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PROCEEDINGS
SUPPLEMENTS

# New Dark Matter Limits from the Boulby NaI Detectors

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Using pulse shape analysis of data from 173 operating days of our 6.2 kg NaI detector in the energy range 7-10 keV we present new limits on weakly interacting massive particles that may constitute the dark matter. An improvement of a factor >30 has been obtained over Ge for spin-dependent dark matter interactions while limits for coherent interactions are comparable to Ge for masses > 100 GeV.

## 1. INTRODUCTION

We have been running NaI and other detectors in the Boulby underground site (1100 m deep) since 1993 searching for nuclear scattering events expected from weakly interacting massive particles that may constitute the galactic dark matter. These events are expected to form a continuous spectrum below 100 keV, on top of a spectrum of background electron recoils due to gamma and beta interactions. Limits have so far been published based on the low energy background from our 1.3 kg NaI crystal [1]. Presented here are first results from our 6.2 kg NaI detector in which active background reduction is achieved through use of pulse shape differences between the nuclear and background electron recoils, the former having a shorter decay time constant than the latter. The crystal is circumferentially wrapped in ptfe tape and coupled to two EMI 9625A PMTs via 30 cm silica light guides - the assembly mounted in a copper cylinder of 3 mm thickness suspended at the center of 160 tons of high purity water to provide gamma and neutron shielding. All materials were selected for low radioactivity and radon deposits. Integrated coincident pulses from the PMTs were digitized and recorded along with the crystal temperature. The sensitivity achieved was 1.6 pe/keV.

## 2. ANALYSIS

The pulse shapes were characterized by a best fit tau to an exponential rise $1 - \exp[-(t-t_0)/\tau]$ with the start time $\tau_0$ used as an additional variable. The energy E of each pulse was estimated from its asymptotic amplitude. The complete 173 days of events were binned in an array of $N(E,\tau)$ with E in 1 keV bins and $\tau$ in 2.5 ns bins. Distributions of $\tau$ for the energy band 7-10 keV for background gamma and neutron induced recoils were obtained (see fig. 1).

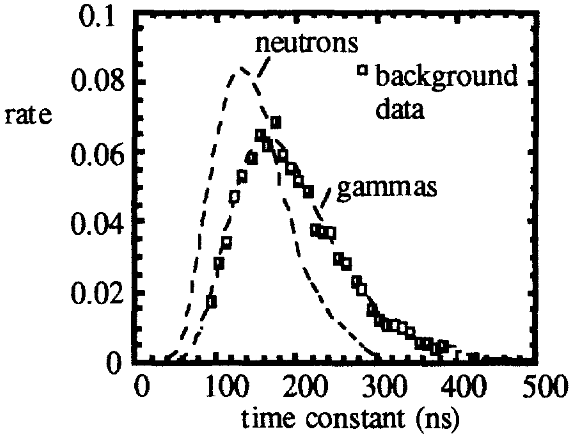

Figure 1. Comparison of background time constant data with gamma and neutron calibrations for 7-10 keV.

Calibration of the energy scale and gamma pulse shape was achieved using $^{57}$Co and $^{60}$Co sources

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while for nuclear recoils a Cf neutron source was used. The latter produces nuclear recoils with an admixture of gammas, but a distribution for pure nuclear recoil events could be extracted by comparison with the pulses from the pure gamma source at the same energy.

The $\tau$ distributions are best fit by a gaussian in $\ln(\tau)$ (confirmed in laboratory tests) :

$$dN/d\tau = N_o[2\pi]^{-1/2}[\tau \ln(w)]^{-1} \exp\{-0.5[(\ln(\tau)-\ln(\tau_o)]^2/[\ln(w)]^2 \quad (1)$$

where $\tau_o$ is the mean of the distribution and w the width. The background data were found to be consistent with predominantly gamma type pulses but could contain a "signal" fraction $g_n$ of nuclear recoils that would produce a proportional displacement of the data towards the neutron curve (smaller $\tau_o$) where $g_n = (t_g - t_d)/(t_g - t_n)$ and $t_d$, $t_g$, $t_n$ are defined as $\tau_o$ for the data, gamma and neutrons. For the present data (7-10 keV) $g_n= 0.1$ +/- 0.01 where the error ($\sigma(g_n)$) arises from the standard deviation in the fitted $t_d$ and $t_g$, and the error from a small temperature correction needed to account for the 2K fluctuation in crystal temperature and its influence on the pulse shapes.

In the 7-10 keV range the background rate was found to be 1.8 $keV^{-1}kg^{-1}d^{-1}$. Multiplying this by $g_n$ gives the signal and error so that, using Bayesian statistics to allow for the unphysical possibility of a negative signal within the errors, a 90% confidence level can be derived as a function of particle mass. This was done separately for the Na and I components, and for coherent and spin dependent, cases and are shown in fig 2, plotted in normalized rate $R_o/r$ ($kg^{-1}d^{-1}$).

The limits of fig. 2 were derived as follows:

The expected differential rate R (in $keV^{-1}kg^{-1}d^{-1}$) due to a flux of particles of mass $M_D$ scattering off nuclei of atomic number A and mass $M_T$, can be approximated by [2]:

$$dR/dE_R = (c_1 R_o/E_o r) \exp(-c_2 E_R/E_o r)\, F^2(E_R, A) \quad (2)$$

where $E_R$ (KeV) is the recoil energy, $E_o$ (GeV) = 1/2 $M_T$ $(v_o/c)^2$, $v_o$ = 230 $kms^{-1}$, $M_T$ (GeV) = 0.932A, $r = 4 M_T M_D/(M_T + M_D)^2$, and $F^2(E_R, A)$ is a nuclear from factor correction. $R_o$ is defined as the total rate for a detector comprising point like nuclei for which $F^2(E_R, A) = 1$ at rest with respect to an isotropic Maxwellian dark matter flux, and assuming motion through the Galaxy. In this case best fits give $c_1 = 0.751$ and $c_2 = 0.561$. For a given nuclei there is an additional efficiency factor $f_n$ needed to account for the difference between $E_R$ and the energy actually observed $E_v$ such that $dR/dE_R = f_n\, dR/dE_v$. For Na and I here we use our measured values of $f_{Na} = 0.3$ and $f_I = 0.08$ [3].

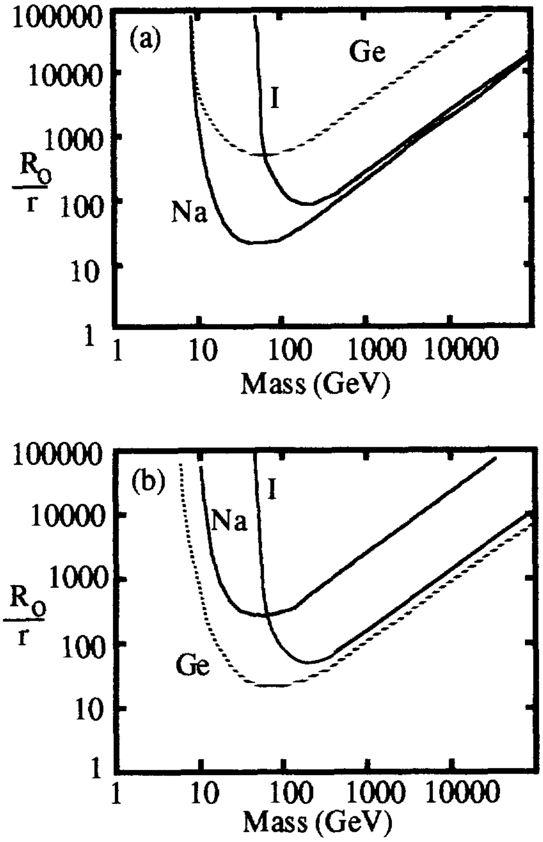

Figure 2. 90% confidence limits for (a) normalised rate (spin-dependent, with form factor correction) (b) normalised rate (coherent, with form factor correction and normalised to Ge using $(A-Z)^2_{Ge}/(A-Z)^2_{target}$).

$R_o$ (in $kg^{-1}d^{-1}$) is related to the cross section by $R_o/r = 126\ (\sigma_o/m^2)$ where $m = M_T M_D/(M_T + M_D)$. $\sigma_o$ can contain spin-dependent and/or spin-independent terms $\sigma_o = \sigma_1 I(A)$ where $\sigma_1$ denotes point-like cross sections for a WIMP incident on a single proton ($\sigma_{W-p}$) or neutron ($\sigma_{W-n}$). I(A) contains the nuclear coherence factor ($I(A) = A^2$ if all nucleons participate or $(A-Z)^2$ for Dirac neutrinos), or spin factors

($I(A) = C_H{}^2 C_N{}^2$ where $C_H$ is the hadronic term and $C_N$ the nuclear structure term [2]). (To give limits in terms of WIMP-proton cross section ($\sigma_{W\text{-}p}$) we adopt the odd group model with values for $C_H{}^2$ and $C_N{}^2$ [4] that yield I(A)/(Iproton) = 0.055 (sodium), 0.009 (iodine), 0.043 ($^{73}$Ge)).

We take the form factor, in terms of q (momentum transfer in fermi$^{-1}$) and R (effective nuclear radius in fermi) as modified Bessel functions [5,6] to be:

coherent:

$$F_c{}^2(qR) = [3\, j_1(qR)/qR)]^2 \exp[-(qs)^2] \qquad (3)$$

$$R \sim 1.1 A^{1/3} f, \quad 0.9 < s < 1f$$

spin-dependent:

$$F_s{}^2(qR) = [j_0(qR)/qR)]^2 \qquad qR < 2.55,\ qR > 4.5 \qquad (4)$$

$$F_s{}^2(qR) = 0.047 \qquad 2.55 \le qR \le 4.5$$

$$R \sim 1.1 A^{1/3} f$$

## 3. CONCLUSIONS

In this initial analysis using pulse shape discrimination, only the energy band 7-10 keV was used where the background rate was found to be minimum at 1.8 keV$^{-1}$kg$^{-1}$d$^{-1}$. Nevertheless, it has been possible to set 90% confidence limits on nuclear recoil events at 1/10th of background. We set limits for spin-dependent interactions more than a factor 30 improved on previous Ge limits for WIMP masses above 10 GeV. In the case of coherent limits the results from iodine are found to be comparable to existing Ge limits above 100 GeV.

In the future substantial improvements on these results can be expected. In particular, with existing data by combining similar analysis applied to all the energy bands up to 25 keV. This is expected to achieve a further factor x 2-3. However, additional improvement of 1-2 orders of magnitude are also anticipated through improvements to the experiment. In the present analysis systematic errors arising from the variation of time constant with temperature dominate (~ 2.3 ns/K). This is to be countered by temperature stabilisation. Further factors that will contribute to lowering limits, that have be confirmed possible, include: improved light collection, lower intrinsic background through purification of crystal material, lower photomultiplier activity, increased detector mass and longer running time.

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