Neutrino Oscillations as a Probe of Dark Energy

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We consider a class of theories in which neutrino masses depend significantly on environment, as a result of interactions with the dark sector. Such theories of mass varying neutrinos were recently introduced to explain the origin of the cosmological dark energy density and why its magnitude is apparently coincidental with that of neutrino mass splittings. In this Letter we argue that in such theories neutrinos can exhibit different masses in matter and in vacuum, dramatically affecting neutrino oscillations. As an example of modifications to the standard picture, we consider simple models that may simultaneously account for the LSND anomaly, KamLAND, K2K, and studies of solar and atmospheric neutrinos, while providing motivation to continue to search for neutrino oscillations in short baseline experiments such as BooNE.

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I. Introduction and motivation.—In the past decade, two of the greatest advances in physics have been the experimental confirmation of neutrino oscillations and the observation of acceleration of the cosmological expansion from a mysterious dark sector. In this Letter, we link the two, discussing how neutrino oscillation experiments could reveal nongravitational interactions between matter and the dark sector.

In recent years great progress has been made in understanding neutrino masses and oscillations. As first pointed out by Wolfenstein [1], and Mikheev and Smirnov [2,3], the forward scattering of neutrinos by matter via the weak interactions, while having a very small cross section, can have a significant effect on neutrino oscillations. As a consequence, in all theoretical analyses of the oscillations of neutrinos passing through the Sun or Earth, matter effects on neutrino propagation have played a central role. A plethora of neutrino mass experiments [4] have converged to a consistent picture of neutrino mass: large angle Mikheev-Smirnov-Wolfenstein (MSW) explaining the solar deficit, and a large mixing angle explaining the atmospheric neutrino deficit as well. In spite of this convergence, very little is really known about the interactions and properties of neutrinos. Aside from mild constraints from big bang nucleosynthesis (BBN) and supernovae, interactions of low energy neutrinos with themselves or with ordinary matter are poorly known. Given that we already know that neutrino masses have tremendous environmental dependence even with purely weak interactions, and given our experimental ignorance of neutrino interactions, we must ask whether new interactions could offer additional medium dependence, and what physics such new interactions could probe.

A natural origin for new interactions would be the sector responsible for dark energy. Neutrinos and neutrino oscillations are ideal windows into the dark sector, not only because the neutrino's known interactions are weak and masses small, but also because, if the lepton number is broken, neutrinos carry no conserved charges and are uniquely capable of mixing with fermions in the dark sector. The dark energy offers an important clue in that its scale, $(2 \times 10^{-3} \text{ eV})^4$, is comparable to the scale of neutrino mass splittings, $\delta m_\nu^2 \sim (10^{-2} \text{ eV})^2$. If there should be new particles at this scale, their interactions and mixings with neutrinos could be significant.

Here we broaden the discussion of a class of theories first proposed in Ref. [5] to explain the nature of the dark energy. These theories explain the similarity between the dark energy scale and the measured scale of neutrino mass splittings by postulating that neutrino masses are variable, depending on the value of a scalar field $\mathcal{A}$. The potential for $\mathcal{A}$ is taken to be very flat, so that the magnitude of $\mathcal{A}$ depends upon the cosmological density of neutrinos. As a result, neutrinos become heavier as their density decreases, and the total energy of the fluid (both in neutrinos and in the $\mathcal{A}$ field), identified with the dark energy, can vary slowly as the neutrino density decreases.

Here we show that subgravitational strength interactions between ordinary matter and the $\mathcal{A}$ field naturally occur, and can cause the value of $\mathcal{A}$ to differ in the presence of matter from its vacuum value. This leads to medium-dependent neutrino masses and novel features in neutrino oscillations. Observing these effects would not only extend our understanding of neutrinos, but would also shed light on the mysterious dark sector that governs the evolution of the Universe on the grandest scales.

After explaining in the next section how such effects arise, we proceed in Sec. III to consider how these matter effects can improve agreement between the results of the

Liquid Scintillator Neutrino Detector (LNSD) experiment [6] and other experiments.

II. Dark bosons, dark fermions, and the standard model.—For all we know, there could be a profusion of new particles with no standard model gauge interactions. We refer to such particles as "dark." The main constraint on such indiscernible beasts comes from cosmology; the success of BBN strongly suggests that the only relativistic species in thermal equilibrium with visible matter at a temperature of order an MeV are those we already know about. Thus dark particles must be either much heavier than an MeV or too weakly interacting to thermally equilibrate with visible matter in the early Universe when the temperature was a few MeV. Dark particles are also constrained from the requirement that they not contribute excessively to supernovae cooling. In Ref. [5], however, it was shown that significant neutrino-dark fermion mixing today can be reconciled with BBN and supernova cooling constraints, due to the strong medium dependence of neutrino properties.

In this section we explore the potential impact of the dark sector on neutrino oscillations. We consider a dark sector consisting of a scalar, $\mathcal{A}$, and fermions, n. We take the dark energy scale, $\sim 2 \times 10^{-3}$ eV, to be the typical mass scale of this sector. Taking a cue from the standard model, where masses range over nearly 6 orders of magnitude for the charged fermions, we consider mass parameters within a few orders of magnitude of the dark energy scale, but, in particular, not Hubble-sized Compton wavelengths as are required in slow-roll quintessence models.

A general Lagrangian for the dark sector includes

$$\delta\mathcal{L} = -m_n(\mathcal{A})nn - V_0(\mathcal{A}), \qquad (1)$$

where we ignore operators involving more than two fermions, which are irrelevant to our discussion. The Majorana mass $m_n(\mathcal{A})$ may be linear in $\mathcal{A}$ or some more complicated function. The only renormalizable interaction allowed between the dark sector and the standard model is $y_\nu h\ell n$, where y_ν is the Yukawa coupling of the Higgs boson to a standard model (SM) neutrino and a dark fermion. This interaction yields a Dirac mass $m_D = y_\nu v$. If the dark fermion Majorana mass is well below the weak scale, y_ν must be extremely small. If $m_n(\mathcal{A}) > m_D$, then the seesaw mechanism yields an effective $\mathcal{A}$-dependent neutrino mass, $m_\nu(\mathcal{A}) = m_D^2/m_n(\mathcal{A})$. We also assume there may be other contributions to the neutrino mass, e.g., from a grand unified theory seesaw mechanism, which are $\mathcal{A}$ independent.

As in [5] the energy density of the cosmic background neutrinos tends to drive m_ν to smaller values and, consequently, m_n to larger values. That is, the effective neutrino mass is a function of the background neutrino density. The neutrinos also have an effective coupling to $\mathcal{A}$ with strength $\lambda_\nu = \partial m_\nu/\partial\mathcal{A}|_{\langle A \rangle}$.

For a nonrelativistic neutrino background, we can find the value of $\mathcal{A}$ by minimizing the effective potential

$$V(\mathcal{A}) = n_\nu m_\nu(\mathcal{A}) + V_0(\mathcal{A}), \qquad (2)$$

where V_0 is the effective potential in vacuum.

Up to this point, we have not considered the possible interactions of $\mathcal{A}$ with other matter. To begin, we consider couplings radiatively generated from SM loops. There are a number of possibilities to consider. The most potentially significant are corrections to the electron wave function renormalization (and hence to the electron mass) from W and Higgs loops, and to the Z propagator (and hence to quark masses at higher loop). If we consider the theory to contain just the standard model with variable ($\mathcal{A}$-dependent) masses, these corrections also appear to depend on $\mathcal{A}$, at order $G_f m_\nu^2$. In matter with density of 3 g/cm^3, such an interaction has a comparable effect on the $\mathcal{A}$ potential as the cosmic neutrino background, with the vastly higher density of electrons compensating for the much weaker coupling.

However, the electroweak radiative corrections are dominated by high ($\sim M_W$) momenta; thus, if the n fermions are lighter than M_W, they should also be considered in the loops. A careful treatment finds that the leading corrections in this case are proportional to $G_f m_D^2$, and independent of $\mathcal{A}$. Terms depending on $\mathcal{A}$ are suppressed by an additional factor of $G_f m_n^2(\mathcal{A})$ and are too weak to be relevant. We conclude that radiatively generated couplings of the dark scalar to quarks and charged leptons are not interesting if (and only if) the scalar-neutrino interaction arises solely due to neutrino mixing with a dark fermion that is much lighter than the W boson.

We also consider nonrenormalizable operators that couple the dark scalar to visible matter, such as might arise from quantum gravity. At low energies, these interactions appear as Yukawa couplings of $\mathcal{A}$ to the proton, neutron, and electron, which we parametrize as $\lambda_i m_i/M_{\rm Pl}$, with $i = p, n, e$, respectively, and where $M_{\rm Pl}$ is the Planck scale. Couplings $\lambda_{n,p} \lesssim 10^{-2}$ are consistent with tests of the gravitational inverse square law for an $\mathcal{A}$ mass larger than $\sim 10^{-11}$ eV [7], and (for $\lambda_p \sim \lambda_n$) with tests of the equivalence principle for an $\mathcal{A}$ mass larger than $\sim 10^{-8}$ eV [8,9].

In the presence of matter, and ignoring the electron contribution, we have a new effective potential for $\mathcal{A}$,

$$\bar{V} = \frac{\lambda_B \rho_B \mathcal{A}}{M_{\rm Pl}} + V(\mathcal{A}), \qquad (3)$$

where ρ_B is the mass density of baryonic matter, and we have set $\lambda_p = \lambda_n = \lambda_B$.

The change in the neutrino mass in the presence of matter may be estimated to be

$$\Delta m_\nu \sim 1 \text{ eV}\left(\frac{\lambda_\nu}{10^{-1}}\right)\left(\frac{\lambda_B}{10^{-2}}\right)\left(\frac{\rho_B}{\bar{\rho}_B}\right)\left(\frac{10^{-6} \text{ eV}}{m_\mathcal{A}}\right)^2, \quad (4)$$

where $m_\mathcal{A}^2 \equiv V''(\mathcal{A})$, and $\bar{\rho}_B = 3$ g/cm^3, a baryon mass density that is typical of the Earth's crust. This estimate

assumes the shift in $\mathcal{A}$ is sufficiently small to allow for a Taylor expansion of V about the present epoch background value of $\mathcal{A}$, and demonstrates the rough order of parameters necessary to yield a significant effect on m_ν.

In a simple model introduced in [5] to explain the size of the dark energy, where $V_0(\mathcal{A}) = \mu^4 \log(\mathcal{A}/\mu)$ and $m_n(\mathcal{A}) = \lambda_n \mathcal{A}$, Δm_ν can be even larger. The generic point is that the neutrino mass is environment dependent, and the neutrino mass in rock or in a star can vary considerably from the neutrino mass in air and in space. Significant matter effects on neutrino propagation are familiar, as in the standard model MSW mechanism. The possibility of such medium dependence was noted early by Wolfenstein [1], and a scenario where Dirac neutrinos have mass only in matter has been considered previously [10]. New scalar contributions to the effective neutrino mass can be distinguished experimentally from standard MSW contributions as they are energy independent, and equal for neutrinos and antineutrinos, absent CP violation.

III. Matter effects in existing experiments.—Since dark energy now provides us with motivation to consider the possibility of medium-dependent neutrino mass, we want to examine what the effects could be on existing neutrino data. In particular, it is instructive to examine the LSND evidence for short baseline $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ oscillations in light of these possible matter effects. Here, we study whether the ability to have different δm^2's in air and matter can lead to an improved agreement between both the other positive results and the existing negative results.

Let us begin by discussing the relevant experiments. We can loosely group oscillation experiments into three categories. There are long baseline (LBL) experiments, which include solar neutrino experiments, KamLAND, K2K, and Super-K, as well as earlier studies of atmospheric neutrinos. These experiments have all seen evidence for neutrino oscillations, and involve significant propagation through dense matter. The positive results are interpreted through neutrino oscillations to require two small mass squared splittings, $\mathcal{O}(8 \times 10^{-5} \text{ eV}^2)$ for the solar neutrinos and KamLAND, and $\mathcal{O}(2 \times 10^{-3} \text{ eV}^2)$ for K2K and atmospheric neutrino studies. The Super-K atmospheric results should not be classified entirely as positive, as the through-going muon data show no evidence for oscillation. This result relies on knowledge of very high [$O(100 \text{ GeV})$] neutrinos and may be subject to systematics not present in, e.g., the angular dependence of the multi-GeV events. There are null short baseline (NSBL) experiments, including the CHOOZ, Bugey, and Palo Verde reactor experiments, and the higher energy CDHS, KARMEN, CHORUS, and NOMAD experiments, involving muon neutrinos. These experiments have all produced no evidence for neutrino oscillations. Last, there is LSND, whose results are consistent with oscillations with a mass squared splitting greater than $3 \times 10^{-2} \text{ eV}^2$ [6]. These results are summarized in [11].

Because three neutrinos can accommodate only two independent mass squared splittings, LSND has generally been interpreted to necessitate an additional sterile neutrino or neutrinos. However, recent studies (see [12] and references therein) demonstrate that this, too, gives a poor fit to the data. Incorporating LSND by invoking CPT violation seems in conflict with recent KamLAND data, while a $3 + 2$ sterile scenario [13] improves the fit in a seemingly contrived way by setting the masses of the sterile neutrinos to lie in regions where the NSBL constraints are weakest.

Four-neutrino scenarios have a poor fit due in large part to the differences in how neutrino oscillations affect disappearance experiments compared with the positive appearance signal at LSND. Atmospheric and solar neutrino data are inconsistent with a large mixing angle of ν_e and ν_μ with any sterile neutrino, implying that the mass eigenstates associated with solar and atmospheric oscillations are almost entirely active. Thus, in a four-neutrino scenario, the mass eigenstate associated with the LSND mass squared difference must be mostly sterile, with a small admixture of ν_e and ν_μ. With these constraints, the amplitude for the LSND $\nu_\mu \rightarrow \nu_e$ transition is the product of two small mixings (the component of the heavy eigenstate which is ν_μ and the component which is ν_e), while only one small mixing angle appears in the SBL disappearance experiments (the component which is ν_e for reactor experiments). Put another way, LSND is sensitive only to $\nu_\mu \rightarrow \nu_e$, while disappearance experiments are sensitive to $\nu_e \rightarrow \nu_\mu$ as well as $\nu_e \rightarrow \nu_s$, which is, in general, larger.

The experimental limits of exotic matter effects on neutrino oscillations have barely been explored. Here we see to what extent matter effects can improve agreement of LSND with other experiments. Of the NSBL experiments, the Bugey experiment involves dominantly propagation through air [14,15]. The Palo Verde results involve neutrinos dominantly propagating through Earth [16]. The CHOOZ experiment neutrinos propagate roughly 10%–20% through Earth [17]. Of the terrestrial positive signal experiments, both KamLAND and Super-K study the propagation of neutrinos through Earth.

Within the context of purely three neutrino oscillations, one might want to consider what the limits are on the δm^2's and mixing angles in air and earth separately. The possibility that LSND is testing the "air" values of the neutrino mass matrix seems excluded by the fact that KARMEN has similar air path length as LSND, and hence would constrain such an oscillation scenario more strongly than ordinary neutrino oscillations.

If one wants to understand the LSND signal from a "matter" value for the neutrino mass matrix, there are a number of experiments to consider. KamLAND gives evidence for large mixing of ν_e with some other neutrino in earth with a mass splitting $5 \times 10^{-5} \leq \delta m^2 \leq 10^{-3} \text{ eV}^2$ where the upper bound comes from CHOOZ

and Palo Verde. Super-K atmospheric and K2K show evidence for ν_μ mixing significantly with ν_τ and a mass squared splitting $\delta m^2 \gtrsim 10^{-3}$ eV^2. In fact, the strongest evidence for the scale of the mass splitting comes from the zenith-angle dependence of the multi-GeV events. In this scenario, one has the exciting possibility that the presently quoted value of mass splitting for atmospheric neutrinos is merely an artifact of the significant depletion of those neutrinos originating below the horizon, which could arise in this scenario from a much larger mass splitting in matter. This speculation, however, seems at odds with the through-going muons, which, together with the stopping muons, give an upper bound on the mass squared scale for oscillations of about 10^{-2} eV^2 [18].

These results would suggest that by using only three neutrinos one cannot reconcile LSND with the other experiments. However, should there be some systematic effect in the $O(100 \text{ GeV})$ neutrinos, or if some unknown process contributes to the production of high energy atmospheric neutrinos, one can consider a scenario where $(\nu_\mu + \nu_\tau)/\sqrt{2}$ has a larger mass in matter in order to explain the LSND result, and a mass $\sim 3 \times 10^{-2}$ eV in air to explain the atmospheric result. Leaving the lightest two mass eigenstates to be essentially constant in air and matter, and a small admixture of ν_e in the heaviest, it appears that the matter parameters of $0.07 \lesssim \Delta m^2 \lesssim 0.26$ eV^2 and $0.02 \lesssim \sin^2 2\theta \lesssim 0.12$ appear to fit all of the results outside the through-going muons. (The range in the mixing angle could, in fact, be much larger, depending on the details of how the CHOOZ experiment changes when restricted to limits on matter parameters.)

However, the presence of light SM-singlet states in the theory seems to be necessary for naturalness, and so we should also consider the effects on these states in oscillations. Indeed, medium effects can improve the fit of four-neutrino scenarios. The medium dependence of the light mass eigenstates arises most simply from changing the mass of the heavy dominantly singlet mass eigenstates.

The principal limitation on four-neutrino scenarios in the region near 0.1 eV^2 is from Bugey. Since Bugey does not constrain the matter values of the neutrino properties, but only the air values, it is straightforward to reconcile LSND with the NSBL experiments. If the singlet state is $\mathcal{O}(0.3 \text{ eV})$ in matter, but in air is much heavier and with smaller mixings, one can achieve a good fit to all existing data.

Of course, by lowering the mass of this singlet state in matter, some dominantly active mass eigenstate should also have a resulting change in its mass. From the LSND result, we expect some mass splitting to change in matter by an amount

$$\Delta m^2 > \sin^2\theta_{\text{LSND}} \, \delta m^2_{\text{LSND}} \gtrsim 3 \times 10^{-4} \text{ eV}^2. \quad (5)$$

This scale suggests that the scenario is very interesting

for more precise studies of the differences between air and earth mass parameters, even in existing data sets. A careful study of the implications of the atmospheric neutrino data would be worthwhile to see whether it is consistent with different oscillation lengths in air and in matter. It would be interesting to see whether a general fit of the atmospheric and K2K data can constrain δm^2 abd $\sin^2 2\theta$ independently in air and in rock for $\nu_\mu - \nu_\tau$ oscillations.

A more detailed discussion may be found in Ref. [19].

IV. Conclusions.—Neutrinos could be significantly affected by interactions with the dark sector, which are subgravitational in strength to other visible matter. Such interactions can make the neutrino mass a dynamical quantity, depending on the environment.

Future neutrino experiments should be designed and analyzed with the possibility in mind of matter density dependent neutrino oscillations and mass.

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[1] L. Wolfenstein, Phys. Rev. D **17**, 2369 (1978).
[2] S. P. Mikheev and A. Y. Smirnov, Sov. J. Nucl. Phys. **42**, 913 (1985).
[3] S. P. Mikheev and A. Y. Smirnov, Nuovo Cimento Soc. Ital. Fis. C **9**, 17 (1986).
[4] M. c. Gonzalez and Y. Nir, Rev. Mod. Phys. **75**, 345 (2003), and references therein.
[5] R. Fardon, A. E. Nelson, and N. Weiner, astro-ph/0309800.
[6] LNSD Collaboration, C. Athanassopoulos *et al.*, Phys. Rev. Lett. **77**, 3082 (1996); **81**, 1774 (1998).
[7] E. G. Adelberger, B. R. Heckel, and A. E. Nelson, Annu. Rev. Nucl. Part. Sci. **53**, 77 (2003).
[8] Y. Su *et al.*, Phys. Rev. D **50**, 3614 (1994).
[9] G. L. Smith *et al.*, Phys. Rev. D **61**, 022001 (2000).
[10] R. F. Sawyer, Phys. Lett. B **448**, 174 (1999).
[11] Particle Data Group Collaboration, K. Hagiwara *et al.*, Phys. Rev. D **66**, 010001 (2002).
[12] T. Schwetz, hep-ph/0311217.
[13] M. Sorel, J. Conrad, and M. Shaevitz, hep-ph/0305255.
[14] M. Abbes *et al.*, Nucl. Instrum. Methods Phys. Res., Sect. A **374**, 164 (1996).
[15] J. Favier (private communication).
[16] F. Boehm (private communication).
[17] D. Steinberg (private communication).
[18] Super-Kamiokande Collaboration, Y. Fukuda *et al.*, Phys. Lett. B **467**, 185 (1999).
[19] K. M. Zurek, hep-ph/0405141.