Recent results from the SIMPLE dark matter search

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Abstract. We present the results of the recent Phase II SIMPLE search effort, comprising two stages each of ~14 kgd exposure of 15 Superheated Droplet Detectors with ~0.2 kg active mass and recoil energy threshold of 8 keV. In the second stage, the neutron shielding was increased to reduce the on-detector rate by a factor 3.5. Combined with an improved nucleation efficiency and analysis of the detector pressure evolution during the measurements, the results yield improved results in the phase space of both spin -dependent and -independent WIMP interactions.

1. Introduction
The SIMPLE [1,2] measurements are based on high concentration superheated droplet detectors (SDDs), 1-2% suspensions of superheated liquid C₂ClF₅ droplets (<r>~30 μm radius) in a viscoelastic 900ml gel matrix, which undergo transitions to the gas phase upon energy deposition by incident radiation. The physics of the superheated liquid response to incident radiation is generic: nucleation of the gas phase in the liquid requires [3]: (i) that the energy deposited be greater than a thermodynamically defined minimum energy, and (ii) that this energy be deposited within a thermodynamically defined minimum distance inside the droplet. Together, energy depositions of order ~ 150 keV/μm are required for a bubble nucleation, which renders the technique effectively insensitive to the majority of traditional light particle backgrounds which complicate more conventional dark matter search detectors (including electrons, γs and cosmic muons).

The SDDs are operated in the 1500 mwe deep, 60 m³ GESA facility of the Laboratoire Souterrain à Bas Bruit [4] in southern France. The cavern is shielded from the rock environment by a 30-100 cm thickness of concrete, which is internally sheathed by a 1 cm thickness of iron. The SDDs were immersed to a depth of 20 cm in a temperature-controlling, 700 liter water pool within the cavern, which currently rests on a dual vibration absorber placed atop a 30 cm thick wood platform and 10 cm PE, resting on a 50 cm thick concrete floor. The pool was surrounded by layers of sound and thermal

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insulation. An additional 50-75 cm thick water shielding surrounded the pool and platform, with a 75 cm water thickness overhead; 50 cm of water separated the pool bottom from the detector bases. Monte-Carlo simulations of the on-detector neutron field [5], based on radio-assays of the shielding materials and which account for spontaneous fission, decay-induced ($\alpha$,n) reactions and ($\mu$,n) reactions in the rock, show negligible variations for concrete thicknesses ≥ 20 cm, and yielded an expected neutron background of 0.253 ± 0.002 (stat) ± 0.003 (syst) evt/kgd.

The ambient radon level varies seasonally between 28–1000 Bq.m$^{-3}$ as a result of water circulation in the mountain, which is reduced to 50-80 Bq.m$^{-3}$ during measurements by circulating the cavern air at ~ 0.2 m$^2$s$^{-1}$; circulation of the water-pool at 25 liter/min (equivalent to replacing the top 1 cm water layer each minute) through the temperature-controlling external cryothermostat, as well as the short radon diffusion lengths of the SDD construction materials (glass, plastic, metal), the N$_2$ overpressuring, and the glycerin layer covering the gel reduces the overall $\alpha$ contribution to the measurement, including the radon progeny and detector contribution to an estimated 5.72 ± 0.12 (stat) ± 0.29 (syst) evt/kgd.

Each SDD was fabricated in an underground (210 mwe) clean room near GESA, following procedures previously described elsewhere [6]; the gel ingredients, all biologically-clean food products, were $\alpha$-purified using actinide-specific ion-exchanging resins. The freon was single distilled; the water, double distilled. Each was capped with an electret microphone [7] and immersed in the GESA water pool; each was pressurized to 2.00±0.05 bar and maintained at 9.0±0.1ºC by the water pool. The presence of U/Th contaminations in the gel, measured at ~ 0.1 ppb by low-level $\alpha$ and $\gamma$ spectroscopy of the production gel, yielded an overall $\alpha$-background level of < 0.5 evt/kg/d; a similar level is measured for the detector containment materials.

The characterization of the SDDs has been extensively studied [8-10] through fabrication variations, the use of different refrigerants, SDD lifetime, spatial localization of events, calibrations and neutron tomography.

2. Experimental detail and analysis
Phase II of SIMPLE consisted of 2 science runs, the first between October 2009 and February 2010, and the second (following a rebuilding of the neutron shielding, to include addition of the PE, paraffin and wood) later in May-July 2010.

The signals of the 15 SDDs and respective pressure readings in each measurement stage, temperature, plus the acoustic veto, were monitored continuously, as also the radon level. Data losses during the two periods, resulting from the detectors being introduced at one device per day over the three week installation periods, from weather-induced power failures, and from detector failure, yielded a total net exposure of 14.1 kgd and 10.1 kgd, respectively.

Fig. 1 neutron and $\alpha$ calibration results, obtained from irradiations of a single C$_2$ClF$_3$ detector.
Each detector was first inspected for its raw signal rate and pressure evolution over the measurement period. These were analyzed according to their signal characteristics for origin as described in [11], yielding 60 and 45 particle-induced events respectively. The event and pressure records were next correlated, and reduced data sets extracted for pressures below 2.20±0.05 bar corresponding to a recoil energy threshold of 8 keV, with reduced exposures of 13.5 and 6.71 kgd and 56 and 39 particle-induced events, respectively.

At 9°C, the reduced superheat of the devices is 0.3, and the probability of events from backgrounds such as electrons, γ's and MIP's negligible [1] over the exposures. The reduced signal events were compared with similarly-analyzed neutron and α calibration signals [1,11], obtained with weak sources of Am/Be and U₃O₈ respectively, and recently re-confirmed using the same detector module for both calibrations as shown in Fig. 1. These yielded 10 and 1 neutron-like events for Stage I and II, respectively, most likely of neutron origin, with an acceptance of ≥ 97%.

The Stage I data above 2.20 bar was used to precise the C₂ClF₅ nucleation parameter at Λ = 1.40±0.05. Monochromatic (54 and 149 keV) neutron irradiation data, taken at 1 and 2 bar as a function of temperature [12], were re-analyzed to yield a new efficiency of η=1-exp[-Γ(1–E<sub>th</sub>/E_n)] with Γ=4.2±0.3, independent of pressure.

3. Results and conclusions

Upper limits on the number of WIMP events was estimated for each measurement Stage by applying the Feldman-Cousins method [13], based on the observation of j neutron-like events with a background of k events one s<sub>13</sub> below the central value of the expected neutron background. The resulting spin-dependent (SD) exclusion contours are presented in Fig. 2 (a), together with leading direct and indirect search results. Aside from providing the most restrictive limits on a possible spin-dependent WIMP-proton coupling to date, they for the first time intersect with result from the indirect search experiments.

The impact of the results in the spin-independent (SI) sector are similarly shown in Fig 2 (b), in comparison with results from the leading search efforts. The contours differ slightly from [2] as a result of an arithmetic error correction in application of Feldman-Cousins, and relaxation of the previously-reported neutron identification based on single detector double-scatterings pending further investigation. Nevertheless, the results remain in tension with a large part of the phase space recently claimed as indicative of a light mass WIMP discovery.

**Fig. 2** (a) various SD WIMP-proton SIMPLE exclusion contours, together with leading direct and indirect search results; (b) various SI SIMPLE contours, together with those of leading spin-independent search results; shown in both are previous and reanalyzed Stage 1 results, Stage 2, and a merging of the two.
The improved restrictions are a direct result of the more detailed signal analysis permitted by the use of a true microphone-based data acquisition, improved radio-assays of the shielding materials, and the revised nucleation efficiency in the analysis: Stage 2, with the additional benefit of its improved neutron shielding, provides an almost identical sensitivity with about half the Stage 1 exposure.

There remain some concerns regarding these results which require further investigation. First, a full characterization of the GESA measurement site, using a Bonner sphere spectrometer system of the IRSN LSBB partner is being conducted. Second, some of the materials used in the experiment are still under radio-assay, which may impact on the estimates of the neutron backgrounds as used in the contour extraction. Last, the identification of the apparent neutron events by a single detector double scattering is being fully re-examined.

While these issues are in progress, improvement on the above results nevertheless would require an increase in the experiment active mass to provide for increased exposures over shorter measurement times. A new device [14] re-prototyped in 2010, based on a 5 kg superheated C$_3$F$_8$ droplet contained within a gel-sheathed vessel (effectively a bubble chamber), is currently completing development; it will permit a factor 25 increase in the active mass with reduced space requirements. An additional all-around 60 cm of purified water shielding increases the neutron suppression by more than 10$^3$, giving the possibility to achieve exposures of 10$^2$ kgd in measurements of a few weeks duration.

Acknowledgments

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