Nishina School
Training B: NaI Scintillator

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1 Orientation

The following is a list of questions that should be answered and discussed during the orientation.

- What is the main use of NaI detectors?
- What are basic quantities characterizes gamma detectors?
- Interaction of γ rays with matter
  - How is the detection of γ rays different from the detection of charged particles?
  - What processes are involved in γ ray detection?
  - For Compton scattering, how does the energy of the outgoing photon depend on scattering angle? How can this be calculated? What does the Klein-Nishina formula describe?
  - What is the definition of the linear attenuation coefficient? How does it typically look as a function of γ energy?
- Pulse height (=energy) spectrum
  - What is a full-energy peak? Compton-edge? Backscatter peak? Single, double escape peak? Annihilation peak?
  - What is the FWHM and σ of a peak? How are they related?
  - What is centroid of a peak? How is it determined? What is its precision (1σ uncertainty) assuming a peak width of 1σ and N counts in the peak? What is the meaning of "a 68% confidence interval"?
- How does a photo-multiplier tube (PMT) work?
  - What is the plateau curve?

- Signal processing and electronics modules
  - What is the difference between a logic and analog signals?
  - How fast are typical "fast" signals? How fast are typical "slow" signals?
  - What logic standards are most common?
  - What is a pre-amplifier, shaper, fast amplifier, timing filter amplifier, discriminator, time-to-amplitude converter?
  - How do the signals look that go into and come out of these modules?
  - What types of discriminators exist?
  - Cables and connectors: BNC, SHV, LEMO, ...
  - HV supplies
  - ADC, gated and not gated operation
  - TDC, common start, common stop
  - Multi channel analyzer
  - Drawing of electronics circuit
- What is a γ-ray source?
  - How can they be used to measure the (absolute) full energy peak efficiency?

2 Training

The most important task is to **write** a **logbook** about everything you do and everything you observe. It should be written, so that if you (after, say, 1 year) or someone else looks at it, knows exactly what was done.

Concerning the electronics modules: there are manuals where their operation is described in detail. If something is not clear, the manual should be consulted. When cabling up the electronic circuits always check the input and output signals.

The following should be done:

- Connect HV to the NaI(Tl) detector; connect signal out put to oscilloscope; raise HV slowly (typical -1200 V for this detector[1]) until signals can be observed on the oscilloscope.
- Do you remember the rate of cosmic rays? What particles are these? How many should you see per second? Do you "see" them?
- Place a known γ ray source near the detector. Can you see the transition using the oscilloscope?

[1]**NB: polarity and voltage can be very different for other PMTs; for some it might be too low, others will be destroyed. So, always check the data sheet, or raise HV very carefully.**

- Connect the shaping amplifier. Can you distinguish the different γ energies on the oscilloscope now? What shaping time should you used?
- Connect the shaper output to the ADC. Use the MCA to obtain a pulse-height spectrum.
- Look at pulse height spectrum and interpret it (with no γ source and with two different γ sources (probably ^{60}Co and ^{22}Na)
- Remove source and measure the plateau curve (Which HV range? Which HV steps?)
- Decide optimal HV and use that during the remainder of the training.
- Adjust shaper gain to so that γ rays up to 3 MeV can be measured.
- Measure ^{60}Co spectrum. Perform an energy calibration. What is the resolution of the detector?
- Measure room BG spectrum. Identify the most prominent peaks.
- How can you find out easily if the two γ rays of ^{60}Co are emitted simultaneously? (Hint: What happens when two γ rays enter the detector? Estimate the probability of two randomly emitted γ rays being measured simultaneously? What time-window should be used?)
- If there is time: measure the relative efficiency of the detector as a function of distance of the source from the detector. Can you also estimate the absolute efficiency, without knowing the source strength?

Orientation B: NaI Scintillator

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2010年10月7日

Part 2Detection of γ rays **2**
Interaction of γ rays 3
Response Function. 4
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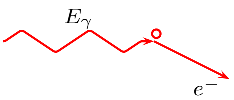
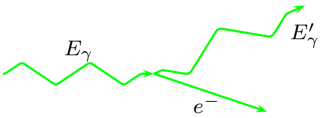
Interaction of γ rays with Matter

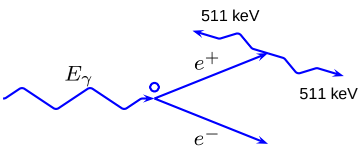
Photoelectric Adsorption

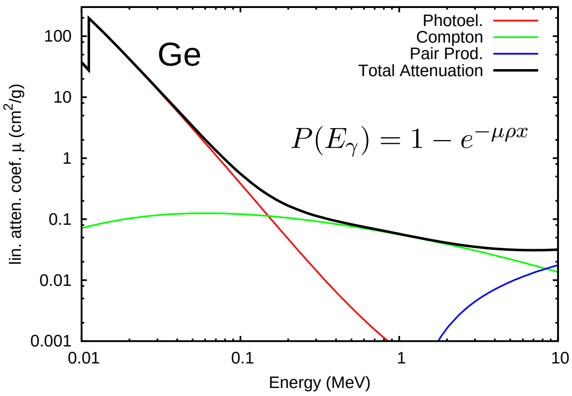


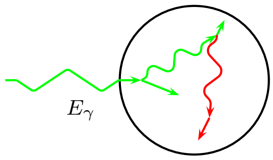
Incoherent Scattering
(Compton)



Pair Production ($E_\gamma > 1022$ keV)







many interactions required to deposit **full energy** inside detector volume

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Response Function

- amplitude distribution for mono-energetic γ rays
- photo effect: full energy absorbed
- Compton scattering: only partial energy

$$E_\gamma^C = E_\gamma \left[1 + \frac{E_\gamma}{m_e c^2}(1 - \cos(\theta)) \right]^{-1}$$

- pair production: full energy absorbed, but 2×511 keV γ rays emitted
- general structure: continuum with several peaks
  - full energy peak
  - Compton background

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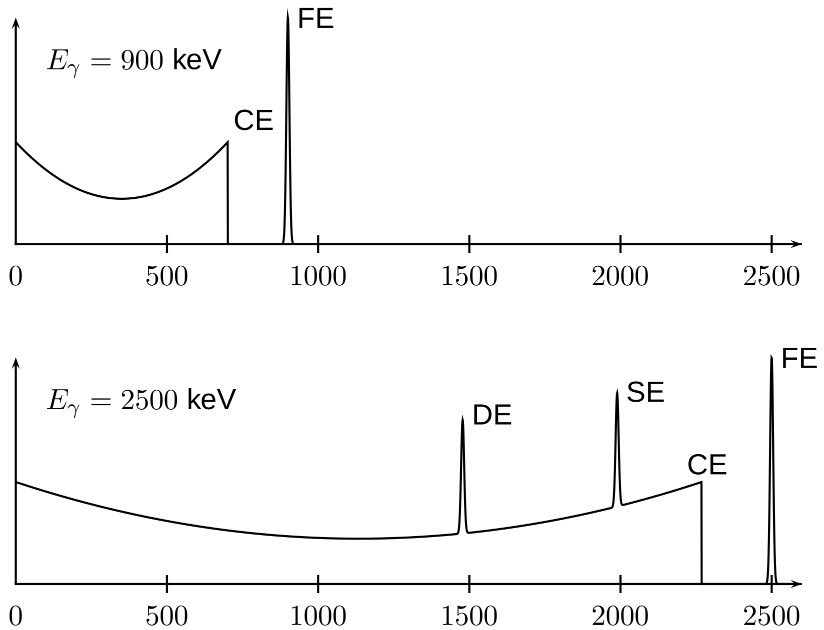
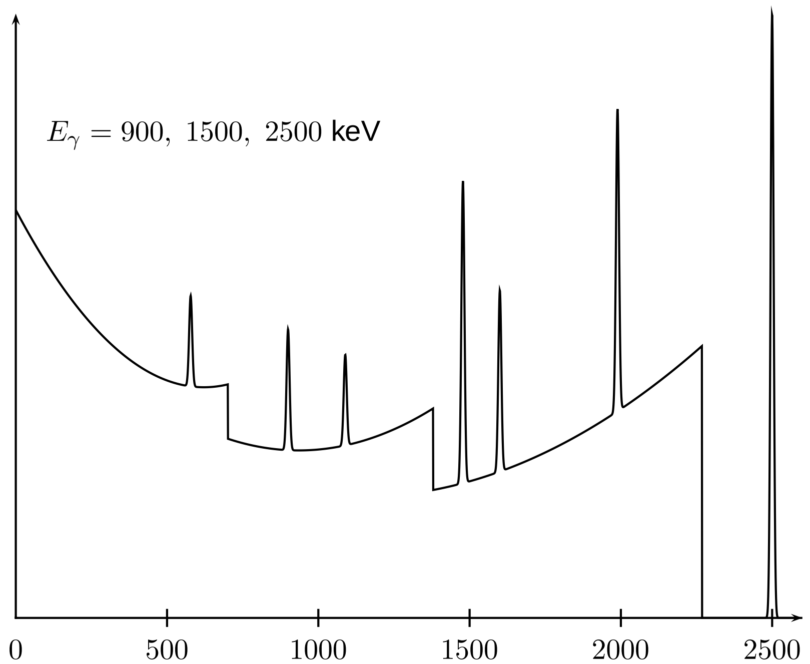
Response Function



Response Function



Nishina School

Experiment: Compton Scattering

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1 Introduction

...

2 Tasks

1. confirm relation between angle and energy of Compton scattered photon
2. confirm Klein-Nishina formula

3 Equipment

- two NaI(Tl) detectors
- HPGe detector if needed
- single channel analyzer
- multi channel analyzer
- anything else you need

4 Preparation/Program

1. - derive the relation between the energy and angle of a Compton scattered photon
   - How can this relation be verified experimentally?
2. - look up the Klein-Nishina formula
   - How can this formula be verified experimentally?

APPENDIX C. NUCLEAR SPECTROSCOPY STANDARDS

1. Gamma-ray Energy and Intensity Standards

Table 1 lists some γ-ray energy standards, from the evaluation of Helmer, et al.[1], and intensity standards, recommended by the IAEA Co-ordinated Research Programme[2,3] (CRP), for calibration of γ-ray measurements. Most of the isotopes given here have half-lives of more than 30 days, and many are commercially available. The γ-ray energies are based on the *gold standard*, the 411.80205 *17* keV transition from ^{198}Au decay. Uncertainties are intended to represent one standard deviation, and include the 0.3 ppm uncertainty in the definition of the electron volt relative to wavelength. The γ-ray energies reported in Table 1 are from absolute wavelength or curved-crystal spectrometer measurements, which are tied directly to the *gold standard*, and from the measurements of small γ-ray energy differences with Ge detectors. Energies that are rounded to the nearest 0.1-keV and tabulated without uncertainty are not recommended values; however, they have been included because these transitions are useful intensity calibration standards. Other, apparently precise, transition energies and intensities have been tabulated in the *Table of Isotopes*, but the reader should use these values with great caution because of unknown systematic uncertainties which may not have been included. Columns 1 and 2 show the isotope names and half-lives, respectively. Columns 3 and 4 list the γ-ray energies and intensities with their corresponding uncertainties (in italics) in the least significant digit(s).

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[1] R.G. Helmer, C. van der Leun, and P.H.M. Van Assche, private communication, draft of a paper to be submitted to *Nucl. Instr. Meth.*, 1995; energies may change in the final publication.

[2] R. Vaninbroukx, *Emission Probabilities of Selected Gamma Rays for Radionuclides Used as Detector-Calibration Standards*, report presented at the Advisory Groug Meeting of the International Atomic Energy Agency (IAEA), Vienna (1985).

[3] *X-ray and Gamma-ray Standards for Detector Calibration*, report by the Co-ordinated Research IAEA Programme, IAEA-TECDOC-619 (1991).

Table 1. Gamma-ray Energies and Absolute Intensities for Some Standard Sources

Source	Half-life	E_γ(keV)	I_γ(%)
^{7}Be	53.29 d	477.6035 *2*	10.45 *10*
^{22}Na	2.6019 y	1274.537 *7*	99.935 *15*
^{24}Na	14.9590 h	1368.626 *5*	99.9936 *15*
		2754.007 *11*	99.855 *5*
^{35}Cl(n,γ)		517.07043 *28*	0.227 *20*
		786.2975 *5*	0.096 *9*
		788.4236 *5*	0.150 *12*
		1164.8587 *6*	0.257 *22*
		1600.8	0.034 *3*
		1951.1291 *15*	0.187 *15*
		1959.345 *8*	0.121 *10*
		2863.9	0.060 *5*
		3061.7	0.035 *3*
		5715.2	0.051 *4*
		6110.8	0.197 *16*
		6619.4	0.081 *7*
		6627.5	0.046 *4*
		6977.6	0.0223 *20*
		7413.7	0.100 *8*
		7790.0	0.086 *7*
		8578.2	0.0294 *24*
^{46}Sc	83.79 d	889.271 *2*	99.9844 *16*
		1120.537 *3*	99.9874 *11*
^{44}Ti	49 y	67.8679 *18*	
		78.3231 *13*	
^{51}Cr	27.702 d	320.0824 *4*	9.86 *5*
^{54}Mn	312.3 d	834.841 *4*	99.9758 *24*
^{56}Mn	2.5785 h	846.8	98.87 *3*
		1810.7	27.2 *8*
		2113.0	14.3 *4*

Source	Half-life	E_γ(keV)	I_γ(%)
^{59}Fe	44.503 d	142.651 *2*	
		192.349 *5*	
		1099.245 *3*	
		1291.590 *6*	
^{56}Co	77.27 d	846.7638 *19*	99.933 *7*
		1037.8333 *24*	14.13 *5*
		1175.0878 *22*	2.239 *11*
		1238.2736 *22*	66.07 *19*
		1360.196 *4*	4.256 *15*
		1771.327 *3*	15.49 *5*
		2015.176 *5*	3.029 *13*
		2034.752 *5*	7.771 *27*
		2113.092 *6*	0.366 *6*
		2212.898 *3*	0.390 *7*
		2213.092 *6*	
		2598.437 *4*	16.96 *6*
		3009.558 *4*	0.995 *21*
		3201.930 *11*	3.13 *9*
		3253.402 *5*	7.62 *24*
		3272.977 *6*	1.78 *6*
		3451.119 *4*	0.93 *4*
		3548.3	0.178 *9*
^{57}Co	271.79 d	14.4	9.16 *15*
		122.06065 *12*	85.60 *17*
		136.47350 *29*	10.68 *8*
^{58}Co	70.82 d	810.7594 *20*	99.45 *1*
		863.951 *6*	0.69 *3*
		1674.725 *7*	0.519 *10*
^{60}Co	5.2714 y	1173.228 *3*	99.857 *22*
		1332.490 *6*	99.983 *6*
^{65}Zn	244.26 d	1115.539 *2*	50.60 *24*

Table 1. Gamma-ray Energies and Absolute Intensities (continued)

Source	Half-life	E_γ(keV)	I_γ(%)
^{66}Ga	9.49 h	833.5324 *21*	6.03 *23*
		1039.220 *3*	37.9 *12*
		1333.113 *5*	1.23 *5*
		1418.753 *5*	
		1508.158 *7*	
		1918.329 *5*	2.14 *8*
		2189.616 *6*	5.71 *21*
		2422.523 *7*	1.96 *7*
		2751.835 *5*	23.2 *11*
		3228.800 *6*	1.48 *12*
		3380.851 *6*	1.40 *12*
		3422.040 *8*	
		3791.009 *6*	1.02 *11*
		4085.853 *9*	1.14 *19*
		4295.7	3.5 *7*
		4461.202 *9*	
		4806.005 *10*	1.5 *4*
^{75}Se	119.779 d	66.0518 *8*	1.10 *2*
		96.7340 *9*	3.41 *4*
		121.1155 *11*	17.1 *1*
		136.0001 *6*	58.8 *3*
		198.6060 *12*	1.49 *1*
		264.6576 *9*	59.0 *2*
		279.5422 *10*	25.0 *1*
		303.9236 *10*	1.31 *1*
		400.6572 *8*	11.5 *1*
^{82}Br	35.30 h	221.4788 *18*	
		554.346 *3*	
		619.104 *3*	
		698.368 *3*	
		776.513 *4*	
		827.825 *5*	
		1043.993 *5*	
		1317.466 *4*	
		1474.874 *5*	
		1650.328 *5*	
^{84}Rb	32.77 d	881.6041 *16*	
		1016.158 *11*	
		1897.751 *11*	
^{85}Sr	64.84 d	514.0048 *22*	98.4 *4*
^{88}Y	106.65 d	898.036 *4*	94.0 *3*
		1836.052 *13*	99.36 *3*
^{95}Zr	64.02 d	724.192 *4*	44.15 *20*
		756.7	54.50 *25*
^{94}Nb	2.0×10^4 y	702.638 *5*	99.79 *5*
		871.114 *3*	99.86 *5*
^{95}Nb	34.975 d	765.8	99.81 *3*
^{99}Mo	65.94 h	40.58323 *17*	
		140.510 *1*	
^{95m}Tc	61 d	204.1161 *17*	
		582.0775 *21*	
		786.1922 *27*	
		820.622 *7*	
		835.146 *6*	
		1039.260 *6*	
^{99m}Tc	6.01 h	140.510 *1*	89.0 *2*
^{106}Ru	373.59 d	511.8534 *23*	
^{108m}Ag	127.0 y	433.937 *4*	
		614.276 *4*	
		722.906 *10*	
^{110m}Ag	249.76 d	446.812 *3*	3.72 *3*
		620.3547 *22*	
		657.7600 *12*	94.4 *1*
		677.6216 *13*	10.40 *8*
		687.0085 *20*	6.44 *3*
		706.6752 *17*	16.6 *1*
		744.2754 *18*	4.70 *4*
		763.9420 *18*	22.39 *8*
		818.0243 *19*	7.32 *4*
		884.6779 *13*	72.7 *3*
		937.484 *4*	34.31 *12*
		1384.2921 *22*	24.25 *8*
		1475.7790 *24*	3.99 *2*
		1505.0273 *24*	13.04 *4*
		1562.2937 *18*	
^{109}Cd	462.6 d	88.0336 *10*	3.63 *2*
^{111}In	2.8049 d	171.3	90.78 *10*
		245.3	94.16 *6*
^{115m}In	4.486 h	336.2	45.9 *2*
^{113}Sn	115.09 d	391.698 *3*	64.89 *13*
^{125}Sn	9.64 d	1806.690 *16*	
		1889.884 *16*	
		2002.132 *13*	
		2201.002 *12*	
		2275.749 *10*	
^{124}Sb	60.20 d	602.7260 *23*	98.0 *1*
		645.8520 *19*	7.3 *1*
		713.777 *4*	
		722.783 *4*	11.3 *2*
		790.708 *6*	
		968.194 *4*	
		1045.125 *4*	
		1325.505 *4*	
		1368.156 *5*	
		1436.556 *6*	
		1690.971 *4*	48.5 *3*
		2090.930 *6*	5.66 *9*
^{125}Sb	2.7582 y	176.314 *2*	6.85 *7*
		380.5	1.518 *16*
		427.874 *4*	29.7 *3*
		463.365 *4*	10.48 *11*
		600.597 *2*	17.73 *18*
		606.713 *2*	5.00 *5*
		635.950 *3*	11.21 *12*
		671.441 *6*	1.80 *2*
^{125}I	59.408 d	35.5	6.58 *8*
^{132}Cs	6.479 d	667.714 *3*	
		1317.916 *7*	
		1985.623 *8*	
^{134}Cs	2.062 y	475.4	1.49 *2*
		563.2	8.36 *3*
		569.3	15.39 *6*
		604.7	97.63 *6*
		795.8	85.4 *3*
		801.9	8.69 *3*
		1038.6	0.990 *5*
		1168.0	1.792 *7*
		1365.2	3.016 *11*
^{137}Cs	30.07 y	661.657 *3*	85.1 *2*

Table 1. Gamma-ray Energies and Absolute Intensities (continued)

Source	Half-life	E_γ(keV)	I_γ(%)
^{133}Ba	10.52 y	53.1625 *6*	
		79.6139 *13*	
		80.9971 *12*	34.11 *28*
		160.6109 *17*	
		223.2373 *14*	
		276.3997 *13*	7.147 *30*
		302.8510 *6*	18.30 *6*
		356.0134 *6*	61.94 *14*
		383.8480 *12*	8.905 *29*
^{139}Ce	137.640 d	165.857 *3*	79.87 *6*
^{141}Ce	32.501 d	145.4433 *14*	48.6 *4*
^{144}Ce	284.893 d	696.505 *4*	
		1489.148 *3*	
		2185.645 *5*	
^{152}Eu	13.542 y	121.7817 *3*	28.37 *13*
		244.6975 *8*	7.53 *4*
		295.9390 *7*	
		344.2785 *13*	26.57 *11*
		367.7891 *20*	
		411.1165 *13*	2.238 *10*
		444.0	3.125 *14*
		778.9045 *24*	12.97 *6*
		867.378 *4*	4.214 *25*
		964.1	14.63 *6*
		1085.836 *9*	10.13 *5*
		1089.737 *5*	1.731 *9*
		1112.074 *4*	13.54 *6*
		1212.948 *11*	1.412 *8*
		1299.140 *9*	1.626 *11*
		1408.011 *4*	20.85 *9*
		1457.643 *11*	
^{154}Eu	8.593 y	123.0706 *9*	41.2 *5*
		247.9289 *7*	6.95 *9*
		591.755 *3*	4.99 *6*
		723.3009 *22*	20.2 *2*
		756.8020 *23*	4.58 *6*
		873.1839 *23*	12.24 *15*
		996.3	10.48 *13*
		1004.7	18.2 *2*
		1274.427 *4*	35.0 *4*
		1494.050 *5*	0.71 *2*
		1596.4804 *27*	1.81 *2*
^{153}Gd	241.6 d	69.67300 *13*	
		75.42213 *23*	
		83.36717 *21*	
		89.48595 *22*	
		97.43100 *21*	
		103.18012 *17*	
		172.85307 *19*	
^{160}Tb	72.3 d	86.7877 *3*	
		197.0341 *10*	
		215.6452 *11*	
		298.5783 *17*	
		879.378 *2*	
		962.311 *3*	
		966.166 *2*	
		1177.954 *3*	
		1271.873 *5*	

Source	Half-life	E_γ(keV)	I_γ(%)
^{161}Tb	6.88 d	25.65135 *3*	
		48.91533 *5*	
		57.1917 *3*	
		74.56669 *6*	
^{166m}Ho	1200 y	80.5725 *13*	
		184.4107 *11*	
		280.4630 *23*	
		300.741 *3*	
		410.956 *3*	
		451.540 *4*	
		529.825 *4*	
		570.995 *5*	
		670.526 *4*	
		711.697 *3*	
		752.280 *4*	
		778.827 *6*	
		810.286 *4*	
		830.565 *4*	
		875.663 *7*	
		950.988 *4*	
		1241.519 *4*	
		1282.102 *5*	
^{170}Tm	128.6 d	84.25474 *8*	
^{169}Yb	32.026 d	63.12044 *4*	
		93.61447 *7*	
		109.77924 *4*	
		118.18940 *14*	
		130.52293 *6*	
		177.21307 *6*	
		197.95675 *7*	
		261.07712 *9*	
		307.73586 *10*	
^{177m}Lu	160.4 d	105.3596 *6*	
		112.9499 *5*	
		121.6211 *5*	
		128.5031 *5*	
		136.7249 *12*	
		153.2844 *5*	
		171.8577 *8*	
		174.3992 *5*	
		177.0009 *5*	
		204.1053 *5*	
		208.3665 *5*	
		214.4340 *6*	
		218.1040 *7*	
		228.4839 *6*	
		233.8609 *8*	
		249.6742 *10*	
		268.7851 *10*	
		281.7874 *9*	
		296.4582 *6*	
		299.0507 *17*	
		305.5030 *14*	
		313.7253 *21*	
		319.0207 *8*	
		321.3164 *16*	
		327.6831 *7*	
		341.6434 *10*	
		367.4178 *10*	

Table 1. Gamma-ray Energies and Absolute Intensities (continued)

Source	Half-life	E_γ(keV)	I_γ(%)
^{177m}**Lu**	(continued)	378.5031 *7*	
		385.0306 *9*	
		413.6638 *7*	
		426.4728 *24*	
		465.8418 *10*	
^{172}**Hf**	1.87 y	23.9330 *2*	
		78.7422 *6* @	
		81.7509 *5* @	
		90.6435 *19*	
^{182}**Ta**	114.43 d	65.71115 *15*	
		67.74970 *10*	
		84.68024 *26*	
		100.10595 *7*	14.23 *25*
		113.67170 *22*	
		116.4179 *6*	
		152.42991 *26*	7.02 *8*
		156.38645 *30*	
		179.39381 *25*	
		198.35189 *29*	
		222.1085 *3*	7.57 *8*
		229.3207 *6*	
		264.0740 *3*	
		1121.290 *3*	35.3 *2*
		1157.302 *3*	
		1189.040 *3*	16.42 *10*
		1221.395 *3*	27.20 *22*
		1231.004 *3*	11.57 *8*
		1257.407 *3*	
		1273.719 *3*	
		1289.145 *3*	
		1373.824 *3*	
		1387.390 *3*	
^{185}**Os**	93.6 d	125.358 *3*	
		162.853 *4*	
		234.156 *4*	
		592.0713 *28*	
		646.127 *4*	
		717.429 *4*	
		874.826 *4*	
		880.2814 *28*	
^{192}**Ir**	73.83 d	136.34257 *26*	
		205.79430 *9*	
		295.95650 *15*	28.7 *1*
		308.45507 *17*	29.8 *1*
		316.50618 *17*	83.0 *3*
		416.4678 *7*	
		468.06885 *26*	47.7 *2*
		484.5751 *4*	
		588.5810 *7*	4.49 *2*
		604.41105 *25*	8.11 *4*
		612.46215 *26*	5.28 *3*
		884.5365 *7*	
^{198}**Au**	2.69517 d	411.80205 *17*	95.6 *5*
		675.8836 *7*	
		1087.6842 *7*	
^{199}**Au**	3.139 d	49.82635 *12*	
		158.37851 *10*	
		208.20481 *12*	
^{203}**Hg**	46.612 d	279.194 *3*	81.48 *8*
^{203}**Pb**	51.873 h	279.194 *3*	
		401.320 *4*	
		680.514 *4*	
^{210}**Pb**	22.3 y	46.539 *1*	
^{207}**Bi**	31.55 y	569.698 *2*	97.74 *3*
		1063.656 *3*	74.5 *2*
		1770.228 *9*	6.87 *4*
^{228}**Th**†	1.9131 y	84.4	1.22 *2*
		238.6	43.5 *4*
		241.0	4.10 *5*
		277.4	2.30 *3*
		300.1	3.25 *3*
		510.8	8.18 *10*
		583.187 *2*	30.6 *2*
		727.3	6.69 *9*
		860.6	4.50 *4*
		1620.7	1.49 *5*
		2614.511 *10*	35.86 *6*
^{239}**Np**	2.3565 d	106.1	26.7 *4*
		228.2	11.12 *15*
		277.6	14.31 *20*
^{241}**Am**	432.2 y	26.3446 *2*	2.4 *1*
		59.5409 *2*	36.0 *4*
^{243}**Am**	7370 y	43.5	5.94 *11*
		74.7	67.4 *10*

@ In equilibrium with ^{172}Lu (6.70 d)

† In equilibrium with decay daughter isotopes