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

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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.

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

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

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

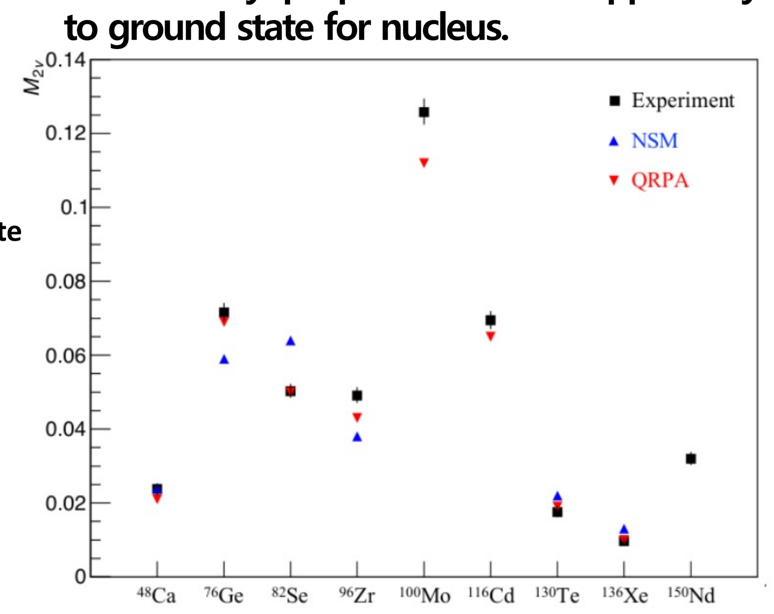
$G_{2\nu}$: Phase space factor
$M^{2\nu}$: Nuclear Matrix Element (NME)

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

$i\rangle, m\rangle, f\rangle$: 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.

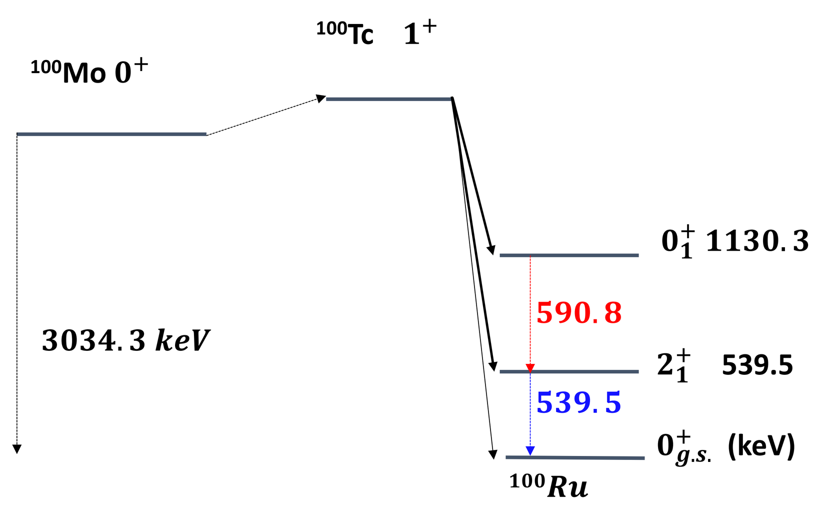
Theoretically proposed NMEs 2νββ decay to ground state for nucleus.



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 2vββ (0⁺ → 0₁⁺) 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.

[1] 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^+)	$6.7^{+0.5}_{-0.4} \times 10^{20}$ [1]

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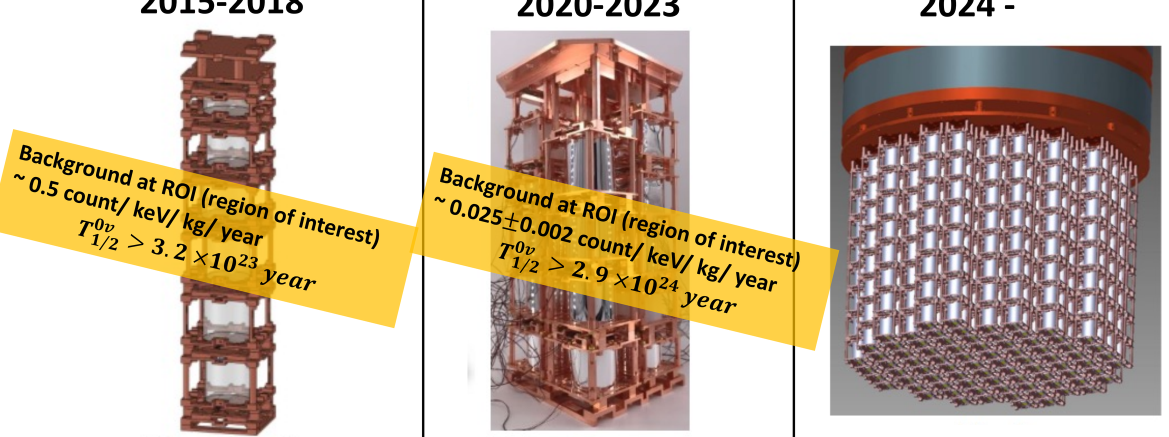
$2\nu\beta\beta$ decay to excited states of ^{100}Mo and AMoRE

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

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

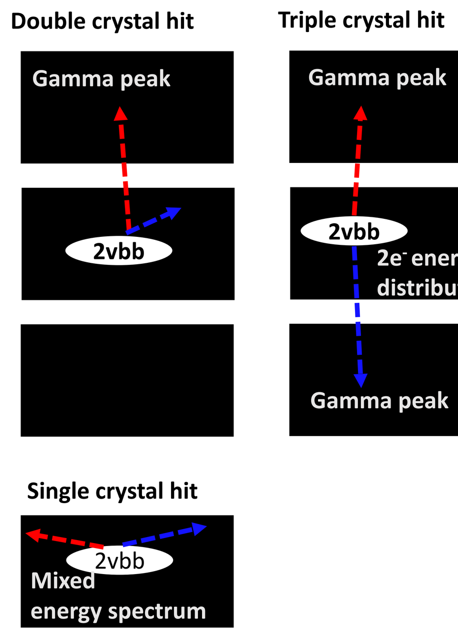


AMoRE-Polit:
- ✓ 6 $^{48dep}CaMoO_4$ Crystals
  - ✓ 1.9 (0.88) kg of CMO (^{100}Mo)
- ✓ In Yangyang Underground Lab (Y2L)

AMoRE-I:
- ✓ 13 $^{48dep}CaMoO_4$ Crystals
- ✓ 5 $LiMoO_4$ crystals
  - ✓ 6.2(3.0) kg of XMO (^{100}Mo)
- ✓ In Y2L

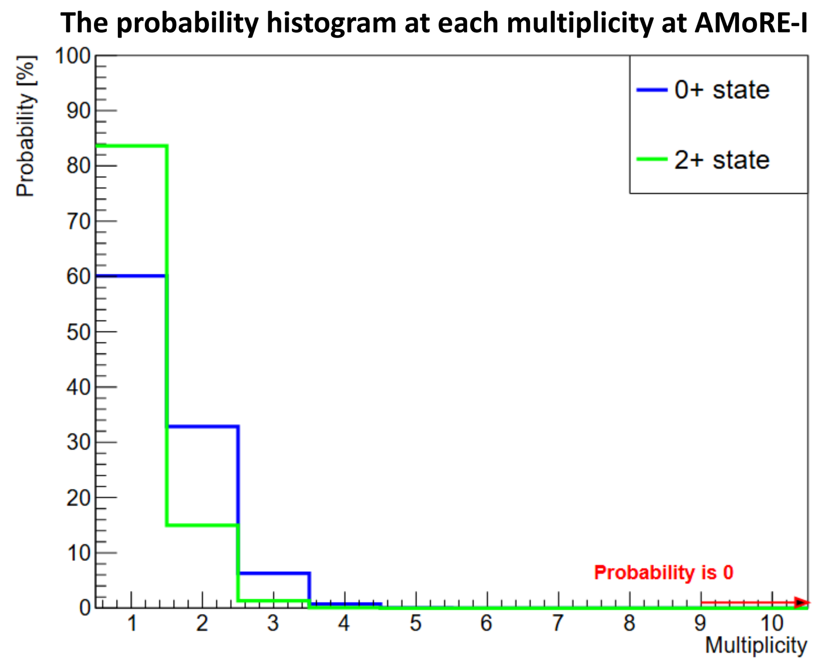
AMoRE-II:
- ✓ 157 kg of XMO
- ✓ Expected exposure > 500 $kg_{100_{Mo}} \cdot yr$
- ✓ In Yemilab

Schematics of multi crystal hit

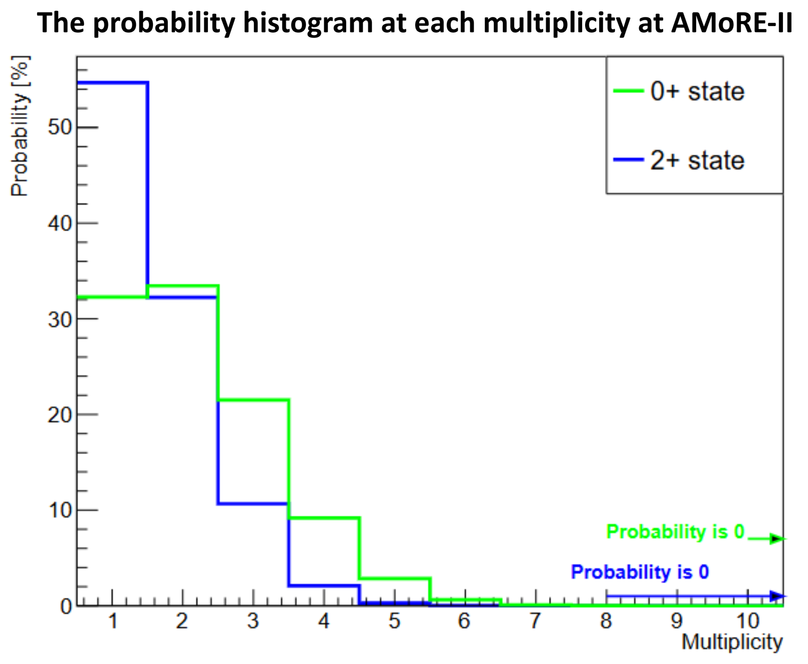


Probability of a multi-crystal hit (Geant4 simulation)

The probability histogram at each multiplicity at AMoRE-I



The probability histogram at each multiplicity at AMoRE-II

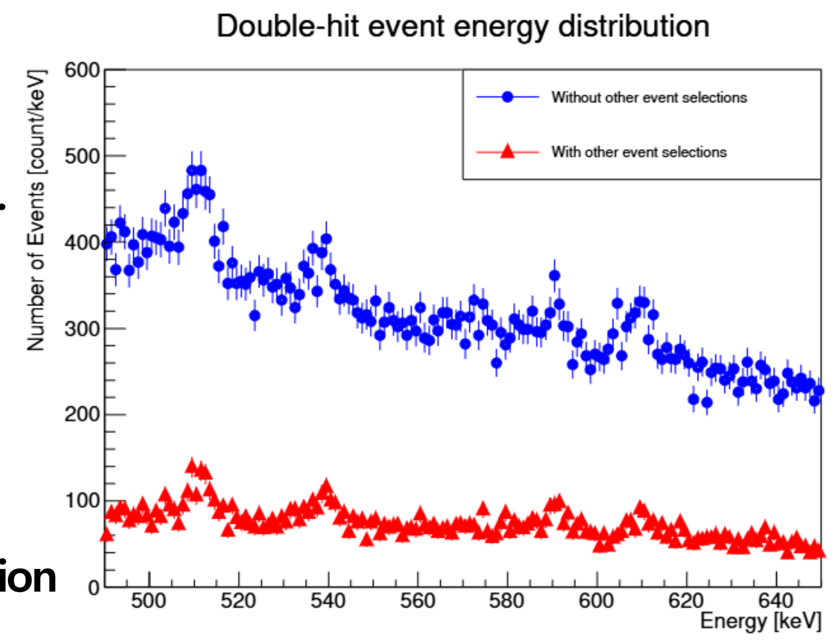


AMoRE-I: Study of $2\nu\beta\beta$ decay to excited states

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%

Double-hit event energy distribution

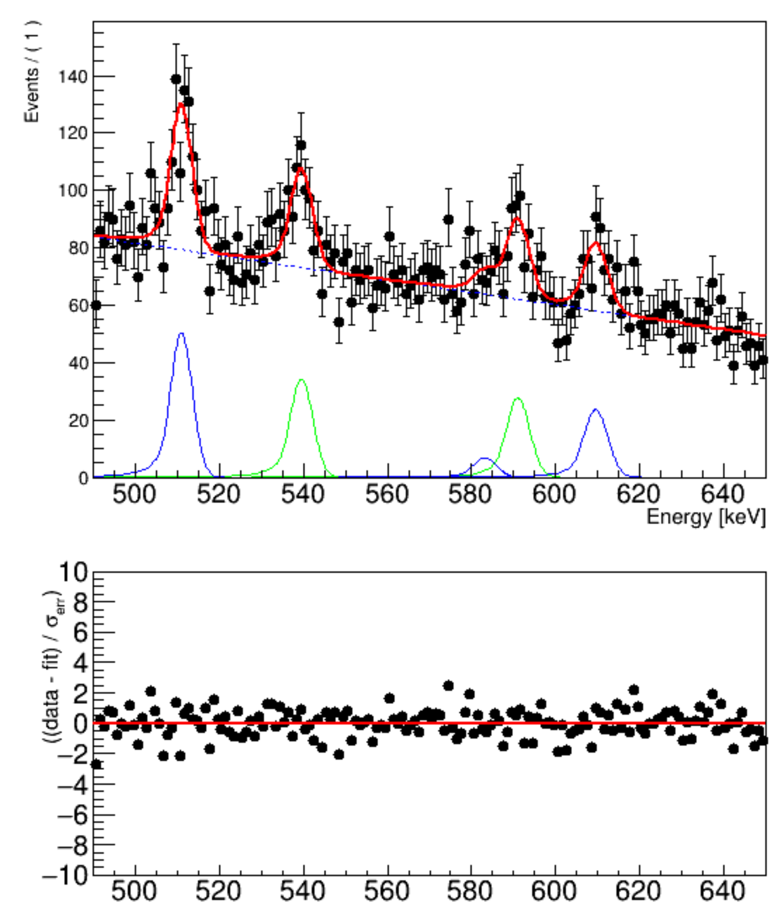


Process

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

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

Fit histogram



The log-likelihood fit with the Gaussian constraints

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

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

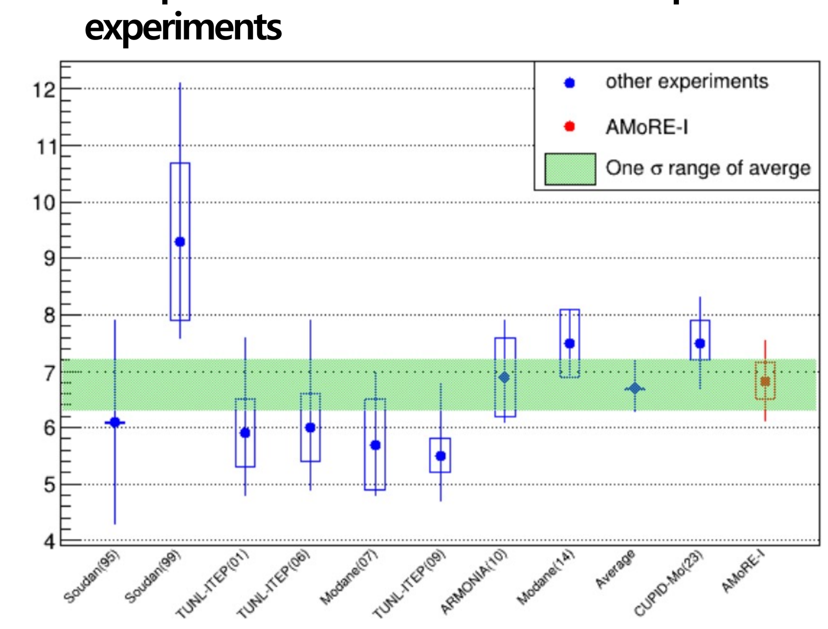
where,

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

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)	$7.5 \pm 0.8^{+0.4}_{-0.3}$

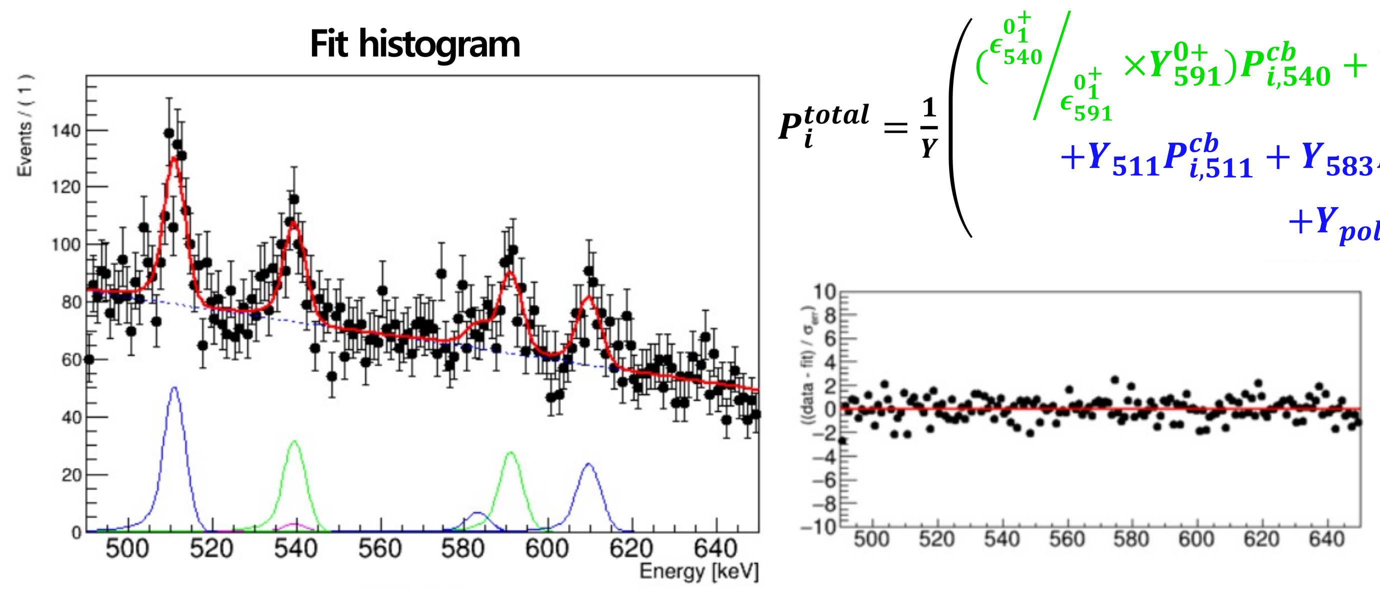
Comparison of the results from the previous experiments



A.S.Barabash et al (1995, 1999); Braeckeleeret 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

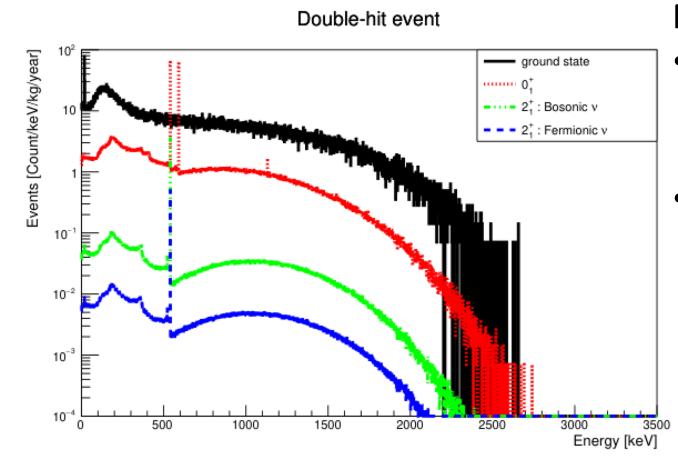
Fit histogram

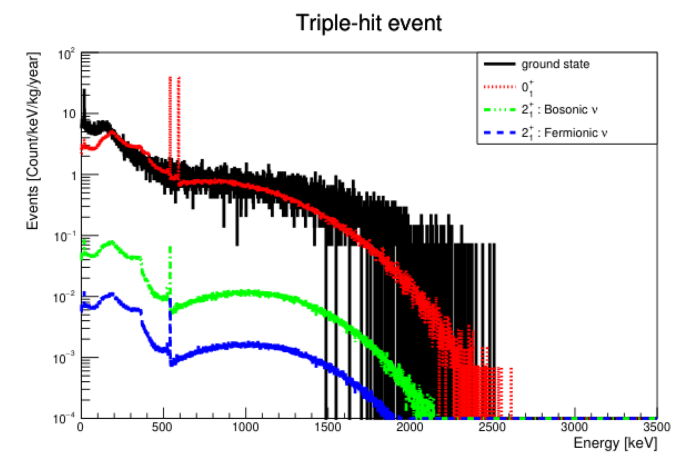


$$P_i^{total} = \frac{1}{Y}\left(\begin{array}{c} \left(\epsilon_{540}^{0_1^+}/\epsilon_{591}^{0_1^+} \times Y_{591}^{0+}\right)P_{i,540}^{cb} + Y_{591}^{0+}P_{i,591}^{cb} + Y_{540}^{2+}P_{i,540}^{cb} \\ +Y_{511}P_{i,511}^{cb} + Y_{583}P_{i,583}^{cb} + Y_{609}P_{i,609}^{cb} \\ +Y_{pol}P_i^{pol} \end{array}\right)$$

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

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





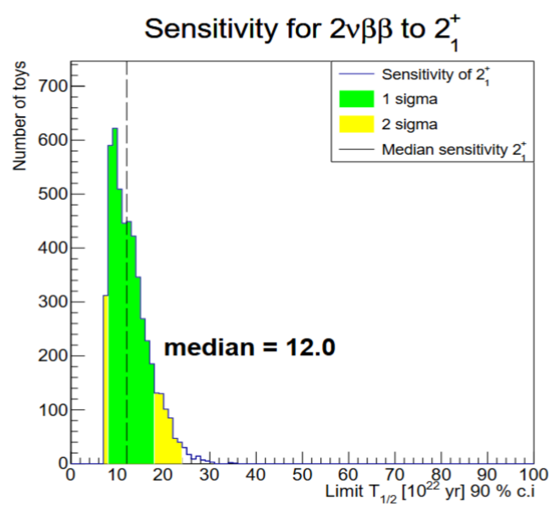
Probability improvement

- Probability of 2vββ to 0+
  - Double crystal hit: 33.4% (32.9%)
  - Triple crystal hit: 21.5% (6.3%)
- Probability of 2vββ to 2+
  - Double crystal hit: 32.2% (15.0%)
  - Triple crystal hit: 10.7% (1.3%)

Statistical improvement

- Ratio of the error to 540 keV peak count at 2vββ to 0+: ~0.3% (AMoRE-I: ~ 6.3%)

Sensitivity for 2vββ to 2_1^+



The conceptual equation

$$N_{540\ keV}^{2+} = N_{540\ keV}^{tot} - N_{540\ keV}^{0+}$$

Expected Half-life limit:
1.20×10^{23} year(90% c.i.)

Summary

study of 2vββ to excited states at AMoRE-II

AMoRE-I: 0_1^+ state	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	$6.83 \pm 0.71 \pm 0.32$
AMoRE-I: 2_1^+ state	> 25 (90% c.i.)

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

- In AMoRE-II, we can observe the triple-hit signal generated by 2vββ to 0+.
- The statistical error of the half-life of 2vββ to 0+ will be reduced by approximately a factor of 0.05.
- The sensitivity of 2vββ to 2+ at AMoRE-II is >1.20×10^{23} year.