History with muons

Development of non-destructive and regioselective elemental analysis method

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demands for non-destructive analysis

elemental analysis of archaeological relics, antiquities, artifacts etc.

- essential information on history of technology and propagation of culture
- damage to materials for analysis is inevitable

⬇

lots of materials, which may provide valuable information, have been left in mystery

surface of material

X-ray Fluorescence Analysis, Electron Probe Micro Analysis, Reflection Spectroscopy

- useful information on composition, chemical state, molecular structure

demands for non-destructive analysis

inside materials

- surface of bronze ware and ironware are rusted
  inside has very different composition from surface

- different composition by surface treatment
  kobans (Japanese oval gold coins), katanas (Japanese sword), gilt bronze • • •

inside composition provides more important information

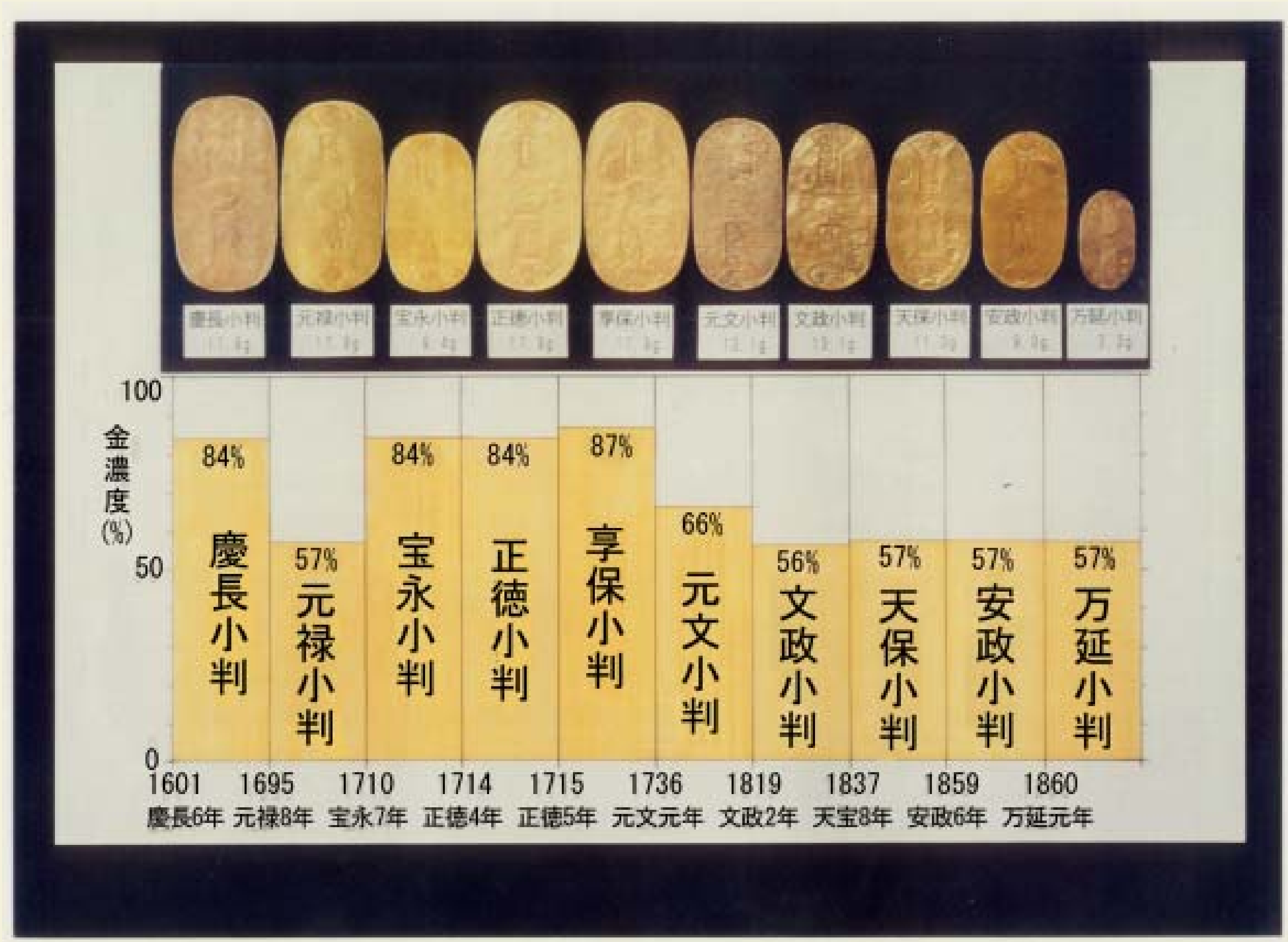
distribution or inhomogeneity of composition in depth

- ICP-AES (Inductively Coupled Plasma - Atomic Emission Spectrometry)
  → destructive
- neutron activation analysis
  → bulk analysis, residual activity

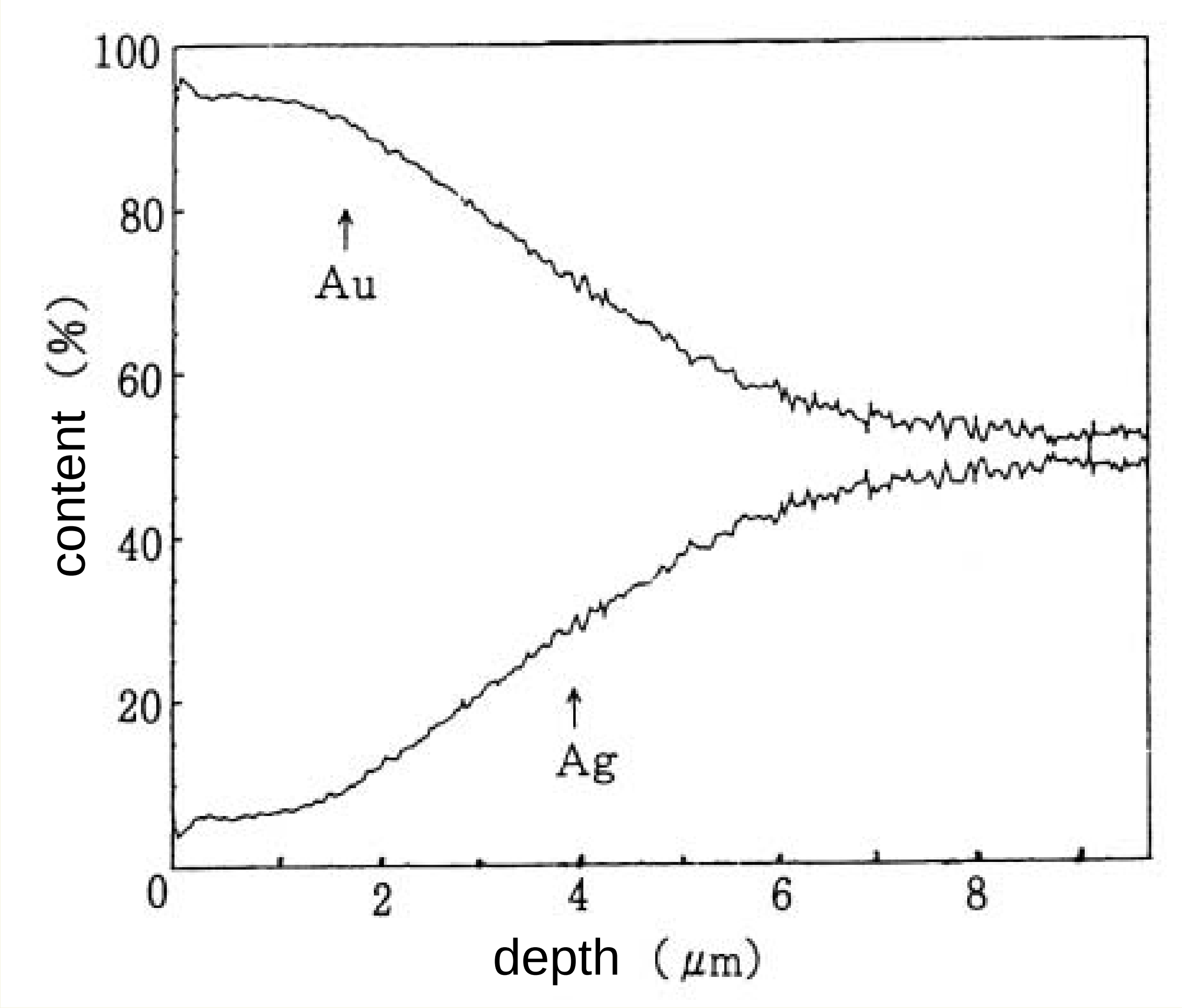
✧invaluable samples in history

→sampling or surface polish are impossible

changes of kobans (gold coins) in Edo era



elemental depth profile of a koban
– difference between surface and inside –



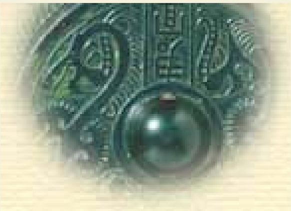
non-destructive analysis with muonic X-rays

requirements for analysis of archaeological relics, antiquities, artifacts etc.

☆ **simultaneous multi-elemental analysis**
comprehensive and systematic analysis for all elements

☆ **non-destructive**
no damage or activity to samples

☆ **regioselective inside material**
elemental analysis of specific parts inside sample



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non-destructive analysis with muonic X-rays

when negative muons stop in material

- muonic atoms form and emit characteristic X-rays
    - X-rays have energy specific to element and transition
- all the elements can be analyzed with same method simultaneously
    - no need for prior knowledge
      unexpected elements cannot be missed
    - less systematic error, high efficiency

⟵ simultaneous multi-elemental analysis

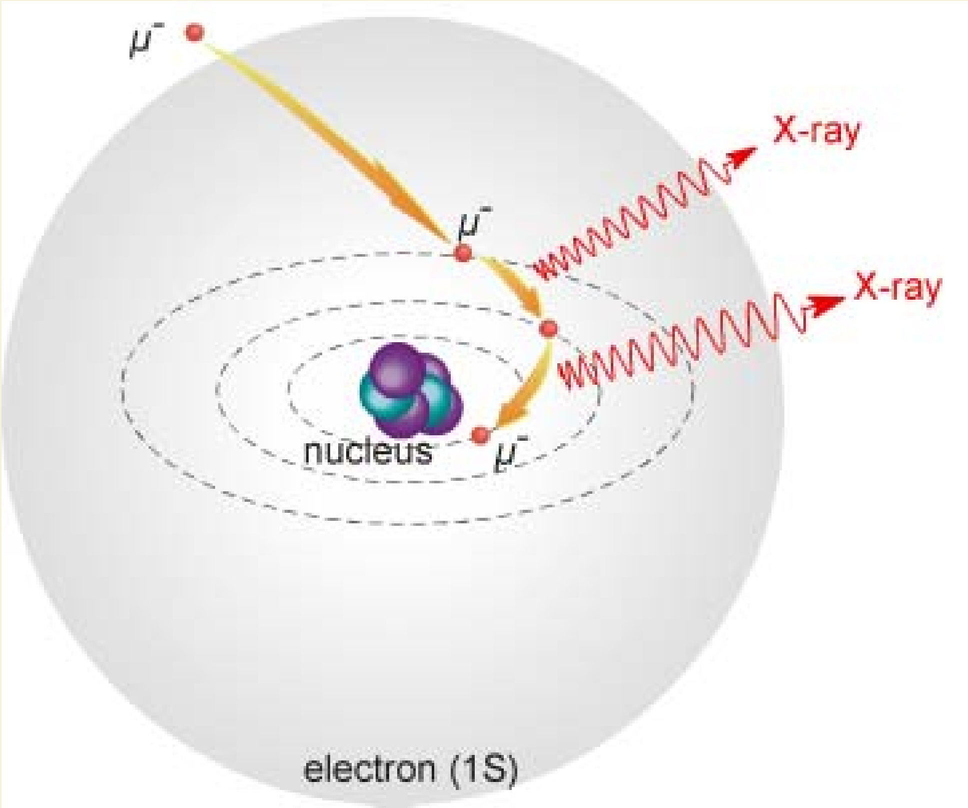
non-destructive analysis with muonic X-rays

Bohr model

$$E_n = -\frac{Z^2 m e^4}{8 n^2 \varepsilon_o^2 h^2}$$

$$r_n = -\frac{4\pi\varepsilon_o n^2 \hbar^2}{Z m e^2}$$

$$\frac{m_\mu}{m_e} \approx 207 \approx \frac{E_\mu}{E_e} \approx \frac{r_e}{r_\mu}$$



wide energy range of muonic X-rays
(10keV ~ 10MeV)

non-destructive analysis with muonic X-rays

energies of typical muonic X-ray (keV)

元素	Kα	Kβ	Lα	Lβ
C	76	89	14	19
O	134	158	25	34
Al	347	422	66	89
Fe	1256	1704	264	357
Cu	1513	2126	307	444

atomic capture rate of muons

$W(Z) \propto Z$ (Fermi-Teller (Z-law))

$Z^{1/3} - 1$ (Petrukhin)

$Z^{1/3} \cdot \ln(0.57Z)$ (Daniel)

non-destructive analysis
with muonic X-rays

when negative muons stop in material

- X-ray energy from a few 10's keV to MeV
  - muonic X-rays can get out from inside material easily
- no needs for any chemical treatments
  - no damage to the materials

← **non-destructive**

↑

X-rays from a material irradiated with negative muons
← X-rays with detectors of good energy resolution and high efficiency

non-destructive analysis with muonic X-rays

negative muons are charged particles

- negative muons can be stopped at certain depth of material by changing incident momentum
- stopping position can be also changed transversally by moving material with respect to muon beam

→ 3-dimensional mapping of elemental distribution

⟵ **regioselective inside material**

⬇

negative muon beam of high intensity and low momentum bite is essential!

➡ PRISM

non-destructive analysis with muonic X-rays

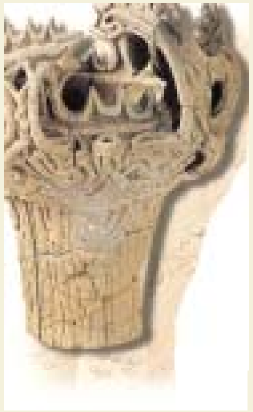
simultaneous multi-element analysis ・ non-destructive ・ regioselective inside material

analysis with muonic X-rays is only the candidate

- much wider range of materials can be analysed
- new knowledge can be obtained in history and archaeology
- **invaluable materials can be analyzed in Japan**

previous examples

- ancient tiles
- chlorine, calcium inside phantom model imitating human body
- ancient base, glass bracelet



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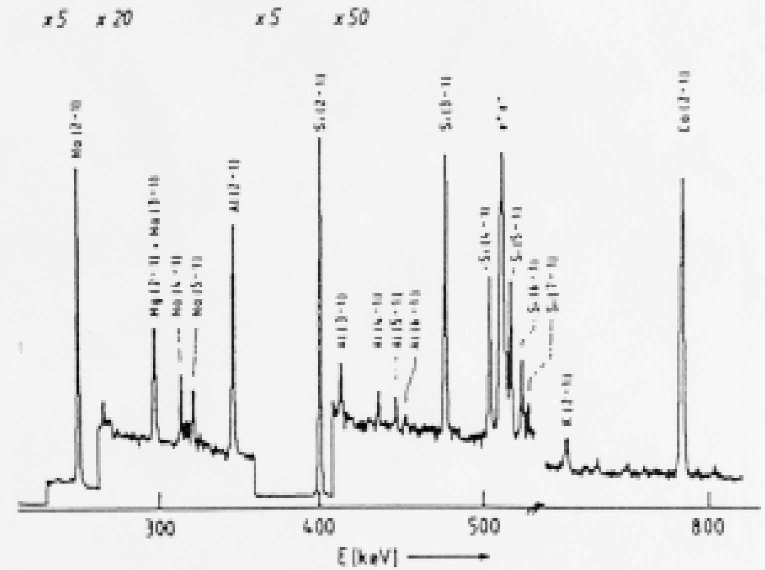
glass bracelet



The photograph above is of a glass bracelet found on the site of a Celtic city near Manching, Bavaria. How can one analyze the composition of the glass without damaging the sample? A group of the Technical University of Munich brought the bracelet to SIN, stopped negative muons in it and recorded the muonic X-ray spectrum. For details, see contribution RA-76-01.

H. Bossy et al.

SIN NEWSLETTER 19 (1987)

ancient base

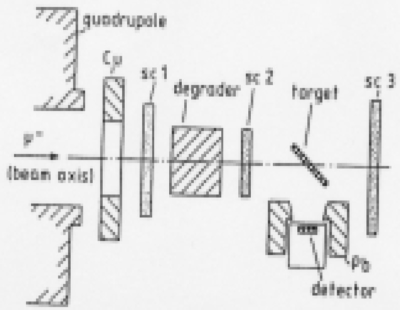


Fig. 1. Experimental setup: Cu–copper shielding, detector–Ge(Li) detector, Pb–lead shielding for detector, sc1, sc2, sc3–scintillation counters forming a telescope.

Table 2
Capture ratios relative to Si for three Egyptian pottery sherds.

	Marl clay	Nile clay	Grave cone
O	3.83 ± 0.08	3.68 ± 0.08	3.78 ± 0.08
Na	0.054 ± 0.003	0.111 ± 0.005	0.059 ± 0.003
Mg	0.086 ± 0.003	0.072 ± 0.002	0.082 ± 0.002
Al	0.367 ± 0.007	0.320 ± 0.005	0.320 ± 0.006
Si	1	1	1
K	0.058 ± 0.006	0.097 ± 0.006	0.075 ± 0.009
Ca	0.600 ± 0.018	0.139 ± 0.004	0.189 ± 0.006
Ti	0.038 ± 0.002	0.047 ± 0.003	0.040 ± 0.003
Fe	0.304 ± 0.018	0.382 ± 0.010	0.387 ± 0.012

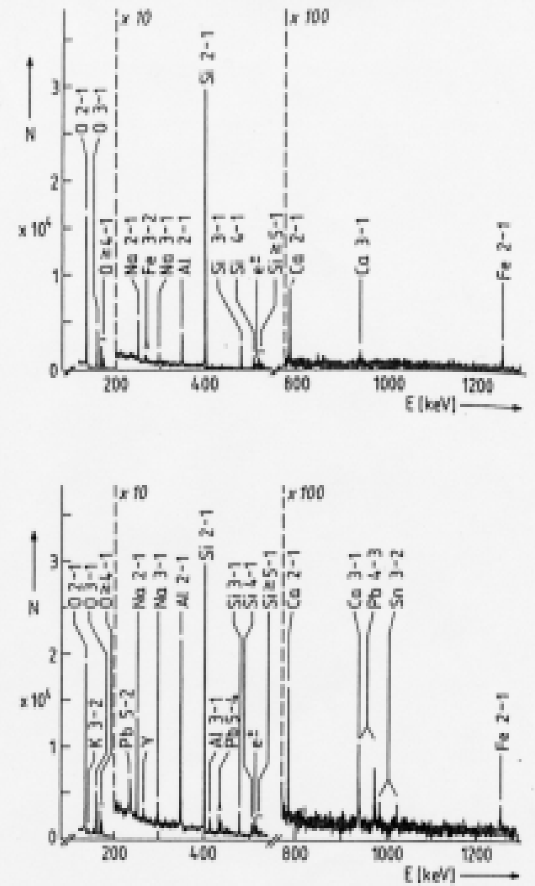
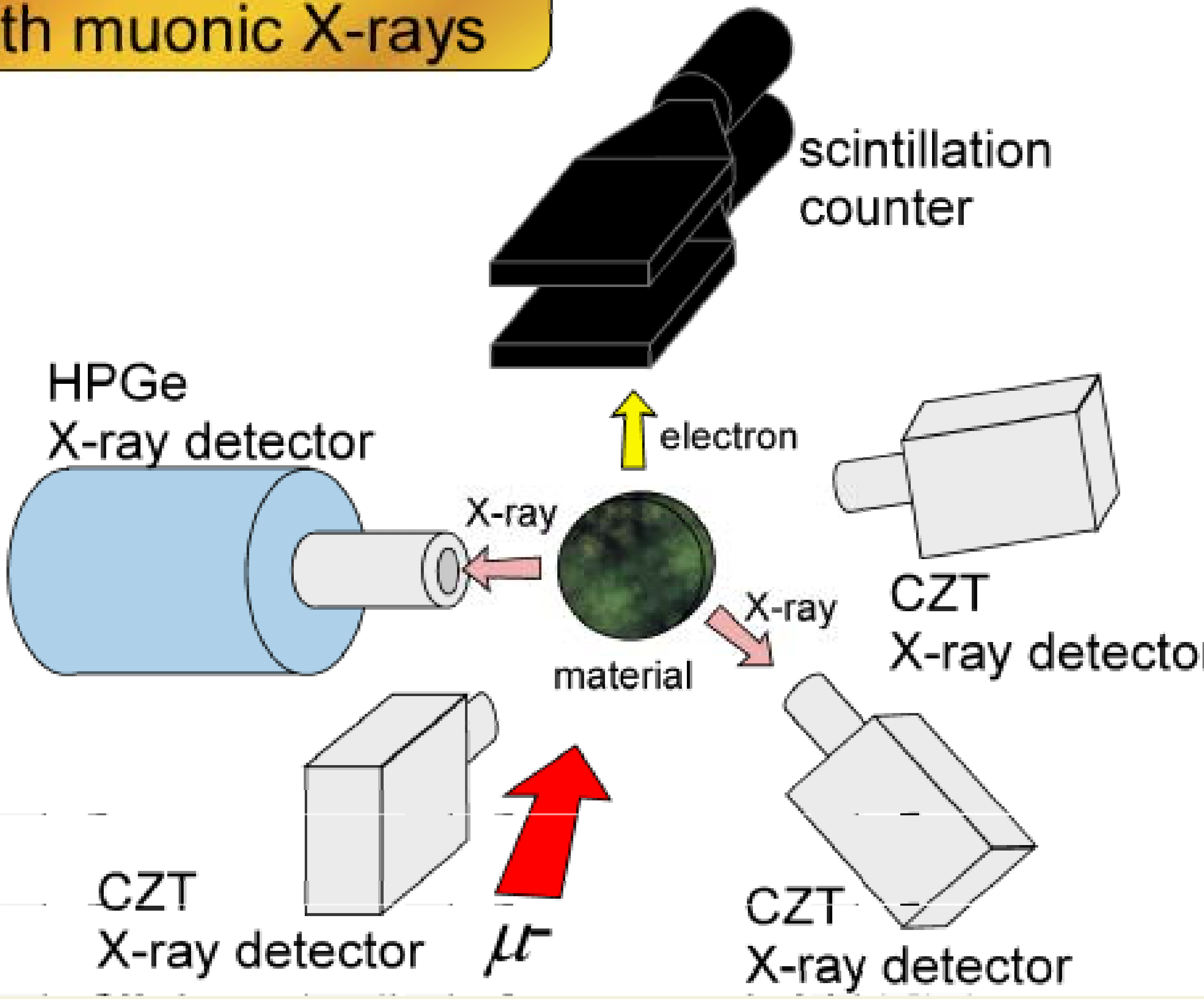


Fig. 2. Spectra of Islamic tile. Above: base material (fire clay); below: glaze.

first step : establishing techniques and procedure of bulk analysis

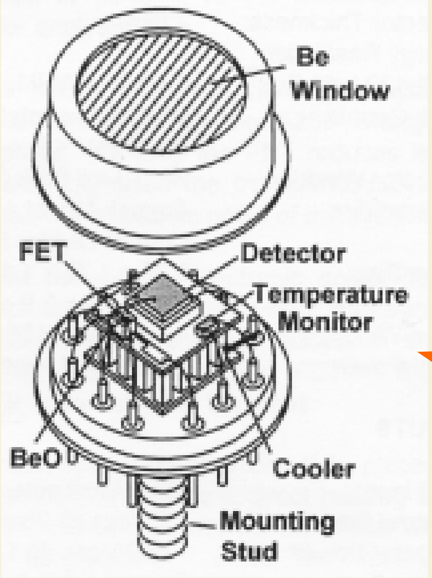
1. materials of single element
   - measuring X-ray yields from each element
2. compounds and alloys of known compositions
   - chemical effects on X-ray yields
   - calibration curve
3. samples of unknown composition
   - estimate composition with observed X-ray yields and calibration curve

Apparatus of non-destructive analysis with muonic X-rays

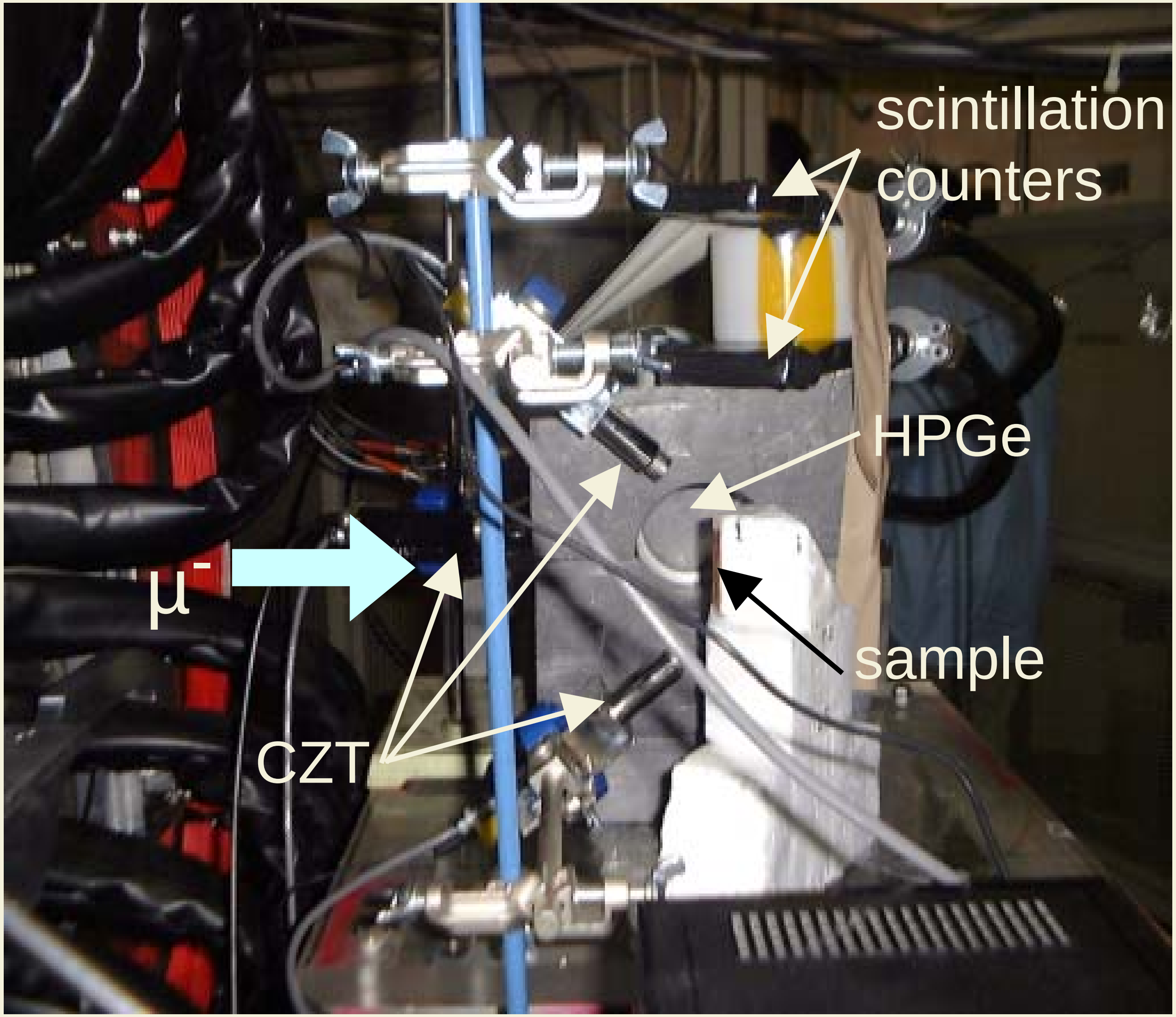


CZT X-ray detector

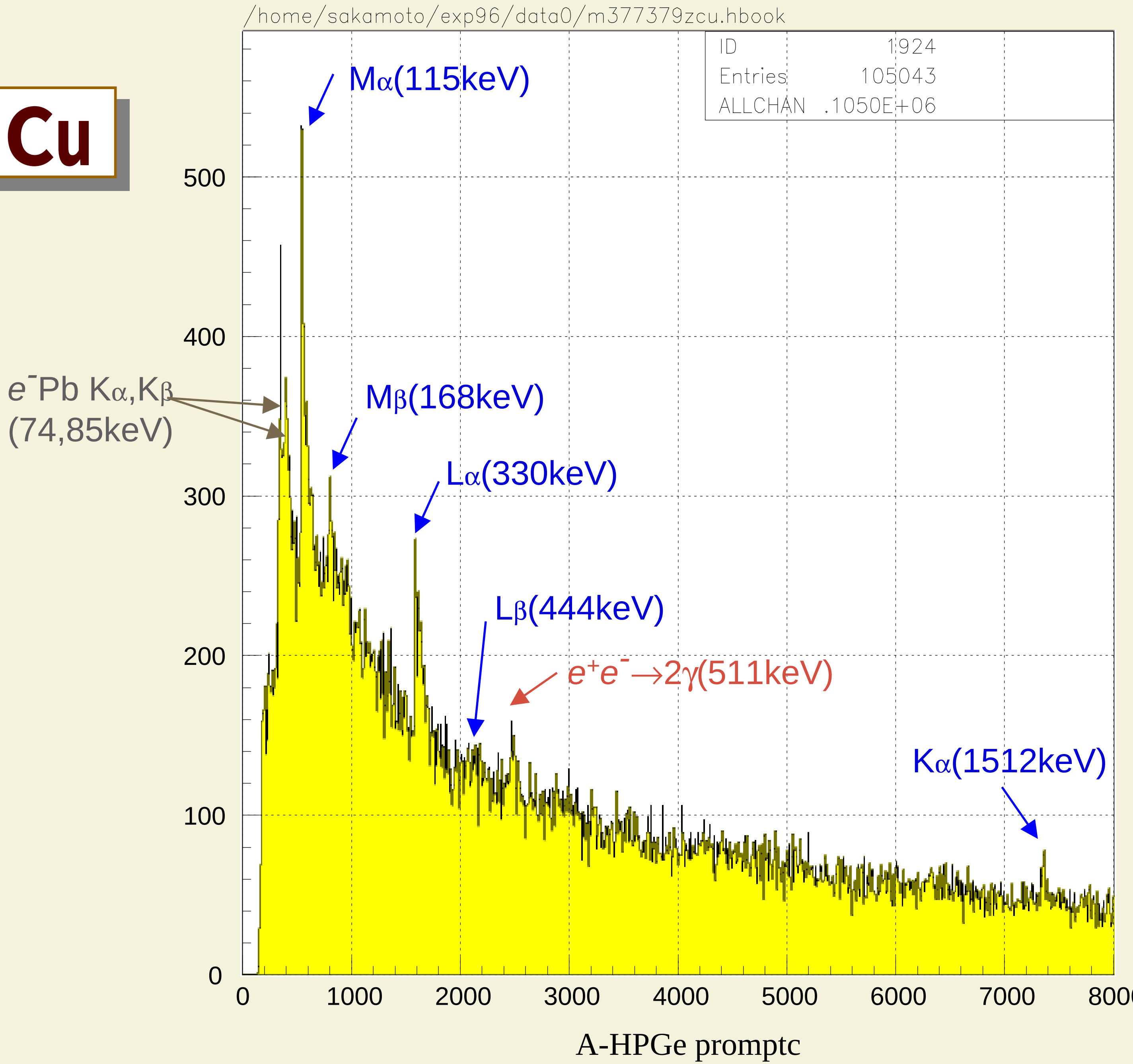
- Cadmium Zinc Telluride semi-conductor detector
- low energy X-rays
- good energy resolution
- Peltier cooler (-30℃) - no liquid nitrogen
- easy to use, just turn on power switch
- small size, suitable for detector array



apparatus at KEK



Cu



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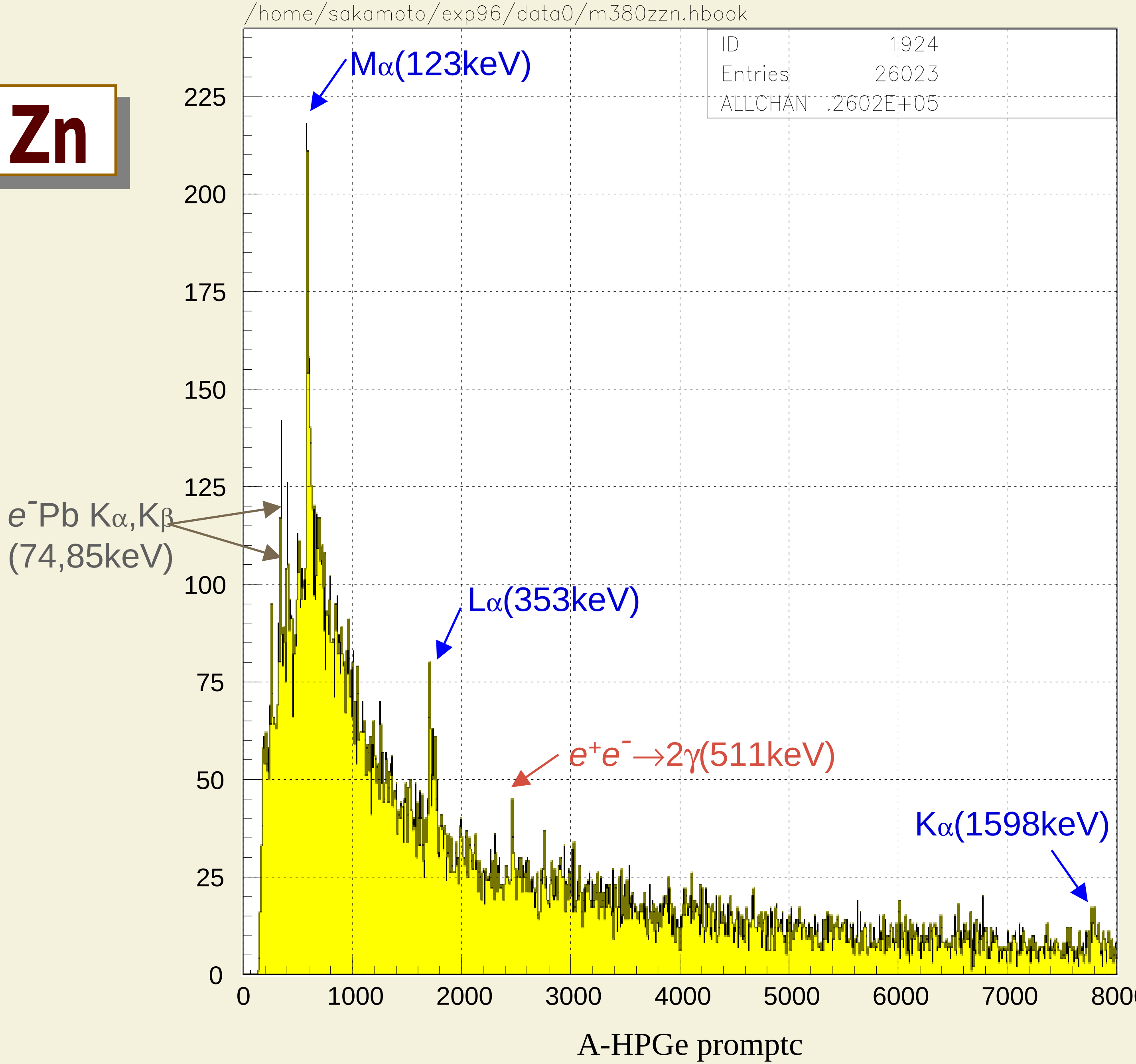
Mα(115keV)
e⁻Pb Kα,Kβ
(74,85keV)
Mβ(168keV)
Lα(330keV)
Lβ(444keV)
e⁺e⁻→2γ(511keV)
Kα(1512keV)
0
100
200
300
400
500
0
1000
2000
3000
4000
5000
6000
7000
8000
A-HPGe promptc

Zn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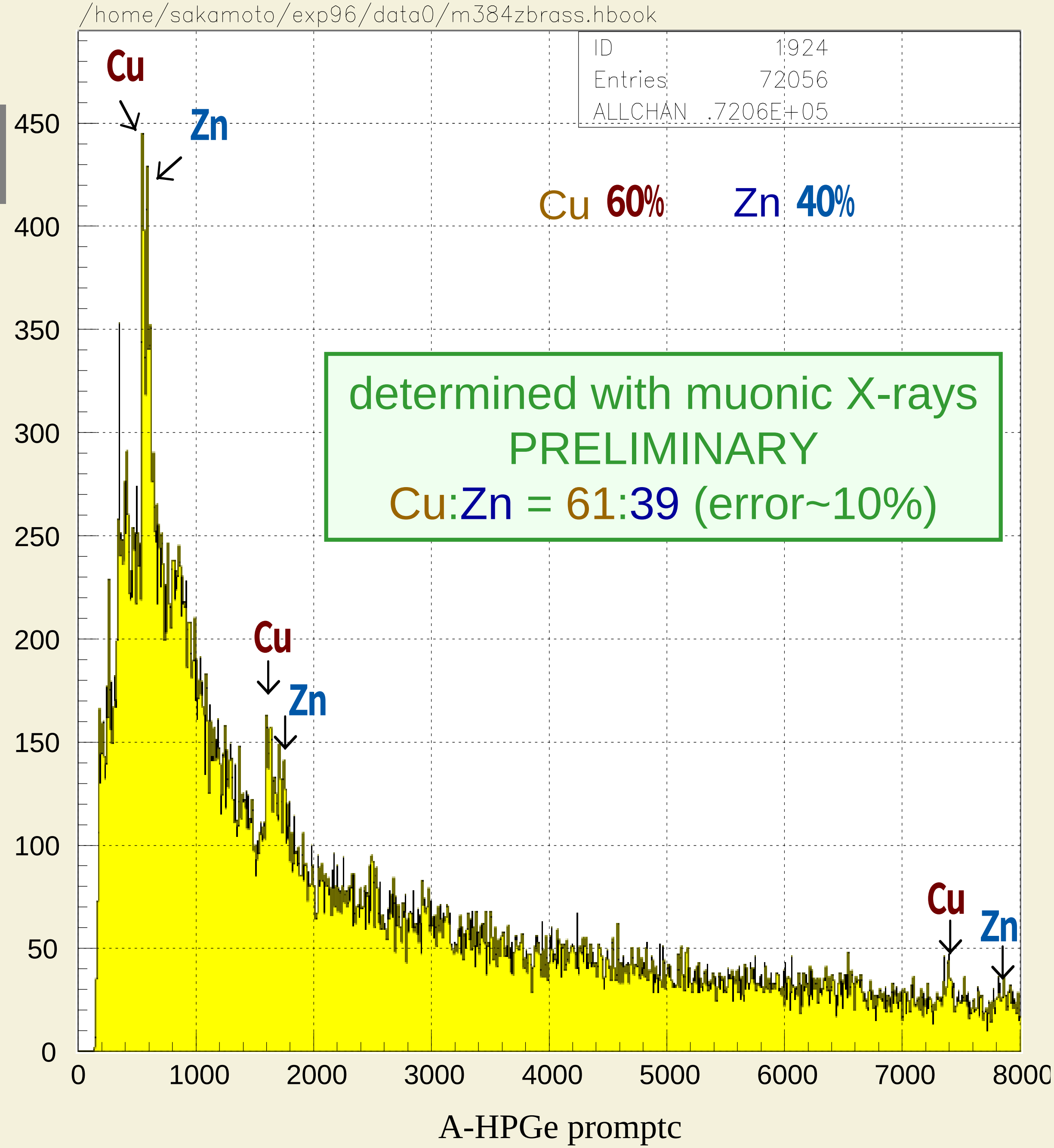
ALLCHAN .2602E+05
Mα(123keV)
Lα(353keV)
e+e-→2γ(511keV)
Kα(1598keV)
e-Pb Kα,Kβ
(74,85keV)
0
25
50
75
100
125
150
175
200
225
0
1000
2000
3000
4000
5000
6000
7000
8000
A-HPGe promptc

brass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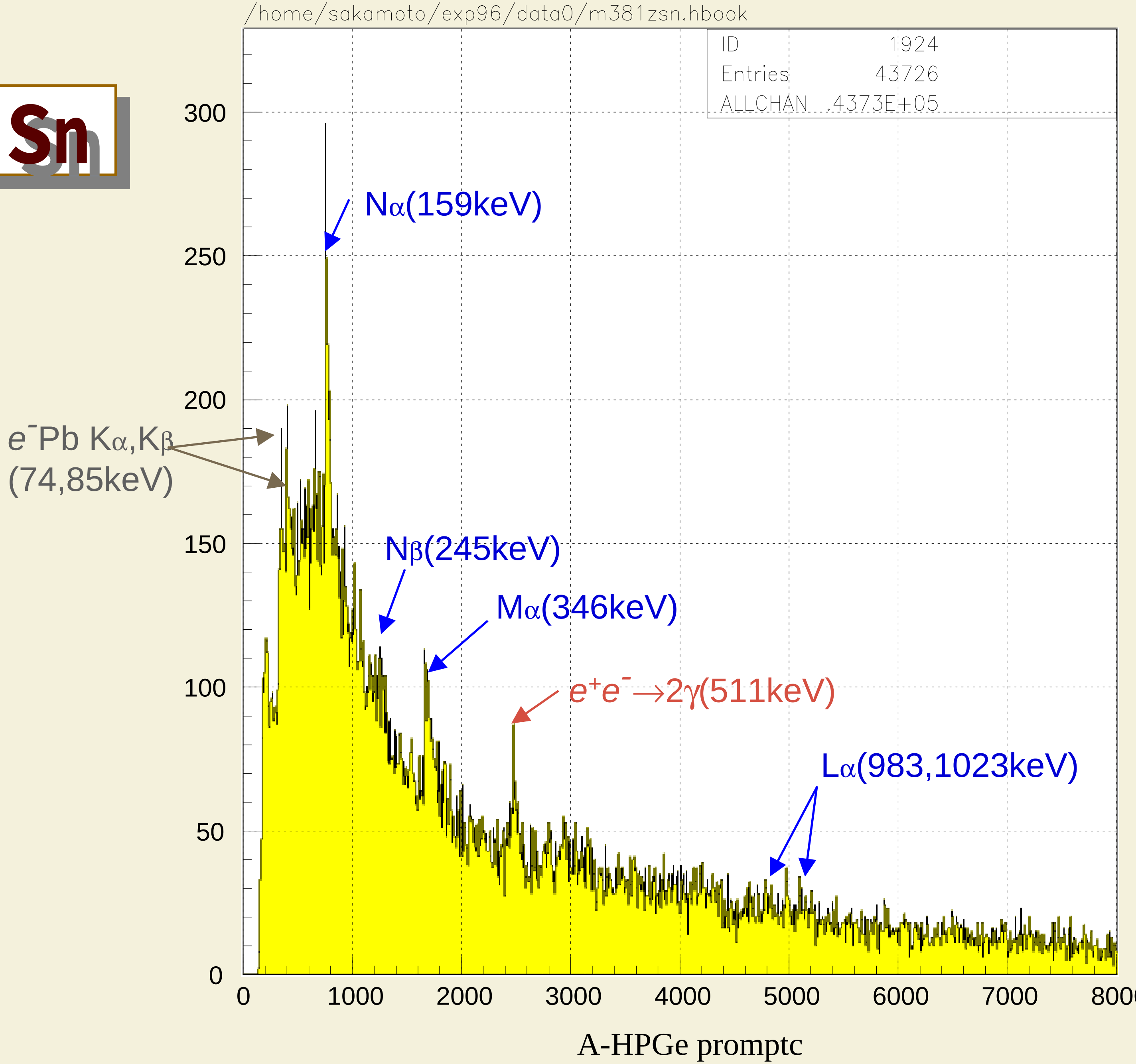
ID 1924
Entries 72056
ALLCHAN .7206E+05
Cu 60% Zn 40%
determined with muonic X-rays
PRELIMINARY
Cu:Zn = 61:39 (error~10%)
Cu
Zn
Cu
Zn
Cu
Zn
0
50
100
150
200
250
300
350
400
450
0
1000
2000
3000
4000
5000
6000
7000
8000
A-HPGe promptc

星雲鏡 Xing-yun Mirror
(star-cloud mirror)

Western Han bronze mirror in China (produced B.C.100-50)
(Cu:Sn=74:20 with chemical analysis)

Sn



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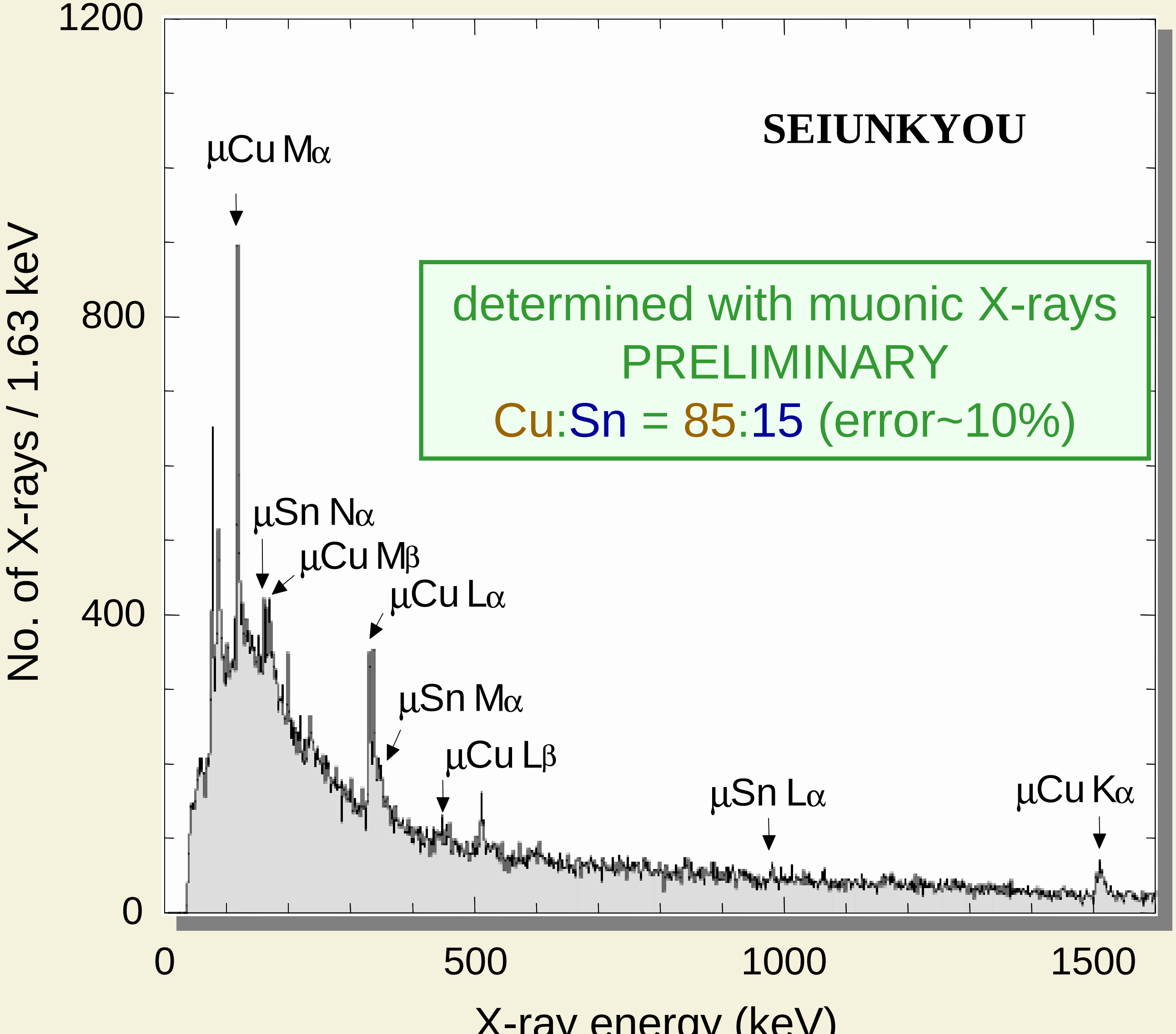
ALLCHAN .4373E+05
Nα(159keV)
e⁻Pb Kα,Kβ
(74,85keV)
Nβ(245keV)
Mα(346keV)
e⁺e⁻→2γ(511keV)
Lα(983,1023keV)
0
50
100
150
200
250
300
0
1000
2000
3000
4000
5000
6000
7000
8000
A-HPGe promptc

μ⁻ 星雲鏡


SEIUNKYOU
μCu Mα
μSn Nα
μCu Mβ
μCu Lα
μSn Mα
μCu Lβ
μSn Lα
μCu Kα
determined with muonic X-rays
PRELIMINARY
Cu:Sn = 85:15 (error~10%)
1200
800
400
0
0
500
1000
1500
No. of X-rays / 1.63 keV
X-ray energy (keV)

elemental analysis inside material

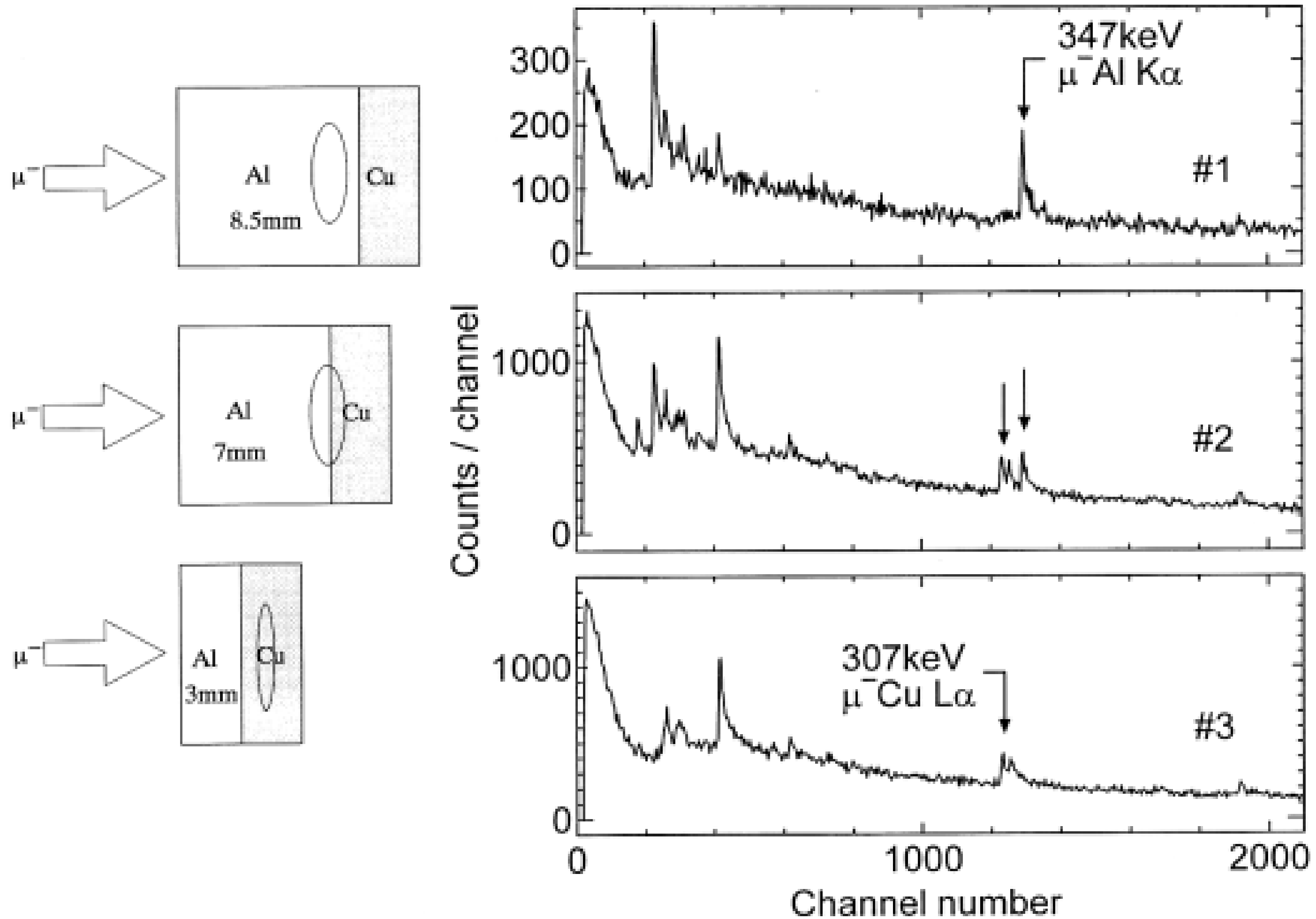
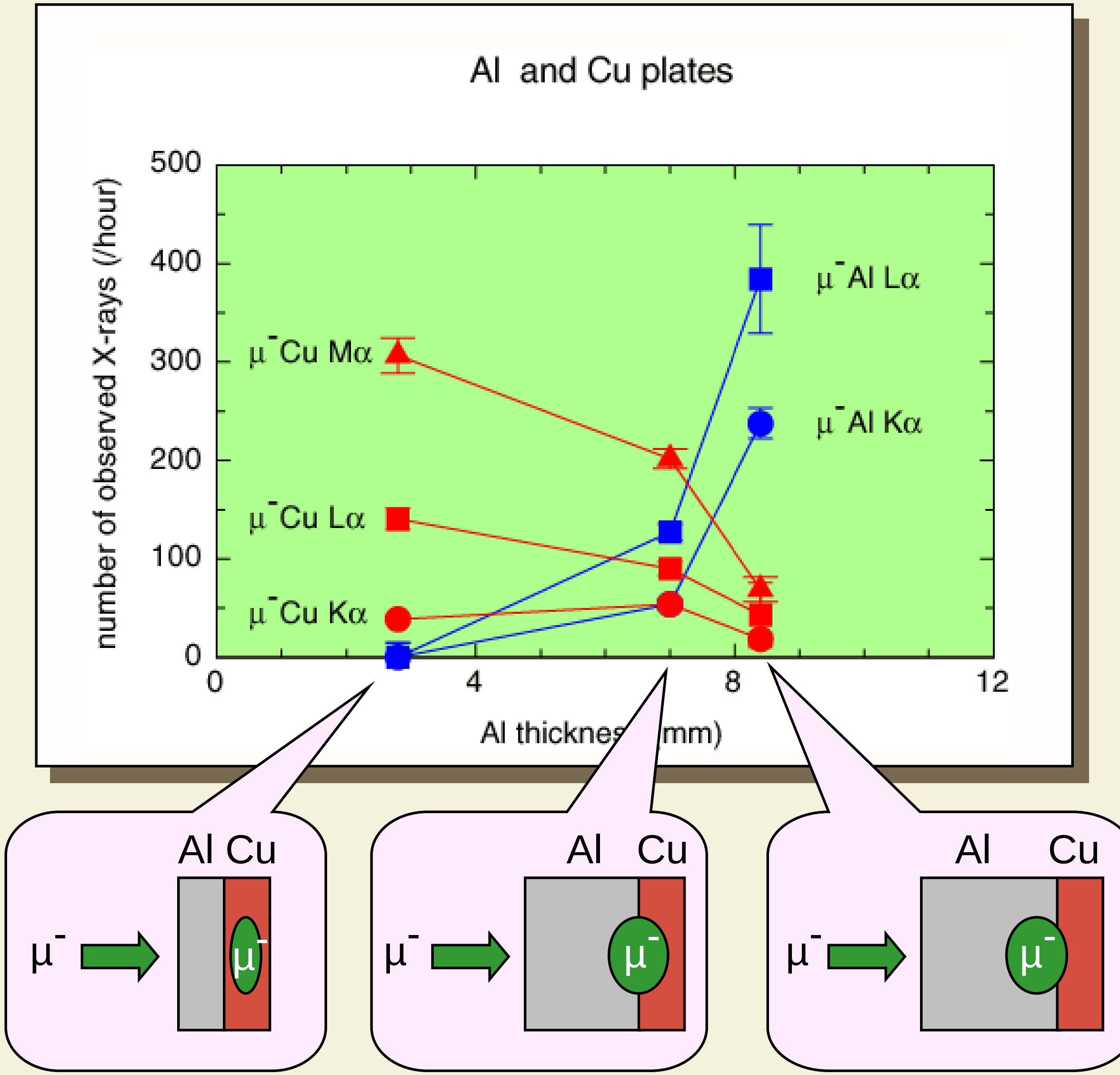


Fig. Muonic X–ray spectra of Al and Cu plate samples.
#1;Al 8.5mm+Cu3mm, #2; Al7mm+Cu3mm, #3; Al3mm + Cu3mm.
Negative muons enters from the Al side.

Al plate + Cu plate



non-destructive analysis with muonic X-rays

summary

large demands for analysis of archaeological relics, antiquities, artifacts etc.

- ☆ **simultaneous multi-element analysis**
  comprehensive and systematic analysis for any elements
- ☆ **non-destructive**
  no damage to materials
- ☆ **regioselective inside material**
  composition of specific parts inside materials

analysis with muonic X-rays is only the candidate

– feasibility study of the method has started

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