AMoRE

25-26 Jun @ K-v Symposium 2025, Chung-Ang University

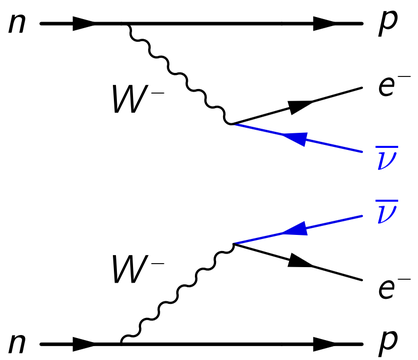
Yoomin Oh, Daehoon Ha for AMoRE Collaboration

CENTER FOR UNDERGROUND PHYSICS ibs

AMoRE physics

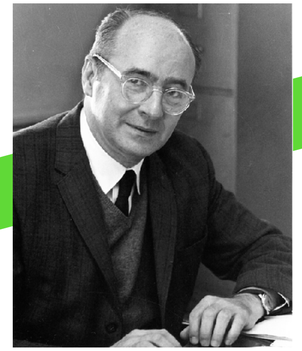
Neutrinoless double beta decay (0νββ)

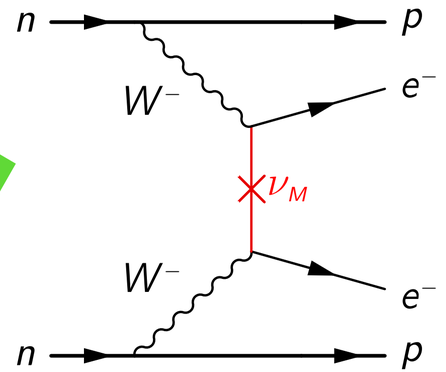
- Fundamental properties of neutrino
  - Majorana or Dirac nature?
  - Absolute mass scale?











TEORIA SIMMETRICA DELL'ELETTRONE
E DEL POSITRONE

Nota di ETTORE MAJORANA

IL NUOVO CIMENTO 14, 171 (1937)

Sunto. - *Si dimostra la possibilità di pervenire a una piena simmetrizzazione formale della teoria quantistica dell'elettrone e del positrone facendo uso di un nuovo processo di quantizzazione. Il significato delle equazioni di* DIRAC *ne risulta alquanto modificato e non vi è più luogo a parlare di stati di energia negativa; nè a presumere per ogni altro tipo di particelle, particolarmente neutre, l'esistenza di « antiparticelle » corrispondenti ai « vuoti » di energia negativa.*

L'interpretazione dei cosidetti « stati di energia negativa » proposta da DIRAC (1) conduce, come è ben noto, a una descrizione sostanzialmente simmetrica degli elettroni e dei positroni. La sostanziale simmetria del formalismo consiste precisamente in questo, che

DECEMBER 15, 1939 PHYSICAL REVIEW VOLUME 56

On Transition Probabilities in Double Beta-Disintegration

W. H. FURRY
Physics Research Laboratory, Harvard University, Cambridge, Massachusetts
(Received October 16, 1939)

The phenomenon of double β-disintegration is one for which there is a marked difference between the results of Majorana's symmetrical theory of the neutrino and those of the original Dirac-Fermi theory. In the older theory double β-disintegration involves the emission of four particles, two electrons (or positrons) and two antineutrinos (or neutrinos), and the probability of disintegration is extremely small. In the Majorana theory only two particles—the electrons or positrons—have to be emitted, and the transition probability is much larger. Approximate values of this probability are calculated on the Majorana theory for the various Fermi and Konopinski-Uhlenbeck expressions for the interaction energy. The selection rules are derived, and are found in all cases to allow transitions with $\Delta i = \pm 1, 0$. The results obtained with the Majorana theory indicate that it is not at all certain that double β-disintegration can never be observed. Indeed, if in this theory the interaction expression were of Konopinski-Uhlenbeck type this process would be quite likely to have a bearing on the abundances of isotopes and on the occurrence of observed long-lived radioactivities. If it is of Fermi type this could be so only if the mass difference were fairly large ($\epsilon \gtrsim 20$, $\Delta M \gtrsim 0.01$ unit).

AMoRE physics + α

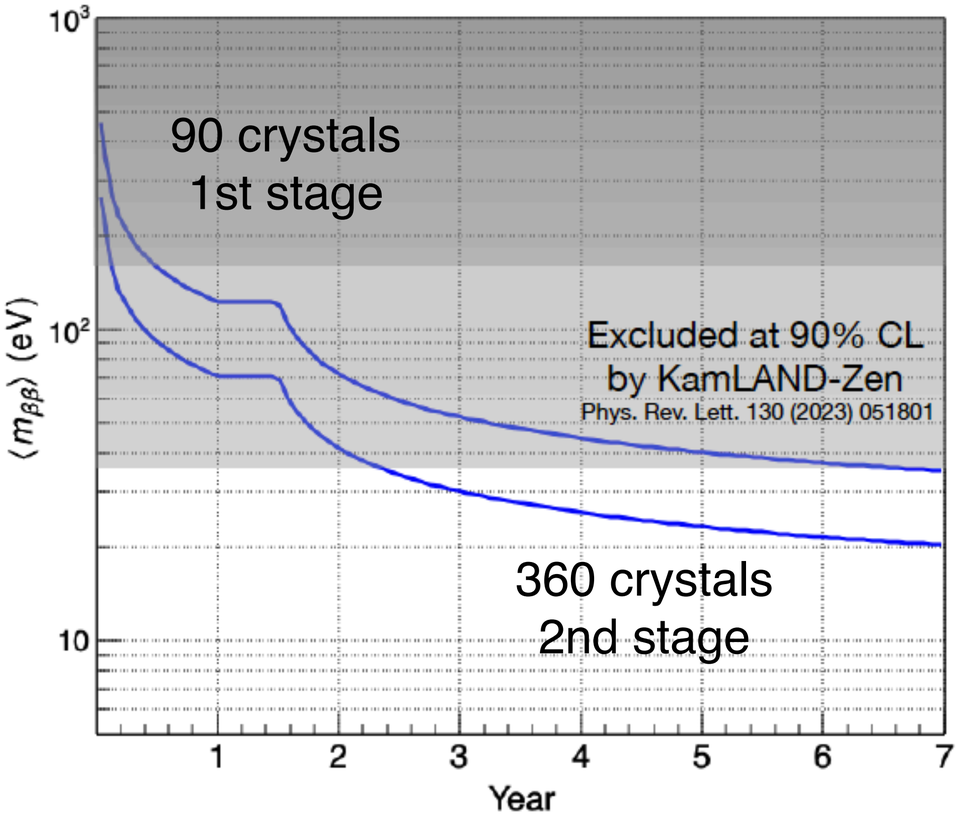
- Solar axion search ($^{7}Li_2MoO_4$).
- Neutrinoless double electron capture ($^{40}CaMoO4$).
- ***ββ* decay of ^{100}Mo to excited state(s) of ^{100}Ru** — Poster by **Daehoon Ha**.

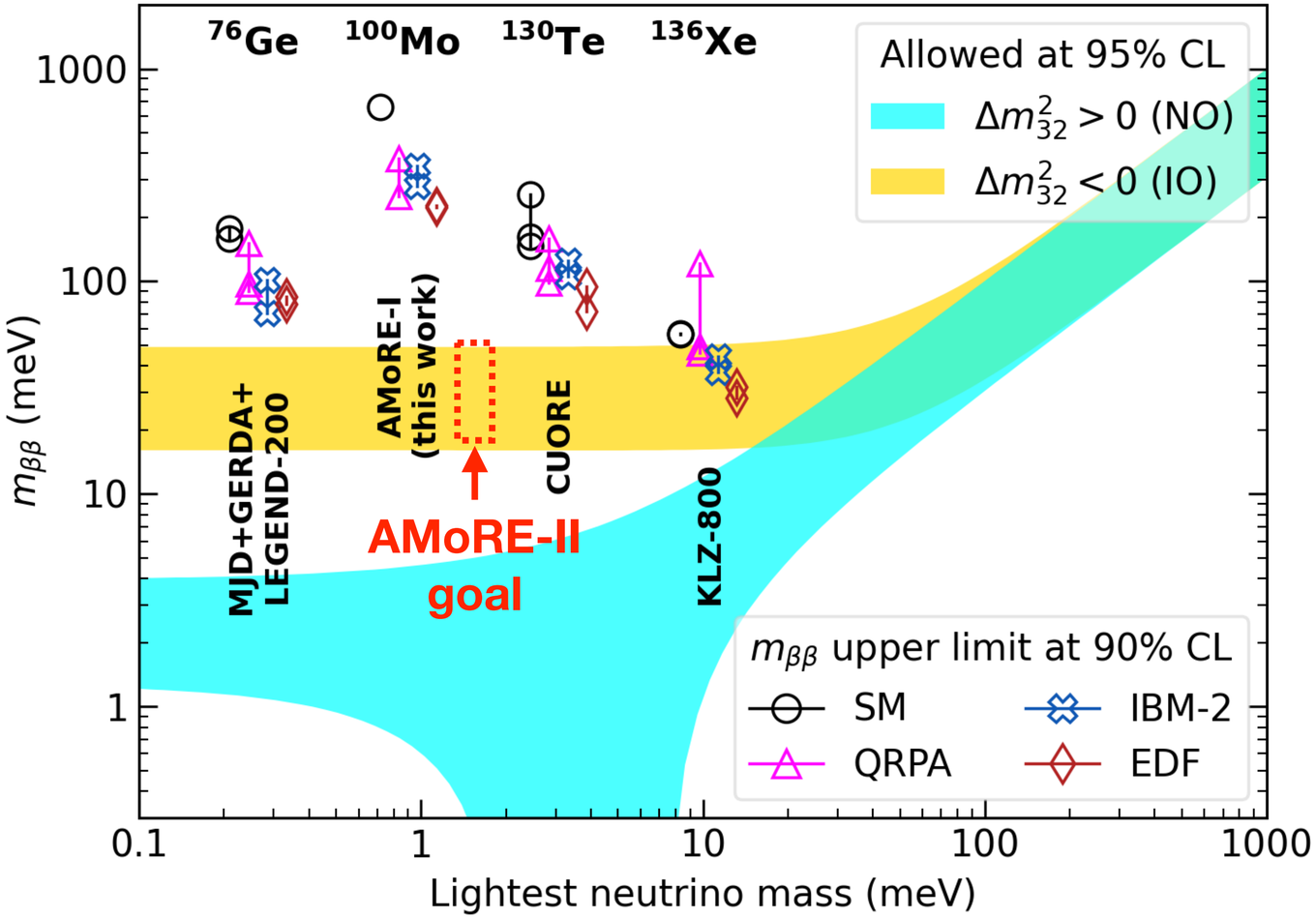
- Crystal production.
- Low temperature detector techniques—MMC.
- Background reduction—shielding optimization.
- Underground laboratory operation, environmental control.
- Radioassay and material purification.

AMoRE phases

- AMoRE-pilot: 2015–2018, Yangyang Underground Laboratory (Y2L)
  - 6 $^{48depl}CaMoO_4$ crystals (1.9 kg).
  - Demonstration of the detection principle.
  - Understanding and reduction of background.
- AMoRE-I: 2020–2023, Y2L
  - 13 $CaMoO_4$ + 5 Li_2MoO_4 (6.2 kg).
  - Shielding enhancements, more background reduction.
  - World best limit for 0νββ half-life of ^{100}Mo.
- AMoRE-II: starting in 2025, Yemilab
  - Starting with 90 crystals, upgrade to 360 crystals

Experimental sensitivity





AMoRE publications: collaborative highlights

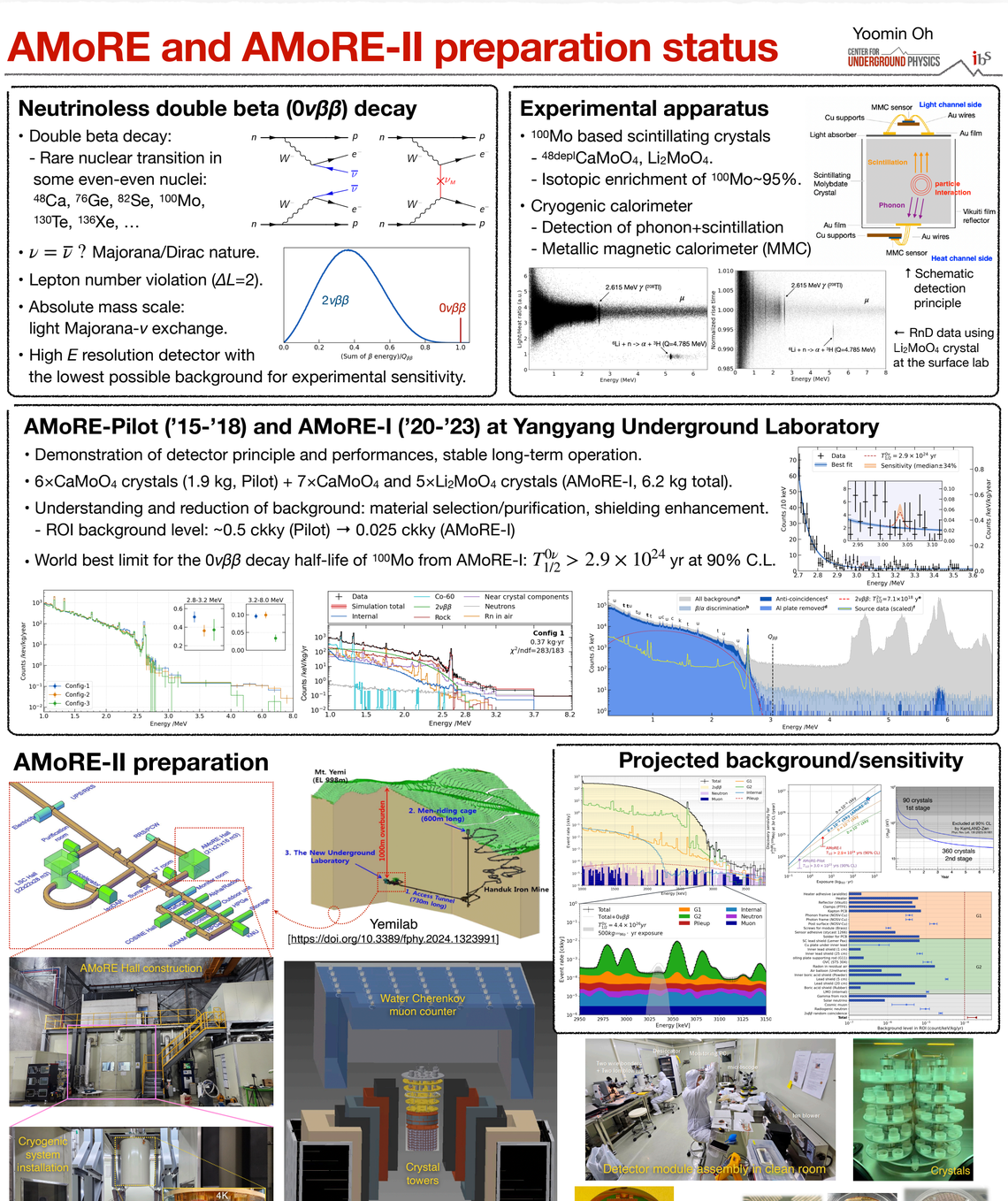
- *"First results from the AMoRE-Pilot neutrinoless double beta decay experiment"*, (2019) https://doi.org/10.1140/epjc/s10052-019-7279-1.
- *"Background study of the AMoRE-pilot experiment"*, (2024) https://doi.org/10.1016/j.astropartphys.2024.102991.
- *"Improved limit on neutrinoless double beta decay of ^{100}Mo from AMoRE-I"*, (2025) https://doi.org/10.1103/PhysRevLett.134.082501.

- *"Radioassay of the materials for AMoRE-II experiment"*, (2024) https://doi.org/10.3389/fphy.2024.1362209.
- *"Development of MMC-based lithium molybdate cryogenic calorimeters for AMoRE-II"*, (2024) https://doi.org/10.1140/epjc/s10052-024-13498-8.
- *"Projected background and sensitivity of AMoRE-II"*, (2024) https://doi.org/10.1140/epjc/s10052-024-13516-9.

Collaboration

~20 institutes, 100+ researchers





Poster 1.

AMoRE and AMoRE-II preparation status

- Overview of the AMoRE project.
- AMoRE phases and existing results, progress.
- AMoRE-II prospects and preparation status.

Poster 2.

Study of ββ decay of ^{100}Mo to the excited states of ^{100}Ru in AMoRE

- Rarer process than ββ decay-to-ground-state.
- Verification of NME calculations.
- Bosonic neutrino?
- More details of data analysis.
- Prospect in AMoRE-II.

Study of double beta decay of ^{100}Mo to the excited states of ^{100}Ru in AMoRE

HA Daehoon[a], *Hongjoo Kim[b], on behalf of AMoRE collaboration
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Abstract

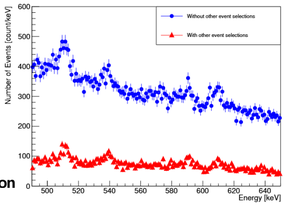
Studies of double beta ($2\nu\beta\beta$) decay to various excited states in different isotopes provide valuable insights into nuclear structure models. The AMoRE, which utilizes an array of ^{100}Mo-enriched $CaMoO_4$ and Li_2MoO_4 crystal scintillators, is advantageous for investigating $2\nu\beta\beta$ decay of ^{100}Mo to the excited states of ^{100}Ru.
In the AMoRE-I phase, we measured the half-life of $2\nu\beta\beta$ transition of ^{100}Mo to the 0_1^+ state of ^{100}Ru using a total of 16 crystal detectors, and the half-life value is (6.83 ± 0.71 (stat) ± 0.32 (sys)) × 10^{20} years. The half-life limit for the $2\nu\beta\beta$ transition to the 2_1^+ state of ^{100}Ru is set as 2.5 × 10^{21} years (90% C.I.).
A prospective study of $2\nu\beta\beta$ decay to the excited states of ^{100}Ru has been conducted for AMoRE-II. Considering the increased crystal mass and measurement time, the error-to-signal ratio for the $2\nu\beta\beta$ decay of ^{100}Mo to the 0_1^+ state is expected to decrease significantly from 6.3% to 0.3%. The half-life sensitivity to the $2\nu\beta\beta$ decay of ^{100}Mo to 2_1^+ state of ^{100}Ru in AMoRE-II is estimated as limit $T_{1/2}$ ~ 1.20 × 10^{23} years. The triple-crystal-hit conditions event can be measured in AMoRE-II, that will be useful for observing the pure elections energy distribution.

AMoRE-I: Study of $2\nu\beta\beta$ decay to excited states

Data
- 486.6 days of PROD data were analyzed.
- SE02 and LMO2 crystals were excluded.
- Only double crystal hit events were considered.
  - Double crystal hit probability: 32.9%
  - Triple crystal hit probability: 6.3%

Process
- Event selections
  - Muon tagging
  - Position
  - Energy
  - Signal time difference
- Calibrations
  - Energy calibration
  - Signal time calibration

Double-hit event energy distribution



Study motivation: $2\nu\beta\beta$ decay to excited states of ^{100}Mo

Half life and NME of $2\nu\beta\beta$ decay

$$\left(T_{1/2}^{2\nu}\right)^{-1} = G_{2\nu}\left|M^{2\nu}\right|^2$$

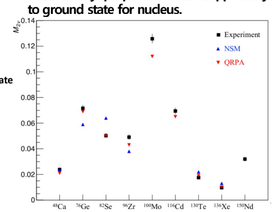
$G_{2\nu}$: Phase space factor
$M^{2\nu}$: Nuclear Matrix Element (NME)

$$M^{2\nu} = \langle f|O'_x|m\rangle\langle m|O_x|i\rangle$$

$i), m), f)$: initial, mediate, final eigenstate function
O_x: transition operator

Due to the dependence of the calculated NME on the nuclear structure model, experimentally measured half lives of $2\nu\beta\beta$ decay transitions to various energy states in different isotopes can provide valuable input for nuclear structure model studies.

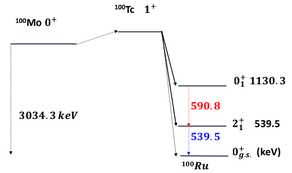
Theoretically proposed NMEs 2νββ decay to ground state for nucleus.



S.Y. Park. Measurements of Double Beta Decay of ^{100}Mo to the excited States of ^{100}Ru using HPGe Detectors.

Half life equation

Decay scheme (^{100}Mo to ^{100}Ru)



- ^{100}Mo has a natural abundance of 9.7% and can be enriched.
- Due to its high Q-value, the 2νββ ($0^+ \rightarrow 0_1^+$) decay of ^{100}Mo to ^{100}Ru has a measurable half-life.
- $2\nu\beta\beta$ decays to ΔJ ≠ 0 excited states study can be sensitive to find the bosonic neutrino.

] A. S. Barabash, et al., Nucl. Phys. B 783, 90 (2007)

Half life table of $2\nu\beta\beta$ to ground state

Nucleus	Average Value ($T_{1/2}^{2\nu}$) [year]
^{48}Ca	$5.3^{+1.2}_{-0.8} \times 10^{19}$
^{76}Ge	$1.88 \pm 0.08 \times 10^{21}$
^{82}Se	$0.87^{+0.02}_{-0.01} \times 10^{20}$
^{96}Zr	$2.3 \pm 0.2 \times 10^{19}$
^{100}Mo	$7.06^{+0.15}_{-0.13} \times 10^{18}$
^{116}Cd	$2.69 \pm 0.09 \times 10^{19}$
^{130}Te	$7.91 \pm 0.21 \times 10^{20}$
^{136}Xe	$2.18 \pm 0.05 \times 10^{21}$
^{150}Nd	$8.4 \pm 1.1 \times 10^{18}$

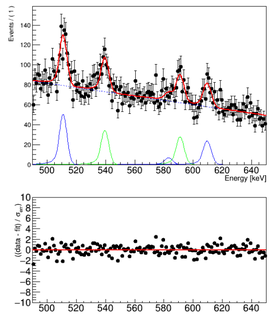
Half life table of $2\nu\beta\beta$ to excited state

Nucleus	Average Value ($T_{1/2}^{2\nu}$) [year]
^{150}Nd to (0_1^+)	$1.2^{+0.3}_{-0.2} \times 10^{20}$
^{100}Mo to (0_1^+)	$6.7^{+0.5}_{-0.4} \times 10^{20}$

National Research Centre "Kurchatov Institute", Institute of Theoretical and Experimental Physics, B. Cheremushkinskaya 25, 117218 Moscow, Russia

AMoRE-I results: Study of $2\nu\beta\beta$ decay the 0_1^+ state

Fit histogram



The log-likelihood fit with the Gaussian constraints

$$\mathcal{L} = \frac{Y^N e^{-Y}}{N!}\prod_i^N P_i^{total}\prod_j^M e^{-\frac{1}{2}\frac{P_j^2}{\sigma_j^2}}$$

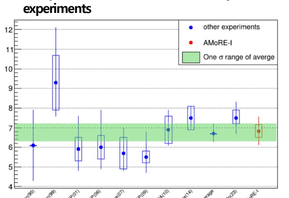
$$P_i^{total} = \frac{1}{Y}\left(\begin{array}{c} Y_{540}P_{i,540}^{cb} + Y_{591}P_{i,591}^{cb} \\ +Y_{511}P_{i,511}^{cb} + Y_{583}P_{i,583}^{cb} + Y_{609}P_{i,609}^{cb} \\ +Y_{pol}P_i^{pol} \end{array}\right)$$

$$where, \quad Y_{pol} = Y - (Y_{540} + Y_{591} + Y_{511} + Y_{583} + Y_{609})$$

Results table of Study of $2\nu\beta\beta$ decay to excited states of ^{100}Mo

AMoRE-I	Results [× 10^{20}year] ± stat ± sys
539.5 keV	$6.57 \pm 0.91 \pm 0.34$
591.8 keV	$7.13 \pm 1.10 \pm 0.32$
weighted average	$6.83 \pm 0.71 \pm 0.32$
Soudan(95)	6.1 ± 1.8
Soudan(99)	$9.3^{+2.8}_{-1.7} \pm 1.4$
TUNL-ITEP(01)	$5.9^{+1.7}_{-1.1} \pm 0.6$
TUNL-ITEP(06)	$6.0^{+1.9}_{-1.1} \pm 0.6$
Modane(07)	$5.7^{+1.3}_{-0.9} \pm 0.8$
TUNL-ITEP(09)	$5.5^{+1.2}_{-0.8} \pm 0.3$
ARMONIA(10)	$6.9^{+1.0}_{-0.8} \pm 0.7$
Modane(14)	$7.5 \pm 0.6 \pm 0.6$
Average	$6.7^{+0.5}_{-0.4}$
CUPID-Mo(23)	$7.5 \pm 0.8^{+0.4}_{-0.3}$

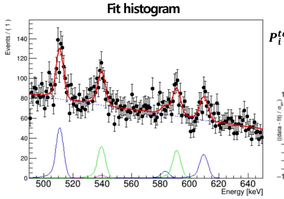
Comparison of the results from the previous experiments



A.S.Barabash et al (1995, 1999); Braedeleeret al (2001); R.Arnold et al (2007); M.F.Kidd et al (2009);P.Belli et al (2010); R.Arnold et al (2014).

AMoRE-I results: Study of $2\nu\beta\beta$ decay to the 2_1^+ state

Fit histogram



$$P_i^{total} = \frac{1}{Y}\left(\begin{array}{c} \left(\varepsilon_{540}^{0_1^+}/\varepsilon_{591}^{0_1^+}\right) \times Y_{591}^{0_1^+})P_{i,540}^{cb} + Y_{591}^{0_1^+}P_{i,591}^{cb} + Y_{540}^{2_1^+}P_{i,540}^{cb} \\ +Y_{511}P_{i,511}^{cb} + Y_{583}P_{i,583}^{cb} + Y_{609}P_{i,609}^{cb} \\ +Y_{pol}P_i^{pol} \end{array}\right)$$

Half-life limit:
2.5×10^{21} **year(90% c.i.)**

$2\nu\beta\beta$ decay to excited states of ^{100}Mo and AMoRE

The multi-crystal hit condition enabled by AMoRE's multi-detector structure offers an advantage for studying 2νββ decay to excited states.

AMoRE-Polit 2015-2018 | AMoRE-I 2020-2023 | AMoRE-II 2024 -



Schematics of multi crystal hit



Prospective study of 2νββ to excited states at AMoRE-II

P2. ββ decay of ^{100}Mo to the excited states of ^{100}Ru

