Results of the DAMA experiment at LNGS

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DAMA is searching for rare processes by developing and using several kinds of radiopure scintillators: in particular, NaI(Tl), liquid Xenon and CaF_2(Eu). Here more recent results are summarized with particular attention to the investigation of the WIMP annual modulation signature.

1. INTRODUCTION

DAMA is devoted to the search for rare processes by developing and using low radioactivity scintillators. Its main aim is the search for relic particles (WIMPs: Weakly Interacting Massive Particles). In addition, due to the radiopurity of the used detectors and of the installations, several searches for other possible rare processes are also carried out, such as e.g. on exotics, on $\beta\beta$ processes, on charge-non-conserving processes, on Pauli exclusion principle violating processes, on nucleon instability and on solar axions[1–13].

The main experimental set-ups running at present are: the $\simeq$ 100 kg NaI(Tl) set-up, the $\simeq$ 6.5 kg liquid Xenon (LXe) set-up and the so-called "R&D" apparatus.

2. THE LXE EXPERIMENT

We pointed out the interest in using liquid Xenon as target-detector for particle dark matter search deep underground since ref. [14]. Several prototypes were built and related results published [15]. The final choice was to realize a pure liquid Xe scintillator directly collecting the emitted UV light and filled with Kr-free Xenon gas isotopically enriched either in ^{129}Xe at 99.5% (used since time) or (more recently) in ^{136}Xe at 68.8%. The detailed description of the set-up and its performances have been given in ref. [16].

After preliminary measurements both on elastic and inelastic WIMP-^{129}Xe scattering [17,18], the recoil/electron light ratio and the pulse shape discrimination capability in a similar pure LXe scintillator have been measured both with Am-B neutron source and with 14 MeV neutron generator [19] and – after some upgrading of the set-up – new results on the WIMP search have been obtained [19,20]. In particular, in ref. [19] the pulse shape discrimination technique has been exploited (see Fig 1), while in ref. [20] (see Fig 2) further results on the inelastic excitation of ^{129}Xe by Dark Matter particles with spin-dependent coupling has also been searched for improving our previous result of ref. [18]. For the sake of completeness, we remind that very large mass would be necessary to approach a suitable sensitivity when investigating such a WIMP-nucleus inelastic scattering.

Moreover, in 2000/2001 further measurements on the recoil/electron light ratio have been carried out at ENEA-Frascati with 2.5 MeV neutron generator; see ref. [21] for details and comparisons.

Other rare processes have been investigated by

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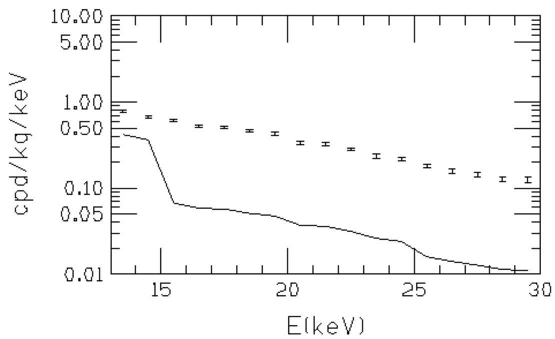

Figure 1. Low energy distribution (statistics of 1763.2 kg·day) measured with the vessel filled by ^{129}Xe; the continuous line represents the upper limits at 90% C.L. obtained for the recoil fractions [19].

filling the detector with the Kr-free Xenon gas enriched in ^{129}Xe at 99.5%. 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. [1]. The latter has been more recently im-

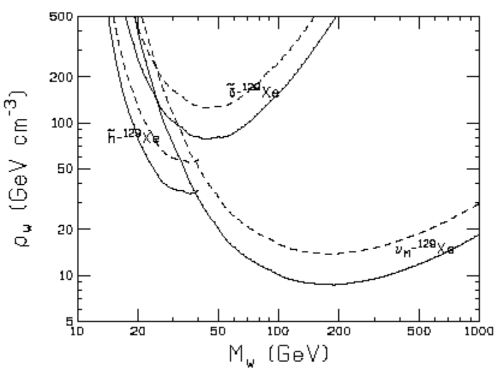

Figure 2. Full lines: limits on the relic halo density for photino, higgsino and and ν_M as a function of the WIMP mass for WIMP-^{129}Xe inelastic scattering. Broken lines: our previous limits of ref. [18]. For the considered model framework see ref. [20].

proved to: $2.0(3.4) \cdot 10^{26}$ y at 90% (68%) C.L. [10]. Furthermore, new lifetime limits on the charge non-conserving electron capture with excitation of ^{129}Xe nuclear levels have 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 [9].

We have also searched for the nucleon and di-nucleon decay into invisible channels [11] 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. 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 [11].

Finally as mentioned above, more recently the set-up has been modified to allow the use of Kr-free Xenon enriched in ^{136}Xe at 68.8%. Preliminary measurements have been carried out during 6843.8 hours [13]. In this way, new experimental limits have been obtained for the given $\beta\beta$ decay processes in ^{136}Xe, improving the limits previously available by factors ranging between 1.5 and 65. In particular, for the 3 possible channels without neutrinos the following half life limits (90% C.L.) have been achieved: $7.0 \cdot 10^{23}$ y for the channel $\beta\beta\ 0\nu(0^+ \rightarrow 0^+)$; $4.2 \cdot 10^{23}$ y for the channel $\beta\beta\ 0\nu(0^+ \rightarrow 2^+)$; $8.9 \cdot 10^{22}$ y for the channel $\beta\beta\ 0\nu M(0^+ \rightarrow 0^+)$. For comparison, we note that the obtained experimental limits on the half life of the process $\beta\beta\ 0\nu(0^+ \rightarrow 0^+)$ is lower only than the one obtained for the case of ^{76}Ge, while the limits (90% C.L.) on the channels $\beta\beta\ 2\nu(0^+ \rightarrow 0^+)$: $> 1.1 \cdot 10^{22}$ y, and $\beta\beta\ 0\nu M(0^+ \rightarrow 0^+)$ are at present the most stringent ones not only for the ^{136}Xe isotopes, but also for every kind of nucleus investigated so far either by active or by passive source method. Furthermore, upper bounds on the effective neutrino mass have been set considering various theoretical models for the evaluation of the elements of the nuclear matrix; they vary between 1.5 eV and 2.2 eV (90% C.L.). Finally, in the framework of the same models we have also obtained upper limits on the effective coupling constant Majoron - neutrino; they range in the interval: $4.8 \cdot 10^{-5}$ and

$7.1 \cdot 10^{-5}$ (90% C.L.) [13].

In conclusion, competitive results have been achieved by the DAMA LXe set-up by using Kr-free isotopically enriched Xenon. Further upgradings to improve the detector performance are under consideration, while the data taking is continuing alternatively with both enrichments.

3. THE "R&D" SET-UP

The "R&D" set-up is used to measure the performances of prototype detectors and to perform small scale experiments. In particular, several experiments on the investigation of $\beta\beta$ decay processes in ^{136}Ce, ^{142}Ce, ^{40}Ca, ^{46}Ca, ^{48}Ca, ^{130}Ba, ^{106}Cd [2,4–6] (see Fig. 3); other measurements are in progress and/or in preparation.

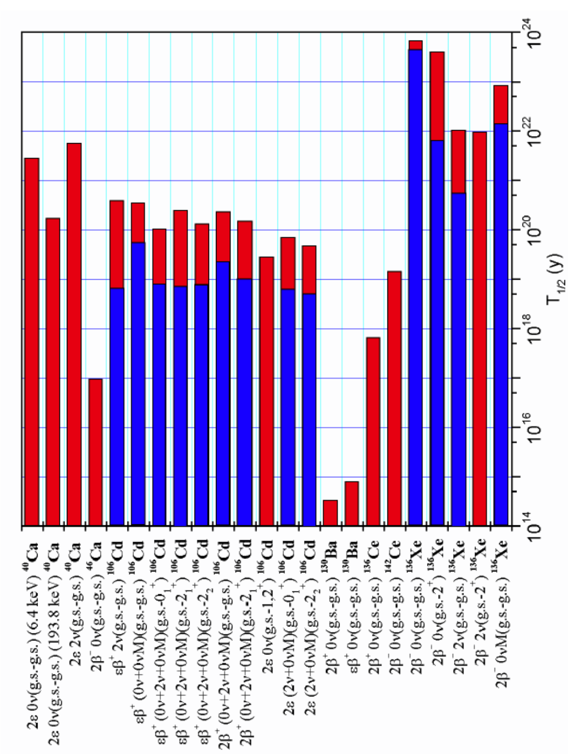

Figure 3. Light gray: experimental limits on $\beta\beta$ decay processes investigated by DAMA (90% C.L. with exception of the results on Barium and Cerium isotopes, which are at 68% C.L.) [2,4–6]. Dark gray: best experimental limits before DAMA results (90% C.L.).

4. THE $\simeq$ 100 KG NaI(Tl) SET-UP

In the framework of the DAMA experiments the $\simeq$ 100 kg NaI(Tl) set-up allowed us to explore several kinds of rare processes regarding WIMPs, processes forbidden by Pauli exclusion principle, exotics, charge non conserving processes and solar axions (see Fig 4) [3,7,8,12,22–29]. A full description of the apparatus can be found in ref.[25]. In the following only recent results on the investigation of the WIMP annual modulation signature will be summarized.

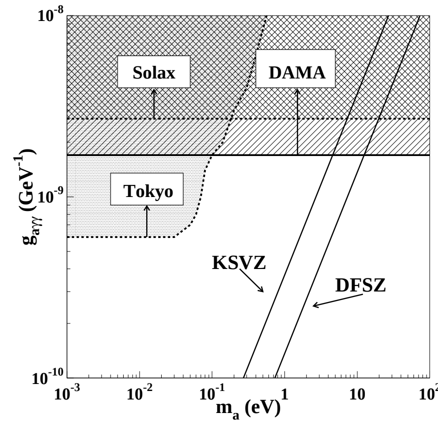

Figure 4. Exclusion plot for the axion coupling constant, $g_{a\gamma\gamma}$, versus the axion mass, m_a. The limit achieved by this experiment is shown together with theoretical expectations and previous direct searches for solar axions[12].

5. INVESTIGATION OF THE WIMP ANNUAL MODULATION SIGNATURE

As we have already pointed out, the annual modulation signature is very distinctive[25–32] because a WIMP induced seasonal effect must simultaneously satisfy several requirements and only systematic effects able to fulfill these requirements could fake this signature. Therefore, for some other effect to mimic such a signal is highly unlikely.

Up to now results have been obtained by analysing the data of four annual cycles; cumulative analyses of a 57986 kg·day statistics have been carried out both in model independent and in model dependent ways [26–32]. A detailed investigation of possible systematics has been also performed[30].

5.1. The model independent analysis

A model independent analysis has given evidence for the presence of an annual modulation of the rate of the single hit events in the lowest energy interval [29,30] (see Fig 5).

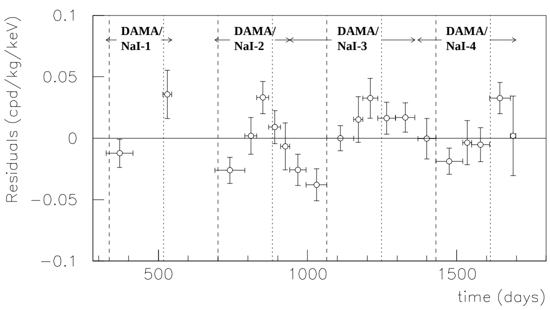

Figure 5. *A model independent analysis:* model independent residual rate for single hit events, in the 2–6 keV cumulative energy interval. The expected behaviour of a WIMP signal is a cosine function with minimum roughly at the dashed vertical lines and with maximum roughly at the dotted ones[29,30].

As discussed in ref. [29,30], the χ^2 test on the data disfavors the hypothesis of unmodulated behaviour (probability: $4 \cdot 10^{-4}$), while a behaviour compatible with the one expected for a WIMP signal is found by fitting the residuals with a cosine function.

No known systematic effect able to mimic such a signature has been identified; see the detailed discussion of ref. [30]. Thus, a WIMP contribution to the measured rate is candidate by the data independently on the nature and coupling with ordinary matter of the possible WIMP particle.

5.2. The model dependent analyses

To investigate the nature and coupling with ordinary matter of a possible particle candidate for the observed effect, an energy and time correlation analysis of the data should be carried out in given model framework. This is identified not only by the general astrophysical, nuclear and particle physics assumptions, but also by the chosen values for all the parameters needed in the model itself and in related quantities, such as for example WIMP local velocity, form factor parameters, etc.

Firstly a model dependent analysis has been carried out in a purely spin-independent model framework [29] (see Fig 6), considering the physical constraint from the measured upper limit on the recoil rate [22,29,30] and the results of accelerator experiments. In Fig 6 ξ is the WIMP local density in 0.3 GeV cm^{-3} unit, σ_{SI} is the point-like spin-independent WIMP cross section on nucleon and m_W is the WIMP mass.

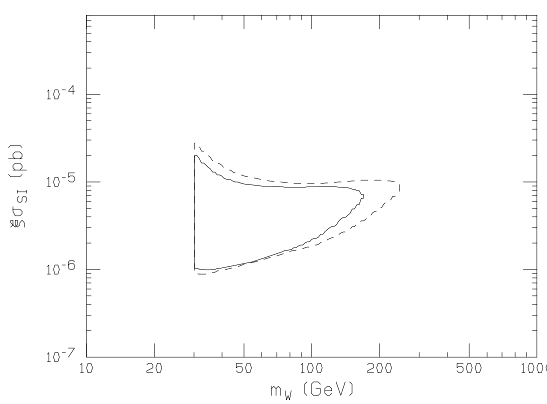

Figure 6. *A purely SI model framework:* regions allowed at 3σ C.L. in the plane $\xi\sigma_{SI}$ versus m_W for a WIMP with dominant SI interaction and mass above 30 GeV in the model framework considered in ref.[29]: i) when the uncertainty on the halo velocity is included (continuous contour); ii) when also a possible bulk halo rotation as in ref. [28] is considered (dashed contour) [29].

Theoretical implications of these results in terms of a neutralino with dominant SI interaction and mass above 30 GeV have been discussed in ref. [33,34], while the case for an heavy neutrino of the fourth family has been considered in ref. [35].

Secondly, since the ^{23}Na and ^{127}I nuclei are indeed fully sensitive to both spin-independent (SI) and spin-dependent (SD) couplings – on the contrary e.g. of Ge and Si target nuclei - we have also extended the analysis to the more general (SI/SD) framework [31]. In this case an allowed volume in the ($\xi\sigma_{SI}$, $\xi\sigma_{SD}$, m_W, θ) four-dimensional space is obtained by the full energy and time correlation analysis of the data. Here σ_{SD} is the point-like SD WIMP cross section on nucleon and $tg\theta$ is the ratio between the effective SD coupling constants on neutron, a_n, and on proton, a_p (therefore, θ can assume values between 0 and π depending on the SD coupling). For simplicity, Fig 7 shows slices for some m_W of this volume allowed at 3 σ C.L. for some fixed θ value [31]. For details see ref.[31].

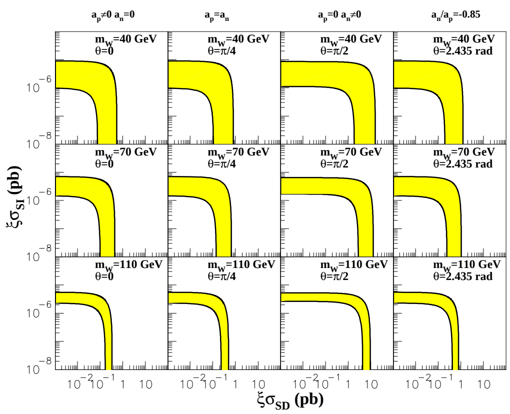

Figure 7. *A mixed (SI/SD) model framework:* examples of slices in the ($\xi\sigma_{SI}$, $\xi\sigma_{SD}$, m_W, θ) allowed four-dimensional volume for some of the possible m_W and θ values (3 σ C.L.) [31].

Moreover, in ref. [31] we have also shown that: i) finite values can be allowed for $\xi\sigma_{SD}$ even when $\xi\sigma_{SI} \simeq 3 \cdot 10^{-6}$ pb as in the region allowed in the pure SI scenario considered in the previous subsection; ii) regions not compatible with zero in the $\xi\sigma_{SD}$ versus m_W plane are allowed even when $\xi\sigma_{SI}$ values much lower than those allowed in the dominant SI scenario previously summarized are considered; iii) minima of the -log-likelihood function with both $\xi\sigma_{SI}$ and $\xi\sigma_{SD}$ different from zero are present for some m_W and θ pairs; the related confidence level ranges between $\simeq 3\ \sigma$ and $\simeq 4\ \sigma$ [31].

For the sake of completeness, more recently the annual modulation effect observed during four annual cycles has been analysed, by energy and time correlation analysis, also in terms of a particle Dark Matter candidate with a preferred inelastic scattering by making a transition to a slightly heavier state [36]. The found allowed volume[32] in the space ($\xi\sigma_p$, m_W, δ), where δ is the mass splitting, largely lies in δ section where experiments with light nuclei (such as e.g. Ge) are disfavoured (see Fig 8).

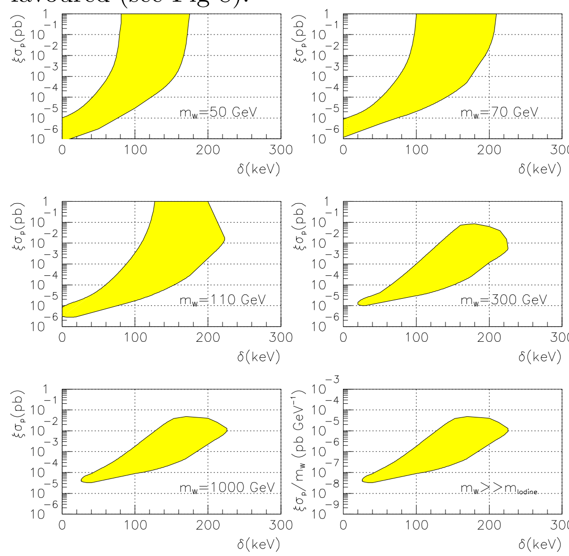

Figure 8. *A "preferred" inelastic scattering model framework:* examples of slices in the allowed volume ($\xi\sigma_p$, δ, m_W) for some m_W values (3 σ C.L.) [32].

We remark that in all the model frameworks considered so far the inclusion of present uncertainties on other astrophysical, nuclear and particle physics parameters would enlarge these regions (varying consequently the best fit positions).

It is worth to note that the results of the model dependent data analyses [29,31,32] summarized here hold for the neutralino (which is, at present, considered the best candidate for WIMP), but are not restricted only to this candidate.

Finally, a comparison with other recent results can be found e.g. in sect. III of ref. [37].

6. TOWARDS LIBRA

When writing these proceedings the 5^{th} and 6^{th} annual cycle are under analysis. The 7^{th} annual cycle is running. Our main efforts are devoted to the realization of LIBRA (Large sodium Iodine Bulk for RAre processes in the DAMA experiment) consisting of $\simeq$ 250 kg of NaI(Tl). New radiopure detectors by chemical/physical purification of NaI and Tl powders as a result of a dedicated R&D with Crismatec have been realized. This will allow to increase the sensitivity of the experiment. Furthermore, additional investigations on models (in particular on halo models) and data interpretation are in progress. All these efforts will allow also to achieve relevant C.L. values and to disantangle different possible model dependent scenarios.

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