1. Introduction

The existence of the neutrino was first suggested by Wolfgang Pauli in a famous letter “Liebe radioactive Damen und Herren” dated December 4, 1930 and addressed to a Conference on radioactivity in Tubingen. The justification of his absence was somewhat surprising: “I cannot be with you due to a ball which is going to take place here in the night from January 6 to 7. In this letter Pauli explains the lack of energy (see later) delivered by the β decay of $^{210}$Bi and the “poor statistics” in this decay as due to the emission of a not yet discovered neutral particle which he named neutron (the real neutron was not yet discovered!) A later report given by Pauli in Italy strongly impressed Enrico Fermi and prompted him to give this particle the Italian name of neutrino and to introduce it in his beautiful theory of weak interactions. Since the very beginning, Fermi suggested that the neutrino had to have a very low mass “even lower than the mass of the electron”. In fact in most later papers the neutrino was assumed to be massless. A great step forward is due to the discovery of oscillations by solar atmospheric, reactor and accelerator neutrinos (Fig.1) which is amply discussed in this Symposium [1-5]. It indicates that the masses of at least two neutrinos of different flavours are finite. The measurement of the effective neutrino mass becomes therefore mandatory and the present and

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1 To whom any correspondence should be addressed.
future developments of new type of detectors like the cryogenic ones can play an important role in this fascinating field of research.

2. The principle of cryogenic detectors
We can date the origin of these detectors [6] since 1880 when Langley first developed resistive bolometers for infrared rays from Sun, while in 1905 Curie and Laborde performed the first calorimetric measurement of radioactivity. An important step towards the discovery of the neutrino is due to Ellis and Wuster who detected a lack of heat in the radioactive decay of $^{210}$Bi which prompted the above mentioned letter by Pauli. In 1935 Simon discovered that the detector sensitivity was enhanced by lowering the temperature. In a period around 1983 T. Niinikosky at CERN recorded pulses induced by cosmic rays in resistors kept at low temperature. The first suggestions for the use of cryogenic detectors in fundamental physics date from 1984 and are due independently to two groups working on the two sides of the Atlantic. In USA [7] S.H. Moseley et al. suggested the use of cryogenic detectors mainly for astrophysics while in Europe T. Niinikosky and myself [8] proposed their use to search for rare events and in particular for double beta decay. Both groups were also interested in other subjects of physics like direct measurement of the neutrino.
mass. An “artist view” and a more serious scheme of the performance of a cryogenic detector is shown in Fig. 2 and 3.

![Diagram of a cryogenic detector](image)

**Figure 2.** An “artist view” of a cryogenic detector.

**Figure 3.** A more serious scheme of a cryogenic detector.

The principle of these detectors is simple. The heat capacity of an absorber, possibly of dielectric and diamagnetic material, in a suitable refrigerator is proportional to the cube of the ratio between the operating and Debye temperatures. It can therefore become so low that even the tiny energy released by a particle incident or generated in it, can induce a sizable increase of temperature which can be measured by a suitable “thermometer”. The outstanding performances of these detectors with masses of the order of a milligram in the region of tens of keV is shown in Fig. 4. The resolution is now around 2 eV, more that an order of magnitude better than in any other detector. For searches for rare events larger masses are needed and the resolution is obviously poorer, but still overcomes the one of germanium detectors. This is show in fig. 5, where the sharp α line of $^{210}$Po can be seen.

### 3. Measurement of the neutrino mass in single ββββ decay

The discovery of neutrino oscillations has strongly stimulated searches to determine or at least to constrain the absolute value of the neutrino mass [9] by the deformation (Fig. 6) of the spectrum in beta decay. The more stringent limits, around 2 eV, were obtained in the decay of $^3$H into $^3$He. An improvement of an order of magnitude is aimed for by the international KATRIN experiment to be carried out in Germany.

A complementary approach can be provided by cryogenic detectors and consists in the bolometric measurement of the energy released by beta decay occurring in a micro-absorber. Even if the sensitivity of cryogenic detectors is still far from those from of spectrometers one should note that bolometric detection enables to record the total energy delivered in the decay and not only the electron one. It could also include the decay energy from excited states. A good friend of mine and an excellent physicist, the late Antonio Vitale of the Genoa University, suggested bolometric experiments on the β decay of $^{187}$Re into $^{187}$Os which has the lowest transition energy ( ~ 2.5 keV ). Bolometric searches on this decay are being carried out in Genoa and Milan with absorbers of metal Re and AgReO, respectively. These experiments will be merged in the international MARE search (Fig. 7).
Figure 5. \( \alpha \) particle spectrum obtained with a 760 grams bolometer. The FWHM resolution on the \( ^{210} \text{Po} \) line is 3.2 keV.

Figure 6. Modification of the \( \beta \) spectrum due to a massive neutrino.
4. Double $\beta$ decay (DBD)

This very rare process, amply discussed at this Symposium [10-15] consists, in the most common case, in the transition (Fig. 8) from the isotope $(A, Z)$ to $(A, Z+2)$ with contemporary emission of two electrons. Several DBD modes are possible: one is the $2\nu$ mode, where two electron antineutrinos are emitted. This decay mode conserves lepton number and it is allowed in the framework of Standard Model (SM) of electroweak interaction; another is the $0\nu$ mode, which violates the lepton number and has been recognized since a long time as a powerful tool to test neutrino properties [20]. A third decay channel, is the process with the emission of one or more light neutral bosons, named Majorons. In the processes where no additional particle is emitted with the two electrons, lepton number conservation is violated (Fig. 9) and a peak appears in the sum of the two electron energies corresponding to the transition energy.

The presence of the second channel, rather improperly called neutrinoless Double Beta Decay (DBD) implies that neutrino is a Majorana [16] massive particle, and would allow to determine the absolute value of its mass $< m_\nu >$. The predicted values from the results of oscillations are of a few tens of meV or of a few meV, for the case of inverse and direct hierarchies, respectively [17].
In “direct” experiments where DBD is actually detected two approaches are possible: the source = detector and the source ≠ detector as shown in Fig. 10 and 11.

No evidence has been obtained so far for neutrinoless double beta decay with the exception of the claim by a subset of the Heidelberg-Moscow collaboration [17] which indicates a value of $< m_{\nu} >$ around 0.5 eV. I leave to the reports by P. Vogel [18] and J. Engel [19] the discussion of the difficult calculations of the nuclear matrix elements for neutrinoless DBD.

Most of the running and planned experiments aiming to detect neutrinoless DBD with the sensitivity suggested by the results of oscillations (Fig. 12) are reported to this Symposium [10-15]. Let me only mention here those, running or in construction, which are based on the use of cryogenic detectors, whose mass has constantly increased with time as shown in Fig. 13.
The most sensitive detector of any type presently running is CUORICINO, by far the largest operating cryogenic setup in the world, shown during its mounting in Fig.14. It consists in a single tower made by absorbers of TeO2 with a total mass of ~ 41 kg. It is devoted to the search for neutrinoless DBD of 130Te, a nucleus with an isotopic abundance of ~34 % and a transition energy of ~ 2530 keV. The CUORICINO array is made by 18 crystals of 33x6 cm3 of which two are enriched in 128Te and two in 130Te, and by 44 cubic crystals of natural Te of 5 cm side. No evidence is found for the peak indicative of neutrinoless double beta decay of 130Te, but with a 90% confidence level lower limit of 3.1 x 10^24 years of DBD0 life time, the corresponding constrains on the effective neutrino mass is in the range of 0.16 - 0.84 eV using the recent calculation of Rodin et al. [18]. The corresponding values coming from the positive indication of Klapdor et al. are in the mass range 0.1-0.9 eV. As a consequence our result, while not confirming the one by Klapdor et al. cannot be used to exclude their evidence.
The only second generation experiment approved so far is CUORE (from Cryogenic Underground Observatory for Rare Events) already in construction at the Laboratori Nazionali del Gran Sasso by a large international collaboration (fig.15). CUORE will be a giant bolometric detector made of 988 cubic crystals of natural TeO2 with a total mass of ~ 750 kg corresponding to ~ 203 kg of 130 Te. It could reach the sensitivity on the effective neutrino mass predicted by the results on neutrino oscillations under the inverse hierarchy hypothesis.

I would like to add that many other compounds can be chosen as bolometric candidates for searches on neutrinoless double beta decay. All those reported in Table 1 have been successfully tested as bolometers, the only exception being so far the compounds of 150 Nd.

**Table 1. Candidates for bolometric detection of neutrino-less DBD**

| Compound     | I. A. (%) | ΔE (keV) |
|--------------|-----------|----------|
| \(^{48}\)CaF₂ | 0.0187    | 4212     |
| \(^{76}\)Ge  | 7.44      | 2038.7   |
| \(^{100}\)MoPbO₄ | 9.63    | 3034     |
| \(^{116}\)CdWO₄ | 7.49    | 2804     |
| \(^{130}\)TeO₂ | 34       | 25430    |
| \(^{150}\)NdF₃ | 5.64     | 3368     |
| \(^{150}\)NdGa₀ |          |          |
Figure 15. The CUORE collaboration.

Figure 15. CUORE.

Figure 16. The CUORE hut.
5. Conclusions and acknowledgments

Thermal cryogenic detectors are already playing an important role in nuclear, subnuclear and astroparticle physics, but their impact in these fields is going to increase greatly in the future. In the field of neutrino physics bolometers constitute an approach complementary to the spectrometric measurement of the electron energy. Bolometric measurements of the $\beta$ decay spectrum is an excellent model independent approach, even if its sensitivity is not yet at the level predicted by the results coming from neutrino oscillation experiments. The sensitivity in determination of the absolute value of neutrino mass from neutrinoless DBD is expected to be quite superior, even if less direct, to that from single $\beta$ decay and could allow to test directly if the neutrino is a Dirac and Majorana particle. The efforts devoted with various techniques to this fascinating problem are clearly shown by the description of beautiful experiments reported here in an atmosphere of collaboration and friendship. Both in single and in double beta decay experiments, as in other fields of nuclear, subnuclear and astroparticle physics, the new approach of bolometric detection of particles is definitely going to play a relevant role.

Mine cannot be here the standard acknowledgments at the end of an invited talk. I am really moved by being here with my old friend (in fact he is young, at least younger than myself!) Frank with whom we deeply miss our great friend Peter who stimulated and helped us since the beginning of our searches on DBD. I have no words to adequately express my gratitude to organizers and to the outstanding physicists who came here to give beautiful talks honouring me much more that I deserve. I will always remember with pleasure and gratitude these wonderful days spent in this beautiful city and university.

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