New Constraints on Xenophobic Dark Matter from DEAP-3600

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Abstract

The first-year results from DEAP-3600, a single-phase liquid argon direct-detection dark matter experiment, were recently reported. At first sight, they seem to provide no new constraints, as the limit lies well within the region already excluded by three different xenon experiments: LUX, PandaX-II, and XENON1T. We point out, however, that this conclusion is not necessarily true, for it is based on the untested assumption that the dark matter particle couples equally to protons and neutrons. For the more general case of isosping-violating dark matter, we find that there are regions in the parameter space where DEAP-3600 actually provides the most stringent limits on the dark matter-proton spin-independent cross section. Such regions correspond to the so-called Xenophobic dark matter scenario, for which the neutron-to-proton coupling ratio is close to $-0.7$. Our results seem to signal the beginning of a new era in which the complementarity among different direct detection targets will play a crucial role in the determination of the fundamental properties of the dark matter particle.

1 Introduction

Determining the fundamental nature of the dark matter particle is one of the most important open problems in particle and astroparticle physics today [1,2]. In recent years, direct detection experiments have been able to probe new regions of parameter space and to set stringent limits on the dark matter interactions [3–6]. Unfortunately, the results from direct detection experiments continue to be presented, probably due to historical reasons, in a way that may hinder their true relevance.

Typically, direct detection constraints are shown in terms of the so-called dark matter-nucleon cross section, which differs from the physically meaningful dark matter-proton cross section. They would coincide if the dark matter

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coupled equally to protons and neutrons, but such an assumption is not supported either theoretically or experimentally. In models where the dark matter couples differently to protons and neutrons—the so-called isospin-violating scenario [7–11]—it does not make sense to compare the limits on the dark matter-nucleon cross section obtained from different targets, as is usually done in the literature. Instead, one should compare the limits on the dark matter-proton cross sections, which will depend on the neutron-to-proton coupling ratio of the dark matter particle. As emphasized for example in [12], the interpretation of the experimental results may substantially change within this more general isospin-violating scenario.

Recently, the DEAP collaboration reported the results of a dark matter search, based on 231-live days of data taken during the first year of operation, with the DEAP-3600 experiment [13]. DEAP-3600 is a direct-detection dark matter experiment that uses 3279 kg of liquid argon as target and is located 2km underground at SNOLAB. At first sight, these results seem to provide no new constraints on the dark matter interactions, for the limit on the dark matter-nucleon spin independent cross section lies well inside the region already excluded by three different xenon experiments: LUX [5], PandaX-II [6], and XENON1T [4]. In this paper, we point out that this conclusion is not entirely correct. We reexamine these constraints for isospin-violating dark matter and find that there are regions in the parameter space where the DEAP-3600 limit is up to a factor of two stronger than that from XENON1T. These regions, which we delimit and characterize, correspond to the so-called Xenophobic dark matter scenario [14], for which the neutron-to-proton coupling ratio is close to $-0.7$. Our results seem to signal the end of the xenon-dominated epoch and the beginning of a new era in which the complementarity among different direct detection targets will be essential in the determination of the fundamental properties of the dark matter particle.

The rest of the manuscript is organized as follows. In the next section, the main features of the isospin-violating scenario are briefly reviewed. Section 3 presents our main results. In it we compare the limits from DEAP-3600 and XENON1T for isospin-violating dark matter. Finally, our conclusions are drawn in section 4.

## 2 Theoretical Framework

For completeness, the isospin-violating scenario for dark matter [7–11] is briefly reviewed in this section. In particular, we analyze how the interpretation of the experimental results changes within this more general framework. We refer the reader to [12] for a more general discussion and additional references.

The dark matter-nucleus spin-independent cross section, $\sigma_{A_i}$, is generally given by

$$\sigma_{A_i} = \frac{4\mu_{A_i}^2}{\pi} [f_p Z + f_n (A_i - Z)]^2,$$

where $\mu_{A_i} = M_{DM} M_{A_i}/(M_{DM} + M_{A_i})$ is the dark matter-nucleus reduced mass,
$A_i$ is the number of nucleons, and $Z$ is the nucleus charge. $f_p$ and $f_n$ denote the dark matter coupling to the proton and the neutron respectively, and are determined by the underlying particle physics model that accounts for the dark matter. Notice, in particular, that there is no reason whatsoever to expect $f_p = f_n$. That is, in general the dark matter particle will couple differently to protons and neutrons. In fact, several models for which $f_n/f_p \neq 1$ have been studied in the literature [15–22]. It is just a historical accident that the peculiar case $f_n/f_p = 1$ has become the default dark matter scenario while the more general case $f_n/f_p \neq 1$ is considered special and is referred to as isospin-violating dark matter.

Another relevant quantity is the dark matter-proton spin-independent cross section, $\sigma_p$, which is given by

$$\sigma_p = \frac{4\mu_p^2}{\pi} f_p^2.$$  \hfill (2)
Direct detection experiments, however, typically report their exclusion limits in terms of the so-called dark matter-nucleon cross section, $\sigma_{ZN}$, which can be written as

$$\sigma_{ZN} = \sigma_p \sum_{i} \eta_i \mu_i^2 A_i \left[ Z + (A_i - Z) f_n/f_p \right]^2 \sum_{i} \eta_i \mu_i^2 A_i^2.$$  \hspace{1cm} (3)

For $f_p = f_n$ (isospin-conservation), as assumed in most experimental reports, $\sigma_{ZN}$ and $\sigma_p$ coincide, but in general this is not the case. In particular, if $f_p$ and $f_n$ have opposite signs ($f_n/f_p < 0$), one can have destructive interference between the proton and the neutron contributions to the cross section, so that $\sigma_{ZN} \ll \sigma_p$. In general, it is $\sigma_p$, rather than $\sigma_{ZN}$, that is physically meaningful and that should be used to present and compare different experimental results. It is useful, therefore, to define the ratio between these two quantities,

$$F_Z \equiv \frac{\sigma_p}{\sigma_{ZN}}.$$  \hspace{1cm} (4)

$F_Z$, which depends on the target nucleus and on $f_n/f_p$, gives the factor by which the sensitivity of a direct detection experiment is suppressed for isospin-violating dark matter. In other words, if $\tilde{\sigma}$ is the limit on the spin-independent dark matter-nucleon cross section reported by an experiment (at a given dark matter mass), then $F_Z \tilde{\sigma}$ is the limit on the dark matter-proton cross section that actually applies to the isospin-violating scenario.

Figure 1 shows $F_Z$ for xenon (dashed line) and argon (solid line), and for values of $f_n/f_p$ between $-1$ and $0$. Because argon consists mostly of a single isotope, there exists a value of $f_n/f_p$ for which there is an exact cancellation between the neutron and proton contributions to the cross section, so that the dark matter does not interact with an argon nucleus. At such point, $f_n/f_p \approx -0.82$, argon experiments completely lose their sensitivity ($F_Z \to \infty$), as shown in the figure.

On the other hand, since Xe is composed of several isotopes, an exact cancellation is not possible and $F_Z$ has a maximum value –the relevance of the distribution of isotopes present in each detector was first emphasized in [11]. This maximum value of $F_Z$ is achieved for $f_n/f_p \approx -0.7$ and amounts to about $10^4$. Xenophobic dark matter is defined as a dark matter particle featuring a value of $f_n/f_p$ in the vicinity of $-0.7$ [14]. Notice that, although highly suppressed, the coupling between a xenon nucleus and a Xenophobic dark matter particle is not zero.

According to figure 1, for Xenophobic dark matter ($f_n/f_p \approx -0.7$), the limits from xenon experiments (XENON1T, PandaX-II, LUX) are actually weaker by almost four orders of magnitude whereas those from argon experiments by about two orders of magnitude. Since the gap between the 2018 XENON1T limit and the recent limit from DEAP-3600 can be less than two orders of magnitude, the latter may set the most stringent constraints on Xenophobic dark matter.
3 Results

To begin with, let us illustrate the latest results from DEAP-3600 and how they compare against other experiments under the standard assumption, $f_n/f_p = 1$—see figure 2. This figure is quite similar to that shown by the DEAP collaboration in their recent publication [13]. It displays the current limits on the dark matter-nucleon spin-independent cross section from different experiments: DS-50 (dotted line), DEAP-3600 (solid line), LUX (short-dashed line), PandaX-II (dash-dotted line) and XENON1T (dashed line). The upper two lines correspond to argon experiments whereas the lower three lines to xenon experiments. From this figure it seems that the new results from DEAP-3600 are hardly relevant; they are just excluding a region that had already been excluded by three different experiments. In the following, we will challenge this interpretation.
The crucial point is that figure 2 is valid only for $f_n/f_p = 1$, an assumption without any theoretical or experimental support. And as explained in the previous section, the interpretation of these experimental results may drastically change when we consider the more general scenario of isospin-violating dark matter. In fact, we already know that it is for Xenophobic dark matter ($f_n/f_p \approx -0.7$) that we expect the most significant modifications.

Figure 3 compares the experimental limits from XENON1T, DS-50, and DEAP-3600 for $f_n/f_p = -0.69$. For clarity we dropped from this figure the limits from LUX and PandaX-II, which are always close to and weaker than the XENON1T limit. Notice, first of all, that the scale on the y axis is different from the previous figure, as all limits become weaker –see figure 1. Remarkably, we find that, in this case, the recent limit from DEAP-3600 is actually stronger than that from XENON1T (or any other xenon experiment) in the region $M_{DM} \gtrsim 130$ GeV. At high masses, the difference between these two limits amounts to about
Figure 4: Current limits on the dark matter-proton spin-independent direct detection cross section for the cases $f_n/f_p = -0.68$ (left panel) and $f_n/f_p = -0.70$ (right panel).

A factor of two. That is, the recent results from DEAP-3600 are actually probing new regions of the parameter space for Xenophobic dark matter.

This figure not only demonstrates the main thesis of this paper but it also emphasizes the need to find a better way to present and compare the limits (and future signals) from direct detection experiments using different targets. At the very least, a caveat should be included indicating that the result is valid only for the special case $f_n/f_p = 1$.

Let us now determine graphically the precise range of $f_n/f_p$ for which the limits from DEAP-3600 can be more stringent than those from XENON1T. Figure 4 compares the same limits but for $f_n/f_p = -0.68$ (left panel) and $f_n/f_p = -0.70$ (right panel). From the left panel we see that the cross over point has moved to a larger dark matter mass, $M_{DM} \sim 200$ GeV while the difference at high masses got reduced to about a factor 1.5. From the right panel, on the other hand, it can be seen that these two features did not significantly change with respect to figure 3.

Figure 5 displays the corresponding limits for $f_n/f_p = -0.67$ (left panel) and $f_n/f_p = -0.71$ (right panel). In both cases the limits from DEAP-3600 and XENON1T become practically identical at high masses, with the former being slightly more stringent. Thus, it is only for $-0.71 \leq f_n/f_p \leq -0.67$ that DEAP-3600 probes new regions of the parameter space of Xenophobic dark matter. But, given that DEAP-3600 is still taking data, these regions are expected to get larger in the near future.

In the previous figures we also displayed the recent limit from DS-50 (dotted line), another argon experiment, because we wanted to make a point about the qualitative change that has occurred with the first-year limit from DEAP-3600. Notice that, in all cases, the region excluded by DS-50 lies entirely within the XENON1T exclusion region. Thus, DS-50 is not probing new regions of
Figure 5: Current limits on the dark matter-proton spin-independent direct detection cross section for the cases $f_n/f_p = -0.67$ (left panel) and $f_n/f_p = -0.71$ (right panel). These two cases delimit the range of $f_n/f_p$ for which DEAP-3600 sets, at least for certain dark matter masses, the most stringent limits on isospin-violating dark matter.

the parameter space. In other words, until the recent limit from DEAP-3600, xenon experiments were so dominant that they were imposing the most stringent constraints even on Xenophobic dark matter—see also [12]. It is only now, with the release of the first-year of data from DEAP-3600, that this situation has changed. This new development—the fact that argon experiments have already become competitive—is essential, for it may allow to test, once dark matter signals are observed, if the dark matter interactions are really isospin-conserving ($f_p = f_n$) or not—see e.g. [23] for a recent discussion. The observation of dark matter direct detection signals from different targets is also required to test whether the dark matter particle is its own antiparticle, as proposed in [24,25]. Our results seem to indicate that we have just entered into a new era in which the complementarity among different direct detection targets will play a crucial role in the determination of the fundamental properties of the dark matter particle.

4 Conclusions

We demonstrated that the first-year results from DEAP-3600, a single-phase liquid argon direct-detection dark matter experiment, are more relevant than they appear at first sight, for they set new limits on Xenophobic dark matter ($f_n/f_p \approx -0.7$). In fact, the DEAP-3600 limit may exceed by up to a factor of two the current limits from xenon experiments. The range of parameter space for which DEAP-3600 sets the most stringent limits on the dark matter-proton spin-independent cross section was determined to be $f_n/f_p \in (-0.71, -0.67)$ and $M_{DM} \gtrsim 100 - 300$ GeV—see figures 3-5. We also pointed out that these
new limits from DEAP-3600 seem to signal the end of the xenon-dominated epoch and the beginning of a new era in which the complementarity among different direct detection targets will play a crucial role in the determination of the dark matter nature.

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