Electromagnetic properties of neutrinos and phenomenology of neutrino oscillations

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Neutrinos are one of the most intriguing particles of the Standard Model. The observation of oscillation among different neutrino flavors suggest the existence of an extended theory beyond the Standard Model. These extended theories have several new phenomenological features which might be detected in future neutrino experiments. One such possibility is the existence of neutrino electromagnetic interactions. Despite being electrically neutral, neutrinos acquire their electromagnetic properties through interaction with photons at quantum loop level (Fig. 1). This can generate important new effects such as neutrino spin-flavor oscillations in the presence of background electromagnetic fields [1].

In the present Thesis, we study the phenomenology of neutrino flavor and spin-flavor oscillations in solar and astrophysical environments. In solar interiors the magnetic fields may be sufficiently large to cause appreciable neutrino transitions. Thus the solar neutrinos detected at Earth may act as a messenger of information about the solar magnetic fields. Using the current bounds on Helioseismology we construct analytical models for the magnetic field in all the three regions of the Sun. We also obtained a novel parametrization for the electron density profile in the Sun, which provides a better approximation compared to the usual exponential parametrization. The ^8B neutrinos produced in the solar interior may undergo transitions $\nu_{eL} \to \bar{\nu}_{\mu R} \to \bar{\nu}_e$ due to combined effect of magnetic field and vacuum mixing. We numerically evaluate these transition probabilities and compare our results with the Borexino experiment to place bounds on the solar magnetic fields (Fig. 2b). It is found that whereas the Borexino bounds are too weak to place any upper limit on the magnetic field in the radiative zone of the Sun, for the solar core magnetic field we are able to place an upper bound $B_0 < 1.1 \times 10^6$G, which is an improvement by a factor of almost one-seventh of the current largest helioseismological bound [4]. We also study the neutrino spin transitions for neutrinos produced in extreme environments such as neutron stars (NS). For these calculations we used realistic density and magnetic field profiles both in the interior and outer regions of the NS. We showed that while inside the NS the neutrino propagation is highly adiabatic, as the neutrinos come out of the NS the non-adiabatic effects start to become more important as the distance from the surface increases. In the interior region of the NS, the matter effects strongly dominate over the magnetic field, thus the area of the curve traced by spin-polarization vector is negligible, and hence the associated geometric phase is vanishingly small. As the neutri-

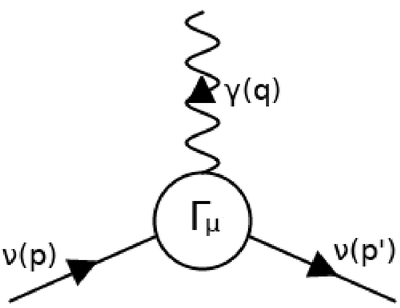

FIG. 1: Effective vertex for neutrino-photon interaction.

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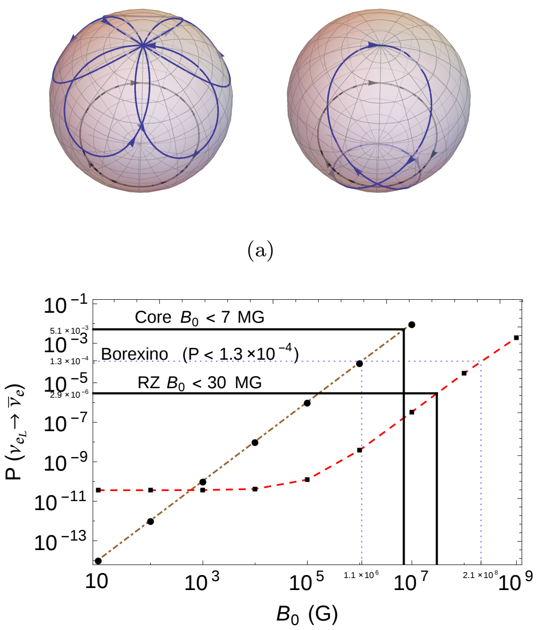

(a)

(b)

FIG. 2: (a)Bloch sphere representation of neutrino spin rotation $\nu_{eL} \to \nu_{eR}$, (b) The probability of solar electron neutrino ($E = 10$ MeV) to anti-neutrino conversion at the Earth's surface and comparison with Borexino results.

nos come out of the NS, matter effects vanish and neutrino eigenstates develop a significant adiabatic geometric phase. In addition, we also studied the transition probability and the cross boundary effects and showed that at a distance of about 200 times the radius of a NS, the initial flux of left-handed neutrinos produced inside the NS is depleted to half of its original value [3].

The study of geometric properties of neutrino flavor and spin-flavor oscillations brings important new insights about the nature of this phenomenon. In this geometric picture the neutrino propagation in space can be visualized by studying the trajectory of neutrino spin-polarization vector in the projective Hilbert space of the system. Such an evolution is known to give rise to geometric phase due to non-trivial geometry of the projective Hilbert space. In case of spin precession $\nu_{\rm L} \to \nu_{\rm R}$ of pure neutrino states, the neutrino spin-polarization traces out cyclic and noncyclic curves on the Bloch sphere for different parameters of the Hamiltonian (Fig. 2a). We derive analytical expressions for the non-adiabatic and non-cyclic geometric phases and show that the area enclosed by the trajectory traced out by the spin-polarization vector is related to the geometric phases acquired by the neutrino state during the evolution [2, 3]. We also show that for resonant transition $\nu_{eL} \leftrightarrow \nu_{eR}$ the geometric phase vanishes, since in this case the spin-polarization vector traces out a great circle on S^2.

In a typical charged-current interaction process pure neutrino states cannot be realized and one needs a more general discussion in terms of density matrices. We discuss the geometric properties of neutrino flavor oscillations for such an incoherent beam of neutrinos and derive expressions for the geometric phase in both two flavor and three flavor models [5]. We also discuss the geometry of the state space of neutrino flavor oscillations and its connection with the appearance of a geometric phase. For two flavor oscillations, the geometric phase is shown to be independent of the Majorana phase. We also show that the geometric phase can be used as a measure of coherence of the neutrino beam. In addition, our expressions of the mixed state geometric phase are a generalization of the previously obtained results of the pure state geometric phase for both two and three flavor neutrino oscillations.

References

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