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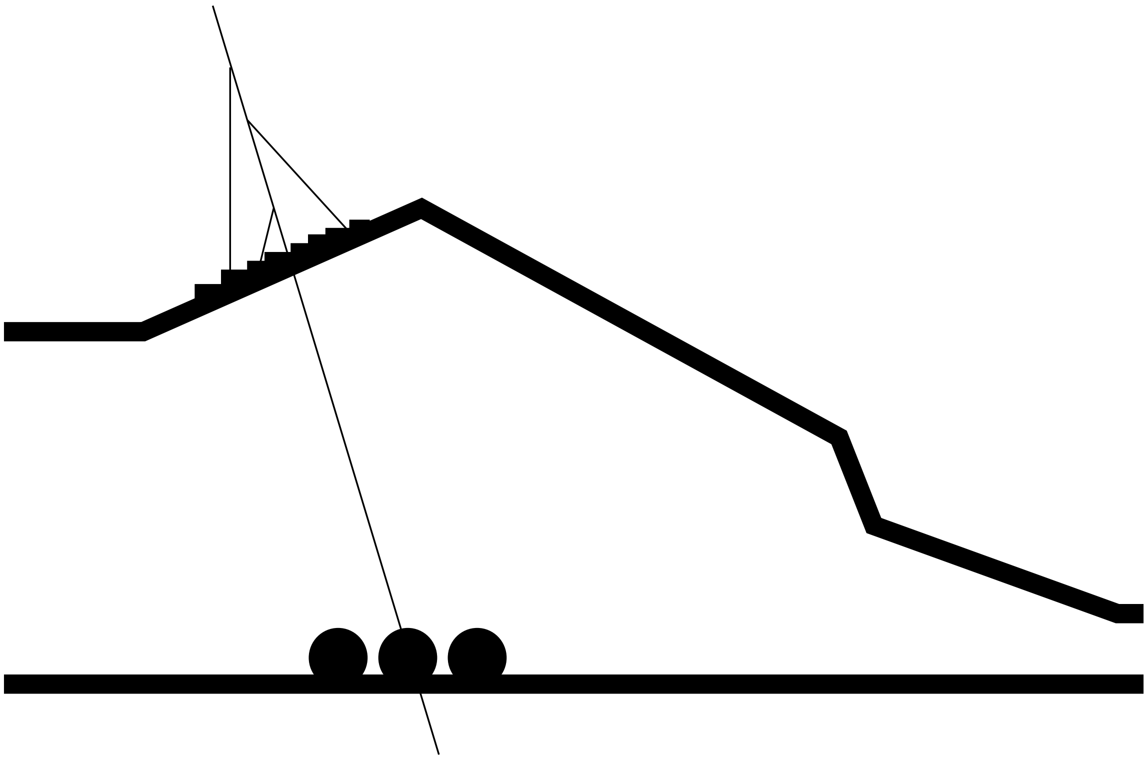

On a further search for a yearly modulation of the rate in particle Dark Matter direct search

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On a further search for a yearly modulation of the rate in particle Dark Matter direct search

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Abstract

The results achieved with a statistics of 14962 kg·day, collected with the large mass highly radiopure DAMA NaI(Tl) set-up, are described and investigated in terms of WIMP annual modulation signature. A maximum likelihood analysis of these data, combined with the statistics of 4549 kg·day previously published (total statistics of 19511 kg·day), favours the hypothesis of presence of an annual modulation at 99.6% C.L.

1 Introduction

The $\simeq$ 100 kg NaI(Tl) DAMA set-up is mainly devoted to the search for an annual modulation of the rate, acting as a signature of a possible relic WIMP contribution [1, 2, 3]. This modulation, due to the Earth's motion around the Sun, would induce — according to the standard WIMP model — a rate variation of $\simeq$ 7% between the two extreme conditions [1, 2, 3].

Results obtained with a statistics of 4549 kg·day (DAMA/NaI-1 running period) have been previously published [3]. In this paper we discuss the results obtained by analysing a further statistics of 14962 kg·day (DAMA/NaI-2 running period). Standard assumptions are considered here for the WIMP model [4]. A detailed description of the radiopurity, of the calibrations, of the efficiencies and of the overall performances of this set-up can be found in ref. [5].

We remark that this new data taking has been performed after a dismounting and remounting of the whole set-up, with some changes in the materials placed nearby the detectors, in the PMTs and in the detectors position with respect to the data taking considered in ref. [3, 6, 7]. The data considered here have been collected about three months after the set-up was reassembled and closed.

2 The experimental data

The present data have been collected with the nine 9.70 kg NaI(Tl) detectors specially built for the annual modulation studies; they are part of the 115.5 kg highly radiopure NaI(Tl) set-up running at the Gran Sasso National Laboratory [3, 5, 6]. Each detector has two 10 cm long tetrasil-B light guides directly coupled to the bare crystal (without any additional window). Two photomultipliers EMI9265-B53/FL collect the light on the two extreme sides; they work in coincidence at single photoelectron threshold and 2 keV is the software energy threshold [3, 5, 6]. The detectors are enclosed in a low radioactive copper box inside a low radioactive shield made by 10 cm of copper and 15 cm of lead; the lead is surrounded by 1.5 mm Cd foils and about 10 cm of polyethylene. A high purity (HP) Nitrogen atmosphere is maintained inside the copper box by a continuous flux of high purity Nitrogen gas from bottles stored deep underground since time. On the top of the shield a glow-box — equipped with a compensation chamber — is directly connected to the Cu box containing the detectors through 4 Cu pipes with O-rings. The glow and Cu boxes are both kept in HP Nitrogen atmosphere with a small overpressure with respect to the external environment. Source holders can be inserted into the pipes to calibrate all the detectors at the same time, avoiding any contact with environmental air. When the source holders are not inserted, Cu bars with O-rings fill completely the pipes and 10 cm of low radioactive Cu and 15 cm of low radioactive Pb are placed in correspondance of each one. The whole shield is wrapped in Supronyl and maintained also in HP Nitrogen atmosphere. The whole installation is subjected to air conditioning, both to assure a suitable working temperature for the electronics and to avoid any possible influence of external seasonal variations (see also later). A hardware/software stability monitoring system is operating; in particular, several probes are read by CAMAC and stored with the production data. Self-controlled computer processes are effective to automatically control the stability parameters and to manage alarms. A much more detailed description of the set-up and of its features can be found in ref.[5]. Here we only recall that the 2 keV software threshold is well supported by the energy calibrations performed with low energy γ sources, by energy calibrations with low energy Compton electrons and by the relatively large available number of photoelectrons/keV [3, 5, 6].

The rejection of the residual noise above the energy threshold profits of the different timing structure between the noise (PMT fast signals with decay times of order of tens ns) and the "physical" (signals with decay times of order of hundreds ns) pulses and it is also enhanced by the number of photoelectrons/keV available here [3, 5, 6]. This rejection can be performed exploiting the distribution function — different for scintillation and noise pulses — of several variables built by using the pulse information recorded over 3250 ns by a Lecroy Transient Digitizer.

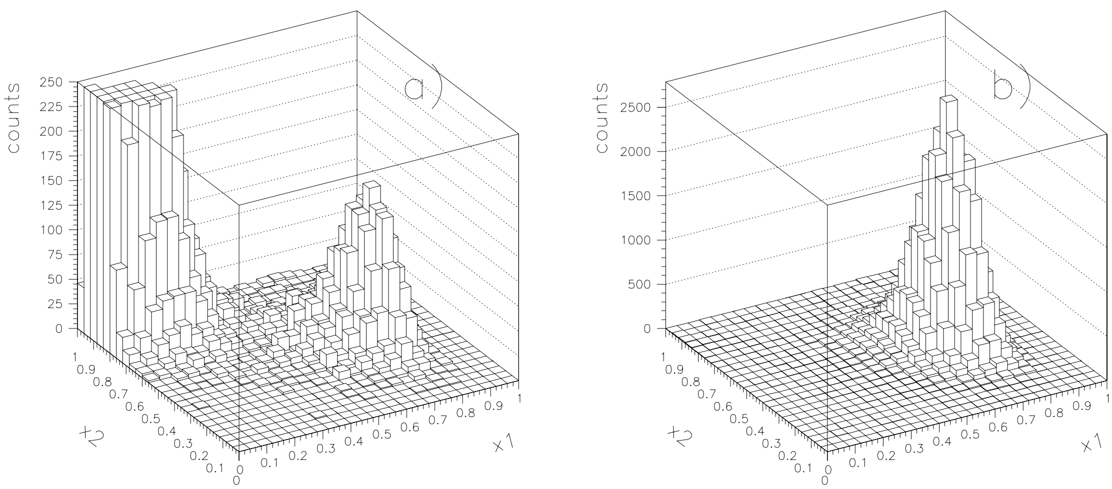

Figure 1: Bidimensional plots for residual noise rejection by using the values of the variables $x1 = \frac{Pulse-Area(from\ 100\ ns\ to\ 600\ ns)}{Pulse-Area(from\ 0\ ns\ to\ 600\ ns)}$ and $x2 = \frac{Pulse-Area(from\ 0\ ns\ to\ 50\ ns)}{Pulse-Area(from\ 0\ ns\ to\ 100\ ns)}$ for each event. a) sample of events from the present production data in the 2-20 keV energy range; b) 2-20 keV data from ^{241}Am source (see text).

As a practical example, in fig. 1 the distribution function of the ratio $x1 = \frac{Pulse-Area(from\ 100\ ns\ to\ 600\ ns)}{Pulse-Area(from\ 0\ ns\ to\ 600\ ns)}$ versus the ratio $x2 = \frac{Pulse-Area(from\ 0\ ns\ to\ 50\ ns)}{Pulse-Area(from\ 0\ ns\ to\ 100\ ns)}$ is shown (fig. 1a) for a data sample of the presently considered production period and (fig. 1b) for ^{241}Am data [5]. In both cases the considered energy range is 2-20 keV. For the first variable the noise events are distributed around zero, while the scintillation pulses are distributed around 0.7; for the second variable indeed the noise events are distributed around 1 and the scintillation events around 0.5[1]. Therefore, the residual noise above the energy threshold can be fully rejected with respect to the scintillation events by applying stringent software cuts. Analysis software cut efficiencies for each considered energy bin can be properly determined by applying the software cuts to the data collected with an ^{241}Am source in the same experimental conditions and energy range (2-20keV) as the production data. This procedure offers clean samples and proper rates by using the overall efficiencies, which are fully dominated by the software cut efficiency (see ref. [5] for a quantitative discussion).

A new statistics of 14962 kg·day is now available for the annual modulation study, corresponding to $\simeq$ 180 days each crystal except for one crystal corresponding to line 8 in fig. 2 ($\simeq$ 90 days). It has been collected roughly from november ($cos\omega(t_i - t_0) = -0.989$) until the subsequent july ($cos\omega(t_i - t_0) = 0.543$). Therefore, these measurements were started in winter period (where a minimum is expected for the modulated possible WIMP signal) towards the summer period (where a maximum is expected).

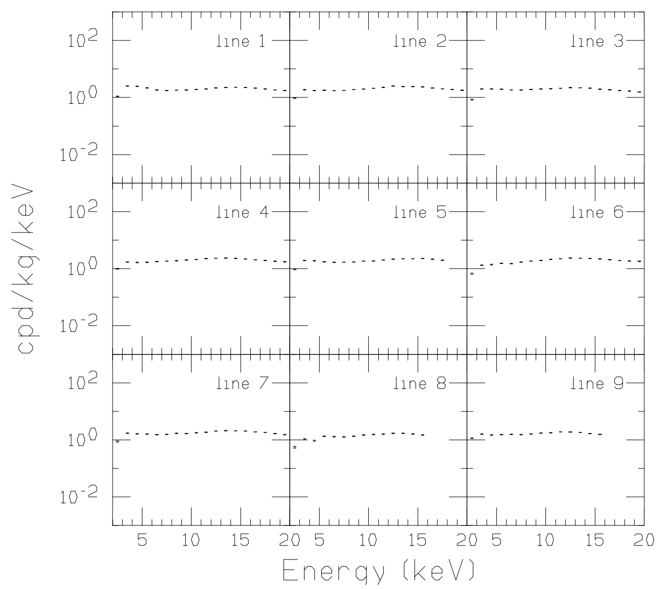

Figure 2: Energy distributions measured by the 9 detectors in the present DAMA/NaI-2 running period; as usual the data have been already corrected for the needed efficiencies. A shorter energy range is shown for the detectors on lines 5,8,9 to exclude saturation effects in this energy range. Note that the numbering order is changed from ref. [3] where a different assembling was used (see sect. 1).

The energy distributions measured during the data taking considered here are shown in fig. 2; they are obviously — as usual in our papers — already corrected for the needed efficiencies.

[1]Qualitatively, hypotizing only one decay costant and a large number of photoelectrons, the expected value for scintillation events should be 0.64 for the first variable and $\simeq$ 0.5 for the second one.

The proper knowledge of the energy calibration was assured by periodical calibrations with ^{241}Am and by monitoring the position and resolution of the ^{210}Pb peak present at level of few cpd/kg in the energy distributions collected by our detectors. This peak is mainly due to a surface contamination by environmental Radon occurred during the first period of the crystals storage deep underground. For this purpose the data are binned in group of $\simeq$ 7 days (see ref. [3]). The distribution of the relative variations of the energy calibration factors (tdcal) estimated from the position of this peak for all the 9 detectors during the whole data taking considered here is shown in fig. 3. The information of the ^{210}Pb peak and the ^{241}Am routine calibrations allow to properly determine the energy scale.

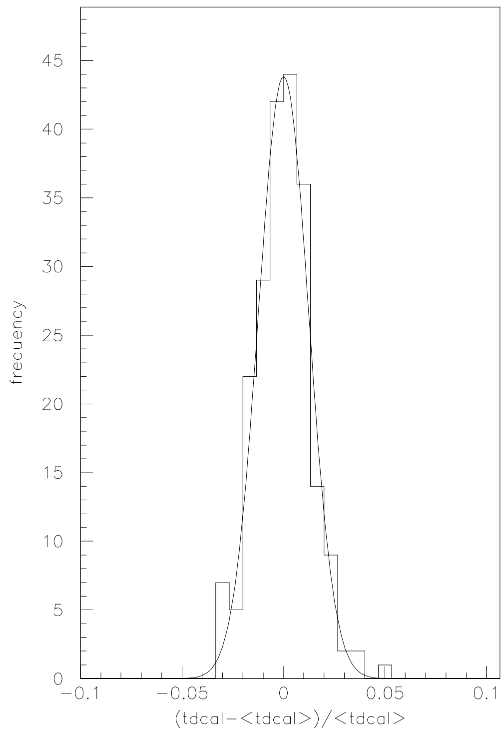

Figure 3: Monitoring of the ^{210}Pb peak stability during the whole data taking period considered here for all the 9 detectors (see text). A gaussian fit is superimposed; it gives $\sigma = (1.24 \pm 0.08)\%$. The information of the ^{210}Pb peak and the ^{241}Am routine calibrations allow to properly determine the energy scale.

To know the set-up working conditions, several parameters are monitored and acquired by CAMAC such as the data. Among them let us remember the level of external environmental Radon (although — as mentioned above — no contact is possible for the detector with the environmental air), the HP N_2 flux and the overpressure of the Cu box in which the detectors are kept, the working temperature and the total and single crystal rates over the single photoelectron threshold (i.e. from noise to "infinity"). In fig. 4 the long term behaviours of some of these parameters are shown. In particular, we comment that sizeable temperature variations could cause a significant systematic contribution to the experimental results only if also the statistical pulse shape analysis (PSA) of the events is used to reject electromagnetic background, which is not the case here. In fact, the PSA is based on the different decay time between recoils and electromagnetic background pulses, this time decay depending on temperature [2]. In a safe annual modulation search, the PSA cannot be used because its statistical nature [6, 8] would affect the annual modulation analysis, that — on the other hand — acts itself as an effective background rejection. In this case, a sizeable temperature variation could only cause a very small light response variation; in fact, around our operating temperature, the average slope of the light output is $\lesssim$ - 0.2%/^{o}C. Therefore, to have a percentage light output variation at level of 2% a variation of 10 ^{o}C is needed; that is, the effect is negligible here considering the possible level of temperature variations (typically fraction of ^{o}C), the energy resolution of the detectors in the keV range and the role of the intrinsic and routine calibrations.

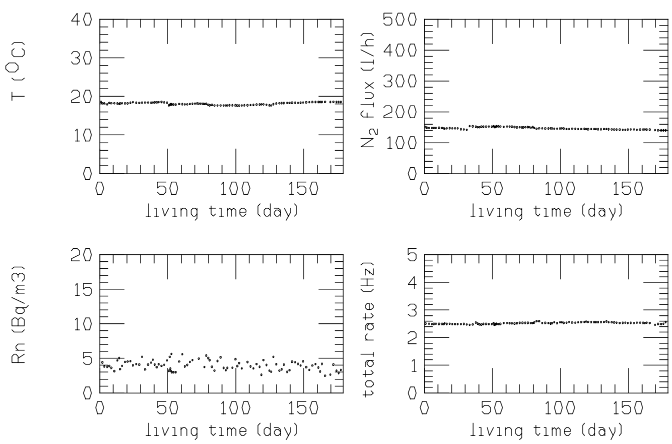

Figure 4: Long term behaviour of some of the monitored parameters during the data taking period considered here, from winter to summer (see text for discussion). Note that total rate means the rate of the OR of the nine crystals above the single photoelectron threshold (i.e. from noise to "infinity").

Finally, although — as described above - our detectors are excluded from environmental air, we examined the behaviour of the external Radon level with time. The fit of this quantity with time gives here for a possible term proportional to the cosine function with 1 year period and the WIMP expected phase a modulated amplitude equal to (-0.02 $\pm$ 0.12) Bq/m^3, evidently consistent with zero. We have also investigated the measured rates at higher energy (above 90 keV); the distribution of their percentage variations with respect to their mean values for single crystal shows a cumulative gaussian behaviour with $\sigma \simeq 1\%$ which is accounted by the expected statistical spread arising from the sampling

[2]A linear variation with a slope of -3ns/^{o}C has been measured in ref. [6] between 17 and 23 ^{o}C; a similar value has been found also in ref. [8], while in the case of ref. [9] -5ns/^{o}C has been empirically estimated and used.

time used there for the rate evaluation. Moreover, fitting the behaviour of this higher energy rate with time, adding also a term modulated according to a cosine function with 1 year period and 152.5 day phase, a value (-0.2 $\pm$ 0.2) cpd/kg has been found for the modulated amplitude, that is consistent with zero. We note that, in case a modulation would be present in the whole energy spectrum at the same level than in the lowest energy region (see later), a modulated term of order of tens cpd/kg should be found in the rate measured above 90 keV (that is from 90 keV to "infinity"); this possibility is excluded by the measured value which is $\simeq$ 100 standard deviations far away. In addition, focusing the attention to an energy region nearer to the one where the possible signal is present (see later), e.g. 10-20 keV, the value (-0.0026 ± 0.0047) cpd/kg/keV is found for the modulated amplitude, still consistent with zero.

3 Data analysis: results and statistical evaluations

Properly considering the time occurrence and the energy of each event, a time correlation analysis of the data collected between 2 and 20 keV has been performed according to the method described in ref. [3]. In this way, the possible presence in the rate of a contribution having the typical features of a WIMP with a dominant spin independent (SI) scalar interaction, modulated by a cosine function with 1 year period and $\simeq 2^{nd}$ june phase, can be effectively tested. This is the case for the most favoured Cold Dark Matter candidate, the neutralino [4].

According to ref. [3], the maximum likelihood function is given by: $\mathbf{L} = \mathbf{\Pi}_{ijk} e^{-\mu_{ijk}} \frac{\mu_{ijk}^{N_{ijk}}}{N_{ijk}!}$. N_{ijk} represents the number of the events in the i-th day, k-th energy bin and j-th detector of mass M_j. It 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 $S_{0,k}$ and $S_{m,k} cos\omega(t_i - t_0)$ are respectively the unmodulated and modulated parts of the signal searched for, while b_{jk} is the background contribution. Here Δt_i represents the detector running time during the i-th day ($\Delta t \leq 1$ day), ϵ_{jk} the efficiencies (see sect. 2) and ΔE = 1 keV. Considering the data collected with all the 9 crystals between 2 and 20 keV, the best fit values of the free parameters are obtained as usual by minimizing the function: $y = -2ln(\mathbf{L}) - const$, where the *const* is chosen such as $y(\sigma_p{=}0){=}0$, being σ_p the WIMP scalar cross section on proton.

We take the occasion to comment that this method — as it is evident from its formal description — allows to extract a possible signal in the energy bins where the sensitivity is maximal (generally at lower energy), while the consistency in the higher energy bins (where a possible signal is fallen down) can offer a further strenght to the result. We also note that the used 1 keV energy bin is a good compromise between an high signal over noise ratio and a suitable statistics.

According to ref. [3] our result is given in term of the quantity $\xi\sigma_p$, where $\xi = \frac{\rho_{WIMP}}{\rho_0}$ with ρ_0 = 0.3 GeVcm^{-3}. The signal contributions $S_{0,k}$ and $S_{m,k}$ can be written in the form: $S_{0,k} = \xi\sigma_p S\prime_{0,k}(M_w)$ and $S_{m,k} = \xi\sigma_p S\prime_{m,k}(M_w)$, pointing out their dependence on $\xi\sigma_p$ and the WIMP mass (M_w). Furthermore, $S\prime_{0,k}(M_w)$ and $S\prime_{m,k}(M_w)$ are calculated according to [6] (e.g. adopting the same astrophysical and detector parameters, the same scaling law for cross sections, the Helm SI form factor for iodine [10], ξ=1, etc.). The $\xi\sigma_p$ and M_w values in the best agreement with the experimental data have been obtained by minimizing the y function with respect to the free parameters: $\xi\sigma_p$, M_w and b'_{jk}s, following the minimization strategy described in ref. [3].

The constraint $M_w \geq 25$ GeV has been imposed to take into account the results achieved at accelerators for neutralino. The minimum value of the y function (see fig. 5) has been found for $M_w = (59^{+22}_{-14})$ GeV and $\xi\sigma_p = (7.0^{+0.4}_{-1.7})10^{-6}$ pb[3].

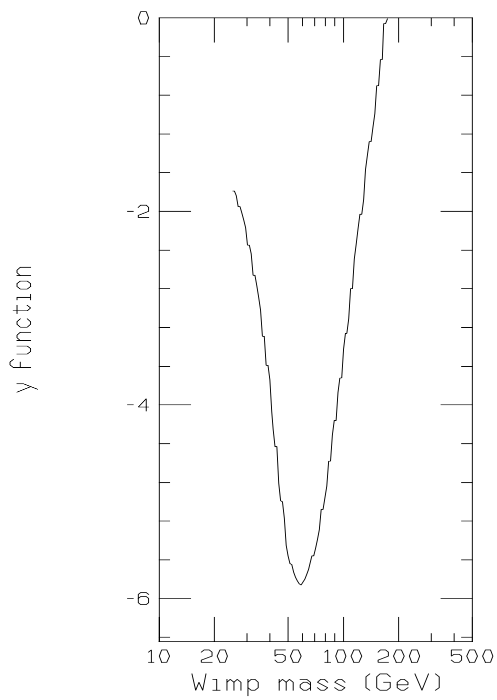

Figure 5: Behaviour of the y function versus the WIMP mass for the data of the DAMA/NaI-2 running period. We remind that the y function is defined in order to have $y = 0$ when no signal is present and that adding 1 (4) to the found y minimum value the bounding at 1σ (2σ) can be obtained.

In table 1 the $S_{0,k}$ and $S_{m,k}$ values — in the region of maximum interest for the possible signal — as obtained by using the above quoted results of the maximum likelihood method, are shown. Above 6 keV negligible $S_{m,k}$ values are present.

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 best fitted M_w and $\xi\sigma_p$) the maximum likelihood ratio, $\lambda = \frac{L(H_0)}{L(H_1)}$ has been considered [3]. From the definition of

[3]As expected, no significant differences in these final results are inferred when applying this method (remind always ΔE=1 keV) to the data collected in other 2keV-E_{max} energy region smaller than the 2-20 keV region considered here, with $E_{max} \gtrsim 6$ keV.

Table 1: The $S_{0,k}$ and $S_{m,k}$ values — in the region of maximum interest for the possible signal — as obtained by using the above quoted results of the maximum likelihood method, are shown. Above 6 keV negligible $S_{m,k}$ values are present.

Energy (keV)	S_o (cpd/kg/keV)	$S_{m,k}$ (cpd/kg/keV)
2-3	0.54 ± 0.15	0.018 ± 0.009
3-4	0.23 ± 0.08	0.012 ± 0.004
4-5	0.09 ± 0.04	0.006 ± 0.002
5-6	0.04 ± 0.02	0.003 ± 0.001

the y function we obtain $\lambda = e^{[y(H_1)-y(H_0)]/2}$; clearly $0 \leq \lambda \leq 1$. To perfom a quantitative statistical test, the variable (-2 lnλ) is used. It is in our case asymptotically distributed as a χ^2 with 1 degree of freedom and its value results here 5.86; this is, therefore, in favour of the hypothesis of the presence of a modulation with the given M_w and $\xi\sigma_p$ at 98.5% C.L.

Furthermore, to test the goodness of the H_1 hypothesis, according to ref. [11] we build the variable $z = \frac{1}{N} \cdot \Sigma_{ijk}[2(\mu_{ijk} - N_{ijk}) + 2N_{ijk}ln(\frac{N_{ijk}}{\mu_{ijk}})]$ where N is the number of considered ijk bins. From our experimental data z comes out to be 1.08 when using the best fitted values for the parameters. The z variable would be a $\chi^2/d.o.f.$ for sufficiently large N_{ijk}, which is not always the case here. To obtain the expected distribution of the z variable, a MonteCarlo code has been realized and 16500 independent experiments with the same statistics as the one presented here have been simulated. For each simulation the parameters b_{jk}, M_w and $\xi\sigma_p$ have been extracted according to the results of the maximum likelihood method, the μ_{ijk} have been calculated and the N_{ijk} have been produced by using a Poissonian distribution. The MonteCarlo distribution of z shows that the probability to get a z value worse than 1.08 is 7.4%.

As an additional check, considering for each detector and for each energy bin the rate $r_{ijk} = \frac{N_{ijk}}{w_{ijk}}$ and its standard deviation $\sigma^*_{ijk} = \frac{\sqrt{N}_{ijk}}{w_{ijk}}$ as a function of the time, we have built the variable $\chi_{test} = \Sigma_{ijk}\frac{(r_{ijk}-r\prime_{ijk})^2}{\sigma^2_{jk}}$ with $r\prime_{ijk} = b_{jk} + S_{0,k} + S_{m,k}cos\omega(t_i - t_0)$ and $\sigma_{jk} =< \sigma^*_{ijk} >_{averaged-on-i}$. It is asymptotically distributed as a χ^2 and can be minimized with respect to the free parameters b_{jk}'s, M_w and $\xi\sigma_p$. To semplify the problem we have defined a function $\chi_{min}(\xi\sigma_p, M_w)$, which is the $\chi_{test}(\xi\sigma_p, M_w, b_{jk})$ after the minimization with respect to the b_{jk}'s. The minimum of this function has been found at: $M_w = (52^{+27}_{-12})$ GeV and $\xi\sigma_p = (7.0^{+0.54}_{-2.0})10^{-6}$ pb, values consistent — within the errors — with the ones obtained by the maximum likelihood method. The corresponding ($\chi_{test,0}$ - χ_{test}) is 5.03, being $\chi_{test,0}$ the value obtained for absence of modulation. In addition, fixing M_w at the found value and considering both $\xi\sigma_p$ and the modulation period T as free parameters, the previous value for $\xi\sigma_p$ is again obtained, while for T the value (1.3 ± 0.4) year is obtained. Fixing indeed both M_w and T, the already found $\xi\sigma_p$ value is obtained, while

t_0 results (140 ± 20) day. These values are largely consistent with 1 year and ∼ 152.5 days, values expected for T and t_0, respectively. Considering the discussion in sect. 2, the search for possible systematics has to be mainly devoted to identify possible effects able to simulate the WIMP signal features. Up to now no candidate effect has been found; in particular, the muon modulation studied in ref. [12] would account roughly only for modulated amplitude $<< 10^{-4}$ cpd/kg/keV, that is much lower than the ones found here and in ref. [3].

In fig. 6 the region allowed at 2 σ C.L. - for a SI coupled candidate - by the obtained $\xi\sigma_p$ and M_w values is shown (continuous contour) superimposed to the upper limit contour for SI coupling obtained with the same detectors using the PSA of the events [6]. The present region is fully embedded in the one preliminarily determined at 90% C.L. (see fig. 6 - dotted contour) in ref. [3] and it is also well embedded in the Minimal Supersymmetric Standard Model (MSSM) estimates for neutralino [4, 14].

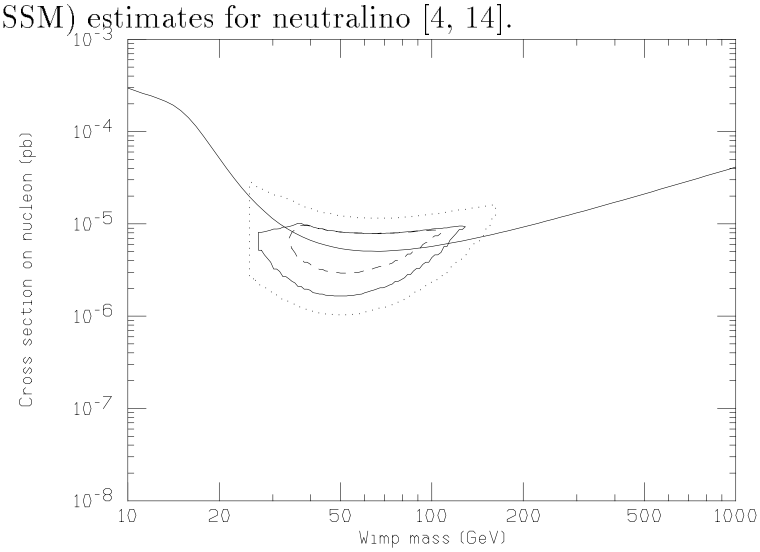

Figure 6: The continuous contour represents the region allowed at 2σ C.L. - for a SI coupled candidate - by the present analysis. It is compared with the 90% C.L. contour achieved in ref. [3] (dotted contour). The present result is fully in agreement with the previous one and offers a more stringent C.L. (see text). The dashed contour represents the region allowed at 2σ C.L. by the combined analysis of the two data taking periods (see text). The SI 90% C.L. exclusion plot obtained by the same experiment, profiting of the PSA of the events [6] is also shown.

We note the consistency of the results obtained here (DAMA/NaI-2 running period) and in ref. [3] (DAMA/NaI-1 running period), although — as stressed in sect. 1 — they have been performed in different operating conditions. At this point we can use the two data sets together analysing them with the maximum likelihood method, properly taking into account that the b_{ijk} for the two running periods can be slightly different (see sect.1). The total statistics is now 19511 kg·day. Following the already described strategy, the minimum value of the y function has been found for $M_w = (59^{+17}_{-14})$ GeV and $\xi\sigma_p = (7.0^{+0.4}_{-1.2})10^{-6}$ pb and the variable (-2 lnλ) results here 8.23, that is in favour of the hypothesis of the presence of a modulation with the given M_w and $\xi\sigma_p$ at 99.6 % C.L.

In fig. 6 the dashed contour represents the region allowed at 2 σ C.L. - for a SI coupled candidate - from the combined analysis of the two running periods.

4 Conclusion

The present analysis, based on a larger statistics, supports the presence of a yearly modulation in the experimental rate measured by $\simeq$ 100 kg highly radiopure NaI(Tl) deep underground in the Gran Sasso National Laboratory. The obtained result in term of possible WIMP candidate is consistent with the one previously achieved in ref. [3] although between the two data takings the detectors in our set-up were dismounted and reassembled with some changes. A maximum likelihood analysis of these data, combined with the statistics of 4549 kg·day previously published (total statistics of 19511 kg·day), favours the hypothesis of presence of an annual modulation at 99.6% C.L. The values singled out by our statistical analysis for the WIMP mass and for the WIMP-proton scalar cross section times the WIMP local density are: $M_w = (59^{+17}_{-14})$ GeV and $\xi\sigma_p = (7.0^{+0.4}_{-1.2})10^{-6}$ pb respectively.

Quantitative investigations of possible sources of random systematics (such as temperature variation) have been performed; furthermore, investigations of yearly modulated possible systematics have not offered up to now any conclusive explanations.

A new large data set is already available for analysis. Moreover, the experiment is continuously running to further investigate this effect over several years; its reproducibility over different cycles should offer the definitive evidence of its nature.

Upgradings of the set-up to increase its performances and sensitivity are already foreseen and in preparation.

5 Aknowledgements

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