DARK MATTER SEARCHES

R. BERNABEI

Dipartimento di Fisica, Universita' di Roma "Tor Vergata" and
INFN, sez. Roma2, I-00133 Rome, Italy
E-mail: Bernabei@roma2.infn.it

ABSTRACT

A short summary on the current strategies to search for Dark Matter candidates are summarized. Emphasis is given in particular to the WIMP direct searches.

Large experimental and theoretical efforts allowed in the last years to change the main question on the Dark Matter problem from its existence to the nature of its constituents.

As an example, we recall the stringent limit on the baryonic constituents arising from the comparison of the measured relative abundances of light elements with the expectations in the nucleosynthesis scenario, which restricts $\Omega_{baryon}h^2 = 0.009\text{-}0.02$[1]) where $h = H_0/100$ km s^{-1} Mpc^{-1}. This limit is substancially supported by the present results on the microlensing searches for MACHO as it has been reported in ref.[1]). There the region allowed at 95% C.L. (for masses roughly from $10^{-1} \cdot M_\odot$ to $1 \cdot M_\odot$) by the MACHO collaboration is shown as well as the one excluded at 95% C.L. (for masses roughly from $10^{-7} \cdot M_\odot$ to $10^{-1} \cdot M_\odot$) by the EROS collaboration, overlapping this last large part of the first one when the EROS candidates are considered as background events. Although the situation is not completely fixed, the limit set by the data on the baryonic halo fraction results at level of $\lesssim 0.1$.

As regards relic light neutrinos, we recall that only indirect supports to their contribution to the Dark Matter can be obtained by investigating if neutrinos could have mass in the range of cosmological interest. At present positive hints on a neutrino mass different from zero arise from: i) the solar neutrino experiments which allow to quote a $\Delta m^2 \simeq 10^{-5}$ eV^2 in the framework of the MSW effect[2]); ii) the atmospheric neutrino anomaly, giving $\Delta m^2 \simeq 10^{-3}$ eV^2 [3]); iii) the LSND result, which quotes $\Delta m^2 \simeq 6$ eV^2 [4]). All these results support the idea of the possible existence of neutrino masses of cosmological interest, in particular if a mass degeneracy would be introduced. However, to reconcile all these results in an unique scenario probably the existence of sterile neutrinos should be also postulated[5]).

On the other hand, the analysis of the results achieved by the cosmic microwave background investigations rules out the pure hot Dark matter scenario (also including the baryonic fraction)[6,7]), resulting the mixed (70% cold, 20% hot and 10% baryonic)

Dark Matter scenario the preferred one. In any case, whatever composition would be considered (even if the cosmological constant is different from zero as it has been recently hypotized by preliminary results on SN-Ia at high red shift[8)]) a large amount of cold Dark Matter is required in form of WIMPs or axions.

As it is well known, the axion has been postulated to explain the absence of CP violation in the strong interactions and has been searched for in the past on a wide range of masses without success[9)]. The consideration that axion masses between 10^{-3} eV and 10^{-6} eV could be of cosmological interest has motivated the search for relic axions; this search has been performed and it is in progress essentially in USA[10)].

Large efforts are devoted to the direct detection of WIMPs in all the underground laboratories around the world and in the following we will discuss essentially some main arguments on this topic.

The WIMPs should be neutral particles in thermal equilibrium in the early stage of Universe, decoupling at freeze-out temperature, with cross section on ordinary matter of order or lower than the weak one; they should form a dissipationless gas trapped in the gravitational field of the Galaxy. To be a suitable WIMP candidate a neutral particle should be stable or have a time decay of order of the age of the Universe. The lightest supersymmetric particle, named neutralino, which results stable in MSSM and SUGRA models with R-parity conservation is the more accredited candidate; it will still remain a good candidate also in case models without R-parity conservation would hold, if the decay time would be of the order quoted above.

WIMPs can be searched for by direct and indirect techniques. As regards the indirect techniques we only recall here the recently improved limit by MACRO collaboration [11)], resulting from the number of up-going muons measured by this experiment from March 89 to March 98. Further results from indirect searches can be foreseen in near future from the other indirect searches deep underground, under-water, under-ice and in space[12)].

In the following we will focus our attention on some of the main points related to the WIMP direct searches by elastic scattering on target-nuclei; as regards the direct searches by investigating the WIMP-nucleus inelastic scattering we mention here ref.[13,14)], stressing that in similar searches much lower counting rates are expected for the signal.

The main strategy to effectively search for this rare events process is based on the use of experimental set-ups realized with "low radioactive" materials deep undergound. Significant improvements in the overall set-up radiopurity can be reached over several years of significant efforts, as for example reported in ref.[15)] for Ge detectors. This is obviously possible for any kind of target-detector, remaining as ultimate limit the sea level activation of the materials. This limitation can be, however, significantly overcome if chemical purifications of the used materials occur just before their storage deep underground and — even more — if all the operations are realized in a controlled environment deep undergound. Moreover, we will comment that the extreme level of radiopurity is not only difficult to reach, but even more difficult to maintain (consider the handling procedures, etc.)

Another crucial point (as always in experiments which require a very low energy threshold) is the possibility to identify and effectively reject the residual noise above the considered energy threshold. This problem has to be faced with any kind of detector. For most of them the rejection is quite uncertain (affecting also the quoted results), because the noise and the "signal" pulses have undistinguishable shapes. We comment that, on the contrary, an almost unique noise rejetion is possible in scintillators having: i) relatively long pulse decay time with respect to the fast single photoelectrons from the PMT noise; ii) really large number of photoelectrons/keV; iii) low noise contribution from the electronic chain; and using the most sensitive rejection procedure (see for istance ref.[16)]) We note in addition, that scintillators are not affected by microphonic noise as it is the case for ionizing and bolometer detectors.

Obviously the distribution of the measured counting rate in the lowest energy region depends — as level and as shape — on the peculiarities of the considered experimental set-up (for some arguments on this point see e.g. ref.[17,18)]). As an example we summarize in table 1 the minimal information which has to be taken into account in order to correctly compare the rate behaviours measured by different NaI(Tl) set-ups. Similar considerations hold also when comparing results achieved by other experiments with any kind of detector and — even more — when comparing results obtained by using different technology.

As we have already outlined the main strategy to be followed in order to realize an effective particle Dark Matter direct search is the continuous effort toward the realization of further improved radiopure set-ups. This is the main strategy followed by all the collaborations which are operative around the world. However, a further improvement in sensitivity is reachable when a pulse shape technique (PSD) can be applied to the data, allowing the rejection of large part of the electromagnetic background contribution. This is possible both in scintillators such as NaI(Tl) and liquid Xenon (where different pulse decay times corresponding to pulses induced by γ/electrons and by recoils or recoil-like events, such as e.g. end-range alphas, allow a statistical discrimination) or in Ge/Si bolometers (γ/electrons events and recoils or recoil-like events are statistically discriminate by comparing the ionizing and the bolometer signals).

As regards the scintillators two successful analyses have been carried out by DAMA[19,20)] and by UK coll.[21)], while as regards the Ge bolometer first results have been presented by CDMS collaboration with a Ge bolometer running at shallow depth[22)].

We will comment that for a successful PSD e.g. in NaI(Tl) the following requirements have to be fulfilled: i) high stability of the temperature during the data taking; ii) full compatibility of the running conditions for the Compton, the neutron and the production data (which have to be compared) collections; iii) full rejection of the residual PMT noise and not relevant contribution from the electronic chain noise. As

Table 1. Minimal information to be suitably considered when comparing the rate behaviours measured by different NaI(Tl) set-ups. The information in this table are summarized from the papers available in literature by the various collaborations at time of this conference.

expt	CANFRANC	DAMA	OSAKA	UK
technology	old	new	old	new
detectors	multi	multi	multi	single
PMTs/detector	1	2 (+10 cm TETRASIL-B light guides)	2 (+ very long light guides)	2 (+30 cm light guides)
threshold on single PMT	not given	single Photoel.	not given	2.4 Photoel.
windows: PMT coinc./afterglow	not given	given	not given	not given
photoel/keV	not given	5.5-7.5	not given	1.7
σ/E	$\sim$ 14% @46.5 keV	7.5% @59.5 keV	$\sim$ 14% @46.5 keV	not given
noise rejection	not given	by PSD	not given	not given
total hardware rate above single photo-electron threshold	not given	given	not given	not given
information on residual contaminants in set-up constituents, external environmental Rn etc	not given	given	ELEGANT V	not given
height of the ^{210}Pb peak (surface and/or internal) in cpd/kg/keV	20	3-6	40	not given
neutron source used in deep underground installation?	no	no	no	yes

regards instead the case of Ge bolometers it is necessary e.g.: i) to demonstrate the identity of the sensitive volumes for the two different signals; ii) to properly evaluate the uncertainty on the rejection factor as a function of the energy; iii) to quantify the noise rejection strategy; iv) to measure the quenching factor value. This last point is crucial for any kind of bolometer being not available at present systematic measurements realized by inducing recoils in the whole sensitive volume with neutrons.

As previously mentioned many groups are operative in the various underground laboratories over the world and many R&D activities have been founded; for a significant list see for istance ref.[23)].

In fig.1 there are summarized the most recent exclusion plots published on review [19,20,21,24)].

Although the exclusion plots are a widely used in the practice, many uncertainties in the comparison of the results arising from different experiments — even more when different techniques are used — are present. It is, therefore, necessary to pursue experiments with a real signature for the possible signal.

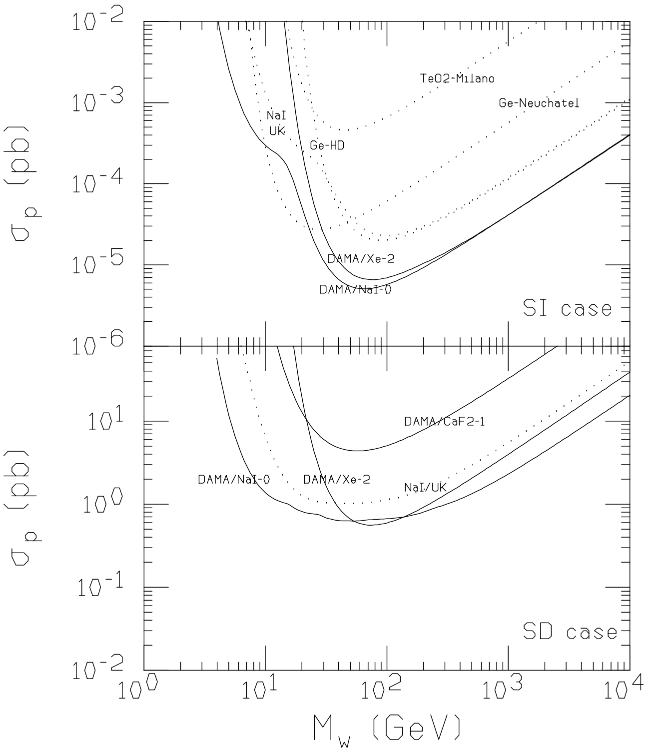

Fig. 1. More sensitive exclusion plots published on review by various authors[19,20,21,24].

Discarding: i) the possible comparison of results from different experiments (being the rate proportional to A^2 for the spin-independent interactions and to the spin factor for the spin-dependent ones), because e.g. of the relevant role played by the different backgrounds; ii) the daily variation of the signal rate[25] (being different the Earth depth crossed by the WIMP during the day), because this effect results practically unobservable at the cross section of interest at present; iii) the correlation of the nuclear recoil track with the Earth's galactic motion (arising from the WIMP velocity distribution), because a real experiment would be practically not realizable due to the shortness of the induced tracks; the only possibility remains the study of the annual modulation of the WIMP wind[26].

In particular, the DAMA collaboration is performing this investigation with the $\simeq$ 100 kg highly radiopure NaI(Tl) set-up at the Gran Sasso National Laboratory of I.N.F.N.[19,27,28,16,29,17,30].

As it has been clearly pointed out by DAMA[28,29], the annual modulation signature is a well distinguished one, requiring the presence not of a "generic" rate variation but of a variation according to the following specifications: i) presence of a correlation with cosine function; ii) proper period for the possible modulation (1 year); iii) proper phase for the possible modulation (about 2 june); iv) only in a well defined low energy region (where recoils could be significantly present); v) for single "hit" events [a]; vi) with modulated amplitude in the region of maximal sensitivity not exceeding $\lesssim 7\%$. The careful verification of the satisfaction of all these requirements is realized by DAMA thanks to: i) the collection of the whole energy spectrum from single photoelectron to the MeV range; ii) to the continuous monitoring and control of several stability parameters; iii) to many consistency checks and statistical tests[16,29,17)]. This allows also to restrict the search for significant systematics — when a positive indication is obtained — to those able to fully satisfy the i) to vi) requirements given above. The only effect which has been suggested so far is the muon flux modulation as measured by the MACRO collaboration at LNGS[31)]; however, this would generally fail some of the above quoted requirements and, in any case, it would account in our set-up roughly only for modulated amplitudes $<< 10^{-4}$ cpd/kg/keV. The hunt is therefore still open.

For some general arguments on systematics refer to[16,17)].

The results achieved so far by the DAMA investigations of the annual modulation signature are summerized in table 2; the quoted results have profited of the values given in ref.[32)] for the astrophysical and nuclear physics needed quantities. They have been obtained by grouping the data in cells of 1 day (i), 1 keV (k) for each detector (j), obtaining the number of events in each *ijk* cell and comparing it with the expectation from the model by a maximum likelihood method[28,29)]. For the sake of completeness we recall that independent analyses by using a χ^2 strategy[29)] and, more recently, by using the Feldman and Cousins approach[33)] give substancially the same results.

Table 2. Summary of the DAMA results on the annual modulation signature[28,29)]

running period	statistics (kg · d)	M_W (GeV)	$\xi\sigma_p$ (pb)	C.L. m.l.ratio
DAMA/NaI-1	3363.8 winter + 1185.2 summer	(59^{+36}_{-19})	$(1.0^{+0.1}_{-0.4})10^{-5}$	90%
DAMA/NaI-2	14962 from middle november to the subsequent end of July	(59^{+22}_{-14})	$(7.0^{+0.4}_{-1.7})10^{-6}$	98.5%
DAMA/NaI-1+2	19511	(59^{+17}_{-14})	$(7.0^{+0.4}_{-1.2})10^{-6}$	99.6%

In fig. 2 the effect of the uncertainties in the local (v_0) and escape velocities (v_{esc}) on the DAMA allowed region is shown; it enlarges the allowed masses: from 30 GeV to 130 GeV (1 σ C.L.). This interval will be further extended from 30 GeV to 180 GeV (1 σ C.L.) when including possible dark halo rotation. For implication see ref.[34,35)].

[a]When using a multi-detector set-up to search for Dark Matter particles, the quoted rate is always referred to single "hit" events, that is to events where only one detector is firing being negligible the probability that a WIMP will interact in more than one.

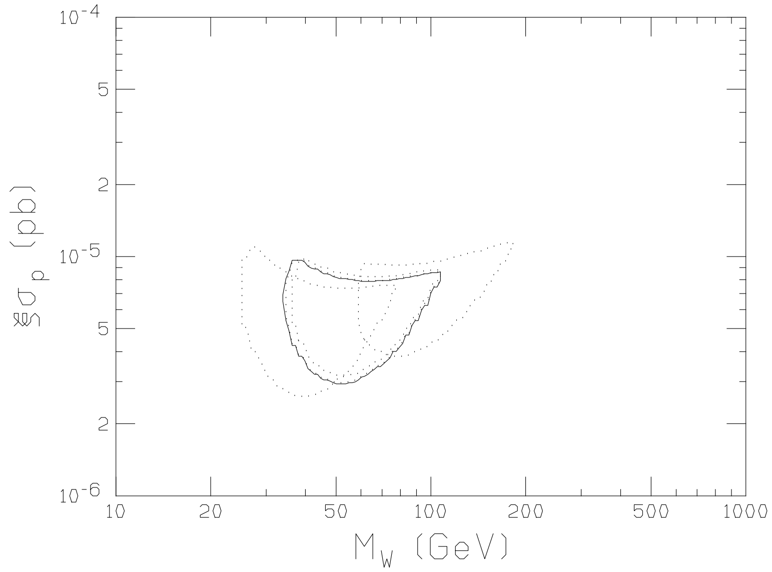

Fig. 2. Effect of the uncertainties in the local (v_0) and escape velocities (v_{esc}) on the DAMA allowed region is shown; the solid contour represents the region at 2σ C.L. for a SI coupled candidate with v_0 = 220 km/s and v_{esc} = 650 km/s. The dotted ones are the obtained extensions when considering v_0 varying between 170 and 270 km/s and v_{esc} varying between 450 and 650 km/s[34,35)]. The quantity ξ is the local neutralino matter density in units of 0.3 GeV cm^{-3}.

The careful investigation of this effect over several annual cycles is in progress by the DAMA experiment.

For the sake of completeness we recall here the efforts of ref.[36)], where less sensitive and poorely (as it can be inferred from the papers) controlled data taking have been carried out.

Finally, we mention the "anomalous" events in PSD data presented by the UK collaboration[37)]; however, this has been substancially overcome by their recent ref.[38)], where it has been found that these events have a time decay shorter than the one expected for recoils induced by neutrons. In any case, as it was evident since the beginning, to account for the rate of these "anomalous" events very high cross section values (very deep inside the UK published exclusion plot) would be necessary.

We can conclude that the Dark Matter problem is now well set; in addition, the multicomponent nature of the Dark Matter is also widely accepted and sufficiently proved. Works are in progress to fully exploit the possible solutions arising from MACHO experiments, from the confirmation of suitably low mass neutrinos and from experiments sensitive to real signatures for WIMPs. Moreover, further results from the indirect searches can be also expected soon.

All these efforts will allow us to pass from the "dark" to the "light" (of the knowledge) soon again.

1. References

1) M. Spiro et al., *Nucl. Phys.* **B70** (Proc. Suppl.) (1999), 14.
2) see for instance: S.T. Petcov, in the volume "Fourth International Solar Neutrino Conference", Heidelberg (1997), 309.
3) Y. Fukuda et al., *Phys. Lett.* **B433** (1998), 9; Y. Fukuda et al., *Phys. Lett.* **B436** (1998), 33; Y. Fukuda et al., *hep-ex/9812014*; MACRO Coll., *Phys. Lett.* **B434** (1998), 451; W.W.M. Allison et al., *hep-ex/9901024*.
4) C. Athanassopoulos et al., *Phys. Rev. Lett.* **70** (1996), 3082.
5) S.M. Bilenky et al., *hep-ph/9812360.*
6) V. Berezinsky et al., *Astrop. Phys.* **5** (1996), 333.
7) E.W. Kolb, *hep-ph/9810362.*
8) A.V. Filippenko and A.G. Riess, *Phys. Rep.* **307** (1998), 31; G. Goldhaber and S. Perlmutter, *Phys. Rep.* **307** (1998), 325.
9) P. Sikivie, in the volume "The Dark Side of the Universe" Rome (1993), 141.
10) C. Hagmann et al., *Phys. Rev. Lett.* **80** (1998), 2043.
11) MACRO Coll., *INFN/AE-99/01.*
12) F. Halzen, *Nucl. Phys.* **B70** (Proc. Suppl.) (1999), 409; L. Trascatti (NESTOR Coll.) , *Nucl. Phys.* **B70** (Proc. Suppl.) (1999), 442; G.V. Domogatsky (BAIKAL Coll.) **B70** (Proc. Suppl.) (1999), 439; S. Ahlen et al., *Nucl. Instrum. Meth.* **A350** (1994), 351; O. Adriani et al. (PAMELA Coll.), LNF-95-051.
13) K. Fushimi et al., *Nucl. Phys.* **B35** (Proc. Suppl.) (1994), 400.
14) P. Belli et al., *Phys. Lett.* **B387** (1996), 222 and **B389** (1996), 783.
15) F.T. Avignone et al., *Nucl. Instrum. Meth.* **A292** (1990), 337.
16) R. Bernabei et al., *INFN/AE-98/23*, in press on *Nuovo Cim.*.
17) P. Belli et al., to appear in the Proc. of "Int. Conf. 3K-Cosmology", Rome (1998), *ROM2F/99/06.*
18) I.R. Barabanov et al., *Nucl. Phys.* **B546** (1999), 19.
19) R. Bernabei et al., *Phys. Lett.* **B389** (1996), 757.
20) R. Bernabei et al., *Phys. Lett.* **B436** (1998), 379.
21) P.F. Smith et al., *Phys. Lett.* **B379** (1996), 299.
22) D.S. Akerib et al., *Nucl. Phys.* **B70** (Proc. Suppl.) (1999), 64.
23) R. Bernabei, in the volume "Phenomenology of unification from present to future", World Scientific pub., (1998), 141.
24) D. Reusser et al., *Phys. Lett.* **B255** (1991), 143; M. Beck et al., *Phys. Lett.* **B336** (1994), 141; A. Alessandrello et al., *Phys. Lett.* **B384** (1996), 316; R. Bernabei et al., *Astrop. Phys.* **7** (1997), 73.
25) J.I. Collar et al., *Phys. Lett.* **B275** (1992), 181.
26) Drukier et al., *Phys. Rev.* **D33** (1986), 3495; K. Freese et al., *Phys. Rev.*

D37 (1988), 3388.
27) R. Bernabei et al., *Phys. Lett.* **B408** (1997), 439.
28) R. Bernabei et al., *Phys. Lett.* **B424** (1998), 195.
29) R. Bernabei et al., *Phys. Lett.* **B450** (1999), 448.
30) P. Belli et al., *ROM2F/99/08*, submitted for publication.
31) M. Ambrosio et al., *Astrop. Phys.* **7** (1997), 109.
32) A. Bottino et al., *Phys. Lett.* **B402** (1997), 113.
33) R. Bernabei, talk given at CERN, april 1999.
34) A. Bottino, these Proceedings.
35) P. Belli et al., *hep-ph/9903501*, submitted for publication.
36) M.L. Sarsa et al., *Phys. Lett.* **B386** (1996), 458; P. Belli et al., *Nuovo Cim.* **19C** (1996), 537; D. Abriola et al., *astro-ph/9809018*; K. Fushimi et al., to appear on the Proc. of *IDM98*, Buxton (UK), sept. 1998.
37) P.F. Smith et al., *Phys. Rep.* **307** (1998), 275.
38) V.A. Kudryavtsev et al., *hep-ex/9902032*.