Physics with calorimeters

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Abstract. Calorimeters played an essential role in the discoveries of new physics, for example neutral currents (Gargamelle), quark and gluon jets (SPEAR, UA2, UA1 and PETRA), W and Z bosons (UA1, UA2), top quark (CDF, D0) and neutrino oscillations (SUPER-KAMIOKANDE, SNO). A large variety of different calorimeters have been developed covering an energy range between several and $10^{20}$ eV. This article tries to demonstrate on a few selected examples, such as the early jet searches in hadron-hadron collisions, direct dark matter searches, neutrino-less double beta decay and direct neutrino mass measurements, how the development of these devices has allowed to explore new frontiers in physics.

1. Historical remarks

The American Astronomer Samuel Pierpot Langley has 1878 invented the bolometer in order to measure the infrared radiation of celestial objects [1]. His bolometer consisted of two platinum strips one of which was thermally isolated while the other was exposed to radiation. The exposed strip could be heated due to the absorption of electromagnetic radiation and thus would change its resistance. The two strips were connected to two branches of a Wheatstone bridge which allowed to measure the resistance change of the exposed strip. Therefor a bolometer behaves like a true calorimeter which measures the absorbed energy in form of heat. The name bolometer stems from the ancient Greec word $\beta\omega\lambda\upsilon\sigma\zeta$ meaning ray and stands for ray-meter. With his bolometer Langley was the first to measure the energy flow in form of electromagnetic radiation from the sun. On Mount Whitney he determined the solar constant to $2.54 \text{ cal/min cm}^2 = 1.77 \text{ kW/m}^2$, which was close to the more accurate average value of $1.37 \text{ kW/m}^2$ obtained today. Modern versions of Langley’s bolometer are still most frequently used in astronomy to measure the energy flow of electromagnetic radiation from celestial objects and more recently also in cosmic microwave background radiation (CMB) experiments.

After the discovery of radioactivity by A.H.Becquerel in 1896, P.Curie and A.Laborde made a first attempt to measure the energy release in radioactive decays with a calorimeter [2]. At that time, a sharp difference between nuclei decaying into $\alpha$ particles which were emitted with the same energy and those decaying into electrons with energies distributed over a wide range was noticed. The beta decay seemed to violate the energy momentum conservation and turned out to be a big puzzle to the physics community. Micro-calorimeters were developed by C.D.Ellis and A.Wooster in 1927 [3] and independently by W.Orthmann and L.Meitner in 1930 [4] to determine the average energy of the electron in the beta decay of $^{210}\text{Bi}$. With the differential calorimeter of W.Orthmann which is shown in Fig.1. and which is based on the same principle as Langley’s bolometer heat transfers of the order of $\mu$W could be measured. He and L.Meitner [5] were able to determine the mean energy of the continuous $\beta$-spectrum in the $^{210}\text{Bi}$ decay.
to $E=0.33\text{MeV}$ with an accuracy of 6%. These findings strongly supported the notion of a continuous $\beta$-spectrum which was leading to W. Pauli's neutrino hypothesis in 1930.

![Figure 1.](image)

Figure 1. The calorimeter of W. Orthmann is shown.

In order to measure the spectrum of high energy cosmic ray particles N.L. Grigorov and collaborators introduced in 1954 a new calorimeter concept [6], the so-called sampling calorimeter. For this calorimeter they used ionization chambers (arrays of proportional counters) and scintillation counters sandwiched between thick iron absorber sheets. The visible energy of the interacting particles in the calorimeter was determined from the number of secondary particles in the shower and their energy loss in the ionization and scintillation counters. Because of the invisible energy loss in the absorber plates and in the detector sheets, sampling calorimeters need to be calibrated with particles of known energy, which turned out to be a problem in these early times due to the lack of high energy particle accelerators. Nevertheless, in 1957 N.L. Grigorov and his collaborators [7] constructed a sampling calorimeter in the Pamir mountains, at an altitude of 3860 m above sea level (Fig.2). Their calorimeter also employed $10m^2$ of emulsion sheets, which they placed between 3 lead sheets to study details of the primary interaction. In order to identify corresponding events in the emulsions and the calorimeter, two layers of emulsion sheets on top of each other were used: one fixed in space, the other moved by a certain amount in a certain time interval with respect to the other. The two emulsion film images were then matched and thus the time of the shower passage determined.

The development of calorimeters for high energy physics started in the late 60'ies. The discovery of the substructure of hadrons by the SLAC experiment in 1969 [8], the description of the results in a parton model of hadrons by R. Feynman and the introduction of the color octet of gluons by H. Fritsch, M. Gell-Mann, and H. Leutwyler were leading to a theory of strong interactions the so-called Quantum Chromo Dynamics (QCD). According to QCD partons would scatter via gluon exchange in central hadron-hadron collisions leading to two large $p_T$ and two spectator jets (Fig.3).

These developments and the discovery of jet-like structure in $e^+ - e^-$ collisions at SLAC in 1975 [9] stimulated the community to introduce calorimeters with the advantage of having a better
Figure 2. The sampling calorimeter of Babayan, Grigorov, Shestoperov and Sobikyakov is shown.

Figure 3. Central proton proton scattering process as described by QCD.

energy resolution than magnetic spectrometers and the capability of measuring the energy of charged as well as neutral particles. The discovery of neutral currents with GARGAMELLE at CERN in 1973 [10] also influenced the use of multi-ton calorimeters in neutrino experiments. A topical review of the development of calorimeters in astro and particle physics can be found in
In the following chapters some examples of calorimeter developments for new physics in the past and the presence are described: Early jet physics, dark matter searches, neutrinoless double beta decay and direct neutrino mass measurements.

2. The early days of jet physics
In the 1970’s two high energy fixed target proton synchrotrons (the 400GeV synchrotron at Fermilab in 1972 and the 450 GeV SPS at CERN in 1976) as well as one proton-proton collider (the ISR at CERN in 1971) and two $\text{e}^+\text{e}^-$ collider ( SPEAR at SLAC in 1972 and DORIS at DESY in 1974) started operation. These new facilities offered a unique playground for versatile research programs among which was the search for jets in hadron-hadron collisions. One of the questions raised was [12]: Do the cross sections for hard hadron-hadron scattering follow a scaling law

$$\frac{d\sigma}{dx_c} = \frac{1}{s} F(\theta_1^*, \theta_2^*, x_c)$$  \hspace{1cm} (1)

with $x_c = \frac{E_{\text{cal}}}{E_{\text{inc}}}$ and $\theta_1^*, \theta_2^*$ the minimum and maximum c.m.s. polar angles of the calorimeter? $E_{\text{cal}}$ is the energy measured in the calorimeter and $E_{\text{inc}}$ is the energy of the incident beam particle. This can be tested when keeping the c.m.s. angle of the calorimeter fixed while varying the incident beam energy. Such an experiment would need a calorimeter with the following features: segmentation in the polar angle $\theta$ and the azimuthal angle $\phi$, large coverage in the central rapidity region, full coverage in $\phi$ in order to provide an unbiased jet trigger as well as a good jet energy resolution. The calorimeter should be movable on rails in order to change the distance to the target when changing the incident beam energy. The NA5 collaboration was among the first who constructed such a segmented calorimeter as shown in Fig.4.

Figure 4. The segmented NA5 calorimeter is shown.
Their calorimeter covers c.m.s. angles between $\theta_1^* = 45^0$ and $\theta_2^* = 135^0$. It consists of an electromagnetic part (scintillator/lead) and a hadronic part (scintillator/iron) and has 24 segments in $\phi$ and 10 in $\theta$. A very compact segmentation was obtained by introducing a novel wavelength shifter (WLS) readout system, which is shown in Fig.5.

![Figure 5.](image)

**Figure 5.** The novel wavelength shifter readout of the NA5 calorimeter is shown. See text for explanation.

By using a different WLS color (yellow) in the electromagnetic part of the NA5 calorimeter[13] than in the hadronic part (BBQ green), it was possible to guide the light of both colors in one rod to the two photomultipliers which, by using appropriate filters, were sensitive to either yellow or green light. This way the energy deposited in the electromagnetic and in the hadronic part of the calorimeter could be measured separately. The NA5 calorimeter was the first tower-structured scintillator sampling calorimeter in operation at CERN. After its first use in 1978 it has been employed in several followup experiments, like NA24, NA35, NA49, and after 30 years is still in operation in the North area of CERN. The central hole of the calorimeter was covered by a downstream calorimeter in order to be able to measure the total energy in the event. The construction parameters and the performance of both calorimeters are described in [14]. The $\phi$ segmentation enabled to set up and study calorimeter triggers with different $\phi$ acceptances like $\pi/2$, $\pi$ and $2\pi$ and compare the results with other experiments with limited calorimeter acceptance, like E260 at Fermilab [15]. The scaling behavior was studied by parameterising the cross section obtained with the azimuthal $\pi/2$ trigger by $\frac{d\sigma}{dp_T^2} \sim p_T^{-n} f(x_T)$ with $x_T = \frac{2p_T}{\sqrt{s}}$ and with the $2\pi$ trigger by $\frac{d\sigma}{d\Sigma |p_T|} \sim (\Sigma |p_T|)^{-n} f(x_T)$ with $x_T = \frac{\Sigma |p_T|}{\sqrt{s}}$. The scaling parameter $n$ was derived from the cross sections $\sigma_1$ and $\sigma_2$ measured at 150 GeV/c and 300 GeV/c respectively for a fixed $x_T$ and a fixed c.m.s. solid angle acceptance of the calorimeter by the relation $n = \ln \frac{\sigma_1}{\sigma_2} / \ln \frac{\sqrt{s}}{\sqrt{s}_1}$. The results are shown in Fig.6. Constituent scattering models in their simplest form predict a constant $n=4$ or 3 respectively. QCD models which include scale breaking effects, predict $n$ to rise by 1 over the entire $x_T$ region. The scaling parameters for the various triggers turn out to increase with $x_T$ and are much larger than predicted by QCD and by the dimensional
scaling of eq.(1). In looking for a jet-like event structure a planarity analysis of the NA5 data taken with the azimuthal $2\pi$ trigger was performed. The planarity $P$ was calculated from a principal axis analysis of the transverse momentum distribution for each event as measured by the calorimeter. Particle momenta were derived from the energy clusters observed in the calorimeter. The planarity was defined as $P=(a-b)/(a+b)$ with $a$ ($b$) being the sum of the squares of the projected transverse momenta to the maximum (minimum) principal $p_T$ axis. For an isotropic event structure one would expect $P=0$ and for pencil like jets $P=1$. The planarity distributions turned out to peak around $P=0.5$ and show practically no change when increasing the $p_T$ trigger threshold. Also in p-p collisions at higher energies ($\sqrt{s} = 63\text{GeV}$) at the ISR, the R401 (Split Field Magnet) [16] and the R807 (Axial Field Spectrometer) [21] experiments show no dominant jet structure and no change of the mean circularity of 0.5 (circularity=1-planarity) with increasing trigger threshold. A detailed description of the NA5 results can be found in [17].

Figure 6. The scaling behavior of the cross sections measured with different calorimeter triggers is shown. For explanations see text.

Considering the expectations put into finding jets in hadron-hadron collisions these results turned out to be rather disappointing. However, as it became clear later the energies available at the SPS ($\sqrt{s} = 24\text{GeV}$) and the ISR ($\sqrt{s} = 63\text{GeV}$) were not sufficient to identify jets unambiguously. Nevertheless, from the experimental techniques which were developed at low energies the next generation experiments at higher energies, like UA1 and UA2 at CERN and CDF at Fermilab, could profit a lot. In fact the central calorimeter of UA2 [18] is a direct transformation of the NA5 calorimeter from the laboratory to the c.m.s. system (Fig.7).

In 1982 the first unambiguous jets were seen by the UA2 [19] and the UA1 [20] experiments at the CERN $\bar{p}p$ collider ($\sqrt{s} = 540\text{GeV}$). In Fig.8 the differential cross section as a function of transverse energy $\Sigma E_T$ as measured by the UA2 experiment is shown. It demonstrates a clear slope change at a transverse energy of around 60 GeV, where the dominant constituent scattering processes set in.

The measured jet angular distributions turned out to be consistent with the QCD predicted t-channel vector boson exchange and ruled out models with scalar gluons. In Fig.9 the results of
UA2 and UA1 at the $\bar{p}p$ collider are compared to the results of R807 [21] at the ISR. Also shown is the LEGO-plot of a typical 2 jet event as seen by the calorimeter. It demonstrates again that constituent scattering processes were born out clearly only at very high energies. This turned out to be the case not only for jets but also for direct photons. Fortunately one could learn a
lot about jets in the meantime such that one is ready to deal with them at LHC energies were they are produced abundantly.

**Figure 9.** The differential cross sections as a function of transverse momentum $p_T$ as measured by the UA2 and UA1 experiments at the $\bar{p}p$ collider and the R807 experiment at the ISR are shown. Also shown is the LEGO-plot of a typical 2 jet event as detected by the calorimeter.

### 3. Physics with cryogenic calorimeters

In the following chapters some examples are given where novel calorimeter techniques so-called cryogenic calorimeters are employed for the quest for the dark matter in the universe and the neutrino-less double beta decay as well as for the direct measurement of the neutrino mass. Although the basic idea of these techniques is going back to F.Simon [22] in 1935, its further development was recently very much stimulated by these searches. F.Simon claimed when cooling a small size calorimeter (1cm$^3$) down to liquid helium temperatures one could measure heat transfers of nW which is a gain of a factor 1000 in sensitivity compared to the W.Orthmann calorimeter. He argued that at low temperatures the heat capacity C of a micro-calorimeter is low and a small energy loss $\Delta E$ of a particle interacting in the calorimeter can lead to an appreciable temperature increase $\Delta T=\Delta E/C$. A typical cryogenic calorimeter is shown in Fig.10. It consists of an absorber with heat capacity C, a thermometer and a thermal link with heat conductance $g$ to a heat reservoir with a constant bath temperature $T_B$. Particles interacting in the absorber cause a change in the resistance of the thermometer which is measured by a voltage drop V when passing a current I through the thermometer. Cryogenic calorimeters can be made from many different materials including superconductors, a feature which turns out to be very useful for different applications. They can be used as target and detectors at the same time. Most calorimeters used in high energy physics measure the energy loss of a particle in form of ionization or scintillation light. In contrast, cryogenic calorimeters are able to measure the total deposited energy in form of ionization and heat (phonons). This feature makes them very effective in detecting very small energy deposits with high resolution. There are several kinds of cryogenic detectors in use or under development. A topical review can be found in [23].
The most frequently employed calorimeters in the above mentioned searches are those which use transition edge sensors (TES) or semiconducting thermistors as thermometers. A TES sensor consists of a very thin super-conducting film or strip which is operating at a temperature in the transition between the super-conducting and the normal phase, where the resistance changes between zero and its normal value. The very strong dependence of the resistance change with temperature makes the TES calorimeter very sensitive to small input energies. A thermistor is a heavily doped semiconductor slightly below the metal insulator transition. Its conductivity at low temperatures can be described by a phonon assisted electron hopping mechanism between impurity sites. With these micro-calorimeters excellent energy resolutions of about 2 eV at 6 keV x-ray energies have been achieved. In Fig.11 a x-ray spectrum obtained with a state of the art Si(Li) solid state device (dashed line) and a cryogenic micro-calorimeter (solid line) using a Bi absorber and a TES sensor (Al-Ag) are compared [24].

3.1. Direct dark matter searches

One of the outstanding mysteries in physics is the existence of dark matter and dark energy. From independent observations of the Cosmic Microwave Background radiation (CMB), the Large Scale Structure surveys (LSS) and the Supernova Type1 surveys (SN) [25] we have learned a lot about the matter budget of the universe. Combining these results one finds the universe contains 72±2% dark energy, 28±1% matter (including baryonic and dark matter), and 4.6±0.2% baryonic matter. However, the true nature of dark matter and dark energy which fills 95% of the universe is still unknown. While the dark energy is not directly detectable with todays technologies the dark matter, provided it consists of particles, can be searched for with earth bound detection systems owing to their large abundance in our galactic halo. There are several candidates for dark matter: massive neutrinos, weakly interacting massive particles, so-called WIMPs, and axions. Although neutrinos belong next to photons to the most abundant particles in the universe their mass turns out to be too small to significantly contribute to the missing mass. Neutrinos being relativistic at freeze out in the early universe are free streaming particles.
and would cluster only at very large scales. Therefore neutrinos would enhance large scale and suppress small scale structure formations. From the LSS power spectrum one can derive a ratio of the neutrino density to the matter density $\Omega_\nu/\Omega_m$. From this and $\Omega_m$ determined from CDM and SN an upper limit for the sum of the neutrino masses $\Sigma m_\nu \leq 0.7 \text{eV}c^{-2}$ was derived [25]. It is interesting to note that this upper limit of the neutrino masses is lower than the ones obtained from direct neutrino mass measurements so far. Axions which are named after a laundry detergent, are predicted by models to solve the CP violation problem in QCD and would be produced abundantly during the QCD phase transition in the early universe. The axion detection technique is based on Primakoff conversion in a magnetic field using microwave cavities. A topical review on dark matter searches including axions can be found in [26]. Today the most favored candidate for a WIMP turns out to be the lightest stable particle predicted by Super Symmetry (SUSY), the so-called neutralino. If the neutralino were to be discovered by the LHC at CERN it still would need to be confirmed as a dark matter candidate by direct detection experiments.

WIMPs can be detected via their elastic scattering with nuclei when penetrating a dark matter detector. In the case of neutralinos spin-independent as well as spin-dependent scatterings are possible. The expressions for the corresponding cross sections can be found in [27]. The WIMP mass can be derived from the characteristic nuclear recoil spectrum. Cryogenic detectors are well suited for this purpose since they are able to measure small recoil energies (order of eV) with high efficiency. They can also be made from many different materials. This turns out to be an advantage in order to verify a possible recoil signal with another detector material. However, cryogenic calorimeters are presently rather limited in their detector masses (kg). More conventional devices like LAr, LXe, Ge, and NaI allow eventually much larger detector masses (ton). This makes them also sensitive to annual modulations of the WIMP signal owing to the movement of the earth with respect to the dark halo rest frame. An effect which is claimed

Figure 11. An x-ray spectrum obtained with a state of the art Si(Li) solid state device (dashed line) and a cryogenic micro-calorimeter (solid line) using a Bi absorber and a TES sensor (Al-Ag) are compared.
to be observed by the DAMA experiment in the Gran Sasso Laboratory. However, due to the quenching of the ionization and photon signals, conventional detectors have lower nuclear recoil detection efficiencies.

Dark matter detectors are located in deep underground laboratories to be protected from cosmic particles. Their sensitivity to WIMPs is very much limited by the background radiation from surrounding materials and rocks in underground laboratories as well as by the radioactivity of the detector material itself. Even the best local shielding and the use of radio-poor material for the detectors provides only limited effectiveness and is expensive. Nevertheless, orders of magnitude better sensitivities have been achieved when employing dual readout of the detectors. The CDMS and EDELWEISS collaborations use cryogenic calorimeters made of Si or Ge absorbers with thermistor or TES sensors. For each event they are recording the heat (phonon) signal as well as the ionization signal separately but simultaneously. The principle of this dual phonon-ionization readout is shown in Fig.12. The CRESST collaboration is using CaWO$_4$ crystal absorbers and measures for each event the heat with a tungsten TES thermometer and the photon signal by a separate cryogenic detector, which consists of a silicon wafer with a tungsten TES thermometer (Fig.13). The dual phonon-ionization and phonon-photon readout of the detectors allows an active background recognition since for the same deposited energy in the absorber the ionization (or photon) signal from nuclear recoils is highly quenched compared to signals from background electrons (from Compton scattering). This feature provides a very effective separation of genuine nuclear recoils from electron background above 10keV recoil energies. This is demonstrated in Fig.14, taken from [28], which shows the energy equivalent of the pulse heights measured in the photon detector versus those in the phonon detector. The scintillating CaWO$_4$ crystal absorber was irradiated with photons and electrons using Cobalt and Strontium sources and with neutrons using an Americium Beryllium source. The upper band in Fig.14 shows the electron recoils (e) and the lower band the nuclear recoils (n).

![Figure 12. The principle of the dual phonon-ionization readout of the CDMS cryogenic calorimeter is shown.](image)

Conventional WIMP detectors like the NaI crystals of DAMA and the LXe calorimeter of
ZEPLIN I are using pulse shape analysis to differentiate between nuclear and electron recoils. The signals from nuclear recoils are faster due to the higher ionization density. A more effective background recognition is obtained by the XENON (LXe calorimeter) and the WARP (LAr calorimeter) detectors which use besides the timing information of the prompt photon signal also the ionization signal, which they obtain by drifting the ionization charges to the surface of the liquid calorimeter and by measuring the recombination photons emitted in the gas above the liquid. However, this very effective method works only at recoil energies above 50 keV. The use of LAr instead of LXe has many advantages, most importantly the lower price. However, LAr detectors have to deal with the radioactive $^{39}$Ar isotope which is produced by cosmic radiation and which is limiting the sensitivity of these devices.

The experimental results are presented in Fig.15 as exclusion plots, which show the WIMP-nucleon cross sections (90% C.L.) for spin-independent interactions versus the WIMP mass. The sensitivities obtained with the cryogenic devices of CDMS II [29] (detector mass: 4.75 kg Ge and 1.1 kg Si) in the Soudan Underground Laboratory (2090 M.W.E.), USA, EDELWEISS [30] (0.96 kg Ge) in the Frejus tunnel (4800 m.w.e.), South of France, CRESST II [31] (0.6 kg CaWO$_4$) in the Gran Sasso Laboratory (3800 m.w.e.), Italy, and with the detectors XENON [32] (15 kg) and WARP [33] (2.6 kg) in the Gran Sasso Laboratory. Not shown in Fig.15 are the results of ZEPLIN I [34] (3.2 kg) in the Boulby mine, U.K., which are similar to WARP. Also shown are the early results of DAMA [35] (100 kg NaI) in the Gran Sasso Laboratory which claimed to see an annual modulation signal consistent with a WIMP mass $m_x = (52^{+10}_{-8})$ GeVc$^{-2}$. Although the other experiments are not in agreement with their results DAMA recently reconfirmed their findings with the DAMA/LIBRA detector (250 kg NaI) [36].

An extraction of the spin-dependent WIMP-nucleon cross section in a model independent way is not possible, since the nuclear and the SUSY degrees of freedom do not decouple from each other. Nevertheless, when using an "odd group" model which assumes that all the nuclear spin is carried by either the protons or the neutrons, whichever are unpaired, WIMP-nucleon cross
sections can be deduced. The CDMS collaboration gives a minimum upper limit of $2.7 \times 10^{-38}$ cm$^2$ at 90\% C-L.\cite{37} for the spin-dependent WIMP-nucleon cross section, which is so far the best limit achieved with cryogenic calorimeters.

From Fig.15 it can be seen, that the experimental results start already excluding certain regions of SUSY model predictions\cite{38}. New projects like EURECA (European Underground Rare Event search with Calorimeter Array) and Super CDMS with detector masses up to 1 ton are already on the drawing boards with the hope to be able to improve the WIMP detection sensitivity by several orders of magnitude.

3.2. Neutrino-less double beta decay

From neutrino oscillations we know that neutrinos have a mass and there is new physics beyond the Standard Model to be expected. However, oscillation experiments provide only mass differences of the neutrino flavors and direct neutrino mass measurements with novel detection techniques are in demand. There remains also the question whether neutrinos are Dirac or Majorana type particles. To answer this question one looks for the neutrino-less double beta decay. Double beta decay was first suggested by Maria Goeppert Mayer\cite{39} in 1935. It occurs via spontaneous transition from a nucleus $(A, Z)$ to its isobar $(A, Z+2)$ and can proceed in two ways: the lepton number conserving process $(A, Z)\rightarrow (A, Z+2)+2e^-+2\bar{\nu}_e$ where two electrons and two antineutrinos are emitted or the lepton number violating process $(A, Z)\rightarrow (A, Z+2)+2e^-$ with no neutrinos in the final state. In the neutrino-less double beta decay $(0\nu\beta\beta)$ the energy spectrum of the decay would show a sharp peak with the energy sum of the two electrons. This process can only occur if the neutrino is a Majorana particle and if it has a non-vanishing mass. From the measured decay rate $(1/T_{1/2}^{0\nu})$ one can derive in principle its effective mass.
Figure 15. Exclusion plots for spin-independent WIMP interactions are shown.

\[ \langle m_\nu \rangle \text{ or a lower limit of it:} \]

\[ \frac{1}{T_{1/2}^{0\nu}} = G_{0\nu}(E_0, Z) \mid M_{0\nu} \mid^2 < m_\nu >^2 \]  \hspace{1cm} (2)

where \( T_{1/2}^{0\nu} \) is the lifetime of the decay, \( G_{0\nu}(E_0, Z) \) is an accurately calculable phase space function and \( M_{0\nu} \) is the nuclear matrix element, which is not very well known [40]. The calculated values of \( M_{0\nu} \) can vary considerably, consequently the search for \( 0\nu\beta\beta \) should be made with several different nuclei in order to confirm an eventual discovery of this important process.

Because of their excellent energy resolution and their wide choice of \( 0\nu\beta\beta \) nuclei cryogenic calorimeters are very well suited for this research. This was first pointed out by E. Fiorini and T. Niinikoski in 1984 [41] who also pioneered the development of these detectors. A cryogenic \( 0\nu\beta\beta \) experiment with the name CUORICINO is currently taking data in the Gran Sasso Laboratory. It consists of an array of 62 TeO\(_2\) crystals with a total weight of 40.7 kg. It is presently the largest cryogenic detector in operation. TeO\(_2\) was chosen because of the high transition energy of 2528.8±1.3 keV and its large isotopic abundance of \(^{130}\text{Te} \) with 33.8%. So far their results [42] show no evidence for \( 0\nu\beta\beta \) decay, but their lower limit of \( T_{1/2}^{0\nu} \geq 1.8 \times 10^{24} \) yr (90% C.L.) corresponding to a neutrino mass range of 0.1 to 0.9eV already has reached the sensitivity of the Heidelberg-Moskow experiment [43], which claimed evidence for \( 0\nu\beta\beta \) in \(^{76}\text{Ge} \). A review of present and future \( 0\nu\beta\beta \) decay experiments can be found in [44]. As a next step, the collaboration is constructing a 1 ton TeO\(_2\) detector, named CUORE, which aims for a neutrino mass sensitivity between 8 and 45 meV. This is quite competitive to the goals of other projects under construction like EXO, GENIUS, GERDA, MOON, NEXT, SUPER-NEMO.

3.3. Direct neutrino mass measurements

The best upper limit for the electron neutrino mass of 2.2eV was obtained by the Mainz and the Troitsk experiments [45] from the electron spectroscopy of the tritium decay \( ^3\text{H} \rightarrow ^3\text{He} + e^- + \bar{\nu}_e \)
with a transition energy of 18.6 keV. In the near future the KATRIN experiment using a much improved electron spectrometer is aiming to reach a sensitivity of 0.2 eV for the neutrino mass. A complementary approach was pioneered by the Genova group [46] by studying the beta decay of $^{187}\text{Re} \rightarrow ^{187}\text{Os} + e^- + \bar{\nu}_e$ with a cryogenic micro-calorimeter. Rhenium is a superconductor with a critical temperature of 1.7K. Their calorimeter consisted of a Re crystal (2mg) coupled to a Ge NTD (neutron transmutation doping) thermistor. Re has the advantage of a low endpoint energy of 2.6 keV and a high natural abundance of 62.8% of $^{187}\text{Re}$. In their first attempt they were able to reach an upper limit of the neutrino mass of 19 eV (90% C.L.) [47]. The Milan group [48] followed this method and has built an array of ten micro-calorimeters consisting of AgReO$_4$ crystals with masses between 250 and 350 µg. Their average energy resolution at the endpoint energy was 28.3 eV (FWHM). From a fit to the Curie plot of the $^{187}\text{Re}$ decay they obtained an upper limit for the neutrino mass of 15 eV.

The main advantage of this calorimetric approach is that the calorimeter measures the total energy of the decay including final state interactions, such as the de-excitation energy of excited atoms. However, in order to be competitive with the spectrometer experiments the cryogenic calorimeter has to have an excellent energy resolution (1 eV) and enough counting rate statistics at the beta endpoint energy. The latter may raise a problem for thermal calorimeters, since their signals are rather slow and limit the counting rate capability to several Hz. A new ambitious international project, named MARE (Micro-calorimeter Array for a Rhenium Experiment) [49], is prepared to deal with these problems and aims to reach a neutrino mass sensitivity of 0.2 eV comparable to the KATRIN experiment. To reach their goal they need large arrays of detectors ($10^4$ detector elements) and energy and time resolutions of 1eV and 1µs respectively.

4. Outlook

In the coming years new physics (Higgs, SUSY etc.) is expected to be discovered with the LHC. The sophisticated calorimeters, as presented at this conference, will play thereby a central role. The decision on the construction of the future linear collider will also depend on the results obtained with the LHC. In the field of astrophysics and cosmology, large arrays of conventional and cryogenic calorimeters are under development or in construction for space-born x-ray and infrared observatories to study the formation and evolution of black holes and their role in galaxy formation, matter in extreme conditions (like in gravitational fields near black holes), supernova remnants, accretion powered systems and polarization in CMB. Large earth-bound calorimeters using the polar ice, the sea and the atmosphere as absorber are already in operation and larger ones are planned to search for high energy sources which emit particles (among them neutrinos and gammas) with energies beyond $10^{20}$ eV. Underground low background experiments are driving their sensitivity for the detection of the dark matter in the universe, the neutrino-less double beta decay and the neutrino mass with massive cryogenic or conventional calorimeters (on a ton scale) by several orders of magnitude beyond the presently achieved values. For the future, the development of new calorimeter techniques needs not only imagination but also continuous financial support for detector R&D.

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