156

UNIVERSITY OF SWAZILAND

FACULTY OF SCIENCE

DEPARTMENT OF PHYSICS

MAIN EXAMINATION 2005

TITLE OF THE PAPER: NUCLEAR PHYSICS

COURSE NUMBER: P442

TIME ALLOWED: THREE HOURS

INSTRUCTIONS: Answer four Questions. Each Question carries 25 Marks. Marks for each section are shown

Do not open this Paper until you are told to do so by the **Invigilator**.

This Paper contains **SEVEN PAGES** including this one. There are several pages of data and other information included .

Question 1

a) Assume a nucleus to be a sphere of uniform charge distribution with charge density ρ. Let the sphere have a radius R.

(i) Find the electric field in and outside the sphere. (5 Marks)

(ii) Evaluate the potential of this charged sphere. (6 Marks)

(iii) Deduce the potential energy that an electron may have if it ventured inside such a charged sphere. (3 Marks)

(iv) Comment on the reasonableness of the answer in (iii). (3 Marks)

[Hint: Gauss' law may be used.]

b) From the known masses of $^{15}_{8}O$ and $^{15}_{7}N$, compute the difference in binding energy. State in which one of the two nuclei are the bonds between the nucleons stronger and explain why. (8 Marks)

Question 2

It is convenient to analyse the deuteron by assuming the nucleon-nucleon potential to be represented by a three-dimensional square-well, as shown in Fig 2.1. The wave

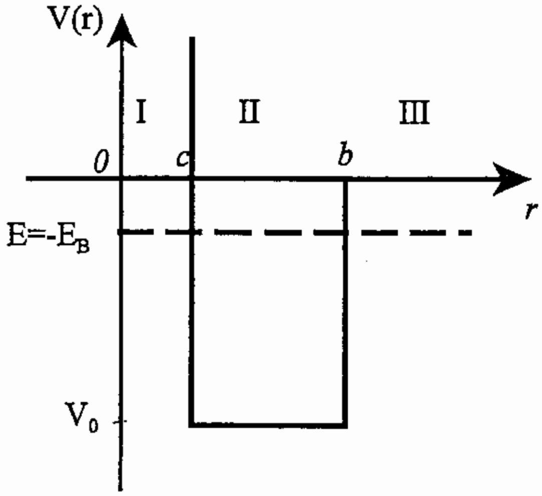

Fig 2.1

function is zero in region I. The Schrodinger equation for region II is of the form:

$$\frac{d^2u}{dr^2}+\frac{2m}{\hbar}\left(V_0-E_B\right)u=0$$

The solutions in regions II and III, respectively, are of the form:

$$u(r)=A\sin k_1 r+B\cos k_1 r$$

and

$$u(r)=Ce^{-k_2 r}+De^{+k_2 r}$$

The symbols have their usual meaning.

a) Use the continuity and normalisation conditions to evaluate the coefficients in the above possible solutions. (12 Marks)

b) From the resulting wave function, evaluate the root-mean-square radius of the deuteron. (13 Marks)

Question 3

a) The low-lying levels of ^{13}C are ground state, $\frac{1}{2}^-$; 3.09 MeV, $\frac{1}{2}^+$; 3.68 MeV, $\frac{3}{2}^-$; 3.85 MeV, $\frac{5}{2}^+$. The next states are about 7 MeV and above. Interpret these four states according to the Shell model. (15 Marks)

b) Find the mean-square radius of a uniformly charged sphere of R. Take that sphere to represent a nucleus. (5 Marks)

c) Compute the expected Shell model quadrupole moment of $^{209}Bi\left(\frac{9^-}{2}\right)$. (5 Marks)

Question 4

a) Three radioactive sources are each having activities of 1.0 μCi at t=0. Their half lives are, respectively, 1.0 s, 1.0 h and 1.0 d. How many radioactive nuclei are present at t=0 in each source? (6 Marks)

b) Among the radioactive products emitted in the 1986 Chernobyl reactor accident, in Russia, were $^{131}I\left(t_{1/2} = 8.0d\right)$ and $^{137}Cs\left(t_{1/2} = 30d\right)$. There are about five times as many ^{137}Cs atoms as ^{131}I atoms produced in fission.

(i) Which isotope contributes the greater activity to the radiation cloud? Assume the reactor had been operating continuously for several days before the radiation was released. (8 Marks)

(ii) How long after the original incident does it take for the two activities to become equal? (6 Marks)

(iii) About 1% of fission events produce ^{131}I, and each fission event releases an energy of about 200 MeV. Given a reactor of the Chernobly size (1000 MW), calculate the activity in curies of ^{131}I after 24 h of operation. (5 Marks)

Question 5

a) In the decay of ^{47}Ca to ^{47}Sc, what energy is given to the neutrino when the electron has a kinetic energy of 1.100 MeV? (5 Marks

b) Supply the missing component(s) in the following processes:

(i) $\overline{\upsilon} + {}^{3}He \rightarrow$ (1 Mark)

(ii) ${}^{6}He \rightarrow {}^{6}Li + e^{-} +$ (1 Mark)

(iii) $e^{-} + {}^{8}B \rightarrow$ (1 Mark)

(iv) $\upsilon + {}^{12}C \rightarrow$ (1 Mark)

(v) ${}^{40}K \rightarrow \upsilon +$ (1 Mark)

(vi) ${}^{40}K \rightarrow \overline{\upsilon} +$ (1 Mark)

c) One of the processes that is most likely responsible for the production of neutrinos in the sun is the electron capture decay of ^{7}Be. Compute the energy of emitted neutrino and the kinetic energy of the ^{7}Li nucleus. (14 Marks)

Question 6

a) The Q-value for the reaction $^{9}Be(p,d)^{8}Be$ is 559.5±0.4 keV. Use this information along with the accurately know masses of ^{9}Be, ^{2}H, and ^{1}H to find the mass of ^{8}Be. Give an error estimation of your result, taking account of the errors suggested in the table of nuclides. (8 Marks)

b) A sample of gold is exposed to a beam of neutrons, and the reaction $^{197}Au(n,\gamma)^{198}Au$ absorbs 10^{8} neutrons per second. ^{198}Au emits β-particles and has a half life of 2.70 days. How many atoms of ^{198}Au are present after two days of continuous irradiation. (11 Marks)

c) Complete the following reactions:

(i)

$$^{13}C(d,\alpha)$$

$$^{27}Al + p \rightarrow \cdots + n$$

$$^{197}Au + ^{12}C \rightarrow ^{206}At +$$

(3 Marks)

(ii) Show whether the first of these equations is endoergic or not. (3 Marks)

Some Useful Data and Information

In the definition of mean radius of nucleus, let constant of proportionality R_0 be 1.2 fm

Single-particle quadruple moment $\langle Q_{sp} \rangle$ of odd proton in shell-model state j is given as

$$\langle Q_{sp} \rangle = -\frac{2j-1}{2(j+1)}\langle r^2 \rangle$$

Relativistic kinetic energy K is given as

$$K = E - mc^2$$

where

$$E = \sqrt{p^2c^2 + m^2c^4}$$

CONSTANTS

Speed of light	c	2.99792458×10^{8} m/s
Charge of electron	e	1.602189×10^{-19} C
Boltzmann constant	k	1.38066×10^{-23} J/K
		8.6174×10^{-5} eV/K
Planck's constant	h	6.62618×10^{-34} J · s
		4.13570×10^{-15} eV · s
	$\hbar = h/2\pi$	1.054589×10^{-34} J · s
		6.58217×10^{-16} eV · s
Gravitational constant	G	6.6726×10^{-11} N · m²/kg²
Avogadro's number	N_A	6.022045×10^{23} mole^{-1}
Universal gas constant	R	8.3144 J/mole · K
Stefan-Boltzmann constant	σ	5.6703×10^{-8} W/m² · K⁴
Rydberg constant	R_∞	1.0973732×10^{7} m^{-1}
Hydrogen ionization energy		13.60580 eV
Bohr radius	a_0	5.291771×10^{-11} m
Bohr magneton	μ_B	9.27408×10^{-24} J/T
		5.78838×10^{-5} eV/T
Nuclear magneton	μ_N	5.05084×10^{-27} J/T
		3.15245×10^{-8} eV/T
Fine structure constant	α	1/137.0360
	hc	1239.853 MeV · fm
	$\hbar c$	197.329 MeV · fm
	$e^2/4\pi\epsilon_0$	1.439976 MeV · fm

PARTICLE REST MASSES

	u	MeV/c^2
Electron	5.485803×10^{-4}	0.511003
Proton	1.00727647	938.280
Neutron	1.00866501	939.573
Deuteron	2.01355321	1875.628
Alpha	4.00150618	3727.409
$\pi^{\pm}$	0.1498300	139.5669
π^{0}	0.1448999	134.9745
μ	0.1134292	105.6595

CONVERSION FACTORS

1 eV = 1.602189×10^{-19} J

1 u = 931.502 MeV/c^2
= 1.660566×10^{-27} kg

1 b = 10^{-28} m²

1 Ci = 3.7×10^{10} decays/s

PERIODIC TABLE OF THE ELEMENTS

1 H 1.0079																	2 He 4.0026
3 Li 6.941	4 Be 9.012											5 B 10.81	6 C 12.011	7 N 14.007	8 O 15.999	9 F 18.998	10 Ne 20.179
11 Na 22.990	12 Mg 24.305											13 Al 26.982	14 Si 28.086	15 P 30.974	16 S 32.06	17 Cl 35.453	18 Ar 39.948
19 K 39.098	20 Ca 40.08	21 Sc 44.956	22 Ti 47.90	23 V 50.942	24 Cr 51.996	25 Mn 54.938	26 Fe 55.847	27 Co 58.933	28 Ni 58.70	29 Cu 63.546	30 Zn 65.38	31 Ga 69.72	32 Ge 72.59	33 As 74.922	34 Se 78.96	35 Br 79.904	36 Kr 83.80
37 Rb 85.468	38 Sr 87.62	39 Y 88.906	40 Zr 91.22	41 Nb 92.906	42 Mo 95.94	43 Tc (97)	44 Ru 101.07	45 Rh 102.91	46 Pd 106.4	47 Ag 107.87	48 Cd 112.41	49 In 114.82	50 Sn 118.69	51 Sb 121.75	52 Te 127.60	53 I 126.90	54 Xe 131.30
55 Cs 132.91	56 Ba 137.33	57–71 Rare Earths	72 Hf 178.49	73 Ta 180.95	74 W 183.85	75 Re 186.21	76 Os 190.2	77 Ir 192.22	78 Pt 195.09	79 Au 196.97	80 Hg 200.59	81 Tl 204.37	82 Pb 207.2	83 Bi 208.98	84 Po (209)	85 At (210)	86 Rn (222)
87 Fr (223)	88 Ra (226)	89–103 Acti-nides	104 Rf (257)	105 Ha	106 (263)	107	108	109									

Rare Earths (Lanthanides)	57 La 138.91	58 Ce 140.12	59 Pr 140.91	60 Nd 144.24	61 Pm (145)	62 Sm 150.4	63 Eu 151.96	64 Gd 157.25	65 Tb 158.93	66 Dy 162.50	67 Ho 164.93	68 Er 167.26	69 Tm 168.93	70 Yb 173.04	71 Lu 174.97
Actinides	89 Ac (227)	90 Th 232.04	91 Pa (231)	92 U 238.03	93 Np (237)	94 Pu (244)	95 Am (243)	96 Cm (247)	97 Bk (247)	98 Cf (251)	99 Es (254)	100 Fm (257)	101 Md (258)	102 No (259)	103 Lr (260)

For each element, the bottom line gives either the atomic mass or (in parentheses, for radioactive elements) the mass number of the most stable isotope.

TABLE OF NUCLEAR PROPERTIES

The following table shows some properties of a selection of isotopes. For each element only the stable and relatively long-lived radioactive isotopes are included. Ground-state atomic masses and spin-parity assignments are shown for all isotopes; uncertain spin-parity assignments are in parentheses. Abundances are given for stable isotopes, and for radioactive isotopes the half-life and principal decay mode are shown (ε—electron capture, possibly including positron emission; β^-—negative beta decay; α—alpha decay; f—spontaneous fission). The masses are those of the corresponding neutral atoms and were taken from the 1983 atomic mass evaluation: A. H. Wapstra and G. Audi, *Nucl. Phys.* **A432**, 1 (1985). In the half-life entries, My = 10^6 y. Uncertainties in the masses are typically 10^{-5} u (10^{-4} u for some cases far from stability); uncertainties in the abundances and half-lives are typically at or below the level of the last digit tabulated.

	Z	A	Atomic mass (u)	I^π	*Abundance* or Half-life
H	1	1	1.007825	$\frac{1}{2}^+$	*99.985%*
		2	2.014102	1^+	*0.015%*
		3	3.016049	$\frac{1}{2}^+$	12.3 y (β^-)
He	2	3	3.016029	$\frac{1}{2}^+$	*1.38 × 10⁻⁴%*
		4	4.002603	0^+	*99.99986%*
Li	3	6	6.015121	1^+	*7.5%*
		7	7.016003	$\frac{3}{2}^-$	*92.5%*
		8	8.022486	2^+	0.84 s (β^-)
Be	4	7	7.016928	$\frac{3}{2}^-$	53.3 d (ε)
		8	8.005305	0^+	0.07 fs (α)
		9	9.012182	$\frac{3}{2}^-$	*100%*
		10	10.013534	0^+	1.6 My (β^-)
		11	11.021658	$\frac{1}{2}^+$	13.8 s (β^-)
B	5	8	8.024606	2^+	0.77 s (ε)
		9	9.013329	$\frac{3}{2}^-$	0.85 as (α)
		10	10.012937	3^+	*19.8%*
		11	11.009305	$\frac{3}{2}^-$	*80.2%*
		12	12.014353	1^+	20.4 ms (β^-)
		13	13.017780	$\frac{3}{2}^-$	17.4 ms (β^-)
C	6	9	9.031039	$\frac{3}{2}^-$	0.13 s (ε)
		10	10.016856	0^+	19.2 s (ε)
		11	11.011433	$\frac{3}{2}^-$	20.4 m (ε)
		12	12.000000	0^+	*98.89%*
		13	13.003355	$\frac{1}{2}^-$	*1.11%*
		14	14.003242	0^+	5730 y (β^-)
		15	15.010599	$\frac{1}{2}^+$	2.45 s (β^-)
N	7	12	12.018613	1^+	11 ms (ε)
		13	13.005739	$\frac{1}{2}^-$	9.96 m (ε)
		14	14.003074	1^+	*99.63%*
		15	15.000109	$\frac{1}{2}^-$	*0.366%*
		16	16.006100	2^-	7.13 s (β^-)

	Z	A	Atomic mass (u)	I^{π}	*Abundance* or Half-life
		17	17.008450	$\frac{1}{2}^{-}$	4.17 s (β^-)
		18	18.014081	1^{-}	0.63 s (β^-)
O	8	14	14.008595	0^{+}	71 s (ε)
		15	15.003065	$\frac{1}{2}^{-}$	122 s (ε)
		16	15.994915	0^{+}	*99.76%*
		17	16.999131	$\frac{5}{2}^{+}$	*0.038%*
		18	17.999160	0^{+}	*0.204%*
		19	19.003577	$\frac{5}{2}^{+}$	26.9 s (β^-)
		20	20.004076	0^{+}	13.5 s (β^-)
F	9	17	17.002095	$\frac{5}{2}^{+}$	64.5 s (ε)
		18	18.000937	1^{+}	110 m (ε)
		19	18.998403	$\frac{1}{2}^{+}$	*100%*
		20	19.999981	2^{+}	11 s (β^-)
		21	20.999948	$\frac{5}{2}^{+}$	4.3 s (β^-)
		22	22.003030	$(3,4)^{+}$	4.2 s (β^-)
		23	23.003600	$(\frac{3}{2},\frac{5}{2})^{+}$	2.2 s (β^-)
Ne	10	17	17.017690	$\frac{1}{2}^{-}$	0.11 s (ε)
		18	18.005710	0^{+}	1.7 s (ε)
		19	19.001880	$\frac{1}{2}^{+}$	17.3 s (ε)
		20	19.992436	0^{+}	*90.51%*
		21	20.993843	$\frac{3}{2}^{+}$	*0.27%*
		22	21.991383	0^{+}	*9.22%*
		23	22.994465	$\frac{5}{2}^{+}$	37.6 s (β^-)
		24	23.993613	0^{+}	3.4 m (β^-)
		25	24.997690	$(\frac{1}{2},\frac{3}{2})^{+}$	0.60 s (β^-)
Na	11	20	20.007344	2^{+}	0.45 s (ε)
		21	20.997651	$\frac{3}{2}^{+}$	22.5 s (ε)
		22	21.994434	3^{+}	2.60 y (ε)
		23	22.989768	$\frac{3}{2}^{+}$	*100%*
		24	23.990961	4^{+}	15.0 h (β^-)
		25	24.989953	$\frac{5}{2}^{+}$	60 s (β^-)
		26	25.992586	3^{+}	1.1 s (β^-)
		27	26.993940	$\frac{5}{2}^{+}$	0.30 s (β^-)
Mg	12	21	21.011716	$(\frac{3}{2},\frac{5}{2})^{+}$	0.123 s (ε)
		22	21.999574	0^{+}	3.86 s (ε)
		23	22.994124	$\frac{3}{2}^{+}$	11.3 s (ε)
		24	23.985042	0^{+}	*78.99%*
		25	24.985837	$\frac{5}{2}^{+}$	*10.00%*
		26	25.982594	0^{+}	*11.01%*
		27	26.984341	$\frac{1}{2}^{+}$	9.46 m (β^-)
		28	27.983877	0^{+}	21.0 h (β^-)
		29	28.988480	$\frac{3}{2}^{+}$	1.4 s (β^-)
Al	13	24	23.999941	4^{+}	2.07 s (ε)
		25	24.990429	$\frac{5}{2}^{+}$	7.18 s (ε)
		26	25.986892	5^{+}	0.72 My (ε)
		27	26.981539	$\frac{5}{2}^{+}$	*100%*
		28	27.981910	3^{+}	2.24 m (β^-)
		29	28.980446	$\frac{5}{2}^{+}$	6.6 m (β^-)
		30	29.982940	3^{+}	3.7 s (β^-)
Si	14	26	25.992330	0^{+}	2.21 s (ε)
		27	26.986704	$\frac{5}{2}^{+}$	4.13 s (ε)
		28	27.976927	0^{+}	*92.23%*
		29	28.976495	$\frac{1}{2}^{+}$	*4.67%*
		30	29.973770	0^{+}	*3.10%*
		31	30.975362	$\frac{3}{2}^{+}$	2.62 h (β^-)
		32	31.974148	0^{+}	105 y (β^-)
		33	32.997920	$(\frac{3}{2}^{+})$	6.2 s (β^-)
P	15	29	28.981803	$\frac{1}{2}^{+}$	4.1 s (ε)
		30	29.978307	1^{+}	2.50 m (ε)
		31	30.973762	$\frac{1}{2}^{+}$	*100%*
		32	31.973907	1^{+}	14.3 d (β^-)
		33	32.971725	$\frac{1}{2}^{+}$	25.3 d (β^-)
		34	33.973636	1^{+}	12.4 s (β^-)
S	16	30	29.984903	0^{+}	1.2 s (ε)
		31	30.979554	$\frac{1}{2}^{+}$	2.6 s (ε)
		32	31.972071	0^{+}	*95.02%*
		33	32.971458	$\frac{3}{2}^{+}$	*0.75%*
		34	33.967867	0^{+}	*4.21%*
		35	34.969032	$\frac{3}{2}^{+}$	87.4 d (β^-)
		36	35.967081	0^{+}	*0.017%*
		37	36.971126	$\frac{7}{2}^{-}$	5.0 m (β^-)
		38	37.971162	0^{+}	170 m (β^-)
Cl	17	33	32.977452	$\frac{3}{2}^{+}$	2.51 s (ε)
		34	33.973763	0^{+}	1.53 s (ε)
		35	34.968853	$\frac{3}{2}^{+}$	*75.77%*
		36	35.968307	2^{+}	0.30 My (β^-)
		37	36.965903	$\frac{3}{2}^{+}$	*24.23%*
		38	37.968011	2^{-}	37.3 m (β^-)
		39	38.968005	$\frac{3}{2}^{+}$	56 m (β^-)
		40	39.970440	2^{-}	1.35 m (β^-)
		41	40.970590	$(\frac{1}{2},\frac{3}{2})^{+}$	31 s (β^-)
Ar	18	34	33.980269	0^{+}	0.844 s (ε)
		35	34.975256	$\frac{3}{2}^{+}$	1.78 s (ε)
		36	35.967546	0^{+}	*0.337%*
		37	36.966776	$\frac{3}{2}^{+}$	35.0 d (ε)
		38	37.962732	0^{+}	*0.063%*
		39	38.964314	$\frac{7}{2}^{-}$	269 y (β^-)
		40	39.962384	0^{+}	*99.60%*
		41	40.964501	$\frac{7}{2}^{-}$	1.83 h (β^-)

	Z	A	Atomic mass (u)	I^{π}	*Abundance* or Half-life
		42	41.963050	0^+	33 y (β^-)
		43	42.965670		5.4 m (β^-)
		44	43.965365	0^+	11.9 m (β^-)
K	19	37	36.973377	$\frac{3}{2}^+$	1.23 s (ε)
		38	37.969080	3^+	7.61 m (ε)
		39	38.963707	$\frac{3}{2}^+$	*93.26%*
		40	39.963999	4^-	1.28 Gy (β^-)
		41	40.961825	$\frac{3}{2}^+$	*6.73%*
		42	41.962402	2^-	12.4 h (β^-)
		43	42.960717	$\frac{3}{2}^-$	22.3 h (β^-)
		44	43.961560	2^-	22.1 m (β^-)
		45	44.960696	$\frac{3}{2}^+$	17 m (β^-)
		46	45.961976	(2^-)	115 s (β^-)
		47	46.961677	$\frac{1}{2}^+$	17.5 s (β^-)
Ca	20	38	37.976318	0^+	0.44 s (ε)
		39	38.970718	$\frac{3}{2}^+$	0.86 s (ε)
		40	39.962591	0^+	*96.94%*
		41	40.962278	$\frac{7}{2}^-$	0.10 My (ε)
		42	41.958618	0^+	*0.647%*
		43	42.958766	$\frac{7}{2}^-$	*0.135%*
		44	43.955481	0^+	*2.09%*
		45	44.956185	$\frac{7}{2}^-$	165 d (β^-)
		46	45.953689	0^+	*0.0035%*
		47	46.954543	$\frac{7}{2}^-$	4.54 d (β^-)
		48	47.952533	0^+	*0.187%*
		49	48.955672	$\frac{3}{2}^-$	8.72 m (β^-)
		50	49.957519	0^+	14 s (β^-)
Sc	21	42	41.965514	0^+	0.68 s (ε)
		43	42.961150	$\frac{7}{2}^-$	3.89 h (ε)
		44	43.959404	2^+	3.93 h (ε)
		45	44.955910	$\frac{7}{2}^-$	*100%*
		46	45.955170	4^+	83.8 d (β^-)
		47	46.952409	$\frac{7}{2}^-$	3.35 d (β^-)
		48	47.952235	6^+	43.7 h (β^-)
		49	48.950022	$\frac{7}{2}^-$	57.0 m (β^-)
		50	49.952186	5^+	1.71 m (β^-)
Ti	22	43	42.968523	$\frac{7}{2}^-$	0.51 s (ε)
		44	43.959690	0^+	54 y (ε)
		45	44.958124	$\frac{7}{2}^-$	3.09 h (ε)
		46	45.952629	0^+	*8.2%*
		47	46.951764	$\frac{5}{2}^-$	*7.4%*
		48	47.947947	0^+	*73.7%*
		49	48.947871	$\frac{7}{2}^-$	*5.4%*
		50	49.944792	0^+	*5.2%*
		51	50.946616	$\frac{3}{2}^-$	5.80 m (β^-)
		52	51.946898	0^+	1.7 m (β^-)
		53	52.949730	$(\frac{3}{2})^-$	33 s (β^-)
V	23	46	45.960198	0^+	0.42 s (ε)
		47	46.954906	$\frac{3}{2}^-$	32.6 m (ε)
		48	47.952257	4^+	16.0 d (ε)
		49	48.948517	$\frac{7}{2}^-$	330 d (ε)
		50	49.947161	6^+	*0.250%*
		51	50.943962	$\frac{7}{2}^-$	*99.750%*
		52	51.944778	3^+	3.76 m (β^-)
		53	52.944340	$\frac{7}{2}^-$	1.6 m (β^-)
		54	53.946442	$(3,4,5)^+$	50 s (β^-)
Cr	24	46	45.968360	0^+	0.26 s (ε)
		47	46.962905	$\frac{3}{2}^-$	0.51 s (ε)
		48	47.954033	0^+	21.6 h (ε)
		49	48.951338	$\frac{5}{2}^-$	41.9 m (ε)
		50	49.946046	0^+	*4.35%*
		51	50.944768	$\frac{7}{2}^-$	27.7 d (ε)
		52	51.940510	0^+	*83.79%*
		53	52.940651	$\frac{3}{2}^-$	*9.50%*
		54	53.938882	0^+	*2.36%*
		55	54.940842	$\frac{3}{2}^-$	3.50 m (β^-)
		56	55.940643		5.9 m (β^-)
Mn	25	50	49.954240	0^+	0.28 s (ε)
		51	50.948213	$\frac{5}{2}^-$	46.2 m (ε)
		52	51.945568	6^+	5.59 d (ε)
		53	52.941291	$\frac{7}{2}^-$	3.7 My (ε)
		54	53.940361	3^+	312 d (ε)
		55	54.938047	$\frac{5}{2}^-$	*100%*
		56	55.938907	3^+	2.58 h (β^-)
		57	56.938285	$\frac{5}{2}^-$	1.6 m (β^-)
		58	57.940060	3^+	65 s (β^-)
Fe	26	51	50.956825	$(\frac{5}{2})^-$	0.25 s (ε)
		52	51.948114	0^+	8.27 h (ε)
		53	52.945310	$\frac{7}{2}^-$	8.51 m (ε)
		54	53.939613	0^+	*5.8%*
		55	54.938296	$\frac{3}{2}^-$	2.7 y (ε)
		56	55.934939	0^+	*91.8%*
		57	56.935396	$\frac{1}{2}^-$	*2.15%*
		58	57.933277	0^+	*0.29%*
		59	58.934877	$\frac{3}{2}^-$	44.6 d (β^-)
		60	59.934078	0^+	1.5 My (β^-)
		61	60.936748	$(\frac{3}{2},\frac{5}{2})^-$	6.0 m (β^-)
		62	61.936773	0^+	68 s (β^-)
Co	27	54	53.948460	0^+	0.19 s (ε)

	Z	A	Atomic mass (u)	I^π	*Abundance* or Half-life
		55	54.942001	$\frac{7}{2}^-$	17.5 h (ε)
		56	55.939841	4^+	78.8 d (ε)
		57	56.936294	$\frac{7}{2}^-$	271 d (ε)
		58	57.935755	2^+	70.8 d (ε)
		59	58.933198	$\frac{7}{2}^-$	*100%*
		60	59.933820	5^+	5.27 y (β^-)
		61	60.932478	$\frac{7}{2}^-$	1.65 h (β^-)
		62	61.934060	2^+	1.5 m (β^-)
		63	62.933614	$(\frac{7}{2})^-$	27.5 s (β^-)
Ni	28	55	54.951336	$\frac{7}{2}^-$	0.19 s (ε)
		56	55.942134	0^+	6.10 d (ε)
		57	56.939799	$\frac{3}{2}^-$	36.0 h (ε)
		58	57.935346	0^+	*68.3%*
		59	58.934349	$\frac{3}{2}^-$	0.075 My (ε)
		60	59.930788	0^+	*26.1%*
		61	60.931058	$\frac{3}{2}^-$	*1.13%*
		62	61.928346	0^+	*3.59%*
		63	62.929670	$\frac{1}{2}^-$	100 y (β^-)
		64	63.927968	0^+	*0.91%*
		65	64.930086	$\frac{5}{2}^-$	2.52 h (β^-)
		66	65.929116	0^+	54.8 h (β^-)
		67	66.931570	?	21 s (β^-)
Cu	29	59	58.939503	$\frac{3}{2}^-$	82 s (ε)
		60	59.937366	2^+	23.4 m (ε)
		61	60.933461	$\frac{3}{2}^-$	3.41 h (ε)
		62	61.932586	1^+	9.73 m (ε)
		63	62.929599	$\frac{3}{2}^-$	*69.2%*
		64	63.292766	1^+	12.7 h (ε)
		65	64.927793	$\frac{3}{2}^-$	*30.8%*
		66	65.928872	1^+	5.10 m (β^-)
		67	66.927747	$\frac{3}{2}^-$	61.9 h (β^-)
		68	67.929620	1^+	31 s (β^-)
Zn	30	61	60.939514	$\frac{3}{2}^-$	89 s (ε)
		62	61.934332	0^+	9.2 h (ε)
		63	62.933214	$\frac{3}{2}^-$	38.1 m (ε)
		64	63.929145	0^+	*48.6%*
		65	64.929243	$\frac{5}{2}^-$	244 d (ε)
		66	65.926035	0^+	*27.9%*
		67	66.927129	$\frac{5}{2}^-$	*4.10%*
		68	67.924846	0^+	*18.8%*
		69	68.926552	$\frac{1}{2}^-$	56 m (β^-)
		70	69.925325	0^+	*0.62%*
		71	70.927727	$\frac{1}{2}^-$	2.4 m (β^-)
		72	71.926856	0^+	46.5 h (β^-)
		73	72.929780	$(\frac{3}{2})^-$	24 s (β^-)

	Z	A	Atomic mass (u)	I^π	*Abundance* or Half-life
Ga	31	64	63.936836	0^+	2.6 m (ε)
		65	64.932738	$\frac{3}{2}^-$	15.2 m (ε)
		66	65.931590	0^+	9.4 h (ε)
		67	66.928204	$\frac{3}{2}^-$	78.3 h (ε)
		68	67.927982	1^+	68.1 m (ε)
		69	68.925580	$\frac{3}{2}^-$	*60.1%*
		70	69.926028	1^+	21.1 m (β^-)
		71	70.924701	$\frac{3}{2}^-$	*39.9%*
		72	71.926365	3^-	14.1 h (β^-)
		73	72.925169	$\frac{3}{2}^-$	4.87 h (β^-)
		74	73.926940	$(4)^-$	8.1 m (β^-)
		75	74.926499	$\frac{3}{2}^-$	2.1 m (β^-)
Ge	32	66	65.933847	0^+	2.3 h (ε)
		67	66.932737	$(\frac{1}{2})^-$	19.0 m (ε)
		68	67.928096	0^+	271 d (ε)
		69	68.927969	$\frac{5}{2}^-$	39.0 h (ε)
		70	69.924250	0^+	*20.5%*
		71	70.924954	$\frac{1}{2}^-$	11.2 d (ε)
		72	71.922079	0^+	*27.4%*
		73	72.923463	$\frac{9}{2}^+$	*7.8%*
		74	73.921177	0^+	*36.5%*
		75	74.922858	$\frac{1}{2}^-$	82.8 m (β^-)
		76	75.921402	0^+	*7.8%*
		77	76.923548	$\frac{7}{2}^+$	11.3 h (β^-)
		78	77.922853	0^+	1.45 h (β^-)
		79	78.925360	$(\frac{1}{2})^-$	19 s (β^-)
As	33	70	69.930929	4^+	53 m (ε)
		71	70.927114	$\frac{5}{2}^-$	61 h (ε)
		72	71.926755	2^-	26.0 h (ε)
		73	72.923827	$\frac{3}{2}^-$	80.3 d (ε)
		74	73.923928	2^-	17.8 d (ε)
		75	74.921594	$\frac{3}{2}^-$	*100%*
		76	75.922393	2^-	26.3 h (β^-)
		77	76.920646	$\frac{3}{2}^-$	38.8 h (β^-)
		78	77.921830	(2^-)	91 m (β^-)
		79	78.920946	$\frac{3}{2}^-$	9.0 m (β^-)
Se	34	71	70.932270	$\frac{5}{2}^-$	4.7 m (ε)
		72	71.927110	0^+	8.4 d (ε)
		73	72.926768	$\frac{9}{2}^+$	7.1 h (ε)
		74	73.922475	0^+	*0.87%*
		75	74.922522	$\frac{5}{2}^+$	119.8 d (ε)
		76	75.919212	0^+	*9.0%*
		77	76.919913	$\frac{1}{2}^-$	*7.6%*
		78	77.917308	0^+	*23.5%*
		79	78.918498	$\frac{7}{2}^+$	< 0.065 My (β^-)

	Z	A	Atomic mass (u)	I^π	*Abundance* or Half-life
		116	115.901747	0^+	*14.6%*
		117	116.902956	$\frac{1}{2}^+$	*7.75%*
		118	117.901609	0^+	*24.3%*
		119	118.903311	$\frac{1}{2}^+$	*8.6%*
		120	119.902199	0^+	*32.4%*
		121	120.904239	$\frac{3}{2}^+$	27.1 h (β^-)
		122	121.903440	0^+	*4.56%*
		123	122.905722	$\frac{11}{2}^-$	129 d (β^-)
		124	123.905274	0^+	*5.64%*
		125	124.907785	$\frac{11}{2}^-$	9.62 d (β^-)
		126	125.907654	0^+	0.1 My (β^-)
		127	126.910355	$(\frac{11}{2}^-)$	2.1 h (β^-)
Sb	51	118	117.905534	1^+	3.6 m (ε)
		119	118.903948	$\frac{5}{2}^+$	38.0 h (ε)
		120	119.905077	1^+	15.8 m (ε)
		121	120.903821	$\frac{5}{2}^+$	*57.3%*
		122	121.905179	2^-	2.70 d (β^-)
		123	122.904216	$\frac{7}{2}^+$	*42.7%*
		124	123.905938	3^-	60.2 d (β^-)
		125	124.905252	$\frac{7}{2}^+$	2.7 y (β^-)
		126	125.907250	8^-	12.4 d (β^-)
		127	126.906919	$\frac{7}{2}^+$	3.85 d (β^-)
Te	52	117	116.908630	$\frac{1}{2}^+$	62 m (ε)
		118	117.905908	0^+	6.00 d (ε)
		119	118.906411	$\frac{1}{2}^+$	16.0 h (ε)
		120	119.904048	0^+	*0.091%*
		121	120.904947	$\frac{1}{2}^+$	16.8 d (ε)
		122	121.903050	0^+	*2.5%*
		123	122.904271	$\frac{1}{2}^+$	*0.89%*
		124	123.902818	0^+	*4.6%*
		125	124.904429	$\frac{1}{2}^+$	*7.0%*
		126	125.903310	0^+	*18.7%*
		127	126.905221	$\frac{3}{2}^+$	9.4 h (β^-)
		128	127.904463	0^+	*31.7%*
		129	128.906594	$\frac{3}{2}^+$	69 m (β^-)
		130	129.906229	0^+	*34.5%*
		131	130.908528	$\frac{3}{2}^+$	25.0 m (β^-)
		132	131.908517	0^+	78.2 h (β^-)
		133	132.910910	$(\frac{3}{2}^+)$	12.5 m (β^-)
I	53	123	122.905594	$\frac{5}{2}^+$	13.2 h (ε)
		124	123.906207	2^-	4.18 d (ε)
		125	124.904620	$\frac{5}{2}^+$	60.2 d (ε)
		126	125.905624	2^-	13.0 d (ε)
		127	126.904473	$\frac{5}{2}^+$	*100%*
		128	127.905810	1^+	25.0 m (β^-)
		129	128.904986	$\frac{7}{2}^+$	16 My (β^-)
		130	129.906713	5^+	12.4 h (β^-)
		131	130.906114	$\frac{7}{2}^+$	8.04 d (β^-)
		132	131.907987	4^+	2.30 h (β^-)
Xe	54	121	120.911450	$(\frac{5}{2}^+)$	40.1 m (ε)
		122	121.908170	0^+	20.1 h (ε)
		123	122.908469	$(\frac{1}{2}^+)$	2.08 h (ε)
		124	123.905894	0^+	*0.096%*
		125	124.906397	$(\frac{1}{2})^+$	17 h (ε)
		126	125.904281	0^+	*0.090%*
		127	126.905182	$(\frac{1}{2}^+)$	36.4 d (ε)
		128	127.903531	0^+	*1.92%*
		129	128.904780	$\frac{1}{2}^+$	*26.4%*
		130	129.903509	0^+	*4.1%*
		131	130.905072	$\frac{3}{2}^+$	*21.2%*
		132	131.904144	0^+	*26.9%*
		133	132.905888	$\frac{3}{2}^+$	5.25 d (β^-)
		134	133.905395	0^+	*10.4%*
		135	134.907130	$\frac{3}{2}^+$	9.1 h (β^-)
		136	135.907214	0^+	*8.9%*
		137	136.911557	$\frac{7}{2}^-$	3.82 m (β^-)
Cs	55	130	129.906753	1^+	29.2 m (ε)
		131	130.905444	$\frac{5}{2}^+$	9.69 d (ε)
		132	131.906431	2^-	6.47 d (ε)
		133	132.905429	$\frac{7}{2}^+$	*100%*
		134	133.906696	4^+	2.06 y (β^-)
		135	134.905885	$\frac{7}{2}^+$	3 My (β^-)
		136	135.907289	5^+	13.1 d (β^-)
		137	136.907073	$\frac{7}{2}^+$	30.2 y (β^-)
		138	137.911004	3^-	32.2 m (β^-)
Ba	56	127	126.911130	$(\frac{1}{2}^+)$	12.7 m (ε)
		128	127.908237	0^+	2.43 d (ε)
		129	128.908642	$\frac{1}{2}^+$	2.2 h (ε)
		130	129.906282	0^+	*0.106%*
		131	130.906902	$\frac{1}{2}^+$	12.0 d (ε)
		132	131.905042	0^+	*0.101%*
		133	132.905988	$\frac{1}{2}^+$	10.7 y (ε)
		134	133.904486	0^+	*2.42%*
		135	134.905665	$\frac{3}{2}^+$	*6.59%*
		136	135.904553	0^+	*7.85%*
		137	136.905812	$\frac{3}{2}^+$	*11.2%*
		138	137.905232	0^+	*71.7%*
		139	138.908826	$\frac{7}{2}^-$	82.9 m (β^-)
		140	139.910581	0^+	12.7 d (β^-)
		141	140.914363	$\frac{3}{2}^-$	18.3 m (β^-)

Z	A	Atomic mass (u)	J^π	*Abundance* or Half-life
	184	183.950928	0^+	*30.7%*
	185	184.953416	$\frac{3}{2}^-$	75.1 d (β^-)
	186	185.954357	0^+	*28.6%*
	187	186.957153	$\frac{3}{2}^-$	23.9 h (β^-)
	188	187.958480	0^+	69.4 d (β^-)
Re 75	182	181.951210	2^+	12.7 h (ε)
	183	182.950817	$(\frac{5}{2})^+$	71 d (ε)
	184	183.952530	3^-	38 d (ε)
	185	184.952951	$\frac{5}{2}^+$	*37.40%*
	186	185.954984	1^-	90.6 h (β^-)
	187	186.955744	$\frac{5}{2}^+$	*62.60%*
	188	187.958106	1^-	16.9 h (β^-)
	189	188.959219	$(\frac{5}{2})^+$	24.3 h (β^-)
Os 76	182	181.952120	0^+	21.5 h (ε)
	183	182.953290	$(\frac{9}{2})^+$	13.0 h (ε)
	184	183.952488	0^+	*0.018%*
	185	184.954041	$\frac{1}{2}^-$	93.6 d (ε)
	186	185.953830	0^+	*1.6%*
	187	186.955741	$\frac{1}{2}^-$	*1.6%*
	188	187.955830	0^+	*13.3%*
	189	188.958137	$\frac{3}{2}^-$	*16.1%*
	190	189.958436	0^+	*26.4%*
	191	190.960920	$\frac{9}{2}^-$	15.4 d (β^-)
	192	191.961467	0^+	*41.0%*
	193	192.964138	$\frac{3}{2}^-$	30.6 h (β^-)
	194	193.965173	0^+	6.0 y (β^-)
Ir 77	188	187.958830	(2^-)	41.5 h (ε)
	189	188.958712	$\frac{3}{2}^+$	13.1 d (ε)
	190	189.960580	(4^+)	11.8 d (ε)
	191	190.960584	$\frac{3}{2}^+$	*37.3%*
	192	191.962580	4^-	74.2 d (β^-)
	193	192.962917	$\frac{3}{2}^+$	*62.7%*
	194	193.965069	1^-	19.2 h (β^-)
	195	194.965966	$(\frac{3}{2}^+)$	2.8 h (β^-)
Pt 78	187	186.960470	$\frac{3}{2}^-$	2.35 h (ε)
	188	187.959386	0^+	10.2 d (ε)
	189	188.960817	$\frac{3}{2}^-$	10.9 h (ε)
	190	189.959917	0^+	*0.013%*
	191	190.961665	$\frac{3}{2}^-$	2.9 d (ε)
	192	191.961019	0^+	*0.78%*
	193	192.962977	$(\frac{1}{2}^-)$	50 y (ε)
	194	193.962655	0^+	*32.9%*
	195	194.964766	$\frac{1}{2}^-$	*33.8%*
	196	195.964926	0^+	*25.3%*
	197	196.967315	$\frac{1}{2}^-$	18.3 h (β^-)

Z	A	Atomic mass (u)	J^π	*Abundance* or Half-life
	198	197.967869	0^+	*7.2%*
	199	198.970552	$(\frac{5}{2}^-)$	30.8 m (β^-)
	200	199.971417	0^+	12.5 h (β^-)
Au 79	194	193.965348	1^-	39.5 h (ε)
	195	194.965013	$\frac{3}{2}^+$	186 d (ε)
	196	195.966544	2^-	6.18 d (ε)
	197	196.966543	$\frac{3}{2}^+$	*100%*
	198	197.968217	2^-	2.696 d (β^-)
	199	198.968740	$\frac{3}{2}^+$	3.14 d (β^-)
	200	199.970670	1^-	48.4 m (β^-)
Hg 80	193	192.966560	$\frac{3}{2}^-$	3.8 h (ε)
	194	193.965391	0^+	520 y (ε)
	195	194.966640	$\frac{1}{2}^-$	9.5 h (ε)
	196	195.965807	0^+	*0.15%*
	197	196.967187	$\frac{1}{2}^-$	64.1 h (ε)
	198	197.966743	0^+	*10.0%*
	199	198.968254	$\frac{1}{2}^-$	*16.8%*
	200	199.968300	0^+	*23.1%*
	201	200.970277	$\frac{3}{2}^-$	*13.2%*
	202	201.970617	0^+	*29.8%*
	203	202.972848	$\frac{5}{2}^-$	46.6 d (β^-)
	204	203.973467	0^+	*6.9%*
	205	204.976047	$\frac{1}{2}^-$	5.2 m (β^-)
Tl 81	200	199.970934	2^-	26.1 h (ε)
	201	200.970794	$\frac{1}{2}^+$	73 h (ε)
	202	201.972085	2^-	12.2 d (ε)
	203	202.972320	$\frac{1}{2}^+$	*29.5%*
	204	203.973839	2^-	3.77 y (β^-)
	205	204.974401	$\frac{1}{2}^+$	*70.5%*
	206	205.976084	0^-	4.20 m (β^-)
Pb 82	201	200.972830	$\frac{5}{2}^-$	9.3 h (ε)
	202	201.972134	0^+	0.05 My (ε)
	203	202.973365	$\frac{5}{2}^-$	51.9 h (ε)
	204	203.973020	0^+	*1.42%*
	205	204.974458	$\frac{5}{2}^-$	15 My (ε)
	206	205.974440	0^+	*24.1%*
	207	206.975872	$\frac{1}{2}^-$	*22.1%*
	208	207.976627	0^+	*52.3%*
	209	208.981065	$\frac{9}{2}^+$	3.25 h (β^-)
	210	209.984163	0^+	22.3 y (β^-)
	211	210.988735	$(\frac{9}{2}^+)$	36.1 m (β^-)
	212	211.991871	0^+	10.6 h (β^-)
Bi 83	206	205.978478	6^+	6.24 d (ε)
	207	206.978446	$\frac{9}{2}^-$	32 y (ε)

	Z	A	Atomic mass (u)	I^π	*Abundance* or Half-life
		208	207.979717	(5^+)	0.368 My (ε)
		209	208.980374	$\frac{9}{2}^-$	*100 %*
		210	209.984095	1^-	5.01 d (β^-)
		211	210.987255	$\frac{9}{2}^-$	2.15 m (α)
		212	211.991255	1^-	60.6 m (β^-)
Po	84	206	205.980456	0^+	8.8 d (ε)
		207	206.981570	$\frac{5}{2}^-$	5.8 h (ε)
		208	207.981222	0^+	2.90 y (α)
		209	208.982404	$\frac{1}{2}^-$	102 y (α)
		210	209.982848	0^+	138.4 d (α)
		211	210.986627	$\frac{9}{2}^+$	0.52 s (α)
At	85	208	207.986510	6^+	1.63 h (ε)
		209	208.986149	$\frac{9}{2}^-$	5.4 h (ε)
		210	209.987126	5^+	8.3 h (ε)
		211	210.987469	$\frac{9}{2}^-$	7.21 h (ε)
		212	211.990725	(1^-)	0.31 s (α)
		213	212.992911	$\frac{9}{2}^-$	0.11 μs (α)
Rn	86	207	206.990690	$\frac{5}{2}^-$	9.3 m (ε)
		210	209.989669	0^+	2.4 h (α)
		211	210.990576	$\frac{1}{2}^-$	14.6 h (ε)
		212	211.990697	0^+	24 m (α)
		218	218.005580	0^+	35 ms (α)
		222	222.017571	0^+	3.82 d (α)
		224		0^+	107 m (β^-)
Fr	87	209	208.995870	$\frac{9}{2}^-$	50 s (α)
		212	211.996130	5^+	20 m (ε)
		215	215.000310	$\frac{9}{2}^-$	0.12 μs (α)
		220	220.012293	1	27.4 s (α)
		223	223.019733	$(\frac{3}{2})$	21.8 m (β^-)
Ra	88	222	222.015353	0^+	38 s (α)
		223	223.018501	$\frac{1}{2}^+$	11.4 d (α)
		224	224.020186	0^+	3.66 d (α)
		225	225.023604	$(\frac{3}{2})^+$	14.8 d (β^-)
		226	226.025403	0^+	1602 y (α)
		227	227.029171	$(\frac{3}{2}^+)$	42 m (β^-)
Ac	89	224	224.021685	(0^-)	2.9 h (ε)
		225	225.023205	$(\frac{3}{2}^-)$	10.0 d (α)
		226	226.026084	(1^-)	29 h (β^-)
		227	227.027750	$\frac{3}{2}^-$	21.77 y (β^-)
		228	228.031015	(3^+)	6.1 h (β^-)
Th	90	228	228.028715	0^+	1.91 y (α)
		229	229.031755	$\frac{5}{2}^+$	7300 y (α)
		230	230.033128	0^+	75,400 y (α)
		231	231.036299	$\frac{5}{2}^+$	25.52 h (β^-)

	Z	A	Atomic mass (u)	I^π	*Abundance* or Half-life
		232	232.038051	0^+	*100 %*
		233	233.041577	$(\frac{1}{2}^+)$	22.3 m (β^-)
Pa	91	229	229.032073	$(\frac{5}{2}^+)$	1.4 d (ε)
		230	230.034527	(2^-)	17.7 d (ε)
		231	231.035880	$\frac{3}{2}^-$	32,800 y (α)
		232	232.038565	(2^-)	1.31 d (β^-)
		233	233.040243	$\frac{3}{2}^-$	27.0 d (β^-)
U	92	233	233.039628	$\frac{5}{2}^+$	0.1592 My (α)
		234	234.040947	0^+	0.245 My (α)
		235	235.043924	$\frac{7}{2}^-$	*0.720%*
		236	236.045563	0^+	23.42 My (α)
		237	237.048725	$\frac{1}{2}^+$	6.75 d (β^-)
		238	238.050785	0^+	*99.275%*
		239	239.054290	$\frac{5}{2}^+$	23.5 m (β^-)
Np	93	236	236.046550	(6^-)	0.11 My (ε)
		237	237.048168	$\frac{5}{2}^+$	2.14 My (α)
		238	238.050941	2^+	2.117 d (β^-)
		239	239.052933	$\frac{5}{2}^+$	2.36 d (β^-)
Pu	94	237	237.048401	$\frac{7}{2}^-$	45.3 d (ε)
		238	238.049555	0^+	87.74 y (α)
		239	239.052158	$\frac{1}{2}^+$	24,100 y (α)
		240	240.053808	0^+	6570 y (α)
		241	241.056846	$\frac{5}{2}^+$	14.4 y (β^-)
		242	242.058737	0^+	0.376 My (α)
		243	243.061998	$\frac{7}{2}^+$	4.96 h (β^-)
Am	95	240	240.055278	(3^-)	50.9 h (ε)
		241	241.056824	$\frac{5}{2}^-$	433 y (α)
		242	242.059542	1^-	16.0 h (β^-)
		243	243.061375	$\frac{5}{2}^-$	7370 y (α)
		244	244.064279	(6^-)	10.1 h (β^-)
Cm	96	246	246.067218	0^+	4700 y (α)
		247	247.070347	$\frac{9}{2}^-$	16 My (α)
		248	248.072343	0^+	0.34 My (α)
		249	249.075948	$\frac{1}{2}^+$	64 m (β^-)
Bk	97	246	246.068720	2^-	1.8 d (ε)
		247	247.070300	$(\frac{3}{2}^-)$	1380 y (α)
Cf	98	251	251.079580	$\frac{1}{2}^+$	898 y (α)
		252	252.081621	0^+	2.64 y (α)
Es	99	252	252.082944	$(4^+, 5^-)$	472 d (α)
		253	253.084818	$\frac{7}{2}^+$	20.5 d (α)