Identification of Weakly Interacting Massive Particles Through a Combined Measurement of Axial and Scalar Couplings

G. Bertone,[1,2] D. G. Cerdeño,[3] J. I. Collar,[4] and B. Odom[4]

[1]*INFN, Sezione di Padova, Via Marzolo 8, Padova I-35131, Italy*
[2]*Institut d'Astrophysique de Paris, UMR 7095-CNRS Université Pierre et Marie Curie, 98bis boulevard Arago, 75014 Paris, France*
[3]*Departamento de Física Teórica C-XI & Instituto de Física Teórica C-XVI, Universidad Autónoma de Madrid, Cantoblanco, E-28049 Madrid, Spain*
[4]*Enrico Fermi Institute and Kavli Institute for Cosmological Physics, University of Chicago, Illinois 60637, USA*

(Received 30 May 2007; revised manuscript received 19 July 2007; published 8 October 2007)

We study the prospects for detecting weakly interacting massive particles (WIMPs) in a number of phenomenological scenarios, with a detector composed of a target simultaneously sensitive to both spin-dependent and spin-independent couplings, as is the case of COUPP (Chicagoland Observatory for Underground Particle Physics). First, we show that sensitivity to both couplings optimizes chances of initial WIMP detection. Second, we demonstrate that, in case of detection, a comparison of the signal on two complementary targets, such as in COUPP CF_3I and C_4F_{10} bubble chambers, allows a significantly more precise determination of the dark matter axial and scalar couplings. This strategy would provide crucial information on the nature of the WIMPs and possibly allow discrimination between neutralino and Kaluza-Klein dark matter.

DOI: 10.1103/PhysRevLett.99.151301　PACS numbers: 95.35.+d, 11.10.Kk, 14.80.Ly, 95.55.Vj

Introduction.—A variety of astrophysical and cosmological observations provide convincing evidence that the matter budget of the Universe is dominated by Dark Matter (DM), made of some new, yet undiscovered, particles that interact weakly or less-than-weakly with those of the Standard Model (SM). The fact that some well-motivated extensions of the SM, such as Supersymmetry (SUSY) and theories with extra-dimensions, naturally provide excellent DM candidates has attracted the interest of the particle physicists community, and many current and upcoming searches are planned to tackle the question of the nature and the properties of DM particles (for recent reviews, see, e.g., Refs. [1–4]).

DM can be searched for directly, as DM particles passing through the Earth interact inside large detectors. The field of direct searches is well-established, with many experiments currently operating or planned. Direct detection relies on one of two modes of interaction with target nuclei. Scalar, or so-called spin-independent, coupling describes coherent interactions of DM with the entire nuclear mass. Axial, or so-called spin-dependent, coupling describes interaction of DM with the spin-content of the nucleus. Overall, more attention has been given to interpretation of direct detection results in terms of the scalar interaction, and most experimental efforts have focused on using heavy-nucleus targets which enhance the scalar-interaction scattering rate. However, as detailed below, it is generally not known whether first direct detection of DM particles is more likely to occur via scalar or axial interactions. Furthermore, determination of the nature of DM parameters will require quantification of both types of interaction by measurement of the scattering cross-section on multiple target nuclei. Finally, spin-dependent couplings are also of special interest since one of the most promising indirect searches aims at the detection of high energy neutrinos from DM annihilations at the center of the Sun, where DM would accumulate precisely due to spin-dependent interactions with the nuclei of the Sun.

In this Letter, we concentrate the discussion around a new experiment, COUPP (Chicagoland Observatory for Underground Particle Physics), which exploits an old technique, the bubble chamber, in the new context of direct dark matter detection [5]. We make a case study of it, given that the target liquid employed (CF_3I) has an extreme simultaneous sensitivity to spin-dependent-proton and spin-independent couplings, via the presence of fluorine [6] and iodine, respectively. We compare expectations with other detectors not profiting from this high degree of simultaneous sensitivity, such as the case of Germanium-based searches. Another important distinguishing feature of COUPP is the ability to run modules containing C_3F_8 or C_4F_{10}, much more sensitive to the spin-dependent than -independent contributions to the signal rate. This multiplicity of targets can be exploited to identify the nature and properties of a WIMP. The conclusions are, however, not unique to COUPP and can be extended to argue the present need for a variety of targets and experiments if a clear picture of the characteristics of a dark matter particle is to be obtained.

Detection challenges and COUPP.—In order to explore extensive regions of the DM parameter space, direct detection experiments must rise to the challenge of constructing ton-scale detectors with only a few background events per year. Even deep underground, where cosmic-ray backgrounds can be substantially reduced, naturally occurring radioactivity poses quite a challenge. COUPP

(Chicagoland Observatory for Underground Particle Physics) uses stable room-temperature bubble chambers to search for DM particles scattering off of nuclei in superheated liquid. The superheated refrigerant initially used, CF_3I, is an inexpensive fire extinguishing agent. CF_3I is an excellent WIMP detector: iodine is an optimal target for spin-independent (SI) interactions, fluorine is the best possible target for spin-dependent-proton (SD_p) interactions, and both iodine and fluorine are good targets for spin-dependent-neutron (SD_n) interactions. Because of COUPP's simplicity, room temperature operation, and the low cost of several target liquids of interest, COUPP detectors are quite inexpensive as compared with other approaches to DM detection.

COUPP presently operates a 2 kg chamber at the 300 meters of water equivalent depth of the Fermilab neutrino tunnel. The potential reach of this CF_3I-filled chamber at the current depth is presented in [7]. Which sensitivity is actually achieved will depend on the level of alpha-emitter contamination in the detection volume (in contrast to most direct detection experiments, COUPP's demonstrated minimum ionizing background rejection of $>10^{10}$ makes reduction of alpha emitters its sole radiopurity concern [7]).

The short-term goals for COUPP are to reduce the alpha-recoil backgrounds in the 2 kg chamber to a level of less than one event per kg per day, and to apply the upgrades tested on it to larger chambers currently under construction. The collaboration is constructing larger devices, totaling 80 kg of CF_3I. Long-term plans involve the deep-underground installation of a target mass of order 1 ton, using a number of different refrigerant targets for an exhaustive exploration of DM models. The ability of COUPP to use the same detector technology to measure interaction rates on a range of targets is considered to be one of the principal strengths of this approach.

Theoretical predictions.—In SUSY extensions of the SM, a discrete symmetry, known as R-parity, is often imposed in order to forbid lepton and baryon violating processes which could lead, for instance, to proton decay. A phenomenological implication of this is that SUSY particles are only produced or destroyed in pairs, thus rendering the lightest SUSY particle (LSP) stable. Remarkably, in large areas of the parameter space of SUSY models, the LSP is an electrically neutral particle, the lightest neutralino, $\tilde{\chi}_1^0$, which therefore constitutes a very well-motivated DM candidate, within the class of WIMPs [1,3].

The neutralino is a linear superposition of the fermionic partners of the neutral electroweak gauge bosons (B-ino and W-ino) and of the neutral Higgs bosons (Higgsinos), and the resulting detection cross-section is extremely dependent on its specific composition. The scalar part of the neutralino-proton cross-section, σ_p^{SI}, receives contributions from Higgs exchange in a t-channel and squark exchange in an s-channel. The latter also contributes to the spin-dependent part of the cross-section, σ_p^{SD}, together with a Z boson exchange in a t-channel. The expressions for the different amplitudes can be found, e.g., in [8]. Thus, a large Higgsino component induces an enhancement of both the Higgs and Z boson exchange diagrams, thereby leading to an increase in both the spin-dependent and -independent cross sections. On the other hand, the presence of very light squarks leads to an enhancement of (mainly) σ_p^{SD}.

In order to determine the theoretical predictions for the neutralino detection cross-section, we have performed a random scan in the effective minimal supersymmetric standard model (effMSSM) scenario, where input quantities are defined at the electroweak scale [9]. The mass parameters have been taken in the range $0 \leq \mu, m_A, M_1, m \leq 2$ TeV with $3 \leq \tan\beta \leq 50$, and $-4M_1 < A < 4M_1$ (see [8,10] for a similar scan). A small nonuniversality in squark soft masses has also been included, taking $m_{Q,u,d}^2 = (1\ldots5)m^2$. The results are depicted in Fig. 1(a) by means of empty circles. Noteworthy, regions with large σ_p^{SD} are obtained, some of which predict a small σ_p^{SI}. In a second scan, we have studied supergravity-inspired models in which the soft terms are inputs at the grand unification scale. We have considered the most general situation, with nonuniversal scalar and gaugino masses, exploring the scenarios presented in [11] for $3 \leq \tan\beta \leq 50$ (see for comparison [12], where the scenario with universal parameters is studied). The results are shown in Fig. 1(a) with gray dots. In this case, a simultaneous increase in both σ_p^{SD} and σ_p^{SI} is observed. We leave the details of these scans and the implications on the SUSY parameter space for a forthcoming work. These results strongly suggest the need of combining spin-dependent and -independent techniques in order to effectively explore the whole SUSY parameter space.

Although theoretically very well motivated, SUSY is not the only possible extension of the SM leading to a viable DM candidate. An interesting alternative arises in theories with Universal Extra Dimensions (UED), in which all fields are allowed to propagate in the bulk [13]. In this case, the Lightest Kaluza-Klein Particle (LKP) is a viable DM candidate, likely to be associated with the first Kaluza-Klein (KK) excitation of the hypercharge gauge boson [14,15], usually referred to as $B^{(1)}$. In absence of spectral degeneracies, the $B^{(1)}$ would achieve the appropriate relic density for masses in the 850–900 GeV range [14]. However, due to the quasidegenerate nature of the KK spectrum, this range can be significantly modified, due to coannihilations with first [16,17] and second [18–20] KK-level modes. The allowed mass range was also found to depend significantly on the mass of the Standard Model Higgs boson [18] and in general on the matching contributions to the brane-localized kinetic terms at the cutoff scale (see the discussion in Ref. [16]).

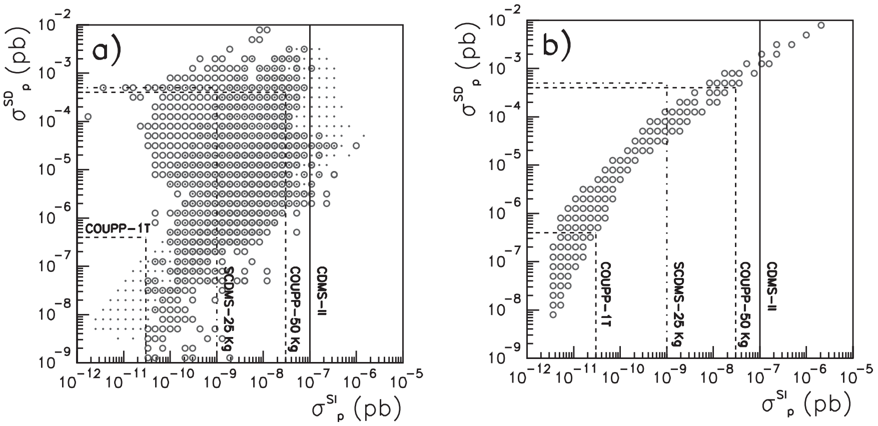

FIG. 1. Theoretical predictions for σ_p^{SD} versus σ_p^{SI} obtained from a set of random scans in the various supersymmetric (effMSSM and supergravity-inspired) scenarios (left) and in the UED scenario (right). All the points fulfil existing experimental constraints and reproduce the correct dark matter relic density. The current and projected sensitivities of the CDMS detector (25 kg stage) are also represented with solid and dot-dashed lines, respectively, together with the potential reach of COUPP (dashed lines). The estimated spin-dependent sensitivity of CDMS-25 kg to supersymmetric WIMP candidates is based on their coupling to neutrons. The sensitivity of COUPP at 1 ton target mass is based on the goal of matching the lowest alpha-emitter concentrations so far achieved in neutrino experiments [7] (e.g., KAMLAND [25]).

Our calculation of the LKP scattering cross-section of nucleons closely follows [21] (see also [14]). In practice, it is performed in a way very similar to the case of SUSY, evaluating the amplitudes for scattering of the $B^{(1)}$ particles off nucleons. In UED, the leading contribution comes from the exchange of the Higgs boson (for scalar coupling) and of first level KK quarks $q^{(1)}$ (for both axial and scalar couplings). We will work under the usual assumption that all first level KK quarks are degenerate with mass $m_{q^{(1)}}$. The resulting spin-dependent and -independent LKP detection cross-section is represented in Fig. 1(b), where (in view of the aforementioned theoretical uncertainties on the $B^{(1)}$ parameters) we took a rather liberal approach and let the $B^{(1)}$ mass $m_{B^{(1)}}$ and the normalized mass difference between the first level KK quarks and the $B^{(1)}$, $R_{q^{(1)}} \equiv (m_{B^{(1)}} - m_{q^{(1)}})/m_{B^{(1)}}$, vary independently in the range $300\ \text{GeV} \leq m_{B^{(1)}} \leq 2000\ \text{GeV}$ and $0.01 \leq R_{q^{(1)}} \leq 0.5$. Note that masses $m_{B^{(1)}} \lesssim 300$ GeV are excluded by electroweak precision data [22,23]. As one can see, LKP models tend to populate a different region of the parameter space with respect to SUSY scenarios, due to the larger spin-dependent cross-section.

WIMP discovery and identification.—The discovery of neutralino DM might take place through either scalar or axial-vector coupling. In contrast, discovery of LKP DM is for most, but not all, models expected to occur through axial-vector coupling. The ability of COUPP to run with a target such as CF_3I, which has optimal SI, SD_n, and SD_p couplings, is an advantage of this experiment in the race for first detection. Supposing an experiment succeeds in directly detecting DM particles, it is interesting to consider how the nature of the DM (e.g., neutralino or LKP) might be determined. The possibility of running with a range of detection fluids makes COUPP well poised to determine the nature of DM upon successful detection. As shown in Fig. 2(a), measurement of an event rate in a single detector does reduce allowed models, but does not generally place significant constraints on coupling parameters or on the nature of detected DM (i.e., neutralino or LKP). However, as shown in Fig. 2(b), subsequent detection of an event rate on a second target does substantially reduce the allowed range of coupling parameters and allows, in most cases, an effective discrimination between neutralino and LKP DM (it has recently been pointed out [24] that a combination of direct and indirect detection techniques might also help distinguishing between these two candidates). The combination of detector fluids used in Fig. 2 is effective in reducing the allowed range of $\sigma_p^{SI}/\sigma_p^{SD}$ because massive iodine nuclei have a large SI coupling, while fluorine nuclei have a large SD_p coupling. It must be noted that fluorine and iodine have very similar neutron cross-sections. Monte Carlo simulations show that CF_3I and C_3F_8 or C_4F_{10} exhibit essentially the same response to any residual neutron background; i.e., neutrons cannot mimic an observed behavior such as that described in the discussion of Fig. 2. Other combinations of targets such as germanium and silicon are more prone to systematic effects where residual neutron recoils can mimic the response expected from a WIMP with dominant spin-independent couplings.

Conclusions.—As we have shown with Fig. 1, in certain phenomenological scenarios, a detector sensitive exclusively to one mode of interaction may lack sensitivity to a large fraction of WIMP candidates. The possibility of operating experiments, such as COUPP, with a range of detection fluids makes them ideally suited to determine the nature of dark matter upon successful detection, i.e., to

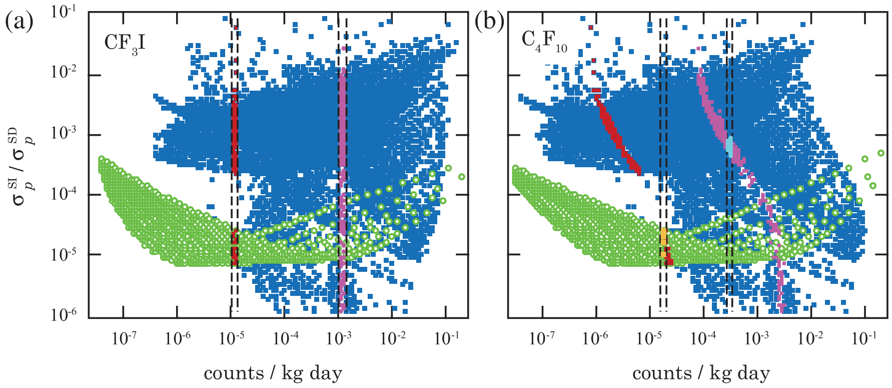

FIG. 2 (color). (a) *Left Panel:* The detection of a DM signal with a CF$_3$I detector can only loosely constrain DM candidates (blue squares for neutralinos, green circles for the LKP) in the $\sigma_p^{\rm SI}/\sigma_p^{\rm SD}$ versus count-rate plane. Red (magenta) dots show the many models consistent with a measurement of $\sim 10^{-5}$ (10^{-3}) counts/kg day on CF$_3$I. (b) *Right Panel:* measurement of the event rate in a second detection fluid such as C$_4$F$_{10}$, with lower sensitivity to spin-independent couplings, effectively reduces the remaining number of allowed models—orange (aqua) dots—and generally allows discrimination between the neutralino and the LKP (a 10% uncertainty in the measurements is adopted here for illustration).

distinguish between LKP and neutralino candidates and in the second case, to pinpoint the properties of the particle in an otherwise vast supersymmetric parameter space. The arguments presented here for the case study of COUPP can be easily generalized to a combination of data from experiments using targets maximally sensitive to different couplings, supporting the tenet that a large variety of DM detection methods is presently desirable.

G. B. was supported during part of this project by the Helhmoltz Association of National Research Centres. D. G. C. is supported by the program "Juan de la Cierva" of the Spanish Ministry of Science and Education. G. B. and D. G. C. also acknowledge support from the ENTApP Network of the ILIAS Project No. RII3-CT-2004-506222. J. I. C. and B. O. are supported by the Kavli Institute for Cosmological Physics through NSF Grants No. PHY-0114422 and No. PHY-0239812.

[1] G. Jungman, M. Kamionkowski, and K. Griest, Phys. Rep. **267**, 195 (1996).
[2] L. Bergstrom, Rep. Prog. Phys. **63**, 793 (2000).
[3] C. Muñoz, Int. J. Mod. Phys. A **19**, 3093 (2004).
[4] G. Bertone, D. Hooper, and J. Silk, Phys. Rep. **405**, 279 (2005).
[5] W. J. Bolte *et al.*, Nucl. Instrum. Methods Phys. Res., Sect. A **577**, 569 (2007).
[6] J. Ellis and R. A. Flores, Phys. Lett. B **263**, 259 (1991).
[7] E. Behnke *et al.* (to be published); http://www-coupp.fnal.gov/.
[8] J. R. Ellis, A. Ferstl, and K. A. Olive, Phys. Lett. B **481**, 304 (2000); J. R. Ellis, A. Ferstl, and K. A. Olive, Phys. Rev. D **63**, 065016 (2001).
[9] L. Bergstrom and P. Gondolo, Astropart. Phys. **5**, 263 (1996); A. Bottino, F. Donato, N. Fornengo, and S. Scopel, Phys. Lett. B **423**, 109 (1998).
[10] V. A. Bednyakov and H. V. Klapdor-Kleingrothaus, Phys. Rev. D **63**, 095005 (2001).
[11] S. Baek, D. G. Cerdeño, Y. G. Kim, P. Ko, and C. Muñoz, J. High Energy Phys. 06 (2005) 017; D. G. Cerdeño and C. Muñoz, J. High Energy Phys. 10 (2004) 015.
[12] L. Roszkowski, R. R. de Austri, and R. Trotta, arXiv:0705.2012.
[13] T. Appelquist, H. C. Cheng, and B. A. Dobrescu, Phys. Rev. D **64**, 035002 (2001).
[14] G. Servant and T. M. P. Tait, Nucl. Phys. B **650**, 391 (2003).
[15] H. C. Cheng, K. T. Matchev, and M. Schmaltz, Phys. Rev. D **66**, 036005 (2002).
[16] F. Burnell and G. D. Kribs, Phys. Rev. D **73**, 015001 (2006).
[17] K. Kong and K. T. Matchev, J. High Energy Phys. 01 (2006) 038.
[18] M. Kakizaki, S. Matsumoto, and M. Senami, Phys. Rev. D **74**, 023504 (2006).
[19] M. Kakizaki, S. Matsumoto, Y. Sato, and M. Senami, Phys. Rev. D **71**, 123522 (2005).
[20] S. Matsumoto and M. Senami, Phys. Lett. B **633**, 671 (2006).
[21] H. C. Cheng, J. L. Feng, and K. T. Matchev, Phys. Rev. Lett. **89**, 211301 (2002).
[22] I. Gogoladze and C. Macesanu, Phys. Rev. D **74**, 093012 (2006).
[23] T. Flacke, D. Hooper, and J. March-Russell, Phys. Rev. D **73**, 095002 (2006); **74**, 019902(E) (2006).
[24] D. Hooper and G. Zaharijas, Phys. Rev. D **75**, 035010 (2007).
[25] Y. Kishimoto, in *Topical Workshop on Low Radioactivity Techniques LRT 2004*, AIP Conf. Proc. No. 785 (AIP, New York, 2005), p. 193.