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SUPPLEMENTS

Direct detection of WIMP dark matter - techniques above 100K

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Searches for rare nuclear recoil events, from interactions with hypothetical weakly interacting dark matter particles, require novel methods of distinguishing nuclear recoils from the much larger gamma and beta background. This review covers detectors which operate at temperatures above 100K. New limits have now been set by pulse shape analysis in NaI targets at 300K, and much improved discrimination may be possible at 100-160K. Achievement of sensitivity to neutralino event rates would be possible using combined scintillation and ionisation processes in liquid xenon (160K). Studies of future directional detectors are also in progress, based on either range effects in solids or tracks in low pressure gases. A comparison is made of potential sensitivities of these techniques, together with a discussion of neutron background reduction.

1 Introduction

In recent years, considerable progress has been made in the development of experiments which could observe rare nuclear recoil events from collisions with weakly interacting particles which may form a major component of the Galactic dark matter. These experiments are in general sited underground to reduce neutron background arising from cosmic ray muons, and further shielding is provided to absorb neutrons arising from U and Th alpha interactions in the rock.

The nuclear recoils would form a continuous spectrum with the majority of events below about 20 keV. The differential energy spectrum, for either background or signal, is expressed in units $\mathrm{keV^{-1}kg^{-1}day^{-1}}$, which we call [1] a 'differential rate unit (dru), with the corresponding integrated rate in $\mathrm{kg^{-1}day^{-1}}$ referred to as the 'total rate unit' (tru). Fig 1 summarises the integral rates as a function of energy threshold and atomic number A, for illustrative values of particle mass.

Nuclear recoils would arise from the interactions of any type of particle with the target nuclei, so limits on interaction rates can be set which are independent of specific particle hypotheses. Nevertheless it is often convenient to relate the objectives to supersymmetry theory, where specific rate predictions can be made for the lightest supersymmetric particle (neutralino). Estimated event rates for different nuclei and for different supersymmetry parameters are usually in the range 0.01-0.1 tru, but can also extend to 0.001-1 tru. Moreover the reaction can be either spin-dependent, requiring a target with nuclear spin, or spin-independent (coherent) and increasing as the square of the number of nucleons (or neutrons in the case of heavy Dirac neutrinos). in supersymmetry, either of these two types may dominate, according to the model parameters.

The experimental problem is not only that the typical recoil energies are small, but also that the predicted rates are much lower than the typical background gamma and beta rates from radioactivity in the target and surroundings. Many years of effort on low background germanium detectors (double beta-decay experiments) using best available detector materials and shielding, has set dark matter limits in the region 10-100 tru [2], still a factor 10^3 higher than the predicted recoil rates for neutralinos. Methods must therefore be devised to discriminate nuclear recoil events from background. Some of these are based on very low temperature techniques, and these are reviewed by Professor Cabrera [3]. The present review covers techniques at ambient or reduced temperatures (down to 100K), and is an update of the similar review presented here in 1994 [4].

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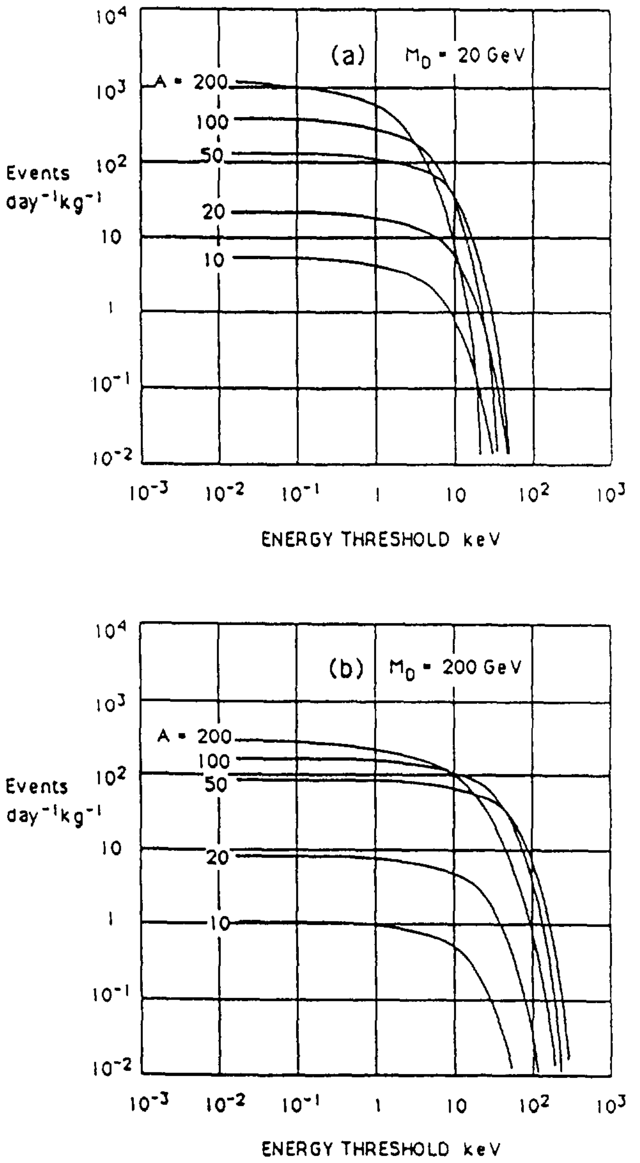

Fig 1 Total count rate versus nuclear recoil detection threshold for weakly interacting dark matter particles with mass (a) 20 GeV and (b) 200 GeV, incident on various target nuclei A. The coherent Dirac neutrino cross section (modified by the energy-dependent nuclear form factor) is taken for purposes of illustration.

2 Discrimination in NaI

The first significant improvements in sensitivity have come from ambient temperature NaI detectors. These are constructed from the lowest radioactivity raw material, and shielded from photomultiplier activity by low background silica light guides (Fig.2). The discrimination is based on pulse time constant, well known for many years as a method of discriminating alpha from gamma events above 1MeV. At lower energies there is considerable overlap between the two classes of event and nuclear recoil events would manifest themselves statistically as a shift in the time constant distribution (Fig.3). Analyses based on this are being carried out by the UK collaboration [5] and by the BPRS collaboration [6]. For the UK experiment of Fig 2, six months of event pulses were binned in time constant and energy. For a given energy band, the distribution is similar to a gamma calibration distribution, the error of the fit determining a 90% confidence limit for a small admixture of nuclear recoils (Fig.4). The analysis also rejects electronic noise pulses. The outcome is to reduce the observed background spectrum to a nuclear recoil spectrum consistent with zero to within the error bars at each energy (Fig 5). This in turn provides new limits on dark matter rates and cross sections, as shown in the detailed paper [5]. In particular, spin-dependent rate limits have been reduced by a factor >50, to the region 5-10tru.

Higher statistical sensitivity will result from larger masses and longer cunning periods, accompanied by good temperature stability and regular energy and time constant calibration. Larger gains will result from improved light collection, since this both sharpens the time constant distributions and reduces the energy threshold. Thus tests are in progress on systems with larger crystals and photomultipliers. Better light collection would also follow from lower background PMTs, which can be placed closer to the crystal, or from the development of fast low-noise APDs directly coupled to the crystal.

An alternative scheme using NaI is to operate undoped crystals at 100-160K, where comparable amounts of uv (300nm) and visible (420nm) light are emitted, in proportions which differ for electron and nuclear recoils [7]. Since the at these temperatures the uv has a time constant 20-40ns and the visible 1000-2000ns, there is a larger pulse shape discrimination for nuclear recoils, compared with that at 300K. To offset this, good optical coupling is more difficult at this temperature. The idea is thus well-matched to APD developments, where the lower temperature is also advantageous in reducing noise. This scheme was discussed in more detail in the 1994 review [4], has lapsed since then through funding shortage, but is still under consideration in the UK.

Depending on the success of these various improvements, it is anticipated that NaI can reach event rates in the range 0.1-1tru, using target masses in the range 10-100kg and running times 1-2 years, provided systematic errors can also be eliminated or rejected to this level.

3 Discrimination in liquid xenon

Interactions in liquid Xe produce the following processes:

(a) Production and decay of excited Xe_2^* states. These decay with time constants 3ns and 27ns, emitting 175nm photons. The proportions of these differ for electron and nuclear recoils, giving significantly different pulse shapes (Fig.6).

(b) Production of an ionised state Xe_2^+. This would recombine giving Xe_2^* states which decay as in (a). However, recombination can be prevented with an electric field, which drifts and accelerates the charge to produce a second (proportional) scintillation pulse (Fig.7).

Thus an electric field will create a double pulse - the primary scintillation pulse S1 from (1), followed a few ms later by a secondary scintillation pulse S2 from (2). From published data on the interaction of electrons, protons and heavy ions with liquid

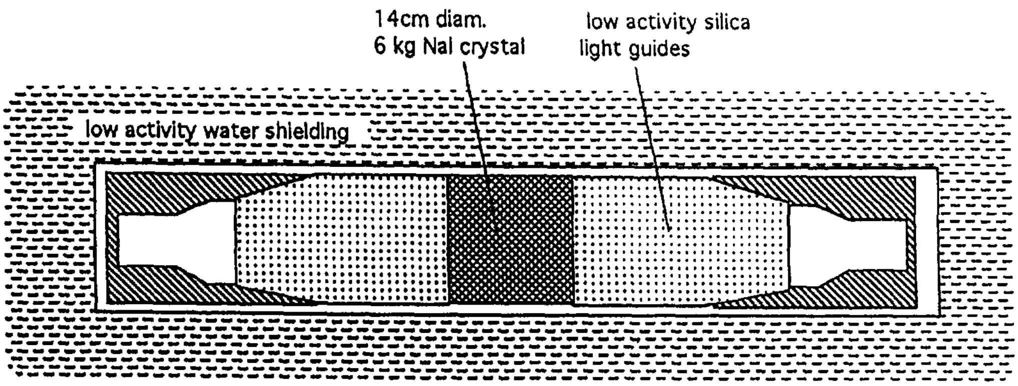

Fig 2 Water-shielded 6kg sodium iodide detector

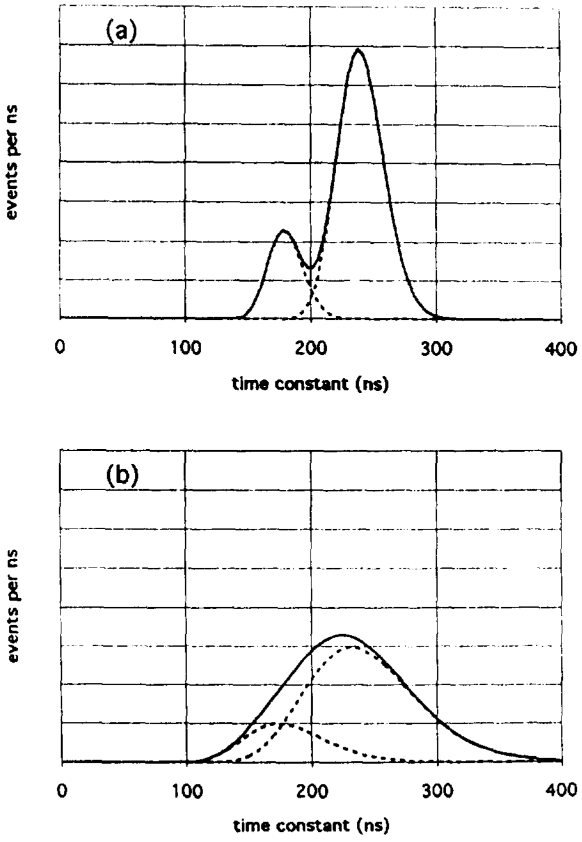

Fig 3 Nuclear recoil discrimination in sodium iodide. Time constant distributions (dashed lines) and sum (full line) for gamma events with admixture of neutron scattering events.
(a) ~ 100 keV, width < separation, distributions separated.
(b) ~ 25 keV, width > separation, single shifted distribution.

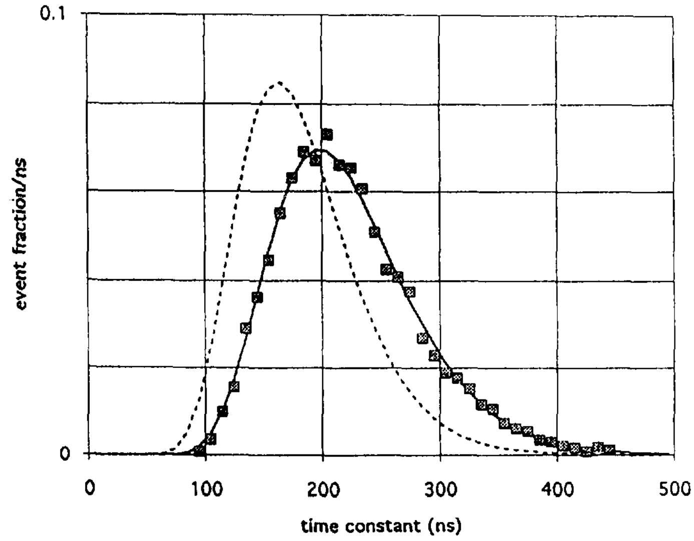

Fig 4 Comparison of time constant data with γ and n calibrations:
Full line: fitted γ calibration. Dashed line: fitted n calibration.
Points: binned data for 13-16 keV energy span.

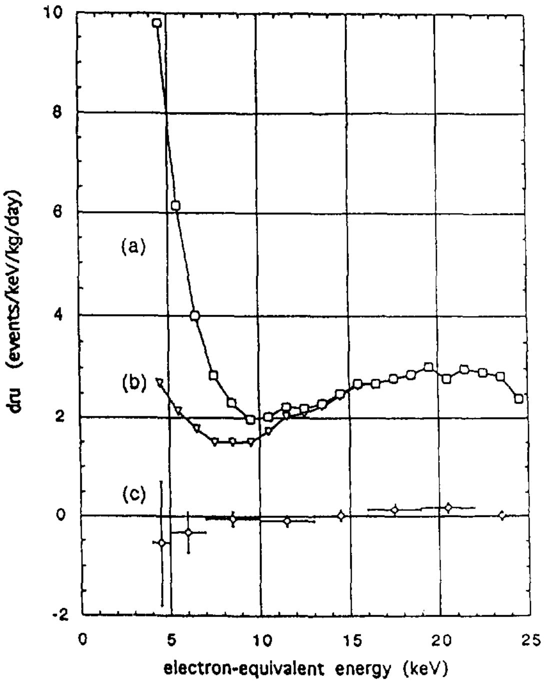

Fig 5 Background differential spectra
(a) observed total rate
(b) after subtraction of fast noise pulses
(c) 2s limits on nuclear recoil pulses

xenon the average ratio S2/S1 is predicted to be 0.1-0.3 for incident nuclei and 1-10 for electrons, with an overlap between the two classes of events estimated to be only a few % at 10 keV. This should provide much greater signal discrimination than the pulse shape differences in NaI.

Discrimination using simple pulse shape differences (a) has been assessed by Monte Carlo [8] but not yet studied experimentally. Practical demonstrations of the double-pulse proportional scintillation technique have been published by the ICARUS team [9], giving the expected S1/S2 pulse ratio differences for alphas and gammas as already shown in Fig 7. More recently, this work has been extended to low energy nuclear recoils produced by neutron scattering [10]. These recent results confirm for the first time that liquid xenon responds to its own recoil nuclei, and that the double-pulse technique will discriminate the nuclear recoils signals from background gammas with a rather small overlap (misidentified gamma fraction) g which varies from about 3% at 5 keV to 0.1% at 20 keV. Otrher liquid xenon studies have been reported by the DAMA collaboration [11].

4 Xe/NaI comparison

Both liquid Xe and NaI have the merit of being available in large quantities with sufficient purity, so that prototypes at the 5-10kg level can be subsequently scaled up to target sizes in the 100-1000kg region - though without single event identification the sensitivity improves only as the square root of target mass. Since light collection is crucial, it will in general be better to duplicate 5-10kg detectors than to make a single detector of large volume.

To compare Xe with NaI, we use the fact that the statistical gain factor results in a signal/background limit of the form S/B = C(E) /√N where N is the number of pulses collected and C(E) is an energy-dependent dimensionless constant which provides a convenient 'figure of merit' for any detector. Fig 8 shows a comparison of the figure of merit for NaI, improved NaI (UVIS), and liquid xenon. This shows the possibility of liquid Xe detectors which could improve on NaI detectors by a factor 10-30 and could thus reach the favoured 'neutralino level' 0.01-0.1 tru.

A complication araises from the effect of detector energy threshold and scintillation efficiency on the nuclear form factor correction F^2 (<1), in particular for the heavier elements I and Xe. The form factor is a function of the dimensionless product qR where R = nuclear radius fermi), and q = momentum transfer (inverse fermis) related to the recoil energy E_R(keV) by $q= 6.9.10^{-3}(AE_R)^{0.5}$. In nuclear scattering of electrons and protons the form factor has a Bessel function trend with the zeros smoothed out for the heavier elements by departures from the Born approximation. However, for the scattering of weakly interacting particles it is expected that the Bessel function zeros will survive in the spin-independent case, but will be still largely smoothed out in the spin-dependent case (for additional details, formulae and references, see [2]).

The form factor results in a loss of sensitivity which depends strongly on the value of qR, and in particular on the lowest detectable recoil energy. This is in general larger than the detector threshold, since observed energy $E_{obs} = f_n E_R$ where f_n is the relative scintillation efficiency for the nuclear recoils (compared with electron recoils of the same energy). Thus a poorer f_n results in a larger E_R at threshold, hence a larger qR and a correspondingly greater form factor loss. Measured recoil efficiencies in NaI are f_{Na} = 0.3 and f_I= 0.09 [12]. Liquid xenon is expected on theoretical grounds to have f_{Xe}=0.5, but an unpublished measurement by the ICARUS group is believed to have given the preliminary result f_{Xe}=0.2. Using these values, Fig.9 shows the variation of F^2 with detector energy for Na and I and for liquid Xe, showing also the predicted difference between spin-dependent and spin-independent interactions. The rapid fall in sensitivity for the heavier elements shows

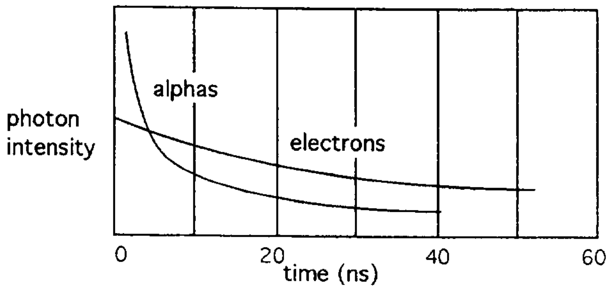

Fig 6 Scintillation pulse shape differences for alphas and electrons in liquid xenon

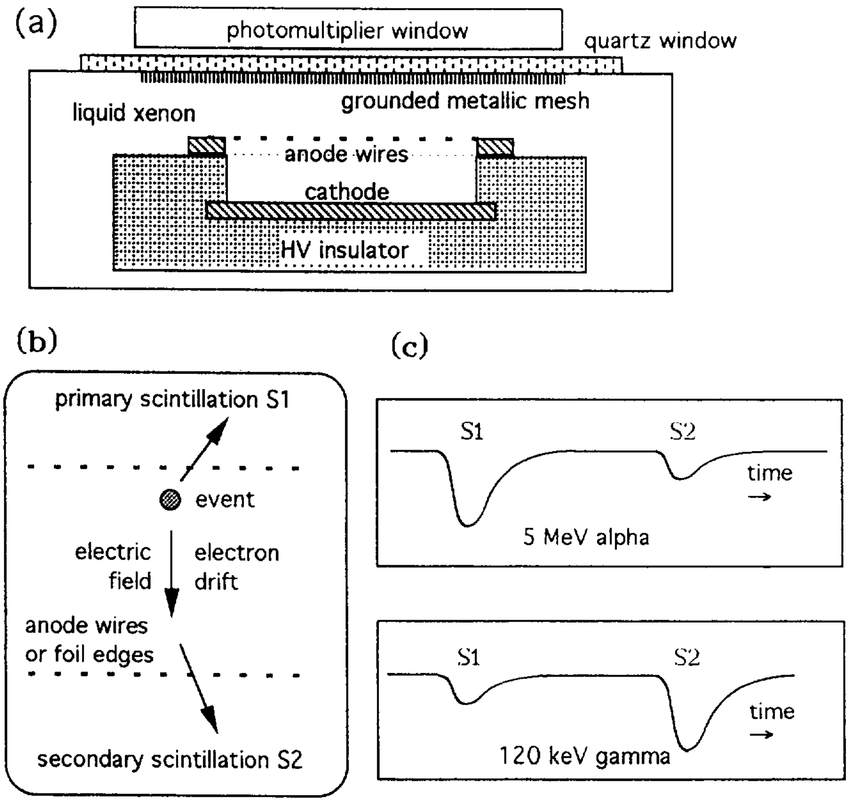

Fig 7 Discrimination by proportional scintillation [9]
(a) Geometry of liquid xenon test chamber.
(b) Processes following scattering event.
(c) Typical appearance of integrated S1 and S2 scintillation pulses: S2/S1 = 0.3±0.2 for alpha events and 3±2 for gamma events.

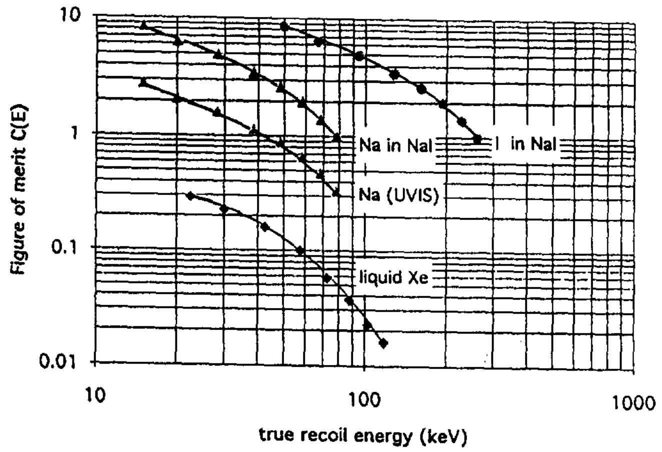

Fig 8 Discrimination figure of merit versus recoil energy for NaI and Xe detectors

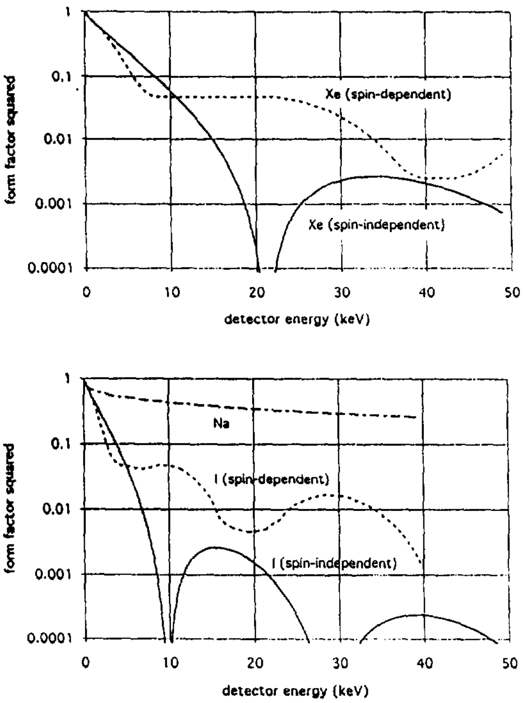

Fig 9 Nuclear form factor correction F^2 for NaI, Xe, versus observed detector energy for recoil efficiencies $f_{Na} = 0.3$, $f_I = 0.09$, $f_{Xe} = 0.2$

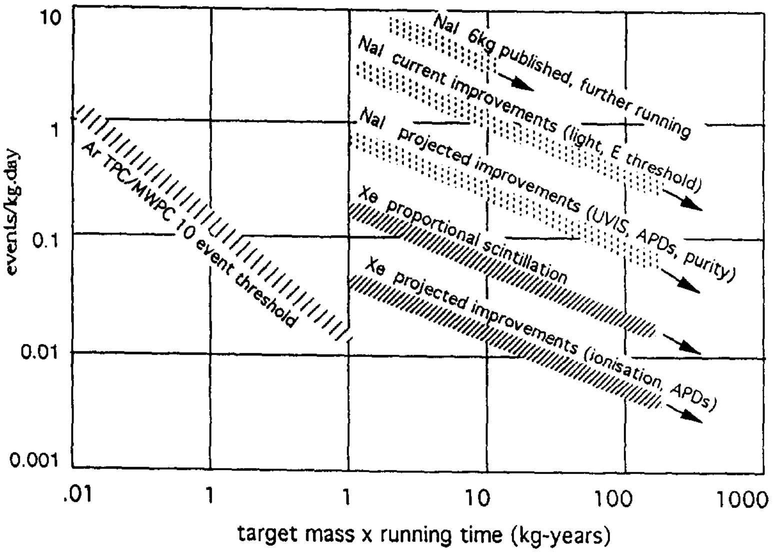

Fig 10 Predicted sensitivity versus running time for dark matter detectors discussed in text

the crucial importance in maximising light collection in experiment design to reach the lowest possible recoil energies. The situation is less crucial for setting spin-dependent limits with Na, because of the much smaller size of the Na nucleus. Other crystal scintillators are also still being considered, in particular CaF_2 which has the merit of not requiring encapsulation like the hygroscopic NaI, but which has a lower recoil efficiency (~10% [13) and usually higher radioactive impurity levels. It should be noted that f_n for liquid or plastic scintillators is extremely low (<1% [13]) and this, together with their already relatively low light output, has precluded their use as targets for dark matter experiments.

5 Gaseous detectors

Nuclear recoils in the keV range can be detected as ionisation tracks in gases at sufficiently low pressure, typically 10-20 torr, and this would also give the recoil direction, which could be correlated with the motion of the Earth and Sun to confirm the Galactic origin of any signal. This appears at first to be ruled out as a useful dark matter detector by the difficulty of achieving a sufficiently large target mass at such low pressures. However, it is remarkable that this detection technique has two properties that recover this target mass disadvantage:

(1) It is in principle capable of observing single events, rather than a statistical admixture as in the case of NaI and Xe. This gives a sensitivity reducing improving with time rather than as √(time).

(2) Since the ionisation efficiency does not affect track length, we have effectively $f_n=1$ for gaseous tracks - ie the observed track length corresponds to the true recoil energy. And since choice of gas pressure allows track lengths of a few mm for a 10 keV recoil, lower true recoil thresholds may be achievable than for solid or liquid targets, and in turn this results in a milder form factor correction.

Fig 10 compares potential sensitivity versus the product of mass and running time for NaI, liquid Xe and low pressure gaseous Ar. It can be seen that the combined advantages (1) and (2) allow a gaseous detector to reach the 'neutralino sensitivity' (0.01-0.1 tru) in a one year running period with 0.2-1kg gas, compared with 10-100kg liquid xenon. A prototype low pressure 'TPC' Ar detector, 1m x 0.4m diameter, has been constructed by the UCSD group [14], demonstrating nuclear recoil tracks from neutron scattering and using a 0.5T magnetic field to coil up the background electron tracks. This prototype chamber provides 5g target mass at 20 torr, and would thus need scale-up by a factor 100-200 to reach a sensitivity 0.01-0.1 tru. The magnetic field requirement makes this difficult, but with shorter drift lengths it should be possible to discriminate nuclear recoils without the magnetic field, enabling a large (25-50m^3) array of stacked detectors to be envisaged A related alternative would be a stacked MWPC configuration, identifying tracks more simply as hits on adjacent wires.

6 Other ideas

Range discrimination can also be considered in solids, although the typical range of 10keV recoils is only 3-10 $\mu g\ cm^{-3}$. One method would be sub-micron scintillator granules in a liquid scintillator of matching refractive index [15] which could also be made directional using needle-shaped granules. Alternative directional ideas include the ejection of atoms from surfaces [16,17,18] and the search for etched damage tracks in ancient mica [19,20] which takes advantage of the 10^9 year integration time. However, the ultimate sensitivity of the latter appears difficult to assess and calibrate convincingly [21,22].

Finally, we note a suggestion [23] for background-free nuclear event detection using moderately superheated liquids - essentially a continuously operating bubble chamber adjusted to respond only to the highly localised ionisation of nuclear recoils. This mechanism would register an event, but not its energy. A further refinement would be to use a liquid which is also a scintillator - for example liquid argon - in order to provide recoil energy measurement.

7 Neutron background

Nuclear recoil events can also be produced by neutron background. Directional detectors would be able to distinguish dark matter events from neutron background through the directional asymmetry relative to the direction of motion through the Galaxy (for example there would be a forward/back ratio of about 4/1). Nevertheless it is clearly preferable to reduce neutron scattering events in the target to below the sensitivity level achievable in a given detector. Neutrons are produced in three main ways:

(a) from capture and spallation of cosmic ray muons in the target and local shielding,

(b) from alpha reactions arising from U and Th in the surroundings, in particular the underground rock, and

(c) from similar processes due to U and Th contamination of the detector components.

Source (a) can in principle be rejected with a surrounding muon veto, but at the earth's surface the rate is inconveniently high, and this is the reason for preferring operation at a depth of about 1000m, where the muon flux is attenuated by a factor 10^6 and the neutron rate in the target will be, from Monte Carlo studies, below 0.01tru. This could be reduced to 0.001tru with a simple 90% veto shield.

Source (b) results in a typical underground flux of $\sim 10^{-5}\text{cm}^{-2}\text{s}^{-1}$, but this is easily attenuated with conventional hydrogenous shielding (polythene, wax, water).

Source (c) can be estimated from the fact that neutrons produced by U and Th are typically 10^{-5} of the gamma flux, so that the observed typical background gamma count rates of 100tru imply a neutron count rate of order 0.001tru, and further reducible with purer detector materials.

We can conclude that neutron events will not limit dark matter sensitivity in any kind of detector down to levels ~.001tru. And on the > 5 year timescale needed to reach that sensitivity level, directional detectors will undoubtedly be available to distinguish those events of Galactic origin.

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