Techniques and Results for the Direct Detection of Dark Matter (review)

Dmitry Akimov[a]*

[a]Istitute of Theoretical and Experimenal Physics, 25 Bol. Cheremushkinskaya, Moscow 117218,Russia

Abstract

A brief review of the current status of experiments on direct Dark Matter detection is given. Cryogenic and noble gas detectors have reached the best sensitivities to WIMPs. The region of SUSY predictions for M_W, σ_p will be investigated in the future with ton- and multi-ton-scale detectors.

1. Introduction

This review contribution to the conference provides an update of the current situation in the very rapidly growing experimental field of so-called direct Dark Matter detection. The exponentially growing interest in the Dark Matter problem is impressively illustrated by fig. 1. This figure represents the distribution of the annual number of publications on Dark Matter taken from the SLAC HEP database [1].

During the last two decades a significant development of Dark Matter detection techniques has taken place, and what is most important, the justification of the existence of Dark Matter in the Universe has become so strong that scientists have nowadays practically no doubts concerning the choice of direction of their experimental research.

Due to the thematic direction of this journal, this review is dedicated to a larger extent to the progress in techniques of the experimental search for Particle Dark Matter, i.e. Dark Matter consisted of WIMPs (Weakly Interacting Massive Particles). The most favored candidate for WIMPs is still a heavy neutralino particle predicted by the Supersymmetry (SUSY) theory. Unfortunately, the interval of interaction cross sections of WIMPs with ordinary matter predicted by this theory is very wide and covers more than five orders of magnitude.

For an introduction to WIMP detection techniques the reader may be referred to reviews [2,3] (including the author's previous reviews [4,5]). Let us remind ourselves here of the basic principles of this technique.

Experimentalists are looking for the elastic scattering of WIMPs off atomic nuclei, which has a very small cross-section. The signals produced by WIMPs in a detector are also characterized by a rather small energy deposition. The spectrum profile can be determined from the kinematics of elastic collisions of WIMPs with detector nuclei taking into account the Maxwellian velocity distribution of WIMPs in our galaxy and the Earth's motion in interstellar space. The resulting energy spectrum has a form very close to an exponential with a decay constant of < 10 keV. Unfortunately, background signals of various origins in detectors have similar exponential shapes of pulse height distributions. This significantly complicates the process of disentangling a weak WIMP signal from a background. A standard representation of Dark Matter search results is an exclusion plot on a parameter space σ_p and M_W, interaction cross section and WIMP mass, respectively. Most of the Dark Matter search results can be found on an on-line plotter [6]. The plots are produced separately for spin-dependent and spin-independent

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* Corresponding author. Tel.: +7-499-789-6406; fax: +7-499-127-0833.
E-mail address: akimov_d@itep.ru.

interactions. In the first case, the cross section is proportional to $J(J + 1)$, where J is the nucleus spin; in the second case, it is proportional to A^2, where A is the mass number. In order to compare the results obtained by using detectors of different elemental composition, a so-called reduced-to-proton cross section σ_p is used:

$$\sigma_p = \frac{m_{red}^2(p,W)}{Cm_{red}^2(N,W)}\sigma_N,$$

where $C = A^2$ for the case of a spin-independent interaction.

The detectors are located deep underground in low-background laboratories to reduce the cosmic muon flux by many orders of magnitude. Due to the progress in the development of DM detection technique, from the pioneer experiments till now the residual background of the setups has been reduced by ~ 5 orders of magnitude. The pioneer experiments used ordinary detectors for particles and radiation. Those were the ββ decay experiments COSME, IGEX, Heidelberg-Moscow and MIBETA [7-11], in which reduction of the background was achieved mainly by traditional methods of improvement of material purity and shield quality.

A serious breakthrough in background reduction took place after applying so-called methods of active suppression of electromagnetic background (electron recoils) by means of simultaneous measurements of energy deposition by two or more different ways. This method allows one to reject gamma

Fig. 1 Annual distribution of the papers on Dark Matter from the SLAC HEP database [1] (search criterion: "Dark Matter" in the title).

and electron events by ≥ 3 orders of magnitude.

The next serious steps in improvement of the sensitivity will be the use of an active neutron veto and increase of the sensitive mass. These steps will allow to cover practically all the space of the parameters σ_p and M_W predicted by SUSY [12-16].

This review is divided into two main parts: the 1st one is dedicated to the experiments which have given new results during the last two years and to those at the commissioning stage, and the 2nd one to future experiments with ton-scale

detectors based on liquid noble gases.

2. Experiments: ongoing and at the commissioning stage.

In this section, the status of the following experiments is reviewed: DAMA/LIBRA, CDMS, ZEPLIN-III, Xenon100, LUX, XMASS and WArP.

2.1. DAMA/LIBRA

The experiment is a continuation of the former experiment DAMA/NaI carried out in the Gran Sasso underground laboratory, Italy. The data taking with DAMA/NaI stopped in July 2002 and the installation of DAMA/LIBRA was started. A new setup LIBRA (Large sodium Iodide Bulk for RAre processes) is built of 25 crystals of NaI(Tl) similar to those used in the former setup (9.7 kg each). Nine crystals are taken from DAMA/NaI, the rest ones are completely similar. Each crystal is viewed with two low-background PMTs EMI9265B53/FL from opposite sides and was packed in envelopes made of ultra-pure copper. The shield is built according to the same scheme, i.e. copper and then lead bricks, cadmium foil, polyethylene, and paraffin. From the outside the whole setup was enclosed in a Plexiglas box flashed by pure nitrogen to protect it from atmospheric radon. The copper bricks from the old setup were etched for removing the surface layer which may have a higher concentration of radioactive elements. Assembling of the shield was performed in a pure nitrogen atmosphere to prevent contamination of the setup by products of atmospheric radon disintegration. A detailed description of the DAMA/LIBRA setup can be found in [17] including estimations of the basic characteristics such as detection efficiency versus energy, light collection efficiency (5.5 – 7.5 photoelectrons/keV depending on crystal), and contamination of crystals by the radioactive isotopes ^{232}Th, ^{238}U, ^{40}K, ^{125}I, ^{129}I, ^{210}Pb, ^{22}Na, and ^{24}Na.

The results are now presented for 13 annual cycles of observations (7 cycles with DAMA/NaI and 6 cycles with DAMA/LIBRA). The latest publication is [18]. The count rates of the crystals were analysed. Only events with an interaction in a single crystal (single-hit event, with a coincidence of two PMTs) were selected as WIMP candidates, because the probability for a WIMP to interact in more than one crystal must be negligible. A pulse shape analysis (PSA) was applied to reject the noise signals.

Periodic annual deviations of the count rate from the mean value have been observed for the lowest energy bin (2 – 6 keV) above the threshold. The discovery of this deviation and interpretation of this effect as a possible signal from WIMPs were first reported in publications [19, 20]. The first confident result was presented in 2000 [21] on the basis of four annual cycles of observations. The experiment then went on till June 2002, for the next three years, during which the authors continued to observe this effect. The measurements were resumed in 2003 with the DAMA/LIBRA setup, and the effect revealed itself again with higher statistics. The total exposure of observation during 13 annual cycles is 1.17 t·y. This
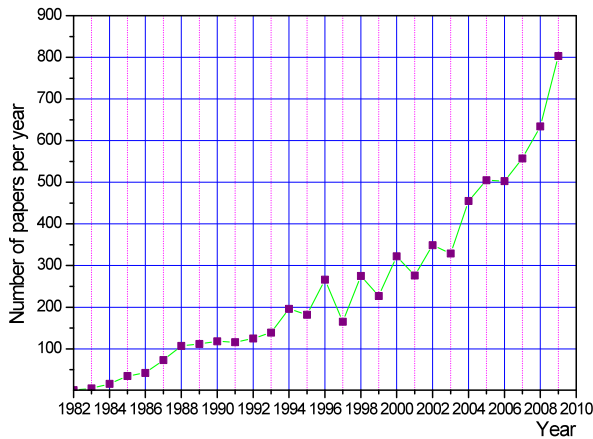
variation is well fitted by the cosine function expected for the WIMP signal with a period $T = 0.999 \pm 0.002$ year, i.e. very close to one year, with a phase $t_0 = 146 \pm 7$ days, which is very close to the signal modulation expected for WIMPs (152.5
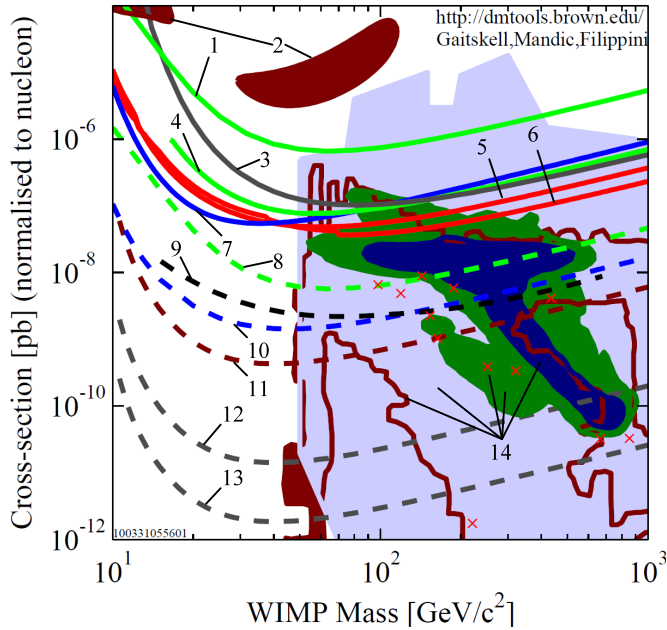

Fig. 2 1 – ZEPLIN-II [23], 2 –DAMA/LIBRA [24], 3 – EDELWEISS [33,34], 4 – ZEPLIN-III 1st phase [38], 5 – CDMS [25], 6 – CDMS [31], 7 – Xenon10 [26], 8 – ZEPLIN-III 2d phase [39], 9 – XMASS [45], 10 – Xenon100 [42], 11 – LUX [43], 12 – Xenon1t [48], LZS [47], MAX G2 LXe [53], 13 – LZD [47], MAX G3 LXe [53], 14 – SUSY predictions [13-16]

days or 2nd of June), and with an amplitude of 0.0131 ev/kg/keV/day. A power spectrum analysis made for the $2 - 6$ keV energy bin shows a sharp peak at a frequency of $2.735 \cdot 10^{-3}$ day^{-1}, which corresponds to a period very close to 1 y and does not show any peaks in other energy bins. The very convincing argument in favour of the WIMP hypothesis, according to the authors' point of view, is that there is no modulation effect for the multiple hit events (for the same energy bin $2 - 6$ keV), i.e. when interactions took place in two or more crystals. The DAMA group has not found any modulation effect in the region of energies above 90 keV. If the effect is caused by variation of the Compton background in the $2 - 6$ keV energy bin it must reveal itself also for the gammas with energies > 90 keV.

Having not found any artificial origin of the observed effect the DAMA group attributes it to a WIMP signal (see on fig. 2 the region of allowed parameters σ_p and M_W obtained for an isothermal halo model). However, there is a serious criticism expressed in [22] by the former participants of the NAIAD experiment (UK): if one subtracts the predicted spectrum for the $M_W = 60$ GeV and $\sigma_p = 7 \cdot 10^{-6}$ pb from the measured spectrum, there will be practically no room for the background in the near-threshold region. These M_W and σ_p are in the middle of the allowed region (with the isothermal halo model) and correspond to the best fit to the data. The authors of paper [22] make a statement that any interpretation of the annual

modulation of the event rate observed by DAMA as a Dark Matter signal should include the full consideration of the background spectrum. In the future the DAMA group plans to use PMTs with higher QE to explore the region below the current 2-keV threshold.

2.2. Cryogenic experiments

In cryogenic bolometers, event-by-event rejection of background gammas and electrons is based on the analysis of the ratio of phonon signals to ionisation (CDMS [27] and EDELWEISS [28] experiments) or to scintillation (CRESST [29]). Such devices operate at temperatures of several tens of mK where the specific heat capacity becomes extremely small, and a phonon signal is measured with extra sensitive thermistors. The part of the energy deposition produced by a particle in a crystal which goes to so-called ballistic phonons is practically independent of the particle type. On the other hand, the energy which goes to ionization or scintillation strongly depends on it. For the nuclear recoils produced in WIMP interactions with the detector's atomic nuclei such a signal is significantly lower (at the same energy deposition) than that for electrons and gammas due to quenching.

The Cryogenic Dark Matter Search (CDMS II) experiment is located at the Soudan Underground Laboratory, USA. It uses 19 Ge (~ 230 g each) and 11 Si (~ 100 g each) detectors operating at temperatures less than 50 mK [30]. Each detector is a disk with a thickness of ~10 mm and a diameter of 76 mm. The detectors are packed into five towers, by 6 in each tower.

The ratio of the ionization to recoil energy ("ionization yield") provides rejection of electron and gammas with a factor better than 10^4 (obtained by calibration with ^{133}Ba gamma and ^{252}Cf neutron sources). It was found that essentially all of the misidentified electron events take place within the first few μm of the detector surface, where ionization collection is sufficiently reduced. It was also found that such events have faster-rising phonon pulses than the events occurring within the bulk of the detectors. Hence, phonon pulse timing parameters were used to improve the rejection of surface events. The resulting rejection factor (with yield and timing analysis) for gammas and electrons was obtained to be more than 10^6. To attenuate external environmental radioactivity and to reject events caused by cosmogenic muons, the detectors are surrounded by layers of lead and polyethylene shielding and an active muon veto [30].

In the data taking run (Oct 2006 – Jul 2007), no events were observed in the WIMP search window. The final results derived from it and combined with the reanalysed previous data (2004 and 2005) were presented in [31] and are shown by curve (6) in fig. 2. During the last run (Jul 2007 – Sep 2008) two events were observed in the window. The authors estimated the expected number of background events during the exposure time to be 0.8 ± 0.1 (stat) ± 0.2 (syst). From this a 90% confidence limit was derived, and a combined limit (with the previous data, curve 5 in fig. 2 [25]) is shown by curve 6 in fig. 2 [31].

The next stage of experiment will be SuperCDMS [32].

With 15 kg of detectors, it is planning to achieve $5 \cdot 10^{-9}$ pb sensitivity at the Soudan underground laboratory, then to reach a sensitivity of $3 \cdot 10^{-10}$ pb with 150 kg at the SNOLAB site, and finally, with a setup called GEODM (1.5 t), to reach the sensitivity $2 \cdot 10^{-11}$ pb at the DUSEL site (2017 - 2022).

The EDELWEISS setup is located in the Laboratoire Souterrain de Modane (LSM), France with 4800 meters of water equivalent rock shielding against cosmic muons. The cryostat housing the detectors is protected from the ambient γ-rays by a 20-cm lead shield. This is surrounded by a 50-cm thick polyethylene shield, covered by a muon veto system with 98% geometric efficiency for the residual muons. The problem of the surface events has been solved by using so-called interleaved electrodes [32]. The EDELWEISS collaboration has presented the results from the first ∼ 6 months exposure of the second phase [33, 34]. The 144 kg·days include the data taken in 2009 with ten ∼ 400-g germanium detectors and the additional data from earlier runs with two detectors in 2008. There is one event with an energy of 21 keV, just above the threshold, observed in a WIMP search region obtained from calibration with gamma and neutron sources. The gamma rejection factor obtained from the calibration was as high as 10^4. This observation of one nuclear recoil candidate at 21 keV in an effective exposure of 144 kg·d is interpreted in terms of a 90% CL limit on the cross-section of spin-independent interactions σ_p of $1.0 \cdot 10^{-7}$ pb for $M_W = 80$ GeV/c^2.

2.3. Liquid noble gas detectors

In this section, the experiments based on liquid noble gases currently ongoing and those at the commissioning stage are discussed. The basic features of the liquid noble gas detection media (LXe, LAr), which stimulated their use for Dark Matter experiments, are the following ones:

- large scintillation yield and the possibility to detect simultaneously both scintillation and ionisation signals, the effect used for particle identification;
- extremely low level of radioactive contaminants such as U/Th chains and ^{40}K: the gases can be easily purified from such contaminants by filtering;
- technical possibility to build large and even very large (with a mass of several tons) detectors, in which one may select the central part which is completely shielded from the outer radioactivity by the peripheral part of the liquid (a concept of a "self-shielded" detector).

A two-phase particle detection technique was proposed in the early 70s for LAr [35]. For the WIMP search it was proposed first time in [36] with the use of liquefied dielectric organic gases.

In a two-phase (also called "dual-phase") detector a particle produces direct excitation of noble gas atoms and ionization. The atoms excited via formation of excited molecules (excited dimers or excimers, Xe$_2$* or Ar$_2$*) produce scintillation. In addition, without electric field the electrons and ions produce another component of scintillation called a recombination component via recombination followed by formation of excimers. If an electric field is applied, this component is partly suppressed because some part of the ionization electrons is extracted from the particle track. These electrons drift towards the boundary between the liquid and the gas phase and then are extracted from the liquid. In the gas phase the electrons accelerated by an appropriate electric field excite the atoms of the gas and produce electroluminescence (EL, called proportional scintillation since the magnitude of this signal is proportional to ionization). The spectrum of both scintillation and electroluminescence is a narrow molecular continuum with a maximum at 175 nm for Xe and 125 nm for Ar. Both scintillation and electroluminescence signals are detected with the same array of photomultipliers. Different mechanisms of excitation and ionization produced by electrons (gammas) and by recoils from WIMP scattering on atomic nuclei, as well as different specific ionization densities and different dependences on the electric field of the electron extraction efficiency from a track results in a different ratio of scintillation to electroluminescence signals. This yields an effective tool for the rejection of electrons and gammas; the rejection factor is greater than 10^4.

2.3.1. ZEPLIN-III

A detailed description of the ZEPLIN-III detector can be found in [37]. The detector comprises 50 kg of xenon, from which 12 kg and ∼ 8 kg are in the active region (between the electrodes) and fiducial volume (FV), respectively. The detector geometry is disc-like and optimised for high electric field and enhanced light collection of scintillation. For this reason, 31 2-inch PMTs are submerged in the liquid xenon and view the active volume from the bottom through two transparent wire grids (with a wire diameter of 0.1 mm and a pitch of 1 mm). Those grids serve as an electric field screen (the one closest to the PMTs, which is kept at the same potential as the potential of the photocathodes) and as a cathode ("–") for the active volume. The "+" HV is applied by a flat polished copper plate anode located 40 mm from the cathode and 4 mm above the LXe surface. The electrode system produces an electric field of 3.9 kV/cm in the liquid and 7.8 kV/cm in the gas. The fields in the active region are configured so that any charge produced from the lateral metal surface of the cathode ring will be collected on the lateral surface of the anode ring under the surface of the liquid xenon. Thus, this charge does not produce an EL signal. Such a configuration of the electric field provides a "wall-less" geometry of the target: it eliminates background events produced by radon progenies, which are usually plated on the surfaces of the walls. The detector is surrounded by plastic and lead shields.

The first science run searching for WIMPs was carried out from February 28th to May 21st, 2008 [38] with a total exposure of 847 kg·days. After applying all cuts and taking into account all efficiencies the live exposure is 126.7 kg·days. A limit on spin-independent interaction of 8.1 x10^{-8} pb was obtained [38] (see curve 4 in fig. 2).

At the time of writing this review an upgrade of the detector has been finished. The upgrade comprised a

replacement of the PMTs by new ones. This should provide a reduction of the radioactive background by a factor of 35 – 40 to the observed background levels in the first phase. An active veto shielding consisting of plastic scintillator and Gd-loaded polypropylene (each 15 cm thick) was added to allow tagging events of single scattering of neutrons produced inside the detector. Neutrons are moderated in the polypropylene mostly via scattering on hydrogen and are then captured by Gd. The latter one produces typically 3 – 4 gamma quanta with a total energy of ~ 8 MeV, which are detected by a plastic veto scintillation detector. The Monte Carlo simulated veto tagging efficiency for such neutrons is about 65 % (for the ZEPLIN–III setup geometry). The veto detector consists of 52 individual slabs of plastic scintillator arranged so as to provide >3π sr coverage around ZEPLIN–III. Each one is viewed by a 3-inch low-background photomultiplier. Thirty-two sections are 1 m long, 15 cm thick prisms with trapezoidal cross section, which form a 'barrel' with an outer diameter of 160 cm. These are arranged to stand on a continuous 30 cm thick base section of passive polypropylene shielding. Between the plastic scintillator and the ZEPLIN–III instrument there are 32 sections of 15 cm thick Gd-loaded polypropylene forming a barrel of an outer diameter of 130 cm. On the top of the propylene barrel there is a 15 cm thick Gd-loaded polypropylene disk on which the remaining 20 scintillator modules are positioned. These modules have different lengths ranging from 50 to 80 cm and a rectangular cross section of 15 x 16 cm^2.

The projected limit on the spin-independent cross section planned to be achieved with this detector is $5.6 \cdot 10^{-9}$ pb (curve 8 in fig. 2).

2.3.2. Xenon100

The Xenon100 experiment [40] is a part of the Xenon project. The experiment is being carried out in the Gran Sasso underground laboratory. The detector design is functionally very similar to the Xenon10, a previous stage detector. The liquid Xe target of ~ 65 kg is enclosed in a vertical hollow cylinder of Teflon of 30 cm inner diameter and 30 cm height with field shaping rings mounted in the walls. Teflon is used as an effective light-collecting material for the VUV light of scintillation and electroluminescence. This active volume is viewed by 178 photomultipliers in two arrays, 98 in the gas phase and 80 in the liquid. The PMTs are Hamamatsu R8520-06-Al 1-inch square optimized for low-temperature operation and for the VUV light of Xe emission. The quantum efficiency of the these tubes is ~35%, and has been improved from ~25% for the tubes used in the Xenon10 detector. The tubes contain very low amounts of radioactive elements: the activities of U, Th, K and Co are 0.17 ± 0.04, 0.20 ± 0.09, 10 ± 1 and 0.56 ± 0.05 mBq, respectively. Nevertheless, the PMTs remain the main contributor of radioactive background in the fiducial volume: 62.6% [41]. The electric field is applied to the LXe target by stainless steel meshes stretched on the rings. The value of the field in the drift region is ~ 1 kV/cm, the field in the electroluminescent region is 13 kV/cm. The surrounding LXe outside the Teflon cylinder and between the container

walls is viewed with 64 photomultipliers of the same type providing vetoing against multiple scattering events. The total amount of Xe in the detector is 170 kg.

The detector is surrounded by 5 cm of OFHC copper, 20 cm of polyethylene and 20 cm of lead.

As mentioned above, the xenon can be easily purified from radioactive elements, the only exception being the technogenic isotope ^{85}Kr. This beta-decaying isotope with E_{max}= 687 keV and $T_{1/2}$ = 10.76 y limits the sensitivity of Xe based Dark Matter experiments. For the Xenon100 experiment the gas was ordered from Spectra Gases Company with a quoted concentration of Kr of ~ 5 ppb. The amount of Kr was estimated by measuring a delayed coincidence rate from the decay ^{85}Kr $\rightarrow$ ^{85m}Kr $\rightarrow$ ^{85}Rb with the known branching ratio of 0.454%. The obtained value of 7 ± 2 ppb is consistent with that quoted by the supplier. In order to reach the projected sensitivity of the Xenon100 detector, Xe must be purified down to < 50 ppt concentration of Kr (corresponding to 10^{-3} ev/kg/keV/day). For this purpose, a 3-m tall cryogenic distillation column by Taiyo-Nippon Sanso with a purification speed of 0.6 kg/h was used.

The Xenon100 experiment started the first blind Dark Matter Search run on January 13, 2010 after stable operation during the previous sixth months [42]. During this period, a non-blind background study, calibration of the detector with gamma and neutron sources and a study of the detector's basic performance were carried out. Due to constant recirculation through a hot getter (SAES) the electron lifetime, the most important operating parameter of a double-phase detector, has increased from ~ 20 μs at the beginning of this period to more than 300 μs by the end. The measured single scatter differential event rate in the fiducial volume is $5 \cdot 10^{-3}$ ev/kg/keV/day in the energy range < 100 keVee (keVee is the unit for electron-recoil equivalent energy). This value is by a factor of 100 lower than the rate obtained in the previous Xenon10 detector and is due to the self-shielding effect. The rejection factor for gammas and electrons was found to be quite similar to that for the Xenon10 detector, i.e. from 10^2 to 10^3 depending on energy for energies < ~20keVee.

With an exposure of 6000 kg·days (30 kg fiducial volume, 200 days background free run) the Xenon100 group expects to reach the 90% confidence level limit on the spin-independent cross section of ~ 10^{-9} pb (curve 10 in fig. 2) or to detect ~ 10 WIMP events if M_W = 100 GeV and σ_p = 10^{-8} pb.

One of the options of the Xenon experimental program before going to a ton-scale detector was to increase the size of the Xenon100 instrument and to replace the bottom array of the PMTs with newly developed (see below) QUPID photodetectors (Xenon100+) [40].

2.3.3. LUX

The detector LUX (abbreviation of *L*arge *U*nderground *X*enon detector) is now at the assembling stage in the USA at SUSEL laboratory at the underground Homestake site (South Dakota) [43]. The design the two-phase detector is very similar to that of Xenon100 but without the LXe veto layer. Instead, the whole detector including the vacuum cryostat

made of titanium will be submersed in a large, 6-m diameter water tank (veto) with Cherenkov readout. The electric field is formed by a dodecagonal field cage with an average diameter of 49 cm, and a height of 59 cm. The total mass of LXe in the detector is 350 kg with 150 kg in the fiducial volume. The volume is viewed by two arrays of 60 Hamamatsu R8778 PMTs each at the top and at the bottom.

The LUX collaboration has performed a surface test run with a reduced amount of LXe (60 kg), the remaining peripheral part of the detector being filled by an aluminium displacement (250 kg), and using four PMTs. In this run, the main LUX subsystems have been tested, such as: cryogenics, recirculation, slow control and safety system, electronics chain, PMT mounts and resistor-chain bases, and analysis software. An important result has been obtained on Xe purification. It was shown that a drift length of free electrons of ~ 2 m can be achieved over a reasonably short time (~ 90 hours) of constant recirculation through a getter starting from a value of less than 1 cm.

Currently the underground laboratory is being prepared at Homestake at the 4850-feet level (~ 4000 m of water equivalent). Assembly of the detector and complete tests of all systems will be performed in a surface building where the detector will be submerged in a 3-m water tank. After that the detector will be moved to the underground site.

It is planned to reach a sensitivity of $4 \cdot 10^{-10}$ pb after 10 months of exposure (curve 11 in fig. 2).

2.3.4. XMASS

The XMASS detector is being built by a collaboration of Japanese and Korean universities and institutes. The detector is currently at the final stage of assembly at the Kamioka underground laboratory, Japan. XMASS [45,46] is a multipurpose detector:

- for detection of solar neutrinos from the pp cycle (*X*enon *MASS*ive detector for Solar neutrinos);
- for double beta-decay search (*X*enon neutrino *MASS* detector);
- for Dark Matter search (*X*enon detector for Weakly Interacting *MASS*ive Particles).

XMASS is a multistage experiment. The first stage of tests with a small-size (~ 30 cm) prototype has been completed. The current stage with an 800-kg detector aims at Dark Matter search, and the next stage of a multiton detector (~ 20 t) will address the whole set of tasks.

XMASS is a single-phase detector: the XMASS scientists rely only on the excellent self-shielding properties of LXe. The geometry is spherical. This allows to have a 67% coverage of the full solid angle by 812 photomultipliers. The expected photoelectron yield is ~ 5 phe/keVee**.**

The PMTs are installed inside a copper sphere containing 800 kg of LXe (the fiducial volume is ~ 100 kg). The copper sphere will be suspended in a water tank equipped with large PMTs for Cherenkov readout. For later it is planned to use this tank for the larger 20-t detector.

The xenon for the XMASS detector has been purified down to a concentration of 3.3 ± 1.1 ppt of Kr by passing it through

a specially designed distillation tower [46]. The background rate estimated by Monte Carlo is expected to be of the order of $1 \cdot 10^{-4}$ ev/kg/keV/day in the fiducial volume of 100 kg in the energy region below 100 keV. Such a background level will allow the XMASS detector to reach a sensitivity of ~10^{-9} pb (curve 9 in fig. 2 [45]).

2.3.5. WArP

WArP (*W*IMP *Ar*gon *P*rogramme) is the first experiment that uses liquid argon (LAr) for direct Dark Matter searches at Gran Sasso [47, 48]. The first stage of researches with a 2.3-litre chamber (2.6 kg in active volume) has been completed [49]. A 140-kg detector is currently at a commissioning stage.

The inner detector (target) is a two-phase 100-l chamber with a drift region (with an electroluminescence gap on the top) formed by field shaping rings. Reflective and wavelength-shifting sheets cover this field cage on the side and on the bottom (the cathode). Readout is performed using a top array of PMTs only. An active veto shield of LAr (with a minimum thickness of 60 cm) completely surrounds the inner detector. The total amount of LAr in this shield is about 5600 litres, and readout of this volume is performed with PMTs positioned on the walls of the container. The veto is surrounded with a passive shield made of polyethylene with a thickness of 10 cm to moderate neutrons coming from the outer cryostat walls. The main outer vacuum cryostat contains all these elements immersed in the LAr. The cryostat is made of stainless steel and has double walls and super-insulation between them. Then there is an external passive shield made of 10 cm thick lead, encapsulated in stainless steel boxes, and a 70 cm thick layer of polyethylene, and, finally, an external, anti-seismic sustaining structure made of carbon steel.

The detector uses both ionisation-to-scintillation ratio analysis and pulse shape analysis. The latter provides very high rejection power (combined with the ratio analysis, a rejection factor of ~ $3 \cdot 10^6$) but requires the number of photoelectrons to be more than several dozens, and this makes the energy threshold very high.

As ^{85}Kr in Xe, the isotope ^{39}Ar (beta-active; Q = 565 keV, $t_{1/2}$ = 269 y) is the main source of internal radioactivity in a LAr detector, which ultimately restricts the sensitivity of a WIMP detector based on non-depleted Ar. The WArP collaboration has recently reported [50] a discovery of large amounts of argon from underground natural gas reservoirs. The estimated concentration of ^{39}Ar in this gas is by a factor of > 20 smaller than that in natural Ar produced from the air. The total quantity of argon currently stored in the National Helium Reserve is estimated to be ~ 1000 tons.

The projected sensitivity of the WArP experiment for 1 y of observations is ~ $4 \cdot 10^{-9}$ pb for a WIMP mass of 100-GeV [48].

3. Future experiments

The future experiments, evidently, will be of the ton and multiton scale. In this section we will focus only on noble gas detectors. Among all types of Dark Matter detectors the noble
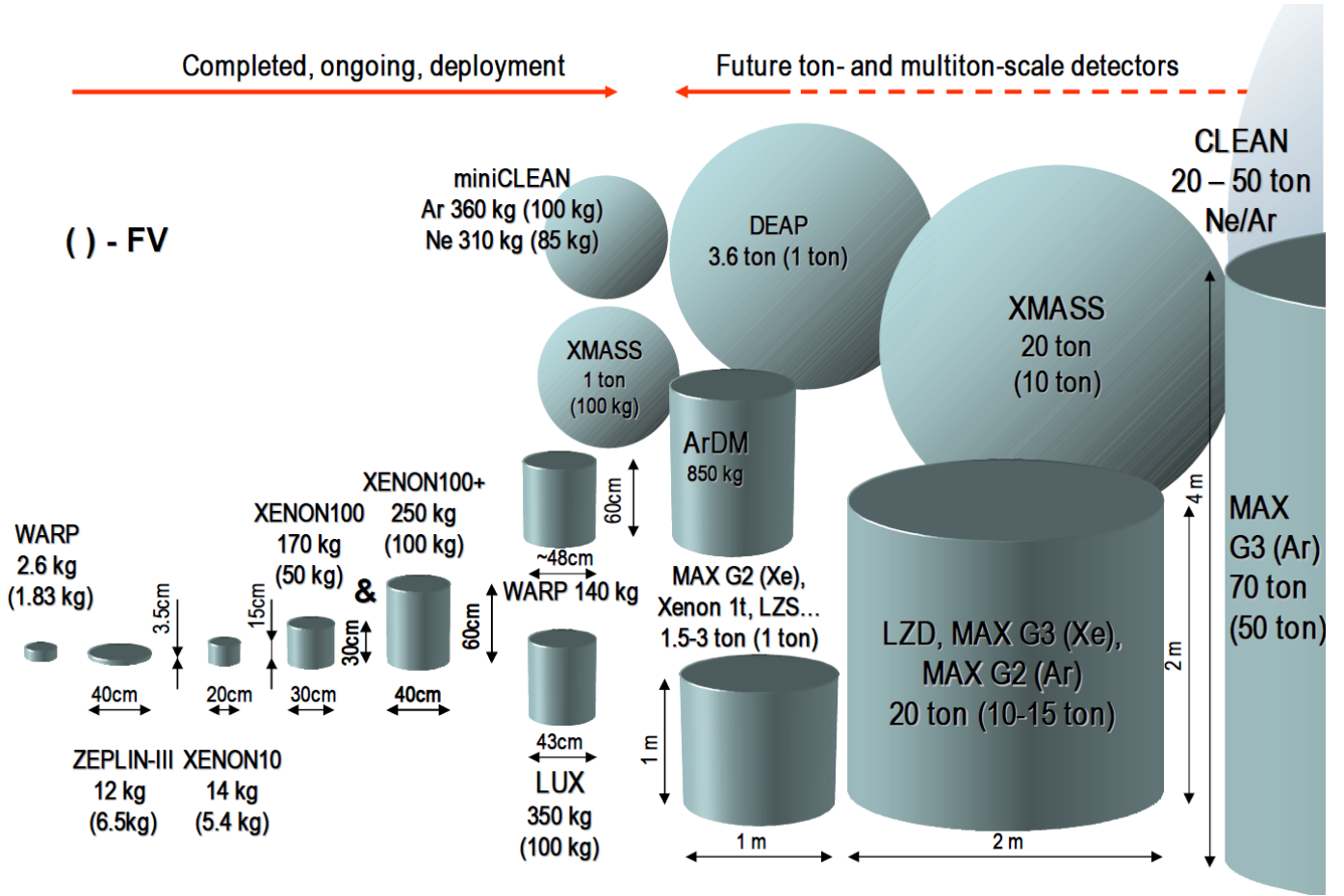
Fig. 3. Family of liquid noble gas Dark Matter detectors. References (not in the text): miniCLEAN [51], DEAP&CLEAN [52]

gas detectors have the advantage that they can be quite easily scaled up without changing the basic detection principles. As mentioned above, another very important advantage of such big detectors is that they do not have any construction elements inside (in the bulk of liquid): this is the concept of a "self-shielded" or "wall-less" detector. Detailed modelling by Monte Carlo [53] shows that for a 3-t detector, the differential count rate is 10^{-6} ev/kg/keV/day for a fiducial mass of ~1 t in the centre of the detector (after a rejection factor of 99.75 is applied to account for gammas and electrons). In this estimate, PMTs were assumed to be the main source of radioactive background. For a 20-t detector this background becomes 10^{-12} and 10^{-10} ev/kg/keV/day for a 3-t and a 6-t central part, respectively. The irreducible background caused by solar neutrinos from the p-p cycle contributes at a level of 10^{-7} ev/kg/keV/day (before applying a rejection); about the same count rate is expected from the ^{85}Kr contribution at a Kr concentration in Xe of 1 ppt (see, for example [54]). Contributions from double beta decay of ^{136}Xe and solar neutrinos from the ^{7}Be cycle are by an order of magnitude smaller. The expected neutron background is ~ 0.1 ev/t/y (integrated over the expected nuclear recoil energy range for WIMPs). All this means that experimentalists will have a practically quiet detector, capable to probe the whole M_W, σ_p

parameter space of SUSY predictions (fig. 2).

The family of noble-gas Dark Matter detectors is presented in fig. 3. The left part of the picture shows experiments already completed, ongoing at the moment, or in the deployment stage. The right part shows the future large-scale detectors which are currently at the stage of modeling and design. Only minor R&D, mostly aimed at technical issues arising when scaling up the dimensions, are expected. The general conceptual design of such experimental setups is already clear now: a liquid noble gas detector will be positioned in the middle of a huge water tank with Cherenkov readout for shielding from external gammas and residual cosmic ray muons. In some versions, the central part of the water is replaced by a liquid scintillator.

3.1. Xenon1t and MAX

The detector Xenon1t is the next stage of the Xenon Dark Matter program for the Gran Sasso underground laboratory. The latest conceptual design was presented in [54]. It is a design scaled up to ~ 1 m in diameter and ~ 1 m in height from the previous two-phase detectors of the Xenon series with top and bottom layers of 121 QUPIDs each. The cryostat will be made of pure copper or titanium. The detector will be

placed in a water tank having ~ 10 m in diameter and ~ 10 m in height. There is also a traditional option with a solid shield which will comprise (from outside to inside) a muon veto, 55 cm of polyethylene, 20 cm of lead, then again 15 cm of polyethylene and 2 cm of lead.

The MAX (Multi-ton Argon & Xenon) program is oriented at Dark Matter search at DUSEL, the new Deep Underground Science and Engineering Laboratory at the Homestake site at a level of 8000 feet. The search will be performed simultaneously with two-phase LXe and LAr detectors. In the case of a positive result of search this will allow to localise with much higher accuracy the region of allowed M_W and σ_p parameters due to the different behavior of the differential cross sections of WIMP-nucleus scattering for a given WIMP mass in Xe and Ar targets.

The latest concept of MAX was presented very recently [55] and assumes two stages of the experiment: MAX G2 and MAX G3. The first one will be performed with detectors having masses of ~ 2 t (with ~ 1 t in FV) for the LXe detector and of ~ 10 t (with ~ 5 t in FV) for the LAr detector, and the second one, with detectors having masses of ~ 20 t (LXe; with ~ 10 t in FV) and of ~ 70 t (LAr; with ~ 50 t in FV). The conceptual design of the MAX G2 LXe detector is absolutely identical to that of Xenon1t (~ 1 x 1 m). It will be equipped with 3-inch QUPIDs. The MAX G2 LAr (~ 2 x 2 m) will have a 4π readout with 595 3-inch QUPIDs at the top and 825 6-inch QUPIDs at the bottom and sides. This detector will serve as MAX G3 LXe at the next stage and the MAX G3 LAr (~ 4 x 4 m) will have a 4π readout with 3746 6-inch QUPIDs. Such new large-area photodetectors are expected to be produced by the time the detector is built. The detectors will be suspended in water tanks (two identical tanks for the LXe and LAr detectors) with a diameter and height of ~ 18 m each. The central part of the water volume (~ 8 x 8 m) will be replaced by a liquid scintillator. All these volumes will be equipped with PMT readout.

3.2. LZ program

This is another grandiose project with two-phase noble gas detectors for the Homestake underground site [53]. The LZ program involves the LUX, ZEPLIN-III and new US and European groups. It is subdivided into LZS, a ton-scale detector for SUSSEL (the place of the LUX detector), and LZD, a multi-ton detector for DUSEL.

In one of the options, the LZS detector will contain 1.5 t of LXe (~ 1 t in FV) with two readout arrays of low-background PMTs. It will be placed in a container filled with liquid scintillator kept at the temperature of LXe. This is to minimize the thickness of the detector and to increase the FV. The whole construction will be placed in a double-walled vacuum cryostat suspended in a water tank (the same tank as for the LUX detector after the LUX experiment is completed). A challenging task will be the development of a stable liquid scintillator for such a low temperature.

The design of the next LZD detector is currently not yet worked out in detail. The presented version is scaled up from

the LZS detector to 20 t (FV=10 t).

4. New developments stimulated by Dark Matter search

Search for weakly interacting massive particles has stimulated several new developments in particle detection.

It is fair to say that the development of such a completely new technology as bolometric measurements for particle detection was prompted by the necessity of detecting very small energy depositions from neutrino and WIMP interactions. The technology used for Dark Matter searches with cryogenic bolometers has never been used before for particle detection. Also, the double-phase technique has found its first real application in the field of Dark Matter search and was significantly improved during the R&D stages of WIMP detectors. This has opened up the possibility of using a combination of the unique detection properties of noble gases such as the possibility to detect simultaneously scintillation and ionisation. Thus we now have these two newly developed technologies which will certainly find applications in other fields.

Another direction of research stimulated by the development of WIMP detection technologies is the selection of pure materials suitable for building Dark Matter detectors. Here, it should be noted that even development of special low-background photomultipliers has become a significant part of programs for future experiments. In such photomultipliers, the content of radioactive elements is almost a factor of 100 less than in their analogues for common usage. These are the newly developed PMTs by Electron Tubes LTD for ZEPLIN-III, the tubes developed by Hamamatsu for Xenon (1-inch square; R8520), LUX (2-inch; R8778), and for XMASS (R8778mod). The last PMT has by far the lowest content of radioactive contamination among all PMT types. Contents of U, Th, and K are 1.8, 0.7, and 1.4 mBq/PMT, respectively. But the newly developed QUPIDs for the future multi-ton WIMP detectors have even much lower radioactive contamination: both U and Th are less than 0.3 mBq/PMT. It is interesting to mention that the bialkali photocathodes used in low-temperature photodetectors are equipped with special radial metal strips to increase their conductivity.

It is worth mentioning here that a newly proposed device called THGEM (a thick GEM) [56] could be used for the readout of a double-phase noble gas detector. This has already been accepted as a base readout option for charge readout in the ArDM Dark Matter detector (double-phase LAr).

4.1. QUPID

A Quartz Photon Intensifying Detector (QUPID) is under joint development by Hamamatsu, Japan and UCLA (University of California in Los Angeles). The principle of operation is illustrated in fig. 4 (taken from [57]). This device is a conventional HPD (Hybrid Photo Detector) but built with the special requirement of low radioactivity and low operating temperature. Its bulb and base are made of quartz (fused silica), which is a very radio-pure material, and the number of
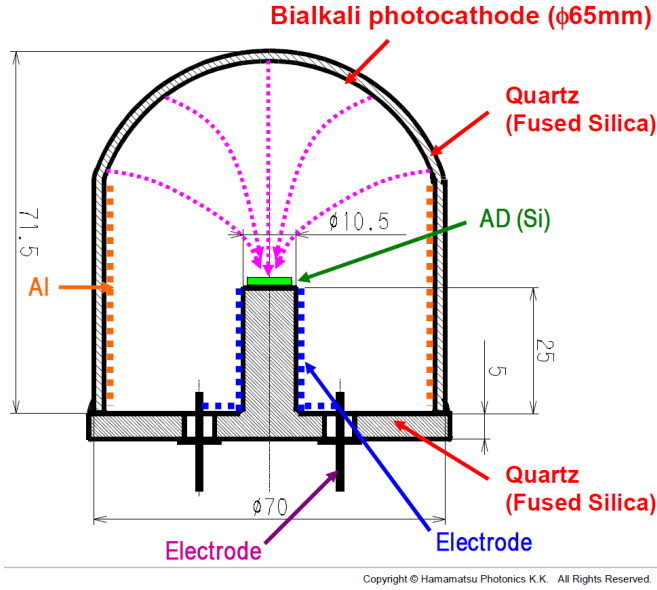
Fig. 4. Diagram of the internal structure of the QUPID.

construction elements in it has been reduced to the minimum. The inner surface of the bulb's spherical window with an outer diameter of 65 cm is deposited by a bialkali photocathode. A conventional silicone avalanche photodiode (AD) with a diameter of ~ 10 mm is positioned at the centre of the device. The photocathode is maintained at a potential of –6 kV with respect to ground (AD surface). Single photoelectrons emitted by the photocathode and accelerated by the electric field are detected by the AD. The pulse height distribution for a weak light signal was demonstrated to have clearly distinguishable peaks corresponding to a single photoelectron, two and three photoelectrons. The quantum efficiency of the tested samples varies from ~20 to ~25% [57] and is expected to reach >30% in the future.

4.2. THGEM

The idea to use THGEM has grown from the wish to obtain high sensitivity for low ionization signals without the top PMT layer. This significantly reduces the amount of radioactivity at the top. A THGEM multiplier is similar to the standard GEM but with dimensions enlarged by a factor of 5 to 20, and it is more suitable for detectors of large size then GEM. It is placed above the liquid noble gas surface.

In the ArDM detector [58] a 850-kg LAr target is viewed by PMTs from the bottom, and a double THGEM structure will be used at the top with readout of the induced signal on the anode placed behind the second THGEM. Between the liquid argon surface and the first THGEM, an electric field with a strength of ~3 kV/cm is formed by the THGEM surface and a grid placed under the surface of the liquid. This field serves to extract ionization electrons from the liquid argon surface. The electric field of ~1 kV/cm between the 1st and the 2nd THGEMs serves to transfer the charge to the second one. Multiplication takes place in both THGEMs (the higher values are reached in the 2nd one where the electric field is ~30

kV/cm).

A readout of THGEM structure by multipixel Geiger avalanche photodiodes (a widely used name is SiPM) is under investigation now [59-62]. In this case, an array of photodiodes is placed behind the last THGEM to view the electroluminescent light created by multiplied electrons moving in the holes. Since such photodetectors are not VUV sensitive, a wavelength shifter (WLS) is used to match the emission bands of the noble gases and their regions of maximum spectral sensitivity. In [59], tetraphenyl butadiene (TPB) painted on the SiPM surface is used to convert the light from ~125 nm of LAr to the green spectral range of the maximum sensitivity of SiPM. In [60,62] a wavelength shifter p-terphenyl is vacuum deposited on a sapphire window and protected by a poly-para-xylilen film to convert the light from ~175 nm of LXe to the blue spectral range. A global photo detection efficiency of ~ 10% was obtained for such a system of WLS + SiPM. Another approach is proposed in [61]: instead of detecting the VUV light, the near-infrared electroluminescence is detected by SiPM which have quite high (~20%) photo detection efficiency in this region. Unfortunately, at present it is quite difficult to imagine that an array of miniature photodiodes can cover the whole area of the surface of the multi-ton detectors described in the previous section. However, the system THGEM+SiPM may appear promising for the use in medium-sized double-phase detectors for coherent scattering of reactor antineutrinos off atomic nuclei.

5. Conclusion

In this review, the current status of Dark Matter detection techniques has been given. This experimental techniques are rapidly developing now, and we expect that new detectors with significantly improved sensitivity will appear in the coming decade.

The experiments on WIMP search over the last years have put the limits on the spin-independent cross section already below 10^{-7} pb. The ultimate goal of Dark Matter search experiments is to reach sensitivities down to 10^{-12} pb. This will allow to probe the whole M_W, σ_p parameter space of SUSY predictions. This goal can be achieved only with the use of next-generation detectors on the ton scale and ultimately of the multi-ton scale.

The LIBRA experiment at Grass Sasso using traditional scintillation technique with low background NaI(Tl) crystals has confirmed with larger statistics the previous observations by the DAMA setup of an effect of annual modulation of the count rate at low energies, which the authors attribute to a WIMP signal. However, other experiments have excluded the region of the allowed parameters M_W, σ_p derived by DAMA/LIBRA from the modulation effect.

New limits on σ_p have been set recently by the ZEPLIN-III, EDELWEISS and CDMS groups. These groups have plans to continue measurements with instruments of improved sensitivity.

The biggest ever Dark Matter detector, Xenon100, has

started data taking very recently. Another similar-size LXe detector, LUX, is under assembly now. The XMASS detector, which is even bigger but with reduced capabilities due to the use of scintillation only, is at the final commissioning stage. The first large-size LAr detector WArP is also at the final stage of commissioning.

There is already a number of projects of building ton and multi-ton scale detectors. These are Xenon1t for Gran Sasso, Italy; GEODM, MAX, LZS/LZD for Homestake, US; DEAP/CLEAN for SNOLAB.

Dark Matter search techniques have produced an impact on low-background technologies: special ultra-low-background photomultipliers and the new QUPID photo detectors have been developed. The recently proposed THGEM technology may find an application in two-phase detectors.

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