5. Neutron Activation Analysis for Thermal Neutron Flux Measurement

Shim, Hyung Jin

Nuclear Engineering Department,
Seoul National University

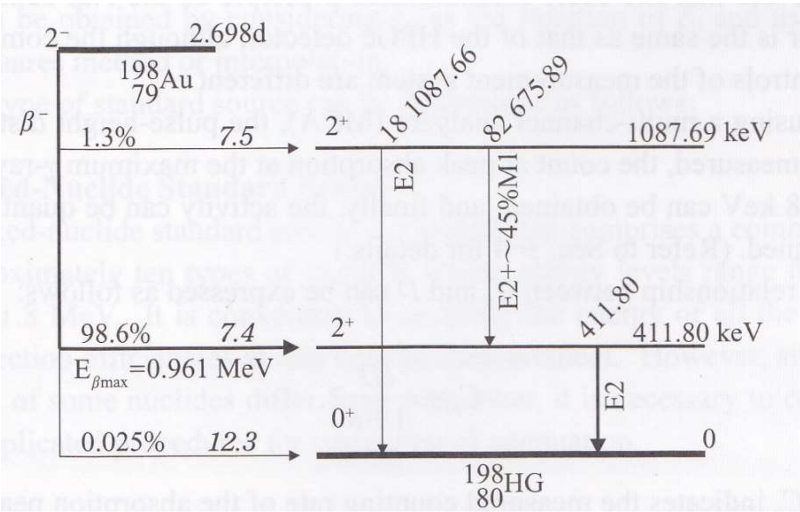
Gold Activation

- ^{198}Au:

  In reactor physics experiments, gold (Au, 100% ^{197}Au) has been widely used as an activation foil or wire for measuring thermal neutrons. By the neutron capture reaction, ^{197}Au is transformed into ^{198}Au with half-life of 2.698 days, which is suitable for measuring radioactivity.

$$^{197}_{79}\mathrm{Au} + \mathrm{n} \rightarrow {}^{198}_{79}\mathrm{Au}$$

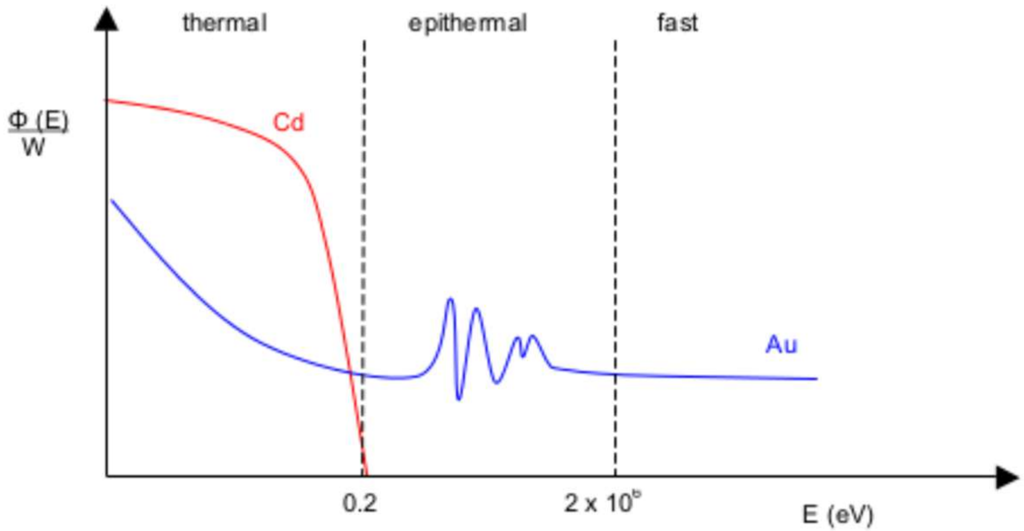
  The radioactive nuclide ^{198}Au transformed into ^{198}Hg by emitting β^- having a maximum energy of $E_{\beta max}$=0.961MeV and transmitted to the ground state through the 1st excited level of ^{198}Hg after an emission of 411.8 keV γ.



T. Misawa et al., *Nuclear Reactor Physics Experiments*, Kyoto University Press (2010).

Cadmium (Cd) Ratio Method

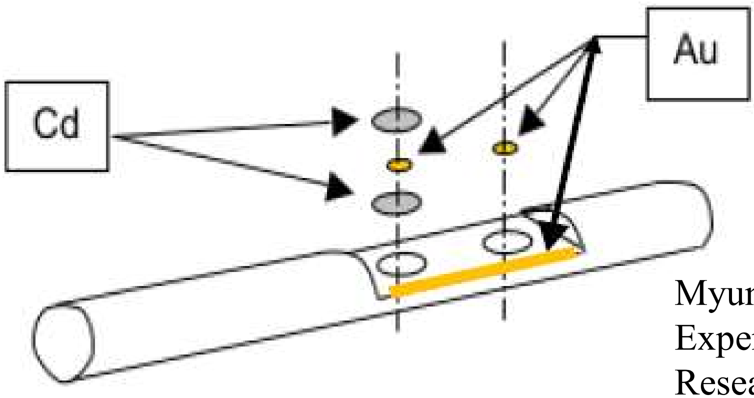
- The γ-ray measurements of the irradiated gold wire include activations from not only the thermal neutron flux but also the epithermal flux. The boundary energy between the thermal and epithermal energies is regarded as ~**0.1 eV** in the zero-power reactor.
- Therefore, in order to exclude the effect of epithermal neutrons, the cadmium (cd) difference (or ratio) method is widely used from the fact that Cd has large absorption cross section for neutron energy below 0.4 eV.

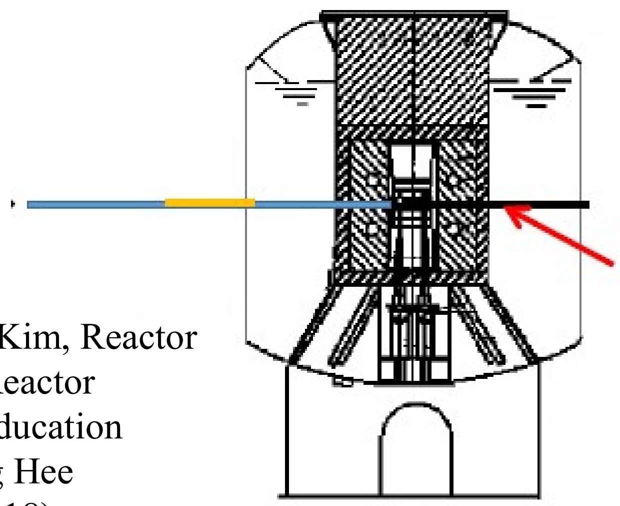


Myung Hyun Kim, Reactor Experiment, Reactor Research & Education Center, Kyung Hee University (2018).

Cd Ratio Method (Contd.)

- In the method, activities are measured at the symmetric positions for the bare Au target and the same target covered by Cd disks of which thickness was selected as 0.5 mm blocking neutrons below 0.4 eV.





Myung Hyun Kim, Reactor Experiment, Reactor Research & Education Center, Kyung Hee University (2018).

- By defining the Cd ratio as

$$R_{Cd} = \frac{\text{Activity of bare Au foil}}{\text{Activity of Cd covered foil}} = \frac{A_{Au}}{A_{CdAu}}$$

activity from thermal flux only, A_{th} can be obtained as

$$A_{th} = A_{Au} - A_{CdAu} = A_{Au}\left(1 - \frac{1}{R_{Cd}}\right)$$

Experimental Procedure

1. A thin gold wire (60 cm long, 0.2 mm thickness, over 99.99% purity) is attached to the sample holder tube. Identify the direction and location of sample when it is loaded to the reactor.

Myung Hyun Kim, Reactor Experiment, Reactor Research & Education Center, Kyung Hee University (2018).

2. Reactor power is raised to the reasonably high level (between 1 watt to 5 watt) and make reactor critical. Operator keeps the same power level during a reasonably long period of time (between 2 hrs to 6 hours). After the planned period time, reactor is shutdown. Then, reactor is let to be cooled with samples on it, usually more than one day as a cooling time. (Conditions of irradiation can be changed by each student team depending on their interest. They should record precisely the condition of irradiation such as power level, start time of irradiation, end time of irradiation, location of sample, etc.)

Experimental Procedure (Contd.)

3. All participants bring out sample to the NAA lab, and cut the wire into small pieces by 5cm long. Each sample of 5cm wire is put into a vial and identify with number tag.
4. One student takes a vial with gold wire and brings to the electronic weighing scale. Precise weight of a sample is recorded to the worksheet. By pincers, takes a gold wire to the sampling location for HPGe detector and begins to count gamma signals. Here a special nuclear instrument module is used for counting; detector with lead shield connected to a digital gamma spectroscopy which is an integrated system of power supplier, amplifier and multi chanel analyzer.
5. Automatically all counts are analysed by the computer program (GAMMAVISION). Student should take a proper peak from the graph on the PC screen and save the proper counting data. With a printed record, most of important information can be found.
6. By logging data into a formula in EXCEL, thermal flux level from each sample (at each sample location) can be calculated.
7. The steps above from (5) to (7) are repeated for all students and final collection of flux data provide a flux distribution curve.

Measured Data Sheet

Flux Measurement by NAA (KUSTAR) - at Glory Hole
Irradiation at: 2012-07-04 (Wed) (21:00-23:00)
Power Level: 4watt Channel#3 : $4.00X10^{-07}$ Amp

Starting of Rx Operation (T_1)	2012-7-4 21:00		
End of Rx Operation (T_2)	2012-7-4 23:00		
Irradiation Period (T_0)	2:00:00	7200	second

Serial #	Sample #	mass (mg)	Cd Cover	Location of Sample (5cm length)
1	238	31.0	No	From the Center of Glory Hole, -17.5cm (from -20.0 to -15.0cm)
2	239	30.2	No	From the Center of Glory Hole, -12.5cm (from -15.0 to -10.0cm)
3	240	31.0	No	From the Center of Glory Hole, -7.5cm (from -10.0 to -5.0cm)
4	241	30.8	No	From the Center of Glory Hole, -2.5cm (from -5.0 to 0.0cm)
5	242	30.3	No	From the Center of Glory Hole, +2.5cm (from 0.0 to 5.0cm)
6	243	31.3	No	From the Center of Glory Hole, +7.5cm (from 5.0 to 10.0cm)
7	120	31.0	No	From the Center of Glory Hole, +12.5cm (from 10.0 to 15.0cm)
8	121	31.9	No	From the Center of Glory Hole, +17.5cm (from 15.0 to 20.0cm)

Measured Data Sheet (Contd.)

Serial #	Sample #	Rx Trip Time	Starting Time of Measurement	Cooling Time(sec)
1	238	12-7-4 23:00	2012-7-5 10:38	41926
2	239	12-7-4 23:00	2012-7-5 10:55	42910
3	240	12-7-4 23:00	2012-7-5 11:07	43630
4	241	12-7-4 23:00	2012-7-5 11:22	44559
5	242	12-7-4 23:00	2012-7-5 11:36	45399
6	243	12-7-4 23:00	2012-7-5 11:40	45604
7	120	12-7-4 23:00	2012-2-13 10:48	168181
8	121	12-7-4 23:00	2012-2-13 10:57	168765

Half-life of ^{198}Au = 2.694 days

sample #	energy (keV)	decay constant (1/sec)	branching ratio(%) p	Detector Efficiency e	mass (mg)	Irradiation Period (sec) t_0	Cooling Period (sec) a	Peak Area C	live time (sec) L	true time (sec) T
238	411.8	2.977928E-06	95.53	9.26500E-04	31.0	7200	41926	41561	600	608
239	411.8	2.977928E-06	95.53	9.26500E-04	30.2	7200	42910	57066	600	609
240	411.8	2.977928E-06	95.53	9.26500E-04	31.0	7200	43630	86267	600	614
241	411.8	2.977928E-06	95.53	9.26500E-04	30.8	7200	44559	94891	600	615
242	411.8	2.977928E-06	95.53	9.26500E-04	30.3	7200	45399	15857	100	103
243	411.8	2.977928E-06	95.53	9.26500E-04	31.3	7200	45604	14194	100	102
120	411.8	2.977928E-06	95.53	9.26500E-04	31.0	7200	168181	17246	240	243
121	411.8	2.977928E-06	95.53	9.26500E-04	31.9	7200	168765	12004	240	242

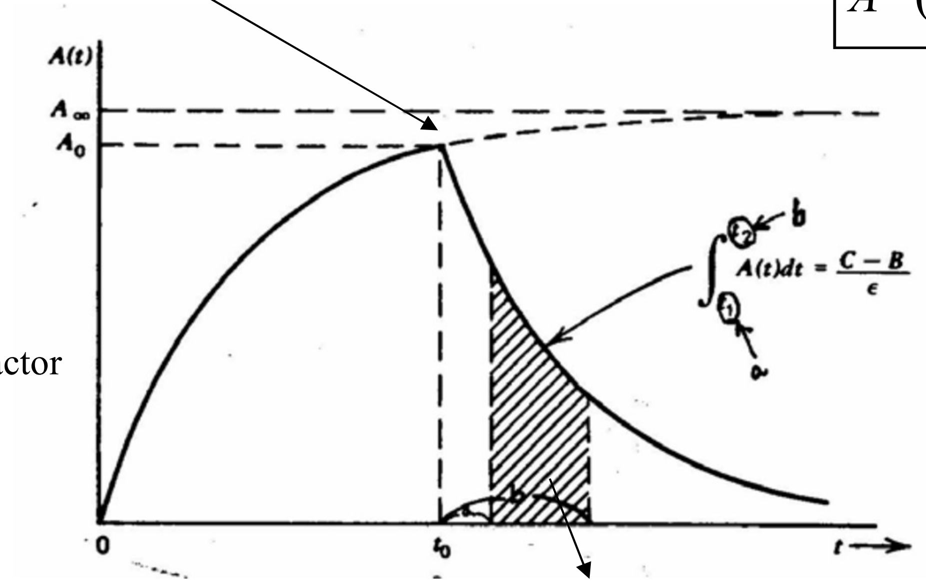
Flux Calculation

$$\frac{dN^{98}}{dt} = N^{97}\sigma_{\gamma th}^{97}\phi_{th} - \lambda N^{98}, \quad N^{98}(0) = 0$$

$$N^{98}(t) = \frac{A_\infty}{\lambda}\left(1 - e^{-\lambda t}\right); \quad A_\infty = N^{97}\sigma_{\gamma th}^{97}\phi_{th} \equiv R_{th}$$

$$A^{98}(t) = A_\infty\left(1 - e^{-\lambda t}\right)$$

$$A^{98}(t_0) \equiv A_0^{98} = R_{th}\left(1 - e^{-\lambda t_0}\right)$$



Myung Hyun Kim, Reactor Experiment, Reactor Research & Education Center, Kyung Hee University (2018).

ε = counting efficiency
p = emission prob. (B.R.)
B = background counts

$$C = \varepsilon p \int_a^b A^{98}(t)dt + B = \varepsilon p \int_a^b A_0^{98} e^{-\lambda t} dt + B = \frac{\varepsilon p}{\lambda} A_0^{98}\left(e^{-\lambda a} - e^{-\lambda b}\right) + B$$

$$A_0^{98} = \frac{\lambda(C - B)}{\varepsilon p\left(e^{-\lambda a} - e^{-\lambda b}\right)}$$

Flux Calculation

sample #	energy (keV)	decay constant (1/sec)	branching ratio(%) p	Detector Efficiency e	mass (mg)	Irradiation Period (sec) t_0	Cooling Period (sec) a	Peak Area C	live time (sec) L	true time (sec) T
238	411.8	2.977928E-06	95.53	9.26500E-04	31.0	7200	41926	41561	600	608
239	411.8	2.977928E-06	95.53	9.26500E-04	30.2	7200	42910	57066	600	609

$$A_0^{98} = \frac{\lambda(C-B)}{\varepsilon p\left(e^{-\lambda a} - e^{-\lambda b}\right)}$$

$$R_{th} = \frac{A_0^{98}}{1-e^{-\lambda t_0}}$$

$$\phi_{th} = \frac{R_{th}}{N^{97}\sigma_{\gamma th}^{97}}$$

$$\sigma_{\gamma th}^{97} = 98.5[\text{barn}]$$

Sample #	(T-L)/T	t2 (sec) a+T	Current Radioactivity (Bq)	A_0	A-infinite R_{th}	Neutron Flux (westcott) Φ_0 = R/(Nσ_0)	Neutron Flux(integral) Φ_T
238	0.013157895	42534	8.874940E+04	8.874940E+04	4.183756E+06	4.46666E+08	5.040696E+08
239	0.014778325	43519	1.222166E+05	1.222166E+05	5.761440E+06	6.31397E+08	7.125411E+08
240	0.022801303	44244	1.851534E+05	1.851534E+05	8.728361E+06	9.31858E+08	1.051615E+09