Industrial Photonuclear Physics

Assay of Gold and other Elements in Mineral Ores using Gamma Activation Analysis

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Outline

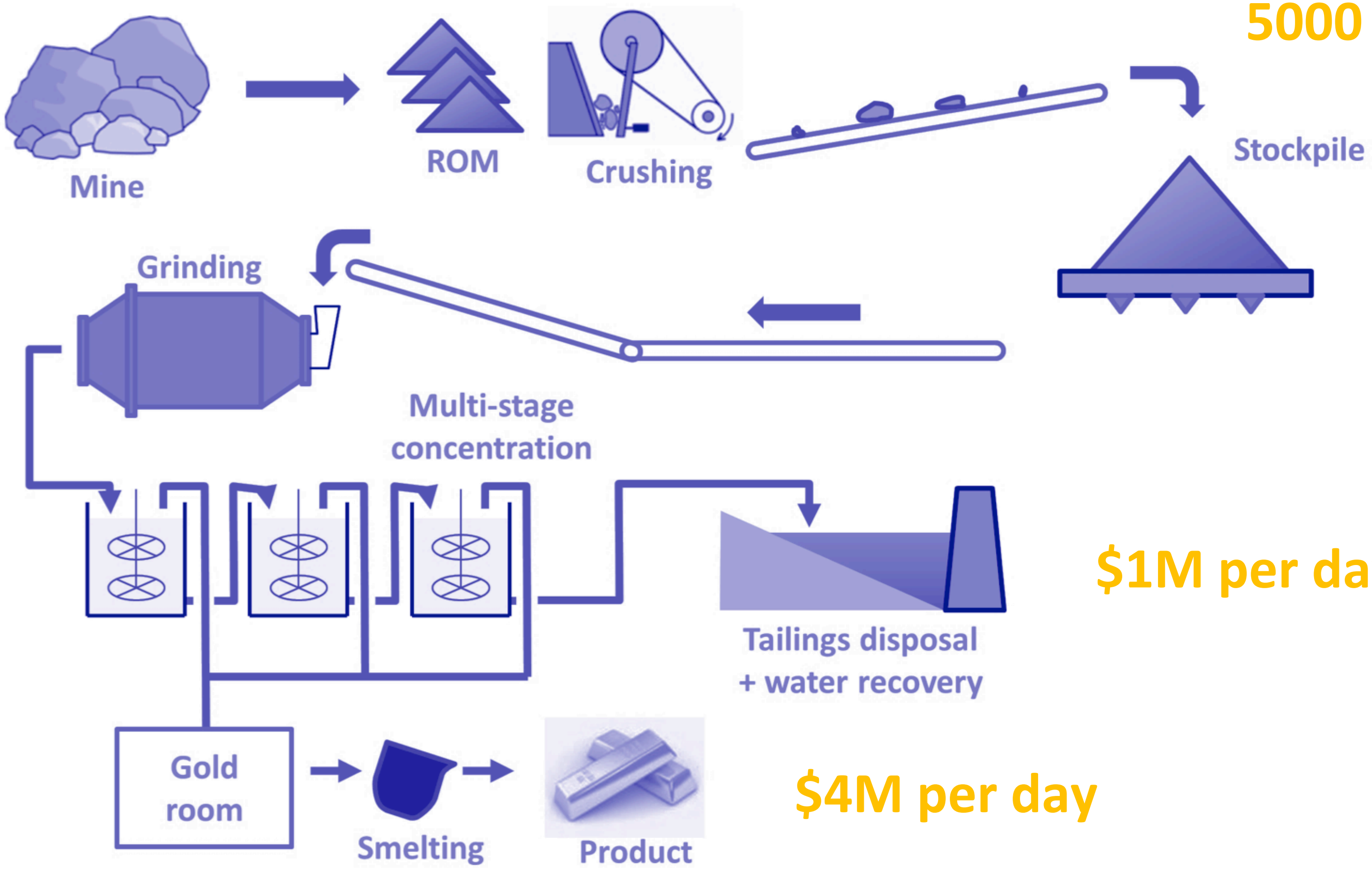
- Minerals processing 101 – why is gold assay both important and difficult?
- Searching for an alternative nuclear method
- Gamma activation analysis
  - Basic mechanism
  - Historical applications
  - Cross-section measurements
- Experimental validation
- Practical implementation of an industrial assay system

CSIRO

Why is gold assay important?

1 g/t Au (1 ppm)

5000 t/hour



$1M per day

$4M per day

Why is gold assay difficult?

- Low concentrations (often parts-per-million levels or lower)
- Non-uniform distribution
- High throughput needed (60 samples/h)
- Ideally, analysis 'in the field'

Current technology (fire assay)

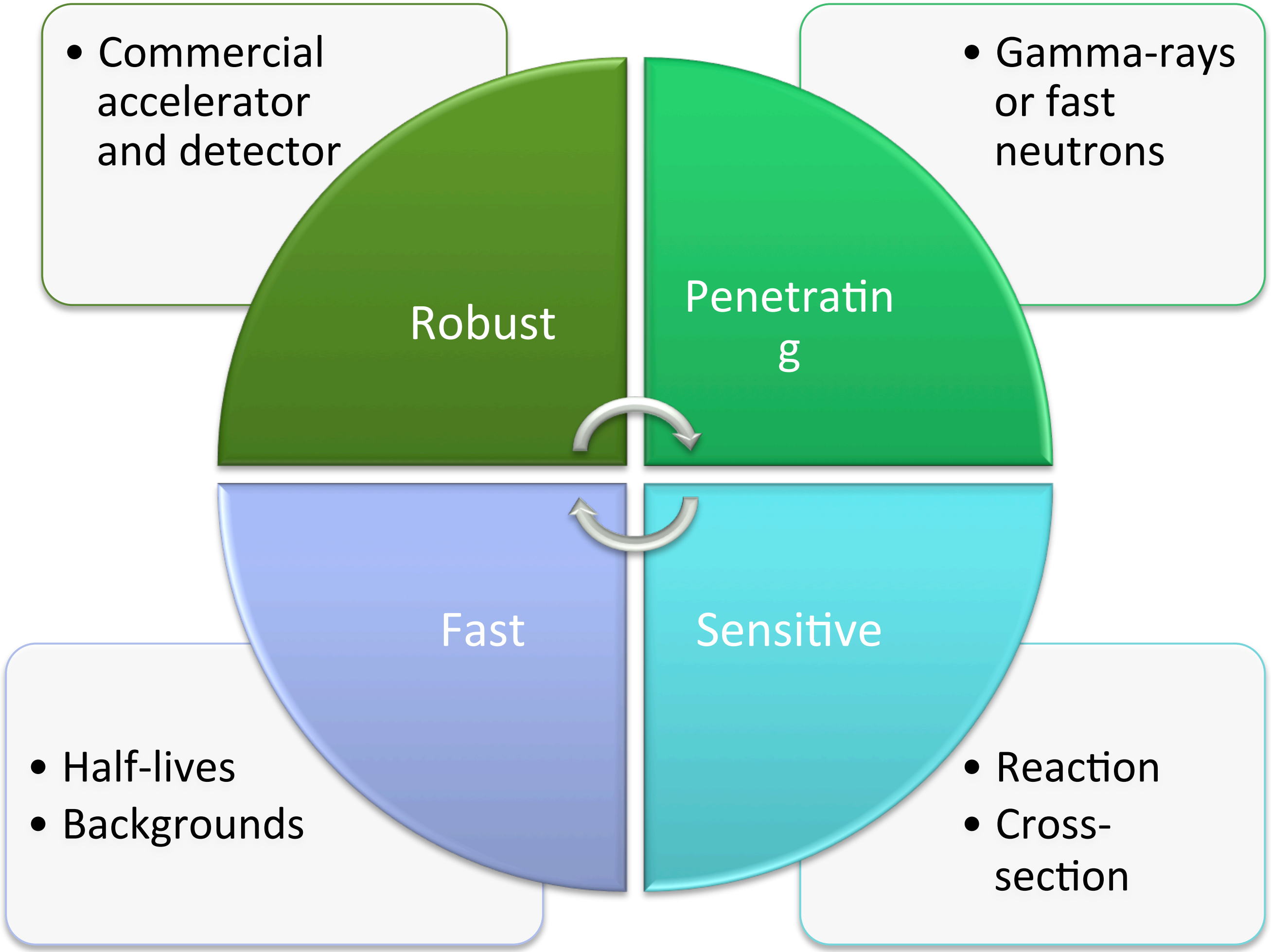
- Measures 15-50 g samples
- Laborious process; many safety issues
- Skilled technicians required

Gold is $10b pa industry in Australia
>$100b world-wide

Requirements for analysis method

Electron LINAC
HPGe detector

8-10 MeV X-ray in
279 keV γ out



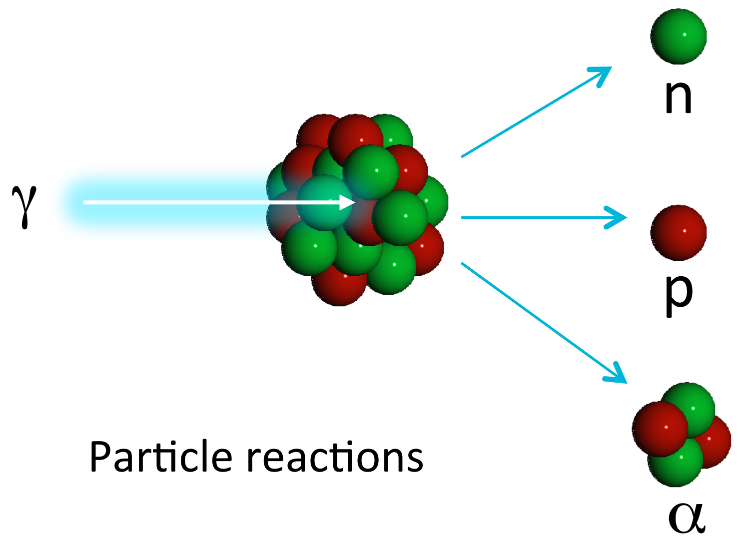
Gamma activation analysis

^{197M}Au, $t_{1/2}$=7.73 s
Little background

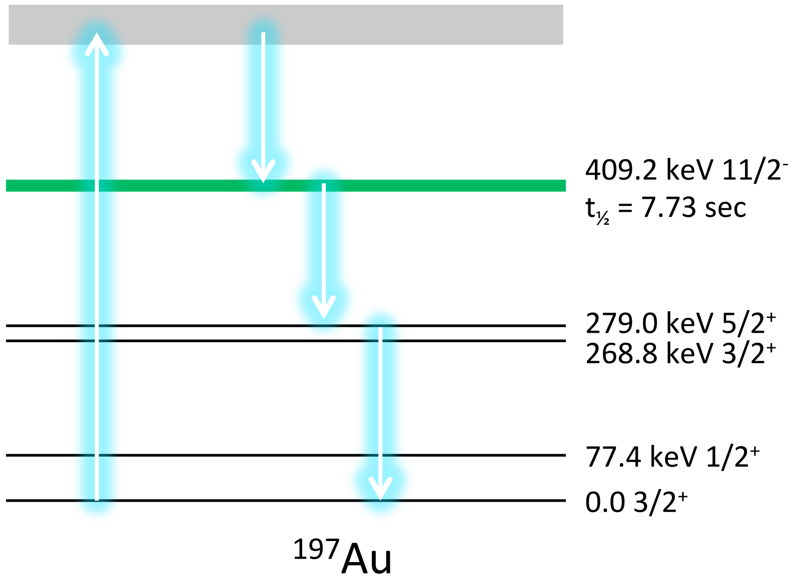
Isomer excitation

Gamma activation analysis (GAA)

- Use high-energy X-rays to induce reactions in target nuclei
- Measure resulting activity and relate to element concentration



Particle reactions



Isomeric reactions

History of GAA for gold and development challenges

History

- Discovery of ^{197}Au meta-state (1940s)
- Photoexcitation of meta-state (1950s)
- Identification of $^{197}Au(\gamma,\gamma')^{197m}Au$ reaction for gold analysis (1960s)
- Establishment of commercial assay lab in former Soviet Union (1970s)

Limited subsequent commercial development

Challenges

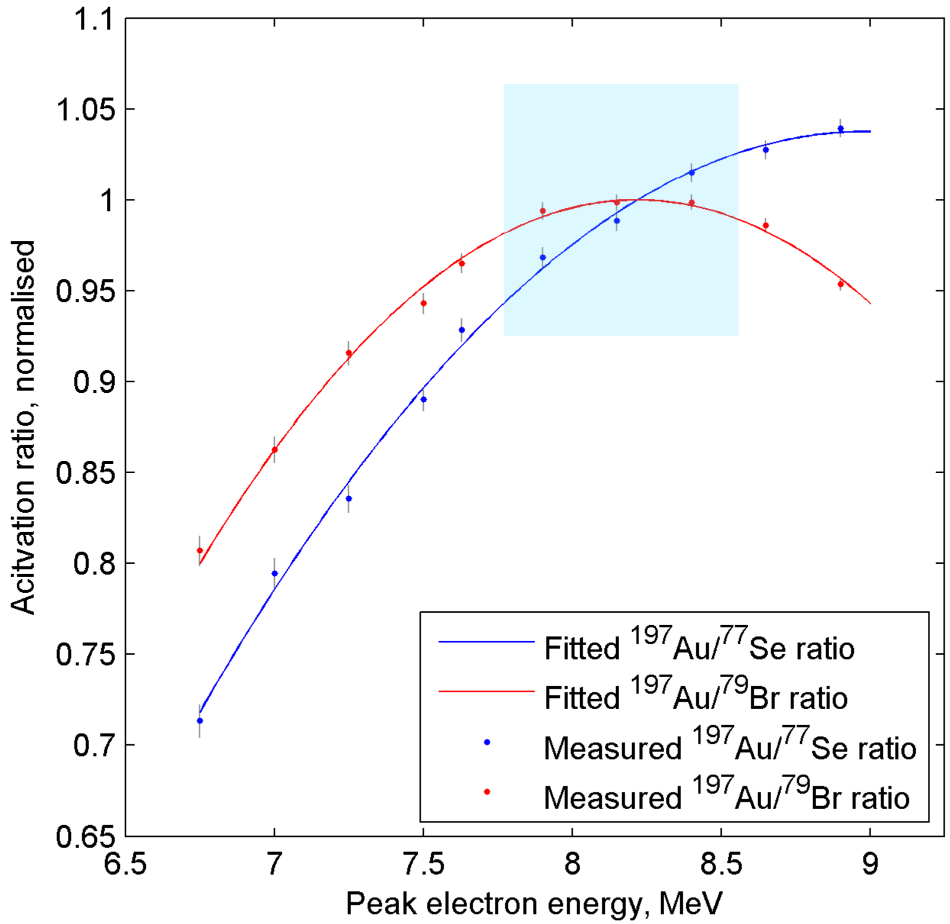
- Improve sensitivity and accuracy
- Limited control of beam energy and power
  - Need to have on-line correction method for accurate analysis
- Need to correct for variations in sample density and composition
  - Need better understanding of mechanism and cross-section for producing isomeric states
  - Develop Monte Carlo model of activation process to determine corrections

Reference foil for on-line stability control

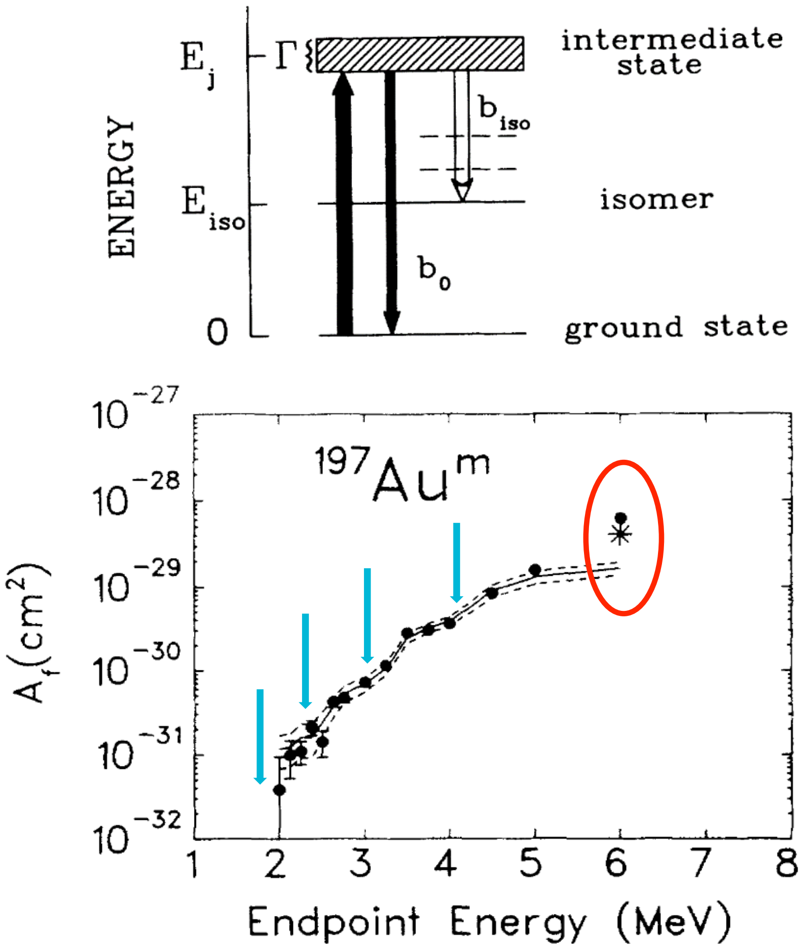
- Basic idea – use a monitor foil of a different element
- Requirements:
  - Isomeric state
  - Similar half-life to ^{197}Au-M
  - Similar but lower gamma-ray emission energy
  - No competing reactions
  - Rare in nature (or at least in gold deposits)
  - Relatively weak activation

~~^{77}Se, 17.5 s, 162 keV γ~~

^{79}Br, 4.86 s, 207 keV γ



Gamma activation cross-sections - expectations

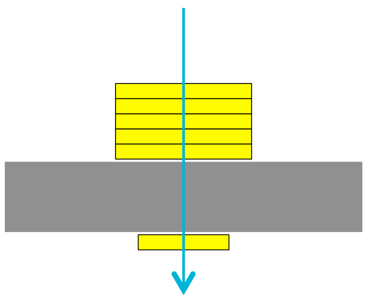


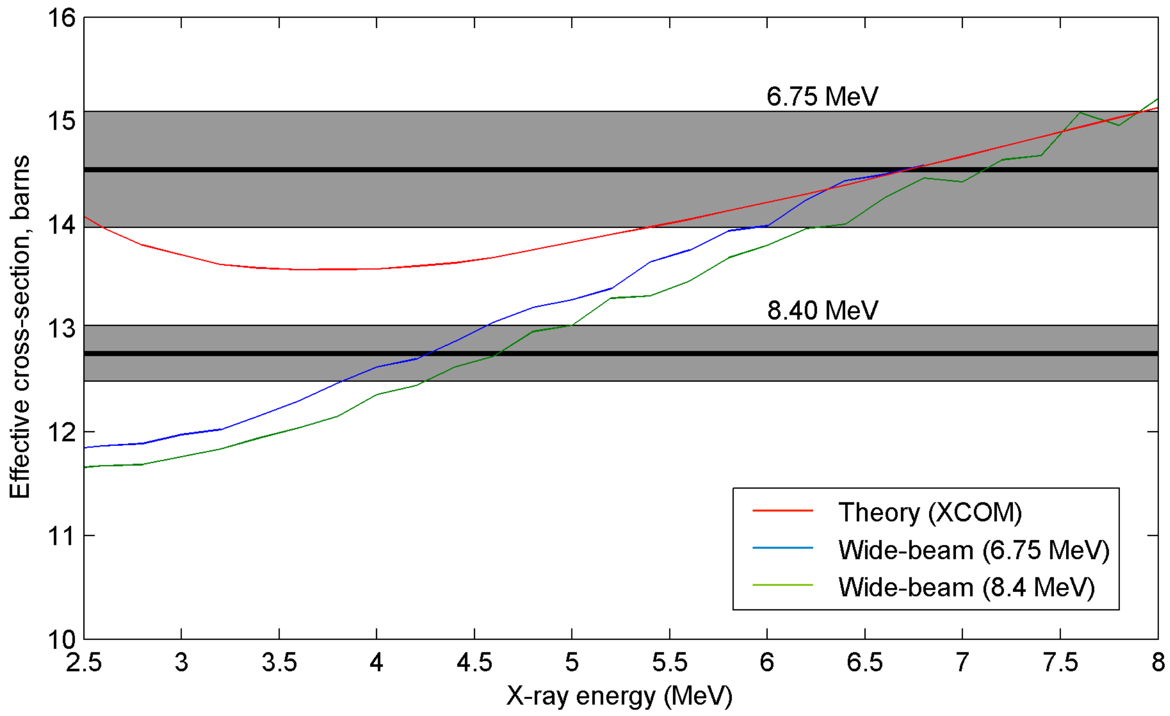
- Results from Collins et al (Phys Rev C 46(3) p952)
- They argue strongly for limited number of gateway levels
- Their model under-shoots data above ~6 MeV

IS energy (MeV)	σΓ (ev.barns)
1.7±0.3	0.7±0.3
2.5±0.1	5±0.5
3.2±0.15	45±5
4.2±0.2	200±40
6.0?	8000?

Experimental cross-section behaviour disagrees

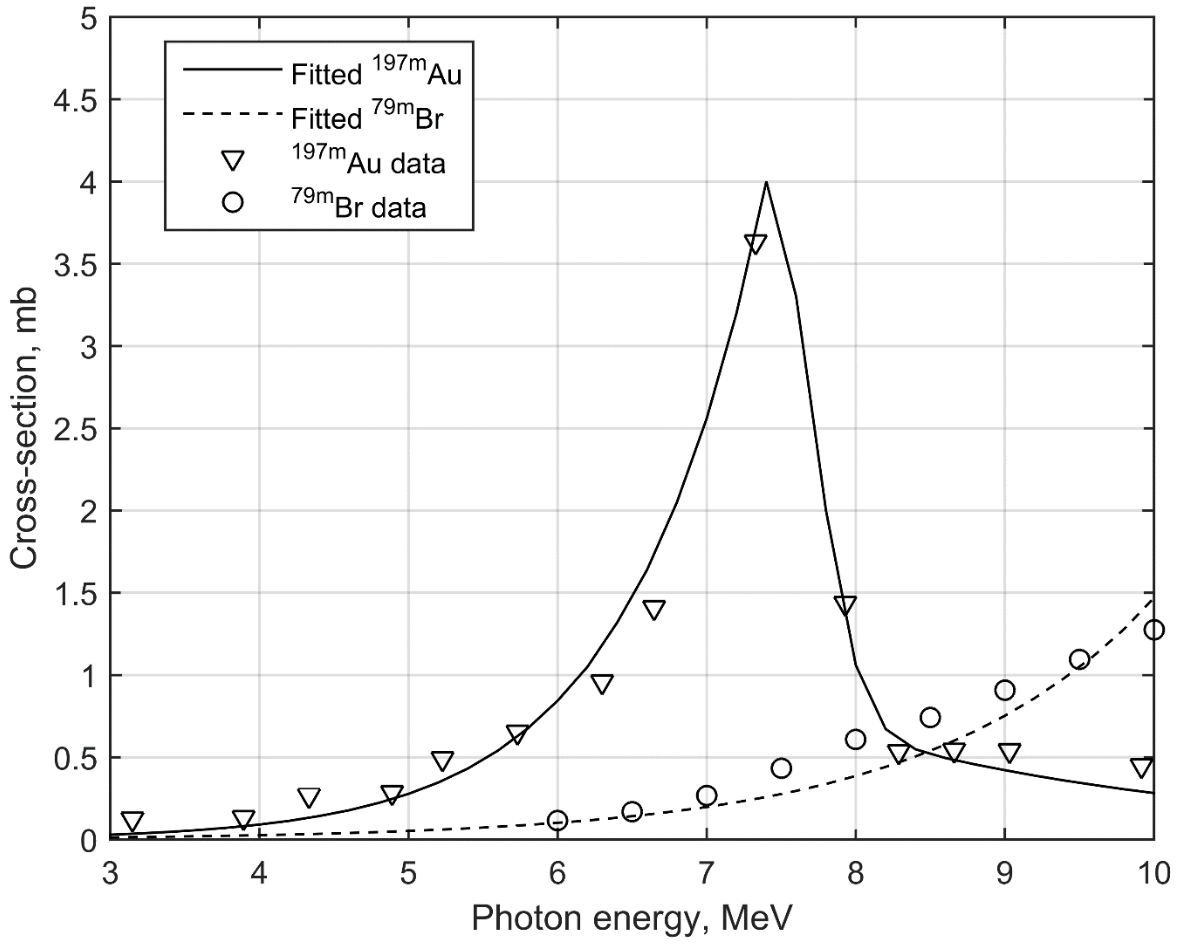
- $\sigma\Gamma \sim 10^3$-10^4 eV.barns
  - Extremely large state widths (>tens eV)
  - Thermal broadening will be negligible
  - Peak cross-section in range tens to hundreds of barns
- Atomic cross-section in gold is only ~12-14 barns in this energy range
- Strong self-absorption should be evident





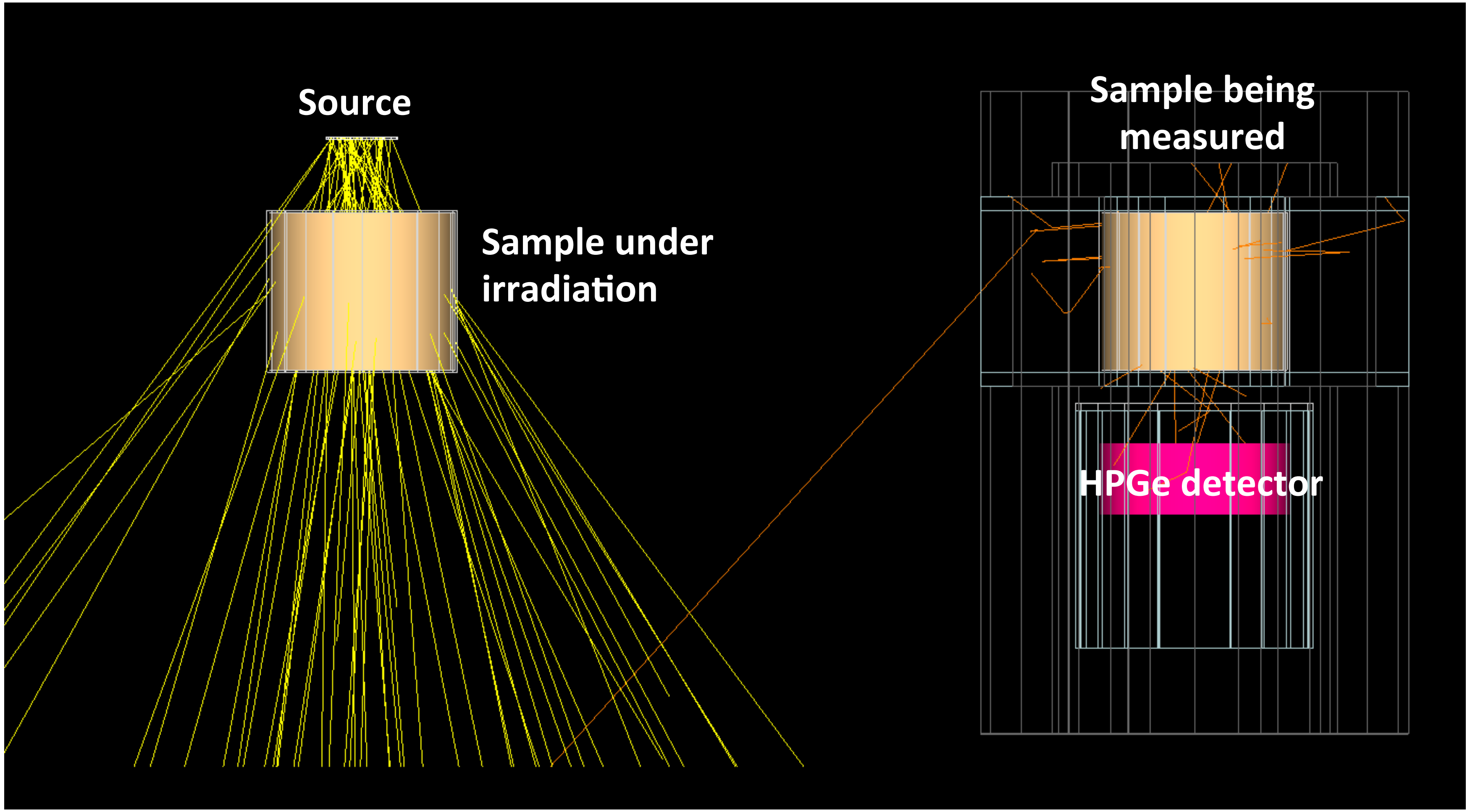
Non-atomic absorption is < 1-2 b

Suggested resolution of disagreement



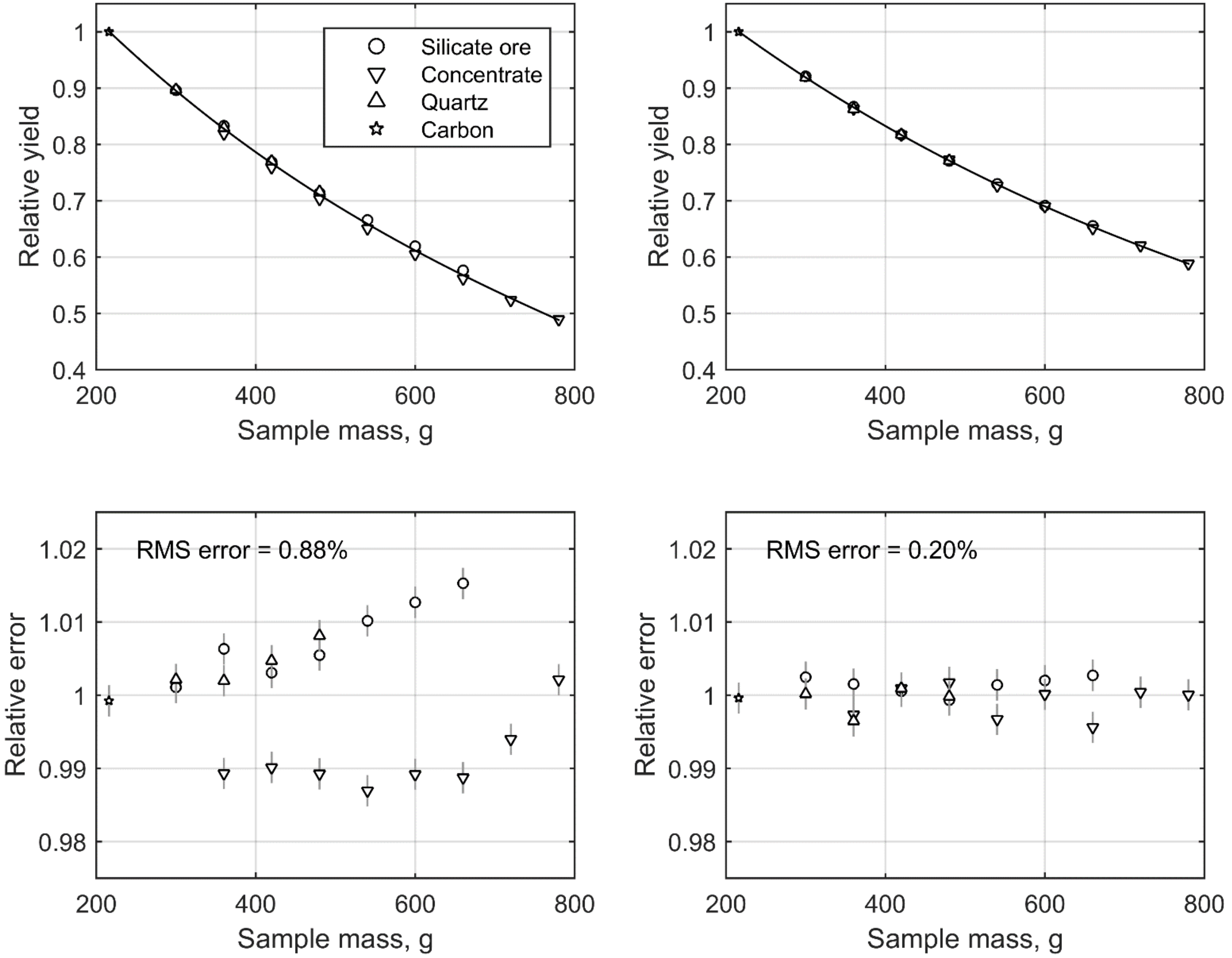
- Quasi-continuous cross-section formed from large number (hundreds/thousands) of discrete resonant states
- Determine cross-sections through semi-empirical fit to:
  - Existing data from literature
  - $^{197m}Au/^{79m}Br$ ratio that we measure

Condensed single-history Monte Carlo implementation



Reference foil correction for sample composition

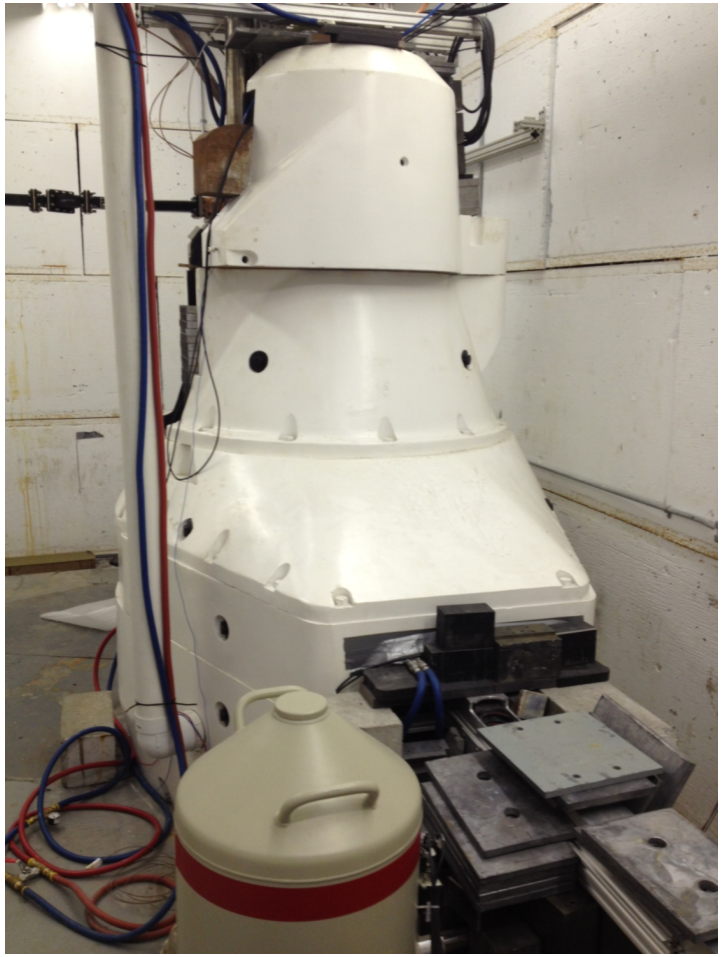
Gold activation signal per unit gold mass versus sample mass



Uncorrected

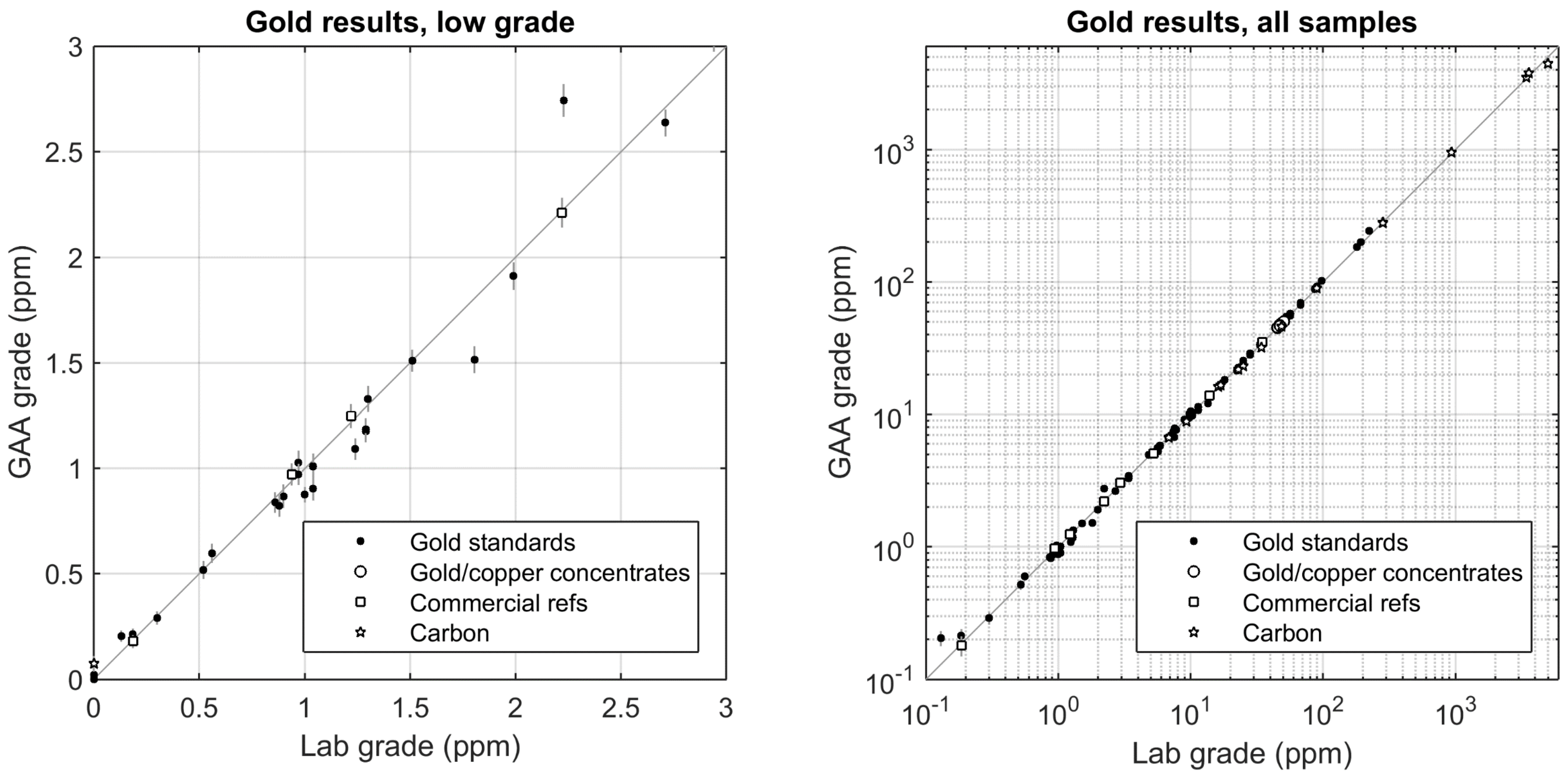
With bromine correction

Experimental validation



- LINAC manufactured by Mevex Corp. (Canada)
- Tests carried out in their facility in Ottawa
- LINAC operated at ~4 kW, 8.4 MeV E_{Peak}
- Planar HPGe detectors
- Pneumatic shuttle system
- Heavy steel shielding
- Concrete bunker
- Manual sample loading

Experimental performance



Experimental performance - summary

- Measurement accuracy defined as difference between GAA result and ‘true’ gold content of sample as presented
- Errors quoted at 1 standard deviation (68% confidence interval)

Parameter	Results to date (demonstrated)	Final system (extrapolated)
Measurement time	7.5 min	1.5 min
Throughput	6 samples/hour	80 samples/hour
Det. limit (3σ)	60-75 ppb	<30 ppb
Accuracy @ 0.1 ppm	35% (0.035 ppm)	15% (0.015 ppm)
Accuracy @ 0.3 ppm	15% (0.045 ppm)	6.5% (0.020 ppm)
Accuracy @ >1 ppm	Better than 5%	Better than 3%
Accuracy @ >30 ppm	< 1-2%	< 1%

Other elements

Fully demonstrated

Experimental validation

Theoretically accessible

1 1.008 H Hydrogen																	2 4.003 He Helium
3 6.941 Li Lithium	4 9.012 Be Beryllium											5 10.811 B Boron	6 12.011 C Carbon	7 14.007 N Nitrogen	8 15.999 O Oxygen	9 18.998 F Fluorine	10 20.180 Ne Neon
11 22.990 Na Sodium	12 24.305 Mg Magnesium											13 26.982 Al Aluminium	14 28.086 Si Silicon	15 30.974 P Phosphorus	16 32.065 S Sulphur	17 35.453 Cl Chlorine	18 39.948 Ar Argon
19 39.098 K Potassium	20 40.078 Ca Calcium	21 44.956 Sc Scandium	22 47.867 Ti Titanium	23 50.941 V Vanadium	24 51.996 Cr Chromium	25 54.938 Mn Manganese	26 55.845 Fe Iron	27 58.933 Co Cobalt	28 58.693 Ni Nickel	29 63.546 Cu Copper	30 65.409 Zn Zinc	31 69.723 Ga Gallium	32 72.640 Ge Germanium	33 74.922 As Arsenic	34 78.960 Se Selenium	35 79.904 Br Bromine	36 83.798 Kr Krypton
37 85.468 Rb Rubidium	38 87.620 Sr Strontium	39 88.906 Y Yttrium	40 91.224 Zr Zirconium	41 92.906 Nb Niobium	42 95.940 Mo Moly'num	43 [98] Tc Technetium	44 101.070 Ru Ruthenium	45 102.906 Rh Rhodium	46 106.420 Pd Palladium	47 107.868 Ag Silver	48 112.411 Cd Cadmium	49 114.818 In Indium	50 118.710 Sn Tin	51 121.760 Sb Antimony	52 127.600 Te Tellurium	53 126.904 I Iodine	54 131.293 Xe Xenon
55 132.905 Cs Cesium	56 137.327 Ba Barium		72 178.490 Hf Hafnium	73 180.948 Ta Tantalum	74 183.840 W Tungsten	75 186.207 Re Rhenium	76 190.230 Os Osmium	77 192.217 Ir Iridium	78 195.078 Pt Platinum	79 196.967 Au Gold	80 200.590 Hg Mercury	81 204.383 Tl Thallium	82 207.200 Pb Lead	83 208.980 Bi Bismuth	84 [209] Po Polonium	85 [210] At Astatine	86 [222] Rn Radon
87 [223] Fr Francium	88 [226] Ra Radium																
			57 138.905 La Lanthanum	58 140.116 Ce Cerium	59 140.908 Pr Pr'dymium	60 144.240 Nd Neodymium	61 [145] Pm Promethium	62 150.360 Sm Samarium	63 151.964 Eu Europium	64 157.250 Gd Gadolinium	65 158.925 Tb Terbium	66 162.500 Dy Dysprosium	67 164.930 Ho Holmium	68 167.259 Er Erbium	69 168.934 Tm Thulium	70 173.040 Yb Ytterbium	71 174.967 Lu Lutetium
			89 [227] Ac Actinium	90 232.038 Th Thorium	91 231.036 Pa Proactinium	92 238.029 U Uranium	93 [237] Np Neptunium	94 [244] Pu Plutonium									

Establishing a commercial analysis facility

- Secured investment funding
- Launched new company
- Establish flexible, high-power X-ray facility in Australia by mid-2017
  - Variable 8-14 MeV e-beam energy
  - Up to 8 kW beam power
- Establish commercial gold assay business
- Work with manufacturer to 'containerise' system for field applications

CHRYSOS CORPORATION
Assays at the speed of light

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Thank you

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