DARK MATTER SEARCHES

N.J.C. SPOONER
Department of Physics and Astronomy, University of Sheffield, Hicks Building, Hounsfield Road, Sheffield S3 7RH
E-mail: n.spooner@sheffield.ac.uk

A brief review is presented of the present status of experiments searching for dark matter in the form of Weakly Interacting Massive Particles by direct means. After an outline of the various detector strategies adopted, emphasis is switched to experiments that have recently produced new search results, followed by an outline of prospects for future more sensitive experiments.

1 Detector Strategies

Since realisation in the 1980s that WIMP dark matter particles may be detectable by direct searches in the laboratory several different detector technologies have been developed for the task by a wide variety of groups. Table 1 lists some of these experiments (as known to the author). Of these arguably the most successful have been based on detection of ionisation, scintillation or phonons (a full overview of these and others can be found in several recent international workshops devoted to the subject[1,2,3]). However, there has developed a general commonality amongst the techniques to progress beyond early counting experiments, such as exemplified by low background Ge detectors used in double beta decay experiments, towards techniques that can combine: (a) a means of positively identifying the nuclear recoil events expected from WIMP interactions, and (b) some means of achieving this with sufficient sensitivity eventually to allow the lowest predicted neutralino cross-sections ($\sigma_{WIMP-p} < 10^{-8}$ pb) to be probed - a combination of high (>10s kg) mass and efficient background rejection.

Experiment	Site	Targets
NAIAD (UKDMC)	Boulby	NaI
DAMA (Rome)	Gran Sasso	NaI, CaF_2, Xe
Saclay	Modane	NaI
USC-PNL-Zaragoza	Canfranc, Soudan	NaI, Ge
ELEGANTS-V	Kamioka	NaI
Osaka-Tokushima	Oto-Cosmo	CaF_2
Heidelberg/Moscow	Gran Sasso	Ge
USC-PNL-Zaragoza- TANDAR	Canfranc-Sierra Grande	Ge
Neuchatel-Caltech-PSI	St.Gottard	Ge
ZEPLIN (UKDMC- UCLA-Torino-ITEP)	Boulby	Xe
SIMPLE (CERN-Lisbon-Paris)	Paris	F,Cl,C
Montreal-Chalk River	Montreal	F,Cl,C

CDMS	Stanford	Ge, Si
Edelweiss	Modane	Ge
CRESST	Gran Sasso	sapphire, $CaWO_4$
Milan	Gran Sasso	TeO_2
SALOPARD	Canfranc	Sn
ORPHEUS	Bern	Sn
Tokyo-Osaka	Tokyo	LiF
DRIFT (UKDMC-Temple-Oxy-Surrey)	Boulby	CS_2, Ar, Xe

Table 1. Selected world dark matter experiments

In addition to recoil identification, and hence rejection of electron background, strategies to achieve signal sensitivity also include: (i) measurement of the expected small annual modulation in the WIMP-induced recoil spectrum (of order 5%) due to modulation of the Earth's orbital velocity component parallel to the galactic plane, and, by extension, (ii) measurement of the direction of nuclear recoils within the detector. Detectors with the latter capability could ultimately provide a definitive dark matter signal by correlating events with the diurnal change in orientation of the experiment, due to the Earth's rotation relative to the galactic dark matter halo. Direction sensitivity provides a final goal for experiments that would yield the maximum information on events. However, although examples, such as the DRIFT gas-based experiment, are under study (see Sec. 3) none have so far been run as experiments, so that current examples still rely on recoil identification and/or annual modulation alone.

Various recoil identification techniques are possible but most success has been achieved so far using NaI scintillation detectors (for example DAMA[4] and UKDMC[5]) and Ge or Si thermal-ionisation detectors (for example CDMS[6] and Edelweiss[7]). In NaI nuclear recoils release scintillation photons typically 30% faster than for equivalent energy electron recoils. This allows identification by statistical means following accumulation of sufficient events processed by pulse shape analysis[8]. The latter technique relies on measurement of the ratio of energy released in the phonon and ionisation channels at mk temperatures - the phonon yield being higher for nuclear recoils[9,10].

In the case of an annual modulation search this would best be performed following recoil discrimination, on that component of events known to be dominated by nuclear recoils. This would exclude as much electron background as possible, assumed to be not modulating, and hence improve signal to noise. This has not so far been achieved. However, several annual modulation experiments have been performed without recoil discrimination including in NaI, for instance by DAMA[11] and ELEGANTS[12], and in Ge, for instance the USC-PNL-Zaragoza-Tandar collaboration[13].

2 DAMA, UKDM, Saclay and CDMS

Significant results have recently been announced by several collaborations. The DAMA (Rome) collaboration has been searching for annual modulation using ~100 kg of NaI at Gran Sasso. More than four years of running has now been achieved yielding ~60,000 kg.days of data[14]. By performing a basic noise cut based on pulse time discrimination the collaboration are able to reject photomultiplier events and hence achieve a low energy threshold of ~2 keV. Annual modulation analysis is then performed in the 2-

6 keV region, sufficient to probe for spin independent neutralino interactions at σ_{WIMP-p} = 10^{-5} - 10^{-6} pb, given the measured background level of 1-2 dru (events/kg/d/keV). Fig. 1 reproduces a plot of the count rate residuals versus time for analysis of the full 4 year data set[14].

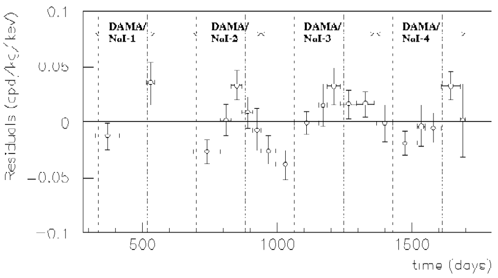

Figure 1. 2-6 keV count residuals from the DAMA 4 year data set[14].

Combining all 4 years, the DAMA group interpret the data as evidence (at 4σ c.l.) for a positive spin independent neutralino signal due to a flux of particles of mass 52 (+10, - 8) GeV of cross section $\zeta\sigma$ = 7.2 (+0.4, -0.9) x 10^{-6} pb (where ζ is the halo parameterisation factor[14]). This interpretation would, for instance, require that ~50% of the raw event rate in the 2-3 keV energy bin are due to WIMP interactions alone, with ~3% responsible for the modulation.

The DAMA results have been subject to great comment in the community (see for instance Gerbier[15] and Smith[16]) since despite considerable efforts by DAMA to eliminate systematic effects the possibility remains that the modulation results from an as-yet unidentified background source or artefact of the detector. Anomalous effects in NaI, though not necessarily related to the DAMA effect, have been observed in NaI operated by the UKDMC group and by Saclay. The UKDMC have been operating NaI dark matter detectors since 1990 in which pulse shape discrimination is used to search for a population of fast nuclear recoil events[5]. Following a sensitivity upgrade of the group's main 5 kg detector (DM46) in 1997 by increasing the light collection efficiency, a population of anomalous fast time constant events was observed (ratio of τ_{anom}:τ_{γ} = 0.65). These events have since been observed in many NaI detectors at very similar rates and with similar exponentially falling energy spectra[17]. More importantly analysis has now been completed of data from a 9.7 kg detector of the Saclay group (DM70) which also shows these events. This crystal was originally part of the DAMA array, fabricated by the same manufacturer and with the same construction as the DAMA 9.7 kg crystals. Fig. 2 shows comparison of the UKDMC and Saclay anomalous event spectra.

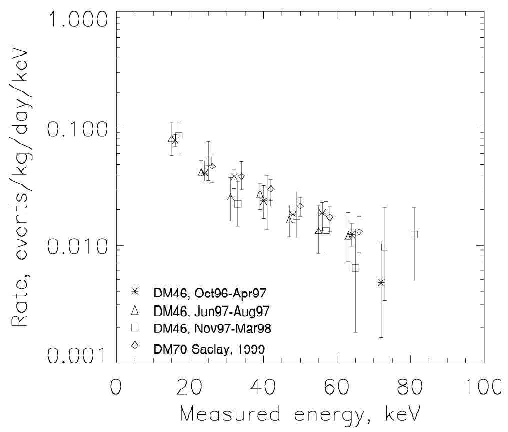

Figure 2. fast time constant event spectra from UKDMC NaI (5 kg DM46) and Saclay NaI (9.7 kg DM70).

Extensive studies by the UKDMC[18,19] suggest that the fast time constant events may result from diffusion of radon gas to the detector surfaces. This could result in implantation of alpha emitters into the sub-micron surface layer. Simulations show that outward going alphas would deposit energy with a spectral form similar to that observed (unlike inward going alphas), though reasons for the quite high count rate (~0.1 dru) relative to the levels of radon known to be present, and the similarity of rate between quite different NaI detectors, are still being investigated.

It is not possible yet to confirm whether or not the fast time constant events seen in the UKDMC and Saclay NaI are related to the modulating signal in the DAMA array, in particular because pulse shape discrimination is not possible below ~4 keV. However, recent long-term analysis of the UKDMC DM46 detector for the period 1997-1999 has revealed that the rate of the fast events does fluctuate with time with a characteristic quite different from the gamma background rate which remains steady (see Fig. 3). This effect is not inconsistent with possible fluctuating levels of radon. Therefore, it may not be unreasonable to assume such effects are possible in any NaI detector, with important implications for annual modulation searches.

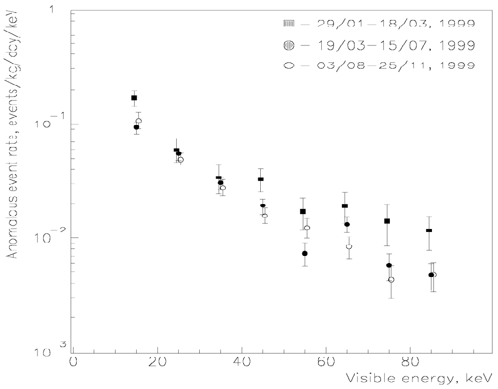

Figure 3. UKDMC fast time constant event spectra from 1999 runs of NaI crystal DM46.

By using the ionisation+thermal technique of recoil discrimination (see Sec. 1) the CDMS consortium have recently obtained first data from their Ge and Si experiment constructed at a shallow (~10m deep) site at Stanford University. Results have now been published for 1.6 kg.days Si and 10.6 kg.days of Ge[6]. Analysis of the Ge data has revealed 17 events lying in a region of low ionisation yield expected for nuclear recoils. The discrimination power is sufficient that in the presence of no WIMP or neutron flux zero counts would be expected. However, the shallow site, despite the presence of a highly efficient muon veto surrounding the detector, ensures that there is a significant neutron background from cosmic ray muon interactions. This is confirmed by the observation that 4 of the events occur in coincidence with recoil-like events in neighbouring detector segments.

The remaining 13 single hit recoils, if interpreted as WIMP events, are compatible with the lower part of the allowed DAMA WIMP region (equivalent to ~2.3 event/kgGe/d - 2 x 10^{-42} cm^2 WIMP-nucleon cross section). However, clearly some or all of these events may be neutrons. By making use of the observed single and double hit ratio CDMS are able to reduce systematic errors in Monte Carlo simulations of muon propagation and neutron production through their complex detector and shielding, sufficient to predict the likely absolute rate of neutrons. Fig. 4 shows the likelihood upper limit on WIMP events that results from subtraction of the neutron events based on this simulation. The result indicates that the DAMA and CDMS results are incompatible at 99% c.l.

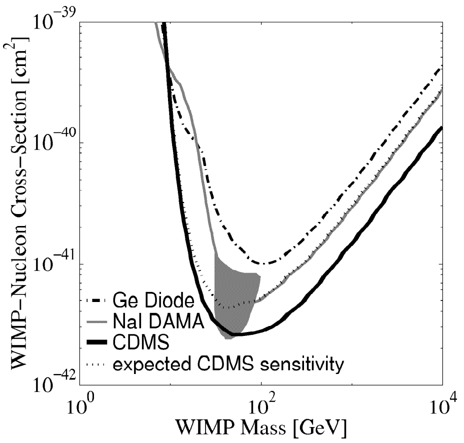

Figure 4. Comparison between the DAMA allowed region and CDMS limit[6].

3 Future plans

The neutron flux at Stanford remains a limiting factor in the CDMS experiment but plans to start operation at Soudan mine from 2001 should resolve this issue. The UKDMC is now operating NaI at Boulby without encapsulation (the NAIAD experiment) having demonstrated that careful preparation of crystal surfaces can eliminate the anomalous events. The collaboration anticipates 50 kg running by early 2001[20]. Meanwhile, the Ge experiment of Heidelberg-Moscow continues to run[21] and several new experiments are expected to become operational in the next few years (see Table 1). Of note are the bolometric experiments Edelweiss[7] and CRESST[22]. The former uses the ionisation+thermal technique in Ge with NTD thermistors and is already running at Modane. Sensitivity estimates for 500 kg.d Ge are comparable with CDMS predictions. CRESST, based at Gran Sasso, has recently developed a recoil discrimination technique based on simultaneous measurement of phonons and light in $CaWO_4$. This supplements their existing technology based on sapphire. They plan upgrades towards 10 kg during 2001.

Several non-bolometric techniques other than NaI are also being developed. These include Superheated Droplet Detectors (for instance, CERN-Paris-Lisbon[23] and Montreal-Chalk River[24] collaborations), liquid Xenon (for instance, DAMA[25] and UKDMC[26]) and low pressure (10-40 Torr) gas TPC (the UKDMC-Temple-Occidental direction sensitive DRIFT experiment[27]). Liquid Xe scintillator is a particularly powerful technique because interactions produce several processes that can provide high discrimination depending on the dE/dx[28]. These are: i) excitation - resulting in Xe_2^* molecules which decay emitting 175 nm photons with a mixture of 3 ns and 27 ns time constants depending on the dE/dx, and ii) ionisation - resulting in Xe_2^+ ions which, after a delay of ~40 ns for gammas and <3 ns for nuclear recoils, can recombine to give Xe_2^*. The latter can decay as in i) or, if an electric field is applied the recombination can be stopped and the charge drifted and accelerated to produce a second (proportional) scintillation pulse. Thus there are two means of discrimination possible, either conventional pulse shape analysis when recombination is allowed or by scintillation-ionization in which the primary scintillation pulse S1 is followed a few ms later by a secondary pulse S2.

The UKDMC has just started operation at Boulby of a 4 kg detector (ZEPLIN I) based on pulse shape discrimination in Xe. Two phase (gas and liquid) Xe detectors ZEPLIN II and ZEPLIN III with full scintillation-ionisation are on schedule for operation by mid 2001 in collaboration with UCLA, Torino, ITEP, CERN and Columbia. The latter is 6 kg and incorporates a high electric field in the liquid to enhance the recoil ionisation signal, the former is a 30 kg detector based on an original UCLA/CERN concept[29].

The technique of measuring the direction of WIMP induced recoiling nuclei is potentially very powerful because the motion of the Solar System through the Galactic halo (at ~230 kms^{-1}) ensures a forward-back asymmetry in recoil directions that increases rapidly with recoil energy[30] (>1 :100 above 100 keV). This is a unique feature of WIMP events and allows the prospect of discrimination from all normal isotropic backgrounds by correlating event direction with motion through the halo. The DRIFT collaboration is now building a 1 m^3 experiment using CS_2 for operation from mid 2001 at Boulby[31]. CS_2 produces -ve ions that are drifted to a MWPC readout, the advantage over conventional gases being that track diffusion is much reduced (<1 mm over 1 m) obviating the need for a magnetic field. Background predictions and tests indicate that zero background is a real possibility with DRIFT. The directional signal is so powerful that only a few 10s of events are required to definitively identify a signal as being due to WIMPs.

4 Conclusion

After some years of intense r&d effort significant progress has been made by several groups notably DAMA, CDMS and UKDMC. However, for these examples each has been hit by phenomena with characteristics close to that expected for WIMPs. They have dealt with the situation in different ways. DAMA observe an annual modulation - they interpret this as a WIMP signal and plan to continue running. CDMS suffers from neutron background that naturally produces WIMP-like events - they are subtracting them, then plan to move underground. The UKDMC have observed recoil-like events that probably arise from surface alpha contamination, they are attempting to remove them. The next 2 years should see these issues resolved.

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