6 RADIATION BASICS

Radiation comes in the form of particles or electromagnetic (EM) waves or both. Very small particles sometimes act like waves, and EM waves sometimes act like particles, so we sometimes call them wavicles. The most commonly known types of radiation are visible light photons and radio waves. But there are many more kinds of radiation, including particles and EM wavicles.

An alpha particle is a Helium nucleus (two neutrons and two protons). A Beta particle is an electron. A Proton ia a Hydrogen nucleus. A Neutron is an un charged particle with about the same mass as a proton. Larger ionic nuclei are also considered to be forms of radiation: e.g., Carbon or Iron nuclei.

The EM spectrum is shown in Figure 1 at right. It includes long, radio, heat, infra-red, visible, UV, x-ray, gamma, and cosmic waves.

All of these radiations can be harmful or helpful, depending on how they are used. Visible light and microwave ovens are very useful, but a laser can blind you or cut steel, and a microwaves can kill your small dog if you try to use them to dry the dog after a shampoo. Americium-241 gives off alpha and beta particles and gamma photons, but it saves lives in smoke detectors. Alpha radiation can light up a watch dial and is not able to penetrate skin or a sheet of paper, but you wouldn't want it in your lungs, where radon gas delivers it.

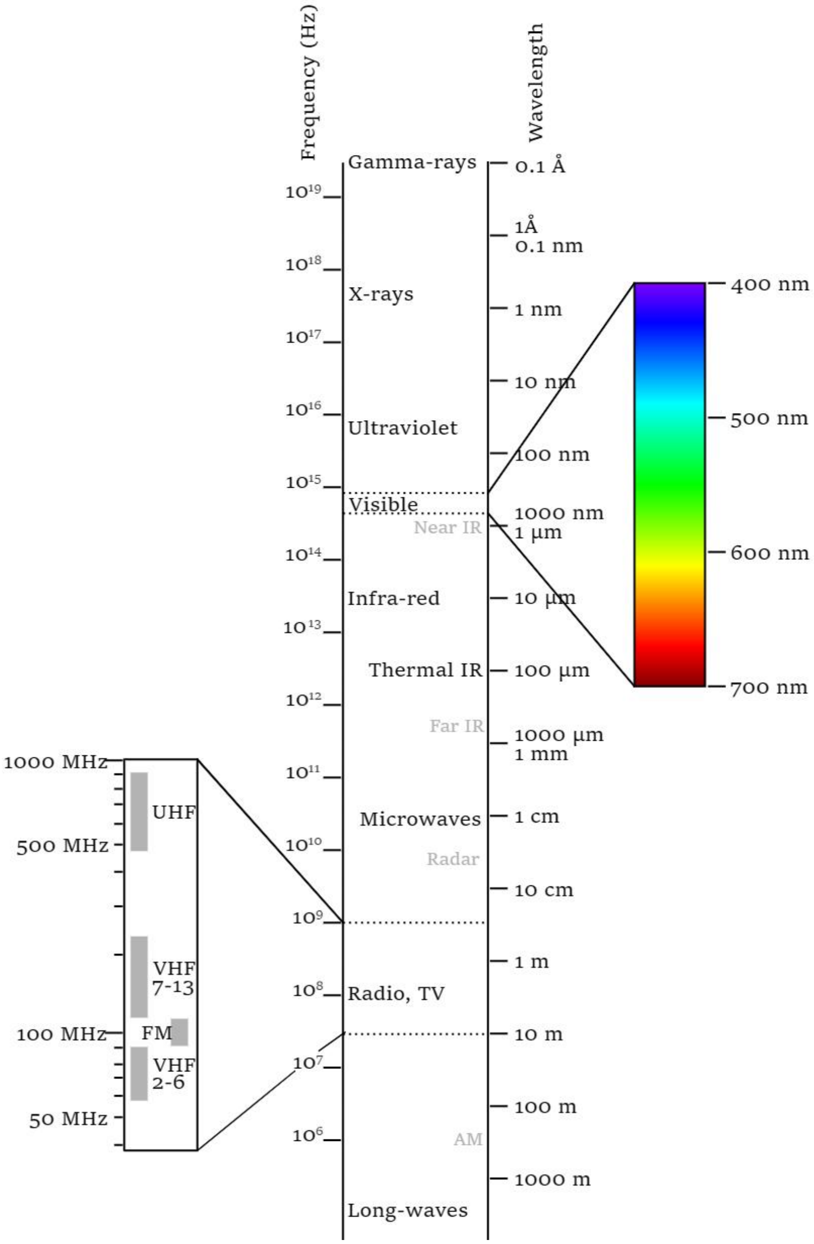

Figure 1 Electromagnetic Spectrum.
https://commons.wikimedia.org/wiki/File:Electromagnetic-Spectrum.svg
Original: Penubag Vector: Victor Blacus, CC BY-SA 3.0 <https://creativecommons.org/licenses/by-sa/3.0>, via Wikimedia Commons

I want to point out some of the worst industrial accidents in history[1] (the top six according to one source[2]). Clearly, the top two were rated high for either cost or social perception, rather than the loss of life. Personally, I would have rated them in order of lives lost. I added the bottom four because they are well known disasters that killed many people.

DISASTER NAME	YEAR	FATALITIES
1. The Chernobyl disaster, Ukraine	1986	43
2. The Deepwater Horizon, USA	2010	11
3. Bhopal accident, India	1984	3,787
4. Benxihu Colliery (mine), China	1942	1,549
5. Courrières mine, France	1906	1,099
6. Oppau explosion, Germany	1921	600
7. Honkeiko mine, China (under Japanese control)	1942	1549
8. Rana Plaza Collapse, Bangladesh	2013	1100
9. Monongah mine, West Virginia	1907	350
10. Triangle Shirtwaist Factory, NY, USA	1911	<150

Note that the following nuclear accidents that some people consider to be disasters didn't kill anyone:

Three-Mile Island, USA	1979	0
Fukushima, Japan	2011	0

They just made an expensive mess and created jobs. Some 2,000 people died from being forcibly relocated due to the Fukushima tsunami, but no one, not even workers, died from radiation[3]. Only the Russians have managed to kill people from radiation at a nuclear power reactor.

But careless handling of radiation can kill, and here's how. Particles and photons have energy that they can transfer to other particles, especially electrons in the DNA of living things. When radiation enters a living organism like plants or humans, the photons and particles tend to collide with electrons. This creates an ion, a charged molecule that is missing an electron (the molecule is also a free radical). This modified ionic molecule is very reactive and unstable, so it reacts almost instantly with whatever other molecule is nearby. The result is changed molecules, some of them in a highly ordered DNA polymer, yielding an error in the cell's gene sequence. This can cause the cell no apparent harm at all, or it can cause the cell to function poorly, or it can kill the cell, or it can cause the cell to grow and divide excessively. It takes several specific DNA mutations to create an immortal cell or cancer. Fortunately, this usually takes decades to occur.

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[1] A complete list of multiply-fatal industrial accidents would be vastly longer, but would have no nuclear power reactors outside of the former USSR.

[2] https://news.gminternational.com/industrial-safety-top-6-worst-accidents-in-history

[3] One Fukushima worker died of lung cancer 7 years after the Fukushima disaster.

However, living cells and DNA and radiation have been around together for 3.8 billion years, and the cells have evolved mutation repair enzymes to correct DNA damage by radiation (and chemical oxidation). So we survive mutations and cancers every day of our lives. Sometimes the error doesn't get fixed but the cell fails to work properly, and self destructs. Or the cell begins to replicate itself and becomes cancer. Then we use radiation and/or toxic chemicals to kill the cancer cells (faster than they kill normal cells).

There is a significant difference between X rays and Ultraviolet radiation: X rays have enough energy to knock electrons out of atoms and molecules; UVB does not. Removing an electron leaves a free radical positive ion in place of a neutral atom or molecule in, e.g., a DNA helix. And that loose electron can knock other electrons free of their atoms, which creates more free radicals. Free electrons eventually find homes around other atoms, thereby creating even more ionic free radicals. Ultraviolet radiation (and visible light, and infrared light, and microwaves, and radio waves) lack the energy to knock an electron completely free of its nucleus. So when we speak of radiation, what we often mean is Ionizing Radiation, the kind of radiation that can cause mutations and cancer: X rays and gamma rays and fast moving particles with 15-30 electron volts (eV) of energy, or more (cosmic particles may exceed 10^{12}MeV).

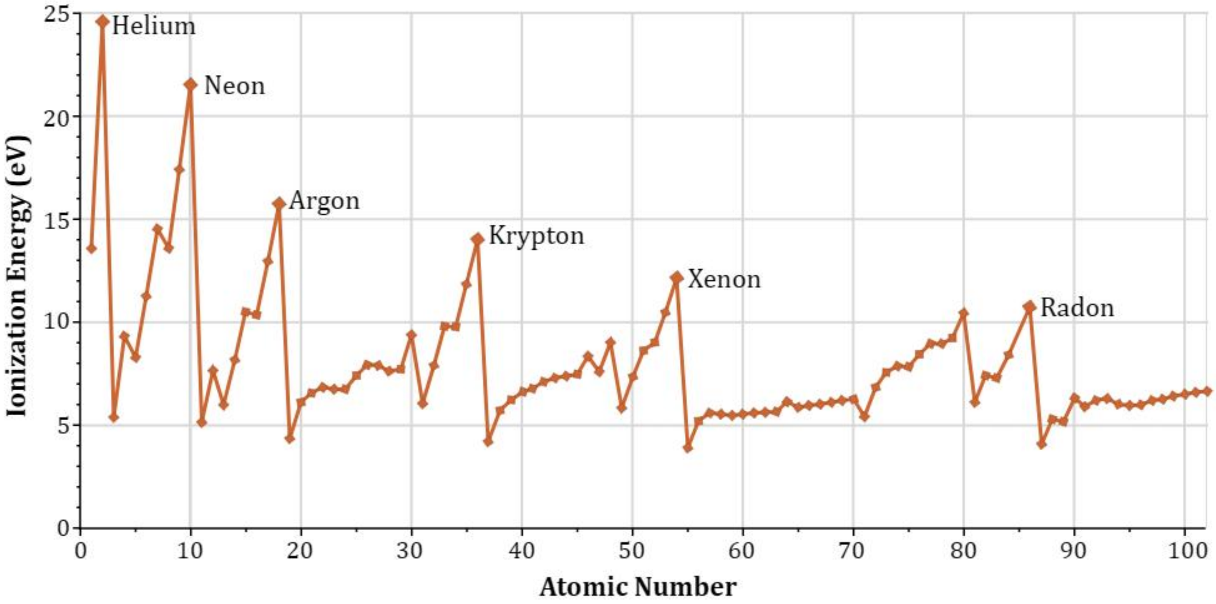

Figure 2 Ionization energies required to free one electron from each atom of the periodic table.
https://commons.wikimedia.org/wiki/File:Ionization_energies.svg
RJHall, Public domain, via Wikimedia Commons

In summary, the characteristic that makes Ionizing Radiation dangerous[4] is its ability to deliver a packet of sufficient energy (>15 eV for H, C, N, and O) directly to single electrons, thereby creating free radical ions in the operational molecules of living cells. (Smaller packets of energy merely provide kinetic energy which we call "heat"). Free radical damage to proteins, lipids, and

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[4] Some chemicals also cause damage to DNA that may result in immortal cells.

carbohydrates, reduces a cells efficiency until the damage can be repaired; but damage to DNA can permanently impair the cells ability to repair and replace itself accurately. So DNA damage at least makes the cell function less efficiently, or kills the cell, or makes a damaged cell immortal.

It requires multiple mutations to create an immortal cell (a cancer cell). That's why we often say that it takes 20 or more years to create a cancer. One of the ways these multiple mutations can occur is by sustaining damage to the genes for one of the DNA repair mechanisms, so that DNA repairs cause mutations, instead of repairing them. Our cells have dozens, possibly hundreds of DNA repair mechanisms.

How much damage can one massless photon do? Let's calculate the energy in an ionizing photon like an extremely high frequency UVB photon[5], then find how many free electrons could be created from that energy[6]. Assume one ion radical and one free electron are created from the first collision, thereby using up some of the collision's energy. Then the freed electron carries the remaining energy to subsequent collisions. For every subsequent collision, assume that the incoming electron gives all extra energy to the freed target electron[7]. Assume that each freed electron requires 15eV of energy. Apply Planck's equation stating that photon energy is equal to photon frequency times Planck's constant.

$$E = hv$$

(The energy of a wavicle equals Planck constant times the wave frequency.)

15 eV is >= the ionization energy for most elements.

C/280nm = $1.1*10^{15}$ = max frequency v in UVB range

E in Joules = h Joule seconds times v Hz (per second)

$$E = 6.63*10^{-34}\text{ J s} * 1.1*10^{15}\text{ s}^{-1} = 7.1*10^{-19}\text{ Joules}$$

$$E = 7.1*10^{-19}\text{ J}$$

E in Joules * $6.24*10^{18}$ eV/J = 4.4 eV

4.4 eV / 15 eV per radical = **0 IonRadical pairs per incoming UVB photon**

I might conclude that UVB cannot free an electron from its nucleus, cannot produce a free radical, and cannot induce mutations in DNA. But I might be wrong. UVB can occasionally cause a lesser form of damage to DNA than forming a free radical: pyrimidine dimers can make it difficult to translate and replicate DNA. Some researchers are concerned about this type of

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[5] UVB is considered to range from 280nm to 315nm, with the lowest wavelength being the highest frequency and energy. UVC includes a wide range of frequencies which are not normally considered to be ionizing. However a very small percentage of the highest frequency UVC photons could theoretically eject an electron from some nuclei. *{Many UVB&C photons have enough energy to cause dimerization of sequential pyrimidine bases (thymine and cytosine) in DNA. Such damage is normally repaired by the Nuclear Excision Repair mechanism}*.

[6] Normally, UVC is completely blocked by our atmosphere, and does not reach us.

[7] The assumption implies that the incoming electron then replaces the target electron, so there is no accumulation of free electrons that we're not counting.

DNA damage. In my opinion, you can safely tan, but only with UVB, being careful not to burn.

A similar calculation for a typical diagnostic X ray, assuming the same resolution as my 4k UHD Nikon camera (8 megapixels = 8megabits = 8x10^{6} photons for black and white Xray image) yields a very different answer:

Typical frequency for diagnostic X ray = 10^{17} Hz
6.63x10^{-34} * 10^{17} gives us 6.6x10^{-17} J * 6.24x10^{18} eV/J = 414 eV
414 eV / 15 eV / ion pair = 27 ion pairs created per photon
Assume that every photon that doesn't hit bone passes through to expose the film.
Assume that bone covers half of the image and absorbs all photons that strike it.
4x10^{6} photons * 27 ion radicals per photon = **1.6 Billion ion radicals per X ray film**

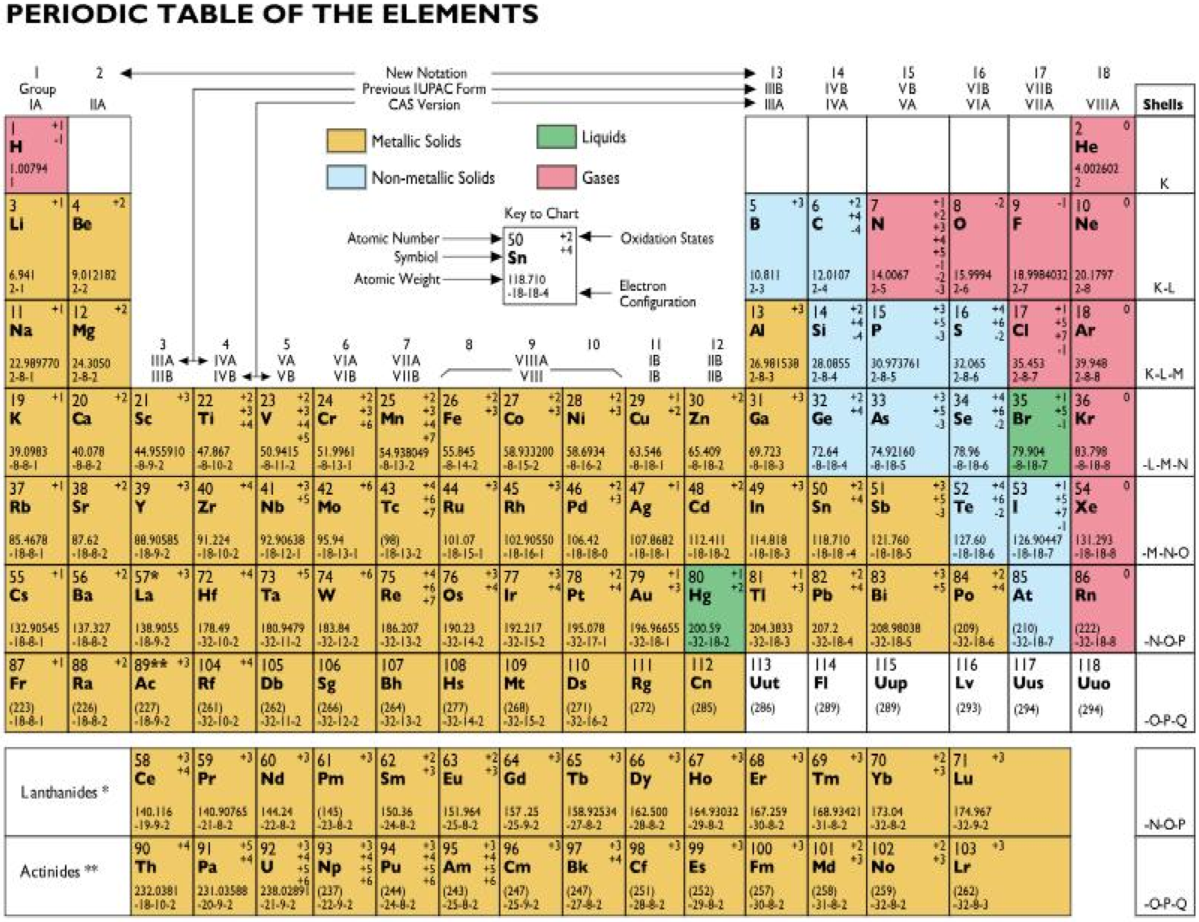
My simplifying assumptions have no doubt led to an underestimate of the total number of photons and radicals per film. Most of the damage that occurs is to proteins, carbohydrates, lipids, and electrolytes, but a small fraction of a billion is still a big number. Then there are all the free radicals that we generate each day just by using oxygen in our cells. Be thankful for all those DNA repair mechanisms that I mentioned earlier. **We survive billions of free radicals and a few mutations every day**. Sooner or later, DNA damage kills us all, unless we die of accidental or intentional events sooner.

Any discussion of DNA repair mechanisms would require a separate volume not currently planned for this project.

Sketch your own image of an Ionizing Radiation colliding with an atomic electron. Choose your radiation from the list of Ionizing Radiations.
Briefly tell me why ionizing radiation is dangerous, and non-ionizing radiation is normally not dangerous. (Note that coherent energy beams of non-ionizing radiation, e.g., lasers and masers,.can harm us but don't cause cancer or mutations).

HOMEWORK

1 What is the smallest part of a chromosome that ionizing radiation can damage to cause a mutation?
2 Is that mutation likely to cause cancer?
3 Arrange the following in order of increasing energy: xrays, UVA, UVC, gamma, radio
4 Which of the radiations above are ionizing?
5 Name three particulate radiations:
6 How likely is it that you or someone you know will die from radiation from a nuclear power plant?
7 How likely is it that anyone will die from radiation from a nuclear power plant, excluding russian built plants?
8 Can a photon with no mass at all impart momentum and kinetic energy to an electron?
9 What does such an interaction create?



PERIODIC TABLE OF THE ELEMENTS

New Notation
Previous IUPAC Form
CAS Version

🟧 Metallic Solids
🟦 Non-metallic Solids
🟩 Liquids
🟥 Gases

Key to Chart
Atomic Number → 50
Symbiol → Sn
Atomic Weight → 118.710
Oxidation States → +2 +4
Electron Configuration → -18-18-4

1 Group IA	2 IIA	3 IIIA IIIB	4 IVA IVB	5 VA VB	6 VIA VIB	7 VIIA VIIB	8	9 VIIIA VIII	10	11 IB IB	12 IIB IIB	13 IIIB IIIA	14 IVB IVA	15 VB VA	16 VIB VIA	17 VIIB VIIA	18 VIIIA	**Shells**
1 **H** +1 -1 1.00794 1																	2 **He** 0 4.002602 2	K
3 **Li** +1 6.941 2-1	4 **Be** +2 9.012182 2-2											5 **B** +3 10.811 2-3	6 **C** +2 +4 -4 12.0107 2-4	7 **N** +1 +2 +3 +4 +5 -1 -2 -3 14.0067 2-5	8 **O** -2 15.9994 2-6	9 **F** -1 18.9984032 2-7	10 **Ne** 0 20.1797 2-8	K-L
11 **Na** +1 22.989770 2-8-1	12 **Mg** +2 24.3050 2-8-2											13 **Al** +3 26.981538 2-8-3	14 **Si** +2 +4 -4 28.0855 2-8-4	15 **P** +3 +5 -3 30.973761 2-8-5	16 **S** +4 +6 -2 32.065 2-8-6	17 **Cl** +1 +5 +7 -1 35.453 2-8-7	18 **Ar** 0 39.948 2-8-8	K-L-M
19 **K** +1 39.0983 -8-8-1	20 **Ca** +2 40.078 -8-8-2	21 **Sc** +3 44.955910 -8-9-2	22 **Ti** +2 +3 +4 47.867 -8-10-2	23 **V** +2 +3 +4 +5 50.9415 -8-11-2	24 **Cr** +2 +3 +6 51.9961 -8-13-1	25 **Mn** +2 +3 +4 +7 54.938049 -8-13-2	26 **Fe** +2 +3 55.845 -8-14-2	27 **Co** +2 +3 58.933200 -8-15-2	28 **Ni** +2 +3 58.6934 -8-16-2	29 **Cu** +1 +2 63.546 -8-18-1	30 **Zn** +2 65.409 -8-18-2	31 **Ga** +3 69.723 -8-18-3	32 **Ge** +2 +4 72.64 -8-18-4	33 **As** +3 +5 -3 74.92160 -8-18-5	34 **Se** +4 +6 -2 78.96 -8-18-6	35 **Br** +1 +5 -1 79.904 -8-18-7	36 **Kr** 0 83.798 -8-18-8	-L-M-N
37 **Rb** +1 85.4678 -18-8-1	38 **Sr** +2 87.62 -18-8-2	39 **Y** +3 88.90585 -18-9-2	40 **Zr** +4 91.224 -18-10-2	41 **Nb** +3 +5 92.90638 -18-12-1	42 **Mo** +6 95.94 -18-13-1	43 **Tc** +4 +6 +7 (98) -18-13-2	44 **Ru** +3 101.07 -18-15-1	45 **Rh** +3 102.90550 -18-16-1	46 **Pd** +2 +3 106.42 -18-18-0	47 **Ag** +1 107.8682 -18-18-1	48 **Cd** +2 112.411 -18-18-2	49 **In** +3 114.818 -18-18-3	50 **Sn** +2 +4 118.710 -18-18 -4	51 **Sb** +3 +5 -3 121.760 -18-18-5	52 **Te** +4 +6 -2 127.60 -18-18-6	53 **I** +1 +5 +7 -1 126.90447 -18-18-7	54 **Xe** 0 131.293 -18-18-8	-M-N-O
55 **Cs** +1 132.90545 -18-8-1	56 **Ba** +2 137.327 -18-8-2	57* **La** +3 138.9055 -18-9-2	72 **Hf** +4 178.49 -32-10-2	73 **Ta** +5 180.9479 -32-11-2	74 **W** +6 183.84 -32-12-2	75 **Re** +4 +6 +7 186.207 -32-13-2	76 **Os** +3 +4 190.23 -32-14-2	77 **Ir** +3 +4 192.217 -32-15-2	78 **Pt** +2 +4 195.078 -32-17-1	79 **Au** +1 +3 196.96655 -32-18-1	80 **Hg** +1 +2 200.59 -32-18-2	81 **Tl** +1 +3 204.3833 -32-18-3	82 **Pb** +2 +4 207.2 -32-18-4	83 **Bi** +3 +5 208.98038 -32-18-5	84 **Po** +2 +4 (209) -32-18-6	85 **At** (210) -32-18-7	86 **Rn** 0 (222) -32-18-8	-N-O-P
87 **Fr** +1 (223) -18-8-1	88 **Ra** +2 (226) -18-8-2	89** **Ac** +3 (227) -18-9-2	104 **Rf** +4 (261) -32-10-2	105 **Db** (262) -32-11-2	106 **Sg** (266) -32-12-2	107 **Bh** (264) -32-13-2	108 **Hs** (277) -32-14-2	109 **Mt** (268) -32-15-2	110 **Ds** (271) -32-16-2	111 **Rg** (272)	112 **Cn** (285)	113 **Uut** (286)	114 **Fl** (289)	115 **Uup** (289)	116 **Lv** (293)	117 **Uus** (294)	118 **Uuo** (294)	-O-P-Q

Lanthanides *	58 **Ce** +3 +4 140.116 -19-9-2	59 **Pr** +3 140.90765 -21-8-2	60 **Nd** +3 144.24 -22-8-2	61 **Pm** +3 (145) -23-8-2	62 **Sm** +2 +3 150.36 -24-8-2	63 **Eu** +2 +3 151.964 -25-8-2	64 **Gd** +3 157 .25 -25-9-2	65 **Tb** +3 158.92534 -27-8-2	66 **Dy** +3 162.500 -28-8-2	67 **Ho** +3 164.93032 -29-8-2	68 **Er** +3 167.259 -30-8-2	69 **Tm** +3 168.93421 -31-8-2	70 **Yb** +2 +3 173.04 -32-8-2	71 **Lu** +3 174.967 -32-9-2	-N-O-P
Actinides **	90 **Th** +4 232.0381 -18-10-2	91 **Pa** +5 +4 231.03588 -20-9-2	92 **U** +3 +4 +5 +6 238.02891 -21-9-2	93 **Np** +3 +4 +5 +6 (237) -22-9-2	94 **Pu** +3 +4 +5 +6 (244) -24-8-2	95 **Am** +3 +4 +5 +6 (243) -25-8-2	96 **Cm** +3 (247) -25-9-2	97 **Bk** +3 +4 (247) -27-8-2	98 **Cf** +3 (251) -28-8-2	99 **Es** +3 (252) -29-8-2	100 **Fm** +3 (257) -30-8-2	101 **Md** +2 +3 (258) -31-8-2	102 **No** +2 +3 (259) -32-8-2	103 **Lr** +3 (262) -32-8-3	-O-P-Q

Figure 3 Periodic table of the elements known to us.
https://commons.wikimedia.org/wiki/File:Periodic_Table_of_the_Elements_svg.svg
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