PROCEEDINGS OF SCIENCE

The study of neutrinos and antineutrinos from astrophysical sources by Borexino

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The recent observation of CNO solar neutrinos by Borexino (BX) has proven the high potential offered by large underground ultrapure liquid scintillators to disclose weak neutrino and antineutrino fluxes. Supernovae explosions, gamma-ray bursts, solar flares and Gravitational Waves (GW) are among the possible extra-terrestrial sources of neutrinos and antineutrinos. The extreme radiopurity of the BX detector has already allowed to get the best upper limits on all flavor fluences in the few MeV energy range from gamma ray bursts, to set limits on the diffuse supernova antineutrino background in the unexplored energy region below 8 MeV and to get the strongest upper limits on fast radio bursts associated neutrino fluences up to 50 MeV. Recently, BX has searched for neutrino events in correlation with GW events from 2015 to 2020 using the BX data-set of the same periods. The strongest upper limits on GW-associated neutrino and antineutrino fluences have been obtained in the (0.5 - 5.0) MeV neutrino energy range.

The present contribution is aimed to describe the analysis procedures and the deduced upper limits for all neutrino flavors.

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1. Introduction

Multi-messenger astronomy started in 1987 with the detection of neutrinos associated with a supernovae explosion SN1987A[1–3]. More recently, the short gamma-ray burst GRB170817A was detected in 1.7 s temporal coincidence with the GW170817 event from a binary neutron-star merger[4]: the observation of GW events triggered an intensive follow-up campaign in neutrino detectors. An underground ultrapure detector like Borexino (BX) is perfectly suited for studies of rare and exotic processes in particle physics and astrophysics: the collaboration has already studied the diffuse supernova antineutrino background below 8 MeV [6, 7] and searched for possible time correlated events with transient astrophysical sources such as γ-ray bursts [8], gravitational wave events [9], solar flares [7], and fast radio burst [10] .

BX has recently updated the search for possible neutrino events in correlation with gravitational wave events for three observing runs (O1, O2 and O3) from 09/2015 to 03/2020 using data-sets of the same periods [11]. GW candidates originated by merging binaries of black holes (BHBH), neutron stars (NSNS) and neutron star and black hole (NSBH) were analyzed separately and in a cumulative approach. In the following sections, after the description of the detector layout, the event selecting cuts are reported together with the limits obtained by investigating both the elastic scattering and the inverse beta decay interaction channels.

2. Borexino detector

Borexino is a liquid scintillator-based large volume detector designed for low energy neutrino detection. The experiment is located at the Laboratori Nazionali del Gran Sasso (LNGS) at the depth of 3800 m of water equivalent and has been operated since from May 2007 till October 2021. The location provides good cosmic muon flux suppression by a factor of $\sim 10^6$. The detector structure represents an implementation of the graded shielding concept. The neutrino target consists of 278 tons ultra-pure organic liquid scintillator and is confined in the innermost detector part, enclosed by a 125 μm nylon vessel with radius of 4.25 m. The scintillator was chosen for the purpose of low-energy neutrino detection and it is made by pseudocumene doped with a PPO as fluor at a concentration of 1.5 g/l. The buffer volume serves as neutron and gamma radiation shield. Charged particles are detected in Borexino from the scintillator light emitted in the sensible volume and detected by $\sim$ 2000 PMTs. Data are used for reconstruction of energy and spatial coordinates of an event and also allows for the identification of a particle type due to the differences in the scintillation time profiles. Both energy and spatial resolutions of the detector were probed with radioactive sources placed at different positions inside the inner vessel: typical values at 1 MeV are $\sigma_E \sim$50 keV and $\sigma_X \sim$10 cm, respectively. The primary electronics of the Borexino detector is optimised for energies up to few MeV with energy calibration reliable up to 16.8 MeV. For higher energies a system of 96 fast waveform 400 MHz digitizers was developed, each of them is reading-in the signal summed from 24 PMTs. A more detailed description of the Borexino detector can be found in [12, 13].

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3. Analysis of the temporal correlations of Borexino signals with GW events

The most comprehensive collection of GW events is provided by the Gravitational-Wave Transient Catalog (GWTC) maintained by the LIGO/Virgo/KAGRA collaborations [14]. During the period of interest from September 2015 to March 2020, 93 GW events have been reported: Borexino was taking data when 70 (out of 87) BHBH mergers, 2 NSNS and 2 (out of 4) NSBH have occurred. Neutrinos and antineutrinos are detected by means of their elastic scattering on electrons, while for electron antineutrinos also the inverse beta-decay (IBD) process can be exploited with an energy threshold of 1.8 MeV.

Both signals of neutrino-electron scattering and inverse beta-decay (IBD) have been investigated within a time window of ± 1000 s centered at the detection moment of a particular GW event. The negative interval of the time window Δt = (-1000 - 0) s was chosen to cover earlier emission of neutrinos in the case of binary mergers [52]. The positive interval accounted for a possible delay of sub-MeV neutrinos propagating at the sublight speed: for a typical z = 0.64 redshift, the delay will reach 1000 s for 0.6 MeV neutrinos with a rest mass of 65 meV, which is the upper limit on neutrino masses from Planck 2018 results [15]. All selected GW events had the BX up time above 95% in the corresponding time interval Δt .

In the case of the scattering interaction, events have been selected in the fiducial volume of 145 tons (75 cm from inner vessel) and with a visible energy in the window (0.25-16.8) MeV. Cosmogenic background was reduced by applying a 0.3 s veto after internal muons. Time correlated events with energy above 0.25 MeV have been compared with the scaled background defined from the intervals [-5000... - 1000, +1000...+5000] s. Only in the case of GW191219 some excess was observed, with 9 events over an expected background of 4.4 ± 0.1, but still compatible with a background fluctuation. The cumulative energy spectra for all the 78 events for the signal and background time window have been compared but no significant excess for any energy interval was observed.

4. Limits on the neutrino fluence from the scattering events

No theoretical model is available to describe the low-energy part of the neutrino emission spectrum for BHBH mergers, therefore the fluence limits have been calculated for two different possible neutrino spectra: monoenergetic lines or a supernovae low-energy continuous spectrum. The latter was assumed to be a quasi-thermal with mean energy $< E >$ and deviation from thermal distribution described by the pinching parameter $\alpha = 3$ for all neutrino flavours. In case of neutrino scattering events the recoiled electron spectrum is continuous also in case of monochromatic neutrinos up to a maximal energy of $E_{e_{max}} = 2E_\nu^2/(2E_\nu + m_e)$. Three possible visible energy thresholds of 0.25, 0.8 and 3.0 MeV have been adopted in the analysis, depending on the neutrino energy, to maximise the signal to background ratio. The lower threshold at $E_1 = 0.25$ MeV was essential to remove the overwhelming ^{14}C component. The second $E_2 = 0.8$ MeV threshold was set in order to exclude ^{210}Po and solar ^{7}Be neutrino events and the third $E_3 = 3$ MeV threshold rejected most part of natural radioactivity. The analysis was done for the energy intervals from $E_{1,2,3}$ to $E_{e_{max}}$, the latter not exceeding the validity range of the detector energy response calibration (0.25-16.8) MeV. In the analysis, the energy resolution of the detector $\sigma(E_e)$ was taken into account.

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For each energy interval the number of time correlated events have been compared with the scaled background. Since there is no statistically significant excess the upper limits on fluences for (anti)neutrinos with the energy E_ν have been calculated as:

$$\Phi_\nu(E_\nu) = \frac{N_{90}(E_\nu, n_{obs}, n_{bkg})}{rN_e\sigma(E_{th}, E_{e_{max}})}, \qquad (1)$$

where $N_{90}(E_\nu, n_{obs}, n_{bkg})$ is the 90% C.L. upper limit for the number of GW-correlated events in the $(E_{th}, E_{e_{max}})$ interval per single GW and N_e is the number of electrons in 145 t of the Borexino scintillator. The limits have been obtained with the assumption that the whole neutrino fluence consists of only one individual flavour: the corresponding cross section in Eq. 1 was set to $\sigma_{\nu_{e,\mu,\tau}}$ ($\sigma_{\bar{\nu}_{e,\mu,\tau}}$), respectively. The limits obtained for the cumulative spectra of the overall 78 GW events are shown in Fig.1. As highlighted in the plot they improve and extend the Super Kamiokande ones below 4 MeV [16]. In the case of supernovae spectrum with a mean energy $< E > = 15.6$ MeV, the deduced limit on total $\bar{\nu_e}$ fluence was $\phi(\nu_e) = 1.2\ 10^{10}$ cm^{-2} (90% C.L.), very close to the one obtained for mono-energetic neutrinos with the same energy. Limits for separate BHBH, NSBH, NSNS events are reported in [11].

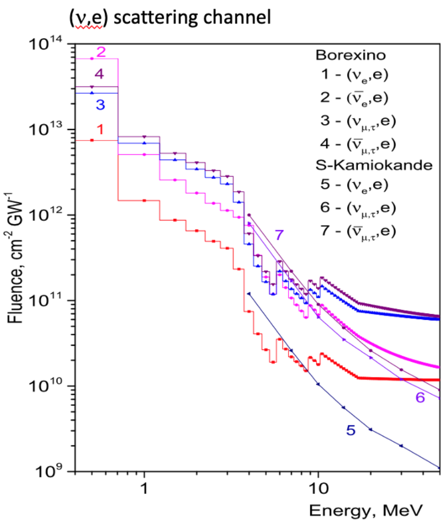

Figure 1: Borexino upper limits on mono-energetic neutrino fluences obtained with elastic scattering reaction through the temporal correlation analysis for 74 GW events (90% C.L.). The limits of Super-Kamiokande obtained for single GW170817 are also shown [16].

5. Limits on the antineutrino fluence from the IBD channel

The IBD offers a unique signature given by temporal and spatial coincidence of two correlated events associated with detection of a positron and a neutron. The procedure of IBD candidates selection and the energy spectrum of prompt positron events are detailed in [7]. The same 16.8 MeV upper boundary of the visible energy range was adopted as in the case of the (ν, e)-scattering analysis. No IBD event was observed in the ± 1000 s interval around the selected GW events and the expected background was almost zero [7] that allowed to adopt for the number of events the conservative limit $N_{90}(E_\nu, n_{obs}, n_{bkg})$= 2.44 at 90% C.L. [59]. Since the cross section of IBD reaction is about two order of magnitude larger than (ν, e)-scattering cross sections at the same energy and the background is small, the obtained upper limits for $\bar{\nu_e}$ fluences are the most stringent. The upper limit is calculated from the relation Eq. 1 but with replacing of the N_e with the number of protons N_p and considering the cross section of IBD reaction [7]. The resulting limit on fluence for 74 GW events reduced per one GW event is shown in Fig. 2.

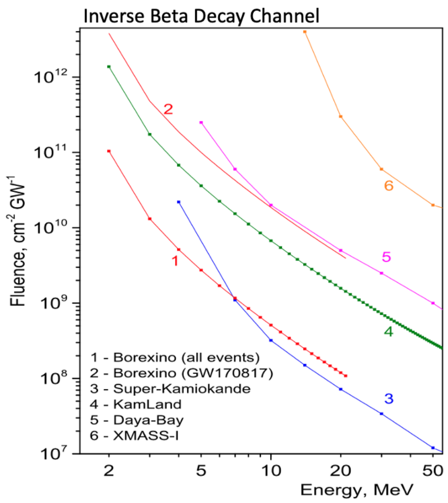

Figure 2: Upper limits on mono-energetic $\bar{\nu_e}$ fluences obtained using IBD interaction channel: Borexino (all events) [11], Borexino (GW 170817) [9], Super-Kamiokande coll. [16] (GW 170817), KamLand coll. [17] (GW 170817), DayaBay coll. [18], and XMASS-I coll. [19] (all for 90% C.L.).

6. Conclusions

Borexino searched for an excess in the number of events produced by neutrino-electron elastic scattering and the inverse beta-decay on protons correlated to 74 GW events from the GWTC-3 database. No IDB candidate was found and no statistically significant increase in the number of scattering events within time windows of ± 1000 s centered at the moment of GW arrival for all three options for merging of black holes and neutron stars. As a result, new limits on the fluence of monochromatic and supernova neutrinos of all flavours were set for neutrino energies in range of 0.5–5 MeV.

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