_i \rightarrow s_b}} = \frac{\text{BR}(s_i \rightarrow s_a)}{\text{BR}(s_i \rightarrow s_b)}. \quad (3.1)$$

We will calculate $R_{\ell^+\ell^-/2\pi^0}^{(\bar{n}n)}$ as an input for $R_{\ell^+\ell^-/2\pi^0}^{(nn)}$. Our input data will be from experiments on \bar{p} annihilation. Therefore, it will be useful to reexpress the ratio $R_{\ell^+\ell^-/2\pi^0}^{(\bar{n}n)}$ in terms of the ratio $R_{\ell^+\ell^-/2\pi^0}^{(\bar{p}p)}$ multiplied by appropriate factors. Thus, for $\ell = e, \mu$, we write

$$R_{\ell^+\ell^-/2\pi^0}^{(\bar{n}n)} \equiv \frac{\Gamma_{\bar{n}n \rightarrow \ell^+\ell^-}}{\Gamma_{\bar{n}n \rightarrow 2\pi^0}} = \frac{\left[\frac{\Gamma_{\bar{n}n \rightarrow \ell^+\ell^-}}{\Gamma_{\bar{p}p \rightarrow \ell^+\ell^-}} \right]}{\left[\frac{\Gamma_{\bar{n}n \rightarrow 2\pi^0}}{\Gamma_{\bar{p}p \rightarrow 2\pi^0}} \right]} \frac{\Gamma_{\bar{p}p \rightarrow \ell^+\ell^-}}{\Gamma_{\bar{p}p \rightarrow 2\pi^0}} = \left[\frac{\Gamma_{\bar{n}n \rightarrow \ell^+\ell^-}}{\Gamma_{\bar{p}p \rightarrow \ell^+\ell^-}} \right] \frac{\text{BR}(\bar{p}p \rightarrow \ell^+\ell^-)}{\text{BR}(\bar{p}p \rightarrow 2\pi^0)}. \quad (3.2)$$

From the isospin invariance of strong interactions, it follows that

$$\frac{\Gamma_{\bar{n}n \rightarrow 2\pi^0}}{\Gamma_{\bar{p}p \rightarrow 2\pi^0}} = 1, \quad (3.3)$$

up to small corrections such as those due to electromagnetism.

Next, we focus on the case $\ell = e$ and make use of experimentally measured quantities. Since photon exchange in the s -channel makes by far the dominant contribution to the reactions $\bar{n}n \rightarrow e^+e^-$ and $\bar{p}p \rightarrow e^+e^-$ and since electromagnetic reactions are invariant under time reversal, we will use experimental data on the reactions $e^+e^- \rightarrow \bar{p}p$ and $e^+e^- \rightarrow \bar{n}n$ to determine the ratio $\Gamma_{\bar{n}n \rightarrow e^+e^-}/\Gamma_{\bar{p}p \rightarrow e^+e^-}$ in the $\ell = e$ special case of Eq. (3.2). The $e^+e^- \rightarrow \bar{p}p$ cross section at center-of-mass energies \sqrt{s} near threshold has been measured in a number of experiments, e.g., at Orsay [25], Frascati [26], BEPC [27], SLAC [28], and Novosibirsk [29,30]. For \sqrt{s} beyond the kinematic zero at threshold, this cross section is relatively flat in the interval I : $1.9 < \sqrt{s} \lesssim 2.0$ GeV, with the value

$$\sigma(e^+e^- \rightarrow \bar{p}p) \simeq 0.9 \pm 0.1 \text{ nb}. \quad (3.4)$$

The cross section $\sigma(e^+e^- \rightarrow \bar{n}n)$ was measured in an early experiment by the FENICE Collaboration at ADONE [31], and more recently in experiments at Novosibirsk, with the result [29,30,32]

$$\sigma(e^+e^- \rightarrow \bar{n}n) \simeq 0.85 \pm 0.20 \text{ nb} \quad (3.5)$$

for $\sqrt{s} \in I$. The uncertainties listed here are estimates based on the comparison of values measured at a given \sqrt{s}

by the different experiments, as weighted by their error bars. In passing, it is interesting to note that the $e^+e^- \rightarrow \bar{p}p$ and $e^+e^- \rightarrow \bar{n}n$ cross sections in this energy interval are nearly equal, to within experimental uncertainties, despite the fact that the proton is charged while the neutron is neutral. (A review of results on $e^+e^- \rightarrow \bar{p}p$ and $e^+e^- \rightarrow \bar{n}n$ up to 2013 is given in [33].) Using time reversal invariance, we thus obtain

$$\frac{\Gamma_{\bar{n}n \rightarrow e^+e^-}}{\Gamma_{\bar{p}p \rightarrow e^+e^-}} \simeq \frac{\sigma_{e^+e^- \rightarrow \bar{n}n; I}}{\sigma_{e^+e^- \rightarrow \bar{p}p; I}} \simeq 0.9, \quad (3.6)$$

where the subscript I indicates that the cross sections on the right-hand side of (3.6) were measured in the interval $\sqrt{s} \in I$ near threshold, but beyond the kinematic falloff at threshold.

Finally, we need to determine the third ratio in the $\ell = e$ special case of Eq. (3.2), $\text{BR}(\bar{p}p \rightarrow e^+e^-)/\text{BR}(\bar{p}p \rightarrow 2\pi^0)$. Measurements of the numerator of this ratio with stopped antiprotons include a CERN experiment that obtained $\text{BR}(\bar{p}p \rightarrow e^+e^-) = (3.2 \pm 0.9) \times 10^{-7}$ [34] and the subsequent PS170 experiment at LEAR (Low Energy Antiproton Annihilation Ring) at CERN, which obtained the more accurate value [35]

$$\text{BR}(\bar{p}p \rightarrow e^+e^-) = (3.58 \pm 0.10) \times 10^{-7}. \quad (3.7)$$

Several experiments have measured $\text{BR}(\bar{p}p \rightarrow 2\pi^0)$ for \bar{p} annihilation at rest, as reviewed, e.g., in [22,23]; in particular, the Crystal Barrel experiment at LEAR obtained the result [36]

$$\text{BR}(\bar{p}p \rightarrow 2\pi^0) = (6.93 \pm 0.43) \times 10^{-4} \quad (3.8)$$

for \bar{p} annihilation in liquid hydrogen. From isospin invariance, this value would also hold for the hypothetical

annihilation of an \bar{n} on a free neutron to yield a $2\pi^0$ final state. Since there is no phase-space suppression of the $\bar{p}p \rightarrow 2\pi^0$ reaction, a remark on the small branching ratio (3.8) is in order. The $|2\pi^0\rangle$ state has a wave function of the form $|2\pi^0\rangle = \chi_I \chi_L$, where I and L denote the isospin and relative orbital angular momentum of the pion pair, respectively. This wave function must be symmetric under exchange of identical bosons. Since the isospin Clebsch-Gordon coefficient $\langle I_a I_b I_{a3} I_{b3} | II_3 \rangle = \langle 1100 | 10 \rangle = 0$, it follows that $|2\pi^0\rangle$ has $I = 0$ or $I = 2$, both of which are even, so χ_I is symmetric. Consequently, χ_L must also be symmetric, and hence L must be even. Therefore, this $|2\pi^0\rangle$ state has $J^{PC} = J^{++}$ with total angular momentum $J = L = \text{even}$. An $|\bar{N}N\rangle$ state, where $N = p$ or $N = n$, with nearly minimal center-of-mass energy $\sqrt{s} \simeq 2m_N$ (e.g., a $|\bar{p}p\rangle$ state resulting from a stopping antiproton beam incident on a hydrogen target) preferentially has $L = 0$, and hence $P = -(-1)^L = -1$. Thus, there is a mismatch between the parity of the dominant, ground-state component in the initial $|\bar{N}N\rangle$ state and the parity of the $|2\pi^0\rangle$ final state. The $\bar{N}N \rightarrow 2\pi^0$ reaction can proceed, but from an initial $|\bar{N}N\rangle$ state with $S = 1$ and a kinematically dispreferred $L = 1$, coupled to $J = 0$ (or $J = 2$). This parity mismatch and resultant suppression contribute to the small value of the branching ratio in (3.8).

Our application of these results is for \bar{n} annihilation in an oxygen nucleus in the water of the SK detector, and for this case, one must take into account the fact that the hadronic products of the annihilation reaction undergo reactions and absorption while propagating through the interior of the ^{16}O nucleus. This has the effect of increasing the branching ratios for two-pion channels relative to the branching ratios for higher-multiplicity pion channels. A Monte Carlo study of the effect of this intranuclear propagation on the branching ratios for various hadronic products of $\bar{n}n$ annihilation was carried out by the SK experiment with the resultant estimate, for $\bar{n}n$ annihilation in ^{16}O [19]:

$$\text{BR}(\bar{n}n \rightarrow 2\pi^0)_{^{16}\text{O}} = 1.5 \times 10^{-2}. \quad (3.9)$$

Since the ratios of two-body phase space factors $R_2^{(e^+e^-)}/R_2^{(2\pi^0)}$ and $R_2^{(\mu^+\mu^-)}/R_2^{(2\pi^0)}$ are nearly equal (with both being quite close to unity), our results can also be applied to the ratio $R_{\mu^+\mu^-/2\pi^0}^{(\bar{n}n)}$. Substituting the various inputs into the right-hand side of Eq. (3.2), we obtain the result

$$\frac{\Gamma_{\bar{n}n \rightarrow \ell^+\ell^-}}{\Gamma_{\bar{n}n \rightarrow 2\pi^0, ^{16}\text{O}}} \simeq 2 \times 10^{-5} \quad \text{for } \ell = e, \mu. \quad (3.10)$$

We next use this experimentally derived ratio for $\Delta B = 0$ $\bar{n}n$ annihilation processes to obtain an estimate of the ratio of $\Delta B = -2$ processes $\Gamma_{nn \rightarrow \ell^+\ell^-} / \Gamma_{nn \rightarrow 2\pi^0, ^{16}\text{O}}$. The

underlying $n - \bar{n}$ transition matrix element factor $(\delta m)^2$ divides out in this ratio. The further analysis thus involves a study of the degree of overlap between the $|\bar{n}n\rangle$ state immediately following the $n - \bar{n}$ transition (or equivalently, the state $|\bar{n}n\rangle$ resulting from the combination of two $|n\rangle_{\text{phys}}$ states) and the two final states. Since the annihilation occurs on the length scale of ~ 1 fm, a reasonable approximation is to consider the initial $|nn\rangle$ and $|\bar{n}n\rangle$ states by themselves, independent of the other nucleons on the nucleus. The wave function of the $|nn\rangle$ state has the form $|nn\rangle = \phi_I \phi_S \phi_L$, where I , S , and L denote the isospin, spin, and orbital angular momentum of the nn dineutron. This wave function must be antisymmetric under interchange of identical fermions, so since $I = 1$ (symmetric), it follows that the product $\phi_S \phi_L$ must be antisymmetric under this interchange. The energetically preferred configuration is the one with lowest energy, i.e., the ground state, which has $L = 0$, so ϕ_L is symmetric, and therefore the neutron spins must combine antisymmetrically to produce $S = 0$. The six-quark operator in the effective Lagrangian that mediates the $n - \bar{n}$ transition is a Lorentz scalar and hence does not change S or L , so the $|\bar{n}n\rangle$ state immediately after this transition also has $S = L = 0$ and hence, in standard spectroscopic notation, is a 1S_0 state. For a fermion-antifermion pair, $P = -(-1)^L$ and $C = (-1)^{L+S}$, so this $|\bar{n}n\rangle$ state has $J^{PC} = 0^{-+}$. This cannot couple directly to the photon, which has $J^{PC} = 1^{--}$, so there is a mismatch in both J and C . The requisite J^{PC} can occur as the result of a spin flip (SF) from $S = 0$ to $S = 1$. We incorporate the probability for this in a factor P_{SF} . As discussed above, for the $|nn\rangle \rightarrow |\bar{n}n\rangle \rightarrow |2\pi^0\rangle$ transition, we use the SK Monte Carlo results.

We thus obtain the improved estimate

$$\Gamma_{nn \rightarrow \ell^+\ell^-} = (2 \times 10^{-5}) P_{SF} \Gamma_{nn \rightarrow 2\pi^0} \quad \text{for } \ell = e, \mu. \quad (3.11)$$

Combining our result (3.11) with the experimental lower limit on $\Gamma_{nn \rightarrow 2\pi^0}^{-1}$ in Eq. (2.2), we infer the lower bound

$$\begin{aligned} \Gamma_{nn \rightarrow \ell^+\ell^-}^{-1} &\gtrsim (2 \times 10^{37}) P_{SF}^{-1} \text{ yrs} \\ &> 2 \times 10^{37} \text{ yrs} \quad \text{for } \ell = e, \mu, \end{aligned} \quad (3.12)$$

where the second line in the inequality (3.12) is a conservative limit that just uses the fact that the spin-flip probability $P_{SF} < 1$. As was true of the bounds derived in [1] and even more so here, this is much stronger than the direct lower bounds on the partial lifetimes (from the SK experiment) [37]:

$$\Gamma_{nn \rightarrow e^+e^-}^{-1} > 4.2 \times 10^{33} \text{ yr} \quad (3.13)$$

and

$$\Gamma_{nn \rightarrow \mu^+\mu^-}^{-1} > 4.4 \times 10^{33} \text{ yr}. \quad (3.14)$$

IV. CONCLUSIONS

In this paper, using experimental data on $\bar{p}p$ and e^+e^- annihilation, we have obtained strengthened lower bounds on the partial lifetimes for the dinucleon decays $nn \rightarrow e^+e^-$ and $nn \rightarrow \mu^+\mu^-$. Our bounds improve upon those in Ref. [1] and are considerably stronger than direct experimental lower bounds on these decays. These bounds should thus be of value in the continuing search for baryon-number violation, which will be

carried on to higher sensitivity at the future Hyper-Kamiokande experiment and Deep Underground Neutrino Experiment (DUNE).

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