Neutrino mass measurement with $^{187}\text{Re}$ and $^{163}\text{Ho}$ in the framework of MARE

Elena Ferri
for the MARE collaboration
Università di Milano-Bicocca & INFN Milano-Bicocca
Outline

➔ Direct neutrino mass measurement
  ➔ calorimetric approach

➔ MARE: Microcalorimeter Array for a Rhenium Experiment
  ➔ calorimetric measurement sensitivity to light neutrinos
  ➔ $^{187}$Re vs. $^{163}$Ho
  ➔ heavy (sterile) neutrinos detection

➔ MARE project status
  ➔ path for isotope and technique selection
  ➔ MARE-1 experimental activities

➔ Conclusions
Direct neutrino mass measurements

neutrino oscillations evidence → $m_\nu \neq 0$
BUT oscillation experiments give only $\Delta m^2$

direct neutrino mass measurement

$K(E_\beta) = (E_0 - E_\beta)^4 \sqrt{1 - \frac{m_\nu^2}{(E_0 - E_\beta)^2}}$

$m_\nu = (\Sigma m_i^2 |U_{ei}|^2)^{1/2}$

- 2 eV → $^3$H ($E_0 = 18.6$keV) & spectrometers
- 15 eV → $^{187}$Re ($E_0 = 2.47$keV) & calorimeters
The calorimetric approach

• Calorimeters: source $\subseteq$ detector

$^{187}\text{Re}$ source

\[ \nu_e \]

β calorimeter ideally measures all the energy $E$ released in the decay except for the $\nu_e$ energy

Excitation energies

General experimental requirements:

• High statistics at the beta spectrum end-point
• high energy resolution $\Delta E$
• high Signal to Noise ratio
• small systematic effects

Calorimeters measure the entire spectrum at once:

• low $E_0$ β decaying isotopes for more statistics near the end-point
• best choice $^{187}\text{Re}$:
  - $E_0 \approx 2.5$ keV, $\tau^{1/2} = 4 \times 10^{10}$ y
• other option $^{163}\text{Ho}$ EC:
  - $E_0 \approx 2.6$ keV, $\tau^{1/2} \approx 4600$ y
Cryogenic detectors as calorimeters

Detection Principle:
- $\Delta T = \frac{E}{C}$ where $C$ is the total thermal capacity
  - low $C$: $C \sim \left(\frac{T}{\Theta_D}\right)^3$ in superconductors below $T_C$ & dielectric
  - low $T$ (10 ÷ 100 mK)
- ultimate limit to energy resolution:
  - statistical fluctuation of internal energy $\Delta E = (k_B T^2 C)^{1/2}$
- detect all deposited energy, including short-lived excited states (100 µs)
- achieve very good energy resolution in the keV range
MARE - A project for a new Rhenium experiment

**Goal:** a sub-eV direct neutrino mass measurement complementary to the KATRIN experiment

**MARE 1**
- activities aiming at isotope/technique selection (\(^{187}\)Re or \(^{163}\)Ho options)
- activities using medium sized arrays to improve \(^{187}\)Re measurement understanding and possibly calorimetric \(m_\nu\) limit
- detector and absorber coupling R&D activities

\[ \sim 100 \text{ detectors} \quad \rightarrow \quad 2-4 \text{ eV} \quad m_\nu \text{ sensitivity} \]

**MARE 2**
- very large experiment with a \(m_\nu\) statistical sensitivity close to KATRIN but still improvable
- requires new improved detector technologies

\[ \sim 10000 \text{ detectors} \quad \rightarrow \quad 0.2 \text{ eV} \quad m_\nu \text{ sensitivity} \]
MARE for sub-eV calorimetric $m_\nu$ measurement

MARE: Microcalorimeter Arrays for a Rhenium Experiment

Università di Genova e INFN Sez. di Genova, Italy
Univ. di Milano-Bicocca, Univ. dell'Insubria e INFN Sez. di Milano-Bicocca, Italy
Kirkhhof-Institute Physik, Universitat Heidelberg, Germany
University of Miami, Florida, USA
Wisconsin University, Madison, Wisconsin, USA
Universidade de Lisboa and ITN, Portugal
UniversitÃ di Roma “La Sapienza” e INFN Sez. di Roma1, Italy
Goddard Space Flight Center, NASA, Maryland, USA
PTB, Berlin, Germany
FBK, Trento e INFN Sez. di Padova, Italy
NIST, Boulder, Colorado, USA
SISSA - Trieste, GSI Darmstad, JPL/Caltech, CNRS Grenoble, ...

http://crio.mib.infn.it/wig/silicini/proposal/
Re - Statistical sensitivity

Beta activity $A_\beta$
Number of detectors $N_{det}$
Resolving time $\tau_R$
Analysis interval $\Delta E$
Pile-up fraction $f_{pp} = \tau_R x A_\beta$
Experimental exposure $t_M = T \times N_{det}$

\[ \frac{\text{signal}}{\text{background}} = 1.7 \quad \text{for 90\% CL} \]

\[ \sum_{g_0}(m_\nu) \approx 1.13 \frac{E_0}{\sqrt{N_{ev}}} \left[ \frac{\Delta E}{E_0} + \frac{E_0}{\Delta E} \left( \frac{3}{10} f_{pp} + b \frac{E_0}{A_\beta} \right) \right]^{1/4} \]

Optimal energy interval: $\Delta E = \max \left( E_0 \sqrt{0.3 f_{pp} + b \frac{E_0}{A_\beta}}, \Delta E_{FWHM} \right)$
Sub-eV $m_\nu$ statistical sensitivity with $^{187}\text{Re}$

A MonteCarlo code has been developed to estimate the sensitivity of a neutrino mass measurement performed with thermal detectors. The results of the analytic approach are then validated through the comparison with the MonteCarlo results over a wide range of experimental parameters.

Possible to scale MonteCarlo results for different statistics

$$\sum_{90} (m_\nu) \propto 4 \sqrt{\frac{1}{N_{\text{ev}}}}$$

MARE statistical sensitivity: Re option

- only statistical analysis
- 50000+ detectors gradually deployed
  - arrays distributed in many laboratories around the world
  - about $10^{13} \div 10^{14}$ events after 5 years

### Exposure required for 0.2 eV $m_n$ sensitivity

<table>
<thead>
<tr>
<th>$A_\beta$ [Hz]</th>
<th>$\tau_R$ [μs]</th>
<th>$\Delta E$ [eV]</th>
<th>$N_{ev}$ [counts]</th>
<th>exposure [det×year]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1</td>
<td>1</td>
<td>0.2 $10^{14}$</td>
<td>7.6 $10^5$</td>
</tr>
<tr>
<td>10</td>
<td>1</td>
<td>1</td>
<td>0.7 $10^{14}$</td>
<td>2.1 $10^5$</td>
</tr>
<tr>
<td>10</td>
<td>3</td>
<td>3</td>
<td>1.3 $10^{14}$</td>
<td>4.1 $10^5$</td>
</tr>
<tr>
<td>10</td>
<td>5</td>
<td>5</td>
<td>1.9 $10^{14}$</td>
<td>6.1 $10^5$</td>
</tr>
<tr>
<td>10</td>
<td>10</td>
<td>10</td>
<td>3.3 $10^{14}$</td>
<td>10.5 $10^5$</td>
</tr>
</tbody>
</table>

### Exposure required for 0.1 eV $m_n$ sensitivity

<table>
<thead>
<tr>
<th>$A_\beta$ [Hz]</th>
<th>$\tau_R$ [μs]</th>
<th>$\Delta E$ [eV]</th>
<th>$N_{ev}$ [counts]</th>
<th>exposure [det×year]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.1</td>
<td>0.1</td>
<td>1.7×$10^{14}$</td>
<td>5.4×$10^5$</td>
</tr>
<tr>
<td>10</td>
<td>0.1</td>
<td>0.1</td>
<td>5.3×$10^{14}$</td>
<td>1.7×$10^5$</td>
</tr>
<tr>
<td>10</td>
<td>3</td>
<td>3</td>
<td>10.3×$10^{14}$</td>
<td>3.3×$10^5$</td>
</tr>
<tr>
<td>10</td>
<td>5</td>
<td>5</td>
<td>21.4×$10^{14}$</td>
<td>6.8×$10^5$</td>
</tr>
<tr>
<td>10</td>
<td>10</td>
<td>10</td>
<td>43.6×$10^{14}$</td>
<td>13.9×$10^5$</td>
</tr>
</tbody>
</table>

bkg = 0

5000 pixels/array
8 arrays
10 years
400 g $^{nat}$Re
MARE extensions: $^{163}$Ho EC measurement

$^{163}$Ho + e$^{-}$ $\rightarrow$ $^{163}$Dy* + $\nu_{e}$

- Calorimetric measurement of non-radiative Dy atomic de-excitations
- Breit Wigner M,N,O lines have an end-point at the Q value
  - finite neutrino mass causes a kink at the end point
- rate at end-point may be as high as for $^{187}$Re but depends on $Q_{EC}$
  - $Q_{EC}$? Measured: $Q_{EC} = 2.3 - 2.8$ keV. Recommended: $Q_{EC} = 2.555$ keV
- $\tau_{1/2} \approx 4570$ years: few active nuclei are needed
  - can be implanted in any suitable microcalorimeter absorber
- $^{163}$Ho production by neutron irradiation of $^{162}$Er enriched Er

### MARE statistical sensitivity: Ho option

#### Exposure required for 0.2 eV $m_n$ sensitivity

<table>
<thead>
<tr>
<th>$A_\beta$ [Hz]</th>
<th>$\tau_R$ [$\mu$s]</th>
<th>$\Delta E$ [eV]</th>
<th>$N_{ev}$ [counts]</th>
<th>exposure [det×year]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1</td>
<td>1</td>
<td>$2.8 \times 10^{13}$</td>
<td>$9 \times 10^5$</td>
</tr>
<tr>
<td>1</td>
<td>0.1</td>
<td>1</td>
<td>$1.3 \times 10^{13}$</td>
<td>$4.3 \times 10^5$</td>
</tr>
<tr>
<td>100</td>
<td>0.1</td>
<td>1</td>
<td>$4.6 \times 10^{14}$</td>
<td>$1.5 \times 10^5$</td>
</tr>
<tr>
<td>10</td>
<td>0.1</td>
<td>1</td>
<td>$2.8 \times 10^{14}$</td>
<td>$9.0 \times 10^5$</td>
</tr>
<tr>
<td>10</td>
<td>1</td>
<td>1</td>
<td>$4.6 \times 10^{14}$</td>
<td>$1.5 \times 10^5$</td>
</tr>
</tbody>
</table>

#### Exposure required for 0.1 eV $m_n$ sensitivity

<table>
<thead>
<tr>
<th>$A_\beta$ [Hz]</th>
<th>$\tau_R$ [$\mu$s]</th>
<th>$\Delta E$ [eV]</th>
<th>$N_{ev}$ [counts]</th>
<th>exposure [det×year]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.1</td>
<td>0.3</td>
<td>$1.2 \times 10^{14}$</td>
<td>$3.9 \times 10^6$</td>
</tr>
<tr>
<td>100</td>
<td>0.1</td>
<td>0.3</td>
<td>$6.4 \times 10^{14}$</td>
<td>$2 \times 10^6$</td>
</tr>
<tr>
<td>100</td>
<td>0.1</td>
<td>1</td>
<td>$7.4 \times 10^{14}$</td>
<td>$2.4 \times 10^6$</td>
</tr>
<tr>
<td>10</td>
<td>0.1</td>
<td>1</td>
<td>$4.5 \times 10^{14}$</td>
<td>$1.5 \times 10^6$</td>
</tr>
<tr>
<td>10</td>
<td>1</td>
<td>1</td>
<td>$7.4 \times 10^{14}$</td>
<td>$2.4 \times 10^6$</td>
</tr>
</tbody>
</table>

$q_{EC} = 2.2\text{keV}$

$bkg = 0$

5000 pixels/array
3 arrays
1 year
\(\approx 2\times 10^{17}\)^{163}Ho nuclei

5000 pixels/array
4 arrays
10 years
\(\approx 3\times 10^{17}\)^{163}Ho nuclei
Connection point between astrophysics, cosmology and elementary particle physics is the explanation of the Dark Matter (DM). A possible candidate is a sterile neutrino with a mass in the keV range.

- to test the assumption of heavy neutrino existence: $^{187}$Re beta decay
- Modification of the MonteCarlo code to evaluate the capability of the MARE experiment to measure the mass of an heavy neutrino from some tens of eV to 2.5 keV

\[ \nu_e = \nu_L \cos \theta + \nu_H \sin \theta \]

\[ N_\beta(E, m_L, m_H, \theta) = \cos^2 \theta N_\beta(E, m_L) + \sin^2 \theta N_\beta(E, m_H) \]
MARE sensitivity to heavy neutrinos - Ho option

heavy neutrino emission in $^{163}$Ho EC decay

$Q_{EC} = 2.2 \text{ keV}$

- $m_H = 0 \text{ keV}$
- $m_H = 0.1 \text{ keV}$
- $m_H = 1 \text{ keV}$
**MARE-1**: collection of activities aiming at isotope/technique selection

- $^{187}\text{Re}$ – high statistics measurement
  - assess systematics
  - test large arrays
  - lower limit to few eV

- $^{163}\text{Ho}$ – high statistics measurement – R&D for $^{163}\text{Ho}$ production
  - measure $Q_{EC}$
  - study spectrum shape
  - assess systematics

**Different techniques:**

- TES – Transition Edge Sensor
- MMC – Magnetic MicroCalorimeter
- MKID – Microwave Kinetic Inductance Detector

- multiplexed readout
- large arrays
MARE 1 @ Milano-Bicocca

- **6x6 NASA/GSFC arrays**
  - pixel 300x300x1.5 μm³
  - developed for X-ray spectroscopy with HgTe absorber (ASTRO-E2)

- **flat AgReO₄ single crystal**
  - mass ~ 500μg per pixel ($A_\beta \sim 0.3$ dec/sec)

All the problems concerning the cryogenic set-up have been solved.

Thanks to the improvements added to the cryogenic set-up the detector target performances have been achieved.

- Acquisition of the first spectrum.
- The assembly of the first array is starting.
MARE 1 @ Milano-Bicocca

first spectrum acquired after the improvements added to MARE-1
cryogenic set-up

![Energy spectrum](image)

- Working temperature $T \approx 85\text{mK}$
- $\Delta E \approx 40\text{ eV} @ 1.5\text{ keV}$
- $\tau_R \sim 500\text{ µs}$
**MARE 1 in Milano: sensitivity**

**MonteCarlo approach**

![Graph showing statistical sensitivity 90% C.L. (eV) vs total statistics (events)]

- Setup designed for 8 arrays
- 288 AgReO₄ crystals
- Now starting with 2 arrays (72 ch.)
- Gradual deployment

Since only two arrays are installed up to now, it is useful to estimate the sensitivity on neutrino mass over the years by increasing the detectors number from year to year.

**Analytic approach (1st order)**

- **Detectors**
  - $\Delta E_{\text{FWHM}} \sim 50$ eV and $\tau_R \sim 500$ µs
  - 1 year and 72 channels $\rightarrow \Sigma(m_\nu) \sim 7$ eV
  - 3 years and 288 channels $\rightarrow \Sigma(m_\nu) \sim 4.2$ eV

- $\Delta E_{\text{FWHM}} \sim 30$ eV and $\tau_R \sim 300$ µs
  - 1 year and 72 channels $\rightarrow \Sigma(m_\nu) \sim 6$ eV
  - 3 years and 288 channels $\rightarrow \Sigma(m_\nu) \sim 3.8$ eV
MKIDs R&D @ Milano-Bicocca

- resonator exploiting the $T$ dependence of inductance in a superconducting film
  - **up detectors** suitable for large absorbers
  - **fast** devices for high single pixel activity $A_\beta$ and low pile-up $f_{pp}$
  - **high energy resolution**
  - **multiplexing** for very large number of pixel

### Sensitivity

- $\Delta E = 5\ eV$
- $t_M = 36000\ detectors \times 3\ years$
- $A_\beta = 20\ c/s/det$
- $\tau_{\text{rise}} = 1\ \mu s \Rightarrow m_\nu < 0.2\ eV$
- $\tau_{\text{rise}} = 100\ \mu s \Rightarrow m_\nu < 0.4\ eV$

- KIDs developed for astrophysics
- Application to bulky absorber still requires further efforts
MKIDs for $^{163}$Ho EC decay end point measurement

The $^{163}$Ho will be embedded in the inductive part of the resonator. $10^{12}$ Ho nuclei are needed for a count rate of 10 Hz

The Ho nuclei have to be deep enough so that all of the energy from the electron capture decay is contained within the film. The minimum thickness will be set by the distance needed to ensure low escape probability for the 2 keV fluorescence X-rays. But very thick films are difficult to grow.

Nitrides with like TiN, TaN and HfN, are being investigated. A thickness of $\sim 0.5\mu$m can be enough.

**theoretical resolution**

$\Delta E_{th} = 2\text{keV}/N_{qp}^{1/2} = 1.5 \text{ eV}$

This work is supported by Fondazione Cariplo through the project ”Development of Microresonator Detectors for Neutrino Physics” (grant 2010-2351).
Ho - Isotope physics investigation

University of Genoa, University of Miami, University of Lisbona ans University of Milano-Bicocca

- Production of the first Ho samples

- Study of the properties of gold films implanted with holmium and erbium in the working temperature range of the TES microcalorimeters.
  - Determination of the heat capacity of gold films with different concentration of Ho and Er.
  - Study of the effect of the implant on the crystal structure of the films and the crystal size

- Chemical processes to extract the Ho-163 isotope and insert it into a detector absorber involve yttrium based compounds.
  - Study the possibility to use the metal yttrium silicide (Y5Si3) as absorber
  - Investigation of the thermal and electrical properties of a Y5Si3 sample in the temperature range 90-300mK.
  - viable candidate as absorber material, although not as good as gold.

- In the near future..
  - Measurement of the 163Ho spectrum with Si thermistors
Conclusion

- Thermal calorimeter with Re can give a sub-eV sensitivity on neutrino mass
- Calorimetry of $^{163}$Ho electron capture decay is an interesting alternative
- $^{187}$Re and $^{163}$Ho calorimetry is sensitive to 1 keV scale heavy neutrinos
- MARE-1 activities are in progress to
  - improve the understanding of $^{187}$Re experiment systematics
  - a few eVs light neutrino sensitivity $^{187}$Re experiment is starting soon
- investigate $^{163}$Ho decay spectrum
  - $^{163}$Ho isotope has been produced and is ready for first tests
- develop the single MARE pixel
  - R&D for coupling TES, MMC and MKID with $^{187}$Re/$^{163}$Ho is in progress
- implement read-out multiplexing schemes
- isotope and technique selection for MARE-2 is in progress