Nucleosynthesis
Making Big Ones Out of Little Ones

"We are star stuff."
Carl Sagan, 1934-1996

Seminar Outline

Getting Started

Big-Bang Nucleosynthesis

Stellar Nucleosynthesis – Stars 0.8 – 8 $M_\odot$

Nuclear Pathways

Stellar Nucleosynthesis – Stars >10 $M_\odot$

Supernova Nucleosynthesis – Stars >10 $M_\odot$

Supernova Nucleosynthesis – Stars 0.8 – 8 $M_\odot$

Loose Ends

Credits

Periodic Table

Getting Started

- The symbol $\mathbf{M}_\odot$ means “solar masses” – how much mass a star has compared to our Sun. A star with $2M_\odot$ has twice as much mass as the Sun.

- Temperatures in this seminar are in Kelvin (“K”). At the temperatures we’ll be using, conversion is easy. To convert Kelvin to Centigrade, don’t do anything. To convert to Fahrenheit, multiply Kelvin by 2 if you’re not fussy, 1.8 if you are.

- I abbreviate “millions of degrees Kelvin” to “M°K” (also called “megakelvin”) and “billions of degrees Kelvin” to “B°K” (“gigakelvin”, can be abbreviated “G°K”).

- An atom is made up of a nucleus, and an orbiting cloud of electrons.
  - The nucleus consists of one or more positively-charged protons, and none or more neutrally-charged neutrons.
  - Protons and neutrons have about the same mass. (Neutrons have slightly more.) An electron has about 1/2000 the mass of a proton.
  - Collectively, the protons and neutrons are called nucleons.
  - Electrons orbit the nucleus. There are normally as many electrons as there are protons, but electrons are loosely-bound and easily lost.

- The number of protons determines what kind of atom it is. One proton, hydrogen. Two protons, helium. Eight protons, oxygen.

- A Free (unbound) proton is exactly the same as hydrogen nucleus. A free neutron doesn’t live long (average 15min). A free electron is more the rule than the exception in nucleosynthesis. This seminar doesn’t much bother with electrons, since temperatures are too high for them to bind.

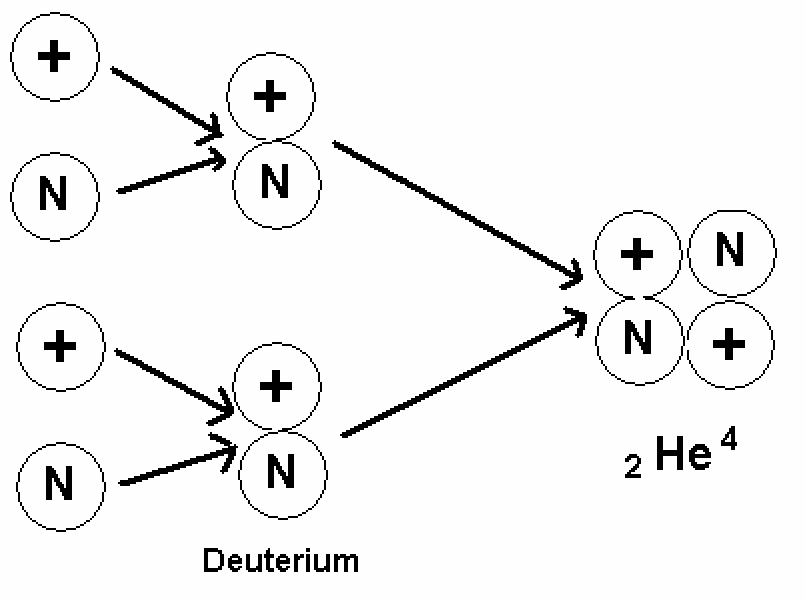
- To add a proton to a nucleus (or another proton), the electromagnetic repulsion (positive charge vs. positive charge, also known as the “coulomb barrier”) has to be overcome. High speed (heat) can do this. Nucleons are held together with a “strong nuclear force” – much stronger than the electromagnetic force.

- An “element” is a general description of that kind of “atom”. To say it another way, an atom is a specific instance of an element. Atoms exist; elements are abstractions of that particular population of atoms.

- Chemical elements are represented as ${}_{\mathbf{p}}\mathbf{E}^{\mathbf{n}}$, where **E** is the abbreviation of the element (e.g. “He” for helium), **p** is the count of protons, and **n** is the count of nucleons (protons + neutrons). Thus, ${}_{\mathbf{2}}\mathbf{He}^{\mathbf{4}}$ symbolizes helium, with two protons, and 2 neutrons (4 nucleons, minus 2 protons, equals 2 neutrons).

Big-Bang Nucleosynthesis

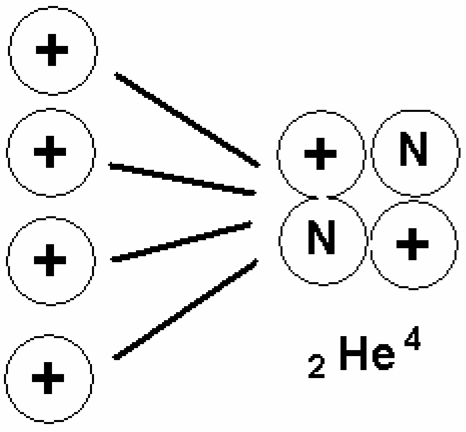
- Occurred 3-20min after the Big Bang, at around ~ 1B°K.
- First step – a proton and neutron combine, forming deuterium ($_1H^2$).
- Second step – two deuterium nuclei combine to form helium ($_2H^4$).
- At 20min, the universe is too cool for further element-creation.
- 75% H, 25% He, traces of lithium (Li), beryllium (Be) and boron (B).



Stellar Nucleosynthesis – Stars 0.4 – 8 $M_\odot$

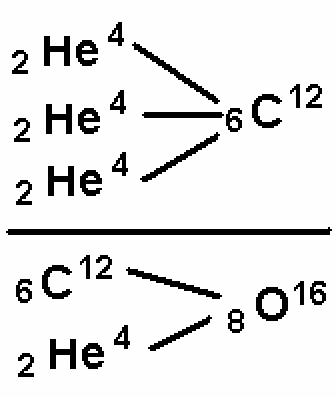
- Two phases – hydrogen to helium, and then helium to carbon and oxygen.
- If the star does not have enough mass (>0.8 $M_\odot$, the second phase isn't done.
- End result – White Dwarf star.

Fusing Helium ($_1H^1 \rightarrow {}_2He^4$)



- Minimum core temperature ~ 6 M°K.
- "Proton-Proton Chain"
- "CNO Cycle"

Fusing Carbon and Oxygen ($_2He^4 \rightarrow {}_6C^{12}$ and $_8O^{16}$)



- Minimum core temperature ~ 100 M°K
- "Alpha" process – Adding "alpha" particles. (An "alpha particle" is a helium nucleus.)
- This is a "Triple Alpha" process to form carbon.

- Simple Alpha Process to make oxygen.

Nuclear Pathways

- Show all the input and output components for the reaction.
- These pathways produce more than just atomic nuclei. For example, a path might produce neutrons, electrons, photons, neutrinos, etc. And, of course, energy.
- However, in this seminar, we’re only concerned with atomic nuclei. The other generated particles aren’t shown.
- And, for a process, there are other pathways. I’ve only shown the simplest ones.

Stellar Nucleosynthesis – Stars >10 $M_{\odot}$
Type II Supernova

- These stars are massive enough to continue fusion in the core.
- They will fuse up to iron (Fe). All these fusions are exothermic (give off energy). But above Fe, fusion is endothermic (need energy to fuse).

Fusing Neon and Magnesium (${}_{10}Ne^{20}$ and ${}_{12}Mg^{24}$)

- Core temperature 600 – 900 M°K
- Continues Alpha progression.
- Some pathways:
  $${}_{6}C^{12} + {}_{6}C^{12} \rightarrow {}_{12}Mg^{24}$$
  $${}_{6}C^{12} + {}_{6}C^{12} \rightarrow {}_{10}Ne^{20} + {}_{2}He^{4}$$

Fusing Silicon and Sulfur (${}_{14}Si^{28}$ and ${}_{16}S^{32}$)

- Core temperature 1.5 - 2.3 B°K
- Some pathways:
  $${}_{8}O^{16} + {}_{8}O^{16} \rightarrow {}_{14}Si^{28} + {}_{2}He^{4}$$
  $${}_{8}O^{16} + {}_{8}O^{16} \rightarrow {}_{16}S^{32}$$

Fusing Iron (${}_{26}Fe^{52}$)

- Core temperature ~ 4.1 B°K
- The Alpha process continues
- Some pathways:
  $${}_{16}S^{32} + {}_{2}He^{4} \rightarrow {}_{18}Ar^{36}$$
  $${}_{18}Ar^{36} + {}_{2}He^{4} \rightarrow {}_{20}Ca^{40}$$
  $${}_{20}Ca^{40} + {}_{2}He^{4} \rightarrow {}_{22}Ti^{44}$$
  $${}_{22}Ti^{44} + {}_{2}He^{4} \rightarrow {}_{24}Cr^{48}$$
  $${}_{24}Cr^{48} + {}_{2}He^{4} \rightarrow {}_{26}Fe^{52}$$
- The process stops here. Elements heavier than Fe need energy added to build bigger nuclei.

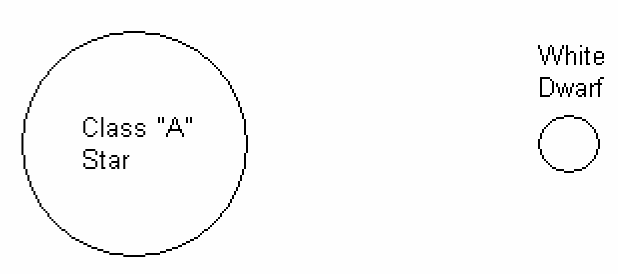
Supernova Nucleosynthesis – Stars >10 $M_{\odot}$

- Core-collapse with speeds up to 70,000km/s (.63c).
- The collapsing core overshoots its equilibrium point and rebounds.
- The rebounding core impacts the collapsing shells, and the star explodes.
- Temperatures up to 100 B°K.
- All elements heavier than Fe are created during this explosion.
- Stars between 10$M_{\odot}$ and 20$M_{\odot}$ leave behind a neutron star. Stars over 20 $M_{\odot}$ form a black hole. We think.

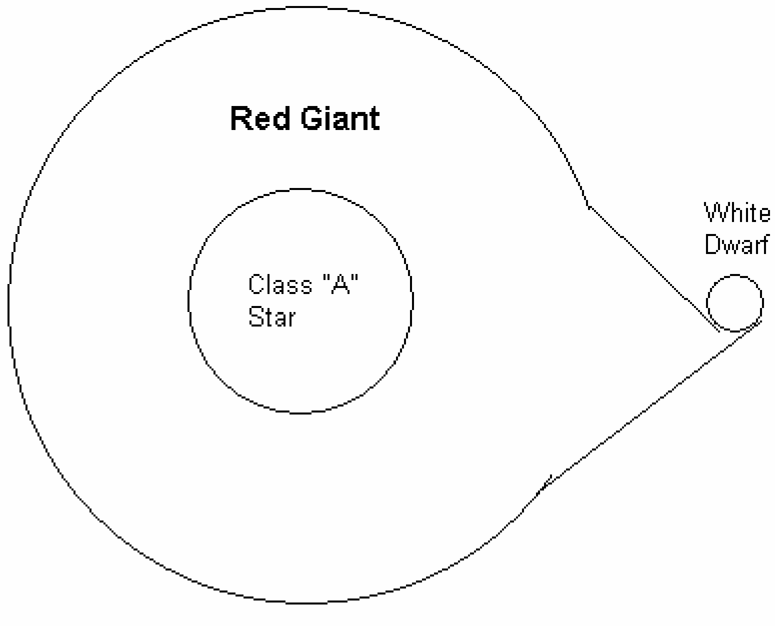
Supernova Nucleosynthesis – Stars 0.8 - 8 $M_\odot$

Type Ia Supernova

- We start with the White Dwarf we left at the end of Stellar Nucleosynthesis.
- If this White Dwarf is part of a binary (or multiple) star system, we can still get a supernova.



- Here we show the White Dwarf, with a medium-size "A" star as its partner.
- Now, the companion goes into a Red Giant phase.



- If the White Dwarf and Red Giant are close enough, the expelled gasses from the Red Giant will enter the gravitational field of the White Dwarf.
- The White Dwarf steals material from the Red Giant.
- The White Dwarf gains mass, and compresses under gravity.
- The core temperature isn't high enough for more fusion, but it does get hotter.
- Eventually, all the free electrons get squeezed to the point where they can't compress any more ("electron degeneracy"). Those in the inner part of the star can't go out (gain energy), and the outer ones can't go in (lose energy).
- As more mass is added, total electron degeneracy happens – the outer electrons are traveling near the speed of light, and can't go out *or* in. And neither can the inner ones. The core continues to heat because of the added gravitational pressure.
- Finally, the core gets hot enough for fusion in the core. In a normal star, this fusion would cause outward expansion to balance the gravitational and fusion forces. But this star cannot expand outward because of the electron degeneracy.

- The core continues to heat from fusion, causing even more fusion. Because no expansion is possible to bleed off the heat, a “thermonuclear runaway” takes place.
- Both exothermic and endothermic reactions take place, since there is no shortage of energy.
- Eventually the heat becomes so high, the star spontaneously explodes.

Loose Ends

- So far, we've seen a lot of "even numbers" – an even number of protons and an even number of neutrons.
- Surely, the odd-numbered atoms must have been created sometime.
- Up to now, we've focused on the Alpha processes. Clearly, something else is needed.

Added Supernova Nucleosynthesis

- During stellar nucleosynthesis, we've needed exothermic reactions – those that produce energy – to keep the star stable.
- But in the supernova stage, we have plenty of energy. We can now allow endothermic reactions – those that need energy to fuse – because there is now an abundance of energy.
- Neutrons – absent up to now – are plentiful, due to electrons colliding with protons, creating neutrons. This requires energy, but again, we have more than enough of that.
- In this extreme heat, neutrons combine with atomic nuclei through what's called "slow neutron capture" and "fast neutron capture", to build on the atom-types (elements) being created.

Lifetime of a 25 $M_\odot$ Star

Stage	Time
H → He	7 million years
He → C, O	500,000 years
C, O → Ne, Mg	600 years
Ne, O → Si, S	6 months
Si → Fe	1 day

Credits

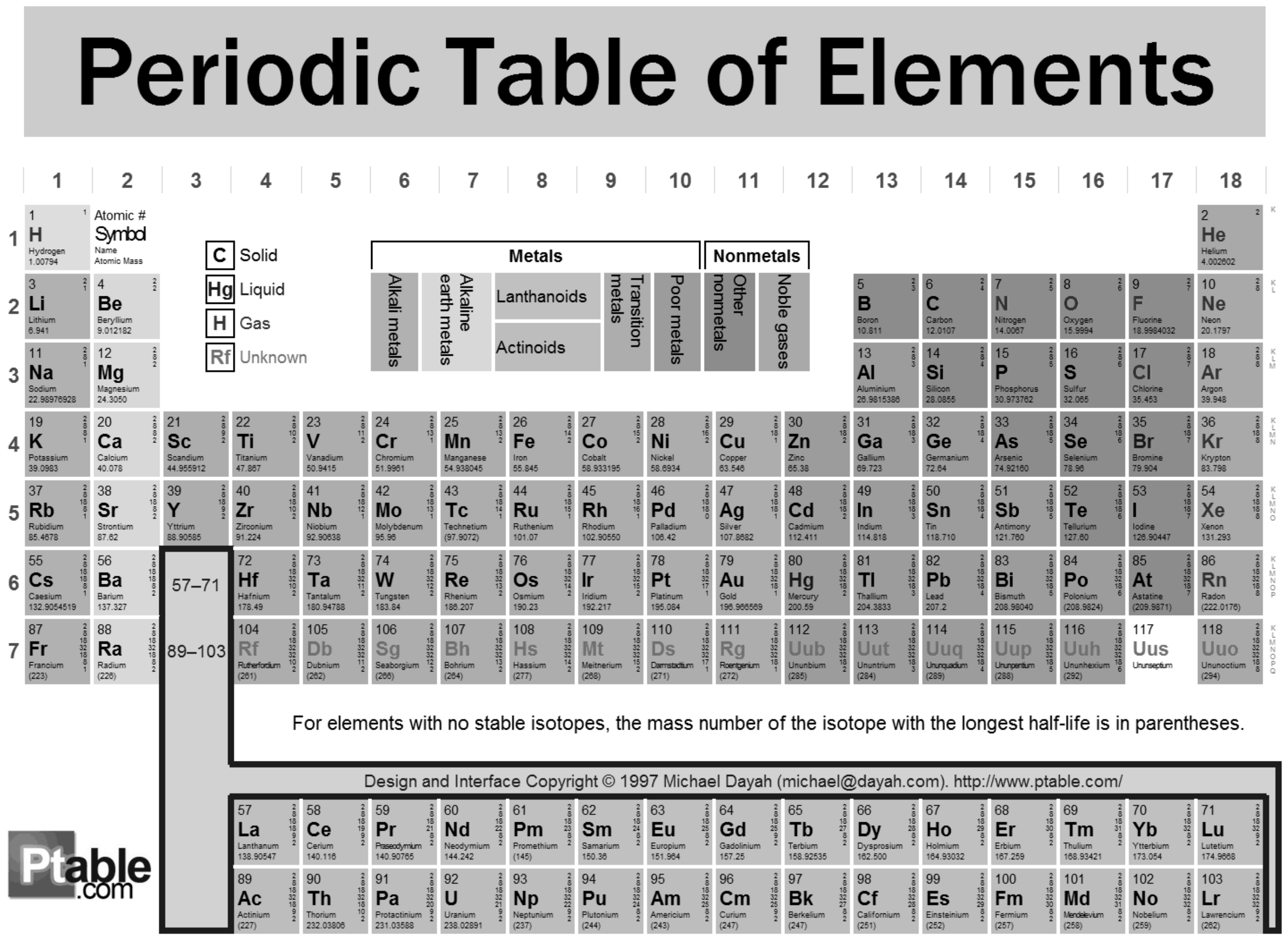
- **Prof. Alex Filippenko**, UC Berkeley, and his Teaching Company DVD series "Understanding the Universe: An Introduction to Astronomy"
- **Prof. Neil deGrasse Tyson**, Director of the Hayden Planetarium, and his Teaching Company DVD series "My Favorite Universe"
- **Wikipedia.com**, for more reference material than can be listed.

Continued Study

Internet Starting Points

- **http://en.wikipedia.org/wiki/Proton-proton_chain_reaction**
  starts at the first nucleosynthetic process, and provides links to related reactions.
- **http://en.wikipedia.org/wiki/Supernova**
  is a good starting point for the supernova process.
- **www.ptable.com**
  is the best Periodic Table on the internet. Interactive.
- **http://en.wikipedia.org/wiki/Alexei_Filippenko**
  provides information on my primary instructor in astronomy.

Periodic Table



Periodic Table of Elements

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	
1	1 **H** Hydrogen 1.00794 1	Atomic # Symbol Name Atomic Mass																2 **He** Helium 4.002602 2	K
2	3 **Li** Lithium 6.941 2 1	4 **Be** Beryllium 9.012182 2 2											5 **B** Boron 10.811 2 3	6 **C** Carbon 12.0107 2 4	7 **N** Nitrogen 14.0067 2 5	8 **O** Oxygen 15.9994 2 6	9 **F** Fluorine 18.9984032 2 7	10 **Ne** Neon 20.1797 2 8	K L
3	11 **Na** Sodium 22.98976928 2 8 1	12 **Mg** Magnesium 24.3050 2 8 2											13 **Al** Aluminium 26.9815386 2 8 3	14 **Si** Silicon 28.0855 2 8 4	15 **P** Phosphorus 30.973762 2 8 5	16 **S** Sulfur 32.065 2 8 6	17 **Cl** Chlorine 35.453 2 8 7	18 **Ar** Argon 39.948 2 8 8	K L M
4	19 **K** Potassium 39.0983 2 8 8 1	20 **Ca** Calcium 40.078 2 8 8 2	21 **Sc** Scandium 44.955912 2 8 9 2	22 **Ti** Titanium 47.867 2 8 10 2	23 **V** Vanadium 50.9415 2 8 11 2	24 **Cr** Chromium 51.9961 2 8 13 1	25 **Mn** Manganese 54.938045 2 8 13 2	26 **Fe** Iron 55.845 2 8 14 2	27 **Co** Cobalt 58.933195 2 8 15 2	28 **Ni** Nickel 58.6934 2 8 16 2	29 **Cu** Copper 63.546 2 8 18 1	30 **Zn** Zinc 65.38 2 8 18 2	31 **Ga** Gallium 69.723 2 8 18 3	32 **Ge** Germanium 72.64 2 8 18 4	33 **As** Arsenic 74.92160 2 8 18 5	34 **Se** Selenium 78.96 2 8 18 6	35 **Br** Bromine 79.904 2 8 18 7	36 **Kr** Krypton 83.798 2 8 18 8	K L M N
5	37 **Rb** Rubidium 85.4678 2 8 18 8 1	38 **Sr** Strontium 87.62 2 8 18 8 2	39 **Y** Yttrium 88.90585 2 8 18 9 2	40 **Zr** Zirconium 91.224 2 8 18 10 2	41 **Nb** Niobium 92.90638 2 8 18 12 1	42 **Mo** Molybdenum 95.96 2 8 18 13 1	43 **Tc** Technetium (97.9072) 2 8 18 14 1	44 **Ru** Ruthenium 101.07 2 8 18 15 1	45 **Rh** Rhodium 102.90550 2 8 18 16 1	46 **Pd** Palladium 106.42 2 8 18 18 0	47 **Ag** Silver 107.8682 2 8 18 18 1	48 **Cd** Cadmium 112.411 2 8 18 18 2	49 **In** Indium 114.818 2 8 18 18 3	50 **Sn** Tin 118.710 2 8 18 18 4	51 **Sb** Antimony 121.760 2 8 18 18 5	52 **Te** Tellurium 127.60 2 8 18 18 6	53 **I** Iodine 126.90447 2 8 18 18 7	54 **Xe** Xenon 131.293 2 8 18 18 8	K L M N O
6	55 **Cs** Caesium 132.9054519 2 8 18 18 8 1	56 **Ba** Barium 137.327 2 8 18 18 8 2	57–71	72 **Hf** Hafnium 178.49 2 8 18 32 10 2	73 **Ta** Tantalum 180.94788 2 8 18 32 11 2	74 **W** Tungsten 183.84 2 8 18 32 12 2	75 **Re** Rhenium 186.207 2 8 18 32 13 2	76 **Os** Osmium 190.23 2 8 18 32 14 2	77 **Ir** Iridium 192.217 2 8 18 32 15 2	78 **Pt** Platinum 195.084 2 8 18 32 17 1	79 **Au** Gold 196.966569 2 8 18 32 18 1	80 **Hg** Mercury 200.59 2 8 18 32 18 2	81 **Tl** Thallium 204.3833 2 8 18 32 18 3	82 **Pb** Lead 207.2 2 8 18 32 18 4	83 **Bi** Bismuth 208.98040 2 8 18 32 18 5	84 **Po** Polonium (208.9824) 2 8 18 32 18 6	85 **At** Astatine (209.9871) 2 8 18 32 18 7	86 **Rn** Radon (222.0176) 2 8 18 32 18 8	K L M N O P
7	87 **Fr** Francium (223) 2 8 18 32 18 8 1	88 **Ra** Radium (226) 2 8 18 32 18 8 2	89–103	104 **Rf** Rutherfordium (261) 2 8 18 32 32 10 2	105 **Db** Dubnium (262) 2 8 18 32 32 11 2	106 **Sg** Seaborgium (266) 2 8 18 32 32 12 2	107 **Bh** Bohrium (264) 2 8 18 32 32 13 2	108 **Hs** Hassium (277) 2 8 18 32 32 14 2	109 **Mt** Meitnerium (268) 2 8 18 32 32 15 2	110 **Ds** Darmstadtium (271) 2 8 18 32 32 17 1	111 **Rg** Roentgenium (272) 2 8 18 32 32 18 1	112 **Uub** Ununbium (285) 2 8 18 32 32 18 2	113 **Uut** Ununtrium (284) 2 8 18 32 32 18 3	114 **Uuq** Ununquadium (289) 2 8 18 32 32 18 4	115 **Uup** Ununpentium (288) 2 8 18 32 32 18 5	116 **Uuh** Ununhexium (292) 2 8 18 32 32 18 6	117 **Uus** Ununseptium	118 **Uuo** Ununoctium (294) 2 8 18 32 32 18 8	K L M N O P Q
				57 **La** Lanthanum 138.90547 2 8 18 18 9 2	58 **Ce** Cerium 140.116 2 8 18 19 9 2	59 **Pr** Praseodymium 140.90765 2 8 18 21 8 2	60 **Nd** Neodymium 144.242 2 8 18 22 8 2	61 **Pm** Promethium (145) 2 8 18 23 8 2	62 **Sm** Samarium 150.36 2 8 18 24 8 2	63 **Eu** Europium 151.964 2 8 18 25 8 2	64 **Gd** Gadolinium 157.25 2 8 18 25 9 2	65 **Tb** Terbium 158.92535 2 8 18 27 8 2	66 **Dy** Dysprosium 162.500 2 8 18 28 8 2	67 **Ho** Holmium 164.93032 2 8 18 29 8 2	68 **Er** Erbium 167.259 2 8 18 30 8 2	69 **Tm** Thulium 168.93421 2 8 18 31 8 2	70 **Yb** Ytterbium 173.054 2 8 18 32 8 2	71 **Lu** Lutetium 174.9668 2 8 18 32 9 2	
				89 **Ac** Actinium (227) 2 8 18 32 18 9 2	90 **Th** Thorium 232.03806 2 8 18 32 18 10 2	91 **Pa** Protactinium 231.03588 2 8 18 32 20 9 2	92 **U** Uranium 238.02891 2 8 18 32 21 9 2	93 **Np** Neptunium (237) 2 8 18 32 22 9 2	94 **Pu** Plutonium (244) 2 8 18 32 24 8 2	95 **Am** Americium (243) 2 8 18 32 25 8 2	96 **Cm** Curium (247) 2 8 18 32 25 9 2	97 **Bk** Berkelium (247) 2 8 18 32 27 8 2	98 **Cf** Californium (251) 2 8 18 32 28 8 2	99 **Es** Einsteinium (252) 2 8 18 32 29 8 2	100 **Fm** Fermium (257) 2 8 18 32 30 8 2	101 **Md** Mendelevium (258) 2 8 18 32 31 8 2	102 **No** Nobelium (259) 2 8 18 32 32 8 2	103 **Lr** Lawrencium (262) 2 8 18 32 32 9 2	

C Solid
Hg Liquid
H Gas
Rf Unknown

Metals
- Alkali metals
- Alkaline earth metals
- Lanthanoids
- Actinoids
- Transition metals
- Poor metals

Nonmetals
- Other nonmetals
- Noble gases

For elements with no stable isotopes, the mass number of the isotope with the longest half-life is in parentheses.