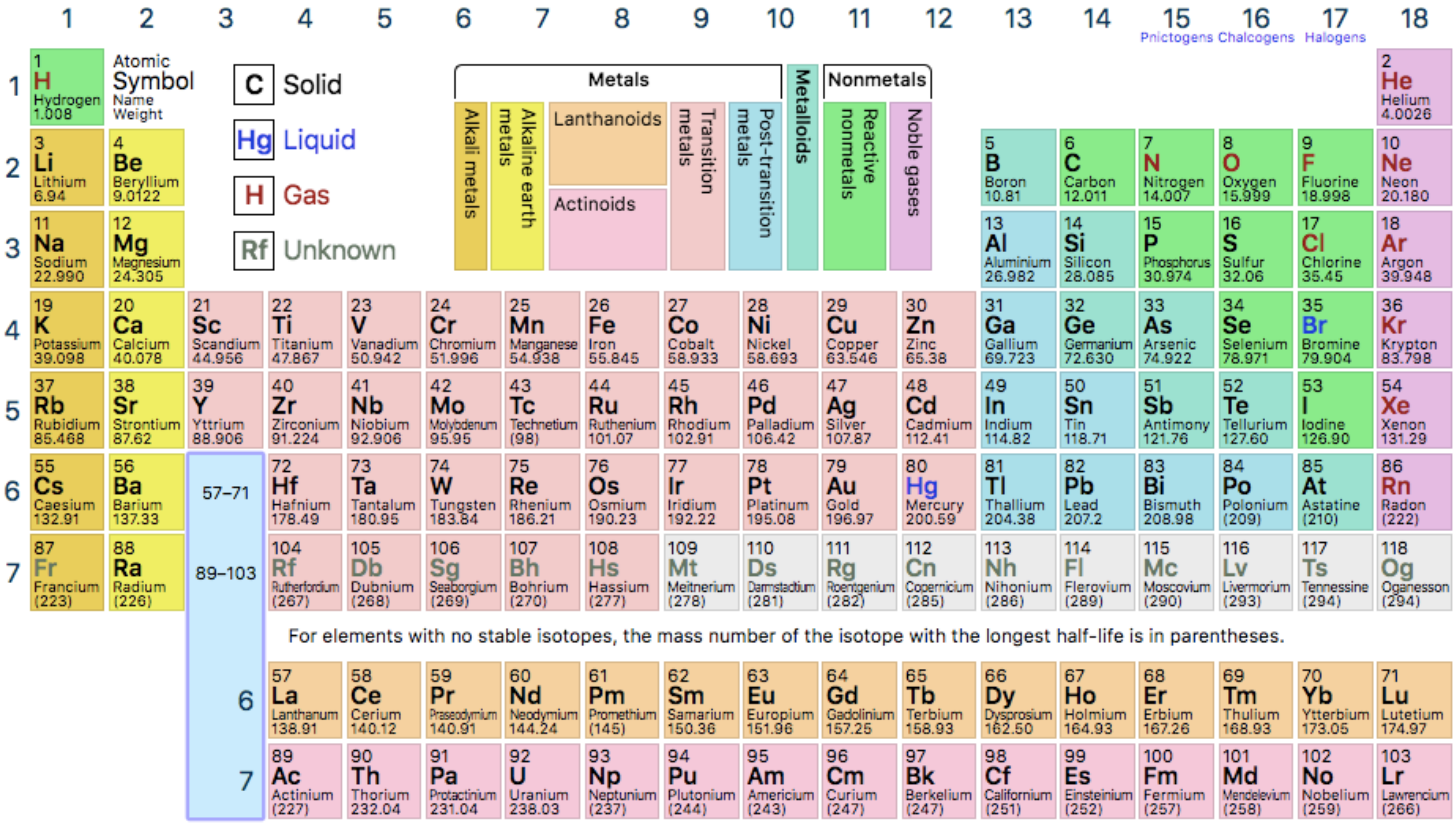
NUCLEAR PHYSICS

an
Introduction
by
Jess H. Brewer

The Periodic Table of the Elements



Atomic
Symbol
Name
Weight

C Solid
Hg Liquid
H Gas
Rf Unknown

Metals
Alkali metals
Alkaline earth metals
Lanthanoids
Actinoids
Transition metals
Post-transition metals

Metalloids

Nonmetals
Reactive nonmetals
Noble gases

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15 Pnictogens	16 Chalcogens	17 Halogens	18
1	1 H Hydrogen 1.008																	2 He Helium 4.0026
2	3 Li Lithium 6.94	4 Be Beryllium 9.0122											5 B Boron 10.81	6 C Carbon 12.011	7 N Nitrogen 14.007	8 O Oxygen 15.999	9 F Fluorine 18.998	10 Ne Neon 20.180
3	11 Na Sodium 22.990	12 Mg Magnesium 24.305											13 Al Aluminium 26.982	14 Si Silicon 28.085	15 P Phosphorus 30.974	16 S Sulfur 32.06	17 Cl Chlorine 35.45	18 Ar Argon 39.948
4	19 K Potassium 39.098	20 Ca Calcium 40.078	21 Sc Scandium 44.956	22 Ti Titanium 47.867	23 V Vanadium 50.942	24 Cr Chromium 51.996	25 Mn Manganese 54.938	26 Fe Iron 55.845	27 Co Cobalt 58.933	28 Ni Nickel 58.693	29 Cu Copper 63.546	30 Zn Zinc 65.38	31 Ga Gallium 69.723	32 Ge Germanium 72.630	33 As Arsenic 74.922	34 Se Selenium 78.971	35 Br Bromine 79.904	36 Kr Krypton 83.798
5	37 Rb Rubidium 85.468	38 Sr Strontium 87.62	39 Y Yttrium 88.906	40 Zr Zirconium 91.224	41 Nb Niobium 92.906	42 Mo Molybdenum 95.95	43 Tc Technetium (98)	44 Ru Ruthenium 101.07	45 Rh Rhodium 102.91	46 Pd Palladium 106.42	47 Ag Silver 107.87	48 Cd Cadmium 112.41	49 In Indium 114.82	50 Sn Tin 118.71	51 Sb Antimony 121.76	52 Te Tellurium 127.60	53 I Iodine 126.90	54 Xe Xenon 131.29
6	55 Cs Caesium 132.91	56 Ba Barium 137.33	57–71	72 Hf Hafnium 178.49	73 Ta Tantalum 180.95	74 W Tungsten 183.84	75 Re Rhenium 186.21	76 Os Osmium 190.23	77 Ir Iridium 192.22	78 Pt Platinum 195.08	79 Au Gold 196.97	80 Hg Mercury 200.59	81 Tl Thallium 204.38	82 Pb Lead 207.2	83 Bi Bismuth 208.98	84 Po Polonium (209)	85 At Astatine (210)	86 Rn Radon (222)
7	87 Fr Francium (223)	88 Ra Radium (226)	89–103	104 Rf Rutherfordium (267)	105 Db Dubnium (268)	106 Sg Seaborgium (269)	107 Bh Bohrium (270)	108 Hs Hassium (277)	109 Mt Meitnerium (278)	110 Ds Darmstadtium (281)	111 Rg Roentgenium (282)	112 Cn Copernicium (285)	113 Nh Nihonium (286)	114 Fl Flerovium (289)	115 Mc Moscovium (290)	116 Lv Livermorium (293)	117 Ts Tennessine (294)	118 Og Oganesson (294)

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

6	57 La Lanthanum 138.91	58 Ce Cerium 140.12	59 Pr Praseodymium 140.91	60 Nd Neodymium 144.24	61 Pm Promethium (145)	62 Sm Samarium 150.36	63 Eu Europium 151.96	64 Gd Gadolinium 157.25	65 Tb Terbium 158.93	66 Dy Dysprosium 162.50	67 Ho Holmium 164.93	68 Er Erbium 167.26	69 Tm Thulium 168.93	70 Yb Ytterbium 173.05	71 Lu Lutetium 174.97
7	89 Ac Actinium (227)	90 Th Thorium 232.04	91 Pa Protactinium 231.04	92 U Uranium 238.03	93 Np Neptunium (237)	94 Pu Plutonium (244)	95 Am Americium (243)	96 Cm Curium (247)	97 Bk Berkelium (247)	98 Cf Californium (251)	99 Es Einsteinium (252)	100 Fm Fermium (257)	101 Md Mendelevium (258)	102 No Nobelium (259)	103 Lr Lawrencium (266)

Conversion of Mass to Energy

Einstein's association of the term mc^2 with a **rest mass energy** E_0 naturally led to speculation about what might be done to *convert* mass into useable energy, since for a *little* mass you get a *lot* of energy!

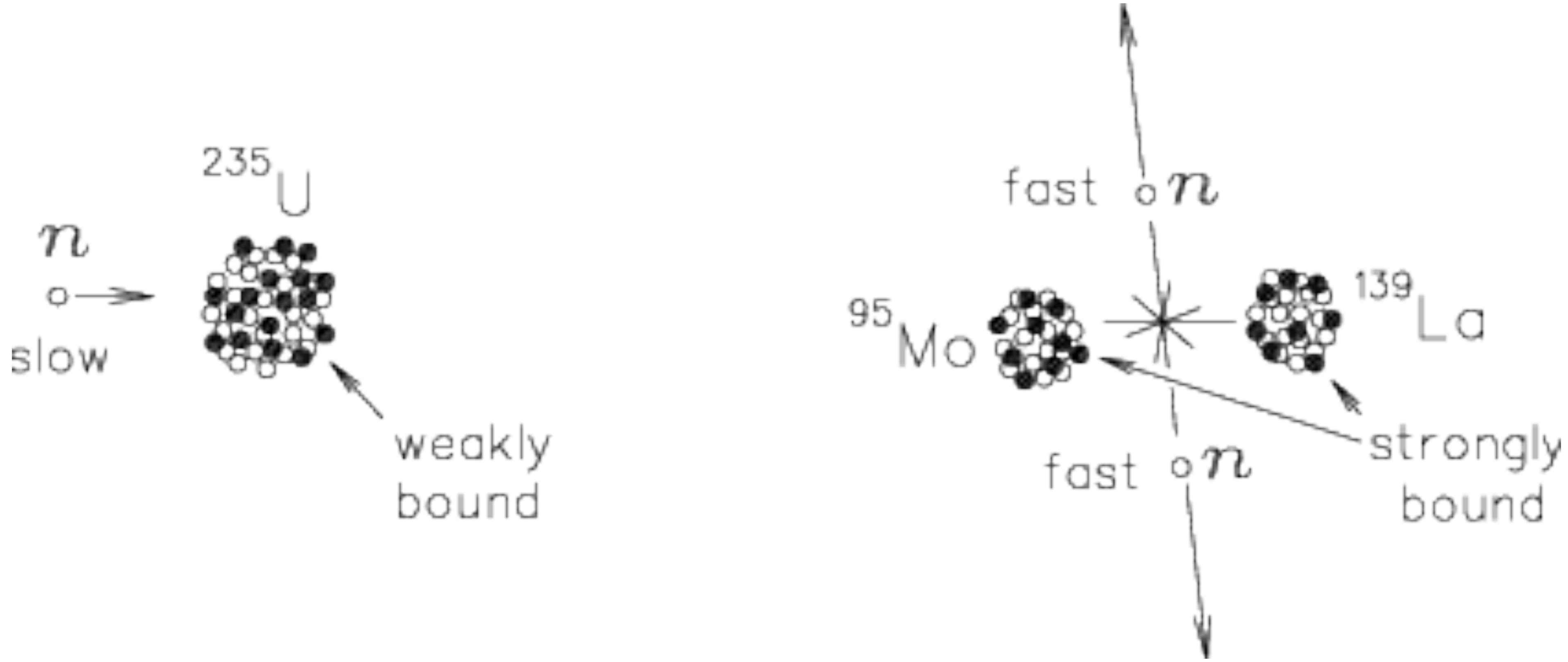
Let's see *just how much*: in *S.I.* units $1 \text{ J} \equiv 1 \text{ kg-m}^2/\text{s}^2$ so a 1 kg mass has a rest mass energy of $(1 \text{ kg})\times(2.9979\times10^8 \text{ m/s})^2 = 8.9876\times10^{16} \text{ J}$ — which is a lot of joules! To get an idea how many, remember that one **watt** is a unit of *power* equal to one joule per second, so a **joule** is the same thing as a **watt-second**. Therefore a device converting *one millionth of a gram* (1 μg) of mass to energy *every second* would release approximately *90 megawatts* [millions of watts] of power!

Bad Things to do with Mass-Energy Conversion

Contrary to popular belief, the first conclusive demonstration of mass-energy conversion was in a controlled nuclear *reactor*. However, not long after came the more unpleasant manifestation of mass-energy conversion: the fission *bomb*. An unpleasant subject, but one about which it behooves us to be knowledgeable. For this, we need a new energy unit, namely the **kiloton** [kt], referring to the energy released in the explosion of one thousand *tons* of TNT [*T*ri*N*itro*T*oluene], a common chemical high explosive. The basic conversion factor is $1 \text{ kt} \equiv 1$ trillion *calories* $= 4.186 \times 10^{12}$ J, which means that one **kiloton**'s worth of energy is released in the conversion of 0.04658 grams [46.58 mg] of mass. Thus a **megaton** [equivalent to one *million* tons of TNT or 10^3 kt] is released in the conversion of 46.58 grams of mass; and the largest thermonuclear device [bomb] ever detonated, about 100 megatons' worth, converted some 4.658 kg of mass directly into raw energy.

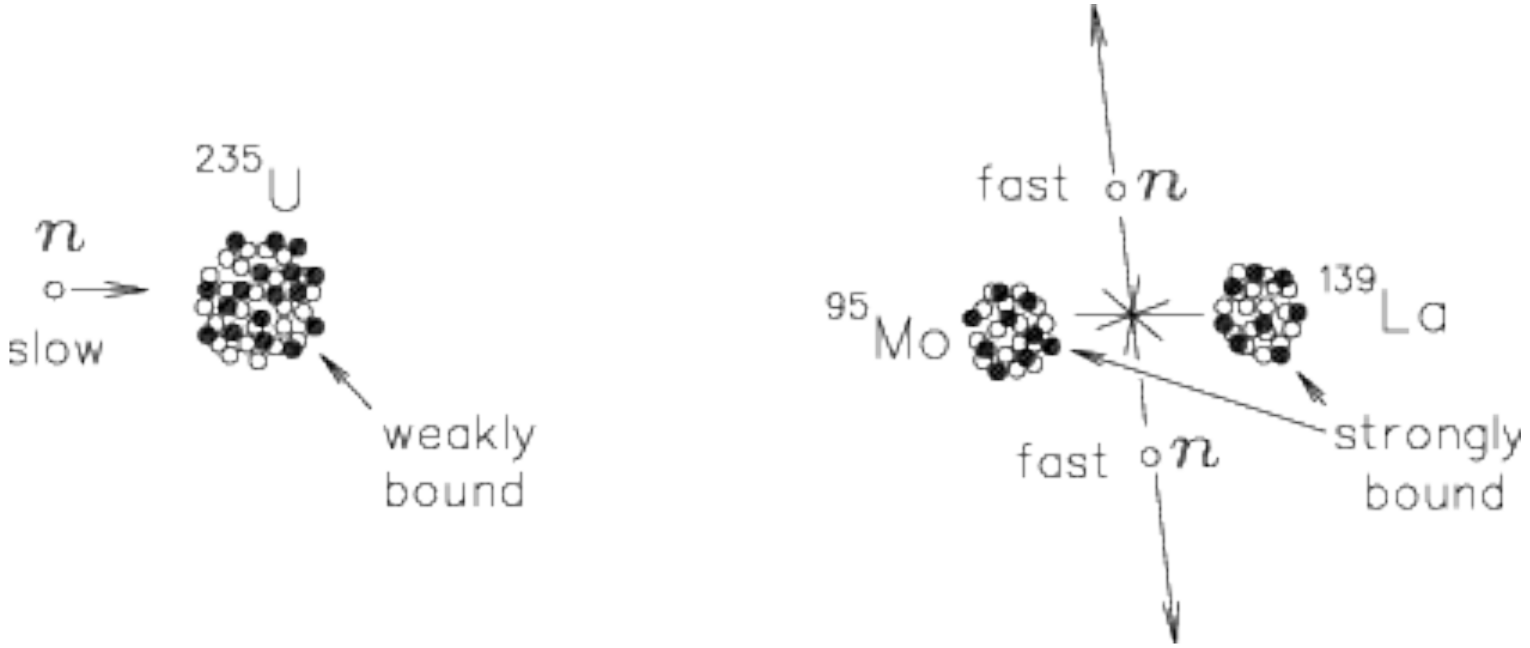
Nuclear Fission

Where did the energy come from? *What* mass got converted? To answer this question we must look at the processes involved on a sub-microscopic scale. First we must consider the natural tendency for oversized atomic nuclei to spontaneously *split* into smaller components. This process is known as NUCLEAR FISSION and is the energy source for all presently functioning NUCLEAR REACTORS on Earth. [Also for so-called "atomic" bombs.]

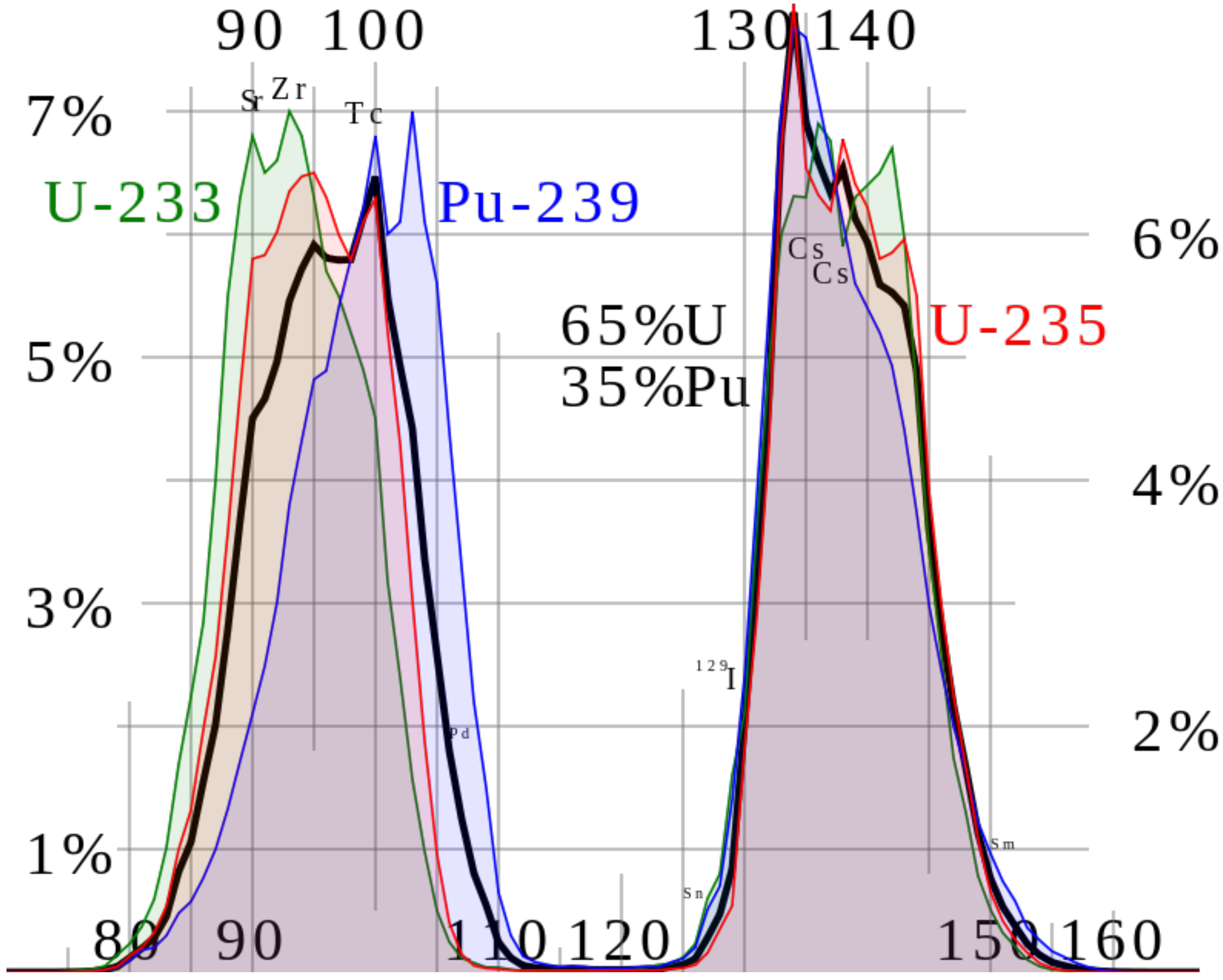


Fission of ^{236}U: The net mass of the initial neutron plus the ^{235}U nucleus is 219,883 MeV/c^2. The net mass of the fission products (two neutrons, a ^{95}Mo nucleus and a ^{139}La nucleus) is 219,675 MeV/c^2 - smaller because of the stronger *binding* of the Mo and La nuclei. The "missing mass" of 208 MeV/c^2 (a little less than 0.1% of the original mass) goes into the *kinetic energy* of the *fragments* (mainly the *neutrons*), which of course adds up to 208 MeV.

FISSION



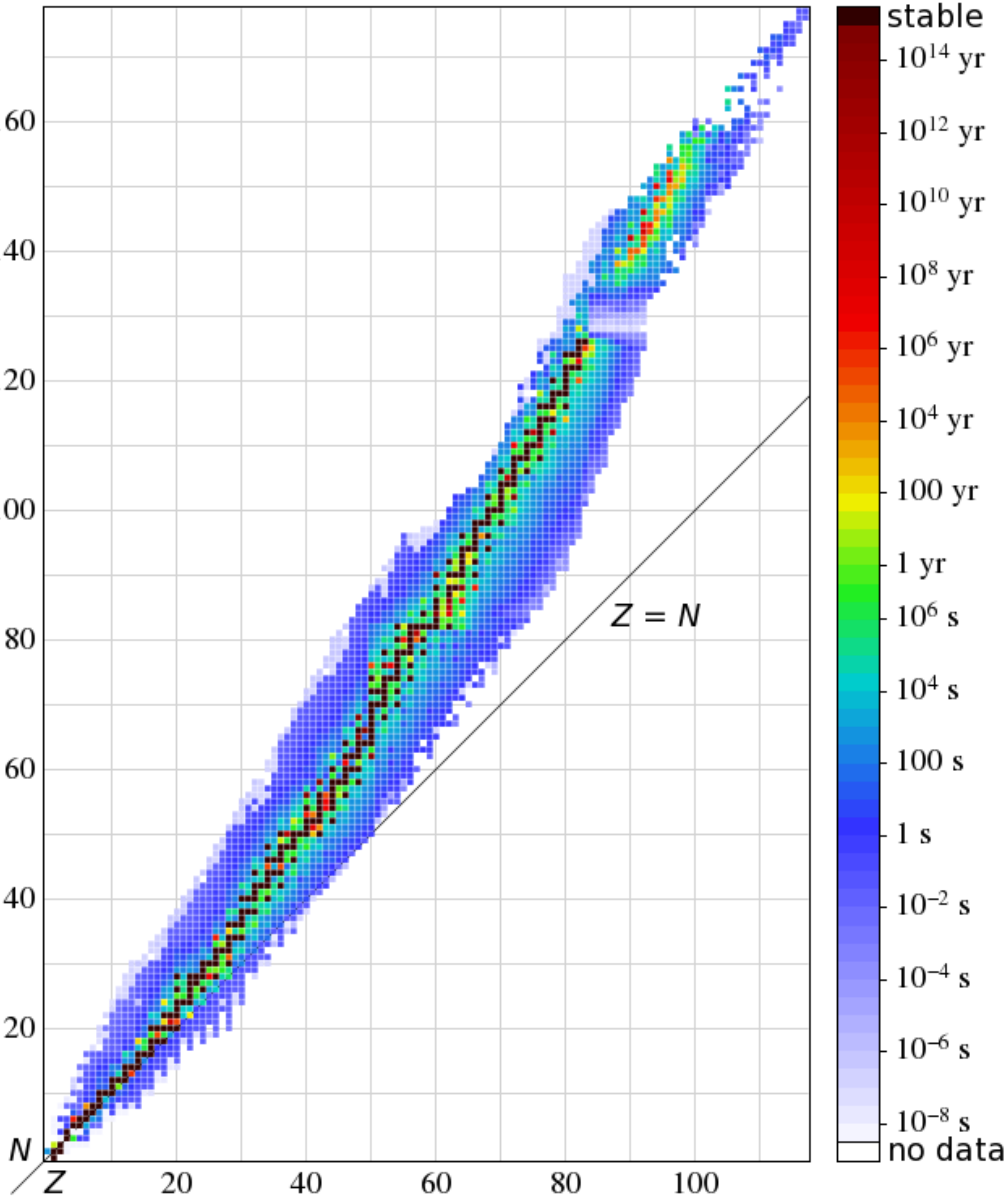
The example shown above has ^{236}U splitting into ^{95}Mo and ^{139}La along with *two* fast neutrons, but there are *many other ways* that ^{236}U can fission. One of its "daughters" usually has 90-100 nucleons, while the other has 130-140. And sometimes there are more than two neutrons emitted. This, plus the long lifetime of ^{235}U and its relatively innocuous alpha-decay, make it a "good" candidate for a **bomb**.



ISOTOPES and their (color-coded) Half-Lives

Z = # of protons

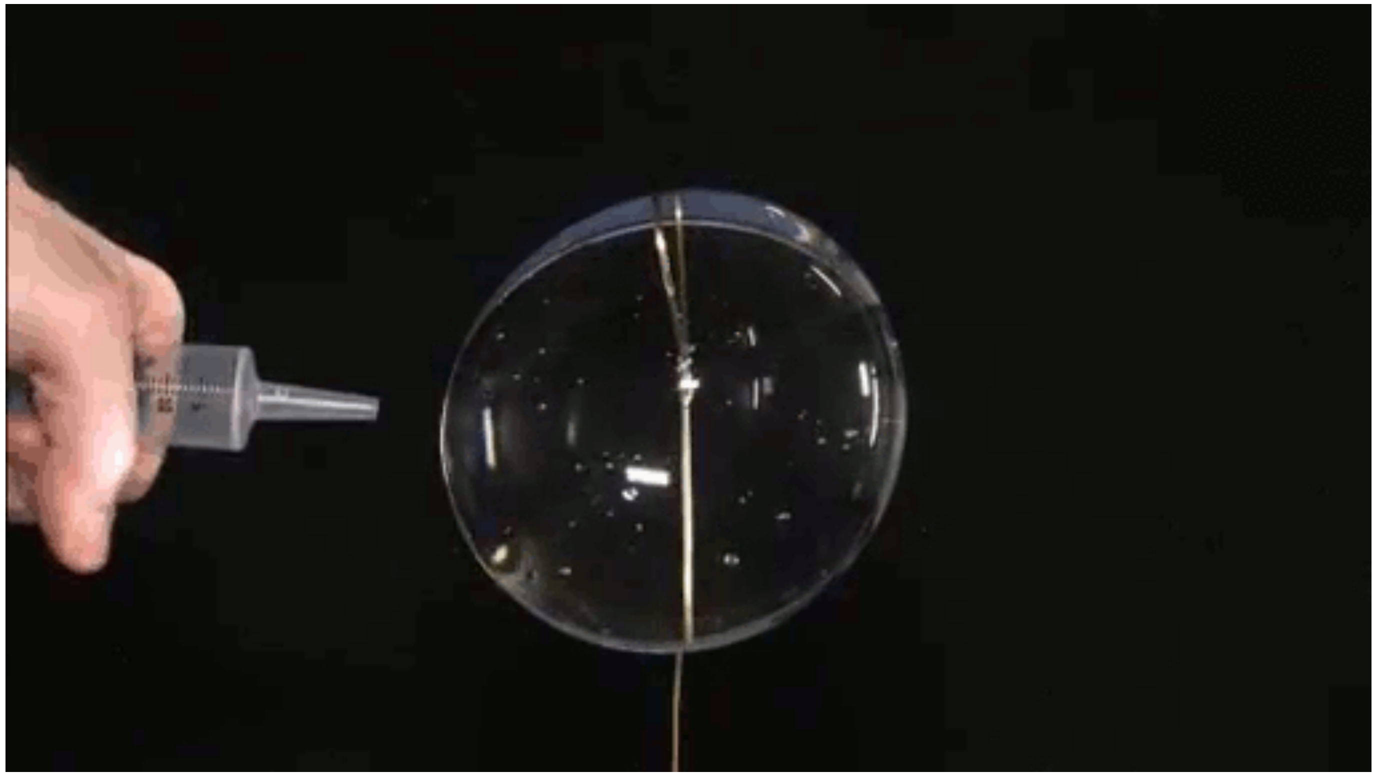
N = # of neutrons



Liquid Drop Model

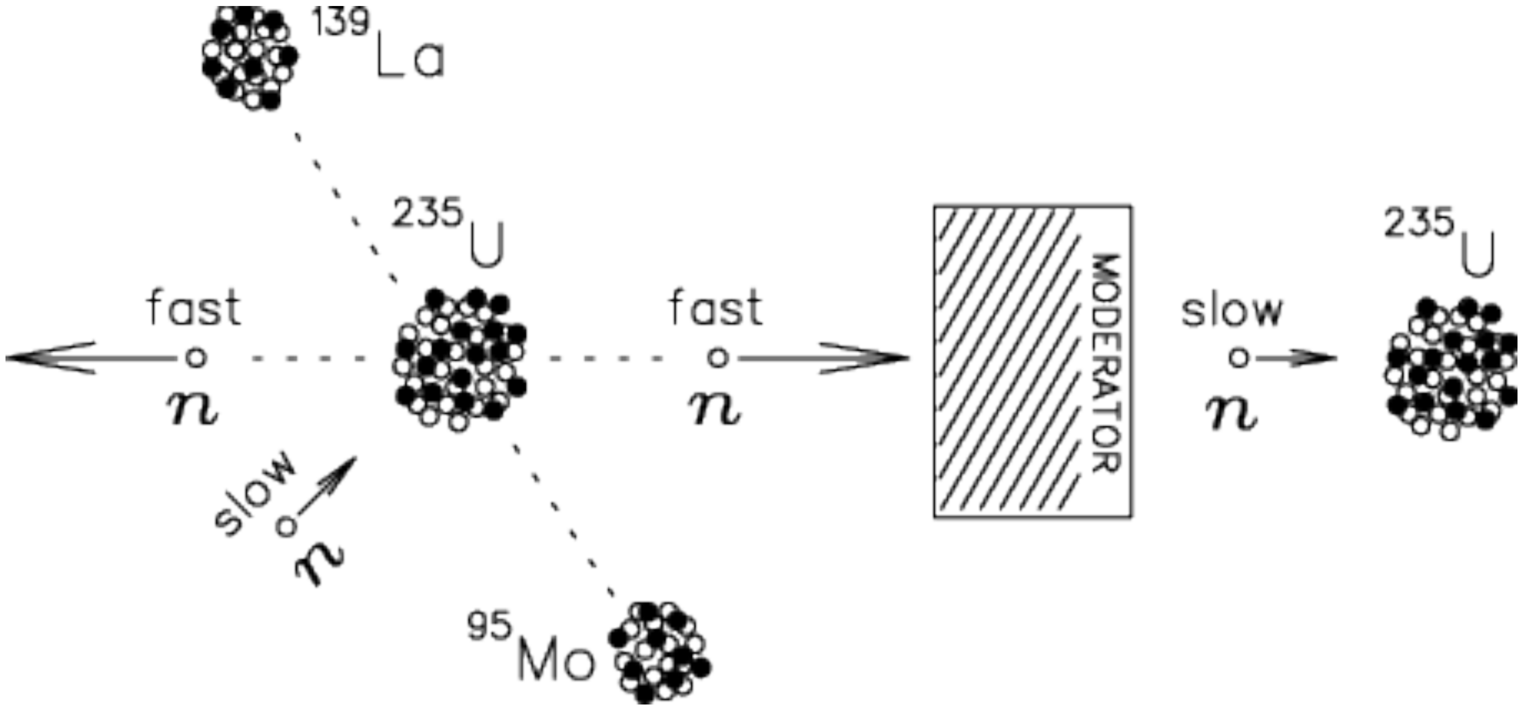
Surface tension keeps *small* water droplets perfectly spherical, but ***big*** water droplets are *unstable* because the attractive force between molecules is *short-range*.

Nuclei are similar: *small* ones are *stable,* but ***big*** ones jiggle and sometimes *split* into smaller nuclei, spitting out neutrons, for the same reason: the **strong attraction** between nucleons is *short* range, while the electrostatic *repulsion* between *protons* is *long* range.

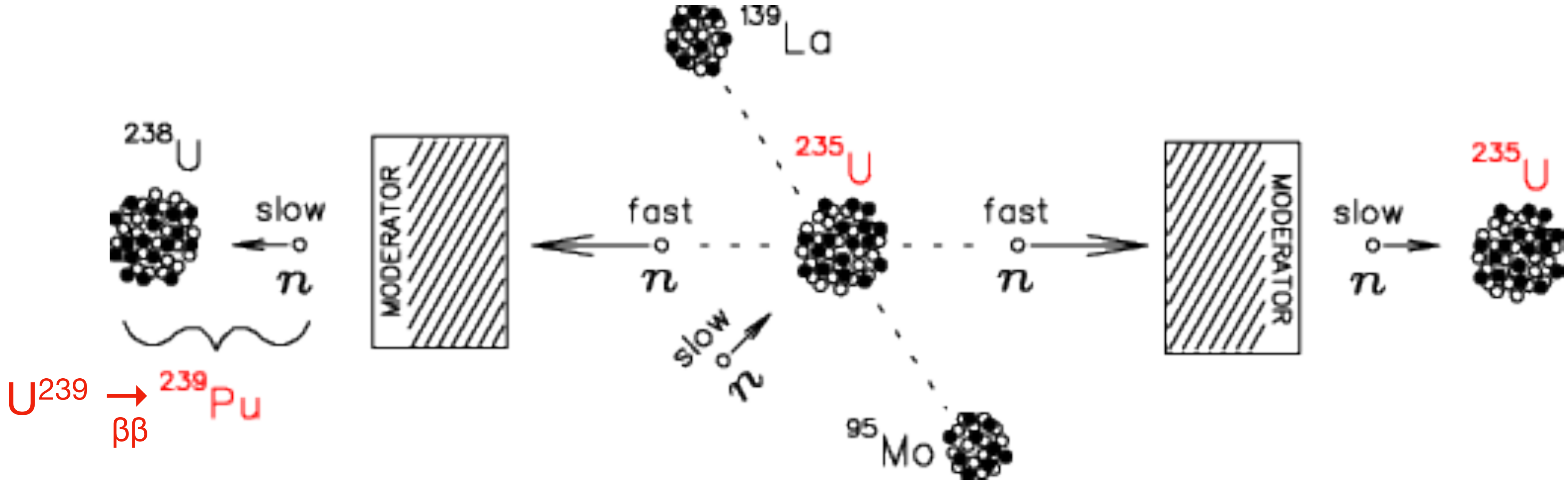


Chain Reactions:

- ^{235}U by itself:



- *Breeding fissile* ^{239}Pu from *fertile* ^{238}U with *neutrons* from ^{235}U:



How (*e.g.*) ^{235}U **Bombs** Work

1. Sub-critical chunks of ^{235}U are blasted together by conventional explosives, producing a temporary blob of *extremely* compressed ^{235}U.
2. A stray neutron is captured by ^{235}U, causing it to fission into two lighter nuclei and *several* neutrons.
3. Those neutrons slow down in the hyperdense metal and capture on other ^{235}U nuclei, causing *them* to fission…

CHAIN REACTION!

How (*some*) “H-Bombs” Work

1. Set off a small (*e.g.*) ^{235}U **fission** bomb to produce extreme pressure and temperature.

2. This triggers the **fusion** of (*e.g.*) deuterium & tritium, releasing huge amounts of energy, mainly in the form of ***fast** neutrons*.

3. *Fast* neutrons hit surrounding ^{238}U nuclei, causing *them* to **fission**…

4. Add as much ^{238}U as you like. It’s a **fission** bomb!

How Reactors Work

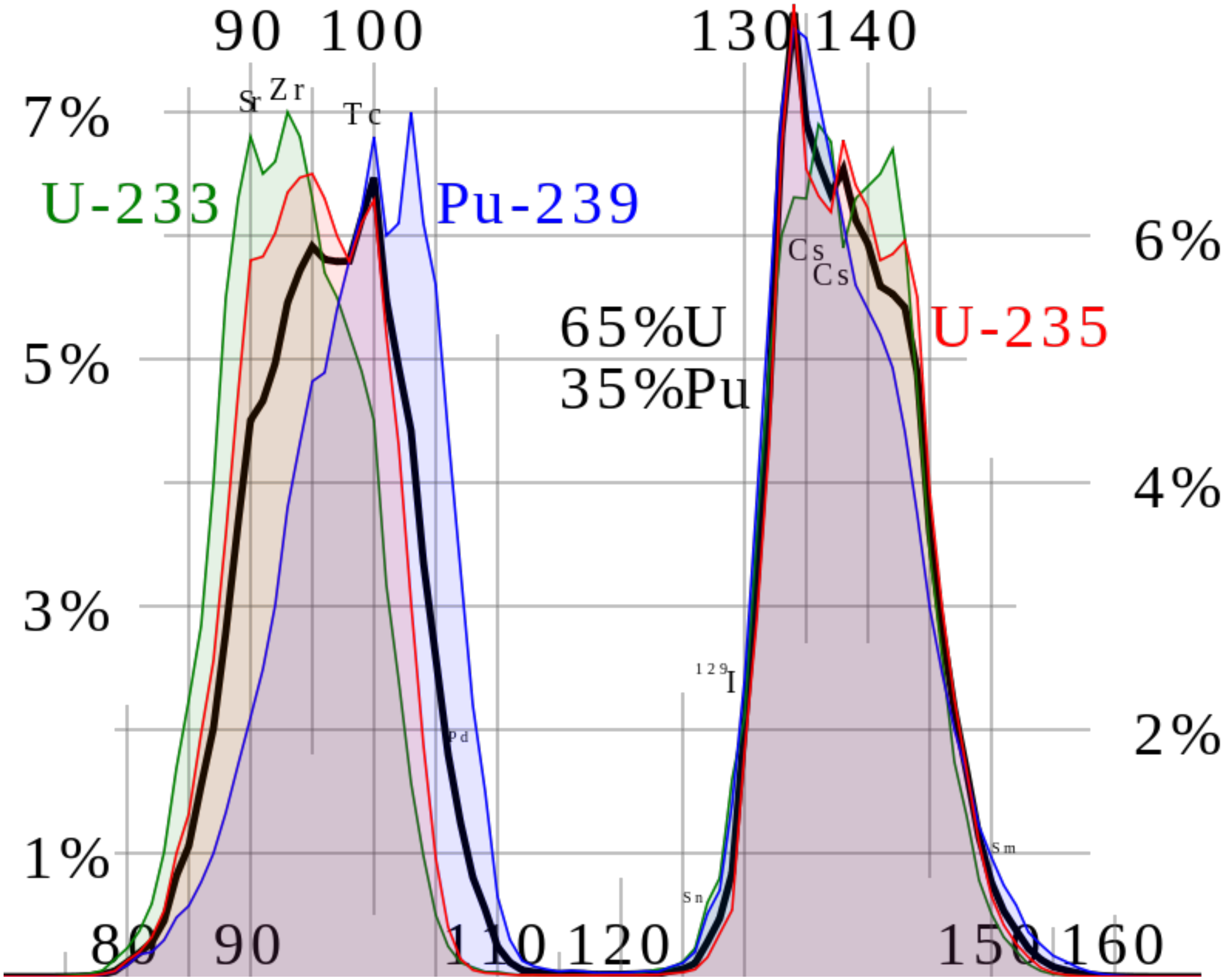
- Establish a *controlled* chain reaction in fission “fuel” using a combination of **moderators** (to slow down the fast fission neutrons so they can be captured and cause additional fissions) and neutron-absorbing “**control rods**” to decrease the slow neutron flux.

- **Heat** results from the energy deposited. Use it to drive a thermodynamic **heat engine** (*e.g.* a steam turbine). The hotter, the higher the efficiency.

  (Carnot efficiency = $1 - T_{\text{cold}} / T_{\text{hot}}$)

- That’s it. There are almost no exceptions *so far*.

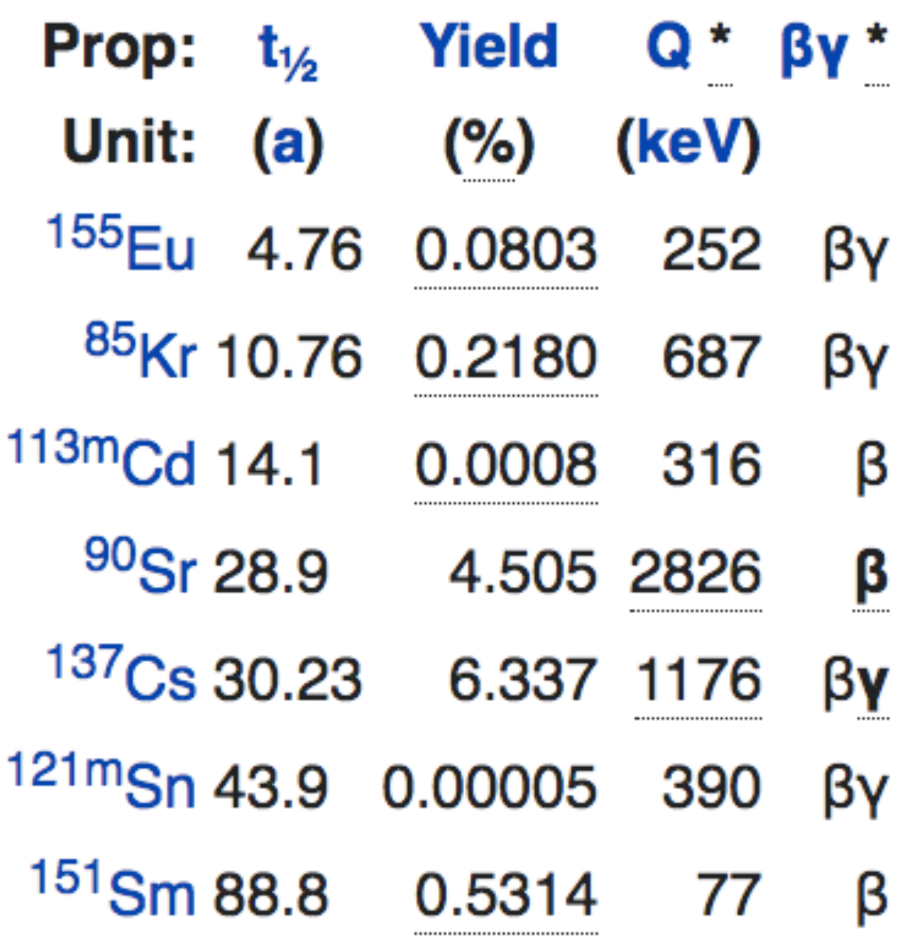
Fission Products



Decay of Fission Products

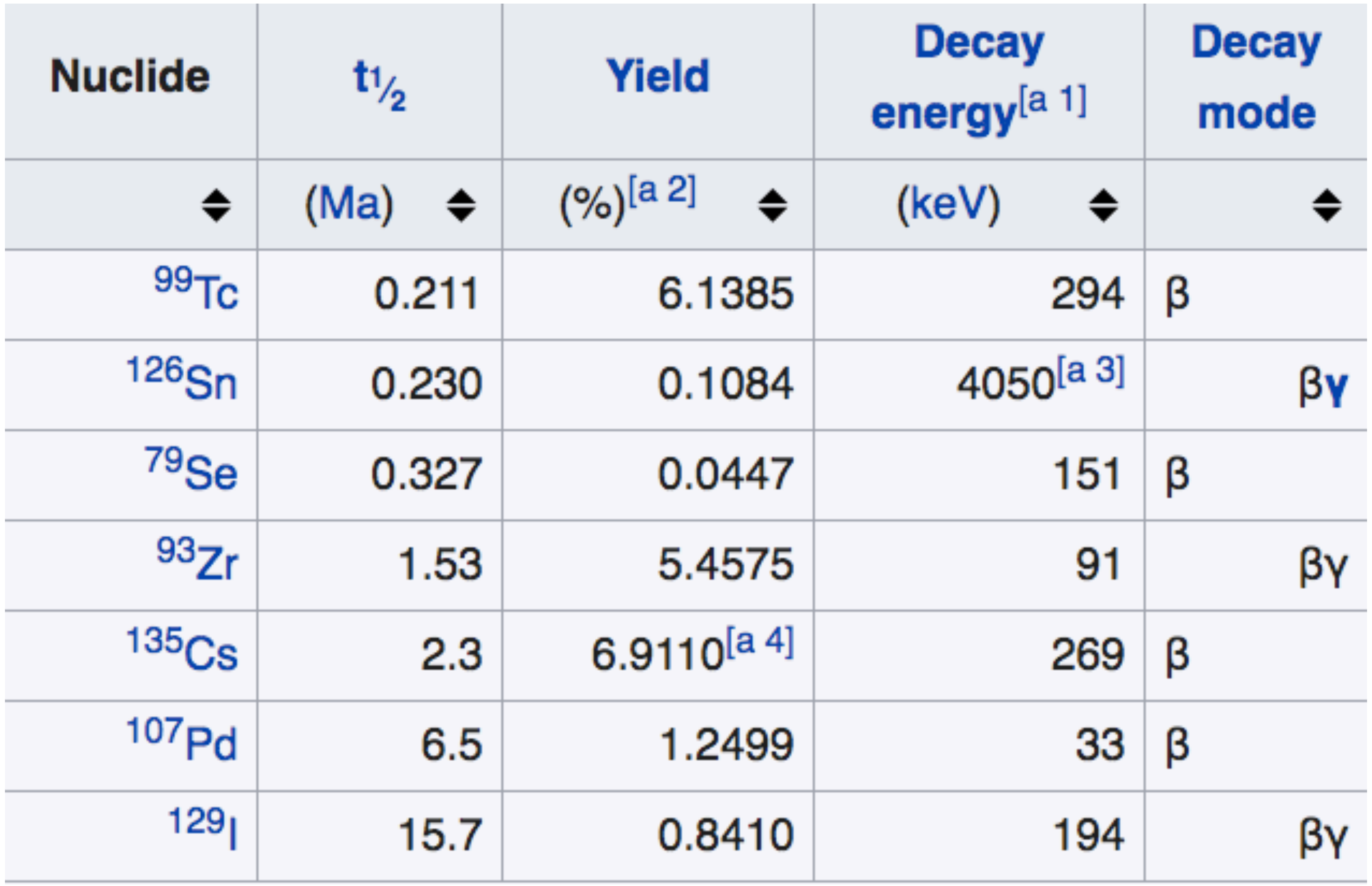
Wikipedia: “The radioactivity in the fission product mixture is [initially] mostly *short-lived* isotopes such as ^{131}I and ^{140}Ba; after about four months ^{141}Ce, ^{95}Zr/^{95}Nb and ^{89}Sr take the largest share, while after about two or three years the largest share is taken by ^{144}Ce/^{144}Pr, ^{106}Ru/^{106}Rh and ^{147}Pm.”

Medium-lived Daughters



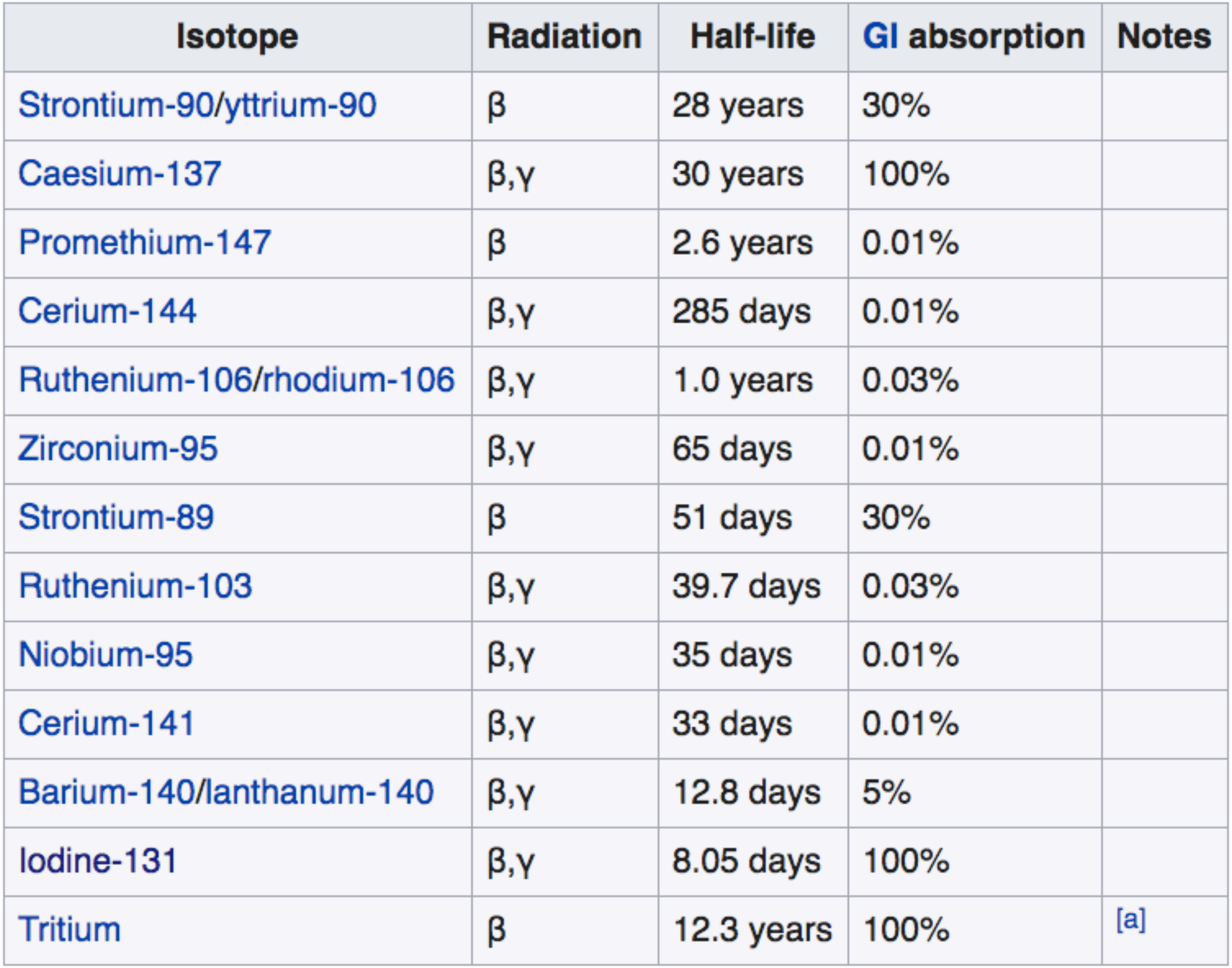
Prop:	**$t_{1/2}$**	**Yield**	**Q ***	**βγ ***
Unit:	**(a)**	**(%)**	**(keV)**	
^{155}Eu	4.76	0.0803	252	βγ
^{85}Kr	10.76	0.2180	687	βγ
^{113m}Cd	14.1	0.0008	316	β
^{90}Sr	28.9	4.505	2826	**β**
^{137}Cs	30.23	6.337	1176	β**γ**
^{121m}Sn	43.9	0.00005	390	βγ
^{151}Sm	88.8	0.5314	77	β

Long-lived Daughters



Nuclide	**$t_{1/2}$**	**Yield**	**Decay energy**[a 1]	**Decay mode**
⬍	(Ma) ⬍	(%)[a 2] ⬍	(keV) ⬍	⬍
^{99}Tc	0.211	6.1385	294	β
^{126}Sn	0.230	0.1084	4050[a 3]	β**γ**
^{79}Se	0.327	0.0447	151	β
^{93}Zr	1.53	5.4575	91	βγ
^{135}Cs	2.3	6.9110[a 4]	269	β
^{107}Pd	6.5	1.2499	33	β
^{129}I	15.7	0.8410	194	βγ

Health Concerns



Isotope	Radiation	Half-life	GI absorption	Notes
Strontium-90/yttrium-90	β	28 years	30%	
Caesium-137	β,γ	30 years	100%	
Promethium-147	β	2.6 years	0.01%	
Cerium-144	β,γ	285 days	0.01%	
Ruthenium-106/rhodium-106	β,γ	1.0 years	0.03%	
Zirconium-95	β,γ	65 days	0.01%	
Strontium-89	β	51 days	30%	
Ruthenium-103	β,γ	39.7 days	0.03%	
Niobium-95	β,γ	35 days	0.01%	
Cerium-141	β,γ	33 days	0.01%	
Barium-140/lanthanum-140	β,γ	12.8 days	5%	
Iodine-131	β,γ	8.05 days	100%	
Tritium	β	12.3 years	100%	[a]