Inert Doublet Model and DAMA: elastic and/or inelastic dark matter candidates

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Abstract. We investigate the compatibility of the DAMA results with the other direct detection experiments in the framework of a specific dark matter model, the Inert Doublet Model. In this model there are three different regimes for which the dark matter candidate is either light, heavy or in the middle mass range. We present our analysis for the light WIMPs cases with elastic interaction on nuclei. The heavy mass regime is instead an inelastic dark matter candidate, while in the middle mass range both interactions are considered. In the three regimes we exhibit regions of the parameter space in agreement with all the experiments, even though they appear to be significantly constrained.

1. Overview on the Inert Doublet Model
The Inert Doublet Model (IDM) is a simple extension of the Standard Model with dark matter (DM), consisting in two Higgs doublets and a $Z_2$ symmetry and it has been widely discussed in the literature. Here we focus our attention on the direct detection phenomenology in the light of the DAMA experiment.

The usual Higgs doublet is denoted by $H_1$, while the extra, or inert doublet, $H_2$, is the only field of the model that is odd under the $Z_2$ symmetry. This ensures the stability of the lightest member of $H_2$, which will be a DM candidate, and prevents from flavor changing neutral currents [1]. We will assume that $Z_2$ is not spontaneously broken and that $H_2$ does not develop a vacuum expectation value. We write $H_2 = \left( H^0 + i A^0 \right) / \sqrt{2}$, similarly to the ordinary Higgs doublet, and $H_1 = \left( h + \left( v_0 + h + i G^0 \right) / \sqrt{2} \right) \cdot \left( \lambda_3 H^0 + \lambda_4 A^0 \right) / \sqrt{2}$. The potential is written as

$$V(H_1, H_2) = \mu_1^2 |H_1|^2 + \mu_2^2 |H_2|^2 + \lambda_1 |H_1|^4 + \lambda_2 |H_2|^4 + \lambda_3 |H_1|^2 |H_2|^2 + \lambda_4 |H_1^* H_2|^2 + \frac{\lambda_5^2}{2} \left[ (H_1^* H_2) + \text{h.c.} \right].$$

After electroweak symmetry breaking, $\langle H_1 \rangle = v = -\mu_1^2 / \lambda_1 = 246 \text{ GeV}$, the masses of the physical scalar fields are given by

$$M_h^2 = \frac{2 \lambda_1 v^2}{\mu_1^2}, \quad M_{H_0}^2 (M_{A_0}^2, M_{H^+}^2) = \mu_2^2 + \lambda_{H_0} (\lambda_{A_0}, \lambda_{H^+}) v^2,$$

with $\lambda_{H_0} \equiv \lambda_3 / 2$ and $\lambda_{H_0, A_0} \equiv (\lambda_3 + \lambda_4 \pm \lambda_5) / 2$. We will consider $H_0$ to be the DM candidate (i.e. $\lambda_5 < 0$) though the results would be exactly the same for $A_0$ changing the sign of $\lambda_5$. In the next section we discuss two particular limits of the mass relations, leading to an elastic scenario with a light DM candidate, and to an inelastic scenario in the multi-TeV DM mass range.

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2. Direct detection analysis – IDM and DAMA

The former DAMA/NaI [2] and present DAMA/LIBRA [3] experiments are designed to detect the dark matter recoil off nuclei through the model independent annual modulation signature due to the motion of the Earth around the Sun. The experimental results obtained by DAMA/LIBRA combined with the ones of DAMA/NaI show a modulated signal with a confidence level (CL) of 8.2 $\sigma$ [3]. The analysis of the DAMA data is based on a goodness-of-fit method and considers the full 36 bins. In addition we take into account the constraint on the total event rate from the unmodulated signal. All the other collaborations for direct searches have reported no positive detection of DM recoils, setting upper bounds on the allowed dark matter scattering cross-section on nucleon. The exclusion limits are calculated with the standard Poisson statistics. A detailed discussion on the analysis procedure and on the astrophysical factors can be found in [4] and references therein.

2.1. Low mass regime ($M_{H_0} \ll m_W$) – elastic dark matter

If we consider $M_{A_0} = M_{H^+}$ the theory posses a global $SU(2)$ symmetry. Consequently it is possible to decouple the extra neutral component in such a way that $M_{H_0} \ll M_{A_0} \simeq M_{H^+}$, where $M_{H_0}$ is now acting as singlet scalar dark matter [5]. The $H_0$ is a light DM candidate and its interaction on nucleon is through spin-independent (SI) elastic scattering exchanging an Higgs boson. In figure 1 we show the allowed regions compatible with the DAMA modulated signal, as a function of the model parameters $|\lambda_{H_0}|, M_{H_0}$. The strongest exclusion limits come from Xenon10 [6], CDMS-Ge [7] and the total unmodulated DAMA rate. Also shown is the prediction for the relic density; we underline the fact that no further adjustment of the parameters is needed to fix the relic abundance. The compatibility between DAMA and the other exclusion experiments, in this mass range, is ameliorated by the channelling on Iodine [8, 9], even though the model appears severely constrained. We remark however that the nuclear and astrophysical uncertainties can play a role in opening the available parameter space, see [4].

2.2. High mass regime ($M_{H_0} \gg m_W$) – inelastic dark matter

The second limit arises from $\lambda_5 \to 0$, in which case the neutral particles are degenerate [11] and the theory is invariant under a $U(1)_{PQ}$ symmetry. The presence of an enhanced symmetry allows to consider a small mass splitting $\delta = M_{A_0} - M_{H_0} \ll M_{H_0}$ (corresponding to $\lambda_5 \simeq$...
\( \mathcal{O}(10^{-7} - 10^{-5}) \) between the neutral components in a technically natural way. This small mass splitting leads to inelastic dark matter [12], with a SI cross-section on nucleon mediated by the Z boson. The predictions for the model parameters \( \delta \) and \( M_{H_0} \) are shown in figure 2. The most constraining exclusion limits come from Crest-II [13] and CDMS-Ge, while the DAMA total unmodulated rate is less restrictive respect to the elastic scenario. There exists a whole range of candidates, between \( M_{H_0} \sim 535 \text{ GeV} \) and \( M_{H_0} \sim 20 \text{ TeV} \), which are compatible with DAMA and all other direct detection experiments and which have the relic density within the WMAP [14] bounds. The viable candidates in the mass range \( 50 - 100 \text{ GeV} \) (light red/grey bottom) have a cosmic abundance below the WMAP value. Either they can be considered as subdominant components of the dark matter halo either one can infer an asymmetry mechanism in the early universe, provided by the smallness of the \( \lambda_5 \) coupling, to account for the suitable relic density amount. More details on the inelastic candidate and on the asymmetry are discussed in [4].

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