36. Particle Detectors for Non-Accelerator Physics

Revised 2021. See the various sections for authors.

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36.1 Introduction

Non-accelerator experiments have become increasingly important in particle physics and astrophysics. From them comes the evidence of physics beyond the SM, with the discovery of neutrino oscillations and adiabatic flavor conversion. Explored energies range from the meV scale to above the EeV, some 24 orders of magnitude. The physics and the design of the detectors vary as a consequence. Some experiments look at astrophysical high-energy phenomena using the atmosphere as a detector in the fluorescence and Cherenkov observatories or the polar ice and the ocean water in neutrino telescopes. Experiments on extremely rare events, such as neutrino-less double beta decay, solar neutrinos and dark matter induced scattering, need dedicated fully equipped deep underground laboratories, existing in different countries. Critical is the research to push back the ultra-low radioactive background frontier, with dedicated facilities in these laboratories. Detectors range from hyper-pure liquid scintillators, both organic and not, to thermalized and ballistic phonon detectors at the sub-Kelvin temperature, to dual phase noble fluid TPCs, etc. Space-based detectors also use some unique instrumentation, but these are beyond the present scope of this review. Gravitational wave detectors are not included as well.

36.2 High-energy cosmic-ray hadron and gamma-ray detectors

36.2.1 *Atmospheric fluorescence detectors*

Revised March 2022 by L.R. Wiencke (Colorado School of Mines).

Cosmic-ray fluorescence detectors (FDs) use the atmosphere as a giant calorimeter to measure isotropic scintillation light that traces the development profiles of extensive air showers. An extensive air shower (EAS) is produced by the interactions of ultra high-energy ($E > 10^{17}$ eV) subatomic particles in the stratosphere and upper troposphere. The amount of scintillation light generated by an EAS is proportional to the energy deposited in the atmosphere and nearly independent of the primary species. With energies extending beyond 10^{20} eV these are the highest energy subatomic particles known to exist. In addition to particle arrival directions, energy spectra and primary composition, the astroparticle science investigated with FDs also includes multi-messenger studies, searches for high energy photons, neutrinos, monopoles and deeply penetrating forms of dark matter. The Pierre Auger Observatory FD also measures UV scintillation that traces the development of ring-shaped atmospheric transient luminous events, called Elves, in the ionosphere that are initiated by strong lightning [1].

Previous experiments with FDs included the pioneering Fly's Eye [2,3], and the High Resolution Fly's Eye (HiRes and HiRes prototype) [4]. A history of the fluorescence technique includes earlier studies in the 1950's and 1960's [5]. The current generation of experiments include the Telescope Array (TA) [6] in the northern hemisphere, and the much larger Pierre Auger Observatory (Auger) [7] in the southern hemisphere. Both are hybrid observatories. Their FD telescopes overlook sparse arrays of particle detectors on the ground. Select parameters are listed in Table 36.1. TA and Auger have each one FD site populated with additional telescopes that view up to 60° in elevation to measure lower EASs using a combination of scintillation and direct Cherenkov light. As part of a fourfold coverage upgrade of TA (TAx4), 12 HiRes refurbished telescopes have been installed at the north and south-east sites of TA. A set of prototype FD telescopes, dubbed FAST [8], have observed EASs at the TA site using design that features wide field of view PMTs, fast timing and economical optics for a next-generation ground-based observatory.

The fluorescence light is emitted primarily between 290 and 430 nm (Figure 36.1) with major lines at 337, 357, and 391 nm, when relativistic charged particles, primarily electrons and positrons, excite nitrogen molecules in air, resulting in transitions of the 1P and 2P systems. Reviews and references for the pioneering and recent laboratory measurements of fluorescence yield, $Y(\lambda, P, T, u)$, including dependence on wavelength (λ), temperature (T), pressure (p), and humidity (u) may be found in Refs. [9–11]. The results of various laboratory experiments have been combined (Figure 36.2) to obtain an absolute average and uncertainty for Y(337 nm, 800 hPa, 293 K, dry air) of 7.04 ± 0.24 ph/ MeV after corrections for different electron beam energies and other factors. The units of ph/ MeV correspond to the number of fluorescence photons produced per MeV of energy deposited in the atmosphere by the electromagnetic component of an EAS.

An FD element (telescope) consists of a non-tracking spherical mirror of less than astronomical quality, a"camera" of photomultiplier tubes (PMTs) near the focal plane, and a flash ADC readout system with a pulse and track-finding trigger scheme [7, 14]. The major experiments listed in Table 36.1 all use conventional PMTs (for example, Hamamatsu R9508 or Photonis XP3062) with grounded cathodes and AC coupled readout. Segmented mirrors have been fabricated from slumped or slumped/polished glass with an anodized aluminum coating or fabricated using shaped aluminum that was then chemically anodized with $AlMgSiO_5$. A broadband UV filter (custom fabricated, BG-3, or Schott MUG-6) reduces background light such as starlight, airglow, man-made light pollution, and airplane strobe-lights.

At 10^{20} eV, where the flux drops below 1 EAS/km^{2}century, the aperture for an eye of adjacent

Table 36.1: Parameters of major fluorescence detectors. Note 1: Year when all FD sites were operational. Note 2: At TA 1 of the 3 FD sites features 24 telescopes from the HiRes experiment. Note 3: A-C for one telescope where A is the full area and C the area obscured by the camera and support structures. Thus A-C is the effective light collecting area. For the modified Schmidt design at Auger, the area of the entrance pupil, A, is listed because the pupil is smaller than the mirror and thus defines the entrance aperture. For the other experiments, the area of the mirror, A, is listed

Observatory	Fly's Eye	HiRes	Telescope Array	Pierre Auger
Location	Dugway UT US	Dugway UT US	Delta UT US	Malargüe AR
Start-End	1981-1992	1996-2006	2008-present	2005-present
Sites (note 1)	2 (1986)	2 (1999)	3 (2008)	4 (2008)
Separation	3.3 km	12.6 km	31-40 km	39-62 km
Telescopes/site	67,18	21,42	12+8,12,14+10+4	6, 6, 6, 6+3
Pixel FOV	5.5°	1°	1°	1.5°
Telescope FOV Azi×Elv	≈18°×≈18°	16°×13.5°	18°×15° (note 2)	30°×28.1°
Light collection area (note 3)	$1.95\,m^2$ - $0.25\,m^2$	$3.72\,m^2$ - $0.5\,m^2$	$6.8\,m^2$ - $0.85\,m^2$ (for 2 sites)	$3.80\,m^2$ - $0.80\,m^2$ (modified schmidt)
Energy Scale Uncertainty	≤40%	≈20%	≈20%	14%

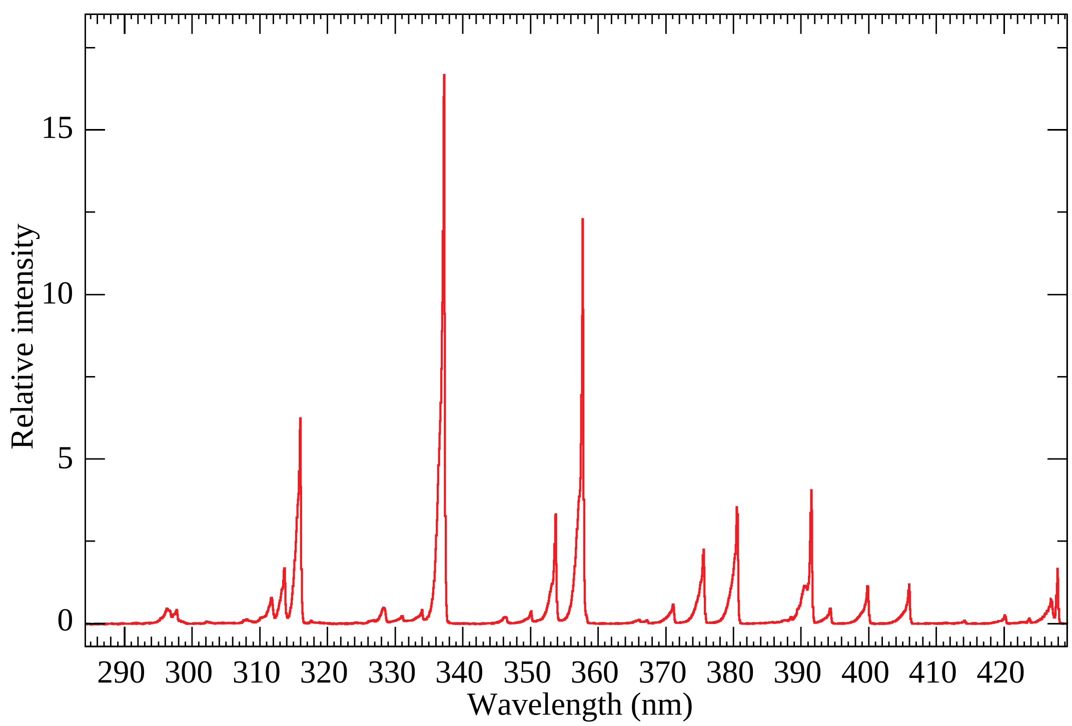

Figure 36.1: Measured fluorescence spectrum excited by 3 MeV electrons in dry air at 800 hPa and 293 K. Airfly experiment. Figure from Ref [12].

FD telescopes that span the horizon can reach 10^4 km^2 sr. FD operation requires (nearly) moon-

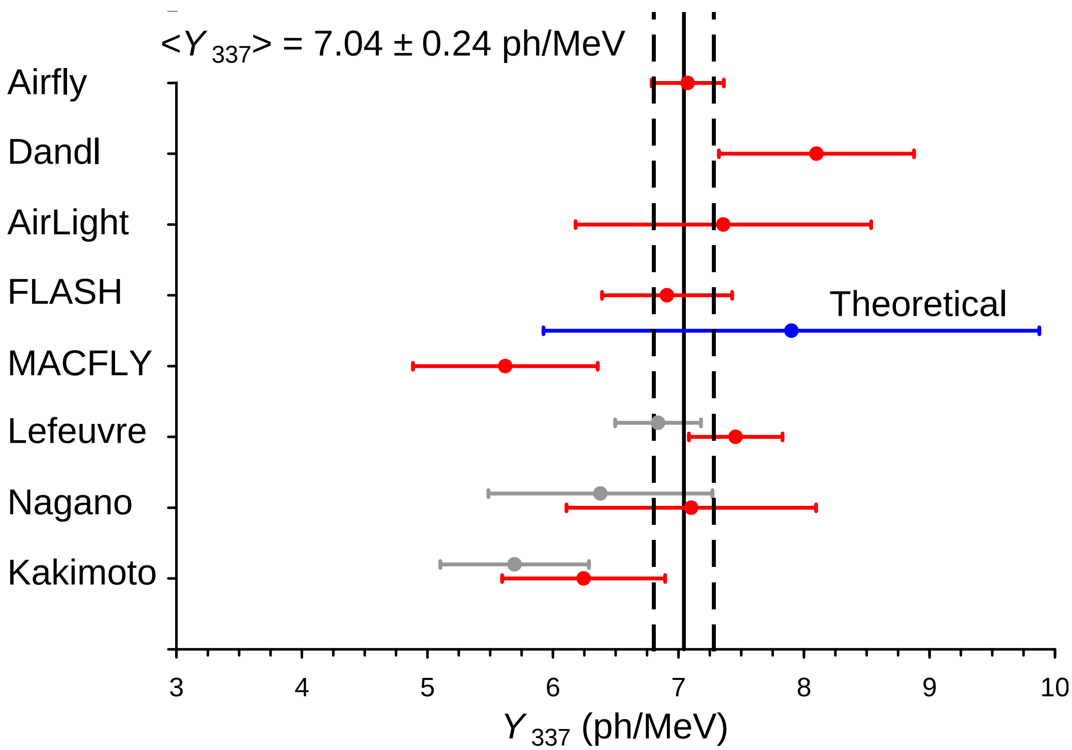

Figure 36.2: Fluorescence yield values and associated uncertainties at 337 nm (Y_{337}) in dry air at 800 hPa and 293 K The methodology and corrections that were applied to obtain the average and the uncertainty are discussed extensively in this reference. The vertical axis denotes different laboratory experiments that measured FY. The gray bars show three of the original measurements to illustrate the scale of the corrections applied. Figure from Ref [13].

less nights and clear atmospheric conditions, which typically imposes a duty cycle of about 10%. Arrangements of LEDs, calibrated diffuse sources [15], pulsed UV lasers [16], LIDARs [1] and IR detectors that are sensitive to clouds are used for photometric calibration, atmospheric calibration [17], and determination of exposure [18]. For purposes of optical transmission, the atmosphere is treated as having a dominant molecular component and a secondary aerosol component. The latter is well described [19] by molecular scattering theory and models derived from radiosonde measurements. The aerosol component can include dust, haze and pollution and the aerosol optical depth profile must be measured on site in the UV during FD data taking.

The EAS generates a track consistent with a light source moving at $v = c$ across the FOV. The number of photons (N_γ) as a function of atmospheric depth (X) can be expressed as [10]

$$\frac{\mathrm{d}N_\gamma}{\mathrm{d}X} = \frac{dE_{\mathrm{dep}}^{\mathrm{tot}}}{dX} \int Y(\lambda, P, T, u) \cdot \tau_{\mathrm{atm}}(\lambda, X) \cdot \varepsilon_{\mathrm{FD}}(\lambda)\mathrm{d}\lambda, \quad (36.1)$$

where $\tau_{atm}(\lambda, X)$ is the atmospheric transmission, including wavelength (λ) dependence, and $\varepsilon_{\mathrm{FD}}(\lambda)$ is the FD efficiency. $\varepsilon_{\mathrm{FD}}(\lambda)$ includes geometric factors and collection efficiency of the optics, quantum efficiency of the PMTs, and other throughput factors. The typical systematic uncertainties, τ_{atm} (10%) and $\varepsilon_{\mathrm{FD}}$ (photometric calibration 10%), currently dominate the systematic uncertainty the absolute EAS energy scale. FD energy resolution, defined as event-to-event statistical uncer-

[1]LIDAR stands for "Light Detection and Ranging" and refers here to systems that measure atmospheric properties from the light scattered backwards from laser pulses directed into the sky.

tainty, is typically less than 10% for final data samples used for science analysis.

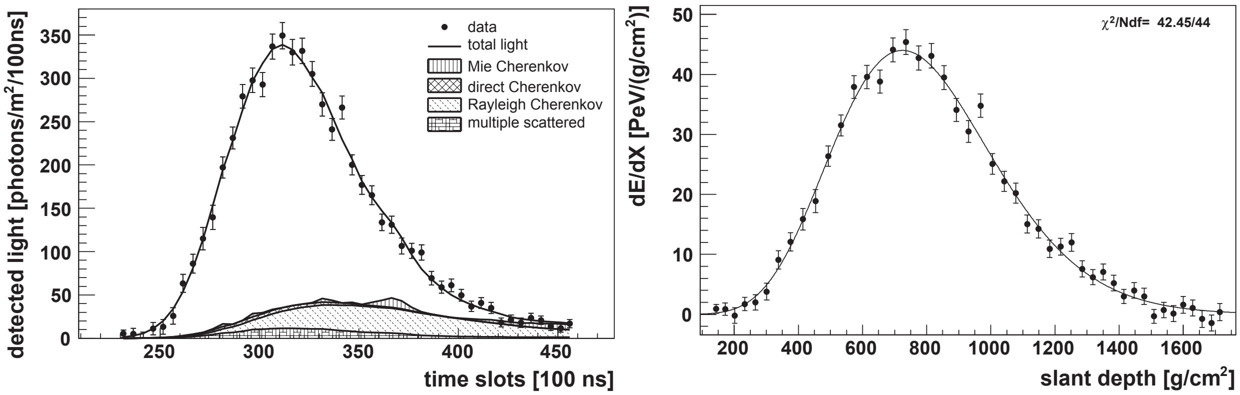

Figure 36.3: Example light profile (left) of one EAS recorded by the Pierre Auger FD and the corresponding profile (right) of energy deposited in the atmosphere vs atmospheric slant depth. The light profiles include the estimated components of Cherenkov light that have been scattered out of the forward beam by the molecular and aerosol (Mie) components of the atmosphere. The reconstructed energy of this EAS was $3.0 \pm 0.2 \times 10^{19}$ eV. Figure from Ref [20].

Analysis methods to reconstruct the EAS profile and deconvolve the contributions of re-scattered scintillation light, and direct and scattered Cherenkov light are described in [2] and more recently in [21]. The EAS energy is typically obtained by integrating over the Gaisser-Hillas function [22]

$$E_{\rm cal} = \int_0^\infty [w_{\rm max} \left(\frac{X - X_0}{X_{\rm max} - X_0}\right)^{(X_{\rm max}-X_0)/\lambda} e^{(X{\rm max}-X)/\lambda}]{\rm d}X, \tag{36.2}$$

where $E_{\rm cal}$ is the energy of electromagnetic energy component of the EAS and $X_{\rm max}$ is the atmospheric slant depth at which the shower reaches its maximum energy deposit rate. This maximum dE/dX is denoted as $w_{\rm max}$. X_0 and λ are two shape parameters. The energy of the primary cosmic ray is obtained by correcting $E_{\rm cal}$ upward by about 10% to account for the invisible energy carried by particles that do not interact in the atmosphere. Auger recently reported a data-driven method to estimate the invisible energy from the muon number at ground level and Xmax to reduce systematic uncertainties [23]. Energy resolution, $\Delta E/E$, of 15-20% is achievable, provided the geometric fit of the EAS axis is constrained, typically by multi-eye stereo projection or hybrid observations, and the profile fit of EAS development along the track is constrained by the observed rise and fall about $X_{\rm max}$. An example of a recorded EAS light profile and its corresponding dE/dX development profile are shown in Fig. 36.3. The EAS generates a track consistent with a light source moving at $v = c$ across the FOV. The number of photons (N_γ) as a function of atmospheric depth (X) can be expressed as [10]

An FD that would look down on the earth's atmosphere from space orbit to view a much larger area than ground based instruments is an active area of R&D. Prototypes that have been built and flown in orbit include the pioneering TUS instrument [24], [25] operated 2016-2018 onboard the Lomonosov satellite. The JEM-EUSO collabration has flown prototype FD telescopes on two stratospheric balloon flights [26] and [27] with a third in preparation. The Mini-EUSO [28] FD is recording terrestial UV emission by looking down through a 25 cm diameter UV window from inside the International Space Station. The Probe of Extreme Multimessenger Astrophysics (POEMMA) project has completed a detailed conceptual design study for a twin-satellite mission [29] that would observe UHECRs and PeV scale cosmogenic tau neutrinos.

36.2.2 *Atmospheric Cherenkov telescopes for high-energy gamma ray astronomy*

Revised August 2019 by J. Holder (Delaware U.; Delaware U., Bartol Inst.).

A wide variety of astrophysical objects are now known to produce high-energy γ-ray photons. Leptonic or hadronic particles, accelerated to relativistic energies in the source, produce γ-rays typically through inverse Compton boosting of ambient photons or through the decay of neutral pions produced in hadronic interactions. At energies below $\sim$30 GeV, γ-ray emission can be efficiently detected using satellite or balloon-borne instrumentation, with an effective area approximately equal to the size of the detector (typically < 1 m^2). At higher energies, a technique with much larger effective collection area is desirable to measure astrophysical γ-ray fluxes, which decrease rapidly with increasing energy. Atmospheric Cherenkov detectors achieve effective collection areas of $>10^5$ m^2 by employing the Earth's atmosphere as an intrinsic part of the detection technique.

As described in Chapter 30, a hadronic cosmic ray or high energy γ-ray incident on the Earth's atmosphere triggers a particle cascade, or air shower. Relativistic charged particles in the cascade generate Cherenkov radiation, which is emitted along the shower direction, resulting in a light pool on the ground with a radius of $\sim$130 m. Cherenkov light is produced throughout the cascade development, with the maximum emission occurring when the number of particles in the cascade is largest, at an altitude of $\sim$10 km for primary energies of 100 GeV–1 TeV. Following absorption and scattering in the atmosphere, the Cherenkov light at ground level peaks at a wavelength, $\lambda \approx 300$–350 nm. The photon density is typically $\sim$100 photons/m^2 for a 1 TeV primary, arriving in a brief flash of a few nanoseconds duration. This Cherenkov pulse can be detected from any point within the light pool radius by using large reflecting surfaces to focus the Cherenkov light on to fast photon detectors (Fig. 36.4).

Modern atmospheric Cherenkov telescopes, such as those built and operated by the VERITAS [30], H.E.S.S. [31] and MAGIC [32] collaborations, consist of large ($> 100\,\mathrm{m}^2$) segmented mirrors on steerable altitude-azimuth mounts. A camera made from an array of photosensors is placed at the focus of each mirror and used to record a Cherenkov image of each air shower. In these imaging atmospheric Cherenkov telescopes, single-anode photomultipliers tubes (PMTs) have traditionally been used (2048, in the case of H.E.S.S. II), but silicon devices now feature in more modern designs. The telescope cameras typically cover a field-of-view of $3 - 10^\circ$ in diameter. Images are recorded at kHz rates, the vast majority of which are due to showers with hadronic cosmic-ray primaries. The shape and orientation of the Cherenkov images are used to discriminate γ-ray photon events from this cosmic-ray background, and to reconstruct the photon energy and arrival direction. γ-ray images result from purely electromagnetic cascades and appear as narrow, elongated ellipses in the camera plane. The long axis of the ellipse corresponds to the vertical extension of the air shower, and points back towards the source position in the field-of-view. If multiple telescopes are used to view the same shower ("stereoscopy"), the source position is simply the intersection point of the various image axes. Cosmic-ray primaries produce secondaries with large transverse momenta, which initiate sub-showers. Their images are consequently wider and less regular than those with γ-ray primaries and, since the original charged particle has been deflected by Galactic magnetic fields before reaching the Earth, the images have no preferred orientation.

The measurable differences in Cherenkov image orientation and morphology provide the background discrimination which makes ground-based γ-ray astronomy possible. For point-like sources, such as distant active galactic nuclei, modern instruments can reject over 99.999% of the triggered cosmic-ray events, while retaining up to 50% of the γ-ray population. In the case of spatially extended sources, such as Galactic supernova remnants, the background rejection is less efficient, but the technique can be used to produce γ-ray maps of the emission from the source. The angular resolution depends upon the number of telescopes which view the image and the energy of the

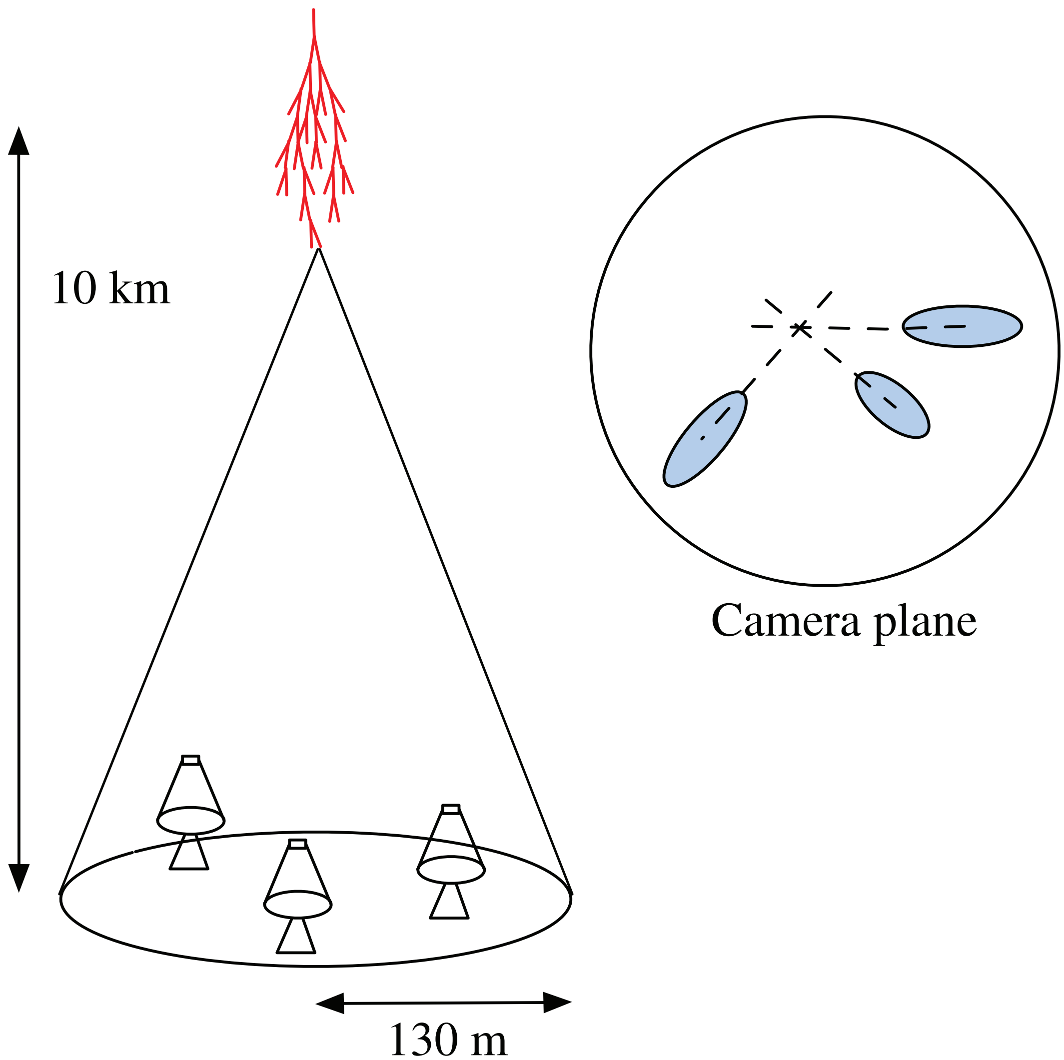

Figure 36.4: A schematic illustration of an imaging atmospheric Cherenkov telescope array. The primary particle initiates an air shower, resulting in a cone of Cherenkov radiation. Telescopes within the Cherenkov light pool record elliptical images; the intersection of the long axes of these images indicates the arrival direction of the primary, and hence the location of a γ-ray source in the sky

primary γ-ray, but is typically less than 0.1° per event (68% containment radius) at energies above a few hundred GeV.

The total Cherenkov yield from the air shower is proportional to the energy of the primary particle. The image intensity, combined with the reconstructed distance of the shower core from each telescope, can therefore be used to estimate the primary energy. The energy resolution of this technique, also energy-dependent, is typically 15–20% at energies above a few hundred GeV. Energy spectra of γ-ray sources can be measured over a wide range, depending upon the instrument characteristics, source properties (flux, spectral slope, elevation angle, *etc.*), and exposure time. The effective energy range is typically from 30 GeV to 100 TeV and peak sensitivity lies in the range from 100 GeV to a few TeV.

The first astrophysical source to be convincingly detected using the imaging atmospheric Cherenkov technique was the Crab Nebula [33], with an integral flux of 2.1×10^{-11} photons cm^{-2} s^{-1} above 1 TeV [34]. Modern imaging atmospheric Cherenkov telescopes have sensitivity sufficient to detect sources with less than 1% of the Crab Nebula flux in a few tens of hours. The TeV source catalog now consists of over 200 sources (see e.g. Ref. [35]). A large fraction of these were detected by scanning the Galactic plane from the southern hemisphere with the H.E.S.S. telescope array [36]. Recent reviews of the field include [37] and [38], and a historical overview can be found in [39].

Major upgrades of the existing telescope arrays have recently been completed, including the addition of a 28 m diameter central telescope to H.E.S.S. (H.E.S.S. II). Development is also underway for the next generation instrument, the Cherenkov Telescope Array (CTA), which will consist of a northern and a southern hemisphere observatory, with a combined total of more than 100 telescopes [40]. Telescopes of three different sizes are planned, spread over an area of > 1 km^2, providing wider energy coverage, improved angular and energy resolutions, and an order of magnitude improvement in sensitivity relative to existing imaging atmospheric Cherenkov telescopes. Baseline telescope designs are similar to existing devices, but exploit technological developments such as dual mirror optics and silicon photo-detectors.

36.3 Large neutrino detectors

36.3.1 *Deep liquid detectors for rare processes*

Revised August 2021 by K. Scholberg (Duke U.) and C.W. Walter (Duke U.).

Deep, large detectors for rare processes tend to be multi-purpose with physics reach that includes not only solar, reactor, supernova and atmospheric neutrinos, but also searches for baryon number violation and lepton number violation, searches for exotic particles and beyond-the-standard-model physics, and neutrino and cosmic-ray astrophysics in different energy regimes. The detectors may also serve as targets for long-baseline neutrino beams for neutrino oscillation physics studies. In general, detector design considerations can be divided into high- and low-energy regimes, for which background and event reconstruction issues differ. The high-energy regime, from about 100 MeV to a few hundred GeV, is relevant for proton decay searches, atmospheric neutrinos and high-energy astrophysical neutrinos. The low-energy regime (a few tens of MeV or less) is relevant for supernova, solar, reactor and geological neutrinos.

Large water Cherenkov and scintillator detectors (see Table 36.2) usually consist of a volume of transparent liquid viewed by photomultiplier tubes (PMTs) (see Sec 35.2); the liquid serves as active target. PMT hit charges and times are recorded and digitized, and triggering is usually based on coincidence of PMT hits within a time window comparable to the detector's light-crossing time. Because photosensors lining an inner surface represent a driving cost that scales as surface area, very large volumes can be used for comparatively reasonable cost. Some detectors are segmented into subvolumes individually viewed by PMTs, and may include other detector elements (*e.g.*, tracking detectors). Devices to increase light collection, *e.g.*, reflectors or waveshifter plates, may be employed. A common configuration is to have at least one concentric outer layer of liquid material separated from the inner part of the detector to serve as shielding against ambient background. If optically separated and instrumented with PMTs, an outer layer may also serve as an active veto against entering cosmic rays and other background events. The PMTs for large detectors typically range in size from 20 cm to 51 cm diameter, and typical quantum efficiencies are in the 20–25% range for scintillation and water-Cherenkov photons. PMTs with higher quantum efficiencies, 35% or higher, have recently become available. The active liquid volume requires purification and there may be continuous recirculation of liquid. For large homogeneous detectors, the event interaction vertex is determined using relative timing of PMT hits, and energy deposition is determined from the number of recorded photoelectrons. A "fiducial volume" is usually defined

Table 36.2: Properties of large detectors for rare processes. If total target mass is divided into large submodules, the number of subdetectors is indicated in parentheses. Projects with first data expected in 2023 or later are indicated in italics.

Detector	Mass, kton (modules)	PMTs (diameter, cm)	ξ	p.e./MeV	Dates
Baksan	0.33, scint (3150)	1/module (15)	segmented	40	1980–
MACRO	0.56, scint (476)	2-4/module (20)	segmented	18	1989–2000
LVD	1, scint. (840)	3/module (15)	segmented	15	1992–
KamLAND	0.41*, scint	1325(43)+554(51)†	34%	460	2002–
Borexino	0.1*, scint	2212 (20)	30%	500	2007–
SNO+	0.78, scint‡	9394 (20)	47%	400–600	2021–
CHOOZ	0.005, scint (Gd)	192 (20)	15%	130	1997–1998
Double Chooz	0.017, scint (Gd)(2)	534/module (20)	13%	180	2011–2017
Daya Bay	0.160, scint (Gd)(8)	192/module (20)	5.6%§	100	2011–2020
RENO	0.032, scint (Gd)(2)	342/module (25)	12.6%	100	2011–
JUNO	20.0*, scint	17613 (51)/25600 (8)	77.9%	1200	2023 (exp.)
IMB-1	3.3*, H_2O	2048 (12.5)	1%	0.25	1982–1985
IMB-2	3.3*, H_2O	2048 (20)	4.5%	1.1	1987–1990
Kam I	0.88/0.78*, H_2O	1000/948 (51)	20%	3.4	1983–1985
Kam II	1.04*, H_2O	948 (51)	20%	3.4	1986–1990
Kam III	1.04*, H_2O	948 (51)	20%¶	4.3	1990–1995
SK I	22.5*, H_2O	11146 (51)	40%	6	1996–2001
SK II	22.5*, H_2O	5182 (51)	19%	3	2002–2005
SK III-V	22.5*, H_2O	11129 (51)	40%	6	2006–2020
SK-Gd	22.5*, H_2O (Gd)	11129 (51)	40%	6	2020–
Hyper-K	187*, H_2O‖	>20000 (51)**	>20%	>6	2027 (exp.)
SNO	1, D_2O/1.7, H_2O	9438 (20)	31%††	9	1999–2006
DUNE	40*, Ar (4)	TBD‡‡	TBD‡‡	TBD‡‡	2029 (exp.)

*Indicates typical fiducial mass used for data analysis; this may vary by physics topic.
†Measurements made before 2003 only considered data from the 43 cm PMTs.
‡SNO+ ran with water fill from May 2017 to July 2019.
§The effective Daya Bay coverage is 12% with top and bottom reflectors.
¶The effective Kamiokande III coverage was 25% with light collectors.
‖A second staged module is being investigated.
**Additional photosensor modules and PMTs are planned.
††The effective SNO coverage was 54% with light collectors.
‡‡Photodetector technology and coverage varies according to TPC type and is not yet fully determined.

within the full detector volume, some distance away from the PMT array. Inside the fiducial volume, enough PMTs are illuminated per event that reconstruction is considered reliable, and furthermore, entering background from the enclosing walls is suppressed by a buffer of self-shielding. PMT and detector optical parameters are calibrated using laser, LED, or other light sources. Quality of event reconstruction typically depends on photoelectron yield, pixelization and timing.

Because in most cases one is searching for rare events, large detectors are usually sited underground to reduce cosmic-ray-related background (see Chapter 30). The minimum depth required varies according to the physics goals [41].

36.3.1.1 *Liquid scintillator detectors*

Past and current large underground detectors based on hydrocarbon scintillators include LVD, MACRO, Baksan, Borexino, KamLAND and SNO+; JUNO is a future detector. Experiments at nuclear reactors include CHOOZ, Double CHOOZ, Daya Bay, and RENO. Organic liquid scintillators (see Section 35.3) for large detectors are chosen for high light yield and attenuation length, good stability, compatibility with other detector materials, high flash point, low toxicity, appropriate density for mechanical stability, and low cost. They may be doped with waveshifters and stabilizing agents. Popular choices are pseudocumene (1,2,4-trimethylbenzene) with a few g/L of the PPO (2,5-diphenyloxazole) fluor, and linear alkylbenzene (LAB), with light yield $\sim 10^4$ photons/MeV. In a typical detector configuration there will be active or passive regions of undoped scintillator, non-scintillating mineral oil or water surrounding the inner neutrino target volume. A thin vessel or balloon made of nylon, acrylic or other material transparent to scintillation light may contain the inner target; if the scintillator is buoyant with respect to its buffer, ropes may hold the balloon in place. For phototube surface coverages in the 20–40% range, yields in the few hundreds of photoelectrons per MeV of energy deposition can be obtained. Typical energy resolution is about $5-7\%/\sqrt{E(\mathrm{MeV})}$ [42, 43], and typical position reconstruction resolution is a few tens of cm at $\sim$ 1 MeV, scaling as $\sim N^{-1/2}$, where N is the number of photoelectrons detected.

Shallow detectors for reactor neutrino oscillation experiments require excellent muon veto capabilities. For $\bar{\nu}_e$ detection via inverse beta decay on free protons, $\bar{\nu}_e + p \to n + e^+$, the neutron is captured by a proton on a ∼180 μs timescale, resulting in a 2.2 MeV γ ray, observable by Compton scattering and which can be used as a tag in coincidence with the positron signal. The positron annihilation γ rays may also contribute. Inverse beta decay tagging may be improved by addition of Gd at ∼0.1% by mass, which for natural isotope abundance has a ∼49,000 barn cross-section for neutron capture (in contrast to the 0.3 barn cross-section for capture on free protons). Gd capture takes ∼30 μs, and is followed by a cascade of γ rays adding up to about 8 MeV. Gadolinium doping of scintillator requires specialized formulation to ensure adequate attenuation length and stability.

Scintillation detectors have an advantage over water Cherenkov detectors in the lack of Cherenkov threshold and the high light yield. However, scintillation light emission is nearly isotropic, and therefore directional capabilities are relatively weak. Liquid scintillator is especially suitable for detection of low-energy events. Radioactive backgrounds are a serious issue, and include long-lived cosmogenics such as ^{14}C. To go below a few MeV, very careful selection of materials and purification of the scintillator is required (see Section 36.6). Fiducialization and tagging can reduce background. One can also dissolve neutrinoless double beta decay ($0\nu\beta\beta$) isotopes in scintillator. This has been realized by KamLAND-Zen, which deployed a 1.5 m-radius balloon containing enriched Xe dissolved in scintillator inside KamLAND, and ^{130}Te is planned for SNO+.

36.3.1.2 *Water Cherenkov detectors*

Very large imaging water detectors reconstruct ten-meter-scale Cherenkov rings produced by charged particles (see Section 35.5). The first such large detectors were IMB and Kamiokande. The only currently existing instance of this class of detector, with fiducial mass of 22.5 kton and total mass of 50 kton, is Super-Kamiokande (Super-K, SK). Hyper-Kamiokande (Hyper-K) plans at least one, and possibly two, detectors with 187-kton fiducial mass. For volumes of this scale, absorption and scattering of Cherenkov light are non-negligible, and a wavelength-dependent factor $\exp(-d/L(\lambda))$ (where d is the distance from emission to the sensor and $L(\lambda)$ is the attenuation length of the medium) must be included in the integral of Eq. (35.6) for the photoelectron yield. Attenuation lengths on the order of 100 meters have been achieved.

Cherenkov detectors are excellent electromagnetic calorimeters, and the number of Cherenkov photons produced by an e/γ is nearly proportional to its kinetic energy. For massive particles, the number of photons produced is also related to the energy, but not linearly. For any type of particle, the *visible energy* E_{vis} is defined as the energy of an electron which would produce the same number of Cherenkov photons. The number of collected photoelectrons depends on the scattering and attenuation in the water along with the photo-cathode coverage, quantum efficiency and the optical parameters of any external light collection systems or protective material surrounding them. Event-by-event corrections are made for geometry and attenuation. For a typical case, in water $N_{\text{p.e.}} \sim 15\,\xi\,E_{\text{vis}}(\text{MeV})$, where ξ is the effective fractional photosensor coverage. Cherenkov photoelectron yield per MeV of energy is relatively small compared to that for scintillator, *e.g.*, $\sim$ 6 pe/MeV for Super-K with a PMT surface coverage of $\sim$ 40%. In spite of light yield and Cherenkov threshold issues, the intrinsic directionality of Cherenkov light allows individual particle tracks to be reconstructed. Vertex and direction fits are performed using PMT hit charges and times, requiring that the hit pattern be consistent with a Cherenkov ring.

High-energy ($\sim$100 MeV or more) neutrinos from the atmosphere or beams interact with nucleons; for the nucleons bound inside the ^{16}O nucleus, nuclear effects must be considered both at the interaction and as the particles leave the nucleus. Various event topologies, with final-state particles contained, exiting, or entering the detector, can be distinguished by their timing and fit patterns, and by presence or absence of light in a veto. At high energies, multi-photoelectron hits are likely and the charge collected by each PMT (rather than the number of PMTs firing) must be used; the energy resolution in this case is approximately $2\%/\sqrt{\xi\,E_{\text{vis}}(\text{GeV})}$. The absolute energy scale in this regime can be known to $\sim$2–3% using cosmic-ray muon energy deposition, Michel electrons and π^0 from atmospheric neutrino interactions. Typical vertex resolutions for GeV energies are a few tens of cm [44]. Angular resolution for determination of the direction of a charged particle track is a few degrees. For a neutrino interaction, because some final-state particles are usually below Cherenkov threshold, knowledge of direction of the incoming neutrino direction itself is generally worse than that of the lepton direction, and dependent on neutrino energy.

Multiple particles in an interaction (so long as they are above Cherenkov threshold) may be reconstructed, allowing for the exclusive reconstruction of final states. In searches for proton decay, multiple particles can be kinematically reconstructed to form a decaying nucleon. High-quality particle identification is also possible: γ rays and electrons shower, and electrons scatter, which results in fuzzy rings, whereas muons, pions and protons make sharp rings. These patterns can be quantitatively separated with high reliability using maximum likelihood methods [45]. Sources of background for high energy interactions include misidentified cosmic muons and anomalous light patterns when the PMTs sometimes "flash" and emit photons themselves. The latter class of events can be removed using its distinctive PMT signal patterns, which may be repeated. More information about high energy event selection and reconstruction may be found in reference [46].

In spite of the fairly low light yield, large water Cherenkov detectors may be employed for reconstructing low-energy events, down to *e.g.* $\sim$ 4-5 MeV for Super-K [47]. Low-energy neutrino interactions of solar neutrinos in water are predominantly elastic scattering off atomic electrons; single electron events are then reconstructed. At solar neutrino energies, the visible energy resolution ($\sim 30\%/\sqrt{\xi\,E_{\text{vis}}(\text{MeV})}$) is about 20% worse than photoelectron counting statistics would imply. Using an electron LINAC and/or nuclear sources, approximately 0.5% determination of the absolute energy scale has been achieved at solar neutrino energies. Angular resolution is limited by multiple scattering in this energy regime (25–30°). At these energies, radioactive backgrounds become a dominant issue. These backgrounds include radon in the water itself or emanated from detector materials, and γ rays from the rock and detector materials. In the few to few tens of MeV range, radioactive products of cosmic-ray-muon-induced spallation are troublesome, and are removed by proximity in time and space to preceding muons, at some cost in dead time. Gadolinium doping using 0.2% $Gd_2(SO_4)_3$ has now been initiated for Super-K to improve selection of low-energy

$\bar{\nu}_e$ and other events with accompanying neutrons [48].

The Sudbury Neutrino Observatory (SNO) detector [49] is the only instance of a large heavy water detector. In addition to an outer 1.7 kton of light water, SNO contained 1 kton of D_2O, giving it unique sensitivity to neutrino neutral current ($\nu_x + d \to \nu_x + p + n$), and charged current ($\nu_e + d \to p + p + e^-$) deuteron breakup reactions. The neutrons were detected in three ways: via capture on deuterons, via capture on dissolved ^{35}Cl, and via specialized ^{3}He counters.

36.3.1.3 *Noble liquid detectors*

Noble liquids scintillate and can be used as the active medium for particle detection. Detectors employing argon and xenon are also used as time-projection chambers (TPCs), either as dual-phase low-energy recoil detectors, or as track-imaging detectors. Noble-liquid detectors with low energy (few to few tens of keV) capability for detecting electronic and nuclear recoils are employed for dark matter and other rare event searches and are described in Sec. 36.4. These detectors can also be employed for some of the same physics (baryon number violation, astrophysical neutrino transient searches, etc.) as for the other large detectors described here, especially as they approach tens of ton scale and higher (e.g., DARWIN, DarkSide-20, ARGO). Track-imaging time-projection chambers, which are described in detail Section 36.4, have a dynamic range reaching down to the few to few tens of MeV scale, enabling sensitivity to e.g., solar and supernova burst neutrinos. Surface LArTPCs have significant cosmic backgrounds, but may still have sensitivity to astrophysical transients such as supernova burst neutrinos. DUNE will be sufficiently deep to have sensitivity to steady-state low-energy neutrino sources such as solar neutrinos.

36.3.2 *Neutrino telescopes*

Revised November 2021 by U.F. Katz (Erlangen U.) and C. Spiering (DESY, Zeuthen).

The primary goal of neutrino telescopes (NTs) is the detection of astrophysical neutrinos, in particular those which are expected to accompany the production of high-energy cosmic rays in astrophysical accelerators. NTs in addition address a variety of other fundamental physics issues like the indirect search for dark matter, studies of neutrino oscillations, searches for exotic particles like magnetic monopoles or study of cosmic rays and their interactions [50–52]. Electromagnetic radio frequency detectors for high energy neutrinos are discussed in "Radio emission from (ultra-) high energy particle showers" section 36.3.3.

NTs are large-volume arrays of “optical modules” (OMs) installed in open transparent media like water or ice, at depths that completely block the daylight. The OMs are sensitive to individual photons of the Cherenkov light induced by charged secondary particles produced in reactions of high-energy neutrinos in or around the instrumented volume. The time of photon-induced signals (“hits”) is registered with a precision of a few nanoseconds. The neutrino energy, E_ν, and direction can be reconstructed from the hit pattern recorded. NTs typically target an energy range $E_\nu \gtrsim 100\,\mathrm{GeV}$; sensitivity to lower energies is achieved in dedicated setups with denser instrumentation.

In detecting cosmic neutrinos, three sources of backgrounds have to be considered: (i) *atmospheric neutrinos* from cosmic-ray interactions in the atmosphere, which can be separated from cosmic neutrinos on a statistical basis, or, for down-going neutrinos, by vetoing accompanying muons; (ii) down-going punch-through *atmospheric muons* from cosmic-ray interactions, which are suppressed by several orders of magnitude with respect to the ground level due to the large detector depths and can be further reduced by selecting upward-going or high-energy neutrinos or by self-veto methods; (iii) random backgrounds due to photomultiplier (PMT) dark counts, ^{40}K decays (mainly in sea water) or bioluminescence (only water). Note that atmospheric neutrinos and muons allow for investigating neutrino oscillations and cosmic ray anisotropies, respectively.

In the last decade, it has become obvious that a precise measurement of the energy-zenith-

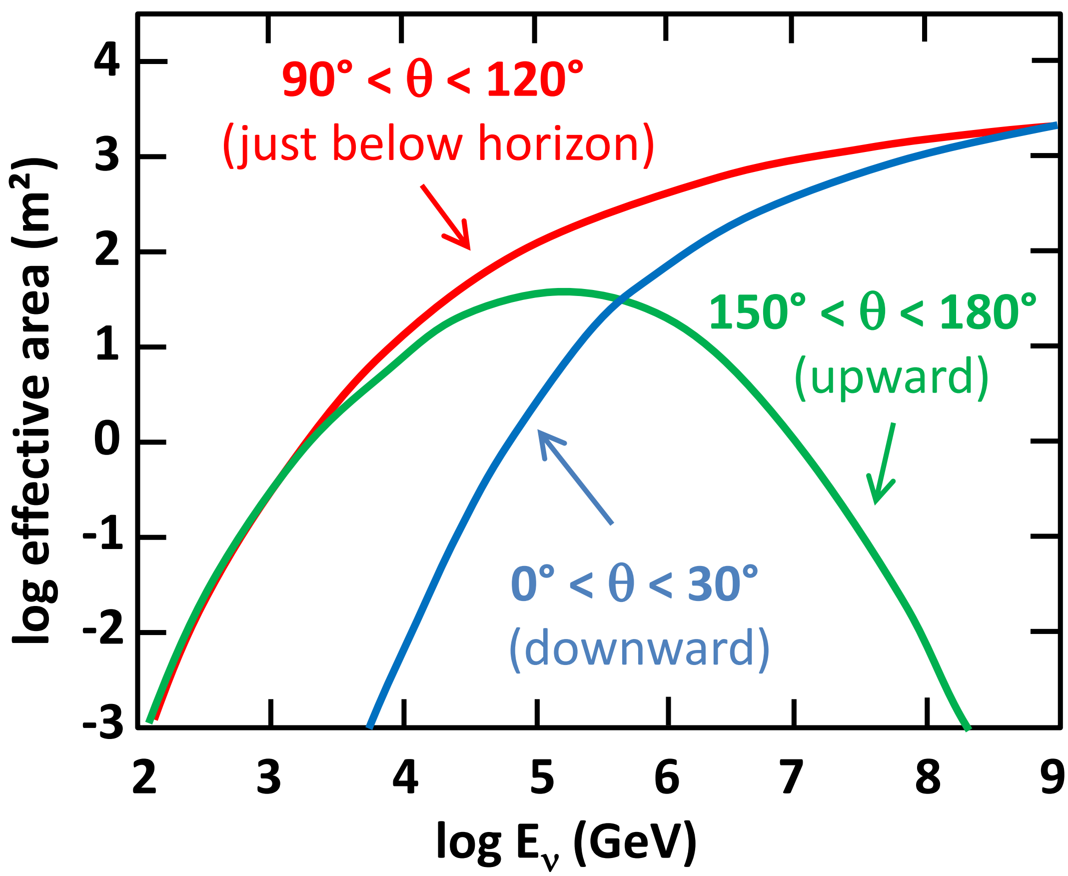

Figure 36.5: Average over the effective ν_μ and $\overline{\nu}_\mu$ areas for IceCube as an example of a cubic-kilometre NT, as a function of neutrino energy for three intervals of the zenith angle θ. The values shown here correspond to a specific event selection for point source searches.

distribution of atmospheric neutrinos in the energy range from a few to about 100 GeV may allow for determining the neutrino mass hierarchy by exploiting matter-induced oscillation effects in the Earth [53, 54].

Neutrinos can interact with target nucleons N through charged current ($\overset{(-)}{\nu}_\ell N \to \ell^\mp X$, CC) or neutral current ($\overset{(-)}{\nu}_\ell N \to \overset{(-)}{\nu}_\ell X$, NC) processes. A CC reaction of a $\overset{(-)}{\nu}_\mu$ produces a muon track and a hadronic particle cascade, whereas all NC reactions and CC reactions of $\overset{(-)}{\nu}_e$ produce particle cascades only. CC interactions of $\overset{(-)}{\nu}_\tau$ can have either signature, depending on the τ decay mode. Of particular interest is the so-called double-bang signature, where the τ decays sufficiently far away from the primary interaction to create a second, distinguishable cascade (typically at PeV energies and above). In most astrophysical models, neutrinos are expected to be produced through the $\pi/K \to \mu \to e$ decay chain, *i.e.*, with a flavour ratio $\nu_e : \nu_\mu : \nu_\tau \approx 1:2:0$. For sources outside the solar system, neutrino oscillations turn this ratio to $\nu_e : \nu_\mu : \nu_\tau \approx 1:1:1$ upon arrival on Earth.

The total neutrino-nucleon cross section is about $10^{-34}\,\mathrm{cm}^2$ at $E_\nu = 20\,\mathrm{TeV}$ and rises roughly linearly with E_ν below this energy and as $E_\nu^{0.3-0.5}$ above, flattening out towards high energies. The CC:NC cross-section ratio is about 2:1. At energies above several TeV, neutrino absorption in the Earth becomes noticeable; for vertically upward-moving neutrinos (zenith angle $\theta = 180°$), the survival probability is $74\,(27, <2)\%$ for $10\,(100, 1000)$ TeV. The energy transferred to the final-state lepton varies between 0 and 100% of E_ν, with a mean of 50% (65%) for neutrinos (antineutrinos) at 100 GeV and 75% for both neutrinos and antineutrinos at 10 PeV.

The final-state lepton follows the initial (anti)neutrino direction with an average mismatch angle of about $\langle\phi_{\nu\ell}\rangle \approx 1^\circ/(E_\nu/\mathrm{TeV})^{0.55}$, with a steeper decrease beyond 10 TeV, reaching 0.005° at 1 PeV [55]. These values indicate the intrinsic kinematic limit to the angular resolution of NTs. For CC $\overset{(-)}{\nu}_\mu$ reactions at energies above about 10 TeV, the angular resolution is dominated by the muon reconstruction accuracy of a few times 0.1° at most. For muon energies $E_\mu \gtrsim 1$ TeV, the increasing light emission due to radiative processes allows for reconstructing E_μ from the measured Cherenkov light intensity with an accuracy of $\sigma(\log E_\mu) \approx 0.3$; at lower energies, E_μ can be estimated from the length of the muon track if it is contained in the detector. These properties make CC $\overset{(-)}{\nu}_\mu$ reactions the prime channel for the identification of individual astrophysical neutrino sources.

Hadronic and electromagnetic particle cascades at the relevant energies are 5–20 m long, *i.e.*, short compared to typical OM spacings. The total amount of Cherenkov light provides a direct measurement of the cascade energy with an accuracy of about 20% at energies above 10 TeV and 10% beyond 100 TeV for events contained in the instrumented volume. Except for double-bang events, the neutrino flavour and reaction mechanism can, however, be determined on a statistical basis at best, and neutrinos from NC reactions or τ decays may carry away significant "invisible" energy. Above 100 TeV, the average directional reconstruction accuracy of cascades is better than 10 (2) degrees in polar ice (sea water), the difference being due to the inhomogeneity of the ice and stronger light scattering in ice. These features, together with the small background of atmospheric $\overset{(-)}{\nu}_e$ and $\overset{(-)}{\nu}_\tau$ events, makes the cascade channel particularly interesting for searches for a diffuse, high-energy excess of extraterrestrial over atmospheric neutrinos. Cascade events can also be used to complement the muon channel in searches for point sources or transient signals, albeit with inferior angular accuracy compared to muon tracks.

The detection efficiency of a NT is quantified by its effective area, *e.g.*, the fictitious area for which the full incoming neutrino flux would be recorded (see Figure 36.5). The increase with E_ν is due to the rise of neutrino cross section and muon range, while neutrino absorption in the Earth causes the decrease at large θ for large E_ν. Identification of downward-going neutrinos requires strong cuts against atmospheric muons, hence the cut-off towards low E_ν at low θ. Due to the small cross section, the effective area is many orders of magnitude smaller than the geometrical dimension of the detector; a $\overset{(-)}{\nu}_\mu$ with 1 TeV can, *e.g.*, be detected with a probability of the order 10^{-6} if the NT is on its path.

Due to the long muon range, CC interactions of up-going $\overset{(-)}{\nu}_\mu$ can be detected from far outside the instrumented volume. This method also works for horizontal neutrinos up to about 10° above the horizon (depth dependent), where the background from atmospheric muons become prohibitive. Alternatively, one can select events that start inside the instrumented volume and thus remove incoming muons that generate early hits in the outer layers of the detector. Such a veto-based event selection is sensitive to neutrinos of all flavours from all directions, albeit with a reduced efficiency since a part of the instrumented volume is sacrificed for the veto. Such a muon veto, or vetoing events with a coincident signal in the surface array, also rejects down-going atmospheric neutrinos that are accompanied by muons from the same air shower and thus reduces the atmospheric-neutrino background. Actually, the breakthrough in detecting high-energy cosmic neutrinos was first achieved with this technique.

Note that the fields of view of NTs at the South Pole and in the Northern hemisphere are complementary for each reaction channel and neutrino energy.

36.3.2.1 *The Projects*

Table 36.3 lists past, present and future neutrino telescope projects and their main parameters.

Table 36.3: Past, present and future NT projects and their main parameters. The milestone years give the times of project start, of first data taking with partial configurations, of detector completion, and of project termination. Projects with first data expected past 2022 are indicated in italics. The size refers to the largest instrumented volume reached during the project development. See [52] for references to the different projects where unspecified.

Experiment	Milestones	Location	Size (km^3)	Remarks
DUMAND	1978/–/–/1995	Pacific Ocean		Terminated due to technical/funding problems
NT-200	1980/1993/1998/2015	Lake Baikal	10^{-4}	First proof of principle
GVD [56]	2012/2015/–/–	Lake Baikal	0.5–1.5	High-energy ν astronomy first 8 clusters installed
NESTOR	1991/–/–/–	Med. Sea		2004 data taking with prototype
NEMO	1998/–/–/–	Med. Sea		R&D project, prototype tests
AMANDA	1990/1996/2000/2009	South Pole	0.015	First deep-ice NT
ANTARES	1997/2006/2008/–	Med. Sea	0.010	First deep-sea NT
IceCube [57]	2001/2005/2010/–	South Pole	1.0	First km^3-sized detector
IceCube-Gen2 [58, 59]	2014/–/–/–	South Pole	5–10	Planned extension of IceCube covering low and high energies, a surface array and radio detection
KM3NeT/ARCA [54]	2013/2021/–/–	Med. Sea	ca. 1	High-energy configuration for neutrino astronomy. Under construction, data taking with 8 strings
KM3NeT/ORCA [54]	2014/2020/–/–	Med. Sea	0.007	Low-energy configuration for neutrino mass hierarchy. Under construction, data taking with 10 strings
KM3NeT Phase 3	2013/–/–/–	Med. Sea	ca. 3	6 ARCA blocks + ORCA
P-ONE [60]	2018/–/–/–	Pacific Ocean	$\mathcal{O}(1)$	Possible future NT, R&D phase

36.3.2.2 *Properties of media*

The efficiency and quality of event reconstruction depend strongly on the optical properties (absorption and scattering length, intrinsic optical activity) of the medium in the spectral range of bialkali photocathodes (300–550 nm). Large absorption lengths result in a better light collection, large scattering lengths in superior angular resolution. Deep-sea sites typically have effective scattering lengths of > 100 m and, at their peak transparency around 450 nm, absorption lengths of 50–65 m. The absorption length for Lake Baikal is 22–24 m. The properties of South Polar ice vary strongly with depth; at the peak transparency wave length (400 nm), the scattering length is between 5 and 75 m and the absorption length between 15 and 250 m, with the best values in the depth region 2200–2450 m and the worst ones in the layer 1950–2100 m.

Noise rates measured by PMTs with a diameter of 25 cm in deep polar ice are about 0.5 kHz per PMT and almost entirely due to radioactivity in the OM components. The corresponding rates in sea water are typically 60 kHz, mostly due to ^{40}K decays. Bioluminescence activity can locally cause rates on the MHz scale for seconds; the frequency and intensity of such “bursts” depends strongly on the sea current, the season, the geographic location, and the geometry of the detector elements. Experience from ANTARES shows that these backgrounds are manageable without a major loss of efficiency or experimental resolution.

36.3.2.3 *Technical realisation*

Optical modules (OMs) and PMTs: An OM is a pressure-tight glass sphere housing one or several PMTs with a time resolution in the nanosecond range, and in most cases also electronics for control, HV generation, operation of calibration LEDs, time synchronisation and signal digitisation.

Hybrid PMTs with 37 cm diameter have been used for NT-200, conventional hemispheric PMTs with 20 cm diameter for AMANDA and with 25 cm diameter for ANTARES, IceCube and Baikal-GVD. A novel concept has been chosen for KM3NeT. Each OM (43 cm) is equipped with 31 PMTs (7.5 cm), plus control, calibration and digitisation electronics. Advantages are that (i) the overall photocathode area exceeds that of a 25 cm PMT by more than a factor of 3; (ii) the individual readout of the PMTs results in a very good separation between one- and two-photoelectron signals which is essential for online data filtering and random background suppression; (iii) the hit pattern on an OM provides directional information; (iv) no mu-metal shielding against the Earth magnetic field is required. Figure 36.6 shows the OM designs of IceCube and KM3NeT.

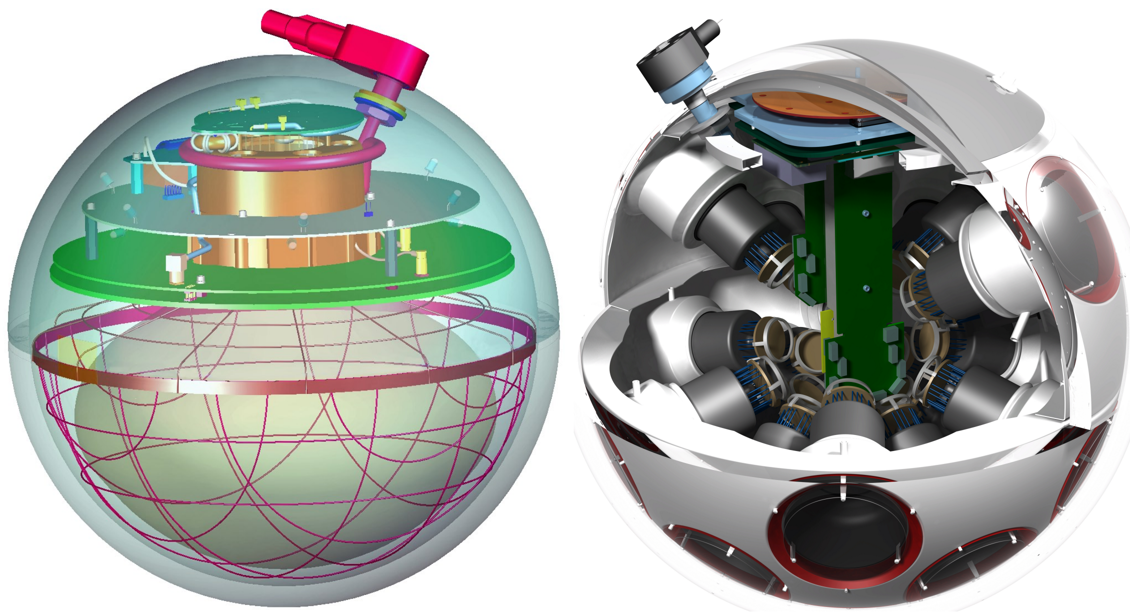

Figure 36.6: Schematic views of the digital OMs of IceCube (left) and KM3NeT (right).

Readout and data filtering: In current NTs the PMT data are digitised in situ: for ANTARES and Baikal-GVD in special electronics containers close to the OMs, for IceCube and KM3NeT inside the OMs. For IceCube, data are transmitted via electrical cables of up to 3.3 km length, depending on the location of the strings and the depth of the OMs; for ANTARES, KM3NeT and Baikal-GVD optical fibre connections have been chosen (several 10 km for the first two and 4 km for GVD).

The full digitised waveforms of the IceCube OMs are transmitted to the surface for pulses appearing in local coincidences on a string; for other pulses, only time and charge information is provided. For ANTARES (time and charge) and KM3NeT (time and time over threshold), all PMT signals above an adjustable threshold are sent to shore.

The raw data are subsequently processed on online computer farms, where multiplicity- and topology-driven filter algorithms are applied to select event candidates. The filter output data rate is about 10 GByte/day for ANTARES and of the order 1 TByte/day for IceCube (100 GByte/day transferred via satellite) and KM3NeT.

Calibration: For efficient event recognition and reconstruction, the OM timing must be synchronised at the few-nanosecond level and the OM positions and orientations must be known to a few 10 cm and a few degrees, respectively. Time calibration is achieved by sending time synchronisation signals to the OM electronics and also by light calibration signals emitted in situ at known times by LED or laser flashers (ANTARES, KM3NeT). Precise position calibration is achieved by measuring the travel time of light calibration signals sent from OM to OM (IceCube) or acoustic signals sent from transducers at the sea floor to receivers on the detector strings (ANTARES, KM3NeT, Baikal-GVD). Absolute pointing and angular resolution can be determined by measuring the "shadow of the moon" (*i.e.*, the directional depletion of muons generated in cosmic-ray interactions). IceCube and ANTARES have both shown that they have angular resolution below 1°, confirming MC calculations which indicate a precision of $\approx 0.5°$ for energies above 10 TeV. For KM3NeT, simulations indicate that sub-degree precision in the absolute pointing can be reached within a few weeks of operation.

Detector configurations: IceCube [57] (see Figure 36.7) consists of 5160 Digital OMs (DOMs) installed on 86 strings at depths of 1450 to 2450 m in the Antarctic ice; except for the DeepCore region, string distances are 125 m and vertical distances between OMs 17 m. 324 further DOMs are installed in IceTop, an array of detector stations on the ice surface above the strings. DeepCore is a high-density sub-array at large depths (*i.e.*, in the best ice layer) at the centre of IceCube.

The NT200 detector in Lake Baikal at a depth of 1100 m consisted of 8 strings attached to an umbrella-like frame, with 12 pairs of OMs per string. The diameter of the instrumented volume was 42 m, its height 70 m. Meanwhile (2021), the Baikal collaboration has installed the first eight clusters of a future cubic-kilometre array, GVD [56]. A first phase, covering a volume of about $0.7\,\mathrm{km}^3$, will consist of 14 clusters, each with 288 OMs at 8 strings; its completion is scheduled for 2024. A next stage could cover up to $1.5\,\mathrm{km}^3$.

ANTARES (see [52] and references therein) comprises 12 strings with lateral distances of 60–70 m, each carrying 25 triplets of OMs at vertical distances of 14.5 m. The OMs are located at depths of 2.1–2.4 km, starting 100 m above the sea floor. An additional string holds devices for calibration and environmental monitoring. A system to investigate the feasibility of acoustic neutrino detection has also been implemented.

KM3NeT will consist of building blocks of 115 strings each, with 18 OMs per string. Operation of prototypes and the first strings deployed have successfully verified the KM3NeT technology [61]. In the upcoming phase 2.0 of its staged implementation, KM3NeT aims at two building blocks for neutrino astronomy, with vertical distances between OMs of 36 m and a lateral distance between adjacent strings of 90 m (ARCA, for *Astroparticle Research with Cosmics in the Abyss*) and at one block for the measurement of the neutrino mass hierarchy, with vertical distances between OMs of 9 m and a lateral distance between adjacent strings of about 20 m (ORCA, for *Oscillation Research with Cosmics in the Abyss*) [54]. The installation of ARCA near Capo Passero, East of Sicily (depth 3440 m) and of ORCA near Toulon (depth 2450 m) is ongoing and as of now (August 2021) for each of both six strings have been deployed and are continuously operated. Completion of the full ARCA (ORCA) arrays is planned for 2026 (2025). The possibility of directing a neutrino beam from the Protvino accelerator to ORCA (P2O) is also under study [62].

P-ONE (*Pacific Ocean Neutrino Experiment*) [60] is a new initiative in an early R&D phase, envisaging a large NT in the Pacific Ocean off the Canadian coast. It is intended to use an existing deep-sea cable infrastructure and to optimise the sensitivity for horizontal neutrinos with energies of about 100 TeV and beyond.

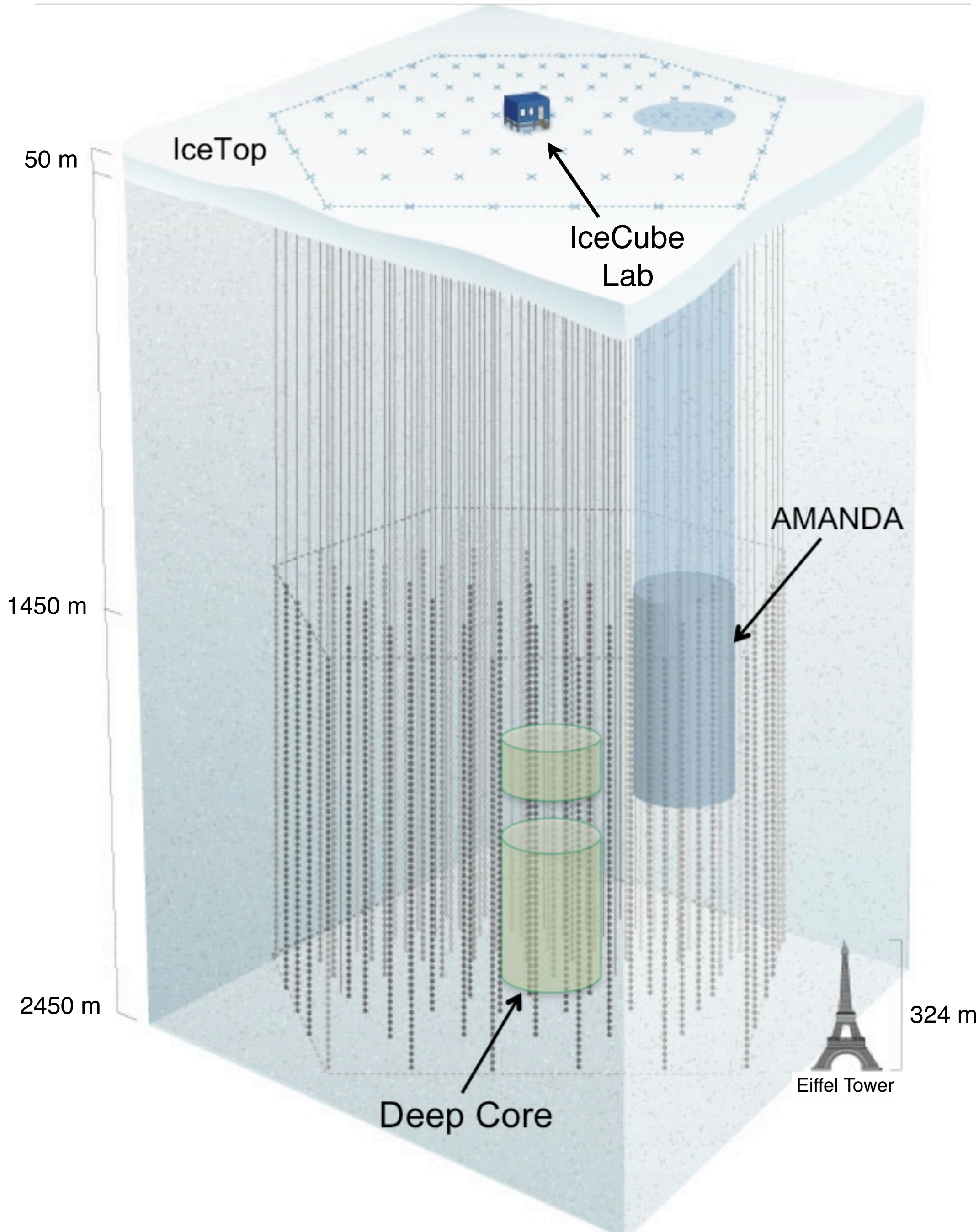

Figure 36.7: Schematic view of the IceCube neutrino observatory comprising the deep-ice detector including its nested dense part DeepCore, and the surface air shower array IceTop. The IceCube Lab houses data acquisition electronics and the computer farm for online processing. Operation of AMANDA was terminated in 2009.

36.3.2.4 *Results*

Atmospheric neutrino fluxes have been precisely measured with AMANDA ($\overset{(-)}{\nu}_\mu$), with IceCube and ANTARES ($\overset{(-)}{\nu}_\mu$, $\overset{(-)}{\nu}_e$) and have recently also been detected with KM3NeT ($\overset{(-)}{\nu}_\mu$); the results are in agreement with predicted spectra.

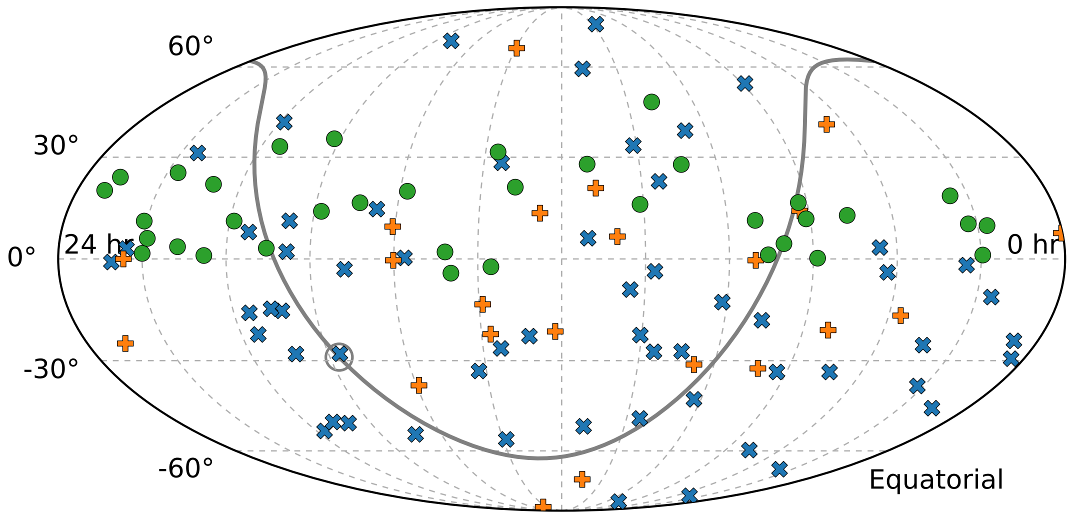

Figure 36.8: Arrival directions of IceCube candidate events for cosmic neutrinos in equatorial coordinates. The plot contains 82 HESE events, with shower-like events marked as blue $\times$ and muon tracks as orange $+$, and in addition 36 through-going muons tracks with an energy deposit exceeding 200 TeV (green circles). Approximately 40% of the events are expected to originate from atmospheric backgrounds. The grey curve denotes the Galactic Plane and the grey circle the Galactic Centre (from [63]).

In 2013, an excess of track and cascade events between 30 TeV and 1 PeV above background expectations was reported by IceCube; this analysis used the data taken in 2010 and 2011 and for the first time employed containment conditions and an atmospheric muon veto for suppression of down-going atmospheric neutrinos (High-Energy Starting Event analysis, HESE). The observed excess reached a significance of 5.7σ in a subsequent analysis of 3 years of data [64] and increased in significance since then. The excess is therefore interpreted to be due to an astrophysical neutrino flux. A consistent observation has also been made by ANTARES [65], albeit with much lower significance. The skymap of HESE and high-energy through-going muon events (see Figure 36.8) does not indicate statistically significant event clusters, nor deviations from an isotropic cosmic neutrino flux. Meanwhile the energy range of IceCube analyses has been extended down to about 10 TeV and the high-energy excess confirmed; also, events with through-going muons showed a corresponding excess of cosmic origin. In [66], the various analyses have been combined. Assuming the cosmic neutrino flux to be isotropic, flavour-symmetric and ν-$\overline{\nu}$-symmetric at Earth, the all-flavour spectrum is well described by a power law with normalisation $6.7^{+1.1}_{-1.2} \times 10^{-18}\,\mathrm{GeV}^{-1}\mathrm{s}^{-1}\mathrm{sr}^{-1}\mathrm{cm}^{-2}$ at 100 TeV and a spectral index -2.50 ± 0.09 for energies between 25 TeV and 2.8 PeV. A spectral index of -2, an often quoted benchmark value, is disfavoured with a significance of 3.8σ.

Multi-messenger observations triggered by a high-energy IceCube neutrino event in 2017 (see Figure 36.9 for an event display), together with a neutrino excess from the same celestial direction in the 2014/15 archival IceCube data, yielded evidence for a first neutrino signal related to a known astronomical object, the blasar[2] TXS 0506+056 [67, 68]. Multi-messenger investigations in conjunction with gravitational waves, ultra-high-energy cosmic rays or gamma-ray observations have not revealed further, similarly significant neutrino signals to date. Also, no further astrophysical neutrino sources were found in a recent combined IceCube/ANTARES search for steady

[2] An Active Galactic Nucleus with a relativistic jet outflow pointing to the observer.

sources [69].

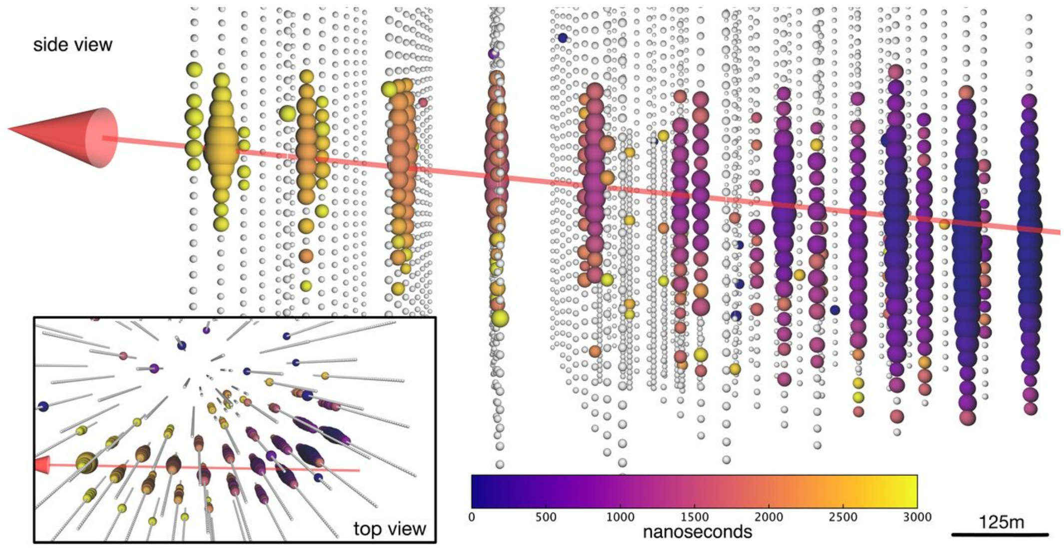

Figure 36.9: Display of the event IceCube-170922A, consistent with a neutrino from the blasar TXS 0506+056. The deposited energy is 24 TeV, the most probable neutrino energy is 290 TeV. The colour code indicates the signal timing (blue: early; yellow: late), the size of the coloured circles is a logarithmic measure of the light intensity registered per DOM. The arrow indicates the reconstructed neutrino direction, corresponding to a zenith angle of $5.7^{+0.5}_{-0.3}$ degrees below horizon. Figure from [67].

IceCube has reported an energy-dependent anisotropy of cosmic-ray induced muons, a measurement of the neutrino-nucleon cross section using neutrino absorption in Earth, and the observation of a cascade event consistent with the process $\overline{\nu}_e + e^- \to W^- \to$ hadrons (Glashow resonance).

No indications for neutrino fluxes from dark matter annihilations or for other exotic phenomena have been found.

At lower energies, down to 10 GeV, IceCube/DeepCore, ANTARES and meanwhile also KM3NeT have identified clear signals of oscillations of atmospheric neutrinos. The closely spaced OMs of DeepCore allow for selecting a very pure sample of low-energy $\overset{(-)}{\nu}_\mu$ (6–56 GeV) that produce upward moving muons inside the detector. The neutrino energy is determined from the energy of the hadronic shower at the vertex and the muon range. Fits to the energy/zenith-dependent deficit of muon neutrinos provide constraints on the oscillation parameters $\sin^2\theta_{23}$ and Δm^2_{23}. The analysis of the same dependence for cascade-like events provides a $\sim 3\sigma$ evidence for ν_τ appearance – an important measurement to test the unitarity of the PMNS matrix [70].

See [71–73] for summaries of status, recent results and future plans of IceCube, ANTARES, KM3NeT, and GVD.

36.3.2.5 *Plans beyond 2021*

Within the future IceCube-Gen2 project, it is planned to extend the sensitivity of IceCube towards both higher and lower energies. To increase the detector sensitivity at high energies, a large-volume extension is envisaged, combined with a radio array for highest-energy neutrinos and a surface array providing also a powerful veto against atmospheric events [58, 59]. A substantially denser instrumentation of a sub-volume of DeepCore will be achieved with 7 closely spaced strings to be deployed in 2024/25 (the IceCube Upgrade), aiming to cover a low-energy program, to better calibrate the existing IceCube detector and the archival data, and to test new technologies. More information on the future extensions of GVD and KM3NeT and on P-ONE are given above, in Table 36.3 and in [54, 72].

36.3.3 *Radio emission from (ultra-)high energy particle showers*

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Coherent radio-frequency (RF) electromagnetic radiation is an attractive signature to search for particle cascades produced by interactions of high-energy particles. RF signatures have been used to study both cosmic-ray air showers and to search for neutrino-induced showers. This article will discuss the radio signal generation, the relevant energy regime and the application in detectors. Air showers are discussed in more detail in two recent reviews [74,75]. At lower energies, incoherent optical Cherenkov radiation is frequently used, as discussed in "Neutrino telescopes" section 36.3.2. This article uses the general definitions and properties of neutrino telescopes as described in 36.3.2.

36.3.3.1 *Signal generation and its characteristics*

As discussed in the "Passage of Particles Through Matter" review Sec. 34 the electromagnetic component of a high energy shower gives rise to radio emission. For the signal generation itself the type of primary particle is irrelevant. However, the signal medium is important. It must be non-conducting (and non-absorptive at RF frequencies). The different shower length scales (radiation length, X_0) between air and the solid materials used for neutrino searches leads to surprisingly large differences in shower development. Due to the interaction with the medium the shower contains more electrons than positrons, which results in a net charge excess and leads to coherent Cherenkov emission, also known as Askaryan effect [76–78]. In air, during propagation through the geomagnetic field, the relative motion of electrons and positrons is affected, which leads to a varying transverse current, usually referred to as the geomagnetic effect [74]. Both effects may be described more generally as being due to radiation from a time-varying net charge [79]. Their relative importance is governed by the density of the medium, as the electric field scales as the net charge excess, and a lower density allows the geomagnetic effect to gain importance. Thus, in solid materials the emission from the Askaryan effect dominates, but it is a $< 20\%$ correction in air showers.

Coherent radiation is possible at wavelengths longer than the instantaneous thickness of the shower along an observer's line of sight. Since air showers have a larger extent than showers in solid media, their coherent radiation appears at lower frequencies.

High-frequency radiation is concentrated around the Cherenkov angle θ_C. Viewed directly on the Cherenkov cone, the electric field strength, $\epsilon_{\rm Ch}$ at a frequency f from an electromagnetic shower from a ν_e with energy E_ν in ice may be roughly parameterized as [80, 81]

$$\epsilon_{\rm Ch}(V/{\rm mMHz}) = 2.53 \times 10^{-7} \frac{E_\nu}{1{\rm TeV}} \frac{f}{f_c} \left[\frac{1}{1 + (f/f_c)^{1.44}} \right]. \quad (36.3)$$

The electric field strength increases linearly with frequency, up to a cut-off frequency f_c, which is set by the transverse size of the shower [82, 83]. The maximum wavelength c/f_c is roughly the Moliere radius divided by $\cos(\theta_C)$ where θ_C is the Cherenkov angle. The cutoff frequencies depend on the density (which affects the Moliere radius). They are about 1 GHz in ice, about 3 GHz in the lunar regolith, and below 100 MHz in air.

Near f_c, radiation is narrowly concentrated around θ_C [82,83]. At lower frequencies, the limited length of the emitting region leads to a broadening in emission angle around the Cherenkov cone.

Away from θ_C, the electric field from Eq. (36.3) is reduced by [80],

$$\frac{\epsilon}{\epsilon_{\mathrm{Ch}}} = \exp\left(-\frac{1}{2}\frac{(\theta-\theta_C)^2}{(2.2^\circ \times [1\mathrm{GHz}/f])^2}\right). \quad (36.4)$$

The angular distribution of the signal around θ_C can be parameterized by a Gaussian peak modulated by a $\sin\theta$. In both ice and the lunar regolith, θ_C is about 56°, in air only 1°. Close to θ_C, the 1 GHz maximum frequency in ice/regolith leads to a generated pulse width of ≈ 1 nsec.

These equations are appropriate for ice. More general parameterizations can be found in [81,84].

More accurate calculations of the predicted radio signal, in particular air showers are not easily parameterized, but require detailed Monte Carlo simulations. For air showers, these are built on microscopic air shower simulations, calculate the emission from all individual particles in the shower development and add them for different observer positions [74]. For neutrinos, most approaches calculate (directly or from a parameterization) the Askaryan signal from a shower profile. The signal is then propagated through the medium and into an antenna model [81].

At energies above 10^{16} eV in ice, the Landau-Pomeranchuk-Migdal effect lengthens electromagnetic showers, by reducing the cross-sections for bremsstrahlung and pair production [85]. The lengthening of the shower leads to a narrowing of the radio emission around the Cherenkov cone, and a reduction in high-frequency emission away from the cone [81]. At higher energies, this leads to two separate components of the Askaryan radiation from a neutrino interaction: an un-altered component from the hadronic portion of the shower and an angularly narrowed component from the LPM-lengthened electromagnetic shower. The width of the narrowed component scales as $E_\nu^{1/3}$. If these two components can be observed separately, they could, in principle, be combined to determine the inelasticity of the neutrino interaction [86], allowing for improved measurements of low$-x$ parton distributions and searches for beyond-standard-model interactions.

Similarly, energetic outgoing $\mu^\pm$ and $\tau^\pm$ from neutrino interactions will dominantly lose energy via stochastic pair production and photonuclear interactions. These secondary particles will produce electromagnetic showers that can be detected by radio detectors, if they are above threshold energy. This will enable multiple detections of the same particle track and thus present interesting reconstruction opportunities [87].

At still higher energies, above 10^{20} eV, the LPM effect strengthens, and the electromagnetic shower splits into multiple subshowers with significant separation. When these separations become large enough, the subshowers will effectively become independent radiators, with the total emission showing substantial event-by-event variation, depending on the division into subshowers [85]. Because of this, many experiments that study higher energy (well above 10^{20} eV) neutrinos focus on the hadronic shower from the struck nucleus. This contains an average of only about 20% of the energy, but with fewer large fluctuations.

36.3.3.2 *Energy regime of radio detectors*

The electric field amplitude is linearly proportional to the shower energy. Since the signal is a radio wave, the field amplitude decreases as $1/R$, plus potential absorption in the intervening medium, while the energy fluence decreases as $1/R^2$, again, plus potential absorption. The detection threshold depends on the distance to the antenna and the bandwidth and noise characteristics of the antenna and detector. For an antenna located in the detection medium, at a distance of 1 km the typical threshold is around 10^{17} eV. For stand-off (remote sensing) detectors, the threshold rises roughly linearly with the distance. These thresholds can be reduced by using directional antennas and/or combining the signals from multiple antennas using beam-forming techniques.

RF detectors are used to search for energetic neutrinos from three types of sources: astrophysical objects (*i.e.* extending measurements of the neutrino energy spectrum observed at TeV to PeV energies upward in energy), cosmogenic neutrinos associated with cosmic-ray-cosmic microwave background radiation (CMBR) interactions, and neutrinos from beyond-standard-model physics. These types are very roughly associated with energies below 10^{18} eV, the energy range 10^{18} to 10^{20} eV, and above 10^{20} eV.

Cosmogenic neutrinos are produced when ultra-high energy (UHE) protons with energy $E > 5 \times 10^{19}$ eV interact with photons from the CMBR, infrared light from old stars, and other extragalactic background light. These protons are excited to a Δ^+ resonance which may decay via $\Delta^+ \to n\pi^+$, leading to neutrinos with energies above 10^{18} eV [88, 89]. The cosmogenic neutrino signal depends heavily on the fraction of UHE cosmic-rays that are protons. For a 100% proton composition (disfavored by most data [90]), observing a cosmogenic neutrino signal of at least a few events per year requires a solid or liquid detector with an active volume of about 100 km^3.

To reach the effective volumes necessary to observe the expected low fluxes of UHE neutrinos, common, naturally occurring, non-conducting solid (or potentially liquid) media, with a long absorption length for radio waves are needed. Optical Cherenkov and acoustical detectors are limited by short (< 100 m) attenuation lengths [91] so would require a prohibitively expensive number of sensors. The radio detection technique has been used to detect air showers, targeting neutrinos as well as cosmic rays, and to search for neutrino showers in ice, salt domes and the lunar regolith.

36.3.3.3 *Reconstruction of particle energy and direction and background suppression*

Since radio detectors view the interaction from afar, the reconstruction techniques differ from optical neutrino telescopes.

Radio detection is a calorimetric measurement, thus provides good energy estimates of the shower energy. The energy fluence (integrated pulse power) of the signal scales quadratically with shower energy. It also depends on the distance to the shower, through potential attenuation losses and the usual $1/R$ loss in electric field amplitude. The arrival times in antennas and a spherical wave approximation can be used to determine the interaction vertex, although some uncertainty due to the viewing angle with respect to the Cherenkov angle may remain, if not corrected for by using the frequency information. If the radio signal travels through media where the index of refraction varies (like the firn of glacial ice), then ray-tracing techniques may be required to follow the signal back to the interaction point. For buried antennas, the bending of the signal trajectories due to the index of refraction creates an opportunity. For some geometries, there may be two paths to the detector: a 'direct' path, with minor bending, and a second where the signal is bent beyond horizontal, bouncing off the surface before reaching the antenna. By measuring the time difference between the two paths, the distance to the interaction vertex may be determined; this greatly simplifies the energy determination [92, 93]. For most neutrino interactions (except for ν_e charged-current interactions), the shower energy is less than the neutrino energy. The uncertainty on the interaction inelasticity is a major contributor to the uncertainty in the neutrino energy, along with uncertainties on the distance between the antenna(s) and the interaction vertex [94].

Reconstruction of the neutrino arrival direction depends on several aspects of the signal. First, the direction from the antenna to the interaction site must be determined. This can be done by using the relative timing from separated antennas, or using beam-forming techniques with multi-element arrays. For air showers, the signal arrival direction is (almost) equal to the particle arrival direction, with corrections being obtainable by fitting a hyperbolic wavefront [74, 75].

For showers in solid/liquid media, the arrival direction with respect to the interaction point - antenna vector is determined from two additional angles. The frequency spectrum can be used to determine the angle between signal arrival direction and Cherenkov cone according to Eq. (36.4) [95]. The second angle can be determined from the polarization of the signal. The radio signal is produced with a linear polarization in the plane containing both the particle direction and the radio wave direction. These two angles can be combined to determine the direction, subject to a (usually) four-fold ambiguity, due to uncertainty as to whether the antenna is inside or outside the Cherenkov cone, and because the particle direction can be flipped 180° without affecting the observed signal. Often, some of these solutions can be rejected because they correspond to long path lengths through the Moon or the Earth, where the neutrino would be absorbed.

Spectral information is crucial for the reconstruction and background rejection. However, large bandwidth antennas typically disperse (i.e. broaden) the pulses. As long as the dispersion can be compensated for and backgrounds controlled, a large bandwidth detector is the most sensitive.

All radio experiments must contend with background. Common sources are anthropogenic noise, antenna/preamp noise, charge generated by blowing snow, lightning, and, at low frequencies, radiation from the Milky Way. While narrowband noise impacts triggering and contaminates signal quality, impulsive backgrounds could mimic a signal. One of the major issues for radio-detection experiments is anthropogenic noise. Most anthropogenic noise has distinctive characteristics (such as being narrow-band, and coming from near the horizon) which makes it relatively easy to reject during data analysis, via narrow-band filters and other techniques [74]. However, these factors complicate triggering and reduce data purity. This is even an issue in Antarctica, where communication radios and passing satellites can mimic showers, at least at the trigger level. The need to limit anthropogenic noise has led most experimental groups to select remote locations for their detectors. Still, experiments have used approaches to reduce trigger-level noise, and/or to reject background at the analysis level. For example, for multi-element arrays, the threshold drops as the square root of number of antennas, since the signal adds in-phase while the backgrounds add with random phases [96].

Most dedicated air shower experiments have used radio antennas in combination with at least one other detector technology, such as scintillation counters, if the site quality is not sufficient and/or computing power on autonomous stations is limited. One exception is ARIANNA, which is located in an uninhabited part of Antarctica, enabling them to efficiently self-trigger on air showers [97].

Lunar experiments (discussed below) use different techniques to reduce the anthropogenic background. Some experiments use multiple antennas, separated by at least hundreds of meters; by requiring a coincidence within a small time window, anthropogenic noise can be rejected. With good enough timing, beam-forming techniques can be used to further reduce the background. An alternative approach is to use beam forming with multiple feed antennas viewing a single reflector, to ensure that the signal points back to the moon.

Due to the similarity in the radio emission of air showers and neutrino showers, the more abundant cosmic rays can act as background to neutrino searches. In-ice detectors need to suppress in-air emission that is refracted into the ice, emission that is created from developing air showers continuing in the ice, as well as from stochastic energy-losses of atmospheric muons. Lunar experiments may faces challenges in separating neutrino interactions from cosmic ray interactions.

36.3.3.4 *Recent experiments*

Figure 36.10 shows some current limits from neutrino searches, including from prototype arrays. Except for LOFAR, which is fully operational, projected limits from future experiments are not shown in the figure.

i. *Ice*

The most common dense medium transparent to radio waves is ice. Natural ice is an attractive medium for neutrino detection with radio attenuation lengths from over 300 m to 1 km [108]. The attenuation length varies with frequency and ice temperature, with higher attenuation in warmer

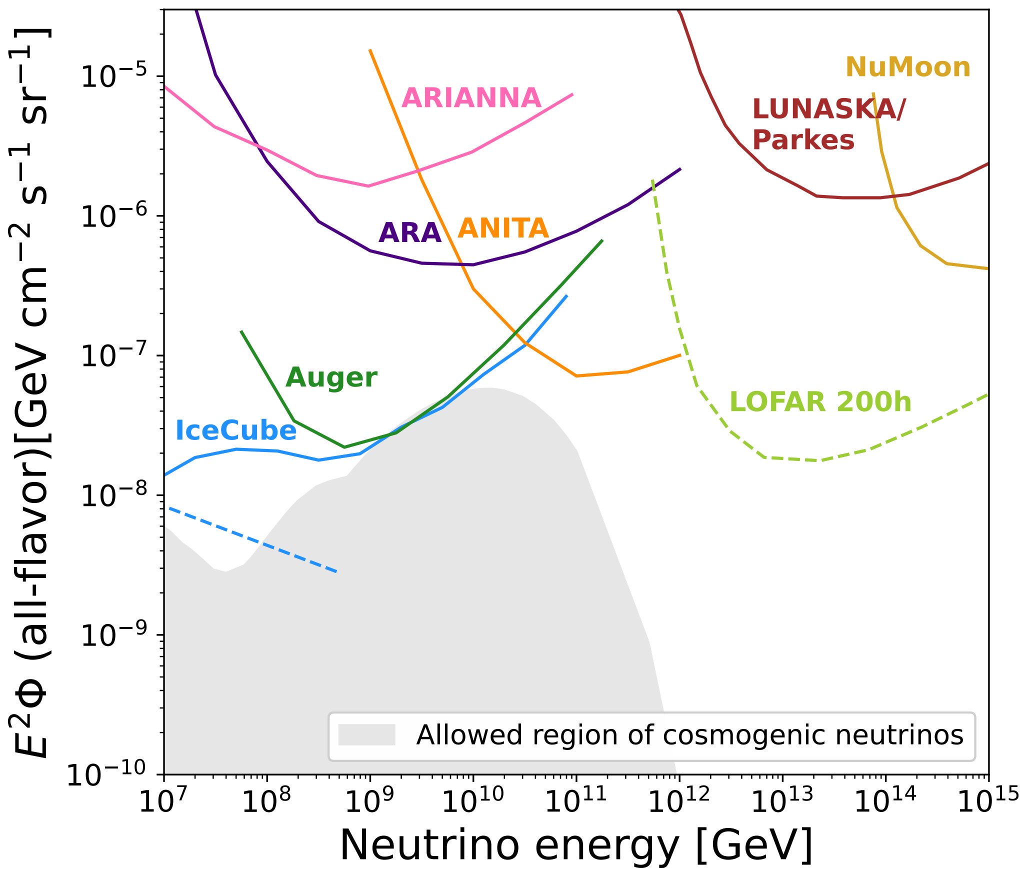

Figure 36.10: Representative 3-flavor (summed, assuming equal fluxes of each flavor) differential (over one decade in energy) limits from different experiments and prototype experiments. Shown are limits from the IceCube ultra-high energy ν search [98], the Auger search for earth-skimming ν_τ [99], the LUNASKA/Parkes [100] and NuMoon lunar searches [101], the ANITA balloon experiment [102], ARA [103] and ARIANNA prototypes [104], along with projections for the LOFAR array [105]. The dashed blue line is the extrapolation of the IceCube through-going ν_μ flux measured at lower energies (few 10s of TeV to 10 PeV), with spectral index $\alpha = -2.28$ [106]. Because of the long extrapolation, this should only be treated as a rough reference. The ARA and ARIANNA limits are from prototype arrays, and indicate the energy range that might be covered, with far higher sensitivity by larger arrays. The shaded area is the allowed region for cosmogenic neutrinos, from a recent global analysis that included the measured cosmic-ray spectrum and composition [107].

ice. Although glacial ice is mostly uniform, the top $\approx$ 100 m of ice, the 'firn,' exhibits a gradual transition from packed snow at the surface (typically $\rho = 0.35$ g/cm^3) to solid ice ($\rho = 0.92$ g/cm^3) below [109]. The thickness of the firn varies with location; it is thicker in central Antarctica than in the coastal ice sheets or in Greenland. The varying density has several implications.

The index of refraction depends linearly on the density, so radio waves curve downward in the firn. This bending reduces the effective volume of surface or aerial antennas. A surface antenna cannot see near-surface interactions at large horizontal distances. There are also indications that the increase in firn density is non-monotonic [110, 111]. This leads to non-monotonic changes in index of refraction which may create waveguides that trap a small fraction of the radio energy and propagate it horizontally.

In one type of experiment, antennas mounted on high-altitude balloons observe the ice from above. Radio signals from in-ice neutrino interactions propagate to the surface, traverse the ice-air interface, and then travel to the balloon. The surface roughness of the ice can affect signals as they transition from the ice to the atmosphere. The best known example, ANITA, has made four flights around Antarctica, floating at an altitude around 35 km [112]. Its 32/40/48 (depending on the flight) dual-polarization horn antennas scanned the surrounding ice, out to the horizon (650 km away). Because of the small angle of incidence, ANITA could use polarization information to separate signals from background; ν signals should be vertically polarized, while most background from cosmic-ray air showers should be horizontally polarized.

As with all radio-detection experiments, ANITA had to contend with anthropogenic backgrounds. The ANITA collaboration uses their multiple antennas as a phased array to achieve good pointing accuracy, with a resolution of 0.2-0.4° in elevation, and 0.5-1.1° in azimuth. They rejected all events that pointed toward known or suspected areas of human activity. ANITA has set the most stringent flux limits yet on neutrinos with energies above 10^{20} eV [102]. The ANITA experiment has also reported several anomalous events, matching cosmic ray signals, but with unexpected polarization signature, which the collaboration has indicated might be from Earth-skimming ν_τ [113, 114]. However, this interpretation is controversial.

Because of the significant source-detector separation, ANITA is most sensitive at energies above 10^{19} eV. A lower energy threshold requires a smaller antenna-target separation.

Other ice based experiments use antennas located within the active volume, allowing them to reach thresholds around 10^{17} eV, or lower with phased array antennas. This approach was pioneered by the RICE experiment [115] which buried 18 half-wave dipole antennas in holes drilled for AMANDA at the South Pole, at depths from 100 to 300 m. The hardware was sensitive from 200 MHz to 1 GHz. Each antenna fed an in-situ preamplifier which transmitted the signals to surface digitizing electronics.

More recently, two groups have deployed prototype arrays which have explored different detector concepts. The Askaryan Radio Array (ARA) deployed surface and buried antennas at the South Pole [116], while the Antarctic Ross Iceshelf Antenna Neutrino Array (ARIANNA) installed surface antennas on the Ross Ice Shelf [104], about 110 km north of McMurdo station. ARIANNA offered the possibility of detecting downward-going ν, from the radio waves reflected off the ice-sea water interface on the bottom of the Ross Ice Shelf, while ARA took advantage of the colder, deeper ice at the South Pole, with its longer radio attenuation length. ARA buried antennas up to 200 m deep to be able to observe a larger portion of ice, due to the refraction of the signal in the firn. In contrast, ARIANNA deployed antennas just below the surface, allowing them to use high-gain, but large log periodic dipole antennas. Recently, phased-array trigger techniques have been demonstrated that can reduce the energy threshold by a factor of several [96, 117].

Both experiments use stations which operate independently, spaced far enough to maximize sensitivity, but where only a small fraction of neutrino events will be visible in multiple stations. Each station includes multiple antennas, which will be sensitive to both horizontal and vertical polarization. The expected angular resolution is a few degrees [95].

In 2021, the Radio Neutrino Observatory Greenland (RNO-G) started deploying stations at Summit Station. RNO-G is planned to consist of 35 stations, which employ ARIANNA-style surface antennas, an ARA-style phased array and deep antennas, and draw heavily on ANITA's electronics heritage [118].

ii. *The Moon*

Because of its large size and non-conducting regolith, and the availability of large radio-telescopes, the Moon is an attractive target [119]. Conventional radio-telescopes are quite well suited to lunar neutrino searches, with natural beam widths not too dissimilar from the size of the Moon. Still, there are experimental challenges. The attenuation length is typically estimated to be 9m/f(GHz) [120], so only near-surface interactions can be studied. The composition of the lunar regolith is not well known, and there are significant uncertainties due to this uncertainty. One big limitation of lunar experiments is that the 385,000 km target-antenna separation leads to energy thresholds above 10^{20} eV.

The effective volume probed by experiments depends on the geometry, which itself depends on the frequency range used. At high frequencies f, the electric field strength is high, leading to a lower energy threshold, but the sensitive volume is limited because the Cherenkov cone only points toward the Earth for a narrow range of geometries. Lower frequency radiation is more isotropic, so the effective volume is larger, but, because the electric field is weaker, the energy threshold is higher. The $1/f$ dependence of the attenuation length in the lunar regolith further increases the effective volume at low frequencies. The frequency range affects the energy dependence of the sensitivity. As can be seen in Fig. 36.10, a low-frequency experiment like NuMoon (which covered 115-180 MHz) has good sensitivity, but only above about 10^{14} GeV, while Lunaska/Parkes, which observed in the range 1200-1500 MHz, has a higher flux limit, but is sensitive above about $10^{12.5}$ GeV.

Current limits and projected sensitivities are sensitive to many details. A recent review [121] compared different radio-detection experiments using a common framework, and found some significant shifts in sensitivities due to, e.g. different assumptions about lunar composition and inelasticities.

With modern technology, it is increasingly viable to search over very broad frequency ranges [122]. One technical challenge is due to dispersion (frequency dependent time delays) in the ionosphere. Dispersion can be largely removed with a de-dispersion filter, using either analog circuitry or post-collection digital processing.

iii. *Air*

Radio detection in air is sensitive to all particles inducing air showers. Radio-detection can be used to determine the energy of cosmic rays, as done by e.g. the Auger and Tunka-Rex experiments [123, 124]. Radio signals can also be used to infer the altitude for shower-maximum, where the shower contains the most particles, as done by e.g. the LOFAR and Tunka-Rex collaborations [124, 125]. This altitude is sensitive to the cosmic-ray composition. Reconstructing the particle arrival direction is much easier in air since the Cherenkov angle, and thus the radio wavefront, aligns with the axis to 1°. Radio-detection is also useful for energy cross-calibrations between different experiments and may be able to provide an independent energy scale calibration for air shower arrays [126].

One variation on the radio-detection approach is to look for radio emission from Earth-skimming ν_τ. Although ν_τ are much less commonly produced than ν_μ and ν_e, over astrophysical distances, oscillations lead to a $\nu_e : \nu_\mu : \nu_\tau$ ratio near $1 : 1 : 1$, for almost all non-exotic acceleration and propagation mechanisms [127].

If the ν_τ traverse the Earth and interact while traveling upward, near the surface, the resulting $\tau^\pm$ may exit the Earth before decaying. 83% of the time, the decay produces a hadronic or electromagnetic shower in the atmosphere [128]. Experiments have searched for these upgoing showers, and for the resulting optical Cherenkov and coherent RF radiation. The threshold energy dependence for these searches depends on several factors, notably including the average $\tau^{\pm}$ decay length, which increases linearly with energy; the Pierre Auger observatory sets stringent limits on the neutrino flux at energies above 10^{17} eV [99].

36.3.3.5 *Future experiments*

Looking ahead, RNO-G [118] will continue deployment until 2024 and reach the largest yearly sensitivity of any radio array thus far. Further out, the proposed IceCube Gen2 expansion includes a substantial radio array component [59], which will be sensitive to both neutrinos from the ice and air showers from cosmic rays. PUEO, a successor of ANITA has been funded and is scheduled for its first flight in 2024 [129].

In the near future, several large radio detector arrays should reach significantly lower energies for lunar neutrino detection. The LOFAR array is taking data with 36 detector clusters spread over Northern Europe [105]. In the longer term, the Square Kilometer Array (SKA) with its 1 km^2 effective area will push thresholds down to near 10^{20} eV [122]. The SKA will also study air showers.

A number of dedicated prototype ν_τ radio-detection experiments exist. The GRAND Collaboration recently proposed to deploy a 10,000 antenna array, eventually growing to 200,000 antennas spread over 200,000 km^2. Its stations are simple autonomous units that sample the 30-100 MHz range using antennas optimized for near-horizontal signals [130]. The first phase GRAND-proto 300 is scheduled for deployment in 2021. The Pierre Auger Collaboration is currently upgrading their surface array to include radio antennas at all water Cherenkov detectors. This array will improve the sensitivity of the instrument to horizontal showers, both for composition sensitivity for cosmic rays and for the detection of Earth skimming neutrinos [131].

36.4 Large time-projection chambers for rare event detection

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Rare event searches require detectors that combine large target masses and low levels of radioactivity, and that are located deep underground to eliminate cosmic-ray related backgrounds. Past and present efforts include searches for the scattering of particle dark matter, neutrinoless double beta decay, and the measurement of solar neutrinos, while next generation experiments will also probe coherent scattering of solar, atmospheric and diffuse supernova background neutrinos. Large time project chambers (TPCs) [132], adapted from particle collider experiments, have emerged as a leading technology for these efforts. Events are measured in a central region confined by a field cage and usually filled with a liquid noble element target. Ionization electrons are drifted (in the z direction) to an anode region by use of electrode grids and field shaping rings, where their magnitude and $x - y$ location is measured. In rare event searches (with no external trigger available) scintillation generated at the initial event site is also measured, and the time difference between this prompt signal and the later-arriving charge signal gives the event location in z for a known electron drift speed. Thus, 3D imaging is a achieved in a monolithic central volume. The relatively slow readout due to the drift of charges ($\sim 1/2$ ms/m at 1 kV/cm) [133] is not a major pile-up concern in low background experiments. Noble elements have relatively high light yields (comparable to or exceeding the best inorganic scintillators), and the charge signal can be amplified by multiplication or electroluminescence. Radioactive backgrounds are distinguished by event imaging, the separate measurements of charge and light, and scintillation pulse shape. For recent reviews of noble element detectors, see [134–137].

Methods for achieving very low radioactive backgrounds are discussed in general in section 35.6. The basic architecture of large TPCs is very favorable for this application because gas or liquid targets can be relatively easily purified, while the generally more radioactive readout and support materials are confined to the periphery. The 3D imaging of the TPC then allows self shielding in the target material, which is quite powerful when the target is large compared to mean scattering lengths of order $\sim$ 10 cm for $\sim$ MeV neutrons and gammas from radioactivity. Most recent experiments have immersed the TPCs in hermetic water shields to eliminate external radioactive backgrounds, and several are also using an active scintillator inner layer to further veto backgrounds from detector materials. While other target fluids are possible, almost all recent efforts have used Xe and Ar. In LHe and LNe the mobility of electrons is $\sim 10^3$ times lower than in the heaver noble elements due to the formation "bubbles" around electrons. [138, 139] It is worth noting that scintillation and electron drift are possible in a number of organic fluids, possibly providing a route to economical large detectors, but with much reduced performance compared to noble elements.

In noble element targets, all non-noble impurities are readily removed (e.g., by chemical reaction in a commercial getter) so that only radioactive noble isotopes are a significant background concern. Xe, Ne and He have have no long lived radioactive isotopes (apart from the ^{136}Xe, discussed below, and the very long-lived ^{124}Xe [140]). Kr has $\sim$ 0.3 MBq/kg of the beta emitter ^{85}Kr created by nuclear fuel reprocessing [141], making it unusable as a target, while the $\sim$ 1 Bq/kg level of the beta emitter ^{39}Ar [142] is a nuisance for Ar-based experiments. Both of these can be backgrounds in other target materials, as can Rn emanating from detector components. Relatively low background materials are available for most of the structures surrounding the central target, with the exception of radioactive glasses and ceramics usually present in PMTs, feedthroughs and electrical components. Very low background PMTs with synthetic quartz windows, available over the last 15 years (see, e.g., [143]), have been a key enabling technology for dark matter searches. Radio-clean SiPMs and related Si-based photon detectors are increasingly being used in cases where their dark rates (which are significantly higher than PMTs) can be tolerated.

An important technical challenge in liquid detectors is achieving the high voltages needed for electron drift and measurement. In general, quench gases which stabilize charge gain and speed electron transport in wire chambers cannot be used, since these absorb and/or quench scintillation light and can trap electrons. It is also important to suppress low-level emission of electrons and associated photons which can otherwise swamp low energy signals. Drift of electrons over meter scales with minimal loss from attachment on trace levels of dissolved impurities (e.g., O_2) has so far required continuous circulating purification.

36.4.1 *Dark matter and other low energy signals*

A major goal of low background experiments is detection of WIMP (Weakly Interacting Massive Particle) dark matter through scattering on nuclei in a terrestrial detector (for a recent review, see [144]). Energy transfers are generally small, a few tens of keV at most. Liquid noble TPCs distinguish single nuclear recoils (NR) from dark matter from the dominant background of electron recoils (ER) from gamma rays and beta decays by rejecting multiple scatters, and, as described below, based on both the ratio of charge to light and the scintillation pulse shape. Neutrons are a NR background, but are present at much lower rates than gammas and betas, and also undergo significant multiply scattering. To detect small charge signals, a dual phase technique is used wherein electrons from interactions in the liquid target are drifted to the liquid surface and extracted with high field ($\sim$ 5 kV/cm) into the gas phase where they create an amplified electroluminescence signal which is usually measured by an array of PMTs located just above the liquid. (While both charge multiplication and electroluminescence are possible in liquid, they require very high fields created by very small electron structures and thus have not seen widespread adoption. For recent progress see [145]) This technique readily measures single electrons with $\sim$ cm $x - y$ resolution.

The measurement of the initial scintillation signal, by contrast, suffers from loss upon reflection from the TPC walls, and inefficiency in the readout, and usually limits the energy threshold. In LXe, the $\sim$ 178 nm wavelength is just long enough to be transmitted through high purity synthetic quartz PMTs windows, and, remarkably, PTFE immersed in LXe has $\sim$ 97% reflectivity. [146] The $\sim$ 128 nm scintillation light of LAr requires waveshifting (usually using TPB) both for reflectivity (usually on PTFE) and for efficient measurement. With both liquids, a second sensor array at the bottom of the TPC is used to maximize light collection, and total photon efficiencies have been in the 10-15% range. Typical raw yields for ER are several tens of electrons and photons per keV, and, in LXe, a NR threshold of $\sim 5\ keV$ has been achieved [147].

The microscopic processes leading to signals in liquid nobles are complex. Energy deposited by an event generates pairs of free electron and ions, and also atoms in their lowest excited state. The latter rapidly form excimers which de-excite by emitting light. Excimers arise in both triplet and singlet states which have the same energy but different decay times. In an event track, some fraction of electrons recombine with ions, while the rest escape and are measured. Each recombined ion creates an additional excimer, and hence another photon. Finally, some part of the energy is lost as heat - a small fraction for ER but a dominant and energy dependent fraction for NR. The branching into these various modes depends on drift field, energy, and particle type, requiring extensive calibrations. These have largely been carried out for LXe (see, e.g., [148]), and have been incorporated into the NEST Monte Carlo framework. [149]

This complexity also gives rise to discrimination between ER and NR: for the same visible energy, the slower NR create short, denser tracks and generate a higher fraction of initial excitons, leading to a smaller ratio of measured charge to light. NR also generate a higher ratio of short-lived singlet state to long-lived triplet states than ER, so that the scintillation signal itself gives pulse shape discrimination (PSD). Charge/light discrimination has been well mapped in LXe, and, remarkably, is very high (>99.9%) below $\sim$10 keV for NR. [147] It has only recently been measured in LAr [150], and has not yet played an important role in LAr based experiments. Qualitatively, PSD is similar in LXe and LAr - strong at high energy and weak at low energy. However it is well mapped only in LAr where it is very high above $\sim$ 50 keV, achieving values above $\sim 10^8$. [151]

This extremely powerful PSD in LAr is sufficient to overcome the ER background from ^{39}Ar, which is roughly 10^7 times higher than the fundamental low energy ER background from p-p solar neutrinos. In a multi-ton detector the event rate from ^{39}Ar poses a significant pile-up challenge, and the DarkSide collaboration is pursuing ^{39}Ar reduction through two methods. One, for which a factor 1400 reduction in $\sim$ 50 kg Ar has been demonstrated, is extracting “aged” Ar from underground (cosmic ray shielded) gas deposits in which the 269 yr half-life ^{39}Ar has decayed. [152] The other method is removal by distillation. The need for ^{39}Ar depleted Ar negates the much lower raw material cost of Ar compared to Xe. Kr must also be removed from both Xe and Ar experiments (and Ar must be from Xe experiments), comparatively easy tasks compared to isotopic separation. This is done through distillation or a chromatographic technique. In current LXe experiments the remaining dominant ER backgrounds is the beta decay of a daughter of ^{222}Rn in the active LXe, where the Rn has emanated from detector materials or external plumbing. Rn will be even more important as experiments scale up in size, but can in principle be reduced by better materials screening and online Rn separation, again by either distillation or chromatography. Neutrons are in general some six orders of magnitude less abundant than gamma rays and betas in U and Th decay chains, but they naturally scatter in the WIMP energy range, and their single scatters cannot be discriminated against. Self shielding is less powerful for neutrons than gamma rays, so that they are an increasingly important background at the current ton scale and future larger experiments, both in Ar and Xe. Active outer shielding layers which tag and veto neutrons are being included in most next generation experiments.

The WIMP sensitivity is a combination of backgrounds, discrimination, and WIMP scattering rates. The scattering rates are model dependent, but are in general dominated by spin-independent coherent scattering on the full nucleus. This has an A^2 dependence, favoring high mass targets. The energy spectrum is close to a falling exponential, so that the lowest possible energy threshold maximizes sensitivity. Experiments using LXe TPCs have had the leading sensitivity for standard WIMP dark matter for well over a decade, for all but the lowest WIMP masses. The ton-scale XENON1T [153] achieved a WIMP-nucleon sensitivity of 4.1×10^{-47} cm^2 at 30 GeV mass, closely followed by PANDAX-II [154] and LUX [155]. The next generation ~ 7 tonne experiments LZ [156] and XENONnT [157], and ~ 4 tonne PandaX-4T [158] are currently in late stages of construction. The DarkSide program is carrying out WIMP searches with LAr TPCs. The 50 kg DarkSide-50 achieved a sensitivity $\gtrsim 40$ times poorer than XENON1T. A 50 ton scale-up, DarkSide-20 is being pursued which features SiPMs instead of PMTs. [159]. (The best current limit using LAr is not from a TPC, but instead the scintillation-only DEAP-3600 experiment. [151])

LZ and XENONnT project sensitivity to WIMPs about a decade above the"floor" of coherent scattering of astrophysical neutrinos, which, absent a directional measurement (see below), are essentially indistinguishable from WIMPs. DARWIN, a proposed a 50 ton LXe TPC would approach the practical limit set by this floor for WIMP masses above ~ 5 GeV [160], while ARGO a ~ 200 ton LAr detector would achieve similar sensitivity for WIMPs masses well above ~ 50 GeV. [159]

There has been recent interest in models featuring low mass dark matter. These give rise to low energy recoils, and also strongly favor low mass target nuclei (despite the A^2 rate penalty). This has led to renewed focus on events below the scintillation threshold, where the charge signal alone achieves very low threshold due to the gain of the electroluminescence readout. This preserves $x - y$ spatial information, but only very weak depth information based on electron diffusion. Thus it is subject to the high backgrounds at the top and bottom of the active region, and decays of Rn daughters on grids. While the first such results came from XENON10, a recent result in LAr from DarkSide-50 extends to much lower dark matter mass because of the lower mass of Ar. To maximize the sensitivity of such searches in the future, studies have begun to understand and minimize the sources of electron backgrounds from both radioactivity and spurious sources such as field emission from grids. There is also an effort to develop a superfluid He TPC [161] read out with superconducting sensors (similar to the proposed HERON solar neutrino experiment). The rich set of signals in this case - scintillation, rotons, and ionization - potentially offer significant background rejection.

Measurement of NR recoil track direction would provide proof of the galactic origin of a dark matter signal since the prevailing WIMP direction varies on a daily basis as the earth spins. This cannot be achieved for the sub-micron tracks in any existing solid or liquid technology, but the mm-scale tracks in a low pressure gas (typically, P ~ 50 Torr) could be imaged with sufficiently dense instrumentation. Directionality can be established with $O(10^2)$ events by measuring just the track direction, while, with finer resolution that distinguishes the diffuse (dense) tail and dense (diffuse) head of NR (ER) tracks, only $O(10)$ events are required. Such imaging requires a high energy threshold, decreasing WIMP sensitivity, but also powerfully rejecting less dense ER background tracks.

A variety of TPC configurations are being pursued to accomplish this, most with a CF_4 target. The longest established effort, DRIFT, avoids diffusion washing out tracks for electron drift distances greater than ~ 20 cm by attaching electrons to CS_2, which drifts with vastly reduced diffusion. Other efforts drift electrons directly and use a variety of techniques for their measurement: DMTPC (electroluminescence + CCDs), MIMAC (MicroMegas), NEWAGE (GEMs), and D^3 (Si pixels). A related suggestion is that the amount of recombination in a high pressure Xe gas with an electron-cooling additive could be sensitive to the angle between the track and electric field [162], eliminating the need for track imaging. Directional measurements appear to be the only possibility to push beyond the floor of coherent neutrino scatters [163], though at the cost of enormous target mass and channel count.

36.4.2 $0\nu\beta\beta$ *Decay*

Another major class of rare event search is neutrinoless double beta decay ($0\nu\beta\beta$). A limited set of nuclei are unstable against simultaneous beta decay of two neutrons. Fortuitously, this includes the Xe isotope ^{136}Xe (Q-value 2458 keV), which can be used as the active material in a detector, and which, as an inert gas, can also be more readily enriched from its natural 8.9% abundance than any other $\beta\beta$ isotope. Observation of the lepton-number violating neutrinoless version of this decay would establish that neutrinos are Majorana particles and provide a direct measure of neutrino mass. For a recent review, see [137, 164]. The signal in $0\nu\beta\beta$ decay is distinctive: the full Q-value energy of the nuclear decay appears as equal energy back-to-back recoil electrons. A large TPC is advantageous for observing this low rate decay for all the reasons described above. The first detector to observe the standard model process two neutrino double beta decay was a gaseous TPC which imaged the two electrons tracks from ^{82}Se embedded in a foil. [165] Modern TPCs use Xe as the detector medium.

The dominant background is gamma rays originating outside the active volume. Most of these undergo multiple Compton-scatters which are efficiently recognized and rejected through sub-cm position resolution, though the few percent of gammas at this energy that photoabsorb are not. Self shielding of gamma rays in the double beta decay energy window is less powerful than in the low energy dark matter window, since in the former case there is some small probability of penetrating to some depth followed by the modestly small probability of photo-absorption. The latter case consists of three small probability processes: penetration to some depth, a very low-energy scatter, and the gamma exiting without a second interaction. Because of this and the fact that background and the signal are both electron recoils (i.e., NR/ER discrimination is of no value), the requirements on radioactivity in all the surrounding materials of a $\beta\beta$ TPC are much more stringent than an otherwise similar dark matter detector, unless other background rejection tools are available. However $\beta\beta$ searches are insensitive to low energy backgrounds (e.g., ^{85}Kr and ^{39}Ar) important for dark matter.

Very good energy resolution is crucial to avoid background from $2\nu\beta\beta$ decays and gammas including the prominent 2615 keV line from ^{208}Tl in the Th chain. Here a combined charge and light measurement largely eliminates the otherwise dominant fluctuations in recombination which lead to anti-correlated fluctuations in charge and light. Because of the high energy of the $\beta\beta$ signal, charge can be read out directly, and the scintillation measurement is easily tolerant of the dark rates of SiPMs. These goals have led $\beta\beta$ detectors to have somewhat different optimization than dark matter detectors, although the next generation large Xe dark matter experiments (LZ, XENONnT, DARWIN) have significant $\beta\beta$ reach.

The recently completed EXO-200 experiment used a single-phase LXe TPC with roughly 110 active kg of Xe enriched to 80.7 % ^{136}Xe to achieve one of the best $\beta\beta$ search limits [166]. The energy resolution obtained is (FWHM) of 2.71% (at 2458 keV), and lower values in LXe appear possible. A multi-ton successor experiment, nEXO, has been proposed which would fully cover the inverted neutrino mass hierarchy. [167] EXO-200 featured LAAPDs for light readout, and direct charge readout, while nEXO will use SiPMs.

A related but different approach is to use high pressure gaseous Xe TPC. [168] The lower density requires a large apparatus for given target mass, but has two significant advantages. The larger track size allows the two-electron topology of $0\nu\beta\beta$ events to be distinguished from single electrons from photoabsorption of background gammas. In addition, the low recombination fraction in the gas phase suppresses recombination fluctuations, allowing higher energy resolution. Recent progress with a 5 kg prototype by the NEXT collaboration has demonstrated the topology based discrimination, and, notably, 1% (FWHM) energy resolution. A $\sim$ 100 kg detector is now under construction, and ton-scale designs being studied. Finally, a long-standing idea that would provide definitive identification of a $0\nu\beta\beta$ signal is to extract and tag the ionized Ba daughter via atomic physics techniques [169], either in gas or liquid and gas phases. Significant recent progress by both the EXO and NEXT collaborations has now achieved the key milestone of demonstrating single Ba ion sensitivity in test setups. [170–172]

36.5 Sub-kelvin detectors

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36.5.1 *Motivation for Sub-kelvin Detectors*

Detectors operating below 1 K are referred to as low-temperature detectors (LTDs). The advantage of using LTDs over conventional detectors resides in their better energy resolutions, lower noise, and improved energy thresholds, which can all be achieved with a versatile choice in materials. In certain applications, these advantages outweigh the potential drawbacks of cooling and reading out a detector payload at sub-kelvin temperatures, and thus enable exploration of new frontiers in fundamental physics, astrophysics and cosmology. Among the endeavors enabled by LTDs are direct searches for dark matter over a wide mass range, precision experiments to measure the electron neutrino mass, searches for neutrinoless double-beta decay, and X-ray observation of the Universe. Large arrays of LTDs are also employed to measure the properties of the cosmic microwave background (CMB) spectrum whose parameters are determined by fundamental physics. These include dark matter and dark energy densities, the sum of neutrino masses and the number of light relativistic species, as well as probing the physics of inflation at energy scales of $\sim 10^{16}$ GeV. This article presents a brief overview of LTDs, their features, and several applications. More detailed treatment of this subject is available in the literature [173–176].

The advantages of LTDs are enabled by the detection of very low energy excitations (e.g. phonons and quasiparticles). In a typical interaction, energy from an incident particle is dissipated through excitation of secondary particles such as electrons, ions, holes, photons, phonons etc. These particles will in turn produce their own secondaries. Thus there is a cascade down in energy until the original energy deposit is converted entirely into heat and the detector reaches thermal equilibrium. Prior to the equilibrium phase, the energy at any given moment is partitioned among multiple excitation modes. Conventional particle detectors work by sensing the higher energy excitation modes, such as ionization and scintillation, which require an average minimum energy of few eV to 10's of eV to produce. For such detectors, a large fraction of the deposited energy remains undetected in the form of heat. Furthermore, the measurements are subject to the fluctuations inherent in the partition of energy across different excitation modes. Secondaries that don't eventually escape the detector, will de-excite or recombine to dissipate their energy in the form of phonons and quasiparticles, which are characterized by energies in the range of meV down to μeV. These can be detected by LTDs at various stages of their final degradation towards thermal equilibrium. Thus LTDs allow for energy resolutions and operational thresholds much lower than detectors that only sense scintillation and ionization. Furthermore, LTDs provide a precise energy measurement owing to the relatively large number of excitation quanta that can be detected. In fact, LTDs designed to measure thermal phonons achieve the highest possible energy resolutions with optimal noise performance.

At thermal equilibrium, energy E deposited in an LTD causes a temperature rise $\Delta T = E/C$ where C is the heat capacity. Thermal equilibrium is characterized by the condition where the average heat flowing to an LTD equals the average heat flowing from the LTD (into a proper heat sink or bath). In this state, the ideal intrinsic energy resolution is determined by the statistical fluctuations in the phonon system. Fluctuations in the total number of phonons in the LTD absorber have variance C/k_B, which yields a minimum resolution of $\Delta E^2 = k_B T^2 C$ to the device energy resolution, where k_B is Boltzmann's constant. Thus, the smaller the heat capacity, the more sensitive the response of the calorimeter and the better the energy resolution. The most relevant feature of this result is that the latter is independent of the energy deposition. The heat capacity itself is the product of the detector volume (V) and the specific heat (c_p). Optimization of LTD response can be achieved by using small detector volumes and materials with low specific heat. Noise contributions from additional sources will increase the variance and are generally parameterized as a multiplicative factor ($\xi \gtrsim 1$) to the variance expression above.

Similarly, the power P from incident particles or radiation can be measured through a temperature rise given by $\Delta T = P/G$, where G is the thermal conductance to a weakly linked bath held at constant temperature. Power fluctuations are limited by G and have a spectral density of $S_P = NEP^2 = 4k_\mathrm{B}T^2G$, where NEP is the noise equivalent power, defined as the power in a 1 Hz bandwidth that gives a response signal with an equal amplitude to the noise. Hence lower conductance yields better sensitivities. To minimize thermal conductance in precise power measurements, weak thermal links can be realized by using thin membranes or by decoupling the electron and phonon systems. However, a compromise must be made. While lower G yields better noise metrics, conversely, larger G is needed to dissipate all incident power (which can be large in the case of CMB detectors) or to have a faster detector response (the characteristic response time being $\tau = C/G$).

LTDs that measure power are sometimes referred to as *bolometers* in literature, as opposed to *calorimeters* that measure energy, generating some confusion. In principle, there is no clear distinction between a calorimeter and a bolometer. The operation mode is generally determined by the ratio of the characteristic time constant and the average time between the arrival of incident particles or quanta [177].Yet another convention is to refer to *non-equilibrium* LTDs as those detectors that measure incident energy or power by counting excitations that have energy $\gg k_B T$. In such detectors, energy resolution is determined by the statistical fluctuations of the energy partition, similar to conventional ionization detectors but with a much lower average excitation energy and hence a larger number of excitation quanta.

Table 36.4: Low temperature dependence on temperature (T) for specific heat, based on different material classes. In the table below Θ_D is the Debye temperature and T_C is the transition temperature of the superconductor.

Heat Capacity	Material
$\left(\frac{T}{\Theta_D}\right)^3$	Dielectric and diamagnetic
T	Conductor
$\exp\left(-\frac{2T_C}{T}\right)$	Superconductor
$\left(\frac{\mu_B B}{k_B T}\right)^2 \mathrm{sech}^2\left(\frac{\mu_B B}{k_B T}\right)$	Paramagnet (in magnetic field **B**)

A variety of possible detector materials and sensor technologies makes LTDs very versatile and highly customizable. Dielectric, superconducting and paramagnetic materials are often used owing to the fact that at very low temperatures, the specific heat decreases strongly as a function of T (see table 36.4). Superconductors offer additional advantages: the abrupt change in resistance when a material transitions from its normal to superconducting state enables highly sensitive measures of temperature changes. Additionally, the existence of a small (less than a meV) but distinct energy gap that is required to break a Cooper pair, provides a means to measure energy deposits by counting the resulting quasiparticles (QP). QP relaxation processes are typically faster than thermal processes making these detectors suitable for high-rate photo-counting. In summary, both the sensitivity and energy resolution of an LTD benefit greatly from low temperature operation.

36.5.2 *Detector Types*

A generalized LTD calorimeter consists of an absorber in thermal contact with a phonon or quasiparticle sensor, and a thermal link to a heat bath at a constant temperature (see figure 36.11). The absorber provides the mass necessary for the interaction of the particle and a fast and com-

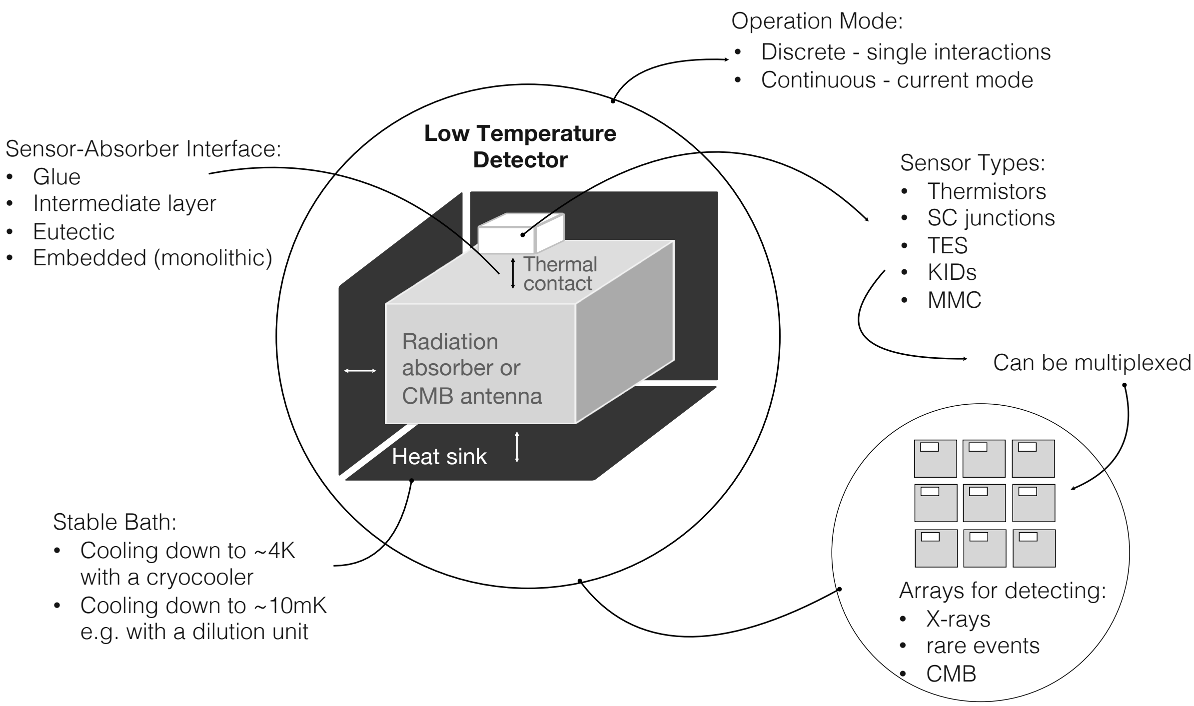

Figure 36.11: A generalized LTD consists of an absorber, a sensor and a thermal link to a stable-temperature bath. Biasing schemes and readout is described in detail in the text for individual sensor types.

plete thermalization of the deposited energy. The sensor accomplishes the task of translating the particle interaction into measurable parameters. It is generally sensitive to equilibrium phonons (e.g. thermistors and MMCs) and thus provides a precise measurement of the temperature. However, non-equilibrium (e.g. STJ's) and mixed (e.g. TES) phonon sensors have been devised and implemented in many applications as well. The goal of the thermal link is to cool the absorber down to its equilibrium temperature after the absorption of a particle. In monolithic detectors the thermometer and absorber are identical, while in composite detectors the thermometer is attached to a separate absorber. This basic design applies to single-event particle detection as well as for continuous radiation measurement devices. In the case of the latter, a suitable absorber whose mass is irrelevant, *e.g.* an antenna at the end of a waveguide, collects the incident power and dissipates it onto a resistive (*e.g.* Au) film, which is put in contact with a sensor capable of detecting tiny temperature changes (e.g. semiconductor thermistors, transition-edge sensors, and kinetic inductance detectors, to name a few).

Superconducting Tunnel Junctions (STJs) and Kinetic Inductance Detectors (KIDs) are examples of non-equilibrium detectors. STJs exploit Josephson tunnelling of particles and QPs between two superconductors. The superconductors act as radiation absorbers, and are separated by a thin insulating layer. When such a junction is DC biased at a voltage just below the gap voltage, the excess quasiparticles generated by the incoming radiation are detected as a tunneling-current proportional to the incoming energy. Statistical fluctuations in the tunnelling process limit the energy resolution which is given by:

$$\sigma_E = \sqrt{\varepsilon(F+G)E_0}, \tag{36.5}$$

where $\varepsilon \sim \Delta$, the band-gap, while $F \sim 0.2$ and $G > 1$ are the Fano factor and tunnelling fluctuation respectively. STJs have been proven to be excellent single photon and UV-VIS spectroscopic detectors with near theoretical energy resolutions, high detection efficiencies and excellent time resolution. In astrophysics they are used as mixers to detect radiation in the 100 GHz to 1 THz range by exploiting the non-linear behaviour of its current versus voltage characteristic curve. STJs share similar design elements to charge qubits, which are being used for the development of quantum computers. Such qubits have also recently been used in dark matter searches as single photon detectors to evade the standard quantum limit in measurement noise [178]. Despite their extremely good energy resolutions, STJs cannot be scaled-up to produce sensors with large observing volumes due to readout complexity and the difficulty in uniformly suppressing the superconducting Josephson current, which is superimposed on the QP current.

KIDs exploit the variation of the kinetic energy T stored in a superconductor by Cooper pairs whose inertia acts as an effective inductance, given by:

$$T = \frac{1}{2}nm^*v^2 = \frac{1}{2}LI^2 \tag{36.6}$$

where n is the number density of Cooper pairs, $m^* = 2m_e$ is the Cooper pair mass and $I = 2nev$ is the Cooper pair current. $L = m_e/2ne$ is defined as Kinetic Inductance and is inversely proportional to the number of Cooper pairs [179]. When a KID is placed in series with a superconducting capacitor, the resonance frequency of the circuit will be temporarily shifted by incident radiation, which converts Cooper pairs to QPs, thus changing the effective inductance. The presence and amount of radiation is observed as a change in amplitude or phase of a tuned sinusoidal signal that is sent through the circuit. In practice the change in L is small, and very high Q microwave resonance circuits are needed to sense this variation (hence the name MKIDs, for Microwave-KIDs). Furthermore, only areas of the film where large currents are flowing will be sensitive to pair breaking, thus making the response of a distributed KID position dependent. To overcome this issue, QP trapping (by coupling two superconductors with different band-gaps) is used for absorbing optical photons and X-rays. To detect lower frequencies (*e.g.* in the 100-1000 GHz range for CMB) a lumped element resonator (LEKID), with little current variation across the device, is used. The device itself, based on a series LC circuit inductively coupled to a microstrip feed line, can act as the absorber as well as the sensing element in a detector system. Macroscopic devices (few mm^2) can be fabricated by shaping the inductor in the form of a meander coupled to an inter-digitated capacitor [180]. The theoretical noise limit of these devices is governed by generation-recombination noise and takes the form:

$$NEP_{QP} = 2\Delta\sqrt{\frac{n_{QP}}{\tau_{QP}}}, \tag{36.7}$$

where n_{QP} and τ_{QP} are the QP number and lifetime respectively. KIDs are easy to fabricate, very sensitive, broad band and easily multiplexable: they can be coupled with a single microstrip that simultaneously reads 1000s of detectors resonating at different frequencies. They provide therefore a promising solution for deploying large arrays of detectors with applications to high-energy physics, astronomy or CMB measurements, although there are still some challenges, especially at frequencies below 100 GHz, related to their worse noise performance when compared to other LTDs, and to the choice of materials with a sufficiently small energy-gap.

Semiconductor thermistors are resistive elements characterised by a strong dependence of the resistance on the temperature. Usually, they consist of small crystals of germanium or silicon with a dopant concentration slightly below the metal-to-insulator transition. However, they can also be realized in the form of amorphous films such as NbSi. At low temperatures, their resistivity (ρ) is governed by variable range hopping (VRH) conduction and is described by the expression $\rho(T) = \rho_0\ \exp\left((T_0/T)^\gamma\right)$, where T_0 and ρ_0 are parameters controlled by the doping level, while γ depends on the compensation level K (ratio of acceptor to donor concentrations). For low values of K it is well approximated by 1/4 while it converges to 1/2 as K increases.

Semiconductor thermistors are high impedance devices (1–100 MΩ) whose performance is usually parameterized in terms of the logarithmic sensitivity $\alpha = \mathrm{d}\log R/\mathrm{d}\log T$, typically in the range of 1–10. Silicon thermistors are fabricated using a multiple ion implantation process in high purity silicon wafers to produce a thin and uniformly doped box-like volume. The best germanium thermistors are fabricated starting from bulk, high-purity germanium crystals doped by means of neutron irradiation in the core of a nuclear reactor, referred to as nuclear transmutation doping (NTD). Individual sensors are then produced by dicing the irradiated samples and finishing them by hand. The great advantage of NTDs is the highly uniform doping level over large volumes which results in a better signal to noise ratio with respect to other doping techniques. The doping level depends on the isotopic composition of the starting material and the irradiation time.

The weak coupling to the heat sink can be provided by the electrical leads used for the read-out. However, nowadays microelectronic planar technologies and silicon micromachining are more commonly preferred, and sensors are suspended on thin silicon nitride membranes or thin silicon beams. Thermistors are read-out in an approximately constant current biasing configuration obtained by inserting large load resistors in the bias circuit, which allows for direct conversion of the thermal signal (ΔT) into a voltage signal (ΔV).

Semiconductor thermistors are very practical to use with some drawbacks. One of these is related to their high impedance which requires a JFET front-end placed as close as possible to the device in order to minimize the signal integration on parasitic electrical capacitances. This can represent a technical challenge, because JFETs must be maintained at significantly higher temperatures ($\gtrsim$100 K). Furthermore, deviations from the exponential behaviour of the conductivity have been observed at low temperatures. They are usually described in terms of a finite thermal coupling between electrons and phonons which results in an intrinsic limit to the signal rise times, which is of the order of hundreds of milliseconds at temperatures below 100 mK. Nevertheless, semiconductor thermistors are an established and robust technology, and arrays of detectors based on these devices have been widely used for neutrinoless double beta decay searches, neutrino mass measurements and X-ray spectroscopy. Energy resolutions lower than 5 eV have been achieved with Sn or HgTe absorbers.

Superconducting Transition Edge Sensors (TESs) exploit the sharp transition between superconducting and normal conducting phases, yielding a high sensitivity to temperature variations. Temperature perturbations, and hence resistance changes, are sensed as modulations in the current through the TES. TESs are operated in a constant voltage biasing configuration where Joule heating, arising from the current flowing in the TES, decreases with a rise in resistance, which then brings the TES back to its nominal operating temperature. This electrothermal feedback (EFT) is achieved by providing a TES with a voltage bias whose power, $P_J = V_{\mathrm{bias}}^2/R(T)$, heats the TES to its nominal operation point, the superconducting transition temperature. Operation in ETF mode improves linearity, speeds up response (to faster than $\tau = C/G$), and in some cases it provides tolerance for T_{C} (critical temperature) variation between multiple TESs in a large array. The low impedance in this configuration makes them well-suited for readout by SQUID (Superconducting QUantum Interference Device) based amplifiers. Logarithmic sensitivities $\alpha = \mathrm{d}\log R/\mathrm{d}\log T$ of the order of several hundreds can be achieved. By using different superconductors, or superconductor-metal pairs patterned in suitable shapes, a wide range of resistances, transition temperatures and time constants are obtainable to meet the requirements of the desired application [181].

Nano-TESs are fabricated by lithographic techniques in the form of long (few μm) and narrow (nm) wires that exhibit extremely small NEPs due to their reduced C and G, enabling single-photon sensing. Superconducting Nanonwire Single-Photon Detectors (SNSPDs) are similarly patterned superconductors or superconducting bilayers maintained at a temperature well below their T_{C}. When a DC current just below the critical current is driven through the nanowire, the absorption of a single photon causes the formation of a hot spot that drives the superconductor to a normal conducting state, resulting in a very fast (tens of picoseconds) current pulse through a shunt resistor. For this reason, nano-TESs and SNSPDs are used as single photon detectors for light dark matter and axion searches in applications where large detecting mass is not critical [182].

Magnetic Metallic Calorimeters (MMC) exploit paramagnetic sensors exposed to a weak magnetic field with a weak thermal link to a heat bath. A temperature rise causes a change in the sensor magnetization, which is sensed by a SQUID magnetometer. A common material is an Au:Er mixture, with the addition of a few hundred ppm of enriched ^{166}Er, which is needed to reduce the unwanted contribution of nuclear magnetic moments of other Er isotopes. The read-out is non-dissipative and avoids the noise sources common to the dissipative devices. The use of a metallic host ensures relatively fast time response, since the typical spin-electron relaxation times are of the order of 0.1 microseconds at ~50 mK [183]. For an optimized MMC, the energy resolution is given by $\Delta_E = \sqrt{2k_B T^2 C}\,(\tau_0/\tau_1)^{1/4}$, where τ_0 (order of micro second) and τ_1 (order of milli second) denote the signal rising and decay times respectively [173]. In order to obtain a fast and efficient energy thermalization, MMC are typically fabricated from gold. The intrinsically large heat capacity of the paramagnet does not spoil the temperature sensitivity and allows the use of relatively large gold absorbers without degrading the device performance. Furthermore, thermal isolation from the heat sink is not generally an issue. Owing to the simple concept of these devices, MMC can be precisely customized and fabricated by employing standard microtechnology. Planar MMC arrays characterized by an excellent energy resolution, large dynamic range and good linearity have been successfully used for the detection of soft X-rays.

Performance and technological constraints limit the maximum size of LTDs. To improve overall experimental sensitivities, a large number of sensors must be deployed, typically at temperatures of a few tens of mK, where cooling power is limited to a few μW. To reduce the readout complexity and the heat load at the colder stages, multiplexing (MUX) techniques are often employed. Multiplexing consists of reading multiple detectors out through a limited number of lines that traverse room temperature to cryogenic temperatures [184]. In frequency-domain multiplexing (FDM), a tuned superconducting LC circuit is placed in series with each sensor, and a frequency comb of AC biases (usually in the MHz range) is sent to a group of sensors in parallel. A synchronous demodulation of the amplified current signal allows the recovery of the resistance variation of each detector. Microwave-multiplexing (μMUX) represents a variation of this concept, based on the usage of rf-SQUIDs, where the frequency comb is in the GHz range. Alternatively, the signal from a single detector can be recovered by readout of one detector at a time (time-domain multiplexing, TDM). KIDs have been gaining popularity owing to the fact that they naturally form resonant circuits, hence multiplexing in the frequency domain is readily achieved by adjusting their capacitance.

36.5.3 *Experimental Applications*

LTDs are sensitive over a wide range of energy, from centimetre wavelength ($\sim$ meV) through the visible spectrum ($\sim$ eV) up to the X-ray domain ($\sim$ keV) and beyond. Several broad categories of LTD applications towards measurements of fundamental physics are described in more detail in the text below and summarized in tables 36.5 and 36.6.

Bolometric detectors are favored as microwave detectors owing to their nearly constant response over frequency, playing an important role in far-infrared astronomy and in the survey of the cosmic background radiation. The high-frequency instrument of the Planck satellite (HFI) used spiderweb bolometers read by NTD-Ge thermistors, but current experiments use mainly TESs or, more recently, KIDs. Depending on the objective of the experiment, antenna coupling or absorber coupling is used. In the former case, the bolometer detects one polarization and one (or a few) modes of the radiation, while absorber-coupled bolometers do not distinguish between polarizations. In order to avoid the absorption or emission from Earth's atmosphere, many (CMB) instruments are operated by observatories located at high altitude, dry places (such as the Atacama desert or Antarctica), balloon-borne platforms, or from space. In Table 36.5, we list a subset of the ongoing or planned CMB experiments (see Section 29 of this Review for the details on present challenges). In the Atacama desert in Chile, CLASS is taking data, POLARBEAR is being upgraded to Simons Array and ACTPol is being upgraded to AdvancedACT-Pol, the next big step being the deployment of the Simons Observatory. At the South Pole, SPTPol has been upgraded to SPT-3G, while BICEP3 and BICEP array will constitute the South Pole Observatory. The most powerful upgrade in terms of both size and sensitivity will be CMB-S4, a consortium of telescopes both at the Pole and in Chile. In the Canary islands, QUIJOTE and GroundBIRD are operating and LSPE/STRIP is in preparation. QUBIC will soon start operations in Argentina and AliCPT is in preparation in Tibet. Regarding balloon projects, SPIDER and EBEX were already launched while LSPE/SWIPE and PIPER will be in the near future. Finally from space, after the success of Planck, LiteBIRD has been selected by the Japan Aerospace Exploration Agency (JAXA) as the next strategic large mission to be launched in the 2020s.

The incoming radiation couples directly to the antenna probes (as in BICEP/Keck) or through micro-machined horn waveguides (AdvancedACT-Pol, CLASS) or lenslets (Simons Array, SPT-3G), depending on the frequency range. All of these experiments have focal planes with hundreds to hundreds of thousands of sensors. To optimize focal plane occupancy, multi-mode or multi-chroic, dual polarization sensitive detectors are used. In the former case, the sensitivity is enhanced by collecting power from a larger number of modes at the expense of angular resolution. In the latter, one single mode of the radiation is focused on a broad band antenna, and on-chip polarization separation and band-pass filters split the signal in different frequency bands directing the power to different absorbers and sensors.

Experimental design is driven by a trade-off between the sensitivity and the complexity of the production processes and readout. On the one front, single-sensor NEP at the level of 10^{-21} W/$\sqrt{\text{Hz}}$ has been achieved in laboratories and research centers. Meanwhile, efforts are in place for the industrialization of the fabrication processes, which is essential for scaling up production for the large number of detectors needed for future experiments.

Massive cryogenic calorimeters have been proposed since the 1980's as particle detectors for the search of rare processes (e.g. dark matter, neutrinoless double beta decay) [185]. Almost simultaneously, the use of arrays of small mass calorimeters was suggested for X-ray astrophysics [186]

Table 36.5: Some selected experiments using LTDs to measure the CMB. These experiments constrain the physics of inflation and the absolute mass, hierarchy, and number of neutrino species. The experiment location determines the part of the sky that is observed. The size of the aperture determines the angular resolution. The table also indicates the type of sensor used, the number of sensors, the frequency range, and the number of frequency bands. Data for planned upgrades or future experiments are provided in parentheses.

Sub-K CMB Experiment	Location	Aperture	Sensor type	# Sensors (planned)	Frequency (planned)	Bands (planned)
Ground-based						
Atacama Cosmology Telescope (2007–)	Chile	6 m	TES	5, 614	30–230 GHz	5
BICEP/Keck (2006–)	South Pole	26/68 cm	TES	2,500	95–270 GHz	6
CLASS (2015–)	Chile	60 cm	TES	3,488	40–220 GHz	4
GroundBIRD (2021-)	Canary Island	30 cm	MKID	322	145–220 GHz	2
POLARBEAR / Simons Array (2012–)	Chile	3.5 m	TES	1,274 (22,764)	150 GHz (90–280 GHz)	1 (4)
South Pole Telescope (2007–)	South Pole	10 m	TES	16,260	90–220 GHz	3
Simons Observatory (2022–)	Chile	6 m/0.5 m	TES	(60,000)	(27–280 GHz)	(6)
CMB-S4 (2024–)	Chile + South Pole	21 telescopes	TES	(500,000)	(20–280 GHz)	(11)
Balloon						
EBEX (2013–)	McMurdo	1.5 m	TES	∼1,000	150–410 GHz	3
PIPER (2016–)	New Mexico	2 m	TES	5,120	200–600 GHz	4
SPIDER (2014–)	McMurdo	30 cm	TES	1,959	90–280 GHz	3
LSPE (2022–)	Longyearbyen	60 cm	TES	(326)	(140–270 GHz)	(3)
Satellite						
Planck HFI (2003-2013)	L2	1.5 m	NTD	52	100-857 GHz	9
LiteBIRD (2028–)	L2	20–40 cm	TES	(4,508)	(34–448 GHz)	(15)

and precision measurements of the neutrino mass [187, 188]. Although essential to understanding the nature of neutrinos, neutrinoless double beta decay (NDBD) has eluded discovery (or definitive exclusion) for over 50 years. Calorimeteric techniques provide the best sensitivities to NDBD. However, before the advent of low temperature calorimeters (LTC), only a few isotopes (^{48}Ca, ^{136}Xe and ^{76}Ge) could be utilized for NDBD studies with the calorimetric approach. This limitation was removed by the advancement of LTC's, and in particular by CUORE, which takes advantage of the naturally high abundance of ^{130}Te in TeO_2 crystals. Additionally, the operation of CUORE at LNGS [189] has demonstrated that the technical challenges of operating ton-sized LTD detectors in a deep, underground location are surmountable. Currently, the most promising future approach is based on the hybrid approach of scintillating LTCs, which unfortunately cannot be used for ^{130}Te. Now, new projects are being proposed based on different scintillating compounds. In particular ^{100}Mo is the choice of CUPID [190] (NTD thermistors glued to $Li_2{}^{100}MoO_4$ crystals), which will use the same infrastracture of CUORE and follows from the successful operation of several demonstrators (CUPID-0 [191] and CUPID-Mo [192]), and AMORE (MMC sensors on $Ca^{100}MoO_4$ or $Li_2{}^{100}MoO_4$ crystals) [193]. With an energy resolution comparable to germanium diodes and a mass of the order of a ton, these experiments aim to probe the inverted hierarchy of neutrino masses. The slow response of these detectors is still a dominant limitation because pile-up may prove to be a serious background. Extremely pure materials, careful assembly procedures, and deep underground laboratories are therefore necessary.

In the 1980's, the calorimetric technique was recognized as a feasible approach to make a direct measurement of the neutrino mass from the end-point of a beta spectrum. Thus, LTCs were proposed as a possible alternative to the standard spectrometric measurements [194]. Calorimetric measurements offer a number of advantages: i) a weak dependence on the final excited states, ii) no source effects (e.g. self-absorption), and iii) lack of back-scattering from the detector. Therefore LTCs provide a faithful reconstruction of the beta spectral shape over a broad energy range below the end-point. However, the difficulty in resolving a small fraction of the spectrum near the end-point is a serious limitation that strongly constrains the source strength and the statistics that need to be accumulated. Such an inconvenience can be mitigated by selecting beta emitters with a small Q value, owing to the fact that the fraction of counts in an interval, δ close to Q, scales as $(\delta/\mathrm{Q})^3$. However, this is generally at the cost of choosing decays with more complex nuclear transitions. In addition, LTCs may be affected by specific systematics (e.g. solid state effects). Ultimately it is recognized that spectrometers and calorimeters have complicated but different systematic effects. It is therefore critical to develop complementary experiments exploiting both techniques.

LTCs were initially proposed as perfect calorimeters to measure the energy spectrum of a low Q beta emitter embedded in an absorber. However, the requirements of excellent energy resolution and a low rate (to avoid pileup) requires a very large number, $\mathrm{O}(10^4-10^6)$, of small mass devices (micro-calorimeters). Early experiments used ^{187}Re, which is a long-lived beta emitter that is naturally abundant in rhenium samples and is characterised by a very low Q value (2.4709 keV [195]). A large number of ^{187}Re based experiments have been developed over the years (MANU [196], MIBETA [197], MARE [198]). Nowadays a different approach is preferred and is based on the measurement of the atomic radiation following electron capture, typically in ^{163}Ho which is also characterized by a very low Q (2.837 keV [199]). Different experiments have been proposed to face the challenge: ECHo in Germany [200] (using MMC sensors), HOLMES in Italy [201] and NUMECS [202] in the US (using TESs). The very large number of microcalorimeters needed to obtain sensitivities comparable to spectrometric measurements is a serious challenge, both for the readout and the thermal heat load. An alternative readout based on the use of KIDs, for their multiplexing capability, has been proposed and is presently under development.

Traditional searches for WIMP-like dark matter aim to measure the scatter of a massive dark matter particle off of a target nucleus. Similar to detectors employed for neutrinoless double beta decay, these searches benefit from large-mass absorbers for the target because the dark matter interaction rate scales directly with the number of nuclei in the target and hence its mass. Among the most successful experiments to date, are those that combine the detection of phonons with another channel such as ionization energy (EDELWEISS and SuperCDMS) or scintilation light (CRESST). This simultaneous, dual measurement takes advantage of the fact that the energy deposited in the absorber is partitioned into these channels differently depending on whether the initial particle interaction produces electron or nuclear recoils (or both). This particle identification allows for the rejection of background from natural sources of radiation, which most commonly manifest themselves as electron recoils in the detector.

In recent years, multi-ton liquid noble detectors have outclassed LTD-based technologies in searches for heavy (>10 GeV/c^2) dark matter owing to their ability to more easily and cheaply

Table 36.6: Selected experiments using low temperature calorimeters. The table shows currently or soon-to-be operating experiments that will search for dark matter or neutrino properties. The dates refer to the start of the program.

Sub-K Experiment	Location	Detection mode	Absorber (Total mass)	Sensor type	# Sensor # Crystal
WIMPs					
CRESST III (2016)	LNGS Italy	Athermal phonon and scint.	$CaWO_4/Al_2O_3$	TES	10
EDELWEISS † (_SubGeV)	LSM Modane France	Thermal phonon and ion.	Ge	NTD Ge	-
SuperCDMS (2023)	SNOLAB Canada	Athermal phonon and ion.	Ge/Si	TES	24
Neutrino mass					
ECHo [200] (2012)	Heidelberg Germany	Thermal phonon	Au:^{163}Ho (0.2μg)	MMC	16
HOLMES [201] (2015)	Milan Italy	Thermal phonon	implanted ^{163}Ho (18 μg)	TES	1000
NUMECS† [202] (2015)	LANL USA	Thermal phonon	implanted ^{163}Ho	TES	4096
$0\nu\beta\beta$ **decay**					
CUORE [189, 203] (2015)	LNGS Italy	Thermal phonon	$^{nat}TeO_2$ (741 kg)	NTD Ge	988
CUPID [190] (2015)	LNGS Italy	Phonon and scint.	$Li_2^{100}MoO_4$ (450 kg)	NTD Ge	1596
AMoRe-I [193] (2018)	Y2L South Korea	Phonon and scint.	$Ca^{100}MoO_4/Li_2{}^{100}MoO_4$ (6 kg)	MMC	13/5

†No payload size quoted for experiments that are primarily in R&D phase.

scale to large target masses. However, the lower thresholds achieved by LTDs continue to make them the technology of choice for low-mass dark matter searches. New advances have enabled these detectors to reach much lower energy thresholds than previously obtained, albeit sometimes at the cost of being able to detect energy in more than one channel as described above. For example, the use of an electric field to generate Neganov-Trofimov-Luke [204, 205] phonons in proportion to the applied voltage, has enabled the detection of single electron hole pairs in Si detectors with thresholds as low as a few eV (SuperCDMS HVeV). This and similar advances in Ge LTDs (EDELWEISS_SubGeV) have enabled sensitive searches for dark photons and dark matter that scatters off electrons [206, 207]. Next generation experiments such as SPICE/HERALD aim to further optimize the intrinsic energy resolution of TES detectors, coupled with a strategic choice of target materials (superfluid He and polar crystals) to enable sensitivites to dark matter with masses below an MeV/c^2 [208]. Current state-of-the-art axion searches use SQUID based quantum amplifies such as Josephson Parametric Amplifiers along with resonant cavities operating below 100 mK to look for a signal above fluctuations in the thermal noise [209]. Future axion experiments are also working to close the sensitivity gap between particle and wave-like dark matter with the help of LTDs. Broad-band axion searches in the THz range are being proposed, which will make use of TES, SNSPDs or KIDs for single photon detection [210]. Finally, LTD-based dark matter detectors are also actively employed to study coherent neutrino scattering, owing to the fact that the hypothesized signal from dark matter-nucleus scattering is nearly identical to that from neutrino-nucleus scattering, with both inducing nuclear recoils in a similar energy range [211, 212].

36.6 Low-radioactivity background techniques

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36.6.1 *Introduction*

The study of rare phenomena in fundamental physics, such as proton decay, neutrinoless double beta decay, dark matter, and MeV-scale neutrino interactions, requires extremely low levels of background radiation. Experiments searching for these rare events record electron recoils or nuclear recoils in the energy scale from a few eV to several MeV. The detector technologies used are multiple from organic and cryogenic liquid scintillators, to bolometers, solide state calorimeters, gaseous detectors, and crystal scintillators. As far as the background contamination is concerned at some extent the application defines the requirements, although the common denominator is that an extreme reduction of all background sources is essential. Leading experiments in rare events search have achieved trace contaminations that generate background events in the region of interest (ROI) as low as order of 50 pBq/kg. As a first and crucial step, a dedicated radio-purity assay of the detector set-up components has to be carried out. Over the last fifty years, special screening and cleaning techniques have been developed to measure and mitigate ultra-low levels of background. In order to characterize the background sources we refer to Heusser [213] and identify the following five main categories:

- environmental radioactivity in the location where the detector is installed;
- radioimpurities in the detector and shielding;
- radon and its progenies;
- cosmic rays and induced radioactivity;
- neutrons from natural fission, (α,n) reactions, and from cosmic-ray muons interactions.

The energy range affected by these background sources is mainly <10 MeV. All materials contain traces of long-lived primordial radioimpurities, such as ^{238}U, ^{232}Th, ^{235}U (^{238}U/^{235}U $\sim$ 138), and ^{40}K (^{40}K/K^{nat} $\sim 1.17\times10^{-4}$). We recall that 1 *ppt* of ^{238}U and ^{232}Th corresponds to 12.36 and 4.06 μBq/kg, respectively; 1 *ppb* of K^{nat} corresponds to 30.25 μBq/kg. In the Earth's crust the abundance of uranium and thorium is of the order of $1-10$ ppm which corresponds to about $10-100$ Bq/kg. Taking into account these contamination levels and the low background requirements, a fundamental background reduction and mitigation is essential to carry out rare phenomena research.

Besides primordial radionuclides other radioactive elements are produced through interactions with matter of secondary cosmic ray particles. Among these so-called cosmogenic radionuclides we recall, in particular, ^{3}H, ^{14}C, ^{7}Be, ^{39}Ar, ^{42}Ar , and, in copper, steel and iron often used as shielding materials, ^{57,60}Co.

A third category of background source in our environment consists of anthropogenic radionuclides. These are artificially produced mainly through nuclear reactions in nuclear power plants, nuclear fuel reprocessing plants, and nuclear weapons testing. Anthropogenic background elements of concern for rare phenomena are ^{85}Kr, ^{137}Cs, ^{241}Am, ^{60}Co, and ^{90}Sr. The concentration of ^{85}Kr ($T_{1/2}$=10.76 y, Q_β=687 keV) in air has been slowly increasing since World War Two with a present activity of order 1 Bq/m^3. As a consequence ^{85}Kr is a crucial background in experiments making use of nitrogen, xenon, and argon from air.

Once detectors components radioactive backgrounds have been assayed and reduced by a careful selection campaign, which can last several years, a further step to push the background level beyond the screening possibilities is needed to reach the required sensitivity. For this purpose special active vetos, purification methods, and offline analyses have been developed. A meticulous background understanding and mitigation is crucial to explain any possible signal excess which may be detected. Background mitigation techniques are based on:

- use of radio-pure materials that absorb ionizing radiation;
- identify radio-pure material for detector construction;
- perform advanced surface and sub-surface cleaning treatment;
- reduce muon flux with underground detector deployment and using active vetos;
- exploit advanced detection and tagging techniques to discriminate signal from background.

In the following we describe radio-assay and background mitigation techniques developed and exploited in the framework of rare phenomena searches in deep underground laboratories.

36.6.2 *Radio-purity assay*

The radio-purity assay of detector components is a basic prerequisite to be carried out in low counting experiments. Several techniques are exploited for radio-purity assay. They are complementary to characterise the radio-purity of materials for shielding or core detector components. Next generation experiments radioassay campaign requires a considerable effort and organization for several years [214–216].

Gamma spectroscopy (GS) via high purity germanium (HPGe) detectors is a powerful and crucial technique [213]. It is nondestructive and thanks to the energy resolution allows to distinguish various radionuclides elements. Radiation from ^{238}U and ^{232}Th comes with all decay products in the radioactive chains. However, if secular equilibrium is broken, this crucial information can be addressed by separating different gamma-ray lines characterizing elements in the decay chains. In the ^{238}U chain one can have three sub-chains out of equilibrium. The first sub-chain can be assessed through ^{234}Th direct progeny of ^{238}U. The second sub-chain, which originates from ^{226}Ra, can be probed by ^{214}Pb and ^{214}Bi. A third sub-chain, which starts from ^{210}Pb, cannot be efficiently probed by GS, yet is of crucial importance and alternative methods must be used. In the ^{232}Th chain again one can probe two sub-chains which can be out of secular equilibrium: the first one through ^{228}Ac from ^{228}Ra; the second from ^{228}Th can be measured through ^{212}Pb, ^{212}Bi and ^{208}Tl. The technology for HPGe operated in deep underground counting facilities [217, 218] or in shallow laboratories with an efficient active veto shielding [219] has been boosted to sensitivities of the order of 10-100 μBq/kg by carefully selecting detector components, electronics and sample handling systems. The HPGe screening method requires order of ≥ 100 g of material, and weeks of acquisition to produce a reliable measurement.

A second crucial technique is based on inductively coupled plasma mass spectrometry (ICP-MS) [220]. This technique can probe primordial parents activity at the level of 1 μBq/kg. It is a destructive method and often needs special sample preparation on a small quantity of material. The ICP-MS does not measure the radioactive decay of isotopes but determines their concentration. At present, it is the most sensitive and rapid screening technique which allows to select materials at sub-ppt level of impurities. The drawback is that ICP-MS cannot assess whether the uranium and thorium chains are out of equilibrium and to reach ultra-high sensitivities one needs to carefully prepare and handle the samples in a cleanroom environment. ICP-MS screening must be coupled with other methods to properly assess the radio-purity of materials in the context of rare events searches. The Glow Discharge Mass Spectroscopy (GDMS) is a trace element analysis technique somehow alternative to ICP-MS. An advantage of GDMS is the possibility to determine the bulk composition of the sample, assuming homogeneity. Sensitivities of the order of 10 ppt can be achieved.

A third screening technique is based on neutron activation analysis (NAA) [221]. A sample exposed to a neutrons flux can be activated to form radioactive isotopes which can be detected using HPGe detectors or ICP-MS. Considering the difficulties to irradiate samples, this method is not often used. NAA can probe sensitivities at the level of 0.01 μBq/kg. This method is not destructive and the irradiated sample can be used if the activated products are not long-lived.

In case out of secular equilibrium conditions are measured for uranium and thorium from GS screening, a rigorous assessment cannot avoid radon emanation measurements. This matter is discussed in Section 36.6.3.

Complementarity between radio-purity assay techniques is a crucial parameter to design detectors for rare phenomena searches. As it has been pointed out above, requirements can be more stringent than the best sensitivity which can be obtained with the current radioassay techniques. In these cases, a number of prototype detectors have been built and operated to prove the feasibility to reach ultra-low backgrounds.

36.6.3 *Radon and its progeny*

Radon is considered to be rare in nature because most of its isotopes are short-lived. However, ^{222}Rn ($T_{1/2}$=3.82 d) is of particular concern in our context. ^{222}Rn is produced by ^{226}Ra and is a radioactive noble gas which can move within active detector components. ^{222}Rn daughters are heavy metals which can deposit on surfaces. If diffusive ^{222}Rn is supported by ^{226}Ra this can deposit on surfaces the long-lived ^{210}Pb, which is a major concern for low counting experiments. In addition, due to $\sim$100 keV nuclear recoil energies from alpha decays in the ^{226}Ra sub-chain, eventually ^{210}Pb can be implanted into a sub-surface layer of a material exposed to radon. This sub-surface contamination can remain even after surface cleaning. Surface contamination of ^{210}Pb is a serious background for direct dark matter experiments through alpha decay of ^{210}Po, which can generate neutrons by (α,n) reactions. Low energy beta/gamma emissions from ^{210}Pb are also a concern. Therefore, radon-free cleanrooms are essential for the assembly of the detector components. Effective radon abatement systems are available for this purpose.

In assembling and commissioning rare events experiments, special care must be dedicated to the estimate of radon emanation of the materials and continuous radon monitoring. For this purpose different methods for radon assay have been developed and exploited since the beginning of solar neutrino observations. ^{222}Rn atoms are collected inside an exhalation chamber for several half-lives before adsorption and counting. Detection limits of the order of 100 μBq (about 50 ^{222}Rn atoms) can be obtained with $\sim$50 l stainless steel electro-polished chambers [222]. This limit can be pushed down to 30 μBq for 1-liter scale chamber. Emanation of large vessels (cryostats, storage tanks, purification columns) can be determined by collecting exhaled radon into transportable charcoal traps [223]. The same method can be used for liquid samples. In this case instead of evacuating the exhalation chamber into a charcoal trap, He is flushed through a sparger tube for about 10 times the volume of the liquid used. Sensitivities of the order of 10 μBq/kg have been reached.

Nitrogen or synthetic air is often used in rare events experiments for purging, stripping, and assembling the experimental apparatus. These gases might contain radon. In gases ^{222}Rn can also be detected using electrostatic collection of ^{218}Po and ^{214}Po [224, 225]. Sensitivities of the order of mBq/m^3 can be obtained. In Borexino three grades of nitrogen purity were used: regular purity, high purity, and low argon and krypton purity. The regular purity is obtained from boil-off gas and has radon, measured with the method reported above, at the level of $< 100\mu$Bq/m^3. For stripping the purified liquid scintillator a higher purity is needed. To remove radon from regular purity nitrogen a dedicated absorber plant has been built. This system can reduce radon by a factor of 100. Finally, we mention that not only radon is found in nitrogen. For specific applications the long-lived ^{39}Ar and ^{85}Kr in nitrogen are an important source of background.

36.6.4 *Surface backgrounds*

Surface contamination of long-lived ^{222}Rn daughters can be challenging in low-counting experiments. Considering required sensitivities of the next generation experiments, this source of background has to be properly quantified and mitigated. Therefore, exposure to ^{222}Rn should be monitored and limited to reduce build-up of ^{210}Pb on surfaces. In addition, ^{222}Rn exposure could also produce sub-surface contamination as discussed in Section 36.6.3. For one cannot avoid radon contamination in many circumstances during production of detectors components, it is crucial to quantify the effectiveness of cleaning aiming at removing surface contamination of ^{210}Pb, ^{210}Bi, and ^{210}Po. A simple cleaning procedure, which implies degreasing, wiping, and rinsing the material surfaces is not effective in removing these surface contaminants. Studies of cleaning procedures have been carried out exposing stainless steel, copper and other materials to a strong radon source. Etching and electropolishing with subsequential passivation and rinsing have been investigated in great details. Several recipes for etching and electropolishing have been proposed [226]. Electropolishing has been shown to be very effective in reducing ^{210}Pb, ^{210}Bi, and ^{210}Po from both copper and stainless steel by a factor greater than 100. Etching, which is easier to perform than electropolishing, followed by passivation and rinsing with deionized water is effective in reducing ^{210}Pb and ^{210}Bi by a factor between 50 and 100. However, it is less effective for ^{210}Po, which in copper is very poorly reduced. Removing ^{210}Po from surfaces is crucial, therefore, naturally ^{210}Po contaminated copper and stainless steel surfaces have been deeply investigated with a high sensitivity ($1\,\mathrm{mBq/m^2}$) alpha spectrometer [227]. After multi-etching steps (≥ 3), followed by a passivation, a reduction of order 100 has been obtained. On the contrary, static etching (single step) is poorly effective. Electropolishing, or multi-etching are recommended in case copper is in direct contact with the active core of the detector and ultra-high radio-purity is essential or when copper electroforming cannot be used. Electroplating of a thin layer of high radio-pure copper onto the surface of less radio-pure copper has also been investigate to mitigate surface background [227]. This technique is shown to be near-perfect in reducing surface activity of ^{210}Po when electroformed copper is used [227].

Besides copper and steel other materials often used, such as polyethylene and teflon, have been investigated to understand how to reduce radon plate-out contaminations [228].

As far as surface contamination is concerned particulate fallout in cleanrooms environment could be of concern. In general, chemical composition of dust reflects local composition of soil and dust. This is not necessarily true in cleanroom spaces, where the composition of dust depends on ongoing activities and handled materials [229]. The rate of fallout is an important information in the framework of rare events experiments, where assembling is performed in cleanrooms. The ^{210}Pb contamination, inferred from stable lead measured by ICP-MS, due to dust fallout has been investigated [229]. This contamination has a different origin with respect to ^{210}Pb from radon progeny implantation. Ultimately, one can conclude that radon exposure is more crucial than dust fallout. Therefore, the best practice for rare events experiments to face surface background contamination is to perform cleaning and assembling in a radon-free cleanroom environment.

36.6.5 *Mitigation of backgrounds and active background discrimination*

In this Section we discuss a selection of different background mitigation techniques used in experiments to search for rare events in deep underground laboratories. This includes both the avoidance or reduction of specific radioactive contamination, as well as active background suppression techniques based on specific event features and topologies.

- *Mitigation of ^{222}Rn daughters deposition.* In dark matter direct search radiogenic (α,n) reactions due to radioactive decays are of great concern. The emitted neutron can mimic a nuclear recoil induced by a dark matter particle interaction. In the DarkSide-50 and LUX-

ZEPLIN (LZ) experiments to mitigate this background, cleaning of parts and assembling of the dual-phase Time Projection Chamber have been carried out in a radon-free cleanroom with ^{222}Rn activity of the order of $\lesssim 50\,\text{mBq/m}^3$.

- *Underground argon.* Liquid argon is an excellent scintillator to search for dark matter interactions due to the high electron-recoils rejection power through pulse shape discrimination. Events from $\beta - \gamma$ background can be rejected at the level of 10^7 or better with respect to nuclear-recoils. Moreover, liquid argon is used as an active shield in GERDA and the upcoming LEGEND experiment searching for neutrinoless double beta decay. However, a major drawback for dark matter search is due to the fact that atmospheric argon contains about 1 Bq/kg of cosmogenic ^{39}Ar ($T_{1/2}$=269 y, Q_β=565 keV) [230]. For neutrinoless double beta decay search with GERDA and LEGEND, ^{42}Ar ($T_{1/2}$=32.9 y, Q_β=599 keV) with its short lived progeny ^{42}K ($T_{1/2}$=12 h, Q_β=3525 keV) is a major source of background. This limits significantly the dark matter and neutrinoless double beta decay sensitivity search. Therefore, a source of argon with reduced ^{39}Ar and ^{42}Ar is crucial. Centrifugation or differential thermal diffusion are established methods to separate $^{39/42}$Ar and ^{40}Ar. However, this is an expensive method for a large fiducial mass. Argon from underground natural gas reservoirs is shown to contain low ^{39}Ar [231], and it is expected that ^{42}Ar is similar or even better reduced. Therefore, the use of underground argon mitigates the $^{39/42}$Ar backgrounds. DarkSide-50, with a mass of 150 kg of underground argon, has shown that this source of argon contains ^{39}Ar at a level reduced by a factor of $(1.4 \pm 0.3) \times 10^3$ with respect to atmospheric argon.
- *Electro-formed copper.* High radio-purity copper is often used as shielding and as core detectors components. The radioimpurities in the copper can be a dominant source of external background. Copper electro-forming is a technique used to reduce this background component in rare events experiments. Copper electro-forming is a well known process to obtain ultra-high radio-purity copper. This technique has been used in the framework of the Majorana Demonstrator experiment to search for neutrinoless double beta decay and in ANAIS to search for dark matter annual modulation. Sub-ppt levels in uranium and thorium have been achieved with electro-formed copper.
- *Background suppression using topological event information.* In addition to rigorous selection of high-purity target and shielding materials from external radiation, additional active suppression techniques must usually be employed in low background experiments to achieve the appropriate experimental sensitivities. While signal and background events may be indistinguishable if only their energy deposition is measured, their event features may differ significantly in time and space. Liquid scintillators use the characteristic photon emission time distributions to distinguish between electron- and alpha-like signals [232] and nuclear recoils [233], respectively. High-purity germanium detectors use the time evolution of the induced charges to separate point-like signal candidates for neutrinoless double-beta decay events from background signals induced, for example, by gamma interactions with multiple interactions within a crystal, or from β or α events on the n+ or p+ electrodes [234]. The operation of bare high-purity germanium detectors in an instrumented liquid argon shield enabled the GERDA experiment to identify backgrounds with signal-like event topology within the HPGe detectors, but with random energy deposition in the surrounding liquid argon. These synergistic background suppression techniques enabled for a first time ever a quasi background-free search for neutrinoless double beta decays with GERDA.

  The NEXT experiment for neutrinoless double beta decay in ^{136}Xe exploits differences in the spatial ionization patterns of double beta decay and single electron events to reject the background [235]. The former is characterized by two Bragg peaks at opposite ends of the

tracks, the latter on the contrary displays only one peak. The combination of topology information and good energy resolution offer a powerful tool for background rejection.
In addition, the 3D location of detected events in a multivariate fit, which accounts for spacial surface and bulk distributions of signal and background together with other properties, such as pulse shape and topological features, is a powerful tool for background mitigation.

- *Signal detection in rare events searches.* In direct dark matter experiments electron recoil events have to be mitigated with respect to nuclear recoil events. In semiconductor bolometers, operating at a few tens of mK under a bias electric field and used as calorimeters, drifting charges produce a large phonon signal proportional to the ionization, which allows to discriminate electron recoils by the combination of charge and phonon signals [236]. In scintillating bolometers the phonon and light signals are used for the same purpose [237]. Cryogenic scintillators, such as xenon and argon, in time projection chambers offer a strong electron recoils background mitigation through the detection of a primary scintillation signal in liquid and a secondary signal in gas from the drift and extraction of ionization electrons. This background mitigation technique is also being used for neutrinoless double beta decay with ^{136}Xe. The accurate fiducialization and good rejection of multiple-scattering events allow dark matter optimized experiments to attempt a search for this very rare phenomenon.
- *Neutron tagging in dark matter searches.* Present and next generation experiments need large neutron tagging detectors. In DarkSide-50 a dedicated active veto has been developed to both suppress and measure *in situ* the rate of neutron-induced background events [238]. The detector consists of a boron-loaded liquid scintillator, which serves both as shielding against γ-rays and as a tag for neutrons. Neutrons are thermalised and captured on ^{10}B. Experimental data has shown a neutron rejection power greater than 99.1% with 5% concentration of TMB in 30 tonnes pseudocumene-based liquid scintillator. The LZ direct dark matter detector with a central TPC of 7 tonnes of liquid xenon makes use of an outer Gd-loaded liquid scintillator neutron tagging veto, which works similarly to the DarkSide-50 veto, replacing boron with gadolinium. The 22 tonnes liquid scintillator is based on linear alkyl benzene (LAB) as solvent. This detector has been designed to operate with a neutron tagging efficiency greater than 95%. The nuclear-recoil background is reduced by a factor of 10. The XENONnT detector makes use of a cylindrical stainless steel tank filled with Gd-loaded water, which surrounds the cryostat with a TPC of 5.9 tonnes of active liquid xenon. The Gd concentration in water is 0.2% in mass. Neutrons leaving the TPC volume will be moderated and captured by the Gd with a probability of 91%. The gamma-rays emitted after the capture are detected from Cherenkov photons, providing a neutron tagging.
- *Mitigation of cosmogenic background.* In recent years the required sensitivity to search for dark matter and neutrinoless double beta decay asks for a strong reduction of cosmogenic background. We have emphasized that muons can produce neutrons that can enter the active volume of the detector from the surrounding rock or from external detector components. The yield of these so-called *cosmogenic neutrons* depend on the muon energies and the material properties of the medium the muon passes through. In addition, muons can produce by spallation radioisotopes inside the detector active volume. Cosmogenic backgrounds are a function of depth and experimental design, and can limit the sensitivity to search for rare events. Most of these radioisotopes are short-lived and their effect can be easily removed by an active veto based on the time correlation with a crossing muon. However, a number of cosmogenic radioisotopes are long-lived and they require an important consideration. Mitigation of these cosmogenic backgrounds produced in-situ deep underground are a major challenge for upcoming and future experiments. Optimizing the detector design and analysis strategies at a given

depth equals an effective muon flux reduction. In particular, we mention two discrimination techniques for muon-induced isotopes: 1) ^{11}C tagging by a three-fold coincidence between the crossing muon, the capture of the ejected neutron from ^{12}C, and the ^{11}C decay [239]; 2) similar delayed coincidence tagging can be exploited to mitigate the background due to ^{77}Ge and its metastable state ^{77m}Ge, which have been identified as dominant cosmogenic background in the search for neutrinoless double beta decay of ^{76}Ge.

- *Purification.* A number of high efficiency specific purification methods have been developed for different detectors in order to remove long-lived radio-isotopes, ^{39}Ar, ^{85}Kr, and ^{210}Pb progeny. For organic liquid scintillators, distillation and water extraction have been shown to be very effective to reach radiopurity levels of the order of $10^{-5}\mu$Bq/kg or better in uranium and thorium, and $10^{-3}\mu$Bq/kg in ^{210}Pb [240]. Distillation has been used to reduce ^{85}Kr in xenon by a factor of 10^3 [241]. Cryogenic distillation will be used to reduce the isotopic abundance of ^{39}Ar in argon extracted from underground with a 350 m column in the ARIA project [242]. For semiconductors [243] and scintillating crystals [244] zone-refining has been exploited to remove impurities at the cost of a small fraction of material kept after the purification.
- *Direct isotope tagging.* In neutrinoless double beta decay in order to explore half-lives greater than 10^{28} y one needs an almost background-free detector. A robust method to reject backgrounds from radioactive decays would be the identification of the daughter atom of the double beta decaying nucleus: for example, for ^{136}Xe, the ^{136}Ba^{2+}. Important step forwards to establish a valid and promising method for this tagging have been recently made [245,246].

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