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Searching for dark matter with liquid-argon detectors

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The nature of dark matter remains unknown and its origin is currently one of the most important questions in physics. In particular direct searches for WIMP dark matter particle interactions with ordinary matter are carried out with large detectors located in underground laboratories to suppress the background of cosmic rays. One of the currently most promising detection technologies is based on the use of a large mass of liquid argon or xenon as a target in the detector. This article discusses dark matter searches with detectors based on liquid argon, in particular DarkSide-20k experiment, which is under construction at the Gran Sasso laboratory, Italy.

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Introduction

The concept of dark matter is results from a wealth of astronomical observational observations. They show that about 26% of the total mass-energy of the Universe exists in the form of cold, non-baryonic, non-dissipative dark matter [1]. It's nature remains one of the key questions in cosmology, astrophysics and particle physics. It seems that other than via gravity, dark matter can interact with standard model sector only weakly although not necessarily through electroweak interactions. It is either stable, or very long lived [2] and may interact with itself. The dark matter particle can have mass of 10^{-21} eV up to the reduced Planck scale (2×10^{18} GeV).

The dark matter candidate that gained a lot of attention are the Weakly Interacting Massive Particles (WIMPs). They could have been produced during the early stage of the Universe through thermal freeze-out and can have masses of the order of GeV to few TeV. The most promising detection method to search for WIMPS is through the scattering of WIMPs off a target nucleus [3], as the nuclear recoil due to the momentum transfer is detectable. In particular liquid argon (LAr) is an excellent choice for a target mass for direct detection experiment.

Dark matter detection with liquid argon

Liquid noble gas detectors with xenon or argon as a target mass play an important role in the field and are currently giving the most stringent limits on spin-independent WIMP-nucleon cross-sections over a broad range of dark matter masses.

Fig. 1 shows the particle interactions caused by the scattering of WIMPs with Ar nucleus. Excited argon atoms Ar^* form an excimer state Ar^*2 by combining with a neutral atom. During the excimer decay scintillation light is produced. If the electrons emitted during the ionization are not removed by an electric field they recombine and produce additional scintillation light. If the electric field is applied the electrons are drifted and the charge can be measured. Therefore the charge signal is anti-correlated with the light signal.

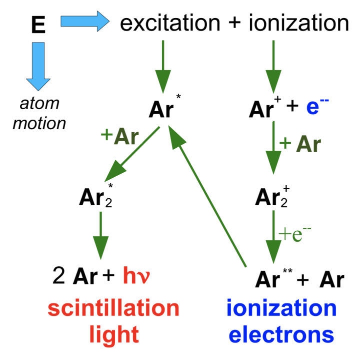

Fig. 1: Scattering of WIMPs off an Ar nucleus. Interactions with Xe work in the similar way[4].

Currently there are two detector designs used in liquid noble gas based dark matter detectors (see Fig. 2). Single phase detectors are built as volume of a noble liquid gas surrounded by photodetectors which detect the scintillation light S1. The S1 signal is short

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which allows for high event rates without pile-up. The geometry of single phase detectors is spherical which allows self shielding and ensures good coverage with photodetectors. The resolution of vertex position reconstruction is typically of order of several cm. Background discrimination rely on excellent pulse shape discrimination (PSD) in LAr. PSD is tool which enables distinguish light from a recoiling electron (background) and nuclear recoil (signal) at the level higher that 10^{-10}[5]. Only the inner part of the argon volume is used as a target mass (fiducialization) while the outer part acts as a shield agains.

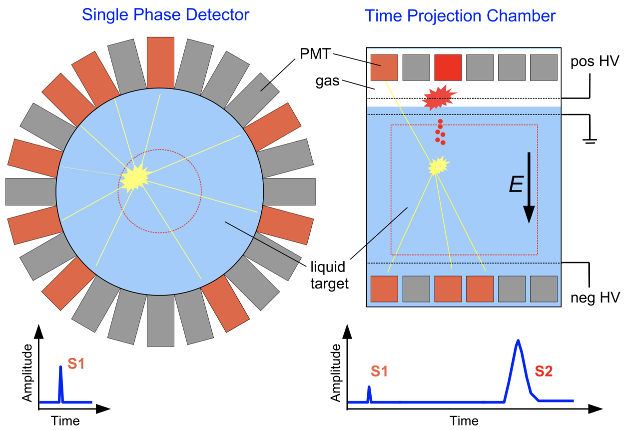

Fig. 2: (left) single phase detector and (right) a dual phase time projection chamber detector design[4].

In a double phase detector operated as a time projection chamber (TPC) on the other hand, besides the S1 signal, also the ionization signal can be measured due to the electric field across the target mass. The electric filed drifts the ionization electrons upwards where the gas layer is formed. The extracted electrons generate scintillation light S2 which is proportional to the charge. The time-delay between S1 and S2 caused by the drift time gives precise information about the vertical position of the interaction. This detector design provides excellent 3-dimensional vertex reconstruction of the order of several mm which allows precise fiducialization. This feature together with pulse shape discrimination results in powerful background rejection at the cost of more challenging design and necessity of dealing with high voltage system.

Global Argon Dark Matter Collaboration

The Global Argon Dark Matter Collaboration (GADMC) which has been formed in 2017 is formed by scientists working on dark matter searches in LAr experiments including ArDM, MiniCLEAN, DarkSide-50, DEAP-3600 and DarkSide-20k. The goal of the GADMC is operation of ongoing experiments such as single phase DEAP-3600 (biggest currently operating LAr experiment) and construction of the dual phase DarkSide-20k detector which will use radio-pure argon extracted by URANIA from underground sources in Colorado in order to reduce ^{39}Ar (background source) by a factor of at least 1400 (to be exactly measured by

DArT[6]). DarkSide-20k in now being constructed in Hall-C of the INFN Gran Sasso National Laboratory (LNGS) in Italy.

DarkSide-20k

The core of the DarkSide-20k experiment (see Fig. 3) is a dual phase TPC with 50 t of underground LAr out of which 20 t will form the fiducial volume of the detector.

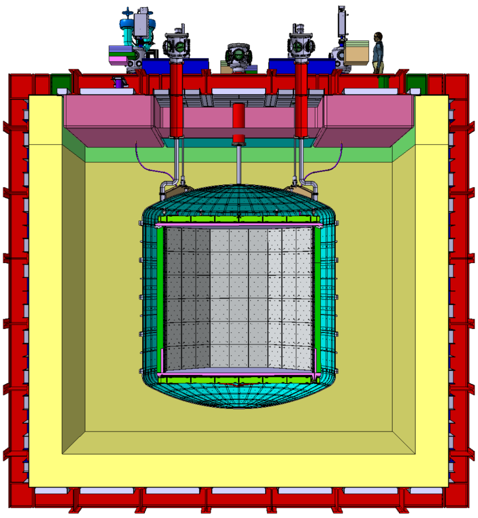

Fig. 3: From the outside: DarkSide-20k detector is contained in a ProtoDUNE-like cryostat (red) and inside is outer veto with atmospheric argon. The steel vessel (blue) separates it from the inner neutron veto. Gadolinium-loaded acrylic shell (green) separates the neutron veto from the TPC (grey).

The octagonal TPC is enclosed in a vessel made from ultra-pure PMMA. The inside of the 3.5 m high TPC will be viewed by photodetector units (PDUs) made with silicon photomultipliers (SiPMs) covering top and bottom surfaces. Since argon scintillates at 128 nm and the SiPMs are most efficient at visible spectrum wavelength-shifting material (Tetra-Phenyl-Butadiene, TPB) is used to coat the inside surfaces of the TPC which will be covered with the Enhanced Specular Reflector (ESR) foils. Next is the 15 cm thick wall of gadolinium-loaded PMMA which separated the TPC from the 40 cm thick layer of liquid argon forming the neutron veto (Fig. 4). The inside of the neutron veto will be covered with ESR reflectors with a layer of polyethylene naphthalate (PEN) foil used as wavelength-shifting material.

The PMMA moderates the neutrons produced in the detector material and then the gadolinium captures the neutron what results in the emission of γ-rays with a typical energy of 8 MeV which in turn are detected by the photodetectors. This provides an efficient veto of radiogenic neutrons that are source of background signal during the nuclear recoil in the TPC.

The neutron veto is placed inside the steel Faraday cage which ensures optical and electrical insulation from the outermost atmospheric argon volume forming outer veto. Outside is the membrane ProtoDUNE-like cryostat designed in CERN.

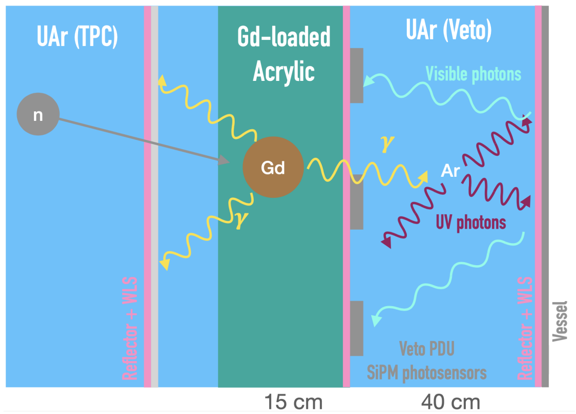

Fig. 4: Cross-sectional view of the neutron veto. The TPC volume is to the left, in the centre is the gadolinium-loaded PMMA wall and to the right is the veto volume filled with LAr.

Both outer and neutron veto will use 156 veto PDUs (vPDUs) for the light detection. The light detectors for DarkSide-20k (see Fig. 5) have been been equipped with a cryogenic preamplifier which shapes the signal in the proximity of the sensor. The sensors have have low noise at 87K, dark-count rate of few mHz/mm^2, tuned sensitivity vs. light spectrum and photon detection efficiency of 45%.

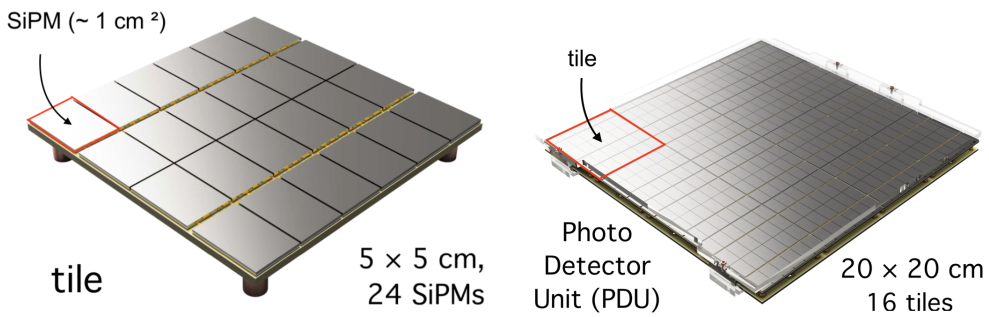

Fig. 5: Custom-made silicon photomultiplier photodetectors for DarkSide-20k. Each PDU (and vPDU) consists of 16 tiles while each tile consists of 20 single SiPMs.

Thanks to the high target mass and ultra-low backgrounds the DarkSide- 20k detector will will be able to achieve 90% C.L. sensitivity to WIMP-nucleon cross sections of 7.4×10^{-48} cm^2 for a WIMP mass of 1 TeV with a nominal exposure of 200 t×yr (Fig 6).