WIMPs search by scintillators: possible strategy for annual modulation search with large-mass highly-radiopure NaI(Tl)

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The DAMA experiments are running deep underground in the Gran Sasso National Laboratory. Several interesting results have been achieved so far. Here a maximum likelihood method to search for the WIMP annual modulation signature is discussed and applied to a set of preliminary test data collected with large mass highly radiopure NaI(Tl) detectors. Various related technical arguments are briefly addressed.

1. Introduction.

The DAMA experiments have already achieved several interesting results using various target-detectors. This paper is devoted to discuss an analysis strategy on annual modulation signature; a practical example is performed by using a preliminary data set collected with large-mass highly radiopure NaI(Tl) detectors. Standard assumptions for the WIMP model have been considered. A more extensive discussion on analysis strategies is in [4].

In the direct searches by WIMP-nucleus elastic scattering, the possible presence of a WIMP signal can be extracted from the background by the annual modulation of the WIMP rate in the target-detector. In fact, the expected recoil energy spectrum depends on the WIMP velocity distribution and on the Earth velocity in the galactic frame, \( v_r(t) \), which varies along the year according to the expression: \( v_r(t) = V_{\text{Sun}} + V_{\text{Earth}} \cos \gamma \cos \omega (t-t_0) \). Here \( V_{\text{Sun}} = 232 \) km/s is the Sun velocity with respect to the galactic one; furthermore, \( \omega = \frac{2\pi}{T} \) with \( T = 1 \) year and \( t_0 \approx 2nd \) June (when the Earth speed is at maximum). The WIMP velocity distribution in the galactic halo frame is considered to be a Maxwellian distribution with velocity parameter \( v_0 \) and a cut-off velocity equal to the escape velocity. The Earth velocity can be conveniently expressed in unit of \( v_0 \): \( \eta(t) = v_r(t)/v_0 = \eta_0 + \Delta \eta \cos \omega (t-t_0) \), being \( \eta_0 = 1.05 \) the yearly average of \( \eta \) and \( \Delta \eta = 0.07 \). Since \( \Delta \eta << \eta_0 \), the signal rate in the \( k \)-th energy interval is accurately given by the first order Taylor approximation: \( S_k[\eta(t)] = S_k[\eta_0] + \frac{\partial S_k}{\partial \eta} |_{\eta_0} \Delta \eta \cos \omega (t-t_0) = S_{0,k} + S_{m,k} \cos \omega (t-t_0) \). The contribution from the highest order terms is lower than 0.1%. To select the \( S_{m,k} \) the highest sensitivity is obtained when considering the smallest energy bins allowed by the available statistics and whole year data taking [4]. Although the time dependent effect is expected to be small, a suitable large-mass low-radioactive set-up with an efficient stability monitoring can point out its presence by time correlation analysis. Note that, with the present technology, the annual modulation remains the
main signature of a possible WIMP signal.

2. The experimental data

The data considered here have been collected with nine 9.70 kg NaI(Tl) detectors, part of the 115.5 kg highly radiopure NaI(Tl) set-up now running at the Gran Sasso Laboratory [4]. A description of the detectors considered here and of the shield can be found in [1]. We recall only that each detector is viewed by two low-background EMI photomultipliers working in coincidence at single photoelectron threshold; 2 keV is the software energy threshold. It corresponds in our case to $\gtrsim 11$ photoelectrons (depending on the detector), i.e. well distinguishable from PMT noise. In fact, this last is present as fast, single, spare photoelectrons, while the "physical" pulses have a time distribution with a decay time of hundreds ns.

Figure 1. Measured energy distributions for nine detectors.

A statistics of 4549.0 kgxdays is available for the annual modulation studies: 3363.8 kgxdays

$^1$We comment, in particular, that a pulse shape discrimination — even under the assumption of an "ideal" electromagnetic background rejection — cannot account alone for a WIMP signature. In fact, e.g. the neutrons and the internal end-range $\alpha$'s induce signals indistinguishable from WIMP induced recoils and cannot be estimated and subtracted in any reliable manner at the needed precision.

$^2$We recall in addition that scintillators are not affected by microphonic noise as ionizing and bolometer detectors.

in winter time and 1185.2 kgxdays in summer period. It is distributed along the year in the following way: $-1 \leq \cos \omega (t_i - t_0) \leq -0.334$ in winter time and $0.932 \leq \cos \omega (t_i - t_0) \leq 0.996$ in summer time. It is evident that part of the time was devoted to systematic studies on calibrations and detector features and qualification (more extensively in the winter period, being the starting one), that is all the available low energy data collected at that time have been considered. Obviously the analysis method properly takes into account both the collected low energy statistics and the cosine range in which it has been taken. In fig.1 the measured energy distributions are shown.

The stability control can profit of the $^{210}$Pb peak at 46.5 keV present at level of a few cpd/kg, mainly due to a surface contamination by environmental radon during the first period of crystals storage underground; both the peak position and the resolution are controlled binning together the data every $\approx 7$ days (see fig.2). This allows an intrinsic monitoring of the threshold and of the calibration stability (e.g. PMT gain and electronic line stability).

Figure 2. Typical $^{210}$Pb peak at 46.5 keV (see text).

Note that here we do not consider any pulse shape analysis (PSA) to reject electromagnetic background (see [1]). In fact: i) the PSA has
3. The maximum likelihood method and the quest for a candidate

To determine the cross section and mass of a possible WIMP candidate, a time correlation analysis of all the data — properly considering the time occurrence and energy of each event — has been performed.

The experimental data collected by a j-th detector of mass $M_J$ are considered as grouped in 1-day time bins and in $\Delta E = 1$ keV energy bins; the number of the events in the i-th day and k-th energy bin, $N_{ijk}$, will follow a poissonian statistics with mean value given by $\mu_{ijk} = (b_{jk} + S_{0,k} + S_{m,k}\cos\omega(t_i - t_0))M_J\Delta t_i\Delta E\epsilon_{jk}$, where a time independent background contribution, $b_{jk}$, has been included in addition to the dark matter signal searched for. Here $\Delta t_i$ represents the detector running time during the i-th day ($\Delta t \leq 1$ day) and $\epsilon_{jk}$ represents the analysis cut efficiency. The maximum likelihood function results: $L = \Pi_{ijk}e^{-\mu_{ijk}}(\mu_{ijk}/N_{ijk})^{N_{ijk}}$.

Firstly, to allow a direct simple comparison of the sensitivity reached here with those of previous experiments, the function $y = -2ln(L) - const = \Sigma_k y_k$, can be minimized with respect to $(b_{jk}+S_{0,k})$ and $S_{m,k}$, using for each k-th energy bin the data collected at the same time with the 9 crystals; the $y_k$ can be here minimized independently. The obtained $S_{m,k}$ values are shown in table 1; they point out the relevance of increasing the collected statistics.

However, from this table, a first qualitative view can be also obtained. In fact, e.g. in the first part of the measured energy region, 2-12 keV (where a signal contribution can "a priori" be expected), $S-m>2-12 = (0.037 \pm 0.008)$ cpd/kg/keV is obtained, while in the second one, 12-20 keV (where any signal is "a priori" expected to be suppressed), $S_m>12-20 = (0.000 \pm 0.010)$ cpd/kg/keV is found. The first value qualitatively supports the presence of a possible modulation, requiring therefore a suitable statistical analysis of the data to verify if it can be in total or in part (as quantified later by the C.L. and the $\chi^2$ values) ascribed to a possible WIMP presence, or it can not. The second value well supports the absence of an overall systematics significantly exceeding the statistical error in the interesting energy region.

We stress that here and in a priori the achieved result (see later) is not linked to this qualitative description (that is, it is not linked to any $S-m>2-12$ value), but to the application of the maximum likelihood method on all the available data (2-20 keV) described in the following. Also an unbiased statistical analysis on all the available data at the same time is then performed to obtain quantitative estimates on a possible effect.

The maximum likelihood method is well suitable to test the following hypothesis: the modulated effect qualitatively described above can (or not) be accounted by a WIMP with cross sec-

| Energy (keV) | $S_m$ (cpd/kg/keV) | Energy (keV) | $S_m$ (cpd/kg/keV) |
|------------|------------------|------------|------------------|
| 2-3        | 0.023 ± 0.037    | 11-12      | 0.053 ± 0.027    |
| 3-4        | 0.017 ± 0.030    | 12-13      | 0.015 ± 0.028    |
| 4-5        | 0.036 ± 0.027    | 13-14      | 0.017 ± 0.029    |
| 5-6        | 0.042 ± 0.021    | 14-15      | 0.023 ± 0.030    |
| 6-7        | 0.038 ± 0.022    | 15-16      | -0.045 ± 0.029   |
| 7-8        | 0.003 ± 0.023    | 16-17      | -0.008 ± 0.030   |
| 8-9        | 0.050 ± 0.024    | 17-18      | -0.031 ± 0.029   |
| 9-10       | 0.065 ± 0.025    | 18-19      | 0.002 ± 0.031    |
| 10-11      | 0.032 ± 0.026    | 19-20      | 0.016 ± 0.030    |

Table 1

$S_m$ values obtained by the maximum likelihood method.

\footnote{This first qualitative approach is introduced in \cite{1} during a preliminary discussion on the Freese et al. method; the values were quite similar (see \cite{1} for details).}
tion and mass allowed for instance for the neutrino, assuming a Spin-Independent (SI) interaction and, if it can, at which C.L.. In particular, we refer our results to the quantity $\xi \sigma_p$ with $\xi = \frac{\rho_{WIMP}}{p_0}$, $p_0 = 0.3$ GeV cm$^{-3}$ and $\sigma_p$ WIMP cross section on proton. For this purpose, we note that $S_{0,k}$ and $S_{m,k}$ can be written — pointing out their dependence on $\xi \sigma_p$ and the WIMP mass, $M_w$ — in the form $S_{0,k} = \xi \sigma_p S_{0,k}(M_w)$ and $S_{m,k} = \xi \sigma_p S_{m,k}(M_w)$ respectively. The $S_{0,k}(M_w)$ and $S_{m,k}(M_w)$ can be calculated according to [1] (e.g. besselian form factor, $\xi = 1$, etc.). The $\xi \sigma_p$ and $M_w$ values in the best agreement with the experimental data have been obtained by minimizing here the $y$ function — using all the events with their energy and time occurrence — with respect to the free parameters: $\xi \sigma_p$, $M_w$ and $b_j^p$. A two-step minimization strategy allowed us to handle this large number of parameters. In fact, by a preliminary $y$ minimization the $(b_jk+S_{0,k})=f_{jk}$ values have been determined and then, by a subsequent one, also the $\xi \sigma_p$ and $M_w$ values. In this last step, the conditions $M_w > 25$ GeV and $(b_jk=S_{0,k}) = f_{jk}$ if $\xi \sigma_p \leq \frac{f_{jk}}{S_{0,k}}$ or $(b_jk+S_{0,k}) = \xi \sigma_p S_{0,k}$ otherwise are required, to take into account both the results achieved at accelerators for SUSY particles and the obtained values for the unmodulated term.

The minimum value of the $y$ function has been found for $M_w = (59^{+30}_{-19})$ GeV and $\xi \sigma_p = (1.0^{+0.1}_{-0.4}) \times 10^{-5}$ pb [4].

4. Consistency checks and statistical evaluations

To verify the consistency of this result $M_w$ has been fixed and both $\xi \sigma_p$ and the modulation period, $T$, have been considered as free parameters, obtaining still the previous value for $\xi \sigma_p$ and $T = (1.3^{+0.5}_{-0.3})$ years, a period compatible with a yearly modulation. Then, both $M_w$ and $T$ have been fixed, while $\xi \sigma_p$ and the phase, $t_0$, have been considered as free parameters, obtaining the already found $\xi \sigma_p$ value and $t_0 = (140^{+46}_{-43})$ days, a phase compatible with $\simeq 2^{nd}$ June ($\simeq 153$-th day in the year 1996). The uncertainties on $T$ and $t_0$ are due to the limited available statistics and to the particular periods of data taking. The analysis of the maximum likelihood ratio, $\lambda = \frac{L(H_0)}{L(H_1)}$, has been performed to test the goodness of the null hypothesis $H_0$ (absence of modulation) with respect to the $H_1$ hypothesis (presence of modulation according to the given $M_w$ and $\xi \sigma_p$). From the definition of the $y$ function we obtain $\lambda = e^{[y(H_1)-y(H_0)]/2}$; clearly $0 \leq \lambda \leq 1$. A $\lambda$ value close to 1 will imply absence of modulation, while a $\lambda$ value close to 0 will support the presence of modulation with the given $M_w$ and $\xi \sigma_p$. To perform a quantitative statistical test, one can use the variable $(-2 \ln \lambda)$ which is asymptotically distributed as a $\chi^2$ (high values of $-2 \ln \lambda$ will support presence of modulation). At 90% C.L. the upper tail $\chi^2_0$ is equal to 2.7 for 1 degree of freedom; in our case $-2 \ln \lambda = 3.14 > \chi^2_0$. Therefore the hypothesis of no modulation can be rejected in favour of the hypothesis of modulation with the given $M_w$ and $\xi \sigma_p$ at 90% C.L. At this point the agreement between $H_1$ and the experimental data has been analysed by a $\chi^2$ test comparing the obtained $S_m$ of table 1 with the expected values; a probability of 6%, to obtain — only because of statistical fluctuations — a $\chi^2$ value higher than we found, has been calculated. This probability is mainly limited by the $S_m$ values between 8 and 12 keV, which show up to $\simeq 2\sigma$ fluctuations from the expected ones. It is, therefore, evident the relevance of data now under analysis with a statistics about 7 times larger than the present one. We note that here the — widely considered — Helm SI form factor has been used for iodine [10]; in any case, no relevant effects — within the present errors — on the quoted $M_w$ and $\xi \sigma_p$ were observed when adopting different SI form factors [11].

Moreover, we have also analyzed the NaI(Tl) data with the procedure described above, to test the hypothesis of a modulation effect due to a spin-dependent (SD) coupled WIMP. The calculation has been performed according to [4], but using here for iodine the recently published Ressel SD form factor [12]. In this way no minimum has

\footnote{To have a qualitative view one can overimpose the $S_m$ curve calculated using the found $M_w$ and $\xi \sigma_p$ values on the $S_m$ of table 1; it is evident that the calculated curve is fully under the $S_m$ points and the divergences are quantitatively represented by the poor value for the C.L.}
been found for the $y$ function in the considered mass region. As mentioned above, preliminary results on searches for the annual modulation signature have been also obtained by using a liquid Xenon scintillator (statistics of 408.2 kgxdays) \[2\] and the Canfranc NaI(Tl) detectors (statistics of 1342.8 kgxdays) \[7\]. This last experiment had a poorer sensitivity than the previous one and, to a larger extend, than the present one, mainly because of the higher background rate. Also these experiments considered only the two extreme periods. In particular, to obtain a comparison, we have examined the Xenon result of \[2\]. In this case we have performed a standard best fit on the $S_m$ values, constraining $M_w$ by the accelerator limits and $\xi\sigma_p$ by the more stringent results obtained with the NaI(Tl) detector \[1\]. An indication for $M_w \approx 60$ GeV and $\xi\sigma_p \approx 5 \cdot 10^{-5}$ pb — values compatible with those obtained above — has been found, but with extremely poor C.L.; this could be ascribed to the reduced statistics (a factor $\approx 11$ smaller than the present one) and sensitivity available there.

5. Is it a robust case?

We have always clearly stressed that this preliminary result needs further investigations \[4\], however we are frequently addressed with questions on its "robustness". We can comment that the present statistical evidence, although in the usual range considered in rare event searches, it is not very stringent. Only very large exposure would possibly allow to reach a firm conclusion; similar exposures will be obtained in next future by our experiment, which is continuously running.

A long list of "possible" systematics has been suggested; however, we have to remark that several of them — if present in an experiment — have to be classified as malfunctioning, not as systematics. This is the case e.g. of possible uncontrolled energy threshold and PMT gain variations. We stress, in any case, that systematics is function of the quality of an experiment, therefore its nature and level is generally very different from one experiment to another. On the other hand, in the annual modulation case systematics — if present — can either simulate the presence of an unexisting signal or cancel the presence of a real one; therefore, an "a priori" decision on the role of its possible "generic" presence is arbitrary. In the data taking considered here, we monitor — in addition to the controls by energy calibration - the external environmental radon, the HP $N_2$ flux and the overpressure of the inner Cu box (in which the detectors are), the temperature and the total and single crystal rates over the single photoelectron threshold (i.e. from noise to "infinity"). In fig. 4 examples of the behaviours of some of the parameters in long term are shown.

\begin{figure}[h]
\centering
\includegraphics[width=0.5\textwidth]{figure3.png}
\caption{\(\xi\sigma_p\) versus $M_w$: the region allowed by this preliminary analysis at 90\% C.L. is shown and superimposed on the best upper limit contour for SI interaction, obtained so far \[1,13\].}
\end{figure}

In fig. 3 the region allowed at 90\% C.L. — for a SI coupled candidate — by the obtained $\xi\sigma_p$ and $M_w$ values is shown; the best upper limit contour for SI interaction obtained so far \[1,13\] is superimposed. The shaded region represents the values for $M_w$ and $\xi\sigma_p$ neither excluded by the present analysis nor by the exclusion plot. It has been noted that this region is well embedded in the Minimal Supersymmetric Standard Model (MSSM) estimates for neutralino \[13\].
Figure 4. Example of behaviours of some parameters. From top to bottom: external radon (see text); operating temperature; HP N\textsubscript{2} flux in the Cu box containing the detectors.

toring the rates; c) the operating temperature is controlled and the environmental temperature in the installation is not influenced by external seasonal variations, being conditioned; d) the stability in the 12-20 keV energy region allows to verify that no appreciable variation of neutron, of electromagnetic background and of environmental conditions were present, although it is not clear how all of them could vary with the same period and phase of a possible WIMP signal; e) the external environmental radon is recorded, although two levels of sealing in supronyl (maintained in HP N\textsubscript{2} long stored underground) isolate the shield containing the Cu box in which the detectors are closed. The HP N\textsubscript{2} flux in the Cu box and its overpressure are monitored; f) as regards the "possible modulation" spread over the crystals, for the sake of completeness we recall that the S\textsubscript{m} on single crystals in \textsuperscript{5} have been calculated with another method (see also the comments there). When properly addressed, observations on spread would demonstrate — as first — the necessity of long data taking to avoid the difficult position of possible "tail" effect (see e.g. also other kinds of rare event searches when comparing their results from different periods of data taking). In any case, we remark that the C.L. found in the overall analysis already accounts for the single crystal response (remember the method features and the L function definition); g) the verification of the period and phase of a possible effect by the maximum likelihood method allows to restrict mainly to systematics effects able to induce an annual modulation with 1 year period and \(\approx 2^{nd}\) june phase. Obviously this will be a stronger constraint when almost whole years data taking (periodical calibrations\textsuperscript{5} and others are obviously needed in any case) will be considered. Finally, we recall that an almost whole year statistics, in improved condition, is already under analysis and the experiment is continuously running, therefore in near future most of uncertainties will be — in any case — overcome.

6. Conclusions

Considering both the difficulty and the relevance of this kind of searches, a cautious attitude is mandatory (see \textsuperscript{4}). Here we have presented a bare status report on first experimental data and analysis method. We are now further carefully investigating — with much larger statistics and in improved conditions — the region singled out in fig. 3.

REFERENCES

1. R.Bernabei et al., Phys.Lett.B389(1996),757.
2. P.Belli et al., Il Nuovo Cimento C19 (1996), 537; Nucl.Phys. B48 (1996),62.
3. P.Belli et al., Astrop. Phys. 5 (1996), 217;
   P.Belli et al., Phys. Lett. B387 (1996), 222;
   R.Bernabei et al., Astrop. Phys. 7 (1997), 73.
4. R.Bernabei et al., pre-print ROM2F/97/33, August 1997;
5. Drukier et al., Phys. Rev. D33 (1986), 3495.
6. K.Freese et al., Phys. Rev. D37 (1988), 3388.
7. M.L.Sarsa et al., Phys.Lett.B386(1996),458.
8. P.F.Smith et al., Phys.Lett.B379(1996),299.
9. A.Bottino et al., Phys. Lett. B402 (1997),
   113; A.Gabutti et al., Astrop.Phys. 6(1996),1.
10. R.H.Helm, Phys. Rev. 104 (1956), 1466.
11. J.D.Lewin and P.F. Smith, Astrop. Phys. 6 (1996), 87.

\textsuperscript{5} such as e.g. the time consuming low energy Compton calibrations needed to assure in advance the possibility of performing later also PSA on the collected data\textsuperscript{4}.
12. M.T. Ressel, D.J. Dean. [hep-ph/9702290].
13. D. Reusser et al., Phys. Lett. B255 (1991), 143.
14. A. Bottino et al., pre-print DFTT 49/97, [hep-ph/9709292]. F. Donato, in this volume.