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DIRECT SEARCH FOR DARK MATTER

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Abstract

DAMA is an observatory for rare processes based on the development and use of various kinds of radiopure scintillators; it is operative deep underground at the Gran Sasso National Laboratory of I.N.F.N.. Several low background set-ups have been realized with time passing and many rare processes have been investigated. In particular, the DAMA/NaI set-up ($\simeq$ 100 kg highly radiopure NaI(Tl)) has effectively investigated the model independent annual modulation signature for Dark Matter particles in the galactic halo. With the total exposure of 107731 kg $\times$ day it has pointed out a model independent evidence for the presence of

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a Dark Matter particle component in the galactic halo at 6.3 σ C.L.; some of the many possible corollary model dependent quests for the candidate particle have also been investigated. At present the second generation DAMA/LIBRA set-up ($\simeq$ 250 kg highly radiopure NaI(Tl)) is in operation deep underground.

1 Introduction

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; the main ones are: i) DAMA/NaI ($\simeq$ 100 kg of highly radiopure NaI(Tl)), which took data underground over seven annual cycles and was put out of operation in July 2002 [1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13]; ii) DAMA/LXe ($\simeq$ 6.5 kg liquid Xenon) [14]; iii) DAMA/R&D, which is devoted to tests on prototypes and small scale experiments [15]; iv) the new second generation DAMA/LIBRA set-up ($\simeq$ 250 kg highly radiopure NaI(Tl)) in operation since March 2003. These set-ups have investigated many rare processes. Moreover, in the framework of devoted R&D for radiopure detectors and PMTs, sample measurements are regularly carried out by means of the low background DAMA/Ge detector, installed deep underground since $\gtrsim$ 10 years and, in some cases, by means of Ispra facilities.

In the following we will focus the presentation only on the $\simeq$ 100 kg radiopure NaI(Tl) set-up, DAMA/NaI, and on its results on the annual modulation signature.

The DAMA/NaI set-up and its performances have been described in ref.[1] and further information on its performances and upgrading can be found in refs.[2, 10]. Two PMTs were coupled to each NaI(Tl) crystal through 10 cm long Tetrasil-B light guides (acting also as optical windows) and worked in coincidence with hardware thresholds at single photoelectron level in order to assure high efficiency for the coincidence at few keV level [1]. The energy threshold of the experiment, 2 keV, was determined by means of X ray sources and of keV range Compton electrons on the basis also of the features of the noise rejection procedure and of the efficiencies when lowering the number of available photoelectrons [1].

The model independent annual modulation signature (originally suggested in [16]) is very distinctive since it requires the simultaneous satisfaction of all the following requirements: the rate must contain a component modulated according to a cosine function (1) with one year period, T, (2) and a phase, t_0, that peaks around $\simeq 2^{nd}$ June (3); this modulation must only be found in a well-defined low energy range, where WIMP induced recoils can be present (4); it must apply to those events in which just one detector of many actually "fires" (*single-hit* events), since the WIMP multi-scattering probability is negligible

(5); the modulation amplitude in the region of maximal sensitivity is expected to be $\lesssim$7% (6). This latter rough limit would be larger in case of other possible scenarios such as e.g. those in refs. [17, 18]. To mimic such a signature spurious effects or side reactions should be able both to account for the whole observed modulation amplitude and to contemporaneously satisfy all the requirements.

2 The final model independent result over 7 annual cycles

A model independent approach on the data of the seven annual cycles offers an immediate evidence of the presence of an annual modulation of the rate of the *single-hit* events in the lowest energy region as shown in Fig. 1 – *left*, where the time behaviour of the measured (2-6) keV residual rate of the *single-hit* events is reported. The data favour the presence of a modulated

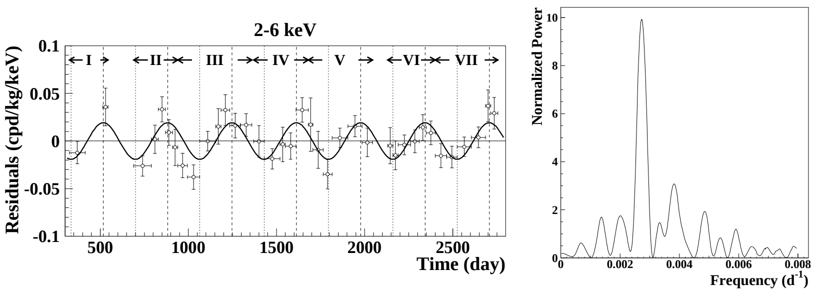

Figure 1: *On the left*: model independent experimental residual rate for *single-hit* events in the (2–6) keV energy interval as a function of the time over 7 annual cycles (total exposure 107731 kg × day); end of data taking July 2002. The experimental points present the errors as vertical bars and the associated time bin width as horizontal bars. The superimposed curve represents the cosinusoidal function behaviour expected for a WIMP signal with a period equal to 1 year and phase exactly at 2^{nd} June; the modulation amplitude has been obtained by best fit. See ref. [2]. *On the right*: power spectrum of the measured (2–6) keV *single-hit* residuals calculated including also the treatment of the experimental errors and of the time binning. As it can be seen, the principal mode corresponds to a frequency of $2.737 \cdot 10^{-3}$ d^{-1}, that is to a period of $\simeq$ 1 year.

cosine-like behaviour ($A\cdot$ cos$\omega(t - t_0)$) at 6.3 σ C.L. and their fit for the (2–6) keV cumulative energy interval offers modulation amplitude equal to (0.0200 ± 0.0032) cpd/kg/keV, $t_0 = (140 \pm 22)$ days and $T = \frac{2\pi}{\omega} = (1.00 \pm 0.01)$ year, all parameters kept free in the fit. The period and phase agree with those expected in the case of a WIMP induced effect (T = 1 year and t_0 roughly at $\simeq 152.5^{th}$ day of the year). The χ^2 test on the (2–6) keV residual rate disfavours the hypothesis of unmodulated behaviour giving a probability of

$7 \cdot 10^{-4}$ ($\chi^2/d.o.f. = 71/37$). The same data have also been investigated by a Fourier analysis as shown in Fig. 1 – *right.* Modulation is not observed above 6 keV [2]. Finally, a suitable statistical analysis has shown that the modulation amplitudes are statistically well distributed in all the crystals, in all the data taking periods and considered energy bins. More arguments can be found in ref. [2]. A careful investigation of all the known possible sources of systematic

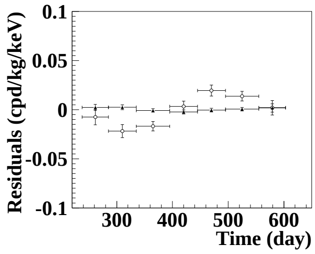

Figure 2: Experimental residual rates over seven annual cycles for *single-hit* events (open circles) – class of events to which WIMP events belong – and over the last two annual cycles for *multiple-hits* events (filled triangles) – class of events to which WIMP events do not belong – in the (2–6) keV cumulative energy interval. They have been obtained by considering for each class of events the data as collected in a single annual cycle and using in both cases the same identical hardware and the same identical software procedures. The initial time is taken on August 7^{th}. See text.

and side reactions has been regularly carried out and published at time of each data release while detailed quantitative discussions can be found in refs. [2, 10]. No systematic effect or side reaction able to account for the observed modulation amplitude and to mimic a WIMP induced effect has been found. As a further relevant investigation, the *multiple-hits* events collected during the DAMA/NaI-6 and 7 running periods (when each detector was equipped with its own Transient Digitizer with a dedicated renewed electronics) have been studied and analysed by using the same identical hardware and the same identical software procedures as for the case of the *single-hit* events (see Fig. 2). The *multiple-hits* events class – on the contrary of the *single-hit* one – does not include events induced by WIMPs since the probability that a WIMP scatters off more than one detector is negligible. The fitted modulation amplitudes are: $A = (0.0195 \pm 0.0031)$ cpd/kg/keV and $A = -(3.9 \pm 7.9) \cdot 10^{-4}$ cpd/kg/keV for *single-hit* and *multiple-hits* residual rates, respectively. Thus, evidence of annual modulation is present in the *single-hit* residuals (events class to which the WIMP-induced recoils belong), while it is absent in the *multiple-hits* residual rate (event class to which only background events belong). Since the same identical hardware and the same identical software procedures have been used to analyse the two classes of events, the obtained result offers an additional strong support for the presence of Dark Matter particles in the galactic halo further excluding any side effect either from hardware or from software procedures or from background.

In conclusion, the presence of an annual modulation in the residual rate of the *single-hit* events in the lowest energy interval $(2-6)$ keV, satisfying all the features expected for a WIMP component in the galactic halo is supported by the data of the seven annual cycles at $6.3\,\sigma$ C.L.. This is the experimental result of DAMA/NaI. It is model independent; no other experiment whose result can be directly compared with this one is available so far in the field of Dark Matter investigation.

3 Some corollary model dependent quests for a candidate

On the basis of the obtained model independent result, corollary investigations can also be pursued on the nature and coupling of the WIMP candidate. This latter investigation is instead model dependent and – considering the large uncertainties which exist on the astrophysical, nuclear and particle physics assumptions and on the parameters needed in the calculations – has no general meaning (as it is also the case of exclusion plots, of expected recoil energy behaviours and of the WIMP parameters evaluated in indirect search experiments). Thus, it should be handled in the most general way as we have pointed out with time passing [6, 7, 8, 9, 10, 11, 12, 13, 2].

Candidates, kinds of WIMP couplings with ordinary matter and implications, cross sections, nuclear form factors, spin factors, scaling laws, halo models, priors, etc. are discussed in ref. [2] and we invite the reader to this reference since these arguments are necessary to correctly understand the results obtained in corollary quests and the real validity of any claimed model dependent comparison in the field.

In the following some of the results obtained in ref. [2] for some of the many possible model dependent quests for a WIMP candidate are shown; obviously, they are not exhaustive of the many scenarios possible at present level of knowledge, including those depicted in some more recent works such as e.g. refs. [18, 19].

DAMA/NaI is intrinsically sensitive both to low and high WIMP mass having both a light (the ^{23}Na) and a heavy (the ^{127}I) target-nucleus; in previous corollary quests WIMP masses above 30 GeV (25 GeV in ref. [6]) have been presented [7, 9, 11, 12, 13] for few (of the many possible) model frameworks. However, that bound holds only for neutralino when supersymmetric schemes based on GUT assumptions are adopted to analyse the LEP data [20]. Thus, since other candidates are possible and also other scenarios can be considered for the neutralino itself as recently pointed out (in fact, when the assumption on the gaugino-mass unification at GUT scale is released neutralino masses down to $\simeq 6$ GeV are allowed [21, 22]), the present model dependent lower bound quoted by LEP for the neutralino in the supersymmetric schemes based on GUT assumptions (37 GeV [23]) is simply marked in the following figures.

For simplicity, here the results of these corollary quests for a candidate particle are presented in terms of allowed regions obtained as superposition of the configurations corresponding to likelihood function values *distant* more than 4σ from the null hypothesis (absence of modulation) in each of the several (but still a limited number) of the possible model frameworks considered in ref. [2]. These allowed regions take into account the time and energy behaviours of the single-hit experimental data and have been obtained by a maximum likelihood procedure (for a formal description see e.g. refs. [6, 7, 9]) which requires the agreement: i) of the expectations for the modulated part of the signal with the measured modulated behaviour for each detector and for each energy bin; ii) of the expectations for the unmodulated component of the signal with the respect to the measured differential energy distribution and - since ref. [9] - also with the bound on recoils obtained by pulse shape discrimination from the devoted DAMA/NaI-0 data [3]. The latter one acts in the likelihood procedure as an experimental upper bound on the unmodulated component of the signal and – as a matter of fact – as an experimental lower bound on the estimate of the background levels. Thus, the C.L.'s, we quote for the allowed regions, already account for compatibility with the measured differential energy spectrum and with the measured upper bound on recoils.

Fig. 3, 4, 6 show some of the obtained allowed regions; details and

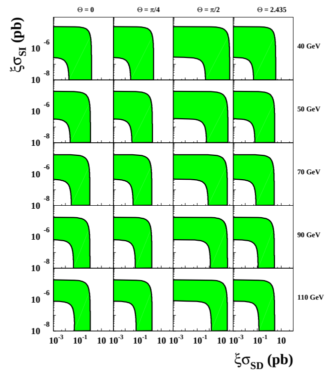

Figure 3: *Case of a WIMP with mixed SI&SD interaction for the model frameworks given in ref. [2].* Coloured areas: example of slices (of the 4-dimensional allowed volume) in the plane $\xi\sigma_{SI}$ vs $\xi\sigma_{SD}$ for some of the possible m_W and θ values. Inclusion of other existing uncertainties on parameters and models would further extend the regions; for example, the use of more favourable form factors and/or of more favourable spin factors than the ones considered here would move them towards lower cross sections. For details see ref. [2].

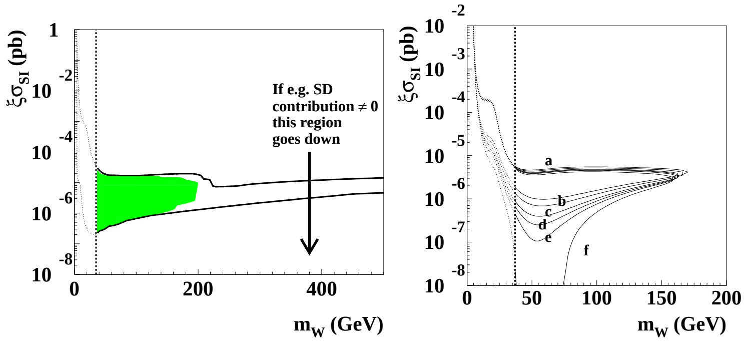

Figure 4: *On the left : Case of a WIMP with dominant SI interaction for the model frameworks given in ref. [2].* Region allowed in the plane (m_W, $\xi\sigma_{SI}$). The vertical dotted line represents a bound in case of a neutralino candidate when supersymmetric schemes based on GUT assumptions are adopted to analyse the LEP data; the low mass region is allowed for neutralino when other schemes are considered (see e.g. refs. [21,22]) and for every other WIMP candidate. While the area at WIMP masses above 200 GeV is allowed only for few configurations, the lower one is allowed by most configurations (the colored region gathers only those above the vertical line). The inclusion of other existing uncertainties on parameters and models would further extend the region; for example, the use of more favourable SI form factor for Iodine alone would move it towards lower cross sections. *On the right: Example of the effect induced by the inclusion of a SD component different from zero on allowed regions given in the plane $\xi\sigma_{SI}$ vs m_W.* In this example the Evans' logarithmic axisymmetric $C2$ halo model with $v_0 = 170$ km/s, ρ_0 equal to the maximum value for this model and a given set of the parameters' values (see ref. [2]) have been considered. The different regions refer to different SD contributions for the particular case of $\theta = 0$: $\sigma_{SD} = 0$ pb (a), 0.02 pb (b), 0.04 pb (c), 0.05 pb (d), 0.06 pb (e), 0.08 pb (f). Analogous situation is found for the other model frameworks. For details see ref. [2].

descriptions of the symbols are given in ref. [2]. Here we only remind that $tg\theta$ is the ratio between the WIMP-neutron and the WIMP-proton effective spin-dependent coupling strengths and that θ is defined in the [0,π) interval. Obviously, larger sensitivities than those reported in the following figures would be reached when including the effect of other existing uncertainties on the astrophysical, nuclear and particle Physics assumptions and related parameters; similarly, the set of the best fit values would also be enlarged as well.

The theoretical expectations in the purely SI coupling for the particular case of a neutralino candidate in MSSM with gaugino mass unification at GUT scale released [22] are also shown in Fig. 5.

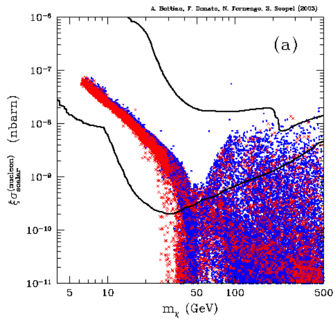

Figure 5: Figure taken from ref. [21]: theoretical expectations of $\xi\sigma_{SI}$ versus m_W in the purely SI coupling for the particular case of a neutralino candidate in MSSM with gaugino mass unification at GUT scale released; the curve is the same as in Fig. 4-*left*.

Specific arguments on some claimed model dependent comparisons can be found in ref. [2]. They already account, as a matter of fact, also e.g. for the more recent model dependent CDMS(-II) claim [24] (based on a statistics of 19.4 kg · day, on data selection and discrimination procedures), where DAMA/NaI is not correctly and completely quoted and the more recent result of the 7 annual cycles [2] is quoted but not accounted for (as also done in some talks at this Conference). In addition, in the particular scenario of [24], uncertainties from the model (from astrophysics, nuclear and particle physics assumptions) as well as some experimental ones (e.g. quenching factor assumed 1, etc.), are not accounted at all and the existing interactions and scenarios to which CDMS is largely insensitive – on the contrary of DAMA/NaI – are ignored. Similar arguments also hold for the EDELWEISS case discussed in this conference.

4 Conclusions and perspectives

DAMA/NaI has been a pioneer experiment investigating as first the WIMP annual modulation signature with suitable sensitivity and control of the running parameters. During seven independent experiments of one year each one, it has pointed out the presence of a modulation satisfying the many peculiarities of an effect induced by Dark Matter particles, reaching a significant evidence. As a corollary result, it has also pointed out the complexity of the quest for a candidate particle mainly because of the present poor knowledge on the many astrophysical, nuclear and particle physics aspects. At present after a devoted R&D effort, the second generation DAMA/LIBRA (a ≃250 kg more radiopure NaI(Tl) set-up) has been realised and put in operation since March 2003. Moreover, a third generation R&D toward a possible ton NaI(Tl) set-up, we proposed in 1996 [25], is in progress.

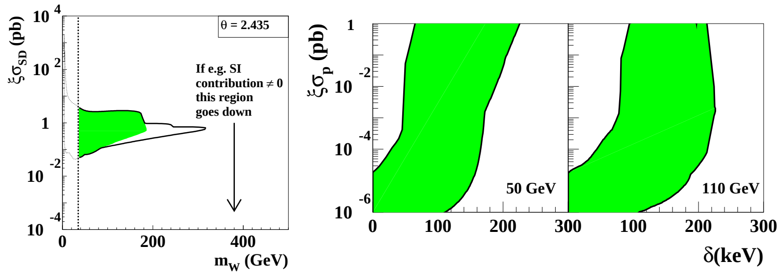

Figure 6: *On the left: Case of a WIMP with dominant SD interaction in the model frameworks given in ref. [2].* Example of a slice (of the 3-dimensional allowed volume) in the plane $(m_W, \xi\sigma_{SD})$ at a given θ value (θ is defined in the $[0, \pi)$ range); here $\theta = 2.435$ (Z_0 coupling). For the definition of the vertical line and of the coloured area see the caption of Fig. 4. Inclusion of other existing uncertainties on parameters and models (as discussed in ref. [2]) would further extend the SD allowed regions. For example, the use of more favourable SD form factors and/or more favourable spin factors would move them towards lower cross sections. Values of $\xi\sigma_{SD}$ lower than those corresponding to this allowed region are possible also e.g. in case of an even small SI contribution (see ref. [2]). *On the right: Case of a WIMP with* preferred inelastic *interaction in the model frameworks given in ref. [2].* Examples of slices (coloured areas) of the 3-dimensional allowed volume $(\xi\sigma_p, \delta, m_W)$ for some m_W values. Inclusion of other existing uncertainties on parameters and models would further extend the regions; for example, the use of more favourable form factors and of different escape velocity would move them towards lower cross sections. For details see ref. [2].

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