First Results from a Prototype CF_3I SIMPLE Dark Matter Search Detector

T. Morlat[a, 1], F. Giuliani[a, 2], M. Felizardo da Costa[b,c]
TA Girard[a, *], A.R. Ramos[b,a], R.F. Payne[d], H.S. Miley[d],
D. Limagne[e], G. Waysand[f,e], J.G. Marques[b,a]

[a] *Centro de Física Nuclear, Universidade de Lisboa, 1649–003 Lisbon, Portugal*

[b] *Instituto Tecnológico e Nuclear, Estrada Nacional 10, 2686–953 Sacavém, Portugal*

[c] *Department of Electronics, Instituto Superior Técnico, Av. Rovisco Pais 1, 1049–001 Lisbon Portugal*

[d] *Pacific Northwest National Laboratory, Richland, WA 99352 USA*

[e] *INSP (UMR 7588 CNRS), Université Paris 7 & 6, 75251 Paris, France*

[f] *Laboratoire Souterrain à Bas Bruit (Université de Nice-Sophia Antipolis), 84400 Rustrel–Pays d'Apt, France*

Abstract

We report a SIMPLE test experiment based on a prototype CF_3I superheated droplet detector with a total exposure of 0.024 kgd. The result, despite the low exposure, is seen to provide restrictions on the allowed phase space of both spin-independent and -dependent interactions which can be compared with those from the significantly larger searches in assessing the potential impact of a full-scale experiment.

Key words: WIMP search, superheated liquids
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The search for weakly interacting massive particle (WIMP) dark matter is traditionally classified as to whther spin-independent (SI) or spin-dependent (SD) according to which interaction channel they are most sensitive, of which the first has generally attracted the most attention. The current status of the SI

* corresponding author: criodets@cii.fc.ul.pt
1 current address: Department of Physics, University of Montreal, H3C 3J7 Canada.
2 current address: Department of Physics and Astronomy, University of New Mexico, Albuquerque NM, 87131 USA.

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search for WIMPs is defined by a number of projects, including DAMA/NaI-NAIAD [1,2], CDMS [3], ZEPLIN [4] and EDELWEISS [5], which as a result of their target nuclei spins also provide significant constraints on the spin-dependent phase space. In fact, this sector is also largely constrained by the results of DAMA/NaI-NAIAD and CDMS [6]. Several new experiments based on large volume, noble liquids, with significant background discrimination capabilities and large active mass potential, have been proposed with sensitivities intended to reach as low as 10^{-10}pb in the WIMP-nucleus cross section.

SIMPLE (Superheated Instrument for Massive ParticLe Experiments) is one of only two experiments to search for evidence of WIMPs using freon-loaded superheated droplet detectors (SDDs), the other being PICASSO [7]. The SDD operation is based on the nucleation of the gas phase by energy deposition in the superheated liquid; two conditions are required for the transition [8]: (i) the energy deposited must be greater than a thermodynamic minimum (E_c), and (ii) this energy must be deposited within a thermodynamically-defined minimum distance (ar_c) inside the droplet. The two conditions together require energy depositions of order ∼150 keV/μm for a bubble nucleation, rendering the SDD effectively insensitive to the majority of traditional detector backgrounds which plague more conventional dark matter search detectors (including γ's, β's and cosmic muons). This insensitivity is not trivial: given the $\sim 10^7$ evt/kgd environmental γ rate observed in an unshielded 1 kg Ge detector [9], this blindness to γ's is equivalent to an *intrinsic* rejection factor several orders of magnitude larger than the bolometer experiments with particle discrimination [10]. Both superheated liquid projects have recently demonstrated an ability to achieve competitive results with significantly reduced measurement exposures.

Because of their fluorine content, and fluorine's high spin sensitivity, these have generally been considered SD search activities. Given their performance, together with the relative inexpensiveness of the technique, the question naturally arises as to whether or not SDDs might have a similar impact in the spin-independent sector. Since the SI cross section generally scales with the squares of both the mass number and the WIMP-nucleus reduced mass, exploring this sector of WIMP interactions suggests a detector composition with nuclei of a significantly higher mass number [9]. Although several readily available "heavy" refrigerants exist ($\rho \sim 2$ g/cm^3), the problem of density-matching with the suspension gels ($\rho \sim 1.3$ g/cm^3) in order to achieve a homogeneous dispersion of the refrigerant, without introducing additional radio-contaminants, has discouraged their development.

We here report results from a prototype CF_3I-based SDD test experiment. Even with the large statistical uncertainty associated with the low exposure of 0.024 kgd, the result can be compared with those of other larger mass/exposure searches in both the SI and SD sectors, and the potential impacts of a full scale experiment assessed.

Two detectors were manufactured in a newly-constructed underground (210 mwe) fabrication facility in the LSBB [11], avoiding previous difficulties with device damage during transportation. One device contained 6.1 g CF_3I, the second 20 g. Both were fabricated from a variation of the standard SIMPLE ingredients with the addition of agarose to modify the viscosity, as well as shift upwards the sol-gel transition temperature [12], resulting in a device with 1-3 times the concentration of the SIMPLE C_2ClF_5 devices [13]. In the current fabrication protocol, and unlike in the C_2ClF_5 fabrications [14], about 50% of the refrigerant dissolves into the gel due to its high solubility in the weak hydrogen bond gel matrix, consistent with the solubility of CF_3I in water (16% of the gel) and glycerin (78% of the gel). This leads to a fracturing of the gel once a bubble nucleates, and performance degradation. This fracturing is inhibited by overpressuring the devices, but not eliminated. There is also a significant presence of clathrates hydrates at low temperature, implying that the device cannot be stored at temperature below 0^oC because clathrates hydrates break down locally the metastability of the droplets.

Given however the significantly lower backgrounds in an underground environment to which the SDD is generally sensitive, a test measurement was conducted to examine the fracturing and its consequences. The devices were capped using a new construction mechanism designed to surpress the previous problems with microleaks. Each detector was instrumented with a single piezo-electric transducer (PKM-13EPY-4002-Bo), immersed in a glycerine layer at the top of the device, which recorded the acoustic shock wave accompanying the bubble nucleation. Rear-end electronics amplified the transducer signal a factor 10^5; their time-tagged waveform traces were recorded in a MatLab platform.

As in the previous SIMPLE measurements [14], the devices were pressurized to 2 bar, and installed at the 1500 mwe level of the LSBB [11]: the set was placed inside a 700 liter water bath, surrounded by three layers of sound and thermal insulation, resting on a dual vibration absorber. Testing yielded a noise level of 6 mV, in contrast to the > 20 mV levels recorded above ground; no pickup resulting from ambient acoustic noise, cable motion or activity in the site was recorded, even when exaggerated.

The detectors were continuously operated for 5 days at the ambient temperature of 16^oC, rather than the programmed 37^oC, owing to the failure of the temperature regulator at the measurement outset. The test was briefly interrupted at various junctures for visual inspection of the detectors and performance checks to verify both were operating properly.

In the first analysis stage, the individual detector responses were inspected with respect to raw signal rate, threshold behavior, and pressure evolution over the measurement period. The device containing 20 g CF_3I was discovered to contain numerous fractures, and a noisy output; a data set corresponding to 3.9 day was extracted from the 6.1 g device records. Since the fast Fourier transform of the transducer signal possesses a well-defined frequency response, with a time span of a few milliseconds and a primary harmonic at $\sim$ 6 kHz, a filtering of this set was imposed in which only the events with a primary harmonic between 5-7 kHz were accepted. This yielded 12 candidate events.

These events were then analyzed with respect to pulse shape and amplitude, and compared with a template inventory of true bubble nucleation signals. Only one of the 12 candidates survived this filtering, the origin of the others being attributed to the slow increase of the fracture lines during the measurement. This fracture phenomenon occurs because of the high solubility of CF_3I gas inside the gel that expands into microscopic gas pocket cavities, causing a visible and audible crack (as tested with a SDD made by dissolving all the refrigerant inside the gel, which produced cracks within 24 hrs). Fig. 1 shows a typical waveform from the experiment (upper), in comparison with a true bubble nucleation event (lower) thermally-stimulated offline, indicating amplitude differences of $>$ 10 and a significantly different pulse structure. The single surviving event corresponds to neither of the waveforms in Fig. 1; while more similar to the upper figure, it however displays an amplitude nearer that of the lower figure, and for this reason is retained.

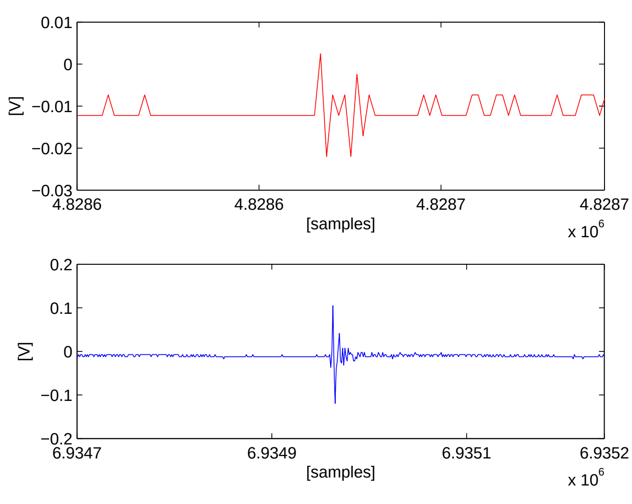

Fig. 1. typical wave form of a measurement signal after first and second stage filtering (upper) and a true bubble nucleation event (lower); note the difference in amplitude and structure.

The background response of the SDD has recently been considered in detail [15]. In review, the response of SDDs, of both low and high concentrations, to both γ's and cosmic-ray muons is similar [10,7], with a threshold sensitivity to these backgrounds occurring for $s = [(T - T_b)/(T_c - T_b)] \geq 0.5$, where T_c, T_b are the critical and boiling temperatures of the refrigerant. The CF_3I operation at 16^oC and 2 bar corresponds to $s \sim 0.16$, sufficiently below threshold for this contribution to be neglected [14].

At 1500 mwe, the ambient neutron flux is primarily a fission spectrum from the rock, estimated at well-below 4×10^{-5} n/cm^{2}s. The surrounding water bath additionally acts as a neutron moderator, as also the gel, further reducing any ambient neutron flux by at least four orders of magnitude. The response of low concentration SDDs to various neutron fields has been studied extensively [16,17,18]; the high concentration SDD response to neutrons has been investigated using sources of Am/Be, ^{252}Cf [10,19] and monochromatic low energy neutron beams [10,20].

The threshold recoil energy (E^A_{thr}) dependence on temperature is shown in Fig. 2, calculated using thermodynamic parameters taken from Ref. [21] and recoiling ion stopping powers precalculated with SRIM 2003 [22]. The bubble nucleation efficiency of an ion of mass number A recoiling with energy E is given by the superheat factor $S_A(E) = 1 - \frac{E^A_{thr}}{E}$ [18]. E^A_{thr} can be set as low as 6.5 keV before onset of the gel melting at 40^oC; the stopping power is ≥ 100 keV/μm for temperatures up to $\sim 5^o$C above the gel melting point. As evident, the same E^A_{thr} and S_A for fluorine, carbon, and iodine obtains at temperatures above $\sim 29^o$C (2 atm); whenever all recoiling ions stop within a pressure- and temperature-dependent critical distance, E^A_{thr} and $S_A(E)$ do not depend on A [20].

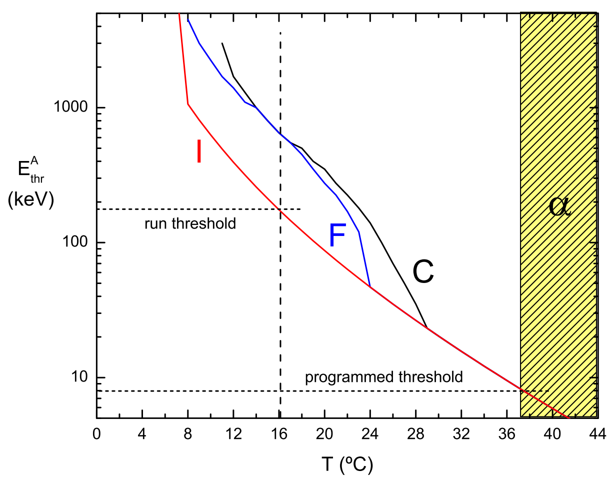

Fig. 2. variation of the threshold recoil energy with temperature for the three CF_3I constituents. The hatched region indicates the area below which the device is insensitive to α's.

The reason that the E^A_{thr} of iodine, fluorine and carbon ions in Fig. 2 do not coincide for all temperatures is that while in the range $E^I_{thr} = E_c$, below $\sim$ 24^oC a fluorine ion above E_c and below E^F_{thr} has insufficient stopping power to trigger a nucleation. More generally, a particle above E_c but below the stopping power threshold cannot directly produce a bubble nucleation, and can only be detected indirectly, with lower efficiency, through a secondary recoiling ion. The fluorine and carbon are insensitive to WIMPs since the maximum WIMP-induced recoil energy (assuming a standard isothermal halo as given in [23]) is $\sim$ 180 and 280 keV, respectively, which are well below the threshold recoil energy as seen in Fig. 2.

Smaller volume CF_3I devices were irradiated with 155 keV neutrons from a filtered beam on the thermal column of the RPI [24]; the results are in good agreement with thermodynamic calculations, and yield a minimum threshold recoil energy at $s = 0.16$ of 175 keV, with $\sim$ 100% detection efficiency.

The metastability limit of a superheated liquid, as described by the homogeneous nucleation theory [25], gives a limit of stability of the liquid phase at approximately 90% of the critical temperature for organic liquids at atmospheric pressure; at 40^{o}C and 2 bar, the probability is 10^{-1800} nucleations/kgd and decreases with decreasing temperature. At $s = 0.16$, given the high purity and the smooth droplet/gel interfaces, the inhomogeneous contribution to spontaneous droplet nucleation is also entirely negligible.

The primary internal background is due to α and α-recoils induced by radiocontaminants in the gel. The current SIMPLE gel ingredients used in the CF_3I prototype, all biologically-clean food products, are purified using pre-eluted ion-exchanging resins specifically suited to actinide removal; the freon is single distilled; the water, double distilled. The presence of U/Th contaminations in the gel, measured at ≤ 0.1 ppb via low-level α spectroscopy, yields an overall α-background level of < 0.5 evts/kg freon/d. The α response of SDDs has been studied extensively [10,19]. The SRIM-simulated dE/dx for α's in CF_3I has a Bragg peak at 700 keV and $\sim$ 193 keV/μm, which sets the temperature threshold for direct α detection to $\sim 37^o$C (see Fig. 2); below this temperature, α's can only be detected through α-induced nuclear recoils. Radon contamination is low because of the 2 atm overpressure, water immersion, and short radon diffusion lengths of the SDD construction materials (glass, metal); the measured radon contamination of the glass is at a level similar to that of the gel.

During the previous C_2ClF_5 measurements, refrigerant-free 'dummy' modules yielded signals indistinguishable from bubble nucleation events [26]. These were found to arise from pressure microleaks through the plastic SDD caps of the submerged devices. While the majority of these were eliminated by coincidence between the detector microphone and the hydrophone, this problem was addressed through capping improvements: a preliminary test of new caps showed no microleaks in three weeks, yielding a 90% C.L. upper limit of $\sim$ 0.11 microleaks/detector/day, corresponding to $\sim$ 11 microleaks/kgd for a 10 g/detector loading, versus the previous 0.5-1 microleaks/detector/day. Pulse shape filtering also provided a means of their discrimination [27].

Although the single un-discriminated event yields a maximum likelihood rate (42 $\pm$ 42 evt/kgd) significantly higher than the rates anticipated from the above background estimates ($\leq$ 1 evt/kgd), it is nevertheless consistent at 1 σ. The upper limit on the WIMP rate at 90% C.L. is then $\frac{3.89}{0.024} = 162$ evt/kgd.

The impact on the SI sector is calculated using the standard isothermal halo and WIMP elastic scattering rate [23]:

$$R = \int_{E_{thr}}^{E_{max}} \frac{\rho\epsilon(E)}{M_W} \frac{\sigma_{SI}}{\mu^2} \frac{F^2(q)}{v_0\sqrt{\pi}} \Phi dE, \tag{1}$$

where E is the recoil energy of the target nucleus, $\rho = 0.3$ GeV/c^2 is the local WIMP halo mass density, $\epsilon = 1$ - $\frac{E_{thr}}{E}$ is the efficiency of the detector, M_W is the WIMP mass, σ_{SI} is the zero-momentum transfer cross section, μ is the WIMP-nucleus reduced mass, $F(q)$ is the Helm nuclear form factor [28] given by $\frac{\sigma(q)}{\sigma(0)}$ with q the momentum transfer, $v_0 = 244$ km/s is the galactic rotation velocity. The factor $\Phi = \frac{\zeta - \varphi}{\chi}$, with

$$\begin{cases} \zeta = \frac{\sqrt{\pi}}{4}\frac{v_0}{v_E}[erf(\frac{v_{min}+v_E}{v_0}) - erf(\frac{v_{min}-v_E}{v_0})] \\ \varphi = e^{-(\frac{v_{max}}{v_0})^2} \\ \chi = erf(\frac{v_{max}}{v_0}) - \frac{2}{\sqrt{\pi}}\frac{v_{max}}{v_0}e^{-(\frac{v_{max}}{v_0})^2} \end{cases}, \tag{2}$$

where v_E is the detector velocity relative to the dark matter halo, v_{max} (the maximum incident WIMP speed) is the sum of the galactic escape velocity (600 km/s) and the detector velocity (244 km/s) with respect to the galaxy, and v_{min} is the minimum incident WIMP speed required to cause a recoil of energy E,

$$v_{min} = \sqrt{\frac{E_{thr}}{2Am_p}}(1 + \frac{Am_p}{M_W}), \tag{3}$$

with m_p the proton mass, and the small difference with the neutron mass neglected. The upper limit of the integral is given by

$$E_{max} = 2\frac{\mu^2}{Am_p}v_{max}^2, \tag{4}$$

again neglecting the small difference between the two nucleon masses.

The result is shown in Fig. 3 together with those from other leading search efforts. The figure indicates a level of ~ 1 pb at ~ 200 GeV/c^2. The region below 100 GeV/c^2 was essentially unaccessible in these measurements, owing to the high measurement recoil threshold resulting from the ambient operating temperature; the dashed line indicates the sensitivity increase assuming the same results had been obtained at the programmed temperature of 37^{o}C, considering only the iodine contribution (at 37^{o}C, all nuclei would be responsive - see Fig. 2).

A large part of this result is simply due to the intrinsic background insensitivity of the technique. As indicated in Fig. 3, assuming the same event registration, a factor 10^3 increase in exposure would be required to approach the current exclusion contour of CDMS-II, equivalent to 0.5 kg of active detector mass operated for ~ 50 d.

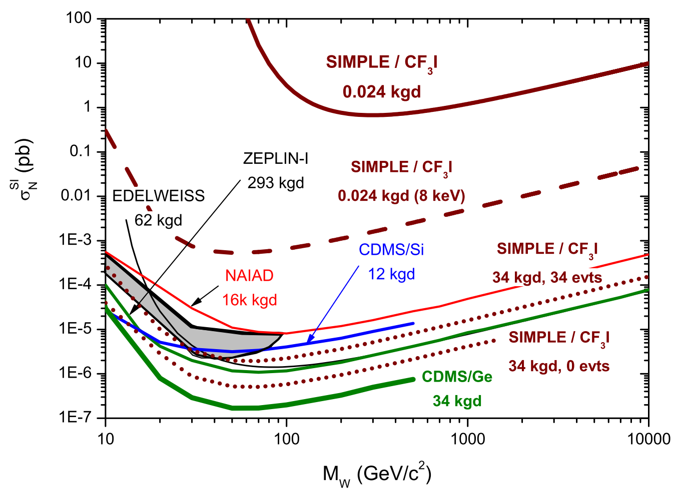

Fig. 3. spin-independent contour for SIMPLE/CF_3I (solid), together with several of the leading spin-independent search results (the allowed DAMA/NaI region is shown as shaded). The dashed line indicates the contour which would have been obtained at 37^{o}C, assuming the same results. Projected 34 kgd SIMPLE/CF_3I exposures are shown (dotted) for comparison, for both a ≤ 1 evt/kgd background level ("34 evts") and full background discrimination ("0 evts").

Assessment of the experiment impact in the spin-dependent sector is calculated within a model-independent formulation [6,29] from Eqs. (1)-(4) by replacing the Helm form factor with those from Ressell and Dean [30] for iodine and from Lewin and Smith [23] for fluorine and ^{13}C, and the zero momentum transfer $\sigma_{SI} = \frac{8}{\pi} G_F^2 \mu^2 A^2$ with the spin-dependent cross section σ_{SD} for elastic scattering [23]:

$$\sigma_{SD} = \frac{32}{\pi} G_F^2 \mu^2 (a_p < S_p > + a_n < S_n >)^2 \frac{J+1}{J} \quad (5)$$

where $< S_{p,n} >$ are the expectation values of the proton (neutron) group's spin, G_F is the Fermi coupling constant, and J is the total nuclear spin. After converting the experimental data to limits on the proton and neutron when $a_{n,p} < S_{n,p} >= 0$ respectively,

$$\sigma_{p,n}^{lim(A)} = \frac{3}{4}\frac{J}{J+1}\frac{\mu_{p,n}^2}{\mu_A^2}\frac{\sigma_A^{lim}}{< S_{p,n} >^2}, \tag{6}$$

where $\mu_{p,n}$ is the WIMP-nucleon reduced mass, and σ_A^{lim} is the upper limit on σ_A obtained from the experimental data, limit contours are constructed from

$$\left(\sum_A (\frac{a_p}{\sqrt{\sigma_p^{lim(A)}}} \pm \frac{a_n}{\sqrt{\sigma_n^{lim(A)}}}\right)^2 \leq \frac{\pi}{24 G_F^2 \mu_p^2} \tag{7}$$

for each nuclide. This can be expanded as

$$\eta a_p^2 + 2\xi a_p a_n + \lambda a_n^2 \leq \frac{\pi}{24 G_F^2 \mu_p^2}, \tag{8}$$

which describes a conic in the $a_p - a_n$ plane, with coefficients given by:

$$\begin{cases} \eta = \sum_A \frac{1}{\sigma_p^{lim(A)}} \\ \xi = \sum_A \pm \frac{1}{\sqrt{\sigma_p^{lim(A)} \sigma_n^{lim(A)}}} \\ \lambda = \sum_A \frac{1}{\sigma_n^{lim(A)}} \end{cases}. \tag{9}$$

The sign of each term in the summation for ξ is determined by the sign of the $< S_n > / < S_p >$ ratio for the isotope of mass number A, which for fluorine is negative while positive for iodine. The coefficients η, ξ and λ determine the contour of the results; for multi-nuclide experiments, the conic of Eq. (8) is an ellipse.

The result is shown in Fig. 4 at 90% C.L. for M_W = 100 GeV/c^2, in comparison with the results from CDMS-II [31], ZEPLIN [4] and NAIAD [2]. In this formulation, the region excluded by an experiment lies outside the indicated band, and the allowed region (shaded) is defined by the intersection of the various bands. Masses above or below this choice yield slightly increased limits. We use the spin values of Strottman et. al. [32]; use of the Divari et. al. values [33] would rotate the ellipse about the origin to a more horizontal position, and make it thinner.

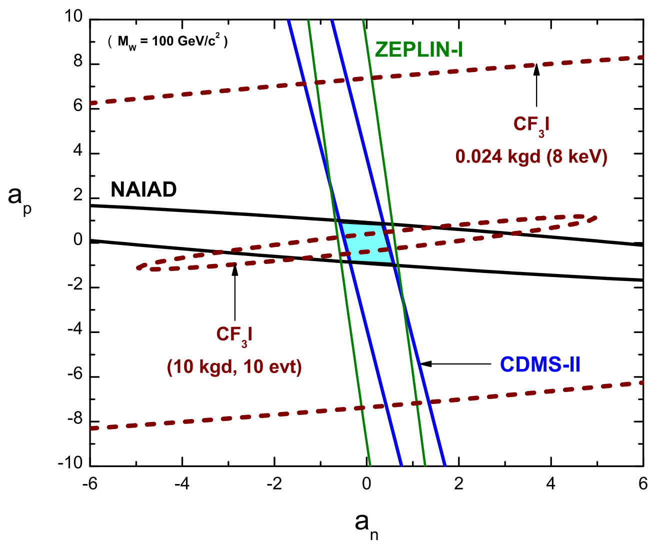

Fig. 4. $a_p - a_n$ for the SIMPLE/CF_3I at M_W = 100 GeV/c^2 which would have been obtained at 37^{o}C (8 keV threshold) assuming the same experimental result (thick dashed), together with the leading search results in this sector. Also shown is a 10 kgd projection for a 1 evt/kgd undiscriminated background. The region permitted by each experiment is the area inside the respective contour.

In this representation, the present SIMPLE/CF_3I result lies well outside the Figure, both as a result of the low statistics and because the fluorine is a spectator at 16^{o}C. Even at 37^{o}C (8 keV threshold, with fluorine active), the result would have contributed little to the overall spin-dependent exclusion, as expected from its low exposure. As also shown in Fig. 4, however, an exposure of as little as 10 kgd assuming a 1 evt/kgd undiscriminated background rate would in contrast begin to significantly impact on the spin-dependent phase space.

The temperature controller has already been replaced and its functioning tested. The background rate, while consistent with previous C_2ClF_5 measurements, suffers from the large statistical uncertainty of the low exposure; previous C_2ClF_5 measurements yielded $\leq$ 1 evt/kgd with the elimination of microleaks [14], slightly above the intrinsic level expected on the basis of the U/Th contaminants in the gel/glass, which a larger exposure will rectify.

In order to achieve the larger exposures required of a full-scale search, however, the CF_3I prototype itself requires further improvements. The recorded event pulse shape corresponds to neither of the events shown in Fig. 1: there is some possibility that it might result from a mechanically-induced fracture triggering a true bubble nucleation, which however remains to be elaborated. Although the current SIMPLE background level would suggest moderately long lifetimes in the underground site, various techniques to include the use of gelifying agents not requiring water as a solvent or the use of others techniques to inhibit the diffusion of the dissolved gas, are being explored. Also under investigation are new constructs in the detector fabrication which would eliminate the fracturing entirely.

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References

[1] R. Bernabei, P. Belli, R. Cerulli, et. al., Phys. Lett. B480 (2000) 23.

[2] G. J. Alner, H. M. Araújo, G. J. Arnison, et. al., Phys. Lett B616 (2005) 17.

[3] D. S. Akerib, M. J. Attisha, C. N. Bailey, et. al., Phys. Rev. Lett. 96 (2006) 011302.

[4] G. J. Alner, H. M. Araújo, A. Bewick, et. al., astro-ph/071858v2.

[5] V. Sanglard and the EDELWEISS collaboration, Phys. Rev. D71 (2005) 122002.

[6] F. Giuliani, Phys. Rev. Lett. 93 (2004) 161301.

[7] N. Boukhira, I. Boussaroque, R. Gornea, et al., Astrop. Phys. 14 (2000) 227.

[8] F. Seitz, Phys. Fluids 1 (1958) 2.

[9] R. J. Gaitskell, Ann. Rev. Nucl. Part. Sci. 54 (2004) 315.

[10] M. Barnabé-Heider, M. Di Marco, P. Doane, et. al., Phys. Lett. B624 (2005) 186; PICASSO is based on C_4F_{10}.

[11] Laboratoire Souterrain Bas Bruit de Rustrel-Pays d'Apt: http://lsbb.unice.fr

[12] T. A. Morlat, D. Limagne, G. Waysand, J. I. Collar, Nucl. Instr. & Meth. A560 (2006) 3339.

[13] The Chicago group has similarly succeeded in developing a CF_3I-based SDD prototype with a polyacrylamide-based gel (J.I. Collar, private communication).

[14] TA Girard, F. Giuliani, et. al., Phys. Lett. B621 (2005) 233.

[15] F. Giuliani, T. A. Morlat, TA Girard, Phys. Rev. D75 (2007) 063503.

[16] F. d'Errico, Nucl. Instr. & Meth. B142 (2001) 229.

[17] M. Harper, PhD thesis, University of Maryland.

[18] Y.C. Lo, R. Apfel, Phys. Rev. A38 (1988) 5260.

[19] J. Collar, J. Puibasset, TA Girard, et. al., New Journ. Phys. 2 (2000) 14.1.

[20] F. Giuliani, C. Oliveira, J. Collar, TA Girard, et. al., Nucl. Instr. & Meth. A526 (2004) 348.

[21] Y. Y. Duan, et. al., Int'l. Journ. of Thermophysics 21 (2000) 393.

[22] http://www.srim.org/.

[23] J. D. Lewin, P. F. Smith, Astrop. Phys. 6 (1996) 87.

[24] Research Reactor of Portugal: http://itn.pt.

[25] J. G. Eberhard, et. al., J. Coll. Interf. Sci. 56 (1975) 369.

[26] J. Collar, J. Puibasset, TA Girard, et. al., Phys. Rev. Lett. 85 (2000) 3083.

[27] M. Felizardo, R. C. Martins, A. R. Ramos, et. al., in Proc. 2005 IEEE Instrumentation and Measurement Technology Conference (IEEE, New York, 2006) 1551.

[28] R. H. Helm, Phys. Rev. 104 (1956) 1466.

[29] D. R. Tovey, R. Gaitskell, P. Gondolo, Y. Ramachers, L. Roszkowski, Phys. Lett. B488 (2000) 17.

[30] M. T. Ressell and D. J. Dean, Phys. Rev. C56 (1997) 535.

[31] D. S. Akerib, M. S. Armel-Funkhouser, M. J. Attisha, et. al., Phys. Rev. D73 (2006) 011102.

[32] A. F. Pacheco, D. Strottman, Phys. Rev. D40 (1989) 2131.

[33] M. T. Divari, T. S. Kosmas, J. D. Vergados, et. al., Phys. Rev. C61 (2000) 054612.