Experimental Studies on Dark Matter using Germanium Detectors with Sub-keV Sensitivity

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Motivation

The curiosity of human beings posed several questions to understand nature. One such question is what are the fundamental constituents of universe? The quest for answer, evolved into a cosmological model of universe ΛCDM (Lambda – cold dark matter). In this model, ~23% of universe energy density is made up of dark matter (DM). DM neither emits nor absorbs electromagnetic radiation. Its presence is inferred from their gravitational effects on baryonic matter. The clearest evidences on existence of DM come from studies on spiral galaxies rotational dynamics. DM is non-baryonic and non-relativistic and should be weakly interacting because of observations from Gravitational lensing, X-ray temperature measurement of galaxies, cosmic microwave background studies, nucleosynthesis and large structural formation studies. The identity of particles which constitute DM still remains a mystery. The most promising candidate for DM is weakly interacting massive particles (WIMP's,χ). Their masses are in range of 1 GeV to 10 TeV. The very general considerations of cosmology and particle physics point independently to existence of WIMP's. Neutralinos are the leading WIMP candidates.

DM experimental introduction

The DM experimental efforts can be broadly classified into three strategies and one of them is direct detection method. In this approach detector self serves as target material. The detectors are placed in underground laboratories and techniques are developed to detect the nuclear recoils caused by the WIMP interaction. The typical recoil energies are in the sub-keV to couple of keV region for WIMP mass below 100 GeV. Therefore, sub-keV energy threshold detector with excellent resolution is required. This energy regime is dominated by cosmic induced background, natural radioactivity, noises induced by detector and its associated electronics. The WIMP interaction rate also depends on finite size of target nucleus, quenching factor (because of detection efficiency for nuclear recoils is different from that of electron recoils) and astrophysical considerations.

Experimental Configuration

Germanium by virtue of its low band gap and well matured nature of HPGe detector technology provides feasible option to pursue experimental studies on DM. The customized 4×5g, 500g and 900g HPGe detectors are used in present studies. The laboratory is equipped with a 50-ton shielding structure depicted schematically in Figure 1, consisting of, from outside in, 2.5 cm thick plastic scintillator panels with photo-multiplier tubes (PMTs) readout for cosmic-ray veto (CRV), 15 cm of lead, 5 cm of stainless steel support structures, 25 cm of boron-loaded polyethylene and 5 cm of Oxygen Free High Conductivity (OFHC) copper are employed to accomplish low background requirement. The inner target volume with a dimension of $100\times80\times75cm^3$ allows different detectors for various physics topics data taking. NaI(Tl) detectors are used as anti-Compton veto detectors to suppress ambient gamma ray background. The detailed description on experimental configuration and detector structure are presented in reference [1].

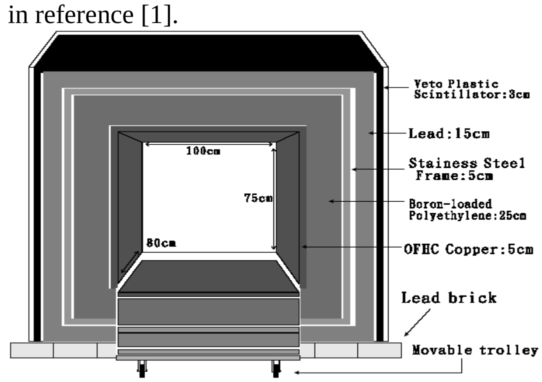

FIG. 1: The shielding design of Kuo-Sheng Neutrino Laboratory Detectors and inner shielding were placed in the inner target volume.

Data analysis

Data of size 0.338 kg-day, 17.53 kg-day and 25.11 kg-day was acquired by 4×5g, 500g and 900g HPGe detectors, respectively. The properties of signal pulse like amplitude, area under pulse, rise time and timing information helps in noise suppression. The temporal correlation between plastic scintillator - HPGe signals and NaI (Tl) - HPGe signals helps in suppression of cosmic ray background and ambient gamma ray, respectively. The effects of cuts and associated efficiency measurement techniques will be explained. The observation of X-ray peaks of energies 10.37 keV, 9.66 keV, 8.98 keV, and 1.21 keV originating from ^{68}Ge (K), ^{68}Ga (K), ^{65}Zn (K) and ^{68}Ge + ^{65}Zn (L), respectively demonstrate low background capability of experiments.

Results and discussion

The salient features of analysis are: An energy threshold of 220 eV, 320 eV and 300 eV at 50% efficiency, for 4×5g, 500g and 900g detectors, respectively. A bench mark low-background of ~4.5 cpkkd (counts/(kg.keV.day)) in 4-8 keV region.

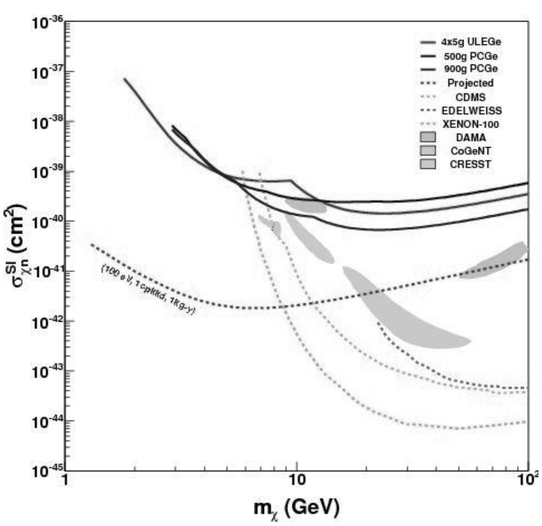

FIG. 2: Exclusion plot for σ^{SI} versus m_χ.

The residual spectrum is compared with expected number of events due to WIMP interactions for each m_χ and upper bounds on WIMP-spin independent and WIMP-spin dependent cross sections (σ^{SI} and σ^{SD}) were obtained. The results are expressed in form of exclusion plot as shown in figures (2 & 3).

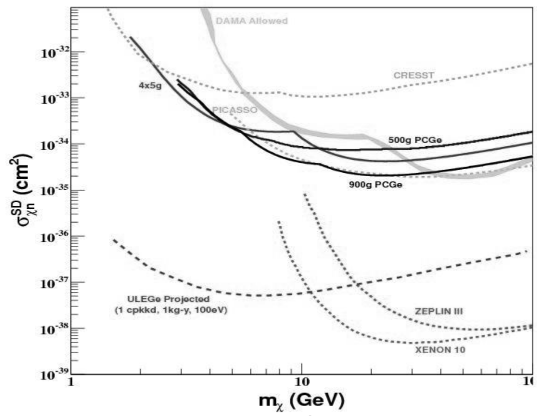

FIG. 3: Exclusion plot for σ^{SD} versus m_χ.

We observed, the new limits set by ULEGe data in both σ^{SI} and σ^{SD} for m_χ=3-6 GeV. The remaining DAMA allowed low m_χ regions in both interactions were probed and excluded. The observable nuclear recoils at m_χ = 5 GeV, σ^{SI} = 0.5 × 10^{-39} cm^2 and σ^{SD} = 0.2 × 10^{-33} are allowed. The obtained limits on σ^{SI} and σ^{SD} from ULEGe data for m_χ > 6 GeV was further constrained by PCGe detectors data sets. For m_χ = 7 GeV, σ^{SI} = 0.2 × 10^{-39}cm^2 and σ^{SD} = 0.7×10^{-34}cm^2 are allowed from 900g PCGe data set. Thus, world level competitive limits are established in low mass WIMP region at 90% confidence level.

The PCGe detectors are massive compared to ULEGe detector and due to self-attenuation in massive detectors causes' reduction in mass-normalized external background and therefore better constrains were obtained for m_χ > 7 GeV. Constrains on σ^{SI} and σ^{SD} are more stringent in m_χ=3-6GeV region for ULEGe because of its low energy threshold of ~220eV as compared to ~300eV for PCGe detectors. The recent results from CDMS, CoGeNT and XENON100 dark matter experiments is further places competitive limits in the low WIMP mass regions. These results further open up tremendous experimental challenges on detection technology and understanding of sub-keV background for experimental studies in the low mass WIMP region.

References

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