Direct and Indirect Searches for WIMP Dark Matter

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I briefly review the present status of searches for Weakly Interacting Massive Particles using both direct detection techniques and through indirect means.

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P401

1 Status of WIMP Direct Searches

The energy deposited by WIMP-induced recoil nuclei has a characteristic exponential spectrum determined mainly by the kinematics of the interaction, the WIMP mass relative to that of the recoiling nuclei, and the velocity of the WIMPs [1]. Based on this the anticipated recoil spectra is expected to have energy ranging from a few keV up to a few hundred keV with rate <1 kg^{-1}day^{-1}, assuming the favoured range of WIMP masses, velocities and likely cross sections (for instance for MSSM). Meanwhile the ambient background rate from electron recoils due to gammas from surrounding natural radioactivity is typically x10^6 higher.

The basic requirements of direct detection technology are determined by these characteristics and imply the need for low energy threshold, passive gamma shielding and some means of identifying genuine recoils from the remaining background electron recoils. Recoil discrimination is possible in principle because the rate of energy loss with distance for electrons (the dE/dx) is typically x10 lower than for nuclear recoils of the same energy [2]. However, cosmic ray muons will produce background neutrons also. These can go on to produce background nuclear recoils indistinguishable from those expected from WIMP interactions. For this reason direct WIMP searches must be performed in deep underground sites, typically <1000 mwe, where in combination with judicious use of hydrogenous material the neutron background can be rendered negligible.

Favoured technologies for achieving the requirements above included at present ionisation, scintillation and low temperature bolometric devices. Of these, ionisation detectors based on germanium semiconductor for double beta decay searches set early dark matter limits. The Heidelberg-Moscow detector and the HDMS prototype Ge detectors, operating at Gran Sasso, have subsequently been particularly successful at further improving sensitivity [3]. Unfortunately, detectors using ionisation alone have no means of actively distinguishing nuclear recoils from electron background. They can measure only the continuum background and hence only set limits. Thus, much of the recent development in Ge technology for WIMP searches has been concentrated on material purification, in an effort to reduce intrinsic radioactivity. However, successful development of larger mass Ge experiments (10s-100s kg), such as the GENIUS detector [4], MAJORANA and others [5], may eventually allow identification of WIMPs through observation of an annual modulation in the event rate. This is expected to arise at the few percent level due to the Earth's varying velocity through the Galaxy [1].

In contrast to the use of basic semiconductors, low temperature and scintillation technology provide prospects for actual identification of nuclear recoils [6, 7]. For instance, in solid scintillators or liquid noble gases pulse decay times are typically x 0.3-0.5 shorter for nuclear recoils than for electron recoils of the same energy. Based on this, statistical analysis can be used to extract or search for faster events as a signature for WIMPs [8, 9]. In 1994-6 first limits were set by the UKDM collaboration using this idea in NaI [9, 10]. Subsequently, the UKDM group at the Boulby site discovered a population of fast, low energy events in NaI. These were also observed at a similar rate by the Saclay group using crystals originally part of a 100 kg array operated by the DAMA collaboration at Gran Sasso. The fast events have been interpreted as due to surface alpha particles [11, 12]. Meanwhile the DAMA group (Rome) has reported an annual fluctuation in the total count rate from their 100 kgs over 4 years - interpreted as consistent with the annual fluctuation predicted for WIMPs [13, 14]. This result is not yet widely accepted because the method used does not separate nuclear recoils from the low energy background which is much larger and, in principle, could be subject to modulating systematics [15]. Construction by DAMA of a larger (250 kg) NaI array is underway in an effort to confirm the result.

Low temperature bolometers in which phonon signals are recorded in suitable crystals at mK temperatures, can also be used to count total events and thus to set limits. Notable examples are the CRESST experiment and the experiments of the Milan group [16, 17, 18]. However, more powerful schemes are possible with bolometers in which nuclear recoil identification is achieved by combining phonon measurement with simultaneous observation of ionisation or scintillation. The CDMS-I and Edelweiss experiments are based on this concept with ionisation, while CRESST has developed the scintillation with phonon idea [19, 20]. The ionisation-phonon experiment of CDMS has produced data that appear to exclude the Rome result [21]. Although not yet located deep underground, and hence needing to subtract neutron background, they have reached a spin independent WIMP-nucleon limit around 2 x 10^{-6} pb in the mass range 20-100 GeV, interpreted as excluding the DAMA allowed region at >99 % c.l. Meanwhile, Edelweiss have also reached a sensitivity that significantly cuts into the Rome region [22]. In this case, since they operate at the deep Modane underground site, no neutron subtraction is needed. Fig. 1 provides a summary of some of the recent results for spin dependent WIMP searches.

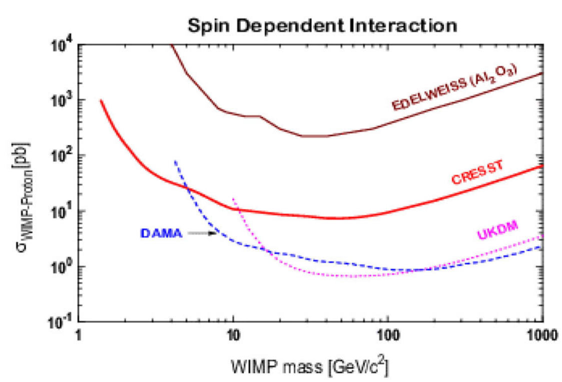

Figure 1: Recent results for spin dependent WIMP searches [22].

It is clear that in order to have sensitivity sufficient to detect WIMPs at the lowest likely cross sections (probably $<10^{-9}$ pb) a new, much more sophisticated, generation of experiments will be needed with mass as high as 1 ton. Various groups are developing new detectors which aim to improve sensitivity but the range of technologies capable of such a large mass is quite limited. The CDMS collaboration are building the CDMS-II experiment, an expansion of the CDMS-I experiment, to be run in the Soudan Mine. This may achieve x100 improvement over 2-5 years but it is not clear that a 1 ton detector using this technology can be achieved at reasonable cost. The CRESST-II proposal, using scintillation plus low temperature technology at Gran Sasso, is predicted to achieve similar sensitivity but also may not easily be expanded to 1 ton. However, liquid Xe, a relatively new technology in dark matter searches, does appear to have the advantage of mass scalability. For this reason there has been recent growth in interest in liquid Xe. Early experiments by the Rome group [23] have been supplemented by a Japanese group in Kamioka [24] and a major effort by the UKDMC/UCLA/Torino/ITEP/Columbia collaboration working at Boulby [25]. The latter is constructing a series of liquid Xe experiments aimed at optimising technology sufficient to build a 1 ton detector. ZEPLIN I, now running at Boulby, is based on pulse shape discrimination. ZEPLIN II and III make use of simultaneous collection of scintillation and charge to achieve factors of 10-100 improved sensitivity. A 1000 kg liquid Xe detector, ZEPLIN-MAX, is currently being designed to achieve sensitivity below 10^{-9} pb. Fig. 2 shows a basic concept design for ZEPLIN-MAX and Fig. 3 shows predicted sensitivity of the ZEPLIN detectors.

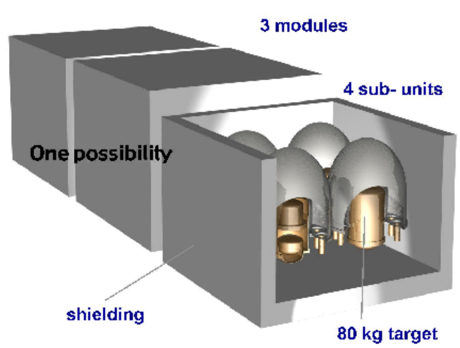

Figure 2: Scematic design concept for the UKDM 1 ton liquid Xe detector.

In addition to the basic ionisation, scintillation and low temperature technologies there exists a series of other novel techniques suitable for dark matter searches. Superheated droplet detectors being developed by the SIMPLE and PICASSO collaborations are one example that may eventually prove very sensitive [26, 27]. However, a new detector concept, called DRIFT, based on the use of low pressure gas Time Projection Chamber, may ultimately provide the most convincing demonstration of

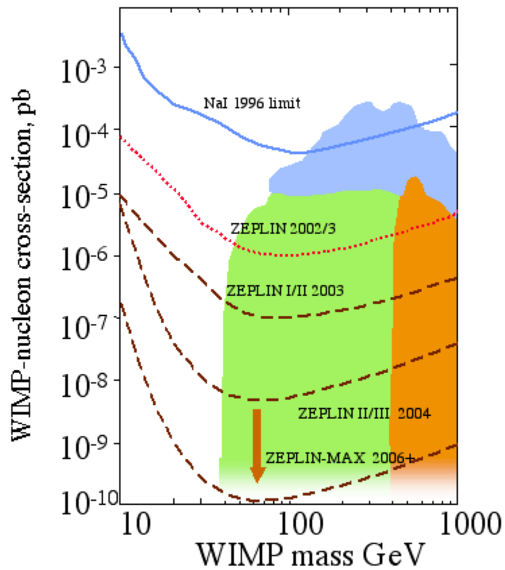

Figure 3: Predicted sensitivity of ZEPLIN liquid Xenon detectors based on data from ZEPLIN I.

the existence of WIMPs. In DRIFT recoil tracks of a few mm length can be imaged and thus, in principle, their direction can be correlated with our motion through the Galaxy. A UK/US collaboration is now running a first stage DRIFT detector of 1 m^3 at Boulby [28, 29]. Such a directional dark matter detector offers the prospect of a dark matter "telescope" able to distinguish possible different velocity components of the dark matter that have been suggested could exist [30]. Fig. 4 shows a schematic of the UK/US DRIFT I detector vessel.

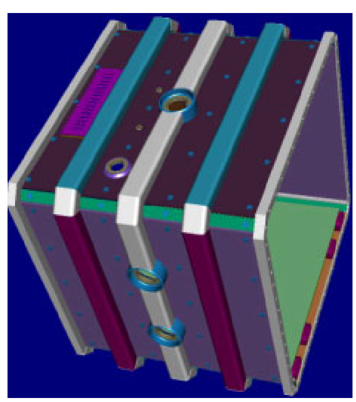

Figure 4: Schematic of the UK/US DRIFT I detector vessel.

2 Status of WIMP Indirect Searches

WIMPs may be Majorana neutralinos in which case pair annihilations can occur to produce neutrinos, gamma rays, positrons or antiprotons that may be detectable. This indirect means of searching for WMPs, though much more model dependent than the direct techniques (see Sec. 1) is quite complementary to direct observation in the laboratory. For instance, indirect searches can be more sensitive to high mass WIMPs. Furthermore, neutralino models which produce low direct detection rates can sometimes produce high annihilation rates, for example via the gamma-gamma channel [31].

Searches for high energy neutrino signals from the Sun, Earth, or galactic centre provide the most likely route since here the WIMP density is likely enhanced by gravitational capture yet the neutrinos can escape. Neutrinos, like annihilation gammas, have the advantage of maintaining their original direction. The possibility that the halo may contain clumps of dark matter may provide a further signal source [32]. Searches for muon neutrinos provide the best hope since the resulting upgoing muons produced in the Earth have long range in Cherenkov neutrino detectors and can be distinguished from background down-going atmospheric muons. The Sun, being mainly hydrogen, is particularly favoured, with predictions of neutralino induced muon rates also easier to calculate. Nevertheless, calculations have been performed for both Sun and Earth. Present and planned neutrino telescopes include AMANDA, ANTARES, IceCube, Baikal and NESTOR [33, 34, 35, 36].

Significant limits on the Sun and Earth muon flux sufficient to constrain MSSM models have already been produced by neutrino telescopes [37, 38]. For instance, 10^3-10^4 muons km^{-2}yr^{-1} has been obtained for the Sun above 10^2 GeV and down to 10^3 muons km^{-2}yr^{-1} above 10^3 GeV for the Earth [39]. Analysis by the SuperK collaboration using combined Sun, Earth and galactic centre data (see Fig. 5) appears to exclude parts of the region allowed by DAMA [40]. The ANTARES and AMANDA experiments are now aiming for km^2 experiments that would provide a x10^4 improvement in sensitivity. This is sufficient to test MSSM parameter space over a wide range [41].

Antiproton, positron and gamma ray annihilation may also provide signals in the halo, though antiproton and positron channels are hindered by the featureless nature of predicted spectra and uncertainty in galactic propagation models. However, experiments to search for neutralino annihilation antiprotons at the top of the atmosphere have been performed using balloons, for instance by the Bess and Caprice groups [42, 43, 44, 45] and will be undertaken in space by AMS [46]. Even though systematic effects, such as from cosmic-ray induced antiprotons, can be large, interesting limits can be placed for the highest annihilation rates [47]. In the case of balloon observation of the positron continuum, excesses have been observed by the HEAT experiment, interpreted as consistent with annihilation of 380 GeV neutralinos [48].

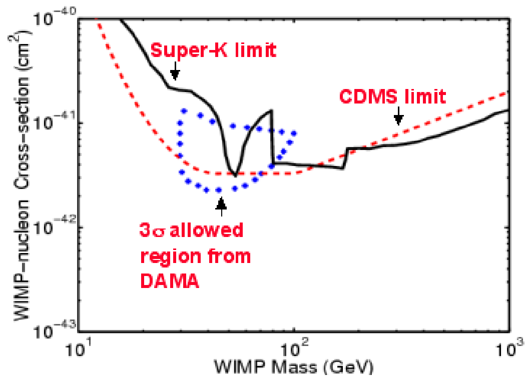

Figure 5: Combined Sun, Earth and galactic centre limit from SuperK [40].

However, other measurements have not observed an excess [49].

Annihilation gamma-ray lines produced in the halo or galactic centre may be observable by planned or existing Air Cherenkov Detectors (ATCs) on the ground or in space. This includes Veritas, HESS, Whipple, STACEE, CELESTE, MAGIC, MILAGRO, EGRET and GLAST. In fact ATCs may be the only way to probe for heavy (TeV) neutralinos. Recent MSSM calculations show that for a "standard" halo, for instance, Veritas and GLAST have discovery potential at least in this mass range [50, 51]. GLAST is of particular interest because its high energy resolution makes it particularly suitable for high precision line searches.

References

[1] P.F. Smith, J.D. Lewin, Phys. Rep. 187 (1990) 203

[2] N.J.C. Spooner, Phys. Rep. 307 (1998) 253

[3] H.V. Klapdor-Kleingrothaus et al., Proc. IDM2000, World Scientific, ed. N. Spooner and V. Kudryavtsev, York, UK, (2000) 415

[4] H.V. Klapdor-Kleingrothaus et al., proc. IDM2000, World Scientific, ed. N. Spooner and V. Kudryavtsev, York, UK, (2000) 593

[5] S. Cebrian et al., Nucl. Phys. B. Proc. Sup 95 (2001) 229

[6] N. J. C. Spooner et al., Phys. Lett. B 321 (1994) 156

[7] N. J. C. Spooner et al., Phys. Lett. B 273 (1991) 333

[8] P. Doll et al., Nucl. Instr. and Meth A285 (1989) 464

[9] P.F. Smith et al., Phys. Lett. B379 (1996) 299

[10] R. Bernabei et al., Phys Lett. B389 (1996) 757

[11] P.F. Smith et al., Phys. Rep. 307 (1998) 275

[12] V. A. Kudryavtsev et al., Phys. Lett. B452 (1999) 167

[13] R. Bernabei et al., Phys Lett. B424 (1998) 195

[14] R. Bernabei et al., Nucl. Phys. B. Proc. Sup. 91 (2001) 361

[15] N.J.C. Spooner, Pub. Boston, Particles, Strings and Cosmology (1998) 130

[16] M. Altmann et al., Proc. 20th International Symposium on Lepton and Photon Interactions at High Energies (Lepton Photon 01), Rome, Italy, 23-28 Jul 2001 (astro-ph/0106314)

[17] A. Alessandrello et al., Nucl. Phys. Proc. Sup. 87 (2000) 78

[18] M. Vanzini et al., Nucl. Instr. and Meth. A461 (2001) 293

[19] N.E. Booth et al., Ann. Rev. Nucl. Part. Sci. 46 (1996) 471

[20] M. Bravin et al., Astropart. Phys. 12 (1999) 107

[21] R. Abusaidi et al., Phys. Rev. Lett. 84 (2000) 5699

[22] A. Benoit et al. Phys. Lett. B513 (2001) 15

[23] R. Bernabei et al., Phys. Lett. B436 (1998) 379

[24] F. Arneodo et al., Nucl. Instr. and Meth. A449 (2000) 147

[25] N.J.C. Spooner et al., Proc. DM 2000, Marina del Rey, ed. D. Cline (2000) 365

[26] N. Boukhira et al., Astropart. Phys. 14 (2000) 227

[27] J.I. Collar et al., New Jour. Phys. 2 (2000) 14

[28] M.J. Lehner et al., Proc. DARK98, Heidelberg, Germany, ed. H.V. Klapdor-Kleingrothaus (1998) 767

[29] C.J. Martoff et al., Nucl. Instr. and Meth. A440 (2000) 355

[30] M. Kamionkowski and A. Kinkhabwala, Phys. Rev. D57(6) (1998) 3256

[31] L. Bergstrom, Rept. Prog. Phys. 63 (2000) 793

[32] L. Bergstrom, et al., Phys. Rev. D59 (1999) 043506

[33] F. Halzen, Comments Nucl. Part. Phys. 22 (1997) 155

[34] F. Montanet et al., Nucl. Phys. Proc. Sup. 87 (2000) 436

[35] E. Andres et al., Astropart. Phys. 13 (2000) 1

[36] L. Bergstrom, et al., Phys. Rev. D58 (1998) 103519

[37] M.M. Boliev et al., Nucl. Phys. Proc. Sup. 48 (1996) 83

[38] M. Ambrosio et al., Astrophys. J. 546 (2001) 1038

[39] N.J.T. Smith, Proc. ICHEP2000, World Scientific, ed. C.S. Lim and T. Yamanaka, vol 1 (2000) 287

[40] A. Habig et al., Proc. ICRC2001 (hep-ex/0106024v1)

[41] D.J.L. Bailey et al., Proc. ICRC2001

[42] A. Moiseev et al., Astrophys. J. 474 (1997) 479

[43] S. Orito et al., Phys. Rev. Lett. B84 (2000) 1078

[44] M. Boezio et al., Astrophys. J. 487 (1997) 415

[45] L. Bergstrom et al., Astrophys. J. 526 (1999) 215

[46] B. Alpat et al., Nucl. Instr. and Meth A461 (2001) 272

[47] S.W. Barwick et al., Astrophys. J. 482 (1997) L191

[48] G. Tarle and M. Schubell, Space. Sci. Rev. (2000)

[49] M. Boezio et al., Proc. 26th ICRC (1999), Salt Lake City, USA

[50] L. Bergsrom et al., Asgtropart. Phys. 9 (1998) 137

[51] Z. Bern et al., Phys. Lett. B411 (1997) 86