ISSN 1063-7788, Physics of Atomic Nuclei, 2010, Vol. 73, No. 11, pp. 1935–1941. © Pleiades Publishing, Ltd., 2010.
Original Russian Text © A.V. Derbin, 2010, published in Yadernaya Fizika, 2010, Vol. 73, No. 11, pp. 1987–1993.

First Results of the Borexino Experiment

A. V. Derbin*
(On behalf of the Borexino Collaboration[1])

Petersburg Nuclear Physics Experiment, Russian Academy of Sciences, Gatchina, 188300 Russia

Received February 10, 2010

Abstract—Data of the Borexino experiment on the detection of the reaction involving elastic solar-neutrino scattering on an electron are presented. The fraction of electron neutrinos in the fluxes of ^{7}Be and ^{8}B neutrinos is in agreement with the LMA MSW oscillation solution. The uniquely low level of the Borexino detector background made it possible to set new limits on the effective magnetic moment of the neutrino, on the possible violation of the Pauli exclusion principle, and on some other rare processes.

DOI: 10.1134/S1063778810110165

1. INTRODUCTION

Borexino is a new detector for solar neutrinos. Its main task is to detect solar neutrinos with an energy below 2 MeV in the on-line mode [1–4]. Measurements with a full-scale version of the detector began in May 2007. The experiment is being performed at the Gran Sasso laboratory. This is largest underground laboratory, both in size and in the number of experiments performed there. Although the laboratory is referred to as an underground laboratory, it is fact deployed at an altitude of 1000 m above sea level. The Apennines ensure muon-flux suppression equivalent to 3500 mwe.

The basic results obtained to date by the Borexino Collaboration are the following: the existence of ^{7}Be neutrinos was reliably established for the first time, their flux being about 10% of the total solar-neutrino flux; owing to measurements of the boron-neutrino flux, the fraction of electron neutrinos as a function of the neutrino energy could be determined in a single experiment for regions where vacuum oscillations and oscillations in matter make different contributions; new limits were obtained for the effective magnetic moment of the neutrino and for the magnetic moments of flavor states; and new limits were set on the probabilities of nucleon transitions in the ^{12}C nucleus that are forbidden by the Pauli exclusion principle. Owing to an extremely low background level in the MeV energy region, the Borexino detector has unique features in what is concerned with searches for rare low-energy processes.

2. BOREXINO DETECTOR

The detection of recoil electrons occurs in a liquid scintillator. For the scintillator, use is made of pseudocumene (PC, C_9H_{12}) with an addition of 1.5 g/l of PPO ($C_{15}H_{11}NO$). The measured value of the light output is 1.1×10^4 photons/MeV. This value determines the energy resolution, the detection threshold, and the accuracy of event-coordinate reconstruction. The scintillator (PC + PPO) of mass 278 t is within a thin nylon sphere, which is surrounded by a PC concentric buffer layer 2.6 m in thickness (see Fig. 1). In order to diminish the yield output and to reduce the loading of photomultiplier tubes with events occurring in the buffer layer, about 5 g/l of dimethyl phthalate (DMP) was added to PC. The buffer layer (PC + DMP) is separated by a nylon film in order to reduce radon diffusion to the scintillation volume. The total mass of PC is 1200 t and is within a steel sphere 13.7 m in diameter. The scintillation light is gathered by 2212 photomultiplier tubes uniformly

*E-mail: derbin@pnpi.spb.ru

[1] The list of Collaboration: G. Bellini, J. Benziger, S. Bonetti, B. Caccianiga, L. Cadonati, F. Calaprice, C. Carraro, A. Chavarria, F. Dalnoki-Veress, D. D'Angelo, H. de Kerret, A. Derbin, A. Etenko, K. Fomenko, D. Franco, C. Galbiati, S. Gazzana, M. Giammarchi, M. Goeger-Neff, A. Goretti, C. Grieb, S. Hardy, Aldo Ianni, Andrea Ianni, M. Joyce, V. Kobychev, G. Korga, D. Kryn, M. Laubenstein, M. Leung, T. Lewke, E. Litvinovich, B. Loer, P. Lombardi, L. Ludhova, J. Machulin, S. Manecki, W. Maneschg, G. Manuzio, F. Mazetti, K. McCarty, Q. Meindl, E. Meroni, L. Miramonti, M. Misiaszek, D. Montanari, V. Muratova, L. Oberauer, M. Obolensky, F. Ortica, M. Pallavicini, L. Papp, L. Perasso, S. Perasso, A. Pocar, R. S. Raghavan, G. Ranucci, A. Razeto, P. Risso, A. Romani, D. Rountree, A. Sabelnikov, R. Saldanha, C. Salvo, S. Schönert, H. Simgen, M. Skorokhvatov, O. Smirnov, A. Sotnikov, S. Sukhotin, Y. Suvorov, R. Tartaglia, G. Testera, D. Vignaud, R. B. Vogelaar, F. von Feilitzsch, M. Wojcik, M. Wurm, O. Zaimidoroga, S. Zavatarelli, and G. Zuzel.

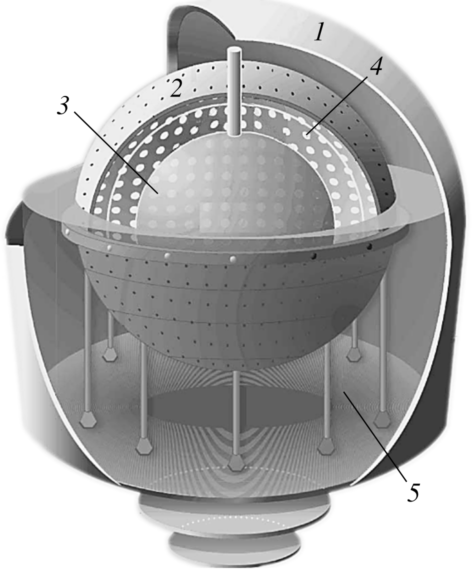

Fig. 1. Borexino detector: (*1*) water tank, (*2*) steel sphere, (*3*) nylon sphere, (*4*) photomultplier tubes, and (*5*) water shield.

distributed over the surface of the sphere. The steel sphere is within a tank containing 2100 t of purified water, which serves as an additional shield from external photons and neutrons. Cherenkov radiation from muons in water is detected by 208 photomultiplier tubes.

Each event in the detector is characterized by the number of actuated photomulplier tubes, for which the amplitude of a pulse and the time of their arrival are recorded. On the basis of these data, one reconstructs the energy of an event and its spatial coordinates and determines the particle type (e, p, or α). For a first approximation, the number of detected photoelectrons is in direct proportion to the deposited energy and is about 500 photoelectron/MeV. The deviation from the linear dependence at low energies is taken into account by introducing the Birks parameter. The energy resolution is about 5% at an energy of 1 MeV. The energy dependence has the form $\sigma(E)/E \approx 0.05/E^{0.5}$, where E is expressed in MeV units.

The reconstruction of event spatial coordinates is necessary since the background associated with photons escaping from the steel sphere and photomultiplier tubes is insufficiently suppressed by the PC + DMP layer. Only the condition $R < 3$ m, which cuts off the internal of 100 t of the scintillator, ensures an effect-to-background ratio that is acceptable for detecting ^{7}Be neutrinos. The spatial resolution in the coordinates x, y, and z, which was determined for the ^{214}Bi $\to$ ^{214}Po sequential decays, is 13 ± 2 cm.

The light output for alpha particles is smaller than that for electrons of identical energy by a factor of about 10. As a result, alpha particles from the natural radioactivity of the uranium and thorium families are recorded as events of energy below 1 MeV—that is, in the region of the signal from ^{7}Be neutrinos. In order to separate signals from electrons and alpha particles, use is made of the ionization-density dependence of the photon-emission rate. The so-called Gatti method [5, 6], in which one calculates the weighted sum $G = \sum P_i S_i$, where S_i is the number of photoelectrons detected within the time interval Δt_i, ensures the most efficient separation. The weights $P_i = (S_{\alpha i} - S_{ei})/(S_{\alpha i} + S_{ei})$ are evaluated on the basis of the time spectra of emission from electrons and alpha particles, these spectra being measured in an independent experiment. The parameter G proves to be distributed about a mean value, which is positive for alpha particles and is negative for electrons.

In order to select events associated with neutrino–electron scattering, use is made of the following criteria: the detected charge and coordinates of an event, the time to the muonic-veto signal or to the preceding event, and the distribution of photon-arrival times. A detailed description of the Borexino detector and of the selection criteria used can be found in [3, 4].

3. RESULTS OF MEASUREMENTS FOR (ν, e) SCATTERING FOR ^{7}Be AND ^{8}B NEUTRINOS

The spectrum measured by the detector central part of mass 78.5 t over 192 days is shown in Figs. 2 and 3. Events that coincide within 2 ms with a muonic-veto signal and consecutive events separated by a time interval not longer than 2 ms were removed from the spectrum. The detection of the consecutive decays ^{214}Bi $\to$ ^{214}Po ($\tau = 237$ μs) and ^{212}Bi $\to$ ^{212}Po ($\tau = 0.43$ μs) makes it possible to determine the background associated with the ^{238}U and ^{232}Th families. Under the assumption of secular equilibrium, the results obtained for the respective concentrations are 1.6×10^{-17} g/g for ^{238}U and 6.9×10^{-18} g/g for ^{232}Th, this corresponding to a record degree of purification of the detector material.

At low energies, the background is determined by ^{14}C beta decays ($E_0 = 156$ keV), and the lower boundary of the region (about 200 keV) accessible to analysis (see Figs. 2 and 3) is determined by precisely these processes. The specific content of the isotope ^{14}C corresponds to the ratio ^{14}C/^{12}C $= 2 \times 10^{-18}$. An intense peak at an energy of about 450 keV is associated with ^{210}Po alpha decay. From Fig. 2, one can see that the rate of ^{210}Po decay is not in equilibrium with ^{210}Bi (neighboring nucleus) beta decay,

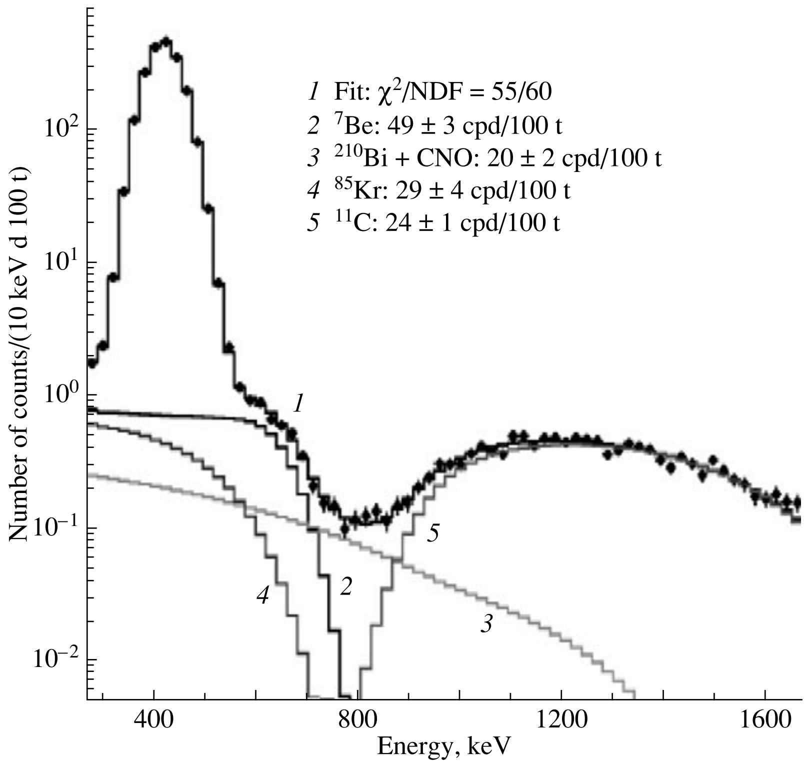

Fig. 2. Energy spectrum measured by Borexino within 192 days. The basic background constituents are shown.

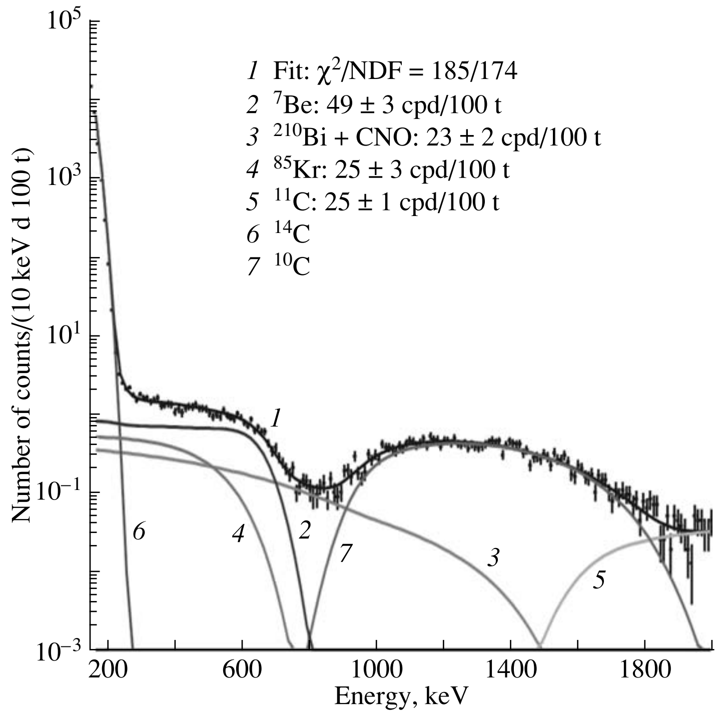

Fig. 3. Energy spectrum after the removal of events associated with ^{210}Po alpha decay.

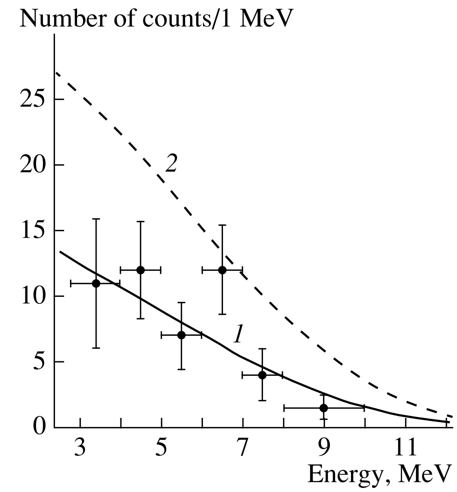

Fig. 4. Spectrum of events in which the energy is in excess of 2.8 MeV. Curve *1* represents the results of the calculation in the case of the LMA MSW solution for the SSM BS06(GS98) [7, 8], while curve *2* corresponds to the absence of neutrino oscillations.

whose endpoint energy is $E_0 = 1.17$ MeV. A lower degree of purification of the scintillator from polonium is associated with its special chemical properties.

A step in the spectrum at an energy of 660 keV corresponds to the beginning of the recoil-electron spectrum in the scattering of monoenergetic ^{7}Be neutrinos (862 keV). In the energy range 1.0–2.0 MeV, the background is determined by the β^+ decay of the isotope ^{11}C ($\tau = 29$ min, $Q = 1.98$ MeV), which is produced from ^{12}C under the effect of muons. The rate of ^{11}C production is 25 ± 1 nucl./(d 100 t). The Borexino background level at energies of about 1 MeV is at least 100 times lower than the background level attained with any other detector.

Neutrino–electron scattering proceeds through the exchange of W and Z bosons. It should be recalled that electron neutrinos are scattered via both the charged (W) and the neutral (Z) current, while muon and tau neutrinos are scattered only via the neutral current. As a result, the expected spectrum of recoil electrons assumes the form

$$\frac{d\sigma}{dE_e} = P_{ee}\left(\frac{d\sigma}{dE_e}\right)_{W+Z} + (1 - P_{ee})\left(\frac{d\sigma}{dE_e}\right)_Z, \quad (1)$$

where P_{ee} is the electron-neutrino fraction. The counting rate for ^{7}Be neutrinos was determined both for the experimental spectrum, which contained the α peak from ^{210}Po decay (Fig. 2), and for the spectrum obtained after the removal of the alpha-particle signal (see Fig. 3). The two fits yielded nearly identical results. Borexino detects 49 ± 3 (stat.) $\pm$ 4 (syst.) events of (ν, e) scattering for ^{7}Be neutrinos in 100 t of PC per day [3]. In the standard solar model (SSM) [7] with a high degree of metallicity [8], the expected counting rate for a nonoscillation solution is 74 ± 4 event/(d 100 t), which differs from the measured value by 4.2σ, σ being a standard deviation.

The counting rate measured for ^{7}Be neutrinos is in good agreement with the predictions of the SSM and LMA MSW oscillation solution at the parameter values of $\Delta m^2_{12} = 7.6 \times 10^{-5}$ eV^2 and $\sin^2(2\theta_{12}) = 0.87$. In the SSM with a high [8] and a low [9] degree of metallicity, the expected counting rate is 48 ± 4 and 44 ± 4 event/(d 100 t), respectively.

The value determined for the probability of electron-neutrino survival at the energy of 862 keV is $P_{ee} = 0.56 \pm 0.1$ and agrees well with the result ($P_{ee} = 0.54 \pm 0.017$) obtained from different solar experiments and with the results of the KamLAND experiment [10].

The reduced flux of ^{7}Be neutrinos that is defined by the measured flux to the flux expected on the basis of the SSM [7, 8] is $f_{^7\mathrm{Be}} = 1.02 \pm 0.1$. Previous estimates of $f_{^7\mathrm{Be}}$ fell within the range 0–1.27. Thus, the existence of ^{7}Be neutrinos was reliably established for the first time by the Borexino experiment [2, 3].

The data obtained for ^{7}Be neutrinos make it possible to improve substantially our knowledge of other solar neutrinos. The flux of pp neutrinos that was determined from the balance equation with allowance for data from other solar experiments and under the condition of a constrained solar luminosity is $f_{pp} = \left(1.005^{+0.008}_{-0.02}\right)(1\sigma)$. Under the same conditions, the contribution of the CNO cycle to the Sun's energy release does not exceed 3.3% at a 90% C.L. This limit on the flux of CNO neutrinos is the most stringent.

Borexino does not observe day–night time variations in the flux of ^{7}Be neutrinos at a level of 4%, $(S_n - S_d)/(S_n + S_d) = 0.02 \pm 0.04$, where S_n and S_d are the average counting rates at night and day, respectively.

The systematic error in determining the flux of ^{7}Be neutrinos exceeds the statistical error and is equal to 8.5%. It is determined primarily by the error in determining the detector sensitive volume, which is singled out by means of the code for the spatial reconstruction of events. The measurements of 2009 with calibration sources arranged within the nylon sphere will make it possible to reduce this error to about 3%.

Highly energetic ^{8}B neutrinos were detected in the experiment in addition to ^{7}Be neutrinos [11]. The counting rate expected for ^{8}B neutrinos is smaller than that for ^{7}Be neutrinos by a factor of about 200.

Figure 4 shows the high-energy section of the spectrum according to measurements with central part (100 t) of the Borexino detector within 246 days. In the region of energies above 3 MeV, a significant part of the background is associated with long-lived isotopes ($\tau \sim 1$ s) of light nuclei (^{12}B, ^{8}B, ^{8}Li, etc.), which are produced by muons interacting with ^{12}C nuclei. An additional cut rejecting signals within 5 s after each muon that traversed the steel sphere was introduced in order to suppress this background component. In order to select more long-lived isotopes (^{10}C, $\tau = 28$ s; ^{11}Be, $\tau = 20$ s), whose production is almost always accompanied by the appearance of neutrons, use was made of triple coincidences of a muon, a neutron, and isotope decay. As a result, the detection of ^{8}B neutrinos became possible starting from a uniquely low threshold of 2.8 MeV. The measured counting rate for ^{8}B neutrinos was $0.26 \pm 0.04\,(\text{stat.}) \pm 0.02\,(\text{syst.})$ event/(d 100 in).

The spectrum of recoil electrons that is expected for the MSW LMA solution and which is shown in Fig. 4 is in good agreement with experimental data; at the same time, the nonoscillation solution deviates from the measured value by more than four standard deviations (4σ). The specific fraction of electron neutrinos in the spectrum of ^{8}B neutrinos proved to be $P_{ee} = 0.35 \pm 0.1$ for a neutrino effective energy of 8.6 MeV. Thus, the fraction of electron neutrinos for neutrino energies featuring various contributions of vacuum oscillations and oscillations in matter was determined for the first time in a single experiment. The ratio $P_{ee}(^{7}\text{Be})/P_{ee}(^{8}\text{B}) = 1.6 \pm 0.33$ deviates from unity by nearly 2σ, and this favors the proposed LMA MSW solution.

4. MAGNETIC MOMENT OF SOLAR NEUTRINOS AND RARE PROCESSES

A uniquely low background level attained at the Borexino detector ensures a high sensitivity to rare low-energy processes. A new limit on the solar-neutrino magnetic moment and on probabilities of transitions in the ^{12}C nucleus that violate the Pauli exclusion principle have been obtained to date.

A number of record limits on the probabilities of electron decays ($e \to \gamma + \nu$) [12], nucleon decays ($N \to 3\nu$, $NN \to 2\nu$) [13], neutrino decays ($\nu_H \to \nu_L + \gamma$) [14], the emission of a massive neutrino in ^{8}B beta decay [15], the emission of axions in the $M1$ transition in the ^{7}Li nucleus [16], neutrino scattering owing to the magnetic moment [17], the detection of antineutrinos from the Sun [18], nuclear transitions violating the Pauli exclusion principle [19], and some other rare processes [20] were obtained by using the Borexino detector prototype (CTF). It is planned to performed searches for these processes with the full-scale Borexino detector.

Since, in contrast to a nuclear reactor, the Sun cannot be switched off, the characteristic energy dependence of the recoil-electron spectrum in the case of scattering caused by the neutrino magnetic moment was used to discover this moment or to set a limit on it. While the cross section for weak scattering approaches a constant as the recoil-electron energy E_e tends to zero, the magnetic-scattering cross section increases in proportion to $1/E_e$:

$$\frac{d\sigma}{dE_e} = \pi r_0^2 \mu_{\text{eff}}^2 \left(\frac{1}{E_e} - \frac{1}{E_\nu} \right). \tag{2}$$

Here, r_0 is the classic electron radius and E_ν is the neutrino energy. Since the neutrinos are mixed, the effective magnetic moment is recorded in neutrino–electron scattering; that is,

$$\mu_{\text{eff}}^2 = \sum_j \left| \sum_k \mu_{kj} A_k(E_\nu, L) \right|^2, \tag{3}$$

where μ_{jk} is an element of the matrix of the neutrino electromagnetic moments and $A_k(E_\nu, L)$ is the amplitude of the k-mass state at the scattering point [21]. For the Majorana neutrino, only the transition moments are nonzero, while the diagonal elements of the matrix are nonzero. For the Dirac neutrino, all matrix elements may be nonzero. The effective magnetic moment can be expanded both in the mass-eigenstate (this is more natural) and in the flavor basis. Under the assumption that $\theta_{13} = 0$, the effective magnetic moment for the MSW oscillation solution has the form [22–24]

$$(\mu_{\text{eff}}^2)_{\text{MSW}} = P_1(\mu_{11}^2 + \mu_{12}^2 + \mu_{13}^2) + P_2(\mu_{21}^2 + \mu_{22}^2 + \mu_{23}^2), \tag{4}$$

where P_1 and P_2 are the probabilities for observing the respective mass eigenstates. The detected magnetic moment can be expressed in terms of the magnetic moments of the flavor states as

$$(\mu_{\text{eff}}^2)_{\text{MSW}} = P_{ee}\mu_e^2 + (1 - P_{ee}) \times (\cos^2\theta_{23}\mu_\mu^2 + \sin^2\theta_{23}\mu_\tau^2). \tag{5}$$

In general, P_{ee} and P_1 depend on the neutrino energy, but, in the region of energies below 1 MeV, a dominant contribution to the recoil-electron spectrum comes from ^{7}Be and CNO neutrinos, for which P_{ee} and P_1 are approximately constant.

In analyzing the spectrum shown in Fig. 2, the spectrum of recoil electrons arising in neutrino–electron scattering caused by the magnetic moment was additionally included in the theoretical function. The minimum of χ^2 corresponds to zero value of the magnetic moment. An upper limit on $\mu_{\rm eff}$ was obtained in a standard way: minimum values of χ^2 were determined at various fixed values of $\mu_{\rm eff}$, the remaining parameters being free. On the basis of the resulting dependence $\chi^2(\mu_{\rm eff})$, it was found that the respective upper limit is 5.4×10^{-11} (where $\mu_{\rm B}$ is the Bohr magneton) at a 90% C.L. This limit is conservative—for the value of $\mu_{\rm eff} = 5.4 \times 10^{-11} \mu_{\rm B}$, almost 20% of events detected in the range 230–310 keV must be due to (ν, e) scattering associated with the magnetic moment.

The above limit is model-independent since only the shape of neutrino spectra but not their intensities is used in the analysis. It is also free from the systematic errors in the detector sensitive volume. The magnetic-moment values correlate strongly with the flux of *pp* neutrinos and with the intensity of the ^{85}Kr beta spectrum. A more stringent limit on $\mu_{\rm eff}$ can be obtained if some constraints are imposed on flux of *pp* neutrinos and on the intensity of the ^{85}Kr beta spectrum. The content of ^{85}Kr can be determined by detecting ^{85}Kr decays to an excited state of ^{85}Rb.

Since $\mu_{\rm eff}$ is the sum of positive definite quantities, one can constrain any term in (4) and (5). By using the most probable values of P_1, P_{ee}, θ_{12}, and θ_{23}, one can obtain the following limits from the condition $\mu_{\rm eff} \leqslant 5.4 \times 10^{-11} \mu_{\rm B}$: $\mu_{\nu e} \leqslant 7.3 \times 10^{-11} \mu_{\rm B}$ for the electron neutrino, $\mu_{\nu\mu} \leqslant 11.4 \times 10^{-11} \mu_{\rm B}$ for the muon neutrino, and $\mu_{\nu\tau} \leqslant 11.4 \times 10^{-11} \mu_{\rm B}$ for the tau neutrino. It is reasonable to compare these limits with those from reactor and accelerator experiments devoted to studying (ν, e) scattering: $\mu_{\nu e} \leqslant 3.2 \times 10^{-11} \mu_{\rm B}$ in the GEMMA experiment [25], $\mu_{\nu\mu} \leqslant 68 \times 10^{-11} \mu_{\rm B}$ in the LSND experiment [26], and $\mu_{\nu\tau} \leqslant 39000 \times 10^{-11} \mu_{\rm B}$ in the DONUT experiment [27]. One can see that the Borexino result improved substantially (by a factor of 6 and by a factor of 3400) the limits on the magnetic moments of the muon neutrino and the tau neutrino.

Similar limits can be obtained for the magnetic moments of the neutrino mass eigenstates, as well as on the fundamental features of the electromagnetic-moment matrix, such as the sum of the squares of the diagonal elements or the sum of the squares of the transition elements: $\mu_{1\to 2} \leqslant 5.4 \times 10^{-11} \mu_{\rm B}$, $\mu_{1\to 1,3} \leqslant 6.8 \times 10^{-11} \mu_{\rm B}$, and $\mu_{2\to 2,3} \leqslant 8.6 \times 10^{-11} \mu_{\rm B}$.

By using unique special features of the Borexino detector—an extremely low background level and a large scintillator mass—the Pauli exclusion principle was tested for nucleons in the ^{12}C nucleus [19, 28]. The approach used consisted in searches for photons, neutrons, and protons, as well as electrons and positrons, emitted in transitions of nucleons from the $1P_{3/2}$ shell to the filled $1S_{1/2}$ shell. As a result, new, the most stringent at the present time, limits on the lifetime of nucleons with respect to transitions in the ^{12}C nucleus that are forbidden by the Pauli exclusion principle were obtained at a level of $\tau \geqslant 10^{30}$–10^{31} yr.

5. CONCLUSIONS

The Borexino detector is detecting solar ^{7}Be and ^{8}B neutrinos in the on-line mode. The measured counting rates and recoil-electron spectra are in good agreement with the LMA MSW oscillation solution. The Borexino data, together with data from other solar and reactor experiments, have substantially improved our knowledge about the fluxes of *pp*, *pep*, and CNO neutrinos. A uniquely low background level in the region of natural radioactivity has made it possible to set new limits on the neutrino magnetic moment and on the probabilities of transitions in the ^{12}C nucleus that are forbidden by the Pauli exclusion principle.

New results obtained for vaster statistics and with smaller systematic errors determined after measurements with calibration sources will be presented by the Borexino Collaboration in the near future. Further plans of this collaboration include detecting CNO and *pep* neutrinos, studying time variations of the neutrino flux, detecting geo- and reactor antineutrinos, and seeking other rare processes.

REFERENCES

1. Borexino Collab. (G. Alimonti et al.), Astropart. Phys. **16**, 205 (2002).
2. Borexino Collab. (C. Arpesella et al.), Phys. Lett. B **658**, 101 (2008).
3. Borexino Collab. (C. Arpesella et al.), Phys. Rev. Lett. **101**, 091302 (2008).
4. Borexino Collab. (G. Alimonti et al.), Nucl. Instrum. Methods Phys. Res. A **600**, 568 (2009).
5. E. Gatti and F. De Martini, *Nuclear Electronics* (IAEA, Wien, 1962), vol. 2, p. 265.
6. Borexino Collab. (H. O. Back et al.), Nucl. Instrum. Methods Phys. Res. A **584**, 98 (2008).
7. J. N. Bahcall, A. M. Serenelli, and S. Basu, Astrophys. J. Lett. **621**, L85 (2005); Astrophys. J. Suppl. **165**, 400 (2006).
8. N. Grevesse and A. J. Sauval, Space Sci. Rev. **85**, 161 (1998).
9. M. Asplund, N. Grevesse, and A. J. Sauval, ASP Conf. Ser. **336**, 25 (2005).
10. KamLAND Collab. (S. Abe et al.), Phys. Rev. Lett. **100**, 221803 (2008).
11. Borexino Collab. (G. Bellini et al.), arXiv: 0808.2868 [astro-ph].

12. Borexino Collab. (H. O. Back et al.), Phys. Lett. B **525**, 29 (2002).
13. Borexino Collab. (H. O. Back et al.), Phys. Lett. B **563**, 23 (2003).
14. A. V. Derbin and O. Yu. Smirnov, JETP Lett. **76**, 409 (2002).
15. Borexino Collab. (H. O. Back et al.), JETP Lett. **78**, 261 (2003).
16. Borexino Collab. (G. Bellini et al.), Eur. Phys. J. C **54**, 61 (2008).
17. Borexino Collab. (H. O. Back et al.), Phys. Lett. B **563**, 35 (2003).
18. Borexino Collab. (M. Balata et al.), Eur. Phys. J. C **47**, 21 (2006).
19. Borexino Collab. (H. O. Back et al.), Eur. Phys. J. C **37**, 421 (2004).
20. A. V. Derbin, O. Yu. Smirnov, and O. A. Zaimidoroga, Fiz. Élem. Chastits At. Yadra **36**, 603 (2005) [Phys. Part. Nucl. **36**, 314 (2005)].
21. J. F. Beacom and P. Vogel, Phys. Rev. Lett. **83**, 5222 (1999).
22. A. Joshipura and S. Mohanty, Phys. Rev. D **66**, 012003 (2002).
23. W. Grimus, M. Maltoni, T. Schwetz, et al., Nucl. Phys. B **648**, 376 (2003).
24. D. Montanino, M. Picariello, and J. Pulido, Phys. Rev. D **77**, 093011 (2008).
25. A. G. Beda, V. B. Brudanin, E. V. Demidova, et al., arXiv:0906.1926 [hep-ex].
26. LSND Collab. (L. B. Auerbach et al.), Phys. Rev. D **63**, 112001 (2001).
27. DONUT Collab. (R. Schwienhorst et al.), Phys. Lett. B **513**, 23 (2001).
28. Borexino Collab. (G. Bellini et al.), arXiv:0911.0548 [hep-ex].

Translated by A. Isaakyan