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JUNO detector sensitivity to ^{7}Be, *pep* and CNO solar neutrinos

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Summary. — Neutrinos are used both to study particle physics and astrophysics. In particular, solar neutrinos were widely investigated by several experiments during the last decades. These studies brought to the discovery of neutrino oscillations and to the validation of the Standard Solar Model. The Jiangmen Underground Neutrino Experiment (JUNO), gigantic detector under construction in China, should increase our knowledge of the solar neutrino spectroscopy thanks to the huge mass which allows to have an unprecedented rate of solar neutrino events. In this work I will present the sensitivity studies on the ^{7}Be, *pep* and CNO solar neutrino fluxes performed using the JUNO Monte Carlo code considering different radiopurity scenarios..

1. – Solar neutrinos

The inner core of the Sun is alimented by nuclear reactions which fuse nuclei releasing energy. In particular in our Sun the principal sequence of reactions is called *pp* chain which contributes to about 99% of the solar luminosity. The remaining part of the luminosity is produced by the CNO cycle. The net effect of these sequences are the fusion of four protons into a Helium nucleus releasing two positrons and two electron neutrinos. Then solar neutrinos immediately escape from the Sun reaching the Earth in 8 minutes, while radiation takes more than 380 000 years.

In spite of their high flux, $6 \times 10^{10} \frac{\nu}{\text{cm}^2\,\text{s}}$, due to their small cross sections and low energies only very radiopure detectors could be able to measure the solar neutrino spectrum. In particular the Borexino experiment obtained the best measurements on solar neutrino fluxes detecting not only the whole *pp* chain, at low energy, but also the CNO solar neutrinos [1].

In this context some open questions still remain, in particular the metallicity problem. The abundance of elements heavier than Helium in the Sun, influences the evolution of our star and is an important input of the Standard Solar Model (SSM) The neutrino fluxes predicted by the SSM depends on the input metallicity. Nowadays there are two possible scenarios called High and Low metallicity and the current best measurements of solar neutrinos slightly favors High Metallicity but with low significance [1]. The two metallicity scenarios reflect directly on the ^{7}Be and CNO fluxes, hence increase our precision on these fluxes could help us to discriminate between these two scenarios. The Jiangmen Underground Neutrino Observatory (JUNO) could improve the current best results on solar neutrinos fluxes.

2. – Jiangmen Underground Neutrino Observatory

JUNO is a multi-purpose neutrino experiment on the way to be completed in the southern region of China. JUNO will be able of determining the neutrino mass ordering with a significance of $\sim 3-4\,\sigma$ in about six year of data, it can be also used to do neutrino astronomy looking to solar neutrino fluxes [2] or to Supernova neutrinos in real-time in case of an explosion [3].

The central detector of JUNO is composed by an acrylic sphere filled by a three component organic liquid scintillator (LAB + 2.5 g/l PPO + 3 mg/l bis-MSB). The sphere has a radius of 17.5 m and is surrounded by a stainless sphere on which 17612 20-inch PMTs and 25600 3-inch PMTs and their electronics boxes are mounted [4]. Both the acrylic and the stainless sphere are submerged by high purity water to shield the detector and to be used as a Cherenkov veto for cosmic rays. To further improve the shield, a top tracker detector will be employed [5], deriving from the OPERA experiment, and the experimental site is built under 700 meter of rocks.

A solar neutrino can interact in the JUNO liquid scintillator via elastic scattering on electrons of the medium. This makes the signal of solar neutrino event indistinguishable radioactive decays and, for this reason, JUNO should be a very radiopure detector. In order to reach the radiopurity levels needed to determine the neutrino mass ordering (called High Background scenario in table I) five purification plants were installed and they will run continuously 6 months, during the detector filling, to reach the best purification possible of the liquid scintillator trying to reduce the radioactive contamination much lower than the JUNO requirements. To check the real contamination of the liquid scintillator during the JUNO filling an ancillary detector called OSIRIS([1]) will be used at the end of the purification chain to check the quality of the liquid scintillator in real time.

3. – Background for solar neutrino analysis in JUNO

The strategies used to discriminate signal over backgrounds are different for different sources of them. We used to classified them in three categories: *cosmogenic*, *external* and *internal*.

3·1. *Cosmogenic backgrounds*. – Cosmogenic backgrounds are produced by the interactions of the comic rays, mostly muons, with carbon atoms of the liquid scintillator. The most dangerous isotope produced by muon interaction with Carbon is ^{11}C. For the aim of this analysis, the rate of production and decay of cosmogenic backgrounds are scaled from the ones seen in the Borexino and KamLAND experiments, to take into account the different shielding from cosmic rays due to different depths. JUNO is shallower than Borexiino, so the cosmogenic background will be higher.

We assume to be able of applying the so-called we applied the so called Three-Fold Coincidence technique to reduce the amount of ^{11}C events which contaminate the solar

([1]) Online Scintillator Internal Radioactivity Investigation System.

TABLE I. – *Summary of the radiopurity scenarios from the minimum required by the JUNO collaboration called High to the maximum obtain in a organic liquid scintillator by the Borexino collaboration, called Very Low.*

	High [g/g]	Medium [g/g]	Low [g/g]	Very low [g/g]
^{40}K	1×10^{-16}	1×10^{-17}	1×10^{-18}	2×10^{-19}
^{85}Kr	4×10^{-24}	4×10^{-25}	8×10^{-26}	8×10^{-26}
^{232}Th-chain	1×10^{-15}	1×10^{-16}	1×10^{-17}	5.7×10^{-19}
^{238}U-chain	1×10^{-15}	1×10^{-16}	1×10^{-17}	9.4×10^{-20}
^{210}Pb-chain	5×10^{-23}	5×10^{-24}	1×10^{-24}	5×10^{-25}

neutrino spectrum. The efficiency of this technique is assumed to be 90% as from the Borexino experience.

3·2. *External backgrounds.* – The external background are mostly deriving by all the materials surrounding the scintillator, starting from the PMTs to the Acrylic and the stainless sphere. This is an irreducible source of background. It is possible to reduce this kind of contamination considering not the whole detector but an internal volume, called "fiducial volume" with a radius of 15 m for this analysis.

3·3. *Internal backgrounds.* – The internal radioactivity is the most dangerous background for analysis in JUNO and in particular for solar neutrino analysis. Table I shows the different radioactivity scenarios considered in the sensitivity studies, from the most optimistic one (Very low) which corresponds to the best levels reached by Borexino, to the most conservative one (High) which is the minimum radiopurity required for the mass hierarchy measurement.

The most important sources of internal backgrounds are the Uranium and Thorium chains, the Lead chain and the Potassium and Krypton. These kind of backgrounds are irreducible, but they can be separated from the signal using a spectral fitter.

4. – Sensitivity studies

In the sensitivity studies, we imagined four different radiopurity scenarios varying from the minimum required from the collaboration to the best radiopurity obtained in a organic liquid scintillator, by the Borexino collaboration (see table I). Then using the JUNO Monte Carlo code we simulate all the energy probability density functions (PDFs) both for radioactive backgrounds in the liquid scintillator and for interaction of the three neutrino species. From these PDFs we simulate thousands of toy Monte Carlo datasets in different radiopurity scenarios and we apply the fitter to separate signal from background as we will do on real data (an example of data-set is shown in fig. 1).

The fitter used for this analysis is a maximum likelihood minimizer which is based on the simulated spectra shapes produced by the Monte Carlo code. The free parameters of the fit are the rates of signals and backgrounds. Applying this fitter to the simulated data, in the four different scenarios, it is possible to evaluate the sensitivity to Solar neutrinos in function of the years of data-taking.

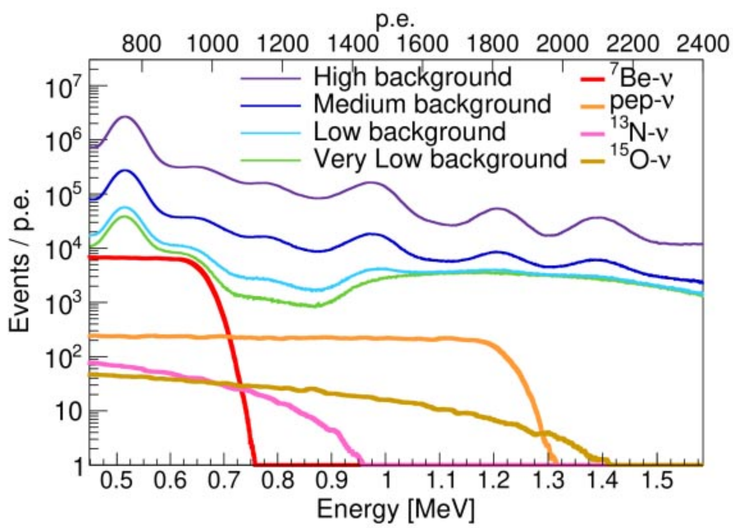
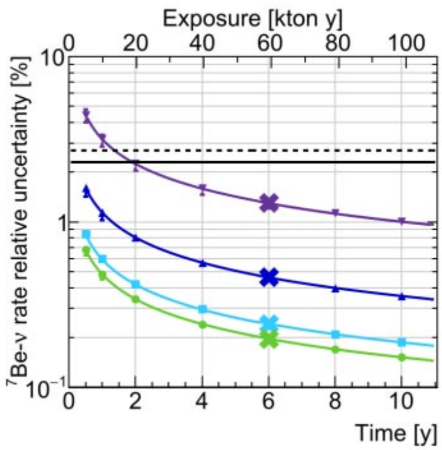


Fig. 1. – JUNO energy spectrum, determined with the JUNO Monte Carlo, for different radiopurity scenario in the energy range of solar neutrinos. Picture taken from [2].

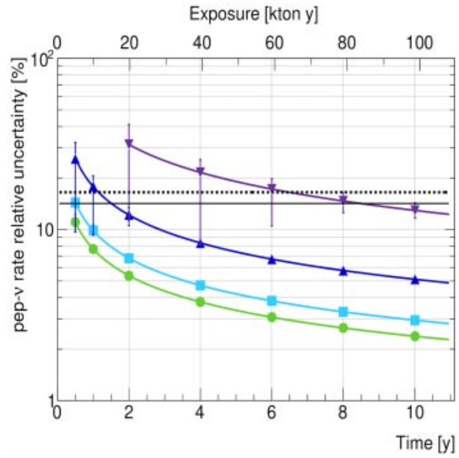
4·1. *Results.* – The results of the sensitivity studies are shown in figs. 2(a)–(c). JUNO will be able to improve the current best measurements (obtained by the Borexino collaboration) on ^{7}Be solar neutrino even in the worst radiopurity scenario in less then six years (the minimum required for neutrino mass ordering). This thanks to the fact the ^{7}Be neutrinos are monochromatic and with an high rate, so they are easy to be disentangled from the backgrounds. For what concerns *pep* solar neutrinos JUNO will be able to measured them in any scenarios except for the worst one. Since current measurements of the radiopurity of the pure LAB which will be used for filling JUNO are promising and the five purification plants are commissioned, we can be optimistic for this measurement. CNO solar neutrinos are the hardest to be measured in this energy region. We performed the analysis on this specie leaving all the other species free to vary or also putting some constrain on *pep*. As shown in fig. 2(c), without putting constrains on *pep* we need a very radiopure liquid scintillator, which could be hard given the huge volume f JUNO. Instead if we fix the pep solar neutrino rate, we can reach or improve the current best measurement on CNO solar neutrino in all the scenarios except for the worst one, like for *pep* solar neutrinos.

5. – Conclusions

JUNO will be a huge detector in the Southern part of China. The technological challenges in bulding such a big will be accompanied by the challenges in producing 20 000 ton of high radiopure liquid scintillator. In this context we evaluated the sensitivity to solar neutrinos in different radiopurity scenarios as function of the data-taking time. We found encouraging results, in particular for ^{7}Be solar neutrino. Now the JUNO solar neutrino group is working in signal over background discrimination methods to further improve the sensitivity to solar neutrinos to set a new best measurement on these fluxes.



(a)



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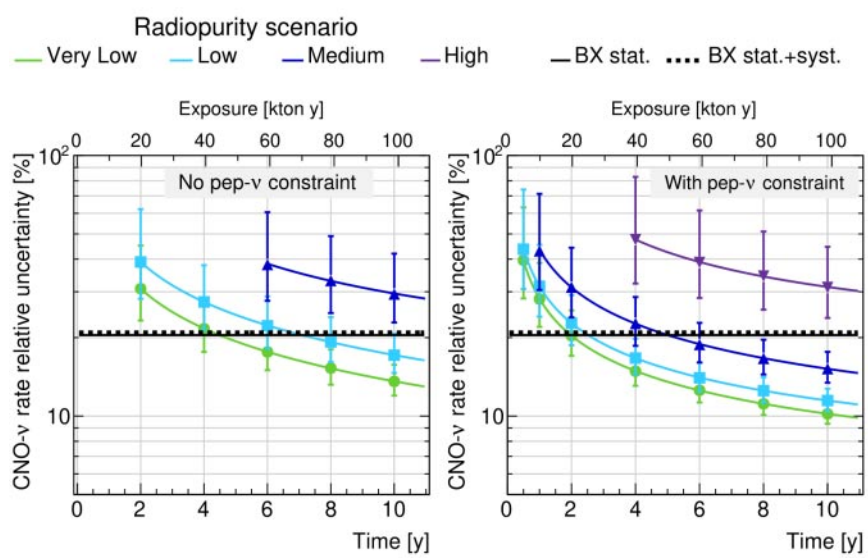

(c)

Fig. 2. – Results of the sensitivity studies on the intermediate energy solar neutrinos. (a) Sensitivity in ^{7}Be solar neutrinos in function of data-taking and radio purity scenarios. Picture taken from [2]. (b) Sensitivity in *pep* solar neutrinos in function of data-taking and radio purity scenarios. Picture taken from [2]. (c) Sensitivity in CNO solar neutrinos in function of data-taking and radio purity scenarios. On the left without any constrain and on the right putting constrain on *pep* solar neutrinos. Pictures taken from [2].

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