

## Test of Electric Charge Conservation with Borexino

M. Agostini,<sup>19,21</sup> S. Appel,<sup>19</sup> G. Bellini,<sup>11</sup> J. Benziger,<sup>15</sup> D. Bick,<sup>4</sup> G. Bonfini,<sup>10</sup> D. Bravo,<sup>17</sup> B. Caccianiga,<sup>11</sup> F. Calaprice,<sup>14,21</sup> A. Caminata,<sup>3</sup> P. Cavalcante,<sup>10</sup> A. Chepurinov,<sup>20</sup> D. D'Angelo,<sup>11</sup> S. Davini,<sup>21</sup> A. Derbin,<sup>13</sup> L. Di Noto,<sup>3</sup> I. Drachnev,<sup>21</sup> A. Empl,<sup>22</sup> A. Etenko,<sup>8</sup> K. Fomenko,<sup>2</sup> D. Franco,<sup>1</sup> F. Gabriele,<sup>10</sup> C. Galbiati,<sup>14,11</sup> C. Ghiano,<sup>3</sup> M. Giammarchi,<sup>11</sup> M. Goeger-Neff,<sup>19</sup> A. Goretti,<sup>10,14</sup> M. Gromov,<sup>20,26</sup> C. Hagner,<sup>4</sup> E. Hungerford,<sup>22</sup> Aldo Ianni,<sup>10,27</sup> Andrea Ianni,<sup>14,10</sup> K. Jędrzejczak,<sup>7</sup> M. Kaiser,<sup>4</sup> V. Kobychyev,<sup>6</sup> D. Korablev,<sup>2</sup> G. Korga,<sup>10</sup> D. Kryn,<sup>1</sup> M. Laubenstein,<sup>10</sup> B. Lehnert,<sup>23</sup> E. Litvinovich,<sup>8,9</sup> F. Lombardi,<sup>10</sup> P. Lombardi,<sup>11</sup> L. Ludhova,<sup>11</sup> G. Lukyanchenko,<sup>8</sup> I. Machulin,<sup>8,9</sup> S. Manecki,<sup>17</sup> W. Maneschg,<sup>5</sup> S. Marcocci,<sup>21</sup> E. Meroni,<sup>11</sup> M. Meyer,<sup>4</sup> L. Miramonti,<sup>11</sup> M. Misiaszek,<sup>7,10</sup> M. Montuschi,<sup>18</sup> P. Mosteiro,<sup>14</sup> V. Muratova,<sup>13</sup> B. Neumair,<sup>19</sup> L. Oberauer,<sup>19</sup> M. Obolensky,<sup>1</sup> F. Ortica,<sup>12</sup> K. Otis,<sup>16</sup> M. Pallavicini,<sup>3</sup> L. Papp,<sup>19</sup> L. Perasso,<sup>3</sup> A. Pocar,<sup>16</sup> G. Ranucci,<sup>11</sup> A. Razeto,<sup>10</sup> A. Re,<sup>11</sup> A. Romani,<sup>12</sup> R. Roncin,<sup>10,1</sup> N. Rossi,<sup>10</sup> S. Schönert,<sup>19</sup> D. Semenov,<sup>13</sup> H. Simgen,<sup>5</sup> M. Skorokhvatov,<sup>8,9</sup> O. Smirnov,<sup>2</sup> A. Sotnikov,<sup>2</sup> S. Sukhotin,<sup>8</sup> Y. Suvorov,<sup>24</sup> R. Tartaglia,<sup>10</sup> G. Testera,<sup>3</sup> J. Thurn,<sup>23</sup> M. Toropova,<sup>8</sup> E. Unzhakov,<sup>13</sup> A. Vishneva,<sup>2</sup> R. B. Vogelaar,<sup>17</sup> F. von Feilitzsch,<sup>19</sup> H. Wang,<sup>24</sup> S. Weinz,<sup>25</sup> J. Winter,<sup>25</sup> M. Wojcik,<sup>7</sup> M. Wurm,<sup>25</sup> Z. Yokley,<sup>17</sup> O. Zaimidoroga,<sup>2</sup> S. Zavatarelli,<sup>3</sup> K. Zuber,<sup>23</sup> and G. Zuzel<sup>7</sup>

(Borexino Collaboration)

<sup>1</sup>*AstroParticule et Cosmologie, Université Paris Diderot, CNRS/IN2P3, CEA/IRFU, Observatoire de Paris, Sorbonne Paris Cité, 75205 Paris Cedex 13, France*

<sup>2</sup>*Joint Institute for Nuclear Research, 141980 Dubna, Russia*

<sup>3</sup>*Dipartimento di Fisica, Università degli Studi e INFN, 16146 Genova, Italy*

<sup>4</sup>*Institut für Experimentalphysik, Universität Hamburg, 22761 Hamburg, Germany*

<sup>5</sup>*Max-Planck-Institut für Kernphysik, 69117 Heidelberg, Germany*

<sup>6</sup>*Kiev Institute for Nuclear Research, 03680 Kiev, Ukraine*

<sup>7</sup>*M. Smoluchowski Institute of Physics, Jagiellonian University, 30348 Krakow, Poland*

<sup>8</sup>*NRC Kurchatov Institute, 123182 Moscow, Russia*

<sup>9</sup>*National Research Nuclear University MEPhI (Moscow Engineering Physics Institute), 115409 Moscow, Russia*

<sup>10</sup>*INFN Laboratori Nazionali del Gran Sasso, 67010 Assergi (AQ), Italy*

<sup>11</sup>*Dipartimento di Fisica, Università degli Studi e INFN, 20133 Milano, Italy*

<sup>12</sup>*Dipartimento di Chimica, Biologia e Biotecnologie, Università e INFN, 06123 Perugia, Italy*

<sup>13</sup>*St. Petersburg Nuclear Physics Institute NRC Kurchatov Institute, 188350 Gatchina, Russia*

<sup>14</sup>*Physics Department, Princeton University, Princeton, New Jersey 08544, USA*

<sup>15</sup>*Chemical Engineering Department, Princeton University, Princeton, New Jersey 08544, USA*

<sup>16</sup>*Amherst Center for Fundamental Interactions and Physics Department, University of Massachusetts, Amherst, Massachusetts 01003, USA*

<sup>17</sup>*Physics Department, Virginia Polytechnic Institute and State University, Blacksburg, Virginia 24061, USA*

<sup>18</sup>*Dipartimento di Fisica e Scienze della Terra Università degli Studi di Ferrara e INFN, 44122 Ferrara, Italy*

<sup>19</sup>*Physik-Department and Excellence Cluster Universe, Technische Universität München, 85748 Garching, Germany*

<sup>20</sup>*Lomonosov Moscow State University Skobel'syn Institute of Nuclear Physics, 119234 Moscow, Russia*

<sup>21</sup>*Gran Sasso Science Institute (INFN), 67100 L'Aquila, Italy*

<sup>22</sup>*Department of Physics, University of Houston, Houston, Texas 77204, USA*

<sup>23</sup>*Department of Physics, Technische Universität Dresden, 01062 Dresden, Germany*

<sup>24</sup>*Physics and Astronomy Department, University of California Los Angeles (UCLA), Los Angeles, California 90095, USA*

<sup>25</sup>*Institute of Physics and Excellence Cluster PRISMA, Johannes Gutenberg-Universität Mainz, 55099 Mainz, Germany*

<sup>26</sup>*Lomonosov Moscow State University Faculty of Physics, 119234 Moscow, Russia*

<sup>27</sup>*Laboratorio Subterráneo de Canfranc, Paseo de los Ayerbe S/N, 22880 Canfranc, Estacion Huesca, Spain*

(Received 3 September 2015; published 3 December 2015)

Borexino is a liquid scintillation detector located deep underground at the Laboratori Nazionali del Gran Sasso (LNGS, Italy). Thanks to the unmatched radio purity of the scintillator, and to the well understood detector response at low energy, a new limit on the stability of the electron for decay into a neutrino and a single monoenergetic photon was obtained. This new bound,  $\tau \geq 6.6 \times 10^{28}$  yr at 90% C.L., is 2 orders of magnitude better than the previous limit.

DOI: 10.1103/PhysRevLett.115.231802

PACS numbers: 11.30.Fs, 12.20.Fv, 14.60.Cd

The conservation of electric charge, suggested since the 19th century, is fundamental to the physics of the standard model as a direct consequence of Maxwell's equations and the unbroken  $U(1)$  gauge symmetry of the electroweak theory. Despite the present undisputed validity of this law, experimental tests of charge conservation remain a way to search for physics beyond the standard model, and they deserve to be investigated with the highest possible sensitivity. An experimental search for the hypothetical charge nonconserving decay of the electron, which is the lightest known charged particle, into a neutrino and a photon is reported in this Letter. No presently viable theory predicts such a decay, and a large charge violation is excluded by the absence of macroscopic effects in matter. The electron decay is, however, discussed in the literature, e.g., Refs. [1–6] and the references therein.

The Borexino detector [7] is a unique tool for undertaking a search for electron decay. The unmatched radio purity of the liquid scintillator [a mixture of 1,2,4-trimethylbenzene (PC) and 2,5-diphenyloxazole (PPO) [8]] was obtained by means of a very careful selection and cleaning of materials, the development of innovative purification techniques [9,10], and the extreme care taken during procurement and handling of the scintillator fluid and the filling of the detector. In addition, the successful measurement of several solar neutrino components with Borexino ( ${}^7\text{Be}$  [11,12],  ${}^8\text{B}$  [13],  $pep$  [14], and  $pp$  [15]) demonstrates an unprecedented sensitivity which can be applied to the search for a two-body  $e \rightarrow \nu_e + \gamma$  decay resulting in the emission of a 256 keV photon.

The Borexino Collaboration has already searched for this decay using the Counting Test Facility (CTF) [16], a 4 m<sup>3</sup> liquid scintillator prototype detector operated to prove the feasibility of Borexino and to develop the necessary purification techniques for the scintillator. This earlier measurement used phenyl xylyl ethane scintillator [17], and set a lower limit for the lifetime of this electron decay mode of  $4.6 \times 10^{26}$  yr [18]. The work reported here uses a mixture of PC and PPO scintillating solution in the Borexino detector instead. A sensitivity improvement of more than 2 orders of magnitude is obtained thanks to a larger fiducial mass, higher statistics, lower background, and significantly improved data analysis. The latter is the result of a deeper understanding of the detector energy response, obtained by extensive calibration campaigns [19] and encoded in a tuned Geant4 simulation.

In Borexino, neutrino interactions and background events are detected by means of scintillation light collected by some 2212 photomultipliers (PMTs) (various PMTs were taken off-line over the years of Borexino operations due to electronic failure). The PMTs are supported by a stainless steel sphere (SSS). The sphere contains a thin concentric nylon vessel which separates the detection scintillator fluid, a PC + PPO (1.5 g/l) scintillating mixture, from an outer buffer liquid, a mixture of PC and dimethylphthalate without PPO. A second, larger nylon

vessel acts as a radon barrier. The SSS is contained in a large water tank (WT) instrumented with PMTs, shielding the inner spheres against external radiation and providing an active muon Cherenkov veto. For more details about the Borexino detector, see Refs. [7] and [20].

The light collected by all of the PMTs provides four basic measurements: (1) the total deposited energy, reconstructed from the number of collected photoelectrons; (2) the event position, reconstructed by means of a time-of-flight fit between the PMT signals; (3) the particle type ( $\alpha$ -like or  $\beta$ -like or muon), reconstructed from pulse shape analysis; and (4) the WT Cherenkov signal. For more details, see Ref. [12].

The analysis performed for this Letter has taken advantage of the recent measurement of  $pp$  solar neutrinos [15], as the expected photon visible energy from the hypothetical two-body electron decay occurs in the region where the  $pp$ -neutrino signal is dominant. The correlation between  $pp$  neutrinos and the electron decay signal is discussed below. The study of the lower energy region of the spectrum (165–590 keV) poses special challenges related to the linearity of the energy response, light quenching processes, and  ${}^{14}\text{C}$  event pileup. These were tackled for the measurement of  $pp$  neutrinos for which special tools were developed, which are also applied in this work.

Data used in this search were collected during the “phase 2” operations of the Borexino experiment, started in 2012 after a set of calibration runs and more than a year of liquid scintillator purification. The calibration was performed with internal  $\gamma$ ,  $\beta$ ,  $\alpha$ , and neutron sources, which yielded a meticulous understanding of the detector response over a large energy range. Scintillator purification, done by means of water extraction and nitrogen stripping, substantially reduced radioactive backgrounds. In particular,  ${}^{85}\text{Kr}$  concentration is now compatible with zero (from  $\sim 35$  cpd/100t in phase 1), and the  ${}^{210}\text{Bi}$  content was reduced by a factor  $\sim 4$ , to about 20 cpd/100t.  ${}^{238}\text{U}$  and  ${}^{232}\text{Th}$  concentrations were at a record low,  $\leq 10^{-19}$  g/g. Data for this work were acquired from January 2012 to May 2013, corresponding to 408 live days.

The energy spectrum used for the electron decay search is shown in Fig. 1 (the black points with error bars) together with the main fitted components (the colored lines). At low energy (below 200 keV), the count rate is dominated by the  $\beta$  decays of  ${}^{14}\text{C}$ , with a measured abundance of  $(2.7 \pm 0.1) \times 10^{-18}$  g/g [15] with respect to  ${}^{12}\text{C}$ . The monoenergetic peak in the central part of the spectrum corresponds to 5.3 MeV  $\alpha$  particles from  ${}^{210}\text{Po}$  decay, which shifts downward to approximately 400 keV electron equivalent by quenching in the scintillator [21]. The arrow indicates the position of the hypothetical 256 keV  $\gamma$  peak from electron decay.

The event rate from  ${}^{14}\text{C}$ , while intrinsically low, still yields large event statistics over the entire scintillator volume, on the order of  $5 \times 10^5$  events for the lowest

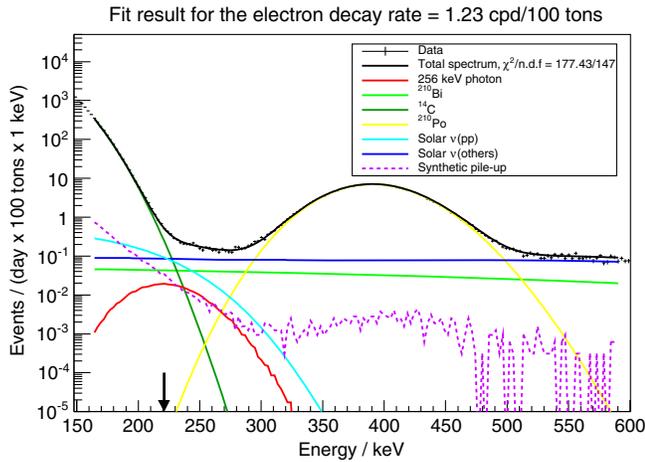


FIG. 1 (color online). Energy spectrum between 150 and 600 keV. The most prominent features are the  $^{14}\text{C}$   $\beta$  spectrum (green line), the peak at about 400 keV from  $^{210}\text{Po}$   $\alpha$  decays, and the solar neutrinos, grouped in the blue curve except for the crucial  $pp$  neutrinos, which are shown in cyan. The effect of event pileup, mostly overlapping  $^{14}\text{C}$  events, is shown in dashed pink. The hypothetical monoenergetic 256 keV  $\gamma$  line is shown in red at its 90% exclusion C.L. with an arrow indicating the mean value of the detected energy, which is lower than 256 keV because of quenching. The fit is done in the range 164–590 keV.

energy bin used in this analysis. This requires very precise fitting models to keep the systematic uncertainties at or below the statistical fluctuations of approximately 0.14%. A consequence of  $^{14}\text{C}$  decays is a non-negligible occurrence of pileup events, when two or more independent decays (mostly  $^{14}\text{C}$ ) occur close enough in time not to be separated. Two events can be distinguished with  $> 50\%$  efficiency when they are separated by more than 230 ns. The energy spectrum of pileup events in the region of interest above the  $^{14}\text{C}$  end point is similar to the electron recoil spectrum induced by  $pp$  solar neutrinos. The pileup spectrum obtained for the measurement of  $pp$  neutrinos [15], shown in magenta in Fig. 1, is included as a separate component in the spectral fit used in this analysis and labeled “synthetic” pileup. The synthetic pileup spectrum is constructed by overlapping triggered events with PMT hits recorded in the tail of the acquisition gate of such events, well after the triggered scintillation pulse has decayed away. These late PMT hits represent a data-driven, thresholdless and random sample of activity (data + noise) in the detector. Added to triggered events, they boost the pileup contribution by a known amount, allowing the pileup spectrum to be extracted.

The scintillation signal from a 256 keV  $\gamma$  produced in the  $e^- \rightarrow \gamma + \nu_e$  decay is equivalent to one produced by a  $220 \pm 0.4$  keV electron [19]. The energy shift is due to the partial light loss from quenching, i.e., the nonlinearity of the scintillation response with electron energy. Quenching is modeled by the standard Birks formalism [21], which

relates the density of light production  $dL/dx$  to the ionization density  $dE/dx$ :

$$\frac{dL}{dx} \sim \frac{\frac{dE}{dx}}{1 + kB \frac{dE}{dx}}, \quad (1)$$

where  $k$  and  $B$  are the Birks parameters. The average number of collected photoelectrons (p.e.)  $Q$  produced by an electron of energy  $E$  can be obtained by integrating Eq. (1). It is convenient to present the result in the form

$$Q = LYef(kB, E), \quad (2)$$

where  $LY$  is the light yield for electrons expressed in p.e.  $\times \text{MeV}^{-1}$  and  $f(kB, E)$  is a light deficit function, i.e., the result of the integration of Eq. (1) along the path normalized to unity at 1 MeV. The  $f(kB, E)$  is a monotonically increasing function in the region of interest. Thus, the average light yield of a  $\gamma$  absorbed by multiple Compton scatterings at low energy followed by photoabsorption, is lower than that released by a single electron of the same initial energy. This fact is crucial because the quenched 256 keV  $\gamma$  energy partially overlaps with the  $^{14}\text{C}$  tail, which then requires a special analysis.

The number  $n$  of PMTs that give a valid hit within a time window of 230 ns is approximately proportional to the energy deposit and, therefore, to the total charge  $Q$  collected by the PMTs. The relation between  $n$  and  $Q$  is

$$Q = -\frac{N_{\text{PMT}} \log(1 - \frac{n}{N_{\text{PMT}}})}{1 + g_c \log(1 - \frac{n}{N_{\text{PMT}}})}, \quad (3)$$

where  $N_{\text{PMT}}$  is the total number of PMTs of the detector, and  $g_c$  is a geometric correction factor obtained by means of Monte Carlo (MC) simulations. This approach is the same used in solar neutrino analysis and is described in detail in Refs. [12] and [15]. The statistics of  $n$  is easier to model with respect to the number of collected photoelectrons  $Q$  because the statistical distribution of multiple hits in PMTs depends on the details of the electronic response, and it is not known with sufficient precision.

The most crucial part of the analysis is the behavior of the energy resolution as a function of the energy. Thus, the variance of the energy resolution (in terms of the used energy estimator) is modeled as [22]

$$\sigma_n^2 = N(p_0 - p_1 v_1) + n^2(v_T(n) + v_f(N)) + \sigma_d^2 + \sigma_{\text{int}}^2, \quad (4)$$

where  $p_0 = 1 - p_1$ ,  $N = \langle f(t) \rangle_T$  is the average number of operating PMTs during the period of the data acquisition, and  $T$ ,  $f(t)$  is the number of operating PMTs as a function of time, normalized as  $f(0) = N_0$ . Here,  $N_0$  is the number of working PMTs at the beginning,  $v_f(N) = \langle f^2(t) \rangle_T - \langle f(t) \rangle_T^2$  is the variance of  $f(t)$  over the period of data acquisition,  $\sigma_d$  is the contribution of the dark noise (fixed

at the measured value as an average over all PMTs), and  $\sigma_{\text{int}}$  is the contribution due to the smearing of the intrinsic line.

The probability  $p_1$  that a single PMT is hit in a given event depends on event position and is related to the energy estimator,  $n$ , as  $n = Np_1$ . The parameter,  $v_1 \equiv (1/\bar{p}_1)\langle p_1(\vec{r})v_1(\vec{r}) \rangle_V$ , is the weighted average variance of the single PMT response, where  $v_1(\vec{r})$  is defined as the variance of the  $p_1$  (averaged over all PMTs) for an event whose position is  $\vec{r}$ . The quantity,  $v_1$ , is calculated over the detector's fiducial volume (FV) using MC simulations. Because of the very narrow energy region of interest—essentially the region of the  $^{14}\text{C}$  tail—the energy dependence of  $v_1$  in this analysis can be neglected. From the above, the value of  $v_1 = 0.17$  is computed.

Finally,  $v_T$  is the variance of the number of triggered PMTs over the FV for a fixed energy. It takes into account the nonuniform light collection over the detector's volume and the additional variability of the number of triggered PMTs in different locations within the FV. It is energy dependent and was found to be proportional to energy in the region of interest. Its energy dependence was modeled as  $v_T = v_T^0 n$  [12], leaving the constant of proportionality as a free parameter of the fit.

The shape of the scintillation line (i.e., the energy response of the detector to a monoenergetic source uniformly distributed within FV) is another important component of this analysis. The familiar Gaussian approximation fails to describe the tails of MC-generated monoenergetic peaks, even for the statistics on the order of  $10^3$  events. In the previous  $^7\text{Be}$  solar neutrino analysis [11], this problem was solved by using a generalized  $\Gamma$  function [23] to fit the monoenergetic  $^{210}\text{Po}$  peak. However, while the quality of the fit to the  $^{210}\text{Po}$  peak is insensitive to the residual deviations in the tails, this is not the case for the  $^{14}\text{C}$  spectrum, as all the events in the fraction of the  $^{14}\text{C}$  spectrum above the  $^{14}\text{C}$  end point originate from spectral smearing, so that the statistics in the tails are much higher. For these reasons, a different procedure was adopted.

The ideal detector response to a pointlike monoenergetic source in the center is an exact binomial distribution which can be well approximated by a Poisson distribution. However, the ideal width of the distribution must be modified to include the additional spreading of the signal due to various factors. The problem, both with binomial distribution and with its Poisson approximation, is that their width is defined by the mean value, which introduces an unwanted and unphysical correlation between the position of the peak and its width. To attack this problem, the response function was approximated by a scaled Poisson distribution (SPD) defined by

$$f(x) = \frac{\mu^{sx}}{(sx)!} e^{-\mu}, \quad (5)$$

where  $x$  is the independent variable whose mean value is  $n$  and variance  $\sigma_n$ . This function has two free parameters,  $\mu$

and  $s$ , which can be evaluated using an expected mean and variance. The agreement of this approximation with the detector response function was tested with the Borexino MC model. It was found at low energies that the function (5) reproduces the scintillation line shape much better than a generalized  $\Gamma$  function (GGF) up to statistics of  $10^8$  events per bin, while at energies just above the  $^{14}\text{C}$  tail, both distributions give comparable results. Therefore, the SPD approximation was adopted, and the quality of the fit was estimated using a  $\chi^2$  criterion. As an example, with  $10^7$  monoenergetic events for  $n = 50$  (approximately 140 keV), we found  $\chi^2/\text{n.d.f.} = 88.0/61$  for the GGF compared to  $\chi^2/\text{n.d.f.} = 59.3/61$  for the SPD. In this example the events were uniformly distributed in the detector before the FV is selected.

As proven by MC calculations, the SPD works well in the region of interest despite the additional smearing due to the aforementioned factors. This is a result of the folding of the relatively narrow nonstatistical distributions by the much wider base function. The MC simulations show that such an absorption results in the smearing of the total distribution without changing its shape.

Only a fraction of the total response for the monoenergetic 256 keV  $\gamma$  enters into the analysis window above threshold, which makes the signal look similar to the  $pp$  spectrum and produces a strong correlation between them (see Fig. 1). Note the correlation between electron decay and  $pp$  solar neutrinos: with an unconstrained  $pp$  flux, 12 cpd/100t of electron decay candidates correspond to about 134 cpd/100t from  $pp$  solar neutrinos in the fit. To break the degeneracy, the  $pp$ -neutrino rate can be constrained either by the value measured by experiments other than Borexino or at that predicted by large mixing angle (LMA)–Mikheev-Smirnov-Wolfenstein (MSW) theory. We chose to use data from radiochemical experiments only to obtain a model-independent result.

The deviation from the observed  $pp$ -neutrino rate is controlled by a penalty term added to the  $\chi^2$  in the form

$$\chi_{pp}^2 = \frac{(pp - \langle pp \rangle)^2}{\sigma_{pp}^2 + \sigma_{\text{FV}}^2},$$

where  $pp$  is the  $pp$ -neutrino count rate found by the fit,  $\langle pp \rangle = 134$  cpd/100t is the rate expected in Borexino, and  $\sigma_{pp} = 13.3$  cpd/100t its variance. These are calculated using the solar  $pp$ -neutrino flux obtained from the combined analysis of the GALLEX/GNO and SAGE experiments [24]. The parameter  $\sigma_{\text{FV}} = 2.7$  takes into account the systematic error (2% as reported in Ref. [15]) due to the uncertainty in the FV mass.

A search for the 256 keV  $\gamma$  line was then undertaken using “standard” fit conditions, defined by (a) an energy estimator: the number of triggered PMTs in a fixed time window of 230 ns (npmts), (b) a fit range: 62–220 npmts, corresponding to 164–590 keV, and (c) a fiducial mass:

75.5t ( $R < 3.02$  m and  $|Z| < 1.67$  m), which is the same as in the solar  ${}^7\text{Be}$  analysis. The values of solar neutrino rates other than  $pp$  are constrained either at the results found by Borexino in a different energy range of  $R({}^7\text{Be}) = 48 \pm 2.3$  cpd/100t [11], or fixed at the predictions of the standard solar model in the MSW/LMA oscillation scenario,  $R(pep) = 2.80$  cpd/100t,  $R(\text{CNO}) = 5.36$  cpd/100t. The  ${}^{14}\text{C}$  rate was constrained at the value found in an independent measurement  $R({}^{14}\text{C}) = 40 \pm 1$  Bq [or  $R({}^{14}\text{C}) = (3.456 \pm 0.0864) \times 10^6$  cpd/100t]. The pileup rate was constrained at the values found with the above algorithm to be  $321 \pm 7$  cpd/100t. Other background components were left free ( ${}^{85}\text{Kr}$ ,  ${}^{210}\text{Bi}$ , and  ${}^{210}\text{Po}$ ) and the rate of  ${}^{214}\text{Pb}$   $R({}^{214}\text{Pb}) = 0.06$  cpd/100t was calculated by means of identified  ${}^{222}\text{Rn}$  events, which were measured by the detection of  ${}^{214}\text{Bi}$ - ${}^{214}\text{Po}$  coincidences. The light yield and the two energy resolution parameters ( $v_T$  and  $\sigma_{\text{int}}$ ) are left free in the fit. The position of the  ${}^{210}\text{Po}$  peak is also left free, and it is decoupled from the energy scale because of its poorly known quenching factor.

The detection efficiency of the 256 keV  $\gamma$ 's was determined by means of the MC code. A set of uniformly distributed  $\gamma$ 's were simulated inside the entire inner vessel. The events passing the same set of cuts used for real data selection and reconstructed within the FV were used to determine a global efficiency of  $\epsilon = 0.264$ , which includes a FV cut.

The upper limit  $S$  for the given confidence level C.L. comes from the following integral:

$$\int_0^S f(\xi) d\xi = \text{C.L.} \int_0^\infty f(\xi) d\xi, \quad (6)$$

where  $f(\xi)$  is the probability distribution function. With this procedure, we found the 90% C.L. upper limit  $S = 379$  events, in a period  $T = 408d$  and fiducial mass of 75.5t.

The corresponding lifetime  $\tau_{BX} \geq 7.2 \times 10^{28}$  yr (statistical only) was obtained using the relation

$$\tau_{BX} \geq \frac{\epsilon N_e T}{S}, \quad (7)$$

where  $N_e = 9.19 \times 10^{31}$  are the electrons in the inner vessel mass of 278t and  $\epsilon = 0.264$  is the detection efficiency.

The systematic error depends on three factors: the choice of the energy estimator, the value of the quenching parameters, and the knowledge of the fiducial volume.

The main one is the choice of the energy estimator, and in particular the length of the 230 ns time window, which affects the relevance of the pileup events and dark noise hits. We have thoroughly studied this effect by means of MC simulations. It amounts, for this analysis, to about 8%.

The second one is that the position of the 256 keV  $\gamma$  peak with respect to the  ${}^{14}\text{C}$  spectrum depends on the quenching factor,  $kB$ , and the precise position of the end point of the  ${}^{14}\text{C}$   $\beta$  spectrum. Since the underlying  ${}^{14}\text{C}$   $\beta$  spectrum is

falling exponentially, a shift of the peak position to lower energy decreases the sensitivity of the search, and vice versa. In the present analysis the  $kB$  parameter is fixed at  $kB = 0.0109$  cm MeV $^{-1}$ , determined from calibration data with monoenergetic  $\gamma$  sources. In order to study the related systematics in a model-independent way, the position of the  $\gamma$  peak within the bounds was obtained by calibration (1%) instead of by varying the  $kB$  value. It should be noted that no degradation of the fit quality for a wide range of  $kB$  values was observed due to the absence of known  $\gamma$  sources in the region of interest and, therefore, in the fit model. The final result is that  $kB$  error adds less than 2% to the total systematic error.

The third systematic error is the knowledge of the FV mass which, at the energies of interest, adds an uncertainty of less than 1% to the electron decay rate.

The three effects described above are correlated. The total systematic error was obtained by building a set of probability profiles for a corresponding set of input parameters. The probability profiles were renormalized to physical regions, excluding nonphysical values in the case of a negative number of candidates where the region below zero was cut and the probability distribution function (PDF) was renormalized to unity. The final probability profile was obtained as the weighted sum of the separate PDFs, with the weights being the probability of an occurrence of the corresponding value of the parameter. The normal distribution was used for both the error on the FV and the relative shift of the 256 keV  $\gamma$  with respect to the electron's scale. The addition of the total systematic error degrades the purely statistical result by about 8%.

The lower limit on the mean lifetime for the decay  $e^- \rightarrow \gamma + \nu$  is  $\tau_{BX} \geq 6.6 \times 10^{28}$  yr (90% C.L.), which improves the existing limit from the CTF [18] by more than 2 orders of magnitude. The sensitivity is such that a 5 $\sigma$  discovery signal would have been possible with an electron lifetime of  $1.9 \times 10^{28}$  yr.

The Borexino program is made possible by funding from INFN (Italy); the NSF (U.S.); BMBF, DFG, and MPG (Germany); RFBR: Grants No. 14-22-03031, No. 15-02-02117, and No. 13-02-12140, as well as Grant No. RFBR-ASPERA-13-02-92440 (Russia); and NCN Poland (Grant No. UMO-2012/06/M/ST2/00426). We acknowledge the generous support and hospitality of the Laboratori Nazionali del Gran Sasso (LNGS).

- 
- [1] L. Okun and Y. Zeldovich, *Phys. Lett.* **78B**, 597 (1978).
  - [2] M. Voloshin and L. Okun, *JETP Lett.* **28**, 145 (1978).
  - [3] A. Yu. Ignatiev, V. A. Kuzmin, and M. E. Shaposhnikov, *Phys. Lett.* **84B**, 315 (1979).
  - [4] A. Dolgov and Y. Zeldovich, *Rev. Mod. Phys.* **53**, 1 (1981).
  - [5] L. Okun, *Soviet Physics Uspekhi* **32**, 543 (1989).
  - [6] Y. Aharanov *et al.*, *Phys. Rev. D* **52**, 3785 (1995).

- [7] G. Alimonti *et al.*, Nucl. Instrum. Methods Phys. Res., Sect. A **600**, 568 (2009).
- [8] G. Alimonti *et al.*, Nucl. Instrum. Methods Phys. Res., Sect. A **609**, 58 (2009).
- [9] G. Alimonti *et al.*, Astropart. Phys. **16**, 205 (2002).
- [10] C. Arpesella *et al.*, Astropart. Phys. **18**, 1 (2002).
- [11] G. Bellini *et al.*, Phys. Rev. Lett. **107**, 141302 (2011).
- [12] G. Bellini *et al.*, Phys. Rev. D **89**, 112007 (2014).
- [13] G. Bellini *et al.*, Phys. Rev. D **82**, 033006 (2010).
- [14] G. Bellini *et al.*, Phys. Rev. Lett. **108**, 051302 (2012).
- [15] G. Bellini *et al.*, Nature (London) **512**, 383 (2014).
- [16] G. Alimonti *et al.*, Nucl. Instrum. Methods Phys. Res., Sect. A **406**, 411 (1998).
- [17] H. O. Back *et al.*, Nucl. Instrum. Methods Phys. Res., Sect. A **585**, 48 (2008).
- [18] H. O. Back *et al.*, Phys. Lett. B **525**, 29 (2002).
- [19] H. Back *et al.*, J. Instrum. **7**, P10018 (2012).
- [20] G. Bellini *et al.*, J. Instrum. **6**, P05005 (2011).
- [21] J. B. Birks, *The Theory and Practice of Scintillation Counting* (MacMillan, New York, 1964).
- [22] P. Mosteiro, Ph.D. thesis, Princeton University, 2014.
- [23] O. Ju. Smirnov, Nucl. Instrum. Methods Phys. Res., Sect. A **595**, 410 (2008).
- [24] J. N. Abdurashitov *et al.*, Phys. Rev. C **80**, 015807 (2009).