A NEW TECHNIQUE FOR DIRECT INVESTIGATION OF DARK MATTER

R. Bertoni, F. Chignoli, D.Chiesa, M. Clemenza, G. Lucchini, R. Mazza, P. Negri(+),
A. Pullia, N. Redaelli, L. Zanotti
University and INFN of Milano Bicocca
D. Cundy
University and INFN of Milano-Bicocca, IFSI Torino and CERN
7-11-2013

+ WE WANT DEDICATE THIS PAPER TO HIS MEMORY, WE MISS HIM DEEPLY

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.

1 INTRODUCTION

WIMPs (Weak Interacting Massive Particles) are one of the more suited hypothesis for the non-baryonic candidate for dark matter; 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; $C_A$ is an enhancement factor which depends on the type of the WIMP interaction. In Supersymmetry the spin-independent (SI) or scalar interactions, proceeds via Higgs or squark exchange or both. and $C_A$ is given by:

$$C_A^{SI} = \left(\frac{1}{4\pi}\right)[Z f_p + (A - Z) f_n]^2$$

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

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

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

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 the largest for nuclei of $^{19}F$. (see Table 1 and \[1\])

Table 1: Enhancement factor for SD reactions

| Isotope | Spin | Unpaired | $\lambda^2$ |
|---------|------|----------|-------------|
| $^7Li$  | 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      |
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 [2] where it is shown that to investigate low Wimp Masses (around 10 GeV) it is necessary to explore low energy recoils (around 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 ($\sigma_{W+F}$ in pbarn in the case of SD interaction [3]). 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 realized to detect directly Dark Matter. In particular we want point out the
Figure 2: Internal Geyser’s view
use of scintillators NaI \cite{4}, Liquid Argon \cite{5}, Xenon \cite{6}, Cryogenic Semiconductors \cite{7} and Detectors based on the nucleation of bubbles \cite{8}, \cite{9}, \cite{10}. 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 \cite{11} to detect transuranic nuclei).

\section{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 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 of energy 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 there is a picture of the apparatus: in the bottom part of this picture the vessel filled by the liquid freon is shown and are
also visible the copper coils that take constant the temperature of
the liquid by circulating the water furnished by the thermostates;
the buffer liquid that separates the freon liquid from the vapour is
Glycol. In the top part of the apparatus two pressure equalizers are
inserted: they are constituted by two elastic membranes that push
the external water when the pressure of the freon gas become higher
and act also in the reverse sense.

The degree of superheat applied must exclude the detection of mini-
umum ionizing particles (electrons and $\gamma$ 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 tech-
niques) are the following:

1) The strong rejection of the particles at minimum ionization
(electrons and $\gamma$).

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 inter-
actions 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 [12].

With reference to the Fig.2 the quartz vessel of 0.33 liters is immersed
in a water bath and it is surrounded by Cu coils with an internal cir-
culating water at the two fixed temperatures.
It contains freon $\text{C}_3\text{F}_8$ 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 degrees and the two regions are separated by a loosely fitting rubber washer.  
The temperature of the cold vapour was varied from 15-21 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 equalizer using rubber membranes is used.  
The freon is illuminated by diffuse light, coming from LEDs.  
To summarize, the Geyser is substantially 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 micron).  
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).  
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 in the initial conditions, with a dead time of a few seconds.
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 have been varied and also the amount of liquid freon and Glycol.

These experiments were carried out in order to find 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 ionizing particles.

Bubble formation is well understood [13] and depends on the critical radius \( R_c = \frac{2\sigma}{\Delta p} \), where \( \sigma \) is the surface tension of the liquid and \( \Delta p \) 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 \( R_c, \sigma, \Delta p \) and the latent heat of evaporation of the liquid.

In Fig.3 is shown the energy loss \( \frac{dE}{dx} \) for C and F ions and also electrons.

Therefore if the energy of recoil is greater than \( E_c \) (the critical energy) and stopping power satisfies the relation \( \left( \frac{dE}{dx} \right) R_c > E_c \), then a bubble will form. On Fig.3 we show also 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.

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

In Fig 4 the critical energy is shown as a function of \( T(\text{vapour}) \) 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 said that the characteristic of a Geyser must be a high rejection of electrons and \( \gamma \) accompanied by an easy detection of nuclear recoils (similar to the recoiling ions due
Figure 3: dE/dx for ions and electrons
Figure 4: Critical energy as a function of DT and T(vap)
Figure 5: Background and a Neutron source

Figure 6: Background and a gamma source
to an interaction of a WIMP).

To test this, we placed outside the detector (at a minimal distance from the freon) a neutron source (\( \text{Am} - \text{Be} - 40 \text{ kBq} \)). The results are shown in Fig. 5 and we can see that we are very sensitive to the detection of neutrons.

After that we put a gamma rays source (20 kBq \(^{22}\text{Na}\)) near the detector and in Fig. 6 are shown the background distribution and that obtained with a Gamma source (\( \text{Na}^{22} \)).

We can remark that in the latter case we obtained compatible results: no excess in events in presence of the radiative source! We can hence evaluate the rejection factor for electromagnetic showers to be \(< 10^{-7}\); this confirms the COUPP result \([14]\): 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. 7.

Fig. 8 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 \([15]\). 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. 9 the emitted neutron spectrum is shown along with neutron spectrum entering the sensitive freon.

Fig. 10 shows the energy distribution of the recoiling nuclei expected per emitted neutron.

In Fig. 11 we compare the distribution (M.C. results + the measured background) with the corresponding experimental distribution and
Figure 7: Followed curve
Figure 8: Recent counts/DT measurements
Figure 9: Neutron spectra from Am-Be source

Figure 10: Monte Carlo calculation
Figure 11: Comparison with the events-Integrated Distribution and (green line) (MC + Background)
Figure 12: Comparison with the events-Differential Distribution
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. 4.

A direct comparison of the M.C. prediction and the measured spectrum of neutrons is reported in Fig. 12 and a good agreement is obtained also in this case.

Another good result we obtained is the following: We have plotted the time difference between successive events and observed the expected exponential (Fig. 13). It is observed that there is a depletion in the first bin and we conclude that the maximum dead time (recovery time) is 5 seconds.

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 internal
Figure 13: Distribution of the time difference between two successive events and time resolution of the detector (about 5 sec.

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 \((8.40 \pm 0.40)\) 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 solved 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 indeed a larger detector of 40 kg; in that detector we believe that the main backgrounds in general will be:
• a) The electron and gamma rays;
we have seen that a rejection of our type of detectors is \( \simeq 10^{10} \) [14].
This background is negligible if the freon is produced from a petroleum source.

• b) The \( \alpha \) 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 is different in at least two cases: an \( \alpha \) decay and a recoil of a nucleus. The range of a recoiling ions is indeed < 0.1\( \mu m \), while the range of an \( \alpha \) particle of 5 MeV is of the order of 40\( \mu m \) and the length of the signal is longer and stronger.
The theory of the sound emission [16] 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 [17] a time sequence of the bubble’s sound emission is reported. In the same Reference the possibility to separate the ion’s recoils from the \( \alpha \) decay is shown at the level \( 10^{-3} \).

• c) 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 possible after, to estimate 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.

The possible results for our detector are reported in Fig.14 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 cold be much better (by 5 order of magnitude) than that obtained for the results published by PICASSO, COUPP and Xenon100.
Figure 14: Expected cross section sensitivity
5 Conclusions

A new technique for the direct investigation of Dark Matter has been developed. The good results obtained with a Geyser prototype (with a low threshold= few keV) motivate the construction of larger detector of this type and the 40 kg detector will be ready as soon as possible to obtain very good physics 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 interaction $\nu + C = \nu + C$.

6 Acknowledgements

We would like to acknowledge the funding authorities of INFN(CSN V) and the Physics Departement of the Milano-Bicocca University for providing us the site and many structures related to the experiments. We would like also thanks colleagues that discussed with us many problems we encountered during the experiments; in particular: A. Ghezzi, P.Dini, E. Previtali, M. Paganoni, S. Ragazzi, D. Menasce, T. Tabarelli.
We thank also Ing. F. Alessandria and Prof. O. Citterio for enlightening discussion and help.
Thanks are due also to Prof. A. Borghesi and Dr. Trabattoni that allowed us to use the Atomic Force Microscope and made the relative measurement.
References

[1] J. Ellis and R. Flores Physics Letters B 263 (1991).

[2] J.D. Levin and P.F. Smith Astroparticle Physics 6,87-112 (1996)

[3] Marc Schumann Astroparticlephysics UZH,Spring 2012.

[4] R. Bernabei et al. (DAMA) Eur. Phys. J. ,C67 ,39 (2010).

[5] P. Benetti et al. Astroparticle Physics Vol. 28 ,495,2008.

[6] E. Aprile,T.Doke Review of Modern Physics Vol 82,2010.

[7] D.S. Akerib et al. NIM A 559(2008)387.

[8] B. Hahn Nuclear Physic B 36 (1994) 459 and W.J.Bolte et al. NIM A 577,569(2007).

[9] Proposal COUPP -A search for Dark Matter with a continously sensitive Bubble Chamber -Chicago University and Fermilab.(Batavia Illinois)19-10-2006.

[10] V. Zacek ; 1994 Nuovo Cimento A 107,1247.

[11] B. Hahn and W.W. Reist, Proc. of the 5th Int. Conf.High-En. Phys.Nucl. struc. (1973).

[12] L. Baudis (Direct Dark Matter Searches-Rapporteur Talks) 'New Opportunities in the Physics Landscape at CERN', CERN May 11-13-2009 CERN.

[13] D.V. Bugg 'Progress in Nuclear Physics’ Pergamon Press -London,1959 Vol.7,Pag.1.

[14] E. Behnke et al., Phys. Rev. Lett. 106,021303 (2011).
[15] Manual (mcp) A general Monte Carlo N-Particle trasport Code, Version-5, 2008.

[16] Y.N. Martynyuk and N.S. Smirnova; Sov. Phys. Acoust. 37(1991)376.

[17] V. Zacek Snolab Opening Workshop May 16 2012. and PICASSO+: Proposal for a 0.5 Ton Dark Matter Experiment at SNOLAB.