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# To what extent does the latest SNO result guarantee the proton stability?

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## Abstract

Experimental data accumulated by the SNO detector (containing 1000 t of $D_2O$) on neutral-current solar neutrinos interactions [Phys. Rev. Lett. 89 (2002) 011301] have been used to set the best up-to-date life-time limit on the proton disappearance (or decay to the weakly interacting particles like neutrinos, majorons, etc.): $\lim \tau(p \to ?) > 5.7(3.5) \times 10^{28}$ yr at 68% (90%) C.L.

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It is well known that standard model (SM) of particle physics explains proton stability by the law of baryon ($B$) charge conservation. However, in the modern gauge theories this law is not considered absolute due to absence of any underlying symmetry principle behind it, unlike the gauge invariance in electrodynamics, which guarantees the masslessness of photon and absolute conservation of the electric charge. Hence, many extensions of the SM—for example, grand unified theories, GUTs—incorporate $B$-violating interactions (or $B - L$, where $L$ is the lepton number), by supposing that the symmetry associated with $B$ conservation is broken at a certain energy scale. Consequently, such interactions can lead to the processes with $\Delta B = 1$, $\Delta B = 2$, $\Delta(B - L) = 0$, $\Delta(B - L) = 2$ (see, e.g., [2–4] and references therein) and, in particular, to decay of protons.

Stimulated by theoretical predictions, proton instability has been searched for in many underground experiments with the help of large mass detectors like IMB, Fréjus, Kamiokande, Super-Kamiokande and others (for details and references see [4–6]), however, no evidence for the nucleons decay has been found up to now. A complete summary of the experimental life-time limits (set for 75 decay modes) is given in the Review of Particle Physics [7]. These bounds are in the range of $10^{30}$–$10^{33}$ yr for the proton decays to the particles which can strongly or electromagnetically interact with the nuclei contained in the detector's sensitive volume.

However, because we do not know a priori which mode of proton decay (from 75 ones listed in [7] and perhaps from some unknown modes) can be realized

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in Nature, "*… it is desirable therefore to set limits for nucleon stability using techniques which are as nearly as possible decay-mode independent*" [8]. With this aim the modes of the proton decay to the weakly interacting products (e.g., neutrinos, majorons, etc.) have been considered. Because these particles escape detection, such decays would look as disappearance of protons. The best obtained bounds on $p$ disappearance are within $10^{23}$–$10^{26}$ yr [7], that is up to 10 orders of magnitude lower than those for the $p$ decays to the strongly or electromagnetically interacting particles.

Nowadays the interest for the proton disappearance has become more actual due to development of theories with more than three spatial dimensions which are not necessary small. Recently the emphasis in such multi-dimensional theories has shifted toward "brane world" picture, in which ordinary matter is trapped to a three-dimensional brane embedded in fundamental multi-dimensional space (see, for example, review [9]). In such a scenario extra dimensions may be large (even infinite), and their existence would manifest themselves as deviation from Newtonian gravity at sub-millimeter range, thus it could be experimentally tested with the new generation of torsion balance experiments [10]. Moreover, if gravity is really unified with the other fundamental interactions at the TeV scale, as predicted by mentioned theories, the measurements on the future colliders would provide a probe of quantum gravity at realistic energies [11]. Besides, one more prediction of this "brane world" picture is that massive fermions may escape our world into extra dimensions [9,11,12], hence, observation, e.g., of the proton disappearance would be a strong argument for the extra dimensions: "*Furthermore, the presence and properties of the extra dimensions will be investigated by looking for any loss of energy from our* 3*-brane into the bulk*" [11]. In recent work [13] the life-time of proton for such an escape was estimated as $\tau(p) = 9.2 \times 10^{34}$ yr.

Several experimental approaches were used to establish limits on proton disappearance.

(1) The bound on nucleon life-time was set in experiment searching for the spontaneous fission of $^{232}$Th [14]. It was assumed that disappearance of the nucleon, which leaves a hole in an occupied shell, would give rise to spontaneous fission of the parent $^{232}$Th nucleus (the excitation energy should exceed the height of the fission barrier). From the $\tau$ limit on spontaneous fission of $^{232}$Th the value $\tau(N \to ?) > 3 \times 10^{23}$ yr is derived [14] (here $N$ is $p$ or $n$). Because the latter is determined for 232 particles (142 neutrons and 90 protons), one can recalculate it for 90 protons as $\tau(p \to ?) > 1.2 \times 10^{23}$ yr.

(2) Geochemical search. In Ref. [15] the bound $\tau(p \to ?) > 7.4 \times 10^{24}$ yr[1] was determined on the basis of mass-spectrometric measurements with Te ore samples ($2.5 \times 10^9$ yr old) by looking for the possible daughter nuclide $^{129}$Xe($^{130}\mathrm{Te} \to \cdots \to {}^{129}\mathrm{Xe}$).

(3) Radiochemical method. In the experiment [16] the target, contained $9.7 \times 10^{27}$ atoms of $^{39}$K (1710 kg of potassium acetate, $KC_2H_3O_2$), was exposed deep underground (4400 m w.e.) for about one year. Then, the candidate daughter $^{37}$Ar, which could arise as result of proton disappearance in $^{39}$K($^{39}\mathrm{K} \to \cdots \to {}^{37}\mathrm{Ar}$), was extracted and its activity was measured as $0.3 \pm 0.6$ decays per day, which leads to the proton life-time limit $\tau(p \to ?) > 1.1 \times 10^{26}$ yr [16].[2]

(4) Search for radioactive decay of daughters (time-resolved from prompt products) created after $p$ disappearance in mother nuclei incorporated in a low-background detector. The best limit was set in the measurements with the BOREXINO Counting Test Facility, a 4 t liquid scintillation detector ($^{13}\mathrm{C} \to {}^{12}\mathrm{B}$): $\tau(p \to ?) > 1.2 \times 10^{26}$ yr [17].

(5) Study of the neutron production rate in deuterium. The decay or disappearance of proton bounded in deuterium nucleus, which consists only of proton and neutron, will result in the appearance of free neutron: $d \to n+?$ In Ref. [18] the life-time limit was established as $\tau(p \to ?) > 3 \times 10^{23}$ yr by searching for neutrons capture rate in the shielded liquid scintillator enriched in deuterium. Recently this bound was improved to the value of $4 \times 10^{23}$ yr at 95% C.L. [19] by reanalyzing the results of the measurements [20] with $D_2O$ target (mass 267 kg), which was installed at Reactor 5 of the Centrale Nucleaire de Bugey (France) and well shielded against cosmic rays and natural radioactivity.

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[1] The value $\tau(N \to ?) > 1.6 \times 10^{25}$ yr is given in [15] for 52 particles (28 neutrons and 24 protons), thus we recalculated it for 24 protons as $\tau(p \to ?) > 7.4 \times 10^{24}$ yr.

[2] The idea to extract limit on proton life-time from mentioned measurements was suggested to the author by J.C. Evans Jr., and R.I. Steinberg (see [8,16]).

It should be noted that each of mentioned methods has both their advantages and limitations [8]. For example, when looking for the $p$ disappearance, it is supposed that both the baryon number and the electric charge could not be conserved. Earlier it was suggested that "*experimenter would be wise not to exclude such processes from consideration a priori*" [15], whereas at present any disappearance of the electric charge and energy would be of great interest for the modern theories with extra dimensions [9]. The main problem of the radiochemical experiments is the feasibility of separation and extraction of a few atoms from target with mass of some tons, while the reliability of the geochemical searches is restricted by uncertainties in the estimation of background effects over geological time spans [8]. The limits [15,16], usually quoted as "independent on channel" [7], are valid only for the case, when the process of proton decay is not disruptive, thus the parent nucleus is not fully destroyed by the strongly or electromagnetically interacting particles emitted. At the same time, bound on the proton decay from the deuterium disintegration requires the less stringent hypothesis on the stability of daughter nuclear system and, hence, it is less model dependent [21].

The most rigorous life-time limit of proton from the deuterium disintegration was established in [19] as $\tau(p \to ?) > 4 \times 10^{23}$ yr at 95% C.L. Besides, in Ref. [19] it was predicted that this value can be highly improved (at least up to $\tau(p \to ?) > 10^{28}$ yr) with the help of solar neutrino Cherenkov detector (1000 t of 99.917% isotopically pure heavy water viewed by 9456 distant photomultiplier tubes) installed in the Sudbury Neutrino Observatory (SNO) [22].

In this Letter we analyze the results of the latest SNO observations of neutral-current neutrino interactions on deuterium, which are reported in Ref. [1], with aim to advance the bound on proton stability.

The SNO detects $^8$B solar neutrinos ($\nu$) through the following reactions with electrons and deuterons: elastic scattering (ES) $\nu_i + e^- \to \nu_i + e^-$; charged current (CC) absorption $\nu_e + d \to e^- + p + p$; and neutral current (NC) disintegration of deuteron $\nu_i + d \to \nu_i + n + p$. The CC absorption is sensitive only to electron neutrinos, while NC reaction and ES are sensitive to all neutrino flavors ($i = e, \mu, \tau$), but for the ES with reduced cross sections to $\nu_\mu$ and $\nu_\tau$. Neutrons released in $d$ disintegration can be detected by their capture on deuterons in pure $D_2O$, or by capture on $^{35}$Cl (dissolving MgCl salt in the heavy water), or by capture on $^3$He (with proportional counters).

The SNO results on CC and ES reactions have been published in Ref. [23]. The NC data reported in Ref. [1] represent a total 306.4 live days, spanning the entire first phase of the experiment, in which only $D_2O$ was present in the sensitive volume. The total flux of active $^8$B solar neutrinos was measured with the NC reaction energy threshold of 2.2 MeV. The corresponding NC signal is the Cherenkov photons from the 6.25 MeV gamma ray resulting from neutron capture on deuterium. In the data analysis the fiducial volume of the detector was restricted by the diameter 11 m, and the energy threshold was set at 5 MeV.

The data recorded during the $D_2O$ phase of the experiment were analyzed using data reducing procedure [23] and neutron cut, which yields 2928 events in the energy region of 5–20 MeV [1]. They are presented in Fig. 2(a) of Ref. [1] as distributions of the selected events versus cosine of the angle between the Cherenkov event direction and direction from the Sun, $\cos\theta_\odot$, and as the energy spectrum of the selected events in Fig. 2(c). In the data (recorded above the energy threshold of 5 MeV) there are contributions from the CC and ES events, capture of neutrons (from NC and background), and low energy Cherenkov background events.

All possible sources of background to NC signal were investigated and determined precisely. The primary contributions are from trace contaminations of the detector materials by nuclides from U/Th decay chains (mainly from $^{214}$Bi and $^{208}$Tl), which generate free neutrons in the $D_2O$ (via a deuteron photodisintegration), and low energy Cherenkov events. Besides, other origins of free neutrons in the $D_2O$ volume were carefully taken into account (e.g., atmospheric, terrestrial and reactor neutrinos, $^2\mathrm{H}(\alpha,\alpha)pn$, $^{17}\mathrm{O}(\alpha,n)$ reactions, etc.). Finally, the total neutron background for 306.4 days measuring period was determined as $78 \pm 12$ events, while low energy Cherenkov events as $45^{+18}_{-12}$ events (in both cases systematic uncertainties are included) [1].

The calibration and background data (detector response functions, resolutions, efficiency, background rates, etc.) and results of Monte Carlo calculations (probability density functions of observed evens in $T_e$ and $\cos\theta_\odot$ assuming the standard $^8$B neutrinos spectral shape) were used to resolve the selected data into contributions from the CC, ES, NC events and background under assumption that there are only electron neutrinos in the solar neutrino flux. The decomposition performed with the help of extended maximum likelihood method yields the following results [1]:

$$\text{(CC)}\quad 1968^{+62}_{-61}(\text{stat}) \pm 102(\text{syst})\ \text{events},$$

$$\text{(ES)}\quad 264 \pm 26(\text{stat}) \pm 13(\text{syst})\ \text{events},$$

$$\text{(NC)}\quad 577^{+50}_{-49}(\text{stat}) \pm 52(\text{syst})\ \text{events}.$$

The analysis of the measured CC, ES, NC rates yields the evidence for the neutrino's flavor transformation in the solar neutrino flux [1]. The corresponding CC, ES, NC distributions are shown in Fig. 2 of Ref. [1]. As it is evident from this figure, in the observed data, which are well described by the mentioned components, there is no room for the neutrons, created in the $D_2O$ volume due to proton decay. Thus, we can only set the limit on the proton life-time, $\lim\tau(p \to ?)$,[3] which can be estimated on the basis of the formula

$$\lim\tau(p \to ?) = \varepsilon N_d t / \lim S,$$

where $\varepsilon$ is the efficiency for the neutron's detection, $N_d$ is number of deuterons in 1000 t of $D_2O$ ($N_d = 6.027 \times 10^{31}$ [24]), $t$ is the time of measurement (306.4 days), and $\lim S$ is the number of proton decays which can be excluded with a given confidence level on the basis of the rate of neutron-like events measured in the experiment. Mean efficiency for single neutrons born isotropically throughout the whole $D_2O$ volume was determined (from calibration with a $^{252}$Cf source) as $\varepsilon = 0.299 \pm 0.011$, while for the fiducial volume of the detector restricted by the diameter 11 m and for the energy threshold of 5 MeV, it was reduced down to 0.144 [1]. Then, applying a correction to account for cut losses (2.28% [24]), we get the final value of efficiency as $\varepsilon = 0.141$.

There are several ways in which estimation of the value of $\lim S$ from the experimental data [1] can be performed. Let us begin with two extreme cases. First, we can very conservatively suppose that nothing is known about possible origins of the neutron-like events observed by the SNO detector (except for the firmly measured neutron background), and thus, all of them ($577 \pm 72$ events) could be—at least in principle—assigned to proton decays. It gives $\lim S = 610$ (669) counts at 68% (90%) C.L. Substituting all values in the formula, we get $\lim\tau(p \to ?) \geqslant 1.2(1.1) \times 10^{28}$ yr at 68% (90%) C.L.

Secondly, we can accept the hypothesis of the neutrino's flavor transformation [1], in accordance with that all of $577 \pm 72$ neutron-like events are caused by the $^8$B solar neutrinos through the neutral current disintegration of deuteron. In this case, one can equal $\lim S$ value to the uncertainties of the number of the NC neutron-like events. It gives $\lim S = 72$ (118) counts at 68% (90%) C.L., and, consequently, leads to the $\lim\tau(p \to ?) \geqslant 9.9(6.0) \times 10^{28}$ yr at 68% (90%) C.L.

Therefore, we can argue that an estimate of the $\tau(p \to ?)$ limit is lying within the interval $10^{28}$–$10^{29}$ yr. In order to fix its value one has to determine the minimal possible contribution of the $^8$B solar neutrinos to the total number of neutron-like events observed by the SNO detector. It can be derived from the analysis of the results of the Super-Kamiokande (SK) [25] and SNO solar neutrino experiments, and on the basis of the theoretical solar neutrinos fluxes calculated within the framework of the standard solar model (SSM) [26]. Again, such an analysis can be performed in two ways.

First, in the most cautious approach when only contribution from $\nu_e$'s is taken into account, we can simply exploit the ratio of the $^8$B solar neutrinos flux measured in the SNO experiment through the CC absorption [1] to the SSM prediction ($0.35 \pm 0.03$ [27]), and the fact that the NC neutrino flux measured by the same SNO detector, $\phi_{\text{NC}} = 5.09 \pm 0.64$ [1] (here and further all neutrino fluxes are in units of $10^6\ \text{cm}^{-2}\,\text{s}^{-1}$), is in a good agreement with the total $^8$B neutrinos flux calculated by the SSM, $\phi_{\text{SSM}} = 5.05$ [26]. Then, conservatively supposing the absence of neutrino's flavor transformation, one can conclude that the minimal relative contribution of the $^8$B neutrino NC interactions to the observed $577 \pm 72$ neutron-like events is $0.35 \pm 0.03$. Hence, the residual that can be assigned to the proton decays is $375 \pm 50$ events. It yields the value of $\lim S = 398$ (439) counts

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[3] In SNO publication [1] it is noted: "*... this rate of neutron events also leads to a lower bound on the proton lifetime for "invisible" modes* {*based on the free neutron that would be left in deuterium* [*V.I. Tretyak, Yu.G. Zdesenko, Phys. Lett. B 505 (2001) 59*]} *in excess of* $10^{28}$ *years ...*".

at 68% (90%) C.L., and, correspondingly, the life-time bound: $\lim \tau(p \to ?) \geqslant 1.8(1.6) \times 10^{28}$ yr at 68% (90%) C.L.

However, the last limit is still too conservative. It is because that existence of a non-electron flavor active neutrino component in the solar flux has been already proved not only by the SNO experiment itself [1]. Such an evidence was also derived [23] by comparing the charged current absorption flux (which is sensitive only to electron neutrinos) measured by the SNO, $\phi_{\mathrm{CC}}$, with the SK flux measured through the elastic scattering. Thus, in addition to the mentioned $\approx 35\%$ part some more neutron-like SNO events are caused by the non-electron solar neutrinos ($\nu_\mu$ and/or $\nu_\tau$).

With aim to determine their contribution let us repeat analysis of Ref. [23] by using the latest SNO data [1], which were obtained with the lower energy threshold and with the higher statistics. The CC absorption flux measured by the SNO is $\phi_{\mathrm{CC}} = 1.76 \pm 0.11$, while the flux measured by the SK through the elastic scattering is $\phi_{\mathrm{ES}}^{\mathrm{SK}} = 2.32 \pm 0.09$ [25].[4] The difference is equal to $0.56 \pm 0.14$, that is statistically significant at the level of $4\sigma$, providing evidence for the flavor transformation of the solar neutrinos. Because cross sections for the $\nu_\mu$ and $\nu_\tau$ elastic scattering on electrons are 6.48 times lower than that for $\nu_e$ (for the energy threshold of the detector above 5 MeV),[5] the $\nu_\mu$ and/or $\nu_\tau$ flux ($\phi_{\mu\tau}$ flux) calculated on the basis of the experimental CC–ES difference is equal to $\phi_{\mu\tau} = 3.63 \pm 0.89$. Then, adding the measured $\nu_e$ flux ($\phi_e = \phi_{\mathrm{CC}} = 1.76 \pm 0.11$), we get the total flux of neutrinos of all flavors: $\phi_e + \phi_{\mu\tau} = 5.39 \pm 0.90$. By comparing the last value with that independently derived from the SNO measurements of the NC solar neutrinos interactions ($\phi_{\mathrm{NC}} = 5.09 \pm 0.64$ [1]), one can conclude that there is no indication for the presence of any additional contributions (e.g., from the proton decays) to the observed NC flux: the difference is $\Delta\phi = -0.30 \pm 1.10$. Conservatively treating such a negative difference as zero, i.e., accepting it as $0 \pm 1.1$, we get the limit on the possible additional contribution to the flux from any unknown sources equal to 1.1 (1.8) at 68% (90%) C.L. The corresponding limit on the number of the SNO neutron-like events is $\lim S = 125$ (204) counts at 68% (90%) C.L. Substituting these values in the formula for $\lim \tau(p)$, it yields the final restriction on the proton life-time:

$$\lim \tau(p \to ?) = 5.7(3.5) \times 10^{28} \text{ yr at 68\% (90\%) C.L.}$$

The obtained limit is higher by five orders of magnitude than previous and most stringent bound on proton life-time derived from the deuterium disintegration: $4 \times 10^{23}$ yr at 95% C.L. [19].

Unfortunately, the present SNO bound cannot be treated as a model independent. It is because of the SNO cut used to remove events which follow a cosmic muon passing through the active volume of the detector. Indeed, if a proton decay that conserves the electric charge as, e.g., $p \to \pi^+ + \nu$, occurs in the detector, and if a remaining neutron from the deuteron is left in the detector volume, we would observe a high energy $\pi^+$ which looks like a contained muon event. Consequently, the muon cut is fired and neutron event following a proton decay will be rejected. Therefore, the derived limit is valid for proton disappearance (or decay to the weakly interacting particles).[6]

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[4] The ES flux determined with the SNO detector itself ($\phi_{\mathrm{ES}}^{\mathrm{SNO}} = 2.39 \pm 0.27$) is in an excellent agreement with that measured by the SK.

[5] It should be noted, that the final result for the proton life-time depends weakly on the $\sigma_e/\sigma_{\mu\tau}$ ratio: e.g., for $\sigma_e/\sigma_{\mu\tau} = 6.0$ and 5.5 the corresponding $\lim \tau(p \to ?) = 3.7 \times 10^{28}$ yr and $3.3 \times 10^{28}$ yr, respectively (at 90% C.L.).

[6] Besides, limits on some other channels of proton decay, in which a low energy release (5–20 MeV) is produced in the detector (e.g., $p \to e^+ +$ several $\nu_i \bar{\nu}_i$ pairs), can be determined on the basis of the SNO data. For example, if the total kinetic energy of positron plus $\simeq 1$ MeV from the $e^+$ annihilation is lying within 13–20 MeV, we can use 12 events detected by the SNO in this energy region for proton life-time estimate. Because this number is in an excellent agreement with the solar neutrino expectations, we, following the procedure recommended in [7], get the value of $\lim S = 7.0$ at 90% C.L. Then, supposing that a neutron left from the deuteron was not registered in the fiducial volume with the probability of $(1 - \varepsilon) \simeq 0.86$, and accounting for the number of deuterons in this volume ($N_d = 4.6 \times 10^{31}$), we obtain the limit on the proton life-time: $\lim \tau(p \to e^+ +$ several $\nu_i \bar{\nu}_i) > 4.7 \times 10^{30}$ yr at 90% C.L.

Moreover, it is possible to establish a model independent limit on the proton life-time by using the SNO disappearance bound in combination with experimental limits for other 75 modes of proton decay to the strongly or electromagnetically interacting particles [7]. Because all of mentioned bounds are much higher than the SNO limit (these are in the range of $10^{30}$–$10^{33}$ yr [7]), the model independent bound is, in fact, determined by the SNO result: $\lim \tau(p \to ?) \geqslant 5.7(3.5) \times 10^{28}$ yr at 68% (90%) C.L. Obviously, the universality of such a "model independent" limit is to certain extent restricted by our present day knowledge, thus, it should be

In conclusion, on the basis of the latest SNO data on neutral-current solar neutrinos interactions on deuterium [1], the best up-to-day life-time bound on the proton disappearance has been set at the level of some of $10^{28}$ yr. In fact, this limit is close to those established for the particular modes of the nucleon decays to charged or strongly interacting particles [7], and it would be of a great importance for the modern physics.

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additionally checked or corrected if possible new channels of proton decay would be predicted or found in the future.