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Recent Results of the Dark Matter Search with NaI(Tl) Detectors at Boulby Mine

B. Ahmed[a], G. J. Alner[b], J. C. Barton[c], A. Bewick[a], M. J. Carson[d*], D. Davidge[a], J. V. Dawson[a], T. Gamble[d], S. P. Hart[b], R. Hollingworth[d], A. S. Howard[a], W. G. Jones[a], M. K. Joshi[a], V. A. Kudryavtsev[d], T. B. Lawson[d], V. Lebedenko[a], M. J. Lehner[d†], J. D. Lewin[b], P. K. Lightfoot[d], I. Liubarsky[a], R. Lüscher[a], J. E. McMillan[d], B. Morgan[d], G. Nicklin[d], S. M. Paling[d], R. M. Preece[b], J. J. Quenby[a], J. W. Roberts[d], M. Robinson[d], N. J. T. Smith[b], P. F. Smith[b], N. J. C. Spooner[d], T. J. Sumner[a] and D. R. Tovey[d]

[a]Blackett Laboratory, Imperial College of Science, Technology and Medicine, London SW7 2BZ, UK

[b]Particle Physics Department, Rutherford Appleton Laboratory, Chilton, Oxon OX11 0QX, UK

[c]Department of Physics, Queen Mary, University of London, London E1 4NS, UK

[d]Department of Physics and Astronomy, University of Sheffield, Sheffield S3 7RH, UK

The NAIAD (NaI Advanced Detector) experiment for WIMP dark matter searches at Boulby Mine (UK) is described. The detector consists of an array of encapsulated and unencapsulated NaI(Tl) crystals with high light yield. Six crystals are collecting data at present. Data accumulated by four of them have been used to set new limits on the WIMP-nucleon spin-independent cross-section.

1. Introduction

The UK Dark Matter Collaboration (UKDMC) has been operating NaI(Tl) detectors at the Boulby Mine underground site for several years [1]. Limits on the flux of weakly interacting massive particles (WIMPs), that may constitute up to 90% of the mass of the Galaxy, have been set using the data from the first encapsulated detector. More stringent limits have since been set by the DAMA experiment, which has used a similar approach (pulse shape analysis, PSA) and larger data statistics [2].

The DAMA group is now studying the annual modulation of the background rate in its crystals without using PSA. The group claims that they have observed annual modulation consistent with the expected signal from WIMP-nucleus interactions with a specific set of WIMP parameters [3].

Although several existing experiments have potential to probe the whole region of WIMP parameters allowed by the DAMA signal (see, for example Refs. [4–6]) they use other techniques and other target materials. This leaves room for speculations about possible uncertainties in the comparison of results. These uncertainties are related to systematic effects and nuclear physics calculations. Probing the DAMA allowed region with similar detection techniques and the same target material remains an interesting and important task.

Following the discovery of an anomalous component in the data from several of our encapsulated crystals (for a complete discussion see Ref.[1]) an array of unencapsulated crystals as a dark matter experiment has been proposed [7]. Such an experiment could probe the region of WIMP parameters allowed by the DAMA experiment using similar detection techniques and reach the region favoured by some SUSY models. NaI has the advantage of having two targets with high and low masses, thus reducing uncertainties related to nuclear physics calculations.

In this paper we present the status of the new

*Corresponding author, m.j.carson@sheffield.ac.uk

†Now at the University of Pennsylvania, Philadelphia, PA 19104, USA

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Table 1
Statistics for NAIAD detectors.

Crystal	Mass, kg	Light yield, pe/keV	Time, days	Exposure, kg×days
DM74 (oil)	8.50	3.5 ± 0.4	117.1	995.7
DM72	3.94	7.0 ± 0.4	274.0	1079.4
DM76	8.32	4.6 ± 0.3	101.2	842.3
DM77	8.41	6.1 ± 0.3	62.2	522.9
DM74 (dry air)	8.40	8.4 ± 0.4	52.2	438.7
Total exposure				3879

NAIAD experiment and present recent WIMP-nucleon cross-section limits obtained with this new array of dark matter detectors.

2. The NAIAD Experiment

The NAIAD array is operational in the UK Boulby Mine laboratory (North Yorkshire) at a vertical depth of about 1100 metres. In its final stage the NAIAD array will consist of eight NaI(Tl) crystals. At present (March 2002) 6 detectors are running with a total mass of 46 kg. Two detectors contain encapsulated crystals, while 4 other crystals are unencapsulated. To avoid degradation due to air humidity, the unencapsulated crystals have been sealed in copper boxes filled with dry air. Each crystal is mounted in a 10 mm thick solid PTFE (polytetrafluoroethylene) reflector cage and is coupled to two 4-5 cm light guides at either end. The light guides are also mounted in the PTFE cages and are coupled to two 5 inch diameter low background photomultiplier tubes (PMTs) of the type ETL 9390UKB. Low background materials are used throughout.

Temperature control of the system is achieved by pumping cooled water through copper coils attached to the outside of each copper box.

The copper boxes containing each detector have been installed into lead and copper "castles" which are used to shield the detectors from background coming from the surrounding rock.

3. Analysis Procedure and Calibrations

Final analysis has been performed on the sum of the pulses from each pair of PMTs. The parameters of the pulses from each PMT have been used to apply so-called asymmetry cuts to reject those events with obvious asymmetry between each pulse. Our standard procedure of data analysis involves fitting a single exponential to each integrated pulse to obtain the index of the exponent, τ, the amplitude of the pulse, A, and the start time, t_s. The scintillation pulses from nuclear and electron recoils were proven to be nearly exponential in shape [8]. In addition to these, the mean time of the pulse, as an estimate of the time constant, χ^2 of the fit, number of photoelectrons and energy are also calculated for each pulse. The conversion of the pulse amplitude into number of photoelectrons and energy has been done using pre-determined conversion factors, which comes from energy and single photoelectron calibrations. Energy calibration is obtained using ^{57}Co gamma-ray sources (122 keV line).

For each run (or set of runs) the "energy – time constant" $(E-\tau)$ distribution has been constructed. If all operational settings (including temperature) are the same for several runs, the $(E-\tau)$ distributions for these runs have been summed together. Data with crystal temperature outside a predefined range have been removed from the analysis.

For any small energy bin (1 keV width, for example), the time constant distribution can be approximated by a Gaussian in $\ln(\tau)$ with the three free parameters: mean time constant τ_o, width w and normalisation factor N_o (for a more detailed discussion of the distributions see [9] and references therein). In experiments where a second population is seen (for example, nuclear recoils from a neutron source or possible WIMP-nucleus interactions), the resulting τ-distribution can be fitted with two log(Gauss) functions with the same width w (we assume the same width for both populations since the width is determined mainly by the number of collected photoelectrons). The aim of the analysis procedure was to search for a second population of events in τ-distributions or to set an upper limit on its rate.

Another critical feature of the detector response is the energy resolution which is important in the procedure of setting limits on the rate of nuclear recoils produced by WIMP-nucleus interactions. The procedure requires the calculation of the recoil spectra as functions of visible energy for various WIMP masses and their comparison with measurements [10]. Recoil spectra calculated in a particular model should be folded with the detector response function to obtain the visible energy spectrum. The detector response function in this case is the energy resolution function, which shows the probability distribution of the deposited energy being seen by a detector as a certain visible energy. Assuming the probability distribution is a Gaussian function (for a Poisson process with large number of photoelectrons), the energy resolution is characterised by the width, σ, of the Gaussian function or by the full width at half maximum of the distribution, FWHM ($= \sigma \times 2.35$).

The energy resolution of the NAIAD detectors is normally measured during the standard procedure of energy calibration with ^{57}Co sources (122 keV line) performed every 2-4 weeks. However, nuclear recoils from WIMP-nucleus interactions can be seen mainly at low visible energies (4-30 keV). Ideally, we need to perform the measurements of energy resolution as a function of energy at low energies. Practically, this is impossible because we cannot access the surface of the crystals sealed in the copper boxes during the experiment and low energy photons will be absorbed in the copper or other materials surrounding the crystal.

Prior to moving the detectors underground the energy resolution of the crystals at various energies has been measured with a number of gamma-ray sources. Figure 1 shows the width of the Gaussian fit to the measured gamma-ray line as a function of photon energy (filled circles) for one of the UKDMC crystals (DM77).

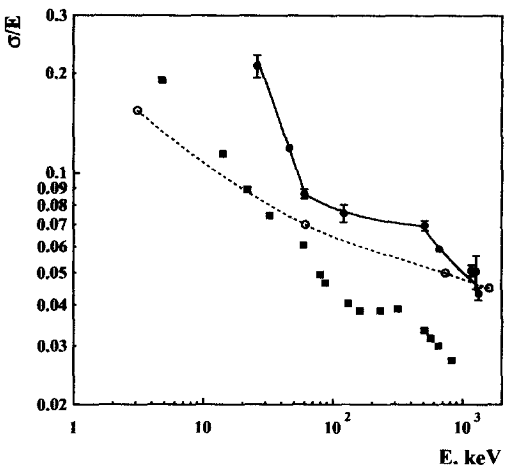

Figure 1. Energy resolution of the UKDMC detector (filled circles with fit), DAMA detector (open circles with smooth curve drawn through the experimental points) [14] and small size crystal (filled squares) [11].

The data presented in Figure 1 cannot be fitted with a single function. Our measurements agree reasonably well with the measurements by Sakai [11], in which a small size ($1 \times 1 \times 2$ cm^3) NaI(Tl) crystal was used. The data from Ref. [11] are shown by filled squares in Figure 1. Both measurements (UKDMC and Ref. [11]) reveal a complicated dependence of the energy resolution on the energy. Three regions with different slopes are clearly seen. Similar effects have been reported previously (see, for example, Ref. [12] and references therein), although for a more restricted energy range. Note, that the resolution of our crystal is worse than the one reported in Ref. [11] due to the much larger crystal used.

According to the theory of scintillation counting (for discussions see Refs. [12,13]) the energy dependence of the resolution function is approximated as $\left(\frac{\sigma}{E}\right)^2 = a + \frac{b}{E}$. The parameters a and b have been determined from the best fits to the data (for each crystal) in three energy regions, as shown in Figure 1. These parameters have then

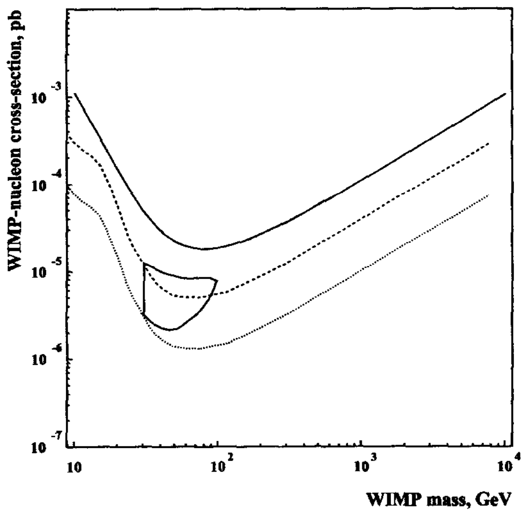

Figure 2. NAIAD limits on WIMP-nucleon spin-independent cross-section as functions of WIMP mass. Also shown is the region of parameter space favoured by the DAMA positive annual modulation signal (closed curve), limits on the spin-independent cross-section set by the DAMA experiment using pulse shape analysis (dashed curve) and the projected limit of DAMA experiment if the group were to apply PSA to all available data sets (dotted curve).

been used to extrapolate the resolution function to lower energies.

Also shown in Figure 1 are the reported measurements of energy resolution by the DAMA group [14]. At high energies the resolution of DAMA crystals is similar to our resolution, while at low energies it appears to be much better than ours and even better than the energy resolution of the much smaller crystal.

4. Results and Conclusions

Figure 2 shows current UKDMC limits on WIMP-nucleus cross-section from the data reported here. The total statistics includes five runs with one of the crystals (DM74) running twice: in mineral oil and in dry air (after re-polishing). Table 1 shows the main characteristics and statistics for all detectors. Following completion of the NAIAD array, improvements to both DAQ and pulse fitting procedure (both currently underway) we expect to improve upon our current limits by a factor of 10 in the next 2-3 years of data taking.

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