Expected backgrounds in AMoRE experiment

Vladislav Kobychev

Institute for Nuclear Research, Kyiv, Ukraine
Kyungpook National University, Daegu, Korea

for AMoRE Collaboration

Kiev RPSCINT 2013.09.17

1. AMoRE
2. Background from radioactive contaminations and DBD random coincidence
3. Background from muons (YangYang Lab)
4. Background from neutrons (YangYang Lab)
5. Conclusions

The main aim of the planned AMoRE experiment is the search for neutrinoless double beta decay of ^{100}Mo.

Motivation:

^{100}Mo is a promising candidate for 2β experiments because of:

- high transition energy (3035 keV)
- large isotopic abundance (9.67%)
- possibility of relatively inexpensive enrichment up to ~ 99%

Middle scale (~10 kg) 2β experiment with the sensitivity level ~10^{25} y

Large scale (~100 kg) 2β experiment with the sensitivity level ~10^{26} y

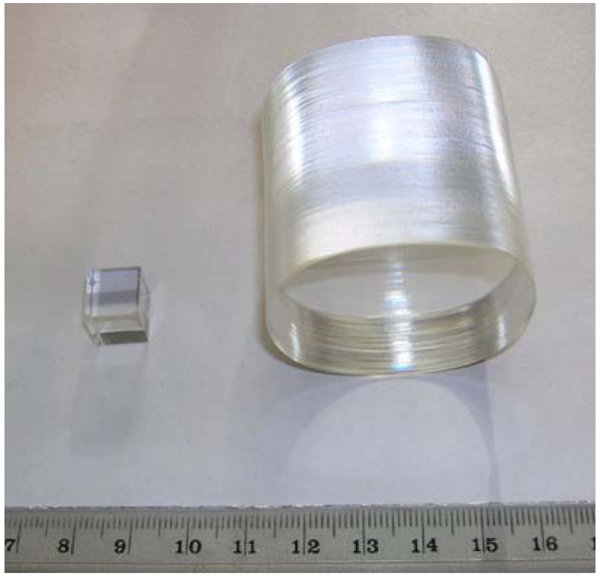
To achieve this goal

- energy resolution has to be less than 5% at the energy of 0ν2β decay of ^{100}Mo

- background has to be < 0.01 counts / (year × keV × kg)

A good answer:

$CaMoO_4$ scintillation bolometer



$CaMoO_4$

* DBD nuclei: ^{100}Mo (3034 keV), ^{48}Ca (4272 keV)

* Light yield: 10-20% of CsI(Tl) @300 K (possibly the best molybdate scintillator), increase at lower temperature.

* Decay time: 16 µs @300 K

* Wavelength: 450-650 nm (good for RbCs PMT)

* High Debye temperature: $T_D = 438$ K, $C \sim (T/T_D)^3$

* Pulse shape discrimination technique

Main features of the project

Isotopically modified components of $CaMoO_4$:

- Molybdenum is enriched in ^{100}Mo
- Calcium is depleted in ^{48}Ca

(the reason is the background from 2ν2β decay of ^{48}Ca with $Q_{\beta\beta} = 4.27$ MeV and $T_{1/2} = 4.2\times10^{19}$ yr. Natural Ca contains 0.187% of ^{48}Ca, so the decay rate is ~500 decays/(yr × kg). Calcium enriched in ^{40}Ca is depleted in the heavy Ca isotopes, so $^{40}Ca^{100}MoO_4$ is used to decrease the 2ν2β background of ^{48}Ca)

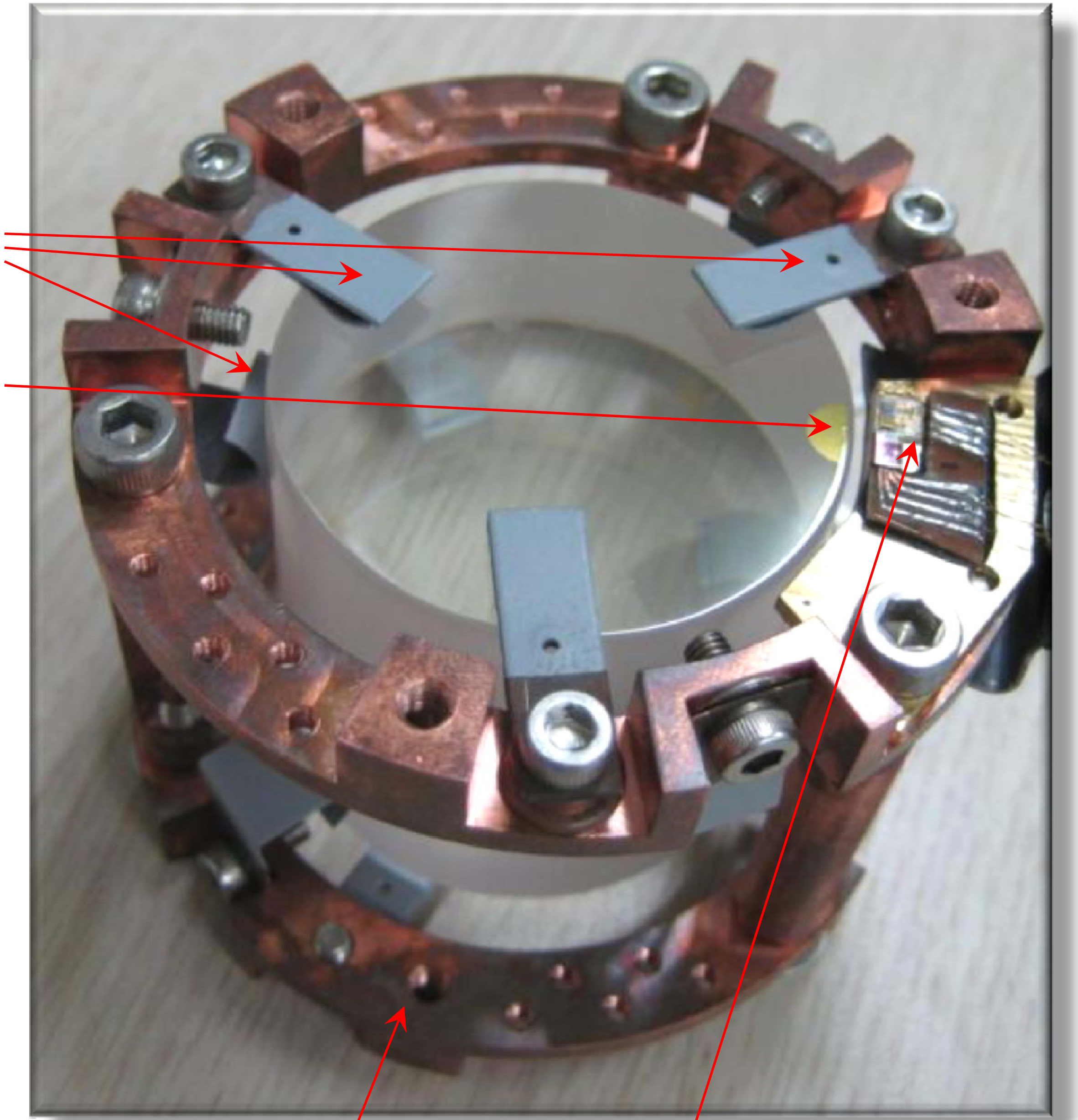
Both thermal and scintillation channels can be used when CMO is operated as a cryogenic bolometer.

See the today talk of H.J.Kim for more complete review of the AMoRE project.

A module with o40x40 CMO crystal (~211 g).

Teflon coated springs

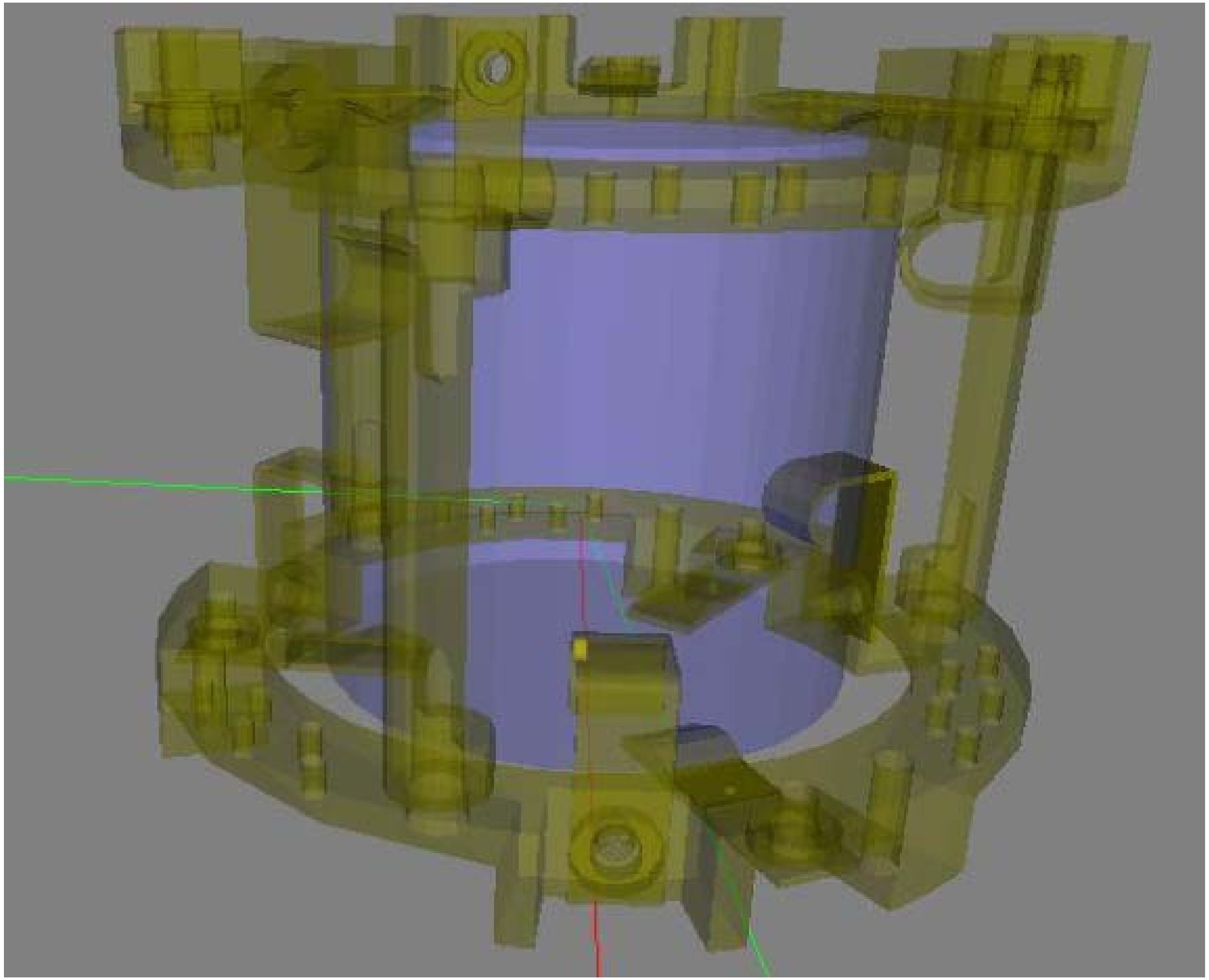
Gold thermalization pad



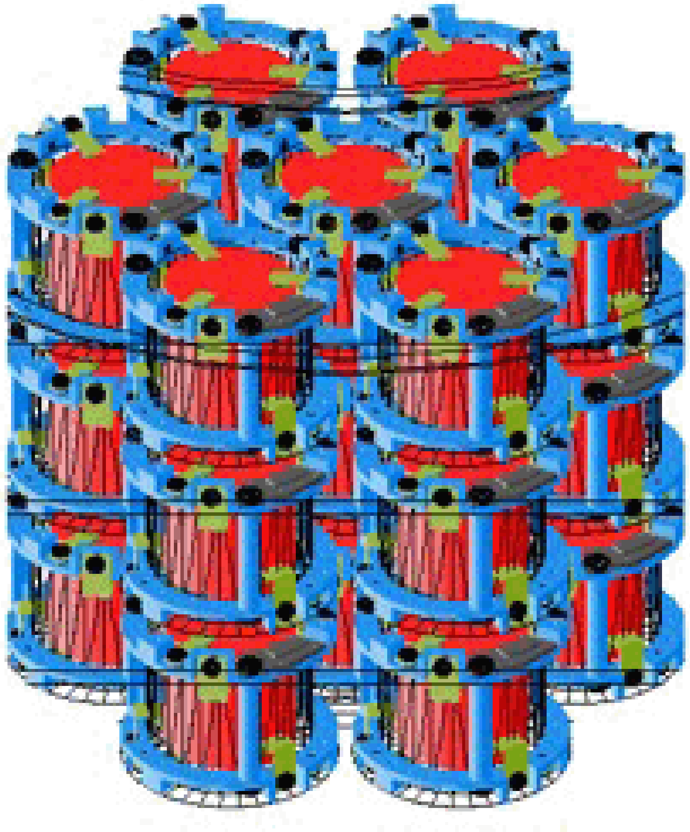
Copper frame

Meander MMC

Model of one cell



"Standard Model" of AMoRE used for Geant4 simulations:



$^{40}Ca^{100}MoO_4$
(cylinders o44x45,
mass 300 *g*) in copper
frames (*m* = 75 *g*)

7 layers x 7 columns =
49 cells (total mass
of CMO is 14.7 kg).

The nuclides that can potentially give events at ~3 MeV:

RADIOGENIC:

- ^{208}Tl in CMO and Cu
  ^{232}Th, BR=36%, Q_b = 5.00 MeV;
- ^{212}BiPo in CMO and Cu
  ^{232}Th, BR=64%, Q_b = 2.25 MeV, Q_a = 8.95 MeV, $T_{1/2}$ = 299 ns;
- ^{214}BiPo in CMO and Cu
  ^{238}U, Q_b = 3.27 MeV, Q_a = 7.83 MeV, $T_{1/2}$ = 164 μs;

COSMOGENIC:

- ^{88}Y+^{88}Zr in CMO
  produced by spallation on ^{100}Mo, Q_{EC}(^{88}Y) = 3.62 MeV,
  $T_{1/2}$ = 83 d (^{88}Zr) + 107 d (^{88}Y)

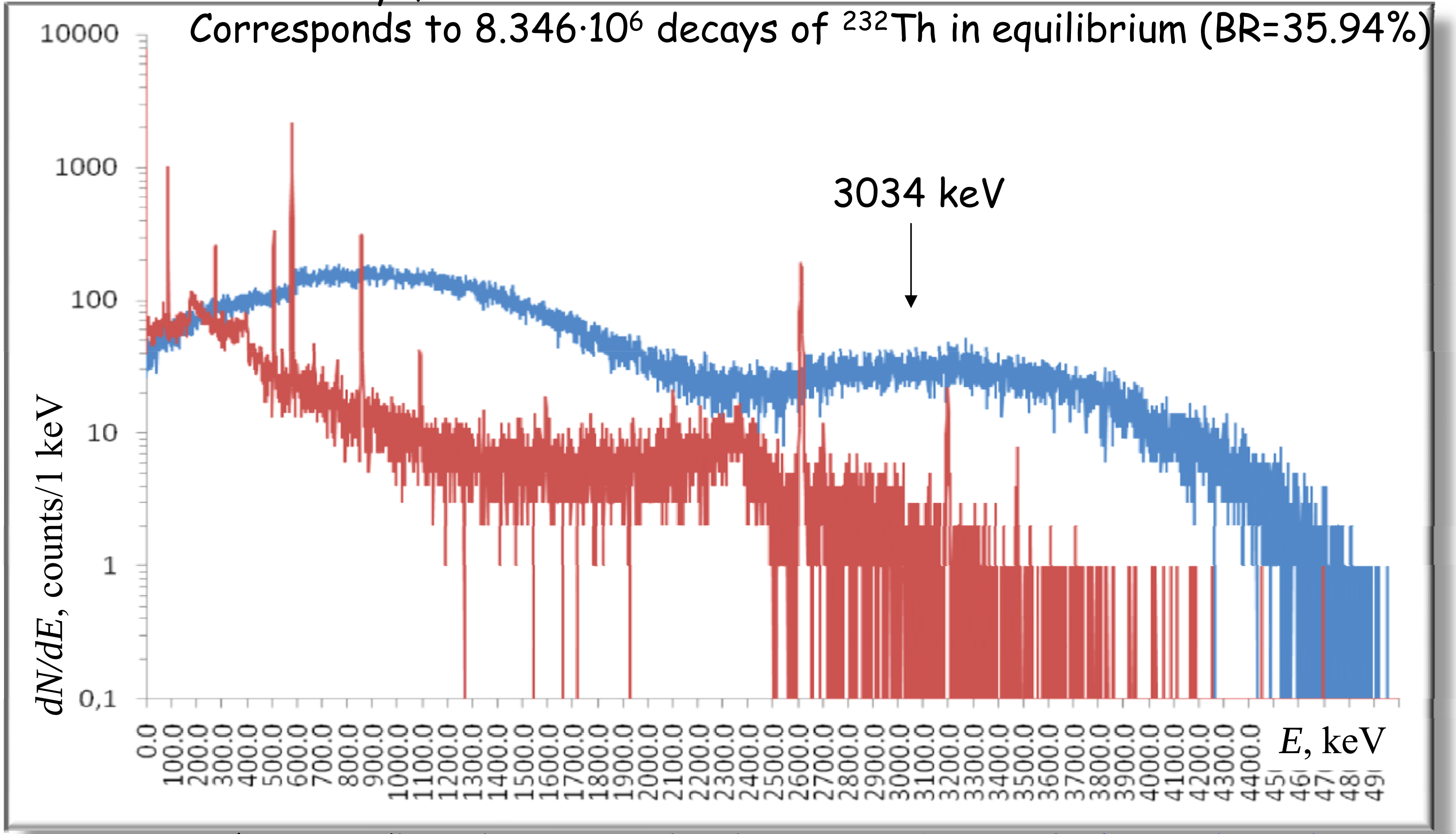
Tl-208

Tl-208 in CMO (central crystal)

Tl-208 in Cu (central frame)

$3 \cdot 10^6$ decays, anticoincidences.

Corresponds to $8.346 \cdot 10^6$ decays of ^{232}Th in equilibrium (BR=35.94%)



$9.8 \cdot 10^{-6}$ counts/keV ($Q_{2\beta} \pm 100$ keV) per one decay of Tl-208 (CMO)

$1.1 \cdot 10^{-3}$ counts/(yr·keV·kg) for 10 μBq/kg of Th-232 (assuming possible reduce from 70 μBq/kg, as in one of tested crystals, SB28).

Tl-208

But the background from ^{208}Tl can be suppressed by detection of 6207 keV alpha particle from ^{212}Bi decaying to ^{208}Tl ($T_{1/2}$ = 3.053 min).

15 minutes (5 half-lives) of vetoing of a crystal after detection of alpha event with E = 6207 keV will reduce the background of ^{208}Tl by 2^5=32 times. The decay rate of ^{212}Bi is expected to be ~1/(2000 min) in one 300 g crystal so the lost of live time is negligible, ~15/2000 < 1%.

Thus, the background from ^{208}Tl in CMO can be decreased by time-amplitude method to

$3.6 \cdot 10^{-5}$ counts/(yr·keV·kg).

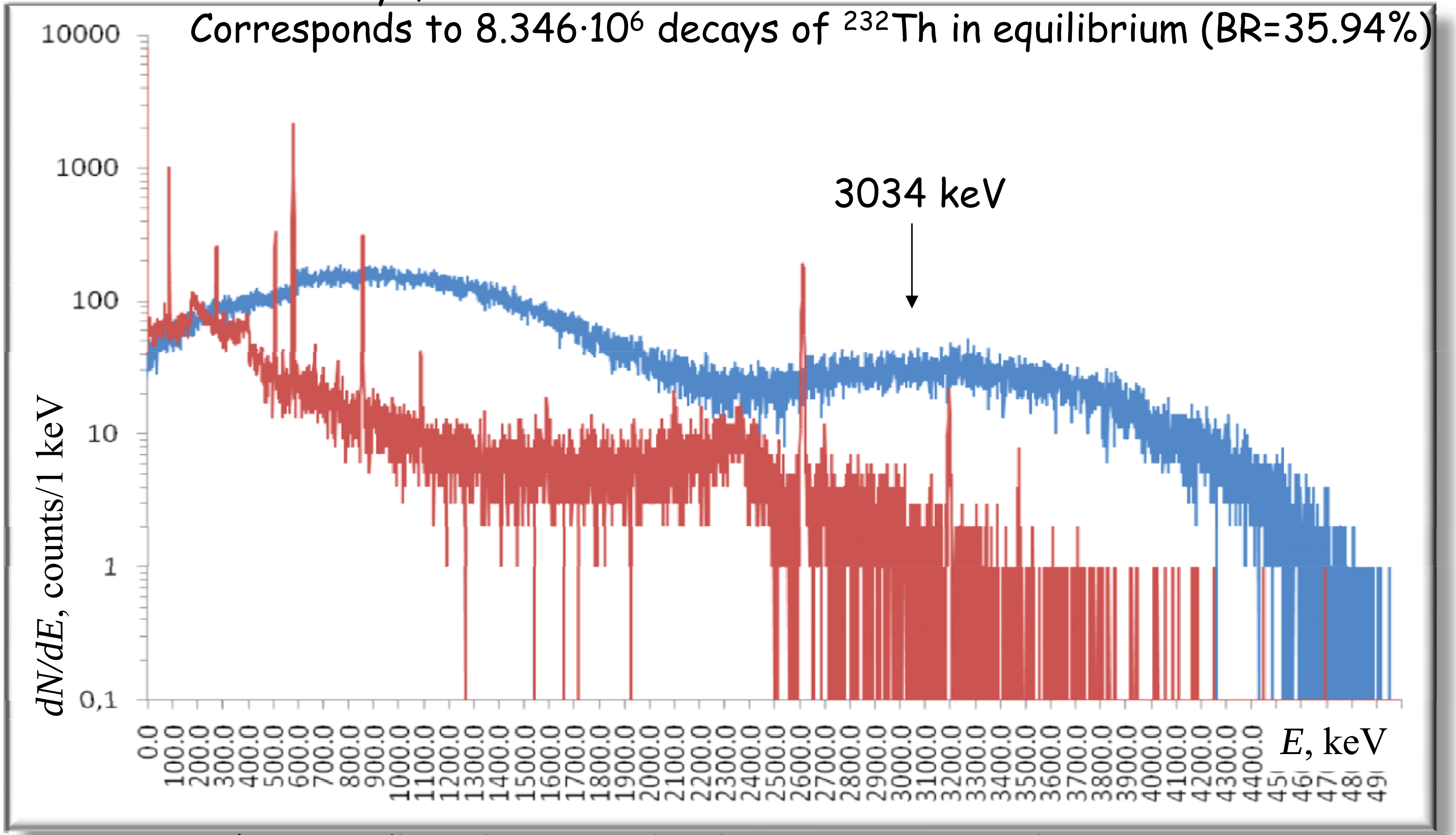
Tl-208

Tl-208 in CMO (central crystal)

Tl-208 in Cu (central frame)

$3\cdot10^{6}$ decays, anticoincidences.

Corresponds to $8.346\cdot10^{6}$ decays of ^{232}Th in equilibrium (BR=35.94%)



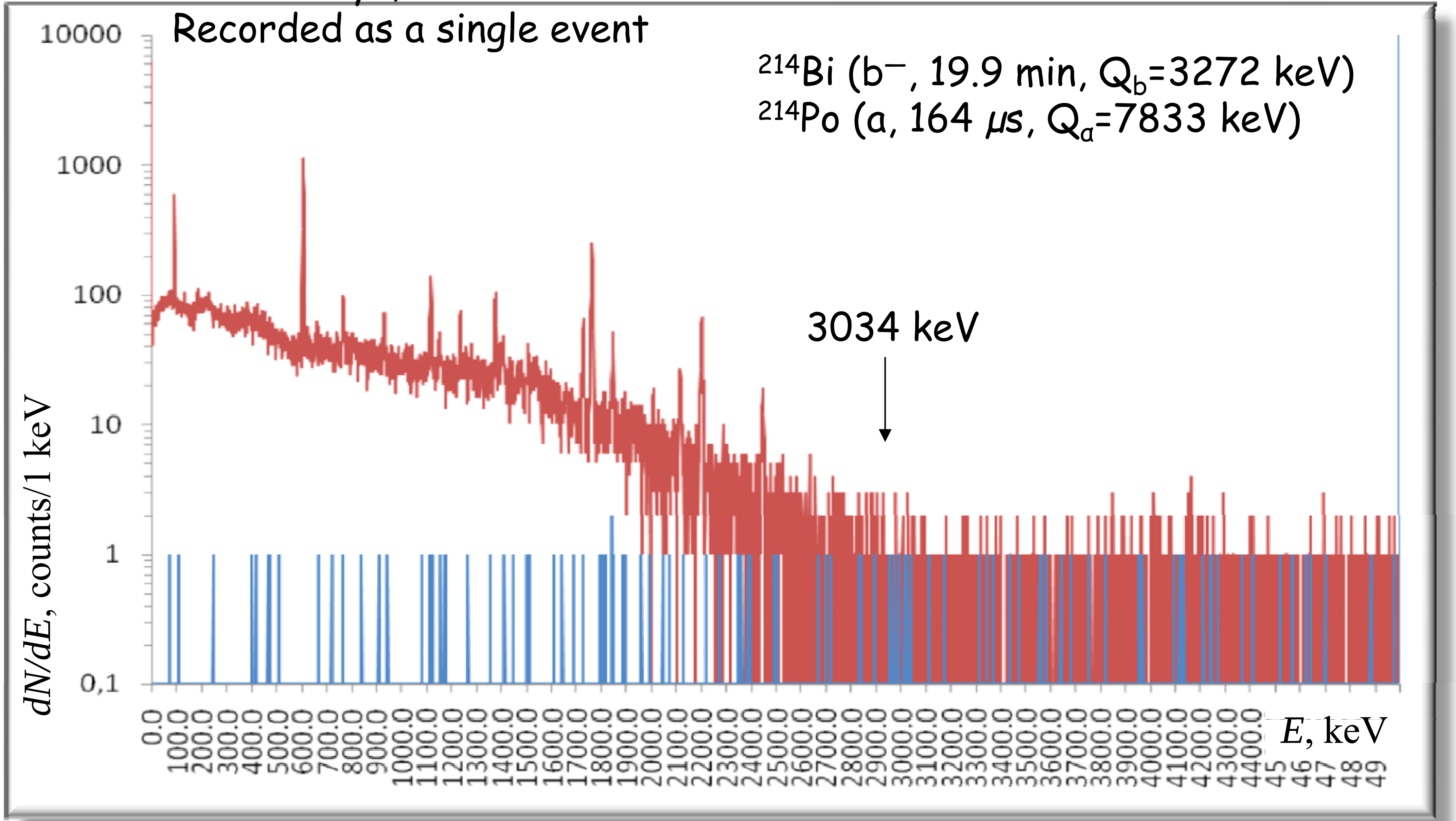
$0.5\cdot10^{-6}$ counts/keV ($Q_{2\beta}\pm$ 50 keV) per one decay of Tl-208 in Cu.

$2.2\cdot10^{-5}$ counts/(yr·keV·kg) for 16 μBq/kg of Th-232 (copper with 4 ppt of Th is mentioned in ILIAS database, http://radiopurity.in2p3.fr).

BiPo-214

BiPo-214 in CMO (central crystal)
BiPo-214 in Cu (central frame)
1·10^{6} decays, anticoincidences.
Recorded as a single event

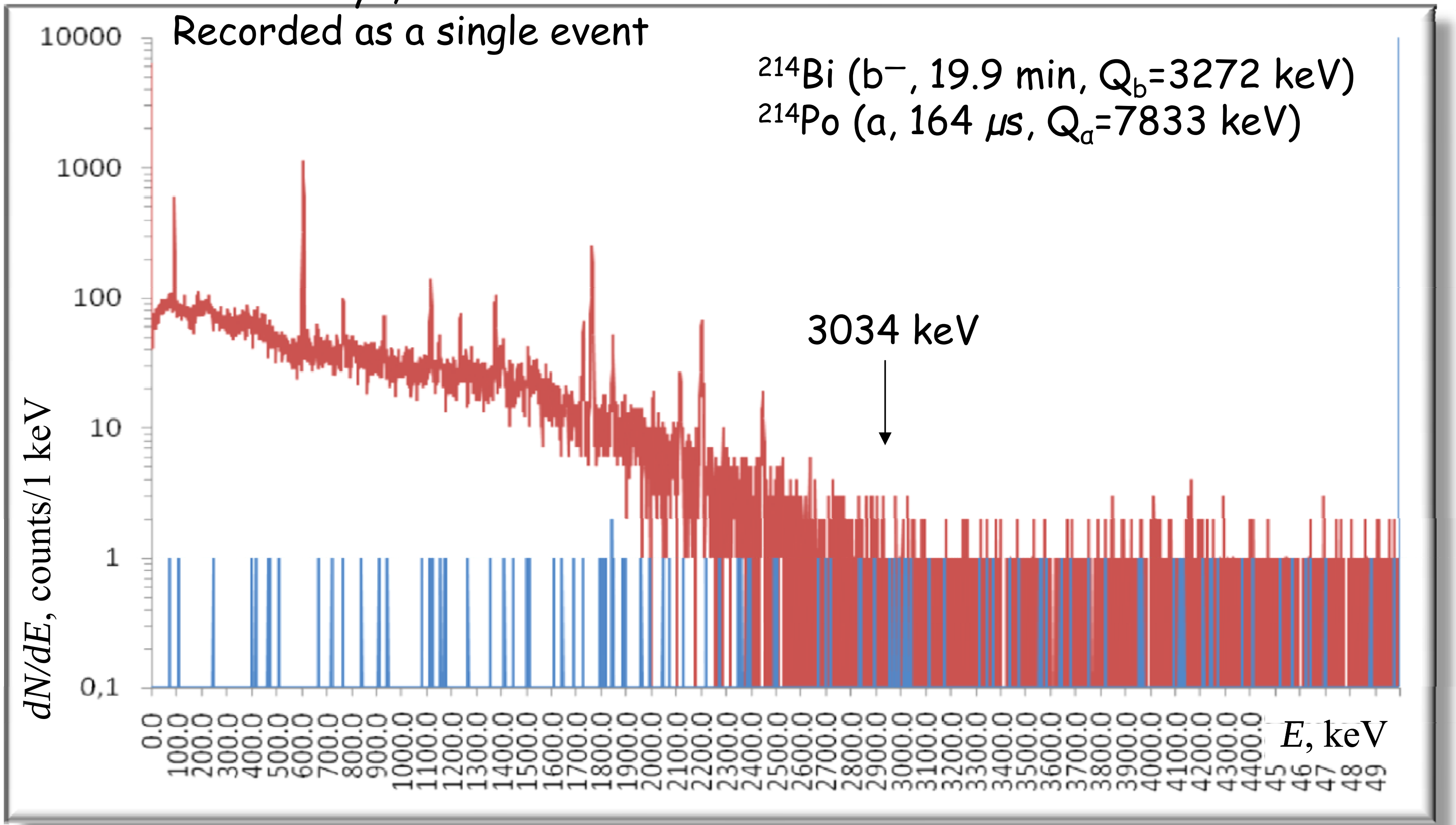
^{214}Bi (b^{-}, 19.9 min, Q_b=3272 keV)
^{214}Po (a, 164 μs, Q_a=7833 keV)



0.035·10^{-6} counts/keV ($Q_{2\beta}$ ± 100 keV) per one decay of Bi-214 in CMO
1.1·10^{-5} counts/(yr·keV·kg) for 10 μBq/kg of Ra-226 (assuming possible reduce from 80 μBq/kg, as in SB28). PSD (a/β) should reduce this even more.

BiPo-214

BiPo-214 in CMO (central crystal)
BiPo-214 in Cu (central frame)
1·10^6 decays, anticoincidences.
Recorded as a single event



^{214}Bi (b^{-}, 19.9 min, Q_b=3272 keV)
^{214}Po (a, 164 μs, Q_a=7833 keV)

3034 keV

0.39·10^{-6} counts/keV ($Q_{2\beta}$ ± 50 keV) per one decay of Bi-214 in Cu.

1.8·10^{-4} counts/(yr·keV·kg) for 60 μBq/kg of Bi-214 in Cu (5 ppt U, ILIAS database).

BiPo-212

BiPo-212 in CMO (central crystal)

BiPo-212 in Cu (central frame)

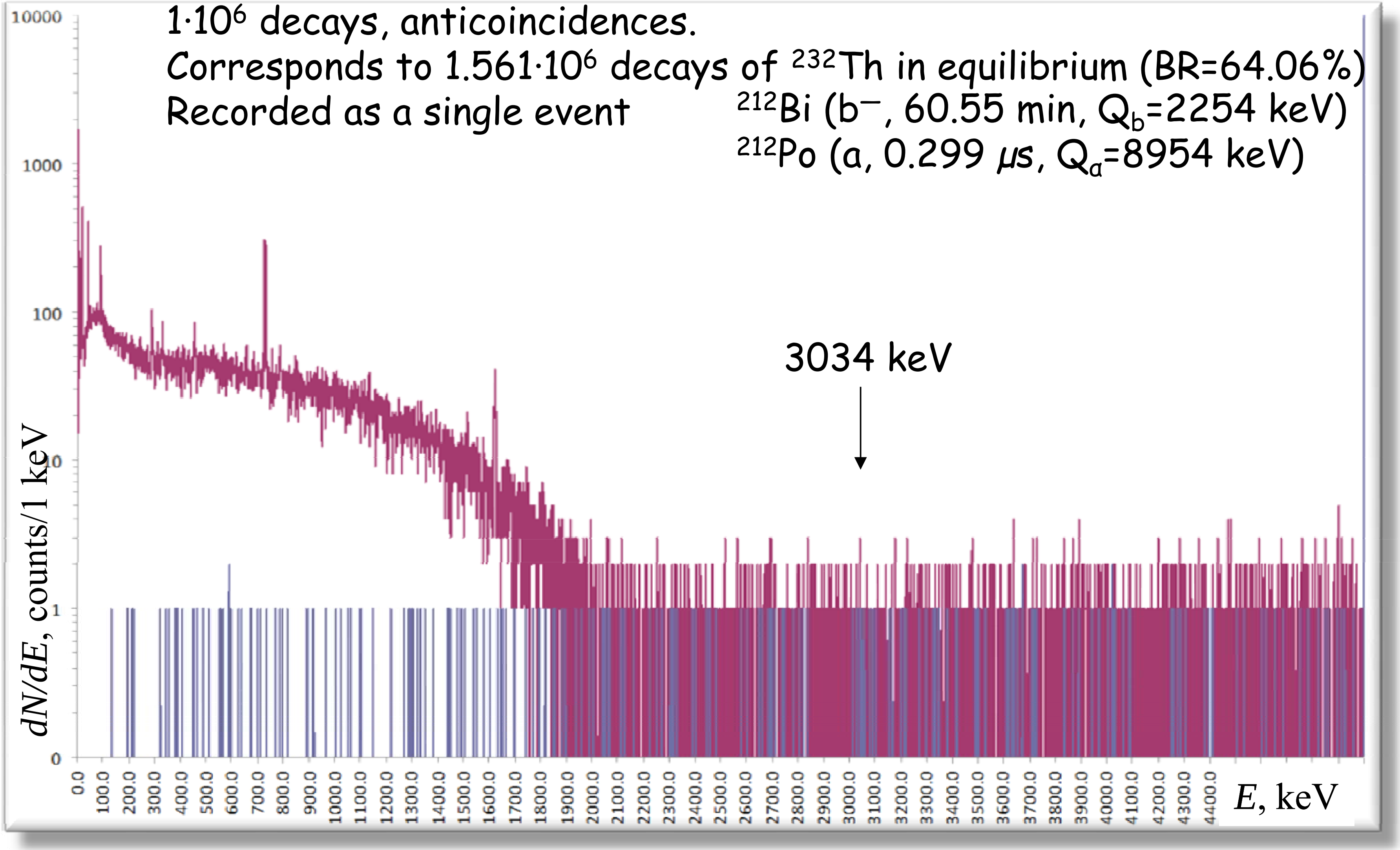
1·10^6 decays, anticoincidences.

Corresponds to 1.561·10^6 decays of ^{232}Th in equilibrium (BR=64.06%)

Recorded as a single event

^{212}Bi (b^{-}, 60.55 min, Q_b=2254 keV)

^{212}Po (a, 0.299 μs, Q_α=8954 keV)



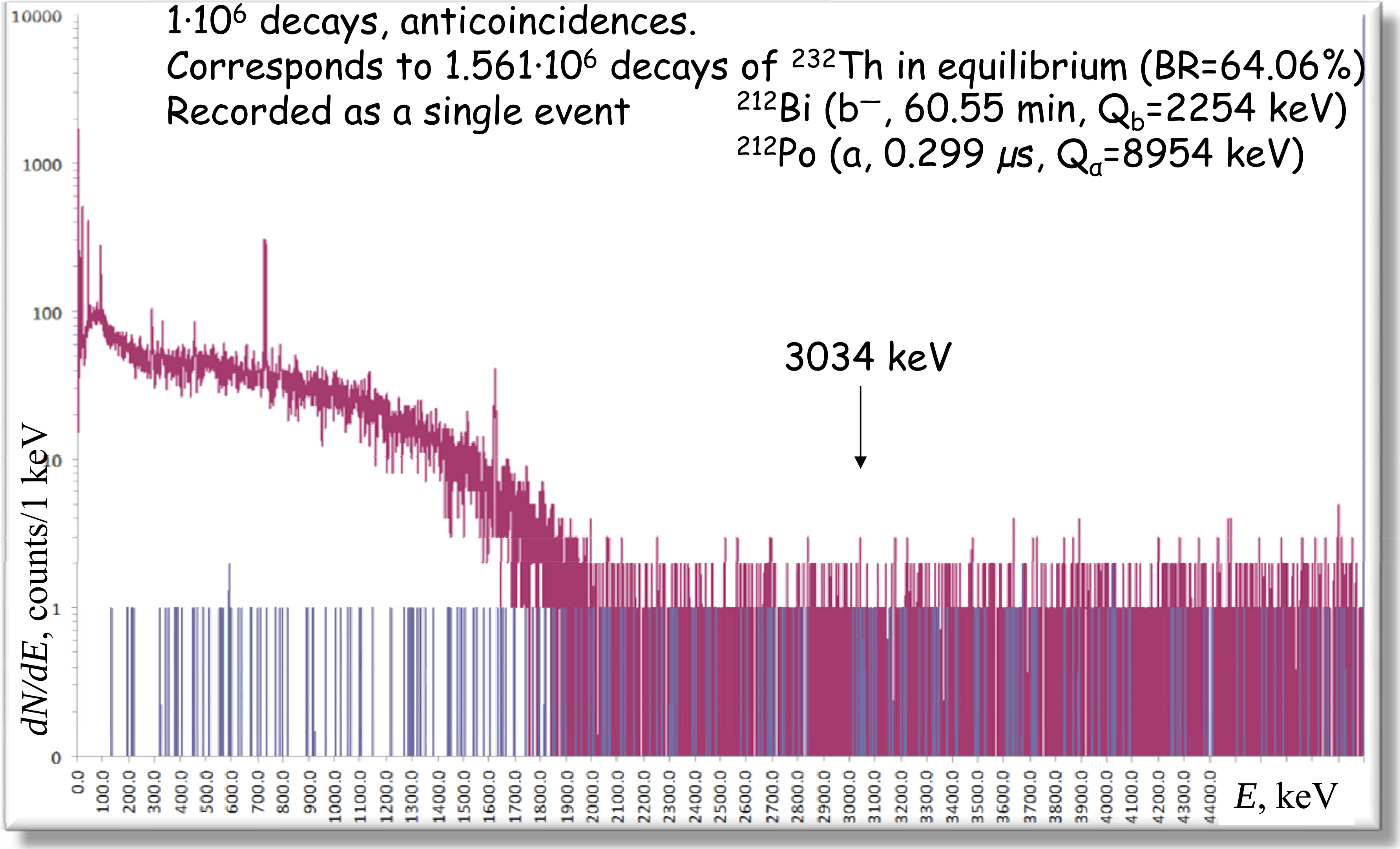
0.04·10^{-6} counts/keV ($Q_{2\beta}$± 100 keV) per one decay of BiPo-212 in CMO

0.8·10^{-5} counts/(yr·keV·kg) for 10 μBq/kg of Th-232 (assuming possible reduce from 70 μBq/kg, as in SB28).

BiPo-212

BiPo-212 in CMO (central crystal)

BiPo-212 in Cu (central frame)



$1 \cdot 10^6$ decays, anticoincidences.
Corresponds to $1.561 \cdot 10^6$ decays of ^{232}Th in equilibrium (BR=64.06%)
Recorded as a single event

^{212}Bi (b^{-}, 60.55 min, Q_b=2254 keV)
^{212}Po (a, 0.299 μs, Q_α=8954 keV)

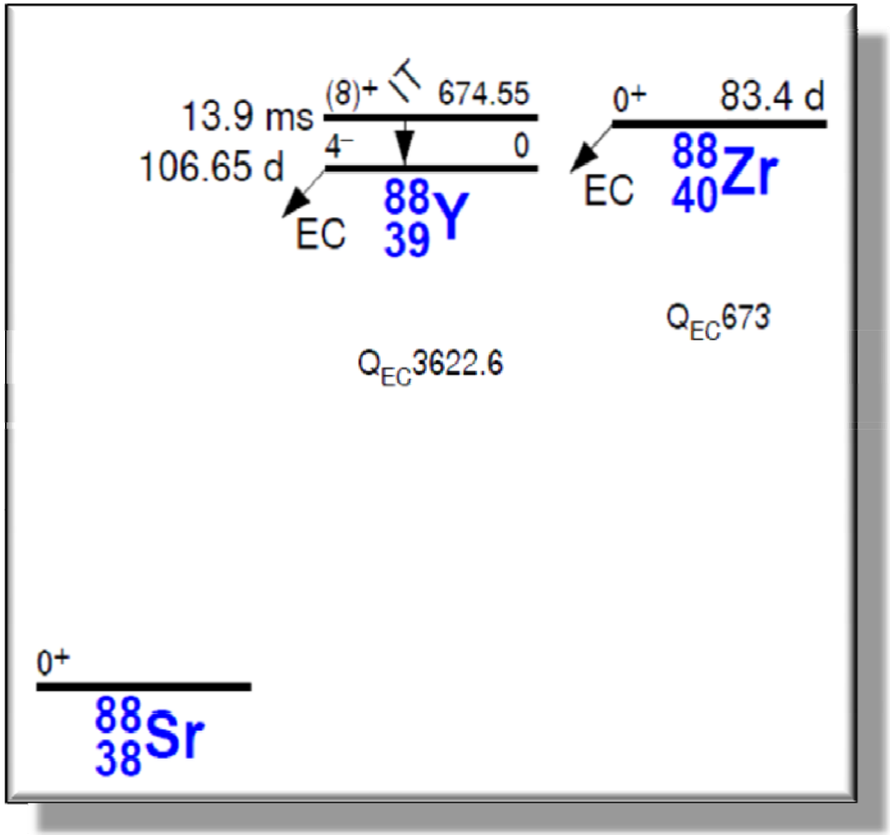
$0.44 \cdot 10^{-6}$ counts/keV ($Q_{2\beta}$ ± 100 keV) per one decay of BiPo-212 in Cu
$3.6 \cdot 10^{-5}$ counts/(yr · keV · kg) for 16 μBq/kg of Bi-212 in Cu (4 ppt Th, ILIAS database).

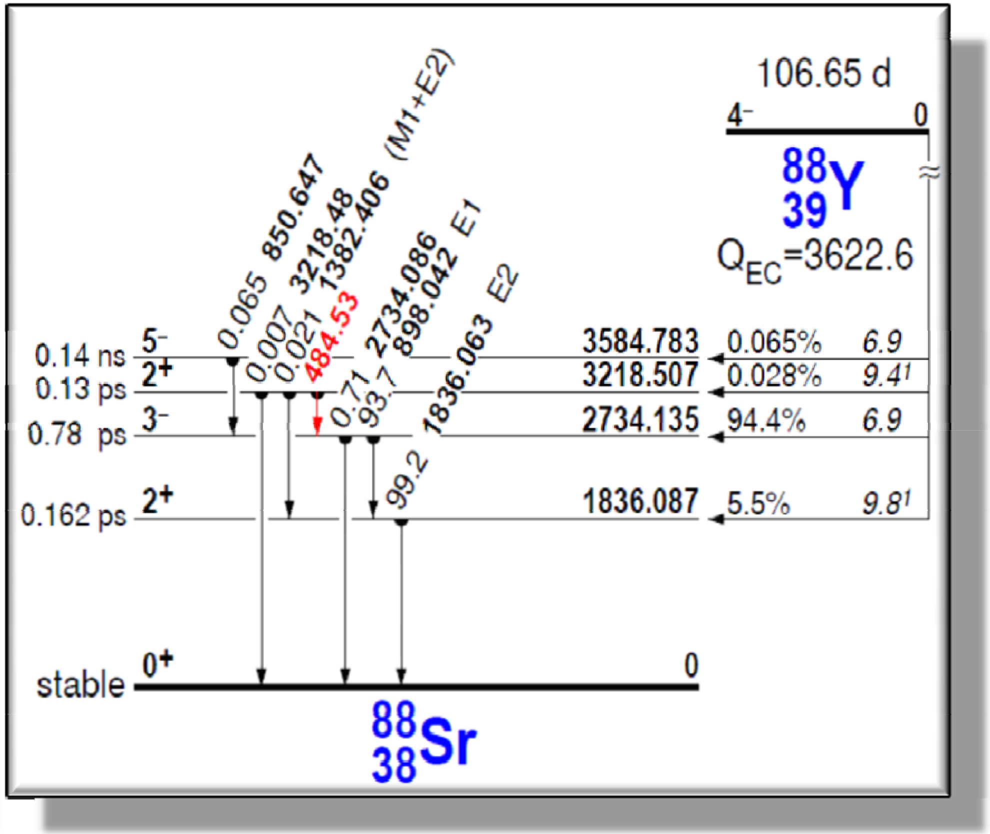
Y-88

- ^{88}Y+^{88}Zr in CMO

  cosmogenic, spallation on ^{100}Mo, $Q_{EC}(^{88}Y)$=3.62 MeV,

  $T_{1/2}$ = 83 d (^{88}Zr) + 107 d (^{88}Y)

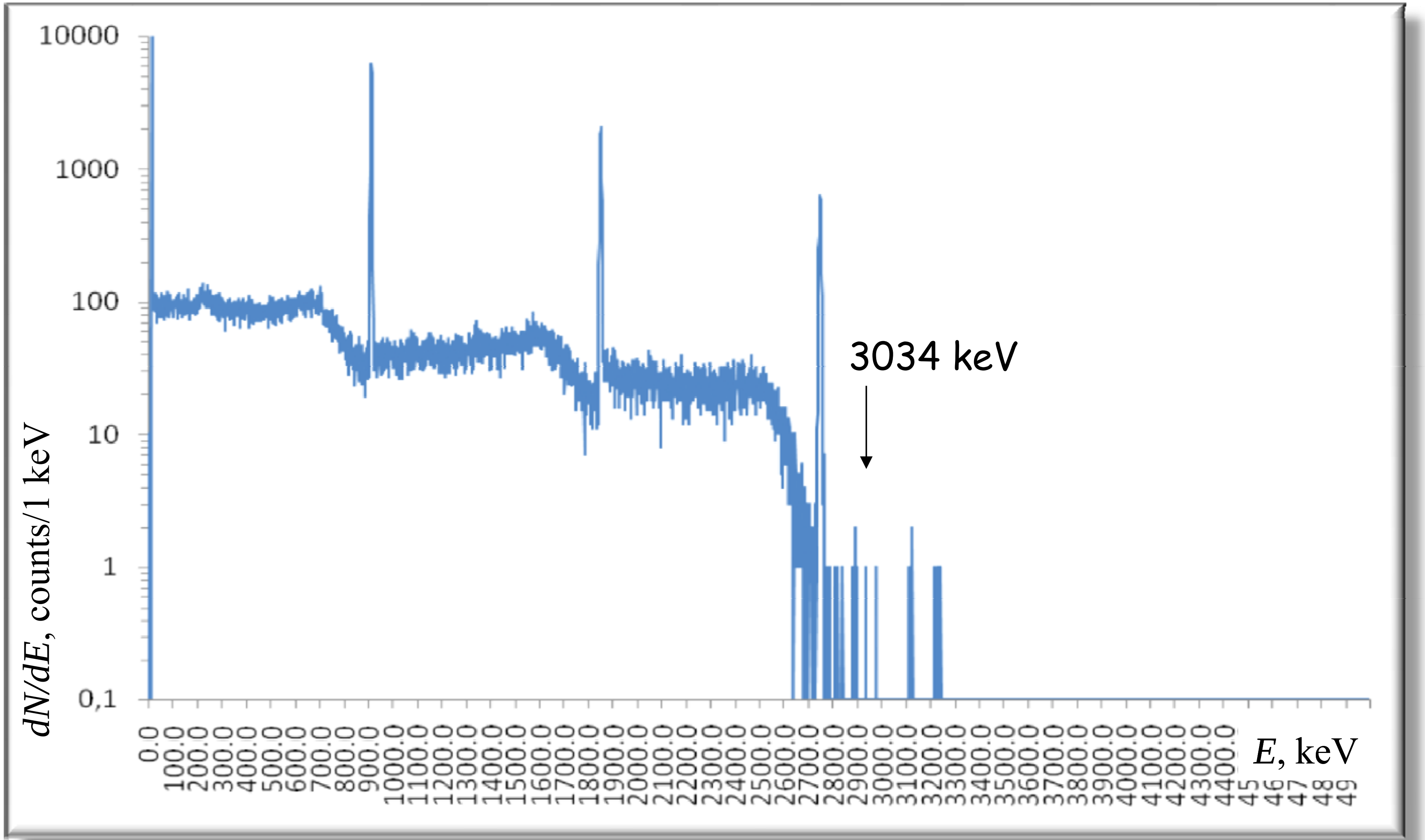




Y-88

Y-88 in CMO (central crystal)

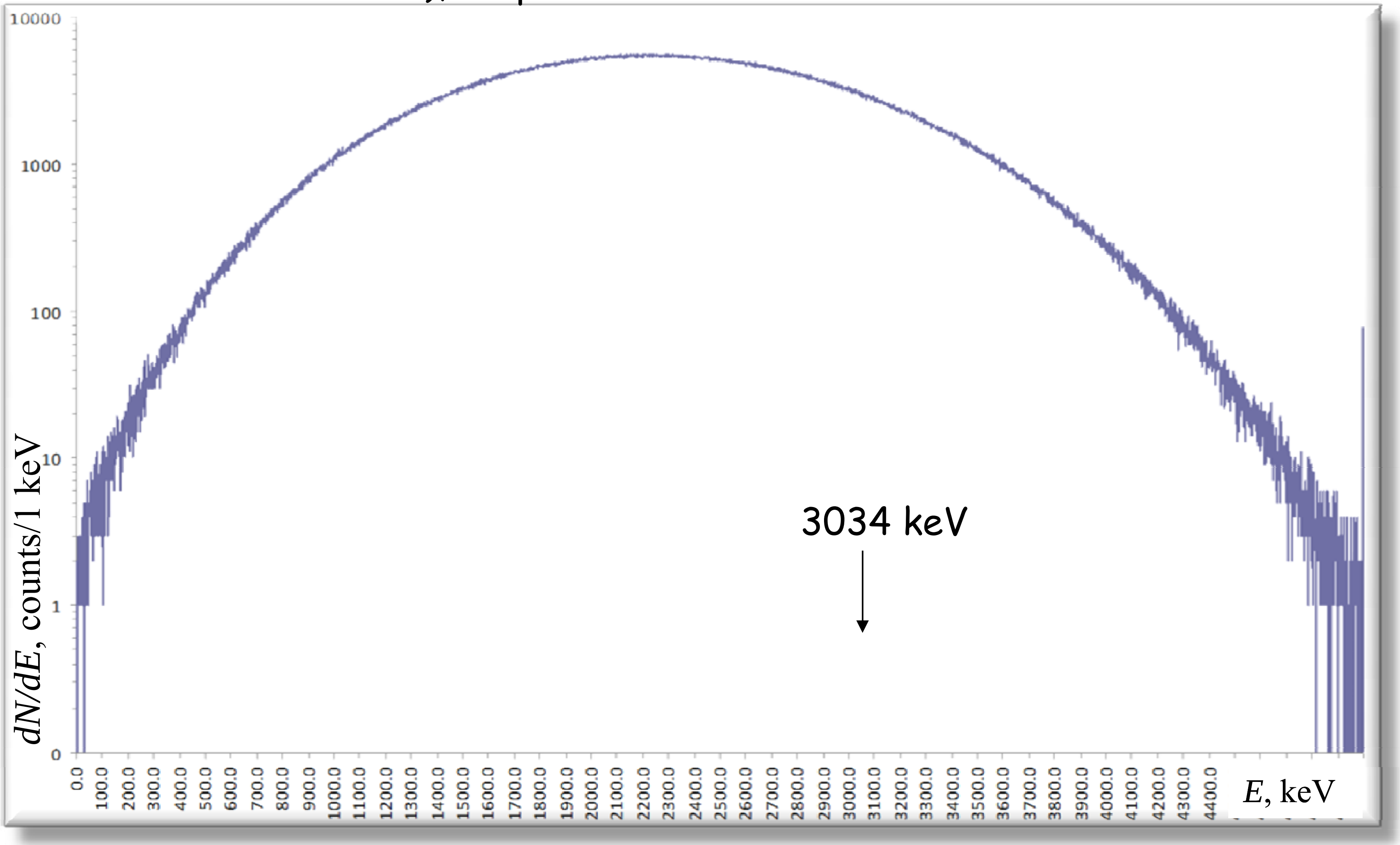
$1 \cdot 10^6$ decays, anticoincidences.



$0.03 \cdot 10^{-6}$ counts/keV ($Q_{2\beta}$ ± 100 keV) per one decay of Y-88 in CMO

$1.9 \cdot 10^{-5}$ counts/(yr·keV·kg) for 20 μBq/kg of Y-88 (calculated with COSMO, 4 months on the surface). Half-life of Y-88 is ~100 days.

Random coincidences of 2n2b events (1e6 pairs of decays, anticoinc., central detector), step function of time resolution with Dt=10 ms



3034 keV

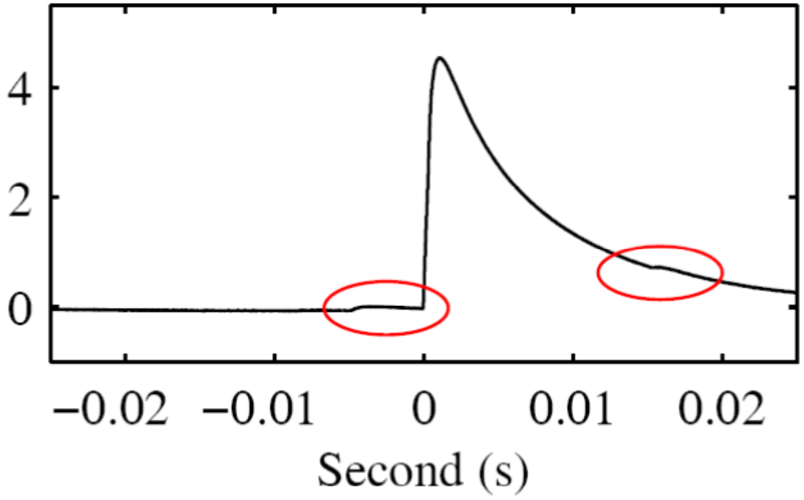
$R = I^2 \cdot \Delta t$; $I = (m/\mu) \cdot N_A \cdot \delta \cdot (\ln 2/T_{1/2})$ see: *D. M. Chernyak, F. A. Danevich, A. Giuliani, E. Olivieri, M. Tenconi, V. I. Tretyak.* Random coincidence of $2\nu2\beta$ decay events as a background source in bolometric $0\nu2\beta$ decay experiments. Eur. Phys. J. C 72(2012)1989.

Pulse shape separation of pile-up signals (method of mean time).

$$f_0(t) = A\vartheta(t)\cdot(1-e^{-t\lambda_r})\cdot e^{-t\lambda_d}$$

[single signal]

[θ(t) – Heaviside step function]



$$E_0 = \int_0^\infty f_0(t)dt$$

$$f_1(t) = \varepsilon f_0(t-\Delta t)$$

[delayed signal]

$$E_1 = \int_0^\infty f_1(t)dt = \varepsilon E_0$$

$$f(t) = f_0 + f_1 = f_0(t) + \varepsilon f_0(t-\Delta t)$$

[double signal]

$$M_0 = \frac{\int_0^\infty t f_0(t)dt}{\int_0^\infty f_0(t)dt}$$

[mean time of single signal]

$$M(f_0 + f_1) - ?$$

[mean time of double signal]

A simple result:

$$M(f_0 + f_1) = M_0 + \frac{\varepsilon \Delta t}{1+\varepsilon}$$

ε is the ratio of amplitudes (or energies) E_1/E_0, and Δt is the time delay of f_1.

Assuming that the separation of a double signal is possible when its mean time is >10% differs from the mean time of a single signal, I simulated 10^7 pairs of 2-neutrino DBD of ^{100}Mo, with the delay time distributed in agreement with the DBD rate in a 300 g CMO crystal. The rise time of the signal is 0.1 ms, the decay time is 10 ms. For the delay, only the range of $0 < \Delta t < 30\ \mathrm{ms}$ was used because the double signals with longer delays are separated with probability close to 100%. For the single DBD signal rate

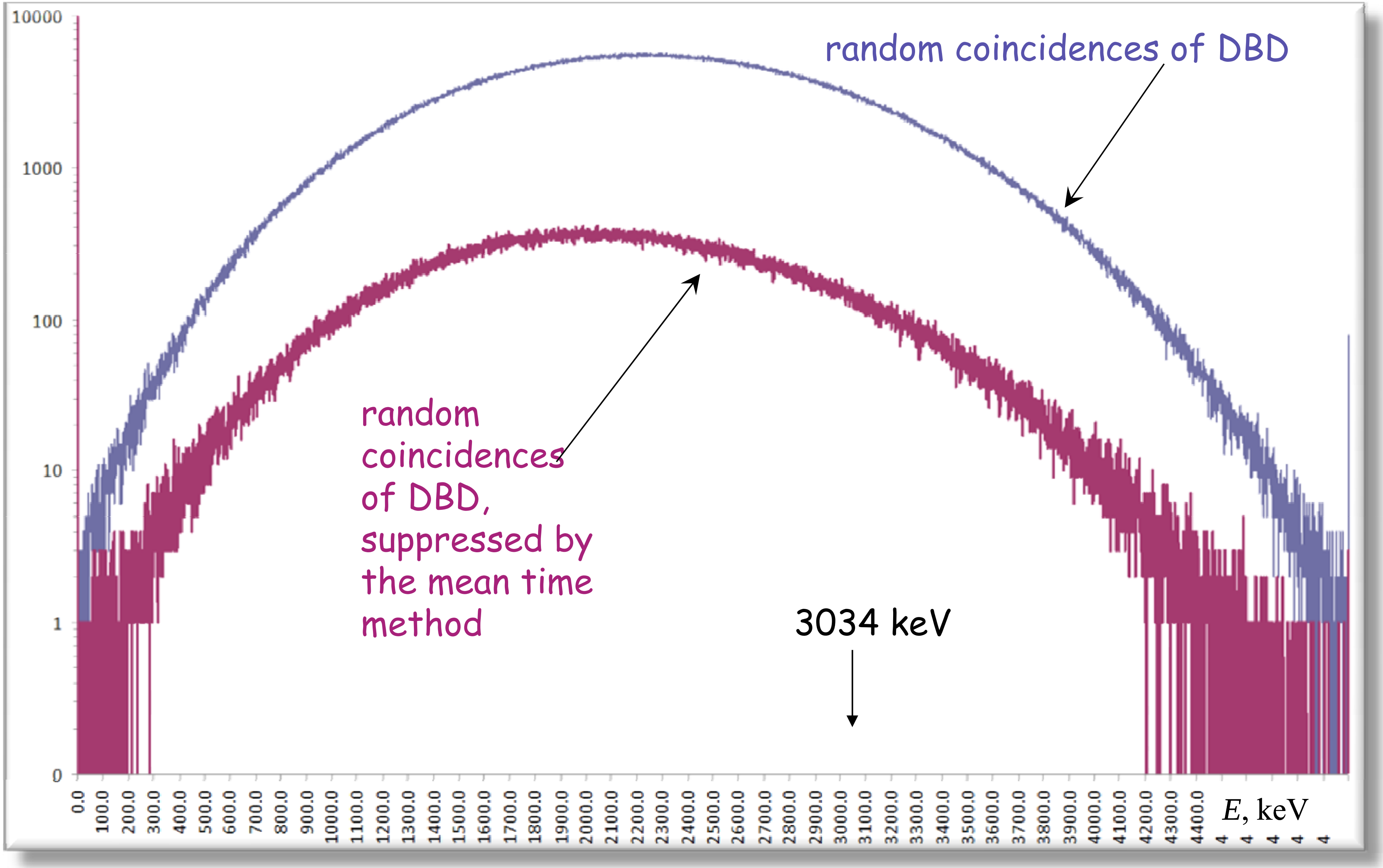
$$I = (m/\mu) \cdot N_A \cdot \delta \cdot (\ln 2/T_{1/2}) = 0.0026\ \mathrm{s}^{-1}$$

the average time between the signals is 380 s. Thus, the probability for the pair to have $\Delta t < 30$ ms is

$$p = I \cdot \Delta t = 30\ \mathrm{ms} \cdot 0.0026\ \mathrm{s}^{-1} = 7.8 \cdot 10^{-5}$$

After applying the suppression procedure, the 61157 pairs in the range $E_1+E_2 = Q_{2b} \pm 10$ keV decreased to 2935. The suppression power is ~21.

(see also a poster of D.Chernyak on more complicated techniques of pulse shape suppression for random coincidences in molybdates).



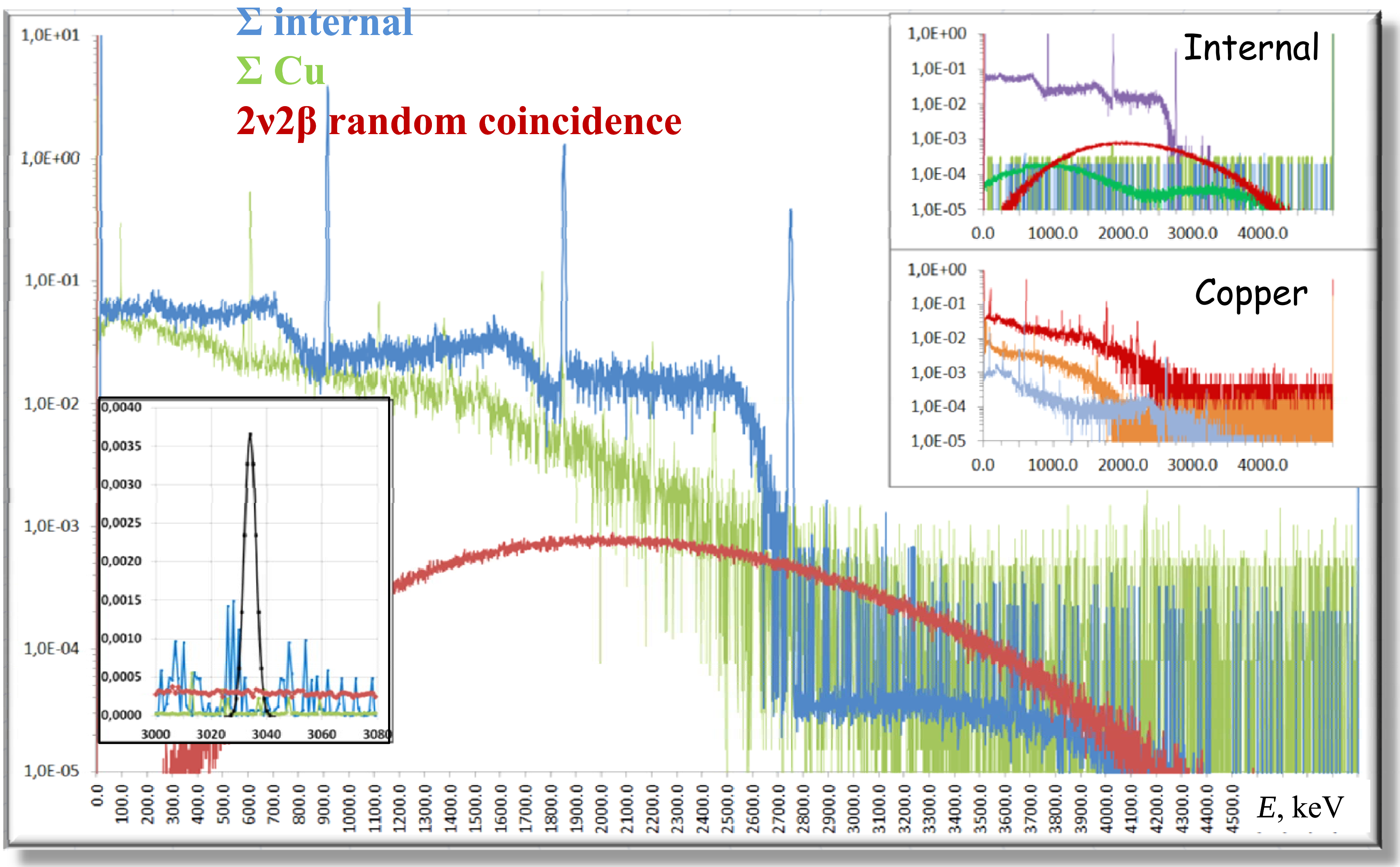
random coincidences of DBD

random coincidences of DBD, suppressed by the mean time method

3034 keV

$2.52 \cdot 10^{-8}$ counts/keV ($Q_{2\beta} \pm 10$ keV) per one pair of $2\beta 2\nu$ decays of ^{100}Mo
$1.2 \cdot 10^{-4}$ counts/(yr·keV·kg).

Backgrounds from radioactive decays in set-up



Main backgrounds from radionuclides:

Background source	**Activity [μBq/kg]**	**Bg [10^{-4} cnt/keV/kg/yr]**	**Bg reduced by PSD [10^{-4} cnt/keV/kg/yr]**
Tl-208, internal	10 (^{232}Th)	0.36	
Tl-208, in Cu	16 (^{232}Th)	0.22	
BiPo-214, internal	10	0.11 1)	$\leq$ 0.01
BiPo-214, in Cu	60	1.8 1) 2)	$\leq$ 0.18
BiPo-212, internal	10 (^{232}Th)	0.08 1)	$\leq$ 0.01
BiPo-212, in Cu	16 (^{232}Th)	0.36 1) 2)	$\leq$ 0.04
Y-88, internal	20	0.19	
Σ int. (w/o 2β2ν)		0.74	$\leq$ 0.57
Σ Cu		2.40	$\leq$ 0.44
Rand. coinc. from 2β2ν decays of ^{100}Mo	8.7×10^3 (single evts.)	3.1 3)	1.2
Total		**6.2**	**$\leq$ 2.2**

1) Can be reduced x0.1 by alpha/beta PSD (FOM=7.7).

2) Can be reduced by teflon coating of Cu (to remove surface alphas).

3) Can be reduced by the leading edge separation with Δt=0.5 ms for delayed events.

Muon background

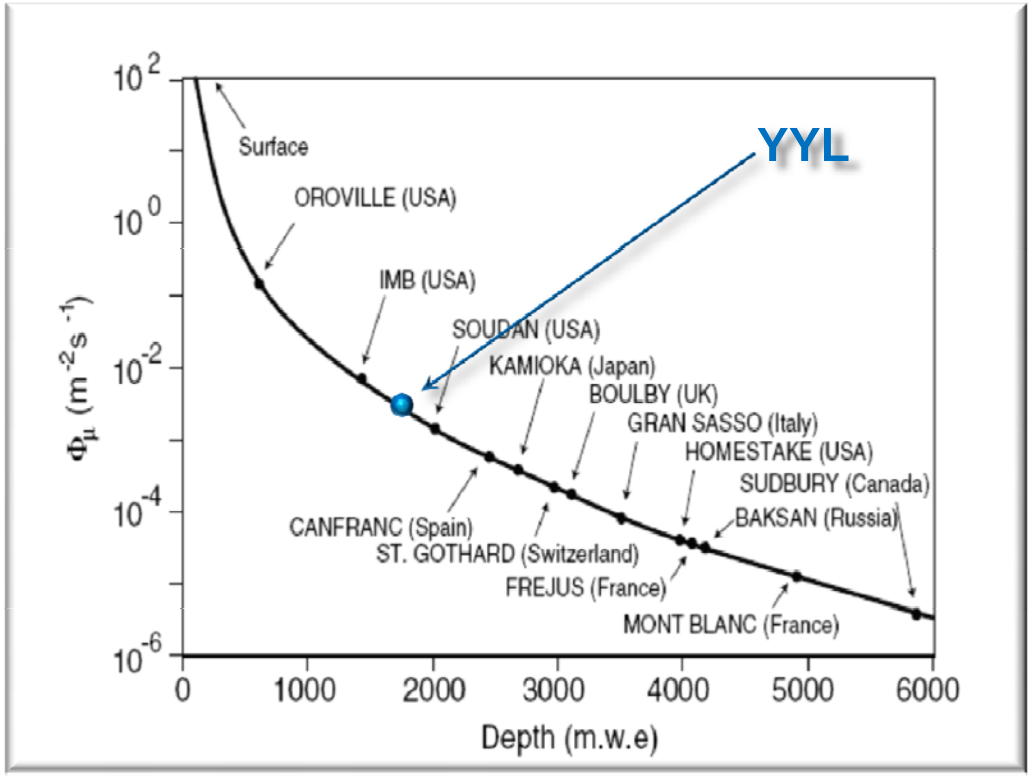
(for YangYang Lab)

(See also the next talk of Dr. Eunju Jeon)

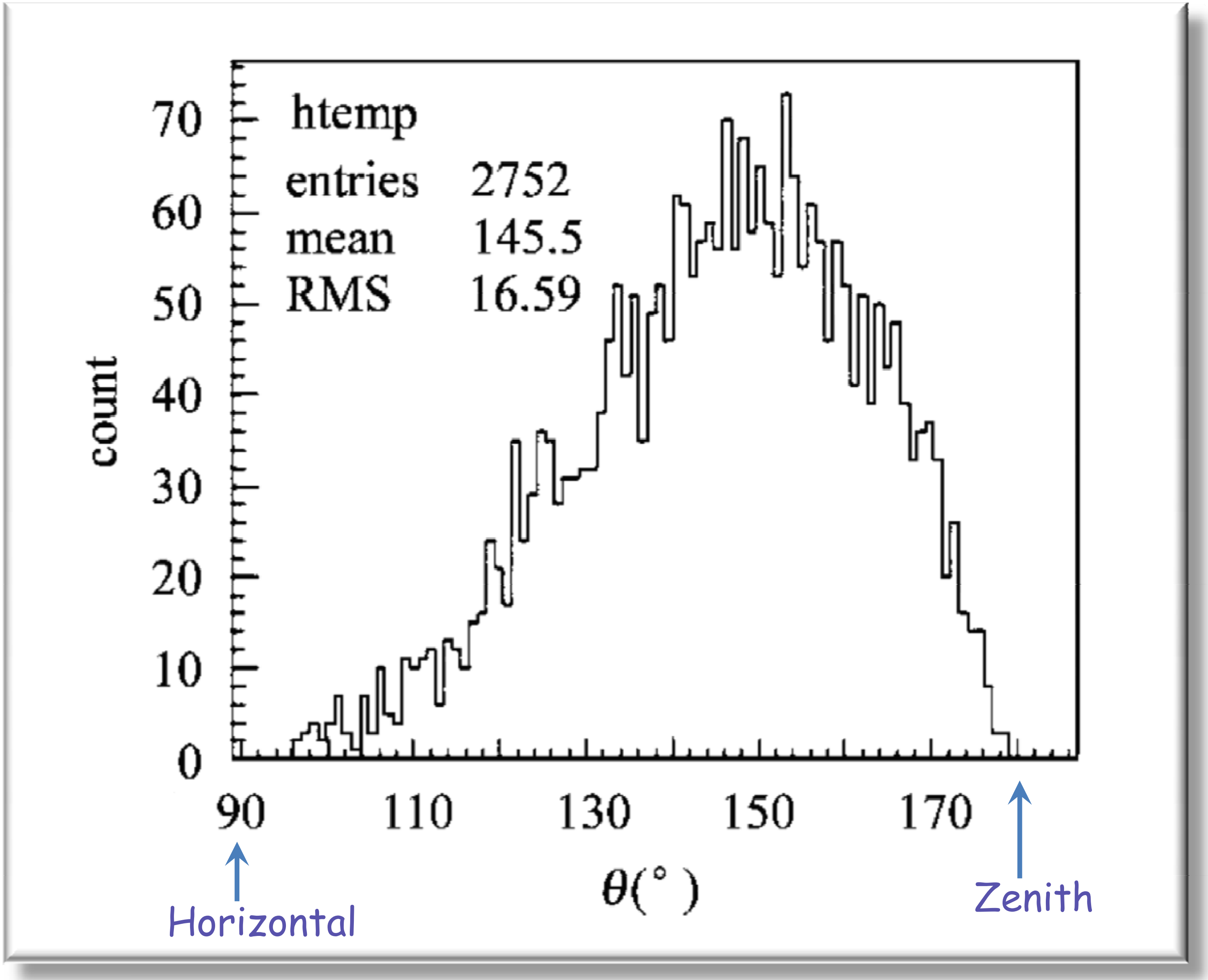
Muon background

YangYang Lab
(0.7 km underground,
~1.8 km w.e.)

2.7e-3 muons/m^2/s
9.7 muons/m^2/h
(~10 times more than LNGS,
~10^5 times less than
at the surface)
8.5e4 muons/m^2/yr



Energy spectrum: from the model described in:
D.-M. Mei, A. Hime. Phys. Rev. D 73 (2006) 053004 [arXiv:astro-ph/0512125].
$I_\mu(h_0) = 67.97\times10^{-6}\exp(-h_0/0.285) + 2.071\times10^{-6}\exp(-h_0/0.698)$,
$dN/dE_\mu = Ae^{-bh(\gamma-1)}\cdot(E_\mu + \varepsilon_\mu(1 - e^{-bh}))^{-\gamma}$, $h = h_0 \sec\theta$.
For h_0=1.815 km w.e. (best for the observed muon flux)
mean energy = **202 GeV (Groom et al.)** or 182 GeV (Lipari et al. – different sets of parameters b, ε_μ , γ).

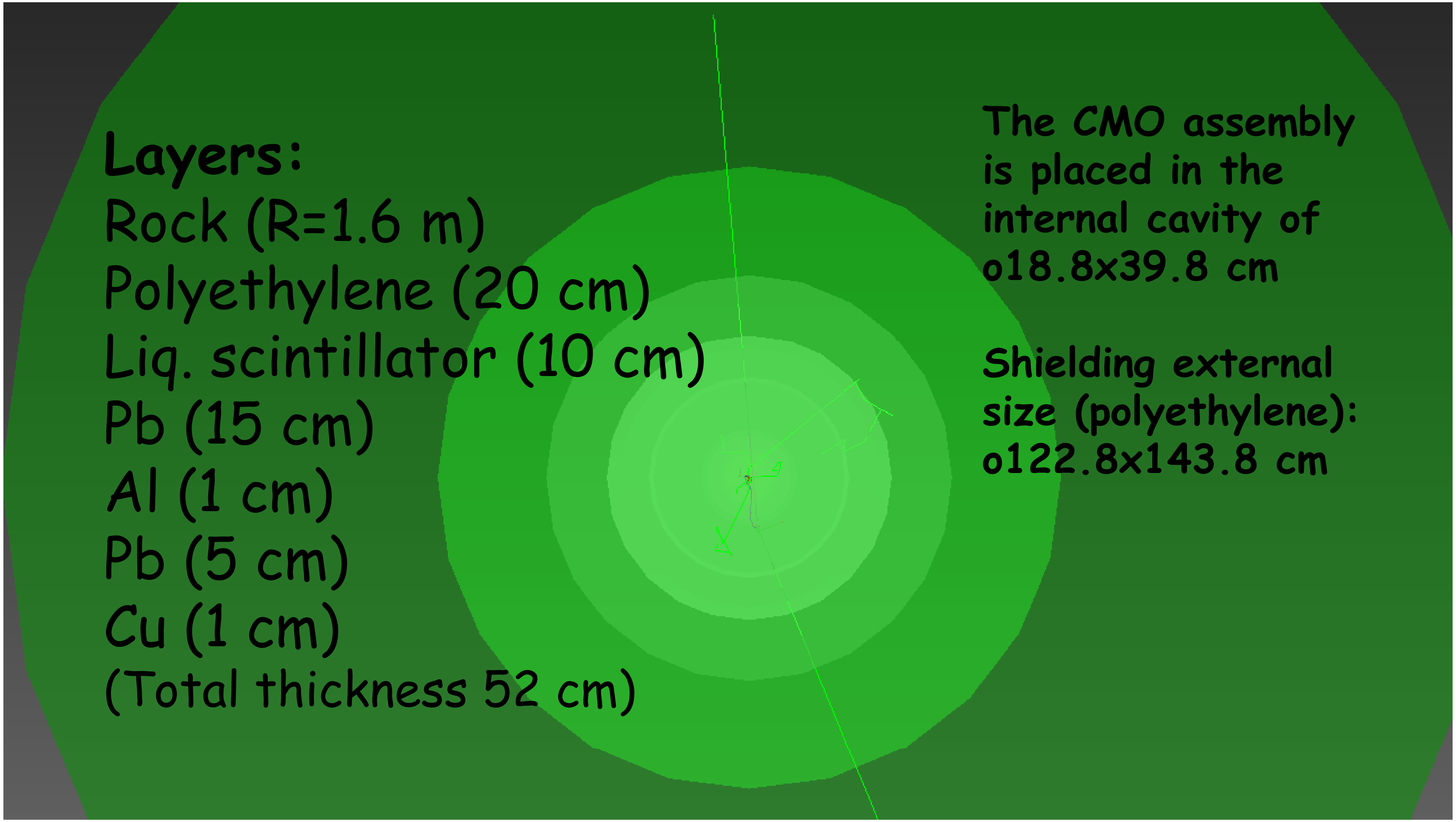


Muon directions:

Theta distribution

(Asimutal distribution is almost isotropic)

From: ZHU Jing-Jun *et al.* (KIMS Coll.) Study on the Muon Background in the Underground Laboratory of KIMS. High En. Phys. and Nucl. Phys. Vol. 29, No. 8 Aug. 2005. p.721-726. http://dmrc.snu.ac.kr/english/documents/paper/Muon_zhu.pdf



Layers:

Rock (R=1.6 m)

Polyethylene (20 cm)

Liq. scintillator (10 cm)

Pb (15 cm)

Al (1 cm)

Pb (5 cm)

Cu (1 cm)

(Total thickness 52 cm)

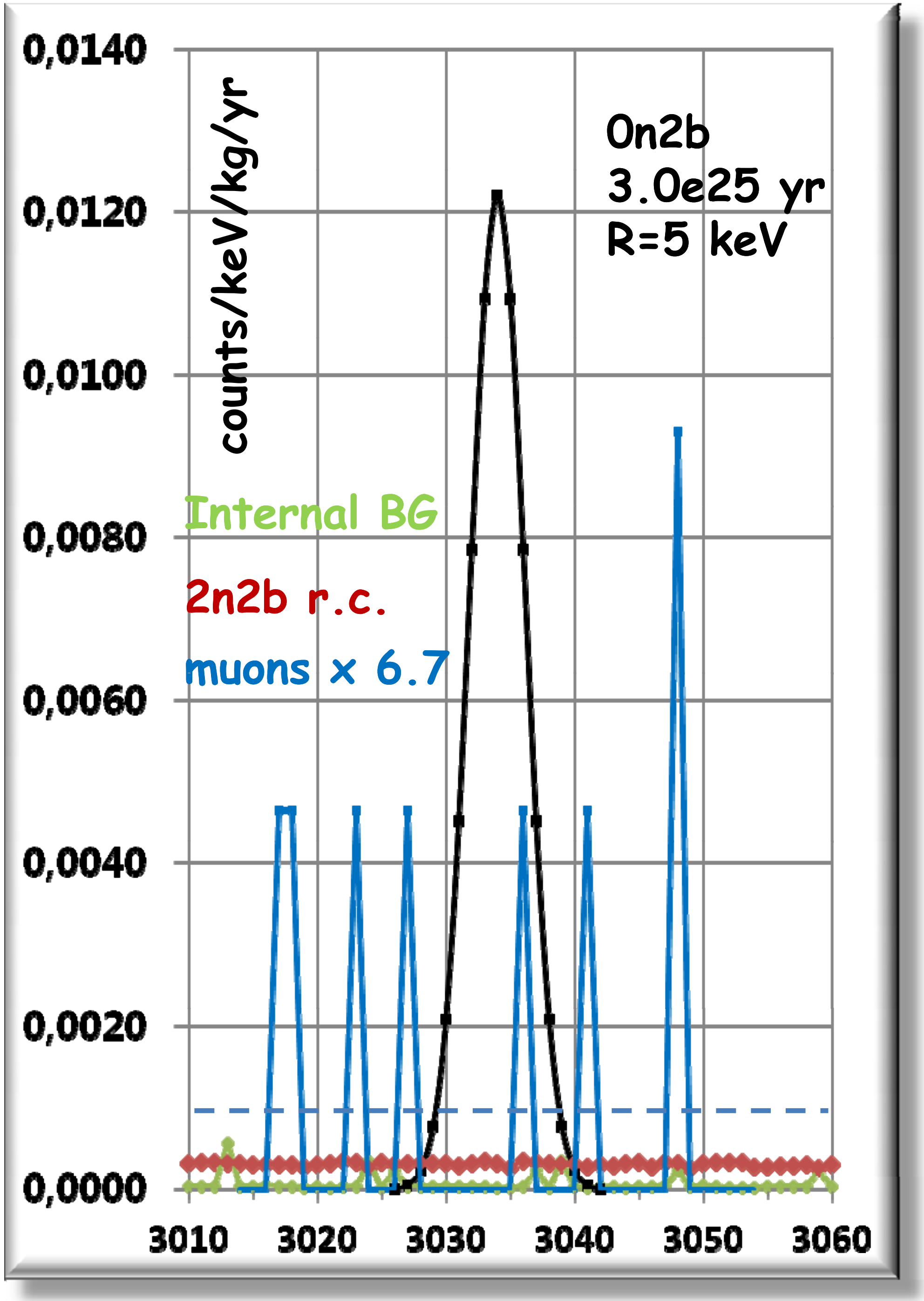
The CMO assembly is placed in the internal cavity of o18.8x39.8 cm

Shielding external size (polyethylene): o122.8x143.8 cm

Thresholds: LS 100 keV, CMO 50 keV.

Long-lived cosmogenic nuclides produced *in situ* were not considered.

LS veto efficiency taken as 95%, the veto time window of 2 ms.



Mu flux=8.5e4 muons/m^2/yr
The lower circle of the shield is
S=1.18 m^2.

1e7 muons simulated (equiv. 99 years);
8 single hits in the 40 keV range

The mean rate of muon-related events (blue) is
1.36e-4 counts/keV/kg/yr
(anti-coinc., in 3034+/-20 keV)

For $T_{1/2}$=3e25 yr and m_{CMO}=0.3 kg, in R_{FWHM} = 5 keV:

r_{0n2b}= **0.0195** counts/yr in one crystal
r_{mu} = **0.00021** counts/yr in one crystal

r_{0n2b}= **4.8** counts/ (5 yr x 49 crystals)
r_{mu} = **0.051** counts/ (5 yr x 49 crystals)

Kiev RPSCINT 2013.09.17

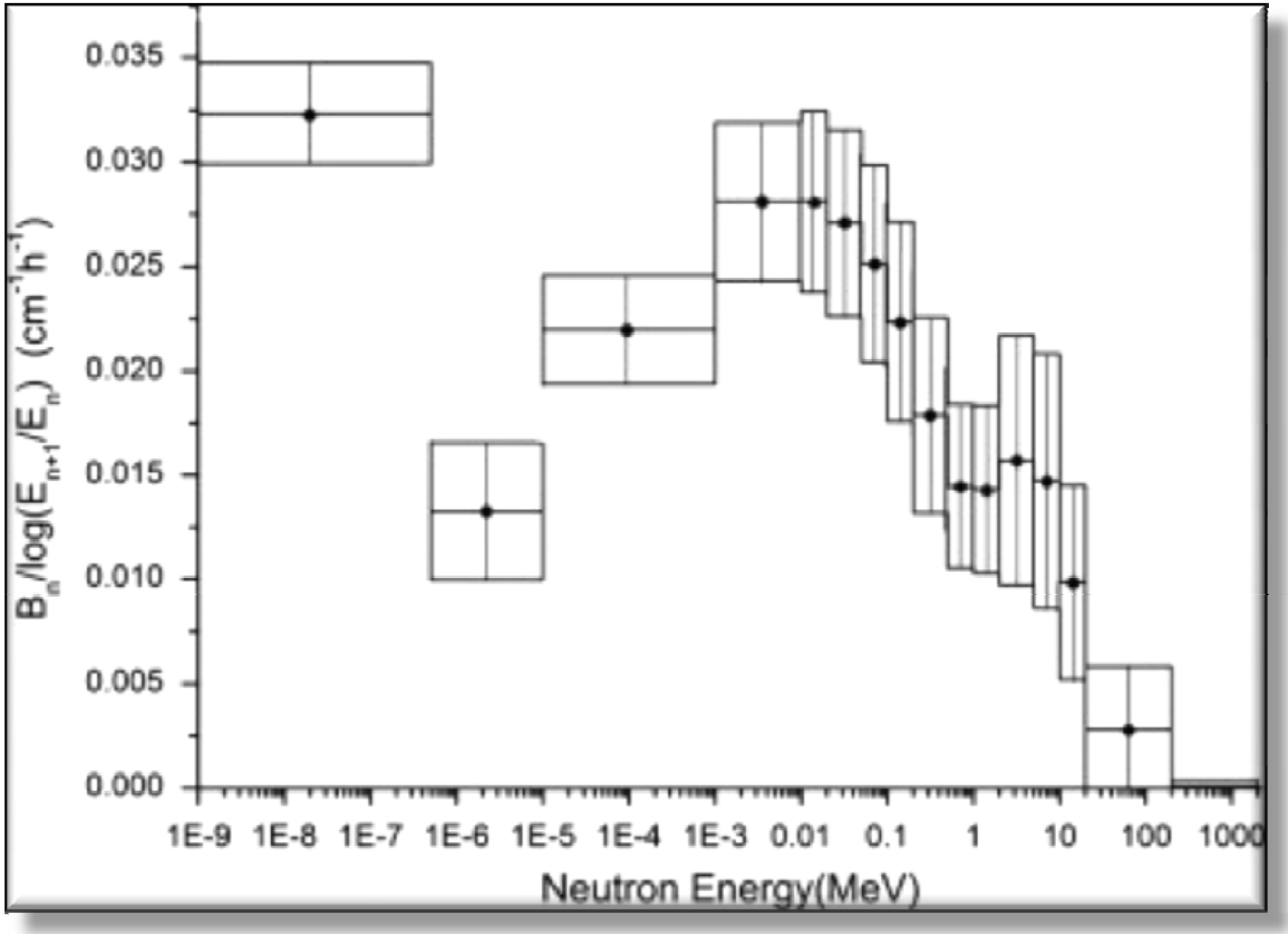
Background from neutrons

Usual sources underground:

- **Spallation of nuclei by cosmic-ray muons;**
- **Spontaneous fission of ^{238}U;**
- **(α,n) reactions;**

Dangerous because to shield is difficult.

Neutron spectrum in Yangyang Lab:



Total flux:
0.242±0.008 cm^{-2} h^{-1}

(for comparison: LNGS flux is 18 times less)

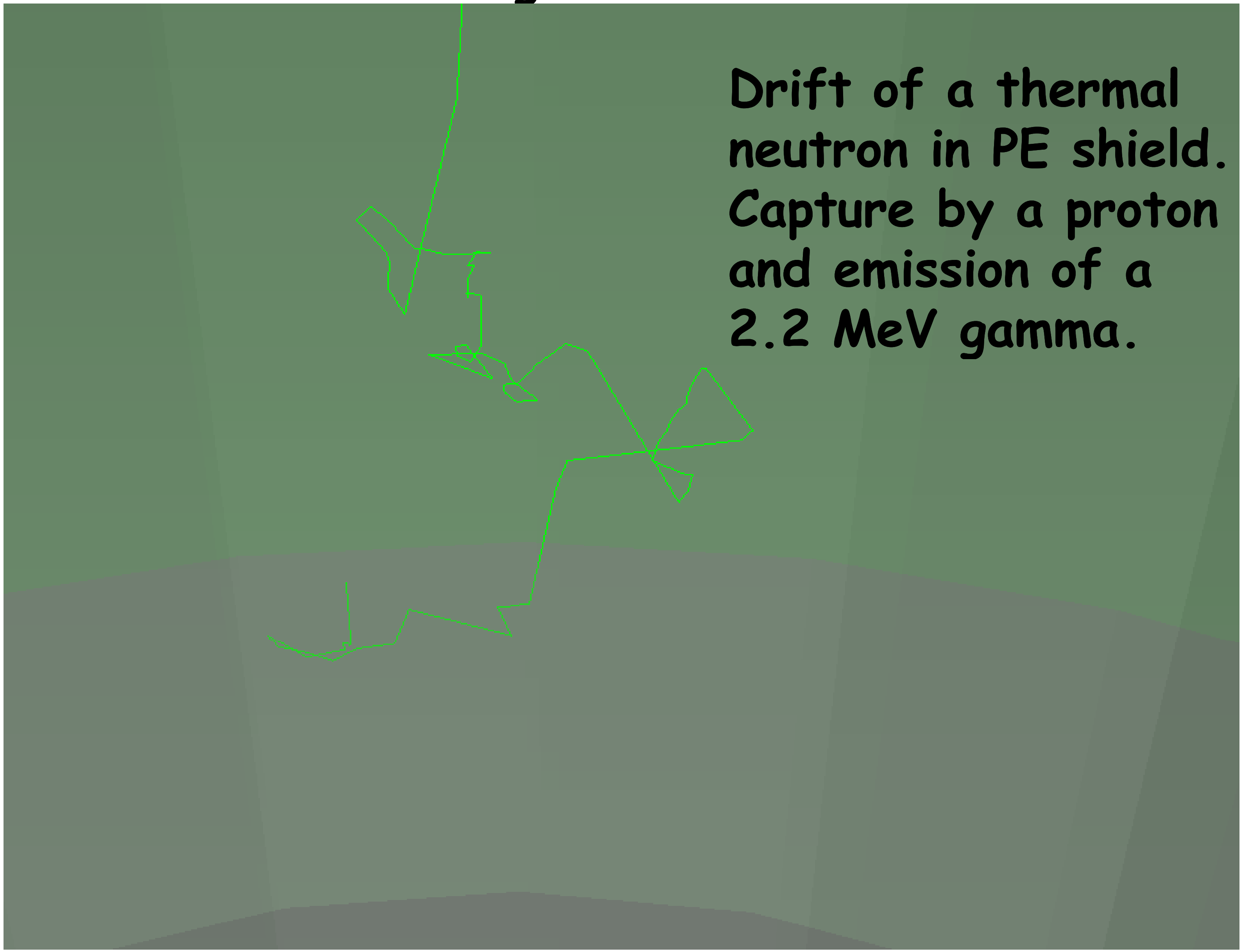
above the cadmium cut-off (0.5 eV):
0.155±0.010 cm^{-2} h^{-1}

(150-200 times less than on the Earth surface).

For E_n in (1-10) MeV:
0.015±0.003 cm^{-2} h^{-1}

From: Hyeonseo Park, Jungho Kim, Y.M. Hwang, Kil-Oung Choi, Neutron spectrum at the underground laboratory for the ultra low background experiment, Appl.Rad.Isot., 2013 (http://dx.doi.org/10.1016/j.apradiso.2013.03.068 , measurements using multi-shell Bonner spheres)

Background from neutrons



Drift of a thermal neutron in PE shield. Capture by a proton and emission of a 2.2 MeV gamma.

Background from neutrons

0.24 neutrons/cm^{-2} h^{-1};
1.7e8 neutrons/yr through the shield total surface (7.9 m^{2}) .

1.7e8 neutrons simulated (corresponds to 1.0 yr).

No single hits in the 40 keV range;
1 single hit in the 400 keV range in 49 crystals (15 kg).
The mean rate of neutron-related events is
<4e-4 counts/keV/kg/yr
(anti-coinc., in 3034+/-200 keV)

Not enough statistics yet!

The backgrounds at 3034 keV in terms of N_{evt}, for T= 5 years, R_{fwhm}= 5 keV, and M_{CMO} = 15 kg:

radioactive contaminations	0.08 events
muons	0.05 events
neutrons (not finished yet*)	~0.15 events
Σ_{bg}	**~0.3 events**
DBD0nu (for $T_{1/2}$=3e25 yr)	**4.8 events**

*) assuming 4e-4 counts/keV/kg/yr (see the previous slide)

Conclusions and prospects:

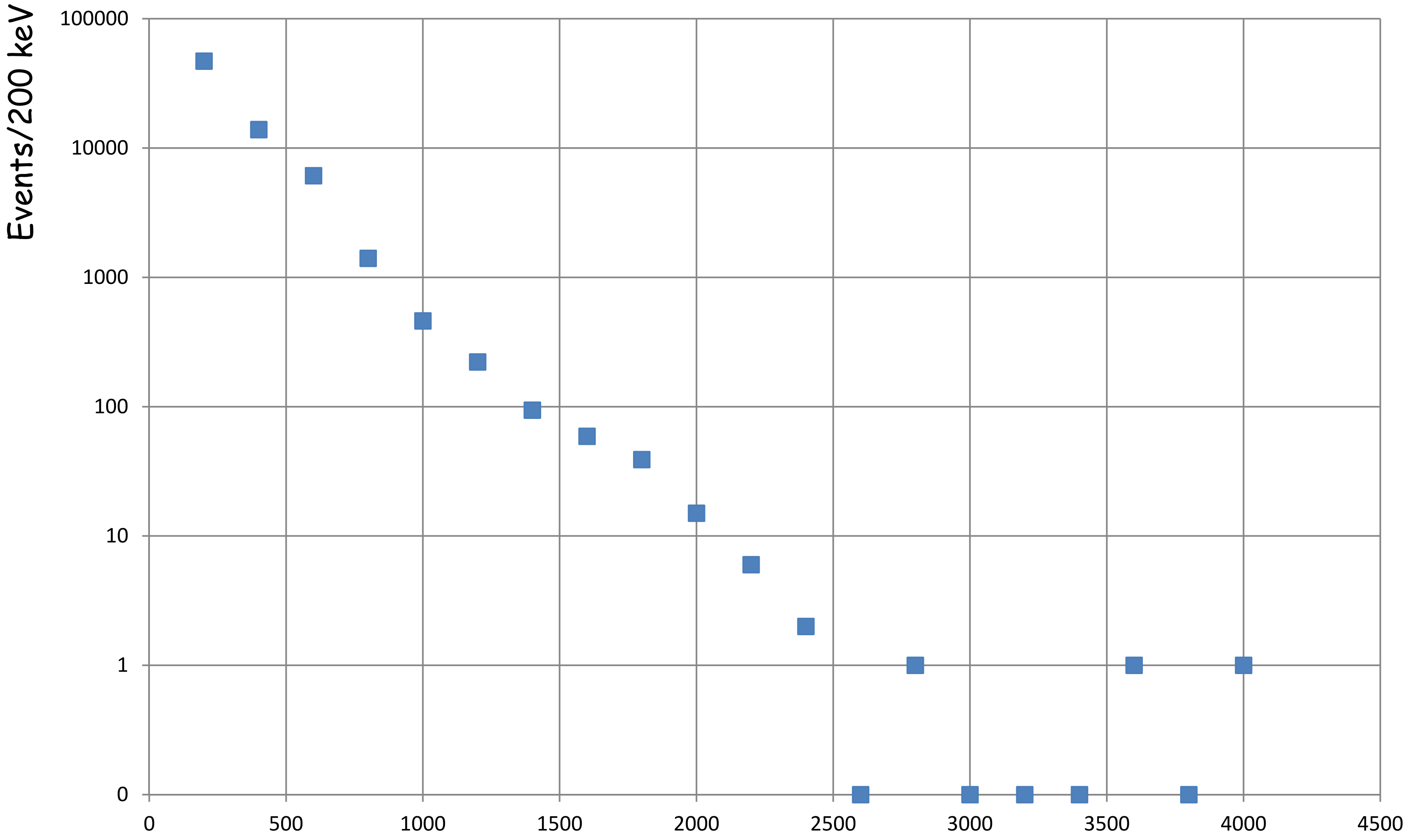
1. The main background radioactive sources (Tl-208, BiPo-212, BiPo-214, Y-88, random coincidences of Mo-100 DBD) were simulated for assembly of ~50 crystals of 300g $^{40}Ca^{100}MoO_4$ in copper frames (75g). Total background can be reduced to 0.08 events in the DBD peak (R = 5 keV) for exposition of 5 yr*15 kg.

2. The simulated muon background is about 0.05 events for this exposition in the YangYang Lab.

3. For neutrons, only the upper limit is obtained now because the statistics is still low, but neutrons can give ~0.15 events, very roughly. The calculation for neutrons continues.

4. Contribution to background from short-living cosmogenic radionuclides being created *in situ* is under estimation now.

Thank you for attention


Events/200 keV
100000
10000
1000
100
10
1
0
0
500
1000
1500
2000
2500
3000
3500
4000
4500