20 years of cryogenic particle detectors: past, present and future.

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In 1984 different authors presented a new approach for detecting elementary particles: the cryogenic (sometimes also called bolometric) particle detector. The basic idea was very simple but at the same time completely different with respect to other classical methods. The generation of the signal is produced by phonons with a mean energy around $10^{-4} - 10^{-5}$ eV and this aspect changes completely the evaluation of the theoretical energy resolution. In these 20 years substantial progress has been made in the development of cryogenic particle detectors, many experiments have been realized and some are still running. Detector performances are greatly improved and very massive detectors have been constructed. For specific experiments, detectors with simultaneous measurements of heat and ionization (or scintillation) were also developed. Cryogenic particle detectors have been applied in many fields, not only in particle physics experiments, thanks to some peculiar characteristics that they exhibit. Experiments on double beta decay take advantage from the good energy resolution and the flexibility in selecting materials; low energy thresholds and high efficiencies to nuclear recoils of these detectors are very interesting in the search for dark matter; the impressively high energy resolution of microcalorimeters is suitable for X-ray spectroscopy and direct neutrino mass measurements. Other experiments in particle physics use the cryogenic approach, but it is important to note that applications to surface analysis with Total Reflection X-ray Fluorescence (TXRF) for industry and measurements of protein fragments for biology have been also proposed. In the near future, new experiments will be realized using this technique. Very important technical challenges are still open, such as: realization of very large detectors (at the one ton scale), improvements in energy resolution and energy thresholds, maximization of the time resolution. A short history and the state of the art of cryogenic particle detectors will be presented; some aspects of their applications in the past and for the future will be briefly discussed.

1. Introduction

The introduction of cryogenic particle detectors is strictly connected with the search of new and better approaches in particle physics experiments. The history of particle detectors tells us that new techniques were introduced to optimize some specific detector characteristics; this is also true in the case of cryogenic particle detectors, in this case we were looking at improving the detector energy resolution.

In the early '80 a group of physicists that worked typically in superconductor physics, indicated the possibility of using cryogenic techniques as an instrument for detecting low energy particles. Two important papers were presented in 1984 by two different groups: Fiorini and Niinikowsky [1] proposed the cryogenic detector approach for elementary particle experiments, like double beta decay and neutrino mass experiments; McCammon [2] and coworkers indicated X-ray astrophysics as a possible field where cryogenic detectors might have an important impact. We normally indicate this year (1984) as the beginning of the cryogenic detectors history.

Starting with the general property that all the energy will be finally degraded into heat, cryogenic particle detectors are used to measure the energy released by a particle that interacts with a solid medium. For a crystal with a heat capacity equal to C, a particle that release an energy E will produce a temperature variation of:

$$\Delta T = E/C \qquad (1)$$

Obviously the heat capacity of the crystal must be as low as possible to increase the temperature variation. So it is necessary to operate cryogenic detectors at temperatures well below 1 K and to select materials in order to avoid contributions that increase the heat capacity. Many material characteristics contribute to the specific heat, in particular important contributions are: the lattice contribution that is proportional to $(T/T_D)^3$ where T_D indicates the Debye temperature of the material; the electron contribution that depends on T/T_F where T_F indicates the Fermi temperature; the paramagnetic component which is proportional to 1/T. For a superconductor the electron heat capacity will decrease as $exp(-2T_c/T)$, where T_c indicates the critical temperature. It is clear that the paramagnetic contribution is very dangerous, but also the use of conductors will be strongly limited by the specific heat of electrons.

The variation in temperature will be converted into a variation of other physical quantities, typically voltage or current, using suitable thermometers. For examples we can convert a variation of temperature ΔT into a variation in voltage ΔV:

$$\frac{\Delta V}{V} = A\frac{\Delta T}{T}, \tag{2}$$

where A indicate the sensitivity of the thermometer that must be maximized to obtain better detector performances.

During the last 20 years many approaches have been studied to optimize the thermometer characteristics [3]: thermistors present an exponential variation in resistance at low temperature; superconducting tunnel junctions (STJ) show strong variation in current with temperature; transition edge sensors (TES) are superconducting films operated at the conductor-superconductor transition temperature, in these conditions the variation of film resistance with temperature is extremely high. Other approaches have been developed and some of them seem to be very promising: magnetic sensors show very good energy resolution and excellent dynamic performances.

2. Energy resolution

Due to the extremely low energy needed to generate a phonon at low temperature the ultimate energy resolution of cryogenic particle detectors can be very high. If we consider the thermodynamic fluctuations as the unavoidable noise of the device we are able to estimate a root mean square energy resolution of:

$$\Delta E_{rms} = \xi\sqrt{CK_BT^2}, \tag{3}$$

where C is the heat capacity of the detector, K_B is the Boltzmann constant and T is the operating temperature. The ξ parameter will be 1 in the ideal case but, in the real word, it depends to the thermistor sensitivity A: $\xi = 2\sqrt{6/A}$ for $A > 6$. For thermistors A is around 10 while for TES A can reach value around 100.

Using the simple formula reported above we can calculate the theoretical energy resolution reachable with 1 g silicon crystal placed at 10 mK and measured with a sensor that shows A = 10. This energy resolution is well below 1 eV. In reality there are many contributions that can deteriorate this beautiful energy resolution: Johnson noise of the sensor and polarization network, phonon noise due to the temperature gradient, electronic noise of the amplifier, microphonic noise, etc. In any case, using a suitable thermometer and with an appropriate electronic readout, energy resolutions of few eV are reachable for the previously mentioned configuration.

If we compare the characteristics of cryogenic particle detectors with the well established performances of the semiconductor ionization detectors we obtain: better energy resolutions; large number of materials usable; very high sensitivity to non ionizing events. As bad news we have that cryogenic particle detectors are normally slow (especially for large mass detectors), they need very complicated apparatus necessary to reach cryogenic temperature, and, finally, the technology is under development, whilst for semiconductors it is possible to use the VLSI approach developed by the electronic industries.

3. Applications

We normally separate cryogenic particle detectors in micro calorimeter, if the detector mass is below 1 g, and macro calorimeter, if the mass is larger. This distinction is mainly related to the technical approach for the detector construction; detectors with masses larger than a few grams

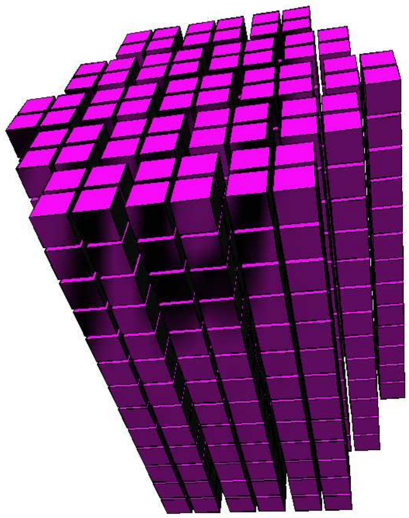

Figure 1. Scheme of the CUORE detector, a cryogenic particle detector at the 1 ton scale [4].

need mounting structures to maintain crystals in the correct position.

3.1. Macro calorimeters

Macro calorimeters show actually very large masses, the most massive cryogenic particle detector in operation is CUORICINO, it presents a total mass around 40 kg. CUORICINO is a segmented detector for double beta decay experiment; it is the prototype, one column, of the CUORE [4] (Fig. 1) detector that will be a one ton segmented cryogenic detector. Many important informations can be extracted from CUORICINO: first, a very massive cryogenic detector can be used with good performances and for long running time (more than 2 years); second, with a very complex apparatus a very low background is reachable.

Macro calorimeters are actually widely used in search of rare events like double beta decay, where high energy resolution spectroscopy is crucial for background reduction, and dark matter search, due to the very high conversion efficiency for non ionizing events.

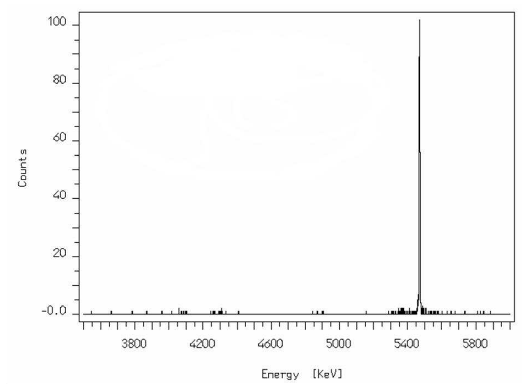

Figure 2. The ^{210}Po spectrum with the best energy resolving alpha spectrometer realized with a TeO_2 cryogenic particle detector [5].

Other important applications of large mass cryogenic detectors are gamma rays and alpha spectroscopy. In gamma rays spectroscopy the energy resolution of these detectors is comparable with that of semiconductor germanium detectors. With a TeO_2 cryogenic particle detector the best alpha spectrometer was realized [5] with an energy resolution for a ^{210}Po line equal to 4.2 keV (Fig. 2). The high energy resolution obtained with such type of detector is mainly due to the absence of a dead layer on the crystals surfaces (cryogenic detectors are sensitive in all the volume).

3.2. Micro calorimeters

Micro calorimeters are used in applications where very high energy resolutions are crucial. These detectors can be suspended using the connecting wires or with specially designed crystal structures. The applications of micro calorimeters are [3]: neutrino mass determination by measuring ^{187}Re beta decay, X-ray spectroscopy for astrophysics and material science, single optical photon spectroscopy, determination of biological fragment masses.

In such applications the performances of cryogenic particle detectors are orders of magnitude better than that of semiconductor ones. For example the typical energy resolution of a germanium (or silicon) diode measuring the X-ray energy of ^{55}Mn is around 120 eV while for a micro calorimeter this value is below 5 eV.

4. Hybrid detectors

One of the most important feature of cryogenic particle detectors is the possibility to have a double readout: it is possible to measure the heat delivered by the impinging particle in parallel with ionization or scintillation (Fig. 3). This possibility permits the discrimination between events that release energy with different efficiency in different channels. Typical examples are neutrons which interact mainly by nuclear recoils, with only a very small fraction of energy that will go into the ionization channels.

During the last few years many cryogenic particle detectors able to measure heat and ionization or heat and light were developed. Both approaches are used for realizing very sensitive dark matter devices. For ionization and heat there are obvious limitations related to the crystal material composition, the only two possible choices being silicon and germanium semiconductor crystals. Moreover the quality of such semiconductor crystals must be very good in order to avoid possible trapping of charge that, at very low temperatures, can substantially deteriorate the energy resolution in the ionization channel. Another important consideration regards surface events that can show very different responses with respect to the bulk events in the ionization channel, this situation can produce a different heat-ionization signal ratio and can deteriorate the non ionizing event selection [3].

To detect heat and scintillation, initially the approach was to read the light signal using photodiodes [6]. It was demonstrated that this approach can solve the problem of the alpha-beta ratio in double beta decay background reduction, but it does not allow for a sufficient low energy threshold to be used in dark matter discrimination experiments. A new technique was implemented in order to reach light energy thresholds of the order of 10 keV; a large surface cryogenic particle detector is now used to measure also the light emission. Using this method a very good discrimination between ionizing and non ionizing events was obtained and also energy thresholds for the two channels around 10 keV were proved, with rejection capabilities larger than 99% [3].

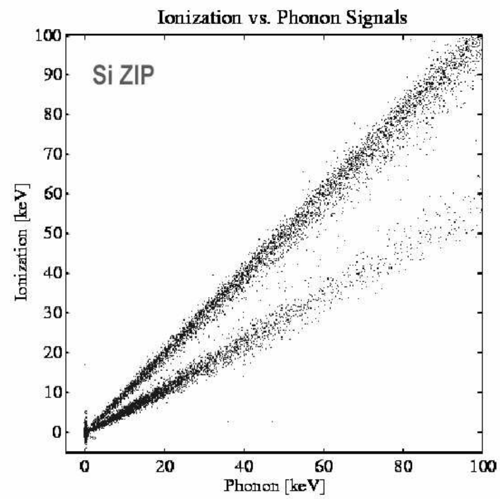

Figure 3. Hybrid detectors are able to discriminate between ionizing and non ionizing events, the example is from the CDMS experiment on dark matter[3]

5. High energy resolution spectroscopy

One of the most important characteristics of these devices is obviously the impressive energy resolution achievable. In alpha and gamma ray spectroscopy energy resolutions comparable with the best semiconductor detectors are normally obtained: in case of alpha measurement cryogenic particle detectors demonstrate slightly better performances. But in the case of X-ray spectroscopy with micro calorimeters the energy resolutions of these devices are at least one order of magnitude better than the resolutions achievable with semiconductor diodes.

High energy resolution X-ray detectors are developed with few different cryogenic detector ap-

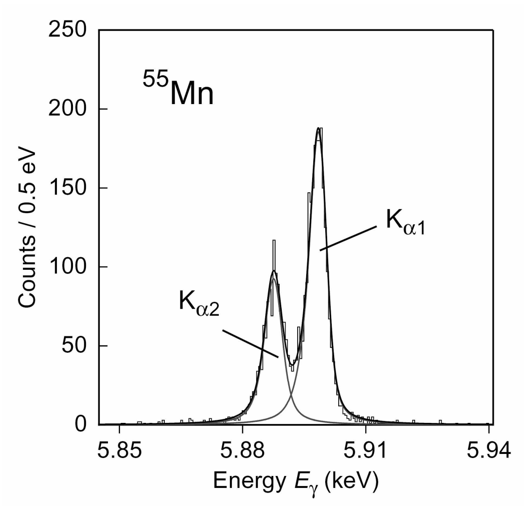

Figure 4. X-ray spectroscopy with high energy resolution microbolometer [7]: energy resolutions are now comparable with wave dispersive spectrometer.

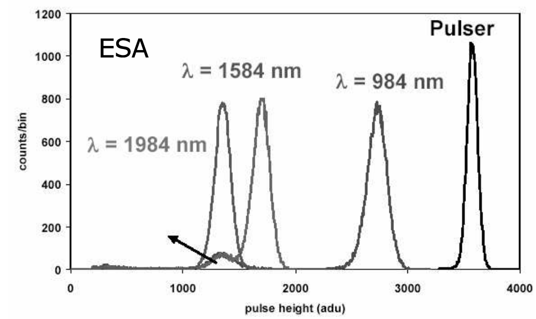

Figure 5. Detection of optical photons with cryogenic particle detectors with contemporary measurement of the energy of the photon, ESA [3]

proaches using: silicon or germanium thermistors, transition (conductor-superconductor) edge sensors, STJs, magnetic sensors on insulators or metals. In general all these methods permit to achieve energy resolutions less than 5 eV (Fig. 4). These performances indicate that cryogenic particle detectors can substitute, in a near future, the crystal diffraction techniques such as X-ray analytical methods; in fact the crystal diffraction method permits to obtain energy resolutions around 2-3 eV, but the detection efficiencies are orders of magnitude lower than the cryogenic particle detector ones. Moreover the recent developments in magnetic sensors and TES solve also one of the main disadvantages of these devices: the slowness. Normally, with thermistors and also with STJs, the typical rise time of these detectors is a few hundreds of microseconds. With magnetic sensors it was demonstrated that few microsecond rise times are reachable, this maintaining very high energy resolution performances (3.4 eV) [7].

Another interesting application is the possibility to detect single optical photons measuring also their energies, or better their wavelengths, as shown in Fig. 5 [3]. Thank to this feature it is possible, in astrophysical applications, to obtain a three dimensional view of the sky using the red shift of the light emitted by the stars. Arrays of TES and STJ have been realized in order to built a cryogenic CCD able to look at the sky in the optical photon range.

6. Other applications

The use of cryogenic particle detectors can help also in measurement very far from particle physics and astrophysics experiments. In particular applications in biology and material science are under development [3].

For biologist the time of flight mass spectrometry is an important tool to study DNA and protein fragments. The general idea is to determine the mass of the various fragments produced when DNA or proteins are destroyed. Standard technique show strong limitations related to the detection mass limits (around 20000 proton masses) and to singly/doubly ionized fragment, for double mass with double ionization we measure the same signal as for single mass-ionization fragments. Cryogenic particle detectors are sensitive to fragments with very high mass, the only request is that the energy delivered to the detector

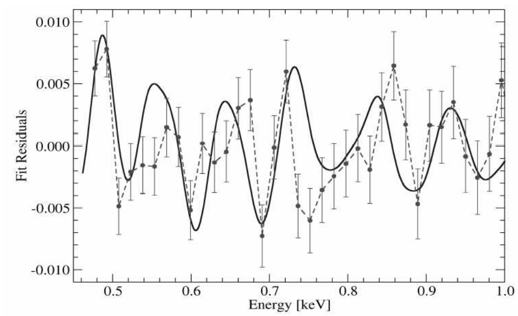

Figure 6. Beta Environmental Fine Structure of an $AgReO_4$ crystal obtained with a high energy resolution cryogenic particle detector for the beta decay of ^{187}Re.

is large enough to generate a measurable thermal signal. At the same time these detectors measure the time of flight and the energy released by the fragment, and this permits us the discrimination between different ionizations in the fragments. In this way the measurement capability of the biological instruments can be strongly improved.

In material science one of the most powerful instrument for measuring crystal structures is Extended X-ary Absorption Fine structure (EXAF). In this approach the interference pattern of X-rays, due to the presence of atoms distributed in well defined sites in the crystal structures, gives precise information on these structures. With cryogenic particle detectors it is possible to study the same interference pattern using a beta decay element placed inside the crystals. In this case the emitted electron is sensitive, due to the electromagnetic interference produced by the crystal lattice, to the position of the atom located around the decayed one. A very precise measurement of crystal structures can also be obtained with a very high detection efficiency. The Beta Environmental Fine Structure (BEFS) techniques are under development and the preliminary results are encouraging; in Fig. 6 the fit to the beta spectrum of ^{187}Re based on BEFS interference is reported.

7. Conclusions

After 20 years of improvements, cryogenic particle detectors are now ready to be used in many high sensitivity experiments in particle physics and in other instrumental applications. Some characteristics of these devices give us the best performing instruments in measurements of: double beta decay, dark matter search, high resolution X-ray detection, single optical photon energy measurement, molecular fragment determination, BEFS. Moreover the history of these devices is so short that all the possible applications and the real potentialities have not yet been well explored. What we expect is continuously improving detector performances and new fields of application in a near future.

Very good news are also related to the improvements obtained in cryogenic techniques, where the ultimate frontiers reached will permit us to cool down the detectors at cryogenic temperatures without using cryogenic liquids (LHe or LN_2). With these new possibilities, cryogenic operations can be greatly simplified and the diffusion and the applications of cryogenic particle detectors can become much more widespread than today.

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