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SEARCHES FOR PARTICLE DARK MATTER :
STATUS AND PROSPECTS

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SEARCHES for PARTICLE DARK MATTER : STATUS and PROSPECTS

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Direct and indirect Particle Dark Matter detection experiments are briefly reviewed by emphasizing the main problems encountered in these approaches and the possible strategies to overcome them.

1. INTRODUCTION [1]

Due to the obvious limitation on the length of this paper, compared to such a wide subject, some choices are needed. So I will :

- a) treat mostly of **WIMPs** (Weakly Interacting Massive Particles) candidates.
- b) consider much more the **direct** than the **indirect** detection type of experiments,
- and c) develop preferentially some **methodology problems** than an exhaustive review of experiments under way (see for more details the Dark Matter parallel session).

I consider first the **direct detection** : its principle, the main detectors involved, the problems to be solved and the consequent possible strategies to be adopted, the present status of the art both in terms of R&D and physical results.

Then the **indirect detection** principle, problems and existing and future detectors are quickly reviewed. Finally a tentative outlook will lead to some conclusions.

Particle (non-baryonic) candidates can be non-thermal relics (like Axions or GUT-Monopoles) or thermal relics. These last, in turn, can belong to the "**Hot Dark Matter**" or to the "**Cold Dark Matter**" depending if, at the moment of their decoupling they were relativistic or not relativistic.

The **Hot Dark Matter** can be made of **light neutrinos** (ν_e, ν_μ, ν_τ), while **Cold Dark Matter** can be made of **WIMPs** (that is **massive neutrinos**, of both Dirac or Majorana type, or **Supersymmetric -SUSY- particles**) or **SIMPs** (Strongly Interacting Massive Particles).

Masses and **cross sections** of WIMPs, interacting with ordinary matter, are **largely unknown**. Masses can range between 1 GeV and 1 TeV, while cross sections on nuclei can range within some orders of magnitude around a typical "weak interaction value" ($\approx 10^{-38} \text{ cm}^2$).

Of special interest is the **Lightest** of the Supersymmetric Particles (**LSP**), the **neutralino**. In the simplest versions of SUSY (with R-parity conservation) the neutralino is **stable**, so that it is a good candidate as a relic particle in the Universe.

The **neutralino** interaction with ordinary matter is depending on several parameters (≥ 5) which are free, to some extent, in the present formulations of the SUSY theory [2]. These parameters controle the actual relative proportion of **two basic couplings** :

α) **SPIN-INDEPENDENT (COHERENT)** : $\sigma_{\text{WIMPS-N}} \approx A^2$, where A is the Atomic mass number of the target nucleus N, and

β) **SPIN - DEPENDENT (AXIAL)** : $\sigma_{\text{WIMPS-N}} \approx C \lambda J(J+1)$, where C = < Hadronic Matrix Element > of the "odd nucleon" in the nucleus N, and λ is the Landé factor of the single-particle Shell Model of nuclei.

2. DIRECT DETECTION

WIMPS can be detected **directly** by elastic scattering on nuclei [3], that is by measuring the recoil energy of the scattered nucleus. In spite of the simplicity of this detection principle 3 kinds of difficulties appear immediately :

a) the **rates** of these events are **small** and depend on the type of dominant coupling. Typical values are : 1 to 100 events/day/kg for a dominant **coherent coupling** (neutralino with both zino and Higgsino(s) components, Dirac ν , and s -neutrino), and 0.01 to 1 events/day/kg for a dominant **spin dependent coupling** (neutralino which is mainly photino and/or zino or is pure Higgsino, and Majorana ν).

b) the **recoil energies** are also **small** (typically from ≈ 1 to ≈ 30 keV)

c) and, last but not least, the **background** is **comparatively very high**. This is of two origins :

α) the **secondary cosmic rays** which are disturbing in two ways : by directly depositing energy in the detectors and by activating the nuclei of the materials (crystals, housings, etc) composing these detectors (cosmogenic radioactivity).

For this reason it is essential to install the detectors **deep underground**.

β) the **radioactive background**. For that it is necessary :

- to **shield** (with Pb, Cu, etc) the detectors from the environment
- to use **very low activity materials** (by selection and/or purification)
- to maximize the **intrinsic rejection power** of the detectors against low energy electrons (by Pulse Shape Discrimination (PSD) of the signals and/or by the simultaneous detection of 2 different physical quantities : heat and ionization or heat and scintillation).

Now the important question is : which are the possible **signatures** for the WIMPS direct detection ?

Due to the orbital motion of the Earth around the Sun, the **average WIMPs velocity** ($\beta \approx 10^{-3}$), relative to the Earth, is **not constant** in time, thus producing a **modulation**, between June and December, of the **average WIMPS flux** (and of the average nuclear recoils energy) of the order of 5 to 10%.

This **annual modulation** potentially represents the **basic signature** of WIMPS in their **direct detection**, by proving in this way their **astrophysical origin**.

It is important, in this respect, to realize :

- **how large must be the mass** of a detector in order to be sensitive to such effect : $\text{Mass}_{\text{det}} (\text{kg}) \approx 50 / \text{WIMPs interaction Rate (evts/kg/day)}$.
- that the **intrinsic background rejection power** must be of the type "event by event" to be useful for this purpose.

The **diurnal modulation**, based on the WIMPs interactions inside the Earth, is also a **possible and interesting signature** for sufficiently high cross sections [4].

An **additional signature** can be obtained by considering that the event rate is depending on the type of nuclei used as targets, in a way predicted by the theory.

Let us now review the different kinds of WIMPS direct detection experiments which depend on the different types of detector used or under development.

We consider first the **classical semiconductor detectors** (Germanium and Silicium), at liquid N_2 temperature, then the **crystal and liquid scintillators**, at room temperature, the **Bolometers**, at few tens of millikelvin, and finally the **Track Projection Chambers (TPC)** and the **Superconducting grains**.

i) "Classical" Semiconductor Ge (Si) detectors :

Traditionally used for 2β experiments (MeV energy range), these detectors have been optimized also for Dark Matter (WIMPs) search (energy range of a few keV).

Table 5 of ref. [5] summarizes the experimental situation from this point of view : here the performances of the Heidelberg-Moscow experiment [6] have to be stressed, although the threshold is much higher than in the other quoted experiments.

Limitations of these detectors are the **microphonics problem** at low energies, the **electronic noise** and, more generally, the **technical and financial problems** rapidly increasing with the mass of the crystals.

ii) Scintillation detectors :

In spite of their poorer resolution compared to Ge detectors, scintillators play at present an important role in this field for several reasons. Scintillation detection is a well known and simple technique (usually no cooling needed), the ratio cost/mass is reasonably low, and there is a wide choice of target nuclei.

In particular some of the scintillators (e.g. NaI(Tl)) have a good light output (resulting in 5 to 10 photoelectrons/keV) and a possible (although problematic at low energy) Pulse Shape Discrimination (PSD). In addition scintillators include non zero spin target nuclei (^{23}Na , ^{127}I , ^{19}F , ^{129}Xe ,.....). Other specific reasons of interest are the very high predicted axial coupling for the ^{19}F nucleus and the high estimated Quenching Factor of liquid Xenon (see below).

The Quenching Factor (QF) for nuclear recoils (the scintillation efficiency for nuclear recoils relative to that of electrons of the same kinetic energy) is measured by using a neutron beam of a few MeV of kinetic energy. The results are quoted on Table 6 of ref. [5].

The present situation of the scintillator experiments, summarized in Table 1.

Table 1. Scintillator Experiments

Collaboration	Underground Laboratories	Type of scintillators	Mass	Thresh (keV) (+)	Rate near threshold (evts/keV /kg/day)	Resolu- -tion σ/E at 60keV	Comments
BPRS (Beijing, Paris, Roma, Saclay)[7,8,9]	GranSasso/Fréjus Mentougou	NaI(Tl)	760 g	≈ 4	≈ 7	$\approx 7 \%$	dedicated expt.(R&D up to 10 kg)
		NaI(Tl)	7 kg	≈ 4	≈ 2	$\approx 7 \%$	
		CaF ₂ (Eu)	370 g	≈ 4	≈ 15	$\approx 12 \%$	
Saragoza [4 a]	Canfranc tunnel	NaI(Tl)	3 $\times$ 10.7kg	≈ 8	≈ 8 (at 18 keV)	$\approx 12 \%$	-----
Osaka (Japan) [10, 11]	Kamioka mine (≈ 2400 mwe)	NaI(Tl)	36.5kg	≈ 5	≈ 6	$\approx 10 \%$	-----
Imp.College/ /Oxford/ [12] /Rutherford	Boulby mine (≈ 3000 mwe)	NaI(Tl)	1 kg 6 kg	≈ 4 ≈ 7	≈ 7 ≈ 2	$\approx 10 \%$	dedicated expt.
DAMA (Roma) [13]	Gran Sasso	Liq. Xe	6.5 kg	≈ 10	≈ 3	$\approx 26 \%$	dedicated expt.

(+) Electron Equivalent Energy

iii) Bolometers :

These are very sensitive thermometers (including, by extension, the associated heat absorber) operating at very low temperature (≈ 10 mK).

Typical crystals are Sapphire (Al_2O_3), Germanium, LiF, TeO_2 , etc (see Table 2).

Why using bolometers to detect WIMPs ?

As discussed in section 2, the main challenge is the suppression and/or rejection of the radioactive background. To do that the maximum information is highly desirable, while in usual detectors the "pure" heat, which represents a large fraction ($\approx 2/3$ in Silicon) of the deposited energy, is generally lost. In addition the quanta of thermal energy (phonons) are very tiny (10^{-4} - 10^{-5} eV) so a potentially very low threshold and very good resolution are expected.

Table 2. Bolometers : present status of the R&D and data taking.

Colla- -boration	Undergr. Laborat.	Crystal	Mass (g)	Thresh (keV) (*)	Temp (mK)	Rate evts/keV /kg/day	Resolution σ/E	Com- -ments
CfPA(Berkeley Stanford/UCSB /INR) Sadoulet [14] CDMS	shallow site at Stanford 17 mwc	Ge	≈ 60	≈ 3	24	—	0.5% at 60keV (1% Ionizat.)	both : - HEAT - IONIZ.
MUNICH Max Plank/Gar- -ching/Oxford [15] CRESST	Gran Sasso (1995 - 96)	Al_2O_3 (Sapph- -ire)	31	≈ 0.3	15 44	—	3% at 1.5 keV 1.5% at 6 keV $\approx 1\%$ at 1MeV	only HEAT (WIMPS < 15 GeV)
CEA/IN2P3/ INSU (France) [16] EDELWEISS	Fréjus 4800 mwc	Al_2O_3 Ge	24 7 (from Berkeley)	≈ 2.0 ≈ 1.7	60 34	≈ 25 (2nd- -run) at 16 keV	2.5% at 60 keV 3.0 % (2.0% Ionizat.)	only HEAT both:HEAT and IONIZ.
TOKYO [17]	Kamioka	LiF	2.8	≈ 4	12		6% at 60 keV	only HEAT
Milano Univ. Fiorini et al. [18]	Gran Sasso 3400 mwc	TeO_2 " LiF NaF CdWO_4 CaF_2	334 73 100 30 60 2	—	≈ 25	≈ 9 at 13 keV —	0.4 % at 1 MeV 1 % at 60 keV 5 % at 1 MeV 2 % at " 0.2 % at " 2 % at "	for $\beta\beta$ " for DarkMat for DarkMat HEAT+SC? HEAT+SC.

(*) Real Energy (Heat channel) (provided that the QF ≈ 1.0 down to low energies).

Moreover, the possibility of measuring simultaneously another form of deposited energy (ionization or scintillation) makes these detectors especially adapted to background rejection.

The problem now is to minimize microphonics, electronic noise, radioactive background at low energy and reach long time (years) stable operating conditions with large masses of crystals (at least hundred kg) not only in the heat detection, but also for the ionisation (or scintillation) detection.

The present status of the R&D is summarized in Table 2.

Concerning heat detection the most impressive results (threshold and resolution) have been obtained by the Munich group.

Concerning the simultaneous measurement of heat and ionization, the first partially successful result has been obtained by the Berkeley group, while the French group has recently well improved the stability of the ionization channel (a crucial point!). On the other hand the Milano[19], Roma[20], Lyon(IPN)/Paris (ENS)[21a] and Lyon(IPN)/Orsay (IAS) [21b] groups are developing scintillation detection at low temperatures, although, for the moment, at a much higher threshold (≥ 100 keV).

iv) Track Projection Chambers (TPC) :

A TPC detector at low pressure has been first investigated by a Saclay group [22] (Ethane) and then by a San Diego group [23] (Hydrogen). The main advantage here is the directionality detection possibility, and the main drawback is the very low density of the detector medium.

v) Superconducting grains :

A Lisbon, Zaragoza, Paris Collaboration [24] is preparing a pilot experiment with 100 g Sn superconducting grains, at 100 mK, in the Canfranc Laboratory. They claim an energy threshold ≤ 1.75 keV and a background rejection factor of 95%.

From experimental rates to exclusion plots

By comparing the measured energy spectra with the calculated WIMPs nuclear recoil spectra, it is possible to deduce limiting curves : cross section versus mass ("exclusion plots") for WIMPs interacting with each type of nuclei in a given crystal detector.

The ingredients for that are: quenching factors (see section 2), astrophysical assumptions on the WIMPs halo velocity distribution and WIMPs local density (≈ 0.3 GeV/cm³, multiplied by an appropriated "rescaling factor") and nuclear form factors (these last depending on the type of coupling : coherent or spin-dependent).

Moreover, for a comparison between results coming from different target nuclei it is necessary to obtain, e.g., σ (WIMPs - proton) from σ (WIMPs - Nucleus).

For explicit results on the exclusion plots of the different experiments and for a preliminary PSD analysis of NaI (BPRS Collaboration and Boulby mine Experiment) and LiXe (DAMA group) data, see the Dark Matter parallel session.

3. INDIRECT DETECTION [25, 26]

When Galactic WIMPS cross a compact object like the Sun or the Earth, they have some probability to be captured in it by elastic scattering : for that to happen it is sufficient that the scattered WIMPS velocity be lower than the escape velocity from the object.

The capture rate of the WIMPs is therefore proportional to the elastic scattering of the nuclei in the considered compact object. A steady state is reached if the capture rate is balanced by the annihilation rate, a process which takes place in the core of the object.

Annihilations in the Sun or in the Earth would yield a flux of high energy (GeV region) neutrinos either directly ($w\bar{w} \rightarrow \nu\bar{\nu}$) or by decay of annihilation products. These neutrinos can be observed in underground detectors.

The best signature comes from ν_μ interacting in the rock around the detector yielding muons crossing it ("upward going muons"). These muons can be distinguished statistically from those due to the interactions of atmospheric neutrinos because their momenta point in the direction of the Sun or of the Earth's core.

The Sun is mainly made of Hydrogen (and Helium) so it is more sensitive to axial coupling interactions, while the Earth's core, rich in Iron, is more interesting for coherent coupling interactions.

So far the best flux limits for such muons (and indirectly on WIMPS parameters) have been obtained by the Kamiokande water Cerenkov experiment [27]. Results of the BAKSAN[28] and MACRO[29] experiments have been presented at this Conference. These limits are complementary to those obtained in direct detection experiments. Nevertheless, they must be considered with some caution because of the additional hypotheses needed to their derivation [25].

In fact, assumptions have to be made on the annihilation cascade processes leading to the observable neutrinos, on the detailed composition of the Sun and of the Earth, and on the existence or not of a steady state in their core.

Another remark concerns the different types of background in the two kinds of experiments. In indirect detection experiments, this consists in the atmospheric neutrinos : their flux is proportional to the effective area of the detectors and evidently cannot be shielded, while in direct detection experiments the background is radioactivity so there are no fundamental impossibilities to decrease it [30].

Several new experiments dedicated to the detection of high energy upgoing muons are in preparation (see Table 3). Their main purpose is the detection of very high energetic neutrinos eventually produced (e.g.) in Active Galactic Nuclei (AGN), so that the corresponding detectors are called "Neutrino Telescopes". Of course, they will be also able to obtain interesting results in the non baryonic Dark Matter sector.

Table 3. Projects of "Neutrino Telescopes": for High Energy Neutrino Astrophysics and WIMPs indirect search.

Experiment	Site	Area (m ²)	Depth (mwe)	in 1996 (97)
SUPERKAMIOKA	Japan	1 000	3 500	11 200 PMTs
DUMAND II (Learned J.G.)	Hawaï	10 000	4 800	216 PMTs (3 strings/out of 9)
LAKE BAÏKAL (Domogatsky G.)	Siberia	3 000	1 000	192 PMTs
NESTOR (Resvanis L.K.)	Greece	20 000	3 800	168 PMTs (1 tower)
AMANDA (Halzen F.)	South Pole (ice)	8 000	1 000/1 500	200 PMTs (4 strings/out of 10)
"BAND" World project	?	1 000 000 ("1 km ³ ")	?	≈ the year 2000

4. OUTLOOK

Some examples of present experimental projects for a better WIMPs investigation are :

- 1) the Heidelberg-Moscow Collaboration is preparing a new detector with a ^{73}Ge enriched crystal [6].
- 2) a NaI(Tl) detector, of about 100 kg, which is being installed in the Gran Sasso Laboratory, by the BPRS Collaboration, mainly to start studying the annual modulation effect [7]. Moreover, a still better crystal purification is under way.
- 3) the CfPA group is preparing an "ice-box" low activity cryostat to be installed in a shallow site at Stanford as a test bench for future R&D on bolometers [14].
- 4) the Munich group is preparing a set of 4 x 250 g Sapphire (Al_2O_3) bolometers to be installed in Gran Sasso Laboratory by the end of 1996. They are focusing on phonon detection only and low mass WIMPs ($< 20 \text{ GeV}$) [15].
- 5) the French Collaboration EDELWEISS is preparing more massive bolometers ($\approx 1 \text{ kg}$ Sapphire) with thin film thermal sensors (under development) and 70 g Ge diodes with simultaneous detection of heat and ionization signals.
- 6) the future development of indirect detection experiments can be argued from Table 3.

5. CONCLUSIONS

As discussed throughout this paper, there is no "universal" detector for WIMPs!

- 1) The "reference" detectors are the classical Ge crystals operating at LN2 temperature.
- 2) Scintillators have proved to be very useful and realistic detectors for WIMPs search, mainly in view of an investigation of the annual (and diurnal) modulation effects. Further efforts to still reduce and/or reject residual background are in progress.
- 3) Bolometers represent the most ambitious developments, in particular by measuring 2 physical quantities : Heat + Ionization or Heat + Scintillation. The remaining problems are a big challenge for the concerned groups.
- 4) TPC detectors and superconducting grains need further developments to reach a competitive level and challenge the other detectors already in operation.
- 5) direct and indirect detection experiments are complementary. Indirect detection experiments depend on more assumptions than the direct ones and the corresponding background (atmospheric neutrinos) cannot be decreased.

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