Underground Cryogenic Detectors

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The joint effort of cryogenics, particle physics, and astrophysics to exploit thermal detectors should lead to exciting and perhaps unexpected results.

Fundamental physics, having successfully unified the electromagnetic and weak interactions, is now attempting to unify the strong force and hopefully even the gravitational force. The so-called astrophysics connection is destined to play an important role. Searches with high-energy particle accelerators can be complemented in a wonderful way by studying, for example, the origin of the Universe and its remnants, the physical processes accompanying the origin, and the life and the death of a star. The astrophysics approach has led to the construction of large laboratories placed deep underground to investigate the interactions of the penetrating component of cosmic rays as well as the rare processes arising from the spontaneous decay of particles or nuclei. Noise from cosmic rays is suppressed because the rays are absorbed by the rock overburden.

The astrophysical approach has also stimulated the development and application of techniques which are either totally new or at least seldom or never used in particle physics. The thermal detection of nuclear radiation, perhaps the most promising of these techniques, played an important rôle in the development of nuclear physics. In 1903, Curie and Laborde published a paper entitled Le chaleur dégagée spontanément par les sels de radium (The heat released by radium salts) and in 1927 Ellis and Wooster found in the decay of $^{210}$Po missing thermal energy which was subsequently attributed by Pauli to the emission of neutrinos. The thermal detection of single particles was suggested independently in Europe [1] and the USA [2] for experiments in elementary particle physics some eight years ago. Since then, the development of these techniques has been impressive [3] and their application in experiments of the passive type [4], namely without accelerators, seems almost within reach.

Techniques

Some of the thermal techniques for detecting elementary particles are based on the effect that the thermal "action" of a particle may play on a metastable system. Consider, for instance, a granule of a Type I superconductor kept at a fixed temperature in a magnetic field slightly below the critical field. The granule is in a metastable superconductor state and as such repels the magnetic field owing to the Meissner effect (Fig. 1a). Heat delivered by an incoming particle raises the temperature of the granule, bringing it suddenly to the normal state and the field is no longer repelled. The result is a magnetic pulse that can be detected.

Another technique, based on the Josephson effect, exploits a detector comprising a pair of superconductors separated by a thin, insulating layer. The superconductors induce breaking of the Cooper pairs to give a current pulse passing through the insulator which is amplified and measured (Fig. 1b).

More appropriate for "underground cryogenics" would appear to be another and in some ways simpler technique, which like the others, is generally called bolometric. Consider a very pure diamagnetic and dielectric crystal: its heat capacity $C_v$ (in joules per degree Kelvin) at low temperatures is given quantitatively by the expression:

$$C_v = 1944 \left( \frac{V}{V_m} \right) \left( \frac{T}{T_D} \right)^3$$

where $V$ and $V_m$ are the crystal and molecular volumes, and $T$ and $T_D$ are the operating and Debye temperatures. It is clear that for $T_D$ sufficiently large and $T$ sufficiently small, the heat capacity can be so small that even the minute amount of energy delivered by an incident particle in the form of heat can produce, in the crystal, a sizable increase of temperature. This temperature pulse can be transformed into an electric pulse using a suitable thermistor in thermal contact with the crystal (Fig. 2). The thermistor, whose resistance we call $R_b$, is biased by a battery and a load resistor with resistance $R_L$ possibly considerably larger than $R_b$. The energy delivered by the particle to the crystal produces a negative voltage pulse across the thermistor which can then be amplified and measured.

Fig. 1 — Techniques based on superconductivity for detecting fundamental particles: schematic illustrations of flux exclusion from a granule (a, left) and of a Josephson-type detector (b, right).

Performance

When comparing cryogenic detectors with standard detectors based on semiconductors and on ionization or proportional counters, one should note that the standard devices collect only the fraction of energy delivered by the particle in form of ionization (about 30% of the total energy). The remainder of the energy goes mainly into phonons (heat), with perhaps a component into lattice dislocations in the case of nuclear recoils. Thermal detectors collect directly and in the form of heat at least 70% of the energy delivered, and up to 100% if the electron-ion and electron-hole pairs recombine within a sufficiently small time interval. Bolometers have in fact proved to be excellent detectors of nuclear recoils, which deliver a much lower fraction of energy as ionization than fast, charged particles, and consequently a much larger fraction in the form of heat. However, thermal detectors are "slow" since the rise time is related to the velocity of sound (the...
Unfortunately, we are still quite far from these limits owing to various important problems including:
- non-uniformity in collecting phonons, especially in large detectors;
- spatial non-uniformity of the recombination of electron-hole pairs trapped by various impurities;
- noise due to electromagnetic sources, especially microphonics [5];
- difficulties in keeping constant the temperature of the bolometer, and consequently its gain.

Results
Despite these difficulties the performance of some thermal detectors is already very promising. In the limit of very small detectors (where the heat capacity is obviously very small), in a bolometer and the heat sink. Thermal detectors are consequently excellent for searching for rare events in underground experiments, but usually unsuitable for working at the high counting rates and large backgrounds found at accelerators.

An important figure-of-merit for thermal detectors is the energy resolution. It can be optimized by adapting the characteristics of the preamplifier to the impedances of the bolometer and the load resistors, and by choosing the best value for the difference between the temperatures of the bolometer and the heat sink. The overall resolution of the detector (full width at the half maximum: FWHM) can be as small as:

$$\Delta E = 2.36 \xi \sqrt{k C_v T^2}$$

where \(k\) is Boltzmann's constant and \(\xi\) is a dimensionless parameter usually of the order of a few tenths. The following examples demonstrate that the resolution should be, in principle, much better than for any other detector:
- A cubic crystal of silicon (\(T_D = 645\) K) of 1 mm side kept at 20 mK would have a heat capacity of \(5 \times 10^{-15}\) J/K and a FWHM resolution of 0.1 eV.
- A germanium thermal detector (\(T_D = 370\) K) with 100 mm side (more than 5 kg in weight) operated at the same temperature would have an heat capacity around \(2.5 \times 10^{-9}\) J/K and a resolution of about 150 eV. Both the overall mass and the resolution would be much larger than for existing germanium diodes.

High-energy gamma-ray detection
It is well known that gamma rays are normally detected by searching for peaks in energy due to interactions in a detector involving the photoelectric effect and pair formation. The cross-sections for these processes increase strongly with atomic number. Excellent gamma-ray spectroscopy can therefore be carried out with thermal bolometers constructed using a high-Z material, as has already been demonstrated for a tellurium oxide detector (Fig. 4b) made by the Milan group [11].

Fig. 3 — A comparison between the x-ray spectroscopic performance of a Si(Li) diode (upper) with that for the NASA-Wisconsin 155Tb detector (lower). The bolometric device gave a resolution which is some 20 times better than for the semiconductor detector.

Fig. 4 — Cryogenic TeO₂ detectors that have been developed by the Milan group to search for double-beta decay (a, upper) and to perform gamma-ray spectroscopy (b, lower). The diagram gives a cross-section through the copper frame holding the TeO₂ crystal which was used for (a); the photograph shows a similar detector that was employed for (b).
surface without special shields, the thermal energies delivered by cosmic rays and by radioactivity are comparable, amounting in total to 0.3 pW/g; this is only an order of magnitude less than the total heat leak encountered experimentally in the microkelvin region. It will therefore become essential in the near future to carry out searches for rare events in an underground laboratory where contributions from cosmic rays and radioactivity are reduced by many orders of magnitude. This single example shows how the joint effort of cryogenics, particle physics and astrophysics should lead to exciting and perhaps unexpected results.

Cosmology with Supernovae

Hans Hippelein from the Max Planck Institute for Astronomy in Heidelberg, Germany, describes the significance of a recent observation of a Type 1a supernova "candle" at a record distance.

Type 1a supernovae (SN1a) are the result of deflagration and detonation of accreting stars. These exploding stars shine half as brightly as a whole galaxy (maximum brightness \( M_B = 19.8 \text{ mag} \)) for about a week and can be easily detected up to a redshift of \( z = 0.5 \), corresponding to a distance of about 5.10^9 light years. The scatter in maximum brightness is small (0.5 mag; ~25%) because all Type 1a supernovae arise from exactly the same kind of star: a white dwarf which is fed by material from a companion star until it reaches a critical mass of 1.4 times that of the sun and explodes.

Because of the high brightness and the small scatter in brightness, SN1a are probably the best "candles" for studying the expansion of the universe due to gravitational forces between galaxies is comparable to the variation in the maximum brightness of supernovae.

By observing a large number of supernovae one can plot a curve describing the apparent brightness as a function of the redshift (see figure). The deceleration parameter \( q_0 \) is given by the slope of the curve, without knowing the Hubble constant which relates redshift and the distance of galaxies in the expanding universe. Using \( q_0 \), astronomers can directly estimate \( \Omega \), the mean density parameter in the universe (e.g., for the Friedman model \( \Omega = 2q_0 \)).