New approaches in the analysis of dark matter direct detection data

Kookhyun Yoon¹; Stefano Scopel²
Departments of Physics, Sogang university, 35 Baekbeom-ro, Mapo-gu, Seoul 04107, Korea.
E-mail: ¹koreasds@naver.com; ²scopel@sogang.ac.kr

Abstract. We show how compatibility between the DAMA modulation result (as well as less statistically significant excesses such as the CDMS Silicon effect and the excess claimed by CRESST) with constraints from other experiments can be achieved by extending the analysis of direct detection data beyond the standard elastic scattering of a WIMP off nuclei with a spin-dependent or a spin-independent cross section and with a velocity distribution as predicted by the Isothermal Sphere model.

1. Introduction
Many underground experiments are currently searching for Weakly Interacting Massive Particles (WIMPs), which are the most popular candidates to provide the Dark Matter (DM) which is believed to make up 27% of the total mass density of the Universe, and more than 90% of the halo of our Galaxy. One of them (DAMA[1]) has been observing for more than 15 years a yearly modulation effect in the low part of its energy spectrum which is consistent with that expected due to the Earth rotation around the Sun from the elastic scattering of WIMPs off the sodium iodide nuclei that constitute the crystals of its scintillators. Many experimental collaborations using nuclear targets different from NaI and various background subtraction techniques to look for WIMP elastic scattering (LUX[2], SuperCDMS[3], COUPP[4] and PICASSO[5]) have failed to observe any anomaly so far, implying severe constraints on the most popular WIMP scenarios used to explain the DAMA excess and the excesses claimed by CDMS–Si[6] and CRESST[7] give similar situation.

However, those are concluded by assuming as elastic scattering of a WIMP off nuclei with a spin–independent or a spin–dependent cross section and Isothermal velocity distribution \( f(\vec{v}) \) of WIMPs and the assumptions are well motivated. On the other hand, new directions have been explored in the recent past both to remove as much as possible the dependence on specific theoretical assumptions (both of particle physics and astrophysical origin) from the analysis of DM direct detection data and to extend its scope to a wider class of models.

2. Contents
Starting from [8] which is called halo–independent method a general strategy has been developed [10, 11, 9] to factor out the dependence on \( f(\vec{v}) \) of the expected WIMP–nucleus differential rate \( dR/dE_R \) at the given recoil energy \( E_R \). This approach exploits the fact that \( dR/dE_R \) depends on \( f(\vec{v}) \) only through the minimal speed \( v_{\text{min}} \) that the WIMP must have to deposit at least \( E_R \),
i.e.:
\[
\frac{dR}{dE_R} \propto \eta(v_{\text{min}}) = \int_{|\vec{v}|>v_{\text{min}}} \frac{f(\vec{v})}{|\vec{v}|} d^3v.
\]

By mapping recoil energies \(E_R\) into same ranges of \(v_{\text{min}}\) the dependence on \(\eta(v_{\text{min}})\) and so on \(f(\vec{v})\) cancels out in the ratio of expected rates on different targets. Since the mapping between \(E_R\) and \(v_{\text{min}}\) depends on the nuclear mass the factorization of \(\eta(v_{\text{min}})\) is only possible in the case of detectors with a single nuclear target, or for which the expected rate is dominated by scatterings on a single target. However in the following we will extend this procedure to check the compatibility between a candidate signal (such as that from the DAMA experiment) and a null experiment also in the case when the latter contains different targets. Indeed, we can find the smallest assumptions of \(\eta(v_{\text{min}})\) as followings:
\[
\tilde{\eta}_0(v_{\text{min},2}) \leq \tilde{\eta}_0(v_{\text{min},1}), \quad \text{if } v_{\text{min},2} > v_{\text{min},1},
\]
\[
\tilde{\eta}_1 \leq \tilde{\eta}_0,
\]
\[
\tilde{\eta}_0(v_{\text{min}} \geq v_{\text{esc}}) = 0,
\]
where \(\tilde{\eta}_0\) and \(\tilde{\eta}_1\) are unmodulated and modulated part of \(\tilde{\eta}\), respectively.

A scenario proposed to alleviate the tension among different direct detection experiments is Inelastic Dark Matter (IDM). In this class of models a DM particle \(\chi\) of mass \(m_{DM}\) interacts with atomic nuclei exclusively by upscattering to a second state \(\chi'\) with mass \(m_{DM}' = m_{DM} + \delta\). In the case of exothermic DM \(\delta < 0\) is also possible: in this case the particle \(\chi\) is metastable and downscatter to a lighter state \(\chi'\). In particular, to analyze IDM case using halo–independent method is significantly more complicated compared to the elastic case for instance, mapping between recoil energy \(E_R\) and its WIMP velocity \(v_{\text{min}}\) is no more one–to–one. According to this property, self–consistency checking[9] is required for excess, since two different energy bins of the same experiment give same \(v_{\text{min}}\).

Furthermore, we will rely on the analysis of Ref.[12], where the most general non–relativistic Hamiltonian \(\mathcal{H}\) describing the elastic scattering of a fermionic WIMP particle off nuclei was written in terms of the sum of all the terms invariant by Galilean transformations. According to that analysis the most general Hamiltonian density for the process can be expressed in terms of a combination of five Hermitian operators, which act on the two–particle Hilbert space spanned by tensor products of WIMP and nucleon states. Including terms that are at most linear in nucleon and WIMP spins and incoming WIMP velocity, 15 non–relativistic quantum mechanical operators can be constructed out. Using this approach, we will single out all the possible spin–dependent interactions compatible to Galilean invariance that will be one of the subject of our phenomenological analysis.

3. Result
In this section, it will show following scenarios: i) IDM of spin–independent interaction with halo–independent method[9], ii) elastic DM of generalized spin–dependent interaction using Galilean invariant Hamiltonian with halo–independent method[13].

3.1. IDM of spin–independent interaction
One notice to analyze IDM case using halo–independent that the effect of mapping energies to velocities with \(\delta \neq 0\) is only to shift the \(\tilde{\eta}\) determination in the \(v_{\text{min}}\) space compared to the \(\delta=0\) case, without changing their normalization (with the exception of moderate changes due to possible modifications in the data binning). Therefore, compatible region is arisen by when upper bounds are shifted to the high velocity and excesses are shifted to the low velocity by using \(\delta\). Figure 1 represents compatible region for DAMA–Na and CDMS–Si in the left panel and for CRESST in the right panel. Furthermore, coupling constants of proton and neutron is adopted in this analysis, but this scenario is not achieved as shown Figure 6 and 10 in Ref.[9].
3.2. Elastic DM of generalized spin–dependent interaction
According to Ref.[12], spin–dependent interaction is represented by $\Sigma'$ and $\Sigma''$ which components of the nucleon spin are perpendicular and parallel of the transferred momentum, respectively. The non–relativistic EFT implies dependence on not only transferred momentum but also the incoming velocity. However, the incoming velocity dependence is negligible when the WIMP–nucleus scattering amplitude has both dependence and independence on incoming velocity terms. In this scenario, we take $O_4$, $O_6$, $O_9$, $O_{10}$ and $O_{46}$ (linear combination of $O_4$ and $O_6$) as defined the $O_i$ in Ref.[12]. To find compatible region in parameter space, we develop compatibility factor through comparing excesses and upper bounds. Figure 2 represents compatible regions in $m_{DM}$ and $c_n/c_p$ parameter space. The $O_6$ ($\simeq O_{46}$) and $O_{10}$ ($O_9$) have compatible region while $O_4$ is not. For two of them compatibility between DAMA and other constraints can be achieved for a WIMP mass below 30 GeV, but only for a WIMP velocity distribution in the halo of our Galaxy which departs from a Maxwellian. This is achieved by combining a suppression of the WIMP effective coupling to neutrons (to evade constraints from xenon and germanium detectors) to an explicit quadratic or quartic dependence of the cross section on the transferred momentum (that leads to a relative enhancement of the expected rate off sodium in DAMA compared to that off fluorine in droplet detectors and bubble chambers). For larger WIMP masses the same scenarios are excluded by scatterings off iodine in COUPP.

4. Conclusion
Using ordinary assumptions to analyze direct detection experimental results, DAMA excess result is incompatible with other constraints. However, using halo–independent method, Inelastic Dark Matter scattering, isovector couplings and non–relativistic EFT, tensions between upper bounds and excesses is relaxed. This shows that we are only starting now to scratch the surface of the most general WIMP direct detection parameter space.

Figure 1. Compatible region in low mass (left) and high mass (right) for WIMP with respect to mass splitting $\delta$ by kinematics. Left: The closed solid line (red) represents compatible region for DAMA–Na and horizontally hatched area (red) represents compatible region for CDMS–Si. Right: The closed solid line (red) represents compatible region for CRESST. (details are in Ref.[9])

XIV International Conference on Topics in Astroparticle and Underground Physics (TAUP 2015) IOP Publishing
Journal of Physics: Conference Series 718 (2016) 042065 doi:10.1088/1742-6596/718/4/042065
Figure 2. Contour plot in the $m_{\text{WIMP}} - c_i^0 / c_p^0$ plane for the compatibility factor $D$ defined in Eqs. (5.1,5.2) of Ref.[13]. $D \leq 1$ implies compatibility between DAMA and other constraints. The constant value $D=1$ is shown for models $O_i$, $i = 6, 46, 9, 10$ (which represent generalized spin–dependent interactions including explicit momentum and velocity dependence), while a value close to the minimum ($D=1.7$) is plotted for $O_4$, which represents the standard spin–dependent interaction, for which DAMA and other constraints cannot be reconciled.

References
[1] Bernabei R et al [DAMA and LIBRA Collaborations] 2010 Eur. Phys. J. C 67 39
[2] Akerib D et al [LUX Collaboration] 2014 Phys. Rev. Lett. 112 9 091303
[3] Agnese R et al [SuperCDMS Collaboration] 2014 Preprint arXiv:1402.7137 [hep-ex]
[4] Behnke E et al [COUPP Collaboration] 2012 Phys. Rev. D 86 5 052001 [2014 Erratum-ibid. D 90 7 079902]
[5] Archambault S et al [PICASSO Collaboration] 2012 Phys. Lett. B 711 153
[6] Agnese R et al [CDMS Collaboration] 2013 Phys. Rev. Lett. 111 251301
[7] Angloher G, Bauer M, Bavykina I, Bento A, Bucci C, Ciennia C, Deuter G and Fvon Feilitzsch F et al 2012 Eur. Phys. J. C 72 1971
[8] Fox P, Liu J and Weiner N 2011 Phys. Rev. D 83 103514
[9] Scopel S and Yoon K 2014 JCAP 1408 060
[10] McCabe C 2011 Phys. Rev. D 84 043525; Frandsen M, Kahlhoefer, F McCabe C, Sarkar D and Schmidt-Hoberg K 2012 JCAP 1201 024
[11] Gondolo P and Gelmini G 2012 JCAP 1212 015; Del Nobile E, Gelmini G, Gondolo P and Huh J 2013 Preprint arXiv:1304.6183 [hep-ph]; Del Nobile E, Gelmini G, Gondolo P and Huh J 2014 JCAP 1403 014
[12] Fitzpatrick A, Haxton W, Katz E, Lubbers N and Xu Y 2013 JCAP 1302 004 Anand N, Fitzpatrick A and WHaxton W 2014 Phys. Rev. C 89 6 065501
[13] Scopel S, KYoon K and Yoon J 2015 JCAP 1507 07 041