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NEUTRINOS

Geoneutrino Detection and Other Non-Solar Neutrino Physics Achievements of Borexino

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Abstract—The cosmic silence of the underground Gran Sasso laboratory together with the exceptional radio purity of the liquid scintillator, has allowed Borexino to investigate the radiogenic heating of the Earth's interior and to contribute to various fields of experimental neutrino astronomy. This contribution is aimed to summarize the results obtained by Borexino on geo-neutrinos and on possible extra-terrestrial sources of antineutrinos such as supernovae explosions and solar flares.

Keywords: geoneutrino, Borexino, neutrino physics

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1. INTRODUCTION

Borexino is an unsegmented liquid scintillation detector developed for the spectral measurement of low—energy solar neutrinos and installed in the hall C of the underground Gran Sasso Laboratory in Italy. The target mass is made of 278 tons of ultra—pure liquid scintillator (PC doped with 1.5 g/L of PPO), enclosed within a spherical nylon inner vessel (IV) with a radius of 4.25 m and viewed by 2212 8″ photomultiplier tubes. The detector has been in operation from May 2007 to October 2021. Low energy neutrinos such as solar neutrinos are typically detected through the elastic scattering process on electrons but for electron antineutrinos a specific interaction channel can be exploited, the inverse beta-decay (IBD) on the free protons: the cross section is on average a factor $\sim$100 higher than elastic scattering at few MeV and the emitted positron energy is connected by a simple offset to the incoming neutrino energy, allowing for a spectral analysis of the events. Moreover, the fast time coincidence between the positron annihilation and the neutron capture provides an almost back-

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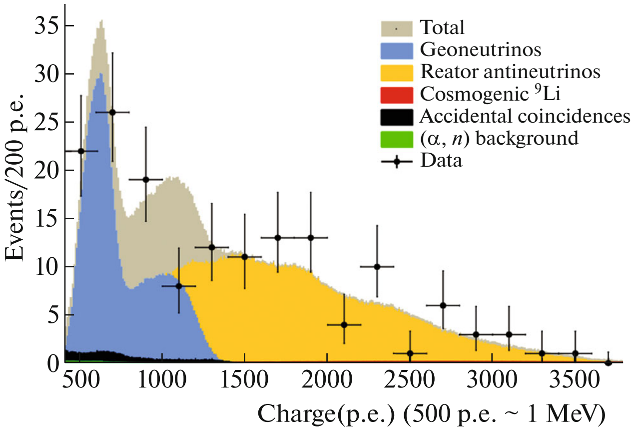

Fig. 1. Spectral fit of the data (black points) assuming the chondritic Th/U ratio.

ground free signature, that allows to investigate also small flux components.

2. GEO-NEUTRINOS AND THE EARTH'S ENERGETICS

Earth's surface is emanating heat at a rate of 47 ± 2 TW [1]: a sizeable fraction of this heat is provided by the radioactive decays but it is not at all known its proportion respect to primordial sources like gravitational energy or kinetic energy after accretion bombardment. Long-living unstable isotopes such as ^{40}K and the ^{238}U, ^{235}U, and ^{232}Th decay chains are responsible for 99% of the present radiogenic heat production: in the β decays of these isotopes electron antineutrinos ($\bar{\nu}_e$) are emitted.

Their fluxes provide direct information on the amount of heat producing elements (HPE's) inside the Earth, giving us a direct way of measuring the total radiogenic heat power, a fundamental quantity for understanding the plate tectonics and mantle convection. Two large-volume, liquid-scintillator neutrino experiments, KamLAND in Japan [2–4] and Borexino in Italy [5–8], have measured the geoneutrino signal with high statistical significance. The most recent Borexino analysis is based on 3263 days of data taking in the period between December 2007 and April 2019 [8]. IBD candidates have been selected by searching for space-time correlated events in the proper energy windows and reconstructed in the fiducial volume at a distance larger the 10 cm from the inner vessel. Further cuts are applied to reject muons and cosmogenic isotopes (cosmogenic cut) and to select β/γ-like events (pulse shape cut). In the total exposure of $(1.29 \pm 0.05) \times 10^{32}$ protons × year, 154 candidates passing all the selection cuts have been identified. The most relevant sources of $\bar{\nu}_e$ backgrounds are reactor and atmospheric $\bar{\nu}_e$, but they are more energetic respect to the geo-neutrinos and they have been disentangled thanks to an unbinned likelihood fit of prompt event energies (Fig. 1). By using the value ratio for the masses of Th and U, $m(\mathrm{Th})/m(\mathrm{U}) = 3.9$, suggested by the chondritic metheorites, the best fit yielded $N_{\mathrm{geo}} = 52.6^{+9.4}_{-8.6}(\mathrm{stat})^{+2.7}_{-2.1}(\mathrm{sys})$ events, with 18% precision. On the base of this result [8], the null-hypothesis of observing a geoneutrino signal from the mantle has been excluded at a 99.0% C.L. and the overall production of radiogenic heat constrained to $38.2\ ^{+13.6}_{-12.7}$ TW. This last value is compatible with different geological predictions, in the particular with the geodynamical BSE models [9], however there is a $\sim 2.4\sigma$ tension with Earth models predicting the lowest concentration of HPE's in the mantle, such as cosmochemical ones [9].

3. SUPERNOVAE DIFFUSE BACKGROUND

The signal due to faint extraterrestrial $\bar{\nu}_e$ fluxes, such as old supernovae neutrinos, can be highlighted as an excess of events respect to the backgrounds and the known sources of $\bar{\nu}_e$. Borexino made a search for this signal, on the base of the data sample collected between December 2007 and October 2017. The events are selected with approach similar to the one followed in the geo-neutrino analysis, the main differences being more conservative fiducial volume and cosmogenic cuts [10]: in the overall statistics 101 candidates have been identified. To quote conservative limits, the minimal expected number of events for each background was considered: for the geoneutrino signal the minimal radiogenic Earth model has been adopted, which only includes the radioactivity from the crust and that, in this case, predicts to 17.9 ± 2.1 events in the data sample. Under similar very conservative assumptions 61.1 ± 1.7 events among candidates have been attributed to reactor $\bar{\nu}_e$ and 6.5 ± 3.2 IBD-like events to atmospheric neutrinos. Upper limits are computed by following a model independent approach or by following the predictions of the Huedepohl [11] and Nakazato [12] models. Borexino model dependent limit for the 7.8–16.8 MeV range, $\Phi_{\bar{\nu}_e} < 112.3$ cm^{-2} s^{-1} (90% C.L.) is slightly better with respect to the one obtained by KamLAND ($\Phi_{\bar{\nu}_e} < 139$ cm^{-2} s^{-1} (90% C.L.)) that indeed refers to a larger energy range (8.3–31.8 MeV), and it is complementary to the SuperKamiokande one, $\Phi_{\nu_e} < 2.9$ cm^{-2} s^{-1} (90% C.L.)) for $E_{\nu_e} > 17.3$ MeV [10]. Borexino model independent limits are the best existing below 8 MeV, thanks to the exceptional detector radiopurity and the small reactor $\bar{\nu}_e$ flux at the Gran Sasso site [10].

4. SOLAR FLARES

During solar flares charged particles could be accelerated because of the solar magnetic field variation. Pions, eventually produced in the flares by adronic collisions, could then decay by emitting neutrinos with mean energies around ∼10 MeV. The higher threshold of π^- generation in pp-collisions makes the production of $\bar{\nu}_e$ disfavoured respect to ν_e: for this reason ν_x and $\bar{\nu}_x$ $(x = e, \mu, \tau)$ signals correlated with solar flares have been searched by looking their elastic scattering on electrons. In the Borexino study, an excess of single events above the measured background at the time of a flare was searched for. For the correlated signal a time window equal to the flare's duration was chosen according to the GOES database [13], while the background was estimated in a time window of the same length but opened before the flare time. The analysis was based on the statistics collected between November 2009 and October 2017. After removing muons and muon daughters, single events were selected without any fiducial volume cut in the interval of 1–15 MeV, while at lower energies a fiducial volume cut of 145 t (75 cm from the IV) was applied to decrease the external radioactivity. No statistically significant excess of events was observed in correlation with the flares. As of today, Borexino set the strongest limits on fluence of all neutrino flavors from the solar flares below 3–7 MeV [10]. By assuming that the neutrino flux is proportional to the flare's intensity, Borexino's data ruled out an intense solar flare occurred during run 117 of the Cl-Ar Homestake experiment as a possible explanation for the observed excess of events [14].

CONFLICT OF INTEREST

The author declares that they have no conflicts of interest.

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