FRM II
Forschungs-Neutronenquelle
Heinz Maier-Leibnitz

MLZ
Heinz Maier-Leibnitz Zentrum

DEVELOPMENTS AT THE NUCLEAR ANALYTICAL FACILITIES AT MLZ, GARCHING

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Technical University Munich, Garching, Germany

MLZ is a cooperation between:

JÜLICH
FORSCHUNGSZENTRUM

Helmholtz-Zentrum
Geesthacht
Zentrum für Material- und Küstenforschung

TUM
Technische Universität München

Analytical techniques at MLZ

Shut down since March 2020, until ~Sep 2024, then only thermal operation

Cold neutron beam (PGAA)

- Prompt Gamma Activation Analysis (PGAA)
  - In-beam activation analysis
  - In-beam liquid scintillation
  - Neutron radiography-driven PGAA + PGAI
- Neutron Depth Profiling (NDP)

Thermal neutrons – irr. channel in reactor, counting lab at RCM

- Neutron Activation Analysis (NAA)

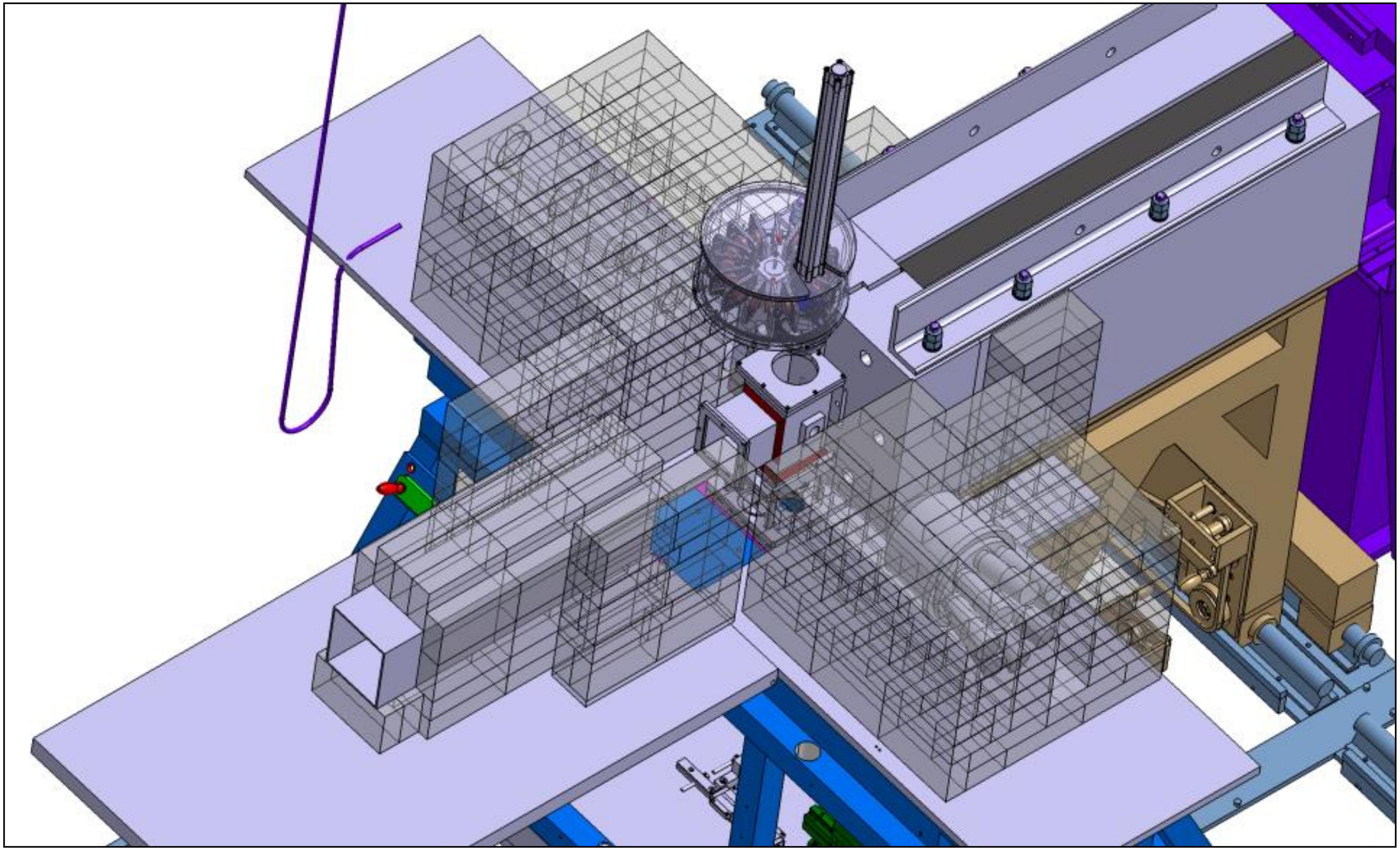
Fast neutron beam (MedApp and Nectar)

- Fast Neutron induced Gamma Spectrometry (FaNGaS)
  - Eric Mauerhofer, Niklas Ophoven (Jülich Center for Neutron Research)
- GRAINS at Nectar (with Adrian Losko)

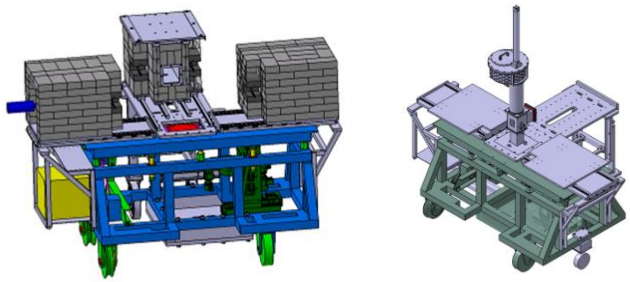
PGAA and in-beam NAA

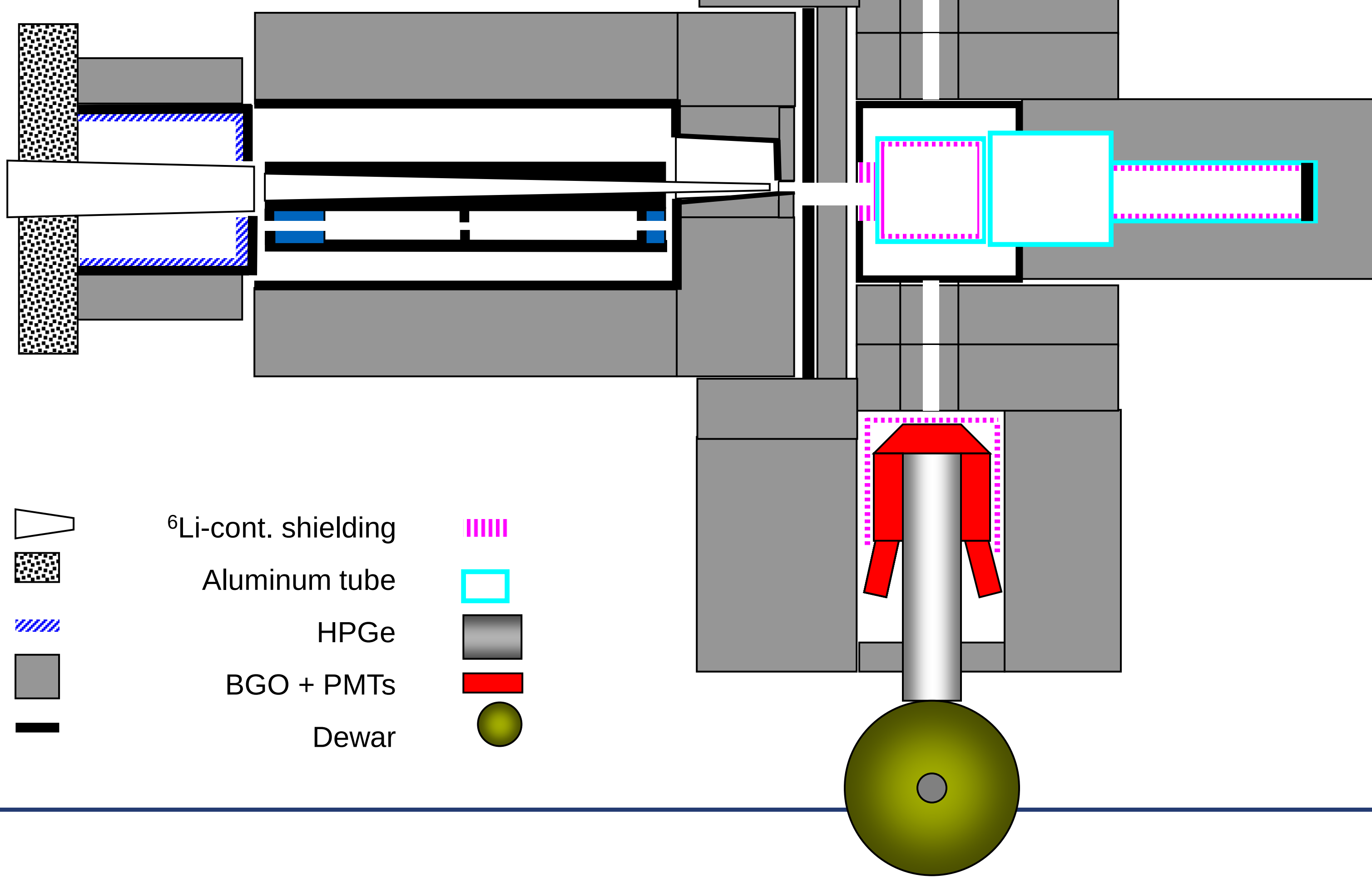
PGAA facility at the neutron guide hall

The PGAA facility



Shielding arrangement at PGAA



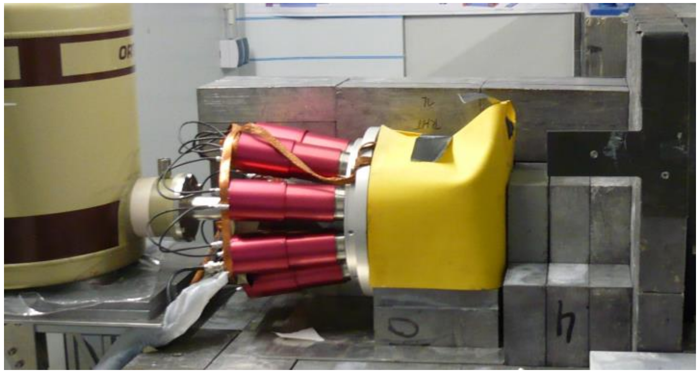


Neutron guide
Concrete
Steel
Lead
Boron-cont. shielding

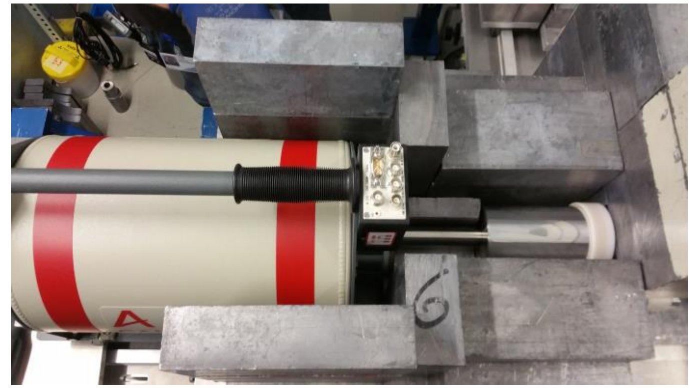
^{6}Li-cont. shielding
Aluminum tube
HPGe
BGO + PMTs
Dewar

Detectors

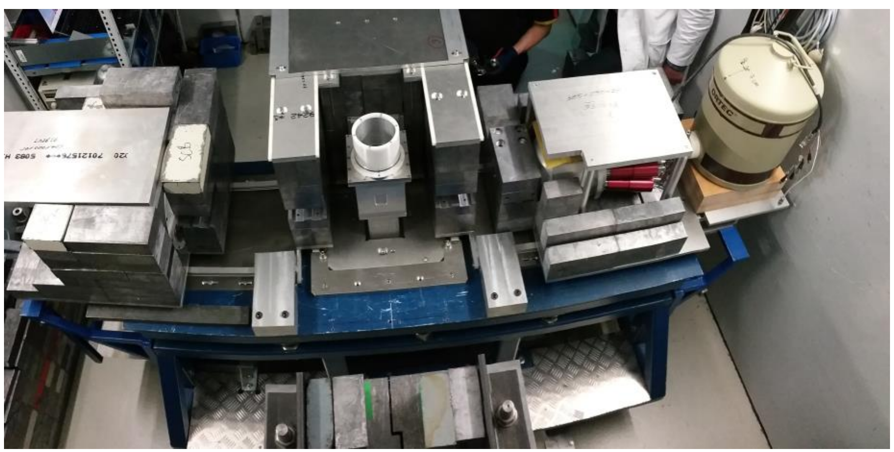
- HPGe detectors in BGO
  - 60% PopTop +Lithoflex

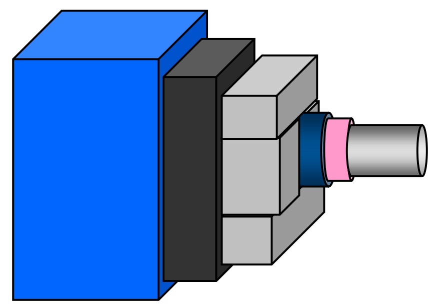


LEGe

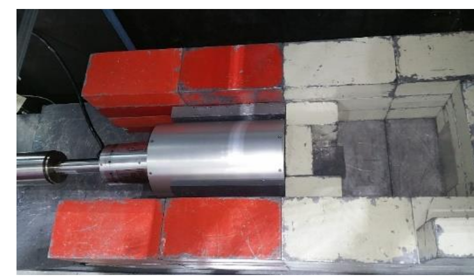


  - PGAA facility and the low-background counting station



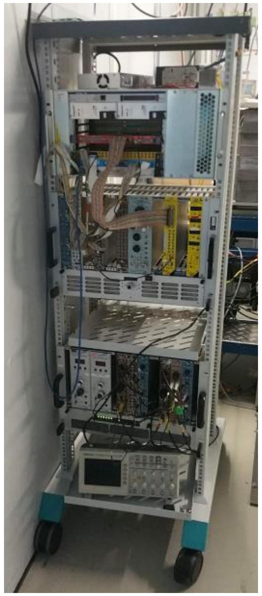


- ^{6}Li-containing plastic (2.5 mm)
- Sn sheets (4 mm) – instead of Cd
- 10 cm of lead
- 5mm boron rubber (40% B_4C)
- 5cm boron plastic (20% H_3BO_3)
- **BGO annulus (Anti-Compton)**



Status 2023

electronics



PGAA

low-bkg counting station

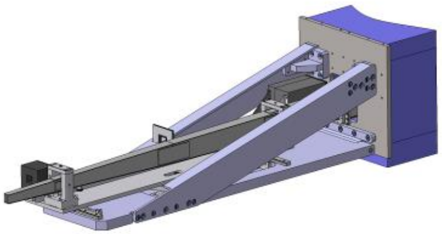
64k spectrometers, cooling without LN2 filling

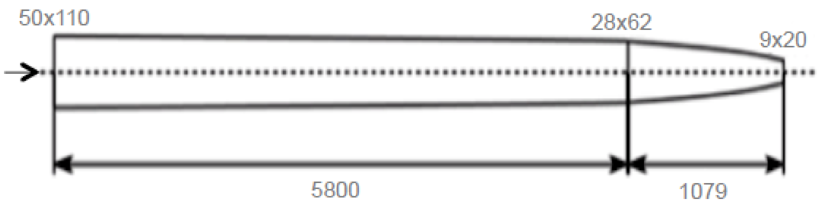
New Focusing Guide Extension

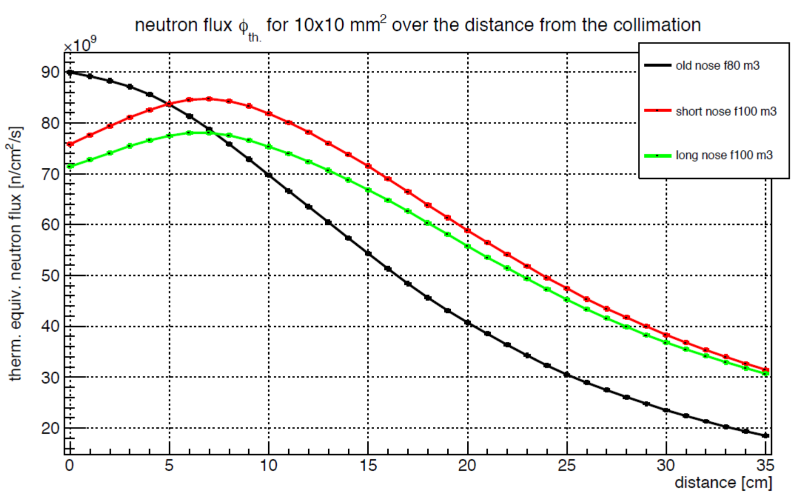
More homogeneous

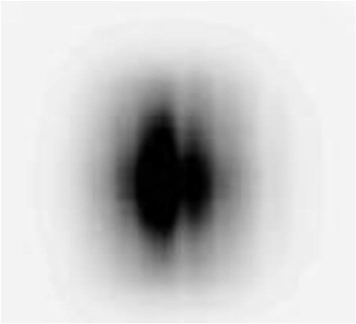
High flux at every setup

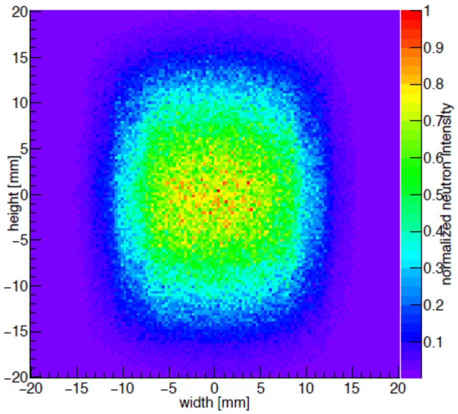
at sample:4×10^{10} cm^{-2} s^{-1}

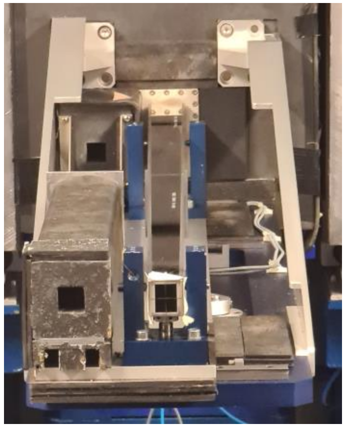








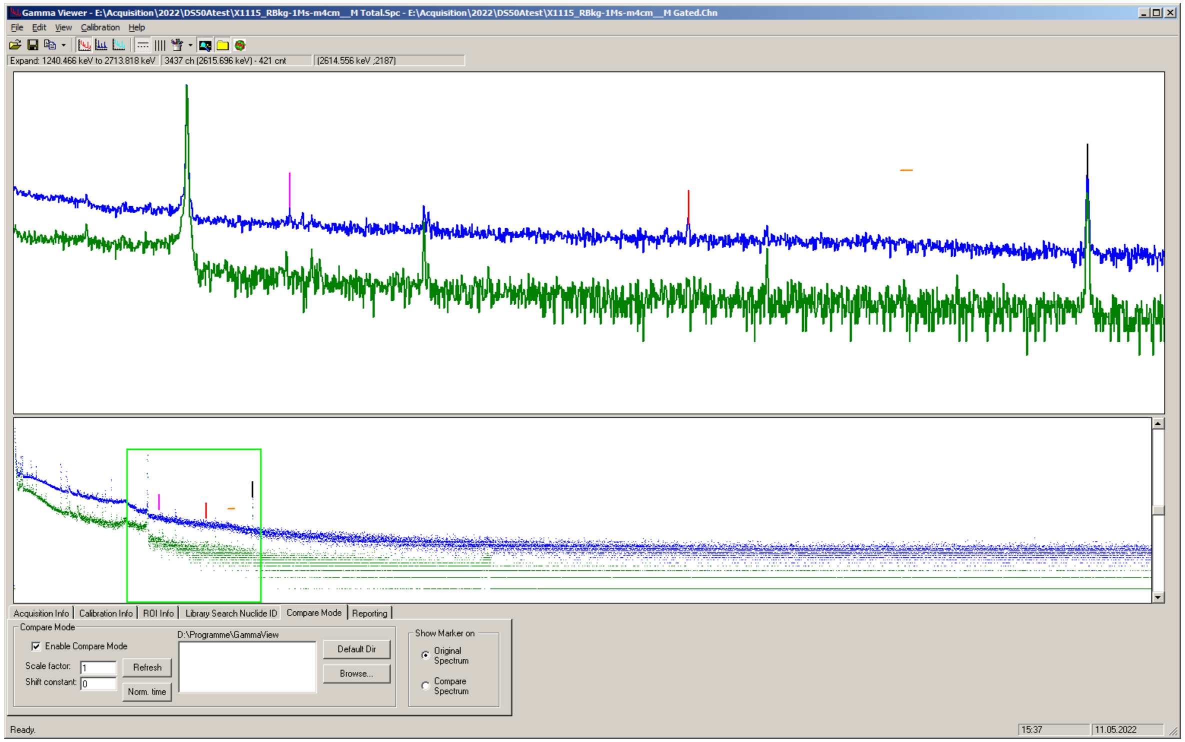


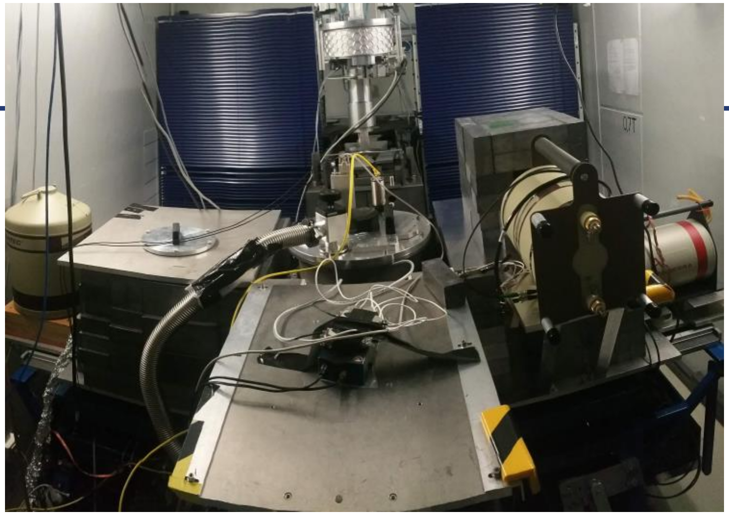


64k spectrometers

- Better resolution
- Better peak shapes for narrow peaks
- Simultaneous acquisition of Compton-suppressed and –unsuppressed spectra

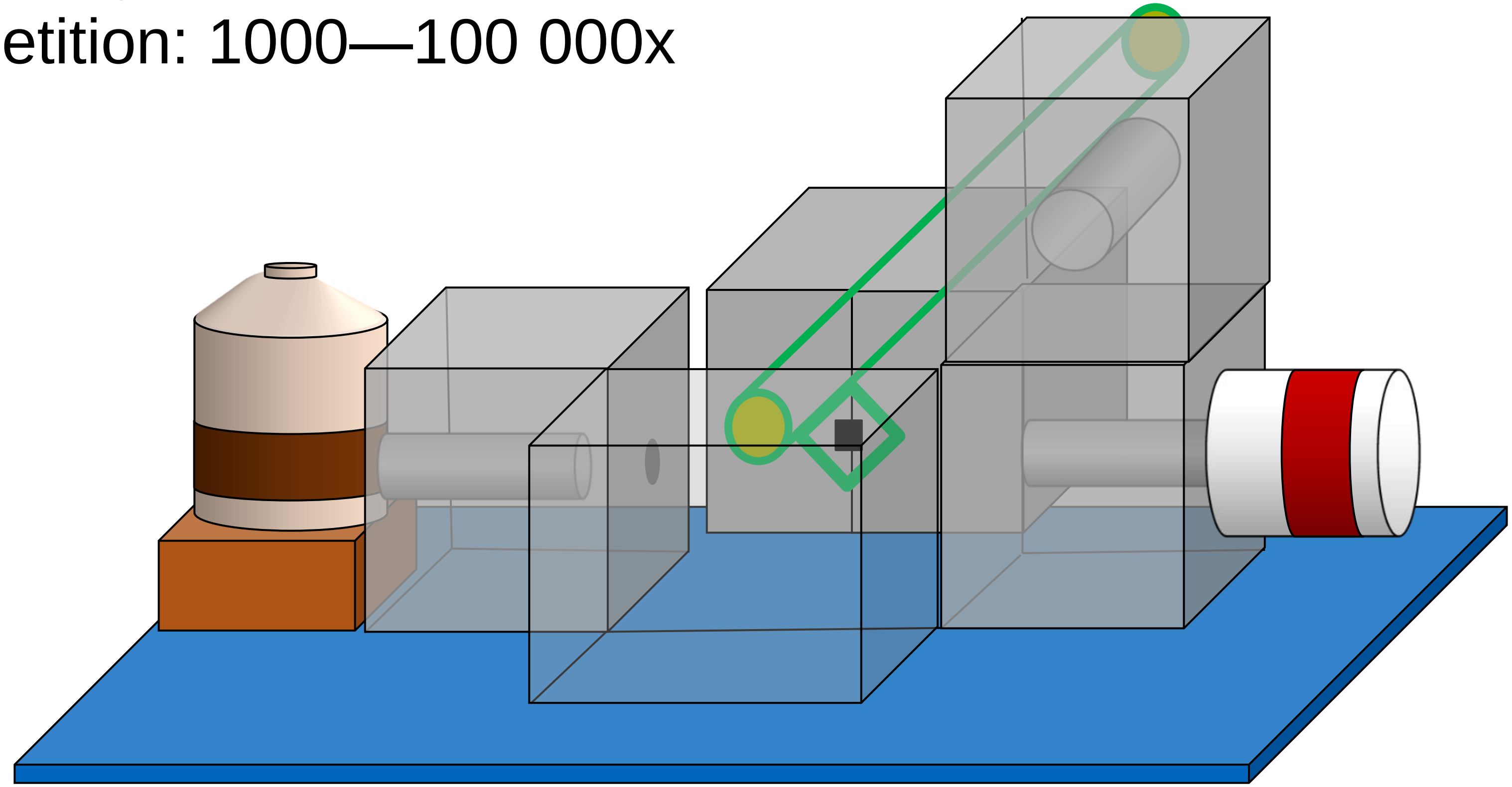
- List mode
  - Complete time dynamics



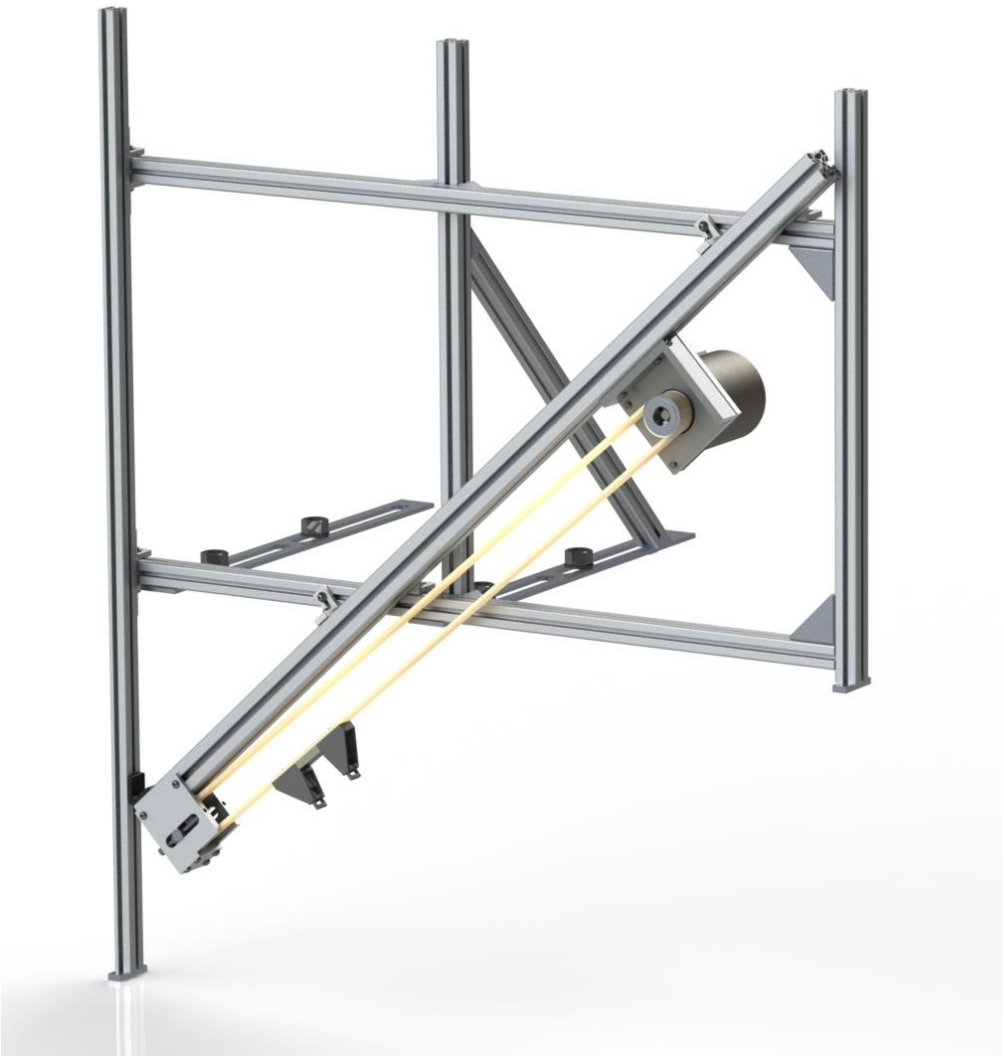


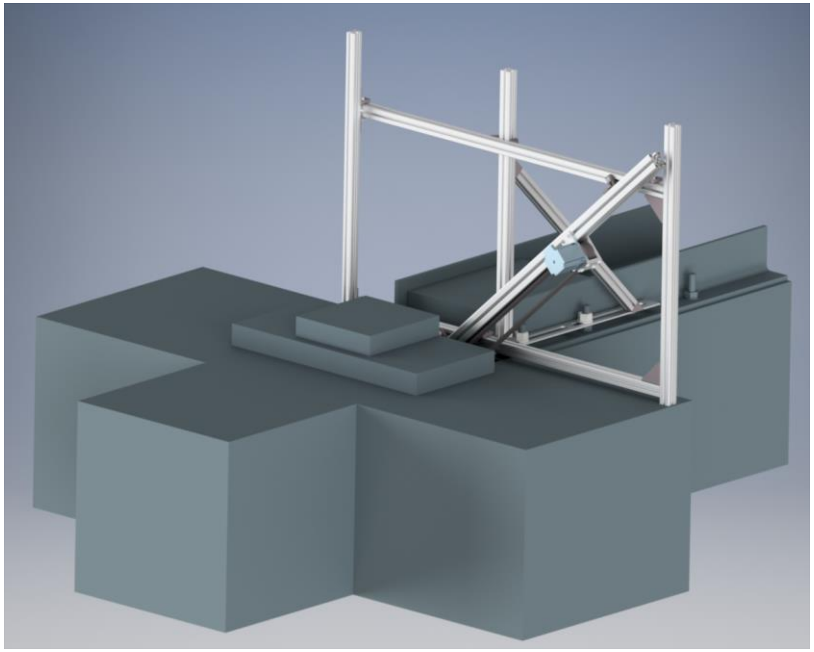
Fast-cyclic NAA

Transfer time: ~0.2s
Irradiation: 1—10s
Counting: 1—10s
Repetition: 1000—100 000x

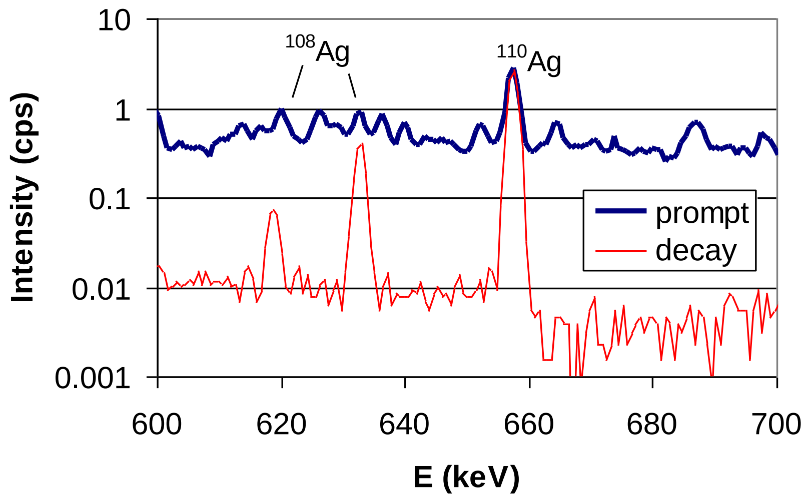


Cyclic activation for short-lived nuclides (offline)

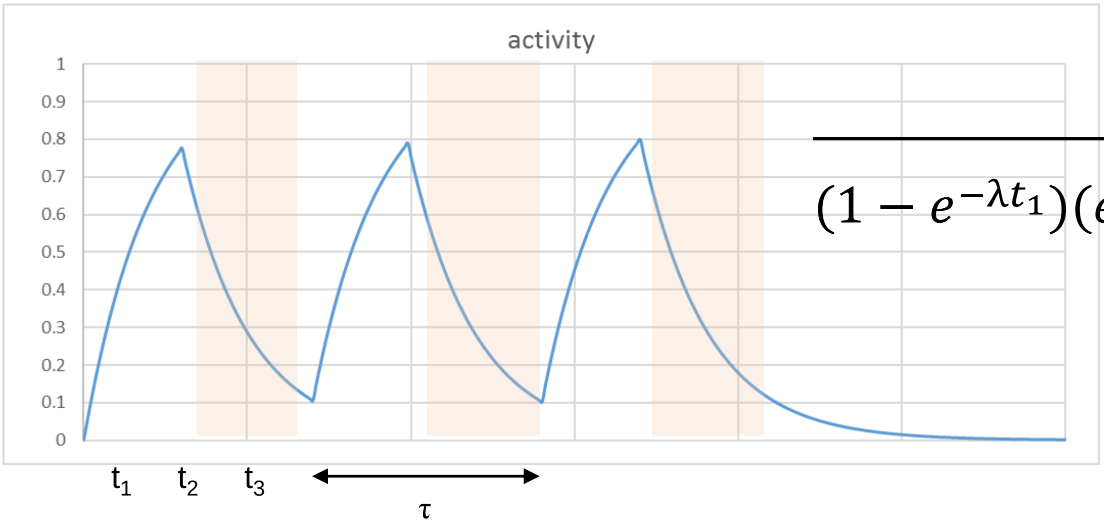




Prompt and decay γ spectra of Ag



In decay spectra baseline is much lower, ~1 OoM better DL ~3--4 OoM is possible in a separate counting position

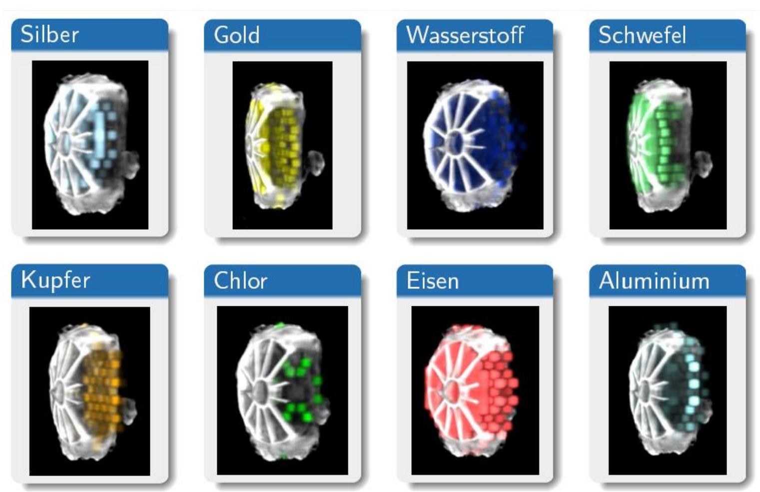


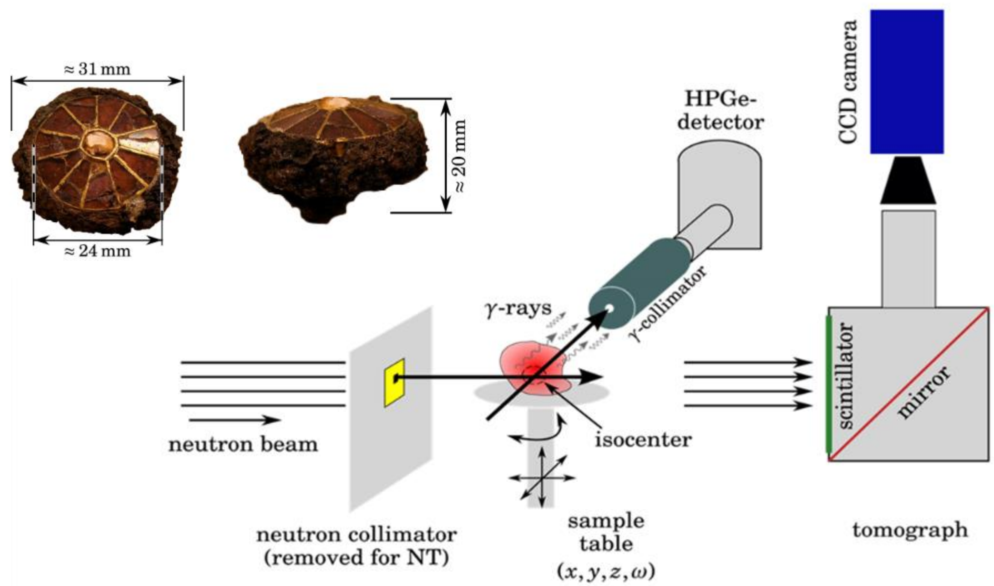
$$\frac{A}{(1-e^{-\lambda t_1})(e^{-\lambda t_2})\frac{1-e^{-\lambda t_1}}{\lambda t_3}\,{\color{red}(1-e^{-\lambda\tau})}}$$

MORIS: upgrade of Prompt Gamma Activation Imaging (PGAI)

Feasibility shown (ANCIENT CHARM project, FRM2-Budapest collaboration)

- Collimate neutron beam and gamma detection.
- Acquire prompt gamma spectra of single voxels (in isocenter), non-destructive analysis.
- Test: 3D elemental map, too long
- Only selected spots

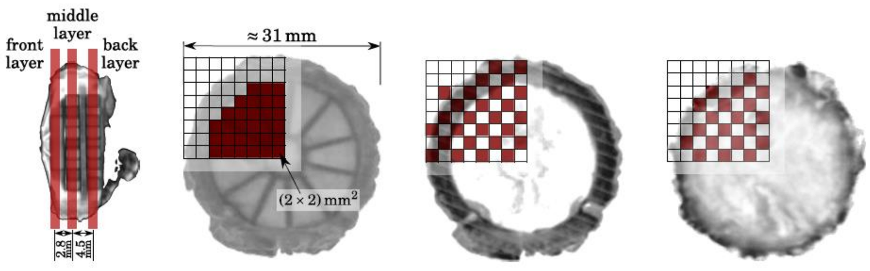




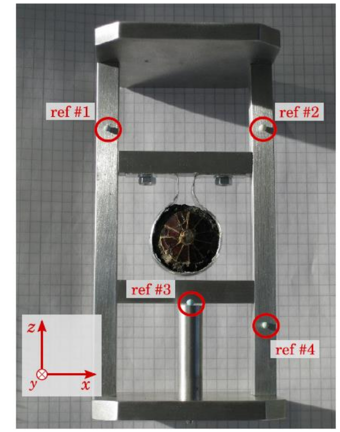
Belgya, T. *et al. J Radioanal Nucl Chem* **278**, 713–718 (2008).
R. Schulze PhD Thesis 2010 Köln
Kluge, E., *et al.* NIM A**932**, 1-15 (2019)

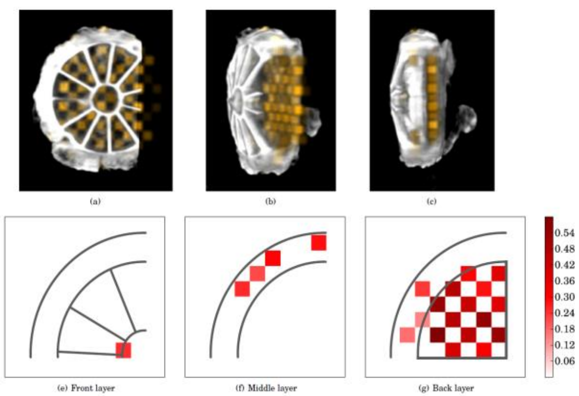
2009: inside an object at many spots

Fibula from Frankish Kingdom (8th century) found in Hungary, fragile, unknown production, unknown composition

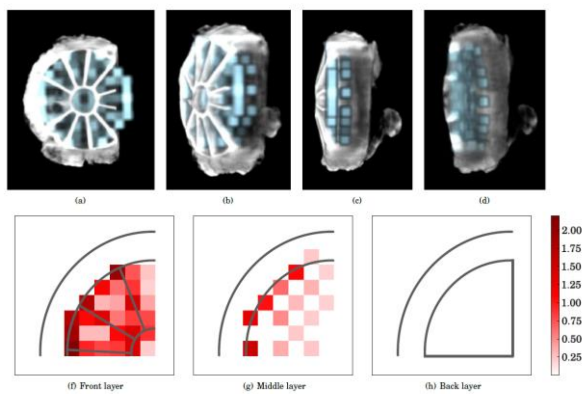


(a) Layers (b) Positions in front layer (c) Positions in middle layer (d) Positions in back layer

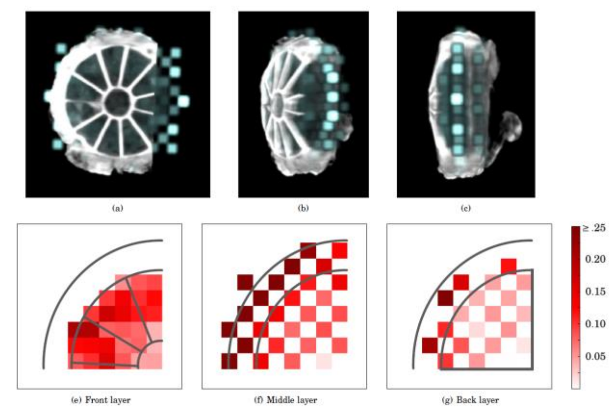




Cu



Ag

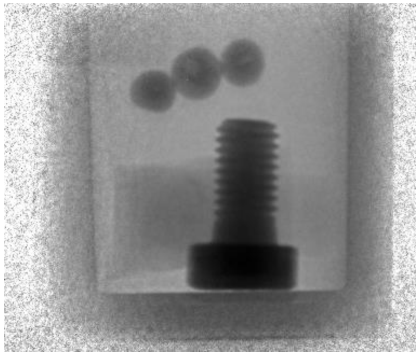


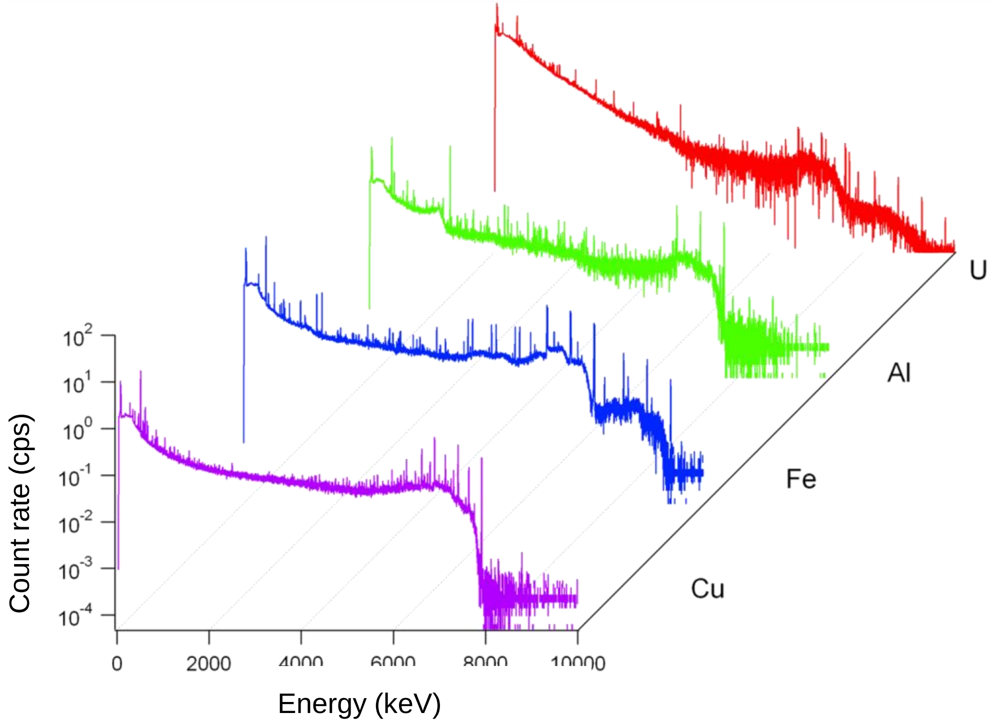
Al (glasslike almandine cover)

3D elemental map: 3hours/voxel, 77 (30+27+20) voxels, 2 × 2 × 2 mm³, 10 days in FRM2

Applications of PGAI-NR

Test samples (U, Fe, Cu, Al) in closed lead container
Analysis of a few interesting spots





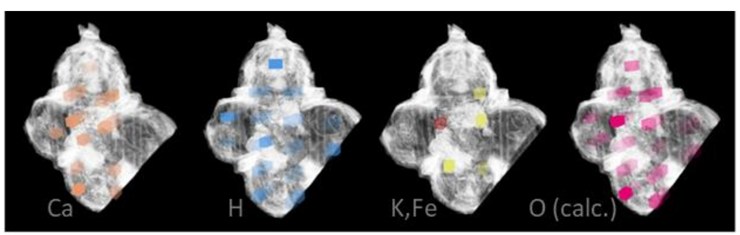
- Radiography to find spots of interest inside sensitive complex objects nondestructively.
- Then gamma counting

2018-19: PGAI experiment at MLZ

Guided copper reliquiary pendant (phylacterion), rare piece from Mainz, 12th century
Inside rich in Ca, probably bone
PGAI-NT, attenuation is also used for identifying phases
16 voxel, 3 hours/voxel, voxel ~ 2 × 2 × 3mm^3 (too large)

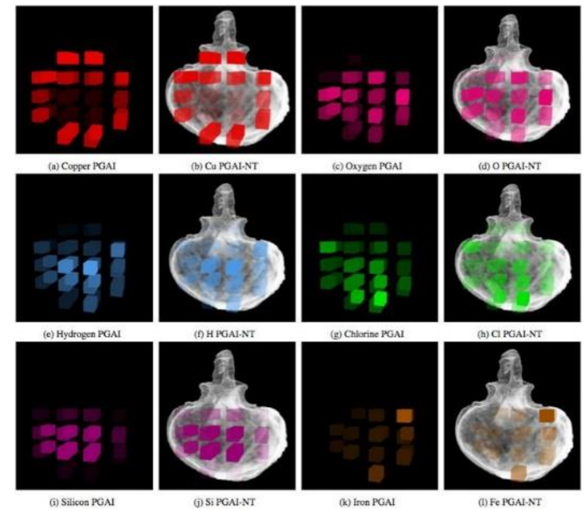
photo:
S. Steidl, RGZM

NT: B. Schillinger, Antares
PGAI: E. Kluge, Köln

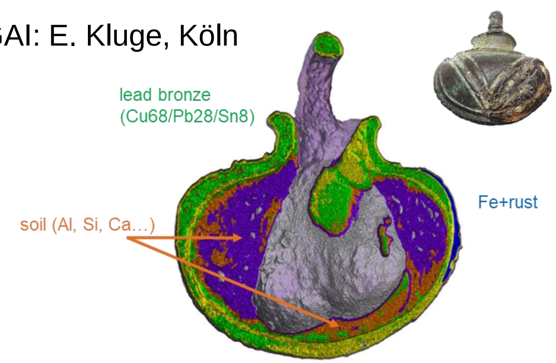


Heinzel, M., Schillinger, B., Kemper, D., Stieghorst, C., & Kluge, E. (**2022**). Discovery of a 12th-Century Enamelled Reliquary Pendant: Elemental Analysis and Content Visualisation Using Prompt Gamma Neutron Activation Analysis and Neutron Tomography. In *INTERIM MEETING OF THE ICOM-CC METALS WORKING GROUP*

Roman amulet
16 pixel, 3 hours/pixel
voxel ~ 2 × 2 × 3mm^3

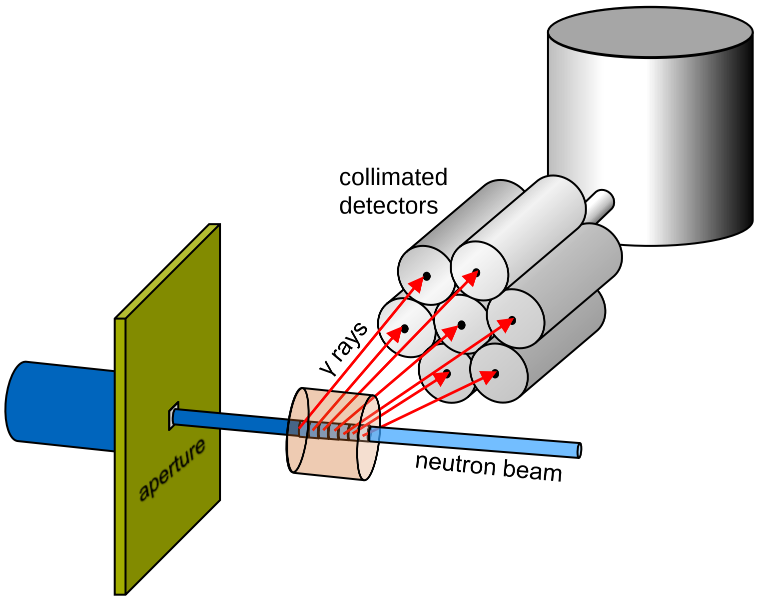


NT, PGAI: E. Kluge, Köln

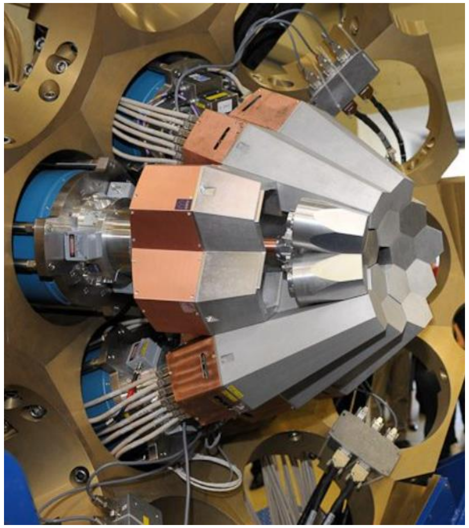


Detector upgrade for PGAI

Analysis of several voxels at the same time
Detector cluster with a multichannel spectrometer



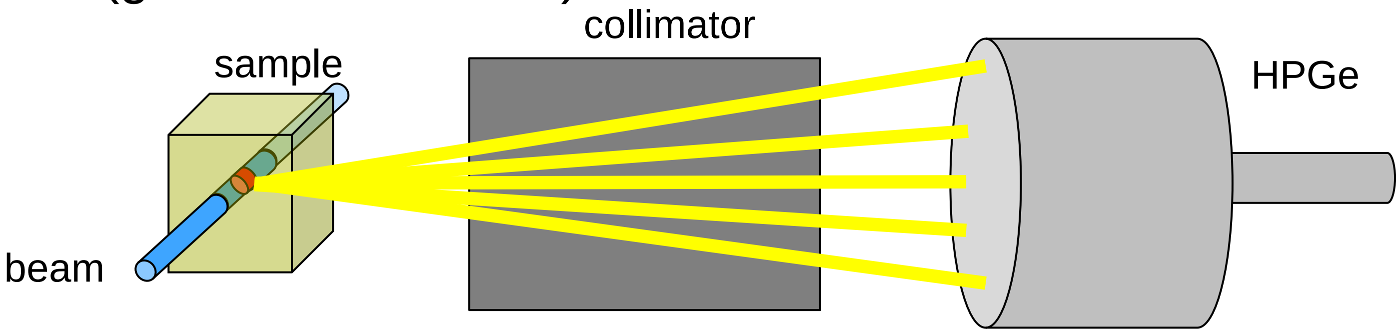
Detector cluster (7 – 15 detectors)
7—15 spots in parallel



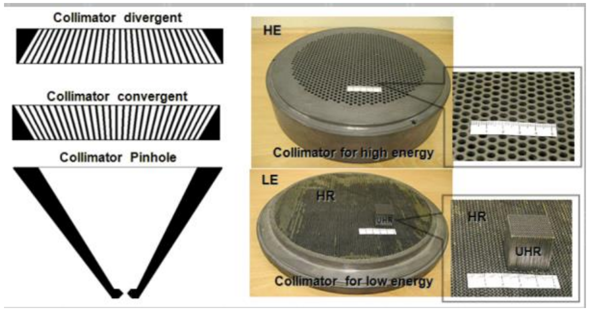
Like Advanced Gamma Tracking Array (AGATA)

Improved collimators

- One detector – one voxel
- Multi-channel collimators to increase detection efficiency (goal: 10-20x faster)



Ideas from nuclear medicine
We need thicker blocks
Simulations/calculations
Manufacturing

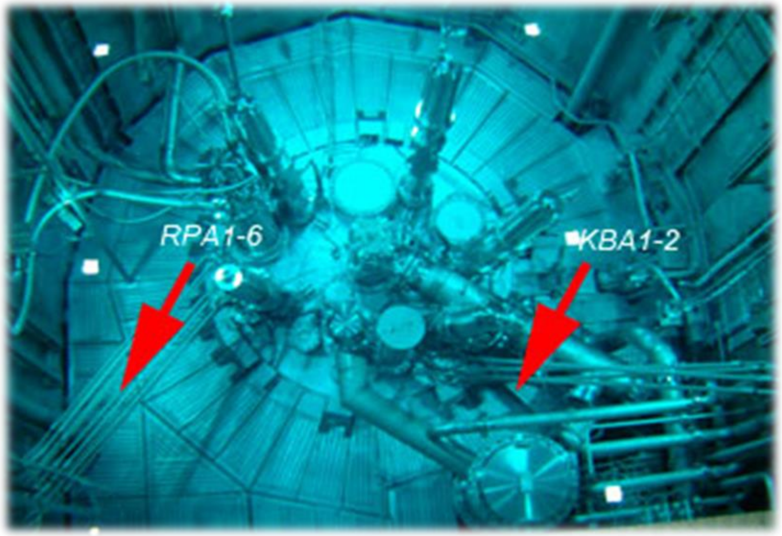


Speeding up the measurement with 2 OoM

NAA
Neutron Activation Analysis
collaboration with Radiochemie München

NAA instrument

- The unique possibilities of FRM2 reactor have not been exploited until now.
  - Highly thermalized
  - High flux

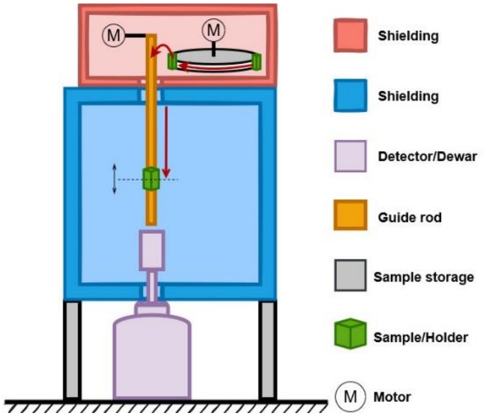


Recent developments

- NAA is now an instrument
- 3 HPGe detectors with digital spectrometers (Lynx, Canberra)
- Evaluation: Hyperlab + k0-SolCoi

- Too much manual work
- During working hours only
- High demand → 40 ↔ 168 hours/week

Planned developments at NAA



- **Main task for NAA instrumentation:**

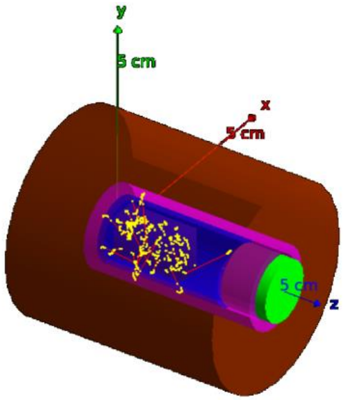
  increase sample throughput.

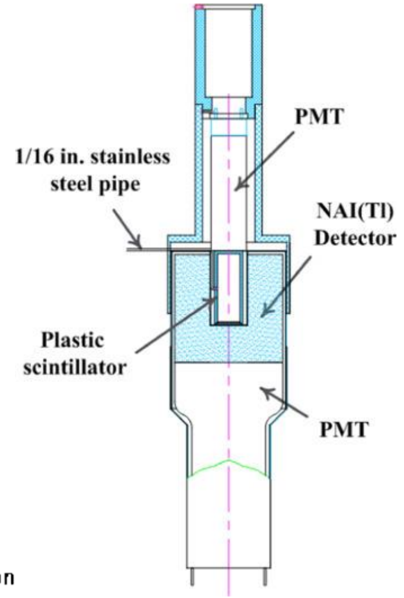
  - Automation of counting
    - enabling measurements 24/7 with automatic
    - SMART-controlled sample changers (automatically measurement optimizing conditions)
  - Shorten transfer time between reactor and lab
    - Rabbit system to RCM
  - Improve the evaluation procedure (ErUM-Data proposal).
  - Following the time dynamics with list mode acquisition
  - Automation of the spectrum evaluation and the analysis

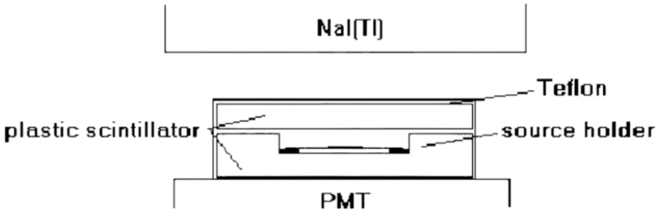
β-γ correlation NAA

MORIS upgrade plans

- In radioactive decay, a β particle is emitted, often followed by γ radiation.
  - Famous pure β emitters: ^{32}P, ^{35}S, ^{209}Pb, ...
  - Isomers (pure γ emitters): e.g. Hg, ^{207}Pb
  - (Neutrino remains undetectable)
  - β spectrum is not characteristic
- One can use β-γ coincidence/anticoincide
  - The pure emitters
  - Low-activity decay products
  - β detection ~100%, γ should be high too
- Several geometries depending on the emphasis
  - 4πβ-γ
  - 4πβ + ~4πγ
  - γ-γ concidence
- List-mode acquisition
- Dynamic on-the-fly evaluation







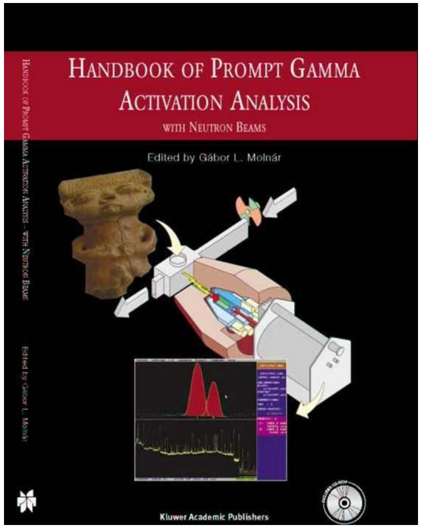
The PGAA database project

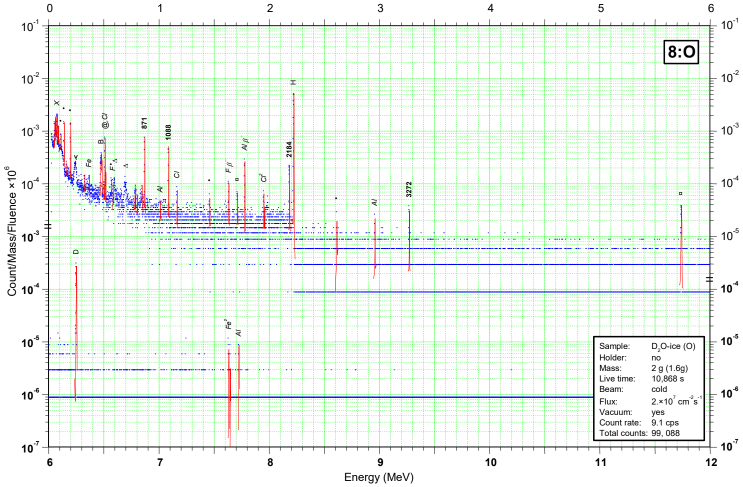
Budapest
1997–1998 establishment of PGAA data library in thermal beam
2001—2004 measurements in cold beam
2006 – partial revision of data (NIST, Budapest, Garching)

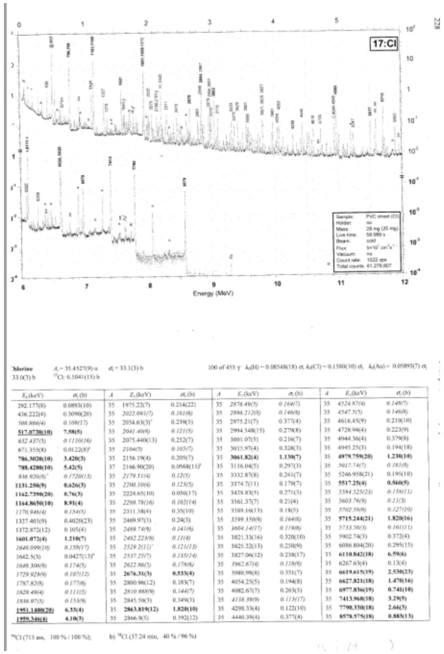
2012 – 2020, new measurements for the library

2021, 2022 library updates

2023 new standardization measurements in Budapest







Data library 2021—2022

lib20220315.xlsm - Excel

I43 | 2

	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O
1	Z	El	MW	E	dE	A	sigma	stat u%	tot u%	RelInt	RelArea	No.	decay	T1/2 (unc)	7/22/2020
2	1	H	1.008	2223.259	0.019	1	0.3326	0.20	0.20	100.00	100.00	1	P2002		standard
3	2	D	2.014	6250.243	0.003	2	0.000515	3.00	3.00	100.00	100.00	1			updated 2022.03
4	3	Li	6.941	477.586	0.05	6	0.00129	2.60	2.60	3.30	7.00	4			updated 2022.03
5	3	Li	6.941	980.559	0.046	7	0.00422	2.70	2.70	10.84	16.30	2			updated 2022.03
6	3	Li	6.941	1051.817	0.048	7	0.00426	2.00	2.00	10.95	15.90	3			updated 2022.03
7	3	Li	6.941	2032.31	0.07	7	0.0389	2.10	2.10	100.00	100.00	1			updated 2022.03
8	3	Li	6.941	6769.633	0.263	6	0.00124	2.30	2.30	3.20	1.10	6			updated 2022.03
9	3	Li	6.941	7246.8	0.275	6	0.00193	2.10	2.10	5.00	1.58	5			updated 2022.03
10	4	Be	9.012	853.631	0.011	9	0.00172	2.00	3.50	36.30	100.00	1			updated 2022.03
11	4	Be	9.012	2590.014	0.025	9	0.00163	2.00	3.50	34.40	84.00	3			updated 2022.03
12	4	Be	9.012	3367.484	0.035	9	0.00245	3.00	3.50	51.70	60.00	2			updated 2022.03
13	4	Be	9.012	3443.421	0.036	9	0.00103	4.00	3.50	21.70	24.00	5			updated 2022.03
14	4	Be	9.012	5956.602	0.092	9	0.00011	5.00	5.50	2.31	1.60	6			updated 2022.03
15	4	Be	9.012	6809.579	0.099	9	0.00474	2.50	3.50	100.00	59.00	4			updated 2022.03
16	5	B	10.811	477.6	5	10	712.5	0.30	0.30	100.00	100.00	1			
17	6	C	12.011	1261.708	0.057	12	0.00117	1.00	1.00	45.10	100.00	1			updated 2022.03
18	6	C	12.011	3684.016	0.069	12	0.00116	0.80	0.80	44.70	38.00	3			updated 2022.03
19	6	C	12.011	4945.302	0.066	12	0.002594	0.60	0.60	100.00	60.00	2			updated 2022.03
20	7	N	14.007	1678.244	0.029	14	0.006254	1.50	1.50	26.34	47.15	3			
21	7	N	14.007	1681.174	0.043	14	0.001296	2.70	2.70	5.46	9.76	14			
22	7	N	14.007	1853.944	0.052	14	0.000474	4.50	4.50	2.00	3.31	19			unc updated 2022.03
23	7	N	14.007	1884.853	0.031	14	0.0145	0.50	0.50	61.07	100.00	1			
24	7	N	14.007	1988.532	0.077	14	0.000294	5.80	5.80	1.24	1.94	22			
25	7	N	14.007	1999.693	0.032	14	0.003208	1.70	1.70	13.51	21.12	11			
26	7	N	14.007	2520.446	0.039	14	0.004246	1.80	1.80	17.88	22.99	10			
27	7	N	14.007	2830.8	0.048	14	0.001331	2.60	2.60	5.61	6.47	17			
28	7	N	14.007	3013.631	0.061	14	0.000642	3.80	3.80	2.70	2.94	20			
29	7	N	14.007	3531.98	0.051	14	0.006857	1.80	1.80	28.88	26.56	9			
30	7	N	14.007	3677.802	0.05	14	0.011359	1.30	1.30	47.84	42.06	4			
31	7	N	14.007	3855.552	0.08	14	0.000606	3.80	3.80	2.55	2.13	21			
32	7	N	14.007	3884.353	0.106	14	0.000424	4.30	4.30	1.79	1.47	23			
33	7	N	14.007	4508.687	0.063	14	0.012862	1.60	1.60	54.17	37.24	6			
34	7	N	14.007	5268.984	0.072	14	0.023743	1.50	1.50	100.00	55.69	2			
35	7	N	14.007	5297.662	0.153	14	0.016728	1.60	1.60	70.46	38.94	5			
36	7	N	14.007	5533.251	0.076	14	0.015677	1.60	1.60	66.03	34.28	7			
37	7	N	14.007	5561.948	0.078	14	0.008627	1.80	1.80	36.33	18.72	12			
38	7	N	14.007	6322.301	0.088	14	0.014899	1.70	1.70	62.75	26.63	8			
39	7	N	14.007	7298.901	0.104	14	0.007716	2.10	2.10	32.50	10.93	13			
40	7	N	14.007	8310.171	0.128	14	0.003361	2.80	2.80	14.15	3.81	18			
41	7	N	14.007	9149.235	0.173	14	0.00133	4.60	4.60	5.60	1.27	24			
42	7	N	14.007	10829.1	0.208	14	0.010664	3.50	3.50	44.91	7.47	15			
43	8	O	15.999	870.682	0.034	16	1.55E-04	2.00	2.00	100.00	100.00	1			updated 2022.03
44	8	O	15.999	1087.714	0.031	16	0.00013	2.00	2.00	84.00	75.00	2			updated 2022.03
45	8	O	15.999	2184.381	0.039	16	0.00013	3.00	3.00	84.00	50.00	3			updated 2022.03

	P	Q	R	S	T	U	V	W	X	Y	Z	AA	A
1	FWHM	Singlet	Elements	El-1 ΔE	σγ/M	2	σγ/M	3	σγ/M	4	σγ/M	5	.
2	2.991385												
3	4.924523		GeAu	Ge 1.53	0.000266	Au 1.87	0.024446						
4	1.521455		DyTmYbB TaOs	Dy -0.48	0.079001	Tm -0.40	0.001422	Yb -0.35	0.003058	B 0.01	65.9051	Ta 0.35	0.00
5	2.055754		DyNdBa	Dy -0.57	0.042686	Nd 0.05	0.009505	Ba 0.92	2.89E-05				
6	2.120591		AgCuCe	Ag -0.45	0.002083	Cu -0.40	0.000147	Ce 0.71	7.57E-05				
7	2.867539		Co	Co 0.43	0.005928								
8	5.120997												
9	5.295077												
10	1.93489		MoErCoTmNb	Mo -0.69	0.000463	Er -0.13	0.035754	Co 0.41	0.002821	Tm 0.60	0.008352	Nb 0.78	3.2
11	3.215906		ThAlSe	Th 0.02	2.98E-05	Al 0.08	0.000299	Se 0.84	0.000371				
12	3.646428		Nb	Nb -0.22	2.35E-05								
13	3.685783		DyP	Dy 0.01	0.053197	P 0.53	4.11E-05						
14	4.809895		Ir	Ir 1.49	0.009299								
15	5.135796		AsSe	As 0.53	0.002137	Se 1.55	0.000369						
16	1.521473		TmYbLiTaOs	Tm -0.41	0.001422	Yb -0.37	0.003058	Li -0.01	0.000202	Ta 0.33	0.000486	Os 0.51	0.0
17	2.300976		ZnBaSm	Zn -0.54	0.000662	Ba -0.17	7.61E-05	Sm 0.35	0.186094				
18	3.807789												
19	4.392283												
20	2.622466												
21	2.624588		CeGd	Ce 1.05	5.1E-05	Gd 1.10	0.766319						
22	2.746814		Ba	Ba -0.73	5.39E-05								
23	2.768112		SnSc	Sn 0.39	2.23E-05	Sc 0.93	0.001991						
24	2.838384		Zr	Zr -0.39	5.56E-05								
25	2.845845		Cr	Cr 1.32	0.000377								
26	3.174539												
27	3.355151												
28	3.457137		F	F 0.98	2.14E-05								
29	3.731156		Pr	Pr 0.74	0.000214								
30	3.804688		CoPrLa	Co -0.85	0.001646	Pr 0.25	0.000283	La 1.44	0.000985				
31	3.892441												
32	3.906474		Dy	Dy 0.82	0.025652								
33	4.199168												
34	4.530137		CrSnCoSiOs	Cr -0.88	0.000877	Sn 0.05	1.68E-05	Co 0.93	0.006098	Si 1.38	6.41E-05	Os 1.85	0.00
35	4.542149		SnI	Sn 0.30	1.88E-05	I 0.89	0.000256						
36	4.63965		TlIr	Tl 0.10	0.00026	Ir 1.48	0.007234						
37	4.651387		I SnBaSb	I -1.81	0.000492	Sn -0.35	2.33E-05	Ba -0.30	2.76E-05	Sb 1.43	0.000164		
38	4.952246		Te	Te 0.41	0.000855								
39	5.313739												
40	5.663802												
41	5.93861	1											
42	6.453727	1											
43	1.951561		GdYbNBBa	Gd 0.17	2.762187	Yb 0.35	0.000415	NB 0.41	8.18E-05	Ba 0.85	9.01E-05		
44	2.152513		Lu	Lu 0.34	0.003336								
45	2.966589	1											

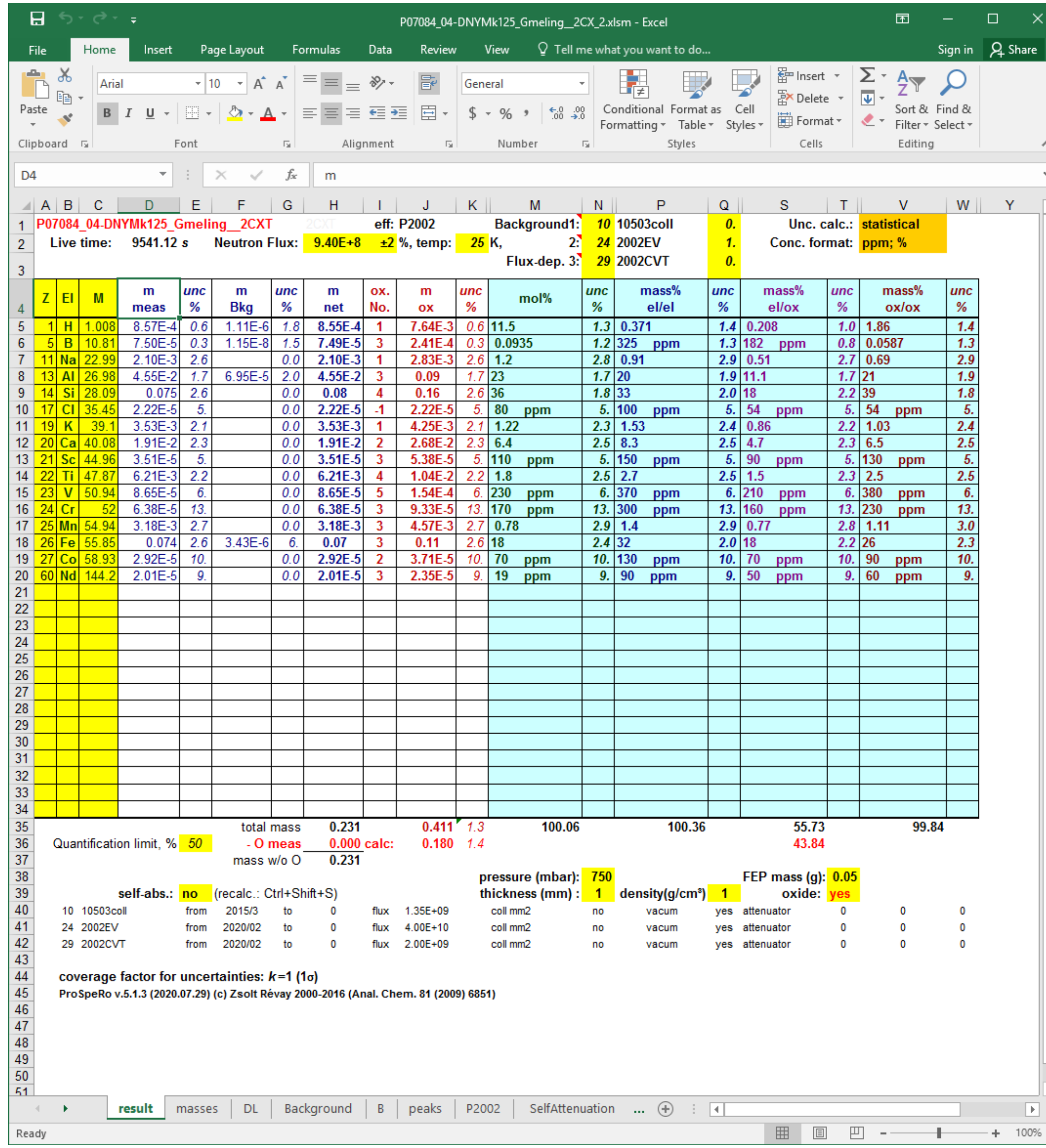
lib20200722

Ready

ProSpeRo 5

fitsmasses and energies to E and σ values of the library

O from stoichiometry
detection limits
corrects for backgrounds
N using pressure
corrects for interference with B
interference correction
unc-s may increase
self-attenuation iteratively
from Hubbel (NIST) γ-attenuation database



P07084_04-DNYMk125_Gmeling__2CXT eff: P2002 Background1: 10 10503coll 0. Unc. calc.: statistical
Live time: 9541.12 s Neutron Flux: 9.40E+8 ±2 %, temp: 25 K, 2: 24 2002EV 1. Conc. format: ppm; %
Flux-dep. 3: 29 2002CVT 0.

Z	El	M	m meas	unc %	m Bkg	unc %	m net	ox. No.	m ox	unc %	mol%	unc %	mass% el/el	unc %	mass% el/ox	unc %	mass% ox/ox	unc %
1	H	1.008	8.57E-4	0.6	1.11E-6	1.8	8.55E-4	1	7.64E-3	0.6	11.5	1.3	0.371	1.4	0.208	1.0	1.86	1.4
5	B	10.81	7.50E-5	0.3	1.15E-8	1.5	7.49E-5	3	2.41E-4	0.3	0.0935	1.2	325 ppm	1.3	182 ppm	0.8	0.0587	1.3
11	Na	22.99	2.10E-3	2.6		0.0	2.10E-3	1	2.83E-3	2.6	1.2	2.8	0.91	2.9	0.51	2.7	0.69	2.9
13	Al	26.98	4.55E-2	1.7	6.95E-5	2.0	4.55E-2	3	0.09	1.7	23	1.7	20	1.9	11.1	1.7	21	1.9
14	Si	28.09	0.075	2.6		0.0	0.08	4	0.16	2.6	36	1.8	33	2.0	18	2.2	39	1.8
17	Cl	35.45	2.22E-5	5.		0.0	2.22E-5	-1	2.22E-5	5.	80 ppm	5.	100 ppm	5.	54 ppm	5.	54 ppm	5.
19	K	39.1	3.53E-3	2.1		0.0	3.53E-3	1	4.25E-3	2.1	1.22	2.3	1.53	2.4	0.86	2.2	1.03	2.4
20	Ca	40.08	1.91E-2	2.3		0.0	1.91E-2	2	2.68E-2	2.3	6.4	2.5	8.3	2.5	4.7	2.3	6.5	2.5
21	Sc	44.96	3.51E-5	5.		0.0	3.51E-5	3	5.38E-5	5.	110 ppm	5.	150 ppm	5.	90 ppm	5.	130 ppm	5.
22	Ti	47.87	6.21E-3	2.2		0.0	6.21E-3	4	1.04E-2	2.2	1.8	2.5	2.7	2.5	1.5	2.3	2.5	2.5
23	V	50.94	8.65E-5	6.		0.0	8.65E-5	5	1.54E-4	6.	230 ppm	6.	370 ppm	6.	210 ppm	6.	380 ppm	6.
24	Cr	52	6.38E-5	13.		0.0	6.38E-5	3	9.33E-5	13.	170 ppm	13.	300 ppm	13.	160 ppm	13.	230 ppm	13.
25	Mn	54.94	3.18E-3	2.7		0.0	3.18E-3	3	4.57E-3	2.7	0.78	2.9	1.4	2.9	0.77	2.8	1.11	3.0
26	Fe	55.85	0.074	2.6	3.43E-6	6.	0.07	3	0.11	2.6	18	2.4	32	2.0	18	2.2	26	2.3
27	Co	58.93	2.92E-5	10.		0.0	2.92E-5	2	3.71E-5	10.	70 ppm	10.	130 ppm	10.	70 ppm	10.	90 ppm	10.
60	Nd	144.2	2.01E-5	9.		0.0	2.01E-5	3	2.35E-5	9.	19 ppm	9.	90 ppm	9.	50 ppm	9.	60 ppm	9.

total mass 0.231 0.411 1.3 100.06 100.36 55.73 99.84
Quantification limit, % 50 - O meas 0.000 calc: 0.180 1.4 43.84
mass w/o O 0.231
pressure (mbar): 750 FEP mass (g): 0.05
self-abs.: no (recalc.: Ctrl+Shift+S) thickness (mm) : 1 density(g/cm³) 1 oxide: yes
10 10503coll from 2015/3 to 0 flux 1.35E+09 coll mm2 no vacum yes attenuator 0 0 0
24 2002EV from 2020/02 to 0 flux 4.00E+10 coll mm2 no vacum yes attenuator 0 0 0
29 2002CVT from 2020/02 to 0 flux 2.00E+09 coll mm2 no vacum yes attenuator 0 0 0
coverage factor for uncertainties: k=1 (1σ)
ProSpeRo v.5.1.3 (2020.07.29) (c) Zsolt Révay 2000-2016 (Anal. Chem. 81 (2009) 6851)

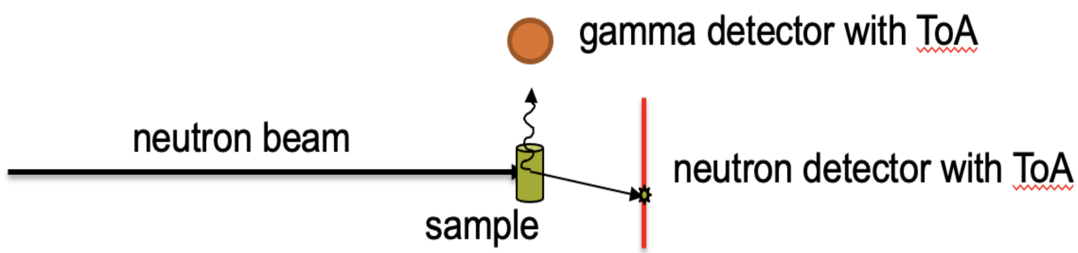
MORIS: Gamma-Ray Analysis from Inelastic Neutron Scattering (GRAINS)

- New, unique instrument
- Offers simultaneous elemental mapping and fast neutron radiography
  - n and γ penetrate through matter easily
    - Sample can be several mm thick
  - Any complex sample
    - Cultural heritage, energy, electronic waste (heavy elements)
- Principle: fast neutron in, fast neutron and gamma-ray out in coincidence
  - Delayed coincidence because of neutron ToF
- Fast neutrons detected by a scintillator screen
- Gamma rays detected perpendicularly
  - Neutron energy, detection angle, niveau lifetime cause peak broadening
    - Worse energy resolution
    - Affect coincidence timing

Planned at NECTAR

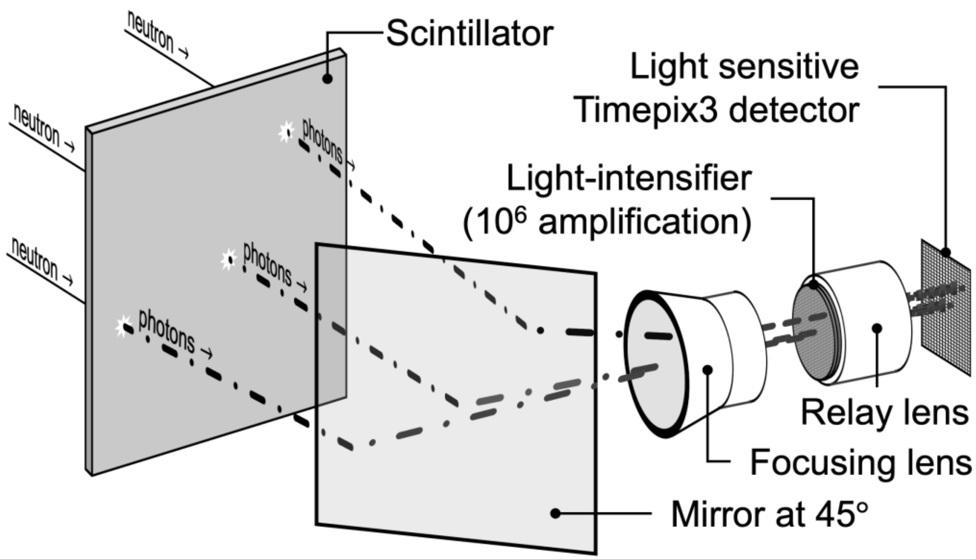
- Flux: 5×10^{7} cm^{-2} s^{-1}
- Low gamma background
  - (<MedApp, <Fangas)
- Fast neutron imaging is practically available
  - Neutron direction is assumed to remain the same
  - Time resolution ~10ns
- Gamma detection perpendicular to beam at sample
  - Energy shift due to angle change
  - Time resolution ~10ns

Utilizing prompt gamma in combination with neutron Time-of-Arrival



Neutron imaging + gamma detection

- Many new developments in imaging
- Timepix detector

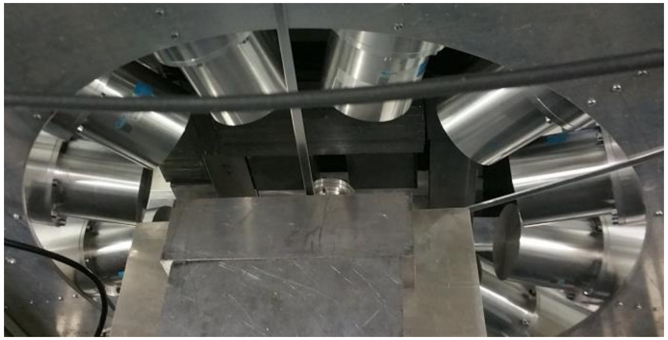


- To reduce beam background:

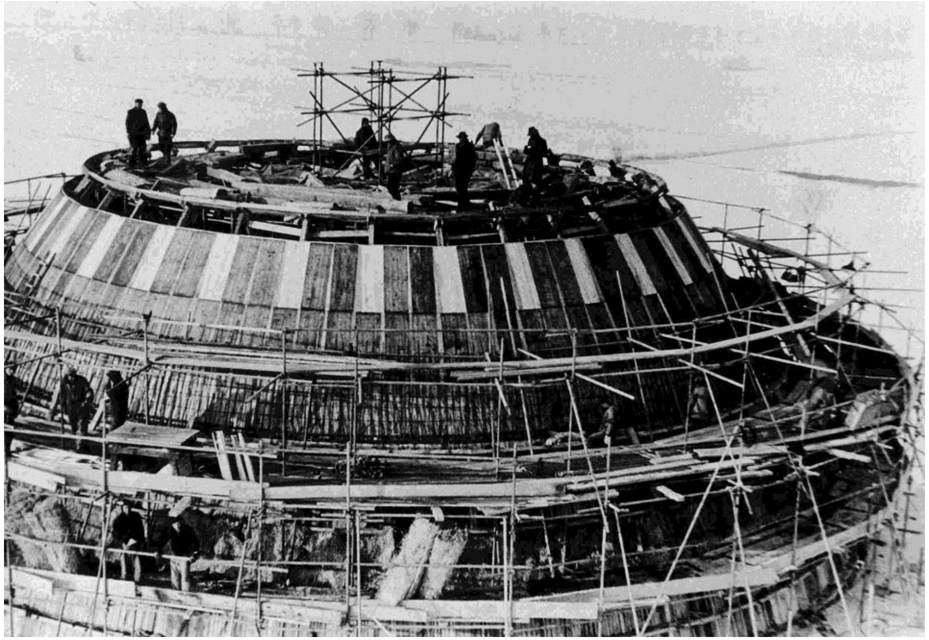
Scraping/Collimating the incoming beam

Using as many modules as SR10 can fit

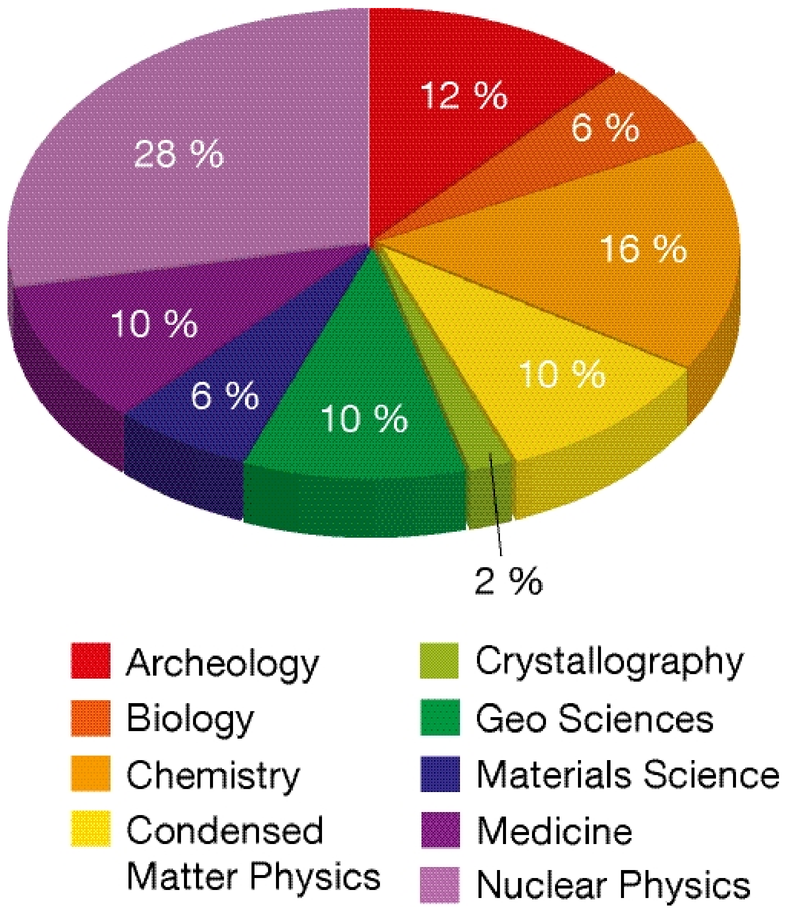
“portable” design on wheels to move in/out



Applications



User statistics: PGAA and in-beam AA



- Archeology
- D/H rate in deuterated samples
- B in different matrices
- H in difefernt matrices
- Air filters, other environmental
- Nuclear data measurements
- Nuclear physics
- High-flux irradiation

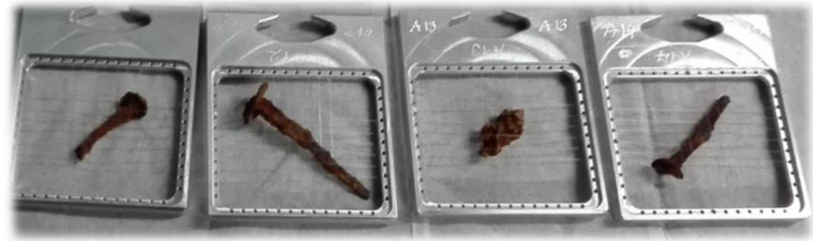
Overbooking factor around 2

Applications

Archaeometry

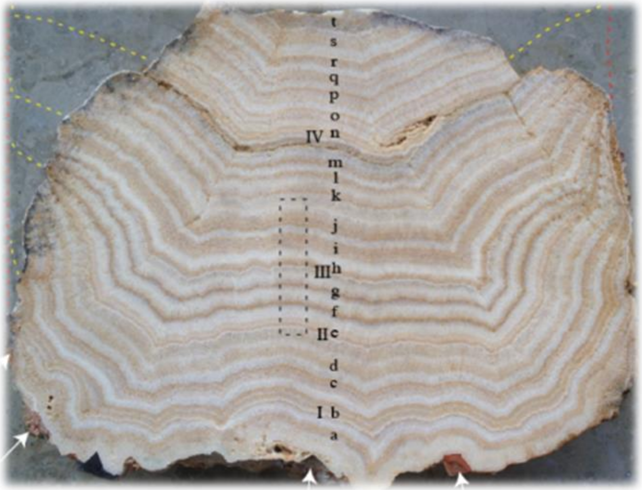
Chlorine in iron objects

- Slow down the corrosion of artifacts
- Understand the corrosion of iron
- Britta Schmutzler, Friedrich Wagner



Carbonate layers in aqueducts

- Trace elements
- Cornelius Passchier



Lichen checking air pollution

Z	El	M	m meas	unc %	m Bkg	unc %	m net	ox. st.	m ox	unc %	mol%	unc %	w% el/el	unc %
1	H	1.008	1.18E-2	0.4	2.44E-7	1.7	1.18E-2	1	0.11	0.4	48.6	2.2	6.17	4.
5	B	10.81	1.14E-6	0.4	3.87E-9	0.9	1.13E-6	3	3.65E-6	0.4	4.35 ppm	2.2	5.92 ppm	4.
6	C	12.01	0.107	3.1	3.50E-2	3.0	0.07	4	0.26	5.	25	4.	38	5.
7	N	14.01	2.32E-3	2.1		0.0	2.32E-3	5	8.95E-3	2.1	0.69	3.0	1.21	5.
13	Al	26.98	7.32E-4	2.1	1.38E-4	2.0	5.93E-4	3	1.12E-3	2.6	0.091	3.4	0.31	5.
14	Si	28.09	1.85E-3	3.1		0.0	1.85E-3	4	3.95E-3	3.1	0.27	3.7	0.97	5.
16	S	32.07	2.47E-4	2.6		0.0	2.47E-4	6	6.17E-4	2.6	320 ppm	3.3	0.129	5.
17	Cl	35.45	9.91E-5	1.7	9.27E-8	2.4	9.90E-5	-1	9.90E-5	1.7	116 ppm	2.7	0.052	4.
19	K	39.1	9.92E-4	1.7		0.0	9.92E-4	1	1.20E-3	1.7	0.105	2.7	0.52	4.
22	Ti	47.87	3.50E-5	3.0		0.0	3.50E-5	4	5.84E-5	3.0	30 ppm	3.7	180 ppm	5.
25	Mn	54.94	5.05E-6	7.		0.0	5.05E-6	3	7.25E-6	7.	3.8 ppm	8.	26 ppm	9.
48	Cd	112.4	3.06E-8	4.0		0.0	3.06E-8	2	3.49E-8	4.0	0.0113ppm	5.	0.16 ppm	6.
62	Sm	150.4	3.73E-8	2.8		0.0	3.73E-8	3	4.33E-8	2.8	0.0103ppm	3.5	0.19 ppm	5.
64	Gd	157.3	4.45E-8	6.		0.0	4.45E-8	3	5.13E-8	6.	0.012ppm	6.	0.23 ppm	7.
		0												
8	O	16	0.096	7.		0.0	0.10	-2		7.	25	6.	50	4.
		0												
11	Na	22.99	5.22E-5	0.7		0.0	5.22E-5	1	7.03E-5	0.7	94 ppm	2.3	273 ppm	4.
17	Cl	35.45	1.02E-4	3.0		2.4	1.02E-4	-1	1.02E-4	3.0	120 ppm	3.7	0.053	5.
20	Ca	40.08	5.54E-3	13.		0.0	5.54E-3	2	7.75E-3	13.	0.6	13.	2.9	13.
21	Sc	44.96	3.36E-8	4.		0.0	3.36E-8	3	5.15E-8	4.	0.031ppm	5.	0.18 ppm	6.
23	V	50.94	6.64E-7	23.		0.0	6.64E-7	5	1.19E-6	23.	0.5 ppm	23.	3 ppm	23.
25	Mn	54.94	5.06E-6	2.2		0.0	5.06E-6	3	7.28E-6	2.2	3.8 ppm	3.1	26 ppm	5.
26	Fe	55.85	1.00E-4	15.		8.	1.00E-4	3	1.43E-4	15.	70 ppm	15.	0.05	15.
27	Co	58.93	1.25E-7	12.		0.0	1.25E-7	2	1.59E-7	12.	0.09 ppm	13.	0.7 ppm	13.
35	Br	79.9	2.00E-6	8.		0.0	2.00E-6	-1	2.00E-6	8.	1.0 ppm	9.	10 ppm	9.
38	Sr	87.62	1.09E-5	8.		0.0	1.09E-5	2	1.29E-5	8.	5.2 ppm	8.	57 ppm	9.
63	Eu	152	7.21E-9	8.		0.0	7.21E-9	3	8.35E-9	8.	0.0020ppm	9.	0.038ppm	9.
		0												

PGAA

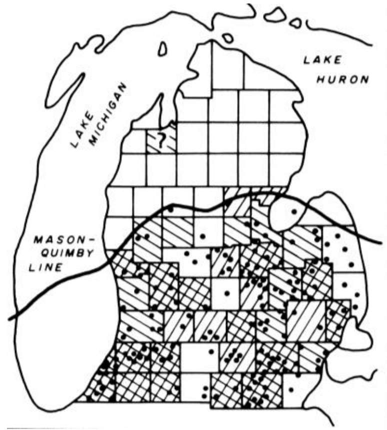
stoichiometry

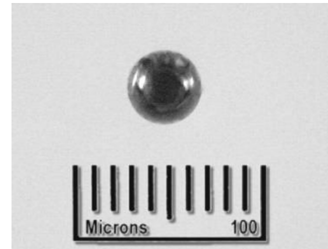
ibNAA

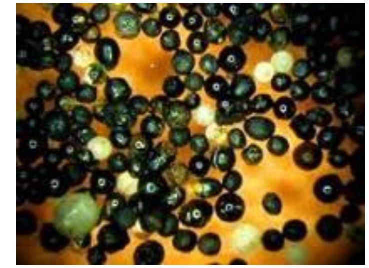
Typical sample: many major and minor components

- **Micro-meteorites**

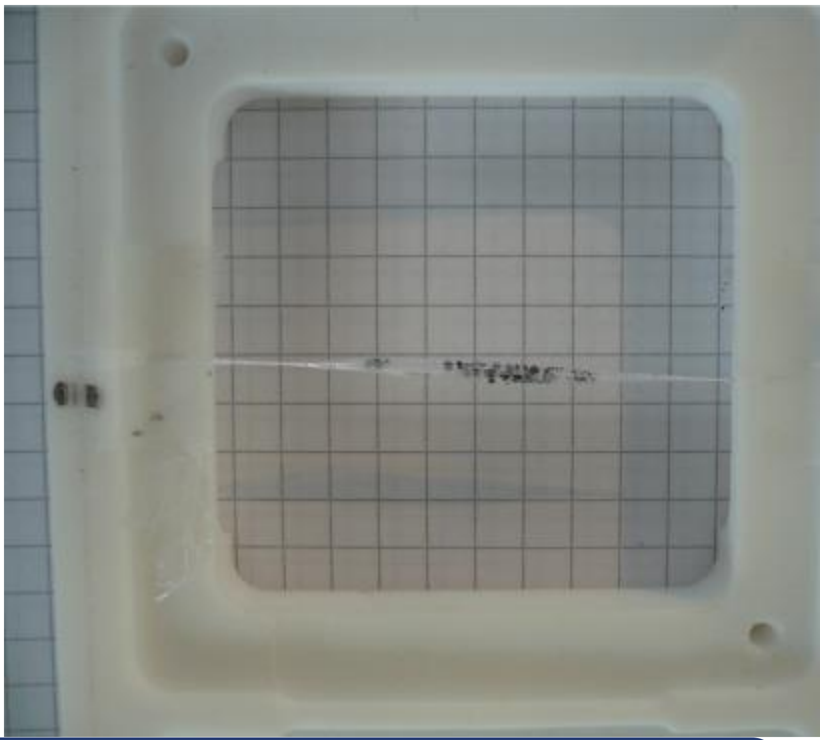
- Mass ~0.3—2mg
- In 0.5µm Mylar (PET) foil
- No Teflon string







Z	El	M	m meas	*unc %*	m Bkg	*unc %*	m net	ox. st.	m ox	*unc %*
1	**H**	1.008	5.47E-6	*0.8*	1.36E-6	*1.5*	**4.11E-6**	**1**	**3.67E-5**	*1.2*
5	**B**	10.81	6.74E-7	*0.3*	1.15E-8	*1.0*	**6.63E-7**	**3**	**2.13E-6**	*0.3*
13	**Al**	26.98	4.51E-5	*2.2*	1.96E-5	*2.5*	**2.55E-5**	**3**	**4.82E-5**	*4.*
14	**Si**	28.09	9.22E-5	*2.8*	1.96E-5	*3.7*	**7.26E-5**	**4**	**1.55E-4**	*3.7*
16	**S**	32.07	4.67E-6	*14.*		*0.0*	**4.67E-6**	**6**	**1.17E-5**	*14.*
17	**Cl**	35.45	1.09E-6	*18.*	1.15E-7	*22.*	**9.71E-7**	**-1**	**9.71E-7**	*20.*
20	**Ca**	40.08	2.10E-5	*19.*		*0.0*	**2.10E-5**	**2**	**2.94E-5**	*19.*
22	**Ti**	47.87	2.45E-4	*2.6*	1.40E-7	*22.*	**2.45E-4**	**4**	**4.09E-4**	*2.6*
24	**Cr**	52	4.03E-6	*14.*		*0.0*	**4.03E-6**	**3**	**5.89E-6**	*14.*
25	**Mn**	54.94	8.75E-6	*2.0*		*0.0*	**8.75E-6**	**3**	**1.26E-5**	*2.0*
26	**Fe**	55.85	2.31E-4	*2.4*	1.16E-6	*10.*	**2.30E-4**	**3**	**3.28E-4**	*2.4*
27	**Co**	58.93	3.06E-6	*3.1*		*0.0*	**3.06E-6**	**2**	**3.89E-6**	*3.1*
60	**Nd**	144.2	8.89E-7	*13.*		*0.0*	**8.89E-7**	**3**	**1.04E-6**	*13.*
62	**Sm**	150.4	5.32E-8	*6.*		*0.0*	**5.32E-8**	**3**	**6.16E-8**	*6.*
64	**Gd**	157.3	9.89E-8	*7.*		*0.0*	**9.89E-8**	**3**	**1.14E-7**	*7.*



1 mg

Thank you!