AMoRE experiment: a search for neutrinoless double beta decay of 100Mo with $^{40}Ca^{100}MoO_4$ cryogenic scintillation detector

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ITEP (Moscow)

on behalf of AMoRE Collaboration

TAUP 2011

Munich, Germany

September 8, 2011

A*Mo*RE Collaboration: since October 2009 (Advanced Mo based Rare process Experiment)

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- **China (3)**
  Tsinghua University : J.Li, Y.Li, Q.Yue(3)

4 countries

8 institutes
69 participants

Goals of AMoRE Collaboration

- **Investigation of neutrinoless double beta decay of Mo-100 isotope**:
  - ➢ $Q_{\beta\beta}$ = 3034 keV: the biggest of the DBD isotopes can be produced ***at tenths – hundred kg scale*** (by centrifuges, in Russia);

  $T_{1/2}(2v)$ = $7{,}1*10^{18}$ years $\rightarrow$ need for high energy resolution.

- **Dark Matter Search**

AMoRE:
cryogenic scintillation detector based on $CaMoO_4$ single crystal

- $CaMoO_4$ sheelite-type self-activated scintillator
- T_{melt} = 1445 ^oC (Pt or Ir crucible)
- Technology: Chochralsky method
- Light yield (RT): up to 9300 photon/MeV
- Emission peak at 9 K: 540 nm
- Kinetics of scintillation light (<u>main component</u>):

  under RT = 16 μsec

  at 6 K = 345 μsec
- Debaye temperature: 438 K (Ge: 360 K, Si: 625 K)

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

"Detector = Source": ε ~ 80 - 90% efficiency;

- High content of working isotope (Mo) in compound: 50% (stoichiometry ratio);
- Good energy resolution and high light yield for scintillation mode;
- High energy resolution for phonon mode (comparable with the resolution for HPGe detectors): no $2\nu\beta\beta$ of Mo–100 background;
- α/β- pulse shape discrimination (α/β-ratio = 0,20)
- Scalability of the experiment (increasing of mass by break-in "crystal by crystal");
- Chochralsky technology of the production → High purity, including radioactive isotopes
- Mo-100 production at **hundred kg scale**: centrifuges

AMoRE:
$^{40}Ca^{100}MoO_4$ cryogenic scintillation detector

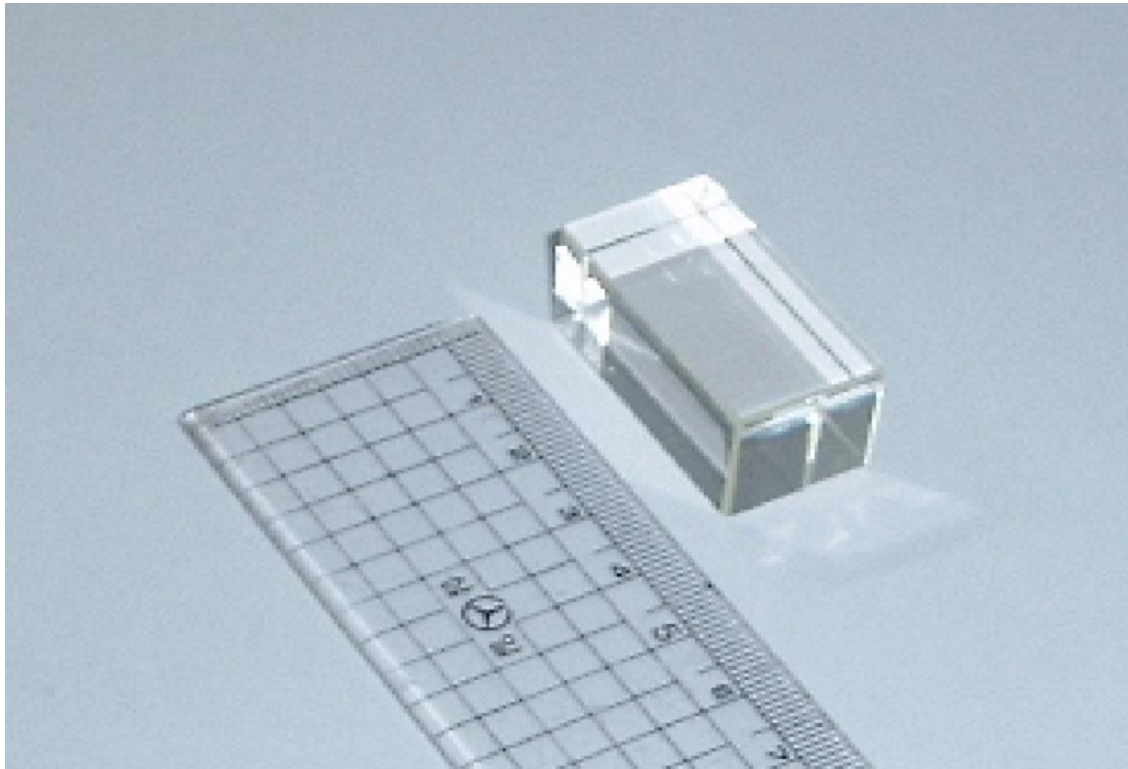
Light detector →

1. Absorber:
-Isotope enrichment
-Purification
-Crystals growing
-Isotope recovery from waste

2. Bolometer: R&D on
MMC&SQUID
TES &SQUID

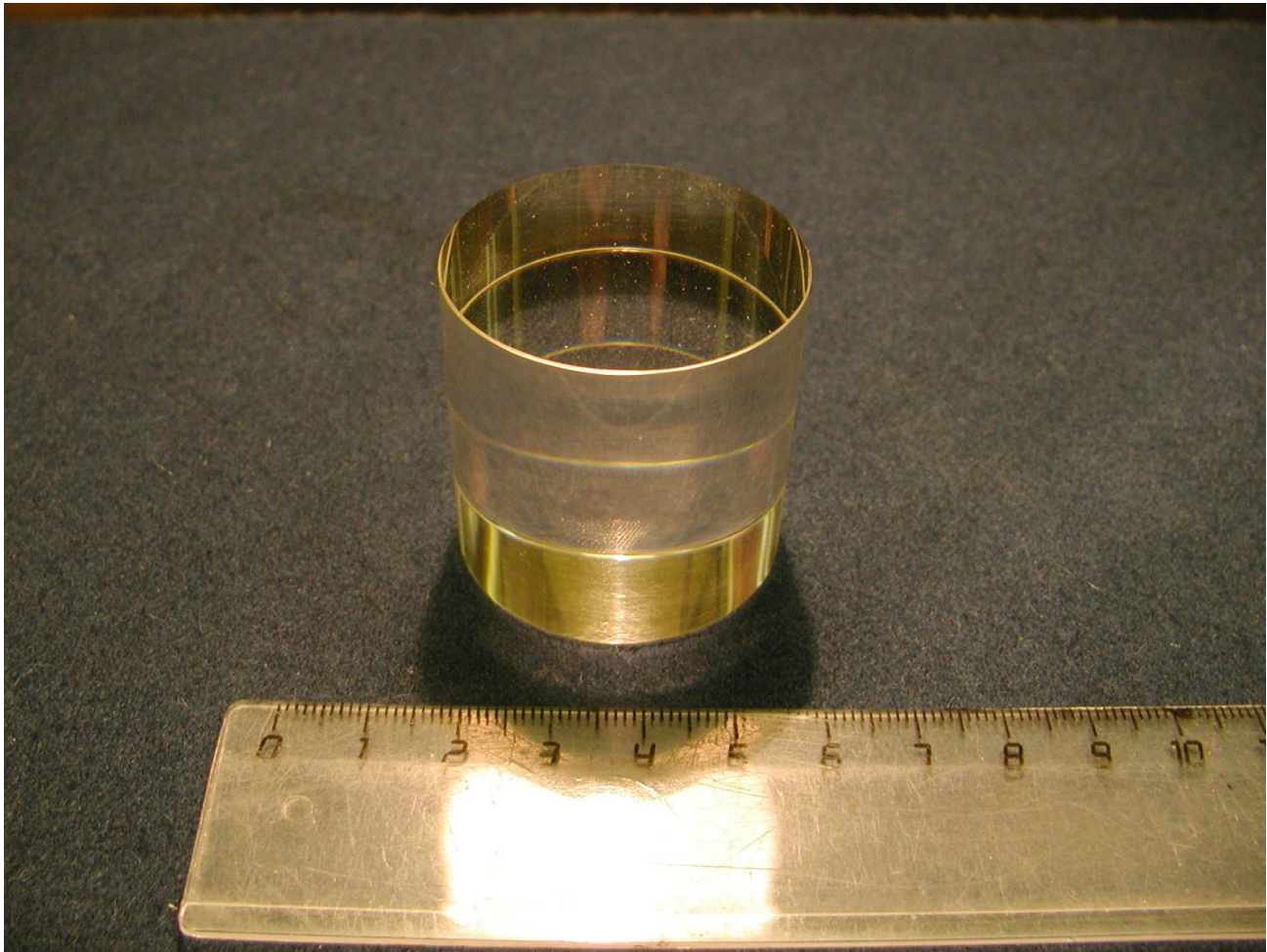
Beginning of R&D: 2004

- Dimensions of $CaMoO_4$ crystals up to 15 cm^3;
- LY ~ 400 photons/MeV;
- Low transparency (absorption band at 395 nm was observed).
- High content Bi-214(U-238) = 286 mBq/kg
- Th-232(Tl-208) ≤ 25 mBq/kg



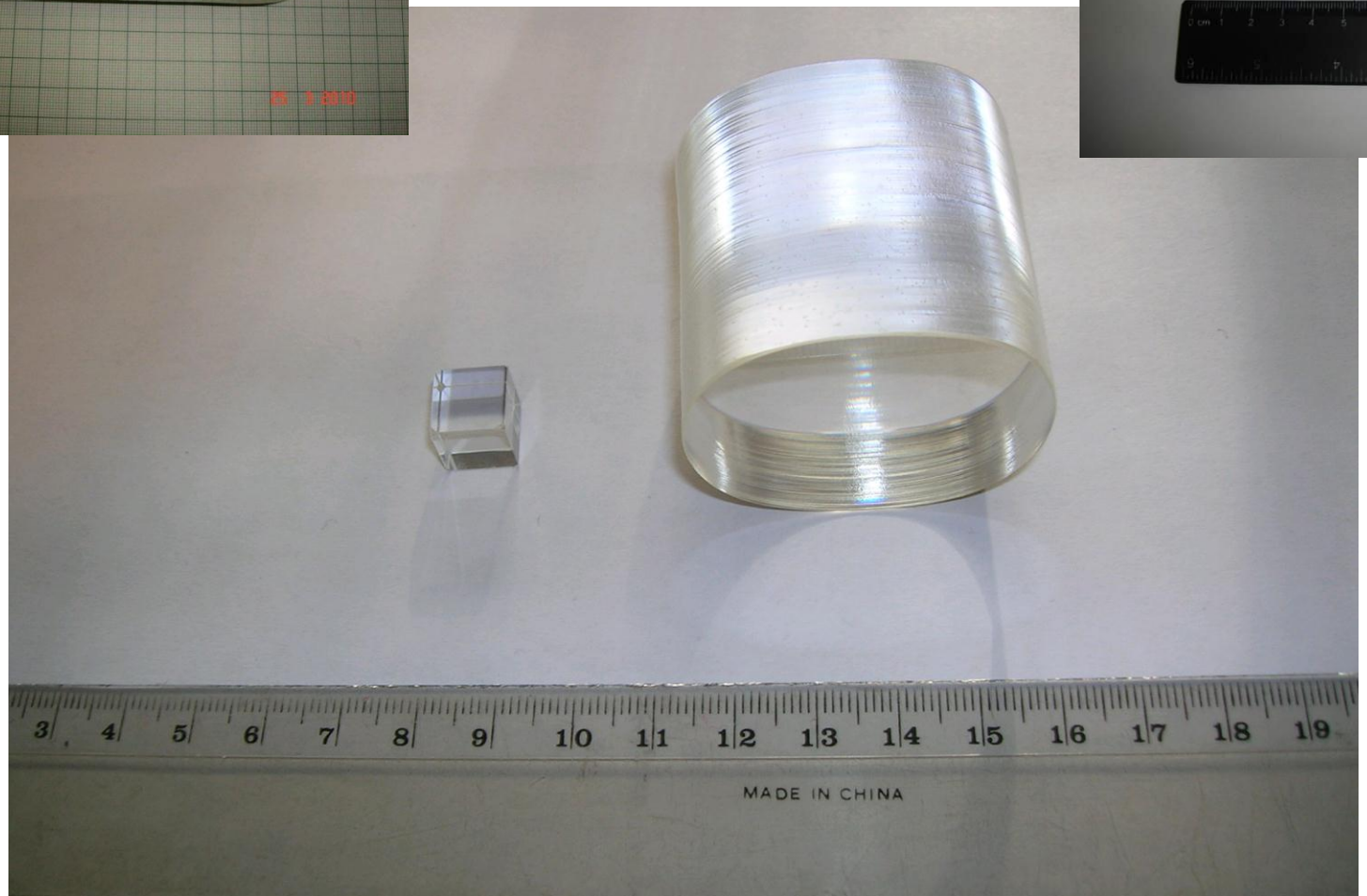
The results: 2007

The scintillation natural $CaMoO_4$ crystal of cylindrical geometry with dimensions of D40x40 mm



Scintillator element $^{40}Ca^{100}MoO_4$
D(42 x 40) x 42 mm, m = 260 g

Annealing →



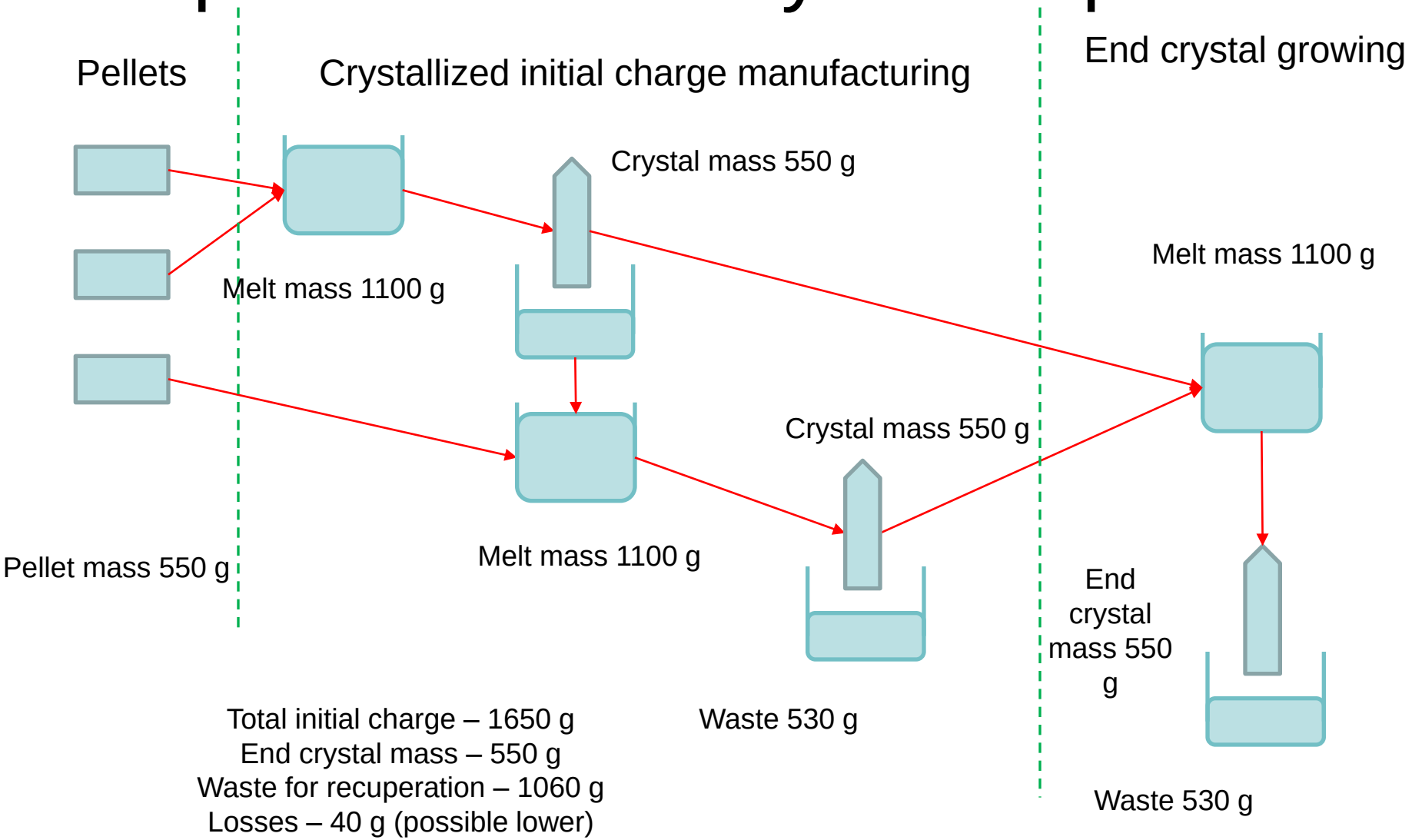
JSC FOMOS Materials (Moscow): Equipment for crystal growth, heat and mechanical treatment

Puller KRYSTAL 2M

Furnace

Saw

Flow chart of the crystal growth process.” One-by-one” option.



Bkg measurements at Baksan Neutrino Observatory: HPGe detectors (3 x ~1 kg) at low background underground lab (H = 660 m.w.e.)

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 $^{40}Ca^{100}MoO_4$	$\leq1,2*10^{-2}$	$\leq3,1*10^{-3}$	$\leq8,3*10^{-4}$ [$\leq2,4\cdot10^{-3}$]	$\leq6,4*10^{-3}$
Calcium formate, $Ca(HCOO)_2$	$<= 7,0*10^{-3}$	$<= 3,0*10^{-3}$	$<= 8,9*10^{-4}$ [$<= 2,5*10^{-3}$]	$<= 1,7*10^{-3}$

Ac228 ≤ 3,1 mBq/kg
Tl208 ≤ 0.83 mBq/kg
Bi214 (Ra226) ≤ 6,4 mBq/kg

Double crystallization procedure: Purification ≥ 35 times!

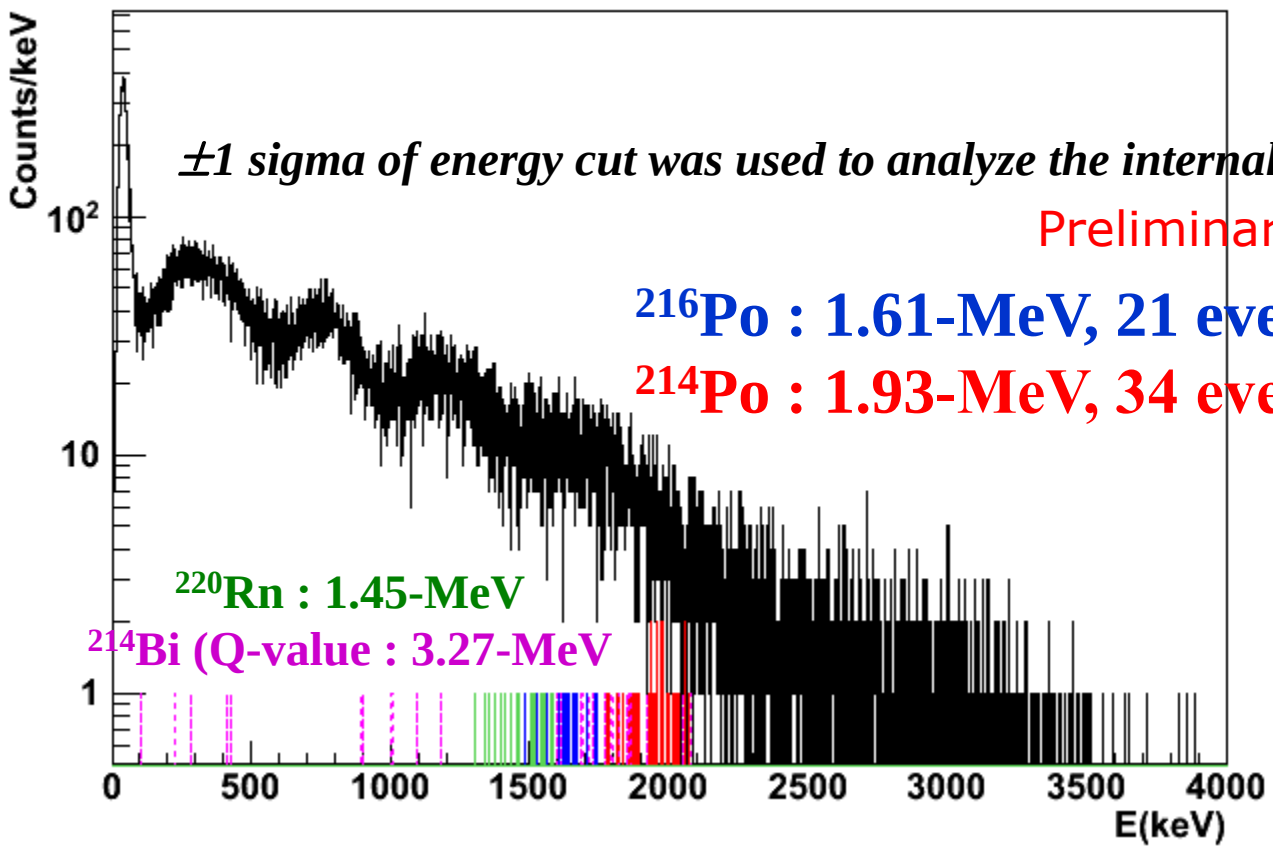
Background measurement at YangYang of SB28 $^{40}Ca^{100}MoO_4$ crystal

β–α decay in 238U

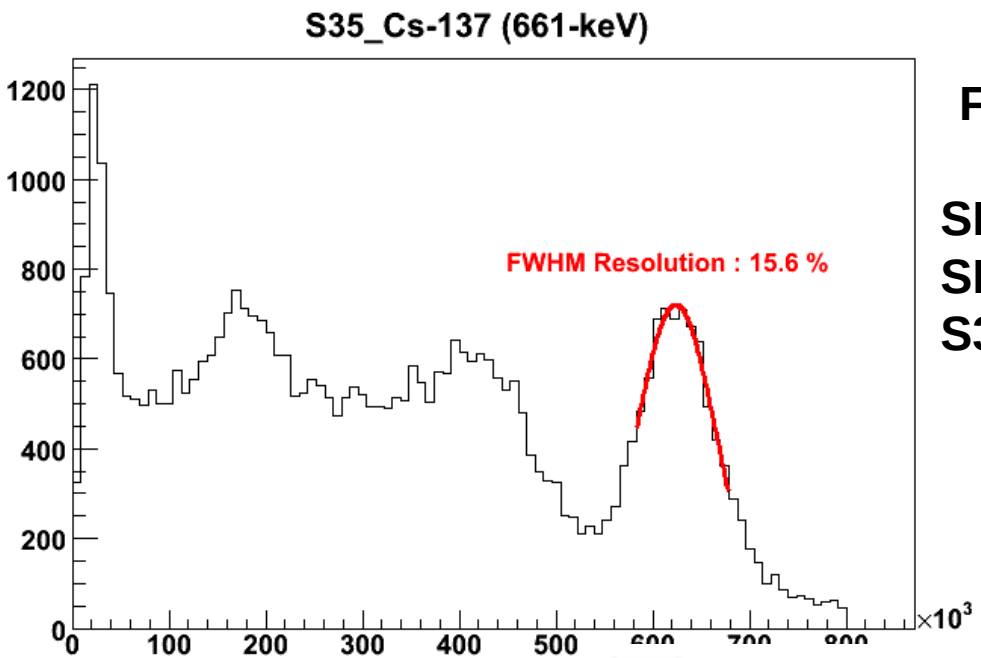
214Bi (Q-value : 3.27-MeV) → 214Po (Q-value : 7.83-MeV)→ 210Pb

α–α decay in 232Th

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



Measurements of the energy resolution at YangYang laboratory (Example: S35 element at 661 keV (Cs-137).

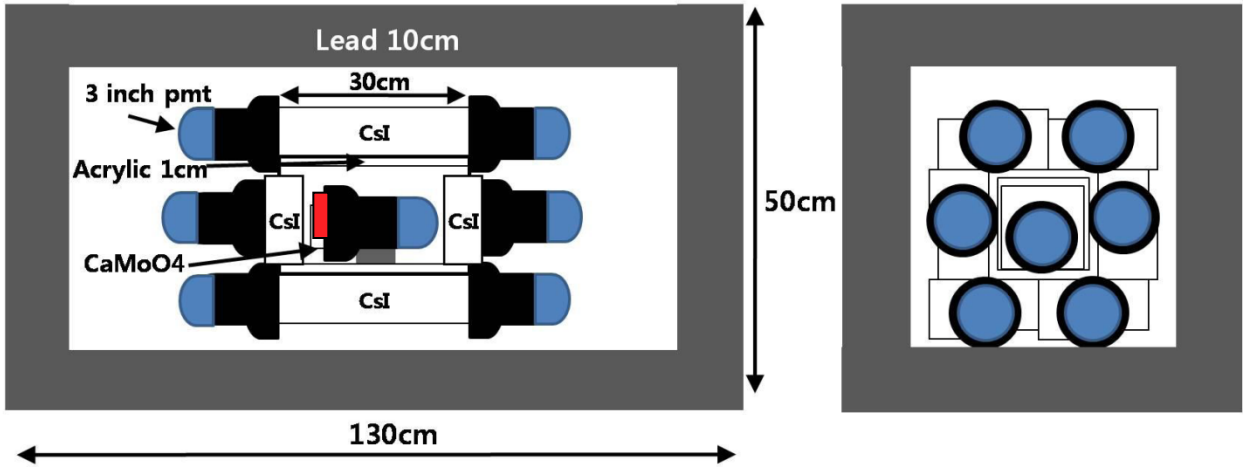


First enriched 40Ca100MoO4 crystals tested at YangYang:

SB28: D(50x41 mm) x 26 mm, m =196 g

SB29: D(48x51 mm) x 50 mm, m =390 g

S35: D(44x40 mm) x 42 mm, m =259 g



Mo-100 isotope production: ECP (Zelenogorsk, Russia)

- **We bought $^{100}MoO_3$ oxide (2,5 kg of Mo-100)**

Enrichment:

Mo-100 = 96,1%

Impurities (the results from ICP MS measurements):

U ≤ 0.07 ppb

Th ≤ 0.1 ppb

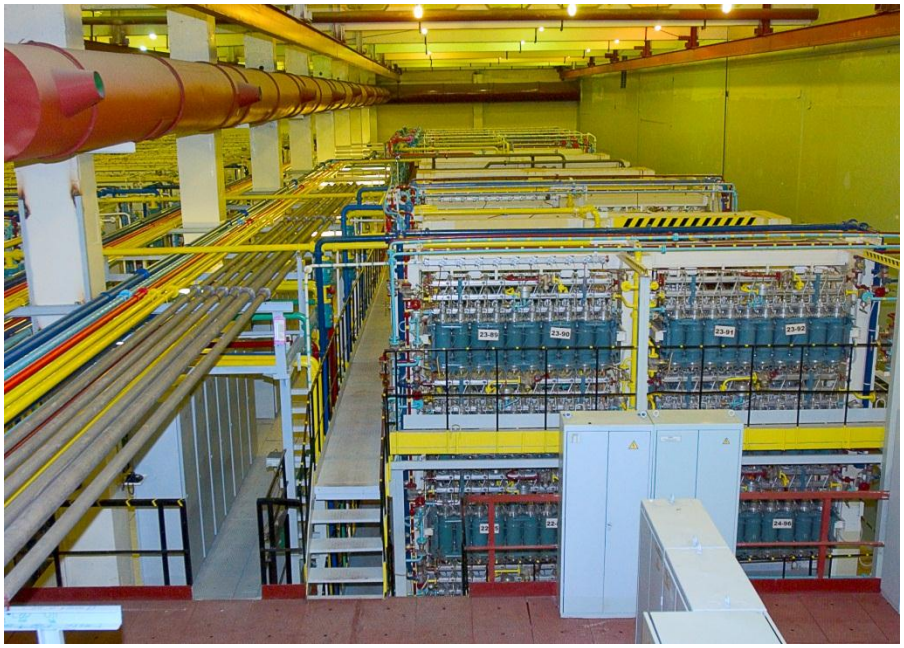
HPGe (Baksan): **^{226}Ra ≤ 2.3 mBq/kg,**

^{228}Ac ≤ 3.8 mBq/kg

Regular productivity of Mo-100 is up to ~ 30 kg per year

Svetlana Department, ECP

Anatoly Shubin (1939 - 2008)



Ca-40 isotope production in Russia Electrochimprobor

$^{40}CaCO_3$ compound: 1,25 kg of Ca-40

Enrichment:

Ca-40 = 99.964+/-0,005%

Ca-48 < 0,001% (K depletion is 187 times)

Impurities (ICP-MS): **U <= 0.2 ppb**

Th <= 0.8 ppb

HPGe (Baksan): **^{226}Ra = 260 mBq/kg,**

^{228}Ac = 160 mBq/kg

The industrial separator SU20

30 kg of Ca-40 ($^{40}CaCO_3$) is available now

Ca-48 < 0,001%

Good for 150 kg of $^{40}Ca^{100}MoO_4$

Productivity: 4 – 5 kg/year

Ca-48 Enrichment/Depletion at KAERI

(Korean Atomic Energy Research Institute)

- ALSIS (**A**dvanced **L**aser **S**table **I**sotope **S**eparation)

  - Features : Isotope-Selective Optical Pumping (ISOP)

    followed by Non-selective Resonant Photoionization (RPI)

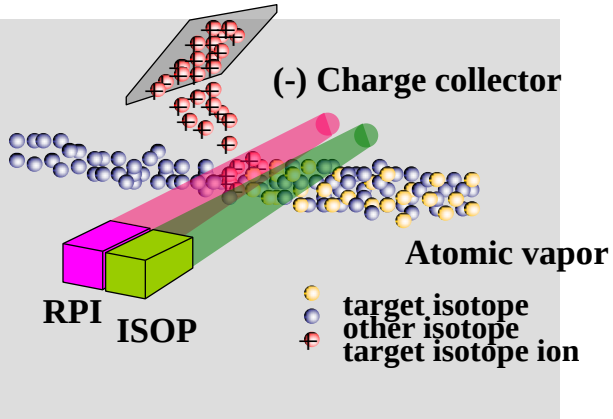
  - ISOP gives good isotope-selectivity and non-selective RPI high yield.

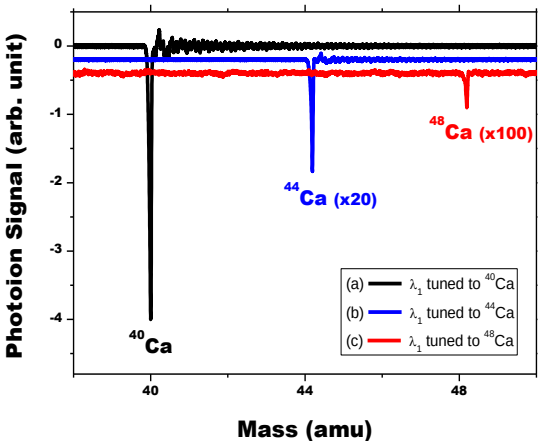
Engineering Demonstration (2010~2012)

- **Production capability : 1kg/yr**

Production Demonstration for (2013 – 2014)

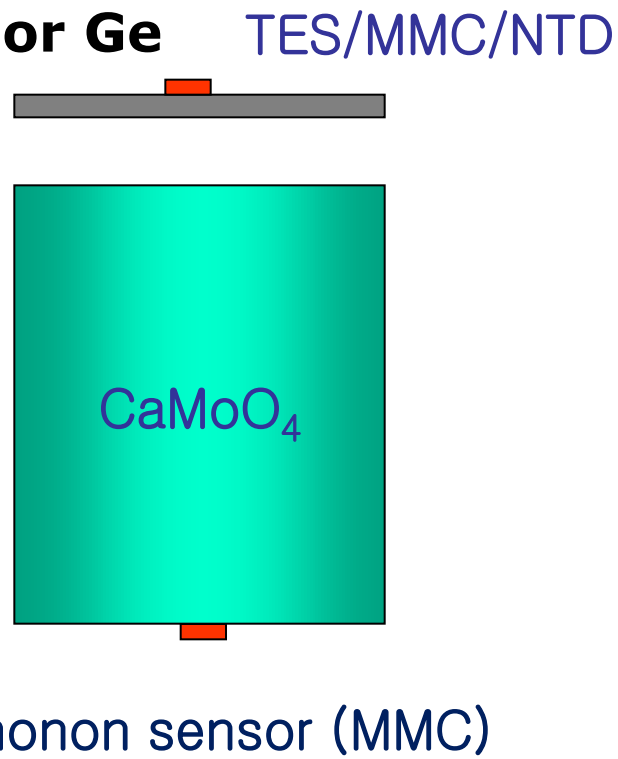
- **Production capability : 5 kg/yr**





AMoRE:
$^{40}Ca^{100}MoO_4$ cryogenic scintillation detector

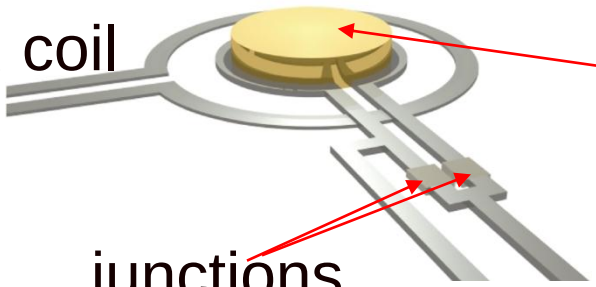
Light detector →



1. Absorber:
-Isotope enrichment
-Purification
-Crystals growing
-Isotope recovery from waste

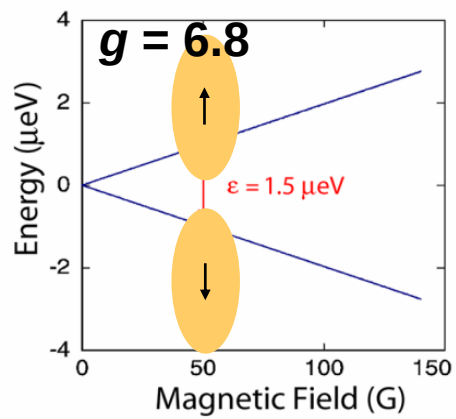
2. Bolometer: R&D on
MMC&SQUID
TES &SQUID

Metallic Magnetic Calorimeter



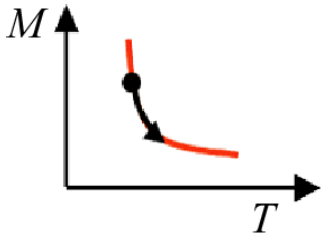
Magnetic material (Au:Er) in dc SQUID

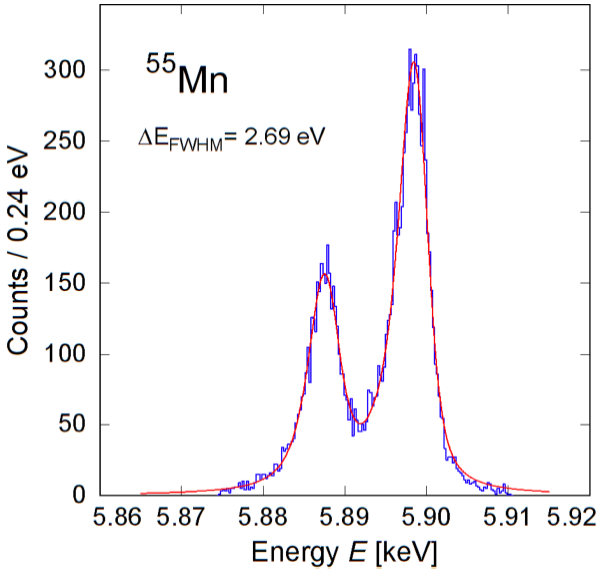
Au:Er(10~1000ppm)
- paramagnetic system
- metallic host: fast thermalization (~ 1ms)
- Can control heat capacity by magnetic field



5 mT $\rightarrow$ $\Delta\varepsilon$ = 1.5 μeV

1 keV $\rightarrow$ 10^9 spin flips

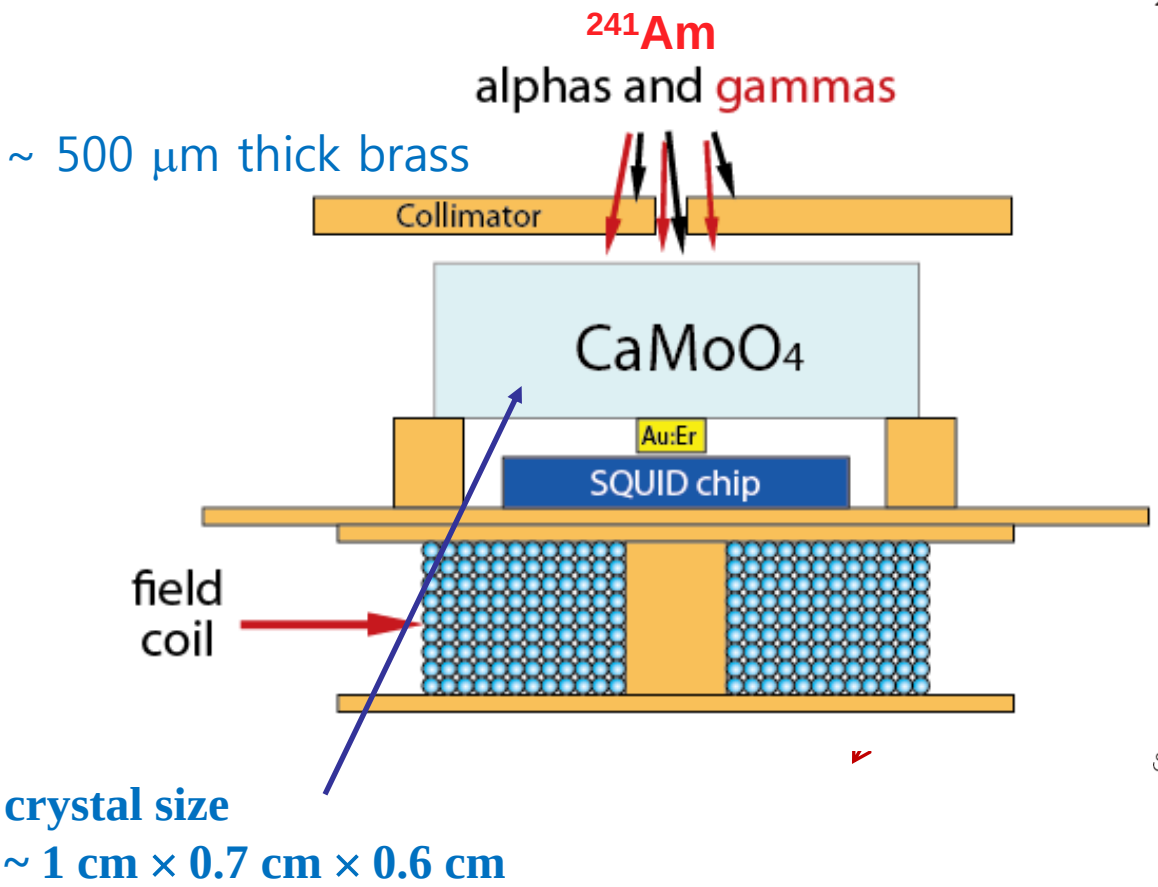


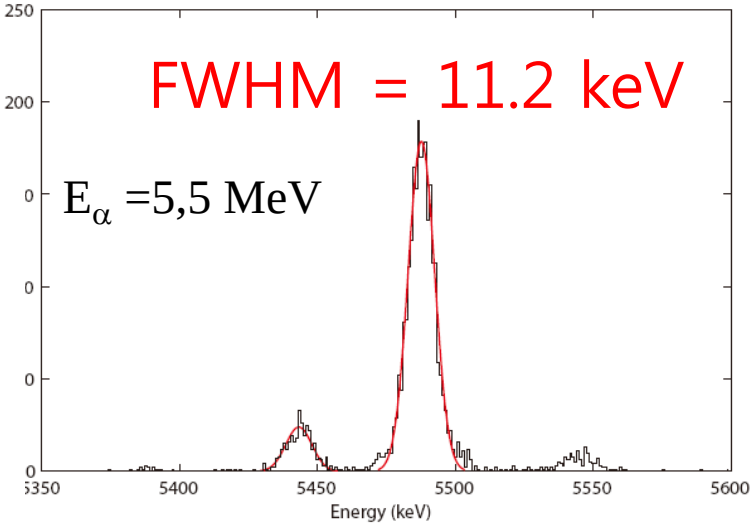


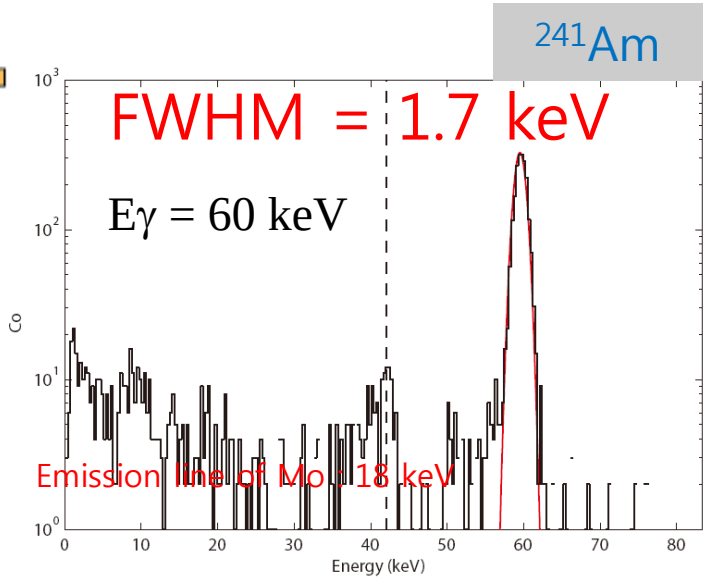
U. of Heidelberg

- **Fast**
- **Wide working temperature**
- **Absorber friendly**

AMoRE cryogenic scintillation detector: R&D at KRISS (Korea)

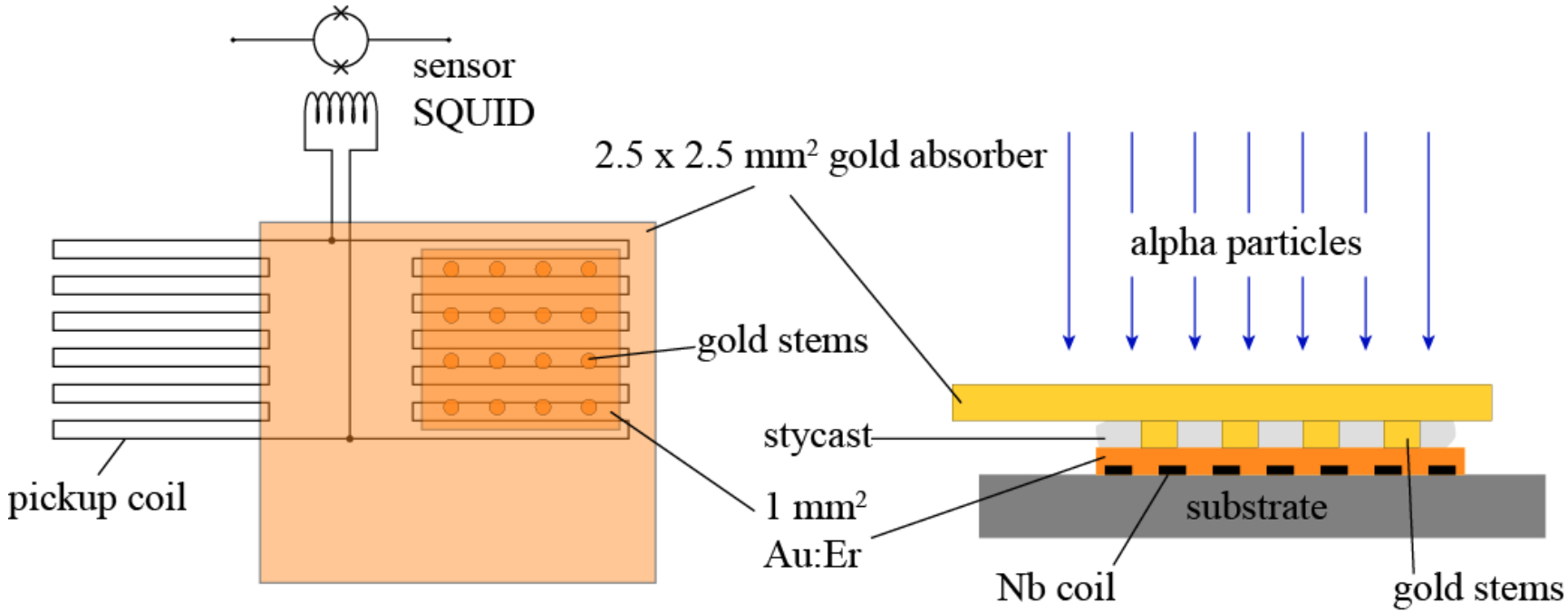






For details: Astropart. Physi.34, 732, 2011

New sensor for large heat capacity



Meander is made in U. of Heidelberg.

2.5 x 2.5 x 0.07 mm³ gold foil

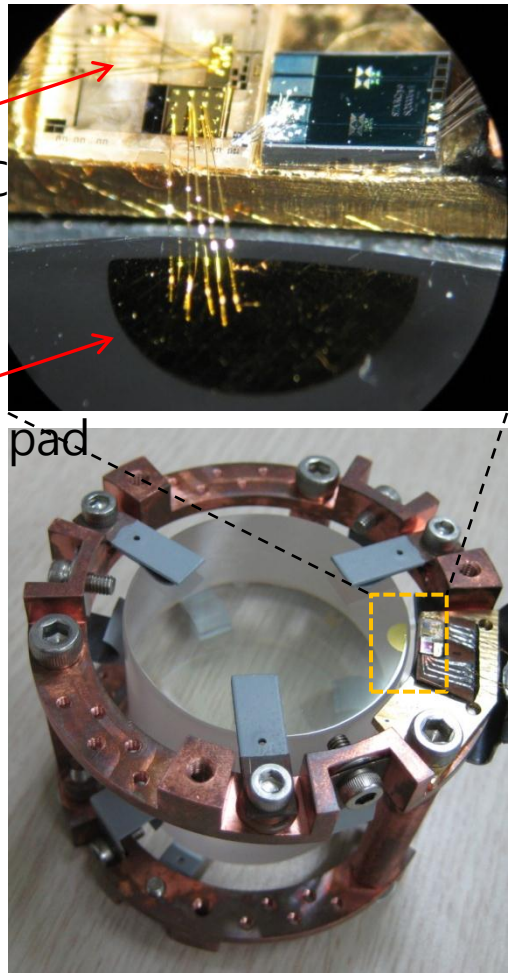
C = 0.6 nJ/K at 20 mK

60 cm³ CaMoO4
C = 0.17 nJ/K at 10 mK
1.4 nJ/K at 20 mK

KRISS (Korea): July 2011: Experimental setup (crystal D40 x 40 mm)

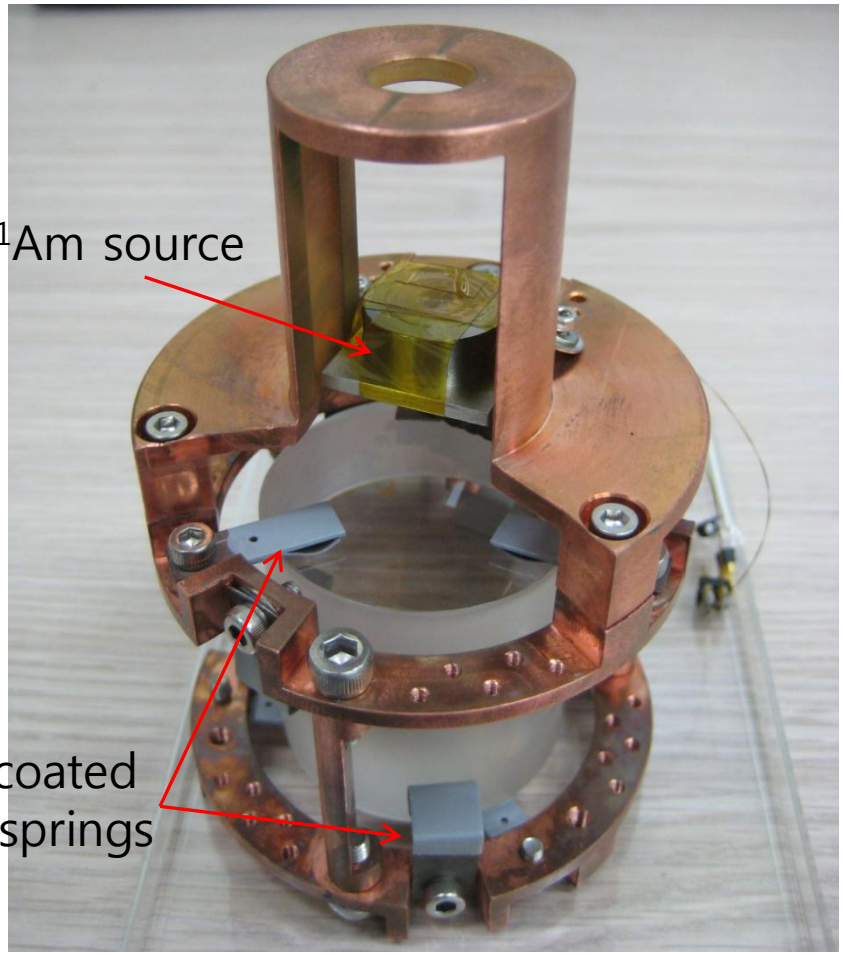
meander MMC from Heidelberg

thermalization pad (gold film)



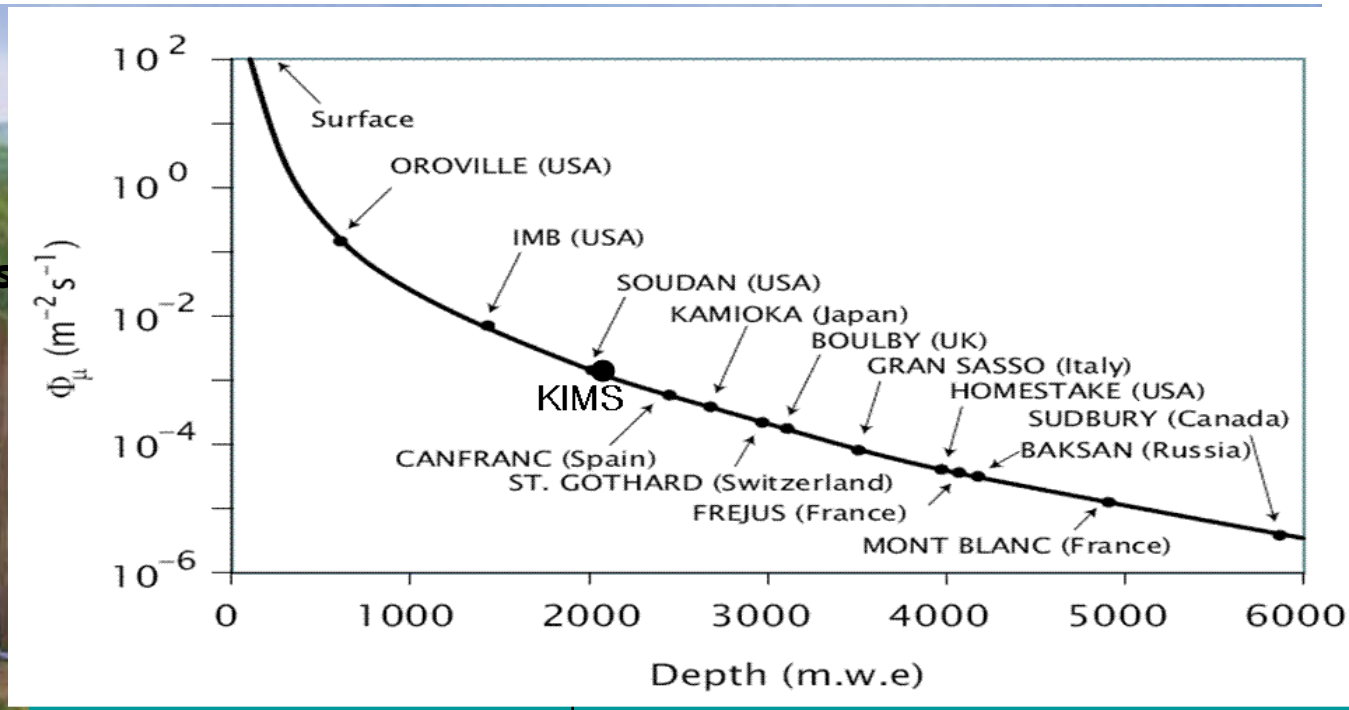
^{241}Am source

teflon-coated copper springs



YangYang underground laboratory

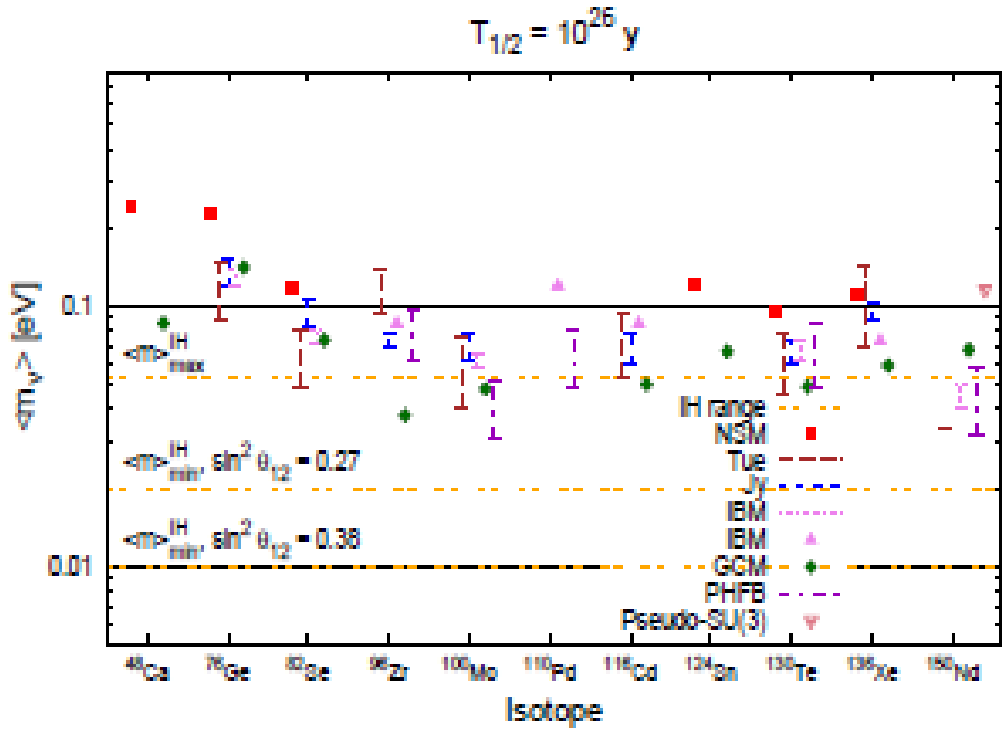
YangYang underground laboratory



Depth	**700 m**
Temperature	**20 ~ 25 °C**
Humidity	**35 ~ 60 %**
Composition of the rock	**^{238}U ≤ 0.5 ppm** **^{232}Th 5.6 +- 2.6 ppm** **^{40}K 270 ppm**
Muons flux	**2.7 x 10^{-7} /см^2/сек**
Neutrond flux	**8 x10^{-7} /cm^2/sec**
Content of ^{222}Rn	**1~2 pCi/L**

AMORE: $CaMoO_4$ DBD projected sensitivity

100 kg $^{40}Ca^{100}MoO_4$ Cryogenic detector
Mo-100 ~ 50 kg
Efficiency ~ 0.8
After 5 years: 3×10^{26} years ~ 50 meV



Werner Rodejohann, Int. J. M. Phys., 2011

Conclusion

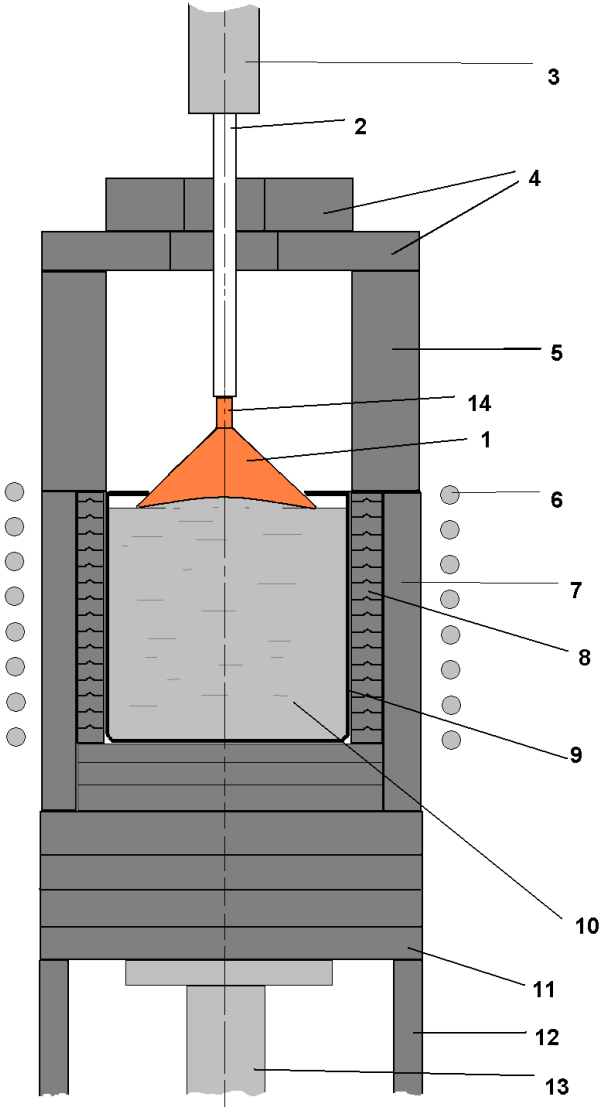
- Large volume $^{40}Ca^{100}MoO_4$ crystals with enriched material have been developed (JSC FOMOS Materials, Moscow)
- Big quantity of Ca depleted on Ca-48 and availability of industrial scale production of Mo-100 permits to plan next generation experiment for search of $0\nu2\beta$- decay of Mo-100
- 100kg $^{40}Ca^{100}MoO_4$ cryogenic detector:

  ~3 x 10^{26} yrs (~ 0.05 eV)
- Included in the National Facility Road Map (Republic of Korea) and Federal Aiming Program (Russia)

Back up slides

Sketch: Chochralsky method

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



Just grown $^{40}Ca^{100}MoO_4$ crystal before annealing

m = 0,55 kg, D49 x 42 mm, $L_{cylinder}$ = 53 mm

CMO crystal growth process at JSC Fomos-Materials Co.

Process stages:

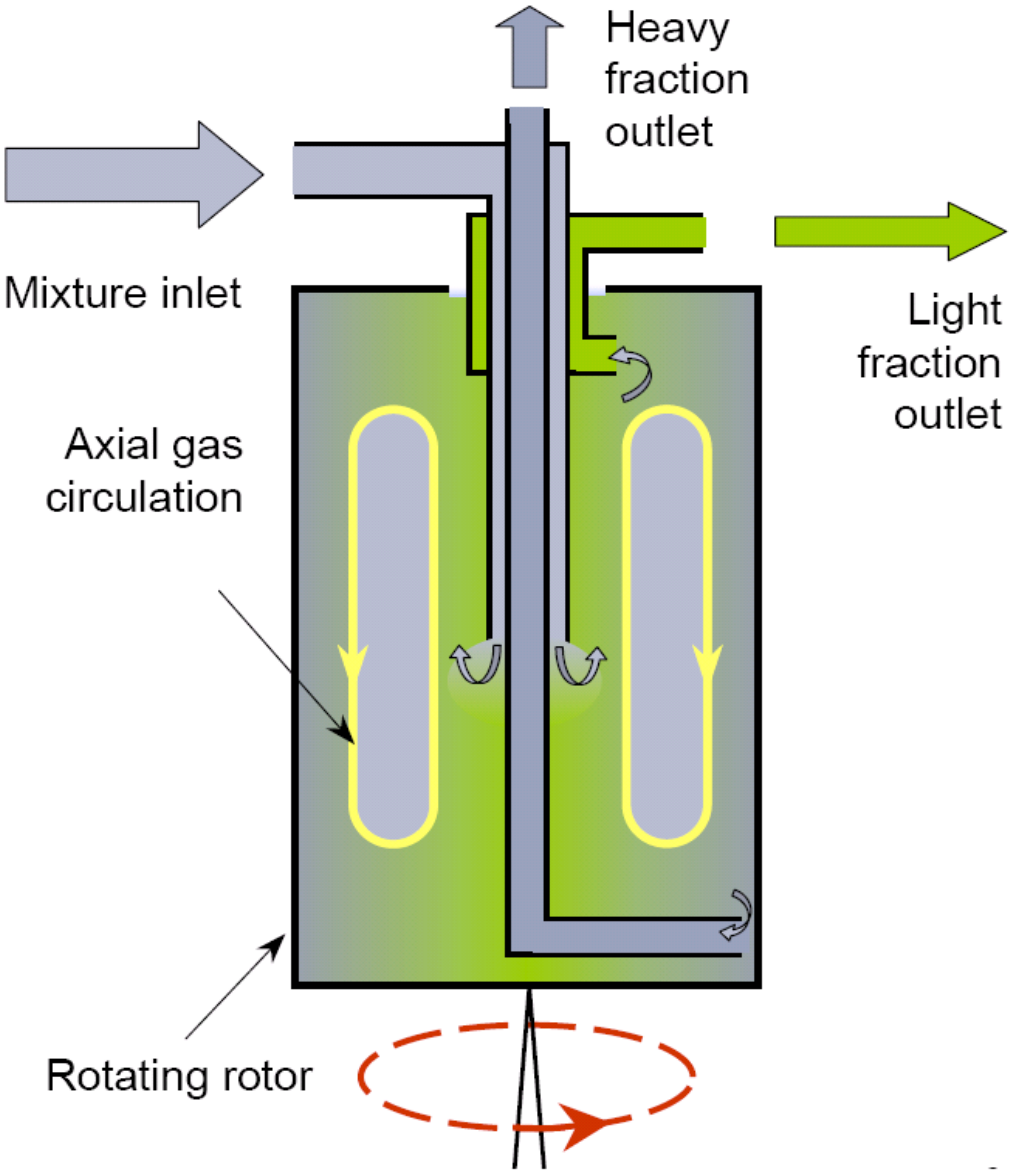
1. Initial powder ICP analysis
2. Initial pellets preparation – pellets manufacturing 550g in mass each
3. Initial charge for crystal growing preparation including MoO_3 adds - 2 pellets + up to 3 mass % of MoO_3
4. Growth of the initial crystallized charge – crystals up to 550 g each
5. Initial crystallized 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

Principle of gas-centrifuge isotope separation

Centrifuge acceleration:
500 000 g
Rotation ~ 1500 s^{-1}

Cascade: many hundred and even thousand units

Operation life of centrifuge:
30 years



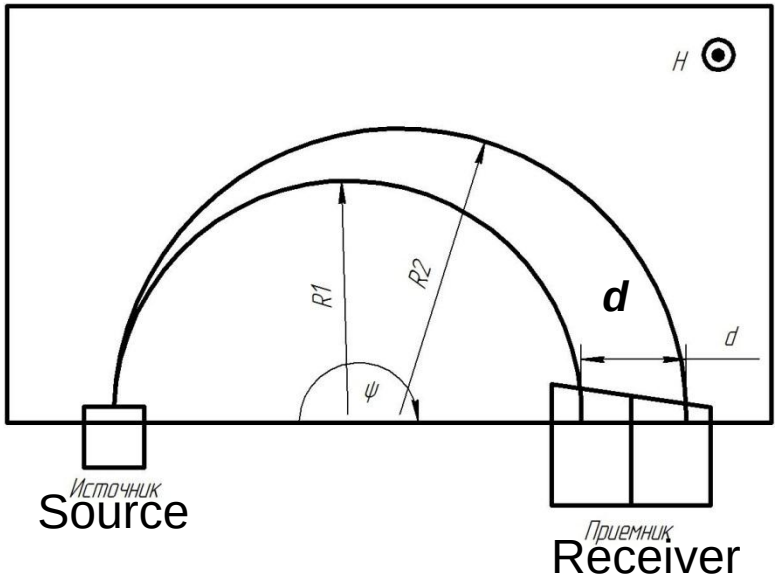
Principle of electromagnetic separation of stable isotopes

Dispersion ***d*** of the EM facility (a distance between ions beams):

$$d = 2\Delta R = R(\Delta M/M)$$

A value of ***d*** for Ca isotopes (**SU 20 facility**) is about 25 mm

2R = 1800 mm



H – magnetic field

Dispersion ***d*** is a distance between ions beams)

The coefficient of the feed material utilization for EM method is in the range of 2 – 20% only

The coefficient of utilization for Ca isotopes is 4,5%

Electromagnet of the SU20 separator

(5-floors building & 3000 tons magnet!)

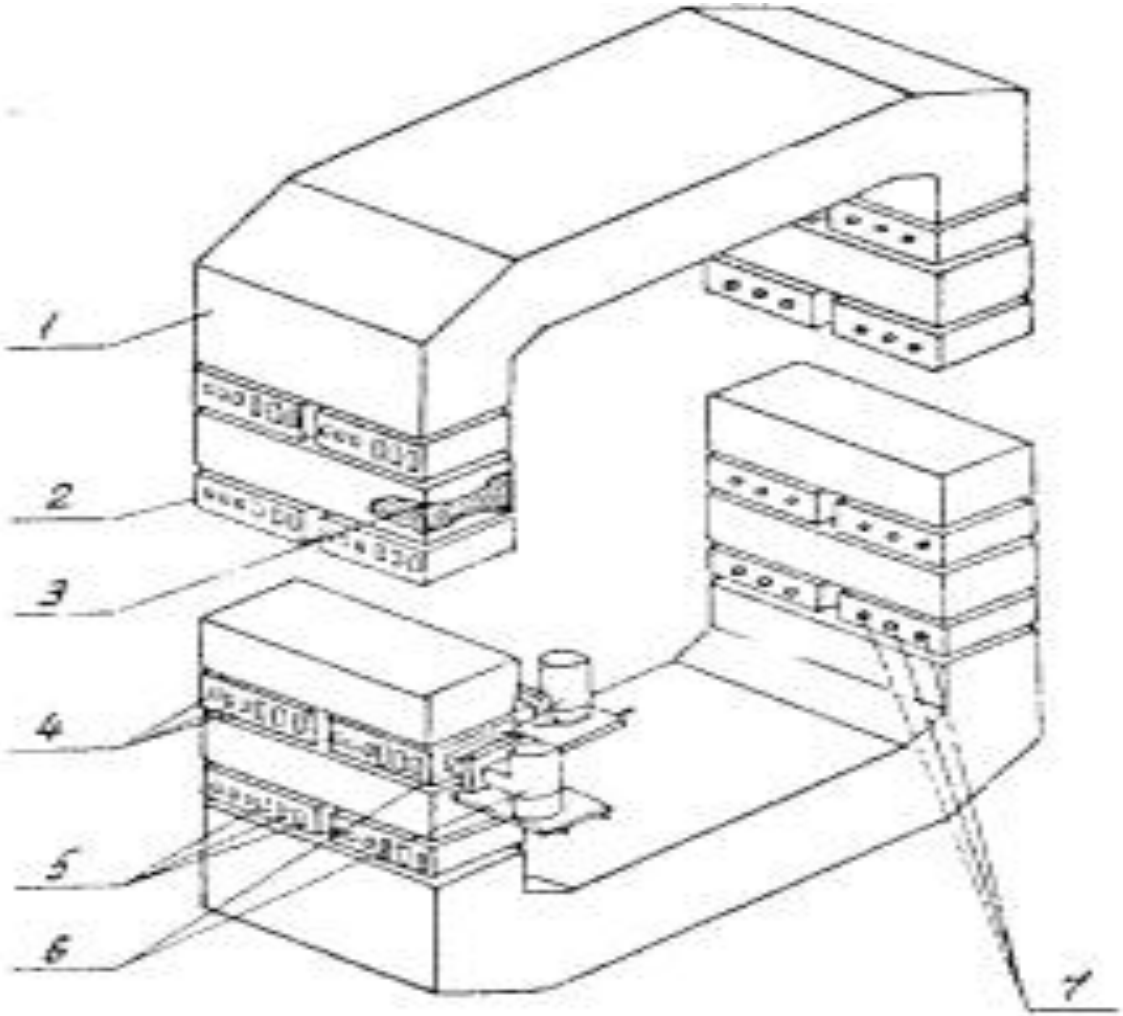


Fig. 1. Electromagnet of the separator. (1) Housing; (2) separation tank (chamber); (3) electromagnet coils; (4) ion source seats; (5) ion receiver seats; (6) diffusion pumps; (7) observation openings.

SU20: Separation tank (2*2*5 = 20)

R = 90 cm

U = 30 kV

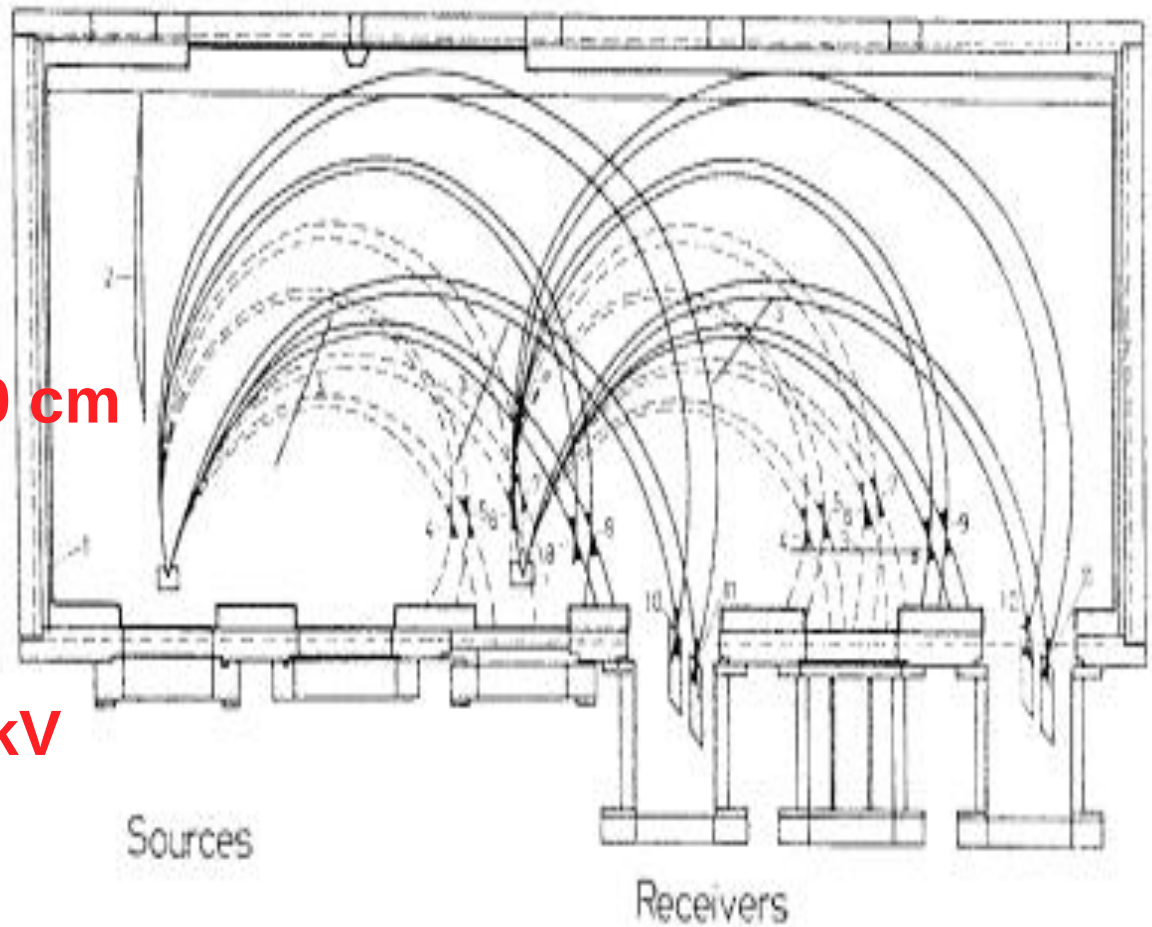
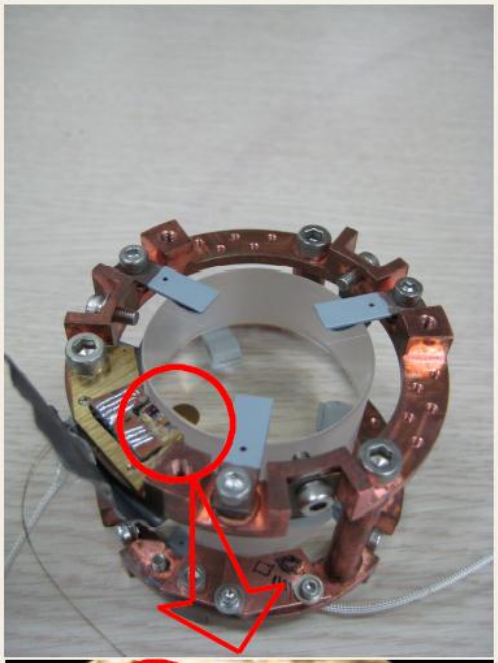
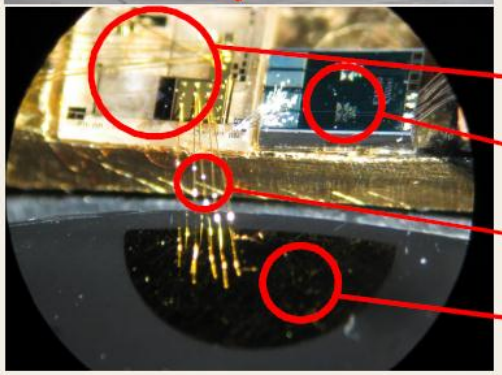


Fig. 3. Location of ion beams in a separation tank, two ion sources operating (feed material is $FeCl_3$): (1) liner; (2) magnet plate profile; (3) graphite plates; (4)–(11) isotope beams: [(4) $^{54}Fe^{3+}$, (5) $^{58}Fe^{3+}$, (6) $^{54}Fe^{2+}$, (7) $^{58}Fe^{2+}$, (8) $^{35}Cl^{+}$, (9) $^{37}Cl^{+}$, (10) $^{54}Fe^{+}$, (11) $^{58}Fe^{+}$].

Detector composition



- Detector for Neutrinoless Double Beta Decay experiment. at few milli-kelvin.
- Large CaMoO4 single crystal is held by springs of holder. ($216g$, $4cm$ diameter, $4cm$ height, 430K Debye temperature)
- Gold film is evaporated on the crystal for make thermal connection between crystal and MMC. ($200nm$ thickness)
- Metallic Magnetic Calorimeter is used to change thermal signals to magnetic signals.
- Gold wires are bonded on the gold film and MMC for thermal connection. ($25\mu m$ diameter)
- SQUID is used to change magnetic signals to voltage signals.
- Meander-type heater is evaporated on the crystal surface. ($7.355\ Ohm$ at 4K.)



MMC

SQUID

Gold wire

Gold film