Proton–philic spin–dependent inelastic Dark Matter (pSIDM) as a viable explanation of DAMA/LIBRA–phase2

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We show that the Weakly Interacting Massive Particle scenario of proton-philic spin-dependent inelastic Dark Matter (pSIDM) can still provide a viable explanation of the observed DAMA modulation amplitude in compliance with the constraints from other experiments after the release of the DAMA/LIBRA–phase2 data. The pSIDM scenario provided a viable explanation of DAMA/LIBRA–phase1 both for a Maxwellian WIMP velocity distribution and in a halo–independent approach. At variance with DAMA/LIBRA–phase1, for which the modulation amplitudes showed an isolated maximum at low energy, the DAMA/LIBRA–phase2 spectrum is compatible to a monotonically decreasing one. Moreover, due to its lower threshold, it is sensitive to WIMP–iodine interactions at low WIMP masses. Due to the combination of these two effects pSIDM can now explain the yearly modulation observed by DAMA/LIBRA only when the WIMP velocity distribution departs from a standard Maxwellian. In this case the WIMP mass $m_\chi$ and mass splitting $\delta$ fall in the approximate ranges $6 \text{ GeV} \lesssim m_\chi \lesssim 17 \text{ GeV}$ and $17 \text{ keV} \lesssim \delta \lesssim 29 \text{ keV}$.

I. INTRODUCTION

About one quarter of the total mass density of the Universe1 and more than 90% of the halo of our Galaxy are believed to be constituted by Dark Matter (DM) and Weakly Interacting Massive Particles (WIMPs) are one of the most popular candidates to compose it. The scattering rate of DM WIMPs in a terrestrial detector is expected to present a modulation with a period of one year due to the Earth revolution around the Sun.2

The DAMA collaboration3,4 has been measuring for more than 15 years a yearly modulation effect in their sodium iodide target. Such effect has a statistical significance of more than 9σ and is consistent with what is expected from DM WIMPs. However, in the most popular WIMP scenarios the DAMA modulation appears incompatible with the results from many other DM experiments that have failed to observe any signal so far.

This has lead to extend the class of WIMP models. In particular, one of the few phenomenological scenarios that have been shown to explain the DAMA effect in agreement with the constraints from other experiments is proton–philic spin–dependent inelastic Dark Matter (pSIDM)5,6,7 for WIMP masses $10 \text{ GeV} \lesssim m_\chi \lesssim 30 \text{ GeV}$ and a mass splitting $10 \text{ keV} \lesssim \delta \lesssim 30 \text{ keV}$.

Recently the DAMA collaboration has released first result from the upgraded DAMA/LIBRA-phase2 experiment8. Compared to the previous data the two most important improvements are that now the exposure has almost doubled and that the energy threshold has been lowered from 2 keV electron–equivalent (keVee) to 1 keVee. Moreover, an important difference with the result of DAMA/LIBRA–phase1 is that the new DAMA/LIBRA–phase2 spectrum of modulation amplitudes no longer shows a maximum, but is rather monotonically decreasing with energy. In light of these differences in the present paper we wish to update the assessment of pSIDM with the new DAMA/LIBRA–phase2 data, both in a scenario where the WIMP speed distribution $f(v)$ is given by a standard Maxwellian and using a halo–independent approach where $f(v)$ is not fixed.

In the present paper we will show that pSIDM can still provide a viable explanation of the modulation effect after DAMA/LIBRA-phase2. In particular, while the pSIDM scenario was able to explain DAMA/LIBRA–phase1 both for a Maxwellian $f(v)$ and in a halo–independent approach5,6,7 in the present paper we will show that for a Maxwellian WIMP velocity distribution it provides a poor fit to the new DAMA data and for a range of the pSIDM parameters in tension with the null results of other DM searches. On the other hand in a halo–independent approach the pSIDM scenario is still viable.

The paper is organized as follows. In Section II we outline the main features of the pSIDM scenario; in Section III A we analyze the DAMA data adopting a standard Maxwellian for the WIMP velocity distribution; in Section III B we analyze the DAMA data in a halo–independent approach. We provide our conclusions in Section IV.

II. THE PSIDM SCENARIO

The most stringent bounds on an interpretation of the DAMA effect in terms of WIMP–nuclei scatterings are obtained by detectors using xenon (XENON1T9,10,
PANDA\textsuperscript{10}, LUX\textsuperscript{11}) and germanium (CDMS\textsuperscript{12,15}) whose spin is mostly originated by an unpaired neutron while, on the other hand, both sodium and iodine in DAMA have an unpaired proton. This implies that if the WIMP particle interacts with ordinary matter predominantly via a spin–dependent coupling which is suppressed for neutrons it can explain the DAMA effect in compliance with xenon and germanium bounds\textsuperscript{16,17}. Actually, present limits from xenon detectors require to tune the neutron/proton coupling ratio $c^n/c^p=-0.028$, that minimizes the xenon spin–dependent response using the nuclear structure functions in\textsuperscript{18}. This scenario is still constrained by droplet detectors and bubble chambers (COUPP\textsuperscript{19}, PICASSO\textsuperscript{20}, PICO-60 \textsuperscript{21}) which all use nuclear targets with an unpaired proton (\textsuperscript{19}F and/or \textsuperscript{127}I). As a consequence, this class of experiments rules out a DAMA explanation in terms of WIMPs with a spin–dependent coupling to protons\textsuperscript{6,17,22}.

In Ref.\textsuperscript{6} Inelastic Dark Matter (IDM) was proposed to reconcile the above scenario to fluorine detectors. In IDM a DM particle $\chi_1$ of mass $m_{\chi_1} = m_\chi$ interacts with atomic nuclei exclusively by up–scattering to a second heavier state $\chi_2$ with mass $m_{\chi_2} = m_\chi + \delta$. A peculiar feature of IDM is that there is a minimal WIMP incoming speed in the lab frame matching the kinematic threshold for inelastic upscatters and given by:

$$v^{*}_{\text{min}} = \sqrt{\frac{2\delta}{\mu_{\chi N}}},$$

with $\mu_{\chi N}$ the WIMP–nucleus reduced mass. This quantity corresponds to the lower bound of the minimal velocity $v_{\text{min}}$ (also defined in the lab frame) required to deposit a given recoil energy $E_R$ in the detector:

$$v_{\text{min}} = \frac{1}{\sqrt{2m_N E_R/\mu_{\chi N}}} \left| m_N E_R + \delta \right|,$$

with $m_N$ the nuclear mass. In particular, indicating with $v^{*_{Na}}_{\text{min}}$ and $v^{*_{F}}_{\text{min}}$ the values of $v^{*}_{\text{min}}$ for sodium and fluorine, and with $v_{\text{esc}}$ the WIMP escape velocity, constraints from WIMP–fluorine scattering events in droplet detectors and bubble chambers can be evaded when the WIMP mass $m_\chi$ and the mass gap $\delta$ are chosen in such a way that the hierarchy:

$$v^{*_{Na}}_{\text{min}} < v^{*}_{\text{esc}} < v^{*_{F}}_{\text{min}},$$

is achieved, since in such case WIMP scatterings off fluorine turn kinematically forbidden while those off sodium can still serve as an explanation to the DAMA effect. So the pSIDM mechanism rests on the trivial observation that the velocity $v^{*}_{\text{min}}$ for fluorine is larger than that for sodium.

### III. ANALYSIS

The expected rate in a given visible energy bin $E'_{1} \leq E' \leq E'_{2}$ of a direct detection experiment is given by:

$$R_{[E'_{1},E'_{2}]}(t) = MT_{\text{exp}} \int_{E'_{1}}^{E'_{2}} \frac{dR}{dE'}(t) dE'$$

$$\frac{dR}{dE'}(t) = \sum_{T} \int_{0}^{\infty} \frac{dR_{T}(t)}{dE_{ee}} G_{T}(E', E_{ee}) \epsilon(E') dE_{ee}$$

$$E_{ee} = q(E_R) E_R,$$

with $\epsilon(E')$ $\leq 1$ the experimental efficiency/acceptance. In the equations above $E_R$ is the recoil energy depleted in the scattering process (indicated in keVnr), while $E_{ee}$ (indicated in keVee) is the fraction of $E_R$ that goes into the experimentally detected process (ionization, scintillation, heat) and $q(E_R)$ is the quenching factor, $G_{T}(E', E_{ee}) = q(E_R) E_R$ is the probability that the visible energy $E'$ is detected when a WIMP has scattered off an isotope $T$ in the detector target with recoil energy $E_R$, $M$ is the fiducial mass of the detector and $T_{\text{exp}}$ is the live–time exposure of the data taking.

In Eq.\textsuperscript{4} the differential recoil rate $dR_{T}(t)/dE_{ee}$ is given by:

$$\frac{dR_{T}}{dE_R}(t) = N_T \frac{\rho_{\text{WIMP}}}{m_{\text{WIMP}}} \int_{v_{\text{min}}}^{v_{\text{max}}} d^3 \vec{v}_T f(\vec{v}_T, t)v_T \frac{d\sigma_T}{dE_R},$$

where $\rho_{\text{WIMP}}$ is the local WIMP mass density in the neighborhood of the Sun (in the following we will assume the standard value $\rho_{\text{WIMP}}=0.3$ GeV/cm$^3$), $f(\vec{v}_T, t)$ is the WIMP velocity distribution (whose boost in the Earth rest frame induces a time–dependence), $N_T$ the number of the nuclear targets of species $T$ in the detector (the sum over $T$ applies in the case of more than one target), while:

$$\frac{d\sigma_T}{dE_R} = \frac{\sigma_0}{E_{\text{max}}^R} = \frac{2m_T}{4\pi v_T^2} \left[ \frac{1}{2j_\chi + 1} \frac{1}{3j_T + 1} |M_T|^2 \right],$$

with $m_T$ the mass of the nuclear target, $j_\chi=1/2$ the spin of the WIMP, $E_{\text{max}}^R = 2j_\chi^2 m_T v_T^2$ and $\sigma_0$ the point–like WIMP–nucleon cross section. In the following, for the calculation of the squared amplitude $|M_T|^2$ we will use
the spin–dependent nuclear form factors from $^{18}$ for all nuclei with the exception of caesium and tungsten, for which we follow the same procedure adopted in Appendix C of $^{24}$.

In particular, in each visible energy bin DAMA is sensitive to the yearly modulation amplitude $S_m$, defined as the cosine transform of $R_{E_1, E_2}(t)$:

$$S_{m,E_1, E_2} \equiv \frac{2}{T_0} \int_0^{T_0} \cos \left[ \frac{2\pi}{T_0} (t - t_0) \right] R_{E_1, E_2}(t) \, dt,$$

with $T_0=1$ year and $t_0=2^{nd}$ June, while other experiments put upper bounds on the time average $S_0$:

$$S_{0,E_1, E_2} = \frac{1}{T_0} \int_0^{T_0} R_{E_1, E_2}(t) \, dt.$$

A. Maxwellian analysis

In this Section we assume that the WIMP velocity distribution in the Galactic rest frame is a standard isotropic Maxwellian at rest, truncated at the escape velocity $v_{esc}$,

$$f_{gal}(v) = \frac{1}{\pi^{1/2} v_0^3 N_{esc}} \exp\left(-v^2/v_0^2 \right) \Theta(v_{esc} - v).$$

Here $v$ is the WIMP speed in the Galactic rest frame, $v_0$ the galactic rotational velocity at the Earth’s position, $\Theta$ is the Heaviside step function, and

$$N_{esc} = \text{erf}(z) - 2 z e^{-z^2}/\pi^{1/2}$$

with $z = v_{esc}/v_0$. The WIMP speed distribution in the laboratory frame can be obtained with a change of reference frame. It depends on the speed of the Earth with respect to the Galactic rest frame, which neglecting the ellipticity of the Earth orbit, is given by

$$v_E(t) = [v_⊙^2 + v_⊕^2 + 2 v_⊙ v_⊕ \cos \gamma \cos[\omega(t - t_0)]]^{1/2}.$$

In this formula, $v_⊙$ is the speed of the Sun in the Galactic rest frame, $v_⊕$ is the speed of the Earth relative to the Sun, and $\gamma$ is the ecliptic latitude of the Sun’s motion in the Galaxy. We take $\cos \gamma \simeq 0.49$, $v_⊕ ≈ 30 \text{ km/s}$, $v_⊙ ≈ v_0 + 12 \text{ km/s}$, $v_0 = 220 \text{ km/s}$ $^{23}$, and $v_{esc} = 550 \text{ km/s}$ $^{20}$.

The velocity integral in Eq. 4 for the truncated Maxwellian distribution is computed from the expression of the speed distribution. We have obtained $S_0$ and $S_m$ by expanding it to first order in $v_⊕/v_0$.

$^{1}$ i.e., for the NREFT operator $\mathcal{O}_4$ in the notation of $^{18}$.

FIG. 1: DAMA modulation amplitudes as a function of the measured ionization energy $E’$ for the absolute minimum of the pSIDM model in the case of a Maxwellian WIMP velocity distribution. The points with error bars correspond to the combined data of DAMA/NaI $^{27}$, DAMA/LIBRA–phase1 $^{11}$ and DAMA/LIBRA–phase2 $^{8}$.

To check how well pSIDM with a Maxwellian distribution fits the DAMA/LIBRA–phase2 data $S_m \pm \delta$, we perform a $\chi^2$ analysis constructing the quantity

$$\chi^2 = \sum_{k=1}^{14} \frac{|S_{m,k} - S_{m,k}^\text{exp}|^2}{\delta_k^2},$$

where we consider 14 energy bins of width 0.5 keVee from 1 keVee to 8 keVee. Here and in the next Section we fix the experimental input (exposure, energy resolution, quenching factors, efficiency, measured count rates, etc.) for both the DAMA/LIBRA experiment and for other DM searches as described in appendix B of $^{24}$ and appendix A of $^{28}$.

The global minimum of $\chi^2(m_\chi, \delta, \sigma_0)$ for pSIDM occurs at $m_\chi = 12.1 \text{ GeV}$, $\delta = 18.3 \text{ keV}$, $\sigma_0 = 7.95 \times 10^{-35} \text{ cm}^2$, and its value is $\chi^2_{\min} = 13.19$ ($p$-value = 0.28 with 14 – 3 degrees of freedom, which is an indication of a good fit). The modulation amplitudes predicted by the pSIDM scenario are compared to the combined data of DAMA/NaI $^{27}$, DAMA/LIBRA–phase1 $^{11}$ and DAMA/LIBRA–phase2 $^{8}$ in Fig. 1.

The 5–$\sigma$ best-fit DAMA region in the $(m_\chi – \sigma_0)$ plane for the pSIDM scenario is compared to the corresponding 90% C.L. upper bounds from other DM searches in Fig. 2 (both in this Figure and in Fig. 3 the legend shows the actual list of experiments that we have tested and that yield some bound, although for readability purposes not all of them fall within the plot boundaries). In the
same plot the IDM mass splitting is fixed to the absolute minimum of the $\chi^2$, $\delta = 18.3$ keV. As can be seen from such figure the DAMA effect is in strong tension with the upper bounds from PICO60, KIMS and PICASSO. We have also performed a combined fit including the upper bounds from such experiments with the addition of COUPP and XENON1T, finding $\chi^2_{\text{min}} = 41.1$ with a $p$-value $1.5 \times 10^{-3}$ and 18 dof. Including $v_0$ and $u_{\text{esc}}$ as nuisance parameters in the $\chi^2$ (we assume $v_0 = (220 \pm 20)$ km/s [25] and $u_{\text{esc}} = (550 \pm 30)$ km/s [26]) does not improve the fit (we find $\chi^2_{\text{min}} = 40.965$). This confirms that, at variance with the analyses of Ref. [6, 7], after the release of the DAMA/LIBRA–phase2 data the pSIDM scenario in the Maxwellian case is ruled out. There are two reasons for this. The first reason is that while the DAMA/LIBRA–phase1 data where only sensitive to scattering events off sodium, the DAMA/LIBRA–phase2 data have a lower threshold and are now also sensitive to scattering events off iodine for $E' < 2$ keVee at low WIMP masses. This makes it more difficult to fit the model to the data since in the pSIDM scenario the scaling between the cross sections off iodine and sodium is fixed (the parameter $c^0/c^\prime$, that would allow to change such scaling is locked to the combination that suppresses the response on xenon). Moreover, in the scenario described in Section II a minimal value of the mass splitting parameter $\delta$ is required in order to comply with the condition of Eq. (3), which, at the same time automatically implies that the recoil energy $E^0_R = E^0_R(v^{*Na})$, and so a single maximum of the modulation amplitude spectrum, falls inside the range of the DAMA signal [6] (the energy $E^0_R$ maximizes the velocity integral in Eq. (15)). Indeed, the DAMA/LIBRA–phase1 data showed a single maximum in the 2.5 keVee $< E' < 3$ keVee energy bin in the measured modulation amplitudes [6, 7], implying an acceptable fit for the pSIDM model. On the other hand the DAMA/LIBRA–phase2 data show an energy spectrum of the modulation amplitudes more compatible to a monotonically decreasing one, closer to what expected for elastic scattering. As a consequence of this the DAMA/LIBRA–phase2 $\chi^2$ pulls to low values of the $\delta$ mass splitting (indeed, the Maxwellian best-fit configuration $m_\chi = 12.1$ GeV, $\delta = 18.3$ keV falls below the halo–independent compatibility region discussed in the next Section and shown in Fig. 1, entering in conflict with the requirement of Eq. (3).2

2 Repeating the same analysis for the DAMA/LIBRA–phase1 data one finds $\chi^2_{\text{min}} = 8.6$ with 12-3 dof and $m_\chi = 12.8$ GeV, $\delta = 23.6$ keV in agreement with the requirement of Eq. (3).

B. Halo–independent analysis

In the halo–independent approach [29] the expected rate in a direct detection experiment is recast in the form [30]:

$$R_{[E'_1, E'_2]}(t) = \int_0^\infty dv_{\text{min}} \bar{\eta}(v_{\text{min}}, t) R_{[E'_1, E'_2]}(v_{\text{min}}),$$

(13)

where the dependence on astrophysics is contained in the halo function:

$$\bar{\eta}(v_{\text{min}}, t) = \frac{\rho_\chi}{m_\chi} \sigma_0 \eta(v_{\text{min}}, t),$$

(14)

and the WIMP velocity distribution is contained in the velocity integral:

$$\eta(v_{\text{min}}, t) = \int_{v_{\text{min}}}^\infty dv \frac{f(v, t)}{v},$$

(15)

while the response function $R_{[E'_1, E'_2]}(v_{\text{min}})$ is given by:

$$R_{[E'_1, E'_2]}(v_{\text{min}}) = \sum_T \frac{N_T v^2_T}{\sigma_0} \frac{d\sigma_T}{dE_R} \times$$

$$\int_{E'_1}^{E'_2} dE' \epsilon(E') G_T(E', E_{\text{ee}}(v_{\text{min}})).$$

(16)
Notice that for a standard spin–dependent interaction the product \( \eta \) mapped into suitable averages of the two halo functions shows an annual modulation that can be approximated approach measured rates. The result of such procedure is shown in Fig. 3, where the extension of the vertical bar shows the 1\sigma interval around the central value of the measured rate.

To compute upper bounds on \( \tilde{\eta}^0 \) from upper limits \( R_{[E'_1, E'_2]}^{\lim} \) on the unmodulated rates, we follow the conservative procedure in Ref. 29. Since \( \tilde{\eta}^0(\nu_{\text{min}}) \) is by definition a non-decreasing function, the lowest possible \( \tilde{\eta}^0(\nu_{\text{min}}) \) function passing through a point \((\nu_0, \tilde{\eta}^0)\) in \( \nu_{\text{min}} \) space is the downward step function \( \tilde{\eta}^0 = \nu_{\text{min}} \theta(\nu_0 - \nu_{\text{min}}) \).

The maximum value of \( \tilde{\eta}^0 \) allowed by a null experiment at a certain confidence level, denoted by \( \tilde{\eta}^{\lim}(\nu_0) \), is then determined by the experimental limit on the rate \( R_{[E'_1, E'_2]}^{\lim} \) as

\[
\tilde{\eta}^{\lim}(\nu_0) = \frac{R_{[E'_1, E'_2]}^{\lim}}{\int_0^{\nu_0} d\nu_{\text{min}} R_{[E'_1, E'_2]}(\nu_{\text{min}})}. \tag{19}
\]

The corresponding upper limits at 90% C.L. are shown as continuous lines in Figs. 3 for the same experiments shown in Fig. 3.

For the specific benchmark \( m_\chi = 11.4 \text{ GeV}, \delta = 23.7 \text{ keV} \) shown in Fig. 3 one can see that pSIDM cannot be ruled out as an explanation of the DAMA/LIBRA effect since in all the energy range of the signal one has \( |\tilde{\eta}^0|_{[v_{\text{min}}, v_{\text{min}}]} < \tilde{\eta}^{\lim} \). The same benchmark is represented by a starred point in Fig 4 and lies inside the the closed contour where the compatibility factor defined as \( \tilde{\eta}^0(\nu_{\text{min}}) \) is less than unity. In the equation above \([v_{\text{min}}, v_{\text{min}}]\) and \( \nu_0 \) represent intervals and averages of \( \nu_{\text{min}} \) for each of the \( i=1...14 \) DAMA/LIBRA bins below \( E' = 8 \text{ keV} \), while \( \sigma_i \) is the 1–\sigma fluctuation on \( \tilde{\eta}^0(\nu_{\text{min}}) \).

In particular, the requirement \( D(m_{\text{DM}}, \delta) < 1 \) ensures that within the closed contour of Fig. 4 no 1–\sigma interval of the quantities \( \tilde{\eta}^0(\nu_{\text{min}}, \nu_{\text{min}}) \) obtained from the DAMA/LIBRA data lies completely above any of the upper bounds \( \tilde{\eta}^{\lim} \).

From Fig. 4 one can see that in a halo–independent approach the pSIDM scenario can explain the DAMA/LIBRA data for \( 6 \text{ GeV} \lesssim m_\chi \lesssim 17 \text{ GeV} \) and \( 17 \text{ keV} \lesssim \delta \lesssim 29 \text{ keV} \).
m_\chi = 11.4 \text{ GeV}, \delta = 23.7 \text{ keV}

FIG. 4: In the region inside the closed contour the compatibility parameter \( D \) defined in Eq. (20) is less than unity, implying that no 1–\( \sigma \) interval of the quantities \( \tilde{\eta}_{\text{lim},1}^{\text{v}\text{min}} \) obtained from the DAMA/LIBRA data lies completely above any of the upper bounds \( \tilde{\eta}_{\text{lim}} \). The starred point corresponds to the benchmark shown in Fig. 3.

IV. CONCLUSIONS

We have shown that the Weakly Interacting Massive Particle scenario of proton-philic spin-dependent inelastic Dark Matter (pSIDM) can still provide a viable explanation of the observed DAMA modulation amplitude in compliance with the constraints from other experiments after the release of the DAMA/LIBRA phase–2 data. The pSIDM scenario provided a viable explanation of DAMA/LIBRA–phase 1 both for a Maxwellian WIMP velocity distribution and in a halo–independent approach. At variance with DAMA/LIBRA–phase 1, for which the modulation amplitudes showed an isolated maximum at low energy, the DAMA/LIBRA–phase 2 spectrum is compatible to a monotonically decreasing one. Moreover, due to its lower threshold, it is sensitive to WIMP–iodine interactions at low WIMP masses. Due to the combination of these two effects pSIDM can now explain the modulation observed by DAMA/LIBRA only when the WIMP velocity distribution departs from a standard Maxwellian. In this case the WIMP mass \( m_\chi \) and mass splitting \( \delta \) fall in the approximate ranges \( 6 \text{ GeV} \lesssim m_\chi \lesssim 17 \text{ GeV} \) and \( 17 \text{ keV} \lesssim \delta \lesssim 29 \text{ keV} \).

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