ISMART 2018
Belarusian State University
(Minsk, Belarus)
October 9 - 12, 2018

Isotopically enriched scintillation single crystals of calcium molybdate $^{40}Ca^{100}MoO_4$ for experiments on the search for neutrinoless double beta decay

V.V.Alenkov[1]

O.A.Buzanov[1]

V.N.Kornoukhov[1,2]

1- JSC Fomos-Materials (Moscow)

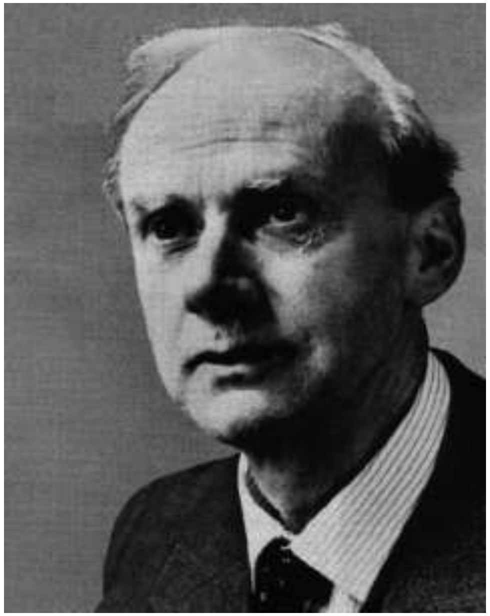
2 - MEPhI (Moscow)

Nature of neutrino ?

No charge, no mass → if particle is own antiparticle?

Dirac neutrino (1928)

$$\nu \neq \bar{\nu}$$



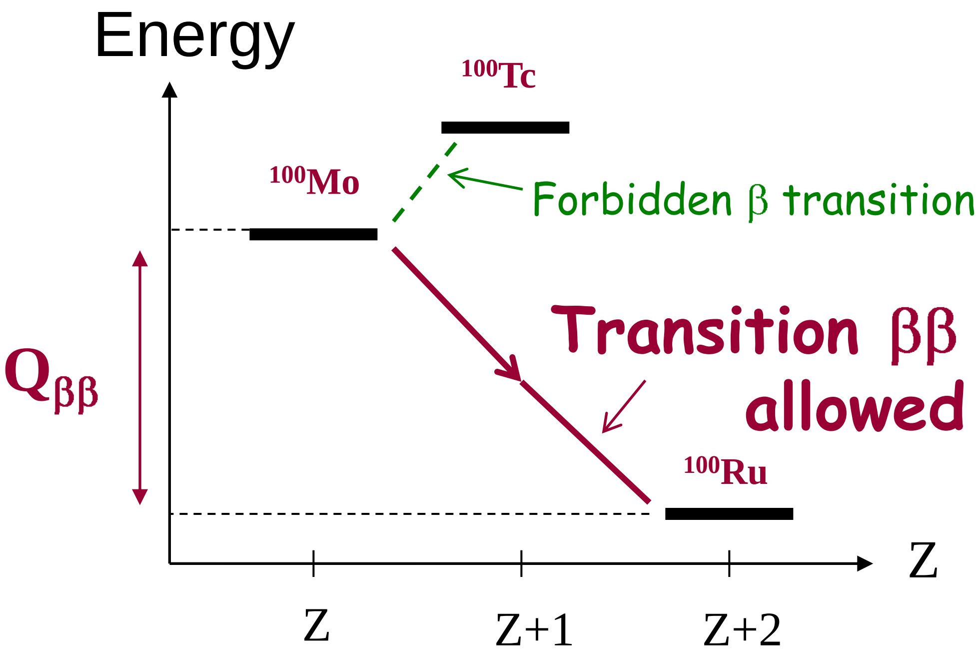
Majorana neutrino (**1937**)

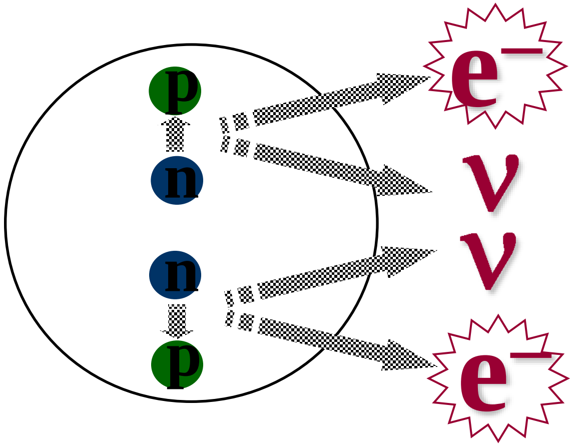
$$\nu = \bar{\nu}$$

How to check it ?

Allowed double beta decay …

For some nuclei single β decay is impossible
But 2β decay is allowed
(M.Goeppert-Mayer (Goettingen,1935))

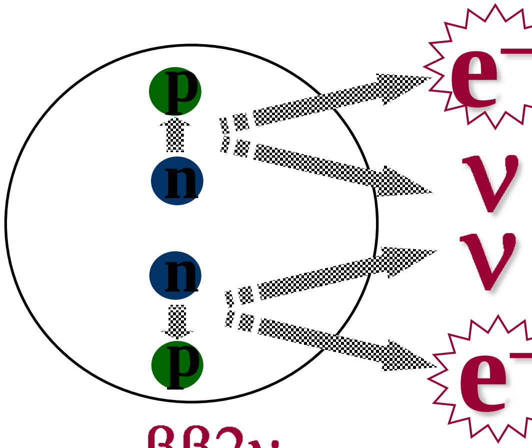




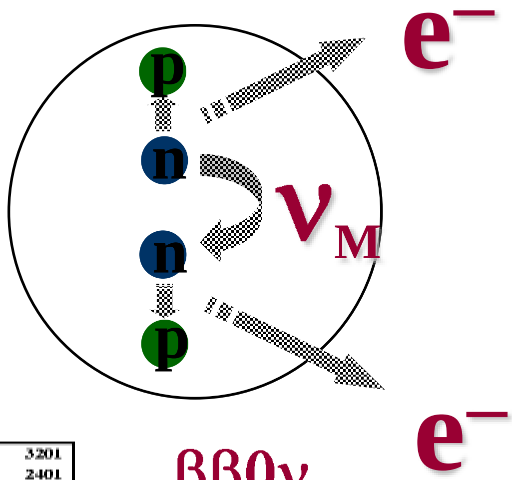
The neutrino is own particle ?

If neutrino is Majorana: ββ **without neutrino emision**

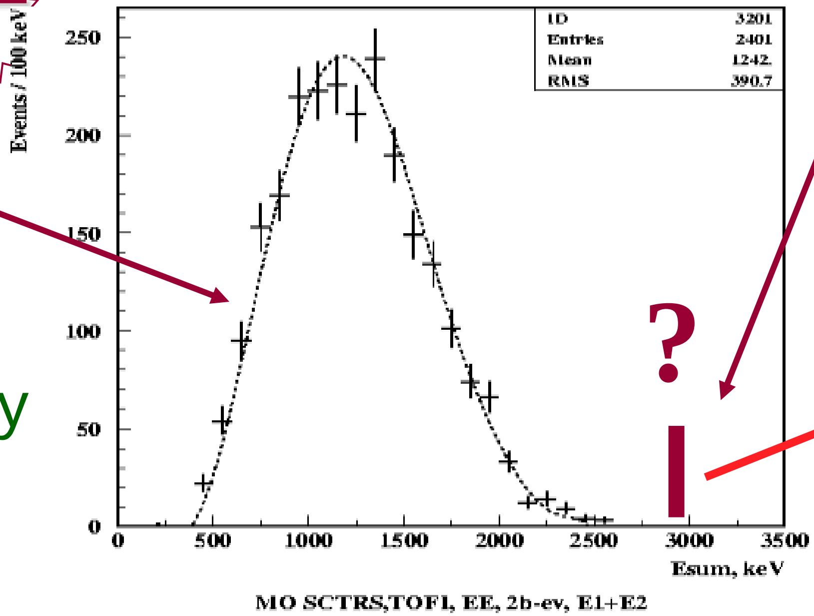
proposed by G.Racah (1937) and W.H.Furry (1939)



ββ2ν



ββ0ν



MO SCTRS,TOF1, EE, 2b-ev, E1+E2

$T_{1/2}$ (ββ2ν) ≈ 10^{20} y

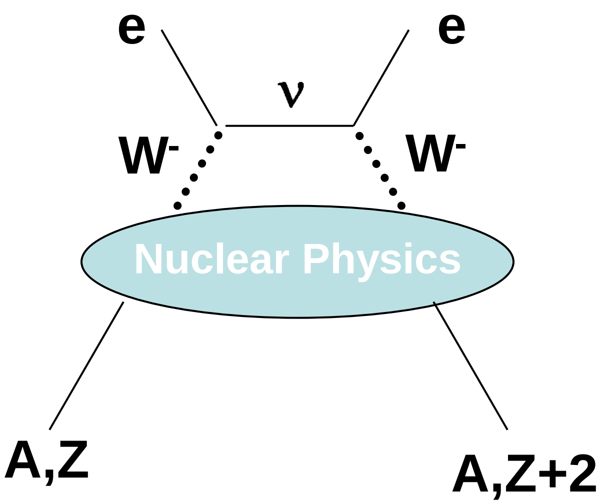
$T_{1/2}$ (ββ0ν) ∝ m_ν^{-2}

$> 10^{25}$ y !

$0\nu\beta\beta$ decay and the properties of neutrino

(reason to care)

- Nature of neutrino (Majorana or Dirac particle?)
- Lepton number conservation
- Absolute scale of the neutrino mass
- Hierarchy of neutrino masses



Decay rate if $T_{1/2} \geq 10^{25}$ years : how many events?

- Probability of the process $\tau = 1/T_{1/2}$

$T_{1/2} \geq 10^{25}$ years *(U-238 = $4{,}5 * 10^{9}$ yr)*

- If 1 kg of Mo-100 then after 1 year exposure time expected

$N = 0.693 * 6{,}02 * 10^{23} * (1000\ \text{gr}/100\ \text{g-mole}) * 1/10^{25}$ **~**

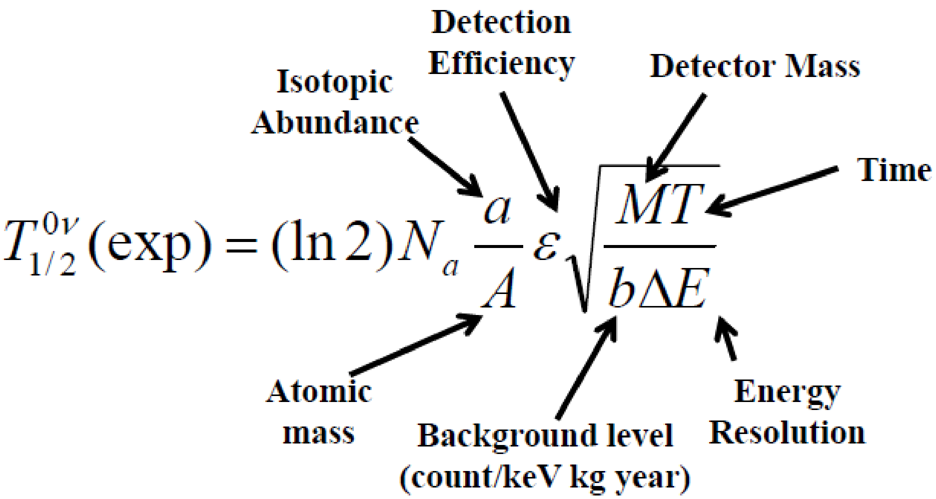
$\leq$ 1 events/year

This is a very rare decay

(expected for 31 even-even nuclei: ^{48}Ca, ^{76}Ge, ^{82}Se, ^{96}Zr, ^{100}Mo, ^{116}Cd, .. etc).

Sensitivity of DBD experiments (as $T^{0\nu}_{1/2}$ and $m_{\beta\beta} \sim (T^{0\nu}_{1/2})^{-1/2}$)

For sizeable background case;



$$T^{0\nu}_{1/2}(\exp) = (\ln 2) N_a \frac{a}{A} \varepsilon \sqrt{\frac{MT}{b \Delta E}}$$

Isotopic Abundance

Detection Efficiency

Detector Mass

Time

Atomic mass

Background level (count/keV kg year)

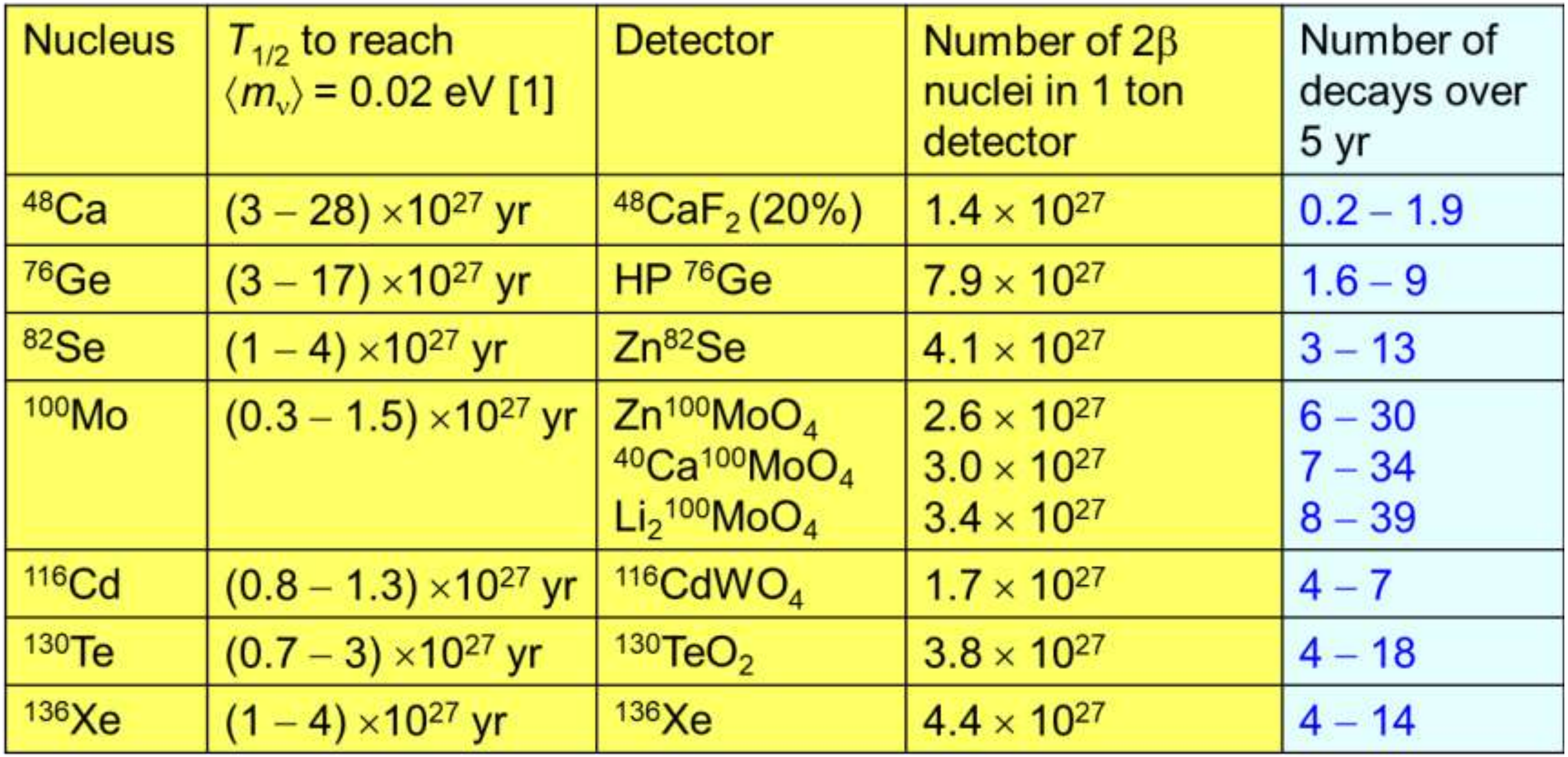
Energy Resolution

For "zero" background case;
# of background events ~ 0 (1)

$$T^{0\nu}_{1/2}(\exp) = (\ln 2) N_a \frac{a}{A} \varepsilon \frac{MT}{n_{CL}}$$

- **Low background level (low radioactivity), *b***
- **High energy resolution, ΔE**
- **High enrichment of working isotope, ε**
- **Big mass, *M***
- **Low cost of enrichment of working isotope**

Correlation "$T^{0\nu}_{1/2} \Longleftrightarrow$ expected number of events" (mass of an isotope is equal to 1 ton)



Nucleus	$T_{1/2}$ to reach $\langle m_\nu \rangle = 0.02$ eV [1]	Detector	Number of 2β nuclei in 1 ton detector	Number of decays over 5 yr
^{48}Ca	$(3 - 28) \times 10^{27}$ yr	$^{48}CaF_2$ (20%)	1.4×10^{27}	0.2 – 1.9
^{76}Ge	$(3 - 17) \times 10^{27}$ yr	HP ^{76}Ge	7.9×10^{27}	1.6 – 9
^{82}Se	$(1 - 4) \times 10^{27}$ yr	$Zn^{82}Se$	4.1×10^{27}	3 – 13
^{100}Mo	$(0.3 - 1.5) \times 10^{27}$ yr	$Zn^{100}MoO_4$ $^{40}Ca^{100}MoO_4$ $Li_2{}^{100}MoO_4$	2.6×10^{27} 3.0×10^{27} 3.4×10^{27}	6 – 30 7 – 34 8 – 39
^{116}Cd	$(0.8 - 1.3) \times 10^{27}$ yr	$^{116}CdWO_4$	1.7×10^{27}	4 – 7
^{130}Te	$(0.7 - 3) \times 10^{27}$ yr	$^{130}TeO_2$	3.8×10^{27}	4 – 18
^{136}Xe	$(1 - 4) \times 10^{27}$ yr	^{136}Xe	4.4×10^{27}	4 – 14

Table 3 in J.D.Vergados, H.Ejiri, F.Simkovic, Rep. Prog. Phys. 75 (2012) 106301

“Imitation” of the useful signal = background events in the energy range ~ MeV)

- Cosmic rays background at the sea level
- Natural radioactivity (isotopes belong to ^{238}U и ^{232}Th series, ^{40}К, artificial radionuclides ^{60}Co, ^{137}Cs….)

Solution:

- To run experiments into deep underground laboratories (≥ several *km of water equivalent*)
- Passive and active shielding of detector of γ- and neutrons radiation from surrounding rocks and concrete
- To use high purity materials:

Content of U and Th < 10^{-11} g/g (*< 10 ppt – part per trillion***)**

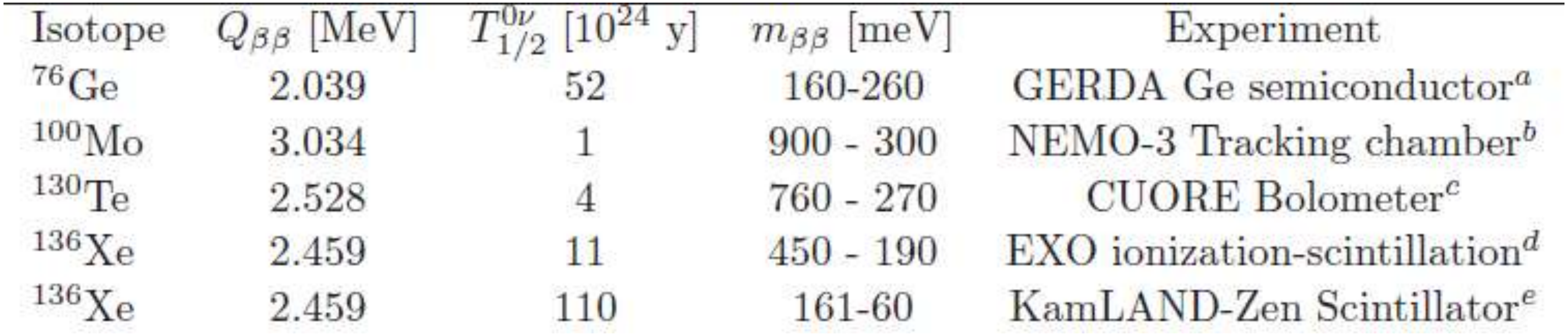
(just for comparison^{238}U и ^{232}Th into surrounding rockss and concrete **(room walls etc..) ~ 10^{-6} g/g (***ppm – part per million***)**

^{238}U(10^{-6} г/г) ~ 10 decay/sec/kg → 3*10^{8} decay/year/kg

Deep chemical and physics-chemical purification of the detector material and the materials of its surrounding structures is necessary!

Today best limit on $T_{1/2}$

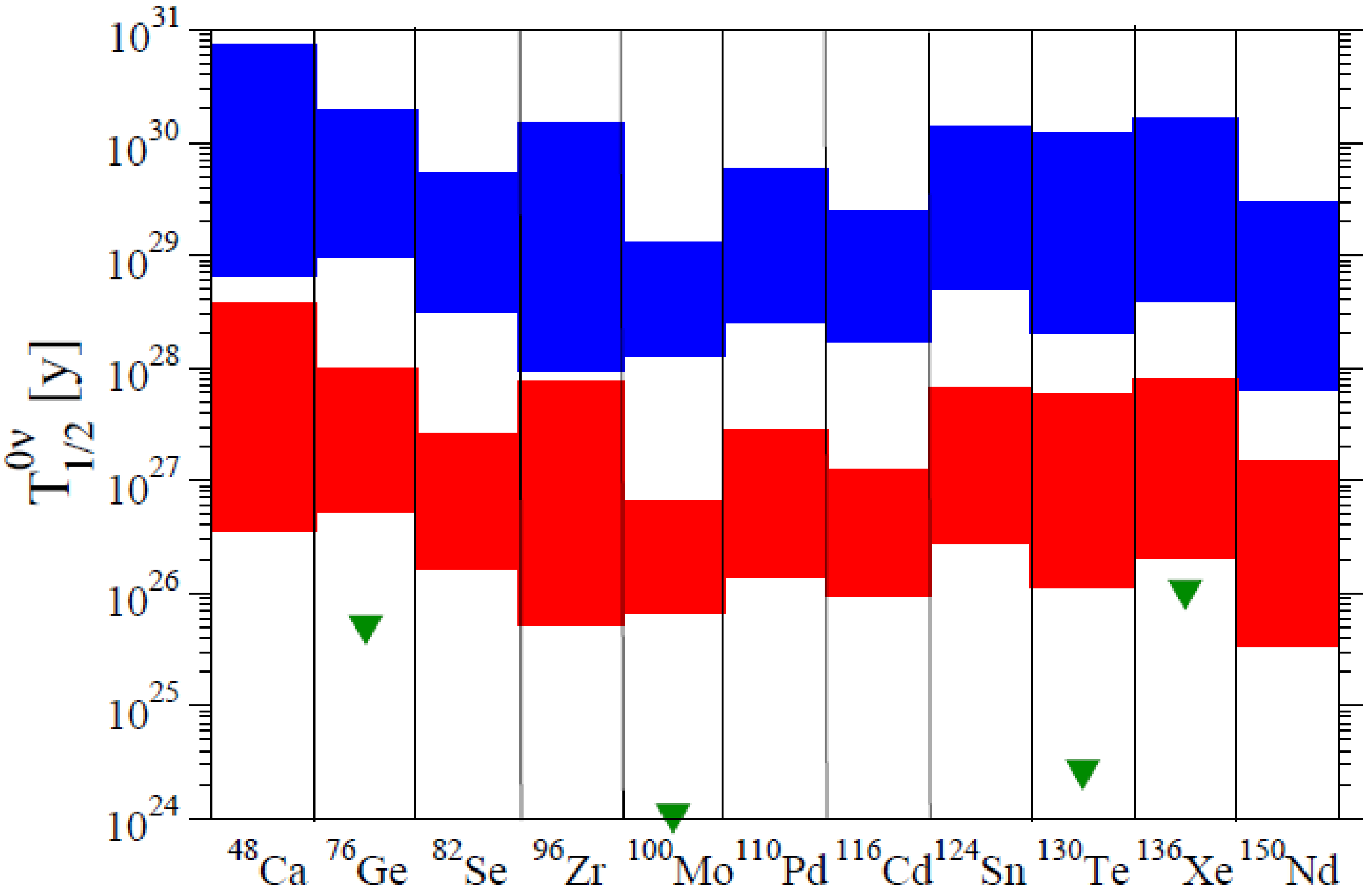
J.D. Vergadods, H. Ejiri, F. Simkovic (ArXiv: 1612.02924. Dec 2016)



Isotope	$Q_{\beta\beta}$ [MeV]	$T^{0\nu}_{1/2}$ [10^{24} y]	$m_{\beta\beta}$ [meV]	Experiment
^{76}Ge	2.039	52	160-260	GERDA Ge semiconductor[a]
^{100}Mo	3.034	1	900 - 300	NEMO-3 Tracking chamber[b]
^{130}Te	2.528	4	760 - 270	CUORE Bolometer[c]
^{136}Xe	2.459	11	450 - 190	EXO ionization-scintillation[d]
^{136}Xe	2.459	110	161-60	KamLAND-Zen Scintillator[e]

The $0\nu\beta\beta$-decay half-lives of nuclei of experimental interest (for the case NH - in blue and IH - in red)

(J.D. Vergadods, H. Ejiri, F. Simkovic (ArXiv: 1612.02924. Dec 2016)



$^{40}Ca^{100}MoO_4$ scintillation cryogenic detector as a tool for ^{100}Mo DBD search

- Detector = Source: ε ~ *85-90% efficiency*

- Energy resolution R ~ a few keV (5 ÷ 10 keV)

  $\Downarrow$

  No $2\nu\beta\beta$ of $Mo{-}100$ background

- Technology of the production → *High purity*

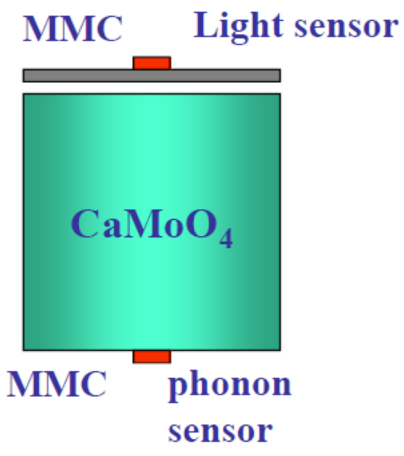
  $\Downarrow$

  very low ^{238}U-, ^{232}Th- intrinsic background

- Production of ^{100}Mo isotope: *centrifuges*

AMoRE (**A**dvanced **Mo**-based **R**are process **E**xperiment) detector technology: $^{40}Ca^{100}MoO_4$ + MMC + SQUID (Korea)

Low Temp. Detector
Source = Detector



<10-50 mK>

$CaMoO_4$

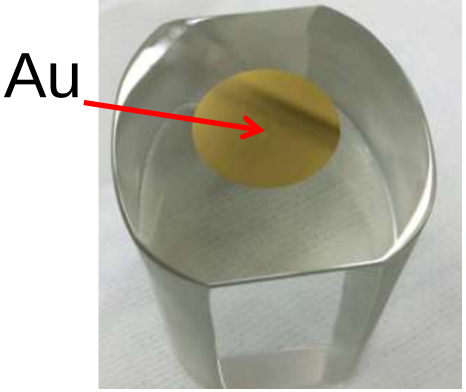
- Scintillating crystal
- High Debye temperature: $T_D = 438$ K, $C \sim (T/T_D)^3$
- ^{48}Ca, ^{100}Mo $0\nu\beta\beta$ candidates
- AMoRE uses $^{40}Ca^{100}MoO_4$ w. enriched ^{100}Mo and depleted ^{48}Ca

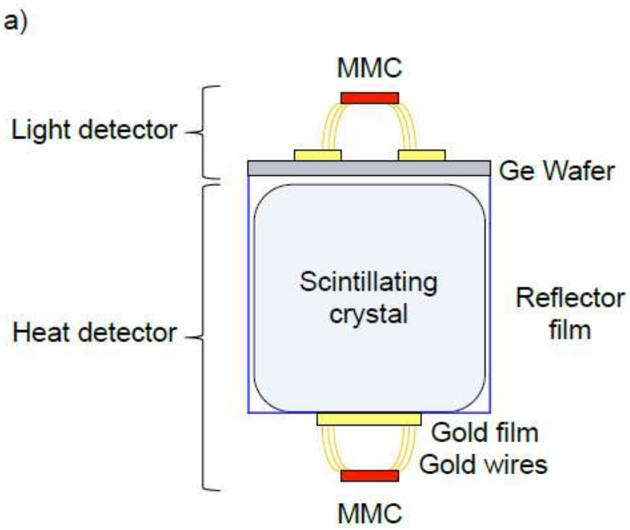
MMC (Metallic Magnetic Calorimeter)

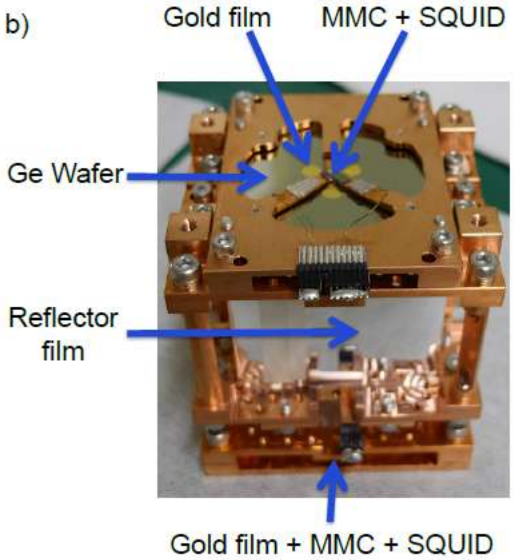
- Magnetic temperature sensor (Au:Er) + SQUID
- Sensitive low temperature detector with highest resolution
- Wide operating temperature
- Relatively fast signals
- Adjustable parameters in design and operation stages

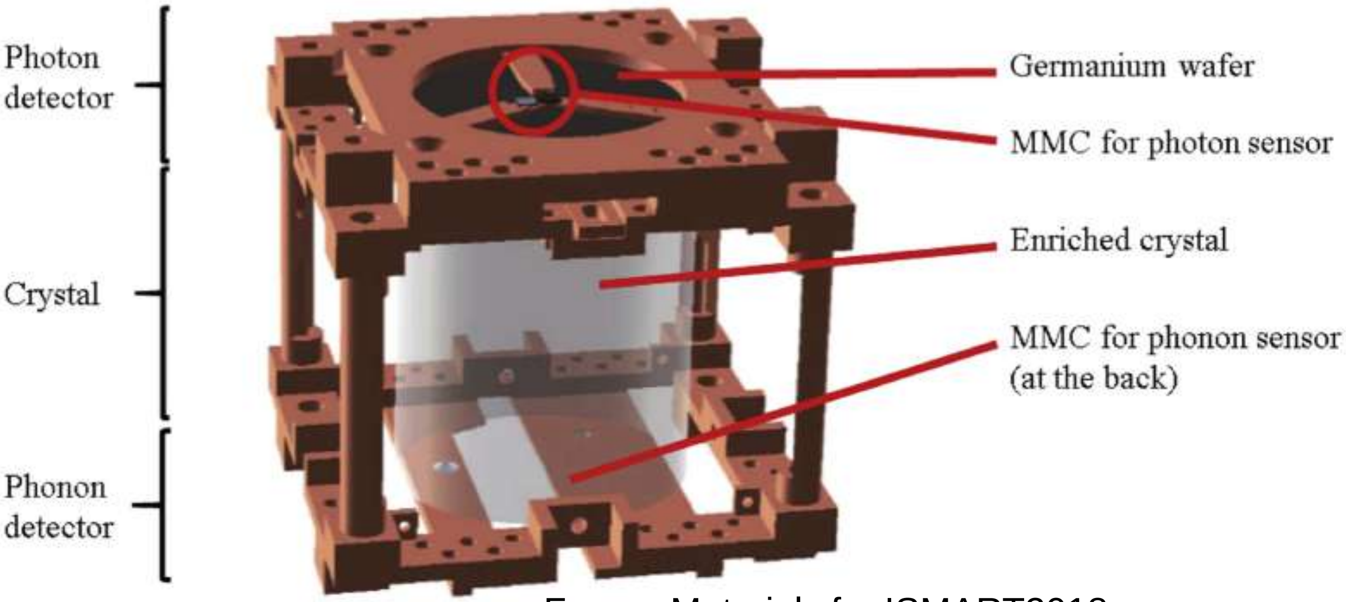
AMoRE detector module

$^{40}Ca^{100}MoO_4$

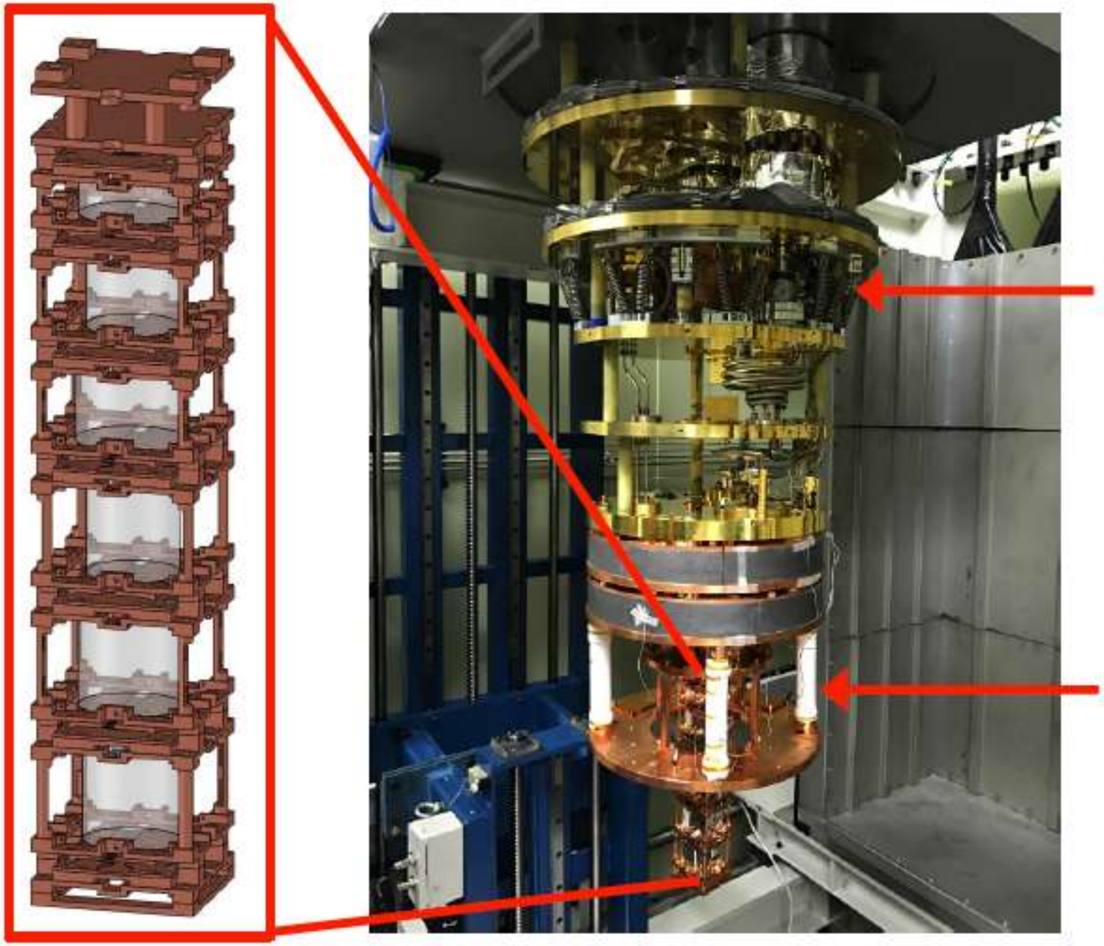








AMoRE Pilot detector tower

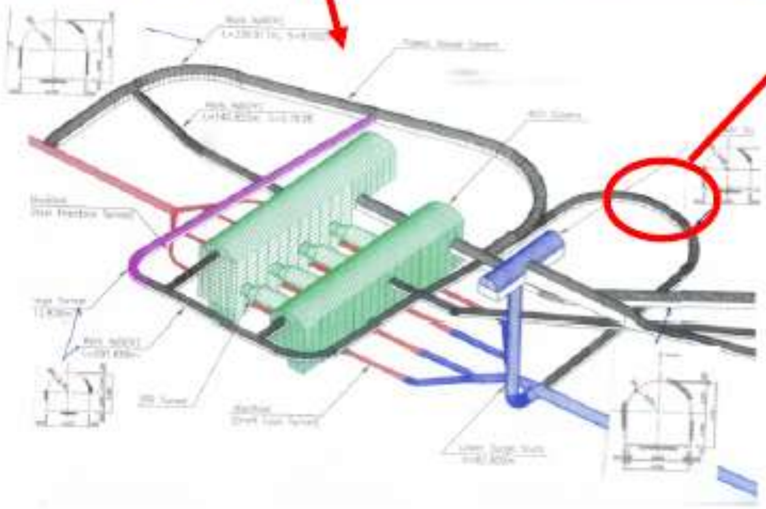


Detector tower

Spring Suspended Still (SSS)

Mass Spring Damper (MSD)

YangYang underground laboratory in Korea (AMoRE Pilot and AMoRE I phases of the experiment)



In Yangyang pumped storage Power Plant

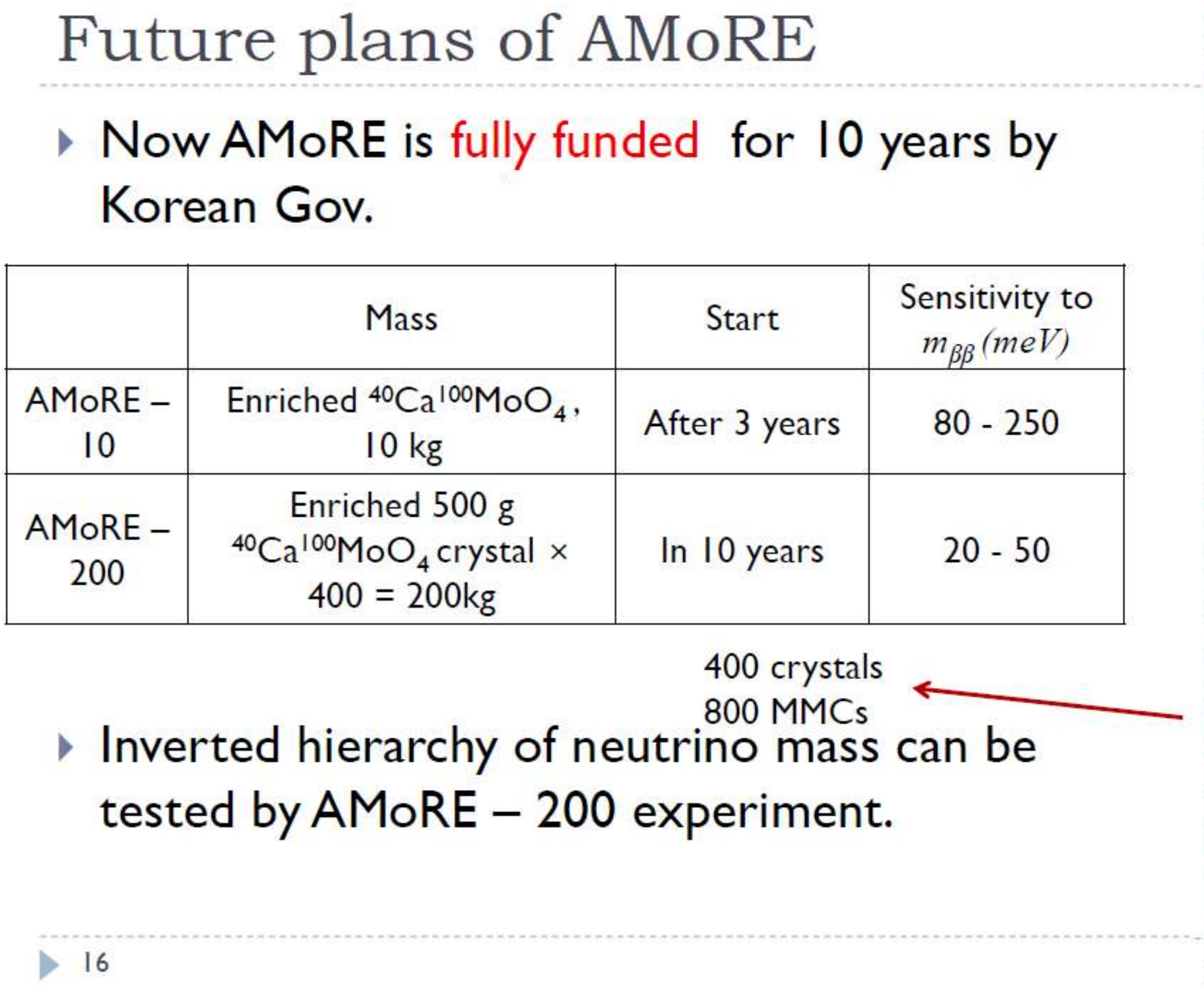
Minimum vertical depth : 700 m

Access to the lab by car : around 2 km

Experiments

- KIMS : dark matter search experiment
- AMoRE : $0\nu\ \beta\beta$ decay search experiment

Full scale AMoRE - 200 detector



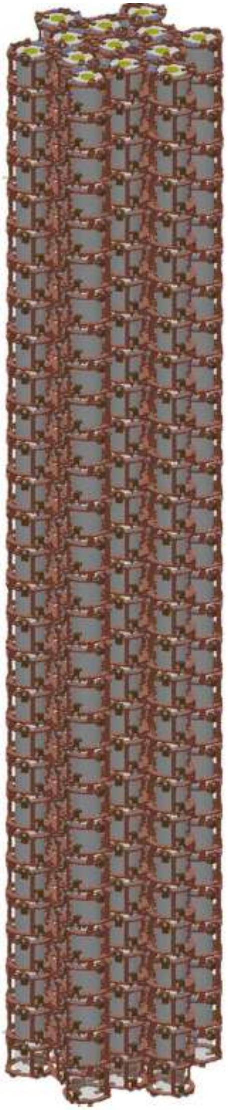
Future plans of AMoRE

- Now AMoRE is fully funded for 10 years by Korean Gov.

	Mass	Start	Sensitivity to $m_{\beta\beta}\,(meV)$
AMoRE – 10	Enriched $^{40}\mathrm{Ca}^{100}\mathrm{MoO}_4$, 10 kg	After 3 years	80 - 250
AMoRE – 200	Enriched 500 g $^{40}\mathrm{Ca}^{100}\mathrm{MoO}_4$ crystal × 400 = 200kg	In 10 years	20 - 50

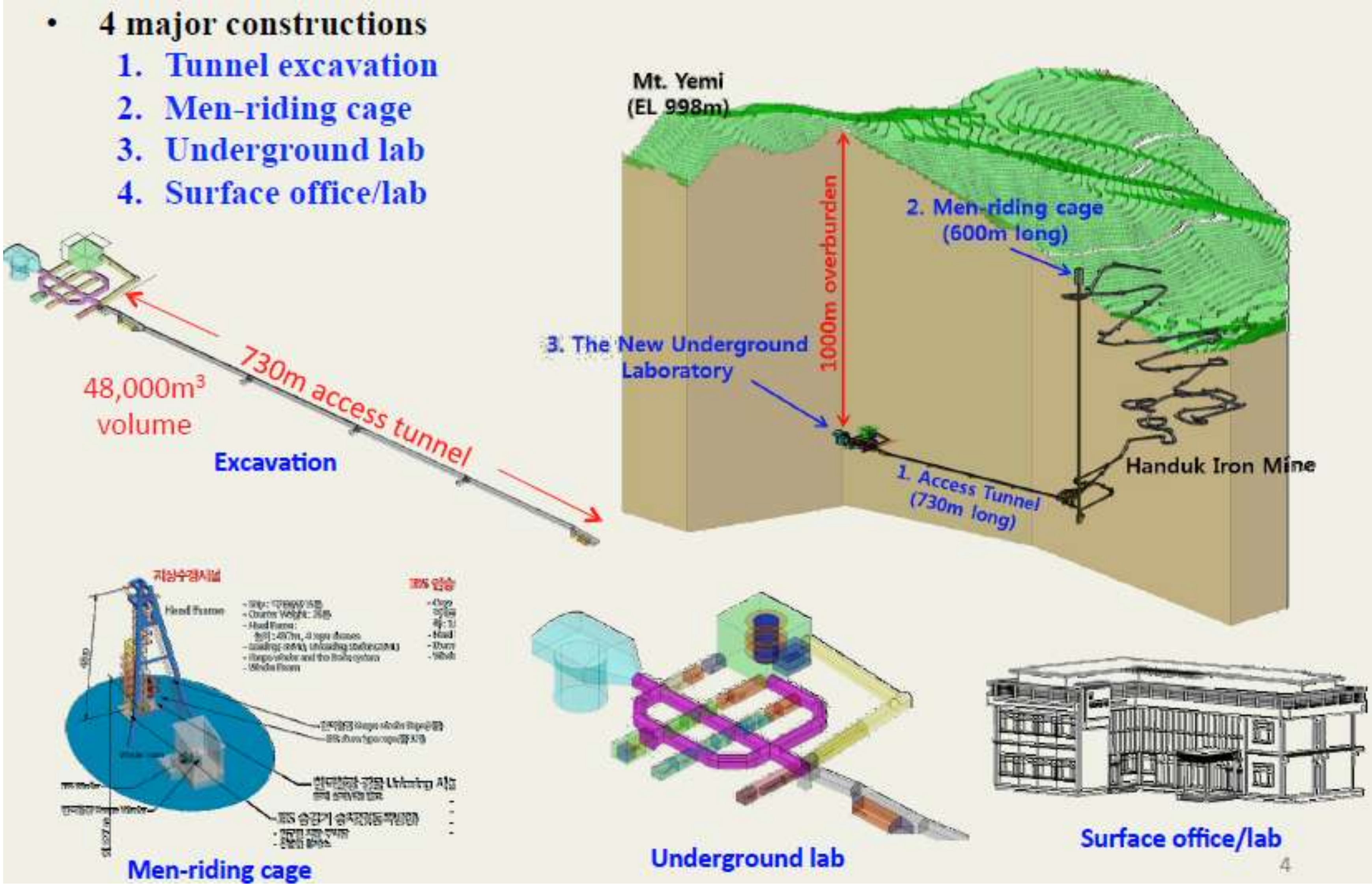
- Inverted hierarchy of neutrino mass can be tested by AMoRE – 200 experiment.

16



400 crystals
800 MMCs

The construction of new underground laboratory



- **4 major constructions**
  1. **Tunnel excavation**
  2. **Men-riding cage**
  3. **Underground lab**
  4. **Surface office/lab**

Production of $^{40}Ca^{100}MoO_4$ Scintillation Elements for AMoRE Pilot and AMoRE I detectors at Fomos Materials Co

Main $CaMoO_4$ single crystal properties

T_{melt} = 1445 ^{o}C (Pt or Ir crucible needed!)

Technology: Czochralsky method

High Light output > 5000 photon/MeV at RT

Kinetics of scintillation (main component):

at room temperature = 16 μsec

at 6 K = 345 μsec

CMO crystal growth process at JSC Fomos-Materials Co.

Process stages:

1. Initial powder ICP analysis
2. Initial pellets preparation – pellets manufacturing 550g in mass each
3. Initial charge for crystal growing preparation including MoO_3 adds - 2 pellets + up to 3 mass % of MoO_3
4. Growth of the initial crystallized charge – crystals up to 550 g each
5. Initial crystallized charge for end-crystal growing preparation
6. Crystallizer assembling and end crystal growing
7. Aftergrowing heat treatment of the end crystal – heat treatment in oxidizing atmosphere
8. Mechanical treatment of the end crystal (cutting, lapping and polishing) – manufacturing of the CMO element according to the specification.

Mechanical Treatment of the Crystal at Fomos-Materials

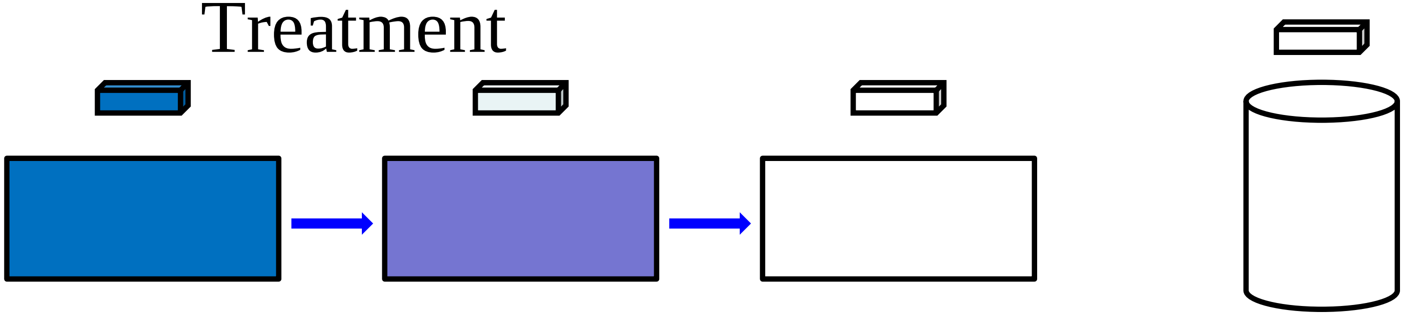
Initial crystal

Cutting

Rounding

High Temperature Treatment

Lapping and Polishing



Synthesis of $CaMoO_4$ raw material (initial charge for growth)

There are two techniques to synthesize $CaMoO_4$ raw material (charge):

- solid-phase synthesis of the oxides - CaO (or $CaCO_3$) and MoO_3 - mixed into stoichiometric ratio with compensation of volatile molybdenum oxide)
- Co-precipitation reaction

Synthesis of $CaMoO_4$ raw material at NEOKHIM company (Moscow)

Co-precipitation reaction:

$(NH4)_6Mo_7O_{24} + 7{*}Ca(NO_3)_2 + 8{*}NH_4OH \rightarrow$

$\rightarrow 7{*}CaMoO_4 + 14{*}NH_4NO_3 + 4{*}H_2O$

- guaranteed stochiomery
- additional purification in the process
- NH_4OH and NO_3 are easy can removed by washing and heat treatment

Now new Ca-compound (calcium formiate):

$(NH_4)_6Mo_7O_{24} + 7\ Ca(HCOO)_2 + 8\ NH_4OH \rightarrow$

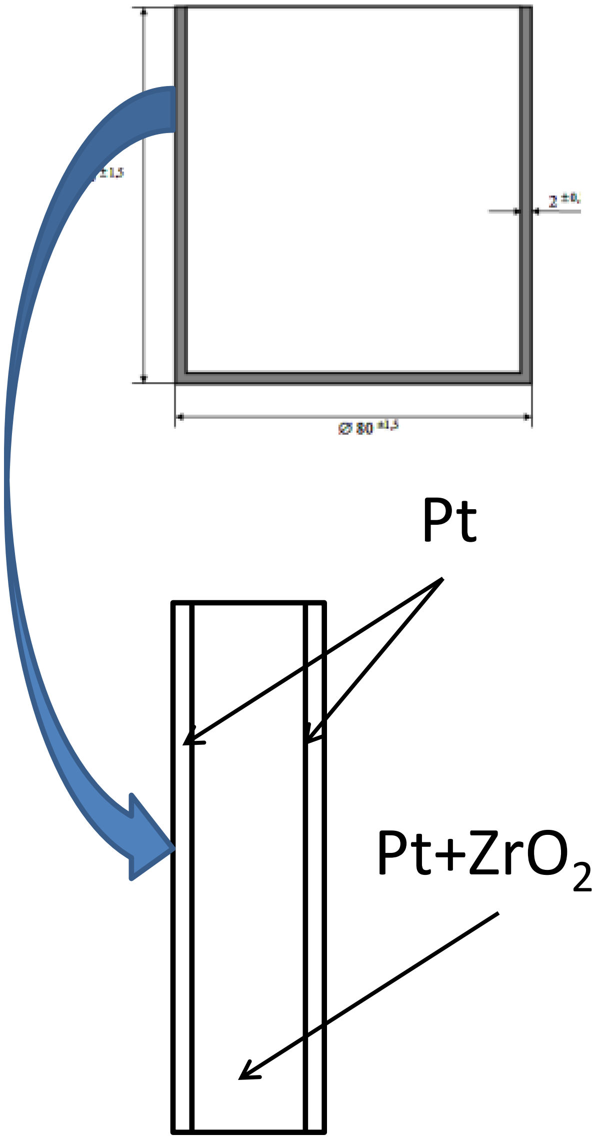
$\rightarrow 7\ CaMoO_4 + 14\ NH_4\ (HCOO) + 4\ H_2O$

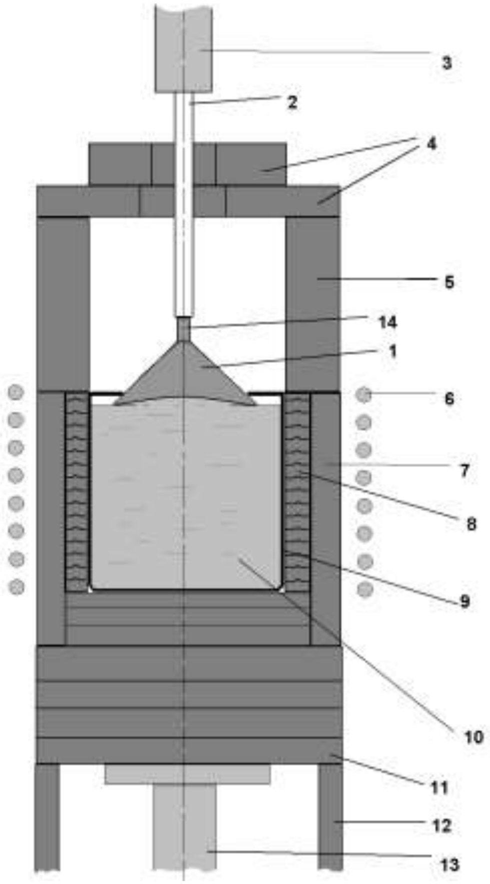
^{40}Ca^{100}MoO$_4$ raw material

JSC NeoChem (Moscow)

After melt at FOMOS-Material

Crucible for CMO crystal growing

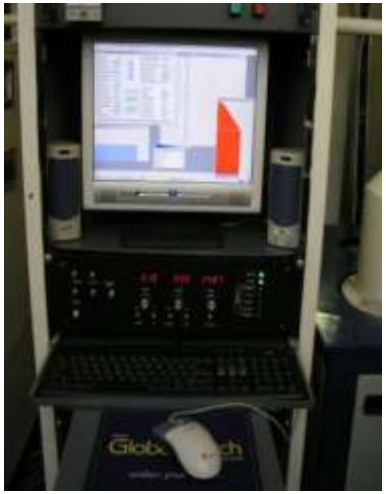




1 – growing crystal
2 – seedholder
3,13 – water-cooling shaft
4,11 – ceramic plates
5,7,12 – ceramic tubes
6 – inductional coil
8 – heat insulation ceramic
9 – crucible
10 – melt
14 - seed

Equipment for crystal growth, heat and mechanical treatment at Fomos-Materials

Crystal growth setup KRYSTAL-3M at Fomos-Materials



New control

- Unique soft
- Modern hard

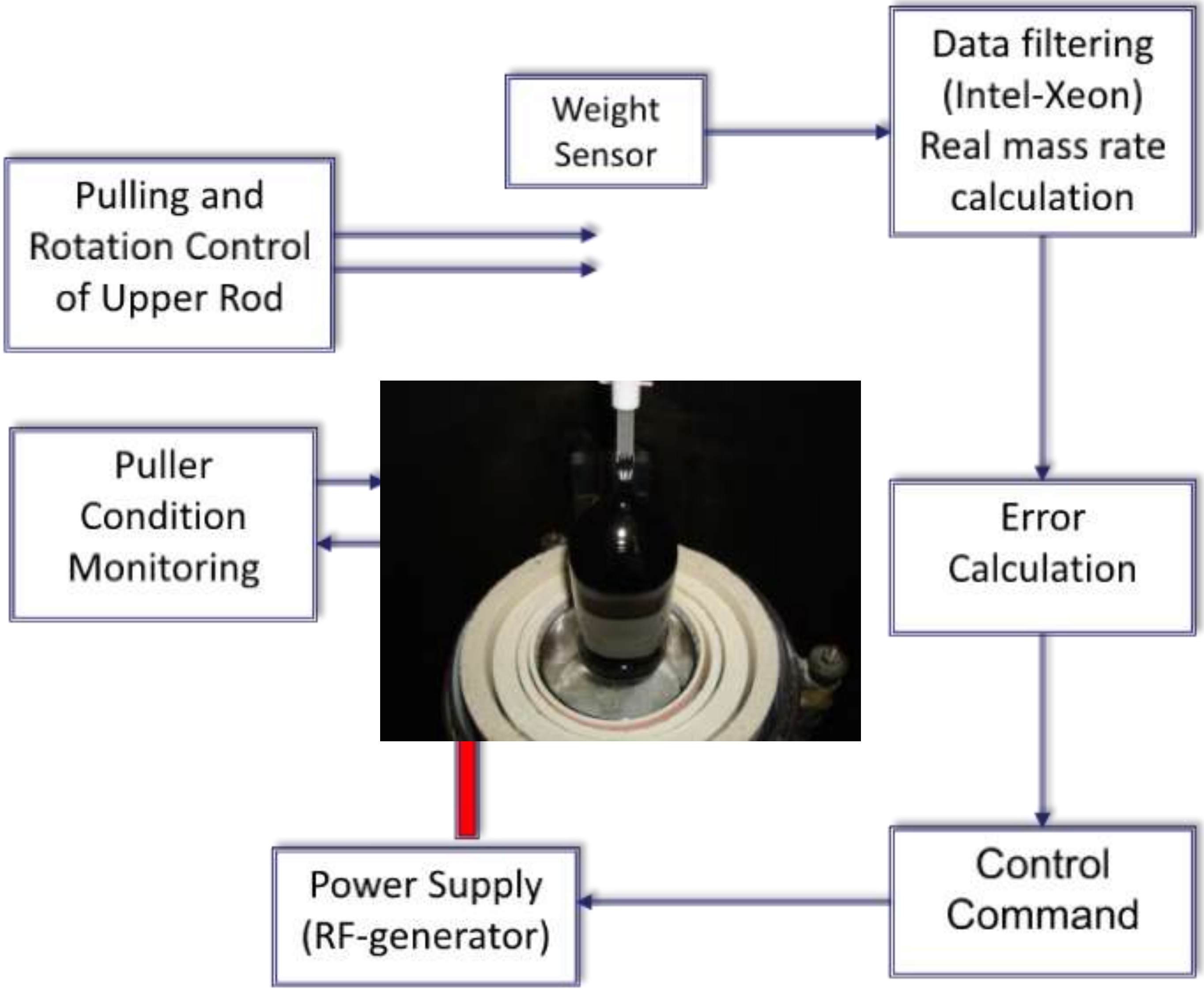
Energy-saving power supply

- Power - 60 kW
- Stability within- ± 0.05%

New upper stock drive arrangement

Crystal growth facilities at Fomos-Materials Co.

Crystal Growth Control System at Fomos-Materials



Weight Sensor

Data filtering (Intel-Xeon) Real mass rate calculation

Pulling and Rotation Control of Upper Rod

Puller Condition Monitoring

Error Calculation

Control Command

Power Supply (RF-generator)

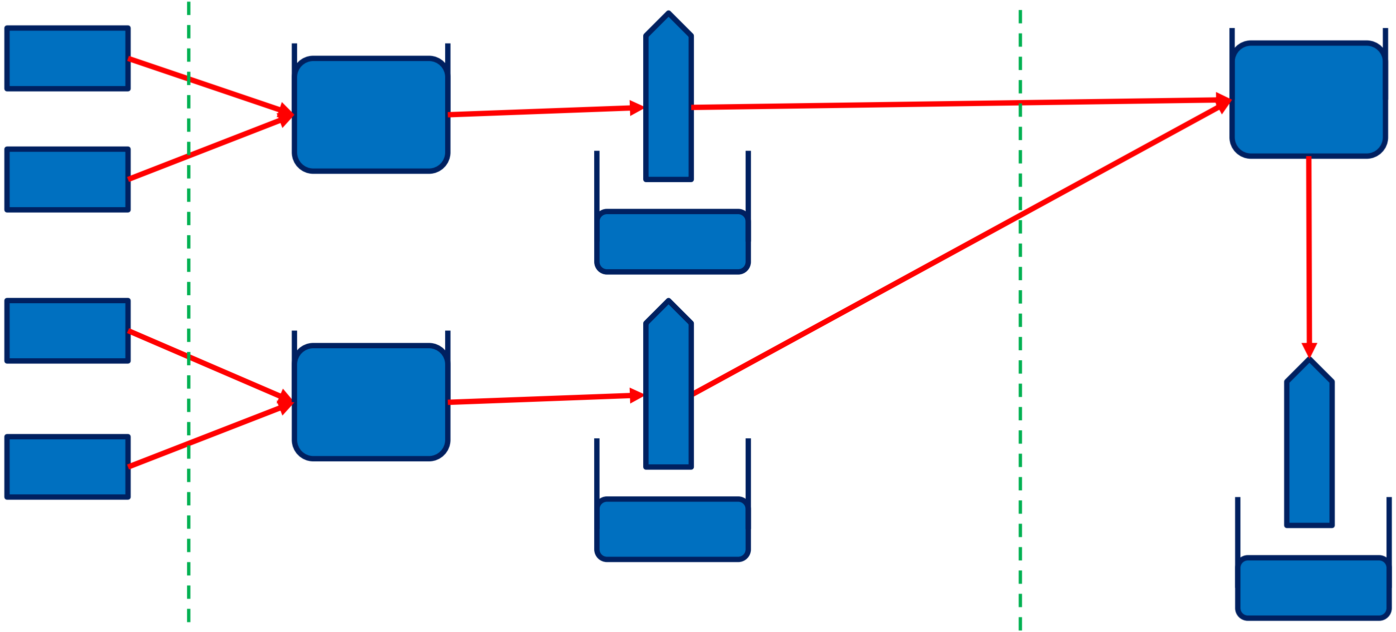
Equipment for heat treatment and optical measurement at Fomos-Materials

High Temperature Heat Treatment
(Carbolite SFT 15/450)

Optical Measurement System (Cary 300 UV-Vis)

CMO crystal grown at JSC Fomos-Materials Co.

Scheme of the Parallel crystal growth process



Pellets

Growth of the crystallized initial charge

End-crystal growth

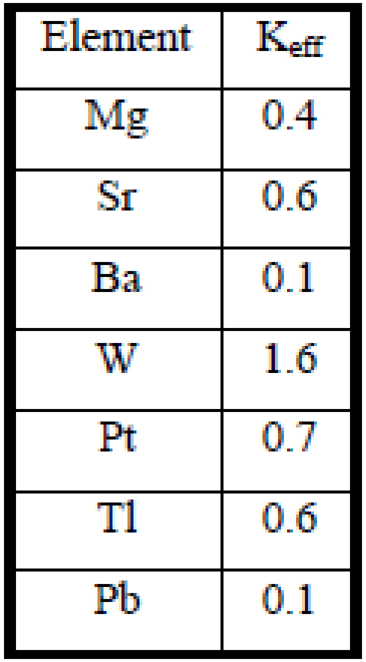
Pellet mass 640 g
Total mass 2560 g
Total loss 5 g

Melt mass 1277,5 g
Total mass 2555 g

Crystal mass 640 g
Total crystal mass 1280 g
Total loss 15 g
Waste 1260 g

Melt mass 1280 g
Crystal mass 640 g
SE mass 345 g
Losses during growth 10 g
Losses during mech. treat. 5 g
Waste (melt and cuts) 920 g

Effective distribution coefficients for some impurities. Recrystallization technique for purification.

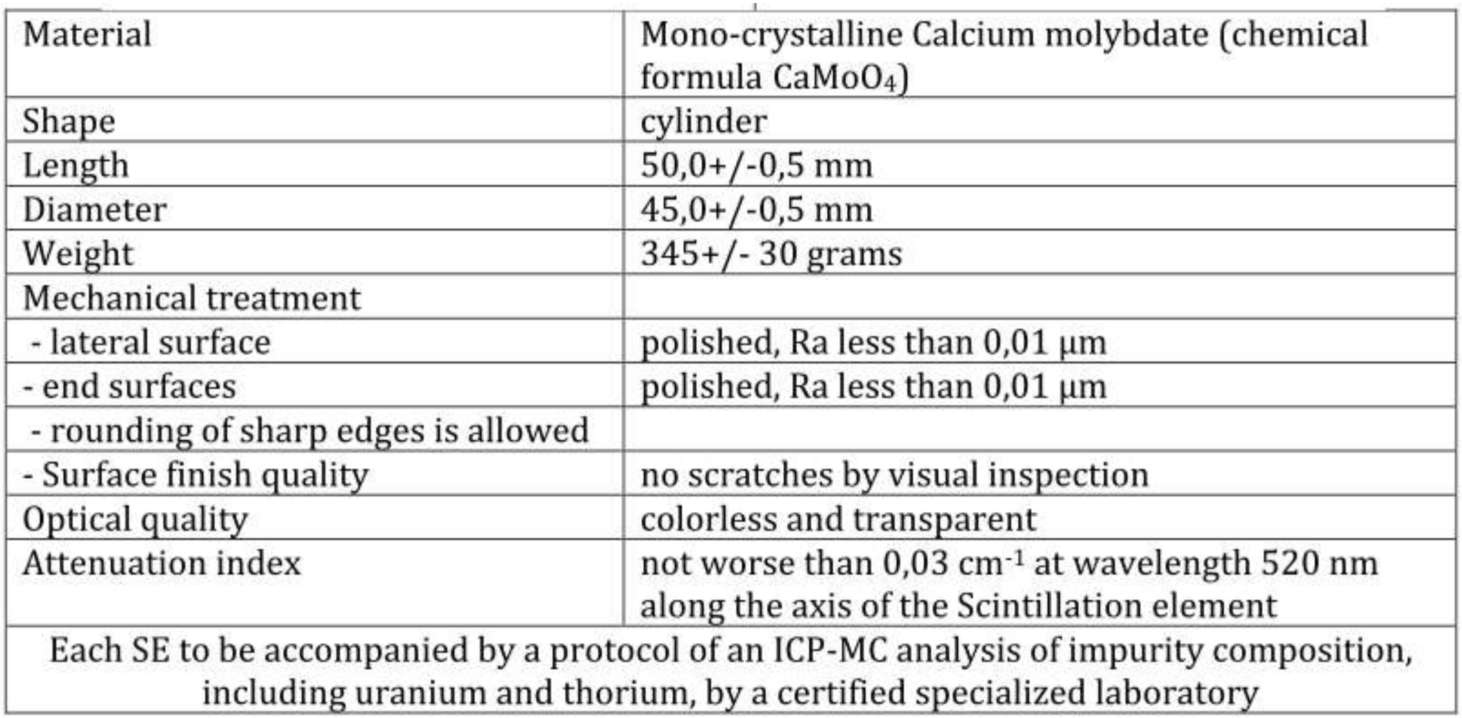


Element	K_{eff}
Mg	0.4
Sr	0.6
Ba	0.1
W	1.6
Pt	0.7
Tl	0.6
Pb	0.1

Concentration of impurities can be substantially reduced by recrystallization technique. Only the central parts of the initial crystals were w/o upper and bottom cones were used for the final crystal growth (double crystallization)

Spassky et al., ISMART 2016:
Engineering of Scintillation Materials and Radiation Technologies pp 242-258

Specification to IBS/CUP - Fomos Material contract for production of $^{40}\mathrm{Ca}^{100}\mathrm{MoO}_4$ SEs for AMoRE Pilot and AMoRE I detectors



Material	Mono-crystalline Calcium molybdate (chemical formula $\mathrm{CaMoO_4}$)
Shape	cylinder
Length	50,0+/-0,5 mm
Diameter	45,0+/-0,5 mm
Weight	345+/- 30 grams
Mechanical treatment	
- lateral surface	polished, Ra less than 0,01 µm
- end surfaces	polished, Ra less than 0,01 µm
- rounding of sharp edges is allowed	
- Surface finish quality	no scratches by visual inspection
Optical quality	colorless and transparent
Attenuation index	not worse than 0,03 cm^{-1} at wavelength 520 nm along the axis of the Scintillation element
Each SE to be accompanied by a protocol of an ICP-MC analysis of impurity composition, including uranium and thorium, by a certified specialized laboratory	

Enrichment: >95% of Mo-100 and depletion of Ca-48 <0.002%

Radioactive contamination:

Bi-214 (U-238 chain) < 100 µBq/kg and Rn-220 (Th-232 chain) < 50 µBq/kg,
Total alpha activity of U and Th < 10000 µBq/kg

Main challenge for Producer:

Radiopurity!

Potential Sources of Radioactive Contamination During Crystal Growing, Annealing and Mechanical Treatment

- Dust in the air/atmosphere of the room
- Atmosphere/Air with high concentration of ^{222}Rn. emanation from floor, ceiling and walls of the room
- "Dirty" material of the insulation ceramics inside Czochralsky puller.
- Not enough radiopurity of grinding and polishing materials.
- Availability of pure water and chemicals:
  - alcohol for cleaning procedures
  - pure water (de-ionized water)

Measures to ensure “the purity condition” at FOMOS Materials

- Selected crystal growth setup (no more different crystals except $CaMoO_4$ can be grown)
- Selection of materials for the insulation ceramics inside puller
- Facility for production of De-ionized water (sub-boiling facility for purification of water and chemicals)
- Glove boxes and other purity insurance methods for manipulations with $CaMoO_4$ powder

An example of Protocol for SE2 (SS88): Results of ICP MS ELAN DRC-e by EKP (Lesnoy)

0,0001% = 1 ppm

Элемент	Содержание, вес.%	Элемент	Содержание, вес.%	Элемент	Содержание, вес.%	Элемент	Содержание, вес.%
Li	<0.0001	Zn	<0.0002	Sb	<0.0001	Lu	<0.0001
Be	<0.0005	Ga	<0.0001	Te	<0.0002	Hf	<0.0001
B	<0.001	Ge	<0.0001	I	<0.0005	Ta	<0.0001
Na	<0.002	As	<0.0001	Cs	<0.0001	W	0,0022
Mg	<0.0003	Se	<0.002	Ba	<0,0001	Re	<0.0001
Al	<0.0003	Br	<0.005	La	<0.0001	Os	<0.0001
Si	<0.005	Rb	<0.0001	Ce	<0.0001	Ir	<0.0001
P	<0.005	Sr	<0.0001	Pr	<0.0001	Pt	<0.0001
K	<0.005	Y	<0.0001	Nd	<0.0001	Au	<0.0001
Sc	<0.0002	Zr	<0.0001	Sm	<0.0001	Hg	<0.0001
Ti	<0.0004	Nb	<0.0001	Eu	<0.0001	Tl	<0.0001
V	<0.0003	Ru	<0.0001	Gd	<0.0001	Pb	<0.0001
Cr	<0.001	Rh	<0.0001	Tb	<0.0001	Bi	<0.0001
Mn	<0.0001	Pd	<0.0001	Dy	<0.0001	Th	<0.0001
Fe	<0.005	Ag	<0.0001	Ho	<0.0001	U	<0.0001
Co	<0.0001	Cd	< 0.002	Er	<0.0001		
Ni	<0.0001	In	<0.0001	Tm	<0.0001		
Cu	<0.0001	Sn	<0.0001	Yb	<0.0001		

CONCLUSION: only limits except W (22 ppm)!

Analysis of U and Th into raw material and Ca- and Mo components: ICP MS & AES MS

- Pre-concentration (*extraction of Mo-matrix*)

  a) autoclave decomposition into 1 mL HCl and 0.1 mL HNO_3 under 160 ^{o}C

  b) extraction of Mo-matrix

- Analysis by an mass spectrometer with an inductively coupled plasma

- Sensitivity: U-238 is up to 0,07 ppb and Th-232 is up 0,1 ppb

^{100}Mo enriched & ^{48}Ca depleted materials

- **^{100}Mo isotope production**:
  - ECP (Electro Chemical Plant), Krasnoyarsk, Russia
  - $^{100}MoO_3$ powder:
    - ^{100}Mo Enrichment: $\geq$ 95%
    - Radioactive impurities:

ICP-MS at CUP	**U: ~ 0.2 ppb**	**Th: < ~0.05 ppb**
HPGe at Y2L	**^{226}Ra: 8.3 mBq/kg**	**^{228}Ac < ~1.0 mBq/kg**

- **^{40}Ca with depletion of ^{48}Ca isotope production**:
  - ELEKTROCHIMPRIBOR (EKP), Lesnoy, Russia
  - $^{40}CaCO_3$ powder:

- ^{48}Ca $\leq$ 0.001%

- Impurities: U $\leq$ 0.1 ppb, Th $\leq$ 0.1 ppb, Sr = 1 ppm, Ba = 1 ppm

^{226}Ra = 5 mBq/kg (1.4 by NEOKHIM later), ^{228}Ac(^{228}Th) = 1 mBq/kg

HPGe measurements at Baksan Neutrino Observatory INR RAS

HPGe detectors (3 x ~1 kg) at low background underground lab (H = 660 m.w.e.)

$V_{int} = 30 \times 30 \times 30$ cm^3

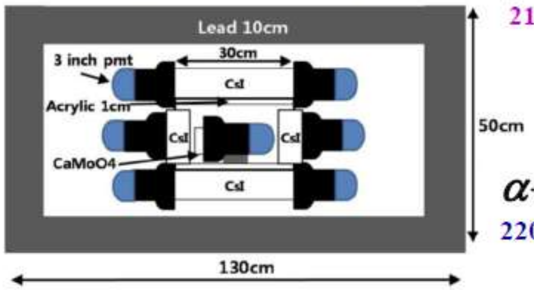
Principle:
Registration of
γ–rays from samples

The spectrometer sensitivities at the levels of
≤ 3.4*10^{-3} Bq/kg (^{232}Th)
≤ 5.3*10^{-3} Bq/kg (^{238}U)

Internal background of ^{40}Ca^{100}MoO$_4$ crystals: measurements in YangYang underground lab in Korea

4π CsI(Tl) active setup with Pb shielding at Y2L

4π gamma veto system



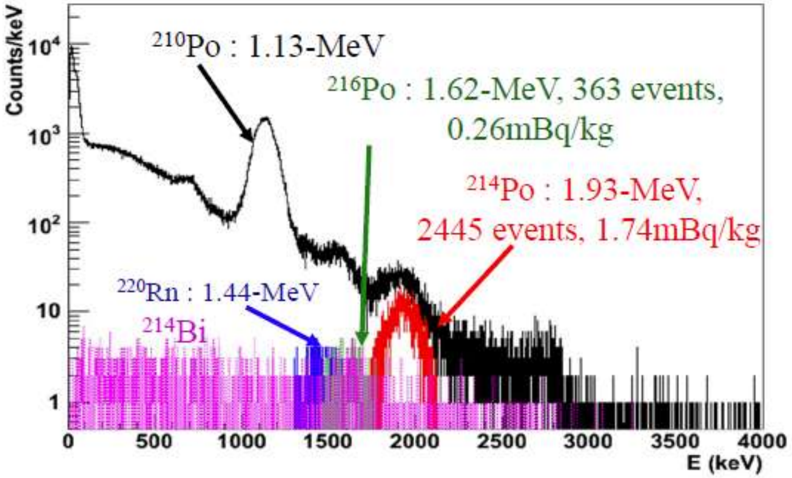
β–α decay in ^{238}U

^{214}Bi (Q-value : 3.27-MeV) → ^{214}Po (Q-value : 7.83-MeV)→ ^{210}Pb

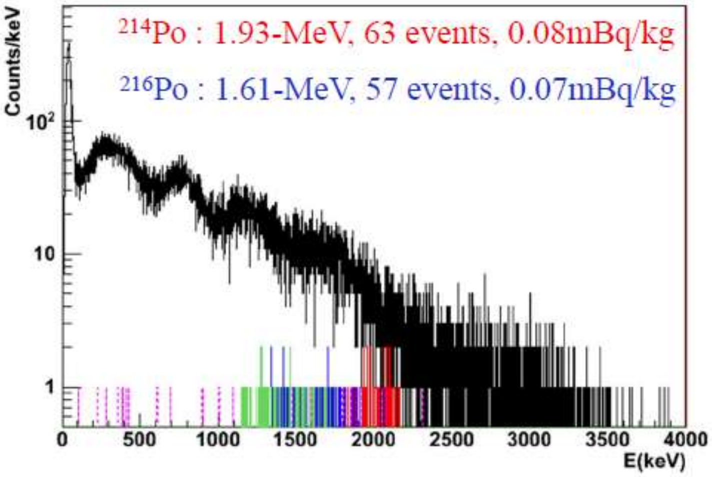
α–α decay in ^{232}Th

^{220}Rn (Q-value : 6.41-MeV) → ^{216}Po (Q-value : 6.91-MeV)→ ^{212}Pb

Crystal S35



Crystal SB28



$^{40}\mathrm{Ca}^{100}\mathrm{MoO}_4$ Scintillation Elements for AMORE I from Fomos Materials Co

Status of SE1 – SE5 at Aug 2016:
already delivered to CUP

SE1

SE2

SE3

SE4

SE5

Fomos Materials for ISMART2018

56

Status of SE6 – SE9: Delivered to CUP in Nov and Dec 2016

SE6
22d Nov 2016

SE7
13th Dec 2016

SE8
27th Dec 2016

SE9
27th Dec 2016

Fomos Materials for ISMART2018

55

Dimensions and weight of the SE1-SE9 (SE10)

Name of SE	Crystal	Length, mm	D/d, mm	Mass, gr
SE 1	81SS	50,5	45,0/42,8	352,2
SE 2	88SS	50,0	47,0/40,0	339,56
SE 3	122SS	50,48	52,0/45,0	424,2
SE 4	131SS	50,36	54/47	473,38
SE 5	133SS	50,5	47/42	373,45
SE 6	135SS	50,3	48/40	355,45
SE 7	136SS	50,5	48,4/41	357,45
SE 8	137SS	50,8	48/41	358,2
SE 9	140SS	50,5	40,0/48,0	354,0
TOTAL				***~ 3387,9***
SE 10 (reserved)	**143SS**	**51,3**	**40,5/48,5**	**357,54**

Mechanical treatment: Lateral surface - as-grown or grinding
End surfaces - optically polished

Optical quality: No cracks, colorless and transparent

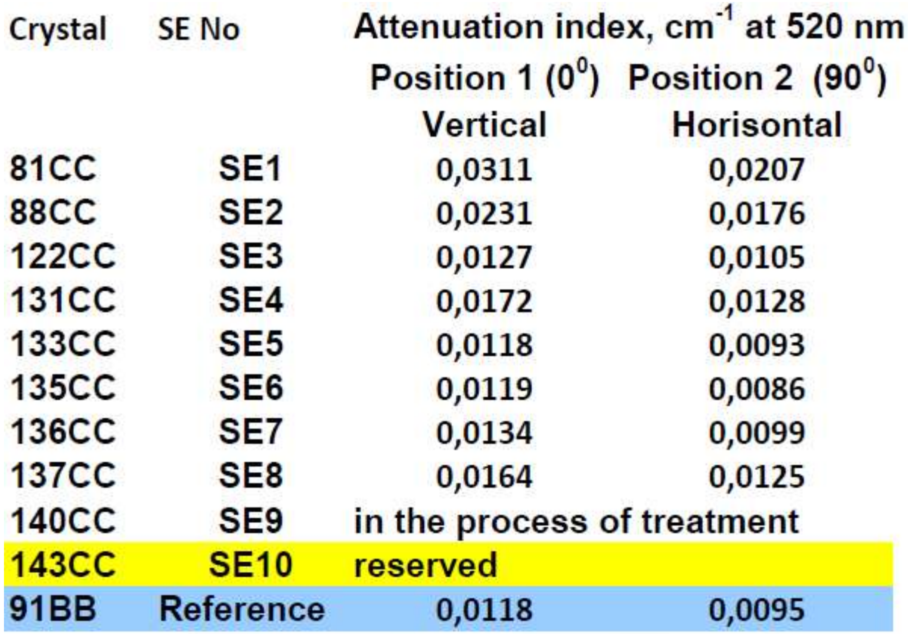
Activity measurements of SE1-SE-9 at mK and SE3 - SE-9 at RT ^{40}Ca^{100}MoO$_4$ Scintillation Elements for AMORE I (Fomos Materials)

	AMoRE I	SE1	SE2	SE3	SE4	SE5	SE6	SE7	SE8	SE9	AMoRE II
	Spec	Yang-Yang	CUP/IBS	Yang-Yang	Yang-Yang	Yang-Yang	Yang-Yang	Yang-Yang	Yang-Yang	Yang-Yang	Spec
	µBq/kg										(?)
Bi-214 (U-238 chain)	<100	<18	60,2	6	10	10	100±10	30±5	20±5	≤11	< 24
Rn-220 (Th-232 chain)	<50	<14	25,8	35	40	10	70±10	65±10	40±6	50±6	< 1,2
Bi-211 (U-235 chain)	<500	83	103	35	30	40	35±6	80±10	40±6	50±6	
Total Alfa	≤10000	4600	2700	28000	3200	≤3200	DL 1000	DL 1000	DL 0	DL0	
Po-210		1600									
U-238		670	1700								
Temperature measurement											
		mK	mK	RT	RT	RT	RT	RT	RT	RT	

Important note!

SE1 - SE9 crystals have been grown starting with ^{40}Ca^{100}MoO$_4$ waste of different types created after R&D at NEOKHIM and Fomos Materials

SE1 ÷ SE8: Attenuation index, cm^{-1} at 520 nm



Crystal	SE No	Attenuation index, cm^{-1} at 520 nm	
		Position 1 (0^{0})	Position 2 (90^{0})
		Vertical	Horisontal
81CC	**SE1**	0,0311	0,0207
88CC	**SE2**	0,0231	0,0176
122CC	**SE3**	0,0127	0,0105
131CC	**SE4**	0,0172	0,0128
133CC	**SE5**	0,0118	0,0093
135CC	**SE6**	0,0119	0,0086
136CC	**SE7**	0,0134	0,0099
137CC	**SE8**	0,0164	0,0125
140CC	**SE9**	in the process of treatment	
143CC	**SE10**	reserved	
91BB	Reference	0,0118	0,0095

Conclusion (1)

- JSC FOMOS has developed – the first in the world - the technology of single crystal growing based on charge of double enriched components: $^{40}Ca^{100}MoO_4$ crystal based on Moly enriched on ^{100}Mo and Calcium enriched on ^{40}Ca and depleted on ^{48}Ca isotopes.

  * Mass of single crystal – up to 0,6 kg

  * Diameter up to 50 mm
- Good radiopurity of Scintillation elements ***grown from waste enriched material***: Bi-214 (U-238 chain) < 100 µBq/kg and Rn-220 (Th-232 chain) < 50 µBq/kg, and total alpha activity of U and Th < 10000 µBq/kg
- 10 $^{40}Ca^{100}MoO_4$ Scintillation Elements (3,4 kg) have been grown for AMoRE I phase of the experiment.
- Total mass of AMoRE detector is 200 kg (~ 500 crystals).

Conclusion (2)

Successful jobs done at Fomos Materials Co “stimulated” Producers of stable isotopes from RosAtom Corporation (Russia):

- A 5-years long contract for big scale production of ^{100}Mo (**120 kg**) has been concluded between CUP/IBS (AMoRE Collaboration) and ECP (Zelenogorsk, Siberia) (current productivity is 28 kg per year)
- **27 kg of ^{40}Ca** (in the form of “primary” **$^{40}CaCO_3$** carbonate) is already available at ELEKTROKHIMPRIBOR (EKP, Lesnoy, Sverdlovsk region).

CONCLUSION (3)

- Based upon FM' experience of growing $CaMoO_4$ and $^{40}Ca^{100}MoO_4$ crystals (bouls) and fabricate SE (Scintillation Elements) Fomos Materials has possibilities fabricate SE from different Mo-based crystals:
- ***Li_2MoO_4 (crystals are grown)***
- $Na_2Mo_2O_7$
- $PbMoO_4$
- Double and triple molybdates of REE and others.

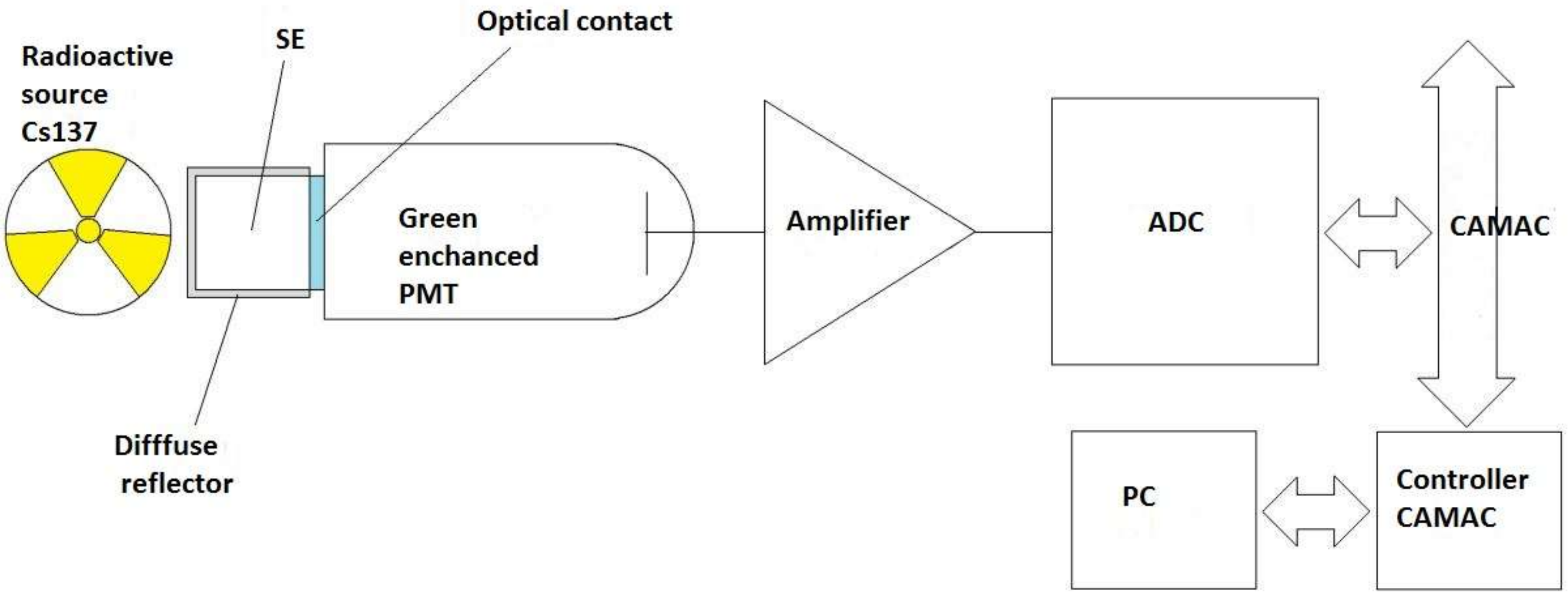
Two Li_2MoO_4 crystals and Li_2MoO_4 SE (just after cutting and grinding + PET band on lateral surface; no polishing)

Back up slides

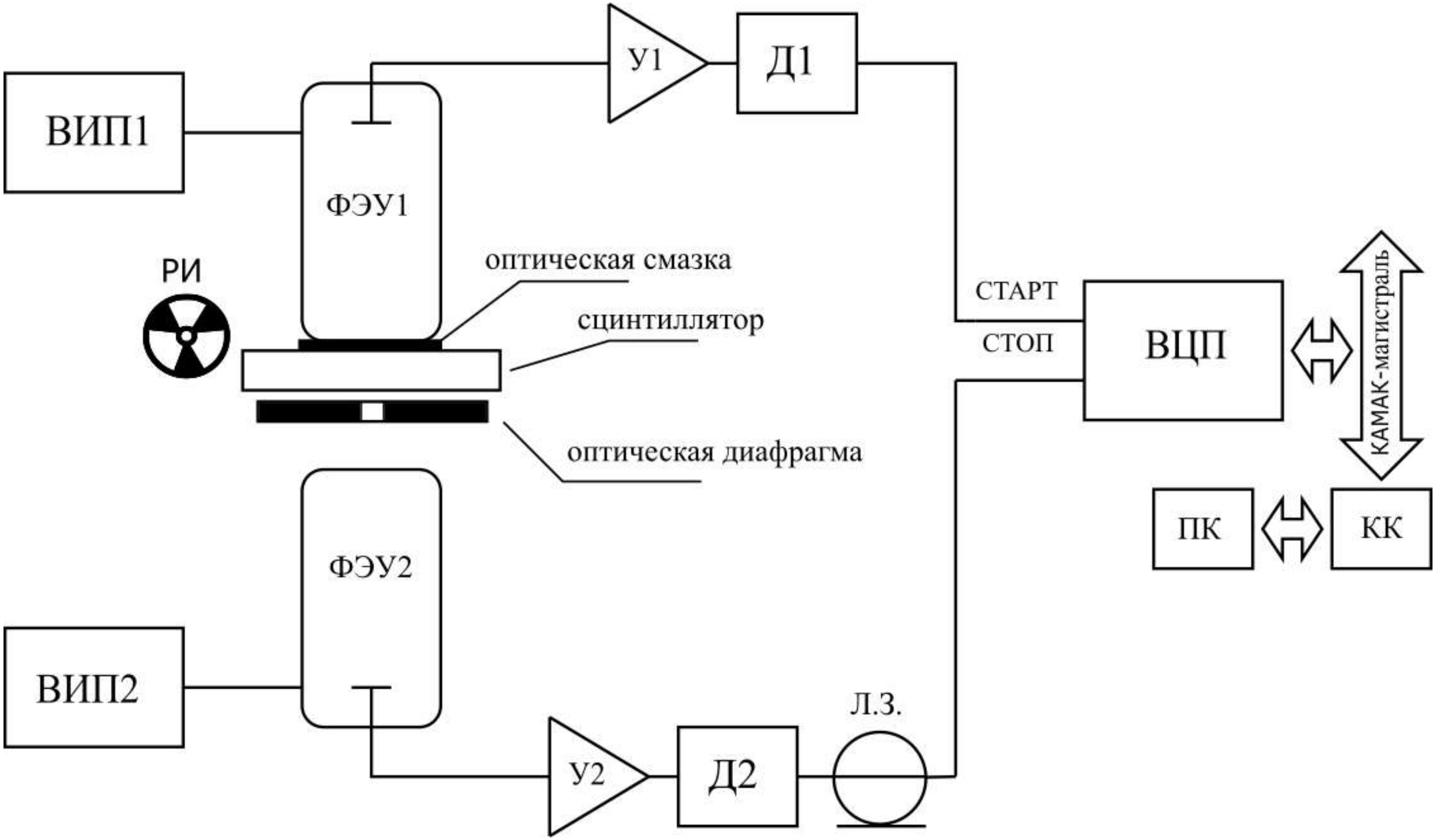
Facility at FM for measurement of the LY and the energy Resolution of SEs.

Geometry: SE in direct contact with PMT vis optical grease

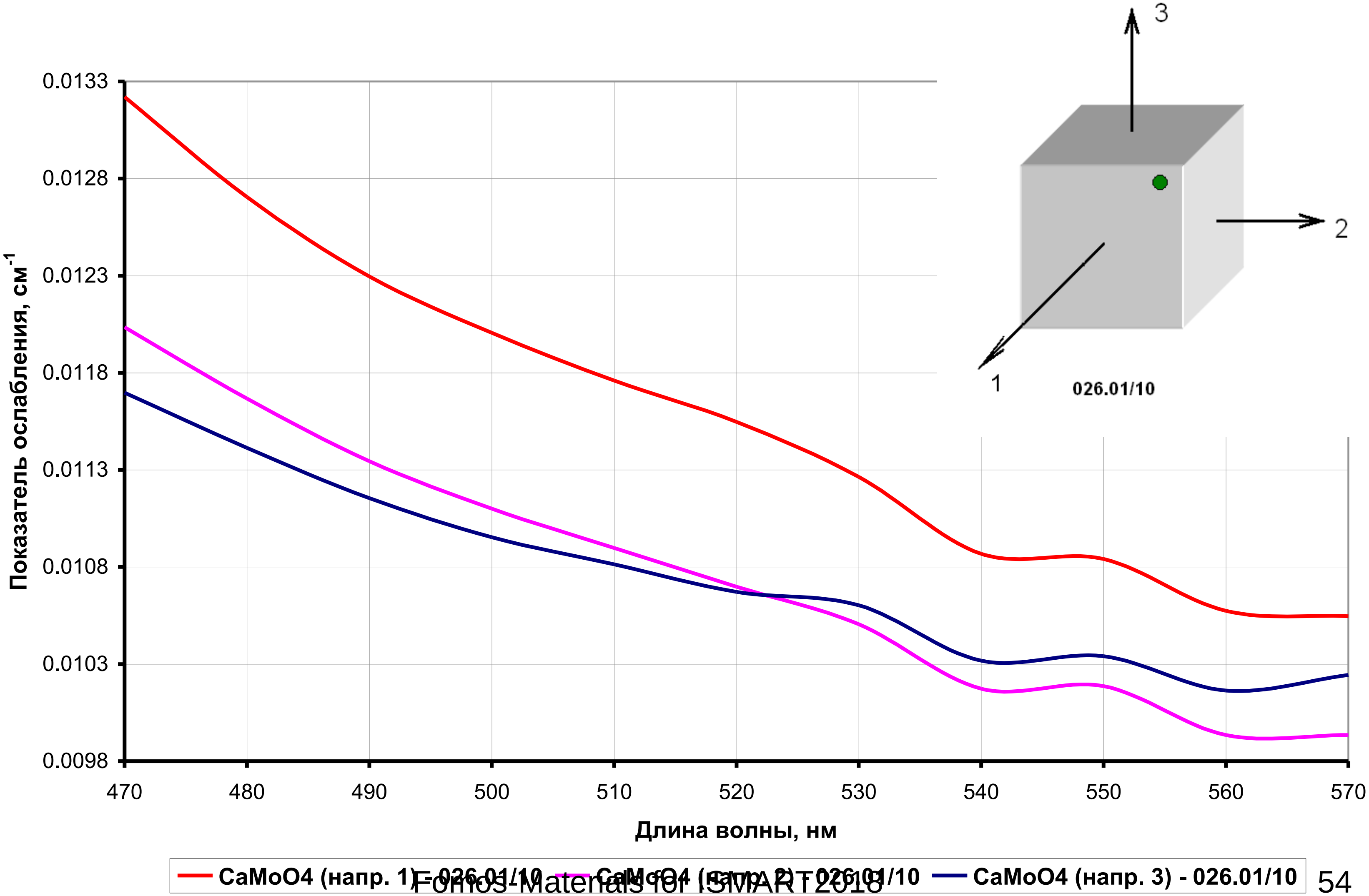
Photocathode - green extended super S20

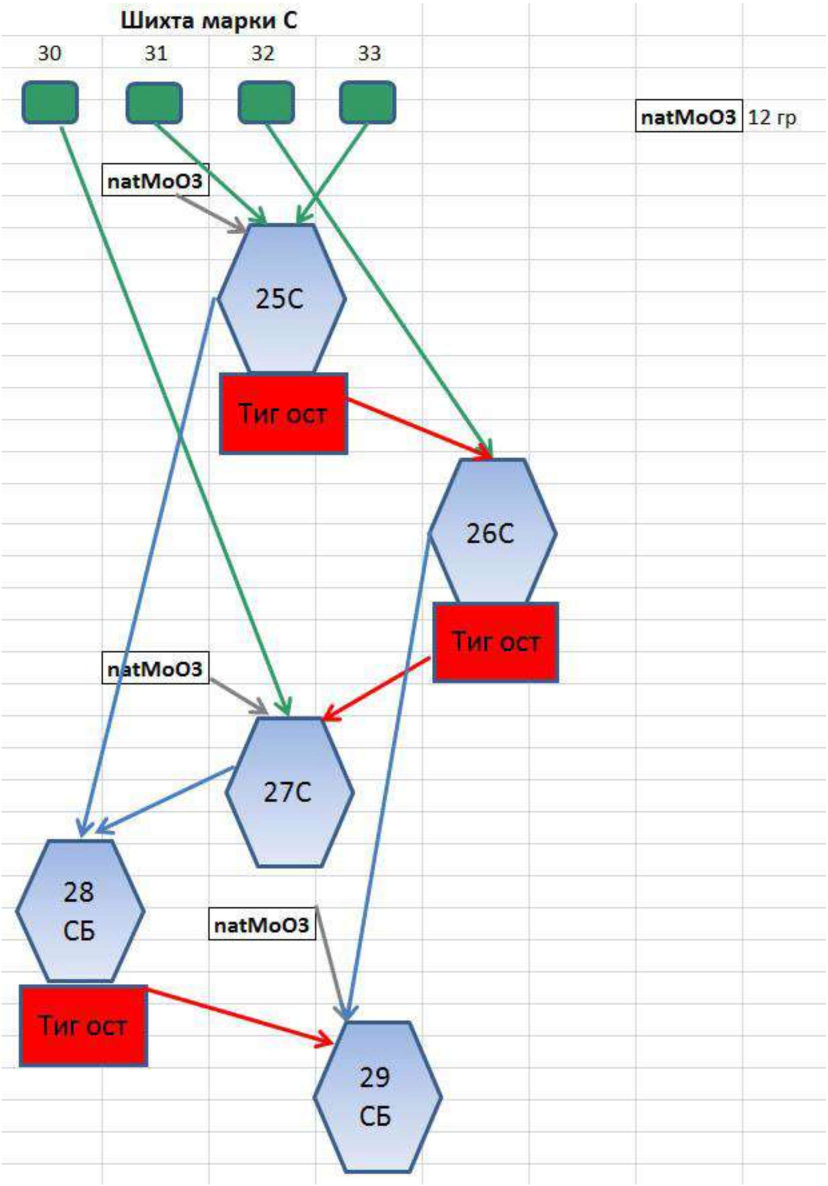


Facility at FM for measurement of the scintillation decay kinetics of $CaMoO_4$



S 35: Attenuation length, cm^{-1}

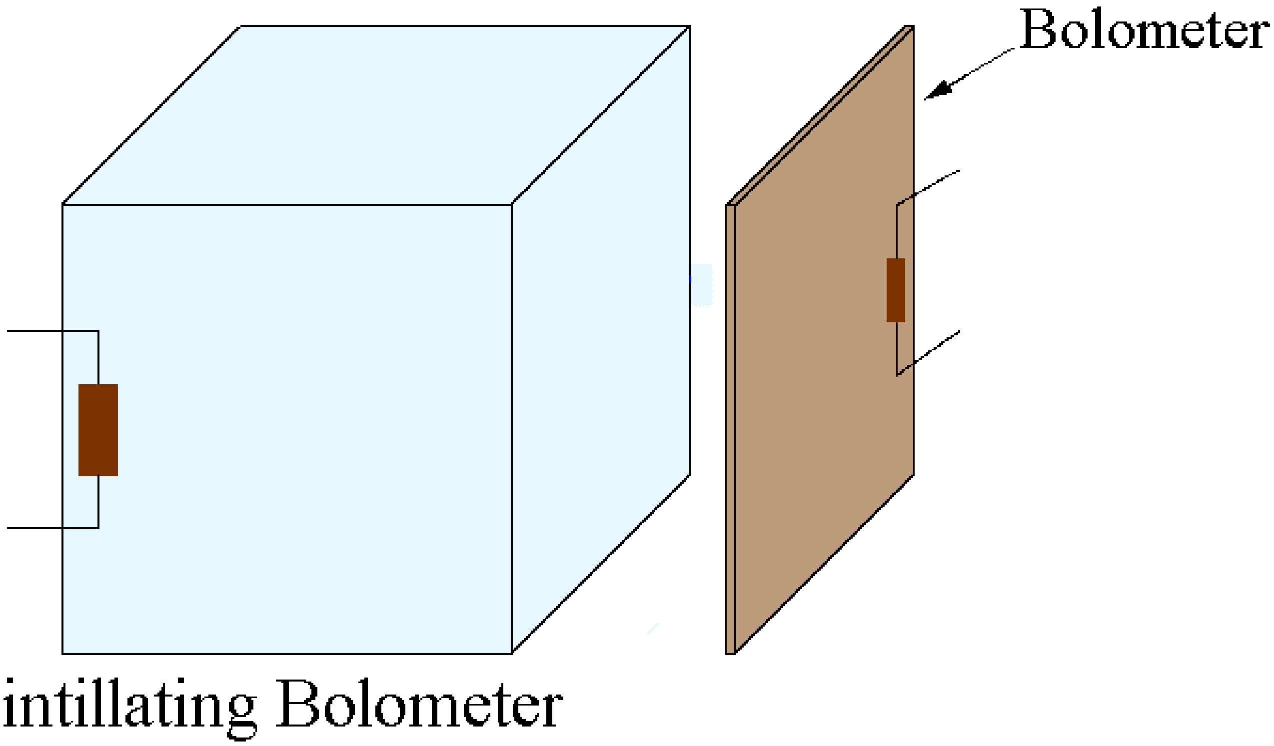



Шихта марки С
30
31
32
33
natMoO3
12 гр
natMoO3
25С
Тиг ост
26С
Тиг ост
natMoO3
27С
28
СБ
natMoO3
Тиг ост
29
СБ

Scintillation cryogenic bolometer: how it works

$\tau = C/G$

$\Delta T = \Delta E/C$

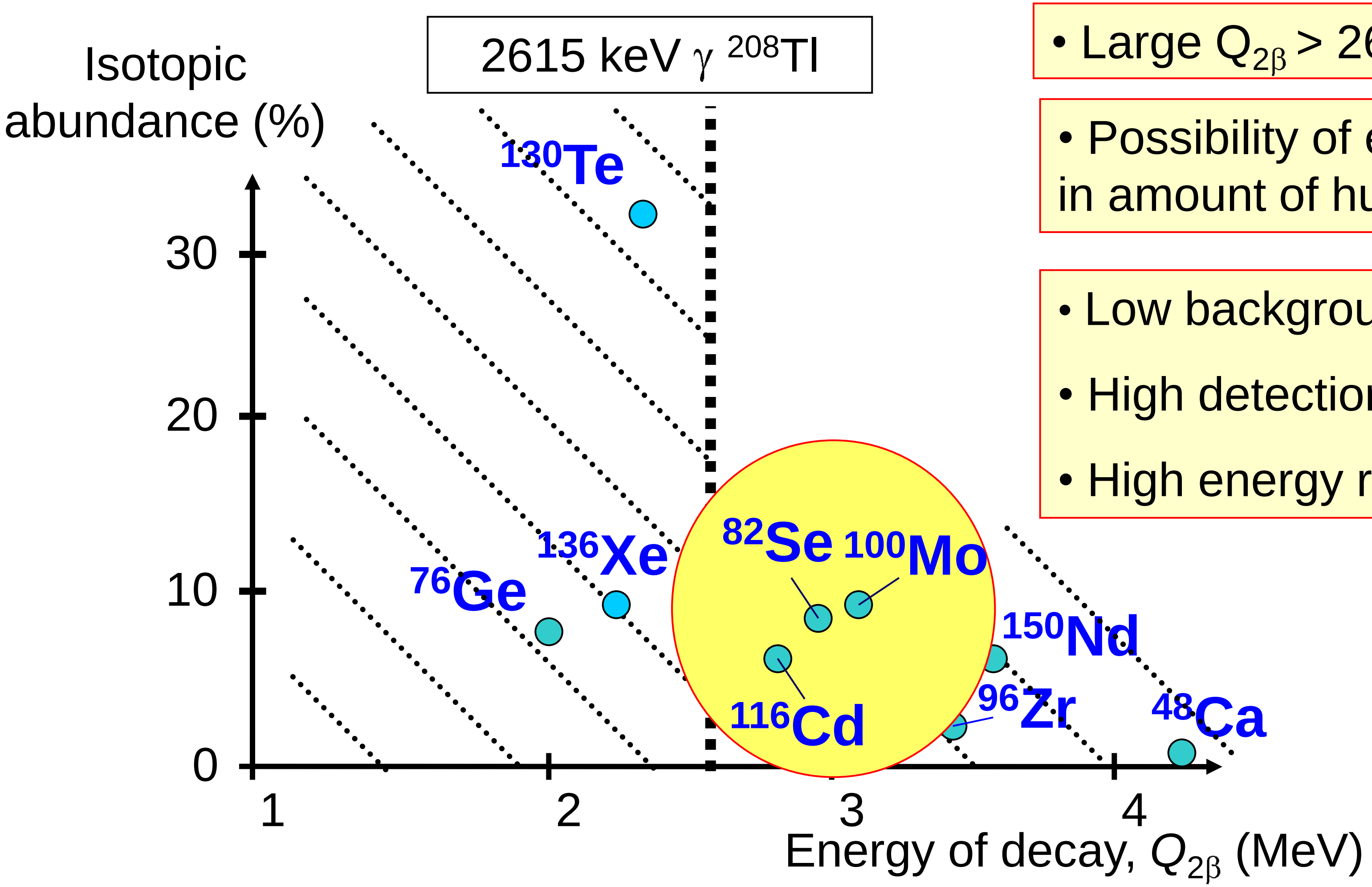


Width : ~1 mK

Signal: few μ K

Stability: ~ μ K

The most “promising” 2β nuclei from the point of view of experiment



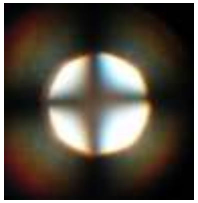
- Large $Q_{2\beta}$ > 2615 keV

- Possibility of enrichment in amount of hundreds kg

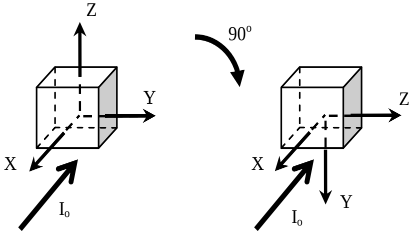
- Low background
- High detection efficiency
- High energy resolution *)

Anisotropy of Optical Properties (dichroism) of the $CaMoO_4$ Single Crystals

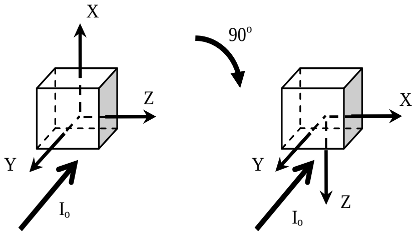
Cube, made from “As-grown” $CaMoO_4$ crystal. Orientation accuracy +/- 2 angle min



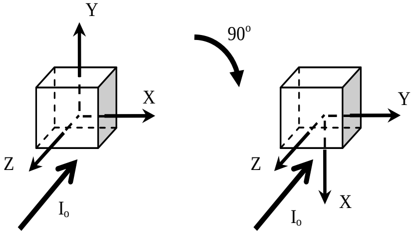
Identification of C-oriented plane by conoscopy



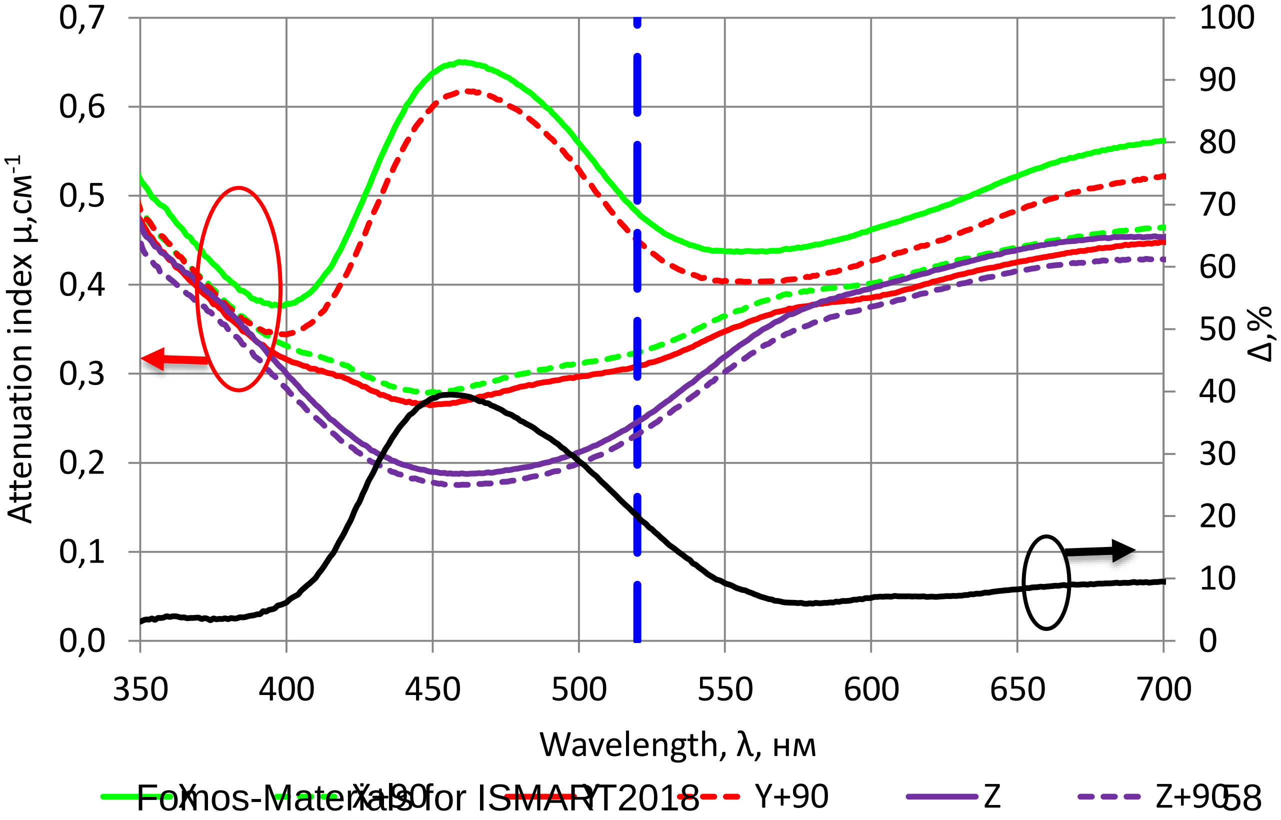
X and X+90



Y and Y+90



Z and Z+90



$CaMoO_4$ single crystal growing in Russia: Short Recent History

- Beginning: Autumn, 2003

School of Physics, SNU (KIMS Collaboration) and ITEP/BTCP, Bogoroditsk

- Project ISTC 3293 (March 2006 – May 2007)

ITEP (Leading organization), MSAI (&Bogoroditsk Plant, Russia)

IPN, Minsk (Belorussia), School of Physics, Seoul National University (Korea)

- Federal Aiming Program (August 2008 – October 2009)

JSC FOMOS-Materials (Moscow), IMTM RAS (Chernogolovka, Moscow region), ITEP (coordination)

- Project ISTC 3893 (May 2009 – January 2012)

ITEP (Leading organization)

MSAI (Moscow), JSC FOMOS-Materials (Moscow), Seoul National University (Seoul, Korea), Kyungpook National University (Daegu, Korea)

- Federal Aiming Program (August 2011 – October 2013)

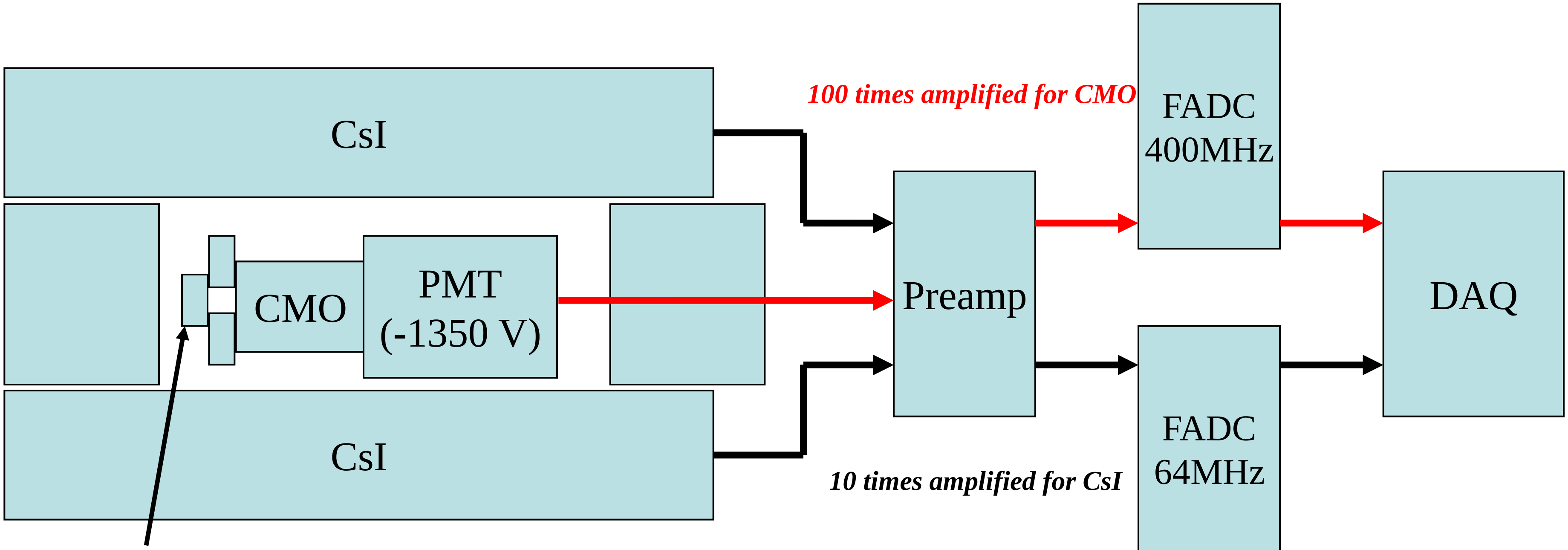
JSC FOMOS-Materials (Moscow)

HPGe measurements at Baksan Neutrino Observatory: the results

Sample, material	Isotope			
	^{40}K	**^{228}Ac = (^{232}Th)**	**^{208}Tl [(^{232}Th)]***	**^{214}Bi = (^{238}U)**
	Specific activity, Bq/**kg**			
Mo oxide, $^{100}MoO_3$	**$(5,3\pm0,8)\cdot10^{-2}$**	**$\leq3,8\cdot10^{-3}$**	**$\leq1,0\cdot10^{-3}$ $[\leq2,8\cdot10^{-3}]$**	**$\leq2,3\cdot10^{-3}$**
Calcium carbonate, $^{40}CaCO_3$	**$(7,3\pm3,1)\cdot10^{-2}$**	**$(1,6\pm0,2)\cdot10^{-1}$**	**$(4,4\pm3,6)\cdot10^{-3}$ $[(1,2\pm1,0)\cdot10^{-2}]$**	**$(2,6\pm0,2)\cdot10^{-1}$**
Single crystal SB-29 $^{40}Ca^{100}MoO_4$	**$\leq1,2*10^{-2}$**	**$\leq3,1*10^{-3}$**	**$\leq8,3*10^{-4}$ $[\leq2,4\cdot10^{-3}]$**	**$\leq6,4*10^{-3}$**

Sensitivity at level of up ~1 mBq/kg for
~0,5 kg samples & several weeks measurements

Scheme of setup at YangYang



CsI

CMO

PMT
(-1350 V)

CsI

100 times amplified for CMO

Preamp

FADC
400MHz

FADC
64MHz

10 times amplified for CsI

DAQ

^{137}Cs gamma ray source: 661-keV

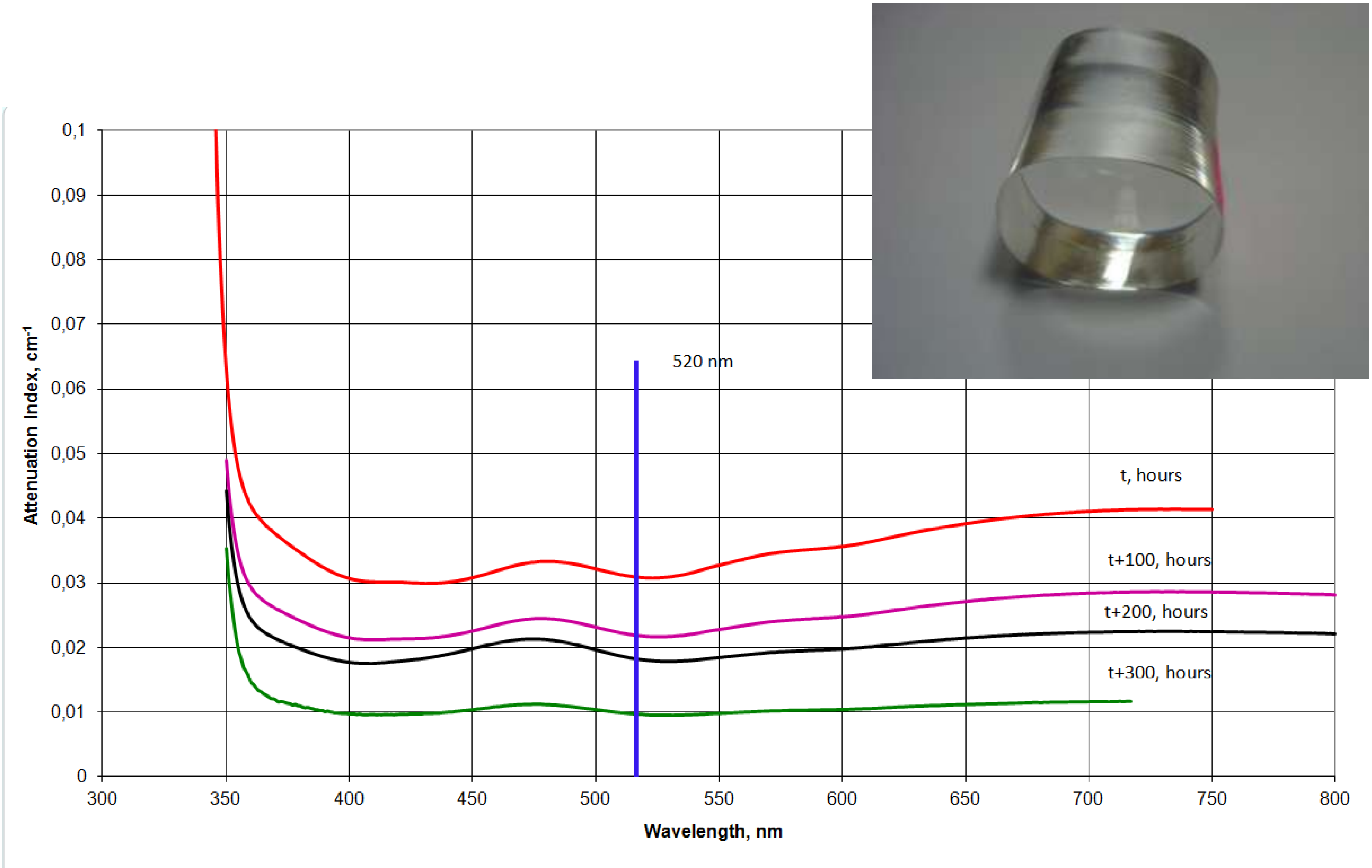
CsI: - 6.5x5.5x30 см (12 crystals)
- 9x9x6 см (2 crystals)

- Trigger conditions

- Threshold: 25 ADC (1V/1024 = 1ADC)
- Pulse width: 200 ns
- Cluster number: 6

Attenuation index vs Wavelength depend on heat treatment (annealing) duration

(horizontal position of SE reference No 91)



Attenuation index vs Wavelength depend on heat treatment (annealing) duration

(vertical position of SE Reference No 91)