Searches for Sterile Neutrinos at CERN: Contribution to European Strategy for Particle Physics

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These are some suggestions concerning ongoing and future tests that can be performed at CERN to search for possible sterile neutrinos and set constraints on their masses and mixings. In addition to European participation in neutrino oscillation experiments, in searches for neutrinoless double beta decay, and in KATRIN, it is emphasized here that sensitive searches for sterile neutrinos can be carried out onsite at CERN, including further searches for heavy neutrinos by NA62 and the proposed SHIP experiment, and related general searches for long-lived neutral weakly interacting particles.

I. BACKGROUND

This is a response to the call for input to the planning process for the European Strategy for Particle Physics. Neutrino masses and lepton mixing are the first confirmed physics beyond the original Standard Model (SM), and there are still many important questions about neutrino properties amenable to experimental investigation. We take for granted that Europe will continue to play an important role in accelerator and reactor (anti)neutrino oscillation experiments throughout the world. These include, in particular, the ongoing Fermilab SBL program and the Deep Underground Neutrino Experiment (DUNE) in the U.S., and T2K and the planned Hyper-Kamiokande in Japan, as well as a number of reactor experiments in several countries. We also take for granted that Europe will continue to play a key role in other types of experiments relevant to neutrinos, including the KATRIN tritium beta decay experiment, and searches for neutrinoless double beta decay in Gran Sasso and elsewhere, and in the ICECUBE detector, among others. In the coming years, these experiments should yield more precise determinations of properties pertaining to neutrino masses, squared mass differences, mass ordering, leptonic mixing angles, CP violation, and the question of whether neutrinos are self-conjugate or not. Astrophysical and cosmological observations by ground-based telescopes and space-based missions have also given, and will continue to give, very important information on neutrino properties.

Rather than submitting recommendations on priorities among the above-mentioned experiments, we would like to focus here on one specific topic, namely whether, in addition to the three known neutrino mass eigenstates ν_j, $j = 1, 2, 3$, comprising the three weak eigenstates ν_e, ν_μ, and ν_τ, there are also additional neutrino mass eigenstates that are primarily electroweak-singlets, i.e., sterile, with masses in a range such that current or future experiments could observe them. This question has been with our community for several decades, but remains unanswered. (A few recent reviews include [1]-[4].) Although the original seesaw mechanism involved electroweak singlet neutrinos with primary mass eigenstates having masses of order the GUT (grand-unified theory) scale, low-scale seesaw mechanisms are also possible. Two examples of ideas for low-scale seesaw models for neutrino masses are [5, 6], and there are many others.

The claims for (mostly) sterile neutrinos with masses of order 1 eV from LSND, and data from subsequent experiments investigating this claim have been intensively analyzed. Some recent fits to data including possible sterile neutrinos are [7]-[11]. Many current accelerator neutrino oscillation experiments, including MiniBooNE, MINOS, NOVA, T2K and the Fermilab SBL program with MicroBooNE and ICARUS, as well as a number of reactor experiments including Chooz, Daya Bay, RENO, NEOS, STEREO, SoLiD, DANSS, and PROSPECT, and, in addition, the ICECUBE detector, have carried out searches for effects of sterile neutrinos on neutrino oscillations. Non-observation of neutrinoless double beta decay also places very tight constraints on heavy neutrinos if they are Majorana [12].

Observations from the cosmic microwave background radiation (CMB), baryon acoustic oscillations (BAO), and other cosmological inputs, including primordial big bang nucleosynthesis (BBN), place quite restrictive constraints on properties of neutrinos, both the active ones and possible sterile neutrinos (some recent reviews include [13]-[19]). The current era of precision cosmology is exemplified by the data from the Planck mission [20]. These cosmological constraints involve assumptions, and hence a number of suggestions have been made of ways to evade them and still have sterile neutrinos with a wide variety of masses [15], [21]-[23], while work continues to exclude some of these (e.g., [24]).

II. DIRECT SEARCHES FOR STERILE NEUTRINOS

We would like to emphasize that, in addition to European participation in the above-mentioned neutrino experiments and astrophysical/cosmological observations, there are experiments onsite at CERN that can yield valuable information concerning possible sterile neutrinos.

Direct bounds from particle and nuclear physics on massive sterile neutrinos remain crucial, since they are arguably more robust and less dependent on prior assumptions than many of the cosmological bounds. One type of search experiment that is still of interest is the search for massive mostly sterile neutrinos emitted via lepton mixing in two-body leptonic decays of π^+, K^+, D^+, and B^+. In 1980, a method of searching for such decays was proposed and was applied to existing data to set the first limits on such emission [25]-[27]. In this test, one measures the charged lepton momentum from the two-body leptonic decay of the charged pseudoscalar meson and searches for peaks that would occur if the charged lepton were emitted in conjunction with a massive neutrino. This search yields an upper limit on the magnitude of the relevant lepton mixing matrix element as a function of heavy neutrino mass and has been performed in a series of experiments at KEK, SIN/PSI, TRIUMF, BNL, and CERN [28]. The most recent of these include the BNL limit on $K^+ \to \mu^+\nu_h$ [29], the limits on $K^+ \to \mu^+\nu_h$ and $K^+ \to e^+\nu_h$ from NA62 at CERN [31, 32], and the limits on $\pi^+ \to e^+\nu_h$ from the PIENU experiment at TRIUMF [30].

We note that although the NA62 experiment has, as a major goal, a more accurate measurement of the branching ratio for the decay $K^+ \to \pi^+\nu\bar{\nu}$, it has set very stringent upper bounds on the emission of a heavy neutrino in the mass ranges allowed in $K^+ \to \mu^+\nu_h$ and $K^+ \to e^+\nu_h$ decays [31, 32]. Furthermore, as discussed, e.g., in [33], the NA62 experiment plans a further run after the long shutdown 2, LS2, and this will provide a further opportunity to extend the search for heavy (sterile) neutrino emission in these decays. This could involve running in a beam-dump mode.

The proposed SHIP (Search for Hidden Particles) experiment [34, 35] would also provide a powerful probe for sterile neutrinos. The present author is a theorist (and coauthor of [34]) and hence is not able to provide information on costs of construction and operation of SHIP. The physics case for the SHIP experiment was presented, e.g., in [34]. The anticipated timeline and estimated costs for SHIP construction have been discussed, e.g., in [35].

III. SEARCHES FOR LONG-LIVED NEUTRAL WEAKLY INTERACTING PARTICLES

Given the small mixing angles associated with sterile neutrinos, they may have long lifetimes and hence propagate a substantial distance before decaying. Thus, another useful type of search is for long-lived, neutral weakly interacting particles. In 1978, in [36], a search was proposed for these particles at Fermilab, using a time-of-flight method, and this search was later carried out in Experiment E733 at Fermilab [37]. There is a possibility that a new test of this type might be performed in a future configuration of the NA62 experiment. This type of search can also be done for still heavier particle masses with detectors at the Large Hadron Collider, via searches for displaced vertices, as has been discussed recently (e.g., [38–40]. In addition to heavy sterile neutrinos, it can test more generally for a wide range of neutral, weakly interacting, long-lived particles.

IV. CONCLUSIONS

In conclusion, we have stressed in this short contribution that, in addition to European participation in many valuable ongoing and future experiments probing neutrino properties, there are also experiments onsite at CERN that can yield valuable information on possible sterile neutrinos. These include (i) the current run of NA62 and its future run after LS2; (ii) the possible SHIP experiment, and, (iii) searches for long-lived neutral, weakly interacting particles.

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