Chapter 8

Dark matter search with innovative techniques

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The evidence that most of the matter in the universe does not shine has firmly established the concept of dark matter (DM). It is by now clear that there is room in our galactic halo for DM in the form of exotic particles (WIMPs—Weakly Interacting Massive Particles—or axions) [1,2], whose supposed properties make their experimental observation within the reach of frontier detection methods. This stimulates the creativity of experimental physicists, who are induced to push the existing techniques to their extreme limits or to elaborate new ones in order to attempt DM detection.

The scope of this chapter is to give a survey of the most innovative detection techniques (sections 8.3 and 8.4), comparing their potential with existing results, after a brief elementary introduction on the general concepts of CDM direct detection (section 8.1). Since I consider the approach based on phonon-mediated particle detection one of the most promising, an entire section (8.2) is devoted to this subject.

8.1 CDM direct detection

8.1.1 Status of the DM problem

The abundance of the luminous matter in the universe, inferred by direct observations, is in the range $0.002 < \Omega_{\text{lum}} < 0.005$, if a reduced Hubble constant $h = 0.65$ is taken as a reference value. In contrast, primordial nucleosynthesis suggests $0.015 < \Omega_{\text{baryon}} < 0.025$, while gravitational effects lead to $\Omega_{\text{matter}} > 0.3$. This scenario [3] shows that there are two separate DM problems: the gap between Ω_{lum} and Ω_{baryon} requires baryonic matter in some exotic form (like MACHOs or hot intergalactic gas), while the gap between Ω_{baryon} and Ω_{matter}

can admit particle physics solutions. In particular, axions and neutralinos look like plausible candidates and their detection is within the reach of the present technologies.

Recent observational achievements, suggesting an accelerating universe expansion and a flat universe, lead to a scenario which accommodates an important contribution from the vacuum energy ($\Omega_\Lambda \simeq 2/3$), leaving some room for baryonic and non-baryonic DM, since it is expected that $\Omega_\Lambda \simeq 1/3$. Which features do we require for the particles which are supposed to form, at least in part, the non-baryonic fraction of the matter that escapes our observation? They should be

- neutral,
- massive,
- weakly interacting,
- steady, or at least long living with respect to the universe age, and
- with a relic abundance $\Omega \simeq 0.1$–1.

DM is usually classified as cold dark matter (CDM) and hot dark matter (HDM), consisting, respectively, of fast and slow moving particles (for a review see for example [4]). Neutrinos with masses below 30 eV are an example of HDM, since they were relativistic at the decoupling time. The mechanism of galaxy formation requires, however, a substantial amount of CDM; therefore neutrinos cannot represent a complete solution for the DM problem. Axions and neutralinos are examples of CDM. Axions, although their mass is expected to lie in the range 10^{-6}–10^{-3} eV, are slow moving since they were never in thermal equilibrium and were non-relativistic since their first appearance at 1 GeV temperature [5]. Techniques for axion detection [6] are beyond the scope of this chapter and will not discussed here. Neutralinos will be briefly introduced in the next subsection.

8.1.2 Neutralinos

Neutralinos (χ) [2, 7–9] are supersymmetric Majorana fermions consisting of four mass eigenstates, defined as the linear superposition of the two neutral gauginos and higgsinos. The lowest mass eigenstate may play the role of the lightest supersymmetric particle (LSP) and constitute a viable CDM candidate. Supersymmetric models involve several free parameters, whose choice fixes the neutralino properties, such as the χ–χ annihilation rates and interaction rates with ordinary matter. It is therefore possible, once an assumption has been made about the free parameters, to calculate the neutralino relic density Ω_χ and the cross section with atomic nuclei. There are wide regions in the parameter space which correspond to Ω_χ values relevant for the DM problem ($\Omega_\chi \simeq 0.1$–1) and to measurable interaction rates with reasonable mass detectors. Typical neutralino masses are in the range 30–300 GeV, where the lower limit is due to accelerator constraints.

Neutralinos are supposed to interact with quarks within the nucleons [10,11]. This interaction can be described by a total χ–nucleon cross section σ_{p}. The parameter experimentally accessible is of course the χ–nucleus cross section σ_0, that can, in a very general way, be expressed as

$$\sigma_0 \propto \frac{g_\chi^2 g_{\mathrm{N}}^2}{M_{\mathrm{E}}^4}\mu^2 k,$$

where M_{E} is the mass of a virtual particle exchanged between the neutralino and the nucleus in a t-channel interaction, g_χ and g_{N} the coupling constants of this particle with neutralino and nucleus respectively, μ the reduced mass of the neutralino–nucleus system and k a dimensionless constant. Since g_χ and g_{N} are weak interaction couplings and M_{E} is in the Fermi scale (it is, for example, one of the Higgs masses in the case of Higgs boson exchange), the total cross section has a typical weak size: for this reason, neutralinos are sometimes referred to by the more generic term 'WIMPs'. Two types of couplings are usually discussed:

- scalar spin-independent (SI) coupling, for which

  $$k = A^2 F_{\mathrm{N}},$$

  where A is the nucleon number and F_{N} [12] a nuclear form factor; the term A^2 describes an enhancement of the cross section determined by the coherent interaction with the nucleons;
- axial spin-dependent (SD) coupling, which requires odd A (non-zero nuclear spin); in this case

  $$k = (\lambda C_{\mathrm{W}})^2 J(J+1),$$

  where λ and C_{W} [12] are nuclear form factors and J the nuclear spin.

Due to the coherence effect, SI coupling is expected to lead to much higher cross sections. Knowledge of the nuclear form factors allows us to express σ_0 in terms of the χ–nucleon cross section σ_{p}. This makes comparisons among experiments with different nuclear targets possible.

8.1.3 The galactic halo

There is kinematic evidence that there is a halo of DM around spiral galaxies. The evidence comes from the observation of the galactic rotation curves, in which the velocity of the galactic objects is expressed as a function of the object distance from the galactic centre. Since this function is flat sufficiently far way from the centre, instead of the Keplerian decline expected from the distribution of the luminous matter, it is inferred that an invisible mass $M(R)$ is contained in a radius R, with $M(R) \propto R$.

Many uncertainties, however, affect the shape profile and the mass distribution in the halo. Moreover, a substantial component could be of baryonic origin (MACHOs). Standard assumptions [12] are the following:

- $\rho_l = 0.3$ GeV cm^{-3}, where ρ_l is the local halo density (at the sun position); and
- $\rho_\chi = \xi\rho_l$, with $\xi < 1$, where ξ is the neutralino fraction of the halo density.

The neutralino velocity distribution is unknown; it is usually taken is Maxwellian:

$$\mathrm{d}n \propto (\pi v_0^2)^{-3/2} \exp\left[-\left(\frac{v}{v_0}\right)^2\right] \mathrm{d}^3\boldsymbol{v}.$$

To be more exact, v^2 should be replaced by $|\boldsymbol{v} + \boldsymbol{v}_\mathrm{E}|^2$, where $\boldsymbol{v}_\mathrm{E}$ is the Earth velocity with respect to the DM distribution. In addition, the Maxwellian should be truncated at $|\boldsymbol{v} + \boldsymbol{v}_\mathrm{E}| = v_\mathrm{esc}$, v_esc being the galactic escape velocity. The usual assumptions for the Maxwellian parameters are $v_0 = 230$ km s^{-1} and $v_\mathrm{esc} = 600$ km s^{-1}. A complete discussion about the halo structure and the possible choices for the Maxwellian parameters can be found in [12].

An important point for DM direct detection concerns the motion of the Earth inside the DM distribution [12]. This motion is the composition of the Sun's motion in the galaxy and of the orbital terrestrial motion. The velocity of the sun in the halo affects the WIMP flux as seen by a terrestrial detector (one speaks about a 'WIMP wind'); in addition, the terrestrial orbital velocity adds to the Sun's velocity in summer and subtracts from it in winter. This determines an expected seasonal modulation (typically up to 7%) in the WIMP interaction rate in terrestrial detectors, with a maximum on 2 June. As we shall see in section 8.1.4, this modulation may be a signature for DM identification. The rotational motion of the Earth can also be responsible for a diurnal modulation in the average impact direction of the WIMPs. This effect, much more difficult to detect but also much more pronounced (the modulation would be of the order of some 10%), can also constitute a precious tool for DM detection [13, 31].

8.1.4 Strategies for WIMP direct detection

The interaction of the WIMPs supposed to compose part of the galactic halo determines a nuclear recoil rate in a terrestrial detector. In the case of elastic scattering, isotropic in the centre of mass, the differential energy spectrum of the nuclear recoil $\mathrm{d}R/\mathrm{d}E_\mathrm{R}$ can be easily evaluated [12]. It is exactly exponential in case of stationary Earth:

$$\frac{\mathrm{d}R}{\mathrm{d}E_\mathrm{R}} = \frac{R_0}{E_0 r} \exp\left[-\left(\frac{E_\mathrm{R}}{E_0 r}\right)\right], \tag{8.1}$$

where E_R is the recoil energy, R_0 the total rate, r a kinematic factor given by

$$r = \frac{4M_\chi M_\mathrm{N}}{(M_\chi + M_\mathrm{N})^2}$$

(with M_χ is the neutralino mass and M_{N} the target nucleus mass) and E_0 a characteristic WIMP velocity expressed by

$$E_0 = \tfrac{1}{2} M_\chi v_0^2.$$

When the finite velocity of the Earth in the Galaxy is accounted for, equation (8.1) no longer holds and must be replaced by a more complicate expression [12], which preserves anyway an almost exponential shape. Therefore, the expected energy spectrum is featureless and dangerously similar to any sort of radioactive background, which can often be well represented by an exponential tail at low energies. The typical energies over which the spectrum extends can be estimated from the expected M_χ and from the nuclear target mass. It is easy to check with equation (8.1) that most of the counts are expected below 20 keV in typical situations, for example with $M_\chi = 40$ GeV and $A = 127$ (iodine-based detector). This means that the spectrum must be searched for in a region very close to the physical threshold of most conventional nuclear detectors.

In the simplified assumptions that $v_{\mathrm{E}} = 0$ and $v_{\mathrm{esc}} = \infty$, the total recoil rate is given by [12]

$$R_0 = \left(\frac{2}{\pi^{1/2}}\right)\left(\frac{N_{\mathrm{av}} 1000}{A}\right)\left(\frac{\rho_\chi v_0}{M_\chi}\right)\sigma_0, \tag{8.2}$$

where, after a numerical factor, we can identify the number of targets in one kilogram (second factor), the neutralino flow (third factor) and the cross section for each target (last factor). Equation (8.2) predicts rates so low as to represent a formidable challenge for experimentalists. Since neutralinos relevant for the solution of the DM problem are expected to have a nucleon cross section lower than 10^{-41} cm^2, total rates lower than 1 event/(day kilogram) and 10^{-3} event/(day kilogram) are predicted for SI and SD couplings, respectively.

Now that we know the features of what we are looking for, it is possible to conceive an ideal device for WIMP detection. We need a *low-energy nuclear detector* with the following characteristics:

- A very low-*energy threshold* for nuclear recoils (given the nearly exponential shape of the spectrum, a gain in threshold corresponds to a relevant increase in sensitivity). Thresholds of $\sim$10 keV are reachable with conventional devices, while with phonon-mediated detectors (see section 8.2) thresholds down to 300 eV have already been demonstrated.
- Very low *raw radioactive background* at low energies. In general, it requires hard work in terms of material selection and cleaning to reduce raw background below 1 event/(day kilogram keV). Backgrounds lower than 10^{-1} event/(day kilogram keV) have already been demonstrated. Furthermore, an underground site is necessary to host high sensitivity experiments, since cosmic rays produce a huge number of counts at low energies.

- Sensitivity to a *recoil-specific observable*. This allows the ordinary γ and β background for which the energy deposition comes from a primary fast electron to be rejected. When such an observable is available, the only relevant background source left consists in fast neutrons.
- Sensitivity to a *WIMP-specific observable*; it is necessary for an undisputable signature and consists typically in the seasonal modulation of the rate.

A simple measurement of a background level performed with a low-energy nuclear detector produces information on the neutralinos in the galactic halo. Usually, this information is expressed in the form of an *exclusion plot* in a $(\xi\sigma_{\mathrm{p}}, M_\chi)$ plane. The challenge is to test those regions in this plane which are populated by points corresponding to neutralinos viable for DM composition, in the sense explained in section 8.1.2. A simple background measurement cannot prove the existence of neutralinos; it can only exclude neutralinos with given features.

The parameters which affect the shape of the exclusion plot are the threshold, the background spectrum and the target mass. The exclusion plot is constructed by first fixing a neutralino mass: given the nuclear target mass, this allows the recoil spectrum shape apart from a normalization factor to be determined using the exact version of equation (8.1); the value of $\xi\sigma_{\mathrm{p}}$ which leads the recoil spectrum to 'touch' the background spectrum at one point constitutes the upper limit to $\xi\sigma_{\mathrm{p}}$ for that neutralino mass. (Higher values of $\xi\sigma_{\mathrm{p}}$ would produce a recoil spectrum with more counts in one energy bin than those experimentally observed.) The repetition of this procedure over the whole mass range provides the exclusion plot.

The effect on the exclusion plot of the relevant detector parameters can be so summarized: reducing the background improves the exclusion plot for any WIMP mass; reducing the nuclear target mass, the exclusion plot improves at low WIMP masses, but worsens at high WIMP masses; reducing the threshold improves the exclusion plot mainly at low WIMP masses. It is useless nowadays to operate detectors with low target masses (say $A < 50$), since in this case the region with higher sensitivity is already excluded by accelerator constraints. It is important to point out that the exclusion plot does not improve with longer exposition times or with higher detector masses. Relevant results can therefore be achieved even with small detectors and short measurements, provided the background level is low.

In order to get a DM signature, it is important to realize detectors sensitive to a WIMP-specific observable, like the seasonal modulation. For a detailed discussion of this subject, see [12, 14]. Here, we shall follow the simplified discussion reported in [15]. In the presence of halo WIMP interactions, a component of the background must present a seasonal modulation with very specific features, hard to mimic with fake effects:

- the modulation must be present only in a *definite energy region*;
- the modulation must be ruled by a *cosine function*;
- the *proper period* is $T = 1$ year;

- the *proper phase* is 152.5th day in the year (2 June); and
- the *proper modulation amplitude* is <7% in the maximum sensitivity region.

In order to have a signal at the 1σ level, we require:

$$S_{\text{sum}} + B_{\text{sum}} - (S_{\text{win}} + B_{\text{win}}) > (S_{\text{sum}} + B_{\text{sum}} + S_{\text{win}} + B_{\text{win}})^{1/2}, \tag{8.3}$$

where S_{sum} and B_{sum} are the signal and background counts in summer, while S_{win} and B_{win} represent the corresponding observables in winter. Equation (8.3) ensures that the difference between the summer and winter number of counts is statistically significant. If one assumes that

$$\begin{aligned}
B_{\text{sum}} &= B_{\text{win}} \\
S_{\text{sum}} - S_{\text{win}} &= a(\mathrm{d}R/\mathrm{d}E)M_{\text{det}}T\Delta E \\
S_{\text{sum}} + S_{\text{win}} &= 2(\mathrm{d}R/\mathrm{d}E)M_{\text{det}}T\Delta E \\
B_{\text{sum}} + B_{\text{win}} &= 2BM_{\text{det}}T\Delta E,
\end{aligned}$$

where a is the relative modulation amplitude, B a background coefficient that is expressed in event/(day kilogram keV), $(\mathrm{d}R/\mathrm{d}E)$ an average signal rate per unit mass and energy, also expressed in event/(day kilogram keV), M_{det} the detector mass, T the experiment duration and ΔE the energy range relevant for the signal expressed in keV. Inserting these observables in (8.3), one has as a condition on a:

$$a > \left[\frac{2}{(\mathrm{d}R/\mathrm{d}E)\Delta E}\right]^{1/2}\left[1 + \frac{B}{(\mathrm{d}R/\mathrm{d}E)}\right]^{1/2}\frac{1}{(M_{\text{det}}T)^{1/2}}. \tag{8.4}$$

The second term in the inequality (8.4) represents the lower limit for the modulation amplitude. The sensitivity of the experiment scales therefore as $(M_{\text{det}}T)^{1/2}$, since the signal, growing as $(M_{\text{det}}T)$, is in competition with background fluctuations growing as $(M_{\text{det}}T)^{1/2}$.

Unlike experiments aiming at exclusion plot production, searches for a real signal imply large detectors and long exposition time. Of course, the same set-up can produce an exclusion plot both from a background measurement and from the non-observation of a modulation amplitude. Increasing the detector mass and the exposition time, the second method becomes more stringent than the first, since in the first case the sensitivity is constant, while in the second one it grows with $(M_{\text{det}}T)^{1/2}$. If we take, for example, $A = 127$, an energy threshold $\simeq$20 keV, $B \simeq 1.5$ event/(day kilogram keV), a modulation analysis requires a detector mass around 100 kg to get the same sensitivity as a background analysis, assuming $M_\chi \simeq 40$ GeV.

In sections 8.2 and 8.3, we shall focus attention on how detectors which are sensitive to a recoil-specific observable can be realized, with total masses high enough to ensure a significant sensitivity to a seasonal modulation.

Table 8.1. Nuclear quenching factors.

Q_n	Detector	Recoiling nucleus
0.25	Ge diode	Ge
0.30	Si diode	Si
0.30	NaI(Tl) scint.	Na
0.09	NaI(Tl) scint.	I
0.80	Liquid Xe scint.	Xe

8.2 Phonon-mediated particle detection

Conventional nuclear detectors [16] (like scintillators and semiconductor diodes) are sensitive to the amount of ionization that an energetic particle produce in them. Since a slow nuclear recoil (like those produced by WIMP interactions) is a scarcely ionizing particle, the response of a conventional device to such an event is much lower than the response to an electron depositing the same energy. An important quantity characterizing a WIMP detector is, therefore, the nuclear quenching factor Q_n, defined by

$$Q_n(E) = \frac{R_n(E)}{R_e(E)}$$

where $R_n(E)$ and $R_e(E)$ are the responses of the detector (measured for example in volts, since detectors have typically voltage outputs) to a nuclear recoil and to an electron respectively, for a deposited energy E. In principle Q_n depends on energy, but it can be considered constant with an excellent approximation over the energy range of interest for WIMPs. Q_n can also depend on the type of recoiling nucleus. Some experimentally important values are reported in table 8.1.

Since a detector is usually calibrated by means of β and γ sources, the obtained energy scale must be divided by Q_n in order to get the nuclear recoil energy scale. The real threshold is therefore higher than that determined by the calibration; as a trade-off, the background, if not due to fast neutrons, is reduced by a factor Q_n, since to an energy interval ΔE in the electron scale there corresponds an energy interval $\Delta E/Q_n$ in the nuclear recoil energy scale.

Phonon-mediated detectors have the unique feature [17] that their Q_n is very close to one [18]. Joined with the extraordinary energy sensitivity of these devices, this property allows these detectors to reach impressively low energy thresholds. On the other side, the raw β and γ background is a serious problem. One possible solution consists of developing a detector which combines a phonon-mediated with a conventional read-out. The remarkable advantages of this approach are reported in section 8.3. In this section, as an introduction, we shall present briefly the basic principle of a phonon-mediated detector (PMD).

Over the last few years, PMDs have provided better energy resolution, lower energy thresholds and wider material choice than conventional detectors for many applications.

8.2.1 Basic principles

PMDs were proposed initially as perfect calorimeters, i.e. as devices able to thermalize thoroughly the energy released by the impinging particle [19, 20]. In this approach, the energy deposited by a single quantum into an energy absorber (weakly connected to a heat sink) determines an increase of its temperature T. This temperature variation corresponds simply to the ratio between the energy released by the impinging particle and the heat capacity C of the absorber. The only requirements are therefore to work at low temperatures (usually <0.1 K and sometimes <0.015 K) in order to make the heat capacity of the device low enough, and to have a sensitive enough thermometer coupled to the energy absorber. The thermometer is usually a high sensitivity thermistor consisting either in a properly doped semiconductor thermistor (ST) or in a superconductive film kept at the transition edge, usually called the transition edge sensor (TES).

8.2.2 The energy absorber

The energy-absorbing part of the detector is usually a diamagnetic dielectric material in order to avoid dangerous contributions to the specific heat in addition to the Debye term, proportional to T^3 at low temperatures. In such devices, the energy resolution can be fantastically high and close to the so (but not properly) called 'thermodynamic limit' $\sqrt{kT^2C}$ [20]. However, the constraint set by the heat capacity limits the maximum mass for the energy absorber to about 1 kg.

In fact, the real situation is far more complicated. The interaction of an elementary particle with a solid-detecting medium produces excitations of its elastic field; in other terms, the energy spectrum of the target phonon system is modified. Only when the time elapsed after the interaction is long enough to allow the phonon system to relax on a new equilibrium energy distribution, does the detector really work as a calorimeter. In contrast, if the sensor response is very fast, excess non-equilibrium phonons are detected long before they thermalize. (In this case, the sensing element should be defined a 'phonon sensor' rather than a 'thermometer'). In many experimental situations, it is difficult to distinguish between these two extreme cases, and the nature of the detection mechanism is still poorly known. Nevertheless, even when PMDs are not pure calorimeters, their intrinsic energy resolution is better than for conventional detectors, since the typical energy of the excitations produced (high-frequency phonons) is the order of the Debye energy ($\sim$10 meV), instead of 1 eV or more as in ordinary devices (in conventional Ge diodes, for instance, the energy required to produce an electron–hole pair is around 3 eV). Since the energy resolution is limited intrinsically by the fluctuations of the excitation number, its value scales as the square root of the energy required on the average to produce a single excitation.

Detection of non-equilibrium phonons is very attractive because it can, in principle, provide information about interaction position (space resolution has already been proved with this method), discrimination about different types of interacting radiation and the direction of the primary recoil in the target material. The last two points remain to be proved.

8.2.3 Phonon sensors

As anticipated, the commonly used phonon sensors are STs and TESs. STs consist usually of Ge or Si small crystals with a dopant concentration slightly below the metal–insulator transition [21, 22]. This implies a steep dependence of the sensor resistivity on temperature at low temperatures, where the variable range hopping conduction mechanism dominates.

TESs are much more sensitive devices, since their resistivity changes rapidly from a finite value to zero in a very narrow temperature interval. Normally, the superconductive film is deposited on the absorber crystal, with a typical thickness of few hundred nanometres, and the shape is defined after deposition by photolithography and wet etching. With a rectangular shape the normal resistance near the critical temperature is typically between several mΩ and several Ω, and SQUID technology is required for the readout, but with meander shape resistances of $\sim$10 kΩ can be obtained, and a standard voltage-sensitive preamplifier can be used. Films are usually made of a single superconductor. (The most interesting results have been obtained with tungsten [23, 24].) In another approach, the film consists of two layers (a normal metal in contact with a superconductor): this structure allows the critical temperature to be tuned.

8.3 Innovative techniques based on phonon-mediated devices

8.3.1 Basic principles of double readout detectors

An important feature of PMDs is that a high response is expected for energies deposited by slow (<100 keV) nuclear recoils, which are difficult to detect with conventional devices because of their scarce ionizing power. In a perfect calorimeter, a nuclear recoil produces the same signal of a fast electron of the same energy, since it deposits the same amount of heat. In spite of the naiveness of this approach, it has been proven with *ad hoc* measurements that the detecting efficiency for recoiling nuclei and electrons is indeed the same within 2% in dielectric ST-PMDs [18]. In other terms, as already anticipated, $Q_{\mathrm{n}} \simeq 1$ for PMDs. As a consequence, impressively low thresholds can be achieved in large amounts of low specific heat material (typically sapphire). If properly operated in a low radioactive background environments, these low threshold PMDs can be very sensitive DM detectors. The CRESST experiment has installed in the Gran

Sasso laboratory 4×250 g sapphire-TES detectors with a threshold of about 300 eV, which is well beyond the reach of any conventional scheme [23].

Perhaps, the best strategy for PMDs around WIMP search is the achievement of an active rejection of background through the recognition of nuclear recoils, expected from WIMP interactions. The basic idea consists of realizing a detector with both a phonon-mediated and a conventional readout, which could be a charge signal (in the case of semiconductor diodes) or a light signal (in the case of scintillators). The charge signal is proportional to the number of electron–hole pairs, while the light signal is proportional to the amount of scintillation produced by the interacting particle. I will define the *non-phonon signal* S_{np} as the output provided by the conventional (charge or light) readout, and the *phonon signal* S_{ph} the output given by the phonon sensor.

The basic point is that the same event produces, in general, both a phonon and a non-phonon signal. If we consider the observable:

$$R = \frac{S_{\mathrm{np}}}{S_{\mathrm{ph}}} \tag{8.5}$$

the value of R depends on the *type* of primary interaction. In the case of slow nuclear recoil R is significantly higher than for a fast electron of the same energy, since the non-phonon component, connected to the amount of ionization, is much less important. The parameter R defined in (8.5) therefore represents a powerful recoil-specific observable in the sense exposed in section 8.1.4.

In practice, a nuclear detector which follows all the specifications of section 8.1.4 could consist in one of the two following possibilities:

- An array of large Ge or Si diodes operated as conventional semiconductor devices with an additional phonon sensor. The total mass must be large enough to make the detector competitive in terms of seasonal modulation sensitivity (WIMP-specific observable). Therefore, the array must consist of tens of individual elements. The double readout provides the recoil-specific observable R. The raw background and the energy threshold must be conveniently low.
- An array of large scintillators with an additional phonon sensor and with the same features as in the previous point in terms of total mass, threshold and background. A remarkable technical difficulty consists of the necessity to operate a light detector at very low temperatures.

Three collaborations in the world are successfully developing detectors fulfilling these two requirements. That is the topic of the next section.

8.3.2 CDMS, EDELWEISS and CRESST experiments

The American collaboration CDMS (‘Cold Dark Matter Search’) [24] is realizing silicon and germanium detectors cooled to 20 mK and capable of measuring both the charge and the phonon component of any single energy release. The charge is measured by means of conventional charge amplifier technology [16], whereas the phonon measurement is performed with two different technologies. One is based on eutecticly bonded Ge ST, and the other on W TES elements sensitive to non-equilibrium phonons. In the second approach [25], non-equilibrium phonons created by particle interactions break Cooper pairs in superconductive Al films which cover a large fraction of the crystal surface. The created quasiparticles are then trapped in a W film (with a critical temperature around 70 mK) which is grown above the Al films. The W film is operated as a TES and, heated by the trapped quasiparticles, provides the signal, proportional to the initially deposited energy. The system of Al and W films presents a pattern which allows reasonable space resolution (of the order of 1 mm) in the plane where the films lie (the crystal surface) to be achieved. In the dimension orthogonal to this plane, space resolution is also possible exploiting the risetime of the phonon signal. This allows the events which occur close to the crystal surface to be recognized. This detector capability helps substantially in background identification. The point is that background events generated by β contamination in the surface can mimic nuclear recoil events, since events at the surface suffer from incomplete charge collection, while the phonon signal is, of course, unchanged. The space resolution permits us to identify these close-to-surface events and to reject them. Therefore, at the price of an acceptable loss of sensitive volume, the background identification is much safer. In preliminary tests, a rejection capability better than 99% was achieved down to 20 keV. In figure 8.1, the points in the upper band correspond to γ interactions, while the ones in the lower band to nuclear recoils. In these tests, the nuclear recoils are induced by means of external sources of fast neutrons.

The French collaboration EDELWEISS [26] adopts a scheme similar to the first type of CDMS detector. The best results were obtained with a 70 g high-purity Ge detector with a disk shape. The charge signal is provided by a conventional readout, based on charge amplifier technology, while the phonon signal comes from a Ge ST glued on the disk. In the range 15–70 keV a raw background of about 40 event/(day kilogram keV) is reduced down to 0.6 event/(day kilogram keV). This collaboration aims at operating a large mass experiment, realized by means of many independent detectors, in the Frejus underground laboratory (France).

The German–English collaboration CRESST [27] is developing a detector sensitive to phonons and scintillation light. A test device was realized, consisting of a 1 cm^3 $CaWO_4$ crystal scintillator. A W film (with a critical temperature around 11 mK) is deposited on the crystal and operated as a TES. The scintillation photons which escape from the crystal are collected by auxiliary Al_2O_3 PMDs which surround the scintillator. Due to the very low threshold of the auxiliary detectors, a few photons can be detected by them, allowing a safe threshold to be set down to 15 keV (for nuclear recoils). The rejection capability at this energy is, impressively enough, 99.7%. This result can be appreciated in figure 8.2, where

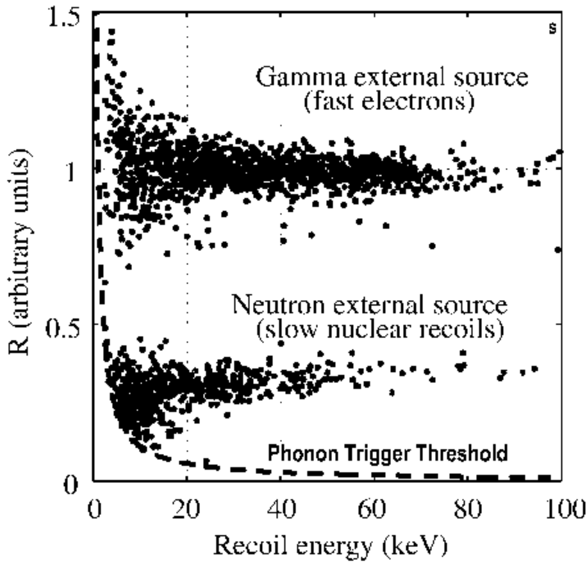

Figure 8.1. Discrimination capability of the CDMS experiment.

the parameter R in (8.5) is given by the slope of the bands. Even in this case, the total detector mass can be increased only through the realization of a large array of independent devices, which should be operated underground, for example in the Gran Sasso Laboratory (Italy).

8.3.3 Discussion of the CDMS results

The CDMS collaboration was able to perform up to now the most sensitive experiment in terms of exclusion plot [24] (see figure 8.4). This shows clearly the potential of the double readout technique based on phonon-mediated detection. The CDSM experiment, even if largely preliminary, is particularly important since it allows us to probe, at least partially, the region in the $(\xi\sigma_{\mathrm{p}}, M_{\chi})$ plane corresponding to the modulation evidence claimed by the Italian collaboration DAMA [28]. I shall just recall here that this modulation evidence can be interpreted in terms of halo neutralino interactions with the most probable values of $M_{\chi} = 44$ GeV and $\xi\sigma_{\mathrm{p}} = 5.4 \times 10^{-41}$ cm^2. The corresponding 3σ region is reported in figure 8.4.

The CDMS detectors are operated at Stanford beneath only a 16 m water equivalent overburden. A plastic scintillator veto is therefore necessary in order to reject cosmic ray events. The results are based on two data-sets:

- *Two month exposure in 1998*, providing 33 live days collected with one *100 g Si detector* operated with a W–Al film phonon readout (see previous section).

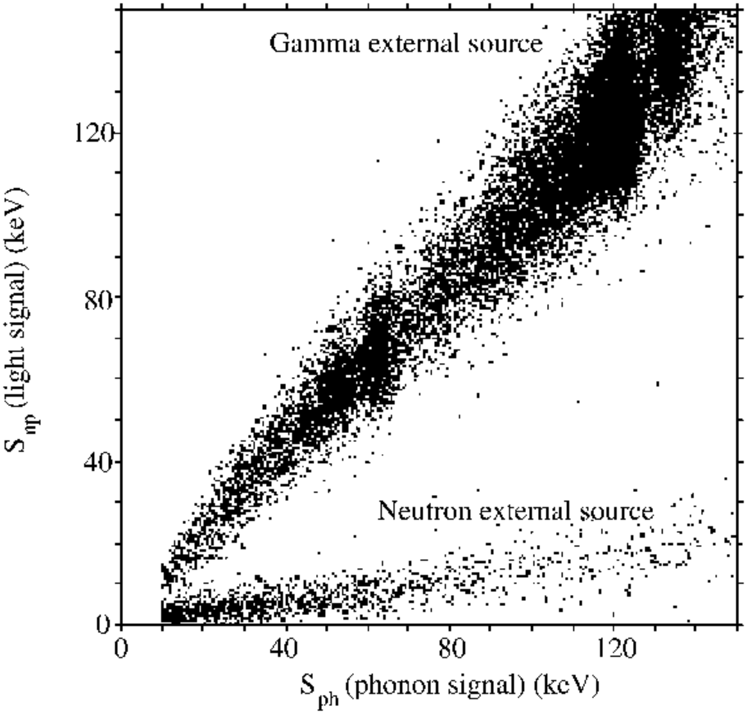

Figure 8.2. Discrimination capability of the CRESST test detector.

In this exposition, the collected statistics correspond to $M_{\text{det}}T = 1.6$ kg day. After the background rejection, only four events survive as slow nuclear recoils.

- *Twelve month exposure in 1999*, providing 96 live days collected with *four 165 g Ge detectors* operated with a Ge ST phonon readout (see previous section). In this exposition, the collected statistics correspond to $M_{\text{det}}T =$ 10.6 kg day. After the background rejection, only 17 events survive as slow nuclear recoils. The four Ge detectors are tightly packed in order to increase the neutron multiple scattering probability. Since four recoil events were cut as in coincidence between two detectors (of course the probability of WIMP double scattering is completely negligible), only 13 recoil events attributable to WIMPs survive. (In figure 8.3 the nuclear recoil events are represented by circled points.)

The 13-nuclear-recoil energy spectrum is compatible with the expected WIMP-caused spectrum as deduced by the DAMA neutralino parameters. However, the CDMS collaboration claims that there is clear evidence that these 13 single events are caused by background neutrons. In fact, the background

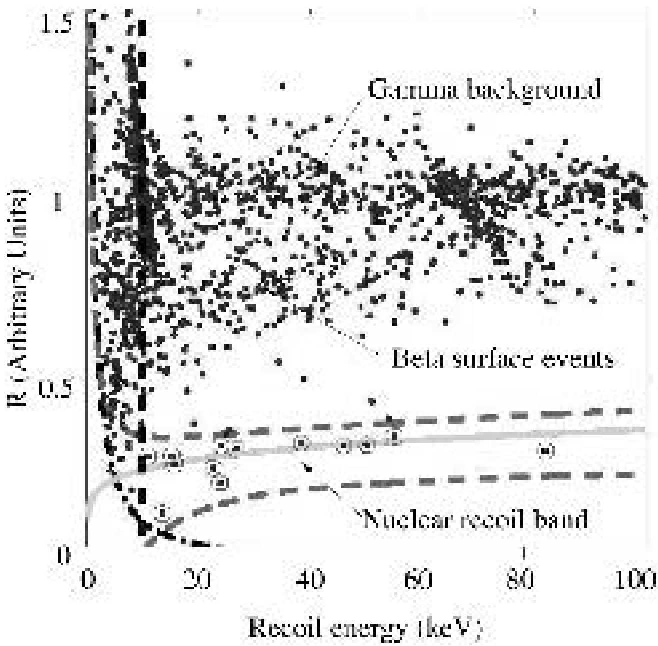

Figure 8.3. Gamma/beta background and nuclear recoils in CDMS results.

neutron spectrum can be estimated by the four Ge multiple events and the four Si nuclear recoils. (Si events cannot be due to WIMPs, otherwise the WIMP rate in Ge would be much higher than observed because of the A^2 term (section 8.1.2) in the cross section.) These safe neutron events, if analysed by means of a Monte Carlo simulation of the neutron background, are fully compatible with 13 background neutron single events in the Ge experiment. In other terms, the Ge multiple events and the Si single events fix the neutron background, that can be subtracted by the Ge single event spectrum, leaving a WIMP signal compatible with zero. Following this analysis, the CDMS collaboration claims to have substantially falsified the DAMA interpretation of the seasonal modulation in terms of the neutralino. In figure 8.4 the CDMS exclusion plot (black thick curve) is compared with the shadow region which represents the DAMA 3σ evidence. The CDMS sensitivity is also reported (as fixed by the *a priori* estimated neutron background). The exclusion plot provided by a powerful conventional technique (Ge semiconductor diodes, no double readout) is shown for comparison.

Anyway, the contrast between DAMA and CDMS looks far from being clarified by the existing data. If it is true that the DAMA results have raised not only excitement but also criticism in part of the DM community [29], it is also clear that the CDMS results would require confirmation with higher statistics and in an environment less affected by the cosmic neutron background. Information

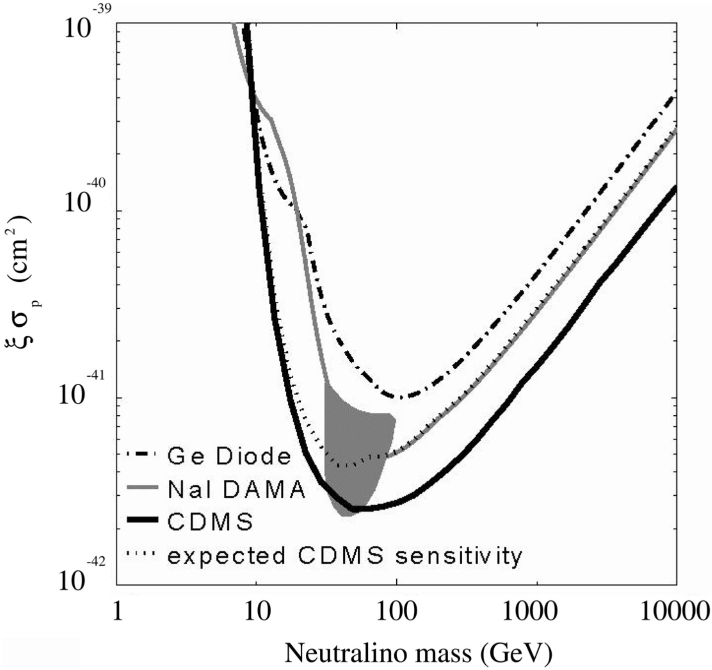

Figure 8.4. Exclusion plots (90% C.L.) and DAMA evidence.

to resolve the dilemma could come from the much larger underground set-up that CDMS is going to operate in the near future and from the DAMA upgrading in terms of total detector mass.

8.4 Other innovative techniques

There are many mid-term projects which are not based on a phonon readout channel but which, however, point to a substantial increase in sensitivity to neutralino interactions. I shall mention here, for lack of space, only three projects. This selection was admittedly also made on the basis of personal taste, besides scientific relevance. For a complete review, I suggest the reader refers to the proceedings of a recent specific conference, for example [30].

The DRIFT experiment [31] represents the only attempt to detect the direction of the nuclear recoil already at a test-phase. It consists of a low-pressure TPC using a 20 Torr Xe–CS_2 gas mixture. Such a device must be able to detect the tiny tracks from nuclear recoils with less than 1 mm track resolution. In addition, large detector masses are necessary. This requirement suggests that the magnetic field should be abandoned, with a consequent deterioration in the space resolution due to enhanced diffusion. In order to solve this problem, the new concept consists of detecting not the drift electrons, but the negative CS_2 ions, with a considerably reduced diffusion because of the large ion mass. This experiment points directly at the most decisive WIMP signature, the diurnal modulation of the recoil average direction (section 8.1.4). By the end of 2001 a 20 m^3 TPC should be in operation.

The ZEPLIN programme [32] is based on double readout (scintillation and charge) in liquid xenon. When an ionizing particle deposits energy in liquid xenon and an electric field is applied, two scintillation pulses are developed. The primary pulse (amplitude S_1) is due to the excitations in Xe atoms produced directly by the particle interaction. The secondary pulse (amplitude S_2) is generated by the drift of the charge created by the primary interaction. Therefore, a low ionizing particle like a slow nuclear recoil will exhibit a secondary pulse depressed in amplitude with respect to the first one, if compared with an electron of the same energy. On a similar footing as in section 8.3.1, S_1/S_2 plays the role of a recoil-specific observable.

The project CUORE [33] ('Cryogenic Underground Observatory for Rare Events') consists of the largest PMD set-up ever conceived. It is based on the experience collected by the Milano group on large mass arrays of low-temperature calorimeters for rare decays [34]. It should consist of a tightly packed array of 1020 TeO_2 crystals for a total mass of 0.8 ton, to be cooled down to 10 mK. Each element has a mass of about 800 g and uses a Ge ST (section 8.2.3) as a thermometer. The relevant points of the project are the huge mass (which provides sensitivity to seasonal modulation) and the low background, which can be reduced significantly with respect to the $\sim$1 event/(day kilogram keV) already demonstrated with similar devices. This reduction should be achieved by the operation of the detectors in coincidence, particularly effective in this case due to the minimal amount of inert material among them. A preliminary test of CUORE is in preparation at the underground Gran Sasso Laboratory (Italy).

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