LATEST LIMITS ON COLD DARK MATTER INTERACTION RATES FROM THE UK UNDERGROUND NaI DETECTOR

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ABSTRACT

New improved limits have now been obtained for the spin-dependent interaction cross-sections in NaI for weakly interacting dark matter particles assuming they are responsible for the dark matter halo of our Galaxy. The underground facility and experimental configuration will be described together with data extraction techniques. The background rate in a 1 kg NaI(Tl) crystal scintillator of low radioactivity construction is reported after exposure in the underground facility. A level of ~ 7 events/kg.day.keV at 4 keV (equivalent photon energy) provides an improved limit for the possible spin-dependent weakly interacting massive particle (WIMP) cross section for elastic scattering from NaI nuclei. A minimum value of $1.5\ 10^{-33}\ cm^2$ is obtained for a 25 GeV WIMP mass. Our results are compared in a consistent model independent way with previous data.

Introduction

First results are presented from room temperature NaI scintillator experiments being carried out by the UK dark matter consortium in a deep underground laboratory in Boulby, U.K. The laboratory is at a depth of 1100 m (3000 m water equivalent) and contains two shielded enclosures. One of these is a 6 m diameter tank filled with recirculated pure water to a depth of 6 m into which experiments can be lowered. The second is a lead and copper castle constructed from materials which have been stored underground for some time. The data used here were acquired from a 1.27 kg NaI(Tl) crystal operating in the castle. The non-zero nuclear spin of both Na and I make such a crystal a useful target for Weakly Interacting Massive Particles (WIMPs) assuming they couple predominently via an axial spin-dependent scattering process. WIMPs, it has been postulated, may account for the missing matter within the Galaxy, and if this is indeed the case, then experiments of the type reported here currently provide the best limits to their spin-dependent scattering cross-sections and should eventually through improved background suppression lead to direct positive detections. Here the measured background rate in the NaI(Tl) detector has a marginally improved threshold over other experiments and new upper limits for the spin-dependent neutralino elastic scattering cross-sections are derived. Our results are compared in a consistent *model independent* way with previous data.

Experimental details and observations

The shielded 'castle' comprised 10 cm Pb with 10 cm of Cu inside. Observations were carried out with a 1.27kg NaI(Tl) crystal observed by two EMI 9265A photomultipliers whose 3" diameter matched that of the crystal. The photomultipliers viewed at opposite crystal faces through 30 cm water light guides. Precautions to reduce the contribution to the crystal counting rate from phototube radioactivity via external scattering included use of a C101 copper shield, 3 cm thick, surrounding the crystal. The crystals were prepared using low activity material. Encapsulation was in PTFE with a Cu outer jacket, the window was made of Spectrosil and the glue employed was Epotek, all of known low activity.

Pulse shape recording of the coincident output of the two photomultipliers was performed via a LeCroy 9430 oscilloscope and an analogue pulse height distribution was captured in parallel. The system was calibrated with ^{137}Cs and ^{60}Co sources. An electronic noise threshold corresponding to 2.93 keV was set before waveform capture. The run reported here was of 9.6 10^5 s live time duration, starting on July 29^{th} 1993, and it was possible to scan the pulse profiles of each individual event with an energy loss less than 80 keV. In this manner, spurious electrical noise interference and some forms of spurious photomultiplier pulses could be easily rejected. At this stage no further rise time or pulse shape discrimination was attempted.

Figure 1 shows the counting rate obtained in the high energy part of the background spectrum. The continuum region from 750 keV to 900 keV can be used to put a limit of 0.9 ppm on the internal ^{40}K level from the expected beta-decay spectrum. The photoelectric peak at the 1.4 MeV ^{40}K line gives a 50% higher value and this indicates the presence of an external component. The spectrum obtained at lower energies is shown in figure 2. The peak at 47 keV could be due to ^{210}Pb gamma ray production due to contamination, possibly within the NaI(Tl). Cosmogenic activity due to sea-level exposure to secondary cosmic rays can also produce short lifetime peaks from ^{129}I at the 10 events/kg.day.keV level[1)]. An average event rate of $\sim$7 events/kg.day.keV was achieved at 4 keV equivalent photon energy loss in the crystal. The photoelectron yield from the assembly was 1.6 photoelectrons/keV. The data were binned into channels 0.5 keV wide.

Data analysis and interpretation

To interpret the data of figure 2 and to compare with other work, we adopted a procedure for evaluating the upper limit to a spin-dependent cross section which is virtually independent of the particle physics involved in the scattering process, as there remains significant theoretical uncertainty in the details. We concentrated on the spin-dependent cross section since this is where our work becomes significant. For a given WIMP mass we first predicted the expected form for a measured differential recoil spectrum assuming the WIMPs constitute all the necessary Galactic dark halo mass. The predicted recoil spectrum was then scaled so that it did not exceed the 2σ error bars on the actual measured background spectrum on more than three consecutive data bins[2)]. The maximum allowed interaction rate was given by integrating the scaled predicted spectrum over all energies and an effective cross section was then be derived from this rate.

To predict the measured recoil spectrum we started with a Maxwellian dark matter velocity distribution, with $kT = E_o$, modified for the motion of the Earth through the dark matter WIMP population and the Galactic escape velocity cut-off. This gave the WIMP flux passing through the detector. The expected measured differential recoil spectrum in an ideal detector, assuming isotropic centre of mass scattering is then

$$\frac{\partial R}{\partial E_V} = \frac{1}{f'(E_r)E_r + f(E_r)} \frac{R_T}{A} \exp - \frac{E_r}{A} \qquad (1)$$

where $A = E_o r E_c/(E_c + E_o r)$, r is a kinetic factor which depends on the target nucleus mass, M_T and the WIMP particle mass, M_D, such that $r = \frac{4 M_T M_D}{(M_T+M_D)^2}$, f is the ratio of measured energy to recoil energy, E_r, i.e. $f = E_V/E_r$, and E_c arises due to a form factor correction. This form factor correction was treated in a relatively simple way at this stage, namely[3], with $|F(E_r)|^2 = \exp -E_r/E_c$. Values of E_c for axial spin-dependent coupling were taken from Ellis & Flores[4]. R_T is the total event rate expected in the crystal integrated down to zero energy.

The finite detector resolution, including the Poissonian statistics of the photoelectron generation, was taken account of by convolving the resolution with equation 1. Once this was done we deduced an upper limit to the total interaction rate R_T which was converted into an effective cross-section for each individual target nuclear species, of mass M_T, by

$$\sigma_T = \frac{R_T M_D M_T}{\rho \overline{v}_D} \tag{2}$$

For NaI(Tl) we treated the nucleii of ^{23}Na and ^{127}I separately. The quenching factor, f, is different for each and appears to be independent of energy in the range of interest[5,6,7]. We used values of $f_{Na} = 0.25$ and $f_I = 0.07$. For comparison with Ge results, we used the energy dependent form of f derived from the observations of Sattler et al.[8], which are lower than those predicted by the commonly used theory of Lindhardt et al.[9]. However this turned out to have a relatively small effect.

The method of Reusser et al.[2] was used to establish the exclusion limits on the effective total cross-section and we show the results of this in figure 3. Data from other experiments were treated similarly and are displayed in figure 3. Our results are seen to provide the best cross-section limits for axial-coupling when displayed in this model-independent way. Results from a 6 kg NaI(Tl) crystal will be published separately[12].

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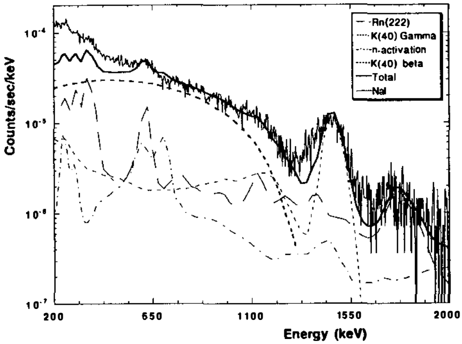

Figure 1: High energy pulse height spectrum from a 1.27 kg NaI(Tl) crystal.

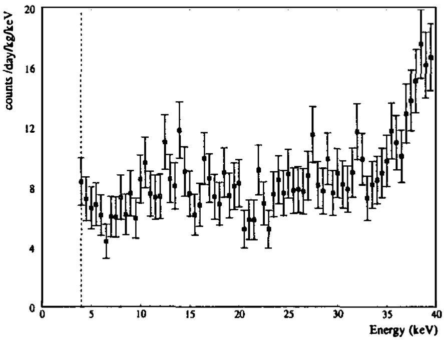

Figure 2: Low energy pulse height spectrum from a 1.27 kg NaI(Tl) crystal. The dashed vertical line is positioned at the lowest energy at which we remain confident of the validity of our pulse scanning technique.

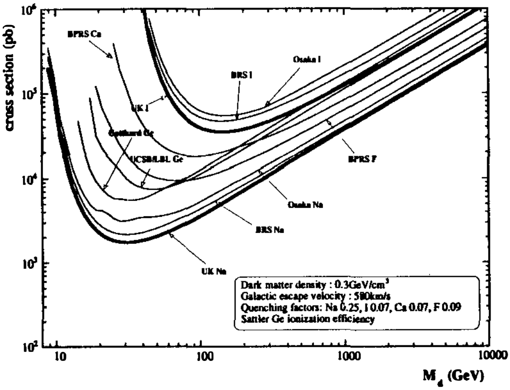

Figure 3: Upper limits to WIMP interaction total cross sections. Na and I curves are calculated from background spectra arising from this work (UK), from the BRS collaboration[6)], and from the Osaka experiment[5)]. The Ca and F curves use the data from the BPRS collaboration[10)]. The ^{73}Ge curves use data from the UCSB[11)] and Gotthard[2)] experiments.