After introducing several aspects of the motivation for particle dark matter search, experimental principles and the present state of the main experiments are presented. Direct searches for WIMPs are explained in some detail; indirect WIMP searches and axion searches are presented more briefly.

1 Introduction

All viable models in present-day cosmology require the existence of non-baryonic cold dark matter with a cosmological density dominating over all other forms of matter in the universe.

The generally accepted inflationary cosmological models require the universe to be flat, i.e., the total matter and energy density $\Omega = 1$ in units of the critical density separating a universe with positive from one with negative curvature of space-time, to avoid the “fine-tuning problem”: any deviation of the cosmological density from unity would have increased by many orders of magnitude during inflation, contradicting observations. Thus $\Omega$ should be precisely equal to one from the beginning. The flatness of the universe is confirmed, $\Omega = 1$ to within a few per cent, by measurements of the first acoustic oscillations in the angular power spectrum of the cosmic microwave background (CMB) with the BOOMERANG, MAXIMA, DASI and other mostly satellite or balloon borne instruments.

The observation of the brightness-to-distance relationship of type Ia supernovae reveals evidence for the presence of some form of Dark Energy $\Lambda$ with a density $\Omega_\Lambda \approx 0.7$. A similar value ($0.65 - 0.85$) has been obtained by a combined analysis of CMB data and the power spectrum of the matter density distribution. This leaves an overall matter density $\Omega_m \approx 0.3$, in good agreement with the value inferred from the dynamics of galaxies within clusters. On the other hand, the theory of big bang nucleosynthesis combined with measurements of the cosmic abundances of helium and, more recently, deuterium relative to that of hydrogen limit the cosmic density of baryonic matter quite strictly to $\Omega_b h^2 = 0.020 \pm 0.002$, where $h$ denotes the Hubble parameter. Also this value agrees well with that resulting from CMB measurements.

Thus the missing matter must be in form of non-baryonic particles which interact only weakly with normal matter. Most particles in the universe have frozen out of thermal equilibrium with the primordial plasma at a temperature corresponding to their respective mass. Dark matter candidates that were relativistic at the time of freeze-out are referred to as hot dark matter (HDM); those which were non-relativistic as cold dark matter (CDM). This dark matter “temperature” can be “measured” by means...
of the power spectrum of the matter density distribution as it results from all-sky galaxy surveys. HDM would have, due to its relativistic streaming while structure formation in the early universe, wiped out small-scale structures, i.e. prohibited the early formation of individual galaxies. CDM instead, freezing out earlier than baryons due to its weak interaction, could have fallen into density fluctuations very early thus enhancing the formation of small scale structures. The observed structures are best described by the matter content being dominated by CDM, with some HDM being allowed. A small HDM component can readily be explained by low-mass neutrinos since neutrinos are now, after the intriguing results from Superkamiokande and SNO \cite{8,9}, generally considered having a small mass: the present neutrino mass limits correspond to a contribution to the cosmic density in the range $0.001 < \Omega_\nu < 0.189$.

This article will concentrate on CDM candidates and approaches to their detection, and within this frame it will be further constrained to those candidates that are well motivated in that they emerge from well-established theories in particle physics and can at the same time constitute the required matter density without arbitrary assumptions of their physical parameters: supersymmetric Weakly Interacting Massive Particles (WIMPs) and axions.

2 SuSy WIMPs

Supersymmetry introduces a global symmetry between the fermionic and the bosonic sectors of the thus extended standard model, ascribing to each fermion a supersymmetric bosonic partner and vice versa. In most supersymmetric models with conservation of the newly introduced quantum number R-parity the lightest supersymmetric particle (LSP) is stable. In the minimal supersymmetric extensions of the standard model (MSSM) the LSP is the lightest neutralino $\chi$, a linear combination of the superpartners of the gauge and Higgs bosons: bino, wino and the two neutral higgsinos. The neutralino is an electrically neutral Majorana fermion with a mass range between few GeV and few TeV and a WIMP-nucleon cross section in the range $10^{-10} \text{pb} \leq \sigma_{\chi-n} \leq 10^{-5} \text{pb}$. Accelerator searches set a lower mass limit $m_\chi \geq 45 \text{GeV}$ \cite{10}.

Standard assumptions for WIMP dark matter searches are that WIMPs are gravitationally bound to the galaxy forming an isothermal spherical halo with a local density of $0.3 \text{ GeV/cm}^3$ and a Maxwellian velocity distribution with a mean value of 270 km/s, truncated at the escape velocity from the galaxy of 650 km/s.

Beyond the MSSM discussed here, other SUSY models put into play several other DM particle candidates like s-neutrinos, axinos, self-interacting DM, wimpzillas, simpzillas, cryptons, Q-balls, see e.g. ref.\cite{11} and references cited therein.

3 Direct WIMP searches

The exclusive possibility to directly detect WIMPs is to measure the small amount of energy (few to few ten keV) deposited in a detector when a WIMP scatters elastically off a nucleus of the detector’s target material. Due to the small WIMP-nucleon cross section event rates are expected in a range below one event per day and per kg of detector mass. Therefore, evidently, a large mass is required to have a realistic chance to observe WIMP signals, in conjunction with a very low detection threshold.

Both scalar, i.e. spin-independent, and axial, i.e. spin-dependent, coupling of WIMPs to nucleons must be considered. If the coupling is predominantly scalar, the coupling to nuclei is coherent, and the WIMP-nucleus cross section roughly proportional to $A^2$. In this case heavy target nuclei strongly enhance the detection efficiency. In the case of axial coupling the WIMP couples to the unpaired spin in a nucleus with non-zero, half-integral net spin. This requires a high natural abundance or enrichment of isotopes with half-integral spin in the target material.

The main challenge for WIMP searches arises from the low count rate, demanding a very low radioactive and cosmic ray background. Careful selection of radiopure materials for the experimental set-up and very efficient shielding against radioactivity from the laboratory environment are needed as well as the installation of the experiment in a deep underground site. Remaining radioactive background causes mostly electron recoils, hence the detector should allow to discriminate electron recoils from the nuclear recoils caused by WIMPS. Neutrons however scatter of nuclei and can’t be distinguished from potential WIMP events (if they scatter only once - multiple scatter events in a segmented detector can obviously be attributed to neutrons). This implies for experiments of ultimate sensitivity an efficient neutron shield as well as a muon veto since the few muons from secondary cosmic radiation that penetrate even into the
deepest underground sites can induce neutrons inside the neutron shield. A typical set-up uses several
tons (10 - 20 cm) of lead shield, with an inner layer of archeological lead or high purity copper, 30 - 50 cm
of paraffine or polyethylene, possibly a cadmium sheet, a nitrogen-flushed box or plastic bag to keep off
radon, and a plastic scintillator muon veto.

A relatively simple rejection of electron recoils by pulse shape discrimination (PSD) relies on different
signal decay times in scintillators for electron and nuclear recoils, respectively, reaching low to moderate
rejection capabilities. In the low energy range where WIMP signals are expected the difference in decay
time becomes very small. More efficient rejection can be realised using two detection channels for two
types of excitations created by a particle interaction in the detector target: Scintillation and ionization,
scintillation and phonons or ionization and phonons. Typically two types of excitations have different
quenching factors: a quenching factor expresses a lower detectable energy yield for nuclear recoils than for
electron recoils of the same deposited energy. Hence, the ratio of signal amplitudes in the two detection
channels provides a powerful means to distinguish the two interaction types.

Positive evidence for a WIMP signal could arise from the kinematics of the earth within the pre-
sumably non-rotating WIMP halo. The sun is orbiting about the galactic center with a velocity of
\(~ 220 \text{ km/s}\). The resulting relative sun-halo velocity is modulated by the earth’s orbit about the sun
at \(~ 30 \text{ km/s}\). An annual modulation of the count rate by few per cent could yield positive signature.
The most convincing evidence would arise from a modulation of the directionality of the recoil nuclei
corresponding to the above mentioned kinematics, given a direction sensitive detector. In this case the
directionality is additionally modulated diurnally by the earth’s rotation about its axis.

3.1 Classical germanium detectors

For several years the Heidelberg-Moscow Experiment, using classical Ge detectors at liquid nitrogen
temperature (77 K) and originally designed to search for neutrinoless double-beta decay, achieved the
lowest background (0.05 ev/kg/keV/day above 10 keV) and the highest sensitivity of any dark matter
search\cite{12}. This was possible due to the available high purity of Ge and a substantial, fundamental
work on low background conditions. The Heidelberg group is presently operating in the Gran Sasso
underground lab a 200 g p-type Ge detector surrounded by a 2 kg n-type Ge veto detector in a well
arrangement (HDMS)\cite{13}. Photons or neutrons interacting in the inner detector have a considerable
probability to generate a coincident signal in the veto detector. Background level and sensitivity are
comparable to the previous experiment. In the GENIUS project\cite{14} proposed by the same group 100 kg
of unencapsulated Ge crystals shall be surrounded by a large volume of highest purity liquid nitrogen to
assure a very radiopure surrounding as well as shielding from external radioactivity. A test facility for
this project has recently been approved.

The IGEX detector, deployed in the Canfranc tunnel in the Pyrenees, has reached the highest dark
matter sensitivity (\(\sigma_{\chi-n} \approx 7 \times 10^{-6} \text{ pb}\)) of all experiments using classical Ge detectors, excluding the
upper part of the DAMA region (see section 3.2)\cite{15}. It consists of up to three 2 kg Ge crystals enriched
to 86% in \(^{76}\text{Ge}\) and has a lower energy threshold than the experiments described above.

The principal problem of these experiments is the lack of any background discrimination capability.
Even at the lowest background level some events will occur which will never be identifiable as electron
or nuclear recoils.

3.2 Scintillator detectors

Scintillators constitute the second class of classical detectors in use for dark matter search. Scintillation
in both solids and liquids is a well established detection technique and large detector masses are readily
installed.

The DAMA collaboration is operating \(~ 100 \text{ kg of NaI crystals, each viewed by two photomultiplier}
tubes (PMTs), in the Gran Sasso underground lab and has collected within four years \(~ 58000 \text{ kg-days of}
statistics. The non-zero spin of the sodium nucleus makes these detectors also sensitive to axial coupling.
The DAMA group claims to observe annual modulation of their count rate, as shown in fig. 1, which is
compatible in amplitude and phase with a signal from WIMPs of \((52^{+10}_{-8}) \text{ GeV mass and a WIMP-nucleon}
cross section of } (7.2^{+0.4}_{-0.3}) \times 10^{-6} \text{ pb}\cite{16}, see also fig. 2(b). Background rejection is based on PSD, using
a statistical method which is less efficient than an event-by-event discrimination. Moreover, scintillators
suffer from a relatively large quenching factor, hence the threshold for nuclear recoils is several times
higher than that of “visible” energy. The major part of the data interpreted as a WIMP signal lies
in the first (2 - 3 keV) energy bin above the PMT noise where PSD seems questionable. Despite these difficulties the observed annual modulation amplitude corresponds to the most optimistic value that could be expected for a pure WIMP signal. Severe criticism has arisen in the community\cite{17,18} ascribing the observed annual modulation rather to systematics than to a WIMP signature.

Background rejection by PSD is remarkably more efficient in liquid xenon scintillator detectors. This allows the UKDMC group to reach competitive dark matter sensitivity, excluding the upper half of the DAMA region\cite{19}, already with low statistics collected within a few months with a 4 kg prototype detector, ZEPLIN-I, mounted in the Boulby mine in the UK. The scintillator is viewed by three PMTs which allow, by triple coincidence, to reject spurious events in or near the PMTs. A liquid scintillator Compton veto and a lead shield complete the set-up. The ZEPLIN group is presently developing two even more efficient background rejection techniques that allow discrimination on an event-by-event basis. They are both exploiting ionization occurring in the liquid Xe in addition to scintillation. In the simpler detector design the ionization charges are drifted within the liquid and generate a delayed secondary scintillation signal. In a more sophisticated two-phase liquid and gas detector ionization electrons are extracted from the liquid into the gas phase, where they are accelerated and generate electroluminescence that is registered as a delayed signal by the same two PMTs that are viewing the liquid Xe. Since nuclear recoils generate much less ionization than electron recoils the secondary signal is much smaller for nuclear than for electron recoils. A one ton project is hoped to cover a large fraction of the WIMP parameter space\cite{20}.

The ELEGANT V and VI experiments based in the Japanese Oto Cosmo Observatory are employing, beside a 730 kg NaI crystal array, 7.2 kg of CaF$_2$ scintillators\cite{21,22}. The $^{18}$F nucleus offers a non-zero spin and a very advantageous form factor which makes it particularly sensitive for axial coupling. Unfortunately both materials in these experiments are not of the highest purity.

3.3 Cryogenic detectors

A third class of detectors, operated at temperatures of $\sim$ 10 - 100 mK, is using phonons as principal excitations and detecting them as temperature pulses. Phonons offer two advantages as compared to ionization and scintillation: firstly, almost the entire energy of nuclear recoils is transformed into phonons, whereas ionization and scintillating detectors have relatively high quenching factors. Secondly, the excitation energy of phonons, typically meV, is roughly three orders of magnitude lower than that of electron-hole pairs or scintillation photons. These two advantages result in a considerably lower energy threshold as well as in a higher energy resolution. Combining phonon detection with either ionization or scintillation measurement allows very efficient event-by-event background rejection.

The very low temperatures are required since the phonons are detected as thermal signals: thermal noise is strongly suppressed at such low temperatures, and heat capacities go dramatically down with temperature: linearly for metals, and even as $T^3$ for dielectrics.

The CRESST experiment\cite{23} in the Gran Sasso underground lab has used in its recently finished first phase 262 g sapphire (Al$_2$O$_3$) crystals and superconducting thin tungsten films on the crystal surface as
temperature sensors. The detectors are operated at a temperature within the superconducting phase transition, \( \sim 15 \text{ mK} \), where the film’s electrical resistance is an extremely sensitive measure for temperature variations. The low resistances \( \sim 0.1 \text{ \( \Omega \)} \) of the films are read out with SQUIDs. These detectors have extremely low energy thresholds (580 eV) and very good energy resolution (130 - 330 eV for 1.5 keV X-rays) and reached the highest sensitivity for both scalar and axially coupled WIMPs with masses below 5 GeV. With their low-mass Al and O nuclei and without background rejection, these detectors were not competitive in the higher WIMP mass range favoured by theory and accelerator mass limits.

For a second phase the CRESST group has developed detectors with scintillating 300 g CaWO\(_4\) target crystals and superconducting W thermometers for phonon detection. A separate small cryogenic detector measures scintillation light, the high quenching factor allowing an impressive rejection power. Up to 10 kg of CaWO\(_4\) detectors will be mounted in the existing cryogenic set-up in phase II of the experiment.

The CDMS collaboration operates Ge and Si cryogenic detectors with both superconducting thin films as described above and more conventional NTD Ge thermistors as temperature sensors. Additionally, ionization charges are drifted to thin film electrodes on the crystal surfaces and provide efficient electron recoil discrimination. With one 100 g Si and four 165 g Ge detectors run in 1998 and 1999 CDMS could cover a large part of the 3\( \sigma \) allowed region of the DAMA evidence (see fig. 2(b)), excluding the DAMA most likely candidate at \( > 99.9 \% \text{ CL} \). The experiment is however situated in a shallow underground site in Stanford and suffers from muon induced neutron events. Therefore a (not unproblematic) neutron subtraction is required to derive dark matter limits: using a Monte Carlo simulation of the neutron background, all candidate nuclear recoil events have been found to be compatible with the expected background. Within the year 2002 the experiment shall move to the Soudan deep underground lab.

The EDELWEISS collaboration is using 320 g Ge detectors similar to those of CDMS, with NTD Ge phonon sensors and aluminium thin film charge collection electrodes, split on one crystal surface into a central electrode defining a fiducial volume and an outer ring electrode to reject events due to radioactive impurities near the detector circumference. The detectors are operated at \( \sim 20 \text{ mK} \) in the Modane underground lab in the French-Italian alps. In data taking runs in the years 2000 and 2002 (12.1 kg-days fiducial) no nuclear recoil events were observed in the relevant energy range in one of the detectors of each run, see fig. 2(a). A dark matter limit has been derived that excludes almost the entire DAMA allowed region, and the central value at 99.94 \% CL. At present this appears to be the most sensitive direct WIMP search.
sensitive limit of all dark matter searches for WIMP masses above 35 GeV, moreover, due to the absence of any candidate events it is certainly the cleanest of all published limits. It is also the first experimental limit that excludes a small part of the MSSM parameter space. For an upgrade of the experiment to ∼30 kg a large volume reversed dilution refrigerator has been developed. The present limits of both the CDMS and EDELWEISS experiments are shown in fig. 2b), together with the IGEX Ge diode limit and the allowed region of the DAMA WIMP candidate.

CRESST, CDMS and EDELWEISS expect, after upgrading their respective experiments to ∼10−30 kg detector mass and improving background rejection efficiencies, very similar sensitivities of about 10−8 pb in the relevant WIMP mass range, thus testing a significant part of MSSM models.

ROSEBUD, up to now using low threshold sapphire and Ge cryogenic detectors, are now studying phonon-scintillation detectors and have obtained interesting results with ∼50 g CaWO4 and BGO crystals. The recently terminated MIBETA experiment, conceived mainly for double-beta decay search and with 20 × 340 g TeO2 detectors the hitherto biggest cryogenic experiment worldwide, is presently being replaced by 56 × 760 g TeO2 (CUORICINO), later to be extended to 1000 × 760 g TeO2 (CUORE), however without background rejection. A Japanese collaboration is testing a 8 × 21 g LiF crystal array, with the 19F nucleus sensitive to axial coupling, in the Kamioka underground lab.

3.4 More recent techniques

The PICASSO31 and SIMPLE32 experiments are testing superheated Freon droplets, containing 19F and immersed in a gel matrix, as target material. A nuclear recoil inside a droplet above a certain threshold energy evaporates the droplet. The formation of a bubble inside a droplet above a certain threshold energy can be registered as an acoustic pulse (“pop”) by a piezoelectric transducer. The threshold energy can be adjusted by varying the temperature. The advantage of this concept is, beside relative simplicity and cost efficiency, that the superheated droplets are insensitive to electron recoils with their much lower dE/dx (energy dissipation per track length) such that the radioactive background problem essentially doesn’t exist for these detectors, with the exception of alpha contaminants. Disadvantages are the small target masses employed up to now and the fact that the signals yield no information about the recoil energy.

The most promising attempt to reach directional sensitivity is the DRIFT-I detector in the Boulby mine, a low pressure CS2 time projection chamber that allows imaging of recoil tracks. Beside a low sensitivity to electron recoils, the track length provides a means for discrimination. A problem is the low target density (∼180 g in the 1 m3 DRIFT-I detector), i.e. the large volume required for a large-scale experiment. However, the convincing evidence that would arise from the observation of a modulation of recoil directions as expected from WIMP interactions seems attractive enough to pursue this development.

4 Indirect WIMP searches

Neutralinos can be gravitationally captured in celestial bodies. Since they are Majorana particles, pair annihilation can give rise to substantial fluxes of neutrinos, gammas or positrons. Indirect WIMP searches are trying to detect these annihilation products.

In particular, indirect searches for neutralino annihilations inside the Sun, the Earth or the Galactic center are being undertaken by looking for neutrino fluxes resulting from the decay of gauge bosons and hadrons produced in the annihilations. Muon neutrinos can be detected via the up-going muons produced in charged-current interactions in the rock underneath the big underground (Baksan, MACRO, SuperK) and underwater/ice (AMANDA, BAIKAL, ANTARES) experiments. Since both the neutrino-nucleon cross section and the muon range increase with the neutrino energy, the neutrino indirect detection of neutralinos improves with the parent neutralino mass.

Different frameworks have been considered to estimate such signals. A low energy parameterization of the MSSM is usually used. Fig. 3a) shows experimental limits of various indirect searches on the neutrino induced muon flux coming from the center of the Earth. The dots show model predictions from the MSSM framework estimated with the DarkSUSY package. Resonances in the cross section of neutralino capture in the center of the Earth could considerably enhance the signal, in particular at the mass of the Fe nucleus (56 GeV), main constituent of the Earth’s core.

A more theoretically motivated framework is provided by SuperGravity inspired models (CMSSM/mSugra) based on the unification of the gauge couplings and masses at high scale and radiative electroweak symmetry breaking. Fig. 3b) shows the expected 90% CL sensitivity to the neutrino-induced muon
flux coming from the Sun with the ANTARES 0.1 km$^2$ 10 string detector after three years of data taking as a function of the neutralino mass $m_\chi$ for a hard neutrino spectrum ($\chi\chi \rightarrow WW$) (lower solid line), as well as for a soft spectrum (upper solid line), compared to current experimental limits. Also shown is the predicted signal from a wide range of mSugra parameter spaces calculated with the SUSPECT program for the SuSy particle spectrum and DarkSUSY for neutralino relic density and the neutrino/muon fluxes. Different point colours (tones of grey) show the sensitivity for three years of direct search by EDELWEISS II.

Indirect detection of relic neutralino dark matter through annihilations into neutrinos, photons from the galactic center and from the galactic halo, and positrons has also been studied in ref. 39, 40. Fluxes are computed for a set of benchmark CMSSM models. Gamma fluxes are compared to estimated sensitivities of the future experiments GLAST 41 and MAGIC 42. A cosmic ray positron excess observed by the HEAT collaboration has been critically discussed in the light of a possible origin from WIMP annihilations in ref. 43.

5 Axions

The axion has been proposed by R. D. Peccei and H. R. Quinn as a solution to the strong CP problem in QCD: the CP violating electric dipole moment of the neutron expected from the non-Abelian structure of QCD has been experimentally found to be suppressed to a vanishingly small value. This can be explained by the assumption of an additional global U(1) “Peccei-Quinn” symmetry. The explicit breaking of this symmetry is associated with a massive Goldstone boson, the axion. Dynamically produced in the early universe by relaxation of topological defects or by vacuum realignment - as opposed to the freeze-out from the primordial plasma of most other particles - , they constitute in spite of their small mass a CDM candidate. To date, the axion mass has been limited by astrophysical (too efficient cooling of SN 1987 A) and cosmological (too high axion DM density in the universe) constraints to $\sim 1 \mu eV < m_a < 10 \text{ meV}$, see fig. 4(a).

Axions can couple to two photons via the Primakoff effect. Sikivie proposed to provide virtual photons by means of a static magnetic field in a laboratory experiment to allow cosmic axions to convert to real photons that can be detected in a high-Q tunable microwave cavity. The open axion mass range can be covered by slowly scanning through the corresponding microwave frequency range. The coupling strength differs by roughly an order of magnitude for models with or without tree level lepton coupling (DFSZ or KSVZ axions, respectively).

The U. S. Dark Matter Axion Search follows the proposal of Sikivie, using a single cavity of
Figure 4: (a) Astrophysical and cosmological limits on the axion mass: the mass range sensitivities of the two principal axion search experiments are also shown. (b) Set-up of the U. S. Dark Matter Axion Search experiment.

50 cm diameter and 1 m length or a set of four cavities of 20 cm diameter and 1 m length fitting the same superconducting 7.6 T magnet. Cavities and GaAs HFET electronics are cooled to 1.3 K to reduce thermal noise. This configuration, schematically represented in fig. 4(b), is presently scanning part of the axion mass range at KSVZ sensitivity. In near future a newly developed SQUID based amplifier will be installed to further reduce the noise temperature, which should meet the requirements to search for KSVZ axions.

The CARRACK-II experiment in Kyoto is also using a microwave cavity inside a superconducting magnet to convert axions to photons, however following a different strategy for photon detection. Microwaves are coupled to a separate, field-free detection cavity. Both cavities are cooled to 10 mK. For photon detection a beam of two-step laser excited rubidium Rydberg atoms is passed through the detection cavity. Rydberg atoms whose excitation state has been enhanced by microwave photon absorption are selectively ionized by a precisely matched electric field, and the liberated electrons are detected in a channeltron electron multiplier. The single photon sensitivity should enable also this experiment to search for KSVZ axions.

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