Absence of a day–night asymmetry in the ^{7}Be solar neutrino rate in Borexino

G. Bellini[h], J. Benziger[l], D. Bick[r], S. Bonetti[h], G. Bonfini[e], M. Buizza Avanzini[h], B. Caccianiga[h], L. Cadonati[p], F. Calaprice[l], C. Carraro[c], P. Cavalcante[h], A. Chavarria[l], D. D'Angelo[h], S. Davini[c], A. Derbin[m], A. Etenko[g], F. von Feilitzsch[n], K. Fomenko[b], D. Franco[a], C. Galbiati[l], S. Gazzana[e], C. Ghiano[e], M. Giammarchi[h], M. Göger-Neff[n], A. Goretti[l,e], L. Grandi[l], E. Guardincerri[c], S. Hardy[q], Aldo Ianni[e], Andrea Ianni[l], V. Kobychev[f], D. Korablev[b], G. Korga[e], Y. Koshio[e], D. Kryn[a], M. Laubenstein[e], T. Lewke[n], E. Litvinovich[g], B. Loer[l], P. Lombardi[h], F. Lombardi[e], L. Ludhova[h], I. Machulin[g], S. Manecki[q], W. Maneschg[i], G. Manuzio[c], Q. Meindl[n], E. Meroni[1], L. Miramonti[1], M. Misiaszek[d], D. Montanari[e,l], P. Mosteiro[l], V. Muratova[m], L. Oberauer[n], M. Obolensky[a], F. Ortica[j], M. Pallavicini[c], L. Papp[q], C. Peña-Garay[o], L. Perasso[h], S. Perasso[c], A. Pocar[p], R.S. Raghavan[q], G. Ranucci[h], A. Razeto[e], A. Re[h], A. Romani[j], A. Sabelnikov[g], R. Saldanha[l], C. Salvo[c], S. Schönert[i], H. Simgen[i], M. Skorokhvatov[g], O. Smirnov[b], A. Sotnikov[b], S. Sukhotin[g], Y. Suvorov[e,g], R. Tartaglia[e], G. Testera[c], D. Vignaud[a], R.B. Vogelaar[q], J. Winter[n], M. Wojcik[d], A. Wright[l], M. Wurm[n], J. Xu[l], O. Zaimidoroga[b], S. Zavatarelli[c], G. Zuzel[d]

[a] *APC, Laboratoire AstroParticule et Cosmologie, 75231 Paris cedex 13, France*
[b] *Joint Institute for Nuclear Research, Dubna 141980, Russia*
[c] *Dipartimento di Fisica, Universitá e INFN, Genova 16146, Italy*
[d] *M. Smoluchowski Institute of Physics, Jagiellonian University, Krakow, 30059, Poland*
[e] *INFN Laboratori Nazionali del Gran Sasso, Assergi 67010, Italy*
[f] *Kiev Institute for Nuclear Research, Kiev 06380, Ukraine*
[g] *NRC Kurchatov Institute, Moscow 123182, Russia*
[h] *Dipartimento di Fisica, Universitá degli Studi e INFN, Milano 20133, Italy*
[i] *Max-Plank-Institut für Kernphysik, Heidelberg 69029, Germany*
[j] *Dipartimento di Chimica, Universitá e INFN, Perugia 06123, Italy*
[k] *Chemical Engineering Department, Princeton University, Princeton, NJ 08544, USA*
[l] *Physics Department, Princeton University, Princeton, NJ 08544, USA*
[m] *St. Petersburg Nuclear Physics Institute, Gatchina 188350, Russia*
[n] *Physik Department, Technische Universität München, Garching 85747, Germany*
[o] *Instituto de Fìsica Corpuscular, CSIC-UVEG, Valencia E-46071, España*
[p] *Physics Department, University of Massachusetts, Amherst 01003, USA*
[q] *Physics Department, Virginia Polytechnic Institute and State University, Blacksburg, VA 24061, USA*
[r] *Institut für Experimentalphysik, Universität Hamburg, Germany*

Abstract

We report the result of a search for a day–night asymmetry in the ^{7}Be solar neutrino interaction rate in the Borexino detector at the Laboratori Nazionali del Gran Sasso (LNGS) in Italy. The measured asymmetry is $A_{dn} = 0.001 \pm 0.012$ (stat) $\pm$ 0.007 (syst), in agreement with the prediction of MSW-LMA solution for neutrino oscillations. This result disfavors MSW oscillations with mixing parameters in the LOW region at more than 8.5 σ. This region is, for the first time, strongly disfavored without the use of reactor anti-neutrino data and therefore the assumption of CPT symmetry. The result can also be used to constrain some neutrino oscillation scenarios involving new physics.

Keywords:
solar neutrinos, day–night effect, CPT violation, neutrino oscillations

In the last two decades solar neutrino [1, 2, 3] and reactor anti-neutrino [4] experiments have demonstrated that solar electron neutrinos undergo flavor conversion along their trip from the Sun's core to the Earth. The conversion is well described by the so-called Mikheyev-Smirnov-Wolfenstein (MSW) matter-enhanced neutrino oscillations [5] with Large Mixing Angle (LMA) oscillation parameters. A generic feature of matter-enhanced neutrino oscillations is the potential for the coherent regeneration of the ν_e flavor eigenstate when solar neutrinos propagate through the Earth [6], as they do during the night. Thus, there is the potential for those solar neutrino experiments that are principally, or entirely, sensitive to ν_e to detect different solar neutrino interaction rates during the day and during the night. Solar neutrino day-night asymmetry measurements are sensitive to both ν_e appearance and disappearance.

The magnitude of this day-night effect is expected to depend on both neutrino energy and the neutrino oscillation parameters. Previous experiments [7, 8] have shown that for high energy (~5-15 MeV) solar neutrinos, the day–night asymmetry is less than a few percent, in agreement with the MSW-LMA prediction. At lower neutrino energies (around 1 MeV), the predicted day–night asymmetry for MSW-LMA is also small (<0.1%) [9]; however, other scenarios including different MSW solutions and neutrino mixing involving new physics [10] predict much larger day–night effects. For example, in the so-called LOW region (10^{-8} eV^2<δm^2<10^{-6} eV^2) of MSW parameter space, which is currently strongly disfavored only by the KamLAND anti-neutrino measurement under the assumption of CPT symmetry, the day-night asymmetry would range between about 10% and 80% for neutrino energies near 1 MeV. We present here the first measurements sensitive to the day–night asymmetry for solar neutrinos below 1 MeV. This result is an essentially new and independent way to probe the MSW-LMA prediction and is potentially sensitive to new physics affecting the propagation of low energy electron neutrino in matter. Particularly, this result is independent from the KamLAND measurement, which probes anti-neutrino interactions at higher energies (>1.8 MeV).

The Borexino experiment at LNGS detects low energy solar neutrinos by means of their elastic scattering on electrons in a large volume liquid scintillator detector. Real-time detection (with ≈1 μs absolute time resolution) of all events is made by collecting the scintillation light with a large set of photomultipliers. The very low intrinsic radioactivity of the scintillator and of the materials surrounding it allows a clean spectral separation between the neutrino signals and the residual background. As the neutrino-electron elastic scattering cross section is different for ν_e and ν_μ-ν_τ, Borexino can measure the electron neutrino survival probability and is, as a result, sensitive to the day-night effect.

We recently released a precise measurement of the ^{7}Be neutrino interaction rate in Borexino with a total uncertainty less than 5% [11]. In this Letter, we present a study of the day-night asymmetry in the same ^{7}Be solar neutrino rate, placing a stringent limit on the size of the possible effect. We show that this limit improves the constraint on the solar neutrino oscillation parameters from solar neutrino experiments alone and excludes new physics scenarios that cannot be rejected with the currently available data.

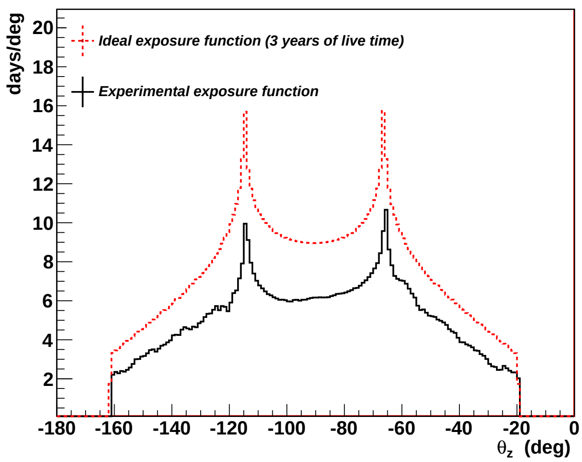

Figure 1: The experimental exposure function (black continuous line) and the ideal exposure function (red dotted line). The interval from $-180°$ to $-90°$ corresponds to day time and the one from $-90°$ to 0° to night time. We recall that at LNGS latitude the Sun is never at the zenith.

The Borexino detector [12, 13] is located in Hall C of the Laboratori Nazionali del Gran Sasso (latitude 42.4275° N) in Italy and has taken data since May 2007. The sensitive detector consists of ~278 tons of very pure organic liquid scintillator contained in a 4.25 m radius nylon vessel. The scintillator is viewed by 2212 photomultipliers and is shielded against external neutrons and γ radiation [14]. The energy of each candidate event is measured by the total amount of collected light, while the position of the event is reconstructed using the time-of-flight of the light to the photomultipliers.

The data used in this analysis were collected between May 16th, 2007 and May 8th, 2010 and correspond to 740.88 live days after applying the data selection cuts. We define "day" and "night" using θ_z, the angle between the vertical z-axis of the detector (positive upward) and the vector pointing to the detector from the Sun, following [2]. Note that, with this definition, $\cos\theta_z$ is negative during the day and positive during the night. The distance that the neutrinos propagate within the Earth is small for negative $\cos\theta_z$ (the ~1.4 km LNGS overburden) and ranges up to 12049 km for positive $\cos\theta_z$. Our day and night livetimes were 360.25 and 380.63 days, respectively. The distribution of θ_z corresponding to the live time (experimental exposure function) is shown in Fig. 1 and its asymmetry with respect to -90° is mainly due to maintenance and calibration activities which are normally carried out during the day.

As discussed in [11], scintillation events due to ^{7}Be solar neutrinos cannot be distinguished from background events (cosmogenics and radioactivity) on an event-by-event basis. The signal and background contributions are therefore determined using a spectral fit to the energy spectrum of the events reconstructed within a suitable fiducial volume (86.01 m^3 in [11]), and passing a series of cuts which eliminate muons and short–lived cosmogenic events, time correlated background events, and spurious noise events (details of this event selection will be published in [15]). The experimental signature of the mono–energetic 862 keV ^{7}Be solar neutrinos is a Compton-like electron scattering "shoulder" at approximately 660 keV.

In the analysis reported here we use a spherical fiducial volume significantly larger than the one used in [11] in order to increase the size of the data sample. This choice is justified by the fact that the additional external background that enters this larger fiducial volume is due to gamma radioactivity emitted by the materials surrounding the scintillator volume. As this background is expected to be the same during day and night, it should not affect the day–night asymmetry[1].

We determined that our sensitivity to the day–night effect is maximized by a 3.3 m fiducial radius, which gives a 132.5 ton fiducial mass containing 4.978×10^{31} e$^-$. With this choice of fiducial mass, the signal–to–background (S/B) ratio in the "^{7}Be neutrino energy window" (550 to 800 keV) is 0.70 ± 0.04. This value is smaller than the one in [11] due to the increase in spatially non-uniform backgrounds produced by external gamma rays and ^{222}Rn events.

The day–night asymmetry, A$_{dn}$, of the ^{7}Be count rate is defined as:

$$A_{dn} = 2\,\frac{R_N - R_D}{R_N + R_D} = \frac{R_{\rm diff}}{\langle R\rangle} \qquad (1)$$

where R_N and R_D are the ^{7}Be neutrino interaction rates during the night and the day, respectively, $R_{\rm diff}$ is their difference, and $\langle R\rangle$ is their mean.

Fig. 2 shows the day and night energy spectra superimposed and normalized to the same live–time (the day one), while Fig. 3 shows the θ_z distribution of the events in the ^{7}Be neutrino energy window normalized by the experimental exposure function. By using the total ^{7}Be count rate measured in [11], a correction has been applied to the exposure function to account for the annual modulation of the neutrino flux due to the seasonal variation of the Earth-Sun distance. Before correction, the asymmetric distribution of our day and night livetime throughout the year is expected to increase the measured ^{7}Be neutrino count rate by 0.37% during the night and decrease it by 0.39% during the day. The day and night spectra in Fig 2 are statistically identical, as proved by the fit to the data shown in Fig. 3. Indeed, by fitting with a constant distribution the data in Fig. 3 we obtain a χ^2 probability = 0.44. Any deviation from a straight line would be a signature of day–night modulation. For illustration, we include in Fig. 3 the expected shape for the LOW solution (Δm^2_{12}=1.0 · 10^{-7} eV^2 and tan$^2(\theta_{12})$ = 0.955). Fitting the distribution with a flat straight line yields χ^2/ndf = 141.1/139, showing that the data are consistent with the no day–night effect hypothesis.

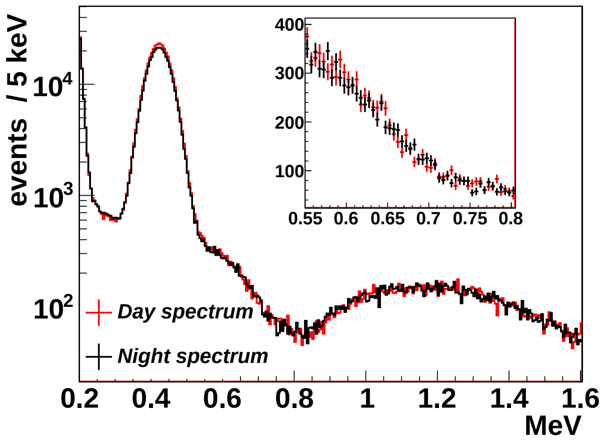

Figure 2: The energy spectrum of events during day (red) and night (black) normalized to the day live–time in the enlarged FV. The insert shows the ^{7}Be neutrino energy window. See [11] for details on this spectral shape.

One way to quantitatively constrain A$_{dn}$ is to determine R_D and R_N separately by independently fitting the day and night spectra using the same spectral fitting technique used in determining the total ^{7}Be flux in [11] and then comparing the results using Eq. 1. Note that because these neutrinos are mono–energetic, we expect the shape of the ^{7}Be electron recoil spectrum to be identical during day and night. This yields A_{dn} = 0.007 ± 0.073. This method has the virtue of allowing for the possibility of different background rates during day and night. However, this analysis is less sen-

[1]As explained later on, not all backgrounds relevant for this analysis are the same during day and night. Particularly, the background induced by ^{210}Po αs is not the same because of the long ^{210}Po lifetime and of the different length of days and nights in summer or winter.

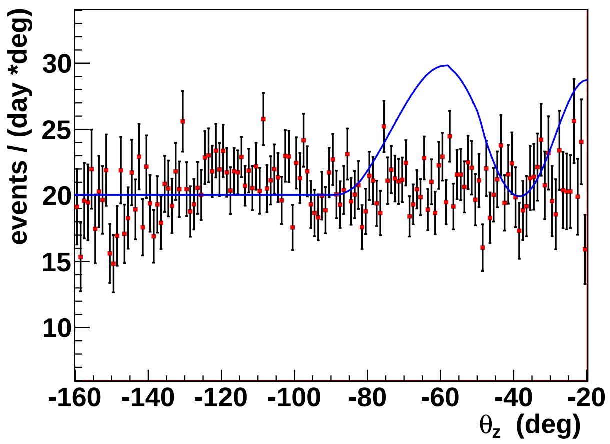

Figure 3: Normalized θ_z–angle distribution of the events in the FV in the ^{7}Be neutrino energy window. The effect of the Earth's elliptical orbit has been removed. The blue line is the expected effect with the LOW solution (Δm^2_{12}=$1.0 \cdot 10^{-7}$ eV^2 and $\tan^2(\theta_{12}) = 0.955$).

sitive than the one described below and is not used for the final result.

A stronger constraint on A_{dn} is obtained by making the very reasonable assumption that the main backgrounds that limit the sensitivity in [11] (^{85}Kr and ^{210}Bi) are the same during day and night. With this assumption, A_{dn} is obtained by subtracting the day and night spectra (normalized to the day live time) following the second term in Eq. (1) and then searching for a residual component having the shape of the electron recoil spectrum due to ^{7}Be neutrinos. If A_{dn}=0 and the background count rates were constant in time the subtracted spectrum would be flat.

The subtracted spectrum is shown in Fig. 4, where the lower plot is a zoom of the upper one in the energy region between 0.55 and 0.8 MeV. The result is a flat spectrum, consistent with zero, except for a clear negative ^{210}Po peak visible in the low energy region. This negative peak arises because the ^{210}Po background count rate in Borexino is decaying in time ($\tau_{1/2}$ = 138.38 days), and the day and night livetime are not evenly distributed over the 3 years of data taking. The ^{210}Po count rate was highest at the time of the initial filling in May 2007, and has since decayed. Therefore, the ^{210}Po count rate has been higher on average during the summers (when days are longer), leading to a noticeable effect in the subtracted spectrum. This effect is taken into account by including both the ^{210}Po and ^{7}Be spectral shapes in the fit. Fitting between 0.25 and 0.8 MeV, we obtain $R_{\rm diff}$ = 0.04±0.57 (stat) cpd/100 t. The amplitude of the resulting electron recoil spectrum induced by the interaction of ^{7}Be neutrinos is too small to be shown in Fig. 4. In order to see its spectral shape we plot the recoil spectrum with an amplitude corresponding to the expected day–night asymmetry for the LOW solution.

The $R_{\rm diff}$ result is confirmed by removing alpha events from the day and night spectra using a pulse shape analysis based statistical subtraction technique [11] before creating the difference spectrum. In this case, no residual ^{210}Po peak is expected or observed in the difference spectrum. Fitting the data between 0.25 and 0.8 MeV using only the ^{7}Be recoil shape yields a result consistent with the previous one. The difference in the central values is included in the systematic uncertainty.

Using $\langle R\rangle = 46 \pm 1.5$ (stat) $^{+1.6}_{-1.5}$ (syst) cpd/100 t [11] we obtain $A_{dn} = 0.001 \pm 0.012$ (stat) $\pm$ 0.007 (syst) from Eq. 1. The statistical error in A_{dn} is given by

$$\sigma_{A_{dn}} = \frac{R_{diff}}{\langle R\rangle}\sqrt{\left(\frac{\sigma^2_{diff}}{R^2_{diff}} + \frac{\sigma^2(<R>)}{<R>^2}\right)} \simeq \frac{\sigma(R_{diff})}{\langle R\rangle}$$

because the total relative experimental error associated with $\langle R\rangle$ is negligible with respect to $\frac{\sigma(R_{diff})}{R_{diff}}$.

The main systematic errors are listed in Table 1. The dominant uncertainties are associated with the difference between the $R_{\rm diff}$ central values obtained with and without statistical subtraction of the α events, and the maximum effect on $R_{\rm diff}$ from potential small changes in the ^{210}Bi background in the detector. These uncertainties will be detailed in [15].

This new tight constraint on the day-night effect in ^{7}Be solar neutrinos has interesting implications on our understanding of neutrino oscillations. To investigate this, we calculated the expected day–night asymmetry for 862 keV neutrinos under different combinations of mixing parameters in the MSW oscillation scenario. The comparison of these predictions with our experimental number is displayed on the right panel of Fig. 5. The red region is excluded at 99.73% c.l. (2 d.o.f.). In particular, the minimum day–night asymmetry expected in the LOW region (10^{-8} eV$^2 \lessapprox \Delta m^2 \lessapprox 10^{-6}$ eV^2) is

Source of error	Error on A_{dn}
Live–time	$< 5\cdot 10^{-4}$
Cut efficiencies	0.001
Variation of ^{210}Bi with time	±0.005
Fit procedure	± 0.005
Total systematic error	0.007

Table 1: List of systematic errors on A_{dn}.

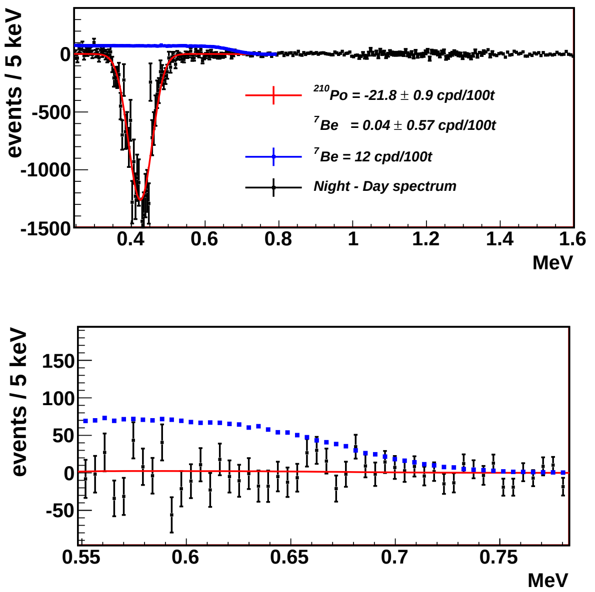

Figure 4: Difference of night and day spectra in the FV. The fit is performed in the energy region between 0.25 and 0.8 MeV with the residual ^{210}Po spectrum and the electron recoil spectrum due to the ^{7}Be solar neutrino interaction. The fit results are in cpd/100 t. The top panel shows an extended energy range including the region dominated by the ^{11}C background while the bottom panel is a zoom of the ^{7}Be energy window between 0.55 and 0.8 MeV. The blue curve shows the shape of electron recoil spectrum that would be seen assuming the LOW solution as in Fig. 3.

0.117, which is more than $8.5\,\sigma$ away from our measurement, assuming gaussian errors for A_{dn}.

This effect can also be seen in a global analysis of all solar neutrino data. We have carried out such an analysis, assuming two neutrino oscillations (i.e. $\theta_{13} = 0$, we have checked that the inclusion of the third family does not change any of the conclusions and will be published in [15]), including the radiochemical data [1], the Super-Kamiokande phase I and phase III data [2], and the SNO LETA data and phase III rates [3]. The analysis takes into account the experimental errors (the systematic and statistical errors summed in quadrature) and the theoretical errors in the total count rates, including the correlation of the ^{7}Be and ^{8}B theoretical fluxes [16]. We use flux predictions from a recent high metallicity standard solar model [17] and we include the bin-to-bin correlations in the uncertainties in the predicted ^{8}B neutrino recoil spectrum resulting from the uncertainties in the predicted neutrino spectrum, and from energy threshold uncertainties and energy resolution in the experiments.

The left panel of Fig. 5 shows the 68.27, 95.45 and

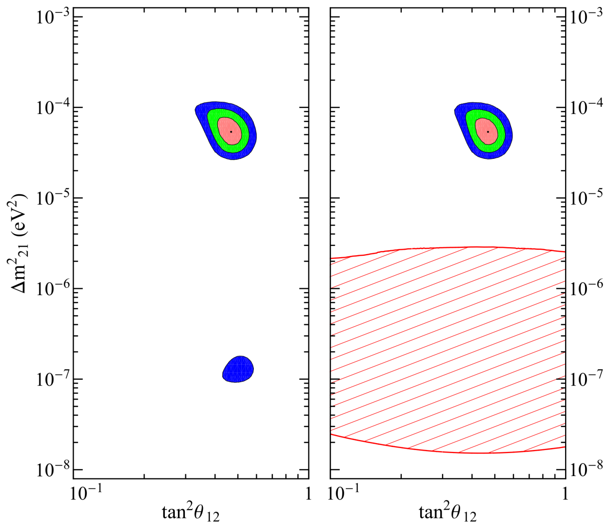

Figure 5: Neutrino oscillations parameter estimation in three solar neutrino data analyses (with 2 d.o.f.): 1) 99.73% c.l. excluded region by the Borexino ^{7}Be day–night data (hatched red region in the right panel); 2) 68.27%, 95.45%, and 99.73% c.l. allowed regions by the solar neutrino data without Borexino data (left panel); 3) Same c.l. allowed regions by all solar neutrino data including Borexino (filled contours in right panel). The best fit point in the left (right) panel is Δm^2 = (5.2 $^{+1.6}_{-0.9}$) $\cdot 10^{-5}$, $\tan^2\theta$=0.47 $^{+0.04}_{-0.03}$ (0.46 $^{+0.04}_{-0.03}$). The LOW region is strongly excluded by the ^{7}Be day–night data while the allowed LMA parameter region does not change significantly with the inclusion of the new data.

99.73% c.l. neutrino mixing parameter regions allowed by all solar neutrino data without Borexino. The best-fit point is in the LMA region (Δm^2 = (5.2 $^{+1.6}_{-0.9}$) $\cdot 10^{-5}$ eV^2 and $\tan^2\theta$ =0.47$^{+0.04}_{-0.03}$) and a small portion of the LOW region is still allowed at $\Delta\chi^2$ = 11.83.

The right panel of Fig. 5 shows the regions of allowed parameter space after adding the Borexino data (the ^{7}Be total count rate [11], the day–night asymmetry reported in this paper, and the ^{8}B total count rate above 3 MeV (0.22 ± 0.04 (stat) ± 0.01 (syst)) cpd/100 t and spectral shape (5 bins from 3 to 13 MeV) [18]) to the analysis. The LMA region is only slightly modified (the new best fit point is Δm^2 = (5.2 $^{+1.6}_{-0.9}$) 10^{-5} eV^2 and $\tan^2\theta$ = 0.46$^{+0.04}_{-0.03}$), but the LOW region is strongly excluded at $\Delta\chi^2 > 190$. Therefore, after the inclusion of the Borexino day–night data, solar neutrino data alone can single out the LMA solution with very high confidence, without the inclusion of anti-neutrino data and therefore without invoking CPT symmetry.

This result is an essentially new and independent way to probe the MSW-LMA prediction and is potentially sensitive to new physics affecting low energy electron neutrino interactions. As an example, we note that our day-night asymmetry measurement is very powerful in testing mass varying neutrino flavor conversion scenarios. We find, for example, that our A_{dn} data excludes the set of MaVaN parameters chosen in [10] to fit all neutrino data at more than $10\,\sigma$.

In conclusion, we have searched for a day–night asymmetry in the interaction rate of 862 keV ^{7}Be solar neutrinos in Borexino. The result is $A_{dn} = 0.001 \pm 0.012$ (stat) $\pm$ 0.007 (syst), consistent both with zero and with the prediction of the LMA-MSW neutrino oscillation scenario. With this result, the LOW region of MSW parameter space is, for the first time, strongly disfavored by solar neutrino data alone. The result constrains certain flavor change scenarios involving new physics.

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This work is dedicated to the memory of our friend Raju Raghavan, the father of this experiment, and a great scientist.

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