THE DAMA/LXE EXPERIMENT AT GRAN SASSO: RECENT PERFORMANCES AND RESULTS

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The DAMA liquid Xenon set-up (DAMA/LXe) is a low background apparatus consisting of 6.5 kg of Kr-free liquid Xenon enriched either in ^{136}Xe or in ^{129}Xe. It has collected data in various configurations investigating several rare processes. In this paper the results achieved so far are briefly summarized and the description of recent upgrades and data taking periods are addressed. Perspectives of reachable sensitivities for some rare processes with new exposure are mentioned.

1. DAMA/LXe set-up

The DAMA/LXe experiment is running in the Gran Sasso underground laboratory of the INFN. The main features of the set-up are described in details in ref. [1].

After having realized several prototype detectors, the DAMA/LXe set-up started measurements with the data taking of refs. [2, 3]. With time passing various upgrades to improve its performances and sensitivity have been carried out and Kr-free Xenon enriched in ^{129}Xe at 99.5 % was also provided [1, 4 - 8]. In 2000 the set-up was deeply modified to handle also Kr-free xenon enriched in ^{136}Xe at 68.8 % [8 - 11, 17]. In this latter case, the interest has mainly been focused on the higher energy region for the investigations of ββ decay modes and other rare processes.

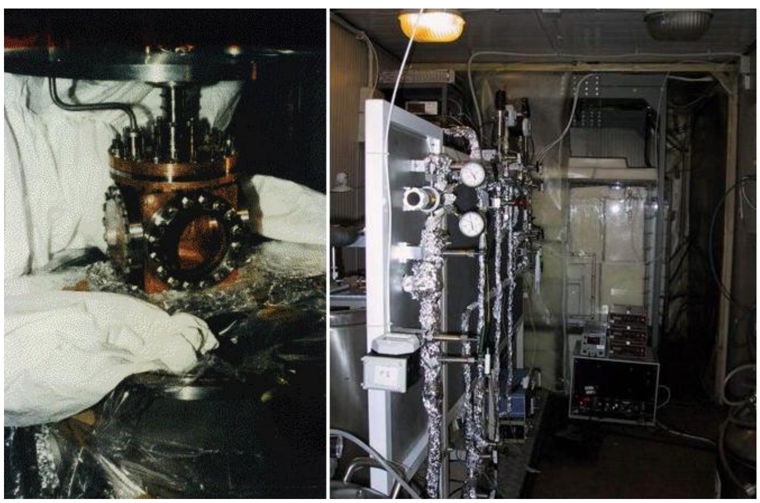

Fig. 1. *Left*: inner Cu vessel of the LXe set-up. *Right*: behind: the shield; in front: the vacuum/purification/filling/recovery system [1].

In 2007 new upgrades have been performed on the water cooling system of the Helium compressor and on the monitoring system of the experiment. As regards the refrigeration system a new chiller has been put in operation. Thus, at present there is a redundant system composed by two chillers and a back-up device to assure continuous operative condition. As regards the monitoring a new data acquisition system for the measurement of all the cryogenic parameters has been integrated with the previously existing one; in particular, a new serial read-out system for the PT100 sensor has been put in operation. The same system also allows the remote control of the voltage supply of the heater superimposed on the cryogenic head in order to obtain suitable temperature for LXe.

In particular, DAMA/LXe set-up is composed by the following parts: (i) the inner vessel, made of highly radiopure OFHC, which has a 2 liters of sensitive volume, corresponding to 6.5 kg of liquid Xenon. To optimize the light collection, the inner sensitive volume has been excavated smoothly and three optical windows, 10 cm in diameter, made of cultured crystal quartz (transparency of about 80% to the UV emission at 178 nm) are viewed by three UV optimized photomultipliers (PMTs); (ii) the external insulation vessel, where the vacuum is made, is a 316 stainless steel cylinder having various vacuum feedthroughs and flanges; there the three photomultipliers are positioned; (iii) a multi-component shield made of 5–10 cm of low radioactive copper inside the vacuum insulation vessel, 2 cm of steel, 5 - 0 cm of low radioactive copper, 5 cm of Polish lead and 10 cm of Boliden lead, about 1 mm cadmium and >10 cm of polyethylene plus paraffin is in operation; (iv) the LEYBOLD cryogenic system constituted by a He compressor drives a one-stadium cold head and a cryopump; a heater and a turbomolecular pump are also operative; (v) a vacuum/filling/purification/recovery system for the Xenon having electropolished 316L stainless steel tubes with VCR fittings and valves is present. An ultra-high vacuum, UHV, (typically not worse than 10^{-6} mbar) is required for the vacuum/filling/purification/recovery line and for the inner vessel, while less stringent requirements are needed for the insulation chamber (typically not worse than 10^{-3} mbar). The insulation vacuum is assured by a turbomolecular pump and read out by a Pirani gauge through a controller. The UHV for the inner vessel and the vacuum/filling/purification/recovery line are firstly produced by a turbomolecular pump and, secondly, by a cryo-pump. The UHV is read out by a Bayard-Alpert gauge through a LEYBOLD module. The stable working temperature of liquid is obtained with a heater directly connected to the cold head. The temperature on the cold head is monitored by a PT100 sensor. The compressor and the turbomolecular pump are water cooled and a correct operation must respect fixed parameters of flux and temperature of the water.

As regards the purification system, during the procedure of gas filling, a cold nitrogen trap is used (working typically at 190 K); it purifies Xe from possible Rn, H_2O and other impurities that condense at this temperature. A Monotorr getter and a getter made of pills, both by SAES, activated at 400°C, reduce impurities to <1 ppb for any component: O_2; N_2; CO, etc.

In the present configuration the set-up can use Kr-free Xenon gas enriched at 99.5 % in ^{129}Xe or, alternatively, Kr-free xenon gas enriched at 68.8% in ^{136}Xe. In fact, two lines of filling/recovery allow the separate use of the two gases.

All the materials composing the set-up have been selected for their low-background characteristics mainly by sample measurements with Ge detector deep underground in the Gran Sasso National Laboratory. Most of the detectors and the shield materials as well as the used Xenon gases have been kept deep underground since many years. Due to the enrichment procedure, giving the separation from Kr, the radiopurity of the gas is greatly increased with respect to natural Xenon.

As regard PMTs, they are 3.5 inches diameter flying leads photomultipliers with magnesium fluoride windows collecting the scintillation light through the cultured crystal quartz optical windows. The photomultipliers used in this experiment were specially realized with the peculiar requirements of UV light collection and maximization of quantum efficiency at the UV wavelength of interest. The PMTs have 10 dynodes with linear focus, their measured quantum efficiency ranges between 18 % and 32 % at the LXe scintillation wavelength with a flat behavior around the light wavelength of interest, they have also good pulse height resolution for single photoelectron pulses, low dark noise rate and a gain of 10^6 - 10^7. The three PMTs work in coincidence at a single photoelectron threshold.

After a long stop due to the forbiddance of using cryogenic liquids and, in particular, the water plant in the Gran Sasso underground laboratory because of the known problems occurred there in August 2002, the data taking has been restarted at the end of 2007, after the mentioned upgrades, by using Xenon enriched in ^{134,136}Xe. Two new periods of data taking have already been carried out in this configuration: the first one started in November 2007 and ended in December 2008, while the second one started in September 2009 and ended in January 2010. Before the second period of data taking some maintenance operations were performed. At the moment we are carrying on some planned maintenances and we are going to start the data taking again in the incoming weeks.

2. DAMA/LXe results

The performances and the low-background features of the DAMA/LXe set-up, in its different configurations, have allowed us to study many topics obtaining competitive results: i) investigations by considering elastic and inelastic scattering of some Dark Matter (DM) candidate particles on ^{129}Xe; ii) several neutron calibrations for quenching factor measurements; iii) investigations on charge non conserving (CNC) processes as nuclear level excitation of ^{129}Xe and possible decay of ^{136}Xe in ^{136}Cs, electron decay; iv) the nucleon and di-nucleon decay into invisible channels in ^{129}Xe, and nucleon, di-nucleon and tri-nucleon decay into invisible channels in ^{136}Xe; v) double beta decay in ^{134}Xe and in ^{136}Xe. In the following, these results will be briefly summarize.

We pointed out the interest in using liquid Xenon as target-detector for DM particle investigation deep underground at end of ‘80 [12], while already in 1996 we pointed out the intrinsic problems in realizing larger detector with good performances.

In the 90’s the recoil/electron light ratio and the pulse shape discrimination capability of the realized LXe scintillator was measured with Am-B neutron source and with 2.5 and 14 MeV ENEA-Frascati neutron generator [6, 7].

Preliminary measurements both on elastic and inelastic DM particles-^{129}Xe scattering were performed in given scenario [2, 4]; then, after upgrading the set-up, some new results on the DM particles investigation have further been obtained [5, 7].

As regard the study of electron stability, limits on the lifetime of the electron decay in both the disappearance and the $\nu_e + \gamma$ channels were set with Xe gas enriched in ^{129}Xe [3]. The latter limit has been more recently improved up to: 2.0 (3.4) $\cdot 10^{26}$ yr at 90 % (68 %) C.L. [13]. Moreover, lifetime limits on the CNC electron capture with excitation of

^{129}Xe nuclear levels have also been established to be in the range (1 - 4) · 0^{24} yr at 90 % C.L. [14] deriving also stringent restrictions on the relative strengths of CNC processes: $\varepsilon^2_W < 2.2 \cdot 10^{-26}$ and $\varepsilon^2_\gamma < 1.3 \cdot 10^{-42}$ (both at 90 % C.L.) [14].

An additional CNC investigation has been performed by using Kr-free Xenon gas enriched in ^{136}Xe [8] searching for a decay (firstly considered in [15]) similar to a β decay (A, Z)→(A, Z + 1) + e^- + $\overline{\nu}_e$ but with the emission of e.g., ν_e or γ or Majoron instead of electron. Having in this case 511 keV energy at disposal, 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 the set-up, after the CNC decay of ^{136}Xe, the daughter nucleus ^{136}Cs will be created. It is β unstable ($T_{½}$ = 13.16 d) with quite high energy release (Q_β = 2.548 MeV). Comparing the experimental energy distribution with the expected response function, no evidence for the effect searched for has been found. By performing different analysis strategy, the life-time limit: $\tau_{CNC}(^{136}Xe \rightarrow ^{136}Cs) > 1.3 \cdot 10^{23}$ yr at 90 % C.L. has been obtained [8]. It is one of the highest available limits for similar processes, and it holds for whatever CNC ^{136}Xe decay with emission of massless uncharged particle (γ, Majoron(s), ν, etc., even some other possible interesting physics which could appear in future).

Nuclear instabilities have been also investigated. In fact, some modern theories of particle physics (GUTs, SUSY) foreseen the decay of the protons and of the otherwise stable bound neutrons. Different mechanisms for nucleon, di-nucleon and also tri-nucleon decay have been proposed in literature, moreover, disappearance of particles (electrons, e^-, or nucleons, *N*) are expected also in theories with extra dimensions. No process with baryon number violation was detected to date. The nucleon instabilities into invisible channel have been investigated both for ^{129}Xe and for ^{136}Xe with a new approach based on the search for the radioactive daughter nuclei, created after the nucleon or di-nucleon or tri-nucleon disappearance in the parent nuclei [16, 17]. This approach assures a high detection efficiency – since the parent and the daughter nuclei are located in the detector itself – and a branching ratio ~ 1 (the obtained results are valid for every possible disappearance channel) with the respect to other different approaches which necessarily should be pursued with very large mass apparatus to compensate the much lower values for those quantities.

As regards the nucleon and di-nucleon decay of ^{129}Xe into invisible channel, the following limits (at 90 % C.L.) have been obtained [16]: $\tau_{(p \rightarrow \text{invisible channels})} > 1.9 \cdot 10^{24}$ yr; $\tau_{(pp \rightarrow \text{invisible channels})} > 5.5 \cdot 10^{23}$ yr and $\tau_{(nn \rightarrow \text{invisible channels})} >$ $> 1.2 \cdot 10^{25}$ yr; they were similar to or better than those previously available and, for example, the limit for the di-nucleon decay in $\nu_\tau \overline{\nu}_\tau$ was set for the first time.

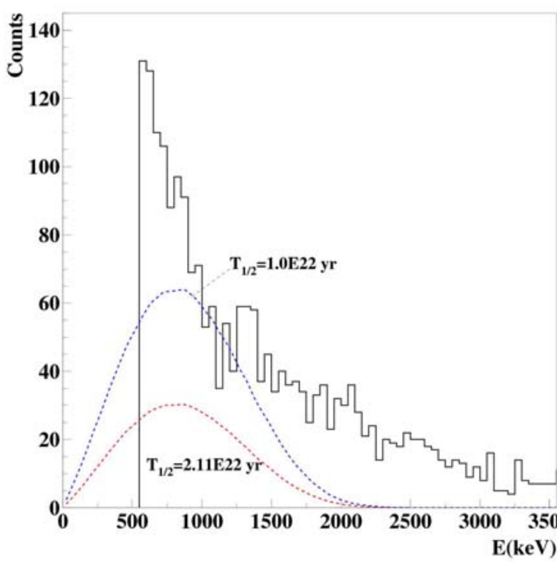

Fig. 2. Comparison between the experimental data (histogram) previously collected during 8823.54 h [10] and the signal expected in the highest theoretical estimate [19] of the half life of the 2νββ decay mode ($T_{1/2} = 2.11 \cdot 10^{22}$ yr, red/dashed line). The blue/dashed curve corresponds to the signal excluded at 90% C.L. in [10] ($T_{1/2} = 1.0 \cdot 10^{22}$ yr).

An additional investigation for the *N*, *NN* and *NNN* instabilities in the ^{136}Xe isotope has also been performed by using the data collected during 8823.54 h by the LXe scintillator, filled with enriched in ^{136}Xe at 68.8%, and using the same experimental approach [17]. In general, the created daughter nucleus – with one, two or three holes in nuclear shells due to disappeared nucleons – will be in an excited state, unless the nucleons were on the outermost shell. The holes will be filled in the subsequent deexcitation process in which different particles could be emitted. The response functions for the *N*, *NN* and *NNN* disappearances have been estimated; we compared the functions with the experimental spectrum. No evidences for the signals searched for have been obtained and only limits on the lifetime of these processes have been set at 90 % C.L. In particular for: **i)** *n* disappearance ($\tau_n > 3.3 \cdot 10^{23}$ yr); **ii)** *p* disappearance ($\tau_p > 4.5 \cdot 10^{23}$ yr); **iii)** *np* disappearance ($\tau_{np} > 4.0 \cdot 10^{22}$ yr); **iv)** *pp* disappearance ($\tau_{pp} > 1.9 \cdot 10^{24}$ yr); **v)** *nnp* disappearance ($\tau_{nnp} > 1.4 \cdot 10^{22}$ yr); **vi)** *npp* disappearance ($\tau_{npp} > 2.7 \cdot 10^{22}$ yr); **vii)** *ppp* disappearance ($\tau_{ppp} > 3.6 \times \times 10^{22}$ yr) [17]. All the achieved limits are valid for every invisible decay channel, including disappearance in extra-dimensions or decay into particles which weakly interact with matter, moreover, NNN decays into invisible channels have been investigated there for the first time.

Measurements to search for double beta decays in Xe isotopes 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 h have been considered to investigate the ^{134}Xe and ^{136}Xe double beta decay modes. After some preliminary results (see e.g. Ref. [9]) a joint analysis of the 0νββ decay mode in ^{134}Xe and in ^{136}Xe has been carried out [10]. In principle, this kind of analysis could improve the information obtained when separately studying the two isotopes. New lower limits on various $\beta\beta$ decay modes have been obtained: for the $0\nu\beta\beta(0^+ \to 0^+)$ decay mode in ^{134}Xe and in ^{136}Xe the limits at 90% C.L are: $T_{½} = 5.8 \cdot 10^{22}$ yr and $T_{½} = 1.2 \cdot 10^{24}$ yr, respectively. The latter corresponds 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: $T_{½} > 5.0 \cdot 10^{23}$ yr (90 % C.L.); for the $2\nu\beta\beta(0^+ \to 0^+)$ and the $2\nu\beta\beta(0^+ \to 2^+)$ decay modes in ^{136}Xe the limits at 90 % C.L. are: $1.0 \cdot 10^{22}$ yr and $9.4 \cdot 10^{21}$ yr, respectively. The experimental limit on the $2\nu\beta\beta(0^+ \to 0^+)$ decay mode is in the range of the theoretical estimates [19, 20].

In the next 2 years, considering the new data collected so far (which are under analysis) as well as the new ones available in future, higher sensitivity for the rare processes mentioned above will be reached. In particular, the following achievements are foreseen for the next years:

Electron decay into invisible channels: the foreseen sensitivity on the lifetime will be least of order of some 10^{24} yr.

Electron decay in the channel $e^- \to \nu_e\gamma$: the foreseen sensitivity on the lifetime will be at least of order of 10^{26} yr; this is an interesting sensitivity also to further study some discrepancy present in literature [21, 22].

Excitation of nuclear levels of ^{129}Xe due to CNC processes: the foreseen sensitivities on the lifetimes will be at least of order of 10^{25} yr, depending on the considered nuclear level.

CNC decay $^{136}\text{Xe} \to {}^{136}\text{Cs}$: the sensitivity on the lifetime of this CNC process will be improved at least up to some units in 10^{23} yr, in such a case one of the highest sensitivity for similar processes will be reached.

Nucleon, di-nucleon and tri-nucleon decay of ^{129,136}Xe into invisible channels: the sensitivity on the lifetime will be improved at least of one order of magnitude.

2β decay in ^{136}Xe: the limit on the half-life of $0\nu\beta\beta(0+\to0+)$, already obtained by DAMA/LXe is one of the best limits achieved in this field. The sensitivity on the half-life can be improved at level of $T_{1/2} \approx 2.2 \cdot 10^{24}$ yr at 90 % C.L. Moreover, improvements of at least about a factor 2 in the sensitivity to the channels with neutrinos and with Majoron emission will be reached. Furthermore, since the previously obtained limit on the $2\nu\beta\beta(0^+\to0^+)$ decay mode was already in the interval of interest for the detection, the new data will be very important. In fact, by analyzing the data in the energy region (0.55 - 3.55) MeV we can improve the sensitivity at least up to a factor about 2. In addition, even higher sensitivity will be achieved by extending the energy region considered in the data analysis below 0.50 MeV where a significant part of the signal is expected (see Fig. 2). In this case, all the theoretical estimations of the half life for the process will be tested.

2β decays in the ^{134}Xe isotope: the sensitivity on the half-life of the $0\nu\beta\beta(0^+\to0^+)$ decay mode will be improved at least up to some times 10^{23} yr (90 % CL). Moreover, also in this case improvement of about a factor 2 in sensitivity for the decay modes with neutrinos and with emission of Majoron can be achievable.

New combined analysis of the 2β decay modes in ^{134}Xe and ^{136}Xe isotopes will also be performed with sensitivity for detection of some channels.

3. Conclusions

Performances, results and future perspectives of the DAMA/LXe apparatus have shortly been addressed. In particular several new results on different rare processes with increased sensitivity will soon be achievable. At present the analysis of the data collected during the new data taking periods is in progress; new results with partial exposure will be released in near future.

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