Chapter 9

Signature for signals from the dark universe

The DAMA Collaboration
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The DAMA experiment is located at the Gran Sasso National Laboratories of the INFN and is searching for dark matter (DM) particles using various scintillators as target-detector systems. In particular the results, presented here, were obtained by analysing, in terms of the WIMP annual modulation signature, the data collected with the highly radiopure ($\sim$100 kg NaI(Tl)) set-up during four annual cycles (total statistics of 57 986 kg day).

9.1 Introduction

In the past few years, the many experimental and theoretical studies have changed the main question on the DM problem from its existence to the nature of its constituents. The stringent limit on the baryonic part (arising from a comparison between the measured relative abundance of light elements with their expectations in the nucleosynthesis scenario) and the results achieved in investigations of the cosmic microwave background (which have ruled out the pure hot DM scenario) support the view that—whatever the DM composition turns out to be (even if a cosmological constant different from zero is definitively demonstrated)—a large amount of CDM is necessary. This can be in the form of WIMPs or axions.

In particular, the WIMPs should be neutral particles in thermal equilibrium in the early stage of the universe, decoupling at the freeze-out temperature, with a cross section for ordinary matter of the order of or lower than the weak one, forming a dissipationless gas trapped in the gravitational field of the galaxy. To be a suitable WIMP candidate a neutral particle should be stable or have a decay time of the order of the age of the universe. The neutralino, which results in stable MSSM and SUGRA models with R-parity conservation, is at present the more studied candidate; it also remains a good candidate in the case of models without R-parity conservation, if the decay time is of the order of the age of the universe. Other candidates can also be considered; moreover, since this type of search requires investigation beyond the SM of particle physics, the possible nature of WIMPs is, in principle, fully open.

WIMPs can be searched for by direct and indirect techniques. However, we have to remark that significant uncertainties exist in every model-dependent analysis and—as can be easily understood—they are even larger in the indirect approach.

In the following we will focus our attention on some of the main points related to the WIMP direct searches by investigating elastic scattering on target nuclei. As regards investigation of WIMP–nucleus inelastic scattering, we only mention them here [1–3], stressing that much lower counting rates for the signal are expected in this case.

The main strategy to search for these processes effectively is based on the use of low radioactive experimental set-ups located deep underground. Significant improvements in the overall radiopurity of the set-up have been reached over several years of work, the ultimate limit remaining as the sea level activation of the materials. This limitation would, however, be significantly overcome if chemical/physical purifications of the used materials could occur just before their storage deep underground and—even more—if all the operations for detector construction were to be performed deep underground.

Another crucial point (as always in experiments which require a very low energy threshold) is the possibility of identifying and effectively rejecting the residual noise above the considered energy threshold. This problem has obviously to be faced with every type of detector. For most of them the rejection is quite uncertain (also affecting the quoted results), because the noise and the 'physical' pulses have indistinguishable features. In contrast, an almost unique effective noise rejection is possible in scintillators:

(i) when the pulse decay time is relatively long with respect to the fast single photoelectrons from the PMT noise;
(ii) when the number of photoelectrons/keV is really large;
(iii) when the noise contribution from the electronic chain is low; and
(iv) when a sensitive rejection procedure is used.

We note, in addition, that scintillators are unaffected by microphone noise in contrast to ionizing and bolometer detectors.

Although exclusion plots are widely used in practice, many uncertainties arise in comparisons of the results arising from different experiments—even more so when different techniques are used. Furthermore, direct comparison is impossible when different target nuclei are used. To overcome this, it is mandatory to realize experiments with a real signature for the possible signal. If we discard the following possibilities:

(i) a possible comparison between results from different experiments (which can, in principle, be considered since the rate is proportional to A^2 for the spin-independent interactions and to the spin factor for the spin-dependent ones), because e.g. of the relevant role played by the different backgrounds;
(ii) the daily variation of the signal rate [4] (which can, in principle, be considered since the Earth depth crossed by the WIMPs varies during the day inducing a daily variation rate), because this effect is effective only in the case of high cross sections; and
(iii) the correlation of the nuclear recoil track with the Earth's galactic motion (arising from the WIMP velocity distribution), because of the shortness of the induced tracks.

Only the possibility of studying the annual modulation of the WIMP wind [5, 6] remains. This so-called *annual modulation signature* is the annual modulation of the WIMP rate induced by the Earth's motion around the Sun [5–9].

In particular, the DAMA collaboration is performing this investigation with the highly radiopure ~100 kg NaI(Tl) set-up at the Gran Sasso National Laboratory of INFN [7–15].

As has been clearly pointed out by DAMA [7–9, 12, 15], the annual modulation signature is a well-distinguished one, requiring the presence not of a 'generic' rate variation but of a variation according to the following specifications:

(i) the presence of a correlation with the cosine function;
(ii) an appropriate proper period (1 year);
(iii) the proper phase (about 2 June);
(iv) only in a well-defined low-energy region (where WIMP-induced recoils could be significantly present);
(v) for events where only one detector of many actually fires (single 'hit' events) since the probability of a WIMP multi-scattering is negligible (in practice each detector has all the others as a veto);
(vi) with modulated amplitude in the region of maximal sensitivity not exceeding $\lesssim 7\%$.

That all these requirements have been realized by DAMA has been verified by the following actions.

(i) The collection of the whole energy spectrum from single photoelectron to the MeV range;
(ii) the continuous monitoring and control of several parameters; and

(iii) many consistency checks and statistical tests [7–9, 12, 13, 15].

Therefore, to mimic the WIMP annual modulation signature a systematic effect should not only be quantitatively significant, but also able to satisfy the six requirements for a WIMP-induced effect.

In the following, we will summarize only the more recently released results on the WIMP search using the annual modulation signature using the $\simeq$100 kg NaI(Tl) DAMA set-up [12].

However, for the sake of completeness it is worth recalling that the DAMA DM searches are based on the use of

(i) the $\sim$100 kg NaI(Tl) set-up;
(ii) the $\sim$2 l liquid xenon pure scintillator; and
(iii) the CaF_2(Eu) prototypes.

Recent references are, for example, [2, 3, 7–10, 12, 13, 16–21]. Moreover, several results on different topics have also been achieved [11, 14, 17, 19, 22–28].

9.2 The highly radiopure ∼100 kg NaI(Tl) set-up

A detailed description of the DAMA set-up and of its performances is given in [12], while the stability control of the various parameters, the noise rejection, the efficiency, the calibrations, the higher energy stability, the total hardware rate, etc have been discussed in [8, 9, 12, 13, 15]. Nine 9.70 kg NaI(Tl) detectors have been especially built for the experiment on the WIMP annual modulation signature by means of a joint effort with Crismatec company. The materials used for these detectors have been selected—as well as those for the PMTs—by measuring sample radiopurities with low background germanium detectors deep underground in the low background facility of the Gran Sasso National Laboratory [12]. As regards the samples of powders, their U/Th content was measured in Ispra with a mass spectrometer, while their K content was determined in the chemical department of the University of Rome 'La Sapienza' with an atomic absorption spectrometer. A single growth has been used for all the crystals. The crystals are enclosed in a low radioactive copper box inside a low radioactive shield made from 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/paraffin. The copper box is maintained in a nitrogen atmosphere by continuously flushing high-purity nitrogen gas. Each detector is viewed through 10 cm long light guides by two low background EMI9265B53/FL—3 in diameter—PMTs working in coincidences; the hardware threshold for each PMT is at single photoelectron level. The 9.70 kg detectors have tetrasil-B light guides directly coupled to the bare crystals (also acting as windows). Four other crystals of 7.05 kg—originally developed for other purposes—are used as a cut-off for the other detectors and for special triggers; they have tetrasil-B windows and are coupled to the PMTs in one case by tetrasil-B and in the others by noUV-plexiglass light guides. All the crystals

Table 9.1. Released data-sets; the number 1 to 4 refer to different annual cycles.

Period	Statistics (kg day)	Reference
DAMA/NAI-1	4 549	[7]
DAMA/NaI-2	14 962	[8]
DAMA/NaI-3	22 455	[9]
DAMA/NaI-4	16 020	[9]
Total statistics	57 986	[9]
+ DAMA/NaI-0	Limits on recoils fraction by PSD	[10]

have surfaces polished with the same procedure and enveloped in a TETRATEC-4 (Teflon) diffuser such as the light guides.

On the top of the shield a glove-box, maintained in the same nitrogen atmosphere as the Cu box containing the detectors, is directly connected to it through four Cu thimbles in which source holders can be inserted to calibrate all the detectors at the same time without allowing them to enter in direct contact with environmental air. The glove-box is equipped with a compensation chamber. When the source holders are not inserted, the Cu bars completely fill the thimbles. Since this set-up has been realized with the main purpose of studying the annual modulation signature of WIMPs, several parameters are monitored and acquired by CAMAC. A monitoring and alarm system operates continuously by a self-controlled computer processes.

Finally, we recall that the measured low-energy counting rate has been published in various energy intervals [8, 9, 14, 15, 20], while in [26] higher energy regions are shown.

9.3 Investigation of the WIMP annual modulation signature

The present result concerns four years of data-taking for the annual modulation studies, namely DAMA/NaI-1,2,3 and 4 [7–9] for total statistics of 57 986 kg day, the largest statistics ever collected in the field of WIMP search. Moreover, in the final global analysis the constraint, arising from the upper limits on the recoil rate measured in [10] (DAMA/NaI-0), has also been properly included (see table 9.1).

9.3.1 Results of the model-independent approach

In figure 9.1 we show the model-independent residual rate for the cumulative 2–6 keV energy interval as a function of the time [9], which offers immediate evidence for the presence of modulation in the lowest energy region of the experimental data.

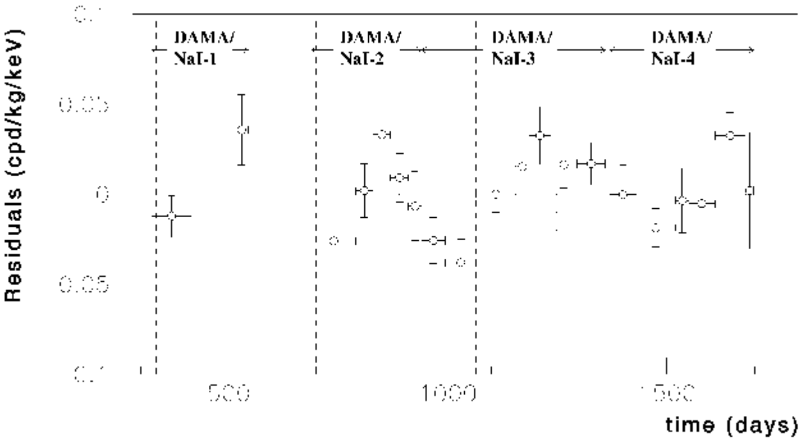

Figure 9.1. Model-independent residual rate in the 2–6 keV cumulative energy interval as a function of the time elapsed since 1 January of the first year of data-taking. The expected behaviour of a WIMP signal is a cosine function with a minimum around the broken vertical lines and with a maximum around the dotted ones.

The χ^2 test of the data in figure 9.1 is not favourable towards the hypothesis of unmodulated behaviour giving a probability of 4×10^{-4}. However, fitting these residuals with the function $A \cos \omega(t - t_0)$ (obviously integrated in each of the considered time bins), one gets for the period $T = 2\pi/\omega = (1.00 \pm 0.01)$ years, when fixing t_0 at 152.5 days and for the phase $t_0 = (144 \pm 13)$ days, when fixing T at 1 year (similar results, but with slightly larger errors, are found when both these parameters are kept free). The modulation amplitude as a free parameter gives $A = (0.022 \pm 0.005)$ cpd kg^{-1} keV^{-1} and $A = (0.023 \pm 0.005)$ cpd kg^{-1} keV^{-1}, respectively. As is evident, the period and the phase fully agree with the ones expected for a WIMP-induced effect.

As we will further comment, this model-independent analysis provides evidence for the possible presence of a WIMP signal independently of the nature of the WIMP and its interaction with ordinary matter. In the following we will briefly summarize the investigation of possible systematics able to mimic such a signature, that is not only quantitatively significant, but also able to satisfy the six requirements given earlier; none has been found. A detailed discussion can be found, for example, in [15].

9.3.2 Main points on the investigation of possible systematics in the new DAMA/NaI-3 and 4 running periods

We have already presented elsewhere the results of the investigations of all the possible known sources of systematics [7–9, 12, 13, 15]; however, in the following we will briefly discuss, in particular, the data from the DAMA/NaI-

3 and DAMA/NaI-4 running periods, which have been recently released [9]; a devoted discussion can be found—as previously mentioned—in [15]. Similar arguments for the DAMA/NaI-1 and DAMA/NaI-2 data have already been discussed elsewhere [7, 8, 13] and at many conferences and seminars.

In our set-up the detectors have been continuously isolated from environmental air for several years; different levels of closures are sealed and maintained in a high-purity nitrogen atmosphere. However, the environmental radon level in the installation is continuously monitored and acquired with the production data; the results of the measurements are at the level of the sensitivity of the used radonmeter. For the sake of completeness, we have examined the behaviour of the environmental radon level with time. When fitting the radon data with a WIMP-like modulation, the amplitudes (0.14 ± 0.25) Bq m^{-3} and (0.12 ± 0.20) Bq m^{-3} are found in the two periods respectively, both consistent with zero. Further arguments are given in [15]. Moreover, we remark that a modulation induced by radon—in every case—would fail some of the six requirements of the annual modulation signature and, therefore, a radon effect can be excluded.

The installation, where the $\sim$100 kg NaI(Tl) set-up operates, is air-conditioned. The operating temperature of the detectors in the Cu box is read by a probe and stored with the production data [12]. In particular, sizeable temperature variations could only induce a light variation in the output, which is negligible considering:

(i) that around our operating temperature, the average slope of the light output is $\lesssim -0.2\%/°\mathrm{C}$;
(ii) the energy resolution of these detectors in the keV range; and
(iii) the role of the intrinsic and routine calibrations [12]; see [15].

In addition, every possible effect induced by temperature variations would fail at least some of the six requirements needed to mimic the annual modulation signature; therefore, a temperature effect can be excluded.

In long-term running conditions, knowledge of the energy scale is ensured by periodical calibration with an ^{241}Am source and by continuously monitoring within the same production data (grouping the data approximately into 7 day batches) the position and resolution of the ^{210}Pb peak (46.5 keV) [7–9, 12, 15]. The distribution of the relative variations of the calibration factor (proportionality factor between the area of the recorded pulse and the energy), *tdcal*—without applying any correction—estimated from the position of the ^{210}Pb peak for all the nine detectors during both the DAMA/NaI-3 and the DAMA/NaI-4 running periods, has been investigated. From the measured variation of *tdcal* an upper limit of $<1\%$ of the modulation amplitude measured at very low energy in [7–9] has been obtained [15].

The only data treatment which is performed on the raw data is to eliminate obvious noise events (which sharply decrease when increasing the number of available photelectrons) present below approximately 10 keV [12]. The noise in our experiment is given by PMT fast single photoelectrons with decay times of the order of tens of nanoseconds, while the scintillation pulses have decay times of the order of hundreds of nanoseconds. The large difference in decay times and the relatively large number of available photoelectrons response (5.5–7.5 photoelectron/keV depending on the detector) ensures effective noise rejection; see, e.g., [12] for details. To investigate quantitatively the possible role of a noise tail in the data after noise rejection on the annual modulation result, the hardware rate, R_{Hj}, of each detector above a single photoelectron, can be considered. The distribution of $\Sigma_j(R_{Hj} - \langle R_{Hj}\rangle)$ shows a Gaussian behaviour with $\sigma = 0.6\%$ and 0.4% for DAMA/NaI-3 and DAMA/NaI-4, respectively, values well in agreement with those expected on the basis of simple statistical arguments. Moreover, by fitting its time behaviour in both data periods including a WIMP-like modulated term a modulation amplitude compatible with zero $(0.04 \pm 0.12) \times 10^{-2}$ Hz, is obtained. From this value, considering also the typical noise contribution to the hardware rate of the nine detectors, the upper limit on the noise relative modulation amplitude has been derived to be [15] less than

$$\frac{1.6 \times 10^{-3}\ \text{Hz}}{9 \times 0.10\ \text{Hz}} \simeq 1.8 \times 10^{-3} \qquad (90\%\ \text{C.L.}).$$

This shows that even in the worst hypothetical case of a 10% contamination of the residual noise—after rejection—in the counting rate, the noise contribution to the modulation amplitude in the lowest energy bins would be less than 1.8×10^{-4} of the total counting rate, that is a possible noise modulation could account only for less than 1% of the annual modulation amplitude observed in [9]. In conclusion, there is no evidence that a hypothetical tail of residual noise after rejection plays any role in the results.

The behaviour of the efficiencies during the whole data-taking periods has also been investigated; their possible time variation depends essentially on the stability of the cut efficiencies, which are regularly measured by dedicated calibrations [9, 15]. In this way, the unlikely idea of a possible role played by the efficiency values in the observed effect in [7–9] has also been ruled out [9, 15].

In order to verify the absence of any significant background modulation, the measured energy distribution in energy regions not of interest for the WIMP–nucleus elastic scattering has been investigated [7–9, 13]. For this purpose, we have considered the rate integrated above 90 keV, R_{90}, as a function of time. The distributions of the percentage variations of R_{90} with respect to their mean values for all the crystals during the whole DAMA/NaI-3 and DAMA/NaI-4 running periods show cumulative Gaussian behaviour with $\sigma \simeq 1\%$, well accounted for by the statistical spread expected from the used sampling time [9, 15]. This result excludes any significant background variation. Moreover, including a WIMP-like modulation in the analysis of the time behaviour of R_{90}, an amplitude compatible with zero is found in both the running periods: $-(0.11 \pm 0.33)$ cpd kg^{-1} and $-(0.35 \pm 0.32)$ cpd kg^{-1}. This excludes the presence of a background modulation in the whole energy spectrum at a level much lower than the effect found in the lowest energy region in [7–9]; in fact, if it were otherwise—considering the R_{90} mean values—the modulated term should be of the order of tens of cpd kg^{-1}, that is $\sim 100\sigma$ far away from the measured value. This also accounts for the neutron environmental background; see for further arguments [15]. A similar analysis performed in other energy regions, such as the one just above the first pole of the iodine form factor, leads to the same conclusion.

As regards possible side reactions, the only process which has been found as a hypothetical possibility is the muon flux modulation reported by the MACRO experiment [29]. In fact, MACRO has observed that the muon flux shows a nearly sinusoidal time behaviour with a 1 year period and with a maximum in the summer with amplitude of $\sim 2\%$; this muon flux modulation is correlated with the temperature of the atmosphere. This effect would give, in our set-up, modulation amplitudes much less than 10^{-4} cpd kg^{-1} keV^{-1}, that is much smaller than we observe. Moreover, it will also fail some of the six requirements necessary to mimic the signature. Thus, it can be safely ignored [15]. The search for other possible side reactions able to mimic the signature has so far not offered any other candidate.

For the sake of completeness, we recall that—using pulse shape discrimination—no evidence for the anomalous events with a decay time shorter than the recoils has ever been found in our data [10, 15].

As a result of the model-independent approach and a full investigation of known systematic effects, the presence of an annual modulation compatible with WIMPs in the galactic halo indocates that WIMPs are possible candidates to account for the data, independently of their nature and coupling with ordinary matter.

In the next section a particle candidate will be investigated; for that a model is needed as well as an effective energy and time correlation analysis. We take this occasion to remark that a large scenario exists in the model-dependent analyses not only because various candidates with different couplings can be considered but also because of the large uncertainties affecting several parameters involved in the calculation which are generally neglected, although they should generally play a significant role.

9.3.3 Results of a model-dependent analysis

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 [7–9]. This allows us to test effectively the possible presence in the rate of a contribution having the typical features of a WIMP candidate. In particular we have considered a particle with a dominant spin-independent scalar interaction (which is also possible for the neutralino [30]). A detailed discussion is available in [9]; here the main result is outlined. In the minimization procedure by the standard maximum likelihood method [7–9] the WIMP mass has been varied from 30 GeV up to 10 TeV; the lower bound accounted for results achieved in accelerators. The calculations have been performed according to the same astrophysical, nuclear and particle physics considerations given in [7–9] and to the 90% C.L. recoil limit of [10] (DAMA/NaI-0). Alternative analytical approaches, such as the one based on the χ_{test} variable described in [8] and the Feldman and Cousins method [31], offer substantially the same results.

Since the analysis of each data cycle independently [7–9, 13] gave consistent results, a global analysis has been made properly including both the known uncertainties on astrophysical local velocity, v_0 [21] and the constraint arising from the upper limit on recoils measured in [10] (DAMA/NaI-0). According to [21], the minimization procedure has been repeated by varying v_0 from 170 to 270 km s^{-1} to account for its present uncertainty; moreover, the case of possible bulk halo rotation has also been analysed. The positions of the minima for the log-likelihood function consequently vary [21]; for example, in this model framework for $v_0 = 170$ km s^{-1} the minimum is at $M_{\mathrm{W}} = (72^{+18}_{-15})$ GeV and $\xi\sigma_{\mathrm{p}} = (5.7 \pm 1.1) \times 10^{-6}$ pb, while for $v_0 = 220$ km s^{-1} it is at $M_{\mathrm{W}} = (43^{+12}_{-9})$ GeV and $\xi\sigma_{\mathrm{p}} = (5.4 \pm 1.0) \times 10^{-6}$ pb. The results obtained in this model framework are summarized in figure 9.2, where the regions allowed at 3σ C.L. are shown:

(i) when $v_0 = 220$ km s^{-1} (dotted contour);
(ii) when the uncertainty on v_0 is taken into account (continuous contour); and
(iii) when possible bulk halo rotation is considered (broken contour).

The latter two calculations have been performed according to [21]. The confidence levels quoted here have also been verified by suitable Monte Carlo calculations; in particular, we note that the Feldman and Cousins analysis [31] of the data gives quite similar results. These regions are well embedded in the Minimal Supersymmetric Standard Model (MSSM) estimates for the neutralino [32]. A quantitative comparison between the results from the model-independent and model-dependent analyses has been discussed in [9].

Finally, many assumptions on the nuclear and particle physics used in these calculation (as well as in those of exclusion plots) are affected by uncertainties, which—when taken into account—would enlarge the regions of figure 9.2 and, as mentioned, consequently vary the positions of the minima for the log-likelihood function. For example, as in [9] we mention the case of the iodine form factor, which depends on the nuclear radius and on the thickness parameter of the nuclear surface; it has been verified that, varying their values with respect to those used in the analysis in [9] by 20%, the locations of the minima will move toward slightly larger M_{W} and toward lower $\xi\sigma_{\mathrm{p}}$ values, while the calculated 2–6 keV S_{m} values will increase by about 15%.

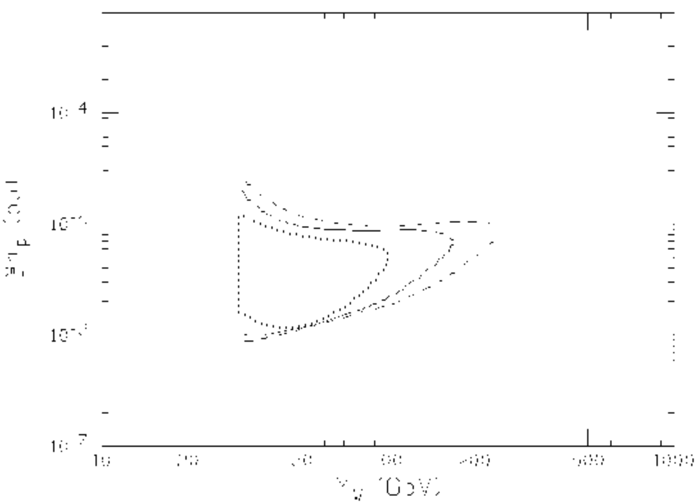

Figure 9.2. Regions allowed at 3σ C.L. in the plane $\xi\sigma_{\mathrm{p}}$ ($\xi = \frac{\rho_{\mathrm{WIMP}}}{0.3\ \mathrm{GeV\ cm^{-3}}}$ and σ_{p} = WIMP scalar cross section on proton) versus M_{W} (WIMP mass) by the global analysis: (i) for $v_0 = 220\ \mathrm{km\ s^{-1}}$ (dotted contour); (ii) when accounting for v_0 uncertainty ($170\ \mathrm{km\ s^{-1}} \le v_0 \le 270\ \mathrm{km\ s^{-1}}$; continuous contour); and (iii) when considering also a possible bulk halo rotation as in [21] (broken contour). The constraint arising from the measured upper limit on recoils measured in [10] has been properly taken into account. We note that the inclusion of present uncertainties on some nuclear and particle physics parameters would enlarge these regions since the positions of the minima for the log-likelihood function would consequently vary; full estimates are in progress.

9.4 DAMA annual modulation result versus CDMS exclusion plot

As is well known, intrinsic uncertainties exist in the comparison of results achieved by different experiments and, even more, when different techniques are used as in the case of DAMA [7–9] and of CDMS [33]. In fact, DAMA is searching for a distinctive signature by using a large mass NaI(Tl) set-up deep underground, while CDMS is exploiting a widely unknown hybrid bolometer/ionizing technique at a depth of 10 m to reject a huge background. Moreover, always when different target nuclei are used (as is also the case in DAMA and CDMS), no absolute comparison can be pursued at all; only model-dependent comparisons can be considered with further intrinsic uncertainties. In table 9.2 a few numbers are given to offer an immediate view on the two experiments.

The techniques used by CDMS would require several technical papers to be credited at the necessary level (quenching factor values, sensitive volumes, windows for rejection, efficiencies, energy calibrations, etc; the stability of

Table 9.2. Several numbers on the DAMA and CDMS experiments as in [9, 33].

	DAMA	CDMS
Exposure	57 986.0 kg day	10.6 kg day
Depth	1400 m	10 m
Number of events in the observed effect	Total modulated amplitude $\sim$2000 events	13 evt in Ge, 4 evts in Si 4 multiple evts in Ge + Monte Carlo on neutron flux

these quantities during the running period; justification of the performed data selection; quantitative control of systematic uncertainties in the various hardware and software handlings), which have not been made available. Every small deviation from the assumptions used by CDMS in [33] can significantly change their conclusion.

The exclusion plot quoted by CDMS [33] arises from the joint analyses of two different experiments with two different target nuclei (Si and Ge) and, practically, by a neutron Monte Carlo subtraction.

In the Si experiment (used exposure was $\sim$1.5 kg day of the $\sim$3.3 kg day available) a large number of events survived the ionizing/heat discrimination in the whole energy region allowed for recoil candidates. Thereafter, by the so-called athermal pulse shape discrimination, four events remained and were classified as 'mostly neutrons', while all the others as 'surface electrons'. The amount and the Y (ratio between ionizing and heat charges) and energy distributions of the latter ones give a hint that the four 'mostly neutrons' events could indeed be—all or partially—ascribed to the tail of the huge population of 'surface electrons' surviving the ionizing/heat discrimination. Obviously this possibility would significantly change the conclusions in [33].

In the Ge experiment (used exposure was $\sim$10.6 kg day of the $\sim$48 kg day available for three Ge detectors, having already excluded a fourth detector), 13 recoil candidates survive the ionization/heat discrimination. This number of events is largely compatible with the DAMA allowed region estimated in [9] in the framework of a model for a spin-independent candidate with mass above 30 GeV. The interpretation on the real nature of these 13 candidates strongly depends on the Monte Carlo estimates of the neutron background, which is constrained by the hypothesized nature of the four Si candidates and of four multi-hit events. A similar procedure is strongly uncertain since it is based on the previously mentioned assumptions and on the neutron transport code; the latter—as is widely known—is affected by huge uncertainties due to the assumptions on the original neutron energy spectrum and to the transport calculations in all the involved materials. This can be verified by considering that the result of such a calculation gives in [33] about 30 expected neutrons to be compared with the 13 quoted recoil candidates; this, in particular, can suggest an overestimate of the neutron background and, therefore, of the given exclusion plot.

Summarizing we can state that the CDMS result can be expressed by the combination of two quantities: the real number of recoil candidates (when accounting for realistic values of the physical parameters) and the expected number of neutron background. Varying these quantities several different conclusions can be obtained. In every case, a CDMS representative has stated that analysing these data to determine their compatibility with DAMA, the result gives an upper limit for presence of WIMPs in CDMS Ge data of eight events at 90% C.L. [34], evidently compatible with the DAMA allowed region in the model considered in [9]. Moreover, simple calculations assuming again ideal values for the CDMS physical parameters and the values measured for the related quantities in our experiment [7–10, 12] show that in the framework of the model of [9], CDMS should measure from $\sim$15 events down to less than 1, that is compatibility is still substantially present.

Moreover, we note that the comparison through a model requires, for each considered target nucleus, fixing not only the coupling and the scaling laws, but also several specific different nuclear and particle physics parameters, which are affected instead by uncertainties. The same is for the choice of the astrophysical model, such as the WIMP velocity distribution and the various related parameters. For example if the real WIMP velocity distribution should be such as to enhance, to a certain extent, the modulated part of the signal with respect to the unmodulated one, a comparison in the framework of usual assumptions would fail. The same would hold if the candidate were to have a partial (or total) spin-dependent interaction component (as is also possible for the neutralino) and one of the two experiments is insensitive to spin-dependent interactions (such as practically those using natural Ge). Several other scenarios could also be considered.

For the sake of completeness, we note that in [33] the complete DAMA result has not been considered.

Briefly, many experimental and theoretical reasons do not support the conclusion of [33] to the necessary extent.

9.5 Conclusion

In conclusion, a WIMP contribution to the measured rate is a candidate by the model-independent approach and by the absence of any known systematics able to mimic the signature [7–9, 13, 15] independently of the nature and coupling of the possible particle. The complete global correlation analysis in terms of a spin-independent candidate with a mass greater than 30 GeV favours modulation at approximately 4σ C.L. in the given framework [9]. Moreover, neutralino configurations in the allowed region appear to be of cosmological interest [32].

In [35] a possible heavy neutrino of the fourth family has been considered instead. Further studies on model frameworks are in progress.

The data for a fifth annual cycle are now at hand, while new electronics and data acquisition systems were installed in August 2000. Moreover, after new dedicated R&D for the radiopurification of NaI(Tl) detectors, efforts to increase the experimental sensitivity are in progress; the target mass will become approximately 250 kg.

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