Testing neutrino magnetic moments with AGNs

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Abstract

We propose to test the magnetic transition moments of Majorana neutrinos by comparing the fluxes of different flavours of neutrinos coming from active galactic nuclei (AGN). We show that, with reasonable assumptions about the magnetic field of the AGN, it is possible to obtain limits on $\nu_\tau\nu_e$ and $\nu_\tau\nu_\mu$ transition moments which are three to five orders of magnitude better than the laboratory limits. We also point out that with certain parameter values the ratio $\nu_\tau/\nu_{e, \mu}$, when measured from different sources, is expected to vary from zero to values somewhat higher than one, providing an unambiguous signal of a magnetic transition within the AGN which cannot be explained by neutrino oscillations.

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1. Introduction. Recent Super-Kamiokande [1] results imply that neutrinos have a non-vanishing mass and therefore also a non-vanishing magnetic moment. As a consequence, the wave function of a neutrino traversing in a magnetic field will be subject to spin rotation. For a large enough magnetic moment this effectively results in a helicity flip. If neutrinos are Dirac particles, helicity flip induces a conversion of an active left-handed state $\nu_{iL}$ into a sterile right-handed state $\nu_{jR}$, thereby depleting the measurable neutrino flux. Majorana neutrinos do not have diagonal magnetic moments but may have non-diagonal transition magnetic moments which give rise to $N_{iL} \rightarrow N_{jR}$ ($i \neq j$) conversions. In contrast with the Dirac case, the right-handed state $N_{jR}$ is here active and detectable ($N_{jR} \sim \nu_{jR}^c$), and hence the measurable neutrino flux is not depleted in the Majorana case, only its composition is changed. This is of particular interest for the ultrahigh energy neutrino flux emitted by active galactic nuclei (AGN), which are believed to be powered by black holes and sustain large magnetic fields to accelerate protons, which through collisions produce neutrinos [2]. It is therefore possible that magnetic moment induced helicity flips could affect the intensity and/or composition of the AGN neutrino flux measured in detectors on Earth, such as AMANDA, Nestor, Baikal and ANTARES.

For the purposes of the present study, there are two types of sources of interest, blazars and hot spots. Magnetic fields in blazar jets are assumed be of the order of 1 G and in hot spots some fraction of mG [2, 3]. The characteristic size of these objects is of the order of $10^{-2}$ pc and 1 kpc, respectively, and as we shall show, then magnetic moments of the order of $10^{-15} - 10^{-14} \mu_B$ would be large enough to cause detectable effects. Intergalactic magnetic fields are too weak to induce any additional transitions, the estimated upper limit for their field strength being about $10^{-23} - 10^{-20}$ G. Galactic magnetic fields have a strength of the order of $10^{-6}$ G [5] but have much smaller spatial dimensions and can be neglected as well in first approximation.

The most unambiguous signal of a magnetic transition would be the appearance of a tau neutrino component in the neutrino flux. The tau neutrinos $\nu_\tau$, in contrast with $\nu_e$ and $\nu_\mu$, are not produced in any substantial amounts in the processes inside the source, but they may be generated by magnetic interactions. Therefore in the following we will focus on the appearance of tau neutrinos. We assume that neutrinos are Majorana particles with non-vanishing transition magnetic moments that allow $\nu_e \rightarrow \nu_\tau$ and $\nu_\mu \rightarrow \nu_\tau$ transitions. The magnetic flavor transitions would result in a neutrino spectrum different from the expected one.

There are two suggested signatures for tau neutrino detection in neutrino telescopes: the so-called double bang event, and the absence of absorption by the Earth. In a double bang event [6] the tau neutrino, interacting with a nucleus via $W$-boson exchange in the detector, will produce a tau lepton and a hadronic jet and the decaying tau lepton will, if its energy is around 1 PeV, produce another jet of particles inside the detector. The energy and direction of the tau neutrino can be quite well defined if two practically same timed jets are tagged. The absence of absorption, a more recent idea to detect tau neutrinos [7], is based on the opacity of the Earth at high neutrino energies [8]. All neutrino species scatter from matter, but in the case of the tau neutrino there is always a less energetic $\nu_\tau$ from the decaying tau
lepton in the final state. When propagating through the Earth the sustained tau neutrino component will lose its energy in sequential scattering processes. Finally the energy will be low enough and the neutrinos will not interact any longer, resulting in an excess of upgoing events at energies around 10 - 100 TeV.

As mentioned above, the AGN neutrinos are sensitive to magnetic moment values of the order of $10^{-15} - 10^{-14} \mu_B$. This is an interesting region since such small values cannot be tested in laboratory experiments, nor completely by traditional astrophysics or cosmology. Laboratory limits for the magnetic moments of the different neutrino species are [9, 10]

$$\mu_{\nu_e} < 1.8 \times 10^{-10} \mu_B, \quad (1)$$
$$\mu_{\nu_\mu} < 7.4 \times 10^{-10} \mu_B. \quad (2)$$

These limits are based on elastic scattering cross sections and are therefore valid for both Dirac neutrino helicity flips and Majorana neutrino magnetic transition moments. The most stringent astrophysical limit, $\mu \leq 1.4 \times 10^{-12} \mu_B$, is based on the cooling rates of red giants [11] and is valid for all Majorana neutrino flavors. Limits from the energy loss of SN1987A are valid for Dirac neutrinos only. Nucleosynthesis constraints [12] are of the order of $10^{-11} \mu_B$ and apply also to Majorana neutrinos.

2. **Neutrino production and magnetic conversion in the sources.** In blazars protons are accelerated in jets of plasma [13] bursting out along the rotation axis of the central engine, a supermassive black hole. Hot spots are created when a jet collides with plasma and gas of a lobe. They may be even around 1 Mpc away from the center of the host galaxy. In the sources high energy protons are believed to be accelerated by the first order Fermi acceleration mechanism by repeated scatterings back and forth across a shock front in a partially turbulent magnetic field. The gyroradius of the proton will grow as the kinetic energy increases [14]. This process can go on until the particle either escapes the area of acceleration or scatters from another particle. Electron and muon neutrinos are produced in pion photoproduction process, the most important chain being $p\gamma \rightarrow n\pi^+ \rightarrow \mu^+\nu_\mu \rightarrow e^+\nu_e\bar{\nu}_\mu$ [15], whereas tau neutrinos are produced in the source only in negligible amounts. There are numerous different models to estimate the neutrino spectrum from the observed photon spectrum [16], the average neutrino energy being $1/20$ of the primary proton energy.

In this paper we will consider particle acceleration in so-called parallel shocks, i.e. the situation where the main component of the magnetic field is parallel to the shock front velocity. At the shock front the magnetic field is turbulent, which is crucial for the acceleration of the protons. Outside the shock region the perturbations of the field are assumed to be smaller. Although neutrinos can be produced in the turbulent region, in most of the cases a neutrino observed at Earth propagates out of the acceleration region not through the shock plane but through the region of less turbulent magnetic field. We will make the assumption that the main component of the magnetic field is homogenous and constant and that the perturbations can be neglected. The effects of the magnetic field turbulencies on neutrino propagation have been considered in [17].
In the case of Majorana neutrinos the magnetic interaction is described by the Lagrangian
\[ \mathcal{L} = \frac{\mu_{ij}}{2} \bar{\nu}_i \sigma_{\alpha\beta} \nu^c_j F^{\alpha\beta} \] (3)
where \( \mu_{ij} \) is the magnetic transition moment of the interaction and \( F^{\alpha\beta} \) is the electromagnetic field strength tensor. This term allows the flavour flip between \( \nu_i \) and \( \nu^c_j \). The equation of motion with magnetic transition in case of two neutrino families, e.g. \( \nu_\mu \) and \( \nu_\tau \), is of the form
\[ i \left( \begin{array}{c} \dot{\nu}_\mu \\ \dot{\nu}_\tau^c \end{array} \right) = \frac{1}{2E} \left( \begin{array}{cc} m_1^2 & 2E \mu B \\ 2E \mu B & m_2^2 \end{array} \right) \left( \begin{array}{c} \nu_\mu \\ \nu_\tau^c \end{array} \right), \] (4)
where \( B \) is the field transverse to the neutrino propagation. For a magnetic transition to take place, the diagonal elements have to be smaller than the off-diagonal elements:
\[ \mu B \gg \frac{\Delta_0}{2E}, \] (5)
where \( \Delta_0 = m_2^2 - m_1^2 \). In case of blazars, by estimating \( B \simeq 1 \text{ G} \simeq 2 \times 10^{-2} \text{ eV}^2 \), \( \mu_B \approx 3 \times 10^{-7} \text{ eV} \) and \( E = 10^{15} \text{ eV} \), this yields the condition
\[ \Delta_0 \ll 2EB \frac{\mu}{\mu_B} \simeq 1.2 \times 10^7 \text{ eV}^2 \frac{\mu}{\mu_B} \frac{E}{1 \text{ PeV}} \frac{B}{1 \text{ G}}. \] (6)
Hence to be able to probe magnetic moment values of e.g. \( 10^{-12} \mu_B \) the mass difference has to be \( \Delta_0 < 1.2 \times 10^{-5} \text{ eV}^2 \). Notice that the smaller the mass difference, the stronger the field or the higher the energy of the neutrino the smaller values of magnetic moment can be tested. If the mass difference \( \Delta_0 \) obeys the condition of Eq. (6), the Majorana neutrino flavor conversion probability in magnetic field is given by
\[ P(\nu_L \to \nu_R; r) = \sin^2 \left( \int_0^r \mu B(r') \, dr' \right). \] (7)
The conversion is dependent only on neutrino magnetic moment \( \mu \), magnetic field strength perpendicular to the neutrino propagation \( B \) and the path length \( r \) in the field. All neutrinos traversing the same distance will thus undergo the same transition, independent of their energy.

3. A simple model for neutrino flavor conversion in a constant homogenous magnetic field.
In order to evaluate the conversion probability Eq. (7) one should have a model for the structure of the magnetic field in the jet. As mentioned above, we assume a parallel shock model for the acceleration where the shock wave propagates along the magnetic field. This field is assumed to be constant and homogenous in a circular region, perpendicular to the field, and to drop quickly to zero outside that region. Inside the region charged protons have a gyroradius \( R = E_\mu / B \), which enlarges as the proton gains energy in each crossing of the shock. All protons gyrate to the same direction, and when a proton hits a gamma, a pion is produced. The daughter neutrinos are born right after the collision, since the pion and its longer living decay product muon stays in the region of acceleration: with \( E_\mu = 10^{16} \text{ eV} \) the
Muon will fly $\gamma \tau c \simeq 6 \times 10^{10}$ m, which is much less than the size of the accelerator (typically of the order of $10^{14}$ m). We will also assume that the photon number density in different parts of the field is the same so that the pion photoproduction (and neutrino production) rate is constant.

Let $L$ denote the distance neutrino propagates in the direction perpendicular to the magnetic field and towards the observer. According to Eq. (7) we can then write

$$P \simeq \sin^2 \left( 8.7 \times 10^{12} \frac{\mu_B}{1 \text{ G}} \frac{B}{10^{-2} \text{ pc}} \right).$$

The typical values $B \simeq 1 \text{ G}$ and $L \simeq 10^{-2} \text{ pc}$ correspond to a blazar jet near the central engine.

The effective distance $L$ depends on the site of creation of the neutrino. As this is not known one has to calculate the average conversion probability taking into account all possible path lengths. This obviously depends on the energy of the neutrino, since the most energetic neutrinos can be produced only at outskirts of the disk of the jet cross section (or hot spot area), i.e. where the gyroradius $R = E_p/B$ of the primary proton is close to the radius $R_0$ of the disk, while neutrinos with a lower energy can originate also deeper in the disk. Following the geometry presented in Fig. 1, we can write the average conversion probability for a given proton gyroradius $R$ in the form:

$$P_{\nu e, \nu_{\mu} \rightarrow \nu_{\tau}} = \frac{1}{\pi (R_0 - R)^2} \int_0^{R_0-R} \int_0^{2\pi} r \, P_{\nu e, \nu_{\mu} \rightarrow \nu_{\tau}} (\mu_B L(r, \phi)).$$

Here $(r, \phi)$ is the location of the center point of the circular path of the primary proton in polar coordinates with respect to the jet axis. By simple geometry and algebra one can express the neutrino path length $L$ in terms of the polar coordinates (see Fig. 1).

In Fig. 2 we have plotted the neutrino flavour ratio $\nu_{\tau}/\nu_{e,\mu} = P_{\nu e, \nu_{\mu} \rightarrow \nu_{\tau}}/(1 - P_{\nu e, \nu_{\mu} \rightarrow \nu_{\tau}})$ as a function of energy for different magnetic moment values. One can see that the tau neutrino component in the flux is practically independent of the neutrino energy. At very high energies, however, when gyroradius is close to the radius of the magnetic area, the ratio clearly increases provided the magnetic moment is large enough. This is because with increasing energy the average distance $L$ that neutrino propagates in the magnetic field decreases and becomes close to the value favourable to a helicity transition. This can be seen as an increase of the neutrino flavour ratio for the highest energies achievable by the source. More important, however, is that with certain magnetic moment values the transition probability is higher than 0.5 and consequently the flavour ratio is larger than 1. This is the case e.g. for a blazar with $R_0 = 10^{-2}$ pc and magnetic field of 1 G for magnetic transition moment value $\mu \approx 1.4 \times 10^{-13} \mu_B$.

We have plotted in Fig. 3 some examples of the neutrino flavour ratio $\nu_{\tau}/\nu_{e,\mu}$ as a function of magnetic transition moment at 1 PeV neutrino energy. We have used as examples a blazar with $R_0 = 10^{-2}$ pc and a magnetic field of 1 G and a hot spot with $R_0 = 1$ kpc and 0.1 mG. For comparison, two other blazars are also represented, one with $R_0 = 10$ mpc and with a weaker magnetic field, 0.1 G, the other with a larger jet $R_0 = 1$ pc and 1 G field. The plot shows that the averaged ratio of the two flavours is zero when the magnetic moment.
is too small to cause the conversion. It increases from zero to about 1.3 as the magnetic moment grows one decade and finally settles slowly to 1. The region of the magnetic moment value where the increase occurs depends on the characteristics of the source, i.e. its size and magnetic field. One can see that the magnetic moment of the order of $10^{-13}\mu_B$ will already provide a flux with equal amounts of tau and muon (or electron) neutrinos in a blazar with $R_0 = 10^{-2}$ pc and $B = 1$ G. In the case of hot spots one can test the magnetic moment down to values around $10^{-14}\mu_B$. However, one has to remember that the real distinction between the two cases is the mass difference of Eq. (6): with the first example blazar it is $\Delta_0 \lesssim 1.2 \times 10^{-6}$ eV$^2$ and with the hot spot $\Delta_0 \lesssim 1.2 \times 10^{-11}$ eV$^2$. It is interesting to note that the mass differences of these sizes have been used to explain the solar neutrino problem via the MSW effect and vacuum oscillations \cite{19}, respectively.

The recent results of Super-Kamiokande on atmospheric neutrinos \cite{1} can be explained by the existence of $\nu_{\mu} \leftrightarrow \nu_{\tau}$ or $\nu_{\mu} \leftrightarrow \nu_s$ oscillations ($\nu_s$ is a sterile neutrino) with the oscillations parameters $\Delta m^2 \nu = 10^{-3} - 10^{-2}$ eV$^2$ and $\sin^2 2\theta > 0.8$. In the former case there would be a $\nu_{\tau}$ component in the AGN neutrino flux which would shadow the effect we are considering. It should be emphasized, however, that if tau neutrinos are created by the $\nu_{\mu} \leftrightarrow \nu_{\tau}$ oscillations with the oscillation parameters indicated by Super-Kamiokande results the flavour ratio would always average to 0.8 - 1. Thus the values of the $\nu_{\tau}/\nu_{\mu}$ larger than 1, or smaller than 0.8, could not be explained solely in terms of oscillations. In the case of $\nu_{\mu} \leftrightarrow \nu_s$ oscillations the appearance of $\nu_{\tau}$ would indicate magnetic transitions at AGN source, the oscillations affecting only the relative fluxes. Let us note that the constraints from the primordial nucleosynthesis seem to disfavour these oscillations in the Super-Kamiokande parameter range as these would increase the effective number of neutrino species \cite{20}. However, the present status of the limit on the number of neutrinos is somewhat unclear because of uncertainties in the $D/\He$ and $\He$ abundance determinations \cite{21}.

4. Summary and discussion. It is interesting to speculate about possible future data sets. Let us suppose that we see $\nu_{\tau}$ from all extragalactic sources. If, as believed, these neutrinos are not produced in the processes of the source, this will then give a certain allowed area in the parameter space for both neutrino oscillations and magnetic moments. If, however, we see $\tau$ neutrinos from some sources and not from all the other sources, we can rule out the oscillations since the distance of all sources is of the same order of magnitude \cite{5}.

In that case we have been lucky to find the magnetic transition moments of Majorana neutrinos and confirmed the Majorana nature of neutrinos. In the mechanism we propose the ratio $\nu_{\tau}/\nu_{e,\mu}$ varies from zero to values somewhat higher than one depending on the source as the transition probability is different for different source parameters, i.e. magnetic field strength and size. This variation can be used as a signal to distinguish between possible oscillations and magnetic transition moment as a reason to the appearance of tau neutrino component in the flux. One special case is to try to see difference in hot spot neutrino flux compared to blazar neutrinos. Hot spot neutrinos have propagated in spatially large but weak source fields, while the blazar neutrinos have propagated in much stronger but less extended fields. To see tau neutrinos from hot spots but not from blazars
would allow us to probe magnetic moment down to values of the order of \((10^{-15} - 10^{-14})\mu_B\). Another example would be \(\nu_\tau\) flux seen emanating from blazars only, but not from hot spots. That would mean that the neutrino mass difference of Eq. (6) is greater than required for hot spot neutrinos, of the order of \(\Delta_0 \gtrsim 1.2 \times 10^{-11} \text{ eV}^2\). In these cases one has to distinguish between the possible neutrino flux of the main engine and the hot spot. Finally, if we see no \(\nu_\tau\)’s from any of these astrophysical sources one can set an upper limit for the transition magnetic moments of the order of \((10^{-15} - 10^{-14})\mu_B\).

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Figure 1: Geometry of the AGN. $R_0$ and $R$ are respectively the radius of the magnetized area and the gyroradius of the proton, $(r, \phi)$ is the center point of this gyration motion in polar coordinates and $L$ the neutrino path length in the magnetic field.

Figure 2: Neutrino flavour ratio $\nu_\tau/\nu_{e,\mu}$ as a function of energy for selected values of magnetic moment $\mu_\nu$. Here $R_0 = 10^{-2}$ pc and magnetic field 1 G.
Figure 3: Neutrino flavour ratio $\nu_\tau/\nu_{e,\mu}$ from different sources.