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Dark Matter and Experiments for its Identification

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Abstract: After Fritz Zwicky, through various theoretical models, several dark matter events have been proposed. But none of them is yet discovered. Recent experiment shows that only around 5% of the total matters present in the whole universe are visual. Rest matter is still unknown to us by any present experimental tools. This leads that detection of dark matter is one of the very challenging & curios goal for experimental physicists. For the search of suitable dark matter candidates and for rear physics events, High Purity Germanium detectors, Spherical gaseous chamber detector and few more hybrid-detectors are suitable for these purposes. We proposed that any suitable detector hosted under deep sea water will be more effective than the under ground or mountain caverns.

Keywords: Dark Matter Direct Detection, Under Deep Sea water, Spherical Gaseous Chamber.

1. INTRODUCTION

Observation of universe on larger scales shows that galaxies are concentrated into groups called clusters. A cluster includes millions of galaxies and a hot gas filling the space between them. The force holding a cluster is gravity - the mutual attraction of everything in the universe for everything else. Studying the distribution and temperature of the hot gas allows us to measure the compression of the gas by gravity from all matter in the cluster and hence the total material forming the cluster. Measurements on the total matter in the cluster turns to be five time more material than expected from galaxies and the hot gas. This leads to a conclusion that most of the stuff inside a cluster is invisible or dark. The term dark matter was coined by a Swiss astrophysicist, Fritz Zwicky who discovered evidence for missing mass in galaxies in the 1930's. By studying the rotation of a group of galaxies called the Coma Cluster, Zwicky calculated that the visible mass of galaxies was 400 times less than the mass needed to explain their gravitational motion.

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Various dark matter candidates have been proposed by several models but till date none of them is discovered. All that we know about dark matter is that it is transparent, heavy and travels at a speed of around nine kilometer per second.

Out of the entire dark matter in the universe, a small fraction is assumed to be baryonic such as massive compact halo objects and the rest is believed to be non-baryonic – thus not formed out of atoms. The non-baryonic dark matter is assumed to have no electric charge and hence it does not interact with ordinary matter via electromagnetic forces. The non-baryonic category of dark matter includes neutrinos and hypothetical entities such as axions or light super symmetric particles. Unlike baryonic dark matter, non-baryonic dark matter did not contribute to the formation of elements in the early universe and therefore its presence is revealed only via its gravitational attraction. The non-baryonic dark matter is categorized into three sub divisions:

Cold dark matter – This category of non-baryonic dark matter wins the scientific acceptance for explaining the observable phenomena. Cold dark matter travels at classical velocities, generally less than 0.1c. Weakly interacting massive particles (WIMPs) are the candidates of cold dark matter which in most commonly accepted theories are the sole components of dark matter.

Warm dark matter – This division of dark matter includes particles that move relativistically with velocity in the range 0.1c to 0.95c. It cannot explain the galaxy formation from the Big Bang because it moves too fast to be bound to galaxies and thus explain the problems of galactic rotational curves and velocity dispersions that dark matter was postulated to address. Sterile neutrinos are the candidates of warm dark matter.

Hot dark matter – This portion of dark matter travels at ultra-relativistic velocity over 0.95c. Neutrinos are candidates of hot dark matter.

Hot and warm dark matter moves to fast to stay together to form the large scale structures (e.g. galaxy clusters).

The dark matter component has much more mass than the visible component of the universe. Only about 4.82±0.05% of the universe mass is ordinary matter [5] and 25.8±0.4% is thought to be composed of dark matter and the remaining 69±1% is dark energy, an even stranger component, distributed diffusely in space.

2. DARK MATTER DETECTION

If the dark matter is composed of WIMPs, then a huge number must pass through the earth every second [13]. There are many experiments currently

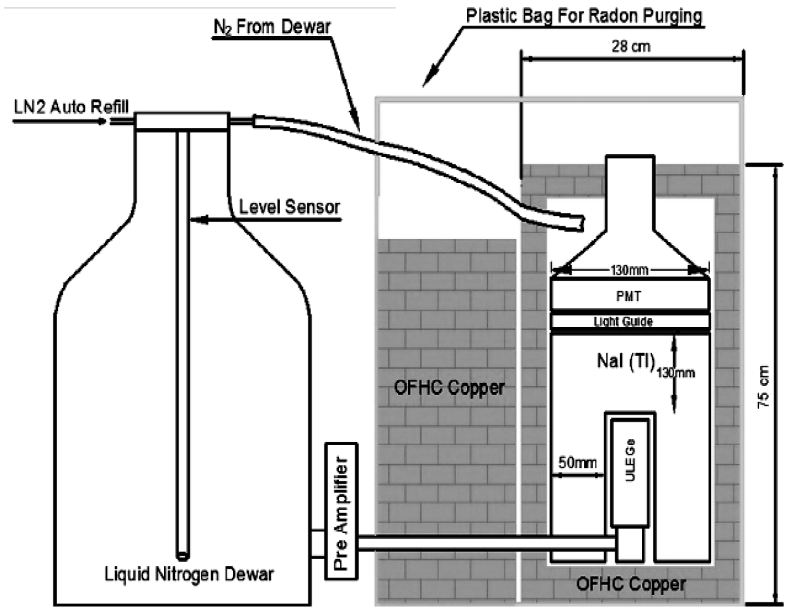

Figure 1: Schematic diagram of the experimental setup with p-type point contact germanium detector [3].

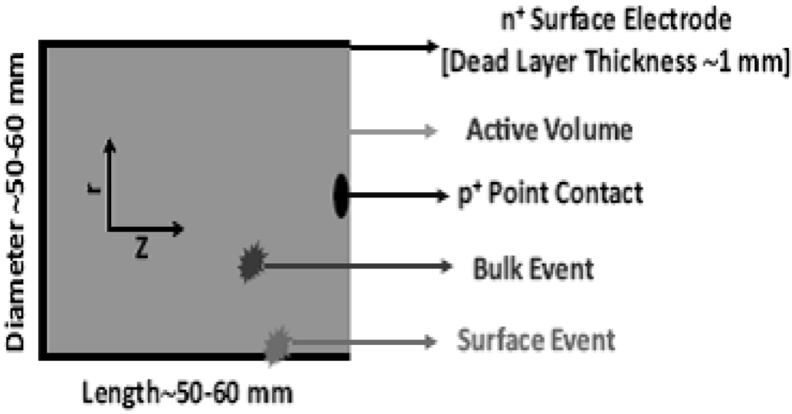

Figure 2: Schematic diagram of the germanium crystal in p-type point contact Ge detector [3].

running, or planned, for dark matter searches. These experiments can be divided into three classes: direct detection experiments – which search for the scattering of dark matter particles off atomic nuclei within a detector; indirect

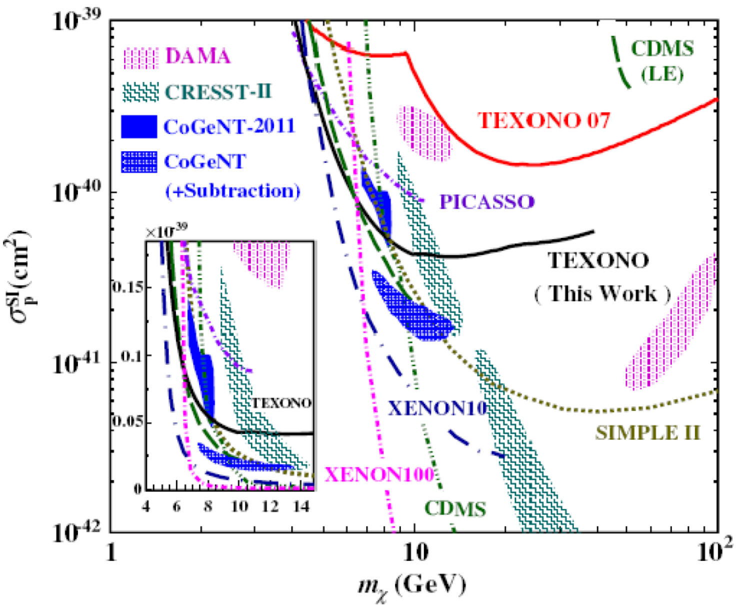

Figure 3: Exclusion plot of $\sigma^{SI}_{\chi N}$ versus WIMP mass, superimposed with the results of other experiments and CoGeNT with and without surface background subtraction [4].

detection experiments – which look for the products of WIMP annihilations; and directional detection experiments – based on the motion of solar system around the galactic center.

CDMS, CRESST, ZEPLIN, XENON etc are direct detection experiments for dark matter searches. High energy neutrino telescopes such as AMANDA, IceCube and ANTARES are indirectly searching for dark matter. DMPTC, DRIFT, Newage and MIMAC are experiments based on directional detection strategy.

3. RUNNING EXPERIMENTS FOR DARK MATTER SEARCHES

Detection of dark matter candidates is one of the major goals of present day experimental physics. Many experiments are currently running with the aim to detect WIMPs. **TEXONO-CDEX** Collaboration is one such effort searching for WIMPs via the direct detection mechanism. This experiment is using a kg-mass scale of high purity germanium (Ge) as the detection medium. Point contact ULE-HPGe detector has a low energy threshold which is critical for detecting low mass WIMPs. This low energy threshold is achieved due to the small capacitance (<1pF) of the point contact and the rapidly changing electrical weighting field in the vicinity of the readout contact. Another major advantage offered by this detector is effective background separation by pulse shape analysis with only one readout channel and hence minimizing the amount of potentially radioactive materials, particularly close to the detector. Apart from WIMP searches, this detector is also used for studying neutrino nucleus coherent scattering with reactor neutrinos [13,10] via the interaction channel

$$\nu + \mathrm{N} \rightarrow \nu + \mathrm{N}$$

where ν is the neutrino and N represents the nucleus. This highly efficient detector setup is located at Kuo-Sheng Reactor Neutrino Laboratory (KSNL). Figure 1 shows the schematic diagram of the experimental setup employing ULE-HPGe detector. The schematic diagram of p-type point contact Ge detector is shown in Figure 2.

Using 39.5 kg days of data taken with the above shown experimental setup using p-type point contact germanium detector (840 g fiducial mass) at KSNL, the TEXONO collaboration has reported new limits on the spin independent WIMP-nucleon interaction cross section [6]. The results are an order of magnitude improved over the previous results from TEXONO [6].

At 90% confidence level, an exclusion plot of spin independent WIMP-nucleon interaction cross section (σ^{SI}_{N}) with respect to WIMP mass (m_χ) is shown in Figure 3 [6]. The plot is superimposed by the bounds set by other experiments.

The experiment **CDEX** at the new China Jinping Underground Laboratory is also taking data for dark matter searches using sub-keV germanium detectors [9].

A series of experiments named **Cryogenic Dark Matter Search** is also running with the goal to detect and identify dark matter candidates (WIMPs) via their interaction with the detector medium and hence determining the spin independent WIMP- nucleon elastic scattering cross section. The CDMS experiments use germanium or silicon disks cooled to milli-Kelvin temperature as the detection medium. The detection technology adopted by CDMS detectors involves the measurement of ratio of ionization signal to the phonon signal produced for each particle interaction in the germanium and silicon crystal substrates [15]. This ratio differs for particle interactions with atomic electrons and atomic nuclei. Whereas most of the background particles interact with atomic electrons producing electronic recoils, WIMPs interact with atomic nuclei producing nuclear recoils allowing their identification. Figure 4 illustrates the schematic of WIMP detection in CDMS detector.

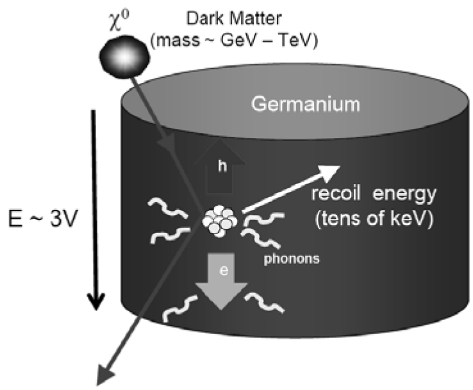

Figure 4: Schematic of WIMP detection in germanium detector.

CDMS has set the most sensitive limits on WIMP interaction with ordinary matter. Recent results from CDMS collaboration in 2013 have reported the detection of three WIMPs having masses comparable to the expected WIMP masses at 99.8% confidence level [11].

The **Large Underground Xenon (LUX)** experiment located 1478.3 meters underground at the Sanford Underground Laboratory in the Homestake Mine, South Dakota is another experiment running with the aim to detect WIMP-nucleon interactions. This experiment is using 370 kg liquid xenon as the detection medium where both photons and electrons are produced as a result of particle interactions. The two phased (liquid and gaseous xenon) cylindrical detector of this experiment with gas phase above the liquid phase is a Time Projection Chamber with a uniform axial electric field maintained by evenly arranged voltage rings [12]. Two arrays of photomultiplier tubes are located at the top and bottom of the detector to detect the photons produced by particle interactions in the liquid xenon medium and the electroluminescence photons produced by the drifted electrons in the xenon gas [17]. The detector is suitably shielded to reduce the rate of neutron interactions in the liquid xenon as they produce nuclear recoils similar to those produced by WIMPs interactions with atomic nuclei.

Whereas WIMPs are being very feebly interacting have an almost negligible probability to cause multiple interactions in the detection medium, the neutrons have a fair chance to interact more than once with the atomic nuclei. This difference can separate WIMPs from neutrons. Furthermore, observation of an excess in single interaction events over multiple interaction events can lead to the detection of dark matter candidates WIMPs.

LUX results from the analysis of 85-day run data rule out the low mass WIMP signal hints such as those from CoGeNT and CDMS-II Si [5].

The **Coherent Germanium Neutrino Technology (CoGeNT)** experiment is also an effort searching for WIMPs. Located at Soudan Underground Laboratory in Soudan, the CoGeNT experiment uses a single, 440 gm, high purity germanium crystal cooled to liquid nitrogen temperature as the medium for WIMP detection via their interaction with the atomic nuclei in the medium [14]. Having the advantage of very low energy threshold (~ 0.5 keV), the CoGeNT detector is capable of detecting nuclear recoil events due to low mass WIMPs. Measurement of the rise time of the detector's signal makes possible the rejection of background events. By sensing the ionization charge from nuclear recoils, the CoGeNT detector has put limits on WIMPs masses and their interaction cross section with the ordinary matter.

Recent data collected by CoGeNT has reported an excess of events compatible with the WIMPs in the mass range 7-11 billion electron volts [14]. The detector continues to take data with the planned upgrade to deploy four, larger mass detectors.

Other experiments joining the effort for dark matter search include ADMX at University of Washington, ANAIS at Canfranc Underground Laboratory, ArDM and CAST at CERN, CRESST and DarkSide at Gran Sasso National Laboratory, DAMA/LIBRA and DAMA/NAI at Laboratori Nazionali del Gran Sasso, DEAP and PICASSO at SNOLAB, DMTPC at Waste Isolation Pilot Plant (New Maxico), EDELWEISS at Modane Underground Laboratory, ZEPLIN-III at Boulby Underground Laboratory etc.

3. PLANNED EXPERIMENTS FOR DARK MATTER SEARCHES

A suitable detector for dark matter searches must have: a large volume with 4π coverage, very low noise and rejection/identification capability of all kinds of background particles/radiations. Furthermore, it should be cost effective, modular and easy in operation. In most of the ongoing and planned experiments, detectors have major problems of rejecting internal background generated by the impurities of the construction materials of detector and surroundings. These issues initiated us to think about a detector that is able to efficiently reject such type of backgrounds. Spherical Gaseous Chamber Detector is one such detector that meets all the listed needs and also is capable to efficiently reject backgrounds and achieve low threshold.

4. SPHERICAL GASEOUS CHAMBER DETECTOR

As shown in Figure 5, a very large sphere (1-10 mm thick) of pure copper enclosing a small sphere (1-5 mm diameter of solid pure copper) will form

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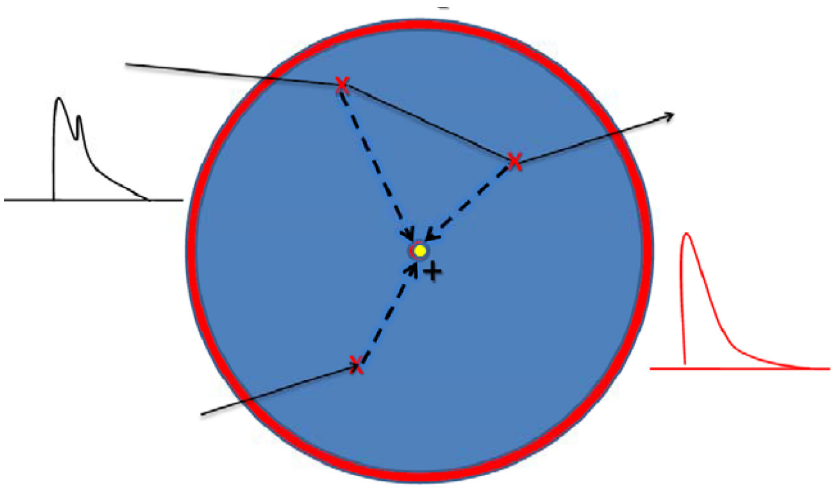

Figure 5: Schematic view of spherical gas chamber detector and pulse shapes for single and multiple scattering events.

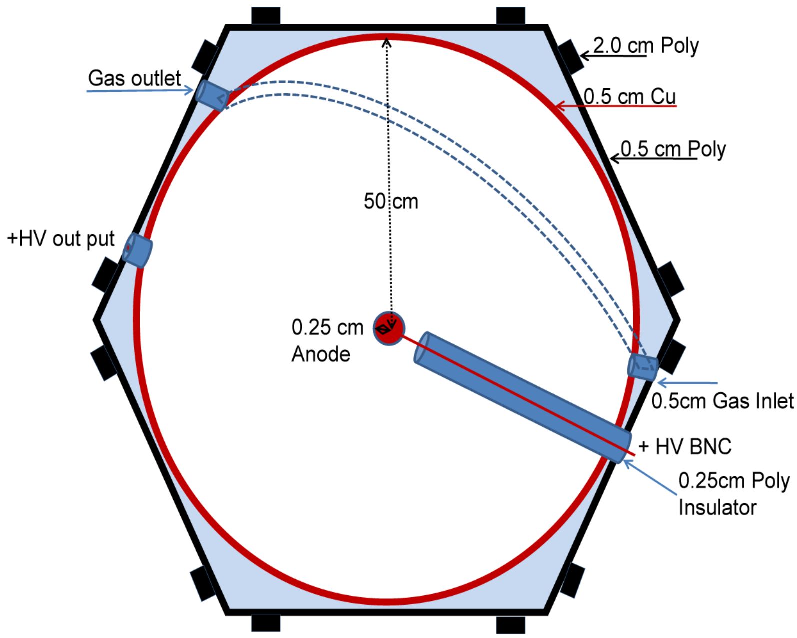

Figure 6: Schematic view of the SGCD design.

the Spherical Gaseous Chamber Detector (SGCD). Radial electric field having large field strength will be produced by connecting the inner sphere to the positive high voltage through a copper wire.

A suitable gas mixture (such as $Ar:He:N_2$ in the ratio 200:50:1.5) having stable drift velocity and minimum diffusion over the entire range of electric field will fill the detector chamber. A neutrino or WIMP entering the detector chamber will interact with the gas molecules creating electron ion pairs. During its drift towards the positive electrode (anode) at the center of the sphere, the electron will gain sufficient energy from the electric field to create an avalanche that will make single peak strong signal.

Multiple interactions will occur for other charge and neutral backgrounds entering the chamber producing multiple peaked signals. Pulse Shape Discrimination (PSD) techniques will be used to separate background from the signal analyzing the difference in peak shapes and will also help in achieving low detection threshold. The gas mixture filled in the chamber will give drift velocity $v \propto \sqrt{(E)}$. The diffusion constant D and the drift time t will characterize the electron distribution along the track (roughly Gaussian) by $\sigma = \sqrt{(2\,Dt)}$. The copper wire connecting inner sphere to the positive high voltage will be covered with a suitable insulator such as ceramic to ensure radially symmetric electric force line in the entire chamber.

For the sake of stability, when using a large number of detectors, the spherical chamber will be surrounded by a half cm thick hexagonal shaped boron loaded polyethylene (BLP). This structure of SGCD facilitates the mounting of pre-amplifier and other electrical terminals as shown in figure 6.

Apart from advantages listed before, SGCD offers many other practical advantages such as natural focusing, ease in extracting spatial information, symmetry, low capacity, no field cage etc.

5. DARK MATTER DETECTION USING SGCD

We are planning to search for the galactic dark matter bound in our solar system. The distribution of dark matter is not uniform but may show annual/seasonal and diurnal variation. A large collection of SGCDs will not only act as a counting detector with very high signal acceptance but will also provide directional, annual and diurnal properties of dark matter. In our experiment neutrinos and other baryonic particles will act as background. This detector is capable to identify and separate signals from baryonic particles. Neutrino event rates will show similar count rate in all the modules of such a detector throughout the year but dark matter candidate will not show such things. Directional detection of dark matter in direct detection experiments not only provides signature of galactic WIMPs but also serves as a potentially powerful probe to the structure and dynamics of dark matter.

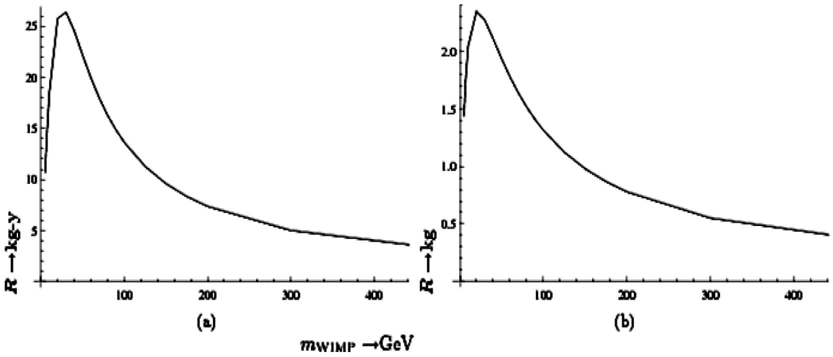

Figure 7: WIMP nucleus coherent scattering event rates w. r. t. the WIMP mass for zero threshold energy.

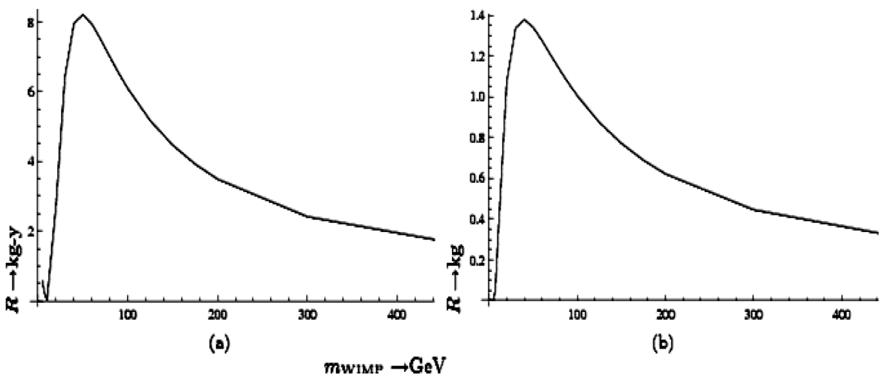

Figure 8: WIMP nucleus coherent scattering event rates w. r. t. the WIMP mass for 5 keV, threshold energy.

Unlike most of the detectors based on directional detection techniques which involve reconstruction and head-tail discrimination of nuclear recoil tracks (induced by the scattering of WIMPs off the detector nuclei), this detector will accumulate all this information only by analyzing the variation in event rates in detectors of a certain direction. Directional description of the WIMP induced nuclear recoil rates in terms of angular coordinates defined and realized in the laboratory frame of a detector exhibits temporal variation over a sidereal day due to diurnal motion of the earth. It would also have an annual modulation owing to yearly variations of the component of earth's orbital velocity along incoming WIMP direction. Analytical details of the

annual and diurnal variations are determined by the dynamics and geometry of the sun-earth system and the location of the detector on the earth. Proper transformations of coordinate systems are also needed to obtain the results in laboratory frame of reference. This is very crucial for any detector based prediction of such directional modulations of dark matter signals.
The number of dark matter events occurring during time t is given by:

$$R \cong 1.60 \times 10^{-3} \times (t / 1y) \times [\rho(0) / 0.3\ \mathrm{GeV\ cm^{-3}}] \times (m / 1\mathrm{Kg}) \times (\sqrt{<v^2>} / 280\ \mathrm{km\ s^{-1}}) \times (\sigma^S_{p,\chi o} / 10^{-6}\,\mathrm{pb})\ [\{f_{coh}(A, \mu_r(A))\} / A]$$

$$\text{With } f_{coh}[A, \mu_r(A)] = (100\mathrm{GeV} / m_{\chi o})\ [(\mu_r(A)) / (\mu_r(p))]^2 A^2\, t_{coh}\,(1 + h_{coh} \cos\alpha).$$

Where t_{coh}, h_{coh} depend on the nuclear physics, the WIMP mass and the velocity distribution. In the above formula standard Maxwellian velocity distribution and the phase of the Earth α is considered. $\rho(0)$ is the local WIMP density which we generally take as 0.3 GeV/cm^3 and $\sigma^S_{p,\chi}$ is the WIMP-nucleon cross section. It can be extracted from the data once $f_{coh}(A,M_\chi)$ is known to us.

Figure 7 illustrates the character of WIMP-nucleus coherent scattering event rates with respect to the WIMP mass for (a) heavy (^{127}I, ^{131}Xe) and (b) light (^{19}F, ^{23}Na) detector materials for zero threshold energy with $\sigma_{p,\chi} = 10^{-7}$ pb.

Figure 8 shows similar distribution with 5 keV threshold energy.

6. DIURNAL VARIATION

Considering WIMP of mass 60 GeV and WIMP nucleon cross section of 10^{-44} cm^2, estimation of the directional rates of WIMP events in directional detectors sensitive to spin independent WIMP-nucleus interactions (CS_2 target) for all possible recoil directions are found to lie within the range ~ 10^{-6} - 10^{-4} per day per steradian per kg of target mass of the detector. The diurnal variations in the laboratory frame description of directional anisotropy of the WIMP induced nuclear recoils amount to a wide daily fluctuations of the ratio of WIMP rates corresponding to the two chosen orthogonal directions of nuclear recoils (east and north). Energy integrated rates for different WIMP masses ranging from 0 - 100 GeV have daily variation which is most prominent for WIMP masses around 20 GeV. The range of daily modulation increases with the increase in recoil energies but the drop in overall yield for higher recoil energies makes it difficult for a detector to register this modulation. SGCD design supports the search of WIMPs with mass below

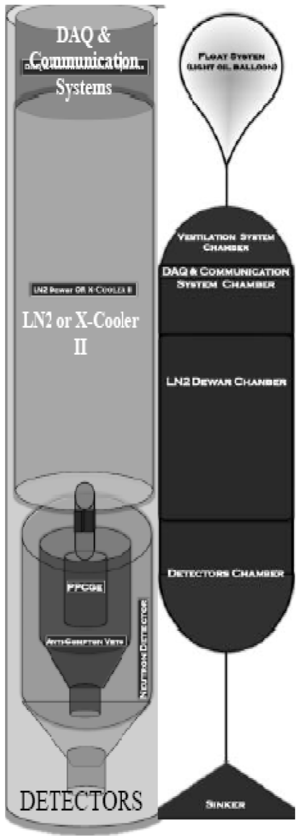

Figure 9: Schematic layout of the proposed detector [12].

20 GeV due to its capability of high background rejection rate over the entire range of WIMP's mass. SGCD is efficient and precise enough to detect the yield corresponding to higher recoil energy ranges than for lower values of WIMP masses and therefore this detector will observe considerable daily modulation of the signal.

7. DARK MATTER SEARCH WITH HPGE DETECTOR UNDER DEEP SEA WATER

WIMP searches pose a challenging requirement of low background (particularly neutron background as its interaction rate with the detector material is much higher than WIMP interaction rate) and highly reduced cosmogenic radioactivity. Therefore the experimental efforts aiming WIMP searches are using mountains, Antarctic Ice and sea water as natural radiation shields

Table 1: Possible locations for underwater experiments with distance less than 50 km from the sea shore [12].

Location	Depth (in meter)	Distance from the shore (Approx.)
16°10′05.37″ S / 54°47′48.60″ E Tromelin Island (South Africa)	4900	45 km
20°53′05.86″ S / 57°49′44.53″ E Flacq (Mauritius)	4757	50 km
20°44′16.84″ S / 56°57′42.53″ E Savanne (Mauritius)	4309	50 km
08°34′22.07″ N / 93°44′07.67″ E Tillanchong Island (India)	4161	15 km
08°14′54.58″ N / 93°51′04.68″ E Trinkat Island (India)	3993	35 km
12°43′ N / 81°06′ E Chennai (India)	3350	70 km

[4]. Along with the advantages (stable and long term active lab, easy access, installation and maintenance etc.) of using mountain as an overburden, there are several disadvantages such as uncertainties in rock composition, impurities of shielding material, mountain topology, inhomogeneous density and water content, uncertainty in muon flux calculation, neutron backscattering through cavern walls etc. On the other hand using sea water offers many advantages as well understood composition, almost flat surface, low neutron production rate, excellent neutron absorption capability, no neutron backscattering, cost effective etc. The benefits of using sea water overburden initiated us to plan an experiment for dark matter search under deep sea water using high purity germanium detector. The best site for setting up such an experiment is the Mariana Trench located at 11"21'N and 142"12'E near the Japan in the Pacific Ocean which is the deepest location on the Earth with the depth of 10994 m. Other possible sites around the world are tabulated in Table 1. We are planning to explore the Tillanchong Island in Andaman and Nicobar Islands for our experiment. It is 4161 m deep at a distance of 15 km from the sea shore where the control laboratory can be set up.

Figure 9 shows the schematic diagram of the proposed detector for this experiment. The set-up consists of p^+ point contact high purity germanium detector of initial mass 1 kg. Layered NaI(Tl) anti-Compton and liquid scintillator neutron detectors provide 4π coverage. A dewar of 100 Lt LN_2 is installed to serve as coolant. Gradual evaporation of LN_2 poses a challenge.

At room temperature, LN_2 evaporates at the rate of 0.36 Lt/day [2] and the temperature at 3000 m depth lies in the range 2-4° Celsius [2]. But with a 100 Lt LN_2 dewar our experiment can run for 275 days which is a sufficient period to settle down the cosmic background in the detector. The electronic modules of DAQ will be remotely controlled from the laboratory at the sea shore. The entire structure will be placed inside a water resistant vessel maintained at high pressure.

With the help of a light oil filled balloon, the vessel will float ~ 500 m up from the sea bed. For stability, a heavy Pb sinker will be connected to the vessel as shown in the figure 9. The vessel will be connected to the control laboratory at the shore through power cables. Such an experiment not only offers high probability of detecting WIMPs but is also capable of exploring their properties.

The **European Underground Rare Event Calorimeter Array (EURECA)** is another planned experiment to be located in the Modane Underground Laboratory, France for dark matter search. Using the cryogenic detector technology and an absorber mass of up to 1 tonne, EURECA hopes to detect dark matter candidates (WIMPS) by detecting signals of their interactions with the atomic nuclei of the detection medium [1].

DINO (Dark-matter @ INO) is also a planned experiment for dark matter search to be built in one of the caverns of the upcoming India-based Neutrino Observatory (INO).

Many more experiments aiming dark matter search using different technologies are planned to be located worldwide.

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