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Investigating the DAMA annual modulation data in the framework of inelastic dark matter

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Abstract. In this paper, the model independent annual modulation effect observed by DAMA during four independent experiments of one annual cycle each (57986 kg × day total statistics) is analysed in terms of a particle dark matter candidate which can only inelastically scatter by making a transition to a slightly heavier state, as previously suggested in the literature.

1 Introduction

It has recently been suggested [1] that it is possible that the annual modulation of the low energy rate observed by the $\simeq$ 100 kg NaI(Tl) DAMA set-up [2–8] running deep underground in the Gran Sasso National Laboratory of I.N.F.N. could be induced by possible inelastic dark matter: relic particles that cannot scatter elastically off of nuclei. As discussed in [1], the inelastic dark matter could arise from a massive complex scalar split into two approximately degenerate real scalars or from a Dirac fermion split into two approximately degenerate Majorana fermions, namely χ_+ and χ_-, with a δ mass splitting. In particular, a specific model featuring a real component of the sneutrino, in which the mass splitting naturally arises, has been given in [1].

The discussion of the theoretical arguments on such inelastic dark matter can be found in [1]. In particular, it has been shown that for the χ_- inelastic scattering on target nuclei a kinematical constraint exists which favours heavy nuclei (such as ^{127}I) with respect to lighter ones (such as e.g. $^{\rm nat}$Ge) as target–detectors media. In fact, χ_- can only inelastically scatter by transitioning to χ_+ (a slightly heavier state than χ_-) and this process can occur only if the χ_- velocity, v, is larger than

$$v_{\rm thr} = \sqrt{\frac{2\delta}{m_{\rm WN}}}, \tag{1}$$

where $m_{\rm WN}$ is the WIMP–nucleus reduced mass and here and hereafter $c = 1$. This kinematical constraint becomes increasingly severe as the nucleus mass, m_N, is decreased [1]. For example, if $\delta \gtrsim 100$ keV, a signal rate measured e.g. in iodine will be a factor about 10 or more higher than that measured in Ge [1]. Moreover, this model scenario implies some characteristical features when exploiting the WIMP annual modulation signature [9]; in fact – with respect to the case of WIMP elastically scattering – it gives rise to an enhanced modulated component, $S_{\rm m}$, with respect to the unmodulated one, S_0, and to largely different behaviours with energy for both S_0 and $S_{\rm m}$ (both show a higher mean value) [1].

For the sake of completeness, we recall that – as stressed in [1] – this scenario is suitable to reconcile in every case the DAMA [2,4–8] and CDMS-I [10] results; however, it is worth to note that – as discussed e.g. in Sect. III of [11] – in reality the claim of a contradiction made by CDMS-I was largely unjustified both for experimental and theoretical reasons.

Anyhow, the proposed inelastic dark matter scenario [1] offers a further possible model framework, which has also the merit that it recovers the sneutrino as a WIMP candidate. Therefore, to quantitatively exploit it we present in this paper the results of a dedicated energy and time correlation analysis of the DAMA experimental data collected by the $\simeq$ 100 kg NaI(Tl) DAMA set-up [2,4–8]. These data show a model independent annual modulation of the low energy counting rate with proper features and have been already analysed both in terms of a WIMP with dominant spin independent (SI) interaction [6] and in terms of a WIMP with mixed spin independent/spin dependent interaction [8] for given model frameworks[1].

[1] We remind the reader that a model framework is identified not only by the general astrophysical, nuclear and particle physics assumptions, but also by the set of parameter values used (such as WIMP local velocity, v_0, form factor parameters, etc.). In fact, the latter ones are generally taken at fixed values while they are instead affected by significant uncertainties

At present, both these scenarios can hold as well as the purely spin dependent (SD) one[2].

The experimental set-up has been described in detail in [3], while a complete investigation of possible systematics has been given in [7].

2 Detection rates of inelastic scattering

As mentioned above the investigation of the WIMP annual modulation signature can offer model independent evidence for a WIMP component in the galactic halo [7]. The identification of the nature of such a particle is instead model dependent as well as any possible exclusion region from other methods of WIMP search.

The process considered in the following is the WIMP–nucleus inelastic scattering and the related quantity measured in underground set-ups is the recoil energy.

The differential energy distribution of the recoil nuclei can be calculated by means of the differential cross section of the WIMP–nucleus inelastic processes:

$$\frac{\mathrm{d}\sigma}{\mathrm{d}\Omega^*} = \frac{G_\mathrm{F}^2 m_\mathrm{WN}^2}{\pi^2}\left[Zg_\mathrm{p} + (A-Z)g_\mathrm{n}\right]^2 F_\mathrm{SI}^2(q^2) \times \sqrt{1 - \frac{v_\mathrm{thr}^2}{v^2}}, \quad (2)$$

where G_F is the Fermi coupling constant; $\mathrm{d}\Omega^*$ is the differential solid angle in the WIMP–nucleus c.m. frame; Z is the nuclear charge and A is the atomic number; $g_\mathrm{p,n}$ are the effective WIMP-nucleon couplings for SI interactions; $F_\mathrm{SI}^2(q^2)$ the SI form factors [14], and q^2 is the squared three-momentum transfer.

In the inelastic process the recoil energy depends on the scatter angle, θ^*, in the c.m. frame according to

$$E_\mathrm{R} = \frac{2m_\mathrm{WN}^2 v^2}{m_\mathrm{N}} \cdot \frac{1 - \frac{v_\mathrm{thr}^2}{2v^2} - \sqrt{1 - \frac{v_\mathrm{thr}^2}{v^2}} \cdot \cos\theta^*}{2}. \quad (3)$$

Thus, we can write

$$\mathrm{d}E_\mathrm{R} = \frac{2m_\mathrm{WN}^2 v^2}{m_\mathrm{N}} \cdot \sqrt{1 - \frac{v_\mathrm{thr}^2}{v^2}} \cdot \frac{\mathrm{d}\Omega^*}{4\pi}. \quad (4)$$

From (2) and (4) we derive the differential cross section as a function of the recoil energy E_R and the WIMP velocity v:

$$\frac{\mathrm{d}\sigma}{\mathrm{d}E_\mathrm{R}}(v, E_\mathrm{R}) = \frac{2G_\mathrm{F}^2 m_\mathrm{N}}{\pi v^2}\left[Zg_\mathrm{p} + (A-Z)g_\mathrm{n}\right]^2 F_\mathrm{SI}^2(E_\mathrm{R}). \quad (5)$$

Here we apply the relation $q^2 = 2m_\mathrm{N}E_\mathrm{R}$.

The minimal WIMP velocity, $v_\mathrm{min}(E_\mathrm{R})$, providing E_R, the recoil energy in the inelastic process, is

$$v_\mathrm{min}(E_\mathrm{R}) = \sqrt{\frac{m_\mathrm{N}E_\mathrm{R}}{2m_\mathrm{WN}^2}} \cdot \left(1 + \frac{m_\mathrm{WN}\delta}{m_\mathrm{N}E_\mathrm{R}}\right), \quad (6)$$

and it is always $\geq v_\mathrm{thr}$.

Finally, setting the WIMP local density, $\rho_\mathrm{W} = \xi\rho_{0.3}$ ($\rho_{0.3} = 0.3\,\mathrm{GeV\,cm^{-3}}$ and ξ equal to the WIMP local density in units of $\rho_{0.3}$), and the WIMP mass, m_W, one can write the energy distribution of the recoil rate (R) in the form

$$\frac{\mathrm{d}R}{\mathrm{d}E_\mathrm{R}} = N_\mathrm{T}\frac{\rho_\mathrm{W}}{m_\mathrm{W}}\int_{v_\mathrm{min}(E_\mathrm{R})}^{v_\mathrm{max}} \frac{\mathrm{d}\sigma}{\mathrm{d}E_\mathrm{R}}(v, E_\mathrm{R}) v f(v)\mathrm{d}v = N_\mathrm{T}\frac{\rho_{0.3}\cdot m_\mathrm{N}}{2m_\mathrm{W}\cdot m_\mathrm{Wp}^2}\cdot A^2\xi\sigma_p F_\mathrm{SI}^2(E_\mathrm{R})\cdot I(E_\mathrm{R}). \quad (7)$$

Here N_T is the number of target nuclei; m_Wp is the WIMP-nucleon reduced mass; v_max is the maximal WIMP velocity in the halo evaluated in the Earth frame; $I(E_\mathrm{R}) = \int_{v_\mathrm{min}(E_\mathrm{R})}^{v_\mathrm{max}} \mathrm{d}v(f(v)/v)$ with $f(v)$ the WIMP velocity distribution in the Earth's frame [15,5]. In the following, we assume as a halo model the simple isothermal sphere and maxwellian WIMP velocity distribution; in such a case, the explicit expression of $I(E_\mathrm{R})$ can be inferred from the formulae given in [13] as well as the annual dependence of the WIMP rate. It is worth to note that several other approaches can be considered implying a further enlargement of the allowed regions. Moreover, as derived in [8], $\sigma_\mathrm{p} = (4/\pi)G_\mathrm{F}^2 m_\mathrm{Wp}^2 g^2$ is a generalized SI point-like WIMP–nucleon cross section. The coupling g is a function of g_p and g_n and can be written [8]

$$g = \frac{[Zg_\mathrm{p} + (A-Z)g_\mathrm{n}]}{A} = \left(\frac{g_\mathrm{p}+g_\mathrm{n}}{2}\right)\left[1 - \frac{g_\mathrm{p}-g_\mathrm{n}}{g_\mathrm{p}+g_\mathrm{n}}\left(1 - \frac{2Z}{A}\right)\right].$$

Thus, it can be assumed – in a first approximation – to be independent on the used target nucleus since Z/A is nearly constant for the nuclei typically used in WIMP direct searches. The extension of formula (7) e.g. to detectors with multiple nuclei can be easily derived.

Finally, the Earth's velocity in the Galactic frame can be written

$$v_\mathrm{e} = v_\mathrm{sun} + v_\mathrm{orb}\cos\gamma\cos[\omega(t - t_0)], \quad (8)$$

where $v_\mathrm{sun} = v_0 + 12\,\mathrm{km/s}$ with v_0 the local velocity, $v_\mathrm{orb} = 30\,\mathrm{km/s}$, $\omega = 2\pi/\mathrm{year}$ and $t_0 \simeq$ June 2nd and $\cos\gamma \simeq 0.5$. Thus, the expected detection rate in a given energy bin, ΔE with index k, can be written as the sum of a time independent contribution plus a time dependent one [9]:

$$S_k = S_{0,k} + S_{m,k}\cdot\cos[\omega(t - t_0)]. \quad (9)$$

The $S_{0,k}$ and $S_{m,k}$ are functions of $\xi\sigma_\mathrm{p}$, m_W and δ.

3 Data analysis and results

By considering the data collected during four annual cycles (statistics of 57986 kg $\times$ day) [2,4–8], we have performed a maximum likelihood analysis exploring the energy and time dependence of the events and considering

[2] We recall that the claim against a pure SD coupled candidate made in [12] is incorrect

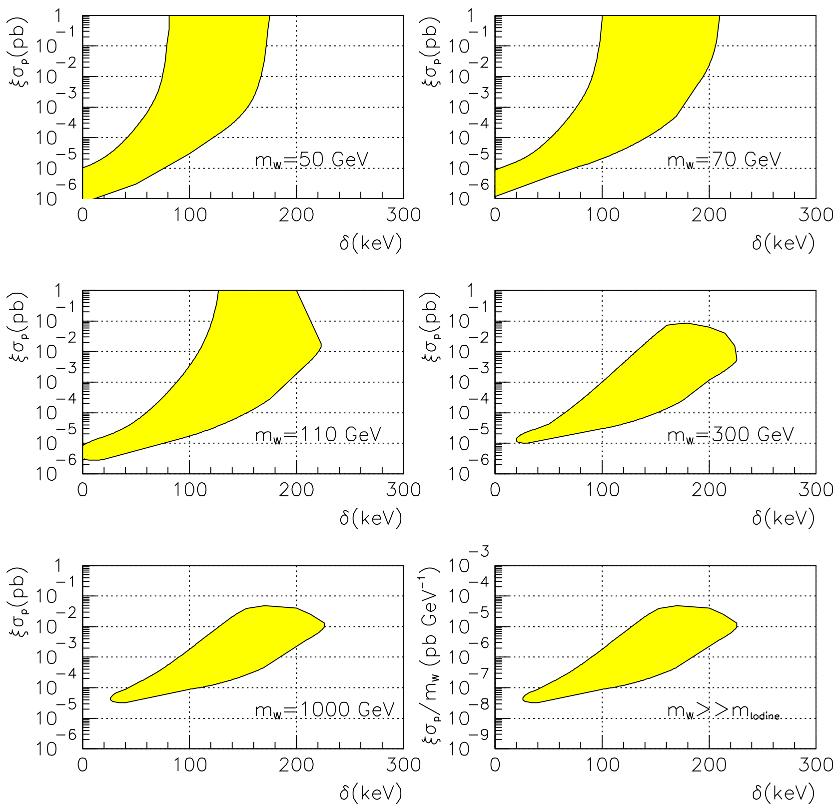

Fig. 1. Slices (coloured areas) at fixed WIMP masses of the volume allowed at 3σ C.L. in the space ($\xi\sigma_{\rm p}$, δ, $m_{\rm W}$); the uncertainties on some of the used parameters have been included. See the text

for the calculation of the expected rate the above mentioned formulae and assumptions. In this way we have compared the experimental data with the expectations given by a flat background and the signal of (9).

Here aspects other than the interaction type have been handled according to [8], fixing in this way a given model framework. In particular, the existing uncertainties on the WIMP local velocity as well as some effects of the uncertainties on the nuclear form factor parameters and on the measured quenching factors have also been included here according to [8]. Moreover, the escape velocity of the WIMP particles in the galactic frame and its uncertainty has been properly taken into account in the calculations similarly as in [13,5,6]. Finally, consistency with the upper limits on recoils measured in [13] and with accelerator results has been required. In this way, the evolution of the region allowed in [6] in the present inelastic dark matter model framework has been investigated.

In this inelastic dark matter scenario an allowed volume in the space ($\xi\sigma_{\rm p}$, $m_{\rm W}$, δ) is obtained. For simplicity, Fig. 1 shows slices of such an allowed volume at some given WIMP masses (coloured areas; $3\,\sigma$ C.L.). It can be noted that when $m_{\rm W} \gg m_{\rm N}$, the expected differential energy spectrum is trivially dependent on $m_{\rm W}$ and in particular it is proportional to the ratio between $\xi\sigma_{\rm p}$ and $m_{\rm W}$; this particular case is summarized in the last plot of Fig. 1. The allowed regions reported there have been obtained by the superposition of those obtained when varying the values of the previously mentioned parameters according to their uncertainties. This also gives as a consequence that the cross section value at given δ can span several orders of magnitude. The upper border of each region is reached when $v_{\rm thr}$ approximates the maximum WIMP velocity in the Earth's frame for each considered model framework (in particular, for each v_0 value).

Note that each set of values (within those allowed by the associated uncertainties) for the previously mentioned parameters gives rise to a different expectation; thus, to different best fit values. As an example we mention that when fixing the other parameters as in [8], the best fit values for a WIMP mass of 70 GeV are (i) $\xi\sigma_{\rm p} = 2.5 \times 10^{-2}$ pb and $\delta = 115$ keV when $v_0 = 170$ km/s, and (ii) $\xi\sigma_{\rm p} = 6.3 \times 10^{-4}$ pb and $\delta = 122$ keV when $v_0 = 220$ km/s.

Finally, we note that a significant enlargement of the given allowed regions should be expected when including complete effects of the model (and related experimental and theoretical parameters) uncertainties. Moreover, possible different halo models can also be considered.

4 Conclusions

The DAMA annual modulation data of four annual cycles [2,4–8] have been analysed by energy and time correlation analysis in terms of inelastic dark matter as suggested in [1]. The found allowed volume in the space ($\xi\sigma_{\rm p}$, $m_{\rm W}$, δ) largely lies in the δ section where detection by experiments with light nuclei (such as e.g. Ge) is disfavoured. This scenario can be added to those of WIMP elastic scattering with purely spin independent coupling, with purely spin dependent coupling and with mixed couplings as discussed in [6,8], which also may hold.

To effectively discriminate among the different possible particle scenarios further investigations are in progress. In particular, the data of the 5th and 6th annual cycles are at hand, while the set-up is running to collect the data of a 7th annual cycle. Moreover, the LIBRA (large sodium iodine bulk for rare processes) set-up of $\simeq 250\,\mathrm{kg}$ is under construction to increase the experimental sensitivity.

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