The search for elusive dark matter: large scale experiments and new detection techniques

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Abstract

We focus on dark matter candidates which do not exhibit the large event rates characteristic of coherent scattering off nuclei or cosmion interactions. Theoretical motivation for particle dark matter candidates is briefly reviewed, and specific problems related to the detection of each kind of "new" particle are dealt with. Current experiments and possible new detection techniques are described, with particular emphasis on WIMP (weakly interacting massive particles). Particle identification with hybrid cryogenic detectors is discussed as a new way to reject radioactive background.

1 INTRODUCTION

If dark matter is not baryonic, several types of candidates can be investigated. Apart from light neutrinos, all candidates presently envisioned are "new" particles whose existence has not yet been confirmed experimentally. Finding one of such candidates with a dark matter detector would therefore amount to the discovery of a new particle. Dedicated techniques that may eventually be used to detect these objetcs are presently being developed.

A galactic halo of non-baryonic dark matter would have an approximate particle density $n \simeq 0.3/m_x\ GeV/cm^3$, where m_x is the dark matter candidate mass. With a speed $v \approx 10^{-3}\ c$, such particles would present appreciable fluxes and lead to observable effects. However, their detection poses several problems concerning detector sensitivity and intrinsic radioactive background. This is the subject of the present talk.

2 MONOPOLES

In a Workshop entitled "The Quest for Fundamental Constants", it seems well suited to start our review by magnetic monopoles. The elementary magnetic charge would certainly be a very basic constant in Physics.

The monopole problem is a fundamental issue in modern physics, as the existence of magnetic charges would naturally complete the dual symmetry of Maxwell's equations. A dual transformation means exchanging (up to some phases): a) electric and magnetic charges; b) electric and magnetic currents; c) the electromagnetic strength tensor $F_{\mu\nu}$ by its Hodge transform ${}^*F_{\mu\nu} = \epsilon_{\mu\nu\rho\sigma}F^{\rho\sigma}$, which implies exchanging $\vec{E}$ (electric field) and $\vec{B}$ (magnetic field). Already noticed by Maxwell, the idea was further pursued by Dirac [1] within the framework of quantum mechanics, leading to quantization of electric and magnetic charges through the relation: $eg = h$, where e and g are respectively the units of electric and magnetic charge, and h the Planck constant.

Monopoles which are non-perturbative solutions (topological solitons) of grand-unified Yang-Mills theories appear at the classical level [2] and may have been formed in the early universe. The mass of such objects would be in the range $10^{16} - 10^{19}\ GeV$, and their flux is hard to determine from standard inflationary cosmology. Any program to search for such monopoles deserves a few words of caution. First, they are not genuine ($\Omega = 1$) dark matter candidates if Parker's bound [3] is to be believed. This bound is obtained from the persistence of the galactic magnetic field, and leads to F_{mon} (monopole flux) $\lesssim 10^{-15}\ cm^{-2}\ sr^{-1}\ s^{-1}$ for $m = 10^{16}\ GeV$. Secondly, bounds on monopole flux from the persistence of neutron stars are even more stringent [4] if monopoles are assumed [5] to catalyze baryon decay. Nevertheless, the cosmological implications of a precise knowledge of the monopole flux (if any) would be very far-reaching and searches with large area detectors are being undertaken.

1989 is an important date for monopole searches, as the first large surface detector, MACRO [6,7] has started running at GRAN SASSO Laboratory and will reach 10000 $m^2 sr$ in 1990. MACRO uses several conventional techniques in coincidence: a) liquid scintillator (horizontal and vertical layers); b) streamer tubes (He , C_5H_{10} again in horizontal and vertical layers); c) plastic track-etch detectors (CR 39 in horizontal layers). The detector will be 72 m long (6 x 12 m), 12 m wide across hall, and 10 m high. 3 modules 12 m long x 12 m wide are presently installed. At the Parker limit, ≈ 4 $events/year$ are expected.

MACRO will thus be able by 1995, after five years of running, to reach a monopole flux sensitivity $\approx$ 10% of the Parker limit, and set 90% confidence limit excluding $\Omega_M > 0.03$ ($\Omega_M = \rho_M/\rho_c$, ρ_M = monopole density, ρ_c = critical density), for $m = 10^{16}$ GeV .

A delicate question is sensitivity to low beta ($\beta = v/c$) , as energy losses decrease at low speed and become smaller than ordinary ionization at $\beta < 10^{-2}$. Liquid scintillators should perform better than $\beta > 10^{-3}$, whereas plastic detectors would be sensitive to at least $\beta > 10^{-2}$ and gaseous detectors using Drell effect [8] may be sensitive to $\beta > 10^{-4}$. However, the interaction of slow monopoles with matter is not fully understood, and current estimates rely at some point on theoretical calculations or extrapolations not derived directly from first principles. The liquid scintillator used by MACRO was calibrated with slow recoil protons from exposure to neutrons [9]. Estimates of the response of several conventional detectors to a magnetic monopole are shown in Fig.1 .

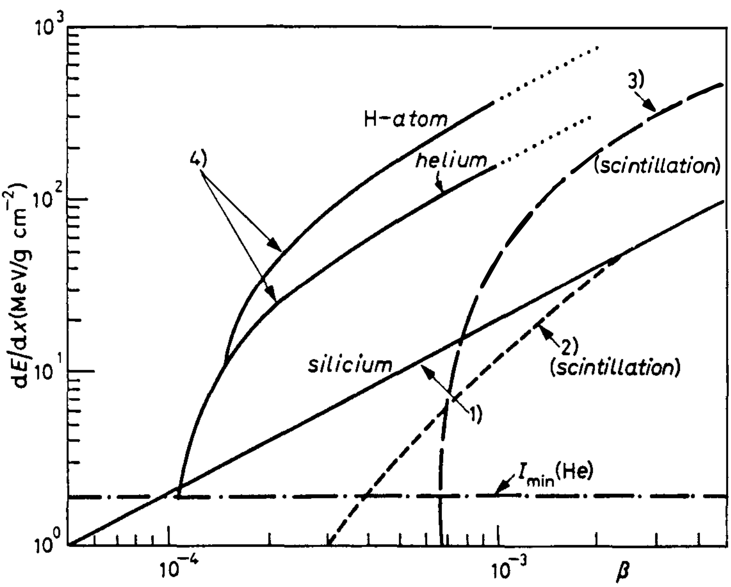
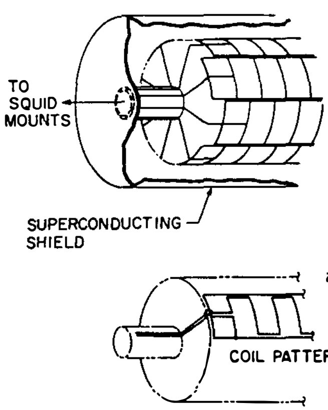


Fig.1 - Theoretical predictions for monopole energy losses in several materials, from: 1) S.P. Ahlen and K. Kinoshita, Phys. Rev. D26, 2347 (1982); 2) D. Ritson, 1983; 3) S.P. Ahlen and G. Tarle, Phys. Rev. D27, 688 (1983); 4) ref. [8] . The figure is from P. Musset, in Underground Physics 85.

A complementary approach is provided by "all beta" detectors, whose basic operating principle is independent of the monopole speed. Superconducting devices fulfill this property: a permanent current directly related to the monopole charge is generated by Faraday's law (a basic principle of electrodynamics) when a magnetic charge crosses the detector. Two superconducting monopole detectors have been proposed:

a) Induction loops. In this case, a monopole of charge g crossing the surface surrounded by a superconducting loop creates a supercurrent $i = 2\phi_0/L$, where ϕ_0 is the flux quantum ($\phi_0 \simeq 2\ 10^{-7}\ G\ cm^2$) and L the loop inductance. The current i is very weak, 1 nA for a circular loop of 25 cm diameter, and must be read out by a SQUID (Superconducting Quantum Interference Device [10]). The main problem for such detectors is electromagnetic background. As an example, fluctuations in the earth's magnetic field are $\approx 10^{-3}\ G$ and would provide a noise exceeding by several orders of magnitude the monopole signal.

Several ingeneous techniques have been used to bypass electromagnetic background problems: expansion at low temperature of initially collapsed superconducting Pb shielding cylinders [11], gradiometric techniques [12] and coincidence between several loops. They have allowed to build operating detectors in the $\approx 1\ m^2 sr$ range (Fig. 2), placing an overall bound $\approx 2\ 10^{-13} cm^{-2} sr^{-1} s^{-1}$ on the monopole flux. Development of new prototypes in the $\approx 1\ m$ diameter range is being carried on successfully, using more performant gradiometric techniques (Fig. 3).



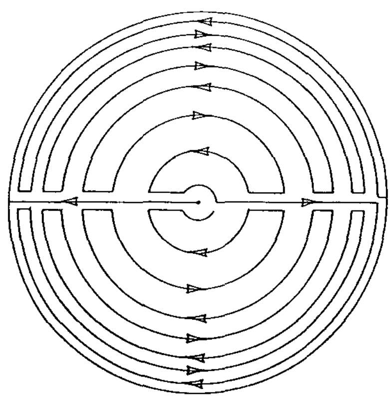


Fig. 2 (left) - A scheme of the Stanford monopole detector, with a eight SQUID 1.5 m^2 sensing area [13].

Fig. 3 (right) - Gradiometric loop studied by the CFM group to minimize electromagnetic noise [14]. Arrows indicate a possible direction for the induced current. The prototype was operated in a 125 $mGauss$ magnetic field.

In spite of technical difficulties, induction experiments are the only way to reach a direct measurement of the monopole charge. If only for that, any effort to pursue such a development appears to be justified.

b) Superheated superconducting granules (SSG). A brief introduction to SSG detectors can be found elsewhere in these Proceeedings [16] . Their use for monopole detection [17] would imply comparatively large grains, in the $30 - 100\ \mu m$ diameter range. A magnetic monopole of charge g crossing a type I superconductor would leave behind a flux tube $\phi = 2\phi_0$ injected into the sample. Inside this vortex, the order parameter is lowered and Cooper pairs broken. If the specimen is in a metastable state (superheating), the ends of the flux tube will originate nucleation centers of the normal state, leading to a phase transition of the whole sample. By this mechanism, the monopole is expected to flip a substantial amount of the grains it will cross, independently of their size and of the monopole speed. A large signal ($\approx 10^5\ \phi_0$) would then be obtained, as well as very good background rejection since large grains are not sensitive to minimum ionization.

A SSG monopole detector would be made of several planes parallel to each other, providing timing and tracking. The large signal expected should allow for a conventional electronic read out. Monopole speed and direction would then be determined with good accuracy.

Finally, a more recent development are Transient Response Induced Current Detectors [14]. The aim in such case would be to: a) work (if possible) with a high T_c superconducting coil; b) use conventional electronics or high T_c SQUIDs; c) escape low frequency magnetic field fluctuations, therefore avoiding expensive shields. The relevant frequency domain for the signal produced by a monopole with speed v in a coil of radius a is: $\omega \lesssim v/a$. For an upper cutoff in frequency ω_c , all monopoles of speed $v > a\ \omega$ turn out to give the same signal in a coil of radius a . It is thus possible to set a lower cutoff in speed, $v_{min} = 3.8\ 10^{-5}\ c$ (the earth's escape velocity) and restrict the allowed size and shape of the monopole signal, improving background rejection. The required frequency cutoff would be $\omega_c \approx 10^5\ Hz$ for $a \approx 10\ cm$.

3 AXIONS

Quantum Chromodynamics has a topological winding number:

$$n = -g^2/32\pi^2 \int d^4x\ \epsilon_{\mu\nu\rho\sigma}\ Tr(F^{\mu\nu}F^{\rho\sigma}) \tag{1}$$

where $F^{\mu\nu}$ is the colour octet strength tensor from the gluon field. For each (integer) value of n , there is a vacuum state $\mid n >$ associated to the relevant topological sector. The ground state is then: $\mid \theta > = \Sigma_n\ e^{-in\theta} \mid n >$, where θ can take any value and is to be determined experimentally. The effect of topological vacua can be expressed in a simple modification of the effective lagrangian density:

$$L = L_{QCD} + g^2/32\pi^2\ (\theta + arg\ detM)\ Tr(F^{\mu\nu}\ {}^*F_{\mu\nu}) \tag{2}$$

where M is the quark mass matrix, and leads to a neutron electric dipole moment $d_n \simeq 10^{-15}(\theta + arg\ detM)\ e\ cm$ (e = electron charge). Experimental bounds [18] then suggest the miraculous cancellation: $\theta + arg\ detM \lesssim 10^{-10}$.

To explain this situation, an additional symmetry $U(1)_{PQ}$, the Peccei-Quinn symmetry [19], was added to the lagrangian. After spontaneous breaking, a pseudoscalar Goldstone boson, the axion a , appears and acquires a small mass through the chiral anomaly:

$$m_a = A\ \sqrt{z}/(1+z)\ f_\pi m_\pi / f_a \tag{3}$$

where: $z = m_u/m_d \simeq 0.56$, $m_\pi = 135\ MeV$, $f_\pi = 93\ MeV$; A is the colour anomaly of $U(1)_{PQ}$; f_a is proportional to $(\theta + arg\ detM)^{-1}$ times $< a >$, the vacuum expectation value of the axion field. We therefore expect: $f_a m_a \approx f_\pi m_\pi \approx 10^{16} eV^2$.

Axion couplings to matter are of the type: $\partial_\mu a\ (\overline{N}\gamma^\mu\gamma_5 N)$ for nucleons; $\partial_\mu a\ (\overline{e}\gamma^\mu\gamma_5 e)$ for electrons and positrons; $a\ \vec{E}.\vec{B}$ for photons. The effective coupling for the last term is:

$$g_{a\gamma\gamma} = 1/\sqrt{2\pi}\ e^2\ (\hbar c)^{1/2}\ m_a/m_\pi f_\pi \tag{4}$$

and, numerically: $g_{a\gamma\gamma} \approx 10^{-34}\ MeV^{1/2}\ cm^{3/2}\ (m_a/10^{-5}eV)$. Laboratory limits on axions come from bounds on the processes: $K^+ \rightarrow \pi^+ + a$ (unseen axion), $J/\psi \rightarrow a + \gamma$ and $\Upsilon \rightarrow a + \gamma$, leading to: $f_a \gtrsim 10^3\ GeV$, $m_a \lesssim 6\ keV$ [20].

Helium ignition in red giants precludes an axion with mass $m_a \gtrsim 10^{-2} eV$ [21]. Even more stringent are bounds from the hot neutron star born as a result of SN1987 collapse, using the fact that too massive an axion would have accelerated the duration of the neutrino burst (less than 1 sec for $m_a \approx 10^{-2} eV$). The bound thus emerging from several works [22] is $m_a \lesssim 10^{-3}\ eV$. Finally, inflationary cosmology leads to and energy density of relic axions:

$$\Omega\ h^2 \approx (\Lambda_{QCD}\ /\ 200\ MeV)^{-0.7}\ (m_a/10^{-5}eV)^{-1.18} \tag{5}$$

so that the universe may be closed by an axion of mass $m_a \approx 10^{-5}\ eV$ [23,24]. These numbers illustrate the difficulty to detect a non-relativistic cosmic axion.

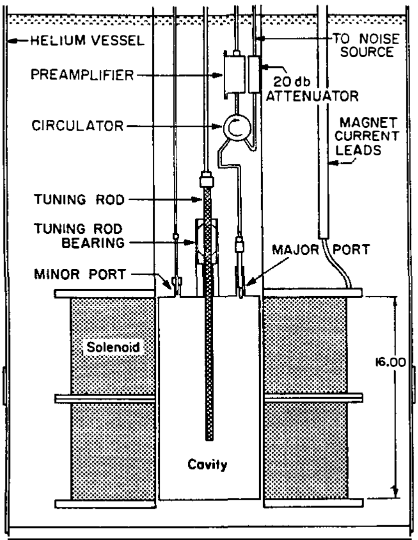
The key mechanism for axion detection lies in the coupling a $a\gamma\gamma$ coming from axion-π_0 mixing. Sikivie [25] proposed to detect cosmic axions by a $a \rightarrow \gamma$ conversion in the presence of a strongly inhomogeneous magnetic field. The energy of the produced γ is then the total energy of the incoming axion. The main signature for cosmic axions would be a very narrow signal in frequency, where the finite width would be due to the axion kinetic energy $\approx 2\ 10^{-6}\ m_a$. Using a variable frequency electromagnetic cavity, with its resonant frequency tuned to a given value of the axion mass, and in the presence of a strong electromagnetic field, galactic axions of the relevant mass can convert into excitation quanta of an appropriate mode of the cavity. In this way, one may attempt to progressively explore the relevant domain of proposed axion masses. This amounts to covering the frequency range $1 - 10^3\ GHz$ by successive narrow band experiments. The expected power for a cylindrical cavity in the best suited vibration mode (T_{110}) is:

$$P \approx 10^{-20}\ Watt\ (V/500liter)(B_0/8T)^2(\rho_a/0.5\ 10^{-24}gcm^{-3})(m_a/6\pi GHz)Min(Q/10^6, 1) \tag{6}$$

where V is the cavity volume, ρ_a the galactic halo density and Q the cavity quality factor.

A search for cosmic axions along these lines has been carried out at BNL [26] , at $\approx 1\ GHz$ frequencies. The experiment (Rochester-BNL-FNAL Collaboration) used a

8.7 T superconducting magnet with 15.2 cm diameter and 40.6 cm long bore, and a copper cavity at liquid helium temperature. The resonant frequency of the cavity is in the range $1\ GHz < f < 4 GHz$, and can be tuned using a sapphire rod (Fig. 4) of electric constant $\epsilon = 10$, leading to an operating Q of 9 10^4 and a bandwidth of 13 kHz . The axion mass for such frequencies varies in the range $4.5\ \mu eV < m_a < 18\ \mu eV$, and the intrinsic bandwidth of the axion signal would be $\approx$ 130 Hz . No signature for axions was found, and the obtained bounds on the axion flux are shown in Fig. 5 , in terms of the energy spectral density $< d\rho/d\nu >_a$ and the coupling $g_{a\gamma\gamma}$ [27].



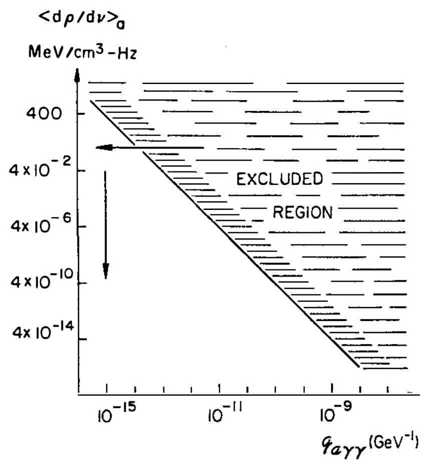


Fig. 4 (left) - A scheme of the Rochester - BNL - FNAL cosmic axion detector.

Fig. 5 (right) - Bounds from the same experiment. The abscissa is the $a\gamma\gamma$ coupling and $d\rho/d\nu$ stands for energy density per unit frequency. The vertical and horizontal arrow indicate respectively the predicted values of both variables for which axions may close the universe [23].

Assuming 100% of the galactic dark matter to be made of such axions, this bound lies 50 times above the value predicted by inflationary cosmological models based on the Peccei-Quinn symmetry [23]. The BNL experiment provides an encouraging start point for more ambitious searches. Technical problems that would be posed by a more efficient search are presently been studied. A second group, in Florida [28], has started a similar experimental program, with a 7 *liter* cavity inside a 9 *Tesla* superconducting solenoid. By cooling the detector down to 2.2 K , it is expected to lower the system noise temperature and to somehow improve the BNL bounds. A third detector is being built at KEK.

If axions are trapped in the solar system, and thermalized by its central core, they can reach earth with an energy of the order of the sun central temperature ($E \approx 1\ keV$). It has indeed been shown [29] that axion-photon conversion in atoms yields acceptable cross-sections (axioelectric effect):

$$\sigma_{axioelectric} = (\alpha_{axion}/\alpha_{electromagnetic})(E_a/2m_e)\ \sigma_{photoelectric} \tag{7}$$

where:

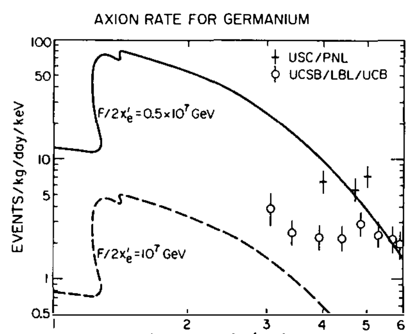
$$4\pi\alpha_{axion} = (2x'_e m_e/f_a)^2 \tag{8}$$

and in most models $2x'_e \approx 1$. The solar axion flux is in turn taken from bremstrahlung and gives:

$$F_a(solar) \approx 10^{13}(10^8 GeV/f_a)^2\ sec^{-1}\ cm^{-2} \tag{9}$$

leading to a few $events/Kg.day$ with most target materials.

Based on this idea, double β germanium detectors [30,31] have been used to provide some interesting upper bounds on solar axions. The PNL-USC group [30] developed a 135 cc intrinsic Ge detector with a very low background in the keV energy region and a threshold at $E \approx 4\ keV$. Installed at a water equivalent depth of 4000 *meters* in the Homestake mine, the PNL-USC detector brought upper bounds allowing to exclude the range $f_a < 0.5\ 10^7\ GeV$. According to the above discussion, theory favors the region: $10^{10}\ GeV < f_a < 10^{12}\ GeV$. Subsequently, the UCSB-LBL-UCB collaboration reported slightly better bounds, $f_a \gtrsim 10^7\ GeV$. These results are shown in Fig. 6, which also exhibits theoretical expectations for the solar axion spectrum. In order to reach cosmological bounds and cover the full spectrum of solar axions, two obvious requirements appear: a) background should still be lowered in order to reach full sensitivity to the expected solar axion flux; b) the energy threshold should be set an order of magnitude lower, which justifies the development of cryogenic devices.



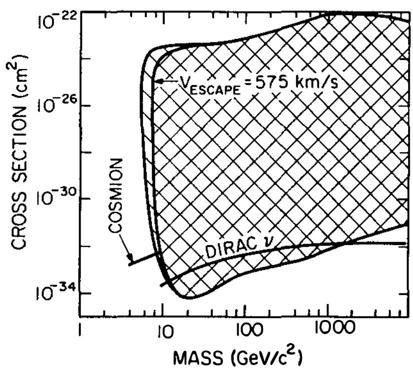


Fig. 6 (left) - Recent results on solar axions, from D.O. Caldwell et al. in [15]. On the figure, $F = f_a$ and theoretical predictions for the solar axion flux are also exhibited.

Fig. 7 (right) - Excluded region for Dirac neutrinos, s-neutrinos and cosmions in terms of the mass and cross section with germanium. From D.O. Caldwell et al. in [15].

4 NEUTRINOS AND MAGNINOS

Light neutrinos are the only well established dark matter candidate, as the existence of three light flavours has been demonstrated experimentally and the role of neutrinos in the generation scheme of quarks and leptons is to some extent understood [32]. The electron neutrino is often thought to be the lightest one, with laboratory bounds on its mass: $m_{\nu_e} < 18 - 32\ eV$ [33]. From cosmological arguments, the average density of neutrinos and antineutrinos in the universe for a given light flavour is:

$$n_\nu \approx 100\ cm^{-3} \tag{10}$$

so that, if light neutrinos close the Universe, the following bound is obtained [34]:

$$\Sigma_i\ m_{\nu_i}\ <\ 100\ eV\ h^{-2} \tag{11}$$

where h is the Hubble constant in units of $100\ Km/Mpc$. For $\Sigma_i\ m_{\nu_i}\ >\ 5\ eV$, the neutrino contribution to the Universe mass density is found to exceed that of baryons. However, at galactic scale fermionic phase space limitations for free neutrinos would be consistent with $\Omega_\nu = 1$ only if $m_\nu\ >\ 30\ eV$ for large galaxies, and $m_\nu\ >\ 500\ eV$ for the smallest ones. These figures may be a difficulty for models where the electron neutrino is the cold dark matter candidate, but it is possible to build models (e.g. singlet Majoron [35]) where $\Omega_\nu\ =\ 1$ with ν_μ or ν_τ having masses in the range $1\ keV\ -\ 35\ MeV$, still leading to an acceptable scenario for galaxy formation.

Detection of non-relativistic light neutrinos is an extremely hard task. If they were clustered in the galactic halo, they would have a kinetic energy $E\ <\ 10^{-4}\ eV$ for ν_e, and $E < 100\ eV$ for other families. It then follows that any recoil energy from elastic scattering with such neutrinos would be very small: at best, E_R (recoil energy) $<\ 10\ eV$ for the heaviest possible neutrino. No detector is known that would be sensitive to such an energy deposition. Furthermore, at such energies elastic cross-sections would also be small and lead to hopeless event rates. If light neutrinos are Dirac fermions, their long wavelength would lead to comparatively large cross sections for coherent scattering and interaction with collective modes in matter (e.g. phonons) may be worth considering. In such case, rather than trying to detect neutrinos individually, the right strategy may be to look for some macroscopic effect (e.g., heat leaks in future very low temperature devices [36]) . Several laboratory experiments to detect cosmological light neutrinos have been proposed in the past, based on the motion of a macroscopic plate under radiation pressure [37], the torque of a ferromagnet under spin-spin interactions [38], coherent momentum transfer to superconducting electrons [39], ... But some of them have been refuted [40] and those which turned out to be correct lead to very small effects. Finally, a sea of cosmological light neutrinos may provide a target for very high energy cosmic rays [41], but again the feasibility of any experiment based on this phenomenon appears extremely difficult.

If the dark matter neutrino is not the lightest one, it will most likely be ustable and decay by ultraviolet gamma emmission. But, again, the expected ultraviolet cosmic photon flux seems very difficult to observe [42] .

Heavy neutrinos ($m_\nu\ > 3\ GeV$) arise from new families of fermions, $SU(2)_L \otimes SU(2)_R$ models or superstring theories. On general grounds, there is no obvious reason why they should be stable, but they may eventually carry a new conserved quantum number. Heavy Dirac neutrinos, as well as s-neutrinos (the supersymmetric partners of the neutrinos), exhibit coherent scattering off nuclei and can therefore be detected through this process (see next section for more details).

The magnino [43] is a Dirac neutrino carrying a conserved number (to prevent unwanted annihilation rates) and an anomalous magnetic moment (to bring a sufficiently large scattering cross-section $\sigma \approx 10^2\ \sigma_{weak}$). Then, with a mass in the range of 4 to 10 GeV and a magnetic moment $\approx 10^2$, the magnino can reproduce the requirements of the cosmion model [44]. The magnino is basically a new sequential neutrino associated to a heavy charged lepton. Therefore, its existence can in principle be checked by accelerator experiments.

Heavy Dirac neutrinos, as well as magninos, are the most accessible dark matter candidates for present and forthcoming experiments, due to the comparatively large cross sections involved. The basic detection principle would be elastic nucleus recoil, with energies in the range $50\ eV < E_R < 10\ keV$ for magninos and possibly much larger for heavier neutrinos. Intrinsic germanium has been able to provide some bounds on the cosmion flux (Fig. 7), but more sensitive detectors are required. The use of intrinsic (semiconductor) silicon is presently being studied [45,46], and some new bounds on dark matter have recently been reported from such a detector [46]. However, the development of cryogenic devices will most likely be the only way to comfortably cover the full range of cosmion masses. Fig. 7 also presents bounds on Dirac neutrinos and s-neutrinos, again based on nucleus recoil, where a large mass domain has been ruled out.

5 WEAKLY INTERACTING MASSIVE PARTICLES

The problem addressed is: how to detect dark matter in the laboratory if it is made of WIMP (Weakly Interacting Masive Particles)? By weak interaction we mean not only W or Z^0 exchange, but any other process leading to cross sections much smaller than electromagnetic. (e.g. the exchange of a scalar quark).

Many WIMP dark matter candidates have been considered, but special attention has in the recent years been paid to new particles generated by supersymmetry. The lightest supersymmetric particle (LSP) is often considered to be stable by R-parity conservation, although the validity of such a hypothesis is not completely general. Gravitinos and scalar neutrinos are not the LSP in most models [47] , the main candidates being the photino ($\tilde{\gamma}$) and the higgsino ($\tilde{H}$). One often has $m_{\tilde{H}} > m_{\tilde{\gamma}}$, which makes the photino the most popular LSP. The photino mass is rather model dependent, and present studies concern mainly the range $5\ GeV < m_{\tilde{\gamma}} < 100\ GeV$, for which $\Omega_{\tilde{\gamma}} \approx 1$ appears to come out quite naturally.

Accelerator experiments provide bounds on the supersymmetric partners of quarks and gluons, to which the photino mass is related in a model dependent way. In general, s-quarks ($\tilde{q}$) and gluino ($\tilde{g}$) are an order of magnitude heavier than the photino. UA1 data give $m_{\tilde{g}} > 53\ GeV$, $m_{\tilde{q}} > 45\ GeV$. Results from CDF at FERMILAB, as well as next runs from UA1 and UA2 at CERN, will push these lower bounds higher in mass. It must also be realized that the photino mixes with higgsino and Zino ($\tilde{Z}$, the supersymmetric partner of the Z^0) . The lightest particle resulting from this mixing is in general photino-dominated and is called the neutralino (χ).

Note also that, within the framework of superstrings, some fashionable supersymmetric grand unified theories are based on flipped $SU(5) \otimes U(1)$ (another way of breaking the SO(10) grand unified symmetry [48]). A new dark matter candidate appears: the flatino [49], a neutral supersymmetric partner of the $SU(5)$ breaking Higgs boson. This neutral fermion may close the universe and be totally undetectable, except for gravitational effects. However, neutralino dark matter is not excluded in flipped $SU(5) \otimes U(1)$ [50].

Laboratory detection of galactic WIMP was discussed by Goodman and Witten [51], mainly based on the recoil energy of scattered nuclei. For a WIMP of kinetic energy E ($\approx 10^{-6}\ m$) scattering a nucleus of mass M, the maximum recoil energy is:

$$T_{max} \;=\; 4\ m\ M\ E\ /\ (M+m)^2 \qquad (12)$$

For a reaction producing an excited nucleus of mass $M' \;=\; M \;+\; \Delta M$, relevant formulae can be found in [52] . WIMP weak cross-sections with nuclei can be cast in three categories:

5.1 Coherent scattering

Coherent scattering appears if a non-relativistic particle of well defined weak hypercharge interacts with a nucleus through the isoscalar components of the Z^0 current. The condition for coherent scattering is that the wavelegth defined by momentum transfer be larger than the size of the nucleus. The relevant matrix element is:

$$M = 4\sqrt{2}\ G_F\ J^0_{WIMP}\ J^0_{TARGET} \qquad (13)$$

If the WIMP is a fermion, we get:

$$J^0_{WIMP} \;=\; 1/4\,(Y_L \;+\; Y_R) \qquad (14)$$

where Y_L (Y_R) is the weak hypercharge of the left (right) chiral component of the WIMP. For a Majorana neutrino, $J^0_{WIMP} \;=\; 0$ and there is no coherent scattering off nuclei. On the contrary, s-neutrinos and Dirac neutrinos are expected to interact coherently with nuclei and should exhibit reasonably large event rates in the case they would form the dark matter of our galaxy.

5.2 Spin-dependent interactions

This is the case for galactic photinos interacting with nuclei through the exchange of a scalar quark (Fig. 8a). The nonrelativistic limit of the relevant Feynman diagram is equivalent to the exchange of a space-like pseudovector current. Then, assuming that valence quarks carry most of the spin of the nucleon, the nucleon couplings are proportional to [51] :

$$< p\ |\bar{u}\vec{\gamma}\ \gamma_5 u\ |\ p >= (1+g_A) < p\ |\vec{S}|\ p > \qquad (15)$$

$$< p\ |\bar{d}\vec{\gamma}\ \gamma_5 d \mid p >= (1 - g_A) < p\ |\vec{S}|\ p > \tag{16}$$

$$< n\ |\bar{u}\vec{\gamma}\ \gamma_5 u \mid n >= (1 - g_A) < n\ |\vec{S}|\ n > \tag{17}$$

$$< n\ |\bar{d}\vec{\gamma}\ \gamma_5 d \mid n >= (1 + g_A) < n\ |\vec{S}|\ n > \tag{18}$$

where experimentally $g_A \simeq 1.2$. Therefore, a u-quark in a proton or a d-quark in a neutron would have a larger matrix element than the converse case. Furthermore, the complete diagrams carry twice the coupling $\tilde{q}q\tilde{g}$, which is proportional to the charge of the interacting quark. It would then follow [51,53] that photino searches should be made with even-odd nuclei carrying an odd number of protons.

This conclusion has been reconsidered at the light of EMC data [54,55] which suggest that a sizeable part of the nucleon spin is carried by gluons or sea quarks. If this is the case for low values of Q (the momentum transfer), the above estimates should be seriously modified and a wide range of target elements could be used for dark matter detection (but with lower event rates). EMC data were taken at $Q^2 > 3\ GeV^2$, and there has been some controversy [56] on their interpretation and validity at $Q^2 \simeq 0$. Recent theoretical work [57] based on the Skyrme model at large N_c (number of colors) seems to support the idea that valence quarks are not the basic ingredient to build the proton spin. A complementary experimental information comes from νp and $\bar{\nu}\ p$ scattering [58], where data are not inconsistent with the EMC result and the new proton models.

Significant corrections to pure photino cross-sections may in some cases come from photino-higgsino-Zino mixing [59], where both higgsino and Zino exhibit coherent scattering (e.g. Fig. 8b).

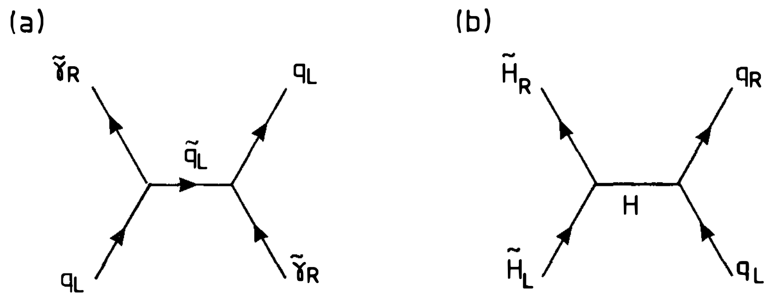


Fig. 8 - Feynman diagrams contributing to photino and higgsino scattering with matter.

Results of a calculation of neutralino cross sections in a minimal supergravity model are shown in Table 1 . In any case, spin-dependent interactions of WIMP with nuclei are likely to lead to event rates of $\approx 1\ event/Kg.day$, whereas the best background rate of germanium detectors at the relevant energies is of 1 $event/keV.Kg.day$, and it is far from obvious that purity rates similar to that of germanium can be reached for other target materials. This is likely to be the main obstacle to the detection of galactic Majorana fermions, especially if purely calorimetric or ionization techniques are used.

Finally, Fig. 9 a and b show low background achievements in UCSB-LBL and USC-PNL double beta germanium detectors.

Isotope \ m_x	4 [GeV]	8 [GeV]	15 [GeV]	20 [GeV]
$^{1}_{1}H$	1.1 3.6	0.12 0.39	0.018 0.059	0.0065 0.021
$^{2}_{1}H$	0.022 2.8	0.0029 0.33	0.00050 0.051	0.00019 0.025
$^{3}_{2}He$	1.4 0.017	0.18 0.0030	0.032 0.00071	0.012 0.00033
$^{7}_{3}Li$	1.0 3.1	0.18 0.55	0.039 0.12	0.016 0.048
$^{9}_{4}Be$	0.66 0.0086	0.14 0.0021	0.030 0.00068	0.013 0.00035
$^{10}_{5}B$	0.016 2.0	0.0035 0.40	0.00090 0.092	0.00039 0.052
$^{11}_{5}B$	0.84 2.6	0.18 0.54	0.044 0.13	0.019 0.055
$^{19}_{9}F$	1.2 3.5	0.29 0.87	0.083 0.25	0.038 0.12
$^{27}_{13}Al$	0.42 1.3	0.11 0.33	0.036 0.11	0.018 0.051
$^{51}_{23}V$	0.23 0.71	0.068 0.21	0.026 0.076	0.014 0.040
$^{69}_{31}Ga + ^{71}_{31}Ga$	0.23 0.70	0.070 0.21	0.028 0.082	0.015 0.045
$^{75}_{33}As$	0.21 0.66	0.066 0.20	0.027 0.079	0.015 0.043
$^{79}_{35}Br + ^{81}_{35}Br$	0.20 0.62	0.063 0.19	0.026 0.075	0.014 0.041
$^{203}_{81}Tl + ^{205}_{81}Tl$	0.15 0.46	0.050 0.15	0.022 0.066	0.013 0.038

Event rates

in

Kg^{-1} day^{-1}

Upper: according to EMC data

Lower: according to naive quark model

Table 1 - Event rates predicted for elastic scattering of neutralino off nuclei, from [55] .

5.3 Inelastic scattering

For particles that do not scatter coherently off nuclei, Goodman and Witten proposed the use of special target nuclei, where the matrix elements for the transition to excited states:

$$\tilde{\gamma} + N \rightarrow \tilde{\gamma} + N^* \tag{19}$$

the excited state N^* decaying subsequently to the ground state:

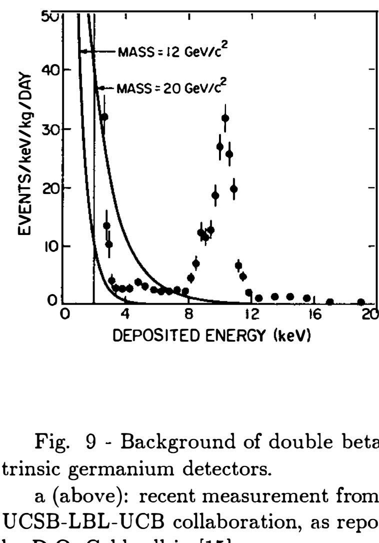
$$N^* \rightarrow N + \gamma \tag{20}$$

may be almost as important as those of elastic scattering. Then, besides the recoil energy, it would be possible to detect a γ ray coming from the decay of the excited state. The main drawback is our lack of knowledge of the actual nuclear wave functions and matrix elements. An estimate of inelastic neutralino scattering cross-sections with the most interesting isotopes has recently been performed [60] . In spite of its not well known cross-sections (a priori quite small), inelastic scattering may in some cases provide a specific signature (delayed time coincidence [52]) which appears potentially able to reject severe backgrounds. This may turn out to be a crucial point even if very large detectors are likely to be required. For isotopes allowing for a delayed time coincidence, 10 *ton* detectors are needed to reach a rate of the order of 1 *event/day* . Some well suited isotopes, after the theoretical calculation from [60] , would be ($i.a.$ = isotopic abundance, τ = excited state lifetime):

$$^{169}Tm\ ,\quad 100\%\ i.a.,\ \Delta E = 8.4\ keV\ ,\ \tau\ = 4\ ns\ ,\ \approx 1\ event/ton.day \tag{21}$$

$$^{57}Fe\ ,\ 2.2\%\ i.a.\ ,\ \Delta E = 14.4\ keV\ ,\ \tau = 98\ ns\ ,\ \approx 0.2\ event/ton.day \tag{22}$$

$$^{119}Sn\ ,\ 8.6\%\ i.a.\ ,\ \Delta E = 23.9\ keV\ ,\ \tau\ =\ 18\ ns\ ,\ \approx 0.1\ event/ton.day \tag{23}$$



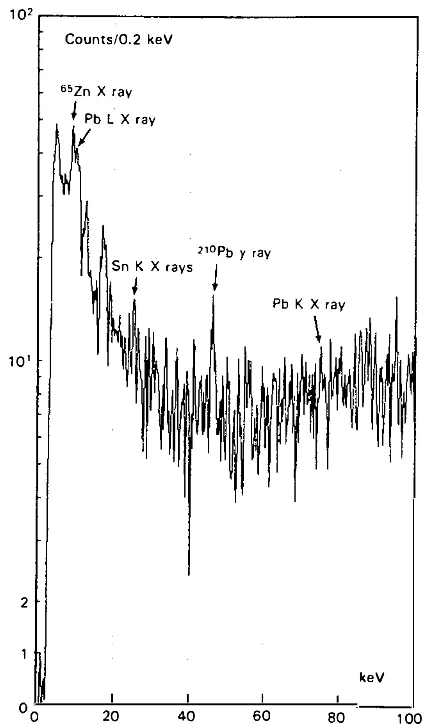


Fig. 9 - Background of double beta intrinsic germanium detectors.

a (above): recent measurement from the UCSB-LBL-UCB collaboration, as reported by D.O. Caldwell in [15].

b (right): result of a 1000 *hour* run by the PNL-USC collaboration [30], using a low background 135 cm^3 prototype. The abscissa is energy deposition.

Because of its long excited state lifetime, ^{57}Fe would be particularly well suited for a delayed coincidence, whereas ^{119}Sn can be used in the form of superconducting granules and ^{119}Tm may possibly be appropriate for very fast luminescent devices.

Assuming that detectors incorporating these matrix elements can be built, with high sensitivity and low background, the delayed time coincidence should in principle allow for a clean identification of dark matter events.

6 DETECTION TECHNIQUES FOR WIMP

For a WIMP mass of 1 GeV (100 GeV), dark matter detectors sensitive to $<$ 1 keV (100 keV) energy deposition are required, if a recoiling target nucleus of mass $M = m$ is used. Since the last condition cannot be fulfilled a priori (the WIMP mass is unknown), a threshold at least an order of magnitude lower (below 100 eV) should be the requirement for a universal WIMP detector. This naturally hints to the development of low temperature devices. However, more conventional detectors have already provided some interesting bounds [61,62] and are still being considered for further experiments. Among the proposed detection techniques for WIMP are:

6.1 Conventional techniques

The pioneering role of germanium double beta detectors has already been mentioned previously. Semiconductor detectors have apparently not finished their role in the field, as intrinsic silicon is now being used [46,63]. The motivation for shifting to silicon is: a) higher energy deposition for light WIMPs; b) higher ionization yield for a given energy deposition; c) lower threshold, claimed to be in the 600 keV range in equivalent electron energy.

Another idea would be WIMP detection through proton recoil in a low pressure time proportional chamber [64] in the presence of a magnetic field. This would be particularly well suited for light photinos, where the track of a recoiling proton from CH_4 or CD_4 gas may well be observable.

The use of scintillators has equally been considered [52] for neutralino detection through inelastic scattering. Two preliminary steps appear to be necessary before going further in this development: a) find a very fast luminescent crystal with a high light yield, incorporating the target element under consideration; b) study in detail the scintillation yield (if any) from nucleus recoil at the expected WIMP kinetic energy scale. As will be seen later, luminescence may also in some cases be combined with cryogenic detection.

6.2 Crystal phonon devices

In a suitable insulating crystal cooled at very low temperature [65], a low energy particle will deposit most of its energy in the form of phonons. If the crystal is of very high quality, part of these phonons will be ballistic and can reach unscattered the walls of the crystal. Ballistic phonons propagate along the main cristallographic axis and can travel a few mm without de-focusing. On the walls of the crystal, a phonon read-out of superconducting tunnel junctions (STJ) [66] or transition-edge superconducting strip, can detect the ballistic phonons in real time. In this way, it is possible to obtain position information on the event.

The alternative is thermal detection. In this case, a resistive thermometer (thermistor) implanted on one of the walls is used. In the theoretical limit where the energy resolution of such a bolometer would be given by energy fluctuations, a commonly used expression [67] is:

$$\Delta E \approx 2.5\ (kT^2C)^{1/2} \tag{24}$$

where C is the heat capacity of the bolometric system (crystal + sensor). Taking

$$C \approx aMT^3 \tag{25}$$

where M is the mass of the crystal, the $T^{5/2}\ M^{1/2}$ dependence of ΔE from (24-25) suggests that it may be possible to obtain high sensitivity for comparatively large detectors if size is compensated by a decrease in working temperature.

A hybrid read-out involving both thermistor and phonon detectors can equally be considered. Phonon detectors are expected to provide low threshold (especially in thermal detection) and high energy resolution. Furthermore, being made of high quality crystals, a low impurity content (necessary to avoid radioactive background) appears to be naturally implemented, even if much higher purity will be required for a dark matter detector.

Recent results on thermal bolometers and ballistic phonon devices are very encouraging, and are dealt with in two contributions to this Workshop [68,16].

6.3 Superheated superconducting granules (SSG)

The idea originates from members of the Orsay Group on Superconductivity [69] , who proposed to use as particle detectors the colloids of metastable type I superconducting granules previously developed by J. Feder [70] . Very small spheres (ϕ , diameter, $\propto$ 1 μm) are mixed with some dielectric at $\propto$ 10 $-$ 30% filling factor in volume. In the presence of an applied magnetic field, they remain superconducting above the critical value and reach a metastable state called superheating, that can be disrupted by the energy deposition of incoming particles. The phase transition of one or several granules is detected in real time through Faraday's law by a transient read-out of current loops sensitive to the disappearence of the Meissner effect in the sourrounding grains. SSG may be used to detect dark matter in several different ways: a) nucleus recoil [71] with Al, Cd, Ga or Zn grains; b) proton recoil using hydrogen from the dielectric material as the target [52] ; c) inelastic scattering with a ^{119}Sn target [72]. However, studies made in the last years [72] suggest that, at least in their conventional version, SSG fail to provide the required performances for dark matter detection (although recent progress in grain fabrication [73] may considerably improve the response of SSG devices).

We have recently proposed [72] a new way for SSG development based on a the concept of "amplification by thermal micro-avalanche". With a better handling of heat exchanges in the detector, and working at temperatures where the released latent heat is slightly positive, the new scenario is particularly relevant for dark matter detection, since: a) the detector response to WIMP interactions is no longer reduced to a single granule flip, therefore energy resolution can be obtained ; b) the dielectric material surrounding the granules becomes part of the active target. However, if experimental evidence for thermal avalanches seems to exist, implementing in practice the micro-avalanche scenario for the required target elements is less simple and more experimental studies on the new version of SSG are required. If the basic physics of the micro-avalanche scenario works as expected, superconducting granules are likely to provide the best suited cryogenic detector for large volume experiments. Recent results on SSG development are presented in [16].

6.4 Hybrid devices

The backgound problems faced by WIMP detection, especially if interaction with nucleus is not full strength coherent, hint to the necessity of finding new, unconventional approaches to dark matter detection. Cryogenic devices are a step in this direction, but it is not obvious that they will be able to solve the problem as long as they remain purely calorimetric.

One possible way to improve background rejection may be the simultaneous detection of ionization and heat, as according to Lindhard et al. [74] and existing data with Ge and Si [75], a low energy nucleus recoil is expected to ionize much less than a beta or gamma particle of the same energy. Two developments have been proposed along these lines:

a) Cold semiconductors. Luke [76] has demonstrated that ionization can be measured in a germanium crystal at 1.3 K by detecting the heat produced when electrons drift in an electric field. More recent results on the subject are described in the talk by B. Sadoulet.

b) Luminescent bolometers [77] . The basic idea is to use a scintillating crystal exhibiting good luminescence properties at very low temperature, which seems indeed to be the case for BGO , $CdWO_4$, CeF_3 , intrinsic CsI and LiI , $GSO : Ce$, ... It would then be possible to simultaneously detect the optical and thermal signals separately, and even to use light as a timing strobe. We discuss this idea in some detail elsewhere in these Proceedings.

The idea of developing such hybrid devices is rather new, so that many practical problems remain to be solved and nontrivial basic studies are still necessary. But, in case of succes, hybrid techniques would provide a significant step forward in the field of dark matter detectors.

7 QUARK NUGGETS

Witten [78] proposed that quarks may form dense stable states where u, d and s quarks fill a Fermi sea up to very high values of the baryon number. Then, the gain in Fermi energy may eventually make the s quark stable inside a heavy nugget.

The interaction of cosmic quark nuggets (nuclearites) with matter has been discussed at length [79] and they turn out to be detectable in real time experiments [80] for masses and speeds in the range $10^{-13}\ g < m < 1\ g$, $\beta > 10^{-4}$. Assuming that nuclearites are gravitationally dominant, present real time experiments exclude at least the region

$m < 10^{-7}\ g$. The $10^4\ m^2\ sr$ underground MACRO detector [7] will be sensitive to much smaller fluxes, allowing to exclude nuclearite masses up to $m < 10^{-2}\ g$.

Nuclearites lighter than $10^{-10}\ g$ would be trapped in earth, and could be detected using heavy ion beams [81] , the crucial point being that strange quark matter is expected to form bound states with ordinary matter. Searches along this line [82] have not reported any positive result.

Very heavy nuclearites ($m > 1\ g$) would leave macroscopic tracks on rock and geological searches are possible [83] . Again, no candidate has been found, but further searches are required to cover such small fluxes.

Finally, it has been pointed out [84] that present day gravitational antennae are sensitive to nuclearites and can provide bounds in the region $m > 10^{-9}\ g$, $\beta \gtrsim 10^{-3}$.

8 CONCLUSION

If dark matter is made of non-relativistic particles, its nature remains completely unknown and diversified laboratory searches would constitute a fundamental step forward. This, however, requires an important research and development effort in order to reach the necessary performance for dedicated detectors. Conventional techniques may still prove useful, but new tools (e.g. cryogenic detectors) are foreseen to completely handle the problem of particle dark matter.

If light neutrinos (as hot, warm or cold dark matter) are the right answer, their detection in the laboratory will be the greatest technological challenge ever faced by particle physics and astrophysics. The success of such an experiment would in turn be one of the most fundamental results in the recent history of science.

Detectors for axions, monopoles and some WIMP candidates are being developed, and the research program along these lines is providing interesting results. Experimental check of the cosmion hypothesis has already started and brought relevant bounds. On the other hand, the most prominent WIMP candidate, the photino-dominated "neutralino", poses rather severe backgound problems and requires quite sophisticated detection techniques, where cryogenic devices should play a crucial role if they indeed reach the theoretically expected sensitivity and energy resolution.

For elusive WIMP, where event rates are expected to fall below the best possible detector background, particle identification (allowing to distinguish between a nucleus recoil and a low energy ionizing particle) may be a surprisingly simple way out. It can possibly be achieved by looking simultaneously, in a well suited cryogenic device, at thermal and ionization signals. Then a recoiling nucleus would be seen to ionize much less than a low energy beta or gamma. We propose, in this perspective, the development of a luminescent bolometer based on some crystal scintillator cooled to very low temperature.

To conclude, Table 2 (next page) shows a list of dark matter candidates in particle physics, including dynamical origin, fluxes on earth and proposed detection techniques.

Table 2 - Dark matter candidates in Particle Physics.

PARTICLE	MASS	PRESENCE NEAR EARTH	ABUNDANCE	INTERACTION WITH MATTER	PROPOSED DETECTION TECHNIQUES
LIGHT NEUTRINO	m < 30 eV (Cosmology) m < 18-32 eV (Experiment) (Supernova ?)	COSMIC GALACTIC	$\Omega \sim 1$ if 5 eV $< m_\nu <$ 30 eV	COHERENT SCATTERING IF DIRAC MASS	??
AXION	m $> 10^{-5}$ eV (Cosmology)	GALACTIC	$\Omega \sim 1$ if $m_a \sim 10^{-5}$ eV ?	a → γ conversion in a strong emf.	LOW TEMPERATURE ELECTROMAGNETIC CAVITIES
	m $< 10^{-3}$ eV (Stars)	SOLAR	flux on earth: 10^5 to 10^{11} cm^{-2}s^{-1}	a → γ conversion in atoms.	.SILICIUM DIODES .LOW TEMPERATURE DETECTORS
HEAVY NEUTRINOS	m > 3 GeV	GALACTIC	Eventually, $\Omega \sim 1$	WEAK (COHERENT IF DIRAC MASS)	.IONIZATION DETECTORS FOR HEAVY PARTICLES . LOW TEMPERATURE DETECTORS FOR ENERGY DEPOSITS BELOW 1 keV: SSG PHONONS (Ballistic and thermal) HYBRID DEVICES
LSP (Lightest supersymmetric particle)	Model--dependent (1-100 GeV ?)	GALACTIC	Eventually, $\Omega \sim 1$	SUPERSYMMETRIC (spin-dependent in most models)	
COSMIONS	4 GeV< m< 10 GeV	SOLAR and GALACTIC	$\Omega \sim 1$ possible	$\sigma \sim 10^2\ \sigma_{weak}$	
MONOPOLES	m $\sim 10^{16}$ GeV (GUTS)	GALACTIC TRAPPED AROUND SUN	• PARKER BOUND • BOUNDS FROM RUBAKOV EFFECT	ELECTROMAGNETIC	.CONVENTIONAL .SUPERCONDUCTING
QUARK NUGGETS	HEAVY (UNKNOWN)	GALACTIC	Eventually, $\Omega \sim 1$	ATOMIC COLLISIONS	ACCORDING TO MASS

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