A new limit on $0\nu\beta\beta$-decay of $^{100}\text{Mo}$ from the CUPID-Mo demonstrator for CUPID

Benjamin Schmidt (CUORE, CUPID/CUPID-Mo)
Single beta decay and the neutrino

Wolfgang Pauli, “Letter to the radioactive ladies and gentlemen”, (1930)

Offener Brief an die Gruppe der Radioaktiven bei der Gauvereins-Tagung zu Züringen.

Abschrift
Physikalisches Institut
der Eidg. Technischen Hochschule
Zürich
Zürich

Liebe Radioaktive Damen und Herren,

Wie der Überbringer dieser Zeilen, den ich halbvolle anzubühren bitte, Ihnen das nähere auszumundet werden, bin ich angewiesen der "falschen" Statistik der Ne und Li6 Kerna, sowie das kontinuierlich-beta-Spektrum auf einen vermeintlichen Ausweg verfallen um den "Neuelektas" (1) der Statistik und den Energien des neu zu retten. Möchte die Möglichkeit, es können elektrisch neutrale Teilchen, die ich Neutrons nennen will, in dem Namen existieren, welche den Spin 1/2 haben und das Ausschliessungsprinzip befolgen und sich von Lichquanten am messen noch durch unterscheiden, dass sie gleich mit Lichtgeschwindigkeit laufen. Wie Namen der Neutrons

2 - body expected e-Energy (18.6 keV)
Single beta decay and the neutrino

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Zürich, 4. Dez. 1930
Gloriastrasse

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vertreten um den "Nachweis" (1) der Statistik und den Energiezust

zu retten. Möchte die Möglichkeit, es käme elektrisch neutrale

Teilchen, die ich Neutrons nennen will, in den Namen existieren,

welche den Spin 1/2 haben und das Ausschöpfungsprinciple befolgen und

dass von Lichtquanten ausserdem noch dadurch unterschieden, dass sie

gleich mit Lichtgeschwindigkeit laufen. Die Name der Neutrons

Neutrinoless double beta decay
Light Majorana neutrino exchange

\[
(T_{1/2}^{0\nu/\beta\beta})^{-1} = G^{0\nu} |M^{0\nu}|^2 \frac{\langle m_{\beta\beta} \rangle^2}{m_e^2}
\]

Effective Majorana mass:

\[
\langle m_{\beta\beta} \rangle^2 = |\sum_{i=1,2,3} U_{e,i}^2 m_i|
\]

Energy (keV)

0
500
1000
1500
2000
2500
3000
3500
4000

Fraction of counts / keV

10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}

\(100\text{Mo}\)

\(2\nu\beta\beta\)

\(0\nu\beta\beta\) (hypothetical)
Neutrinoless double beta decay
Light Majorana neutrino exchange

\[
(T_{1/2}^{0\nu\beta\beta})^{-1} = G_{0\nu}^0 |M_{0\nu}|^2 \frac{\langle m_{\beta\beta} \rangle^2}{m_e^2}
\]

Effective Majorana mass

\[
\langle m_{\beta\beta} \rangle^2 = |\Sigma_{i=1,2,3} U_{e,i}^2 m_i|
\]

Phase space

Nuclear Matrix Element (NME)
CUPID-Mo Neutrino 2020 results, LBNL seminar 06/29/2020

Benjamin Schmidt, Lawrence Berkeley National Laboratory

Normal hierarchy

Inverted hierarchy

Other isotopes

Mo

Se

Ge

Xe


Im

Real

\langle m_{\beta\beta} \rangle^2

m_{\beta\beta} \text{ Vector addition/Cancellation in complex space}

Normal ordering

Inverted ordering

\begin{align*}
\text{atmospheric} & \sim 2 \times 10^{-3} \text{eV}^2 \\
\text{solar} & \sim 7 \times 10^{-5} \text{eV}^2
\end{align*}
The experimental challenge

Probe a process with a half-life larger $> 10^{25}$ yr - $10^{26}$ yr

Next generation:
Need to find single events in a ton of isotope $x$ year(s) of exposure!
$3 \times 10^{-14}$ Bq/g

We go to extreme length to limit ubiquitous radioactivity

x $10^5$ yr

15 Bq / banana
Experimentally considered $0\nu\beta\beta$ isotopes

11 / 35 experimentally considered candidate isotopes

Isotope choice considerations:
high Q-value (3034 keV) -> large phase space, typically low natural radioactivity backgrounds

Backgrounds
-> improve signal/background through good energy resolution
-> dedicated Background suppression/particle ID
Scintillating cryogenic Li$_2$MoO$_4$ calorimeters

Source $^{100}$Mo = Detector Li$_2$MoO$_4$ high efficiency

Copper: Thermal Bath

NTD-Ge thermistor as sensor

$R(T) = R_0 e^{T_0/T}$

Light Detector

Teflon: weak thermal link

C(T) $\propto T^3$

Bolometer

Ge light detector

Balometer

Light

Thermometers

Energy release

NTD-Ge thermistor

Copper: Thermal Bath
Scintillating cryogenic Li$_2$MoO$_4$ calorimeters

Thermal bath @ 20 mK

C(T) $\propto T^3$

Figure 3: Operating principle of a scintillating bolometer. The release of energy inside a scintillating crystal follows two channels: light production and thermal excitation.

A scintillating bolometer functions by operating a scintillating crystal as a cryogenic bolometer (as described above) and coupling it to a light detector, as shown in Fig. 3. As it is for other large mass bolometers, the device works only at extremely low temperatures ($\ll 10$ mK).

When a particle traverses the scintillating crystal and interacts with the lattice, a large fraction of the energy is transferred into the crystal as heat, raising the internal energy, thus inducing the already mentioned temperature rise. A small fraction of the deposited energy produces scintillation light that propagates as photons outside the crystal. These are then detected by a separate light detector facing the crystal. The light detectors used so far for scintillating bolometers are bolometers themselves and consist of germanium wafers, kept at the same temperature as the main bolometer. Scintillation photons deposit heat into the wafer and induce a temperature rise, which is then measured by a second thermistor.

The signals registered by the two thermistors are conventionally named heat (the one generated in the main bolometer) and light (the one induced in the light detector). Although they have the same nature (temperature rises), they originate by different processes.

An interesting feature of scintillating bolometers is that the ratio between the light and heat signals depends on the particle mass and charge. Indeed, while the thermal response of a bolometer has only a slight dependence on the particle
CUPID-Mo at Laboratoire Souterrain de Modane France (2018 - 2020)

- 4800 m.w.e. rock overburden
- shared EDELWEISS cryogenic infrastructure operated at @ 20 - 22 mK
- 20 Li$_2^{100}$MoO$_4$ detectors of ~210 g, ~97% enriched (2.26 kg $^{100}$Mo)
- Ge light detectors
- Ge-NTD based sensor readout
- **All Li$_2^{100}$MoO$_4$, 19 light detectors operational**
- physics data taking March 2019 - June 2020
CUPID-Mo design

As of April 2020:
Accumulated > 2.3 kg*yr of physics data (Blinded)

[Image of a mountain landscape]
Laboratoire Souterrain de Modane

As of April 2020:
Accumulated > 2.3 kg*yr of physics data (Blinded)
Laboratoire Souterrain de Modane
The EDELWEISS/CUPID-Mo cryogenic infrastructure

Active and passive shielding designed for the EDELWEISS-II dark matter search (Final results in 2010)

- 100 m² plastic scintillator muon-veto system
- 50 cm PE shielding
- 20 cm lead shield
  - innermost 2 cm is roman lead
- Radon free air circulation in between lead and Cu cryostat
- Inversed geometry wet dilution refrigerator with GM cryocoolers for 100K screen and He liquefier
  - 10 days between LHe refill
- In-house front end electronics (Grenoble)
The CUPID-Mo design

Crystal growth and $^{100}$Mo enrichment

NIIC, Novosibirsk, Russia

- purification of enriched Mo (from the NEMO-3 experiment) to MoO$_3$
- low radioactivity Li$_2$CO$_3$
- double crystallization (low thermal gradient Czochralski technique)
- surface polish with radio-pure SiO$_2$ oil based slurry
- Storage in dry N$_2$ atmosphere (Li$_2$MoO$_4$ is slightly hygroscopic)

4.158 kg Li$_2$MoO$_4$
2.264 kg $^{100}$Mo
Modular tower design:

- Compatible with existing EDELWEISS cryostat design
- Detector mounting in CSNSM & LAL clean-rooms (Orsay)
- Decoupling of LMO and light detectors from vibrations
- NOSV-Cu for radio-purity
CUPID-Mo tower suspension

Suspended tower design

Particularly important for the LD operation in (dry + wet) cryostat with vibrations from thermal machines
CUPID-Mo calibration

- LMO detectors have relatively low mass ~210 g and low density 3.07 g/cm$^3$
- Significant amount of time dedicated to calibration (2 days / LHe refill) 20-25% of data taking

- Low energy calibration sources are potentially dangerous for the EDELWEISS dark matter search
- Use the Mo x-ray escape peak from high intensity irradiation of the crystals ($^{60}$Co)

CUPID-Mo calibration results

1. **LMO detectors** have relatively low mass (~210 g) and low density (3.07 g/cm$^3$).
2. A significant amount of time was dedicated to calibration (2 days / LHe refill), which accounted for 20-25% of data taking.

Low energy calibration sources are potentially dangerous for the EDELWEISS dark matter search. To mitigate this risk, the Mo x-ray escape peak from high intensity irradiation of the crystals ($^{60}$Co) was utilized.
CUPID-Mo performance

- Li$_{2}^{100}$MoO$_{4}$ scintillates at 600 nm
- Typical measured light yield of ~0.6/0.7/0.9 (keV/MeV) for $\beta,\gamma$
  - Difference in light yield expected from tower design
  - $\alpha$ scintillation light yield of 20% - compared to $\beta,\gamma$
  - > 99.9% alpha separation extrapolated for all detectors

- Good uniformity/performance suitable for larger arrays!
  CUPID-Mo commissioning results
  EPJ-C 80:44 (2020)
CUPID-Mo: The Neutrino 2020 data

- March 2019 - April 2020 (380 days)
- **7 Long datasets**, 1-2 month scale
- 3 Short datasets (single calibration periods)
  Not used in the Neutrino analysis - extra work needed on energy-scale uncertainty
- Rejection of periods of temperature instabilities

<table>
<thead>
<tr>
<th></th>
<th>Days (tot)</th>
<th>Days (sel)</th>
<th>Exposure kg x yr</th>
<th>Retained</th>
</tr>
</thead>
<tbody>
<tr>
<td>Physics</td>
<td>240</td>
<td>200 (224)</td>
<td>2.17 (2.4)</td>
<td>94%</td>
</tr>
<tr>
<td>Calibration</td>
<td>73</td>
<td>59 (65)</td>
<td>0.6 (0.7)</td>
<td>88%</td>
</tr>
<tr>
<td>Special</td>
<td>21</td>
<td>—</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>Downtime</td>
<td>46</td>
<td>—</td>
<td>—</td>
<td>—</td>
</tr>
</tbody>
</table>
CUPID-Mo: Data production and cuts

Trigger efficiency

Base cuts
Single trigger
BaselineSlope

Multiplicity
Pulser rejection
M1 - single crystal

Pulse Shape analysis
Principal component analysis (PCA)

Light Yield
Sum of LD
Consistency of LD

Muon veto anti-coincidence

CUPID-Mo Neutrino 2020 results, LBNL seminar 06/29/2020
Benjamin Schmidt, Lawrence Berkeley National Laboratory
CUPID-Mo: Trigger efficiency

- Use of Optimum Filter to obtain lower thresholds
- Surplus coincidence information
- Choose conservative 10 sigma trigger threshold
- Evaluation of trigger efficiency: Inject avg. pulse template into noise
  - Typical LMO threshold ~ 11 keV (90% efficiency), fully efficient above analysis threshold (45 keV)
  - Typical LD threshold ~ 0.5 keV (90% efficiency)
CUPID-Mo: Data quality cuts

- No energy dependence of these cuts
- No line of sight between LMO detectors
- Appreciable $^{210}\text{Pb}$, $^{210}\text{Po}$ presence
- $^{210}\text{Po}$ serves as a clean sample of events (no pulser, heat-only other event contamination) for the efficiency estimate

Base cuts

- Single trigger
- BaselineSlope

Multiplicity

- Pulser rejection
- M1 - single crystal

(Muon veto anti-coincidence)

Light detector

CUPID-Mo Preliminary

$\varepsilon \sim 98\%$
CUPID-Mo - Pulse Shape Analysis

- Perform a Principal Component Analysis (PCA)
- Train on 1 MeV - 2 MeV 2νββ events in physics data
- 1st component - contains main amplitude information - similar to average pulse
- Define the (Normalized) Reconstruction Error $E$ with respect to 1st (1st plus 2nd) PCA component as pulse shape analysis variable

$$E = \sum_{i} (x_{i,rec.} - x_i)^2$$

1st PCA component

Linear energy dependence

Predictive extrapolation to 3 MeV
CUPID-Mo - Pulse Shape Analysis

- Optimize PCA cut based on the goal of mitigating pile-up on calibration data
- Maximize signal sensitivity using Cowan's metric
  \[ \sqrt{2(S + B) \cdot \ln(1 + \frac{S}{B}) - S} \]
  - \( S \) = NEMO-3 exclusion limit
  - \( B \) = Bg from 2615 keV tails (scaled)
- Under further study to improve pile-up rejection

- Efficiency evaluation (physics data)
  - Evaluate PCA cut with LY cuts applied
  - Fit of 1st order polynomial in high stat. \( 2\nu\beta\beta \) region
  - Evaluation of fit uncertainty at \( Q_{\beta\beta} \); 1% Dataset level

\[ Q_{\beta\beta} (3034 \text{ keV}) \]

\[ \varepsilon \sim 97\% \]
CUPID-Mo - The light yield cuts

Example Heat/Light separation
(PCA cut applied)
200 days of physics data

Light Yield
Weighted sum of LD
Consistency of LD
CUPID-Mo - The light yield cuts

LY cut defined with 3 sigma acceptance on calibration data

Example Heat/Light separation (PCA cut applied)
200 days of physics data
CUPID-Mo - The light yield cuts

- Efficiency evaluation (physics data)
  - Evaluate the LD cut efficiency from the $2\nu\beta\beta$ spectrum after applying the PSA cut

- Systematics from energy extrapolation
  - Excess broadening with respect to expected LD width, $\sqrt{\sigma_{E}^2 + n_{\text{Scint}} \times 2.07 \text{ eV}}$ observed
  - Consider two models
    - Excess broadening $\alpha E$ — excess broadening $\alpha \sqrt{E}$
    - systematic quantification with Toy MC incl. fit uncertainties $^{+0.9}_{-0.2}$ %

Attach diagrams and figures as needed.
### CUPID-Mo - Analysis cut efficiencies

<table>
<thead>
<tr>
<th>Cut \ DATASET</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
</tr>
</thead>
<tbody>
<tr>
<td>Base</td>
<td>99.0(3)</td>
<td>100</td>
<td>99.8(2)</td>
<td>99.9(1)</td>
<td>99.9(1)</td>
<td>99.7(3)</td>
<td>99.7(2)</td>
</tr>
<tr>
<td>Slope</td>
<td>98.2(1)</td>
<td>98.6(2)</td>
<td>98.4(1)</td>
<td>98.8(1)</td>
<td>98.9(1)</td>
<td>98.9(1)</td>
<td>99.0(1)</td>
</tr>
<tr>
<td>M1</td>
<td>97.3(6)</td>
<td>98.0(6)</td>
<td>97.2(6)</td>
<td>97.6(5)</td>
<td>98.3(5)</td>
<td>98.8(6)</td>
<td>97.8(5)</td>
</tr>
<tr>
<td>Light Det</td>
<td>96.8(2)</td>
<td>96.7(2)</td>
<td>95.5(2)</td>
<td>97.5(1)</td>
<td>97.5(2)</td>
<td>97.2(2)</td>
<td>97.2(2)</td>
</tr>
<tr>
<td>PCA</td>
<td>96.6(9)</td>
<td>96.8(11)</td>
<td>97.2(7)</td>
<td>96.2(7)</td>
<td>96.6(10)</td>
<td>97.6(11)</td>
<td>98.9(10)</td>
</tr>
<tr>
<td>Total</td>
<td>88.4(11)</td>
<td>90.5(12)</td>
<td>88.6(9)</td>
<td>90.4(9)</td>
<td>91.4(11)</td>
<td>92.3(13)</td>
<td>92.9(13)</td>
</tr>
</tbody>
</table>

Total efficiency (exposure weighted avg.) \( \epsilon = (90.5 \pm 0.4 \text{ (stat.)} \, ^{+0.9}_{-0.2} \text{ (syst.)}) \% \)
CUPID-Mo the blinded data

- 19/20 detectors with good performance
- Analysis efficiency 90.5%
- 200 days of physics data, 
  ~7 keV FWHM @ 2615 keV (calibration)
CUPID-Mo - ROI definition for counting analysis

Detector resolution

CUPID-Mo Preliminary

CUPID-Mo Preliminary

$0\nu\beta\beta$ containment Bremsstrahlung escape

CUPID-Mo Preliminary

ROI definition

CUPID-Mo Preliminary

CUPID-Mo Preliminary
CUPID-Mo - Energy scale

- Energy scale is set with pol2 in calibration data
- Check consistency in time in calibration data

- Estimate possible energy bias based on physics data, $E_B = (-0.2 \pm 0.4)$ keV
CUPID-Mo - ROI (Ch,DS) based resolution

- Simultaneous unbinned extended maximum likelihood (UEML) fit to extract the Ch,DS-based resolutions
  - Fit model:
    - smeared step function (multi-compton)
    - Gauss (photopeak)
    - Linear (multi-photon + 2νββ)
  - $\rightarrow$ Extract the gaussian width on a Ch,DS basis
CUPID-Mo ROI resolution scaling

- Obtain a global scaling factor Calibration @2615 keV <-> Physics @3034 keV
- Test several hypothesis:
  - linear, sqrt, pol2 fit -> linear is ruled out by calibration data -> take remaining more conservative estimate (pol2)

\[ \chi^2/NDF = 0.9601 / 3 \]
Ratio Extrapolation @3034 keV: 1.0593 ± 0.1024
FWHM at 3034 keV is: 7.6757 keV ± 0.7468 keV

\[ Q_{\beta\beta}^{100\text{Mo}} \]
FWHM at 3034 keV is: 7.6757 keV

\[ p_0 = 1.47590 \times 10^0 \pm 1.5028 e-03 \]
\[ p_1 = 1.83680 \times 10^{-2} \pm 1.9581 e-03 \]

CUPID-Mo, Neutrino 2020
2.17 kg x yr, Preliminary
CUPID-Mo ROI definition
Bg index from Geant4 MC model

- Detailed Geant4 MC model

- Two fits: RooFit and JAGS (MCMC)
  - M1 - Gamma analysis: BI expectation for $0\nu\beta\beta$ ROI
  - 4 ± 2 counts /keV/kg/yr
CUPID-Mo ROI definition
Bg index from sideband data

- Perform unbinned extended maximum likelihood fit on Bg data excluding [3010, 3060] keV
- Phenomenological Bg model:
  - Exponential - approximates both $2\nu\beta\beta$ spectral shape and U/Th calibration tail
  - Flat component - conservative estimate of $2\nu\beta\beta$ pile-up and remaining muon-induced events
CUPID-Mo - ROI

- Optimize signal ROI for Poisson counting analysis in Signal, Background likelihood space
- Maximize mean limiting setting sensitivity for a poisson counting analysis with
  - an expected final CUPID-Mo exposure of 2.8 kg x yr
  - a background index of 0.005 counts /keV/kg/yr

→ Large central ROI ~18 keV average width
CUPID-Mo - Limit setting

Two analyses:
- Bayesian counting analysis in central ROI + sidebands (3 bin fit)
  - Central bin/ROI: 75% Signal & Bg
  - Sideband: 1% Signal & Bg
  - Bg: Exponential + flat
  - Use Gaussian priors on exponential from fit in [2650,2980] keV region
- Poisson counting analysis as cross-check

Toy study

Toy-MC study
- CUPID-Mo, Neutrino 2020 2.17 kg×yr, Preliminary

0 counts in ROI - Poisson limit
- 0 cts ROI
- 1 cts ROI
- 2 cts ROI
CUPID-Mo - New $0\nu\beta\beta$ result

New world leading limit on $0\nu\beta\beta$ of $^{100}\text{Mo}$

$T_{1/2}^{0\nu} > 1.4 \cdot 10^{24}$ yr, 90% c.i. (stat. + syst.)

perfectly consistent with Poisson analysis
CUPID-Mo systematics

- Isotope concentration (96.6 ± 0.2) %
- Containment (~75% on average in peak)
  - Geant4 modeling & density/volume uncertainty: 1.1 %
  - Energy scale and resolution uncertainties included with MC sampling in containment of chosen ROI
- Analysis efficiency
  - All cuts stat. & PCA extrapolation - Gaussian prior
  - LD resolution model - Uniform, asymmetric
    \[ \epsilon = (90.5 \pm 0.4 \text{ (stat.)} \pm 0.9 \text{ (syst.)}) \% \]
- Potential non gaussianity - Containment reduction
  - Use 2615 keV peak in calibration data - (2.5 ± 2.5)\%
CUPID-Mo - Effective Majorana Neutrino mass

With only 1 year of data and ~2 kg of $^{100}$Mo CUPID-Mo is able to set a limit of $m_{\beta\beta} < (0.31-0.54)$ eV 90% c.i. considering $g_A = 1.27$ and the following NME calculations:

New world leading limit on $0\nu\beta\beta$ of $^{100}\text{Mo}$,
Neutrino 2020 poster #419

$T_{1/2}^{0\nu} > 1.4 \cdot 10^{24}$ yr, 90% c.i. (stat. + syst.)

- 2$\nu\beta\beta$ result, CUPID-Mo technology (arXiv: 1912.07272), Neutrino 2020 poster #525

$T_{1/2}^{2\nu} = [7.12^{+0.18}_{-0.14} \text{ (stat.)} \pm 0.10 \text{ (syst.)}] \cdot 10^{18}$ yr

- Preliminary status/results from Bg model analysis Neutrino 2020 poster #418
  - Bg index of $[4 - 5] \times 10^{-3}$ counts/keV/kg/yr in $0\nu\beta\beta$ ROI with non-optimized setup for dark matter search, (lower than expected)

- Further CUPID-Mo updates at NEUTRINO 2020:
  - $0\nu\beta\beta/2\nu\beta\beta$ decay to excited states & low energy prospects, $^{56}\text{Co}$ high energy calibration Neutrino 2020 posters #374, #382, #448
CUPID-Mo - What’s next?

Physics data taking finished as of June 20th
2.8 kg x yr total (before cuts) - 20-30 % more data

Currently ongoing high energy calibration campaign
Fe wire irradiated at 88-inch (LBNL) in collaboration by
Andrew Voyles and Rick Normann -> ~660 Bq activity in $^{56}\text{Co}$
Currently deployed at Laboratoire Souterrain de Modane

Next up:
Focus on Bg model and
$2\nu\beta\beta$ precision analyses,
$0\nu\beta\beta/2\nu\beta\beta$ to excited states
and low mass dark matter search
CUPID-Mo results for CUPID

- Excellent crystal radiopurity *(Neutrino 2020 poster #404)*
  - [0.3 - 1] μBq/kg for U/Th
    - 100 μBq/kg \(^{210}\)Pb

- \(\text{Li}_2\text{MoO}_4\) bolometric performance in non-optimal environment
- Efficient alpha rejection over 1 year of data taking
  - LD performance hit due to AC-biasing/demodulation sampling limitation (0.5 kHz)

- High analysis efficiency \(\epsilon = (90.5 \pm 0.4 \text{ (stat.)} \pm 0.9 \pm 0.2 \text{ (syst.)})\)%
- ~7 keV calibration resolution @ 2615 keV
- ~8 keV physics resolution @ 3034 keV
  - ~20 mK instead of ~10-15 mK
  - Sub-optimal/(No) heater based gain-stabilization
The CUPID-Mo collaboration

UCB and LBNL led analysis team: Giovanni Benato, Toby Dixon, Roger Huang, Laura Marini, Benjamin Schmidt, Vivek Singh and Bradford Welliver
Neutrino 2020 Poster links:
CUPID-Mo $0\nu\beta\beta$ analysis
CUPID-Mo performance
CUPID-Mo $^{56}\text{Co}$ calibration campaign
CUPID-Mo background model
CUPID-Mo low energy analysis prospects
CUPID-Mo sensitivity for $0\nu\beta\beta/2\nu\beta\beta$ decay to excited states
2nbb analysis with CUPID-Mo technology