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NaI dark matter limits and the NAIAD array – a detector with improved sensitivity to WIMPs using unencapsulated NaI

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Abstract

Re-analysis of published data from the UKDMC NaI(Tl) dark matter experiment is presented using latest spin factors and comparison is made with the sensitivity predicted for NAIAD, a 100 kg NaI detector concept based on unencapsulated NaI(Tl). We present experimental results and Monte Carlo simulations for NAIAD and show that a factor of 1.5–2 improvement in energy threshold is achievable over conventional NaI dark matter detectors with consequent $\sim 50\%$ improvement in nuclear recoil discrimination at 10 keV. An overall improvement in sensitivity to spin dependent WIMP interactions of factor 50, based on 100 kg $\times$ yrs of data, is predicted relative to previous UKDMC limits. © 2000 Published by Elsevier Science B.V. All rights reserved.

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1. Introduction

Competitive limits on the flux of weakly interacting massive particles (WIMPs), that may constitute

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up to 90% of the Galaxy, are currently set by low background NaI(Tl) detectors using pulse shape analysis (PSA) to distinguish scintillation arising from background electron recoils from that due to nuclear recoils [1,2]. Discrimination is possible because the sodium and iodine recoils expected from elastic scattering by WIMPs have faster mean pulse decay time than for electrons [3]. The UK Dark Matter Collaboration (UKDMC) has been operating such detectors at the Boulby Mine underground site for several years [4]. At present, because NaI is hygroscopic, detectors are fabricated using an outer copper encapsulation with glued-in quartz windows plus additional thick (typically > 100 mm) quartz lightguides to shield the crystal from photomultiplier activity. However, this design limits detector sensitivity because: (a) it prevents access to potential background sources on crystal surfaces, and (b) it results in reduced light collection. The importance of NaI surfaces has been highlighted recently by indications that they might be a source of anomalous fast time constant events seen in NaI dark matter experiments [4–6]. Greater access would allow improved control of potential contaminants there and hence a possible reduction in such events, leading to greater sensitivity to WIMPs. The poor light collection in conventional encapsulated designs is caused largely by light loss at the many components, boundaries and surfaces required between crystal and PMTs. This results in typical efficiencies of only 3–5 photoelectrons (p.e.)/keV. Any increase towards the theoretical maximum from NaI(Tl), usually taken as 40–60 photons/keV (for instance by using photodiodes with quantum efficiency QE $= 1$ [7]), would also improve sensitivity. Firstly, it would provide reduced energy threshold. This is critical to detector sensitivity since the recoil energy spectrum due to WIMPs is expected to fall faster than the background so that low energy data, near threshold, are the most significant in determining sensitivity [8]. Secondly, it would improve the degree of recoil discrimination because this is partly determined by the statistical accuracy with which τ, the decay time of individual scintillation pulses, can be measured and this is dependent on the number of photoelectrons available for each pulse. In practice, data are analysed by accumulating distribution of τ values for all events N (total number N_o) in energy bins ΔE. For each ΔE this is found to have a log-gaussian form given by [1,9]:

$$\frac{dN}{d\tau} = \frac{N_o}{\tau\sqrt{2\pi}\ln w} \cdot \exp\left[\frac{-(\ln\tau - \ln\tau_o)^2}{2(\ln w)^2}\right], \qquad (1)$$

where τ_o is the effective mean value of τ and $w = 1 + fn^{-1/2}$ is a measure of the distribution width, where f is a crystal-dependent constant and n is the number of photoelectrons. WIMPs are expected to yield a distribution with lower τ_o than for electrons. The effect of improved photoelectron statistics via better light collection is to reduce w and hence improve the ability to separate background and signal distributions. Further details are given in [9]. Based on these deductions we present here the novel concept of the NaI Advanced Detector (NAIAD) designed to tackle points (a) and (b) above. We report the design of NAIAD, based on ~ 100 kg of unencapsulated, low background NaI, suspended in an organic liquid with the latest low background photomultipliers and an assessment of its sensitivity to WIMP dark matter relative to current detectors, based on experimental results and Monte Carlo simulations.

2. Proto-NAIAD tests and light collection simulations

Light is most commonly extracted from encapsulated NaI detectors through a silica window and channeled through a silica light guide to the glass window of a photomultiplier. In this arrangement there are six optical boundaries which can produce substantial reflection and loss of light if mismatched in refractive index. In the simple case of air gaps between components a Monte Carlo simulation shows that an additional 30-40% of the light can be lost. In principle, this can be avoided by using adhesive or grease of nearly matching refractive index between components. Since the reflection coefficient at the interface of refractive indices n_1, n_2, is $[(n_1 - n_2)/(n_1 + n_2)]^2$, matching the index to better than ± 0.1 can reduce the reflection losses to $< 0.25\%$ per interface, as again confirmed by Monte Carlo simulations. However, it is found in practice that such matched interfaces may deteriorate over periods

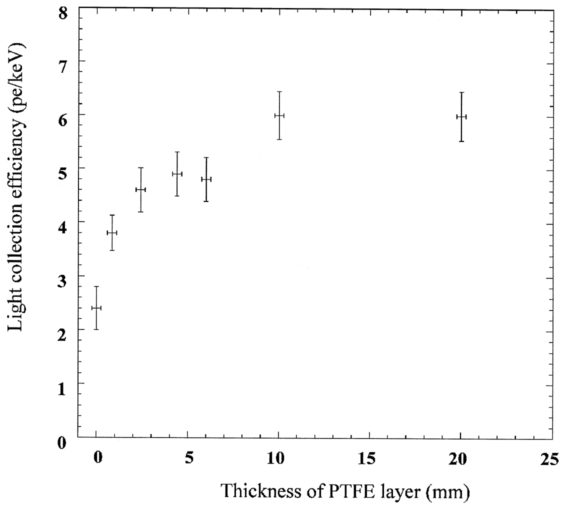

Fig. 1. Light collection versus PTFE thickness in proto-NAIAD.

of time, and can develop cracks, opacity, and gaps, causing significant deterioration of light transmission. There is therefore incentive to develop systems which eliminate the need for matching interfaces, in particular the concept of a windowless NaI crystal directly linked to the photomultiplier through an intervening fluid.

To investigate more thoroughly the influence of design parameters on light collection, including surface reflectance; shape, refractive index and attenuation length of lightguide; shape of crystal and crystal wrapping, tests were performed using a purpose-built apparatus we term ‘proto-NAIAD’ and backed up by further Monte Carlo simulations. Proto-NAIAD consists of a cylindrical unencapsulated NaI(Tl) crystal of 50 mm diameter × 50 mm long mounted inside a light-tight polypropylene barrel (1 m × 0.5 m diameter) filled with high purity, moisture-free, mineral oil of attenuation length > 5 m (further details are given in [10]). The crystal is positioned with flat surfaces viewed by two 75 mm EMI9265KB photomultipliers (PMTs), supported with the crystal by three 1 mm diameter steel rods. This arrangement allows the distance between crystal and PMT to be varied on either side by up to 200 mm and for insertion between crystal and PMTs of hollow lightguides of variable shape and material. The mineral oil provides both a clear fluid lightguide material, filling the hollow lightguides, and a means of protecting the crystal from contact with moisture. Anode signals from the PMT dynode chains (also immersed in the oil) pass to NIM discriminator units set at the peak of the 1 p.e. level with outputs placed in coincidence to suppress PMT random noise. The coincidence signal is used to trigger acquisition of the pulses by a LeCroy 9350 DSO linked via GPIB to a Power Macintosh running an in-house Labview data acquisition program. Analysis is subsequently performed using PSA technique [1]. Light collection results were obtained in photoelectrons per keV (p.e./keV) by calibration with a ^{57}Co gamma source. Monte Carlo results were obtained in terms of a percentage of photons generated isotropically in the crystal that subsequently impinge on the PMT window. Principle results are as follows:

Influence of crystal wrapping: The high diffuse reflectivity (> 99% at 420 nm) and low background of PTFE tape means this is often used as the reflective coating on NaI dark matter detectors (typically ∼ 1 mm [11]). However, the influence on light collection of greater thicknesses, particularly in mineral oil, had not previously been investigated. Fig. 1 shows results of such tests performed on proto-NAIAD with 15 cm oil lightguides (error bars include systematic effects from disassembly/reassem-

Table 1
Influence of lightguide reflectivity on light collection in the unencapsulated proto-NAIAD detector.

Type of reflector	Composition	Measured light collection (p.e./keV)	Predicted light collection (%)
97% specular	Al Ano-Fol^{TM}	6.0 ± 0.4	59.7 ± 0.6
internal reflection	polished Lucite	3.8 ± 0.3	23.1 ± 0.4
internal reflection + 97% specular	polished Lucite surrounded by Ano-Fol^{TM}	4.9 ± 0.4	58.1 ± 0.6
97% specular + 2 cm 97% diffusive strip next to crystal	Al Ano-Fol^{TM} and PTFE strip	4.8 ± 0.4	57.9 ± 0.6

bly). It can be seen that light collection improves as further PTFE layers are added above 1 mm, up to ~5 mm where the efficiency reaches ~5 p.e./keV (note that original UKDMC dark matter limits were obtained using a 6 kg NaI(Tl) detector with light collection ~1.7 p.e./keV [1]). This suggests that the PTFE is acting here as a volume reflector rather than a pure diffuse surface reflector. Encouraged by these results further tests were performed with solid PTFE rings of 10 mm and 20 mm thickness fitted tightly around the crystal (also shown in Fig. 1). These arrangements both achieved light collection of 6 p.e./keV. Finally proto-NAIAD was run in oil with the 10 mm PTFE ring and PMTs close-coupled. This gave 13.6 p.e./keV with 1 σ resolution of 7.4% for the 122 keV line of ^{57}Co (5.2% for the ^{137}Cs 662 keV line). This is higher than we have encountered before and 30% higher than typically quoted by manufacturers.

Influence of lightguide reflector: For this study, the crystal, in 10 mm PTFE, was coupled to the two PMTs using 15 cm oil-filled cylindrical lightguides of various low background reflecting materials including Ano-Fol™ [12], a 97% specular-reflecting foil. Example results are displayed in Table 1. It can be seen that Monte Carlo results for specular and total internal reflection with an outer specular layer predict similar light collection efficiencies, but that the measured values indicate considerably poorer efficiency for the latter. This is believed to arise from difficulty in obtaining, in practice, a sufficiently smoothly polished surface for good total internal reflection.

Influence of lightguide shape: The influence of lightguide shape was also extensively studied using various hallow containers made of Ano-Fol™ filled with oil, including tapered cones and cylinders much larger than the crystal. However, an optimum was achieved with cylinders of diameter similar to the PMTs (as in row 1 of Table 1).

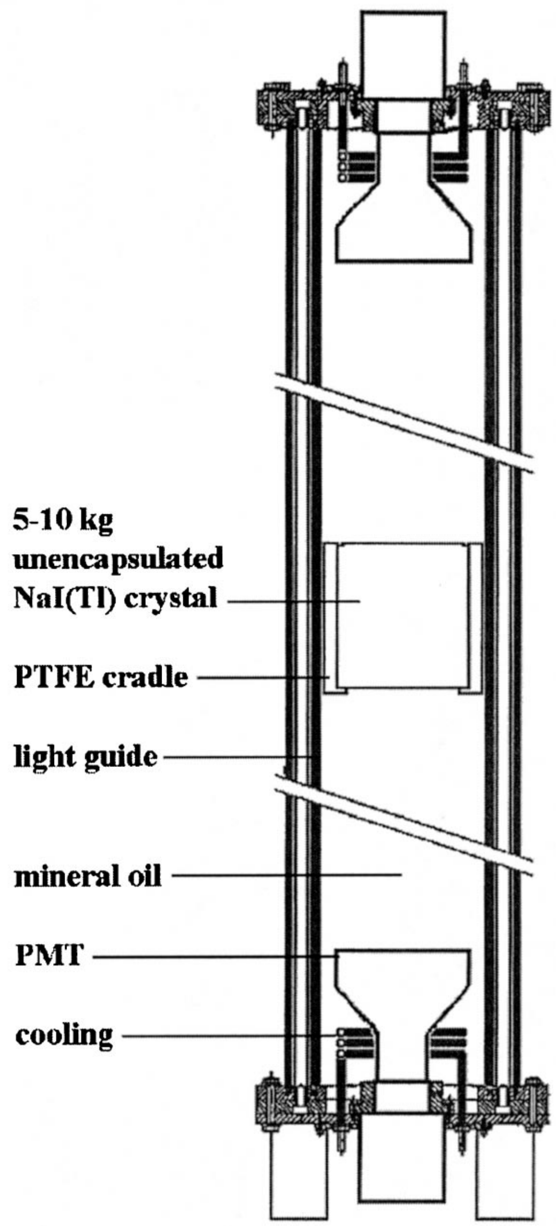

Fig. 2. Schematic of the NAIAD-0 unit.

3. NAIAD design and tests

Based on the proto-NAIAD tests a full 100 kg NAIAD has been designed comprising a close packed array of unencapsulated NaI units. Fig. 2 shows a schematic of one of these completed NAIAD sub-units, termed NAIAD-0. The module comprises two concentric cylinders of Lucite connected to copper flanges supported by copper rods. The unencapsulated crystal is mounted in a 10 mm thick solid PTFE reflector cage suspended in the centre of the inner cylinder using low background steel wires.

Low background 5 inch diameter type ETL 9390KB53 PMTs are mounted at either end of the inner cylinder, filled with high purity dehydrated mineral oil to provide the lightguides. The design uses low background materials throughout (OFHC copper, Lucite and PTFE) and allows for use of either total internal reflection or specular reflection for the lightguide surface. The latter is achieved by insertion of a polished aluminised mylar or Ano-Fol™ cylinder. Temperature control of the crystal is achieved using copper coils within the oil supplied by chilled, de-ionised, water (laboratory tests show an approximate optimum discrimination in conventional NaI(Tl) at ~10°C [4]). A number of denser organic liquids (Bromides and Iodides) were investigated, to give better PMT shielding, but these were found to give too much light attenuation. The unit is designed to accept crystal sizes up to ~10 kg (150 mm diameter) and to allow the oil lightguide to be varied from 0 to 400 mm. The latter is required so that shielding between PMT and crystal can be tailored to the measured PMT and crystal activities found. The NAIAD-0 unit is also designed for submersion in a liquid scintillator Compton veto, to aid background gamma suppression. The wall thickness has been minimised to reduce Compton scattering or absorption of gammas between the NaI and veto, which would otherwise reduce veto efficiency. The full NAIAD is envisaged as comprising 7 × 10 kg NaI modules plus 6 × 5 kg NaI modules, sufficient to allow investigation of annual modulation effects in any discriminated signal found. Experiments on one NAIAD-0 module have been performed using 5, 8.5 and 10 kg crystals from various manufacturers to optimise the light collection and discrimination prior to installation underground. Table 2 shows typical results. It can be seen that even crystals of 10–20 times greater mass than in proto-NAIAD give excellent light collection in this design. In the best close coupled arrangement using an 8.5 kg VIMS crystal, 14 p.e./keV was obtained.

4. NAIAD sensitivity

Using the results in Table 2 we show in Fig. 3 the sensitivity to spin dependent and spin independent WIMP interactions of NAIAD in various configurations. In all cases a pure higgsino is assumed with halo parameters: $\rho_{dm} = 0.3$ GeV cm^{-3}, $v_o = 220$ km/s, $v_{esc} = 650$ km/s and $v_{Earth} = 232$ km/s. In Fig. 3a spin dependent curves are shown firstly for light collection efficiency corresponding to lightguide lengths of 12 cm (8 p.e./keV) and 2 cm (12 p.e./keV) for 10 kg × years of data. The effect of a surrounding Compton veto (discussed below) is also illustrated. Above these curves we show our previously published limits [1] but recalculated here, for the first time, to account for latest form and spin factors appropriate for Na and I [8,13,14]. In this original detector (termed DM46) the efficiency was only 1.7 p.e./keV. Also shown in Fig. 3a is the estimated sensitivity for an encapsulated detector with 30 cm quartz lightguides and 3 p.e./keV efficiency, equivalent to the current sensitivity of our running 5 kg detector, assuming no anomalous fast time constant events [4]. Finally, we show the 1 year sensitivity for a full 100 kg NAIAD array. The results in Fig. 3 take account of several factors: firstly, the background electron recoil rate from internal crystal activity is taken to be flat and 2 counts keV^{-1} kg^{-1} d^{-1} (dru) at 2–20 keV, typical of measured values with >10 cm silica lightguides where the contributions from PMTs is <10%. Addi-

Table 2
Typical light collection efficiencies in NAIAD for various crystals and lightguide lengths

Crystal mass (kg)	PTFE thickness (mm)	Manufacturer	Light collection efficiency (p.e./keV) (LG = lightguide length)		
			LG = 0 cm	LG = 10 cm	LG = 20 cm
5	10	Hilger	10.0 ± 1.0	6.6 ± 0.7	2.9 ± 0.4
8.5	10	VIMS	14.0 ± 1.3	10.5 ± 1.0	4.4 ± 0.6
10	10	Hilger	10.5 ± 1.0		
10	10	Amcrys-H	11.3 ± 1.1	5.8 ± 0.7	3.1 ± 0.4

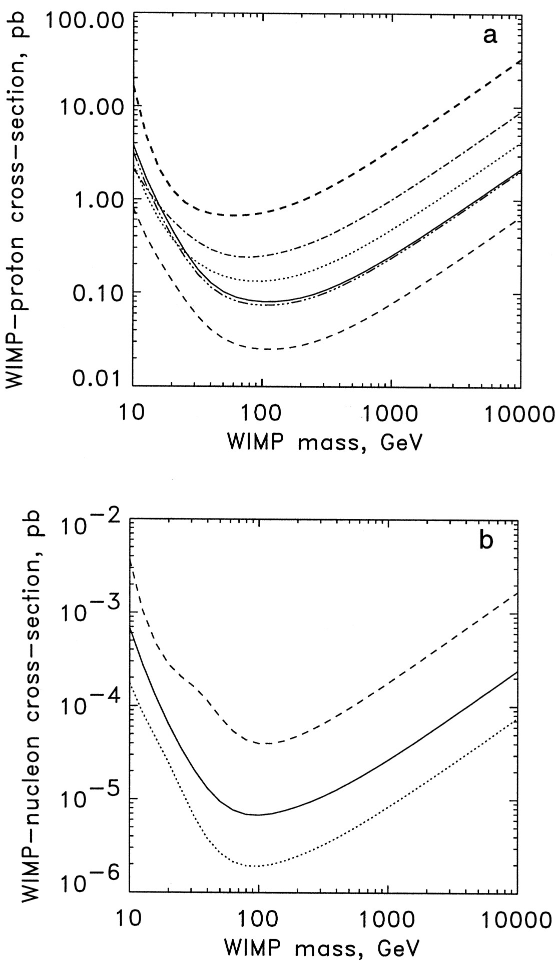

Fig. 3. Estimates of the sensitivity of NAIAD to (a) spin dependent and (b) spin independent WIMP interactions in various configurations: a) upper dashed curve (thick) – recalculated UKDMC limits from [1] (see text), dash-dotted curve – light output 3 p.e./keV, dotted curve – 8 p.e./keV, solid curve – 12 p.e./keV, dash-dot-dot-dotted curve – 12 p.e./keV + veto, lower dashed curve – 12 p.e./keV with 100 kg × yrs of exposure; b) dashed curve – recalculated UKDMC limits from [1], solid curve – 12 p.e./keV with veto, dotted curve – 12 p.e./keV with 100 kg.yrs exposure.

tional background from PMTs, estimated by Monte Carlo from the measured uranium, thorium and potassium activity in latest 9390KB53 PMTs, is then added allowing for the shielding effect of any lightguides used. This yields total assumed background rates for the 3, 8 and 12 p.e./keV set-ups of 2, 3.6 and 4.5 dru respectively. Secondly account must be taken of the recoil discrimination power. Laboratory and underground neutron and gamma tests on many crystals has allowed us to deduce for NaI(Tl) an empirical relation for the ratio of mean gamma to mean neutron time constant R_τ versus energy E at fixed temperature (taken as 10°C) of R_τ ($E > 4$ keV) $= 0.75 + 0.25 \exp[(3 - E)/5]$ and R_τ ($E < 4$ keV) $= 1$, (neutrons are assumed to generate nuclear recoils in the same way as WIMPs). R_τ, together with values for the time constant distribution width w (see Eq. (1)), found for NAIAD-0 to be 1.35–1.11 for 2–20 keV, determine the degree of intrinsic recoil discrimination versus energy. For illustration this can be defined as $D = 1 - S$ (see Fig. 4) where S is the fraction of the gamma and nuclear recoil τ-distributions that are overlapping – the distributions being first normalised to a total count of 1. For fully overlapping distributions, $R_\tau = 1$ and $D = 0$ and there is no discrimination. For separated distributions $D = 1$ and there is full event by event discrimination. Finally, account is taken of the energy resolution as measured for each set-up. It can be seen from Fig. 3a that with unencapsulated operation, and hence higher light collection, an improvement of up to $\sim \times 50$ in spin-dependent sensitivity above ~ 50 GeV appears achievable over the original DM46 limit for 1 year of running. Below 50 GeV the improvement is reduced because of the decrease in

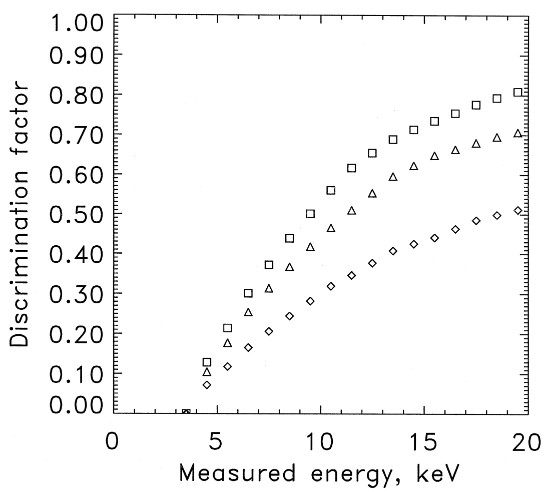

Fig. 4. Intrinsic recoil discrimination D versus energy in NaI(Tl) (see text for details): diamonds: 3 p.e./keV, triangles: 8 p.e./keV, squares: 12 p.e./keV.

discrimination with energy (see Fig. 4) – sensitivity below ~ 4 keV being determined by the raw electron background rate only. Results for incorporation of an active Compton veto assumed immersion of NAIAD-0 in liquid scintillator to give a thickness 30 cm around the crystal and 3 g/cm^2 of intervening material. The veto threshold was taken as 100 keV (as measured in a similar veto [15]), though lower thresholds where not found to alter efficiency significantly. As shown in Fig. 3 the improvement in sensitivity gained was found to be minimal. This arises principally because the background is dominated by internal NaI gamma activity for which there is a low probability of Compton scatters which deposit < 100 keV in the NaI (the energy range of interest for WIMP detection) and > 100 keV in the veto. In Fig. 3b are shown sensitivity curves for spin independent interactions using the same parameters and procedures as above. Here the sensitivity is found not to depend as strongly on light collection efficiency, results for 3, 8 and 12 p.e./keV yield curves lying within a factor 2 of each other (for clarity we show only the result for 12 p.e./keV). This insensitivity to photoelectron number arises because for spin independent interactions the expected WIMP induced recoil spectra are more steeply falling, due to the relatively increased iodine contribution [8]. The overall sensitivity curves are thus dominated by background in the first few energy bins (< 5 keV) for which discrimination is poor or zero and so not greatly improved by better photoelectron statistics. Nevertheless, for the full 100 kg NAIAD array an improvement of $\sim \times 25$ is predicted over the published limit. However, note that in both spin dependent and spin independent cases the improvements are contingent on identification and removal of the cause of the anomalous population of events currently observed in low background NaI experiments [4,5].

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