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SEARCHES FOR RARE PROCESSES BY DAMA AT GRAN SASSO

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DAMA is an observatory for rare processes based on the development and use of various kinds of radiopure scintillators. Several low background set-ups have been realized at the Gran Sasso National Laboratory of INFN and many rare processes have been investigated. Some of them will be summarized here with particular care to searches for ββ decays in several isotopes, for charge-non-conserving (CNC) processes, for nucleon instabilities into invisible channels with a new approach, for superdense nuclear states, for cluster decays, etc.

1. Introduction

DAMA is an observatory for rare processes based on the development and use of various kinds of radiopure scintillators. The main experimental set-ups are: i) the ~ 100 kg radiopure NaI(Tl) set-up, DAMA/NaI, which has completed its data taking in July 2002; ii) the new 250 kg radiopure NaI(Tl) DAMA/LIBRA set-up, in data taking since March 2003; iii) the ~ 6.5 kg liquid Xenon (LXe) pure scintillator; iv) the R&D installation for tests on prototypes and small scale experiments; v) the low background DAMA/Ge detector for sample measurements.

2. Searches for rare processes with DAMA/NaI

The ~100 kg high radiopure NaI(Tl) set-up DAMA/NaI has been mainly devoted to the investigation of Dark-Matter particle in the galactic halo (see [1 - 4] and references therein), but has also investigated several other rare processes such as e.g. [5 - 7]. In particular, in ref. [5] data collected in the tens MeV energy region have been used to investigate possible spontaneous emission of protons due to violation of the Pauli exclusion principle. Moreover, very competitive limits on the electron decay into invisible channels ($\tau >$ $> 2.4 \cdot 10^{24}$ yr at 90 % C.L. [6]) and on the CNC electron capture with excitation of ^{127}I and ^{23}Na nuclear levels have also been established to be in the range $(1.5 - 2.4) \cdot 10^{23}$ yr (90 % C.L.) [7].

DAMA/NaI has also provided several other searches in the astroparticle field, as: for neutral SIMPs [8], for neutral nuclearites [8], for Q-balls [9] and for solar axions [10].

Here, we just mention two more recent investigations [11, 12]. In fact, an exposure of 33834 kg · day collected by DAMA/NaI have been analyzed to investigate the possible existence of superdense nuclear states [11] and possible cluster decays of ^{127}I [12].

In particular, a transition to a possible superdense state can occur if the energy of a nucleus as a function of its density, E(ρ), has a second minimum for $\rho = \rho_s > \rho_0$ (where ρ_0 is the average nuclear density). To realize the density transition $\rho_0 \rightarrow \rho_s$, it must be overcome a potential barrier U_0 whose shape and height cannot be reliably predicted on the basis of the present knowledge. In this framework a nucleus (or a part of a nucleus) can be metastable with a lifetime τ and spontaneously can go over to the superdense state (for details see ref. [11] and references therein). A simple model, allowing to connect U_0, τ, ρ_0 and ρ_s, can be considered; for example, according to ref. [13], the relation

$$U_0(\mathrm{MeV}) = 7.2 \cdot 10^4 A^{-\frac{5}{3}} \left(1 + \frac{1}{55} \cdot \ln \frac{\tau}{10^{20} y}\right) \left[1 - \sqrt[3]{\frac{\rho_0}{\rho_s}}\right]^{-2}$$

can be written.

The used experimental approach has been similar to the one previously exploited in ref. [14], where characteristic γ-radiation, accompanying the occurrence of the transition searched for in NaI(Tl), has been looked for. In particular, we have considered a possible transition of Sodium and Iodine nuclei to a superdense state, releasing a ΔE larger than 10 MeV through γ radiation. Thus, the data have been analyzed searching for events with multiplicity larger than or equal to two and with total released energy, ΔE, larger than 10 MeV. The required features have been satisfied by 1551 events in the given exposure; these events can largely be ascribed to background due to high energy muons surviving the mountain shielding.

Thus, a cautious approach has been considered in order to obtain the lifetime lower limits (90 % C.L.) for ^{23}Na and ^{127}I nuclei – as a function of ΔE – depicted in Fig. 1 – left panel in the range (15 – 90) MeV. From these restrictions, one can derive lower limits for the barrier potential, U_0, as reported for the ^{23}Na and ^{127}I nuclei in Fig. 1 – right panels.

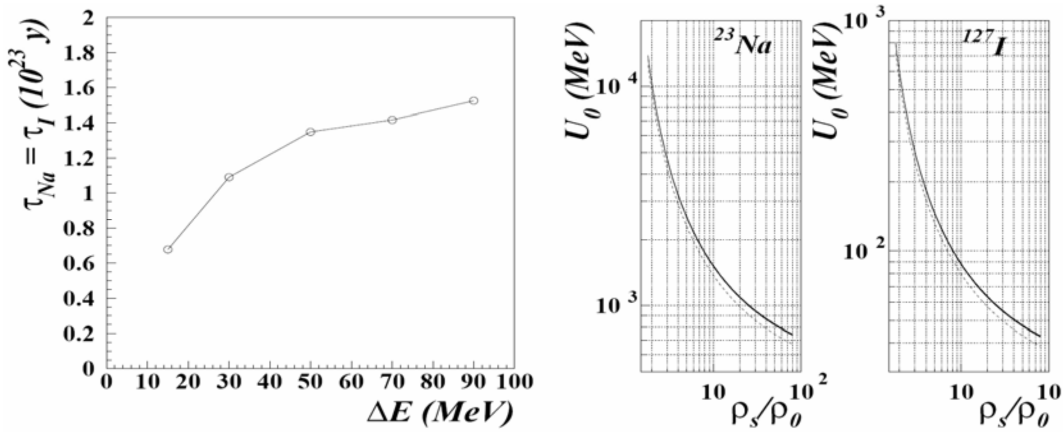

Fig. 1. *Left panel:* obtained lifetime lower limits (90 % C.L.) on the considered process in ^{23}Na and ^{127}I nuclei as a function of the energy release, ΔE. *Right panels*: obtained lower limits (90 % C.L.) on the barrier potential, U_0, as for the ^{23}Na and ^{127}I nuclei (continuous lines); the behaviors for the various energy releases are practically indistinguishable. The dashed lines are the lower limits for U_0 as calculated from the previous best limits in ref. [14]. We note that, although the restriction on τ is increased of about 3 orders of magnitude (thanks to the deeper experimental site, to the much larger exposure, to the effective shielding of the detectors and to the strong improvements in the detectors' radiopurity, occurred during the last decades), the restriction on U_0 is modestly increased because of the logarithmic dependence.

As regards the investigation of cluster decay in NaI(Tl), one can find that 215 different decay modes are possible for ^{127}I with positive energy release Q. However, probably the most interesting ones are those with emission of double magic nucleus ^{48}Ca and its neighbor ^{49}Sc: they have the highest Q values of 28.9 and 29.4 MeV, respectively. Other possibilities, investigated in this work, lie in the region close to ^{100}Sn (for details see [12] and references therein).

Table 1. **Summary of the $T_{1/2}$ limits (at 90 % C.L.) obtained for the investigated cluster decay modes in ^{127}I. The obtained limits allow excluding application of some semi-empirical formulae for cluster radioactivity in investigated nuclear region (such as e.g. those of ref. [15])**

Process	Lower limit of the lifetime (90% C.L.) (y)
$^{127}_{53}I \rightarrow ^{30}_{12}Mg + ^{97}_{41}Nb$	2.1×10^{24}
$^{127}_{53}I \rightarrow ^{34}_{14}Si + ^{93}_{39}Y$	5.5×10^{22}
$^{127}_{53}I \rightarrow ^{24}_{10}Ne + ^{103}_{43}Tc$	1.4×10^{23}
$^{127}_{53}I \rightarrow ^{28}_{12}Mg + ^{99}_{41}Nb$	2.0×10^{22}
$^{127}_{53}I \rightarrow ^{32}_{14}Si + ^{95}_{39}Y$	3.0×10^{21}
$^{127}_{53}I \rightarrow ^{49}_{21}Sc + ^{78}_{32}Ge$	2.8×10^{21}
$^{127}_{53}I \rightarrow ^{48}_{20}Ca + ^{79}_{33}As$	6.8×10^{21}

In Table 1 the summary of the investigated cluster decay modes and the experimental lower limits sets on $T_{1/2}$ are reported.

DAMA/NaI has completed its data taking in July 2002 and has been replaced by the new more radiopure ~250 kg NaI(Tl) set-up, named DAMA/LIBRA, now running.

3. Searches for rare processes with DAMA/LXe

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 refs. [16, 17]. This set-up (having Cu inner vessel filled by ≈ 6.5 kg (i.e. ≈ ≈ 2 l) of liquid xenon) was firstly upgraded in fall 1995 and, then, several other times, [18 - 23]. Firstly it used Kr-free xenon enriched in ^{129}Xe at 99.5 % [16 - 19, 21, 23, 27 - 31]; then, in 2000 the set-up was deeply modified reaching the configuration in Fig. 5 of ref. [23] to handle also Kr-free xenon enriched in ^{136}Xe at 68.8 % [22, 24, 25, 32]. In this latter case, the interest has mainly been focused on the higher energy region for ββ investigations. The main features of

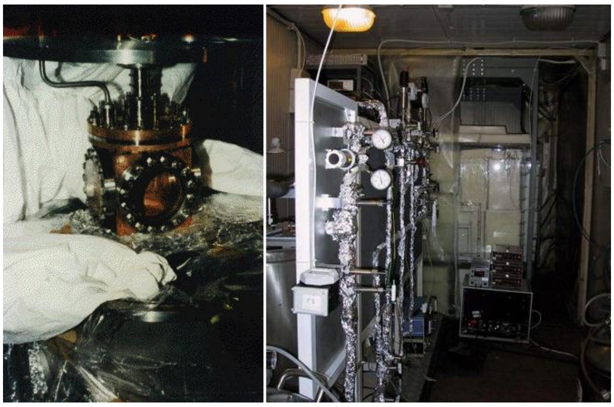

Fig. 2. *Left panel*: inner Cu vessel of the LXe set-up. *Right panel*: behind: the shield; in front: the vacuum/purification/filling/recovery system [23].

the experimental set-up (Fig. 2), details on the data acquisition, on the cryogenic and vacuum systems and on the running parameters control, etc. are described in refs. [21 - 23, 25, 26].

Let us remind at first that we pointed out the interest in using liquid xenon as target-detector for particle Dark Matter (DM) investigation deep underground since long time [27]. 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 [21]. 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. [20] for details and comparisons.

A preliminary measurement both on elastic and inelastic DM particles-^{129}Xe scattering was taken into account in refs. [16, 18] in a given model framework, then, after upgrading of the LXe set-up, new results on the DM particles investigation have been obtained [19, 21]. In particular, in ref. [21] pulse shape discrimination between recoils and electromagnetic component of the measured counting rate in the developed pure LXe scintillator has been exploited. Afterwards the inelastic excitation of ^{129}Xe by DM particles with spin-dependent coupling has further been investigated in the same framework as in ref. [19].

In the following we just summarize some of the many searches for rare processes performed by DAMA/LXe.

3.1 Results on CNC processes with DAMA/LXe

The conservation of the electric charge, which is related with a gauge invariance and masslessness of a photon in accordance with the Weinberg theorem, is considered as an absolute law in the standard quantum electrodynamics. Nevertheless, the possibility of CNC phenomena has widely been discussed in the literature (see [22] and references therein) mainly in connection with future unified theories and with the possible existence of extra dimensions.

Several rare processes have been searched for by means of the detector filled with the Kr-free Xenon gas enriched in ^{129}Xe or ^{136}Xe. In particular, 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 [17]. The latter limit has been more recently improved up to: 2.0 (3.4) $\cdot 10^{26}$ yr at 90 % (68 %) C.L. [28]. Furthermore, new 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) × × 10^{24} yr at 90 % C.L. [29] 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.) [29].

An additional investigation has been recently performed using Kr-free Xenon gas enriched in ^{136}Xe [22]. The searched CNC decay (firstly considered in [30]) is similar to a β decay $(A, Z) \rightarrow (A, Z + 1) + e^- + \overline{\nu}_e$ but some massless uncharged particle would be emitted instead of the electron (e.g., ν_e or γ or Majoron), hence an additional 511 keV energy is at disposal. 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_β = 2.548 MeV). The simulated response function of the ^{136}Cs β decay is shown in the left inset of Fig. 3. Comparing the experimental energy distribution with the expected response function, no evidence for the effect searched for has been found. As a first step, the limit on the amplitude of the ^{136}Cs β decay can be determined by exploiting a very cautious and simple approach, just demanding that the signal cannot exceed the experimental energy distribution in any region (see Fig. 3 left). After, a more realistic strategy consisting in a widely considered two-steps procedure has been applied: (1) the background in an appropriate energy region of the signal is extrapolated from the neighboring regions; (2) the amplitude of the signal is estimated using the residuals in the signal region.

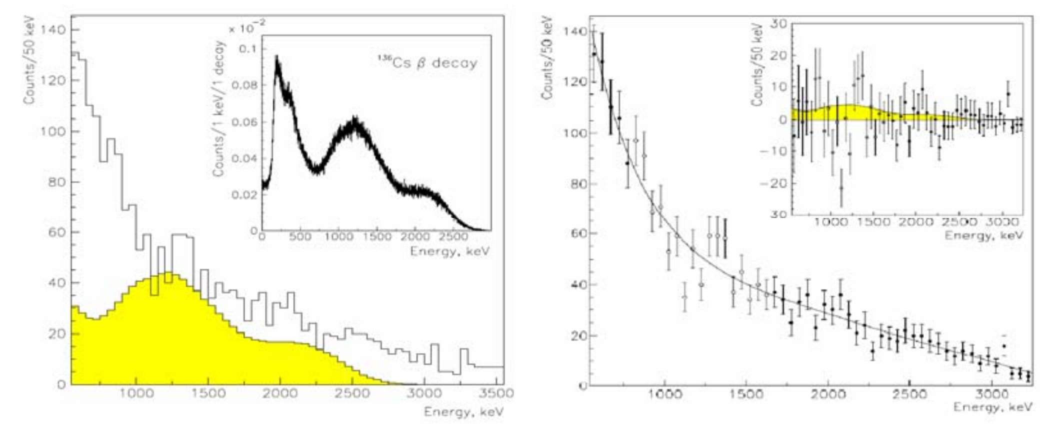

Fig. 3. *Left panel*: Experimental energy distribution measured during 8823.54 h by the ≈ 6.5 kg LXe detector in the 550 - 3550 keV interval (thick histogram). Inset: the expected response function of the LXe detector for ^{136}Cs β decay. The shaded histogram in the main part corresponds to the CNC decay of ^{136}Xe into ^{136}Cs with $\tau_{CNC} = 1.3 \cdot 10^{22}$ yr excluded at 90 % C.L. in the most conservative approach [22]. *Right panel*: The same data are shown as circles with error bars together with fit by the background model (continuous line). Experimental points, excluded from the background fit, are shown as open circles. *Inset*: residuals between the experimental spectrum and the background fit (circles) and 90 % C.L. excluded distribution of the CNC decay of ^{136}Xe into ^{136}Cs with $\tau_{CNC} = 1.3 \cdot 10^{23}$ yr (shaded histogram) [22]. This limit holds for whatever CNC ^{136}Xe decay with emission of massless uncharged particle (γ, Majoron(s), ν, etc., even some other interesting physics which could appear in future).

The background model has been described by the sum of an exponential and a straight line (other parameterizations gave similar results). The fit of the experimental energy distribution by such background model is shown in Fig. 3 (right panel); the energy region 800 - 1650 keV – where a peak in the response function of the ^{136}Cs decay is expected – has been excluded from this fit. The experimental data are well described by the background model: χ^2/n.d.f = 0.74.

The life-time limit: $\tau_{CNC}(^{136}\text{Xe}\rightarrow^{136}\text{Cs}) > 1.3 \cdot 10^{23}$ yr at 90 % C.L. [22] is one of the highest available limit for similar processes, This limit holds for whatever CNC ^{136}Xe decay with emission of massless uncharged particle (γ, Majoron(s), ν, etc., even some other interesting physics which could appear in future).

3.2 The search for nucleon instabilities into invisible channels in the ^{129}Xe and ^{136}Xe isotopes

Modern theories of particle physics (GUTs, SUSY) unifying quarks and leptons into the same multiplets and predicting new interactions which transform quarks into leptons, naturally lead to 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.

Nucleon instabilities into invisible channel have been investigated both for ^{129}Xe and for ^{136}Xe with a new approach [31] based on the search for the radioactive daughter nuclei, created after the nucleon or di-nucleon disappearance in the parent nuclei. This approach assures an 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 [31]: $\tau(p \rightarrow \text{invisible channels}) > 1.9 \cdot 10^{24}$ yr; $\tau(pp \rightarrow \text{invisible channels}) > 5.5 \times \times 10^{23}$ 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 limits for the di-nucleon decay in $\nu_\tau\bar{\nu}_\tau$ were set for the first time.

An additional investigation for the *N*, *NN* and *NNN* instabilities in the ^{136}Xe isotope has been recently performed using data collected during 8823.54 h by the LXe scintillator (enriched in ^{136}Xe at 68.8 %) and using the same experimental approach [32]. The isotopes given in Table 2 are produced [33] after the disappearance of one, two or three nucleons in the parent ^{136}Xe nucleus. 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. We have taken into account the *N*, *NN* and *NNN* disappearance from a few outermost shells in the parent nucleus, when only γ's would be emitted.

Table 2. **Daughter nuclei produced in *N*, *NN* and *NNN* decays in ^{136}Xe when their deexcitation occurs only by γ emission. The half-life of the isotopes involved in the decay chains vary from 2.5 m (^{133}Sb) to 5.243 d (^{133}Xe) assuring that the chains are in equilibrium and that subsequent decays are well separated in time**

Decay	Daughter nucleus	Subsequent decays
n	^{135}Xe	$^{135}\mathrm{Xe} \xrightarrow{\beta^-} {}^{135}\mathrm{Cs}$ *
p	^{135}I	$^{135}\mathrm{I} \xrightarrow{\beta^-} {}^{135}\mathrm{Xe} \xrightarrow{\beta^-} {}^{135}\mathrm{Cs}$ *
nn	^{134}Xe	Stable
np	^{134}I	$^{134}\mathrm{I} \xrightarrow{\beta^-} {}^{134}\mathrm{Xe}$
pp	^{134}Te	$^{134}\mathrm{Te} \xrightarrow{\beta^-} {}^{134}\mathrm{I} \xrightarrow{\beta^-} {}^{134}\mathrm{Xe}$
nnn	^{133}Xe	$^{133}\mathrm{Xe} \xrightarrow{\beta^-} {}^{133}\mathrm{Cs}$
nnp	^{133}I	$^{133}\mathrm{I} \xrightarrow{\beta^-} {}^{133}\mathrm{Xe} \xrightarrow{\beta^-} {}^{133}\mathrm{Cs}$
npp	^{133}Te	$^{133}\mathrm{Te} \xrightarrow{\beta^-} {}^{133}\mathrm{I} \xrightarrow{\beta^-} {}^{133}\mathrm{Xe} \xrightarrow{\beta^-} {}^{133}\mathrm{Cs}$
ppp	^{133}Sb	$^{133}\mathrm{Sb} \xrightarrow{\beta^-} {}^{133}\mathrm{Te} \xrightarrow{\beta^-} {}^{133}\mathrm{I} \xrightarrow{\beta^-} {}^{133}\mathrm{Xe} \xrightarrow{\beta^-} {}^{133}\mathrm{Cs}$ **

* ^{135}Cs is not stable, but has $T_{1/2} = 2.3 \cdot 10^6$ yr and breaks the decay chain.
** Given here only the main part of the chain.

Referring to Table 2, we note that, except for the ^{134}Xe nucleus, all the daughter nuclei reported there are radioactive. In the subsequent decays (third column of Table 2), if we exclude the ^{135}Cs which has $T_{½} = 2.3 \cdot 10^6$ yr and breaks the decay chain, the half-lives of the involved nuclides are relatively small. This ensures chains in equilibrium and thus equal number of decays for ^{135}I and ^{135}Xe (in case of the *p* disappearance), for ^{134}Te and ^{134}I (*pp* decay), etc. The response functions for the *N*, *NN* and *NNN* disappearances are given by a linear combination of the response functions obtained for the single decays of the generated decay chain. Comparison of the experimental spectrum with the calculated response functions gives no indication for the signals searched for; thus only limits on the lifetime of these processes have been obtained (Fig. 4).

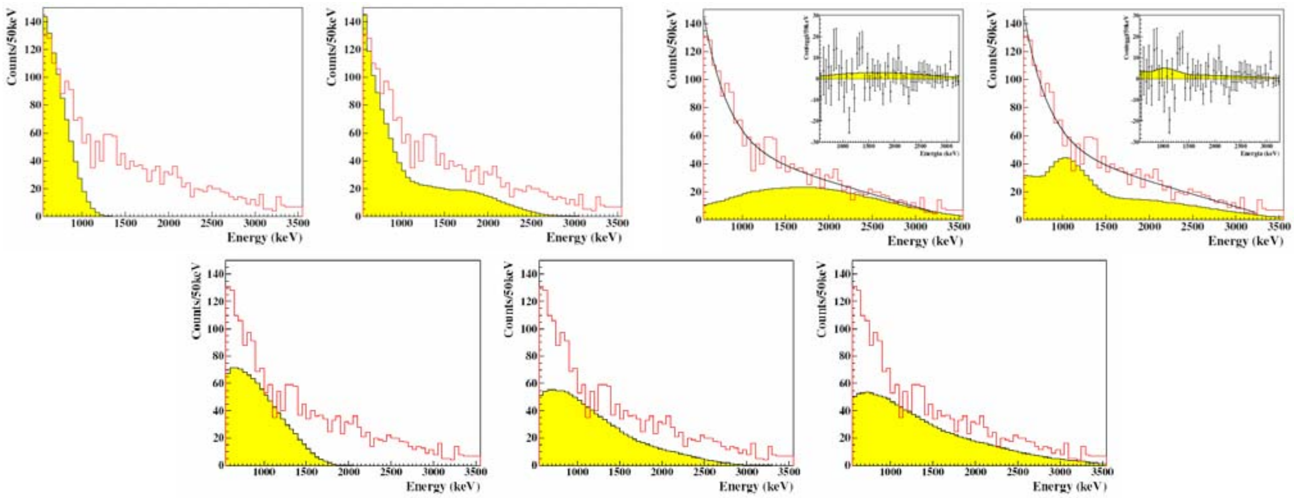

Fig. 4. *From the top-left*: Comparison between the spectrum measured during 8823.54 h (thick histogram) and the excluded signals at 90 % C.L. (shaded histogram) for **i)** *n* disappearance ($\tau_n > 3.3 \cdot 10^{23}$ yr); **ii)** *p* disappearance ($\tau_p > 4.5 \times 10^{23}$ yr); **iii)** *np* disappearance ($\tau_{np} > 4.0 \cdot 10^{22}$ yr); **iv)** *pp* disappearance ($\tau_{pp} > 2.1 \cdot 10^{23}$ 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 ($\tau_{ppp} > 3.6 \cdot 10^{22}$ yr) [32]. Moreover, in the inset of the *np* and *pp* channels the residuals between the experimental spectrum and the background fits are shown together with the excluded distributions for *np* ($\tau_{np} > 3.2 \cdot 10^{23}$ yr) and *pp* ($\tau_{pp} > 1.9 \cdot 10^{24}$ yr) respectively. See ref. [32] for details.

All the limits achieved here 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 here for the first time.

3.3 Double beta decay investigation with DAMA/LXe

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 h have been considered to investigate the ^{134}Xe and ^{136}Xe double beta decay modes. After some preliminary results (see e.g. ref. [24]) a joint analysis of the 0νββ decay mode in ^{134}Xe and in ^{136}Xe has been carried out [25]. In principle, this kind of analysis could improve the information obtained when separately studying the two isotopes. In Fig. 5 the data collected in the (0.55 – 3.55) MeV energy region are shown.

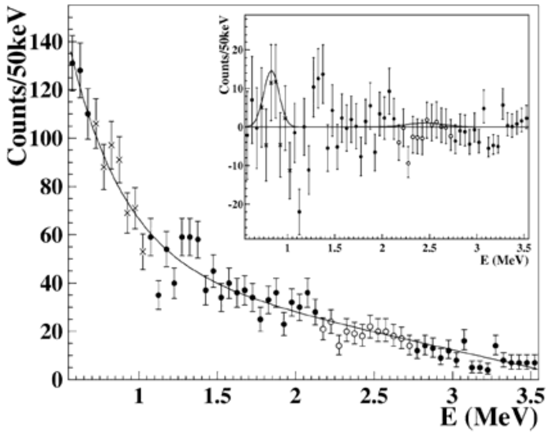

Fig. 5. Experimental data (crosses, filled and open circles) with superimposed the background contribution (continuous line). In the inset: the residuals as a function of the energy; the gaussian peaks represent the expected signals for the $0\nu\beta\beta(0^+ \rightarrow 0^+)$ decay mode in ^{134}Xe and in ^{136}Xe when $T_{½} = 5.8 \cdot 10^{22}$ yr and $T_{½} = 1.2 \cdot 10^{24}$ yr, respectively. For details see ref. [25].

New lower limits on various ββ decay modes have been obtained: for the $0\nu\beta\beta(0^+ \rightarrow 0^+)$ 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 last 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 $2\nu\beta\beta(0^+ \rightarrow 0^+)$ and the $2\nu\beta\beta(0^+ \rightarrow 2^+)$ decay modes in ^{136}Xe the limits at 90 % C.L. are: $1.0 \cdot 10^{22}$ yr and $9.4 \cdot 10^{21}$ yr, respectively. The experimental limit on the $2\nu\beta\beta(0^+ \rightarrow 0^+)$ decay mode is in the range of the theoretical estimate by [34, 35].

4. Searches for rare processes with DAMA/R&D

The set-up DAMA/R&D is used for tests on prototypes and small scale experiments. A view of the passive shield of this installation is given in Fig. 6.

Fig. 6. View of the shield of the R&D installation: closed (*left*) and open (*right*).

This set-up, which has been upgraded several times, is used for measurements on low background prototype scintillators and PMTs realized in various R&D efforts with industries. Moreover, it is regularly also used to perform small scale experiments mainly investigating double beta decay modes in various isotopes. Among the obtained results we remind the search for: i) ββ decay modes in ^{136}Ce and in ^{142}Ce [36]; ii) 2EC2ν decay mode in ^{40}Ca [37]; iii) ββ decay modes in ^{46}Ca and in ^{40}Ca [38]; iv) ββ decay modes in ^{106}Cd [39]; v) ββ and β decay modes in ^{48}Ca [40]; vi) 2EC2ν in ^{136}Ce and in ^{138}Ce and α decay in ^{142}Ce [41]; vii) $2\beta^+0\nu$ and $EC\beta^+0\nu$ decay in ^{130}Ba [42]; viii) cluster decay in ^{138}La and ^{139}La [43]. Both the active and the passive source techniques have been exploited as well as – sometimes – the coincidence technique. Fig. 7 summarizes the many results obtained by DAMA in the searches for double beta decay modes.

In the following we just summarize one of the most recent of the many searches for rare processes carried out with DAMA/R&D; other experiment are in progress and foreseen.

4.1 Measurements with $LaCl_3$:Ce and search for possible CNC decay of ^{139}La into ^{139}Ce

Measurements have been carried out by using a $LaCl_3$(Ce) crystal in the low background DAMA/R&D set-up, providing: i) the investigation of the performance of this scintillator, ii) new limits on cluster decay in ^{138}La and ^{139}La and iii) first limit on CNC decay of ^{139}La into ^{139}Ce. As regards details about the set-up description, the performances of $LaCl_3(Ce)$ crystal scintillator and cluster decay in ^{138}La and ^{139}La, see ref. [43]; here we just report in Fig. 8 the summary of the investigated cluster decay modes and the experimental lower limits set on $T_{½}$.

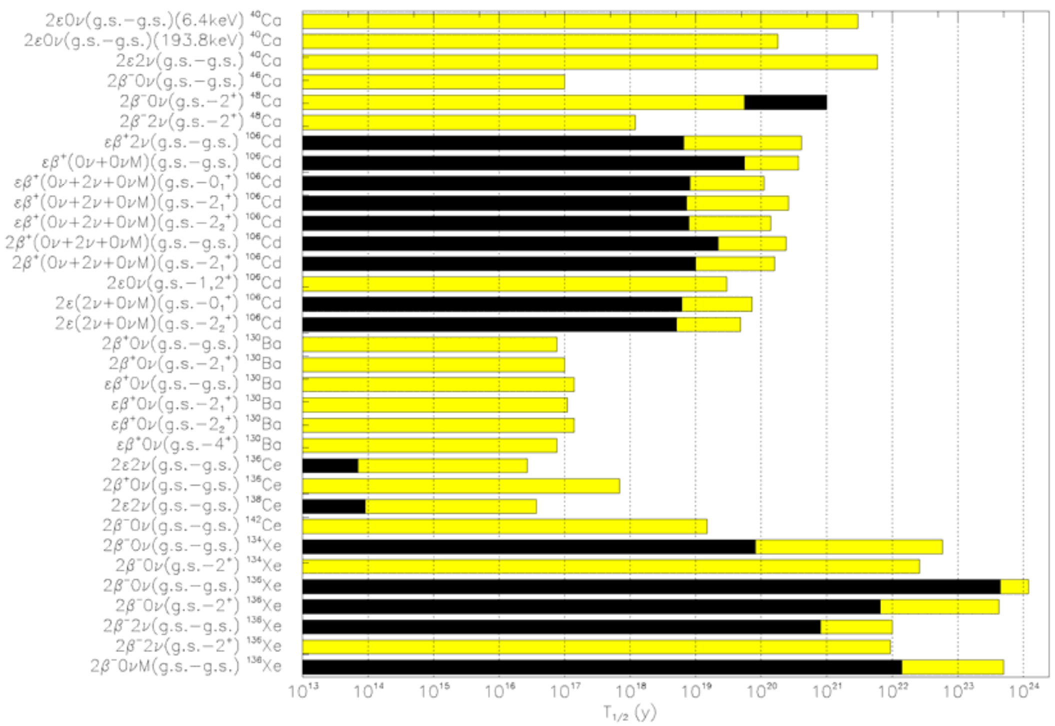

Fig. 7. Summary of the $T_{½}$ limits (at 90 % C.L.) obtained by DAMA (light shaded bars) and by previous experiments (dark bars) on various double beta decay processes.

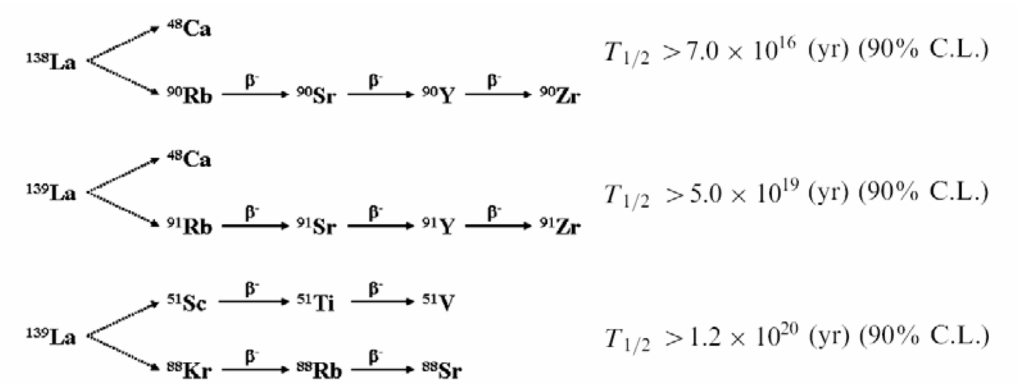

Fig. 8. Summary of the $T_{½}$ limits (at 90 % C.L.) obtained for the investigated cluster decay modes in $LaCl_3(Ce)$. Although the relatively modest values, the obtained limits exclude application of semi-empirical formulae of ref. [15] for cluster radioactivity in the investigated nuclear region.

As regards the search for CNC decay of ^{139}La into ^{139}Ce, we investigate the process scheme given in left panel of Fig. 9: after the possible ^{139}La CNC decay, the daughter nucleus ^{139}Ce will be created, it transforms back to ^{139}La through an electron capture with $T_{½}$ = 137.640 d and Q_{EC} = 279 keV [33]. The simulated response function of the $LaCl_3(Ce)$ detector for EC of ^{139}Ce is given in right panel of Fig. 9.

Comparing the experimental energy distribution (collected during 493 h of data taking) with the expected response function (Fig. 10), no evidence for the peaks at ~ 170 keV and ~ 200 keV are found; thus, only a bound on the probability of the investigated effect can be extracted here. In order to extract the limit on the number of the ^{139}Ce EC decays, the experimental energy distribution, in the region 100 - 240 keV, has simultaneously been fitted by the sum of a background model and of the ^{139}Ce EC response function. In that energy region the experimental energy distribution is mainly due to the β spectrum of ^{138}La decay (0.0902 % abundance in natural La); thus, following a standard procedure, the number of events N_d (which could be ascribed to the considered decay process) has been calculated by minimizing (with the respect to the P_1 to P_5

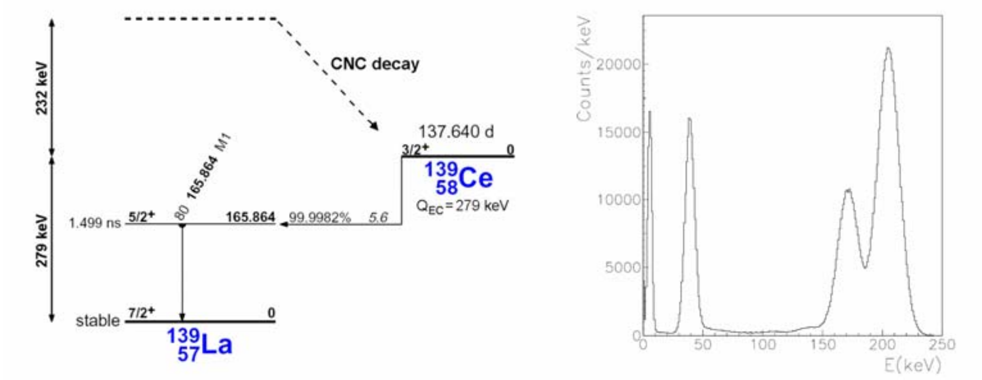

Fig. 9. Left panel: Scheme of the investigated CNC decay of ^{139}La into ^{139}Ce and of subsequent EC of ^{139}Ce. Right panel: simulated response function for EC of ^{139}Ce in $LaCl_3$(Ce).

and N_d free parameters) the function $\chi^2 = \sum_k (f^B_{P_1P_2}(E_k) + f^\beta_{P_3P_4P_5}(E_k) + N_d M_k - N_k)^2 / N_k$, where: the function $f^B_{P_1P_2}(E_k) = P_1 + P_2 \cdot E_k$ accounts for a linear component of the background and $f^\beta_{P_3P_4P_5}(E_k) = \left[\sqrt{E_k(E_k + 2m_ec^2)}\left(Q_\beta - E_k\right)^2\left(E_k + m_ec^2\right)\right]\left(P_3 + P_4E_k + P_5E_k^2\right)$ accounts for the background component arising from the ^{138}La β decay (the polynomial approximation has been included to take into account the overall effect due to mainly the Fermi function, the spread of the energy resolution and the high level of forbiddenness of the ^{138}La β decay). Moreover, E_k is the mean energy of the k-th energy bin; N_dM_k are the expected counts in the k-th energy bin as evaluated by the MonteCarlo code, while N_k are the measured counts in the given running period and in the k-th energy bin.

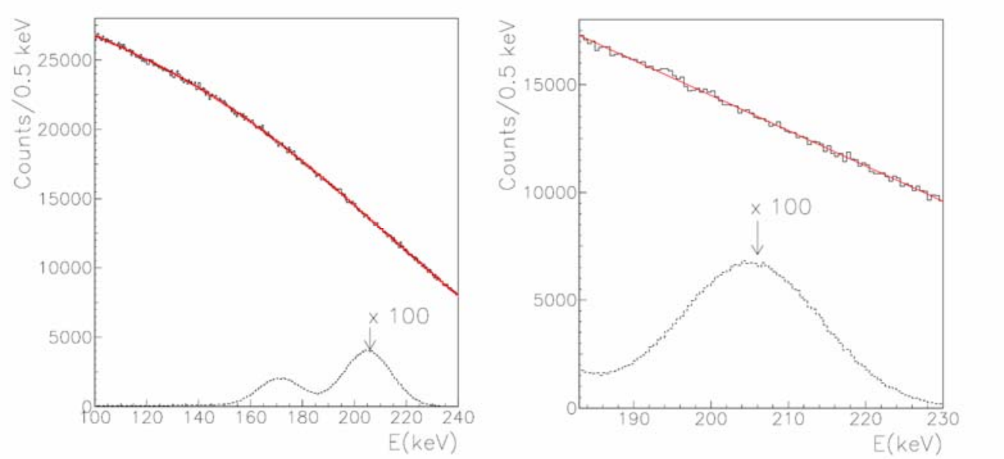

Fig. 10. *Left panel*: Experimental energy distribution in the region 100-240 keV (continuous histogram) with superimposed the best-fit curve. The dashed curve is hundred times the energy distribution expected for τ_{CNC} equal to the 90 % C.L. limit obtained following the first procedure described in the text. *Right panel*: Experimental energy distribution in the region of the higher energy peak: 183 - 230 keV (continuous histogram) with superimposed the best-fit curve. The dashed curve is hundred times the energy distribution expected for τ_{CNC} equal to the 90% C.L. limit obtained by the second approach (see text).

Then, the corresponding lifetime of the CNC decay of ^{139}La into ^{139}Ce can be calculated by means of the known formula: lim $\tau_{CNC} = N \cdot T/N_d$ where N is the number of ^{139}La nuclei ($N = 1.1 \cdot 10^{23}$) and T is the time of measurements (T = 493 h). Thus, with this approach the lifetime limit is (see left panel of Fig. 10): τ_{CNC}(^{139}La→^{139}Ce) > $1.6 \cdot 10^{18}$ yr at 90 % C.L.

To test the robustness of the obtained limit, we pursue a second approach focusing the 183 - 230 keV energy regions which is around the ~ 200 keV peak expected for the ^{139}Ce EC decay searched for. In this case the considered background model is simply a straight line: $f^B_{P_1P_2}(E_k)$. Following this standard procedure the corresponding lifetime of the CNC decay of ^{139}La into ^{139}Ce is (see right panel of Fig 10): τ_{CNC}(^{139}La→^{139}Ce) > $1.0 \cdot 10^{18}$ yr at 90 % C.L.

As it can be seen the approaches give the same order of magnitude and to be on the safest side we will consider the most cautious one. This limit holds for whatever CNC ^{139}La decay with emission of massless uncharged particle (γ, Majoron(s), ν, etc., even some other interesting physics which could appear in future).

5. Conclusions

In this paper some of the results on rare processes achieved by the DAMA experiment at the Gran Sasso National Laboratory of I.N.F.N. have been summarized. Many other investigations are in progress.

The authors wish to thank all the other colleagues which have also contributed to some of the activities summarized here.

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ПОИСКИ РЕДКИХ ПРОЦЕССОВ В DAMA ЭКСПЕРИМЕНТАХ В ГРАН САССО

Р. Бернабеи, П. Белли, Ф. Монтекки, Ф. Ноццоли, А. д'Анжело, Ф. Капелла, А. Инчикитти, Д. Проспери, С. Кастеллано, Р. Черулли, Ц. Ж. Дай, Ф. А. Даневич, В. И. Третяк

DAMA представляет собой обсерваторию для наблюдения редких процессов, основанную на развитии и использовании различных сцинтилляторов, чистых от радиоактивных примесей. Несколько низкофоновых установок были построены в Национальной лаборатории Гран Сассо, и было исследовано много редких процессов. Некоторые из них подытожены здесь с особым вниманием на поиски 2β распада в нескольких изотопах; процессов с несохранением электрического заряда; распадов нуклонов в невидимые каналы с помощью нового подхода; сверхплотных состояний ядер; кластерных распадов и др.

ПОШУКИ РІДКІСНИХ ПРОЦЕСІВ В DAMA ЕКСПЕРИМЕНТАХ В ГРАН САССО

Р. Бернабеі, П. Беллі, Ф. Монтеккі, Ф. Ноццолі, А. д'Анжело, Ф. Капелла, А. Инчікітті, Д. Проспері, С. Кастеллано, Р. Черуллі, Ц. Ж. Дай, Ф. А. Даневич, В І . Третяк

DAMA є обсерваторією для спостереження рідкісних процесів, що заснована на розвитку та використанню різноманітних сцинтиляторів, чистих від радіоактивних забруднень. Декілька низькофонових установок були побудовані в Національній лабораторії Гран Сассо, і було вивчено багато рідкісних процесів. Деякі з них підсумовані тут з особливою увагою на пошуки 2β розпадів в декількох ізотопах; процесів із незбереженням електричного заряду; розпадів нуклонів в невидимі канали за допомогою нового підходу; зверхщільних станів ядер; кластерних розпадів та ін.