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WIMP dark matter detectors above 100 K

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Abstract

Of key motivation in the development of detector strategies in the search for Weakly Interacting Massive Particles (WIMPs) is the need to maximize the information obtainable from the expected elastic recoil events so that these can be distinguished from background interactions and systematic errors can be controlled. Low temperature techniques may provide one route. However, most of the detector technology currently used, and those responsible for the best limits so far, do not involve cryogenic methods but rely on more conventional technology such as scintillators. There is increasing confidence that these techniques can reach the required sensitivity and may even provide the first detector with sensitivity to the direction of WIMP recoils. Reviewed here is the status of these techniques and the improvements planned to allow exploration of possible dark matter signal rates below $0.1\,kg^{-1}\,d^{-1}$.

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1. Introduction

Technology for the detection of Weakly Interacting Massive Particles (WIMPs) relies on devices sensitive to the rare, low energy, nuclear recoils expected from elastic scattering of dark matter particles in the presence of a higher electron recoil background. Much emphasis has been placed on the use of bolometric techniques since these can provide low energy threshold ($< 10\,keV$) and, by the separate collection of ionization and thermal energy for instance, the possibility of efficient electron recoil rejection [1]. However, it is quite feasible for more conventional technology, including NaI and liquid xenon scintillator, also to achieve recoil discrimination and low energy threshold sufficient for dark matter detection and indeed the best limits on WIMPs are currently set by these non-cryogenic techniques. This paper constitutes a review of the technology employed in these devices, recent progress on detector design and characterization, and prospects for the future.

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Table 1 gives a list of the non-cryogenic WIMP experiments presently known to the author [2–15]. This includes experiments that have either obtained limits, are expected to do so soon or are under construction. It excludes Ge, Si and low temperature experiments. The sensitivity of a particular detector technology such as those listed in Table 1 hinges on a series of factors and the extent to which they can be optimized. This can be expressed in terms of a relation between the observed background energy spectrum $\mathrm{d}R/\mathrm{d}E_{\mathrm{obs}}$ and the recoil spectrum expected from dark matter interactions in the form [16]:

$$\frac{\mathrm{d}R}{\mathrm{d}E_{\mathrm{obs}}} = R_0 S(E) F^2(E) I(A)\,, \tag{1}$$

where, R_0 is the total event rate in $\mathrm{kg}^{-1}\,\mathrm{d}^{-1}$ (predicted to be $< 0.1\,\mathrm{kg}^{-1}\mathrm{d}^{-1}$) and arises from the expression $\mathrm{d}R/\mathrm{d}E_{\mathrm{R}} = (R_0/E_0 r)\exp^{-(E_R/E_0 r)}$. This gives the recoil spectrum in terms of recoil energy E_{R} assuming a point like nucleus and zero Earth velocity relative to the dark matter distribution of mean incident energy E_0 [17]. Here r is a kinematic factor $= 4M_{\mathrm{D}}M_{\mathrm{T}}/(M_{\mathrm{D}} + M_{\mathrm{T}})^2$ involving the target nucleus mass M_{T} and WIMP mass M_{D}. In Eq. (1) $S(E)$ contains factors including the detector resolution, threshold effects (such as photoelectron statistics in photomultipliers), allowance for the case of more than one target isotope and the conversion efficiency of recoil energy into observed energy in the detector, f_{D}. $F^2(E)I(A)$ contain the nuclear-WIMP physics, $F^2(E)$ being a form factor correction due to the finite size of the nucleus (< 1) and $I(A)$ the nuclear coherence or spin factor correction which for spin independent interactions allows for coherent enhancement of the cross section. $S(E)$ also contains cosmological factors to correct for the motion of the Earth through the dark matter halo.

In the following sections a summary is given of the principle non-cryogenic techniques. However, prior to this it is worth summarizing the importance of the key factors contained in Eq. (1) and their relevance to obtaining best dark matter detection sensitivity. Firstly, the expected recoil spectrum is featureless, rising sharply at low energy with most recoil events expected in the keV

Table 1
Non-cryogenic dark matter experiments

Experiment	Site	Targets	Reference
UKDMC (IC-Sheffield-RAL)	Boulby	Na, I	2
DAMA (Rome)	Gran Sasso	Na, I	3
ELEGANTS (Japan)	Kamioka	Na, I	4
Saclay	Frejus	Na, I	5
USC-PNL-Zaragoza	Canfranc	Na, I	6
DAMA (Rome)	Gran Sasso	Ca, F	7
ELEGANTS (Japan)	Oto-Cosmo	Ca, F	8
CASPAR (Sheffield)	Boulby	Ca, F (C, H)	9
DAMA (Rome)	Gran Sasso	Xe	10
DAMA (Rome)	Gran Sasso	Xe (inelastic)	11
ZEPLIN (UCLA-UKDMC-Torino)	Boulby	Xe	12
SIMPLE (CERN, Lisbon, Paris)	Paris	F, Cl, C	13
Montreal/Chalk River	—	F, Cl, C	14
DRIFT (UKDMC-Temple-Oxy-Surrey)	Xe, Ar	Boulby	15

range. This determines the need for a low energy threshold. Secondly, this rising spectrum is similar to that expected from background electrons arising from U and Th in the surroundings, but with typically 10^6 lower rate. This determines the need for active discrimination against electron recoils and also the use of high radio-pure shielding materials, such as water, Pb or Cu. Simple energy cuts cannot be used as there are no peaks in the expected recoil spectrum. There is also a need to go deep underground to eliminate cosmic ray muon induced neutron background that could produce background nuclear recoils. Further neutron shielding is also desirable to eliminate remaining neutrons including those arising from alpha-n reactions in the rock. Thirdly, the signal count rate per kg is low and clearly increases linearly with mass. In general this points to a requirement for large detector mass ($>$ kgs) and hence low cost/kg. However, sensitivity to dark matter does not scale with mass but is determined also by the background discrimination power so that high mass is not necessarily required if good event identification is obtainable. Forthly, the choice of target nucleus (particularly spin matrix and A) is important for gaining optimum sensitivity to spin-dependent or spin-independent, and high mass or low mass, dark matter candidates. Finally, the ability with which systematic errors can be controlled must be considered.

2. NaI, CaF_2 and other alkali halide scintillation detectors

Low background NaI(Tl) detectors have become the most widely used non-cryogenic technique. They combine the possibility of high mass ($>$10 s kg), isotopes with nuclear spin, high A for sensitivity to higher mass WIMPs (from iodine), purifiable materials, simplicity of design and, most importantly, the possibility of background discrimination. The latter arises because the scintillation pulse shape for nuclear recoils has a faster decay time in NaI(Tl) than electrons of the same energy. Fig. 1 shows example mean pulse shapes for Na recoils and electron recoils at 15 keV, taken from Ref. [18]. As can be seen, at low energy the difference between the two types of event is not large so that in practice event by event discrimination is not possible. Instead discrimination must be performed statistically by examining the form of the distribution of time constants accumulated for many pulses [19].

PSD analysis in NaI(Tl) is being performed by the UKDMC and the DAMA groups [2,3] using detectors constructed from low background, selected, materials and shielded from photomultipliers by radio-pure light guides. In the UKDMC experiment pulses are binned in a time constant vs. energy array and for each energy interval the time constant distribution is compared to a gamma calibration distribution [2]. The error in the fit determines a 90% confidence limit for a small admixture of nuclear recoils. From this it is possible to reduce the observed spectrum to a nuclear recoil spectrum. Assuming consistency with zero then the error bars allow limits to be placed on the dark matter rate.

Although PSD in NaI(Tl) has proved quite powerful there is a drive to find improved techniques both for better sensitivity and to ensure good control of systematic errors [19]. This has been highlighted recently by UKDMC results from their new 5 kg NaI(Tl) detector now operating with improved light collection. This has revealed a population of fast time constant events of as-yet unknown origin seen at all measured energies (4–80 KeV_{ee}) [20]. This illustrates the need for alternative or additional methods to provide more information on events to help identification. One possibility is to search for the predicted annual modulation in the dark matter event rate.

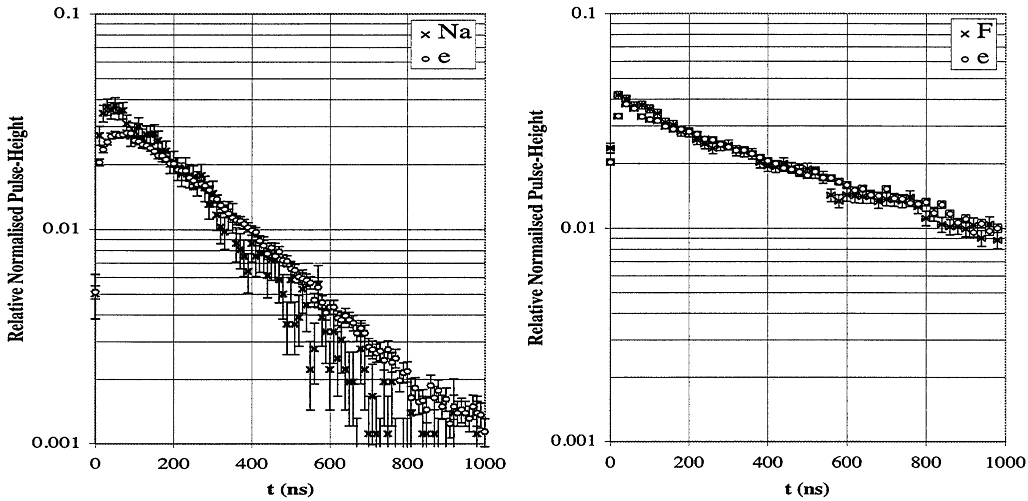

Fig. 1. Mean pulse shapes for Na and electron recoils in NaI (left) and F and electron recoils in CaF_2 (right).

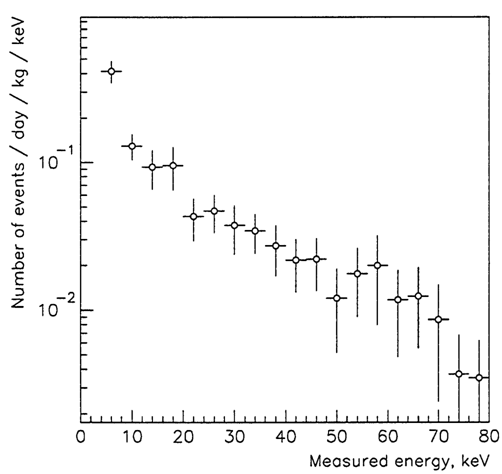

Fig. 2. Energy spectrum of the fast time constant events seen in the UKDMC 5 kg detector.

However, the effect is small so that pulse shape discrimination is, in principle, always more sensitive [19,20]. Nevertheless, a new experiment by the Zaragoza-USC-PNL collaboration at Canfranc has analysed data from a 32.1 kg NaI array for annual modulation and set limits [6] and the DAMA group have also analysed data from part of their 115 kg NaI array. Analysis by the UKDMC has shown a significant (4σ) annual modulation in their fast time constant events but, intriguingly, not in the background gamma events [20]. Fig. 2 shows the energy spectrum of these events. DAMA have claimed an annual modulation signal at low energy in undiscriminated data [22] though this result has been criticized [23].

Alternative alkali halide scintillators have been used. For instance, the DAMA group have published limits from a 0.37 kg CaF_2 crystal [7] and the Osaka group is constructing a large CaF_2 array at the new Oto-Cosmo underground site (1500 mwe) in Japan (ELEGANTS VI) [8]. However, CaF_2 cannot provide as much information on events as NaI since conventional CaF_2 has no pulse shape discrimination (Fig. 1 shows typical mean pulse shapes for nuclear recoils and electrons in CaF_2[18]). Thus annual modulation is likely to be the only means of identifying a signal in CaF_2 (but see Section 4). One advantage of CaF_2 though is the fluorine content which has a favourable spin matrix for neutralinos [24]. CsI has also been examined but this suffers from high radioactivity due to ^{137}Cs contamination [5].

Of the alkali halides then NaI remains the most promising particularly also since there is considerable scope for improvement in NaI technology. Larger mass and increased run time will improve statistical sensitivity by $(\text{mass} \times \text{time})^{0.5}$ and improved light collection will lower the energy and allow better discrimination. The intrinsic light yield in NaI of 40–60 photons/keV means a Na recoil energy threshold < 1 keV is feasible. The UKDMC have demonstrated this using a 50 mm unencapsulated NaI test crystal with PMTs close-coupled. 14 photoelectrons/keV was achieved using a 1 cm thick PTFE reflective coating [25]. There are also prospects for improved discrimination by optimizing temperature, crystal growth technique, doping and analysis methods, and for lower background, by using chemical purification of NaI with Diphonix [26] and the addition of a Compton veto.

3. Liquid xenon detectors

Despite improvements the intrinsic limitations of pulse shape discrimination in NaI will limit the amount of event information available. Consequently, alternative techniques are being sought. One possibility is to use liquid Xe scintillator in which there is potentially much more information because interactions produce several processes that compete depending on the dE/dx [27]. These are: (i) excitation – resulting in Xe_2^* molecules which decay emitting 175 nm photons with a mixture of 3 and 27 ns time constants depending on the dE/dx, and (ii) ionization – 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, with recombination, or by scintillation-ionization in which the primary scintillation pulse S1 is followed by a secondary pulse S2. The mean ratio S2/S1 for nuclear recoils is predicted to be 0.1–0.3 compared to 1–10 for electrons [21].

The realization of these event recognition ideas in liquid Xe represents a challenge because very high purity Xe is needed. However, the reward is more information on events and so better discrimination and control of systematics. Xe is also an attractive target because it can be purified, isotopically enriched and has a high A. To date a liquid Xe dark matter experiment without discrimination has been run by the DAMA group and limits set [10] and the scintillation-ionization techniques at low energy have been demonstrated by the ICARUS group [28, 29] who found near event by event discrimination between electron and nuclear recoils ($\sim 3\%$ overlap at 5 keV). A collaboration involving the UKDMC, UCLA, Torino and ITEP is now planning an experiment based on the technique, called ZEPLIN [12]. The first step will be a 1 kg Xe chamber with pulse shape discrimination followed by a 10–20 kg scintillation-ionization detector with outer Compton veto. The plan is to use new Gas Electron Multiplication (GEM) technology developed at CERN in a two phase Xe design to increase efficiency and discrimination. It may also be possible to operate without the radioactive photomultipliers by using direct amplification and imaging of the ionization clouds produced in liquid Xe with TEA additive [30]. The Doke group (Japan) are also planning a Xe detector with discrimination [31]. Attempts have also been made to search for inelastic events in Xe [11], (and in NaI [21]).

4. Detectors with recoil range discrimination

A further means of obtaining extra event information is to make use of the shorter track range of nuclear recoils compared to recoils from electrons of the same energy [17]. Use has been made of this in geophysical searches for dark matter where ancient mica has been studied for damage caused by nuclear recoil tracks [32]. In principle a real-time range discriminating detector can also be envisaged in a solid. One possibility is to use multi-layer semiconductor or scintillator detectors, but these have proved difficult to fabricate [33]. An alternative, is to use sub-micron scintillator granules suspended in a liquid scintillator of matched refractive index [34]. The Sheffield group has studied this technique using precipitate grown CaF_2 granules suspended in a dioxan–methanol–cabosyl mixture [9], termed CASPAR. This makes use of fluorine as a target. Discrimination arises by pulse shape analysis because WIMP interactions will give rise mainly to short range (<500 nm) Ca and F recoils within the grains yielding slow pulses (~ 900 ns) whereas electron recoils travel further and introduce a 4 ns component from the liquid. Tests with monoenergetic neutrons in a 50 mm dia. $\times$ 50 mm test CASPAR cell have demonstrated $>90\%$ discrimination of Ca and F recoils from electrons at 60 keV [9]. A 1 lt detector is under construction for operation underground. The event information available is much greater than in conventional alkali halide techniques as separate identification of H and C recoils in the liquid is feasible in addition to Ca and F in the precipitate. This may allow separate measurement of background neutron events. Furthermore, the precipitation process used, via the water-soluble precursor $CaCl_2$, allows radio-purification of the grains. The low fabrication cost of the technique, which requires no expensive furnace growth of crystals, means very large detectors may be feasible with CASPAR.

5. Alternative techniques

Several alternative detection schemes have been proposed as a route to discrimination [17] but the Superheated Droplet Detector (SDD) has perhaps progressed the furthest and has potentially complete discrimination against electrons. The SDD consists of a dispersion of 10–100 mm droplets of superheated liquid (freon) in a viscous gel that is sensitive only to highly localized ionization from nuclear recoils. Each droplet acts as a mini bubble chamber so that energy deposited greater than a value E_c within a range R_c invokes a phase change which can be detected by piezo-electric sensors. Progress with prototypes has been made by the SIMPLE collaboration and by the Montreal/Chalk River collaboration [13,14]. In principle the SDD can provide high mass and excellent recoil discrimination with a fluorine component in the target. However, a disadvantage of SDDs is the lack of energy resolution.

6. Direction sensitive techniques

An additional, potentially powerful, source of event information not included in any of the techniques discussed in Sections 2–5 is the possibility of measuring the direction of WIMP induced recoiling nuclei. The motion of the Solar System through the Galactic halo (at $\sim 230\,\mathrm{km\,s^{-1}}$) ensures a forward-back asymmetry in these recoil directions that increases rapidly with recoil energy ($>1:100$ above 100 keV) [17]. 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. This would confirm the Galactic origin of a signal.

One possibility for a direction sensitive detector is an adaption of the CASPAR detector in which the CaF_2 grains are made asymmetric. Ca and F recoils will then either emerge from the grains or remain inside depending on grain orientation relative to the WIMP flux. Production of the necessary single crystal, sub-micron, asymmetric grains of CaF_2 has been demonstrated [35] and the CASPAR group now plan to build test cells. Orientation of the grains can be achieved, in principle, with an electric field. Alternatively, use has been proposed of the anisotropy of scintillation response in organic scintillators such as stilbene [36]. Measurements with monoenergetic neutrons have recently confirmed a directional response of the light output from low energy (<50 keV) carbon recoils depending on their orientation relative to crystal axis [37]. However, the effect is small ($\sim 20\%$) and occurs with 180° symmetry in crystal orientation so that only the weaker perpendicular-parallel change in recoil directions can be observed rather than the full forward-back asymmetry. This means a large mass of material (>100s kg) is probably needed to gain sufficient sensitivity in a dark matter detector.

The most sensitive directional technique so far proposed is to use ionization tracks in a low pressure gas (10–20 torr) TPC [38]. In principle, such a device could provide full 3 dimensional information on all events thereby combining recoil discrimination based on $\mathrm{d}E/\mathrm{d}x$ and track length, direction sensitivity, event location and Compton vetoing all in a low background configuration. The DRIFT detector collaboration (Sheffield-RAL-Temple-UCSD-Oxy-Surrey) is now developing such a gas-based direction sensitive detector for installation at Boulby mine [15]. Although the target mass in DRIFT would necessarily be low this is not a disadvantage because the discrimination power is so high. Event by event discrimination is achievable so that sensitivity improves as mass $\times$ time. The observed track length corresponds to the true recoil energy so that lower threshold can be achieved than in solids. The principle technical challenge with a TPC detector has been the need to minimize electron diffusion during drift so that sufficient track resolution is obtained (<1 mm). Preliminary work by the UCSD group, who constructed a prototype low pressure Ar TPC of $1\,\mathrm{m} \times 0.4\,\mathrm{m}$ diameter, solved this by using a superconducting magnet to provide a 0.5 T magnetic field in the chamber [38]. They demonstrated nuclear recoils from neutron scattering. However, to reach reasonable sensitivity in a dark matter experiment (0.01–$0.1\,\mathrm{ct\,kg^{-1}\,d^{-1}}$) would require a scale up of 5–10 and this rules out the use of magnets on cost grounds. Consequently the DRIFT collaboration has sought alternative methods. One possibility is to use short drift lengths in a stacked array. However, a promising new idea is to use Xe with an

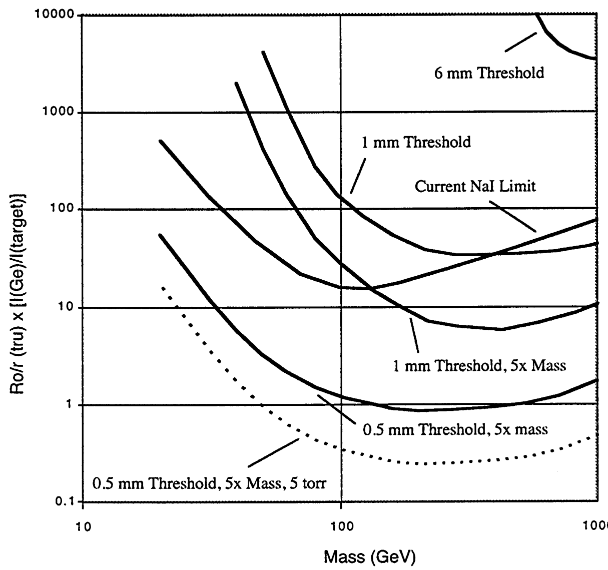

Fig. 3. Predicted sensitivities for a 1 m × 0.4 m diameter directional Xe TPC.

add-mixture of a suitable electro-negative gas such as CS_2 and operate in a negative ion drift mode. Fig. 3 shows results of sensitivity predictions for such a prototype low pressure Xe directional detector.

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