Neutrino Magnetic Moment, CP Violation and Flavor Oscillations in Matter [1]

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In both the Early Universe, and the intense astrophysical neutrino sources such as the core collapse supernovae, neutrinos are believed to undergo nonlinear forms of flavor evolution which result from the many-body effects due to neutrino-neutrino scattering. These oscillations are very different from the vacuum oscillations of the neutrinos or the MSW effect in the sun, and are generally termed *collective neutrino oscillations*. Although the collective neutrino oscillations are highly nonlinear, they were shown to possess several dynamical symmetries under a two-flavor mixing scenario [2].

In this paper, we show that these symmetries also emerge in the realistic three-flavor mixing case and that they are present even when the CP-symmetry is broken in the neutrino sector. One practical consequence of the existence of such symmetries is that they give rise to conserved quantities which reduce the complexity of the nonlinear evolution and allow one to make some model independent statements [2]. For example, although the neutrino energy spectrum itself changes nonlinearly with time, the conserved quantities give rise to *invariant spectra* which are functionals of the former and constant in time (Fig. 1).

We also examine the interplay between the possible CP violation features of neutrinos, their anomalous magnetic moments, and the collective flavor oscillations with a particular focus on the inherent many-body nature and the symmetries of the latter. We show that, as long as neutrino magnetic moment can be ignored (e.g., if the magnetic field is not very strong) the CP-violating effects factor out of the evolution operator and evolve independently of the nonlinear flavor transformations. In particular, this tells us that, even if CP violation exist in the neutrino sector, collective oscillations can not amplify its effects the way they amplify some other features, such as the mass hierarchy.

However, even the tiny anomalous magnetic moments of neutrinos may play a part in some astrophysical and cosmological scenarios [3]. We show that, in this case the CP violating effects cannot be strictly factorized any more. However, one can carry out a mathematical trick and still factor out the CP violating effects from collective oscillations by defining an *effective magnetic moment*. This effective magnetic moment includes the CP-violating Dirac phase in its definition and is different for neutrinos and antineutrinos, reflecting the fact that CP violation and magnetic moment are intertwined in an inseparable way during the flavor evolution. However, since the neutrino magnetic moment is small enough to be conveniently studied in a first order perturbation approach, this allows us to treat the unfactorized CP violation effects perturbatively in the first order as well.

The formulation we use in this paper is based on the symmetries of the Hamiltonian describing the collective neutrino flavor evolution and therefore is valid under very general conditions. In particular, it is valid even in the presence of many-body quantum entanglements which are generally ignored by mean field type approximations.

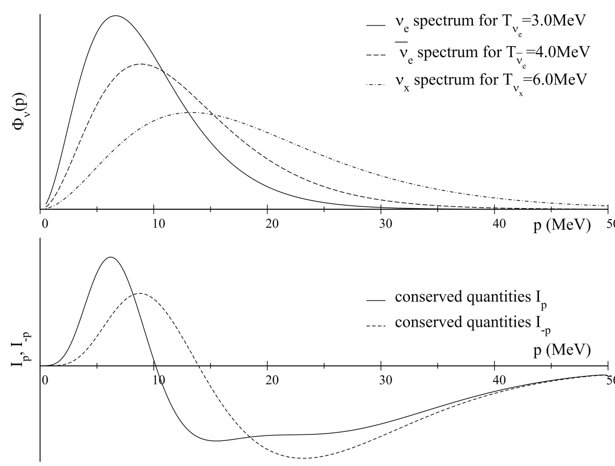

Figure 1: *Upper panel*: Energy spectra of the neutrinos from a proto-neutron star. *Lower Panel*: Corresponding invariant spectra.

References

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[3] Kusakabe, M., et al.: 2013, *Phys. Rev. D*, **87**, 085045.