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A new technique for direct investigation of dark matter

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ABSTRACT

The MOSCAB experiment (Materia OSCura A Bolle) uses a new technique for dark matter search. The Geyser technique is applied to the construction of a prototype detector with a mass of 0.5 kg and the encouraging results are reported here; an accent is placed on a big detector of 40 kg in construction at the Milano-Bicocca University and INFN.

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1. Introduction

WIMPs [1] (Weak Interacting Massive Particles) are one of the more suited hypotheses for the non-baryonic candidate for dark matter [2]; they indeed satisfy the required density compatible with the cosmological constraints; they form galactic halos with a Maxwellian velocity distribution around a mean velocity of about 230 km/s and with a matter density of about 0.3 GeV/cm^3 at the location of the solar system.

The general form of the WIMP interaction with ordinary matter is

$$\sigma_A = 4G_F^2 \left(\frac{M_W M_A}{M_W + M_A} \right)^2 C_A$$

where G_F is the Fermi constant, M_W and M_A are the mass of the WIMP and of the target nucleus respectively; C_A is an enhancement factor which depends on the type of the WIMP interaction. In supersymmetry, the spin-independent (SI) or scalar interactions proceed via Higgs or squark exchange or both and C_A is given by the following:

$$C_A^{SI} = (1/4\pi)[Zf_p + (A-Z)f_n]^2$$

$f_{n,p}$ are the WIMP coupling constant to nucleons.

On the other hand the spin-dependent (SD) interaction with axial-vector coupling involves squarks and Z exchanges and the C_A^{SD} is

$$C_A^{SD} = (8/\pi)[a_p S_p + a_n S_n]^2 \frac{J+1}{J} = (8\pi)(\lambda)^2$$

where $S_{p,n}$ are the average spins over all protons and neutrons; $a_{p,n}$ are the effective WIMP proton (neutron) coupling strengths and J is the total nuclear spin.

The enhancement factor is largest for nuclei of ^{19}F. (see Table 1 and [3]).

The relation between the kinetic energy of the recoiling ions (in the case of F) and the WIMP's mass is reported in Fig. 1 and [4] where it is shown that to investigate low WIMP masses (around 10 GeV) it is necessary to explore low energy recoils (10 keV).

In this figure we have reported indeed the number of expected events per day and per kg of detector divided by the cross-section (σ_{W+F} in pbarn in the case of SD interaction [5]).

The nuclear form factor of fluorine and also a rough integration on the energy spectrum of WIMPs are taken into account.

Many experimental methods have been studied and realised to detect directly dark matter. In particular we want to point out the use of scintillators NaI [6], liquid argon [7], xenon [8], cryogenic semi-conductors [9] and detectors based on the nucleation of bubbles [10–12]. In the following we will describe in more detail the technique based on bubble formation with the NEW TECHNIQUE of the GEYSER.

This kind of detector (Geyser) has never been used for the elementary particle physics (it was constructed only once in Bern in 1964 by Hahn and Reist [13] to detect transuranic nuclei).

2. General considerations of the new technique and description of the prototype

The technique we have chosen for the direct search of dark matter is the "Geyser technique" or "condensation chamber". This technique is a variant of the superheated liquid technique of

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[1] We dedicate this paper to the memory of P. Negri our estimated colleague.

Table 1
Enhancement factor for SD reactions.

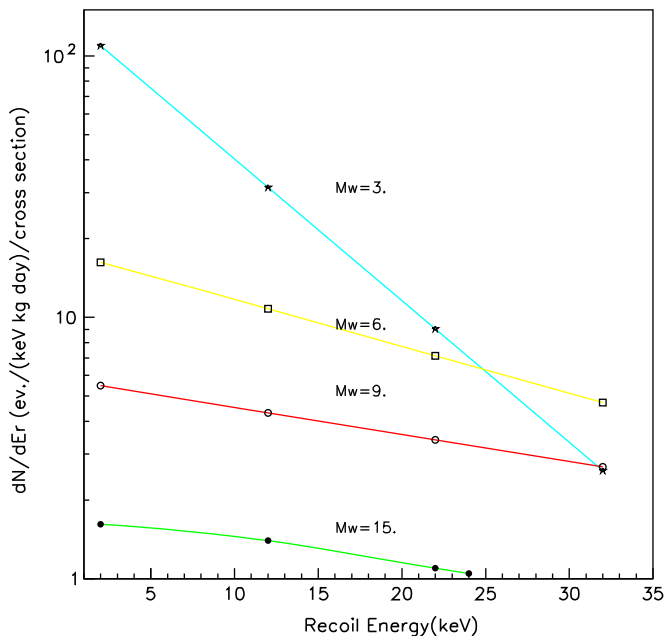| Isotope	Spin	Unpaired	λ^2
^{7}Li	3/2	p	0.11
^{19}F	1/2	p	0.863
^{23}Na	3/2	p	0.011
^{29}Si	1/2	n	0.084
^{73}Ge	9/2	n	0.0026
^{127}I	5/2	p	0.0026
^{131}Xe	3/2	n	0.0147

Fig. 1. Kinematics of the elastic scattering of WIMPs on fluorine.

extreme simplicity. The main volume of the target liquid (C_3F_8 in our case) is kept in a thermal bath at a constant temperature T_L.

The vapour above the liquid is kept at a temperature $T_V < T_L$ by cooling the top of the vessel by a circulating liquid (water).

The equilibrium vapour pressure above the liquid is P_V so the liquid is in a state of under-pressure, and therefore a superheat of $\Delta p = P_V - P_L$ where $P_V = P_{Sat.}(T_L)$ and $P_L = P_{Sat.}(T_V)$. A local energy release due for instance to a recoiling ion induced by a WIMP interaction can produce a vapour bubble which can grow (if over a threshold in energy) to visible size. This vapour bubble rises in the liquid and pushes up part of the liquid in the neck (this is the reason of the name Geyser). When equilibrium pressure is reached, the hot vapour in the top of the vessel recondenses, and the liquid is recovered into the main volume. The original metastable state returns in a few seconds and the system is ready to record a new event. The system does not require external intervention or recompression.

In Fig. 2 a drawing of the principal parts of the Geyser is shown.

The figure represents a vertical section of a cylinder; so the coils used as sources of heat are represented by small circles.

In the top part of the same figure the pressure equalisers are shown; they are constituted by two elastic membranes that push the external water when the pressure of the freon gas increases and acts also in the reverse sense.

In Fig. 3 there is a picture of the apparatus; in the bottom is shown the liquid freon; the buffer liquid glycol that separates the freon liquid from the vapour is also shown. The degree of super-heat applied must exclude the detection of minimum ionising particles (electrons and γ rays) and on the contrary it must allow the detection with high efficiency of the recoiling ions.

The principal advantages of the Geyser (and of the bubble techniques) are the following:

(1) The strong rejection of the particles at minimum ionisation (electrons and γ).
(2) The simplicity of the mechanical construction, also for large size detectors and therefore low cost.
(3) The very interesting possibility to count multiple neutron interactions and hence subtract the neutron background (the interaction length of a neutron is of the order of (6–9) cm in our liquid). The double or triple interaction in the same frame can be used statistically to evaluate the number of events with a single interaction due to neutrons.
(4) The possibility to distinguish the spin dependent interaction of WIMP from spin independent by changing the liquid used.
(5) For the Geyser (ONLY) the reset of the detector is automatic and has a very short time (few seconds).

A prototype of Geyser has been constructed with a mass of 0.5 kg in Milano-Bicocca [14].

With reference to Fig. 2. The quartz vessel of 0.33 l is immersed in a water bath and it is surrounded by Cu coils with an internal circulating water at the two fixed temperatures.

It contains freon C_3F_8 around 25 °C at a pressure of about 6 bar.

The hot freon is separated from the cold freon vapour by the neck of the vessel filled by a buffer liquid (glycol) with thermal capacity greater than that of the water.

We would like to point out that in the original Geyser of Hahn no buffer liquid was used but we found that it improves greatly the stability of the device.

The temperature of the two regions of water is kept fixed by two thermostats with a precision of 0.1° and the two regions are separated by a loosely fitting rubber washer.

The temperature of the cold vapour was varied within 15 and 21 °C.

Everything is surrounded by a cylindrical vessel of plexiglass of thickness 1.5 cm, filled with a water/glycol mixture.

In order that the flask undergoes only a small over pressure with respect to the water an automatic pressure equaliser using rubber membranes is used.

The freon is illuminated by diffuse light, coming from LEDs.

To summarise, the Geyser is essentially a vessel constituted by a "FLASK" containing the overheated liquid (f.i. some kind of freon) and a "NECK" (containing partially a separation liquid and partially the freon vapour).

The scattered ions after an interaction with a neutral particle like a neutron or a WIMP deposit their energy in very small regions (size of the order 0.05–0.1 μm).

In these conditions a bubble can grow and reach a few mm of radius (well visible).

Two professional digital cameras monitor in a continuous way at 50 frames per second (fps) the volume in the freon vessel.

Some pixels undergo a change of luminosity when a bubble is generated.

At this point a trigger is launched and a stream of pictures is registered (between −50 and +50 frames starting from the trigger); in Fig. 4 the evolution of a typical bubble observed in our detector is shown:

The time sequence (period=20 ms) starts in the bottom of this figure (right-hand), where it is possible to see a small bubble; the sequence continues towards the left and passes to the third line (right); the bubble increases its volume and reaches the surface of the liquid freon (second line); here it produces a small Geyser (left side of the second line); in the first line the passage of the bubble in the lower layers of glycol is shown.
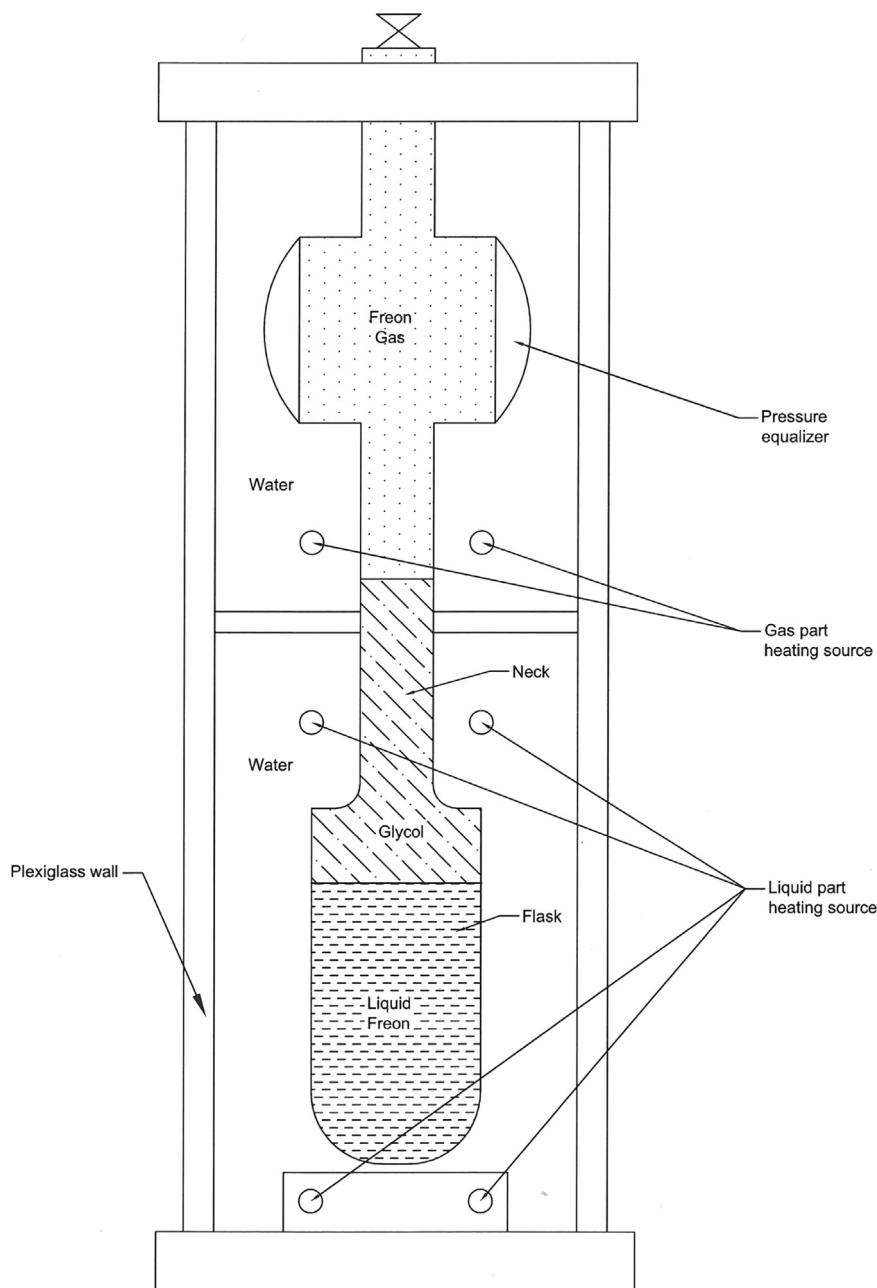
Fig. 2. Sketch of a vertical section of the Geyser.

After that, the stream of data is stored and visually scanned to see the evolution of the bubbles.

The bubble reaching the superior part of the Geyser finds a lower temperature, becomes again liquid and goes back to the hot region of the overheated liquid.

This is the fundamental cycle that brings back our Geyser to the initial conditions, with a dead time of a few seconds.

The ultimate sensitivity of a dark matter search experiment is determined by how well one can reduce the backgrounds that can mimic the true signal. This will be discussed further in Section 4.

3. Results from the prototype

We are working in Milano-Bicocca at the IV floor in a Laboratory provided by the University and INFN.

Over the last couple of years we have carried out a large number of runs in which the temperature of the liquid and vapour has been varied and also the amount of liquid freon and glycol.

These experiments were carried out in order to arrive at a device that was stable over very long periods of time, sensitive to carbon and fluorine recoils of about 5 keV kinetic energy and insensitive to minimum ionising particles.

Bubble formation is well understood [15] and depends on the critical radius $R_c = 2\sigma/\Delta p$, where σ is the surface tension of the liquid and Δp the pressure difference between the vapour inside the bubble and the liquid.

Another important quantity is the critical energy E_c necessary for a visible bubble formation.

E_c is a function of R_c, σ, Δp and the latent heat of evaporation of the liquid.

Fig. 3. Internal Geyser's view.

In Fig. 5 is shown the energy loss dE/dx for C and F ions and also for electrons.

Therefore if the energy of recoil is greater than E_c (the critical energy) and stopping power satisfies the relation (dE/dx)$2R_c > E_c$, then a bubble will form. In Fig. 5 we show several sensitivity zones for various vapour temperatures and liquid–vapour temperature differences DT.

The experimental regions in which we must work are reported in squared boxes in the same Fig. 5.

Note that our work region is far away from that for detection of electrons.

In Fig. 6 the critical energy is shown as a function of T (vapour) for various values of DT.

We can see that to reach a threshold of 10 keV for the recoiling ions we must reach a difference in temperature DT between the liquid and the vapour > 7.5 °C; to reach a threshold of 3 keV we need a DT of 9.0 °C.

In the previous chapter it was stated that the characteristic of a Geyser must be a high rejection of electrons and γ accompanied by an easy detection of nuclear recoils (similar to the recoiling ions due to an interaction of a WIMP).

To test this, we placed outside the detector (at a minimal distance from the freon) a neutron source (Am–Be 40 kBq). The results are shown in Fig. 7 and we can see that we are very sensitive to the detection of neutrons.

After that we put a gamma ray source (20 kBq ^{22}Na) near the detector and in Fig. 8 are shown the background distribution and that obtained with a gamma source (Na^{22}).

We can remark that in the latter case we obtained compatible results: no excess in events in the presence of the radiative source! We can hence evaluate the rejection factor for electromagnetic showers to be $< 10^{-7}$; this confirms the COUPP result [16]: rejection factor $< 10^{-10}$.

By varying the amount of freon in the flask and the height of the glycol we have managed to obtain extremely stable conditions which allowed a complete threshold scan above 5 keV, and run for several months.

The temperature of the fluid was 25 °C and the expected threshold variation with the vapour temperature is shown in Fig. 9.

We have followed indeed the experimental conditions reported in such a figure (temperatures of the liquid and of the vapour freon).

Fig. 10 shows the number of events/hour obtained for the background and the neutron source as a function of DT. An important feature of this cumulative curve is that a plateau seems to be reached. In order to compare our data to what is expected from the neutron source we have performed Monte Carlo calculations using the MCNP package coming from Los Alamos [17]. MCNP is a general purpose coupled neutron/photon/electron Monte Carlo transport code. It is particularly suitable for neutron transport simulation thanks to the capability to model arbitrary three-dimensional configuration of material and the continuous-energy cross-sections treatment used to simulate the transport effects.

The neutron energy regime is from 5–10 keV to 20 MeV for all isotopes.

In Fig. 11 the emitted neutron spectrum is shown along with the neutron spectrum entering the sensitive freon.

Fig. 12 shows the energy distribution of the recoiling nuclei expected per emitted neutron.

In Fig. 13 we compare the distribution (M.C. results + the measured background) with the corresponding experimental distribution and we can see a very good general agreement with a threshold of 5 keV; the reported errors are the statistical errors only.

We also obtained from our data the differential energy distribution of the observed recoils by making:

(a) The background subtraction (difference in rates) at each value of DT.
(b) The energy distribution of neutrons (background subtracted) as a function of the energy threshold and obtained by evaluating the differences between contiguous rates of the previous distribution (b).
(c) The use of the relation between the energy threshold and DT shown in Fig. 6.

A direct comparison of the MC prediction and the measured spectrum of neutrons is reported in Fig. 14 and a good agreement is obtained also in this case.

Another important result is reported in Fig. 15; it demonstrates the exponential behaviour expected for the time difference between successive events.

We remark the depletion in the first bin and we conclude that the maximum dead time (recovery time) is about 5 s.

4. Background for future experiments with larger Geysers

We distinguish two types of problems which would affect the working of larger Geysers:

(a) *Non-particle induced instability found in the prototype*: During the long series of tests and measurements at different temperatures and different values of DT, we came indeed across two problems:

(i) Instability induced by the walls of the vessel (some boiling points). To counteract this effect we decided to cover the
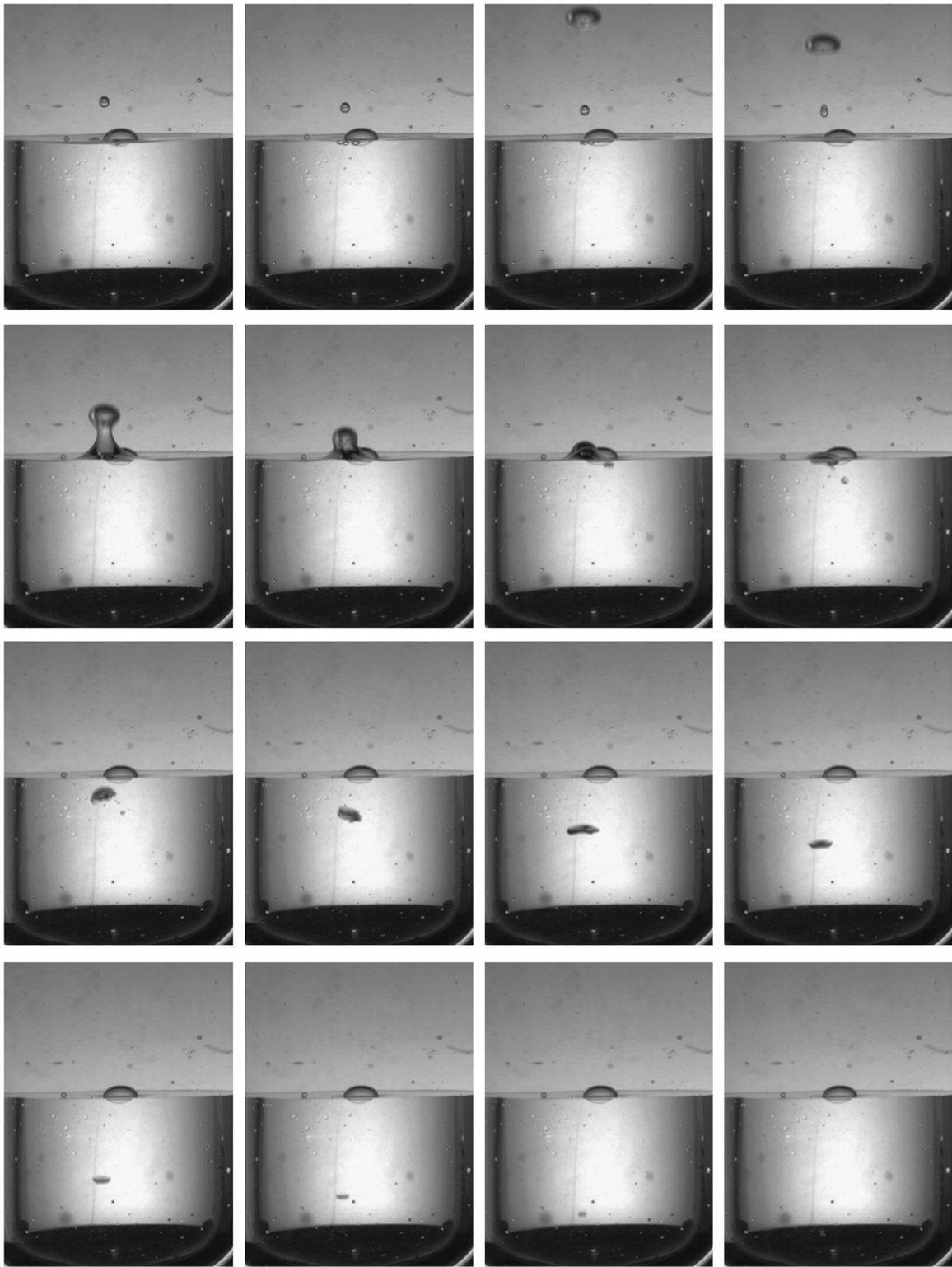
Fig. 4. Evolution of a bubble.

internal wall of the vessel with a layer of special paint with nanotechnological deposition properties; after this we have measured with an Atomic Force Microscope (AFM) the average dishomogeneity of the wall and the result is (8.40 ± 0.40) nm. This kind of problem was very much reduced and practically disappeared.

(ii) Instability from the contact surface between freon (the sensitive liquid) and glycol (the buffer liquid).

This contact instability has been removed by varying the relative quantity of liquid freon with respect to glycol.

We can remark that these kinds of background (not induced by particles) in any case can be removed by the definition of a fiducial volume in a big detector if they are small.

(b) *Particle background for the future detector of* 40 kg: We are assembling at the moment a larger detector of 40 kg; in that detector we believe that the main backgrounds in general will be
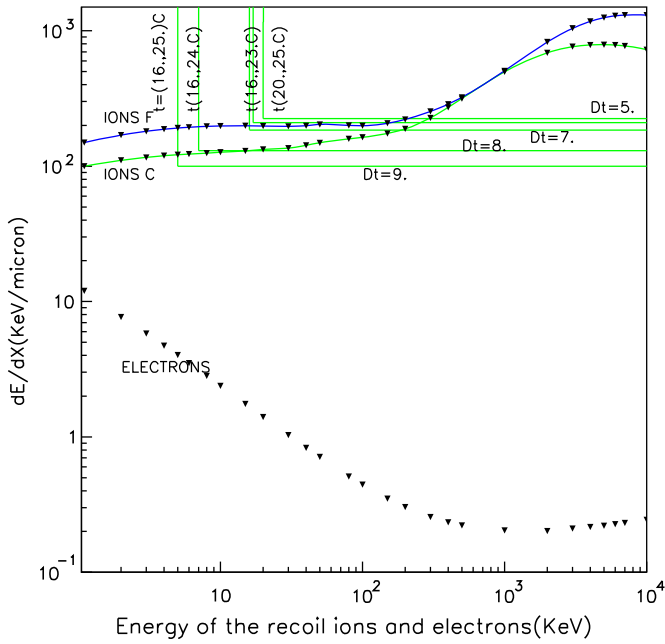
Fig. 5. dE/dx for ions and electrons.

Fig. 6. Critical energy as a function of DT and T (vap).
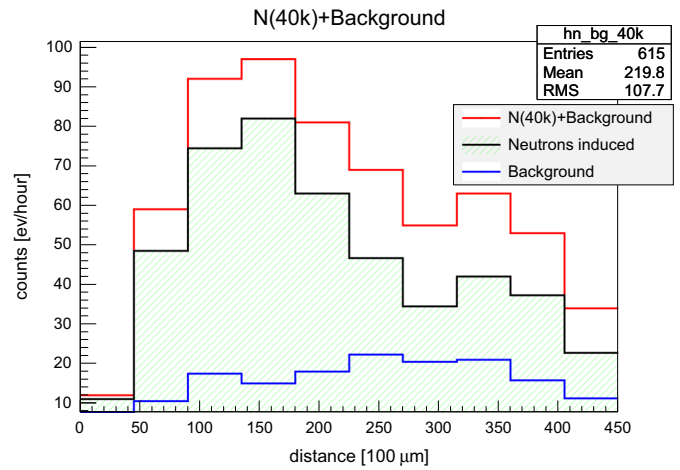
Fig. 7. Background and a neutron source.
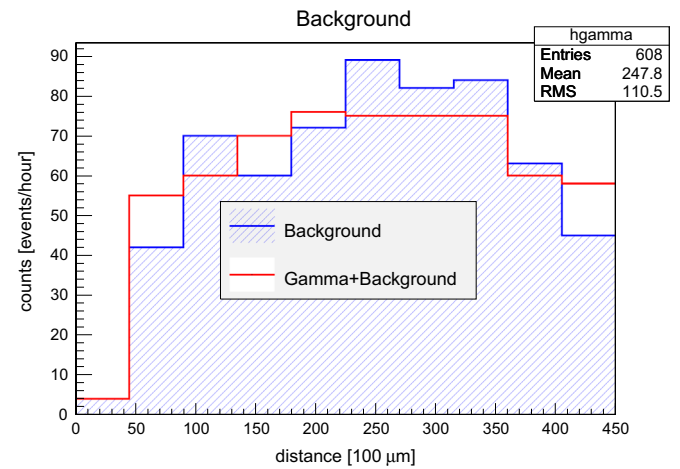
Fig. 8. Background and a gamma source.

Fig. 9. Followed curve as a function of T [°C].

(i) The electron and gamma rays:
   We have seen that a rejection of our type of detectors is $\simeq 10^{10}$ [16].
   This background is negligible if the freon is produced from a petroleum source.

(ii) The α decay of impurities in the liquid or in the wall of the container vessel:
   For this background we are investigating the so called "acoustic trigger". When a bubble is produced a sound is emitted and the intensity and shape of the signal are different in at least two cases: an α decay and a recoil of a nucleus. The range of recoiling ions is indeed < 0.1 μm, while the range of an α particle of 5 MeV is of the order of 40 μm and the length of the signal is longer and stronger.
   The theory of the sound emission [18] in a bubble formation is not well developed, but a lot of experience was reached by the

experiments for dark matter search with Superheated Drop Detector (SDD). In Ref. [19] a time sequence of the bubble's sound emission is reported. In the same reference the
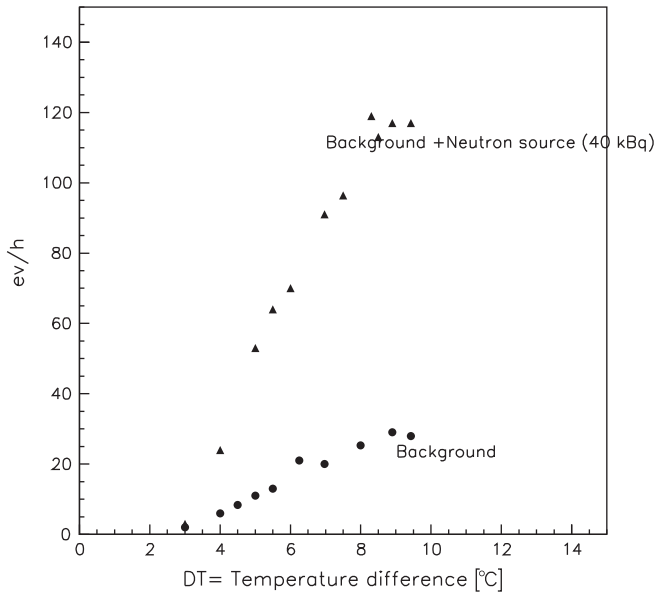
Fig. 10. Measured counts (events/hour) as a function of DT [°C] following the curve reported in Fig. 9.
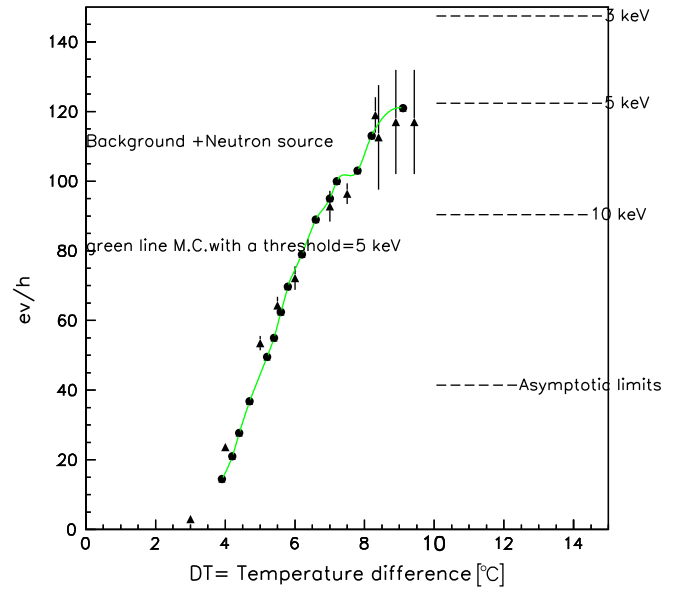

Fig. 13. Comparison of the events-integrated distribution and (green line) (MC+background). (For interpretation of the references to colour in this figure caption, the reader is referred to the web version of this paper.)
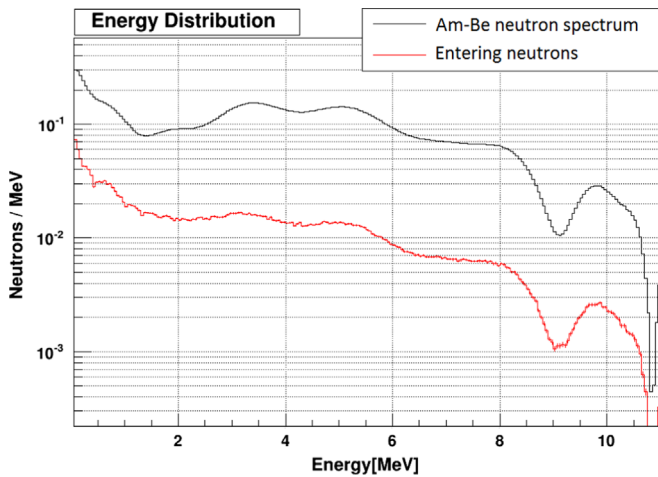

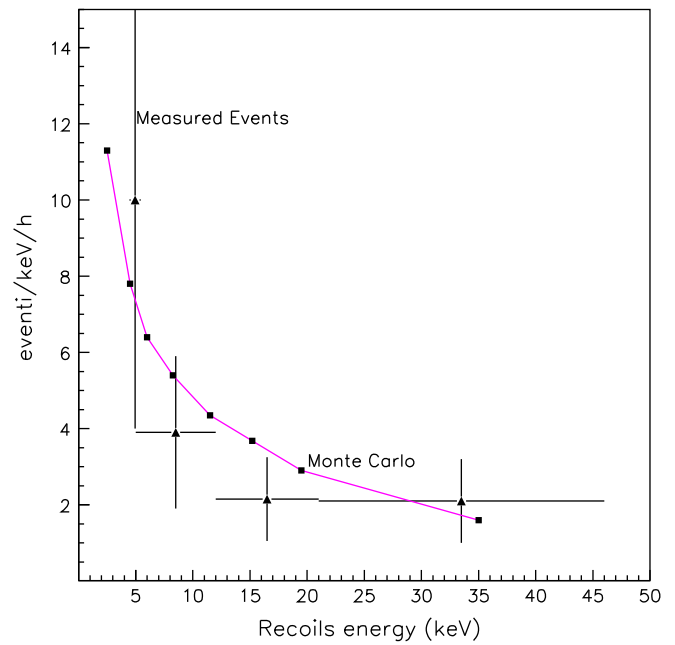**Fig. 11.** Neutron spectra from the Am–Be source.

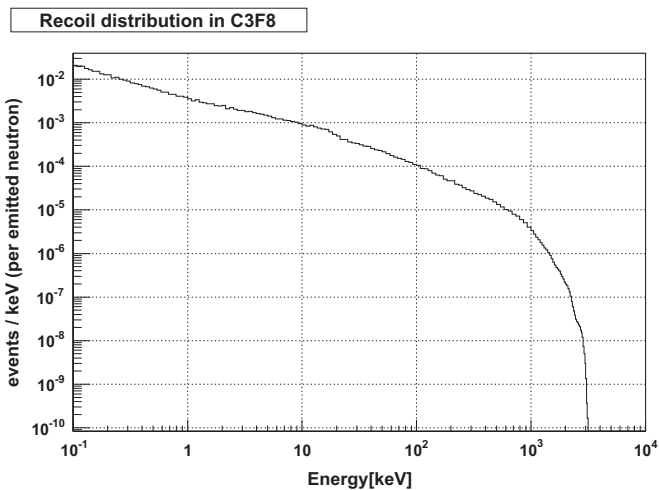
Fig. 14. Comparison with the events-differential distribution.

possibility to separate the ion's recoils from the α decay is shown at the level 10^{-3}.

(iii) Neutrons coming from outside; for this background we plan to count events with two bubbles, three bubbles etc. (The interaction length of a neutron is of the order of (6–9) cm and so they can give multiple interactions in the liquid freon.)

It is then possible to infer the expected number of neutron interaction with only one bubble. The eventual excess of this kind of events could be interpreted as due to WIMPs.

In any case, the best way to reduce the neutron induced background is to install the detector in a deep underground laboratory such as LNGS and use additional active or passive neutron shielding.
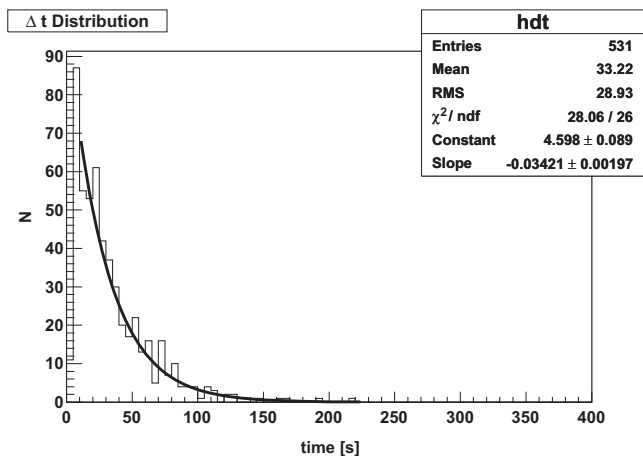

Fig. 12. Monte Carlo calculation.

hdt	
Entries	531
Mean	33.22
RMS	28.93
χ^2/ ndf	28.06 / 26
Constant	4.598 ± 0.089
Slope	-0.03421 ± 0.00197

Fig. 15. Distribution of the time difference between two successive events and time resolution of the detector (about 5 s).
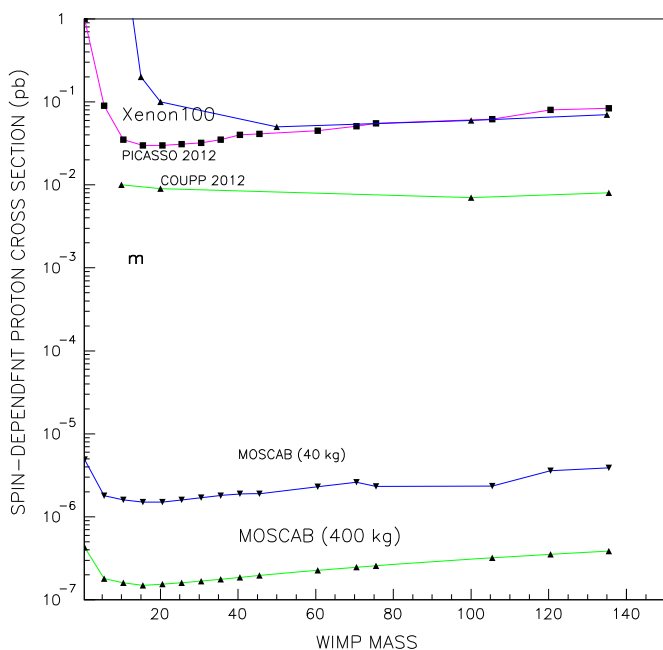

Fig. 16. Expected cross-section sensitivity.

The possible results for our detector are reported in Fig. 16 for two values of the detector mass and in the hypothesis of zero background (this aspect of our experiment will be discussed in a future publication):

40 kg (=first module) and 400 kg (=10 modules).

We remark that in the SD case, our sensitivity could be much better (by 5 orders of magnitude) than that obtained for the results published by PICASSO, COUPP and Xenon100.

5. Conclusions

A new technique for the direct investigation of dark matter has been developed. The good results obtained with a Geyser proto-type (with a low threshold=few keV) motivated the construction of larger detector of this type and the 40 kg detector is in preparation anticipating very good results at the LNGS.

We also would like to claim that this kind of detector would be useful in a neutrino beam to investigate the elastic weak neutral current interaction $\nu + C = \nu + C$.

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