Core-collapse supernova neutrinos and neutrino properties

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Abstract. Core-collapse supernovae are powerful neutrino sources. The observation of a future (extra-)galactic supernova explosion or of the relic supernova neutrinos might provide important information on the supernova dynamics, on the supernova formation rate and on neutrino properties. One might learn more about unknown neutrino properties either from indirect effects in the supernova (e.g. on the explosion or on in the r-process) or from modifications of the neutrino time or energy distributions in a detector on Earth. Here we will discuss in particular possible effects of CP violation in the lepton sector. We will also mention the interest of future neutrino-nucleus interaction measurements for the precise knowledge of supernova neutrino detector response to electron neutrinos.

Keywords: core-collapse supernova neutrinos, neutrino properties, CP violation, neutrino-nucleus measurements, beta-beams

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1. INTRODUCTION

Very massive stars produce violent gravitational explosions at the end of their life. A huge amount of (anti-)neutrinos of all flavours is emitted during this phenomenon that typically lasts a few seconds. The neutrino luminosity curve follows closely the collapse, accretion phase and the cooling of the neutron star left. Stars with masses larger than 20-25 solar masses can leave a black hole instead, with the neutrino time distribution cut after a few hundreds milliseconds [1]. Neutrinos emitted in Gamma-Ray-Bursts can also produce a characteristic neutrino signal [2]. Other interesting features of the supernova dynamics can be extracted from a core-collapse supernova neutrino signal like e.g. information on the shock-wave [3, 4, 5].

Core-collapse supernova neutrinos have been measured only once so far, during the explosion of the SN1987A located in the Large Magellanic Cloud at 50 kpc from us [6]. The few events observed in the Kamiokande [6], IMB [7] and Baksan [8] detectors have brought important confirmation on the theoretical expectations on the neutrino fluxes [6] and information on neutrino properties. Large scale observatories at present under study (LAGUNA Design Study financed within the

1 This observation gave the Nobel Prize to M. Koshiba in 2002 with R. Davis for his pioneering experiment on solar neutrinos, and to R. Giacconi.

2 Some features of the energy and angular distributions remain to be understood.
should reach the sensitivity to observe extra-galactic explosions and for the
discovery of relic supernova neutrinos. Three technologies are under investigation:
water Čerenkov (MEMPHYS/UNO/Hyper-K), scintillators (LENA) and liquid argon (GLACIER). About a hundred events are expected in a detector such as
Borexino, about 10000 in Super-Kamiokande and $10^5$ in MEMPHYS for a typical supernova at 10 kpc. While explosions in our Galaxy are a rare phenomenon (typically 1-3 per century), the rate increases up to 1 per year at a distance as far as 10 Mpc.

Relic supernova neutrinos (also called the diffuse supernova neutrino background) are neutrinos produced in past supernova explosions. The relic fluxes are not only sensitive to the supernova dynamics and neutrino properties, but also on the star formation rate. The latter can be constrained through direct and indirect observations. At redshifts smaller than 1 the rate is rather well known; while very recent works try to constrain at redshifts as high as 4. The experimental present upper limits at 90% C.L. are of $6.8 \times 10^3 \, \nu_e \, \text{cm}^{-2} \text{s}^{-1}$ ($25 \, \text{MeV} < E_{\nu_e} < 50 \, \text{MeV}$) and $1.2 \, \bar{\nu}_e \, \text{cm}^{-2} \text{s}^{-1}$ ($E_{\bar{\nu}_e} > 19.3 \, \text{MeV}$) come from the LSD and the Super-Kamiokande detectors respectively. Present theoretical predictions show that the relic fluxes are very close to the Super-Kamiokande limits, so that they might be discovered with large size detectors. In it has been proposed to improve our present relic electron neutrino limit by using the few events associated to electron scattering on oxygen in MEMPHYS or on carbon in LENA. On the other hand several hundred events might be measured in GLACIER thanks to the large neutrino-argon cross section, as first pointed out in.

Impressive progress has been made in neutrino physics in the last ten years, after the discovery of the phenomenon of neutrino oscillations performed by the Super-Kamiokande experiment. However crucial questions remain open, among which the value of the third neutrino mixing angle, of the CP violating phase(s), of the (Majorana versus Dirac) nature of neutrinos and of the absolute mass scale. The study of neutrinos from the early Universe or from stars brings important elements to progress on some of the open issues. In particular, unknown neutrino properties might have an indirect impact on the supernova environment such as e.g. on the nucleosynthesis of the heavy elements during the r-process or leave an imprint on the time or energy supernova neutrino signal in a detector on Earth. For example in we have shown that in lead-based detectors one can exploit the measurement of the electron neutrino average energy through one and two neutron emission to extract information on the third neutrino mixing angle. A lead-based detector (the HALO project) is planned for construction at SNOLAB. Here we will discuss possible CP violating effects in the supernova context.

In order to use supernova neutrinos to extract information on neutrino properties, we need to progress on the uncertainties that still affect the supernova neutrino predictions. In fact, the theoretical calculations of the neutrino fluxes are affected by uncertainties at the neutrinosphere, due to different supernova modelling. These

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3 Note that if the supernova observatory has an energy threshold of about 10 (5) MeV, the flux is essentially due to $z<1$ ($z<2$).
uncertainties will narrow down once supernova explosions will be successfully obtained for different stellar masses and the relevant microscopic processes included in the neutrino diffusion. Obviously, the number of unknowns can also reduce if planned neutrino experiments progress on some of the neutrino properties like e.g. if Double-Chooz [22] or Daya-Bay [23] measure the third neutrino mixing angle. On the other hand, recent important developments have also shed a new light on our understanding of neutrino propagation in dense media in presence of the neutrino-neutrino interaction (see e.g. [24, 25, 26, 27, 28, 29, 30, 31, 32]. In fact, significant differences arise in some cases compared to the standard Mykheyev-Smirnov-Wolfenstein effect [33, 34]. In the detection process, one also need to take into account the knowledge of the detector response. If we aim at disentangling the different pieces of information, it is obviously essential that we extract as much information as possible from future observations. While neutral current events exploiting the scattering on electrons or on protons [35] will measure the total neutrino fluxes, sensitive to the normalisation factors; charged-current events will be flavour sensitive to both electron neutrino and anti-neutrinos. If electron anti-neutrinos can be detected through their interaction on protons, that is known theoretically at all orders, the measurement of electron neutrinos require interaction on nuclei that is affected by theoretical uncertainties. Here we will briefly discuss the need for future measurements with intense low energy neutrino beams.

2. POSSIBLE CP VIOLATION EFFECTS IN SUPERNOVAE

The possible existence of CP violation in the lepton sector is one of the crucial open issue in neutrino physics that can have tremendous impact on other domains as well. If the value of the third neutrino mixing angle turns out to be very small, only "third generation" accelerator neutrino experiments, namely super-beams, beta-beams and neutrino factories [36], will reach the necessary sensitivity to explore this question. It is important to search for other strategies to learn about the value of the CP violating phase, like for example with neutrino astronomy [37, 38]. In a recent work [21] we have investigated both analytically and numerically possible CP violating effects in the supernova environment. The neutrino fluxes within the supernova are obviously

\[ \phi_{\nu_i} (\delta) = L_{\nu_i} P(\nu_i \rightarrow \nu_i) + L_{\nu_j} P(\nu_j \rightarrow \nu_i) + L_{\nu_k} P(\nu_k \rightarrow \nu_i) \]  

(1)

with the luminosities at the neutrinosphere \( L_{\nu_i}, (\nu_i = \nu_e, \nu_\mu, \nu_\tau) \) given by either Fermi-Dirac or power-law distributions.

Analytically one can show that the following equation holds [21]:

\[ P(\nu_\mu \rightarrow \nu_e, \delta \neq 0) + P(\nu_\tau \rightarrow \nu_e, \delta \neq 0) = P(\nu_\mu \rightarrow \nu_e, \delta = 0) + P(\nu_\tau \rightarrow \nu_e, \delta = 0). \]  

(2)

If \( \nu_\mu \) and \( \nu_\tau \) have equal luminosity at the neutrinosphere (true at tree level), Eqs. (1) and (2) imply that there are no CP violation effects on the electron (anti-)neutrino fluxes for any density profile, as in vacuum. This conclusion is in agreement with the
FIGURE 1. Muon neutrinos flux ratios for a CP violating phase $\delta = 180^\circ$ and $\delta = 0^\circ$ at 1000 km from the neutrinosphere. The different curves correspond to the cases of normal (NH) or inverted (IH) hierarchy and large ($\sin^2 2\theta_{13} = 0.19$, LA) or small ($\sin^2 2\theta_{13} = 3 \times 10^{-4}$, SA) third neutrino mixing angle [21].

FIGURE 2. Same as Figure 1 but for electron neutrino fluxes. In this case $\nu_\mu$ and $\nu_\tau$ neutrino fluxes are taken different at the neutrinosphere by assuming that their temperatures differ by 1 MeV as an example [21].

findings in [38]. However higher order corrections to neutrino scattering on matter and/or physics beyond the Standard Model such as flavour changing interactions can differentiate $L_{\nu_\mu}$ and $L_{\nu_\tau}$. In this case the electron (anti-)neutrino fluxes do depend on the CP violating phase Eqs. (1)-(2).

We have performed for the first time numerical calculations of the neutrino propagation in a dense environment with $\delta$ (for details see [21]). Figure 1 presents the effects on the $\nu_\tau$ fluxes as an example. As one can see the presence of the phase modifies them significantly, even though the effects on the muon and tau neutrino fluxes unfortunately cancel out once one consider neutral current interactions since all neutrino fluxes add. Figure 2 and 3 show the effects on the electron neutrino and anti-neutrino fluxes respectively once we assume that $L_{\nu_\mu} \neq L_{\nu_\tau}$. Such effects are interesting since the electron (anti-)neutrinos play a specific role both for the
nucleosynthesis of heavy elements during the r-process and for a possible signal in a detector where electron (anti-)neutrinos can be measured through charged-current events.

We have also investigated indirect impact on the r-process by calculating how the electron fraction is modified: the effects turn out to be tiny (Figure 4). Finally we have determined the possible impact on the neutrino signal in a detector on Earth. While the δ effect on the total number of events is of the order of $2 \times 10^{-4}$, variations up to 5% are obtained for the events as a function of neutrino energy (Figure 5).

3. ELECTRON NEUTRINO DETECTION AND FUTURE NEUTRINO-NUCLEUS MEASUREMENTS

Neutrino-nucleus interactions is a topic of current great interest for e.g. understanding the neutrino detector’s response, the nucleosynthesis of heavy elements and of the isospin and spin-isospin nuclear response (see e.g. the reviews [40, 41]). For example it is shown in [39] that such measurements furnish a new constraints for neutrinoless double-beta decay predictions that are at present affected by significant variations. In supernova neutrino observatories various nuclei are exploited as neutrino targets: carbon in scintillator detectors, oxygen in water Čerenkov, lead in lead-based detectors, argon in liquid argon, deuteron in heavy water. Deuteron is by far the best case since it can be predicted theoretically with errors of a few percent in Effective Field Theory. Carbon is the best studied case experimentally.

\[4\] To get this result we calculate the neutrino fluxes far our the supernova and average them when vacuum is reached.

\[5\] This conclusion is at variance with section 3.4 of Ref. [38] where the authors find that are no CP violating effects in a detector on Earth, if muon and tau neutrinos have equal or different luminosities at the neutrinosphere. Note that they use the matter eigenstates (in their derivation) which is equal to the physical flavour basis used in our calculations only at very high densities.
FIGURE 4. Ratio of the electron fraction as a function of the distance in the supernova for a non-zero over a zero delta phase. The different curves correspond to normal hierarchy and large (solid), or small (dashed) $\theta_{13}$, and to inverted and large (dot-dashed) or small (dotted) $\theta_{13}$ [21].

although the inclusive cross sections are still affected by significant variations (see e.g. [42]). The only other available measurement is on iron. Theoretical predictions employing microscopic models (in particular the shell model and the QRPA) can present discrepancies arising for example from the treatment of the continuum and from different contributions of the forbidden multipoles (the spin-dipole and higher multipoles).

Future measurements with very intense low energy neutrino beams can provide important information that would put the theoretical predictions on neutrino-nucleus cross sections on a firmer ground. Two avenues are possible: either an intense conventional source (neutrinos from muon decay-at-rest) or low energy beta-beams $[44]$. Intense conventional sources will be available at $\nu$ SNS at Los Alamos $[45]$ and at JPARC. A low energy beta-beam facility might be established, in particular if a beta-beam for the search CP violation in the lepton sector is built. It is shown in $[10]$ that this might require a devoted storage ring while a less expensive option can be to use one/two detectors at off-axis of the storage ring planned for CP violation $[47]$. By varying the Lorentz boost of the ions one can try to disentangle the contribution of the forbidden multipoles for which little information is available right now $[44]$. Besides improving our knowledge of the supernova detector’s response, other interesting supernova neutrino applications are possible with low energy beta-beams. In particular combining measurements at different boosts one could reconstruct the neutrino signal from a supernova explosion $[50, 51]$.

$[44]$ Beta-beams are pure and intense neutrino beams of well known fluxes that exploit the beta-decay of boosted radioactive ions $[48]$. 
FIGURE 5. Ratio of the number of events, for a non-zero over a zero $\delta$ phase, associated to electron anti-neutrino scattering on protons in a water Čerenkov detector on Earth, such as Super-Kamiokande (22.5 kton fiducial volume). A 100% efficiency is assumed. The curves show the effects induced by a non-zero CP violating phase, i.e. $\delta = 180^\circ$ (solid), $135^\circ$ (dashed), $45^\circ$ (dot-dashed) [21].

4. CONCLUSIONS

Supernova neutrino experiments can bring crucial information, if a galactic supernova explosion occurs, or a future large-scale observatory observe an extragalactic event and measure relic supernova neutrinos. Such observations can help unraveling important features of the supernova dynamics, or of the still unknown neutrino properties. Important theoretical developments are also ongoing, in particular in our understanding of neutrino propagation in dense matter, since the neutrino-neutrino interaction included only recently in the calculations produces completely new features in some cases.

Here we have discussed the possible indirect and direct (on a neutrino signal) impact of CP violation in the lepton sector in the supernova environment. Our numerical calculations show that effects on the electron (anti-)neutrino fluxes within the supernova can be as large as factors 2-4, if muon and tau neutrinos have different luminosities at the neutrinosphere (due e.g. to physics beyond the Standard Model such as flavour changing interactions). Possible effects on the electron fraction, relevant for the r-process, are tiny; while variations up to 5% on the events as a function of neutrino energy are found in a detector on Earth.

One of the difficulties of this domain is that the information on the supernova dynamics, on the neutrino properties and the star formation rate (for relic neutrinos) is all entangled. It is therefore important to have observatories sensitive both to electron neutrinos and anti-neutrinos, to extract as much information as possible from observations. In this respect, important progress still need to be made on our knowledge of the neutrino-nucleus interaction, necessary for the electron neutrino detection through charged-current reactions.
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