Search for rare processes with DAMA/LXe at Gran Sasso

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Abstract

The main features of the DAMA liquid Xenon (DAMA/LXe) set-up of the DAMA experiment and some of the more recently achieved results are summarized.

1 The experimental set-up

The DAMA/LXe experiment has realized several prototype detectors and, then, has preliminarily put in measurement the set-up used in the data taking of ref. [1, 2]; this was upgraded at fall 1995 as mentioned in ref. [3, 4, 5, 6, 7].

The inner vessel contains $\simeq 6.5$ kg (i.e. $\simeq 2$ l volume) of liquid Xe. It has previously been filled with Kr-free Xenon enriched in ^{129}Xe at 99.5% [8]; in 2000 the set-up was again deeply modified reaching the configuration reported in fig. 5 of ref. [8] to handle also Kr-free Xenon enriched in ^{136}Xe at 68.8% [9, 10]. In this latter case, the interest has mainly been focused on the higher energy region having identified the possibility to perform high energy calibrations with external sources near a flange located on the top of the detector opening a limited upper part of the external shield.

Some main features of the set-up, which has been described in details in ref. [8], are summarized in the following. The inner vessel, which contains the liquid Xenon, is made by OFHC low radioactive copper (≤ 100 μBq/kg for U/Th and ≤ 310 μBq/kg for K) and its shape largely ensures both the absence of dead spaces and an efficient light collection [8]. The scintillation light is collected by three photomultipliers (PMTs) – working in coincidence – having MgF_2 windows. They are housed in the insulation vacuum and are fully surrounded by low radioactive Cu for an efficient shielding. The measured quantum efficiency of the PMTs for normal incidence has a flat behaviour around the LXe scintillation wavelength ($\simeq 178$ nm); its value can range between 18% and 32%, depending on PMT. The PMTs collect the scintillation light through three windows (10 cm in diameter) made of special cultured crystal quartz (total transmission of the LXe ultraviolet scintillation light is $\gtrsim 80\%$, including

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the reflection losses). The passive multilayer shield is composed of 5-10 cm of low radioactive copper inside the vacuum insulation vessel, 2 cm of steel (wall of the insulation vacuum vessel), 5-10 cm of low radioactive copper, 5 cm of Polish lead and 10 cm of Boliden lead, $\simeq$1 mm of Cadmium and $\simeq$10 cm of polyethylene. Most of the detector (including the Xe) and shield materials have been kept deep underground for about 10 years. The environmental Radon nearby the detector is removed by continuous flushing of a high purity Nitrogen gas from bottles stored underground since a long time. An external plexiglas box encloses the whole set-up during the production runs and is maintained also in high purity Nitrogen atmosphere, offering an additional Radon protection.

Each PMT is connected with a low noise preamplifier and for every event the amplitude and shape of the sum pulse is recorded with the help of a LeCroy transient digitizer. Further details on the data acquisition, on the cryogenic and vacuum systems and on the running parameters control can be found in [6, 7, 8, 10].

Finally, as mentioned, the energy scale in the high energy region is determined with the help of external standard gamma sources; the typical response of the detector in this energy region has been shown in fig. 1 of ref.[10], where the energy resolution for ^{208}Tl line ($E_\gamma = 2614$ keV) is $\sigma \simeq 220$ keV. For ^{137}Cs line ($E_\gamma = 662$ keV), which is the source usually exploited for the routine calibrations, σ yields $\simeq 70$ keV [10].

2 Summary of main results already achieved in searches for various rare processes

We pointed out the interest in using liquid Xenon as target-detector for particle dark matter search deep underground since ref. [11].

After preliminary measurements both on elastic and inelastic WIMP-^{129}Xe scattering [1, 3], the recoil/electron light ratio and pulse shape discrimination capability in a similar pure LXe scintillator have been measured both with Am-B neutron source and with 14 MeV ENEA-Frascati neutron generator [6]. Moreover, in 2000/2001 further measurements on the recoil/electron light ratio with 2.5 MeV ENEA-Frascati neutron generator have also been carried out; see ref. [5] for details and comparisons. Fig. 1 summarizes the measured values.

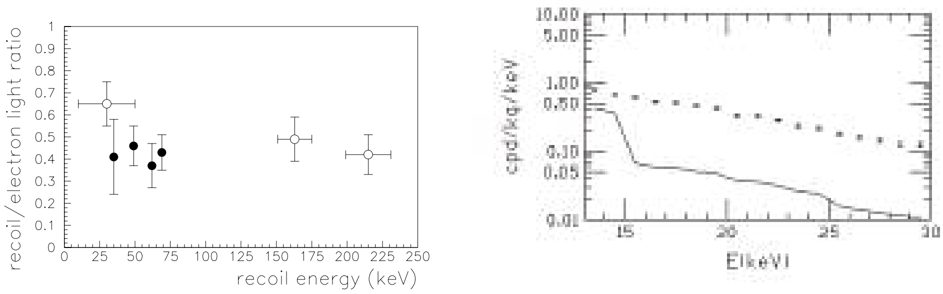

Figure 1: Figure on the left: measured behaviour of the recoil/electron light ratio as a function of recoil energy. Note that the energy of the data point (the open circle at lower energy) obtained with Am-B neutron source is an average which refers also to much lower energies than those explored with the 2.5 MeV neutrons (filled circles); for details see ref. [5, 6]. Figure on the right: low energy distribution (statistics of 1763.2 kg $\cdot$ day – DAMA/Xe-2 period, see ref. [6]) collected with the vessel filled by ^{129}Xe; the continuous line represents the upper limits at 90% C. L. obtained for the recoil fractions by exploiting the Pulse Shape Discrimination technique.

After some preliminary upgrading of the LXe set-up, new results on the WIMP search have been obtained [4, 6]. In particular, in ref. [6] pulse shape discrimination between the recoils and electromagnetic background in pure LXe scintillators has been exploited (see Fig. 1), achieving a significant sensitivity both for spin-independent and spin-dependent coupled WIMPs.

Afterwards the inelastic excitation of ^{129}Xe by Dark Matter particles with spin-dependent coupling, preliminarily searched for in ref. [3], has been further investigated in ref. [4].

Several other rare processes have also been investigated by means of the detector filled with the Kr-free Xenon gas enriched in ^{129}Xe. In particular, as regards the electron stability, limits on the lifetime of the electron decay in both the disappearance and the $\nu_e + \gamma$ channels were set in ref. [2]. The latter has been more recently improved up to: $2.0(3.4) \cdot 10^{26}$ y at 90% (68%) C.L. [12]. Furthermore, new lifetime limits on the charge non-conserving electron capture with excitation of ^{129}Xe nuclear levels have also been established to be in the range $(1-4) \cdot 10^{24}$ y at 90% C. L. for the different excited levels of ^{129}Xe [13]. The stringent restrictions on the relative strengths of charge non-conserving processes have been consequently derived: $\epsilon^2_W < 2.2 \cdot 10^{-26}$ and $\epsilon^2_\gamma < 1.3 \cdot 10^{-42}$ at 90% C. L. [13].

Moreover, we have searched for the nucleon and di-nucleon decay into invisible channels [14] by exploiting a new approach. In fact, the radioactive daughter nuclei, created after the nucleon or di-nucleon disappearance in the parent nuclei, have been investigated [14]. This approach has the advantage of a branching ratio close to 1 and – if the parent and daughter nuclei are located in the detector itself – also of an efficiency close to 1. The obtained limits at 90% C.L. are: $\tau(p \rightarrow$ invisible channel$) > 1.9 \cdot 10^{24}$ y; $\tau(pp \rightarrow$ invisible channel$) > 5.5 \cdot 10^{23}$ y and $\tau(nn \rightarrow$ invisible channel$) > 1.2 \cdot 10^{25}$ y. These limits are similar or better than those previously available; the limits for the di-nucleon decay in $\nu_\tau \bar{\nu}_\tau$ have been set for the first time; moreover, these limits are valid for every possible disappearance channel [14].

Finally, measurements have been carried out by using the Kr-free Xenon gas containing 17.1% of ^{134}Xe and 68.8% of ^{136}Xe. The data collected over 8823.54 hours have been considered to investigate the ^{134}Xe and ^{136}Xe double beta decay modes. After the preliminary results of ref. [9, 15] a joint analysis of the $0\nu\beta\beta$ decay mode in ^{134}Xe and in ^{136}Xe as suggested in ref. [16] has been carried out. In principle, this kind of analysis could improve the information obtained when separately studying the two isotopes. In Fig. 2 the data collected in the $(0.55-3.55)$ MeV energy region is shown. New limits on various $\beta\beta$ decay modes have been obtained: for the $0\nu\beta\beta(0^+ \rightarrow 0^+)$ decay mode in

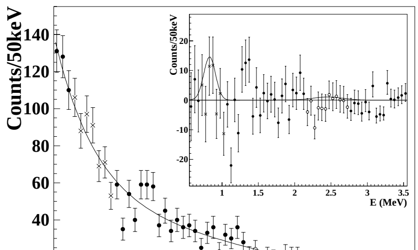

Figure 2: Experimental data (crosses, filled and open circles) with superimposed the background contribution (continuous line). In the inset: the residuals as a function of the energy; the gaussian peaks represent the expected signals for the $0\nu\beta\beta(0^+ \rightarrow 0^+)$ decay mode in ^{134}Xe and in ^{136}Xe when $T_{1/2} = 5.8 \cdot 10^{22}$ y and $T_{1/2} = 1.2 \cdot 10^{24}$ y, respectively. For details see ref. [10]

^{134}Xe and in ^{136}Xe the limits at 90% C.L are $T_{1/2} = 5.8 \cdot 10^{22}$ y and $T_{1/2} = 1.2 \cdot 10^{24}$ y, respectively; they correspond to a limit value on *effective light Majorana neutrino mass* ranging from 1.1 eV to 2.9 eV (90% C.L.), depending on the adopted theoretical model. For the neutrinoless double beta decay with Majoron (M) the limit is $T_{1/2} > 5.0 \cdot 10^{23}$ y (90% C.L.); for the $2\nu\beta\beta(0^+ \rightarrow 0^+)$ and the $2\nu\beta\beta(0^+ \rightarrow 2^+)$ decay modes in ^{136}Xe the limits at 90% C.L. are $1.0 \cdot 10^{22}$ y and $9.4 \cdot 10^{21}$ y, respectively. It is worth to note that the experimental limit on the $2\nu\beta\beta(0^+ \rightarrow 0^+)$ decay mode is in the range of the theoretical estimate by [17] ($2.11 \cdot 10^{22}$ y) and about a factor 5 higher than that of ref. [18] [c].

3 New results

The data collected during 8823.54 hours with the $\simeq 6.5$ kg LXe scintillator enriched in the ^{136}Xe isotope – already published and used for other rare event searches (see before) [10] – have also been considered to search for: i) charge non-conserving decay of ^{136}Xe into ^{136}Cs; ii) the nucleon and di-nucleon decay into invisible channels of the ^{136}Xe isotope.

In the following, we briefly outline some aspects and the relative results.

3.1 The search for charge non-conserving decay of ^{136}Xe into ^{136}Cs

A search for the charge non-conserving decay of ^{136}Xe into ^{136}Cs has been performed for the first time [7], using the data collected during 8823.54 hours and already published in ref. [10].

The approach used here is the investigation of the CNC processes by the search for the possible CNC decay firstly considered in [19]: if in a β decay $(A, Z) \rightarrow (A, Z+1) + e^- + \overline{\nu}_e$ some massless uncharged particle would be emitted instead of the electron (e.g., ν_e or γ or Majoron), an additional 511 keV energy release would occur. Thus, usually forbidden decays to the ground state or to the excited levels of the daughter nuclei would become energetically possible. The presence of the $(A, Z+1)$ isotope or of its daughter products in a sample, initially free from them, would indicate the existence of the CNC decay searched for. In particular, large advantages arise when the so-called "active-source" technique (source = detector) is considered as in the case described here.

In particular, after the possible ^{136}Xe CNC decay, the daughter nucleus ^{136}Cs will be created. It is β unstable ($T_{1/2} = 13.16$ d) with quite high energy release ($Q_\beta = 2.548$ MeV) [7].

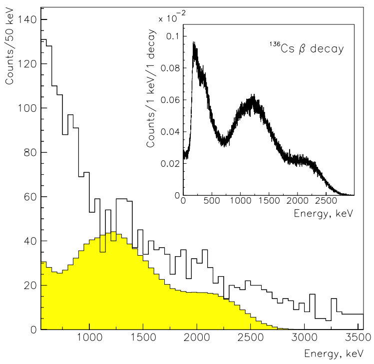

Figure 3: Experimental energy distribution measured during 8823.54 h by the $\simeq 6.5$ kg LXe detector in the 550–3550 keV interval (thick histogram). Inset: the expected response function of the LXe detector for ^{136}Cs β decay. The shaded histogram in the main part corresponds to the CNC decay of ^{136}Xe into ^{136}Cs with $\tau_{CNC} = 1.3 \cdot 10^{22}$ y excluded at 90% C.L. in the most conservative approach.

The simulated response function of the ^{136}Cs β decay is shown in the inset of Fig. 3. Comparing the experimental energy distribution with the expected response function, no evidence for the effect searched for has been found. Thus, the life-time limit[d] is:

$$\tau_{CNC}(^{136}\mathrm{Xe} \rightarrow ^{136}\mathrm{Cs}) > 1.3 \cdot 10^{23} \text{ y at 90\% C.L.}$$

[c] On the other hand, similar theoretical estimates suffer of the large uncertainties typically associated to the calculations of the nuclear matrix elements.

[d] Close results were also obtained by exploiting other procedures for data analysis.

The found $\tau_{CNC}(^{136}\text{Xe}\rightarrow^{136}\text{Cs})$ limit is one of the highest available limit for similar processes [7]; however, the bound on the charge non-conserving admixture in the weak interactions which can be derived, according to ref. [20] is modest mainly due to the high degree of forbiddeness of the considered CNC transition.

3.2 The search for nucleon and di-nucleon decay into invisible channels in ^{136}Xe

The same data used for the analyses described before [7, 10] (8823.54 h of measurements) have been considered to investigate possible nucleon and di-nucleon decays into invisible channels for the ^{136}Xe isotopes: disappearance or decay to neutrinos, Majorons, etc.

The approach, exploited in [14] at the first time, consisted in a search for radioactive decay of unstable daughter nuclei created as result of the N or NN disappearance in parent nucleus. If half-life of the daughter nucleus is of order of 1 s or greater, such a decay will be time-resolved from prompt products if they were emitted and observed in a detector. Here, in contrast with our previous experiment when the set-up was filled in ^{129}Xe at 99.5%, the set-up has been filled with the Xenon enriched in ^{136}Xe at 68.8%; this gives possibility to investigate in addition the case of the np disappearance not studied previously.

After the disappearance of one or two nucleons in the parent ^{136}Xe nucleus, the following nuclei will be created inside the sensitive LXe volume: ^{135}Xe (n decay); ^{135}I (p decay); ^{134}Xe (nn decay); ^{134}I (np decay); ^{134}Te (pp decay). Since the ^{134}Xe nucleus is stable, it is not possible to search for the nn disappearance in this case. The simulated response functions for each channel has been evaluated; for

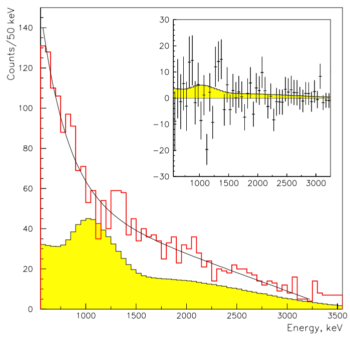

Figure 4: Experimental spectrum measured during 8823.54 h (thick histogram). The shaded histogram is the response function for the chain of β decays ^{134}Te + ^{134}I which corresponds to the pp disappearance with $\tau_{pp} = 2.1 \cdot 10^{23}$ y excluded at 90% C.L. in the most conservative approach. In the inset the residuals between the experimental spectrum and the background fit are shown (points with error bars) together with excluded ^{134}Te + ^{134}I distribution for $\tau_{pp} = 1.9 \cdot 10^{24}$ y (shaded histogram).

example, Fig. 4 shows the response function for the chain of β decays ^{134}Te + ^{134}I which corresponds to the pp disappearance with $\tau_{pp} = 2.1 \cdot 10^{23}$ y excluded by the data at 90% C.L. even considering the most conservative approach.

Comparison of the experimental spectrum (see Fig.4) with the calculated response functions gives no indication for the β decays of the nuclides created in result of the N and NN disappearance in ^{136}Xe. Thus only the limits on the probability of these processes have been extracted: $\tau_n > 3.3 \cdot 10^{23}$ y, $\tau_p > 4.5 \cdot 10^{23}$ y, $\tau_{np} > 3.2 \cdot 10^{23}$ y and $\tau_{pp} > 1.9 \cdot 10^{24}$ y at 90% C.L. These restrictions are valid for any "invisible" channel in which nucleons or di-nucleons disappear (e.g. into extra dimensions) or decay emitting some weakly interacting particles which do not destroy the daughter nucleus (neutrinos of any flavours, Majorons, etc.).

The values for τ_n and τ_p are lower than those given by other experiments, while the τ_{pp} limit is near 3 times higher than that obtained in our measurements with ^{129}Xe: $5.5 \cdot 10^{23}$ y [14] (however, it is lower than the value declared recently by the BOREXINO Collaboration, $\tau_{pp} > 5.5 \cdot 10^{25}$ y [21]). Finally, the τ_{np} limit has been determined here for the first time.

4 Conclusions

The DAMA/LXe set-up has been improved with time passing and has allowed to achieve competitive results in the searches for various rare processes. Further data taking is foreseen.

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