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BSM PHYSICS

Some Recent Results on Physics Beyond the Standard Model

Robert Shrock*

C. N. Yang Institute for Theoretical Physics and Department of Physics and Astronomy, Stony Brook University, Stony Brook, 11794, NY USA

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Abstract—We discuss some recent results on physics beyond the Standard Model, including constraints on sterile neutrinos, charged lepton flavor violation, and baryon number violation.

Keywords: neutrino masses and mixing, baryon number violation, $n - \bar{n}$ oscillations

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1. INTRODUCTION

Although the Standard Model (SM), as extended to include neutrino masses and lepton mixing, has been quite successful in describing a wealth of data, it is recognized as being incomplete in a number of respects, motivating studies of possible beyond-Standard-Model (BSM) physics. Here, we will discuss some recent work on such studies, focusing on constraints on sterile neutrinos, charged lepton flavor violation, and baryon number violation.

2. CONSTRAINTS ON STERILE NEUTRINOS

The observation of neutrino oscillations showed the existence of neutrino masses and lepton mixing, i.e., lepton family number violation (LFV). Writing the weak charged current as $J_\lambda = \bar{\ell}_L \gamma_\lambda \nu_{\ell,L}$, where $\ell = (e, \mu, \tau)$, one has $\nu_\ell = \sum_{i=1}^{3+n_s} U_{\ell i} \nu_i$, where U is the lepton mixing matrix, ν_i denote neutrino mass eigenstates, and n_s is the number of possible additional neutrino mass eigenstates beyond the three observed ones. These n_s additional mass eigenstates would comprise dominant components in electroweak-singlet ("sterile") neutrinos. An outstanding task is to obtain constraints on sterile neutrinos. In [1, 2] with D. Bryman, we derived a number of new constraints of this type. Our methods made use of the earlier work [3–5] in which new tests were proposed to probe for effects of massive neutrinos in nuclear and particle decays and were applied to existing data. For simplicity, we focus here on limits on a single heavy neutrino, ν_4. Using the agreement among $\mathcal{F}t$ values for superallowed nuclear beta decays, we derived an improved upper limits on $|U_{e4}|^2$ for a ν_4 with mass in the MeV range. Moreover, a general effect of heavy neutrino(s) would be to change the ratios $R^{(\pi)}_{e/\mu} = BR(\pi^+ \to e^+\nu_e)/BR(\pi^+ \to \mu^+\nu_\mu)$, $R^{(K)}_{e/\mu}$, $R^{(D_s)}_{e/\tau}$, $R^{D}_{e/\tau}$, and the branching ratios for $B^+ \to \ell^+\nu_\ell$ ($\ell = e,\ \mu$) from their SM values. In [1, 2] we used the agreement of these ratios with the SM predictions to set upper limits on $|U_{e4}|^2$ and $|U_{\mu 4}|^2$ for a wide range of ν_4 masses extending up to a GeV. For example, we obtained the bound $|U_{e4}|^2 < 10^{-7}$ for $m_{\nu_4} = 50$ MeV. We also discussed constraints from pion beta decay, $\pi^+ \to \pi^0 e^+ \nu_e$, μ decay, leptonic τ decays, and other experimental inputs. One of the tests in [3, 4] was to search for emission of a heavy neutrino in two-body leptonic decays of pseudoscalar mesons $M^+ \to \ell^+\nu_\ell$, where $M^+ = \pi^+,\ K^+,\ D^+,\ D_s^+, B^+$, and ℓ is a charged lepton. This test is quite powerful because of the monochromatic signal in the charged lepton energy and the removal of helicity suppression in the decays $M^+ \to e^+\nu_i$ for heavy ν_i, amounting to a relative enhancement factor of up to $\sim 10^4$ in π^+_{e2} decays and $\sim 10^5$ in K^+_{e2} decays. The test proposed in [3, 4] was applied in experiments at SIN/PSI, TRIUMF, KEK, Serpukhov, BNL, CERN, and Belle. Recent results are reported in [6–8] by the TRIUMF PIENU experiment, in [9] by the BNL E949 experiment, and in [10–13] by the CERN NA62 experiment. Constraints from the non-observation of neutrinoless double beta decays of nuclei imply that a ν_4 in this mass range is a Dirac fermion, which can

*E-mail: robert.shrock@stonybrook.edu

be arranged in various BSM models. Cosmological constraints can also be satisfied (see, e.g., [14]).

In addition to affecting $\mathcal{F}t$ values, heavy neutrino emission in nuclear beta decay would produce a kink in the Kurie plot. It was suggested in [3] to search for such kinks. A number of such kink searches have been carried out with various nuclei, and in the future this could be done in the KATRIN experiment (recent reviews include [15, 16]). Another method to search for heavy neutrino emission in nuclear beta decay is to measure both the electron and the recoil ion [17, 18]. One can also obtain limits on $|U_{e4}|^2$ from the analysis of recoil ion spectrum in e-capture in ^{7}Be (e.g., [19]).

Electromagnetic properties of neutrinos are of fundamental interest. A massive Dirac neutrino has a magnetic moment [20] $\mu_\nu = 3eG_F m_\nu/(8\pi^2\sqrt{2}) = (3.2 \times 10^{-19})(m_\nu/[1 \text{ eV}])\mu_B$, where $\mu_B = e/(2m_e)$. Current limits from astrophysics and lab experiments are $\mu_\nu \lesssim (10^{-11} - 10^{-12})\mu_B$ [21]. A proposed new type of search for ν_μ via coherent scattering is [22]. Neutrino transition dipole moments are also of interest [23].

3. CONSTRAINTS ON CHARGED LEPTON FLAVOR VIOLATION

Although lepton flavor violation is well established in the neutrino sector, no charged-lepton flavor violation (CLFV) has been observed. The necessary and sufficient conditions for the diagonality of the weak leptonic neutral current and the suppression of CLFV were proved in [24]. Lee and Shrock [24] showed that the Standard Model, as extended to accommodate the known neutrinos, satisfies this condition, and consequently the branching ratios for CLFV processes such as $\mu \to e\gamma$ is many orders of magnitude too small to observe experimentally; for example, $BR(\mu \to e\gamma) \simeq 10^{-52}$. Searches for CLFV processes such as $\mu^+ \to e^+\gamma$ (MEG and MEG II at PSI), $\mu^+ \to e^+e^+e^-$ (Mu3e at PSI), $\mu \to e$ conversion (Mu2e at Fermilab, COMET at J-PARC) and CLFV τ decay searches at Belle II at KEK are valuable probes of BSM physics. In [25] with Bryman and Ito, we analyzed data from the BABAR experiment to set the first upper limit on the CLFV decays $\tau \to \ell\gamma\gamma$ where $\ell = e$ or μ, namely $BR(\tau \to e\gamma\gamma) < 2.5 \times 10^{-4}$ and $BR(\tau \to \mu\gamma\gamma) < 5.8 \times 10^{-4}$. We also obtained the upper bounds $BR(\tau \to eX) < 1.4 \times 10^{-3}$ and $BR(\tau \to \mu X) < 2.0 \times 10^{-3}$, where X is a neutral, weakly interacting boson that does not decay in the detector. Further searches for these decays will be carried out by Belle II.

4. CONSTRAINTS ON VIOLATION OF BARYON NUMBER AND TOTAL LEPTON NUMBER

Although the Standard Model conserves baryon number, B, perturbatively, baryon number violation is expected to occur in nature, since it is one of the necessary conditions specified by Sakharov [26] for the generation of the baryon asymmetry in the universe. Baryon number violation (BNV) and (total) lepton number violation (LNV) are generic features of grand unified theories. In [27] with S. Girmohanta, we have obtained a number of new results on BNV and LNV processes. In [27], we calculated improved lower bounds on partial lifetimes $\tau/BR = \Gamma^{-1}$ for a number of nucleon decays, including $p \to \ell^+\ell'^+\ell'^-$, $n \to \bar{\nu}\ell^+\ell'^-$, $p \to \ell^+\nu\bar{\nu}$, and $n \to \bar{\nu}\bar{\nu}\nu$, where $\ell,\ \ell' = e,\ \mu$. We also derived lower bounds on $(\tau/BR)_{p\to\ell^+\gamma}$, $(\tau/BR)_{n\to\bar{\nu}\gamma}$, $(\tau/BR)_{p\to\ell^+\gamma\gamma}$, and $(\tau/BR)_{n\to\bar{\nu}\gamma\gamma}$.

Besides $\Delta B = -1$ proton and bound neutron decay, another type of BNV is $n - \bar{n}$ oscillations and associated dinucleon decays, which are $|\Delta B| = 2$ processes. A possible role of $n - \bar{n}$ oscillations in generating the baryon number of the universe was suggested by Kuzmin [28]. Early work on $n - \bar{n}$ oscillations includes [29]. In [30] we analyzed effects of $n - \bar{n}$ oscillations and associated dinucleon decays. We used existing upper bounds on the rates for the dinucleon decays $nn \to 2\pi^0$, $nn \to \pi^+\pi^-$, and $np \to \pi^+\pi^0$ to derive upper bounds on the rates for the decays $nn \to e^+e^-$, $nn \to \mu^+\mu^-$, $nn \to \nu_\ell\bar{\nu}_\ell$, and $np \to \ell^+\nu_\ell$, where $\ell = e,\ \mu,\ \tau$. In [31] with S. Nussinov, we used $\bar{p}p$ and e^+e^- annihilation data to further strengthen the upper bounds on the rates for the dinucleon decays $nn \to e^+e^-$ and $nn \to \mu^+\mu^-$.

Searches for $|\Delta L| = 2$ violation of total lepton number have concentrated on neutrinoless double beta decay. However, one can also search for LNV meson decays such as $K^+ \to \pi^-\mu^+\mu^+$. The first upper limit on this LNV decay was set in [32]. A stronger limit was set by a BNL experiment [33]. The most stringent limits have been set by the CERN NA62 experiment: $BR(K^+ \to \pi^-\mu^+\mu^+) < 4.2 \times 10^{-11}$ [34] and $BR(K^+ \to \pi^-\mu^+e^+) < 4.2 \times 10^{-11}$ [35]. By using the upper limit on $\mu^- \to e^+$ conversion in the field of a nucleus, one can obtain a comparable upper limit $BR(K^+ \to \pi^-\mu^+e^+) < O(10^{-11})$ [36]

It is of considerable interest to investigate BNV and LNV processes in specific BSM models. One such model hypothesizes that the observed four-dimensional spacetime is embedded in a space with additional compactified (spatial) dimensions, such that SM fermions have wave functions that are strongly localized in these extra dimensions [37, 38]. This type of model has the appeal that it can explain the large hierarchy in quark and lepton masses as a consequence of different locations of the centers of the wave functions of these fermions in the extra dimensions without requiring a large hierarchy in dimensionless Yukawa couplings in the higher-dimensional Lagrangian. The characteristic size of the extra dimensions is taken to be $L \simeq 2 \times 10^{-19}$ cm, corresponding to an energy scale $\Lambda_L = 1/L =$ 100 TeV. In [39] with Nussinov, we showed that in this type of extra-dimensional model, although proton decay can easily be suppressed well below experimental limits, $n - \bar{n}$ oscillations and associated dinucleon decays can occur at levels comparable with experimental limits. The results of [39] provide motivation for searches for $n - \bar{n}$ oscillations and resultant matter instability in Super-Kamiokande and the future Hyper-Kamiokande and DUNE experiments, as well as a prospective $n - \bar{n}$ search at the European Spallation Source [40, 41].

The lowest-dimension operators for BNV nucleon decays involve k-fermion operators with $k = 4$. A natural question to ask in the extra-dimension model of [37, 38] is what the implications are for nucleon decays mediated by higher-dimension k-fermion operators with $k = 6$ and $k = 8$. These include a variety of nucleon and dinucleon decays to dilepton and trilepton final states with $\Delta L = -3,\ -2,\ 1$, and 2. In [42] this question was addressed and answered. Using a low-energy effective field theory analysis of relevant operators for these decays, we calculated that, in this extra-dimensional model, the rates for these decays are strongly suppressed and hence are in accord with experimental limits. In these studies, the basic gauge group is the SM group $G_{SM} = \mathrm{SU}(3)_c \otimes \mathrm{SU}(2)_L \otimes \mathrm{U}(1)_Y$. In [43] we extended the analysis of $n - \bar{n}$ oscillations to an extra-dimensional model based on the left-right gauge group $G_{LRS} = \mathrm{SU}(3)_c \otimes \mathrm{SU}(2)_L \otimes \mathrm{SU}(2)_R \otimes \mathrm{U}(1)_{B-L}$. This gauge group provides an interesting alternative to the SM gauge group since baryon and lepton number are gauged, rather than being perturbative global symmetries. With Girmohanta and Mohapatra, we carried out a comprehensive study of neutrino masses and mixing in this type of extra-dimensional model in [44], including a study of dark matter candidates.

These results help to constrain BSM physics. It will be of great interest to perform further investigations constraining physics beyond the Standard Model in future work.

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CONFLICT OF INTEREST

The author declares that he has no conflicts of interest.

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