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New constraints on the ^{12}C lifetime with respect to nuclear transitions violating the Pauli exclusion principle based on Borexino detector data

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This paper presents the results of the Borexino experiment data analysis, with a total exposure of 583 kton · day. The study was intended to search for violations of the Pauli exclusion principle in nuclear transitions of the ^{12}C isotope. The channels studied included radiative decay ($^{12}\mathrm{C} \to {}^{12}\mathrm{C}^{*} + \gamma$, 16.4 MeV), β-decay ($^{12}\mathrm{C} \to {}^{12}\mathrm{N}^{*} + e^{-} + \nu$, 18.9 MeV), and proton emission ($^{12}\mathrm{C} \to {}^{11}\mathrm{B}^{*} + p^{+}$, 8.6 MeV).

Keywords: Pauli principle, Scintillation detector.

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The exclusion principle, which is a cornerstone of modern microscopic physics, has been formulated by Pauli in his famous work [1]. In its original form, it postulated that „there cannot be two or more equivalent electrons in an atom“ [1]. In the context of Bohr's semiclassical atom model, this statement implies that only one electron with a given spin projection may occupy each allowed stationary orbit. As quantum mechanics developed further, this principle was given a strict mathematical formulation: the complete wave function of a system of two identical fermions must be antisymmetric with respect to permutation of particles. On an even more fundamental level (in relativistic quantum field theory), the Pauli exclusion principle (PEP) arises naturally as a direct consequence of the properties of creation and annihilation operators for fermions, which obey anticommutation relations.

Despite its fundamental importance and impeccable experimental verification, the underlying physical mechanisms ensuring the satisfaction of PEP remain a subject of debate and are not fully understood. It was noted by Okun' that „a nonconformist approach to the Pauli principle on the basis of quantum mechanics dates back to Dirac and Fermi“ [2]. The pioneering work of these outstanding physicists [3,4] was focused on the analysis of possible observable corollaries of a hypothetical arbitrarily small violation of the Pauli principle (specifically, its influence on the properties of atoms and the characteristics of atomic transitions).

Experimental searches for PEP violations generally follow two different directions, which, in turn, may be broken further down into four (if electrons and nucleons are examined independently). The first direction is focused on the search for atoms or nuclei that end up in a forbidden non-Pauli quantum state. The second direction is aimed at detecting specific prompt emission that must inevitably accompany the system relaxation (transition of an electron or nucleon from an allowed state to a hypothetical non-Pauli state).

The most stringent current experimental constraints on the probability of non-Pauli transitions for nucleons in the ^{12}C nucleus, which are accompanied by the emission of γ quanta, protons, neutrons, α particles and leptons (β-decay), have been established in the process of analysis of data accumulated by the Borexino detector over 485 days of continuous measurements [5]. Unique characteristics of this facility, which include its significant liquid scintillator mass (278 tons) and the unprecedentedly low level of radioactive background, became key factors that provided an opportunity to tighten (compared to the results published earlier) the upper limits on the lifetime of the ^{12}C nucleus with respect to the considered forbidden processes by several orders of magnitude.

In the present study, the search for non-Pauli transitions was also carried out using the data provided by Borexino: a large-volume low-background detector based on a liquid organic scintillator, which was originally designed and optimized for high-precision detection of low-energy solar neutrinos [6]. The detector has a four-layer design and includes several successive barriers for background suppression.

The outer layer of the system is a steel tank 16.5 m in height and 15.7 m in diameter that is filled with highly purified water. A total of 208 photomultiplier tubes (PMTs) positioned on its inner surface record Cherenkov radiation from cosmic ray muons. Thus, the external tank acts as an active muon veto. A water layer also serves as a passive shield against external gamma and neutron background radiation.

A stainless steel sphere 13.7 m in diameter, which serves as a supporting structure for the internal detector elements, is placed inside the water tank. The central (sensitive) detector region is bounded by a thin nylon sphere with a radius of 4.25 m, which contains 278 tons of a pseudocumene-based scintillator. This sensitive volume is surrounded by two concentric buffer layers of the same

scintillator with a special scintillation quenching additive; the total thickness of this buffer zone is 2.6 m.

Scintillation flashes in the central region are recorded by an array of 2212 PMTs located on the inner surface of the steel sphere. This system provides excellent energy resolution at the level of $\sim 5\,\%$ and a spatial resolution of ~ 13 cm for events with an energy of 1 MeV. Critical to achieving the required sensitivity was an unprecedented purification campaign aimed at removing natural radioactive impurities (in particular, uranium and thorium isotopes) from the scintillator. As a result of these efforts, the concentration of such impurities was reduced by ten or more orders of magnitude relative to the natural radioactivity level.

The search for non-Pauli transitions was performed by analyzing the event statistics accumulated within the interval from January 2008 to December 2016, which corresponded to 1494 days of live time. A similar data set was used and characterized in [7].

Figure 1 shows the spectrum of events that have passed the complete selection chain detailed in [7]. Number of detected photoelectrons $N_{p.e.}$ is converted with a sufficiently high accuracy into an energy scale in accordance with the following relation: $E[\text{MeV}] = N_{p.e.}/500$, where the value of $N_{p.e.}$ is normalized to 2000 photomultipliers. To determine the energy more accurately, one should also take into account the contribution emerging at high energies and related to the loss of energy into Cherenkov radiation. However, since there are no events with energies above 11 MeV in the examined spectrum and the effect is still weak at the indicated energy, this contribution may be neglected. It should be noted that the energy scale is meant to indicate so-called „apparent" energies (i. e., those that are normalized to the signal amplitude from an electron and make an allowance for detector resolution, which is associated both with the statistical spread of detected photoelectrons and the non-uniformity of light collection). The spectrum is

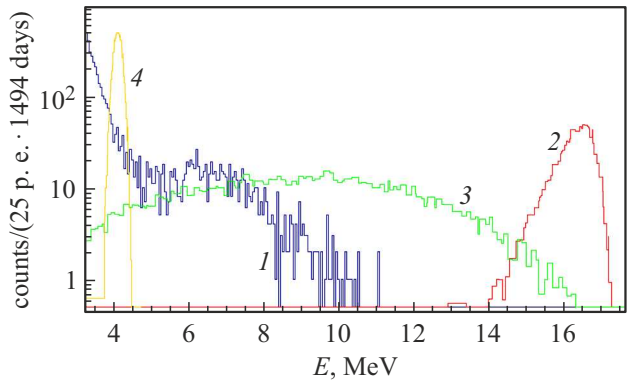


Figure 1. Measured and sought-for spectra. *1* — Spectrum of the Borexino detector within the 3.7–12 MeV interval measured over 1494 days (jump at an energy of 5.8 MeV is associated with a change in sensitive volume), *2* — spectrum of the $^{12}\text{C} \to {}^{12}\text{C}^* + \gamma$ reaction (16.4 MeV), *3* — spectrum of the $^{12}\text{C} \to {}^{12}\text{N}^* + e^- + \nu$ reaction (18.9 MeV), and *4* — spectrum of the $^{12}\text{C} \to {}^{11}\text{B}^* + p^+$ reaction (8.6 MeV).

plotted for the entire sensitive scintillator volume enclosed within the nylon sphere. Additional spatial selection was performed in order to suppress the background from events on the supporting structure of the nylon sphere with energies below ~ 5.9 MeV ($N_{p.e.} < 2950$): events localized vertically more than 2.5 m above the detector center were excluded, which led to a jump in selection efficiency seen in the spectrum at the indicated threshold. The total active detector mass involved in the analysis was 266 ± 5.3 tons. In the low-energy region, the effective volume fraction set by the selection geometry was $\varepsilon = 0.857 \pm 0.006$.

The expected spectral distributions for particles resulting from non-Pauli transitions are shown in Fig. 1. The experimental spectrum reveals no events recorded in the region above $E = 11.3$ MeV (5650 photoelectrons). Since the entire spectrum of the $^{12}\text{C} \to {}^{12}\text{C}^* + \gamma$ transition with an energy of 16.4 MeV is localized precisely in this energy region, an upper limit on the rate of its occurrence may be set.

In the present case (with no events observed in the region of interest), the $S_{\text{lim}} = 2.44$ value was used to calculate the limit on the number of sought-for events at a confidence level of 90 % in accordance with the procedure detailed in [8].

Thus, the following relation was used to establish a lower limit on the lifetime of the ^{12}C nucleus with respect to non-Pauli transition $^{12}\text{C} \to {}^{12}\text{C}^* + \gamma$:

$$\tau \geqslant \epsilon(\Delta E)\frac{N_N N_n}{S_{\text{lim}}}, \qquad (1)$$

where $\epsilon(\Delta E)$ is the efficiency of signal detection within energy window ΔE, N_N is the number of ^{12}C nuclei in the sensitive detector volume, and N_n is the number of valence nucleons in a nucleus that may potentially be involved in a non-Pauli transition. Note that nuclei outside the sensitive volume are located in the buffer with a quenching additive (2,2-dimethoxypropane), which reduces the light yield by approximately an order of magnitude, and the amplitude of these events is outside the amplitude range under consideration. Thus, the following limit on the ^{12}C nucleus lifetime with respect to this transition is obtained: $\tau \geqslant 9.7 \cdot 10^{31}$ years (90 % confidence level).

The spectrum shape corresponding to the β transition with an energy of 18.9 MeV is also shown in Fig. 1. In contrast to the previous case, a part of the spectrum for this channel is located above the threshold of 5650 photoelectrons. The recording efficiency for this part is $\epsilon(\Delta E) = 0.25$. With this factor taken into account, a limit on the lifetime of the ^{12}C nucleus with respect to this non-Pauli transition was obtained using relation (1) at $S_{\text{lim}} = 2.44$: $\tau \geqslant 1.2 \cdot 10^{31}$ years (90 % confidence level).

The transition with an energy of 8.6 MeV (with the emission of a proton) differs fundamentally from the two considered above. First, the apparent energy of the event is significantly lower. Second (this is the key point), protons in an organic scintillator are subject to a significant light yield quenching, which is attributable to the fact that a heavy

charged particle produces a much higher ionization density along its trajectory than an electron of a similar energy.

This factor makes simple analysis of event counts in a predetermined energy window inapplicable. A more complex procedure is needed instead: fitting of the complete spectrum with the sought-for signal included in the model as one of its components. The problem is simplified significantly by the fact that the signal from monoenergetic protons of the sought-for reaction has the shape of a narrow peak, while the main background processes in the energy region of interest, which are associated with recoil electrons from the scattering of solar ^{8}B-neutrinos and with β-decays of nuclei, have continuous spectra. Thus, the experimental spectrum was fitted by expression

$$N(E) = \exp(P_1 + P_2E) + \exp(P_3 + P_4E) + P_5S(E), \quad (2)$$

where P_{1-5} are free model parameters and $S(E)$ is the expected shape of the spectrum of protons produced in the non-Pauli transition.

The result of fitting the experimental spectrum by the maximum likelihood method with this model is presented in Fig. 2. No statistically significant signal was revealed: the area of the peak corresponding to the sought-for transition is consistent with zero within the error limits. Upper limit $S_{\text{lim}} < 150$ (90 % confidence level) on the number of signal events was obtained by analyzing the likelihood function profile. Inserting this value into relation (1), one may obtain the final lifetime limit for this channel, which is $\tau \geqslant 2.7 \cdot 10^{30}$ years (90 % confidence level).

The results of a search for violations of the Pauli principle in nuclear transitions of the ^{12}C isotope based on an analysis of data from the Borexino experiment with a record exposure of 583 kton · day were presented. The detector's high radiation purity and a significant volume of accumulated data made it possible to establish new limits on the probability of non-Pauli decays, which are the most stringent to date.

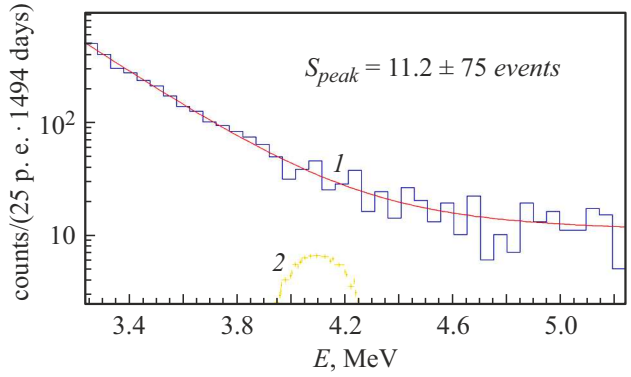


Figure 2. Fit for the Borexino detector spectrum within the 3.3–5.2 MeV range. *1* — Borexino detector spectrum and its fit by function (2); *2* — spectrum of protons of the $^{12}C \to {}^{11}B^* + p^+$ reaction (8.6 MeV) with an area corresponding to the established limit at a confidence level of 90 %.

Three main channels were studied using a unified methodological approach that combines direct analysis of event counts without background and fitting of the full spectrum in the region where background components are present. The following lower limits on the ^{12}C nucleus lifetime were obtained this way for each of these three processes (at a confidence level of 90 %):

$$^{12}C \to {}^{12}C^* + \gamma(16.4\,\text{MeV}): \ \tau \geqslant 9.7 \cdot 10^{31} \text{ years},$$

$$^{12}C \to {}^{12}N^* + e^- + \nu\,(18.9\,\text{MeV}): \ \tau \geqslant 1.2 \cdot 10^{31} \text{ years},$$

$$^{12}C \to {}^{11}B^* + p^+(8.6\,\text{MeV}): \ \tau \geqslant 2.7 \cdot 10^{30} \text{ years}.$$

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Conflict of interest

The authors declare that they have no conflict of interest.

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