FURTHER REDUCTION IN DARK MATTER LIMITS FROM SODIUM IODIDE EXPERIMENTS

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Recently published dark matter limits from NaI detectors running in the Boulby mine are presented. Techniques and plans for improving NaI limits are discussed, including improved light collection, materials purity, increased target mass, noise rejection and improved discrimination. Results of calculations of the underlying neutron background are presented.

1 Introduction.

This paper outlines recently published[1] limits on the interaction rate of Galactic dark matter in the form of hypothetical weakly interacting massive particles, derived from a low background sodium iodide scintillation detector operated in the Boulby mine. The results are from 3kg.years of data from a Kyropoulos grown crystal, using statistical discrimination to compare against gamma calibration data obtained through either Compton scattered ^{60}Co events or the underground cavern background. Details of the low background detector design, shielding arrangement and Boulby mine facility are available elsewhere[2].

Techniques to improve the sensitivity of NaI detectors such that they may reach the neutralino rates predicted by supersymmetric particle physics theories are outlined, with results of calculations of the underlying neutron background that may mimic a WIMP signal and discussion of the reduction of this background.

2 Analysis Technique.

Full details of the analysis technique used are given in the recent paper[1], a brief overview being given here. A statistical comparison is performed between the observed background data and calibration data from gamma and neutron sources. The scintillation pulses recorded from the detector have a characteristic pulse shape distribution dependent on the energy, type of recoil and temperature. Nuclear recoil pulses, due to WIMP or neutron interactions, have faster time constants, τ, than the electron recoil events due to gamma interactions or β-decay. At high enough energies the two distributions may be clearly separated, but at the low recoil energies of interest a statistical comparison must be made.

The observed background data shown in figure 1 are grouped into 3keV wide energy bins for statistical purposes and time constant distributions produced for each energy bin. The distributions may be closely described by a gaussian distribution in $\ln(\tau)$, which allows removable of a population of fast photomultiplier noise pulses at the low energy end of the background spectrum, as shown in figure 1. Comparison is made against the time constant distributions from neutron and gamma calibration data, showing that the background is consistent with purely gamma events, i.e. zero signal. The error in this zero signal is statistically determined, using a conservative non-Bayesian approach.

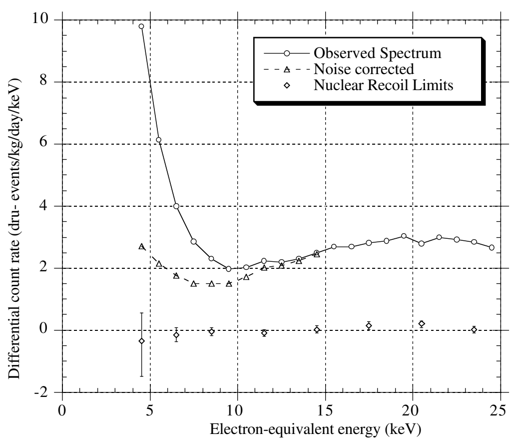

Figure 1: Differential spectra of background event rates, showing observed total rate, rate after subtraction of fast noise pulses and 2σ limits on the nuclear recoil event rate.

The detector was not temperature controlled throughout the background run. However the mean temperature during the background data collection was found to be 0.1˚C from that during calibration. This excludes any systematic effect between the time constant distributions, although an additional statistical variance was combined with that above due to the spread in background temperature.

Monte Carlo simulations show that the pulses observed at low energies in the calibration runs are predominantly produced by single Compton scattered gammas, excluding systematic time constant shifts due to multiple scattering.

3 Dark Matter Limits.

The confidence limits shown in figure 1 can be converted to a 90% confident upper limit in the dark matter signal rate, and hence corresponding interaction cross section, as a function of the WIMP mass[3]. This calculation is performed for each

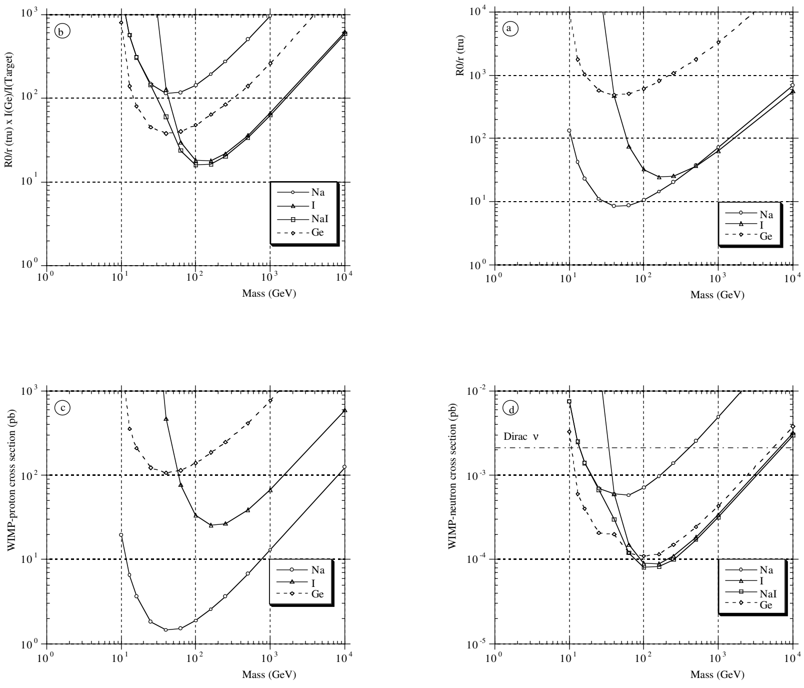

Figure 2: 90% confidence limits on WIMP rates and cross sections: (a) Spin dependent normalised rate; (b) Coherent normalised (to Ge) rate; (c) Spin dependent WIMP-proton normalised cross section; (d) Coherent WIMP-neutron normalised cross section.

energy band, target species and interaction type - spin or coherent. The independence of the energy bands allows statistical combination into a single overall limit for each species and interaction type, as shown in figure 2. Also shown are current limits from double β-decay germanium experiments.

For comparison between different target species normalised rate and cross section are presented, rate normalised to R_0/r where $r=4M_tM_d/(M_t+M_d)^2$ and cross section normalised to σ_0/μ^2, where μ is the reduced mass. These two quantities are related by a numerical factor and are thus both measures of the fundamental interaction. The 'odd group model' has been used to convert the limits to the basic WIMP-proton cross section for spin dependent interactions, the neutron number being used in the coherent case, as for a Dirac neutrino.

4 Future Improvements.

Further improvements to sodium iodide detectors are foreseen which will increase their sensitivity by up to two orders of magnitude, reaching the neutralino rates predicted by supersymmetric particle theories. This section outlines the work currently in progress within the UKDMC to reach these limits.

The most direct technique is to increase the target mass and runtime to reduce statistical errors in the calibration and background spectra, provided no low level, unidentifiable, systematic error is present. This approach is obviously cost limited.

The underlying background rate may be reduced in several ways. A Compton veto surrounding the detector may be used to eliminate events where a high energy gamma Compton scatters in the NaI crystal, giving a low energy signal. In larger crystals the outer layer of NaI will absorb low energy gammas, this self shielding reducing the overall background rate. Quantitative tests of this effect are in progress. The use of higher purity materials for detector construction reduces the underlying background rate, for example work is in progress to remove uranium and thorium contamination from the NaI powder before crystal growth to remove the β-decay events[4]. The replacement of the photomultiplier tubes with large area avalanche photodiodes would exchange a relatively active glass based detector with a low activity solid state device.

An improvement in light collection efficiency of the detector system has a two fold effect. The energy threshold of the detector is lowered, improving detector sensitivity and reducing any nuclear form factor correction. Also the width of the calibration and background distributions in time constant are decreased improving discrimination of gamma events. The light collection efficiency may be improved in several ways including the development of larger area photomultipliers with improved quantum efficiencies and light collection, optimisation of the geometry of the detector system and again use of avalanche photodiode devices directly coupled to

Table 1: Estimated rates of neutron generated nuclear recoils in the energy range 4keV - 20keV and potential reduction possible.

Neutron Source	Rate ($kg^{-1}day^{-1}$)	Reduction Technique	Reduced Rate ($kg^{-1}day^{-1}$)
U-Th contamination in rock	10	Hydrogenous shielding	$< 10^{-4}$
U-Th contamination in detector material	10^{-3}	Purification and electroforming	$< 10^{-4}$
Cosmic ray muon generated in shielding	10^{-2}	Muon veto	$< 10^{-4}$

the crystal. Light losses through the crystal window interfaces may be eliminated by fluid coupling the photomultipliers to unencapsulated crystals.

A further improvement in sensitivity is achieved by increasing the ability of the detector to discriminate the dark matter signals from the gamma background. The discrimination power of NaI crystals is dependent on the operating temperature, dopant level and growth technique used for fabrication, all of which affect the time constant and light output of the scintillation and require optimisation. Through the use of the ‘UVIS’ technique, the study of the fast u.v. and slow visible components in undoped NaI scintillation at 160K, discrimination at least a factor of three better than room temperature doped crystals may be achieved[5].

The underlying background spectrum and discrimination power may also be improved through software by rejection of electronic and photomultiplier noise pulses and investigation of better discrimination parameters and pulse shape fitting techniques, using monoenergetic neutron calibrations as reference.

5 Neutron Backgrounds.

A neutron in the energy range 100keV to 10MeV may cause a 1-30keV nuclear recoil within the sodium iodide target which will be indistinguishable from one generated by a WIMP. It is thus essential to have an understanding of the main sources of neutron background, and the levels to which they may be reduced. Table 1 outlines the three main components of the neutron background, illustrating the techniques required to reduce the event rate to less than $10^{-4}kg^{-1}day^{-1}$.

Uranium and thorium present in the surrounding rock of the cavern produce neutrons through alpha interactions and fission. The predicted neutron rate is typically five orders of magnitude lower than the background gamma flux, giving a rate of $10^{-6}cm^{-2}s^{-1}$ within the cavern, giving a background in an unshielded target of $10kg^{-1}day^{-1}$. These neutrons may be thermalised and absorbed by hydrogenous materials such as water or wax. Monte Carlo studies have also shown that more than

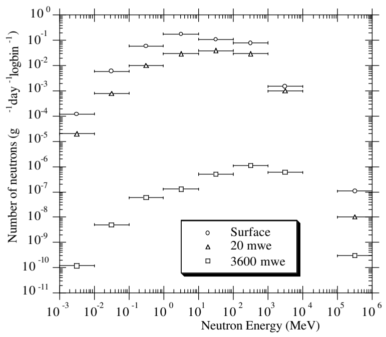

Figure 3: Cosmic ray muon induced neutron spectra as a function of depth.

20cm of lead or copper rescatters a large fraction of neutrons back to the cavern, substantially reducing the flux.

There may also be uranium and thorium contamination within the target or detector materials, again with a neutron rate five orders of magnitude lower than the associated gamma flux. An upper limit may be placed on this background as a shielded detector has a typical rate of $100kg^{-1}day^{-1}$. If all of this was due to U and Th contamination then the upper bound of neutron background from this source would be $10^{-3}kg^{-1}day^{-1}$. This limit will further be reduced as lower background target and detector materials are developed through purification and electroforming.

Cosmic ray muons may interact within the surrounding rock and shielding to produce neutrons through spallation and evaporation. The cosmic ray muon spectrum as a function of depth may be combined with the neutron production cross sections to give the estimated neutron flux as shown in figure 3. Those neutrons generated within the rock, at a flux two orders of magnitude lower than that due to U and Th contamination, may be shielded as above. The response of the detector system to the neutrons generated within the shielding which scatter into the target can be simulated, giving an event rate of $10^{-2}kg^{-1}day^{-1}$. These neutrons generated within the shielding may be excluded though a muon veto, an achievable veto efficiency of 99% reaching the required rate of $10^{-4}kg^{-1}day^{-1}$.

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