Article:

Hooper, D., Morgan, D. and Winstanley, E. orcid.org/0000-0001-8964-8142 (2005) Probing quantum decoherence with high-energy neutrinos. Physics Letters B, 609 (3-4). pp. 206-211. ISSN 0370-2693

https://doi.org/10.1016/j.physletb.2005.01.034

Probing Quantum Decoherence with High-Energy Neutrinos

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(February 7, 2008)

We consider the prospects for observing the effects of quantum decoherence in high-energy (TeV-PeV) neutrinos from astrophysical sources. In particular, we study Galactic sources of electron anti-neutrinos produced in the decay of ultra-high energy neutrons. We find that next generation neutrino telescopes should be capable of placing limits on quantum decoherence effects over multi-kiloparsec baselines, surpassing current bounds by a factor of 10^{12} to 10^{33}, depending on the model considered.

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I. INTRODUCTION

Within the context of standard quantum mechanics, a pure state will never oscillate into a superposition or mixture of states. If quantum fluctuations of the gravitational field are considered, however, this may not be the case. Microscopic black holes forming for short periods of time can lead to a loss of quantum information, potentially converting a pure state into a mixture or superposition of quantum states [1,2]. If evidence of this effect, called quantum decoherence, were observed, it could reveal clues about the quantum nature of gravity with incredible implications for string theory, cosmology and particle physics.

Neutrinos provide a promising sector for observing the effects of quantum decoherence. Although atmospheric, solar and supernova neutrinos have been previously studied in this context [3,4], high-energy neutrinos produced in distant astrophysical sources may also be used to search for these effects. Being weakly interacting, neutrinos can travel very long distances without scattering. Neutrinos generated in distant cosmic accelerators provide us with an opportunity to observe particles which have travelled from elsewhere in our Galaxy (kilo-parsecs), from nearby galaxies (mega-parsecs) or from cosmological scales (giga-parsecs). Neutrino measurements over such long baselines have not yet been conducted and would represent a major step forward in sensitivity to quantum decoherence effects.

As neutrinos propagate, the effects of quantum decoherence would alter the ratios of their flavors toward the values, $\nu_e : \nu_\mu : \nu_\tau \cong \frac{1}{3} : \frac{1}{3} : \frac{1}{3}$, regardless of their initial flavor content. If a flux of neutrinos were to be observed from a astrophysical source with a ratio of flavors differing from $\frac{1}{3} : \frac{1}{3} : \frac{1}{3}$, strong constraints could be placed on the scale of quantum decoherence.

The sources of high-energy cosmic neutrinos most widely studied accelerate protons which interact with photons producing charged and neutral pions. The charged pions then decay producing neutrinos in the chain, $\pi^+ \rightarrow \mu^+ \nu_\mu \rightarrow e^+ \bar{\nu_\mu} \nu_e \nu_\mu$. This initial flavor ratio ($\frac{1}{3} : \frac{2}{3} : 0$) is modified, however, as the neutrinos undergo oscillations. As a result, cosmic neutrinos produced in pion decay reach the Earth with flavors very near the ratio of $\frac{1}{3} : \frac{1}{3} : \frac{1}{3}$; indistinguishable from the signature of quantum decoherence [5].

To test for the effects of quantum decoherence, therefore, a different type of cosmic neutrino source is needed. Such a source must produce neutrinos of flavors which do not follow the standard pion decay ratios. Some possible sources could be neutrinos produced in the annihilations or decays of dark matter particles [6], neutrinos generated as a result of models of top-down origin of the highest energy cosmic rays [7] or neutrinos produced in neutron decays. In this letter, we study the third of these possibilities.

Neutrons are an interesting source of (anti)neutrinos for our purposes because they produce neutrinos in only the electron flavor, *i.e.* $n \rightarrow p\, e^- \bar{\nu}_e$. After standard oscillations, this purely electron anti-neutrino beam converts approximately as 1:0:0 → 0.56:0.24:0.20. If a cosmic neutrino source were to be found with such a ratio, this could be used to constrain the scale of quantum decoherence in the neutrino sector. Alternatively, if we could be confident that a source produced neutrinos mostly via neutron decay, the observation of equal quantities of each neutrino flavor from such a source could potentially constitute a discovery of quantum decoherence effects.

II. COSMIC NEUTRINOS FROM NEUTRON DECAY

There are several potentially viable mechanisms for the production of high-energy cosmic neutrons. For example, ultra-high energy nuclei accelerated in compact objects can undergo photo-disintegration through interactions with infrared and microwave photons, breaking into neutrons and protons [8,9]. For example, an accelerated Iron nucleus can undergo the typical reaction: ^{56}Fe + $\gamma \rightarrow ^{55}$Fe + n. In the region near a cosmic accelerator, sufficiently dense photon fields may be present to induce such interactions. Alternatively, neutrons could be produced in charge exchange interactions of accelerated protons with ambient protons, $p + p \rightarrow n + X$ [10].

There is accumulating evidence for a substantial neutron component in the cosmic ray spectrum at energies around 10^{18} eV. The Akeno Giant Air Shower Array (AGASA) has reported an anisotropy correlated to the Galactic Plane at 4 to 4.5σ significance. This excess constitutes about 4% of the total flux and appears to be concentrated around the locations of the Galactic Center and the Cygnus region [11]. The reanalysis of data taken by the Sydney University Giant Airshower Recorder (SUGAR) has also found evidence for the anisotropy [12]. Thirdly, the Fly's Eye Collaboration has reported an excess along the Galactic Plane at the 3.2σ level [13]. Recently, multi-TeV gamma-rays have been observed from the vicinity of the Galactic center [14], which may be associated with the cosmic ray excess from this region [10,15].

If these cosmic ray sources are truly point-like, as the evidence is beginning to suggest, these events will be somewhat difficult to reconcile with charged cosmic rays, such as protons, which would be deflected in the Galactic magnetic fields. With this motivation, it has been argued that the excess of cosmic rays around 10^{18} eV seen from the Cygnus and Galactic Center regions (or thereabouts) are neutrons generated in the photo-disintegration of heavy nuclei or in pp collisions [9,10]. Energetic neutrons, with a decay length of $c\gamma_n\tau_n \sim 10\,\mathrm{kpc}\times(\mathrm{E_n}/\mathrm{EeV})$, can reach Earth from such sources only at energies above about 10^{18} eV. The fact that this is the same energy at which the cosmic ray anisotropies appear is quite suggestive. Therefore, Galactic sources such as a microquasar, Cygnus X-3 or the Cygnus-OB2 cluster in the Cygnus region or the supernova remnant Sgr A East or the supermassive black hole at Sgr A* in the Galactic Center region (which are each on the order of 10 kpc from Earth) could be the source of EeV neutrons. Neutrons would also be generated in these sources at lower energies which would decay in flight, generating a rich source of electron anti-neutrinos at PeV energies and below.

Normalizing the neutron flux to the 4% anisotropic component observed by AGASA, the authors of Ref. [9] conservatively estimate an integrated anti-neutrino flux of $\sim 2\times10^{-11}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$ above 1 TeV from the Cygnus region. A similar flux would be expected from the Galactic Center region. Note that the Waxman-Bahcall bound [16] on high-energy neutrino fluxes does not apply here due to their Galactic nature.

III. QUANTUM DECOHERENCE EFFECTS

We will adopt a simple phenomenological approach to modelling the effects of quantum decoherence. This is possible, in part, because the effects of quantum decoherence become very simple when very long propagation distances are considered. Averaging the sines and cosines which appear in the general expression, we arrive at the approximate probability of a neutrino transitioning from state a to state b:

$$P[\nu_a \rightarrow \nu_b] = \frac{1}{3} + e^{-2\alpha L}\Bigg[\frac{1}{2}(U_{a1}^2 - U_{a2}^2)(U_{b1}^2 - U_{b2}^2) + \frac{1}{6}(U_{a1}^2 + U_{a2}^2 - 2U_{a3}^2)(U_{b1}^2 + U_{b2}^2 - 2U_{b3}^2)\Bigg]. \quad (1)$$

Here, the U's are elements of the standard neutrino mixing matrix, α is a quantum decoherence parameter, which can be a constant or a function of energy and L is the distance the neutrino has travelled. We have used $\Delta m_{21}^2 = 7.2\times10^{-5}\,\mathrm{eV}^2$, $\Delta m_{32}^2 = 2.6\times10^{-3}\,\mathrm{eV}^2$ and have assumed the normal mass hierarchy. Inserting the measured neutrino mass splittings and mixing angles, this further reduces to:

$$\begin{aligned} P[\nu_e \rightarrow \nu_e] &= \frac{1}{3} + 0.228e^{-2\alpha L},\\ P[\nu_e \rightarrow \nu_\mu] &= \frac{1}{3} - 0.097e^{-2\alpha L},\\ P[\nu_e \rightarrow \nu_\tau] &= \frac{1}{3} - 0.130e^{-2\alpha L},\\ P[\nu_\mu \rightarrow \nu_\mu] &= \frac{1}{3} + 0.044e^{-2\alpha L},\\ P[\nu_\mu \rightarrow \nu_\tau] &= \frac{1}{3} + 0.053e^{-2\alpha L},\\ P[\nu_\tau \rightarrow \nu_\tau] &= \frac{1}{3} + 0.077e^{-2\alpha L}. \end{aligned} \quad (2)$$

In terms of these probabilities, we can write the ratios of neutrino flavors observed

$$\begin{aligned} R_{\nu_e} &= (P[\nu_e \rightarrow \nu_e]\Phi_{\nu_e} + P[\nu_\mu \rightarrow \nu_e]\Phi_{\nu_\mu}\\ &\quad + P[\nu_\tau \rightarrow \nu_e]\Phi_{\nu_\tau})/\Phi_{\mathrm{tot}},\\ R_{\nu_\mu} &= (P[\nu_e \rightarrow \nu_\mu]\Phi_{\nu_e} + P[\nu_\mu \rightarrow \nu_\mu]\Phi_{\nu_\mu}\\ &\quad + P[\nu_\tau \rightarrow \nu_\mu]\Phi_{\nu_\tau})/\Phi_{\mathrm{tot}},\\ R_{\nu_\tau} &= (P[\nu_e \rightarrow \nu_\tau]\Phi_{\nu_e} + P[\nu_\mu \rightarrow \nu_\tau]\Phi_{\nu_\mu}\\ &\quad + P[\nu_\tau \rightarrow \nu_\tau]\Phi_{\nu_\tau})/\Phi_{\mathrm{tot}}, \end{aligned} \quad (3)$$

where the Φ's denote the respective fluxes emitted at the source. In the case of neutrinos from neutron decay, only Φ_{ν_e} is non-zero. Notice that if we insert $\Phi_{\nu_e}{:}\Phi_{\nu_\mu}{:}\Phi_{\nu_\tau} = 1:0:0$ and $\alpha = 0$ (no quantum decoherence) into equations 3 and 2, respectively, we find the observed ratios, 0.56:0.24:0.20, described in the introduction.

At this point, we will consider some phenomenological models:

- **Energy Independent Model**
  If we assume that the quantum decoherence parameter, α, is independent of energy, we find that the

probabilities of Eq. 2 all approach their asymptotic value of 1/3 for distances of $L \gg \alpha^{-1}$. With a source on the order of 10 kiloparsecs distant, values of α on the order of $\sim 10^{-21}$ m^{-1} (or equivalently, $\alpha \sim 10^{-37}$ GeV) could be probed. Current upper bounds on this parameter from the Super-Kamiokande experiment are approximately $\sim 10^{-23}$ GeV [3,17].

- **String Inspired Model**
  It has been suggested that α may scale with E^2, particularly within the context of string theory [18]. If this is the case, a 10 kiloparsecs distant source of TeV neutrinos could be used to test $\kappa \sim 10^{-21}$ m^{-1} TeV^{-2}, where $\kappa \equiv \alpha/E^2$. At the energies observed by Super-Kamionkande ($\sim$GeV), this corresponds to $\alpha \sim 10^{-43}$ GeV. In this model, Super-Kamiokande's upper limits are $\sim 10^{-10}$ GeV [3,17].

- **Lorentz Invariant Model**
  It has been shown that Lorentz invariance can be maintained if α is proportional to $1/E$ [3]. In this case, a 10 kiloparsecs distant source of TeV neutrinos could be used to test $\mu^2 \sim 10^{-21}$ m^{-1} TeV, where $\mu^2 \equiv \alpha E$. At GeV energies, this corresponds to $\alpha \sim 10^{-34}$ GeV. Super-Kamionkande's limit for this model is $\sim 10^{-22}$ GeV [3,17].

In each of these cases, neutrino studies over ~ 10 kiloparsec baselines allow for tests of quantum decoherence at a level many orders of magnitude beyond current bounds.

To measure the flavors of high-energy cosmic neutrinos, we turn to large volume neutrino telescopes [19]. In particular, the IceCube experiment at the South Pole is currently under construction [20]. IceCube will be capable of observing both muon tracks generated by charged current muon neutrino interactions and hadronic or electromagnetic showers generated by charged current electron neutrinos or neutral current interactions by all neutrino flavors. With a full cubic kilometer of instrumented volume, IceCube will be sensitive to neutrinos of energy as low as 100 GeV and as high as 10^{11} GeV. If constructed, a kilometer-scale neutrino telescope in the Mediterranean could have similar capabilities.

The ability to measure the ratios of cosmic neutrinos in high-energy neutrino telescopes has been studied in Ref. [21]. Such measurements have been discussed as a test of neutrino stability [22], pseudo-Dirac neutrinos [23] and as a method to measure the neutrino mixing angle, θ_{13} [24].

Assuming, for example, the neutrino flux calculated from Cygnus in Ref. [9] of $\sim 2 \times 10^{-11}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$ integrated above 1 TeV, we can estimate the ability of IceCube to distinguish the ν_e:ν_μ:ν_τ =0.33:0.33:0.33 and 0.56:0.24:0.20 cases. Practically, experiments do not measure the flux of each neutrino flavor separately, but rather they measure the number of (or spectrum of) muon events and shower events. This can, in turn, be used to infer the fraction of neutrinos which are of muon type. Based on the analysis of Ref. [21], it appears likely that even after one year, this flux would produce enough events in a kilometer-scale neutrino telescope to differentiate these two cases. The precision of this technique would be further improved by accumulating data over a period of several years.

IV. CONCLUSIONS

In this letter, we have studied the possibility of using high-energy neutrino telescopes to test for the effects of quantum decoherence in cosmic neutrinos. Neutrinos produced in the decay of charged pions produce ratios of neutrino flavors which are indistinguishable from the signatures of decoherence after the effects of oscillations are taken into account. Instead, we consider high-energy cosmic neutrinos produced in the decay of neutrons. With evidence accumulating for the presence of a neutron component in the ultra-high energy cosmic ray flux, it is likely that sizable electron anti-neutrino fluxes will also be present. After oscillations, these neutrinos will reach Earth in the ratio of ν_e:ν_μ:ν_τ =0.56:0.24:0.20, in contrast to the ν_e:ν_μ:ν_τ =0.33:0.33:0.33 prediction for a decohered flux. Next generation high-energy neutrino telescopes, such as IceCube, should be capable of distinguishing these cases. Neutrino flavor measurements over multi-kiloparsec baselines could be used to place limits on the scale of quantum decoherence between approximatley 10^{-34} and 10^{-43} GeV, depending on the model. Considering the current bounds from the Super-Kamiokande experiment are in the range of $\sim 10^{-10}$ to 10^{-23} GeV, it is clear that this technique represents a major improvement in sensitivity.

Acknowledgments: We would like to thank Pedro Ferreira and Bob McElrath for helpful comments. DH is supported by the Leverhulme Trust. DM is supported by the University of Sheffield.

[1] S. W. Hawking, Commun. Math. Phys. **87**, 395 (1982).
[2] J. Ellis, J. S. Hagelin, D. V. Nanopoulos and M. Srednicki, Nucl. Phys. B **241**, 381 (1984).
[3] E. Lisi, A. Marrone and D. Montanino, Phys. Rev. Lett. **85**, 1166 (2000) [arXiv:hep-ph/0002053];
[4] G. L. Fogli, E. Lisi, A. Marrone and D. Montanino, Phys. Rev. D **67**, 093006 (2003) [arXiv:hep-ph/0303064]; G. Barenboim and N. E. Mavromatos, arXiv:hep-ph/0404014; R. Zukanovich Funchal, E. M. Santos, W. J. C. Teves and A. M. Gago, *Prepared for Interna-*

tional Europhysics Conference on High-Energy Physics (HEP 2001), Budapest, Hungary, 12-18 Jul 2001; G. Z. Adunas, E. Rodriguez-Milla and D. V. Ahluwalia, Phys. Lett. B **485**, 215 (2000) [arXiv:gr-qc/0006021]; H. V. Klapdor-Kleingrothaus, H. Paes and U. Sarkar, Eur. Phys. J. A **8**, 577 (2000) [arXiv:hep-ph/0004123].

[5] See, for example, D. V. Ahluwalia, Mod. Phys. Lett. A **16**, 917 (2001) [arXiv:hep-ph/0104316].

[6] G. Bertone, E. Nezri, J. Orloff and J. Silk, arXiv:astro-ph/0403322.

[7] C. Barbot, M. Drees, F. Halzen and D. Hooper, Phys. Lett. B **555**, 22 (2003) [arXiv:hep-ph/0205230].

[8] F. W. Stecker, Phys. Rev. **180**, 1264 (1969); F. W. Stecker and M. H. Salamon, Astrophys. J. **512**, 521 (1992) [arXiv:astro-ph/9808110].

[9] L. A. Anchordoqui, H. Goldberg, F. Halzen and T. J. Weiler, Phys. Lett. B **593**, 42 (2004) [arXiv:astro-ph/0311002].

[10] R. M. Crocker, M. Fatuzzo, R. Jokipii, F. Melia and R. R. Volkas, arXiv:astro-ph/0408183.

[11] N. Hayashida *et al.* [AGASA Collaboration], Astropart. Phys. **10**, 303 (1999) [arXiv:astro-ph/9807045]; M. Teshima *et al.*, Proc. 27th International Cosmic Ray Conference, Copernicus Gesellschaft, 2001.

[12] J. A. Bellido, R. W. Clay, B. R. Dawson and M. Johnston-Hollitt, Astropart. Phys. **15**, 167 (2001) [arXiv:astro-ph/0009039].

[13] D. J. Bird *et al.* [HIRES Collaboration], arXiv:astro-ph/9806096.

[14] F. Aharonian *et al.* [The HESS Collaboration], arXiv:astro-ph/0408145; K. Kosack *et al.* [The VERITAS Collaboration], arXiv:astro-ph/0403422.

[15] F. Aharonian and A. Neronov, Submitted to Astrophys. J., arXiv:astro-ph/0408303.

[16] J. N. Bahcall and E. Waxman, Phys. Rev. D **64**, 023002 (2001) [arXiv:hep-ph/9902383]; E. Waxman and J. N. Bahcall, Phys. Rev. D **59**, 023002 (1999) [arXiv:hep-ph/9807282]; J. P. Rachen, R. J. Protheroe and K. Mannheim, arXiv:astro-ph/9908031.

[17] Y. Fukuda *et al.* [Super-Kamiokande Collaboration], Phys. Lett. B **433**, 9 (1998) [arXiv:hep-ex/9803006].

[18] J. Ellis, N. E. Mavromatos and D. V. Nanopoulos, Phys. Lett. B **293**, 37 (1992) [arXiv:hep-th/9207103]; J. Ellis, N. E. Mavromatos and D. V. Nanopoulos, Mod. Phys. Lett. A **10**, 425 (1995) [arXiv:hep-th/9305116]; J. Ellis, N. E. Mavromatos, D. V. Nanopoulos and E. Winstanley, Mod. Phys. Lett. A **12**, 243 (1997) [arXiv:gr-qc/9602011].

[19] For a review of high-energy neutrino astronomy, see F. Halzen and D. Hooper, Rept. Prog. Phys. **65**, 1025 (2002) [arXiv:astro-ph/0204527].

[20] J. Ahrens *et al.* [The IceCube Collaboration], Nucl. Phys. Proc. Suppl. **118**, 388 (2003) [arXiv:astro-ph/0209556]; A. Goldschmidt [IceCube Collaboration], Nucl. Phys. Proc. Suppl. **110** 516 (2002).

[21] J. F. Beacom, N. F. Bell, D. Hooper, S. Pakvasa and T. J. Weiler, Phys. Rev. D **68**, 093005 (2003) [arXiv:hep-ph/0307025].

[22] J. F. Beacom, N. F. Bell, D. Hooper, S. Pakvasa and T. J. Weiler, Phys. Rev. Lett. **90**, 181301 (2003) [arXiv:hep-ph/0211305].

[23] J. F. Beacom, N. F. Bell, D. Hooper, J. G. Learned, S. Pakvasa and T. J. Weiler, Phys. Rev. Lett. **92**, 011101 (2004) [arXiv:hep-ph/0307151].

[24] J. F. Beacom, N. F. Bell, D. Hooper, S. Pakvasa and T. J. Weiler, Phys. Rev. D **69**, 017303 (2004) [arXiv:hep-ph/0309267].