The impact of operator interference and target complementarity in dark matter direct detection experiments

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Abstract. We present a method to determine the limits on the DM-nucleon interaction strengths for one experiment in the non-relativistic effective theory by taking the interference of operators into account. Further, we extend the method to combine several experiments. To apply the developed methods, we use data from the XENON1T and PICO60 collaborations. The relaxation caused by the interference among operators can be up to four orders of magnitude. The strengthening of the limits by combining the analysis of both experiments can be up to four orders of magnitude.

1. Introduction

The Weakly Interacting Massive Particle (WIMP) is a promising dark matter (DM) candidate. Currently there are several operating direct detection (DD) experiments in underground laboratories on the Earth which aim to detect recoils of WIMPs with target nuclei. So far any observed excess of such recoil events has been ruled out. However, the collaborations provide limits on the DM-nucleon scattering cross-section and coupling strength. Following the non-relativistic effective field theory (NREFT) for DM particles with spin up to 1/2, there are 14 possible interactions and 28 coupling strengths, since we assume contact interactions. At this point, it is important to note that a common assumption taken by experimental collaborations is that DM couples equally to protons and neutrons (or in other words, the interaction is isoscalar). In the present paper [1], we introduce a method to derive conservative upper limits on coupling constants of DM-nucleon interactions, using the NREFT approach [2,3], and by taking the interference among operators into account. In an ongoing project [4], we extend this method to do a combined analysis of several experiments. This allows us to further constrain the allowed parameter space due to the complementarity of different targets.

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2. DM-nucleon interactions in the NREFT

A simple Hamiltonian that describes an interaction between DM particles and a proton is for example given by

$$\mathcal{H} = c^p \, (\bar{p}\chi) \, (\bar{\chi}p) \, , \tag{1}$$

with the coupling strength c^p. The DM-proton interaction rate can be factorized as

$$R = (c^p)^2 \, \mathbb{R}. \tag{2}$$

Here, $\mathbb{R}$ is a scalar quantity which depends on the detector material, the DM velocity distribution and mass, and the local DM density. Given the upper limit on the interaction rate, $R^{u.l.} \geq R$, as input from DD experiments, we can constrain the coupling strength c^p. In order to consider also DM-neutron interactions, we further extend the Hamiltonian to

$$\mathcal{H} = c^p \, (\bar{p}\chi) \, (\bar{\chi}p) + c^n \, (\bar{n}\chi) \, (\bar{\chi}n) \, , \tag{3}$$

where c^n is the DM-neutron coupling strength. Adapting the expression for the rate in Eq. 2 accordingly, we obtain

$$R = \mathbf{c}^T \mathbb{R} \mathbf{c}, \tag{4}$$

where $\mathbf{c}$ is a two-dimensional vector containing the DM-proton and DM-neutron coupling strengths, and $\mathbb{R}$ is now a 2×2 matrix. Following [2,3], we extend the set of DM-nucleon interactions by generalizing the Hamiltonian as

$$\mathcal{H} = \sum_{i}^{14} c_i^p \widehat{\mathcal{O}}_i^p + c_i^n \widehat{\mathcal{O}}_i^n. \tag{5}$$

For DM particles with spin up to 1/2, there are 14 independent operators $\widehat{\mathcal{O}}_i^p$ ($\widehat{\mathcal{O}}_i^n$) describing the interaction of type i between DM particle and proton (neutron). In this case, $\mathbf{c}$ has 28 dimensions. According to that, $\mathbb{R}$ is a 28×28 matrix.

3. The effect of operator interference

As discussed in the previous section, relation (4) together with $R^{u.l.}$ can be used to constrain the DM-nucleon coupling strength or cross-section. To obtain limits, experimental collaborations typically assume equal coupling of DM to protons and neutrons, which is not necessarily true. To illustrate the case in which $c_i^p \neq c_i^n$, we consider only one interaction at a time, but we allow interference between proton and neutron. Doing so, the interaction rate has the form of a two-dimensional ellipse, which is schematically illustrated in Fig. 1. We specify the couplings c_α and c_β to be c_i^0 and c_i^1, where "0" ("1") means "isoscalar" ("isovector"). The isospin basis is another way to describe the interactions among DM and the nucleus. The isospin and proton-neutron bases are related via $c_i^p = \left(c_i^0 + c_i^1\right)/2$ and $c_i^n = \left(c_i^0 - c_i^1\right)/2$. The limit assuming isoscalar interactions corresponds to the point $\max\{c_\alpha\} \mid_{\mathrm{Exp.1},c_\beta=0}$, where the isovector component c_i^1 is zero. This excludes the blue cross, however it is still allowed by data.

In [1], we developed a method to obtain the most conservative limit, given as $\max\{c_\alpha\}$, which can be determined by the compact expression

$$\max\{c_\alpha\} = \sqrt{\left(\mathbb{R}^{-1}\right)_{\alpha\alpha} R^{u.l.}}. \tag{6}$$

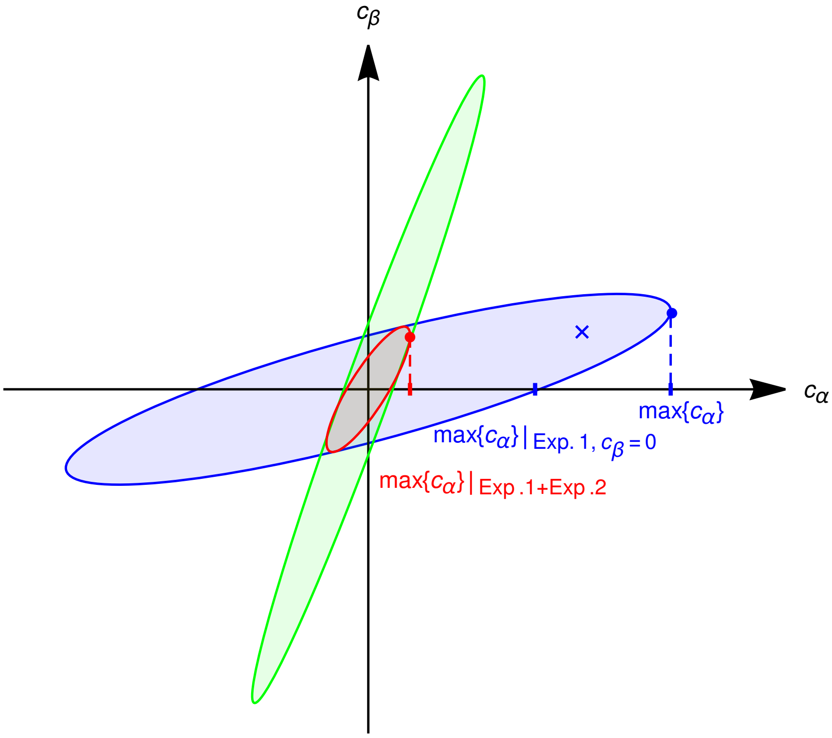

Figure 1. Two dimensional parameter space spanned by the coupling strengths c_α and c_β. The blue and green colored regions correspond each to the allowed parameter space of an experiment at a certain C.L., following the condition $R \leq R^{u.l.}$. The point $\max\{c_\alpha\}\,|_{\text{Exp.1},c_\beta=0}$ is the upper limit for c_α if $c_\beta = 0$. The blue cross is excluded by this limit, but still allowed by the most conservative limit, which is given by the coordinate $\max\{c_\alpha\}$. The interpretation of the green ellipse follows the same logic. The red ellipse is the parameter space allowed by both experiments at a certain C.L. The most conservative limit by the combination of both experiments is given by $\max\{c_\alpha\}\,|_{\text{Exp.1+Exp.2}}$.

4. Combined analysis

The orientation of the ellipsoid is determined by the $\mathbb{R}$-matrix. Since the $\mathbb{R}$-matrix depends on the detector material, we get ellipsoids with different orientations for different experiments. In Fig. 1 we show an example for two experiments with complementary target material, and therefore two ellipses with different eccentricity. This illustrates that doing a combined analysis of several experiments, the region for the allowed parameter space at a certain C.L. can be decreased, which is displayed as red ellipse. The strengthened, but still conservative limit is given as $\max\{c_\alpha\}\,|_{\text{Exp.1+Exp.2}}$. In an ongoing project [4], we developed a method to determine this limit, which only needs the $\mathbb{R}$-matrices, and the number of observed events and background events of each experiment as input.

5. Summary and conclusions

We present our results in Fig. 2 for the spin-independent (SI) and spin-dependent (SD) DM-proton cross-sections, which correspond to the couplings c_1^p and c_4^p, respectively. In order to apply our methods, we used the data from the XENON1T [5] (blue) and PICO60 [6,7] (green) collaborations. Further we chose a Maxwell-Boltzmann velocity distribution for the DM particles and a local DM density of $0.3\,\text{GeV/cm}^3$. We determined the upper limit on the coupling strengths considering different scenarios, namely "isoscalar" (dotted), *i.e.* $c_i^p = c_i^n$, "iso-interference" (dashed), *i.e.* interference between c_i^p and c_i^n for a single operator $\widehat{\mathcal{O}}_i$, and "all operators" (solid), *i.e.* interference between c_i^p and c_i^n and interference between all operators $\widehat{\mathcal{O}}_i$. The most conservative limit can be relaxed by up to four orders of magnitude w.r.t. the commonly presented "isoscalar" limit.

We also present the limits obtained by the combined analysis of the XENON1T and PICO60 data (red). The limits of the combined analysis can be strengthened by up to four orders of magnitude compared to the single-experiment analysis. The results for the other couplings are presented in [4].

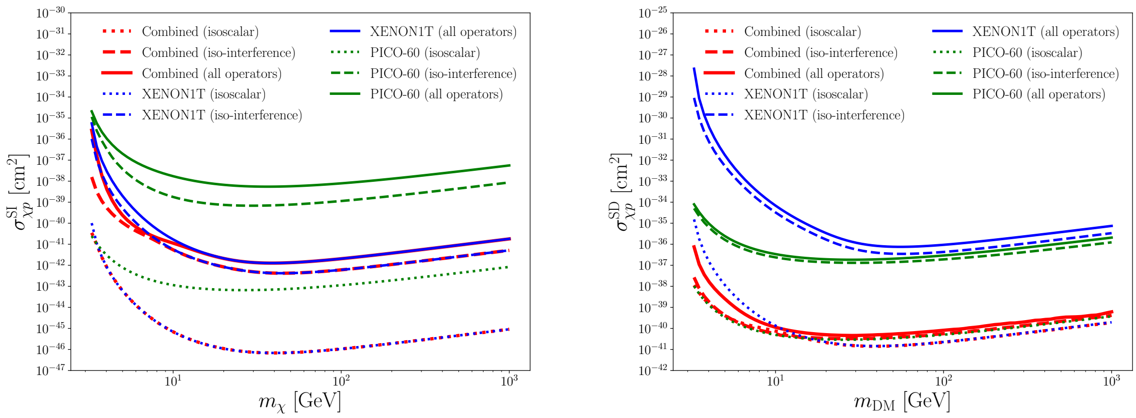

Figure 2. Upper limits at 90% C.L. on the DM-proton cross-sections $\sigma_{\chi p}^{\rm SI}$ (left panel) and $\sigma_{\chi p}^{\rm SD}$ (right panel) using data from XENON1T (blue) and PICO60 (green), considering isoscalar interaction (dotted), "iso-interference" (dashed) and "all operator" interference (solid). The result for the combined analysis is shown in red.

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