Introduction

One of the biggest open questions in today’s particle physics and cosmology is the identification of the Dark Matter (DM) in the Universe. A large collection of cosmological as well as astrophysical observations show strong evidence that a large fraction of the matter in the Universe cannot be made out of the known forms of matter, consisting of protons, neutrons, and electrons. Extensions of the Standard Model of particle physics, which are anyway required for other reasons, contain often so-called Weakly Interacting Massive Particles (WIMPs) which are ideal Dark Matter candidates. Their properties imply that the right magnitude of Dark Matter was automatically produced in the Big Bang and they also fit to all other indirect astronomical and cosmological evidences.

Dark Matter Theory and Phenomenology

The existence of dark matter (DM) has been established, via its gravitational effects, through a variety of observations at different scales from galaxies to the largest structures in the Universe. According to the most recent cosmological data, DM accounts for about 27% of the total energy density of the Universe and about 85% of its matter density. And yet, the fundamental nature of the DM particle (e.g., its mass, spin, quantum numbers, etc.) remains a mystery, providing one of the most important open problems in particle and astroparticle physics today. There are several candidates for dark matter and some of the most compelling are weakly interacting massive particles (WIMPs) and sterile neutrinos.

WIMPs are stable particles and are related to fundamental problems in particle physics. The standard model of particle physics that offers a unified description of strong and electroweak forces is plagued with the so-called hierarchy problem. In simple terms, it means that if there is new physics at an energy scale larger than the weak scale, the theory has to be exceedingly fine-tuned in order to cancel divergent quantum contributions and keep the mass of the Higgs boson at the observed value of 126 GeV. There are ways to circumvent this issue, and a prominent solution is supersymmetry, which naturally predicts the existence of WIMPs. A distinct feature of WIMPs is that they generally reproduce the right relic dark matter density of the universe through a process known as thermal freeze-out, as a result of their interaction strength being at the weak scale. Regardless of the quantum numbers, these WIMPs are capable of yielding the right amount of dark matter, while producing a signal within reach of current and planned direct and indirect detection experiments. These unique elements make WIMPs prominent dark matter candidates.

In order to pin down the properties of the WIMPs, one needs to combine data from different search strategies, namely direct, indirect and collider searches [1].

Direct detection searches probe the WIMP-nucleon scatterings, indirect detection the annihilation cross section into cosmic rays, gamma rays and neutrinos, while collider experiments its production rate induced by the production of unstable new particles. MPIK has been involved in experimental searches for dark matter using gamma rays and neutrinos [2] and in direct and indirect detection to probe new physics models [3, 4].

A promising approach to probe WIMP models is to take advantage of their distinct features such as the possible emission of gamma-ray lines, which is a clear signature to
establish the presence of WIMPs annihilations in our galaxy. However, such line emissions are highly constrained by gamma-ray telescopes. An interesting fact is that direct detection experiments such as XENON1T or XENON1T should see at some level a WIMP signal. This expectation rate has classically a size of 10^{-5} cm^2 to 10^{-2} cm^2.

This explains, for example, also the cross section range for the MSSM case to be set by the De Broglie wavelength. Multiplying the resulting area with a weak coupling or a Higgs portal coupling and a model-dependent factor typically O(1, ..., 0.001) one ends up with spin-independent (SI) cross sections in the range between 10^{-44} cm^2 to 10^{-49} cm^2. This explains, for example, also the cross section range for the MSSM case to be set by the De Broglie wavelength. Multiplying the resulting area with a weak coupling or a Higgs portal coupling and a model-dependent factor typically O(1, ..., 0.001) one ends up with spin-independent (SI) cross sections in the range between 10^{-44} cm^2 to 10^{-49} cm^2.

Fig. 1: Nature of dark matter.

Fig. 2: Search for sterile neutrinos with direct detection experiments.

In the past decades various detector technologies have been developed with the goal of discovering dark matter interactions providing eventually, the answer to one of the most important open question in modern physics. The XENON100 experiment, located at the Gran Sasso underground laboratory (LNGS), has set over the last years most stringent upper limits on the interaction cross section of dark matter with known matter. The detector consists of a three-phase liquid xenon time projection chamber (TPC, see title image), right equipped with two arrays of photomultiplier tubes which detect efficiently tiny signals (only a few photons). The combination of two signals: from scintillation photons (S1) and from charged drifted to the gas phase (S2) allows to reconstruct the event position in three dimensions and gives a separation between common background originated in γ and β particles and the expected nuclear recoil signal. The high stopping power of liquid xenon together with the choice of radio-purest materials for the detector, and a passive shield made by several layers of steel and radiation results in a detector with one of the lowest interaction rates ever measured.

XENON100 and XENON1T

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XENON100 has acquired science data since 2009. Several physics results have been derived from the second major run of 225 live days data. Beside the standard WIMP interpretation of the data, we have investigated other possibilities in which a dark matter candidate interacts with electrons. With no evidence for a signal above the low background of our experiment, we placed limits on axion models and also on leptophobic dark matter candidates [6]. Furthermore, motivated by the annual modulation of the signal observed by the DAMA experiment, we studied if such signature is present in our detector. Following a detailed study to establish the stability of the detector and its background contributions, we searched for periodic variations of the electronic recoil event rate. As the data suggested no statistically significant modulation, we exclude the DAMA/LIBRA signal interpreted as a dark matter signature with axial-vector nature, or the difference of WIMPs to electrons at 4 σ significance.

The final WIMP search results of the XENON100 experiment [7] have been released in 2016, these combine three individual runs summing up to 477 live days with data taken between January 2010 and January 2014. Data from the first two runs had already been published. Extending the analysis to the additional interval, the performance of the photomultiplier tubes, cryogenic, passive shield and system, electric field configuration over several years enables a combination of the runs with minimal changes in the treatment of the data. The ultra-low electromagnetic background of the experiment, \( \sim 5 \times 10^{-7} \text{ events/(keV} \cdot \text{kg day)} \) before electronic recoil rejection, together
with the increased exposure of 48 kg·y improves the sensitivity. Systematic uncertainties are reduced by an improved background modelling, a more robust usage of the derived light collection efficiency and by exploiting both energy scales of the scintillation and charge signal in the computed signal model. A profile likelihood analysis using a common energy range of \((6.6-43.3)\) keV, for all three runs sets a limit on the elastic, spin-independent WIMP-nucleon scattering cross section for WIMP masses above \(8\) GeV/c\(^2\), with a minimum of \(1.1 \times 10^{-49}\) cm\(^2\) at 50 GeV/c\(^2\) and 90% confidence level. In addition, the constraints on the elastic, spin-dependent WIMP-nucleon cross sections obtained with the same data were updated.

To significantly increase the sensitivity with respect to XENON100, a next generation, the XENON1T experiment \([8]\) has been built also at LNGS (see Fig. 3). The detector construction started at LNGS in summer 2013 and the detector was commissioned between 2015 and early 2016. With a target mass 32 times larger than XENON100 and a reduced background rate, the sensitivity to the spin-independent WIMP-nucleon interaction cross section is expected to reach two orders of magnitude down in cross sections compared to the current XENON100 results (see Fig. 4).

With around 1.5 tons of xenon, MPIK has contributed almost half of XENON1T’s required xenon mass of 3.3 tons. Furthermore, we took responsibility of transferring the gas from the purchased bottles to the storage vessel at LNGS and ensuring a high gas purity. Using a customised gas chromatography setup that was optimised in cooperation with the supplier, the entire xenon inventory of XENON1T was measured for contaminations. With its sensitivity of tens of ppb (parts per billion) for the relevant trace impurities, it was possible to identify contaminated xenon bottles before their content would be mixed with the rest high-purity xenon. Rejected xenon bottles were purified in dedicated cryogenic distillation campaigns. Combining all the measurements, the nominal krypton and oxygen contaminations of the XENON1T’s xenon inventory were below 25 ppb and 55 ppb, respectively.

Due to the presence of the anthropogenic radionuclide \(^{40}\)K in the atmosphere, the concentration of natural krypton in xenon has to be reduced to 0.2 parts per trillion (ppt) \([8]\) to achieve the low background required for XENON1T. For this ambitious goal a dedicated distillation column has been constructed by the XENON1T collaboration. Design and development of this device was strongly supported by an analytical tool developed, maintained and operated at MPIK. The rare-gas mass spectrometer (RGMS) combines a gas chromatographic separation of krypton traces from the bulk xenon and a sector-field mass spectrometer to quantify these traces. The RGMS achieves a detection limit of 0.008 ppt \([9]\), more than an order below the requirements for XENON1T, and verified the excellent performance of the XENON1T distillation column. After its final installation at the XENON1T experiment, a Kr/Xe concentration below 0.056 ppt (95% C.L.) was measured. Further, the RGMS is heavily employed to monitor the evolution of the krypton concentration in XENON1T. Based on the frequent and fast feedback of this device, an online purification scheme was devised to reduce the krypton level in parallel to operating the XENON1T detector increasing thereby the duty-cycle of the experiment.

The chemically inert noble gas radon presents another challenging background source in liquid xenon detectors. It is emitted by the construction materials and distributes in the detector. Therefore, a careful material selection of all employed detector components is required. For this purpose not only the world’s most sensitive GeMPI Germanium spectrometers located at LNGS are employed, but also a dedicated radon emanation screening setup developed at MPIK. It is based on miniaturised proportional devices with an ultra low detection limit that count alpha disintegrations subsequent to the radon decay. Before and during the building phase of the XENON1T detector, the emanation measurements were mostly performed locally at the MPIK. Measurements of bigger detector parts and combined sub-systems were directly realised on the construction site at LNGS. By selecting the site materials with a low radon emanation rate, we achieved a reduction of a factor of 5 in XENON1T with respect to XENON100. Nevertheless, the emanation measurements showed that radon will be the main intrinsic background in XENON1T. This knowledge is important for the data analysis in which the MPIK is involved, and serves as a crucial input for the prediction of the electronic recoil background in XENON1T.

The TPC of XENON1T has about 1 m length and 1 m diameter and it is also equipped with an array of photodetectors. Together with the company Hamamatsu, we have developed a photomultiplier optimised for a very low intrinsic radioactivity \([10]\), a high quantum efficiency and a high sensitivity to single photon detection. A total of 248 tubes are currently operated in XENON1T, selected out of 521 tested units. All tubes were tested at MPIK at room temperature and also in a nitrogen atmosphere at cryogenic temperatures. Upon completion of the test, the tubes were installed into the arrays (see Fig. 5) in the cleanroom at MPIK. After installation and also after transportation to LNGS, all tubes were tested successfully. The detector was filled with liquid xenon in April 2016 and since then, the photosensors are operating. First calibration data shows among others an improvement of a factor two in light yield compared to XENON100 which results in an improved energy threshold allowing for better sensitivity at low WIMP masses.

**XENON1T and R&D Activities**

In parallel to the ongoing data taking, the collaboration prepares for a quick upgrade of XENON1T. The so-called XENONnT experiment can reuse many critical hardware components of XENON1T and will have a total xenon mass of 7 tons \([8]\) with a fiducial mass of around 3 tons. At the end of XENON1T the cryostat will be opened and only the cryostat’s inner vessel as well as the XENON1T TPC will be removed and replaced by a
larger inner vessel and the XENONnT TPC. A significant fraction of the necessary funds for XENONnT were already secured and procurement of the required xenon has already started. The design of XENONnT has started and will be continued and finalised in the next year when also the construction of components will start. The current schedule foresees the installation in the underground laboratory end of 2018. Consequently, the commissioning of XENONnT will start beginning of 2019 and at an exposure of 20 ton-years it will reach a sensitivity of $1.6 \times 10^{-46} \text{cm}^2/\text{s}$ for the spin-independent WIMP-nucleon cross section at a WIMP mass of 50 GeV/c² (Fig. 4).

Such an ambitious goal may only be achieved by further optimisation of the detector performance. As in XENON1T, the MPiK will be involved in the procurement of photomultiplier tubes (PMTs) and in the cleanliness of the detector with respect to both, radioactive and chemical impurities. XENONnT will re-use the XENON1T PMTs and needs around 230 new ones of which about 60 will be bought by MPiK. In cooperation with Hamamatsu the R11410 PMT will be further optimised with respect to light emission, tightness and stability.

In XENON1T, the selection of radiopure construction materials will become even more important than before. To enhance throughput and sensitivity we developed the GIOVE spectrometer (see Chapter 1.4, p. 59) with world record sensitivity at shallow depths due to a highly optimised shield as well as a new automated emanation setup (Auto-Ema) for $^{220}\text{Rn}$ screening (see Fig. 6). The time-consuming procedure for sample preparations and extraction of radon from the samples can now be performed in the most efficient way as the machine runs autonomous. Another benefit of Auto-Ema is that the individual measurements have a higher reproducibility which in turn reduces the systematic uncertainty and improves the detection limit. In the future Auto-Ema will not only be used for material screening, but also to investigate other possibilities for radon mitigation. A promising technique is surface coating of the detector surfaces, which should be sufficient to block generated radon and delay its emanation until it decays. First tests with $^{222}\text{Rn}$ already showed promising results.

Another strategy in order to mitigate the $^{210}\text{Rn}$-induced background is the permanent purification of the emanated radon before it disintegrates. We have investigated the development of such a radon removal system based on cryogenic distillation. Dedicated measurements show, that the $^{222}\text{Rn}$ concentration in boil-off xenon is reduced by a factor $R > 4$ with respect to the liquid phase. This reduction power can be enhanced using a multiple-stage distillation column. During a radon distillation campaign at the XENON100 detector, we could demonstrate for the first time the $^{222}\text{Rn}$ reduction in a liquid xenon based experiment by a factor of $D = 20$ by means of an online operated radon removal system. Further R&D projects are currently investigating its applicability in the XENONnT experiment.

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**Indirect Dark Matter Detection in TeV Gamma Rays**

Indirect detection methods for dark matter rely on the annihilation of two dark matter particles into ordinary hadrons or leptons, resulting in final states containing particles, gamma rays and neutrinos. The flux of secondary particles is governed by an astrophysical factor – the line-of-sight integrated squared dark matter density – and a particle physics factor – the velocity-weighted cross section times the spectrum of final-state particles created per annihilation. Since the annihilation rate grows with the square of the density of dark matter, indirect detection techniques concentrate on regions with high dark matter density; most promising is the Galactic Centre region, but also nearby dwarf galaxies. An estimate of the annihilation cross section can be obtained considering the balance between dark matter annihilation and dilution of dark matter density due to the rapid expansion in the early Universe. For velocity-weighted cross sections around $<\sigma v> \sim 3 \times 10^{-26} \text{cm}^3/\text{s}$ the right amount of dark matter is left over at the time when expansion effectively stops the annihilation. Since dark matter particles in galactic halos move at velocities low compared to the speed of light, the annihilation proceeds effectively at rest and the spectrum of secondary particles cuts off at the rest mass of the annihilating particles, providing a characteristic signature. Specific annihilation modes provide line-like signatures at or near this kinematic limit.

Data from 10 years of H.E.S.S. observations of the Galactic Centre region has been analysed searching for signs of annihilating dark matter, based on a total of 254 h of data [11]. In order to minimise contamination from astrophysical emission along the Galactic Plane (see Chapter 1.2), a band of $\pm 0.3^\circ$ in Galactic latitude is excluded; outside this region, the possible contribution of annihilation gamma rays is determined from a likelihood fit making use of the predicted distribution of annihilation gamma rays in space and energy, for a given annihilation channel and dark matter distribution, using regions at larger distance from the Galactic Centre for background estimates. No indication for dark matter annihilation is found, but for the first time, the resulting limits on the velocity-weighted annihilation cross section in the TeV mass range reach the predicted thermal annihilation cross sections for certain modes (Fig. 7), providing a real test of models.

A search for dark matter line-like signals was performed in the vicinities of the Galactic Centre by the H.E.S.S. experiment on observational data taken in 2014, including data from the new H.E.S.S. II telescope and expanding the energy range to lower energies, providing overlap with results from the space-based Fermi gamma-ray observatory (Fig. 8). No significant excess associated with dark matter annihilations is seen in the energy range 100 GeV to 2 TeV, in particular ruling out at 95% C.L. the presence of a 130 GeV line previously reported in Fermi-LAT data. These current H.E.S.S. results define the scale of the art of indirect dark matter detection in the TeV domain. CTA (see Chapter 1.1) will be ready in 10 times more sensitive than H.E.S.S. and will be able to detect dark matter in the TeV range, or exclude a significant region of the parameter space.

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**References:**