Neutrino Physics with Cryogenic Detectors

- Past and present of thermal detectors
- Their role in searches for neutrino physics
- Hybrid techniques
- The impact of the discovery of neutrino oscillation
- Present situation of searches on neutrino mass in single beta decay and the role of thermal detectors
- The second mystery of Ettore Majorana
- Present situation on experiments of neutrinoless double beta decay and the possible impact of thermal detectors in this field
- Conclusions
First ideas

1880 => Langley => resistive bolometers for infrared rays from SUN

1903 => Curie et Laborde => calorimetric measurement of radioactivity

1927 => Ellis and Wuster => heat less then expected => the neutrino

1949 => D. Andrews, R. Fowler, M. Williams => $\alpha$ particle detection

1983 => T.Niinikoski => observe pulses in resistors due to cosmic rays

1984 => S.H.Moseley et LT detectors for astrophysics and $\nu$ mass

=> Fiorini and Niinikoski Low temperature detectors for rare events

=> A. Drukier, L. Stodolsky, => neutrino physics and astronomy
The cryogenic or thermal detectors
Equilibrium detectors

\[ \Delta T = \frac{Q}{C_V} \]

\[ C_V = \frac{1944}{v_m} \frac{V}{V} \left( \frac{T}{\Theta} \right)^3 \text{ J/K} \]

Excellent resolution: 
- <1 eV \sim 2\text{eV}
- ~10 \text{ eV} \sim \text{keV}
- @ 6 \text{ keV}
- @ 2 \text{ MeV}
Various types of thermometers

- a thermistor
- a transition edge sensor (TES)
- an Equilibrium Absorber weakly coupled to a heat bath superconducting tunnel junction (STJ) Cooper pair breaking
- a magnetic thermometer. The temperature information is obtained from the change of a paramagnetic sensor placed in a small magnetic field

Caveat => possibility that the heat capacity of the thermometer be comparable or larger than the absorber one:
Doped Semiconductors

- $\alpha$ negative; $|\alpha| < 10$
- Resistance large
- Current bias and read voltage

Superconducting transition-edge

- $\alpha$ positive; $10 < \alpha < 1000$
- Resistance small
- Voltage bias and read current
The first mini-meeting on thermal detectors
(Ringberg castle 1986)
Simon's wish

2eV FWHM 0.6 keV
By next LTP!
Simon Baudler 8/13/05

<table>
<thead>
<tr>
<th>Device</th>
<th>Energy FWHM</th>
<th>Size</th>
<th>Material</th>
</tr>
</thead>
<tbody>
<tr>
<td>TES</td>
<td>1.8 eV</td>
<td>240x240x6.7µm³</td>
<td>Bi/Au</td>
</tr>
<tr>
<td>Si Thermistor</td>
<td>3.2 eV</td>
<td>410x410x8µm³</td>
<td>HgTe Mn Kα,2</td>
</tr>
<tr>
<td>MMC</td>
<td>2.7 eV</td>
<td>180x180x5µm³</td>
<td>Au</td>
</tr>
</tbody>
</table>
Magnetic sensors

Au:Er paramagnetic sensor

weak thermal link

X-ray

H

dc SQUID

bath
Energy resolution of a TeO$_2$ crystal of 5x5x5 cm$^3$ (~ 760 g):

- 0.8 keV FWHM @ 46 keV
- 1.4 keV FWHM @ 0.351 MeV
- 2.1 keV FWHM @ 0.911 MeV
- 2.6 keV FWHM @ 2.615 MeV
- 3.2 keV FWHM @ 5.407 MeV

(The best $\alpha$ spectrometer so far)
Non equilibrium detectors

⇒ STJ Superconducting tunnel junctions
⇒ SSG Superheated superconducting granules. The field does not enter more in the granule. Often SQUID pickup Suggested for In solar neutrino detection. Considered for Dark Matter Experiments

⇒ **Superfluid** $^3$He and $^4$He detectors (rotons). Also considered for Solar neutrinos

Comparison with conventional detectors:

⇒ They measure the **total** energy delivered (example MARE)
⇒ Slow propagation of the vibration inside the absorber
   Kapitza resistence detector ⇒ heat sink (slow rise and decay times)
⇒ Possible localization of the event (TES)
⇒ Excellent detection of **nuclear recoil**
⇒ Possibility of **hybrid techniques** (heat + ionization and/or scintillation?)
   Crucial in searches for rare events
The “grains”
(operating for Dark Matter and proposed for $\beta\beta$ decay)

Superheated Superconducting Granules
Hybrid techniques

heat + ionization or heat + scintillation
Works with many absorber materials
\textit{CaWO}_4, \textit{PbWO}_4, \textit{BaF}, \textit{BGO}
(other tungstates and molybdates)

\begin{itemize}
  \item Light detector
  \item \textit{W} thermometer
  \item Light reflector
  \item \textit{W} thermometer
\end{itemize}
A very interesting application of thermal detectors

$=> \text{decay of } ^{209}\text{Bi}$

$^{209}\text{Bi}$ considered the only stable isotope of Bi and the stable nucleus with higher Z

Scintillation and hat experiment in Paris by P.de Marcillac et al with a BGO of 47 g

$\Delta E = 3137 \quad 1_{\text{stat}} \quad 2_{\text{syst}} => \quad 1.9 \quad 0.2 \times 10^{19} \quad a$
Planck  High angular resolution measurements of the CMB
52 NTD-Ge bolometers 22 receivers
187 Re

Kurie-Plot:

Counts/(1 keV)

$E_r = \frac{N(E)}{p(E)}$

Energy [keV]

214 Bi

208 Tl

60 Co

130 Te β(0ν)

300 μg
AgReO$_4$

Crystal

760 g TeO

Crystal
Discovery of $\nu$ oscillations $\Rightarrow m_\nu \neq 0$
Cosmology
Cosmo-“conservative”

Cosmo-“aggressive”
Direct measurement of the neutrino mass

$\beta$ decay

Electron capture
Experiments on tritium decay

ITEP

$T_2$ in complex molecule
magn. spectrometer (Tret'yakov)

Los Alamos

gaseous $T_2$ - source
magn. spectrometer (Tret'yakov)

Tokio

$T$ - source
magn. spectrometer (Tret'yakov)

Livermore

gaseous $T_2$ - source
magn. spectrometer (Tret'yakov)

Zürich

$T_2$ - source impl. on carrier
magn. spectrometer (Tret'yakov)

Troitsk (1994-today)
gaseous $T_2$ - source
electrostat. spectrometer

Mainz (1994-today)
frozen $T_2$ - source
electrostat. spectrometer

$m_\nu$

Experimental results

17-40 eV

< 9.3 eV

< 13.1 eV

< 7.0 eV

< 11.7 eV

< 2.2 eV

< 2.2 eV

Year

1 detector
2 magnets (4.5 T)
3 vessel
4 Electrode system
5 electron gun
6 valve
Direct measurement of the electron mass with cryogenic microcalorimeters

\[ ^{187}\text{Re} \rightarrow ^{187}\text{Os} + e^- + \bar{\nu}_e \]

- Radioactive source embedded in the microcalorimeter measured)
- All events are detected
- Rhenium is the beta isotope with the lowest known endpoint energy (2.47 keV)
- Experiment (all the energy, except the neutrino’s, is

**MANU:** Re single crystal with NTD Ge thermistors

**MIBETA:** AgReO\(_4\) with Si implanted therimostors

**END POINT** \[ \rightarrow 2465.3 \pm 0.5(\text{stat}) \pm 1.6(\text{syst}) \text{ eV} \]
\[ 2470 \pm 1(\text{stat}) \pm 4(\text{syst}) \text{ eV} \]

**HALF LIFE** \[ \rightarrow 4.32 \pm 0.02(\text{stat}) \pm 0.01(\text{syst}) \times 10^{10} \text{ yrs} \]
\[ 4.12 \pm 0.02(\text{stat}) \pm 0.11(\text{syst}) \times 10^{10} \text{ yrs} \]

**MASS** \[ \rightarrow m_n < 15 \text{ ev/c}^2 \]
\[ m_n < 26 \text{ ev/c}^2 \]
The full MARE experiment is still in the R&D phase and multiple options are being evaluated. In particular:

**Microbolometer Array for Renium Experiment**

- **Isotope**
  - $^{187}$Re
  - $^{163}$Ho

- **Technology**
  - TES
  - MagCal
ΔE = 33 eV @ 2.6 keV
τ_R ~ 500 μs
Araldit / ST2850

T_{op}=85 mK

MARE Genoa

September 18, 2009
Ettore Fiorini, Erice 2009
The first phase of MARE-1 in Milan is getting ready to start at the end of September with 72 channels.

With 72 channels a sensitivity on neutrino mass of about 5 eV can be achieved in two years can be made.
Few events in the extreme energy region
• Direct neutrino mass determination with 0.1-0.2 eV accuracy
• Beta Decay of $^{187}\text{Re}$ with cryogenic microcalorimeters
• TES coupled to Re absorber
• 1014 event, requiring 10,000-50,000 detectors
MARE: Microcalorimeter Arrays for a Rhenium Experiment

Università di Genova e INFN Sez. di Genova
Goddard Space Flight Center, NASA, Maryland, USA
Kirkhoff-Institute Physik, Universität Heidelberg, Germany
Università dell'Insubria, Università di Milano-Bicocca e INFN Sez. di Milano-Bicocca
NIST, Boulder, Colorado, USA
ITC-irst, Trento e INFN Sez. di Padova
PTB, Berlin, Germany
University of Miami, Florida, USA
Università di Roma 'La Sapienza' e INFN Sez. di Roma
SISSA, Trieste
Wisconsin University, Madison, Wisconsin, USA

...
finite neutrino mass causes a kink at the end-point similarly to beta spectra

\[
^{163}Ho + e^- \rightarrow ^{163}Dy^* + \nu_e
\]
## Relic neutrinos

<table>
<thead>
<tr>
<th>Isotope</th>
<th>Decay</th>
<th>$Q$ (keV)</th>
<th>Half-life (sec)</th>
<th>$\sigma_{NCB}(v_\nu/c)$ ($10^{-41}$ cm$^2$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^3$H</td>
<td>$\beta^-$</td>
<td>18.591</td>
<td>$3.8878 \times 10^8$</td>
<td>$7.84 \times 10^{-4}$</td>
</tr>
<tr>
<td>$^{63}$Ni</td>
<td>$\beta^-$</td>
<td>66.945</td>
<td>$3.1588 \times 10^9$</td>
<td>$1.38 \times 10^{-6}$</td>
</tr>
<tr>
<td>$^{93}$Zr</td>
<td>$\beta^-$</td>
<td>60.63</td>
<td>$4.952 \times 10^{13}$</td>
<td>$2.39 \times 10^{-10}$</td>
</tr>
<tr>
<td>$^{106}$Ru</td>
<td>$\beta^-$</td>
<td>39.4</td>
<td>$3.2278 \times 10^7$</td>
<td>$5.88 \times 10^{-4}$</td>
</tr>
<tr>
<td>$^{107}$Pd</td>
<td>$\beta^-$</td>
<td>33</td>
<td>$2.0512 \times 10^{14}$</td>
<td>$2.58 \times 10^{-10}$</td>
</tr>
<tr>
<td>$^{187}$Re</td>
<td>$\beta^-$</td>
<td>2.64</td>
<td>$1.3727 \times 10^{18}$</td>
<td>$4.32 \times 10^{-11}$</td>
</tr>
<tr>
<td>$^{11}$C</td>
<td>$\beta^+$</td>
<td>960.2</td>
<td>$1.226 \times 10^3$</td>
<td>$4.66 \times 10^{-3}$</td>
</tr>
<tr>
<td>$^{13}$N</td>
<td>$\beta^+$</td>
<td>1198.5</td>
<td>$5.99 \times 10^2$</td>
<td>$5.3 \times 10^{-3}$</td>
</tr>
<tr>
<td>$^{15}$O</td>
<td>$\beta^+$</td>
<td>1732</td>
<td>$1.224 \times 10^2$</td>
<td>$9.75 \times 10^{-3}$</td>
</tr>
<tr>
<td>$^{18}$F</td>
<td>$\beta^+$</td>
<td>633.5</td>
<td>$6.809 \times 10^3$</td>
<td>$2.63 \times 10^{-3}$</td>
</tr>
<tr>
<td>$^{22}$Na</td>
<td>$\beta^+$</td>
<td>545.6</td>
<td>$9.07 \times 10^7$</td>
<td>$3.04 \times 10^{-7}$</td>
</tr>
<tr>
<td>$^{45}$Ti</td>
<td>$\beta^+$</td>
<td>1640.1</td>
<td>$1.307 \times 10^4$</td>
<td>$3.87 \times 10^{-4}$</td>
</tr>
</tbody>
</table>
What about the nature of the neutrino and its mass?

The second mystery of Ettore Majorana
Neutrinoless double beta decay and Majorana neutrinos

\[ \nu \neq \overline{\nu} \quad \Rightarrow \quad \nu = \overline{\nu} \quad \Rightarrow 1937 \]
Neutrinoless $\beta\beta$ decay
Predictions from oscillations

A. Strumia and F. Vissani: hep-ph/0503246

lightest neutrino mass [eV]

\[ \langle m_n \rangle = f( m_{\text{low}}, U_{\text{ek}} ) \]
Claim of Evidence for $0\nu\beta\beta$ in $^{76}\text{Ge}$

\[ T_{1/2}^{0\nu} = (2.23^{+0.44}_{-0.31}) \times 10^{25} \text{ y}. \]

\(<m> \sim 0.2 \text{ to } 0.3 \text{ eV}\)

Looks good to me…not to me (E.F.)

Single-site events in detectors 2, 3, 4, 5 (56.6 kg-y).
### Experimental situation

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Nucleus</th>
<th>Detector</th>
</tr>
</thead>
<tbody>
<tr>
<td>NEMO III</td>
<td>$^{100}$Mo et al</td>
<td>10 kg of enrich. Isotopes -tracking</td>
</tr>
<tr>
<td><strong>Cuoricino</strong></td>
<td>$^{130}$Te + etc.</td>
<td>40 kg of TeO$_2$ bolometers (nat)</td>
</tr>
<tr>
<td><strong>CUORE</strong></td>
<td>$^{130}$Te + etc.</td>
<td>750 kg of TeO$_2$ bolometers (nat)</td>
</tr>
<tr>
<td>EXO</td>
<td>$^{136}$Xe</td>
<td>200 kg - 1 t Xe TPC</td>
</tr>
<tr>
<td>GERDA</td>
<td>$^{76}$Ge</td>
<td>30 Š 40 kg Š 1 t Ge diodes in LN</td>
</tr>
<tr>
<td>Majorana</td>
<td>$^{76}$Ge</td>
<td>180 kg - 1 t Ge diodes</td>
</tr>
<tr>
<td>MOON</td>
<td>$^{100}$Mo</td>
<td>nat.Mo sheets in plastic sc.</td>
</tr>
<tr>
<td>DCBA</td>
<td>$^{150}$Nd</td>
<td>20 kg Nd-tracking</td>
</tr>
<tr>
<td>CAMEO</td>
<td>$^{116}$Cd</td>
<td>1 t CdWO$_4$ in liquid scintillator</td>
</tr>
<tr>
<td>COBRA</td>
<td>$^{116}$Cd, $^{130}$Te</td>
<td>10 kg of CdTe semiconductors</td>
</tr>
<tr>
<td>Candles</td>
<td>$^{48}$Ca</td>
<td>Tons of CaF$_2$ in liquid scintillators</td>
</tr>
<tr>
<td>GSO</td>
<td>$^{116}$Cd</td>
<td>2 t Gd$_2$SiO$_5$:Ce scintill.in liquid sc.</td>
</tr>
<tr>
<td>Xe</td>
<td>$^{136}$Xe</td>
<td>1.56 Xenon in liquid scintillator.</td>
</tr>
<tr>
<td>Xmass</td>
<td>$^{136}$Xe</td>
<td>1 t of liquid Xe</td>
</tr>
</tbody>
</table>

September 18, 2009  Ettore Fiorini, Erice 2009
Double beta decay with thermal detectors

Searches for the $2\beta$ decay in $^{130}\text{Te}$ ($Q=2529\text{ keV}$ and 34\% i.a.)

A series of experiments carried out first by the Milano group and later by the CUORICINO and CUORE collaboration.

**Mibeta** (Milano only) an array of 20 TeO$_2$ bolometers of 320 g

=> total mass 6.8 kg

**CUORICINO** (CUORICINO Coll.) 44 crystals of 150 g and 18 of 320 (4 enriched)n

=> total mass 40.7 kg

**CUORE** (CUORE coll)

988 crystals of 750 g

=> total mass 741 kg
Searches in the LNGS

CUORE R&D (Hall C)

CUORE (Hall A)

Cuoricino (Hall A)
Mass increase of bolometers

- 4 detectors array
- Mibeta
- Cuoricino
- Mass increase over years
At Hall A in the Laboratori Nazionali del Gran Sasso (LNGS)
18 crystals $3 \times 3 \times 6 \text{ cm}^3 + 44 \text{ crystals} \ 5 \times 5 \times 5 \text{ cm}^3 = 40.7 \text{ kg of TeO}_2$
Operation started in the beginning of 2003

**Background** $0.18 \pm 0.01 \text{ c/kev/kg/a}$
CUORICINO
Change of the measured value of $\Delta E$

With $15.53 \text{ kg} \times \alpha$ of $^{130}\text{Te}$ and $\Delta E = 2530.30 \pm 1.99$ keV

$\Rightarrow \tau_{1/2} < 3.1 \times 10^{30}$

With $\sim 18 \text{ kg} \times \alpha$ of $^{130}\text{Te}$ and $\Delta E \sim 2527$ keV

$\Rightarrow \tau_{1/2} < 2.94 \times 10^{30}$
$^{60}\text{Co sum peak}$

$2505\,\text{keV}$

$\sim 3\,\text{FWHM from DBD Q-value}$

$MT = 18.0\,\text{kg}^{130}\text{Te} \times y$

$Bkg = 0.18 \pm 0.02\,\text{c/keV/kg/y}$

$^{130}\text{Te}$

$0\nu\beta\beta$

$T_{1/2}^{0\nu} (y) > 2.94 \times 10^{24}\,\text{y} \quad (90\%\,\text{c.l.})$

$\langle M_{bb} \rangle < 0.20 - 0.68\,\text{eV}$

**Klapdor .1-.9**
Cosmological disfavoured region

Direct hierarchy
\[ \Delta m^2_{12} = \Delta m^2_{\text{sol}} \]

Inverse hierarchy
\[ \Delta m^2_{12} = \Delta m^2_{\text{atm}} \]

"quasi" degeneracy
\[ m_1 \approx m_2 \approx m_3 \]

Possible evidence (best value 0.39 eV)

With the same matrix elements the Cuoricino limit is 0.53 eV

Cosmological disfavoured region (WMAP)

September 18, 2009
Ettore Fiorini, Erice 2009
The COURE building in hall A of LNGS

988 TeO$_2$ 5x5x5 cm$^3$ crystals
=> 741 kg TeO$_2$ => 204 kg $^{130}$Te

Cryostat order placed
The crystals
SICCAS/INFN Clean Room
1) Kushan Jincheng Chemical Reagent Co. Ltd

high purity grade TeO2 powder production unit

high purity water and reagents production units
Growing and lapping at SICCAS

- Order for 63 cristals 4 crystals by flight => OK
- Order for 500 crystals INFN 26 (2 being tested) + 32+36
- Agreement prepared for 500 crystals DOE
- Crystals are arriving at a rate of 30 crystals per month
- In a year all INFN crystals produced. => Validation of the DOE ones

Packaging
The next step: CUORE-0

CUORE-0 will be the first CUORE tower
It will be operated in Hall A dilution refrigerator
(CUORICINO experimental set-up)

GOALS: to test assembling procedures, background reduction, facilities (nitrogen boxes, storage areas), collaboration skills (shifts, organization, management).

2010: Data taking
CUORE expected sensitivity

\begin{figure}
\centering
\includegraphics[width=\textwidth]{CUORE_sensitivity.png}
\caption{CUORE sensitivity to neutrino mass.}
\end{figure}

<table>
<thead>
<tr>
<th>$b$ (counts/keV/kg/y)</th>
<th>$\Gamma$ [keV]</th>
<th>$T_{1/2}$ [y]</th>
<th>$\langle m_\nu \rangle$ [meV]</th>
</tr>
</thead>
<tbody>
<tr>
<td>$10^{-2}$</td>
<td>5</td>
<td>$2.1 \times 10^{26}$</td>
<td>19-100</td>
</tr>
<tr>
<td>$10^{-3}$</td>
<td>5</td>
<td>$6.5 \times 10^{26}$</td>
<td>11-57</td>
</tr>
</tbody>
</table>

In 5 years:

Strumia A. and Vissani F. hep-ph/0503246

September 18, 2009

Ettore Fiorini, Erice 2009
The earthquake

0.64 g => center of L’Aquila

0.29 g => outside laboratory

0.03 g inside
The future

Other possible candidates for neutrinoless DBD

<table>
<thead>
<tr>
<th>Compound</th>
<th>Isotopic abundance</th>
<th>Transition energy</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{48}\text{CaF}_2$</td>
<td>0.0187 %</td>
<td>4272 keV</td>
</tr>
<tr>
<td>$^{76}\text{Ge}$</td>
<td>7.44 %</td>
<td>2038.7 keV</td>
</tr>
<tr>
<td>$^{100}\text{MoPbO}_4$</td>
<td>9.63 %</td>
<td>3034 keV</td>
</tr>
<tr>
<td>$^{116}\text{CdWO}_4$</td>
<td>7.49 %</td>
<td>2804 keV</td>
</tr>
<tr>
<td>$^{130}\text{TeO}_2$</td>
<td>34 %</td>
<td>2528 keV</td>
</tr>
<tr>
<td>$^{150}\text{NdF}_3$</td>
<td>5.64 %</td>
<td>3368 keV</td>
</tr>
<tr>
<td>$^{150}\text{NdGaO}_3$</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Scintillation* + heat
(in coincidence)

*Maybe Cherenkov light T. Tabarelli de Fatis – Milano-Bicocca
First scintillating bolometer (1991)

Scintillation [mV] vs Heat [mV]

CaF$_2$
Already tested different scintillating crystals (CdWO4, CaF2, CaMoO4, SrMoO4, PbMoO4, ZnSe, …).

With some of them we have obtained excellent results (for example CdWO4, CaMoO4 and ZnSe).
Background CdWO$_4$ 3x3x6 (426 g) – Scatter Plot (724 hours)
Background CdWO$_4$ 3x3x6 (426 g) – Beta Spectrum

$^{113}\text{Cd}$

(i.a. = 12.2 %)

$Q_{\beta} = 318$ keV
CONCLUSIONS

Thermal detectors operating at low temperature (10-10 mK) had a great development in the last twenty years. In many fields of physics (e.g., low energy nuclear physics, X-ray spectroscopy, material sciences, even environmental physics etc) they have not yet sufficiently exploited. Their long rise and decay time not a problem for searches on rare events in non-accelerator physics (see however their role in accelerator like DESY). They offer a wide choice of source or target nuclei.

The possibility of hybrid employ association with detector of ionization and/or scintillation => formidable tool in searches for direct interaction of WIMPS.

In experiments on $\beta\beta$ decay especially in its neutrinoless channel they are already competitive with other detector. This property will be further enhanced by the use of scintillation and/or ionization in coincidence. Their multidisciplinary nature => exiting and excellent for learning.