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Search for the nucleon and di-nucleon decay into invisible channels

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Abstract

Data collected deep underground at the Gran Sasso National Laboratory of INFN by using the $\simeq 6.5$ kg DAMA liquid Xenon scintillator have been analysed to search for nucleon and di-nucleon decays into invisible channels (decay to $\nu_i\overline{\nu}_i$ or to $\nu_i\overline{\nu}_i\nu_i$ or to $5\nu_i$, etc., with $i = e, \mu, \tau$) or disappearance. The considered statistics has been 2257.7 kg×day. The new obtained limits are: $\tau_p = 1.9 \times 10^{24}$ yr, $\tau_{nn} = 1.2 \times 10^{25}$ yr and $\tau_{pp} = 5.5 \times 10^{23}$ yr at 90% C.L. The latter values are the same or better than those previously established by the Fréjus Collaboration; in particular, the limits for the NN decay into $\nu_\tau\overline{\nu}_\tau$ are set for the first time.

1. Introduction

The baryon (B) and lepton (L) numbers are absolutely conserved in the Standard Model due to unbroken global symmetry. However, the replacement of global symmetries by local, often spontaneously broken, gauge invariances is the mainstream in the development of the modern field theory. Consequently, most of the current grand unified theories — including those based on supersymmetry — predict violation of baryon and lepton numbers and, thus, the decay of protons and neutrons bounded in nuclei. The processes with $\Delta B = 1$, $\Delta B = 2$, $\Delta(B-L) = 0$, $\Delta(B-L) = 2$ have been discussed in literature (see, e.g., [1–3] and references therein), while the disappearance of nucleon and di-nucleon into "nothing" has been addressed in [4,5] in relation with possible existence of extra timelike dimensions.

Stimulated by theoretical considerations, nucleon instability has been searched for in many underground experiments with the help of massive detectors such as IMB, Fréjus, Kamiokande, SuperKamiokande and others (for experimental activity see [3,6,7] and references therein). About eighty decay modes have been analyzed; however, no evidence for the nucleons decay has been found. A complete summary of the experimental results can be found in the Review of Particle Physics [8].

For the modes in which the nucleon decays to particles strongly or electromagnetically interacting

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in the detector's sensitive volume, the obtained life-time limits are in the range of 10^{30}–10^{33} yr, while for the modes where only weakly interacting decay products (neutrinos) are produced, the limits are few orders of magnitude lower. Since the latest type of decay modes is the subject of this article, we will previously discuss the available experimental results in some details.

The idea to consider the whole Earth as a source with decaying neutrons bounded in nuclei and to search for related events in a massive detector has been used in Ref. [9] in order to determine the life-time limit: $\tau(n \to \nu_\mu \overline{\nu}_\mu \nu_\mu) > 5 \times 10^{26}$ yr at 90% C.L.

Using the same approach, the Fréjus Collaboration has set the limits $\tau(n \to \nu_e \overline{\nu}_e \nu_e) > 3.0 \times 10^{25}$ yr and $\tau(n \to \nu_\mu \overline{\nu}_\mu \nu_\mu) > 1.2 \times 10^{26}$ yr at 90% C.L. [10]; in this case the emitted neutrinos had to produce the detectable events into 700 t of iron in the Fréjus detector. In Ref. [10] the result of [9] was discussed and estimated to be lower by more than one order of magnitude.

The Kamiokande Collaboration has searched for γ quanta with $E_\gamma = 19$–50 MeV emitted in the deexcitation of the ^{15}O nucleus. This nucleus can be produced by the disappearance of a neutron in the internal $s_{1/2}$ shell of an ^{16}O nucleus in the 680 t water fiducial volume of that large Cherenkov detector. The considered decay mode of the ^{15}O is expected to have a branching ratio quite low (2.7×10^{-5}). The following restrictions were found: $\tau(n \to \nu_i \overline{\nu}_i \nu_i,\ \ i = e, \mu, \tau) > 4.9 \times 10^{26}$ yr at 90% C.L. [11].

The most stringent life-time limit for the decay of neutron was determined by J.F. Glicenstein [12] who suggested to search for high energy bremsstrahlung γ quanta ($E_\gamma > 100$ MeV) emitted because of the prompt disappearance of the neutron's magnetic moment. He used the data of the Kamiokande Collaboration to set the limit $\tau(n \to \nu_i \overline{\nu}_i \nu_i, i = e, \mu, \tau) > 2.3 \times 10^{27}$ yr at 90% C.L. The limit for the decay to five neutrinos was also calculated to be: $\tau(n \to 5\nu) > 1.7 \times 10^{27}$ yr at 90% C.L. [12].

For the proton decay, three approaches were used:

(1) In Ref. [13] the limit $\tau(N \to ?) > 3 \times 10^{23}$ yr (N is p or n) was determined on the basis of the limit for the branching ratio of ^{232}Th spontaneous fission and assuming that the nucleon decay will blow up the nucleus;

(2) In Ref. [14] the limit $\tau(p \to ?) > 3 \times 10^{23}$ yr was determined searching for neutrons born in liquid scintillator, enriched in deuterium, as result of p decay in deuterium ($D \to n+?$);

(3) In Ref. [15] the limit: $\tau(p \to 3\nu) > 7.4 \times 10^{24}$ yr was determined [1] searching for possible daughter nuclides on the basis of geochemical measurements with Te ore (^{130}Te $\to$ ^{129}Xe), while in Refs. [16,17] the limit: $\tau(p \to 3\nu) > 1.1 \times 10^{26}$ yr was achieved by deep underground radiochemical measurements with 1710 kg of potassium acetate $KC_2H_3O_2$ (^{39}K $\to$ ^{37}Ar). In the latter cases not only the baryon number but also the electric charge conservation would be violated; however the authors considered that "experimenter would be wise not to exclude such processes from consideration a priori" [15].

As for the processes with $\Delta B = 2$, only the following two bounds were determined by the Fréjus Collaboration [10]: $\tau(nn \to \nu_e \overline{\nu}_e) > 1.2 \times 10^{25}$ yr and $\tau(nn \to \nu_\mu \overline{\nu}_\mu) > 6.0 \times 10^{24}$ yr at 90% C.L. In principle, these limits are valid also for the pn and pp decays to $\nu_i \overline{\nu}_i$ with $i = e, \mu$, which violate the electric charge conservation.

Although the restrictions described above — obtained by exploiting very different ideas — are lower up to ten orders of magnitude than those known for the channels with strongly or electromagnetically interacting decay products, they are listed in the Review of Particle Physics [8] as giving valuable information on the nucleon and di-nucleon stability. From this point of view, the restrictions obtained with some additional approaches can also be of interest.

As already mentioned, in the Fréjus and Kamiokande experiments the prompt and — because of the high energy thresholds — high energy particles produced by nucleon decays have been searched for. Here we use a different method. In fact, if the daughter nuclei, created after the nucleon or di-nucleon disappearance in the parent nuclei, are radioactive (usually with energy release of few MeV or less), we can search for their decay using a proper detector with low energy threshold. If the half-life of the daughter nucleus is greater than about 1 s, its decay will be separated

[1] We recalculated the value quoted in [15] $\tau(N \to 3\nu) > 1.6 \times 10^{25}$ yr (given for 52 particles: 28 neutrons and 24 protons) for 24 protons which should be taken here into consideration.

in time from the prompt products if any of them are observable in the detector. By using this method we can gain in the branching ratio (probability to obtain specific daughter product) which will be close to 1 (instead of, e.g., Kamiokande's 2.7×10^{-5}) and — if the parent and daughter nuclei are located in the detector itself — in efficiency which will be also close to 1 (instead of, e.g., the low Fréjus' efficiency to detect the neutrinos from the Earth).

The present paper describes the search for the nucleon and di-nucleon instability based on this idea and on measurements with the low-background detector operating in the Gran Sasso National Laboratory of INFN: the $\simeq 6.5$ kg DAMA liquid Xe (LXe) scintillator enriched in ^{129}Xe at 99.5%. This detector is operating deep underground since several years; it was mainly developed for dark matter investigations [18], but it was also used to study the electron stability (decays $e^- \to \nu_e \gamma$ and charge non-conserving nuclear excitations), and the best up-to-date half-life limits were set for these processes [19].

2. Experimental set-up and measurements

The LXe DAMA set-up ($\simeq 6.5$ kg — i.e. $\simeq 2$ l of liquid Xenon scintillator) and its performance have been described in Ref. [18] and only the main features of the detector are summarized here.

The used gas is Kr-free Xenon enriched in ^{129}Xe at 99.5% by ISOTEC company. The U/Th contamination of ^{129}Xe does not exceed ≈ 2 ppt at 90% C.L. The vessel for the LXe is made of OFHC low radioactivity copper ($\leqslant 100$ μBq/kg for U/Th and $\leqslant 310$ μBq/kg for potassium).

The scintillation light is collected by three EMI photomultipliers (PMTs) with MgF_2 windows, working in coincidence. The measured quantum efficiency for normal incidence has a flat behaviour around the LXe scintillation wavelength (175 nm); depending on PMT, its value can range between 18% and 32%. The PMTs collect the scintillation light through three windows (3" in diameter) made of special cultured crystal quartz (total transmission of the LXe ultraviolet scintillation light is $\approx 80\%$, including the reflection losses). A low radioactivity copper shield inside the thermo-insulation vacuum cell surrounds the PMTs; then, 2 cm of steel (insulation vessel thickness), 5–10 cm of low radioactivity copper, 15 cm of low radioactivity lead, ≈ 1 mm of cadmium and ≈ 10 cm of polyethylene are used as outer hard shielding. The environmental Rn near the external insulation vessel of the detector is removed by continuously flushing high purity Nitrogen gas (from bottles stored underground for a long time) inside a sealed Supronyl envelope, which wraps the whole shield.

Each PMT is connected to a low noise preamplifier. For every event the following data are stored: (i) amplitudes of each PMT pulse and (ii) amplitude and shape of the sum pulse (recorded by a Lecroy transient digitizer).

The energy dependence of the detector resolution was measured [18] and can be expressed as following: $\sigma/E = 0.056 + 1.19/\sqrt{E}$, where σ and E are given in keV. Some other information can be found in Ref. [18].

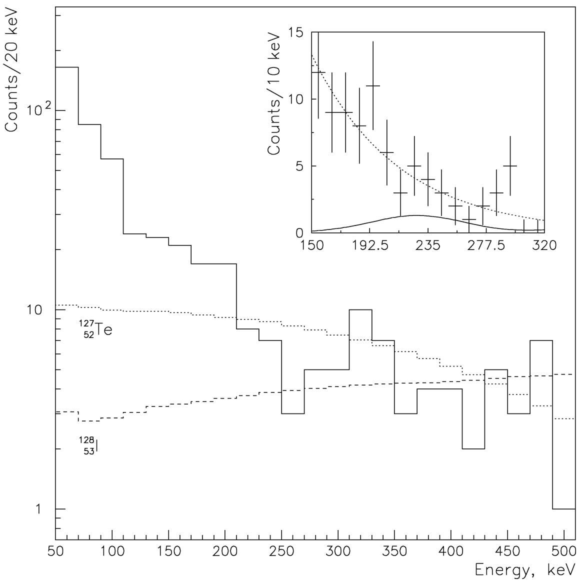

Fig. 1. Energy distribution measured by the LXe detector in the 50–500 keV energy interval; the total statistics is 2257.7 kg×day (full histogram). The dotted line is the 90% C.L. excluded distribution for ^{127}Te decay ($\tau_{pp} = 5.5 \times 10^{23}$ yr); the dashed line is the exclusion for ^{128}I decay ($\tau_p = 1.9 \times 10^{24}$ yr). In the inset the 150–320 keV energy region is shown in linear scale together with the fitting curve (dotted line) and the excluded distribution for the ^{127}Xe decay ($\tau_{nn} = 1.2 \times 10^{25}$ yr).

Table 1
Processes of N and NN decays in the DAMA LXe detector, daughter nuclides and their characteristics [20]. The energy release is given in MeV

Initial nucleus	Decay	Daughter nucleus, half-life, modes of decay and energy release		
$^{129}_{54}$Xe	n	$^{128}_{54}$Xe	stable	
	p	$^{128}_{53}$I	$T_{1/2} = 24.99$ m	β^- 94% ($Q = 2.127$); β^+, EC 6% ($Q = 1.258$)
	nn	$^{127}_{54}$Xe	$T_{1/2} = 36.41$ d	EC ($Q = 0.664$)
	pn	$^{127}_{53}$I	stable	
	pp	$^{127}_{52}$Te	$T_{1/2} = 9.4$ h	β^- ($Q = 0.694$)

The experimental spectrum of the LXe scintillator in the energy region 50–500 keV [2] with total statistics 2257.7 kg×day (8336 h of measurements) is shown in Fig. 1.

3. Data analysis and results

In result of N or NN decay (disappearance), one or two holes in the nuclear shells will be created, and — if the disappeared nucleons were not in the most external shell — the daughter nucleus will be in an excited state. In the subsequent deexcitation process this nucleus will emit γ quanta if the energy of excitation, $E_{\rm exc}$, is lower than binding energy of the least bound proton or neutron. Otherwise, one or even few particles (p, n, α) will be emitted with practically 100% probability. As a result, parent (A, Z) nucleus could be transformed not only to an $(A-1, Z)$ or to an $(A-1, Z-1)$ nucleus after the n or p decay (or to $(A-2, Z)$, $(A-2, Z-1)$ and $(A-2, Z-2)$ after the nn, pn and pp decay) but as well to various nuclides with lower A and Z numbers. [3] In the following we consider only the N and NN decays on a few most external nuclear shells without subsequent emission of p or n.

The list of such daughter nuclides which could be created in the LXe DAMA detector together with their characteristics is given in Table 1. For completeness we take into consideration also the pn and pp decays with electric charge non-conservation. The half-life of all radioactive daughter nuclei is sufficiently long to separate in time the signals in the detector from prompt γ quanta, emitted in deexcitation process, and subsequent nuclides decay.

Response functions for decay of all unstable daughter nuclei in LXe detector were calculated with the help of GEANT3.21 package [21]. The DECAY4 event generator [22] was used to determine the initial kinematics of the events: how many particles and of which types — e^-, e^+, γ quanta, conversion electrons or e^+e^- pairs, X rays and Auger electrons — were emitted in the decay, their energies, times of emission and directions of movement. Simulated response functions are shown in Fig. 2. The efficiencies to detect the decay of each daughter nuclei (^{128}I, ^{127}Xe and ^{127}Te) are calculated on the basis of corresponding response functions and are given in Table 2 for the energy regions where effect is searched for. Comparing the experimental data (Fig. 1) with the calculated response functions we did not find evidence for the N or NN decays. Thus only limits for probabilities of such processes can be determined. To estimate the life-time limit $\tau_{\rm lim}$, we use the formula:

$$\tau_{\rm lim} = \varepsilon_{\rm det} \times \varepsilon_{\Delta E} \times N_{\rm nucl} \times N_{\rm obj} \times \lambda_{\rm obj} \times t / S_{\Delta E}, \quad (1)$$

where $\varepsilon_{\rm det}$ is the detection efficiency (for full response function); $\varepsilon_{\Delta E}$ is the efficiency of the considered energy window (ΔE); $N_{\rm nucl}$ is the number of parent nuclei; $N_{\rm obj}$ is the number of objects (n, p or NN

[2] The energy threshold in the measurements was near 12 keV [18].

[3] It should be noted that such nuclides can also be produced in the target due to nucleon-induced reactions at Earth's surface and their remnants can be really observed in an experiment even after the target's deactivation underground during some time (in dependence on the nuclide half-life).

Table 2
Values of N_{nucl} (number of nuclei), N_{obj} (n, p and NN pairs) and $N_{\text{obj}} \times \lambda_{\text{obj}}$ (number of effective decaying objects) for parent nuclide; detection (ε_{det}) and energy window ($\varepsilon_{\Delta E}$) efficiencies for ^{128}I and ^{127}Te in $\Delta E = 350$–500 keV energy region, while for ^{127}Xe in $\Delta E = 150$–315 keV energy region; excluded number of events in ΔE ($S_{\Delta E}$) and life-time limits (τ_{lim}) for N and NN decays at 90% C.L.

N_{nucl}	Decay	N_{obj}	$N_{\text{obj}} \times \lambda_{\text{obj}}$	Daughter nucleus	ε_{det}	$\varepsilon_{\Delta E}$	$S_{\Delta E}$	τ_{lim}, yr
$^{129}_{54}$Xe	p	24	24	$^{128}_{53}$I	0.986	0.102	35.9	1.9×10^{24}
3.0×10^{25}	nn	283	9	$^{127}_{54}$Xe	0.994	0.516	11.5	1.2×10^{25}
	pp	116	4	$^{127}_{52}$Te	0.992	0.176	35.9	5.5×10^{23}

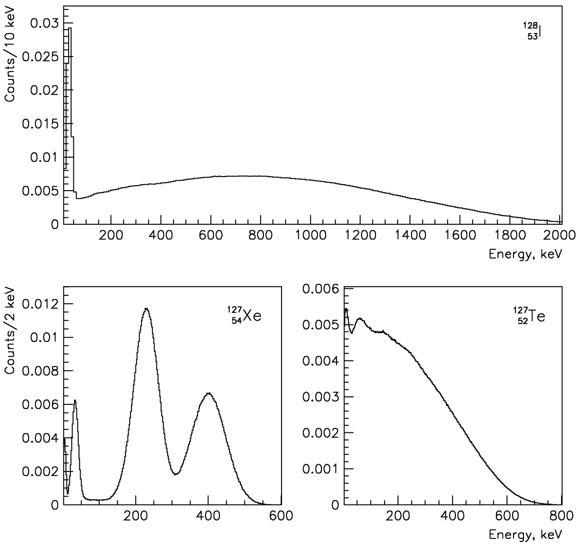

Fig. 2. Calculated response functions of the DAMA LXe scintillator for the decays of $^{128}_{53}$I (created inside the detector after the p decay in $^{129}_{54}$Xe nuclei), $^{127}_{54}$Xe (nn decay) and $^{127}_{52}$Te (pp decay). The area under each spectrum is normalized to 1.

pairs) inside the parent nucleus, whose decay could produce the specific daughter nucleus; λ_{obj} is the average probability to form the effective decaying object inside the parent nucleus; t is the measuring time; $S_{\Delta E}$ is the number of events in ΔE due to the effect, which can be excluded at a given confidence level on the basis of the experimental data.

The number of objects, N_{obj}, was estimated following Ref. [15]. After the decay of a neutron with binding energy $E_n^b(A,Z)$ in an (A,Z) nucleus, the $(A-1,Z)$ daughter will be in excited state; its excitation energy, E_{exc}, can be approximated [15] by $E_{\text{exc}} = E_n^b(A,Z) - S_n(A,Z)$, where $S_n(A,Z)$ is the binding energy of the least bound neutron in the (A,Z) nucleus. The $(A-1,Z)$ daughter will emit only γ quanta, when the value of E_{exc} is lower than the binding energy of the least bound nucleon in the $(A-1,Z)$ nucleus: $E_{\text{exc}} < S_N(A-1,Z)$, where $S_N(A-1,Z) = \min\{S_n(A-1,Z), S_p(A-1,Z)\}$. This gives the following restriction on the $E_n^b(A,Z)$:

$$E_n^b(A,Z) < S_n(A,Z) + S_N(A-1,Z). \quad (2)$$

Similar relations can be written for the p decay:

$$E_p^b(A,Z) < S_p(A,Z) + S_N(A-1,Z-1), \quad (3)$$

and for the nn, pn and pp decays:

$$E_{n_1}^b(A,Z) + E_{n_2}^b(A,Z) < S_{2n}(A,Z) + S_N(A-2,Z), \quad (4)$$

$$E_n^b(A,Z) + E_p^b(A,Z) < S_n(A,Z) + S_p(A,Z) + S_N(A-2,Z-1), \quad (5)$$

$$E_{p_1}^b(A,Z) + E_{p_2}^b(A,Z) < S_{2p}(A,Z) + S_N(A-2,Z-2), \quad (6)$$

respectively. The values of S_n, S_p, S_{2n} and S_{2p} have been taken from Ref. [23], while the binding energies $E_{n,p}^b$ of neutrons and protons in ^{129}Xe have been calculated with the help of the WSBETA code [24] with the “optimal” parameter set of Woods–Saxon potential; this program has been very successful in describing many aspects of the single-particle motion in deformed nuclei. It finds the single-particle energies and wave functions in axially symmetric — but otherwise arbitrarily deformed — Woods–Saxon potential by solving numerically the Schrödinger equation. The used Hamiltonian includes the spin–orbit interaction and, for protons, the Coulomb potential; further details can be found in Ref. [24]. The input values of equilibrium quadrupole, hexadecapole and sixtupole deformations of ^{129}Xe for the code WSBETA are evaluated by using shell correction method of Ref. [25]. Numbers of p and NN pairs, whose binding energies satisfy the inequalities written above, are given in Table 2. It should be noted that the obtained value for number of protons (24) is equal to the number of protons (24) calculated in Ref. [15] for ^{130}Te (i.e., for the nucleus with about the same (A, Z) as our one).

Traditionally λ_{obj} is taken equal to 1 for protons and neutrons ($\lambda_p = \lambda_n = 1$). As for the NN pairs, it is difficult to say something reliable on the value of λ_{obj}. We only note that in previous experimental work on the di-neutron instability [10] the existence of one nn pair per nucleus (i.e., $N_{nn} \times \lambda_{nn} = 1$) was assumed. This is obviously the most conservative choice.

It is known, however, that the pairing effect really exists in nuclei (see, e.g., [26]): under the influence of the short-range nucleon–nucleon force nucleons preferentially form neutron and proton pairs whose total angular momentum is zero. Quantum numbers of nucleons in a pair are equal, except for the magnetic quantum number, which has opposite signs. We can calculate the number of pairs in ^{129}Xe which satisfy the inequality (4) for nn pairs (or (6) for pp pairs) with additional condition $E_{n_1} = E_{n_2}$ (or $E_{p_1} = E_{p_2}$). In this way we obtain $N_{nn} \times \lambda_{nn} = 9$ (neglecting the last unpaired neutron) and $N_{pp} \times \lambda_{pp} = 4$; in both cases, the contributions from other protons and neutrons have been neglected. These estimations can be considered as quite realistic for ^{129}Xe nucleus and will be used in the following.

The number of effect's events $S_{\Delta E}$, which can be excluded at a given confidence level on the basis of the experimental data, have been calculated using two different strategies depending on the expected response function for the decay of specific nuclide. In a very conservative way, we can just require that the theoretical distribution should not exceed the experimental energy spectrum, according to the statistical errors. Such an approach has been used when the simulated distribution had no peculiarities (peaks). When instead the peak in the theoretical distribution was located in a region having a smooth behaviour in the experimental energy spectrum, this was fitted by a sum of some appropriate background model and of the expected peak; the parameters of the background model and the area under the peak were the free parameters of the fit.

For the case of $^{128}_{53}$I we have considered the 350–500 keV interval of the experimental energy spectrum measured by the LXe detector during 8336 h (Fig. 1); it contains 29 events. Considering the statistical fluctuations, the number of events must not be greater than 35.9 at 90% C.L. Taking the latter limit value for the area of the $^{128}_{53}$I spectrum in the given interval and substituting in the formula (1) for τ_{lim} the values of the efficiency in the 350–500 keV energy region ($\varepsilon_{det} = 0.986$; $\varepsilon_{\Delta E}$=0.102), of the number of parent $^{129}_{54}$Xe nuclei ($N_{nucl} = 3.0 \times 10^{25}$), of the number of protons in the external $^{129}_{54}$Xe shells ($N_p = 24$), of the probability of the proton existence in parent nuclei ($\lambda_p = 1$), of the running time ($t = 8336$ h) and of $S_{\Delta E}$, we obtain the limit for the proton life-time:

$$\tau_p = 1.9 \times 10^{24} \text{ yr with 90\% C.L.}$$

Corresponding $^{128}_{53}$I distribution is shown in Fig. 1 together with the experimental energy spectrum. In the same way the limit on the number of events under the $^{127}_{52}$Te spectrum in the 350–500 keV region, $S_{\Delta E} = 35.9$, was obtained. With the value of $N_{pp} \times \lambda_{pp} = 4$ and efficiency $\varepsilon_{det} = 0.992$ and $\varepsilon_{\Delta E} = 0.176$, it results in the restriction $\tau_{pp} = 5.5 \times 10^{23}$ yr with 90% C.L. The corresponding $^{127}_{52}$Te distribution is shown in Fig. 1.

To obtain the limit on the area under the $^{127}_{54}$Xe distribution (Fig. 2), we have fitted the experimental energy spectrum of the LXe scintillator in the energy range 150–315 keV (where the bigger peak in the $^{127}_{54}$Xe model is located) by the sum of a simplified background model (an exponential behaviour) and of the peak due to the $^{127}_{54}$Xe decay. From the fit (χ^2/d.o.f. $= 0.73$), the area under the full $^{127}_{54}$Xe distribution has been obtained to be equal to -4.2 ± 9.3, giving no evidence for the effect searched for. Then, the number of excluded events at 90% C.L. has been calculated in accordance with the Feldman–Cousins procedure [27] recommended by the Particle Data Group [8] as $S_{\Delta E} = 11.5$, giving (with the value of $N_{nn} \times \lambda_{nn} = 9$) the life-time limit $\tau_{nn} = 1.2 \times 10^{25}$ yr at 90% C.L. The fitting curve and the excluded peak are shown in the inset of Fig. 1. All values for excluded numbers of events $S_{\Delta E}$ and obtained limits on N and NN life-times are summarized in Table 2.

4. Conclusion

Using the approach, in which a decay of isotopes created after a nucleon or di-nucleon disappearance in parent nuclei is searched for, the new limits on the N and NN decay into invisible channels have been set: $\tau_p = 1.9 \times 10^{24}$ yr, $\tau_{nn} = 1.2 \times 10^{25}$ yr and $\tau_{pp} = 5.5 \times 10^{23}$ yr at 90% C.L. We can compare the obtained restrictions with those previously available in literature.

The limit on the proton life-time is lower than that obtained in geochemical search ($\tau(p \to 3\nu) > 7.4 \times 10^{24}$ yr [15]) and in radiochemical experiment ($\tau(p \to 3\nu) > 1.1 \times 10^{26}$ yr [16,17]), however it is better than τ_p limits determined on the basis of ^{232}Th spontaneous fission ($\tau(N \to ?) > 3 \times 10^{23}$ yr [13]) and in the search for p decay in deuterium ($\tau(p \to ?) > 3 \times 10^{23}$ yr [14]).

For the processes with $\Delta B = 2$, only two limits were known previously: $\tau(nn \to \nu_e \overline{\nu}_e) > 1.2 \times 10^{25}$ yr and $\tau(nn \to \nu_\mu \overline{\nu}_\mu) > 6.0 \times 10^{24}$ yr at 90% C.L. [10]. Thus our limit for $\nu_e \overline{\nu}_e$ decay is the same as that in [10], and restriction for $\nu_\mu \overline{\nu}_\mu$ is better. The limit for the decay on $\nu_\tau \overline{\nu}_\tau$ is determined for the first time in the present work. It should be also noted that our limits are valid not only for the NN decays to neutrinos (which should fire in the following the detector as in [10]) but also for their disappearance into "nothing". The last possibilities were discussed in [4,5] as a consequence of possible existence of extra timelike dimensions.

The approach used in the present study — search for the decay of daughter nuclides after the N or NN decay in parent nuclei real-time with the help of low-background detector operating deep underground — seems to be promising, especially if one reminds that the competitive limits were obtained here with detector of modest mass ($\simeq 6.5$ kg LXe) with respect to 700 t of iron in the Fréjus detector and 680 t of water in the Kamiokande detector.

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