Journal of Physics: Conference Series

CeSOX: An experimental test of the sterile neutrino hypothesis with Borexino

To cite this article: M Gromov *et al* 2017 *J. Phys.: Conf. Ser.* **934** 012003

CeSOX: An experimental test of the sterile neutrino hypothesis with Borexino

M Gromov[1,†], M Agostini[2,9], K Altenmüller[3], S Appel[3], V Atroshchenko[4], Z Bagdasarian[5], D Basilico[6], G Bellini[6], J Benziger[7], D Bick[8], G Bonfini[9], D Bravo[6,10], B Caccianiga[6], F Calaprice[11], A Caminata[12], S Caprioli[6], M Carlini[9], P Cavalcante[9,10], A Chepurnov[1], K Choi[13], O Cloué[29], L Collica[6], M Cribier[29], D D'Angelo[6], S Davini[12], A Derbin[14], X F Ding[2,9], A Di Ludovico[11], L Di Noto[12], I Drachnev[2,9,14], M Durero[29], S Farinon[12], V Fischer[29], K Fomenko[15], A Formozov[15,6], D Franco[16], F Gabriele[9], J Gaffiot[29], C Galbiati[11], M Gschwender[30], C Ghiano[12], M Giammarchi[6], A Goretti[11], D Guffanti[2,9], C Hagner[8], T Houdy[16], E Hungerford[17], Aldo Ianni[9,18], Andrea Ianni[11], N Jonquères[31], A Jany[19], D Jeschke[3], V Kobychev[20], D Korablev[15], G Korga[17], V Kornoukhov[21], D Kryn[16], T Lachenmaier[30], T Lasserre[29], M Laubenstein[9], E Litvinovich[4,21], F Lombardi[9,22], P Lombardi[6], L Ludhova[5,23], G Lukyanchenko[4], L Lukyanchenko[4], I Machulin[4,21], G Manuzio[12], S Marcocci[2,9,12], J Maricic[13], G Mention[29], J Martyn[24], E Meroni[6], M Meyer[25], L Miramonti[6], M Misiaszek[19], V Muratova[14], R Musenich[12], B Neumair[3], L Oberauer[3], B Opitz[8], V Orekhov[4], F Ortica[26], M Pallavicini[12], L Papp[3], Ö Penek[5,23], N Pilipenko[14], A Pocar[27], A Porcelli[24], G Ranucci[6], A Razeto[9], A Re[6], M Redchuk[5,23], A Romani[26], R Roncin[9,16], N Rossi[9], S Rottenanger[30], S Schönert[3], L Scola[29], D Semenov[14], M Skorokhvatov[4,21], O Smirnov[15], A Sotnikov[15], L F F Stokes[9], Y Suvorov[28,4], R Tartaglia[9], G Testera[12], J Thurn[25], M Toropova[4], A Trantel[30], E Unzhakov[14], C Veyssiére[29], A Vishneva[15], M Vivier[29], R B Vogelaar[10], F von Feilitzsch[3], H Wang[28], S Weinz[24], M Wojcik[19], M Wurm[24], Z Yokley[10], O Zaimidoroga[15], S Zavatarelli[12], K Zuber[25] and G Zuzel[19]

[1]Lomonosov Moscow State University Skobeltsyn Institute of Nuclear Physics, 119234 Moscow, Russia
[2]Gran Sasso Science Institute (INFN), 67100 L'Aquila, Italy
[3]Physik-Department and Excellence Cluster Universe, Technische Universität München, 85748 Garching, Germany
[4]National Research Centre Kurchatov Institute, 123182 Moscow, Russia
[5]Institut für Kernphysik, Forschungszentrum Jülich, 52425 Jülich, Germany
[6]Dipartimento di Fisica, Universitá degli Studi e INFN, 20133 Milano, Italy
[7]Chemical Engineering Department, Princeton University, Princeton, NJ 08544, USA
[8]Institut fär Experimentalphysik, Universität Hamburg, 22761 Hamburg, Germany
[9]INFN, Laboratori Nazionali del Gran Sasso, 67100 Assergi (AQ), Italy
[10]Physics Department, Virginia Polytechnic Institute and State University, Blacksburg, VA 24061, USA
[11]Physics Department, Princeton University, Princeton, NJ 08544, USA
[12]Dipartimento di Fisica, Universitá degli Studi e INFN, 16146 Genova, Italy

[13]Department of Physics and Astronomy, University of Hawaii, Honolulu, HI 96822, USA
[14]St. Petersburg Nuclear Physics Institute NRC Kurchatov Institute, 188350 Gatchina, Russia
[15]Joint Institute for Nuclear Research, 141980 Dubna, Russia
[16]AstroParticule et Cosmologie, Université Paris Diderot, CNRS/IN2P3, CEA/IRFU, Observatoire de Paris, Sorbonne Paris Cité, 75205 Paris Cedex 13, France
[17]Department of Physics, University of Houston, Houston, TX 77204, USA
[18]Laboratorio Subterráneo de Canfranc, Paseo de los Ayerbe S/N, 22880 Canfranc Estacion Huesca, Spain
[19]M. Smoluchowski Institute of Physics, Jagiellonian University, 30059 Krakow, Poland
[20]Kiev Institute for Nuclear Research, 03028 Kiev, Ukraine
[21]National Research Nuclear University MEPhI (Moscow Engineering Physics Institute), 115409 Moscow, Russia
[22]Physics Department, University of California, San Diego, CA 92093, USA
[23]RWTH Aachen University, 52062 Aachen, Germany
[24]Institute of Physics and Excellence Cluster PRISMA, Johannes Gutenberg-Universität Mainz, 55099 Mainz, Germany
[25]Department of Physics, Technische Universität Dresden, 01062 Dresden, Germany
[26]Dipartimento di Chimica, Biologia e Biotecnologie, Universitá degli Studi e INFN, 06123 Perugia, Italy
[27]Amherst Center for Fundamental Interactions and Physics Department, University of Massachusetts, Amherst, MA 01003, USA
[28]Physics and Astronomy Department, University of California Los Angeles (UCLA), Los Angeles, California 90095, USA
[29]Commisariat à l'Énergie Atomique et aux Énergies Alternatives, Centre de Saclay, IRFU, 91191 Gif-sur-Yvette, France
[30]Kepler Center for Astro and Particle Physics, Universität Tübingen, 72076 Tübingen, Germany
[31]Commisariat à l'Énergie Atomique et aux Énergies Alternatives, Centre de Saclay, DEN/DM2S/SEMT/BCCR, 91191 Gif-sur-Yvette, France

E-mail: †`gromov@physics.msu.ru`

Abstract. The third phase of the Borexino experiment that's referred to as SOX is devoted to test the hypothesis of the existence of one (or more) sterile neutrinos at a short baseline ($\sim 5-10\,\mathrm{m}$). The experimental measurement will be made with artificial sources namely with a $^{144}\mathrm{Ce}-^{144}\mathrm{Pr}$ antineutrino source at the first stage (CeSOX) and possibly with a $^{51}\mathrm{Cr}$ neutrino source at the second one. The fixed $^{144}\mathrm{Ce}-^{144}\mathrm{Pr}$ sample will be placed beneath the detector in a special pit and the initial activity will be about $100-150\,\mathrm{kCi}$. The start of data taking is scheduled for April 2018. The article gives a short description of the preparation for the first stage and shows the expected sensitivity.

1. Introduction

A number of extensions of the Standard model in elementary particle physics assume an existence of one or more singlet neutrino flavours called sterile. Depending on their masses these particles might play an important role in cosmological processes and astrophysical phenomena. However the influence is minimal when the masses lie in the interval from $1\,\mathrm{eV}$ to $1\,\mathrm{keV}$ [1]. Additional attention to such kind of light sterile neutrinos is due to the opportunity to explain a few unexpected experimental results at short baseline ($L/E_\nu \sim 1\,\mathrm{m/MeV}$) using extra neutrino types. The unexpected results are well known as the accelerator, gallium and reactor antineutrino anomalies.

For the first time the accelerator anomaly had been observed in the LSND experiment. An excess of $\overline{\nu}_e$ events was registered in a $\overline{\nu}_\mu$ at $\approx 3.8\sigma$ beam [2, 3, 4, 5]. Two similar experiment, KARMEN and MiniBooNE, reported contradictory results. The former didn't find the excess in the transition $\overline{\nu}_\mu \longrightarrow \overline{\nu}_e$ [6] whereas the latter demostrated the excess signals at 2.8σ and 3.4σ

for oscillations $\overline{\nu}_\mu \longrightarrow \overline{\nu}_e$ and $\nu_\mu \longrightarrow \nu_e$ respectively [7, 8].

The gallium anomaly or ν_e disappearance had been revealed in two radiochemical solar neutrino experiments SAGE and GALLEX during processing of calibration data that were acquired with ^{51}Cr and ^{36}Ar artificial radioactive sources [9, 10, 11, 12, 13, 14]. It is reported in [15] that the significance of the anomaly is $\approx 2.9\sigma$.

After revaluation of reactor antineutrino spectra [16, 17] a deficit of counting rate was noticed in almost all reactor neutrino experiments [18] and a recent calculation [15] indicates the effect at $\approx 2.8\sigma$. However the reactor anomaly is strongly weakened by the results of Daya Bay [19].

2. CeSOX overview

The third phase of the Borexino experiment or CeSOX (**S**hort-distance **O**scillations with Bore**X**ino and a **Ce**rium source) [20] is dedicated to the search for sterile neutrinos by means of a compact artificial antineutrino source $^{144}\mathrm{Ce}{-}^{144}\mathrm{Pr}$ [21] with characteristic dimensions of 15 cm. The Borexino detector is a large ultra low background liquid scintillator detector. The Borexino target mass for CeSOX equals ~ 240 t and the fiducial volume has a radius of 4 m. Along with that the spatial resolution is about $10\,\mathrm{cm}/\sqrt{E(\mathrm{MeV})}$. It's planned to place the source right beneath the detector center in a special pit. Such configuration of the experiment will allow to make a measurement at distances 4.5 – 12.5 m from the source. Thus one will be observed not only a deficit of counting rate as it occurs in a standard neutrino disappearance experiment but a spectrum distortion with distance (so-called oscillation waves) as well. This complex approach will provide a clear experimental 2D[1] or 3D[2] pattern [21] in case of the existence of sterile neutrinos with $\Delta m^2_{14} \in (0.5, 5.0)\,\mathrm{eV}^2$ (3+1 model, NH). A few characteristic 2D patterns obtained from the Monte Carlo simulation are shown in Figure 1.

The inverse β-decay reaction, $\overline{\nu}_e + p \longrightarrow e^+ + n$, is applied for antineutrino detection. The process has a clear signature consisting of two consecutive events with a delay of $258.7 \pm 0.8(\mathrm{stat}) \pm 2.0(\mathrm{sys})\ \mu\mathrm{s}$ [23] between them. The former is a prompt event and it's a electron-positron annihilation. The released energy is directly related to the $\overline{\nu}_e$ energy as $E_{\mathrm{prompt}} = E_{\overline{\nu}_e} - 0.789\,\mathrm{MeV}$. The latter is a delayed event and this is a 2.22 MeV de-excitation γ-ray that appears as a result of a neutron capture on a proton (on a ^{1}H nucleus).

The inverse β-decay has one significant disadvantage consisting in the presence of an energy threshold $E_{thr} = 1.806\,\mathrm{MeV}$. For selection a radioactive source it means one need to find a source with the β-decay energy of a few MeV and the life-time of more than a year simultaneously. To satisfy the requirements a two-component antineutrino source was chosen. It consists of a long-lived nuclide with a low β-decay energy (^{144}Ce, $Q = 318\,\mathrm{keV}$, $T_{1/2} = 285\,\mathrm{days}$) and a daughter nuclide with a high β-decay energy (^{144}Pr, $Q_1 = 2996\,\mathrm{keV}$, $Q_2 = 2301\,\mathrm{keV}$, $T_{1/2} = 17.3\,\mathrm{min}$). Thus only ^{144}Pr component will be observed in the CeSOX experiment. Herewith two ^{144}Pr decay branches will be measured namely a non-unique first-forbidden transition $0^- \longrightarrow 0^+$ (97.9%) with endpoint energy 2996 keV and a unique first-forbidden transition $0^- \longrightarrow 2^+$ (1.0%) with endpoint energy 2301 keV.

The $^{144}\mathrm{Ce}{-}^{144}\mathrm{Pr}$ source has an activity of $(3.7 - 5.5) \cdot 10^{15}\,\mathrm{Bq}$ $(100 - 150\,\mathrm{kCi})$. Taking into account the half-life of the source the CeSOX will take data about 1.5 yr. During this period 10^4 events will be acquired. All measurements will be mostly background free. Based on the data of the geo-neutrino study with Borexino [24] it can be argued the background equils ~ 15 ev/yr and it is negligible for CeSOX.

---

[1] The dependence of the counting rate on the L/E_ν, where L is a distance from the source to an antineutrino event and E_ν is an energy of the corresponding event.

[2] The dependence of the counting rate on the energy of the antineutrino event and the distance to the source.

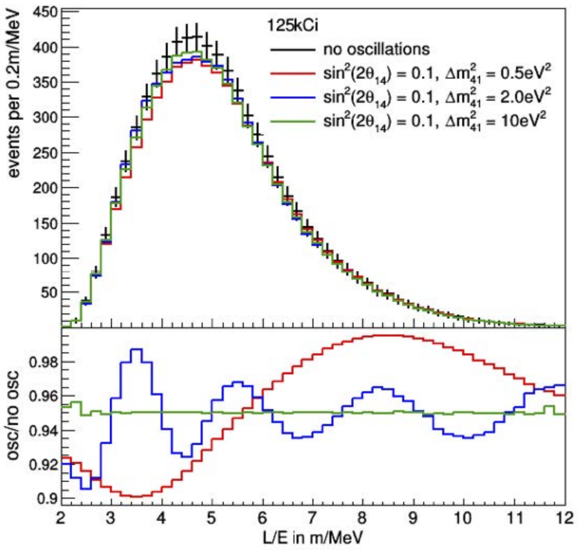

Figure 1. Top plot: the expected counting rate of antineutrino events in the Borexino detector as a function of the ratio L/E_ν for three characteristic sets of the oscillation parameters and for the non-oscillation case. Bottom plot: The ratio of the counting rates that may be observed with and without neutrino oscillations to the sterile component as a function of L/E_ν. There are two clear 2D oscillometric patterns in case of the specific values of the parameters on the plot.

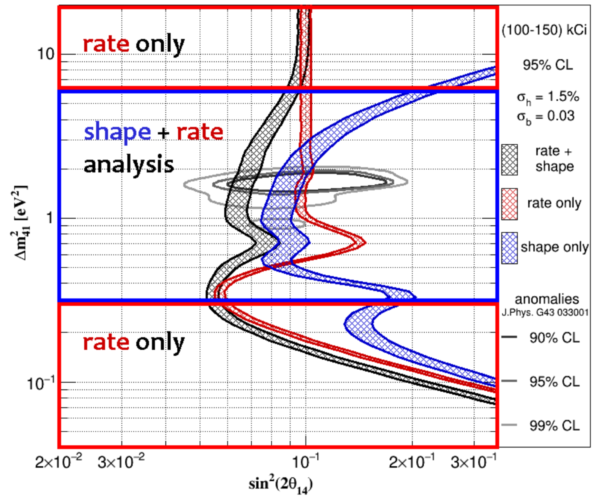

Figure 2. The expected sensitivity of the SOX experiment to the sterile neutrino oscillation parameters for the 3+1 scenario. The possible results are shown taking into account the following systematic uncertainties: a total uncertainty of the normalization rate of 1.5% and an absolute error of 0.03 on the ^{144}Pr electron spectrum shape factor b. The anomalies are taken from [22].

3. Source production and transportation

The ^{144}Ce$-^{144}$Pr antineutrino source is made by extracting cerium from exhausted nuclear fuel. ^{144}Ce is produced in the form of a chemical compound CeO_2 (powder). Due to the cerium β-decay the compound transforms into Pr_2O_3 with the release of oxygen O_2. A special stainless steel capsule was made to withstand high temperature (500 °C) and pressure (up to 6 bar). All additional radioactive backgrounds of the source are almost completely suppressed with a thick tungsten container (minimum thickness 19 cm).

The source will be manufactured by the PA «Mayak» company in Russia and delivered to Gran Sasso in April 2018. During transportation the source capsule and shielding will be inside an extra container (TN MTR). The root to Gran Sasso includes a way to St. Petersbourg (Russia) by train, then to Le Harve (France) by ship, to Saclay (France) by truck and finally to Gran Sasso (Italy) by truck as well. It's expected that the transportation will take three weeks and the source will lose $\sim 5\%$ of its initial activity.

4. Sensitivity and features of the CeSOX experiment

As it is mentioned above the main idea of the experiment is an observation of the 2D or 3D oscillation pattern. The sensitivity of CeSOX is shown in Figure 2. It's clearly seen that the experiment may exclude a large part of the region of the allowed parameters and actually demonstrate the failure of the hypothesis of the sterile neutrino existence at $\sim 3\sigma$. But the results of the investigation largely depend on the precise characterization of the ^{144}Ce$-^{144}$Pr source. This dependence is expressed in the counting rate $N(E_\nu, L, t)$

$$N(E_\nu, L, t) \sim A(t) \times S_\nu(E_\nu, b) \sim \frac{P(t)}{< E(b) >} \times S_\nu(E_\nu, b), \tag{1}$$

where $A(t)$ is an activity of the ^{144}Ce-^{144}Pr source, $S_\nu(E_\nu, b)$ is a shape of the ^{144}Pr spectrum, $P(t)$ is a thermal power of the source, $< E(b) >$ is a mean energy per decay. The b factor is a parameter of the weak finite-size correction $C(Z, W)$ in case of the widespread parameterization: $C(Z, W) \equiv 1 + a \cdot W + b/W + c \cdot W^2$, where a, b and c are parameters, Z is a charge of the nucleus, $W = E_e/m_e + 1$ is a total energy of the β^- particle in units of the electron rest mass. There are two physical quantities, b and $P(t)$, whose influence on the sensitivity of the measurements is crucial. Figures 3 and 4 illustrate that fact.

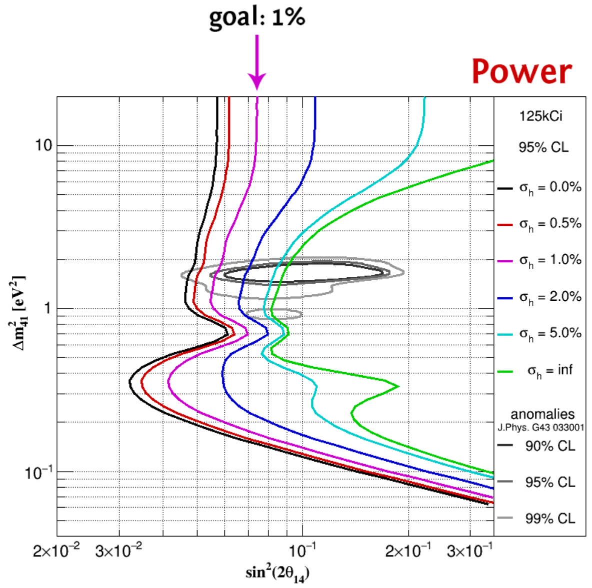

Figure 3. The impact of the calorimetric measurement uncertainty on the sensitivity of the SOX experiment.

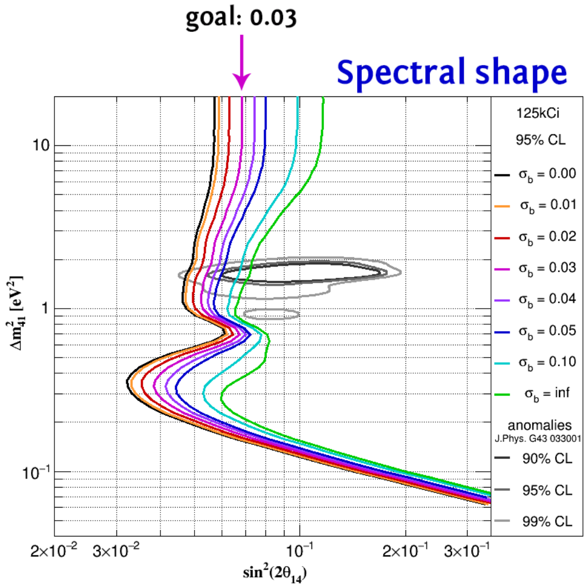

Figure 4. The impact of the uncertainty related to the spectral shape of the main ^{144}Pr β^--decay branch on the sensitivity of the SOX experiment. All curves correspond to 95% CL, unless otherwise explicitly stated.

The thermal power will be measured with two independent calorimeters immediately after delivery of the source to Gran Sasso and also instantly after the end of data-taking. For the precision knowledge of the ^{144}Pr shape factor five spectroscopic experiments are ongoing within the Borexino collaboration. The previous shape factor measurements differ by 10%.

Among other factors affecting the sensitivity it can be mentioned the following: spatial and energy uncertainties, the precise knowledge of the Inner Vessel shape, the Monte Carlo simulation quality and the efficiency of the selection cuts. To minimize the uncertainties introduced by these factors the new comprehensive calibration campaign is scheduled for January and February 2018. A lot of different radioactive sources will be applied: ^{241}Am-^{9}Be+Ni (neutrons), ^{68}Ga-^{68}Ge (positrons), ^{40}K (γ), ^{54}Mn (γ), ^{65}Zn (γ), ^{85}Sr (γ) and ^{222}Rn+^{14}C (α, β and γ) as well.

5. Conclusion

In two years CeSOX may exclude the most part of the region of the allowed parameters. If the oscillation pattern is observed additional measurements with a neutrino source ^{51}Cr might be performed.

Acknowledgments

The author acknowledges the continual support to the SOX project coming from INFN and the Laboratori Nazionali del Gran Sasso. A special thank goes also to CEA-Saclay for their crucial role in the development of the ^{144}Ce$-^{144}$Pr antineutrino source, and to all members of the Borexino collaboration for their active role in the development of the project. The SOX project is funded by the European Research Council project ERC-Adv 320873, P.I. Marco Pallavicini. The research was partly supported by the grants of the Russian Foundation for Basic Research (project №16-29-13014) and the Russian Science Foundation (project №17-12-01009).

References

[1] Gorbunov D 2014 *Phys. Usp.* **57** 503
[2] Athanassopoulos C *et al.* (LSND Collaboration) 1995 *Phys. Rev. Lett.* **75** 2650
[3] Athanassopoulos C *et al.* (LSND Collaboration) 1996 *Phys. Rev. C* **54** 2685
[4] Athanassopoulos C *et al.* (LSND Collaboration) 1996 *Phys. Rev. Lett.* **77** 3082
[5] Aguilar A *et al.* (LSND Collaboration) 2001 *Phys. Rev.* D **64** 112007 (*Preprint* hep-ex/0104049v3)
[6] Armbruster B *et al.* (KARMEN Collaboration) 2002 *Phys. Rev.* D **65** 112001 (*Preprint* hep-ex/0203021v1)
[7] Aguilar-Arevalo A *et al.* (MiniBooNE Collaboration) 2009 *Phys. Rev. Lett.* **102** 101802 (*Preprint* 0812.2243v2)
[8] Aguilar-Arevalo A *et al.* (MiniBooNE Collaboration) 2013 *Phys. Rev. Lett.* **110** 161801 (*Preprint* 1303.2588v2)
[9] Abdurashitov J *et al.* (SAGE Collaboration) 2006 *Phys. Rev.* C **73** 045805 (*Preprint* nucl-ex/0512041v1)
[10] Abdurashitov J *et al.* (SAGE Collaboration) 2009 *Phys. Rev.* C **80** 015807 (*Preprint* 0901.2200v3)
[11] Laveder M 2007 *Nucl. Phys. Proc. Suppl.* **168** 344
[12] Giunti C and Laveder M 2009 *Mod. Phys. Lett.* A **22** 2499
[13] Acero M, Giunti C and Laveder M 2008 *Phys. Rev.* D **78** 073009 (*Preprint* 0711.4222v3)
[14] Giunti C and Laveder M 2011 *Phys. Rev.* C **83** 065504 (*Preprint* 1006.3244v3)
[15] Giunti C 2017 Status of the sterile neutrinos *Recent Developments in Neutrino Physics and Astrophysics* (Assergi and L'Aquila, Italy)
[16] Mueller T *et al.* 2011 *Phys. Rev.* C **83** 054615 (*Preprint* 1101.2663v3)
[17] Huber P 2011 *Phys. Rev.* C **84** 024617 erratum: 2012 *Phys. Rev.* C **85** 029901
[18] Mention G, Fechner M, Lasserre T, Mueller T, Lhuillier D, Cribier M and Letourneau A 2011 *Phys. Rev.* D **83** 073006 (*Preprint* 1101.2755v4)
[19] An F *et al.* (Daya Bay Collaboration) 2017 *Phys. Rev. Lett.* **118** 251801 (*Preprint* 1704.01082v2)
[20] Bellini G *et al.* (Borexino Collaboration) 2013 *J. High Energy Phys.* **2013** 38 (*Preprint* 1304.7721v2)
[21] Cribier M *et al.* 2011 *Phys. Rev. Lett.* **107** 201801 (*Preprint* 1107.2335v2)
[22] Gariazzo S, Giunti C, Laveder M, Li Y and Zavanin E 2016 *J. Phys.* G **43** 033001 (*Preprint* 1507.08204v2)
[23] Bellini G *et al.* (Borexino Collaboration) 2013 *JCAP* **2013** 49 (*Preprint* 1304.7381v2)
[24] Agostini M *et al.* (Borexino Collaboration) 2015 *Phys. Rev.* D **92** 031101 (*Preprint* 1506.04610v2)