A LIGHT SCALAR WIMP, THE HIGGS Portal AND DAMA

MICHEL H.G. TYTGAT
Service de Physique Théorique
Université Libre de Bruxelles
Boulevard du Triomphe, CP225, Brussels 1050, Belgium

In these proceedings, we report on the possible signatures of a light scalar WIMP, a dark matter candidate with $M_{\text{DM}} \sim \text{few GeV}$, which is supposed to interact with the Standard Model particles through the Higgs, and which might be related to the annual modulation observed by DAMA.

1. Introduction

There are many models of dark matter but the most acclaimed is the neutralino. However the most economical extension of the Standard Model with dark matter consists simply in adding a real singlet scalar field $S$,

$$\mathcal{L} \supset \frac{1}{2} \partial^\mu S \partial_\mu S - \frac{1}{2} \mu^2_S S^2 - \frac{\lambda_S}{4} S^4 - \lambda_L H^\dagger H S^2 \quad (1)$$

where $H = (h^+(h+iG_0)/\sqrt{2})^T$ is the Higgs doublet. This Lagrangian has a discrete $Z_2$ symmetry, $S \rightarrow -S$ and, if this symmetry is not spontaneously broken, the $S$ particle is a dark matter candidate, with mass

$$m_S^2 = \mu_S^2 + \lambda_L v^2, \quad (2)$$

where $v = 246$ GeV. This is also one of the simplest instance of dark matter through the Higgs portal, a general scheme according to which a hidden sector interact with ordinary matter through the Higgs sector of the Standard Model. Also the singlet scalar extension effectively encompasses many other models with extra fields, for instance the so-called Inert Doublet Model (IDM). The IDM is a model with two Higgs field, one odd under a discrete symmetry which is introduced to prevent FCNC. The extra Higgs has also couplings to electroweak gauge bosons but decoupling of the extra scalars states (one neutral and one charged in the present case) one has just to make sure not to violate LEPI bounds on isospin breaking. This is
turns out to be natural in the IDM, thanks to a hidden custodial $SU(2)$ symmetry.\(^9\)

The phenomenology of the theory (1) has been much discussed in the literature, but the focus has somewhat been on heavy or moderately heavy dark matter candidates, say in the 50 GeV to a few TeV range. In the present proceeding we consider a lighter candidate, with $m_S \lesssim 10$ GeV. This possibility, first raised in the context of supersymmetric models,\(^10–12\) has received less attention than, say, models with candidates heavier than 50 GeV, but is nevertheless both viable and phenomenologically very interesting.

As in the works just quoted, one of our motivation is the DAMA/NaI and DAMA/Libra experiments, which have observed an annual modulation in the rate of single scattering events, with 8.2 $\sigma$ significance (combined).\(^13\) This signature is supposed to be one of the landmark of dark matter-nucleon interactions, the modulation being due of the combined motion of the Sun and of the Earth with respect to the halo of dark matter of the Galaxy (generically considered to be non-rotating).\(^14\) The DAMA/NaI detector, and its successor, DAMA/Libra, consist of sodium iodide (NaI) crystals and use scintillation to measure the nuclei recoil energy. While the all the other dark matter experiments work hard on eliminating the possible background, the strategy of DAMA is essentially to exploit the possible annual modulation. Most of the background is supposedly eliminated by focusing on single hit events, but of course contamination by mundane radioactivity is still expected to exist. The DAMA data are impressive and no explanation but dark matter really exists. Nevertheless the interpretation in terms of elastic collisions of nuclei in the detector with dark matter from the halo is challenged by the null results of various other direct detection experiments, at least those that are probing similar dark matter mass and cross section ranges.

Elastic scattering has been addressed in various works, possibly taking into account the possible uncertainties regarding the properties of the dark matter halo, or of the interaction of dark matter with nuclei.\(^15–18\) All these works assert that the interpretation of the DAMA results in term of the elastic scattering of dark matter is inconsistent with the null results of other direct detection experiments (CDMS,\(^19,20\) XENON10,\(^21\) TEXONO,\(^22\) CRESST,\(^23\) COUPP\(^24\) and CoGenT\(^25\)), at least if all events the DAMA events are 'quenched'. Quenching relates to the fact that, after a collision with dark matter, a recoiling nuclei may lose energy either through electrons (which are responsible for scintillation) or through collisions with
other nuclei (heat, phonons). The energy measured (which is expressed in electron equivalent keV, or keVee) is thus typically smaller than the true nuclei recoil energy, $E_{ee} = Q E_{recoil}$, where $Q$ is the so-called quenching factor, $Q \lesssim 1$. In a crystal however, like in NaI, some of the recoiling nuclei events may occur along the axis of the crystal, in which case collisions with nuclei are ineffective and $Q \approx 1$. This effect is called channelling. If channelling is taken into account, it may be possible to explain the DAMA results (at $3\sigma$) with a light $m_{DM} \lesssim 7 - 8$ GeV candidate, with a cross section (normalised to a nucleon) $\sigma_n \approx 10^{-5}$ pb. One should emphasise that the fit to data is not very good since the chi-square is minimum for values which are excluded by the other experiments. Furthermore this interpretation implies that the background is small in the relevant region of recoil energies. This is embarrassing but, yet, the possibility that many models, including supersymmetric ones, may actually explain the DAMA data is not excluded.

In the sequel, we focus on elastic scattering and report on the phenomenology of a singlet scalar (including the IDM). For the sake of reference, we refer to the range quoted in the work of Pietrello and Zurek, corresponding to

$$3 \times 10^{-5} \text{pb} \lesssim \sigma_{SI} \lesssim 5 \times 10^{-3} \text{pb},$$

and

$$3 \text{GeV} \lesssim m_{DM} \lesssim 8 \text{GeV}.$$  

This range, which is based on the two bins version of the DAMA data for the spectrum of modulated events, is clearly larger than the one based on the full set of data. If anything, like if channelling turns out to be in-operant, this range is representative of a class of models which are not yet excluded by any experiments.

### 2. Direct Detection and Relic Abundance

For the model (1), the only processes relevant for direct detection and to fix the relic abundance (we consider the standard thermal freeze-out) are those of Fig.1. This is also true for the IDM provided $m_{DM} \ll m_{Higgs}, m_{Z,W}$. Since these processes have the same dependence in the coupling $\lambda_L$ and
the Higgs mass, both processes are closely related. Concretely, if we fix the cross section assuming a cosmic abundance given by cosmological observations (and thermal freeze-out), then the direct detection cross section is fixed, modulo the uncertainty in the coupling of the Higgs to nucleons, parameterised by $f$, with $f m_N = \langle N|\sum_q m_{\bar{qq}}|N\rangle = g_{hN} v$. Here we take $f = 0.30$ as central value, and vary it within the rather wide range $0.14 < f < 0.66$. As Fig.2 shows, compatibility between DAMA (regions in red) and WMAP (black region) is possible. Conversely, one may say that the red regions are not excluded by existing dark matter detection experiments. Notice that the coupling $|\lambda_L|$ tend to be large, but is still perturbative. Incidentally, from (2) we see that $\mu^2 \sim v$ so that a light $m_{DM}$ potentially poses a (small) hierarchy problem. This may perhaps explain why this simple model is systematically overlooked in the current literature even though it has many interesting consequences.

3. Indirect Detection

The dark matter candidates considered here have both large cross sections and a large abundance compared to more mundane, heavier dark matter candidates and their annihilation in the Galaxy may lead to some interesting signals.

In Fig. 3 we show the flux from the annihilation of the dark matter candidate into photons at the centre of the Galaxy. The mass of the DM candidate puts it in the energy range of EGRET data and of the Fermi/Glast satellite. Fig.3 we show the predicted flux of gamma rays from the galactic centre for a sample of scalar DM with parameters which are consistent both with DAMA and WMAP and we compare to EGRET data. It is interesting that the predicted flux is of the order of magnitude of the observed flux at the lowest energies that have been probed by EGRET. A
Fig. 2. For $m_h = 120$ GeV, values of $m_S$ and $\lambda_L$ consistent with WMAP $0.094 < \Omega_{DM} h^2 < 0.129$ (solid black lines), and which match the direct detection constraints (two bins fit to DAMA of Petriello and Zurek). A tentative conclusion is that observations by Fermi/GLAST might constrain the model, modulo the usual uncertainties regarding the profile of the dark matter at the centre of the Galaxy. Similar predictions have been reached in the framework of so-called WIMPless models (see also the talk by Jason Kumar at this conference).

Dark matter may also be captured in the core of the Sun, where its annihilation may be observed by neutrino detectors. In Fig. 4 we show the limit which may be expected from Super-Kamiokande. The dominant source of neutrinos is annihilation, through the Higgs, into tau-antitau pairs (see also the talk by Kumar at this conference).

Finally we may consider the production and propagation of antiparticles coming from the annihilation of dark matter in the Galaxy, a possibility which may be constrained using the new data on the positron and antiproton fluxes in cosmic rays. The flux of positrons and antiprotons is quite large for the candidates considered here (for the same reasons given at the beginning of this section the flux of positrons (and for that matter, other cosmic ray components, including antiprotons). However the fluxes fall in an energy range where solar modulation severely limits the possibilities to constrain the model. In Fig. 5 we show the predictions of the model for the positron fraction, and Fig. 6 shows the $\bar{p}/p$ ratio. The signal in
Fig. 3. Flux of gamma rays from the galactic center from the annihilation of a scalar DM consistent with DAMA, compared with EGRET data ($m_h = 120$ GeV and using a NFW profile).

Fig. 4. Region allowed by DAMA (dashed magenta) together with current limits on the SI cross section from direct detection experiments and the limit from Super-Kamiokande (solid blue, mostly from $\tau - \tau$ annihilations).

positrons is rather weak, unless there is a boost factor (say BF=10). The signature into antiproton is however quite significant and, for instance, a boost factor of order 10 is clearly excluded, a conclusion which is probably robust, even without knowing precisely the impact of solar modulation. A better understanding of solar modulation is nevertheless desirable and
perhaps more severe constraints could be obtained in this way. Interestingly the model also predicts a substantial production of antideuteron. The production of antideuteron by spallation in cosmic rays is typically small and is predicted to fall for kinetic energies below 1 GeV per nucleon. Given its large abundance, a light WIMP may give a substantial contribution to the flux of antideuteron at low energies. For the IDM candidate with $M_D M = 10$ GeV, we obtain, using the DarkSUSY routines, an antideuteron flux at $T_D = 0.25$ GeV/n of $9 \cdot 10^{-7}$ (GeV/n s sr m$^2$) (for BF = 1), which is below the upper limit of $1.9 \cdot 10^{-4}$ (GeV/n s sr m$^2$) set by the BESS experiment, but above the expected acceptance of the future AMS-02 and GAPS experiments, which are $4.5 \cdot 10^7$ (GeV/n s sr m$^2$) and $1.5 \cdot 10^7$ (GeV/n s sr m$^2$) respectively. Thus antideuteron data might turn out to give the strongest constraint on the light WIMP dark matter candidate considered here.

4. A Light Scalar At The LHC

In the present model, the coupling between the Higgs and the dark matter particle is large. This leads to a large Higgs boson decay rate to a scalar DM.
Fig. 6. Flux of antiprotons to protons for a $m_{DM} = 10$ GeV scalar singlet. We show the contribution for no boost factor (long dashed) and for a boost factor of 10 (short dashed). The latter is clearly excluded.

pairs at the LHC.\footnote{\textsuperscript{2,31}} For example, for $m_S = 7$ GeV and $\lambda_L = -0.2$ and for a Higgs of mass 120 GeV we get the branching ratio $BR(h \rightarrow SS) = 99.5\%$, while for $m_h = 200$ GeV and $\lambda_L = -0.55$ we get $BR(h \rightarrow SS) = 70\%$. This reduces the visible branching ratio accordingly, rendering the Higgs boson basically invisible at LHC for $m_h = 120$ GeV, except possibly for many years of high luminosity data taking. Such a dominance of the invisible DM channel is a clear prediction of the framework, although it poses a challenge to experimentalists.\footnote{\textsuperscript{43}}

5. Conclusion

A light, $m \sim$ few GeV, singlet scalar dark matter candidate interacting through the Higgs is perhaps not very motivated theoretically speaking but it may have a very interesting phenomenology. If its relic abundance is fixed by thermal freeze-out, all its cross sections are also essentially fixed. Its elastic scattering with nucleons is in a range consistent with the modulation observed by DAMA and its annihilation into various by-products are within reach of current gamma ray, neutrinos and cosmic ray detectors. A rather clear cut prediction is the production of a rather large flux of antideuteron
in cosmic rays. Also, it predicts that a light Higgs is essentially invisible at the LHC.

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