Symposium on frontiers of underground and space particle physics and cosmophysics

Cosmogenic background simulation and measurement for ^{100}Mo-based bolometric experiment at CJPL

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On behalf of CUPID-CJPL collaboration

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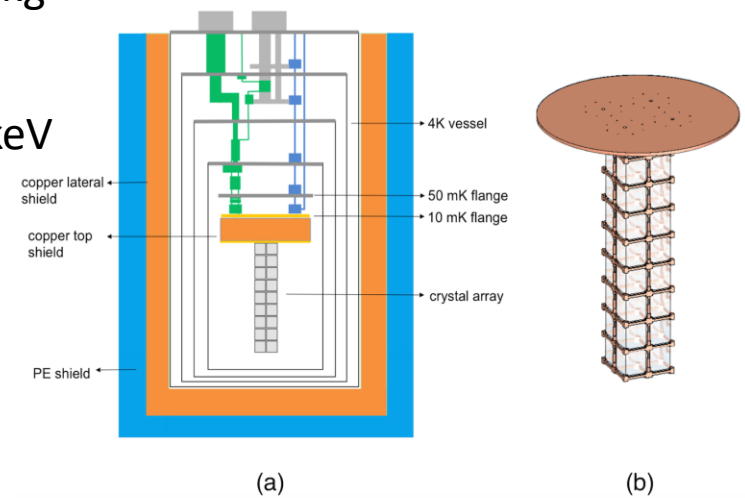
Contents

^{100}Mo based LMO bolometric demonstration experiment

- 4×9 ^{100}Mo enriched Li_2MoO_4 array, total mass 10 kg
- $45 \times 45 \times 45$ mm^3 0.28 kg per cubic crystal
- $Q_{\beta\beta} = 3034.40 \pm 0.17$ keV, ROI = (3000, 3060) keV
- Copper and Polyethylene(PE) shields



Background Studies

- Including external background sources and activation in crystal and shielding
- External background sources including environmental radioactivity like ^{222}Rn, ^{238}U *et al.*, cosmic rays
- Environmental radioactivity can be shielded effectively with copper and PE shields
- Activation in crystal and shielding including cosmogenic and intrinsic contamination

Motivation

Cosmic ray air showers

- High energy particles hit earth at all time
- Last particles come down to the ground mainly are ps, ns, γs, μs

Cosmogenic background sources

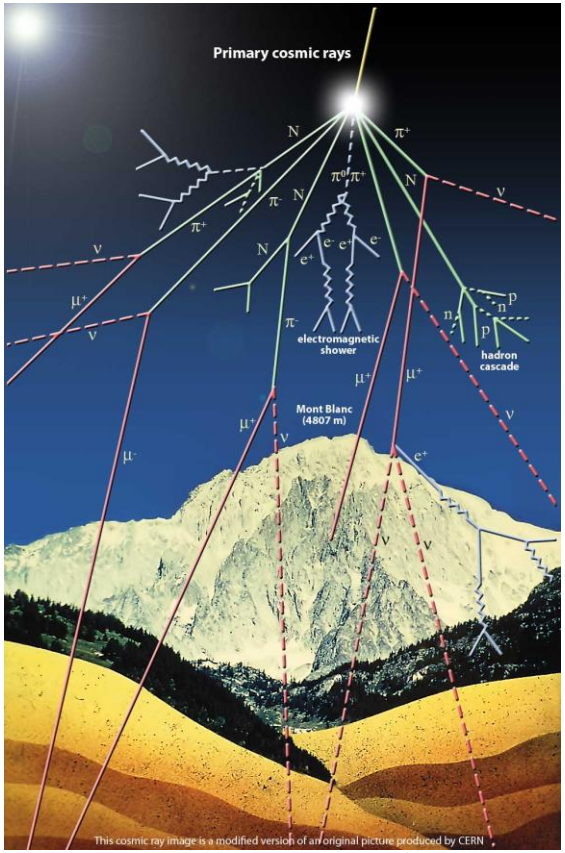
- Direct influence of cosmic ray at deep underground laboratory can be ignored

  Muon vertical intensity at CJPL: $2.0 \times 10^{-10}\ \mathrm{cm^{-2}s^{-1}sr^{-1}}$

  Z.-y. Guo *et al.*, Chinese Physics C **45**, 025001 (2021).

  Muon at sea level: $6.2 \times 10^{-3}\ \mathrm{cm^{-2}s^{-1}sr^{-1}}$

  S. Pal *et al.*, JCAP07(2012)033
- Materials exposure at the surface when produced and transported
- Q > 3000 keV, long life time radionuclides are dangerous
- Potential radionuclides: ^{56}Co, ^{82}Rb from ^{82}Sr, ^{88}Y and ^{88}Y from ^{88}Zr



http://www.scifun.ed.ac.uk/card/card-left.html

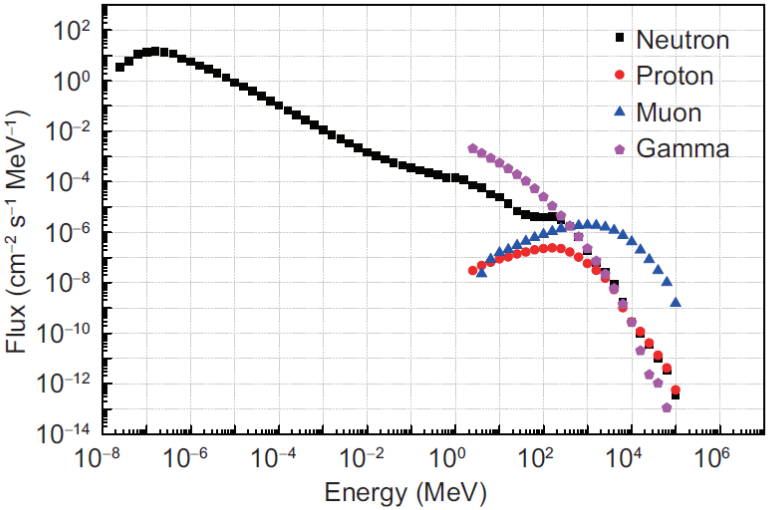
Cosmic-Ray Shower Generator(CRY)

http://nuclear.llnl.gov/simulation

Hagmann, C., *et al.* 2007 IEEE Nuclear Science Symposium Conference Record, 2, 1143-1146.

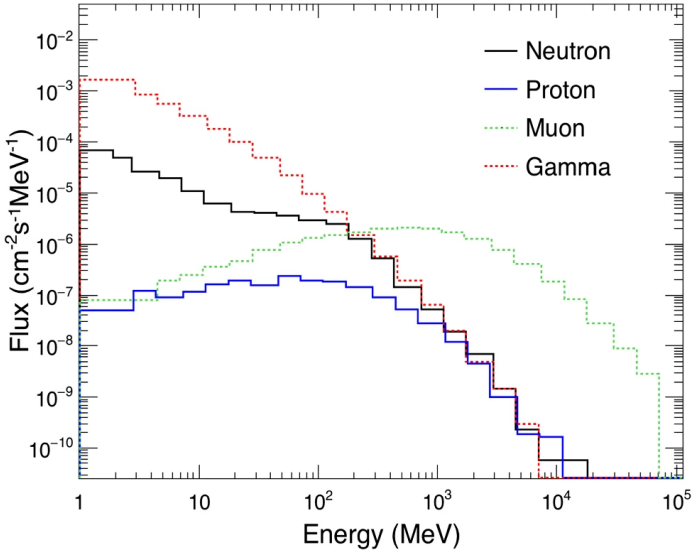
The software library generates correlated cosmic-ray particle shower distributions at one of three elevations(sea level, 2100 m, and 11300 m)

- The cosmic ray distribution at Beijing sea level from J. L. Ma et al.



J. L. Ma *et al.*, Sci China Phys Mech **62** (2019).

- The cosmic ray distribution at Shanghai sea level

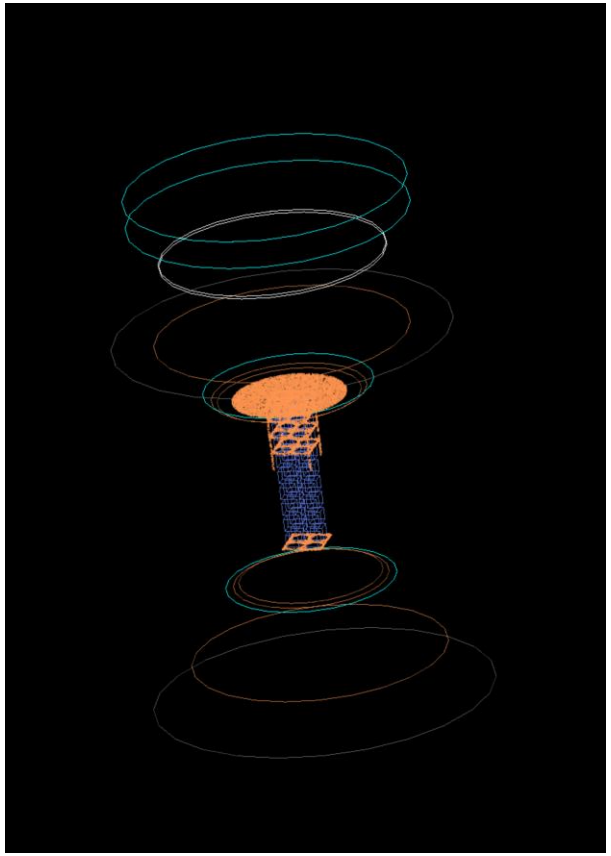


Cosmic-ray fluxes($cm^{-2}s^{-1}$) in Beijing and Shanghai sea level

Areas	Neutron	Proton	Gamma	Muon
Beijing (N 40°)	2.00×10^{-3}	1.657×10^{-4}	1.682×10^{-2}	1.182×10^{-2}
Shanghai (N 31°)	$1.726^{+0.136}_{-0.07} \times 10^{-3}$	$1.386^{+0.094}_{-0.046} \times 10^{-4}$	$1.57^{+0.08}_{-0.04} \times 10^{-2}$	$1.134^{+0.054}_{-0.027} \times 10^{-2}$

Geant4 simulation set-up

Detector & Target



Physics List selection

QGSP_BERT_HP

- same as QGSP_BERT, but with high precision neutron model
- used for neutrons below 20 MeV
- can be used for radiation protection and shielding applications

Shielding

- based on FTFP_BERT
- Mix and match of FTF and BERT at transition region
- JENDL and Barashenkov cross section of neutron used instead

Activation Calculation with Various Toolkit

Production Rate

$$P = \sum_i N_i \sum_j \int_0^\infty \sigma_{ij}(E_j)\phi_j(E_j)dE_j$$

element i

cosmic ray particle j

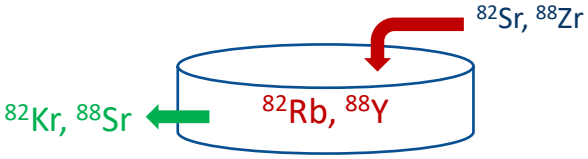
Cross section

Flux of cosmic ray

Number of nucleis

Activation calculation

- $N(t_1) = \frac{P}{\lambda}(1 - e^{-\lambda t_1})$ get the yield after being exposure time t_1
- $N(t_1 + t_2) = \frac{P}{\lambda}(1 - e^{-\lambda t_1})e^{-\lambda t_2}$ get the last yield after cooling time t_2
- For nuclides with cascade the calculation is more complex



Flux of Cosmic-ray

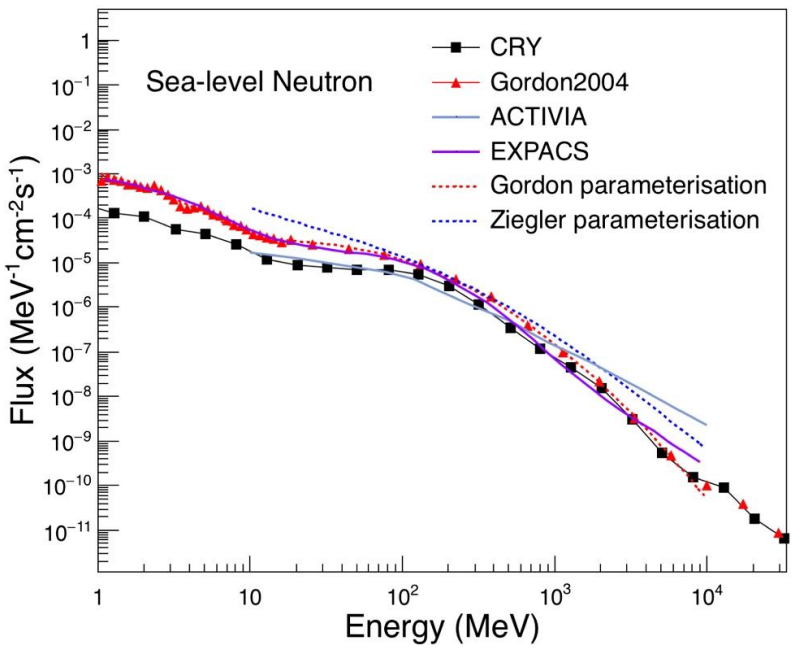
ACTIVIA https://doi.org/10.1016/j.nima.2007.12.008

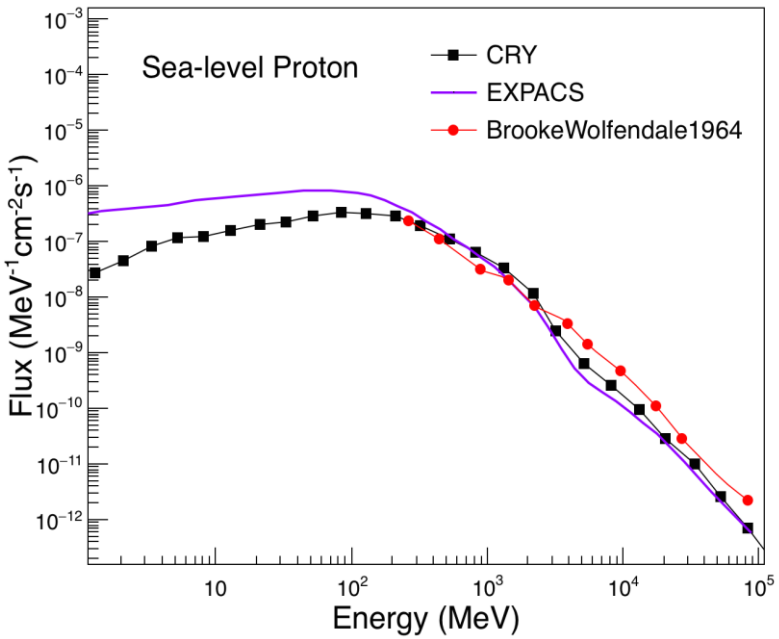
- Using parameterization from Armstrong and Gehrels as cosmic ray spectrum input
- Calculating cross section by using data tables and semi-empirical formulae from Silberberg and Tsao

EXPACS https://phits.jaea.go.jp/expacs/

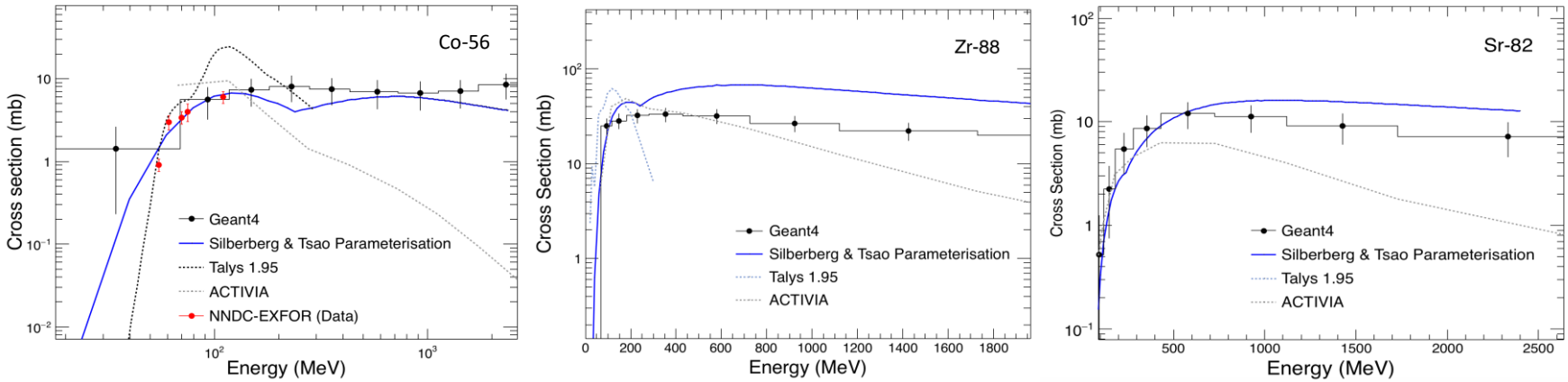
- Represents "EXcel-based Program for calculating Atmospheric Cosmic-ray Spectrum“
- Can instantaneously calculate terrestrial cosmic ray fluxes

- CRY lower than experimental data below 100 MeV
- ACTIVIA lager than CRY at high energy





Cross Section



- Production cross section used in Geant4 compatible with experimental data and parameterized formula below 1 GeV
- All differences were concluded into system uncertainty

Production Rates

Production rates ($kg^{-1}day^{-1}$) at Shanghai sea level

*solar activity in addition

Radionuclide	Target	Half-life (days)	Neutron	Proton	Gamma	Muon	Total	ACTIVIA
^{56}Co	Copper	77.3	6.36 ± 0.51	0.85 ± 0.06	0.10 ± 0.01	0.02 ± 0.00	7.33 ± 0.51	8.70
^{88}Zr	LMO	83.4	5.48 ± 0.43	0.77 ± 0.05	0.10 ± 0.01	0.07 ± 0.00	6.42 ± 0.43	5.18
^{88}Y	LMO	106.6	1.99 ± 0.15	0.28 ± 0.02	0.22 ± 0.01	0.00	2.47 ± 0.15	1.10
^{82}Sr	LMO	25.4	1.85 ± 0.16	0.33 ± 0.02	0.00	0.01 ± 0.00	2.19 ± 0.16	1.25
^{56}Co	LMO	77.3	0.04 ± 0.01	0.03 ± 0.00	0.00	0.00	0.07 ± 0.01	0.04

*almost neutron induced

*2 magnitude lower

Neutron induced production rates at New York sea level

Radionuclide	Target	CRY	Gordon2004[1]	ACTIVIA	Ziegler[2]	EXPACS
^{56}Co	Copper	8.32	15.75	6.30	14.47	11.98
^{88}Zr	LMO	7.15	14.16	5.72	14.30	11.02
^{82}Sr	LMO	2.39	4.54	2.10	4.19	3.00
^{56}Co	LMO	0.05	0.08	0.15	0.13	0.04

[1] M. S. Gordon, *et al.*, IEEE Trans. Nucl. Sci. **51**, 3427 (2004).
[2] J. F. Ziegler, IBM J. Res. Dev. 42, 117 (1998).

Background Evaluation

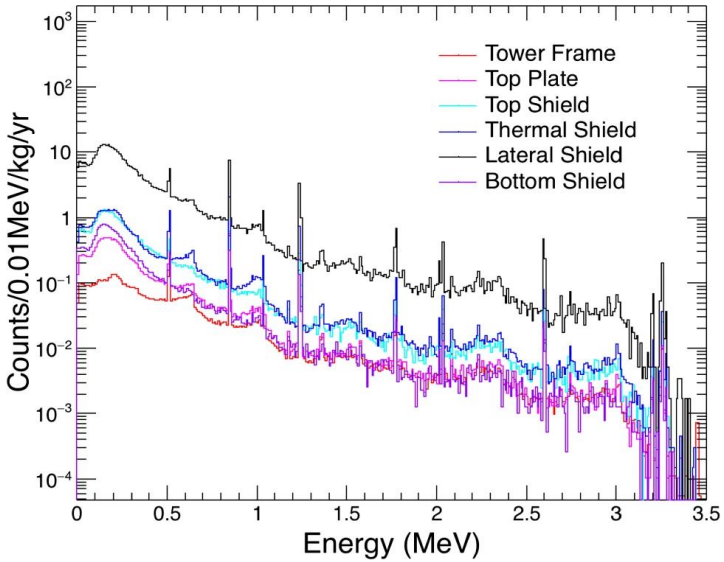
Copper shield component

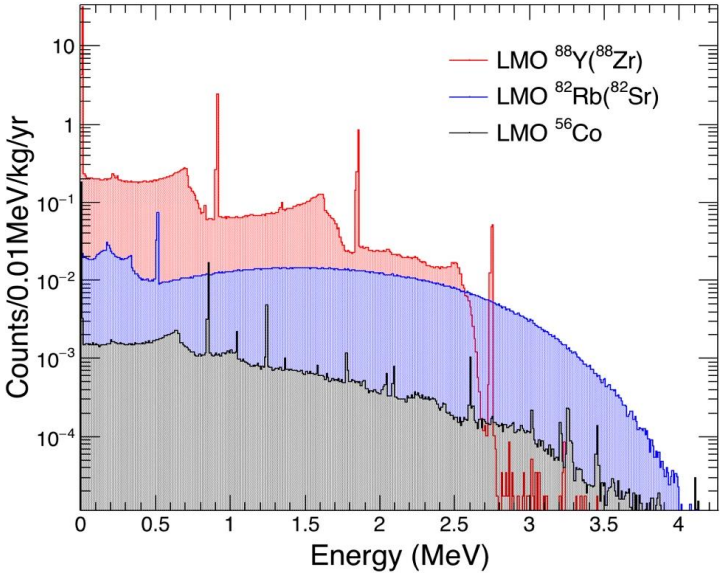
Component	Volume (cm^3)	Mass (kg)
Tower frame	202.0	1.8
Top plate	1590.4	14.2
Top shield	23562.0	209.7
50 mK thermal	2224.7	19.8
4 K thermal	2404.5	21.4
Lateral shield	336000.0	2990.4
Bottom shield	30000.0	267.0

- Energy resolution according to CUPID-Mo:

$$\sigma(E) = \sqrt{0.49 + \left(0.058 \times \sqrt{E}\right)^2}$$

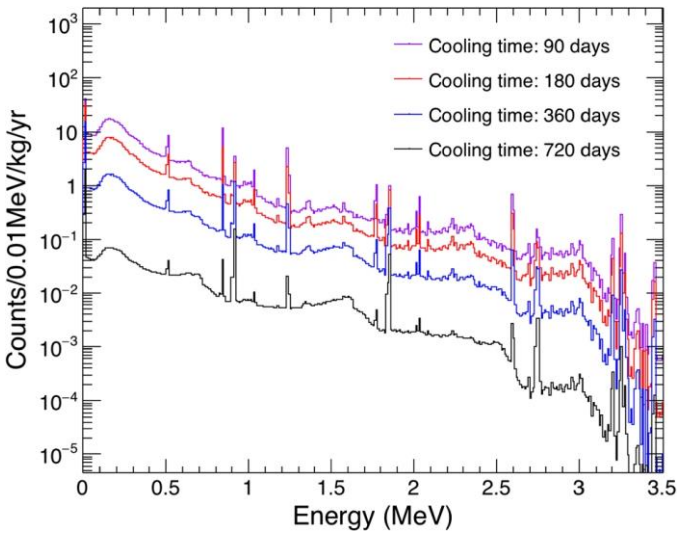
- Most of contribution of ^{56}Co in copper from Lateral shield in ROI
- $^{82}Rb(^{82}Sr)$ and ^{56}Co contribute significantly in ROI





Background spectrum results

The total energy spectra after cooling time



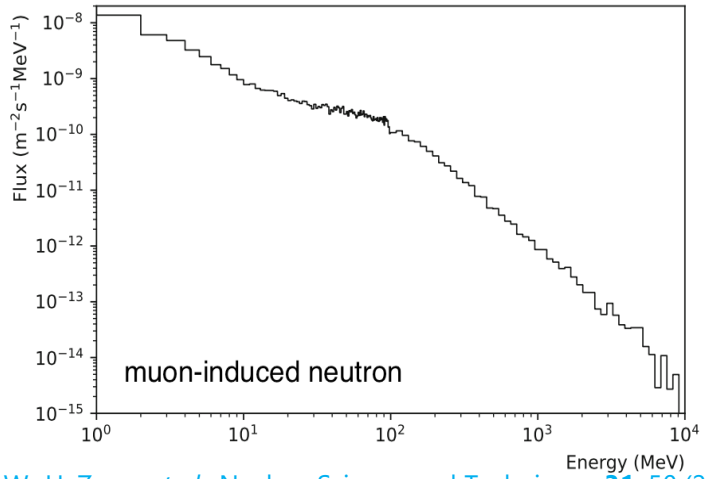
The background simulation result in ROI after cooling time

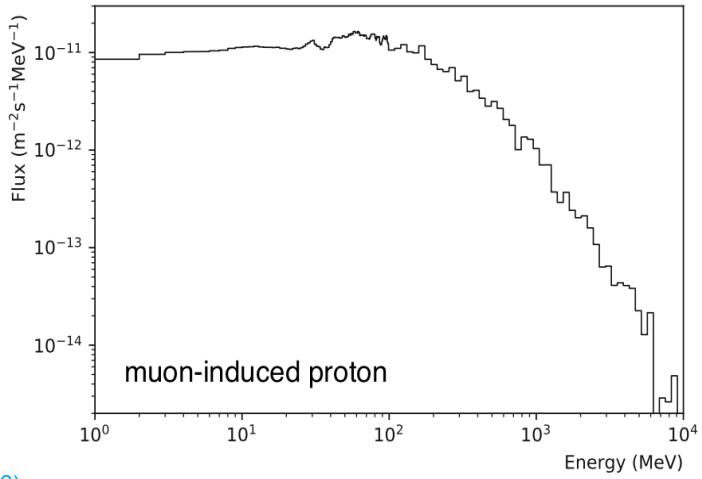
Component	Cooling time(days)			
	90	180	360	720
Copper	$(3.71 \pm 0.26) \times 10^{-3}$	$(1.65 \pm 0.11) \times 10^{-3}$	$(3.30 \pm 0.23) \times 10^{-4}$	$(1.27 \pm 0.09) \times 10^{-5}$
LMO	$(2.88 \pm 0.20) \times 10^{-4}$	$(2.78 \pm 0.19) \times 10^{-5}$	$(1.83 \pm 0.13) \times 10^{-6}$	$(1.42 \pm 0.10) \times 10^{-7}$
Total	$(3.99 \pm 0.26) \times 10^{-3}$	$(1.68 \pm 0.11) \times 10^{-3}$	$(3.32 \pm 0.23) \times 10^{-4}$	$(1.28 \pm 0.09) \times 10^{-5}$

- We got the total cosmogenic background level of $(3.32 \pm 0.23) \times 10^{-4}$ cts/keV/kg/yr after cooling for one year
- ^{100}Mo-based bolometric experiment at CJPL aims at total background $< 10^{-4}$ cts/keV/kg/yr
- To get the goal, longer cooling time and shorter exposure time is necessary.

Background Evaluation

The neutron and proton produced by muon at CJPL are considered





W.-H. Zeng, *et al.*, Nuclear Science and Techniques **31**, 50 (2020).

Long life-time nuclides

Material	Radionuclides	Saturated yield (cts/kg)
Copper	^{56}Co	8.5×10^{-6}
LMO	^{88}Y	1.5×10^{-5}
	^{88}Zr	8.4×10^{-6}

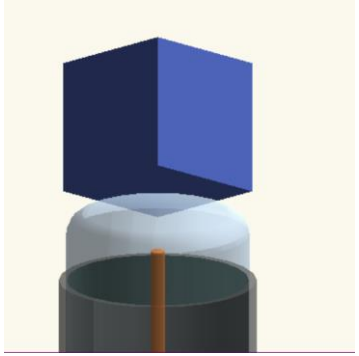
Short life-time nuclides

	Isotope	Decay model	Q-value (keV)	Production Rate(cts/kg/d)
Copper	^{62}Co	Beta-	3013	3.8×10^{-7}
	^{62}Cu	EC	3948.4	1.75×10^{-5}
	^{60}Cu	EC	6127	3.5×10^{-7}
	^{53}Fe	EC	3742.4	2.4×10^{-7}
	^{57}Ni	EC	3264.3	1.49×10^{-6}
LMO	^{91}Mo	EC	4434	2.33×10^{-6}
	^{90}Nb	EC	6111.4	1.4×10^{-6}

Total background estimated to 10^{-10} cts/kg/keV/yr

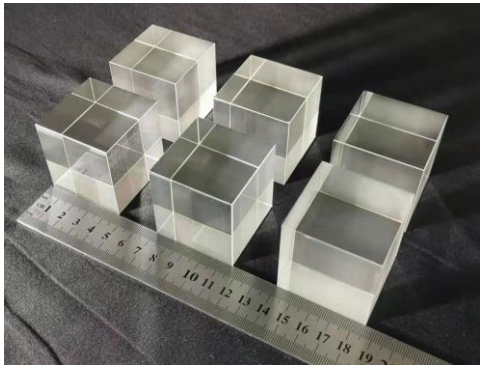
Plan for LMO measurement

HPGe detector could detect the cosmogenic radionuclides activity at CJPL



Detection efficiency simulation

- Detector geometry completed by Z. She *et al.*
- Add LMO crystals and adjust the number and position
- Get the spectra and evaluate the number that we need



Detection experiment

- Produce number of LMO crystals meet the measurement requirement
- Transport to CJPL after a long enough exposure
- Measure cosmogenic background directly with HPGe detector at CJPL

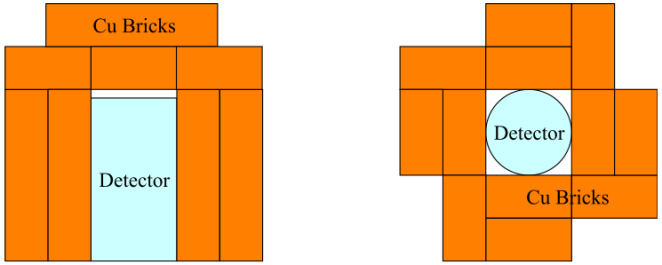


Fig. 1 Schematic diagram of placement of OFHC copper bricks in spectrometer: right view (left) and top view (right)

Z. She, *et al.*, The European Physical Journal C **81**, 1041 (2021).

Summary and discussion

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What we have done

W. Chen, L. Ma, et al, The European Physical Journal C **82**, 549 (2022).

✓ Activation of potential cosmogenic radionuclides

7.33, 6.42, 2.47, 2.19 $kg^{-1}d^{-1}$ for ^{56}Co in copper, ^{88}Zr, ^{88}Y, ^{82}Sr in LMO respectively

✓ Evaluation of cosmogenic background level in ROI

Total cosmogenic background 3.3×10^{-4} cts/keV/kg/yr in the ROI

What we are doing

☐ Detection efficiency for HPGe detector simulation

☐ Cosmogenic activity measurement with HPGe detector at CJPL

Thanks!