Chart of Nuclides and the Production of Elements With Atomic Number Greater Than Iron's

At this point, we know how elements smaller than iron are produced in the core of a healthy star. Specifically:

Small elements with relatively large mass-per-nucleon counts are forced together to make larger elements that have smaller mass-per-nucleon counts.

In the process, the "lost" mass is turned into pure energy via $E = mc^2$.

The cut-off for this process is supposed to be iron. To fuse "small" elements into LARGER THAN iron elements would require a mass-per-nucleon count to go UP via $E = mc^2$. For this to happen, energy would *not* be given off--it would have to be *taken in*.

The temptation is to assume that the process to make elements at the "elements larger than iron" end of the spectrum was just like the process to make elements at the "elements smaller than iron" end, the only difference being that at the higher end you'd need something like a supernova to provide the needed energy to complete the fusion process.

It turns out that that is not how larger elements are produced during supernovas.

Why not? The amount of pressure required to force just *two* protons together to get fusion is enormous (remember, 10,000,000 degrees Kelvin and a billion atmospheres of pressure). Even with quantum mechanical tunneling active, the energies required for a proton to overcome the electrostatic repulsion produced by a proton-rich nucleus of, say, zinc, is considerably greater than the particle energies generated during supernovas. By extension, the electrostatic repulsion generated in an attempt to push two proton-rich zinc nuclei together via fusion is even less likely.

So how are the larger elements created?

Note 1: Supernovas produce enormous numbers of free neutrons. Being without charge, neutrons can effortlessly couple with already existing atoms experiencing no repulsion in the process.

Note 2: Although they are primarily made up of hydrogen and helium, all second and third generation stars have within them the same elements we find on earth.

Sooo, when a supernova blows, a lot of the small, medium and large elements in the star become neutron rich (that is, they have way more neutrons than they'd normally have). As a consequence, each element will end up with numerous radioactive isotopes--versions of themselves with more neutrons than are needed for stability.

Sooner or later, the unstable ones radioactively decay via beta emission (remember, beta emission is produced when a neutron decays into a proton with an electron being ejected as a high energy particle.

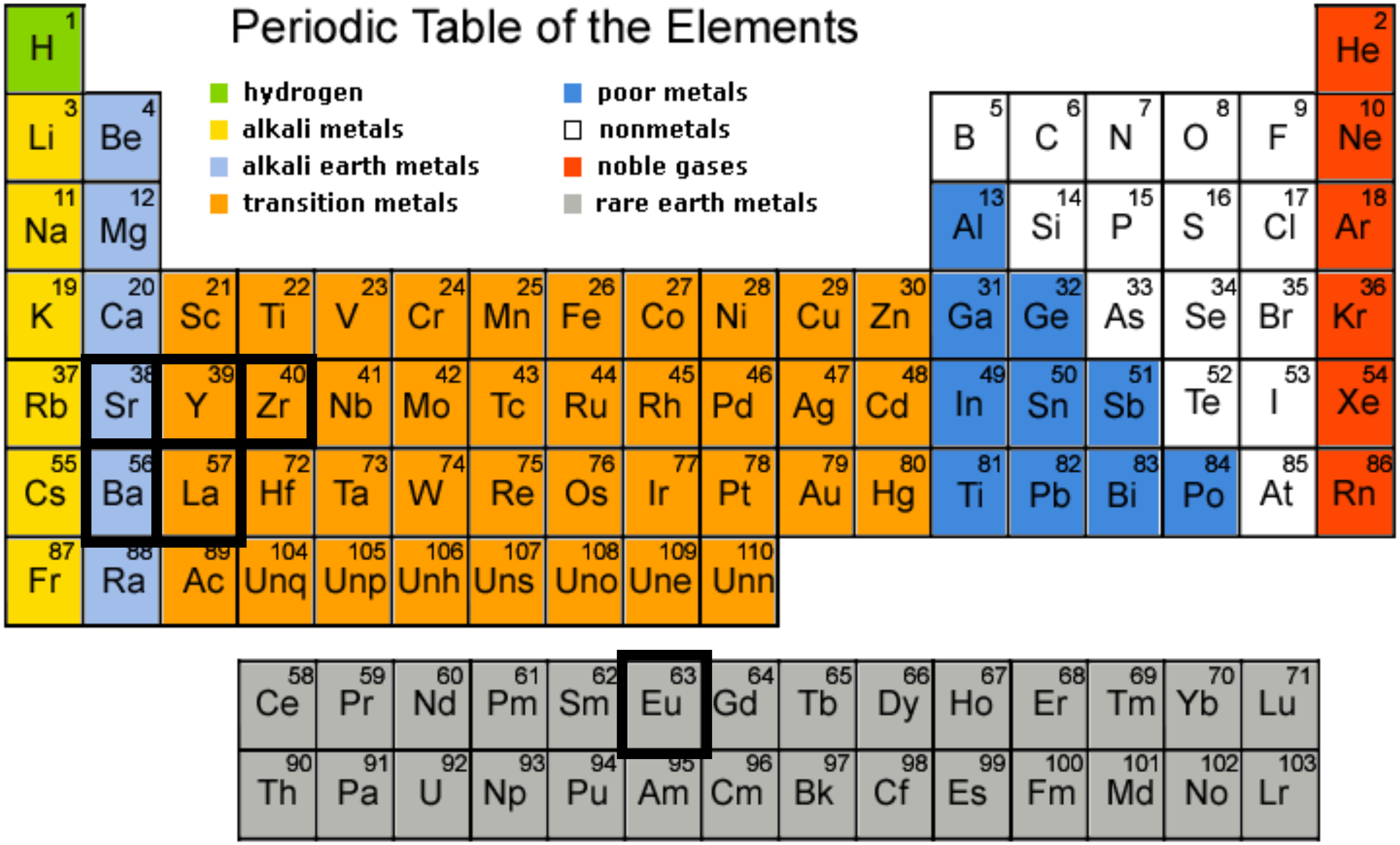
So let's follow one such particle. When the beta decay occurs, the element moves one element up on the Periodic Table (that is, it now has one more proton in its nucleus). It is now a new element with way too many neutrons still in its nucleus to be stable. Sooner or later, one of the extra neutrons will beta decay and the element becomes the next higher element atomic number wise (again, it now has one more proton than it had before). If the new element is still unstable, sooner or later the new element will have another of its extra neutrons beta decay making the particle into yet the next higher element. This process will go on until the element produced is stable. At that point, the process stops.

This is called the "r-process" (the "r" stands for "rapid"--supernovas happen in about a second). This is the mechanism that creates "larger" element during a supernova.

There is another similar process called the “s-process” (the “s” stands for “slow”) in which a free neutron can attach itself to an element during the course of a star’s life (that is, way before the star supernovas), then beta decays making that element into the next element up. This mechanism occurs very slowly in stars taking, maybe, several million years to occur to a particular atom (if at all).

The presence of this mechanism produces, though, an interesting phenomenon. It turns out that there are elements that were generated in first generation stars that were LARGER than iron (atomic number 26) and were not produced as a consequence of the star’s death. Those elements are strontium (atomic number 38), yttrium (atomic number 39), zirconium (atomic number 40), barium (atomic number 56), lanthanum (atomic number 57), and europium (atomic number 63).

From Google Pictures, the Periodic Table shows the elements greater than iron that are produced slowly in stars.

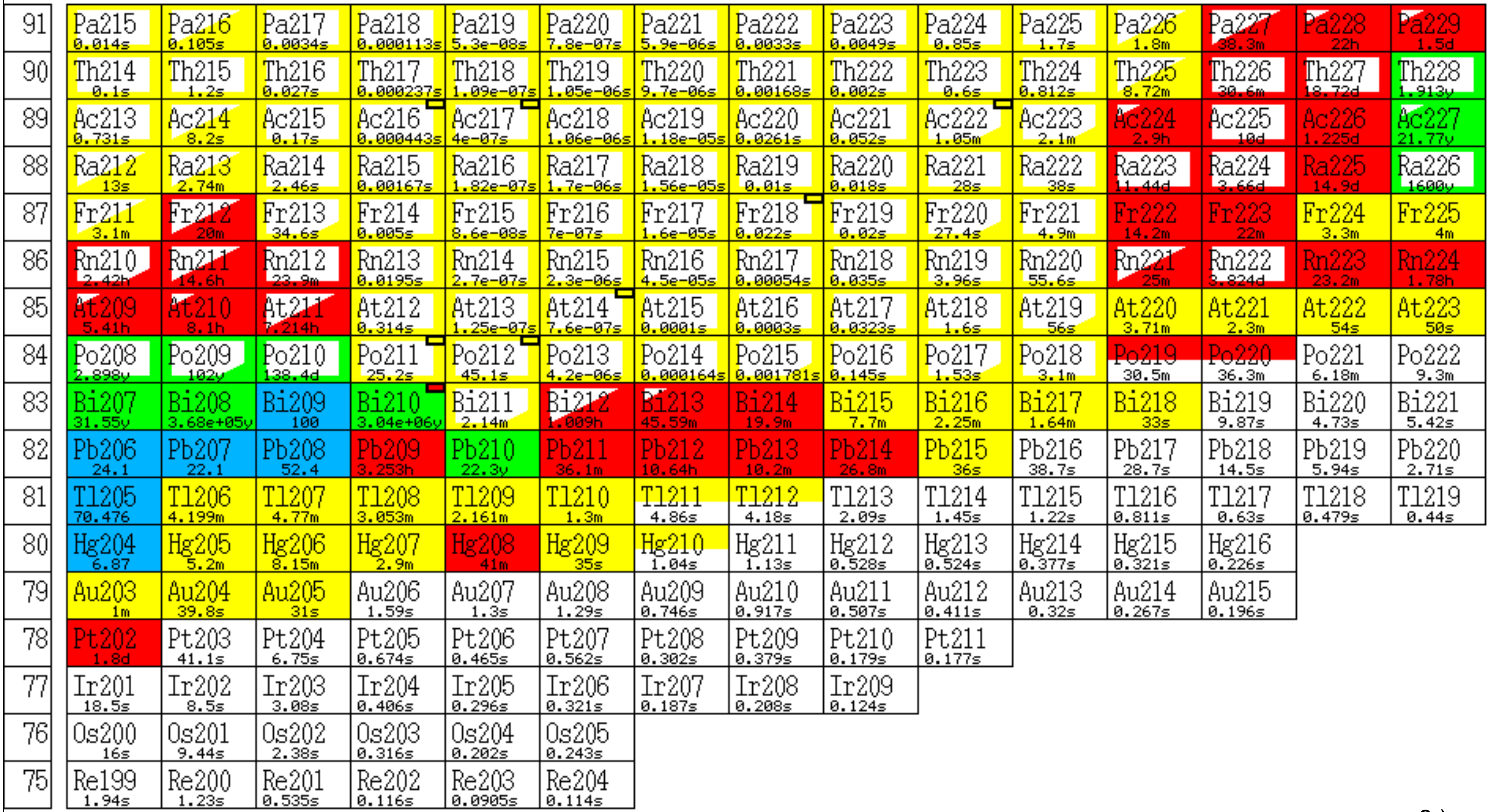


Periodic Table of the Elements

🟩 hydrogen
🟨 alkali metals
🟦 alkali earth metals
🟧 transition metals
🟦 poor metals
☐ nonmetals
🟥 noble gases
▨ rare earth metals

1 H																	2 He
3 Li	4 Be											5 B	6 C	7 N	8 O	9 F	10 Ne
11 Na	12 Mg											13 Al	14 Si	15 P	16 S	17 Cl	18 Ar
19 K	20 Ca	21 Sc	22 Ti	23 V	24 Cr	25 Mn	26 Fe	27 Co	28 Ni	29 Cu	30 Zn	31 Ga	32 Ge	33 As	34 Se	35 Br	36 Kr
37 Rb	38 Sr	39 Y	40 Zr	41 Nb	42 Mo	43 Tc	44 Ru	45 Rh	46 Pd	47 Ag	48 Cd	49 In	50 Sn	51 Sb	52 Te	53 I	54 Xe
55 Cs	56 Ba	57 La	72 Hf	73 Ta	74 W	75 Re	76 Os	77 Ir	78 Pt	79 Au	80 Hg	81 Ti	82 Pb	83 Bi	84 Po	85 At	86 Rn
87 Fr	88 Ra	89 Ac	104 Unq	105 Unp	106 Unh	107 Uns	108 Uno	109 Une	110 Unn								
			58 Ce	59 Pr	60 Nd	61 Pm	62 Sm	63 Eu	64 Gd	65 Tb	66 Dy	67 Ho	68 Er	69 Tm	70 Yb	71 Lu	
			90 Th	91 Pa	92 U	93 Np	94 Pu	95 Am	96 Cm	97 Bk	98 Cf	99 Es	100 Fm	101 Md	102 No	103 Lr	

Here is an example of the process. Below is a chart of nuclides with the number of neutrons increasing by one as you proceed right.

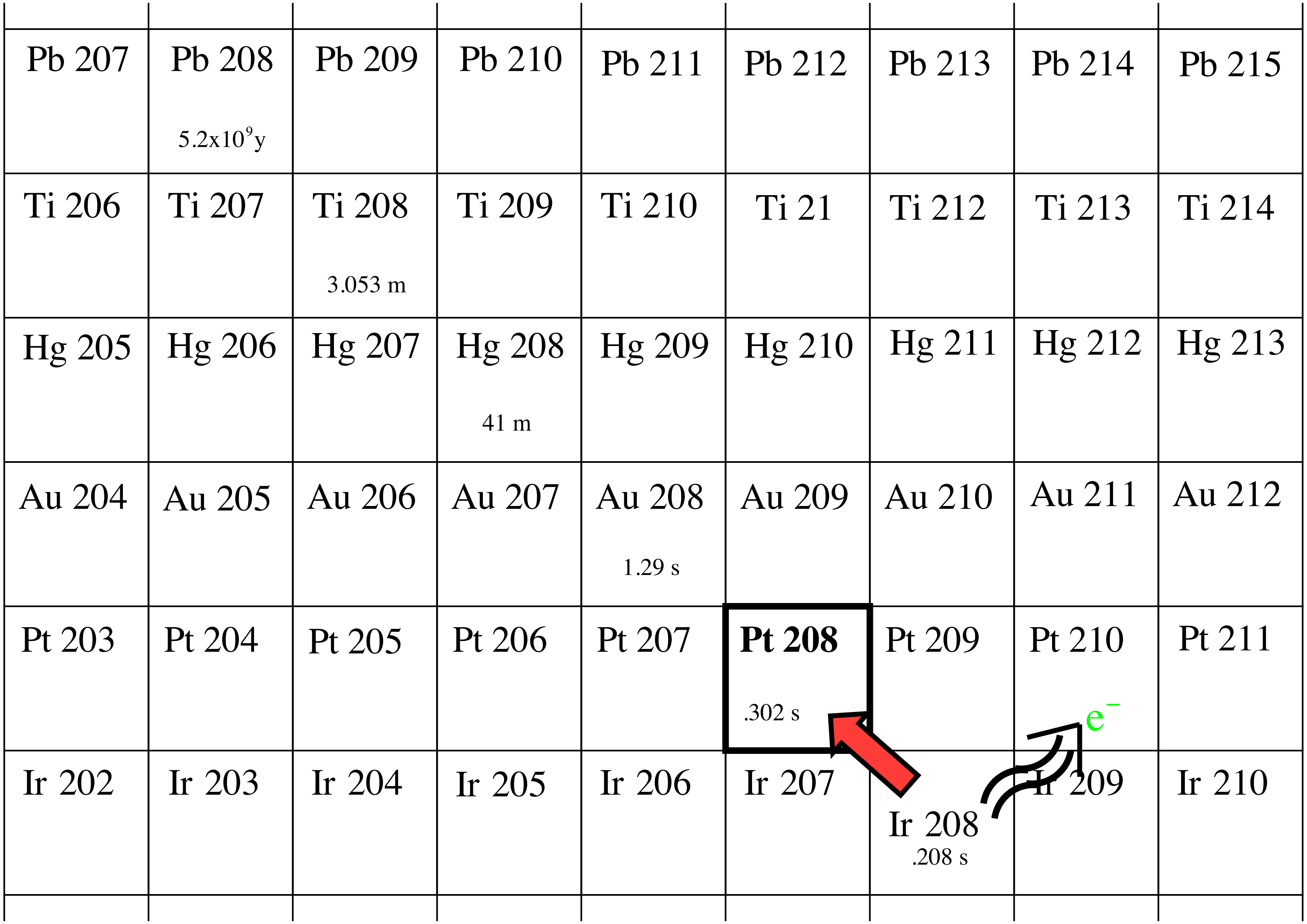


91	Pa215 0.014s	Pa216 0.105s	Pa217 0.0034s	Pa218 0.000113s	Pa219 5.3e-08s	Pa220 7.8e-07s	Pa221 5.9e-06s	Pa222 0.0033s	Pa223 0.0049s	Pa224 0.85s	Pa225 1.7s	Pa226 1.8m	Pa227 38.3m	Pa228 22h	Pa229 1.5d
90	Th214 0.1s	Th215 1.2s	Th216 0.027s	Th217 0.000237s	Th218 1.09e-07s	Th219 1.05e-06s	Th220 9.7e-06s	Th221 0.00168s	Th222 0.002s	Th223 0.6s	Th224 0.812s	Th225 8.72m	Th226 30.6m	Th227 18.72d	Th228 1.913y
89	Ac213 0.731s	Ac214 8.2s	Ac215 0.17s	Ac216 0.000443s	Ac217 4e-07s	Ac218 1.06e-06s	Ac219 1.18e-05s	Ac220 0.0261s	Ac221 0.052s	Ac222 1.05m	Ac223 2.1m	Ac224 2.9h	Ac225 10d	Ac226 1.225d	Ac227 21.77y
88	Ra212 13s	Ra213 2.74m	Ra214 2.46s	Ra215 0.00167s	Ra216 1.82e-07s	Ra217 1.7e-06s	Ra218 1.56e-05s	Ra219 0.01s	Ra220 0.018s	Ra221 28s	Ra222 38s	Ra223 11.44d	Ra224 3.66d	Ra225 14.9d	Ra226 1600y
87	Fr211 3.1m	Fr212 20m	Fr213 34.6s	Fr214 0.005s	Fr215 8.6e-08s	Fr216 7e-07s	Fr217 1.6e-05s	Fr218 0.022s	Fr219 0.02s	Fr220 27.4s	Fr221 4.9m	Fr222 14.2m	Fr223 22m	Fr224 3.3m	Fr225 4m
86	Rn210 2.42h	Rn211 14.6h	Rn212 23.9m	Rn213 0.0195s	Rn214 2.7e-07s	Rn215 2.3e-06s	Rn216 4.5e-05s	Rn217 0.00054s	Rn218 0.035s	Rn219 3.96s	Rn220 55.6s	Rn221 25m	Rn222 3.824d	Rn223 23.2m	Rn224 1.78h
85	At209 5.41h	At210 8.1h	At211 7.214h	At212 0.314s	At213 1.25e-07s	At214 7.6e-07s	At215 0.0001s	At216 0.0003s	At217 0.0323s	At218 1.6s	At219 56s	At220 3.71m	At221 2.3m	At222 54s	At223 50s
84	Po208 2.898y	Po209 102y	Po210 138.4d	Po211 25.2s	Po212 45.1s	Po213 4.2e-06s	Po214 0.000164s	Po215 0.001781s	Po216 0.145s	Po217 1.53s	Po218 3.1m	Po219 30.5m	Po220 36.3m	Po221 6.18m	Po222 9.3m
83	Bi207 31.55y	Bi208 3.68e+05y	Bi209 100	Bi210 3.04e+06y	Bi211 2.14m	Bi212 1.009h	Bi213 45.59m	Bi214 19.9m	Bi215 7.7m	Bi216 2.25m	Bi217 1.64m	Bi218 33s	Bi219 9.87s	Bi220 4.73s	Bi221 5.42s
82	Pb206 24.1	Pb207 22.1	Pb208 52.4	Pb209 3.253h	Pb210 22.3y	Pb211 36.1m	Pb212 10.64h	Pb213 10.2m	Pb214 26.8m	Pb215 36s	Pb216 38.7s	Pb217 28.7s	Pb218 14.5s	Pb219 5.94s	Pb220 2.71s
81	Tl205 70.476	Tl206 4.199m	Tl207 4.77m	Tl208 3.053m	Tl209 2.161m	Tl210 1.3m	Tl211 4.86s	Tl212 4.18s	Tl213 2.09s	Tl214 1.45s	Tl215 1.22s	Tl216 0.811s	Tl217 0.63s	Tl218 0.479s	Tl219 0.44s
80	Hg204 6.87	Hg205 5.2m	Hg206 8.15m	Hg207 2.9m	Hg208 41m	Hg209 35s	Hg210 1.04s	Hg211 1.13s	Hg212 0.528s	Hg213 0.524s	Hg214 0.377s	Hg215 0.321s	Hg216 0.226s		
79	Au203 1m	Au204 39.8s	Au205 31s	Au206 1.59s	Au207 1.3s	Au208 1.29s	Au209 0.746s	Au210 0.917s	Au211 0.507s	Au212 0.411s	Au213 0.32s	Au214 0.267s	Au215 0.196s		
78	Pt202 1.8d	Pt203 41.1s	Pt204 6.75s	Pt205 0.674s	Pt206 0.465s	Pt207 0.562s	Pt208 0.302s	Pt209 0.379s	Pt210 0.179s	Pt211 0.177s					
77	Ir201 18.5s	Ir202 8.5s	Ir203 3.08s	Ir204 0.406s	Ir205 0.296s	Ir206 0.321s	Ir207 0.187s	Ir208 0.208s	Ir209 0.124s						
76	Os200 16s	Os201 9.44s	Os202 2.38s	Os203 0.316s	Os204 0.202s	Os205 0.243s									
75	Re199 1.94s	Re200 1.23s	Re201 0.535s	Re202 0.116s	Re203 0.0905s	Re204 0.114s									

Let’s track a single iridium atom with 208 nuclides.

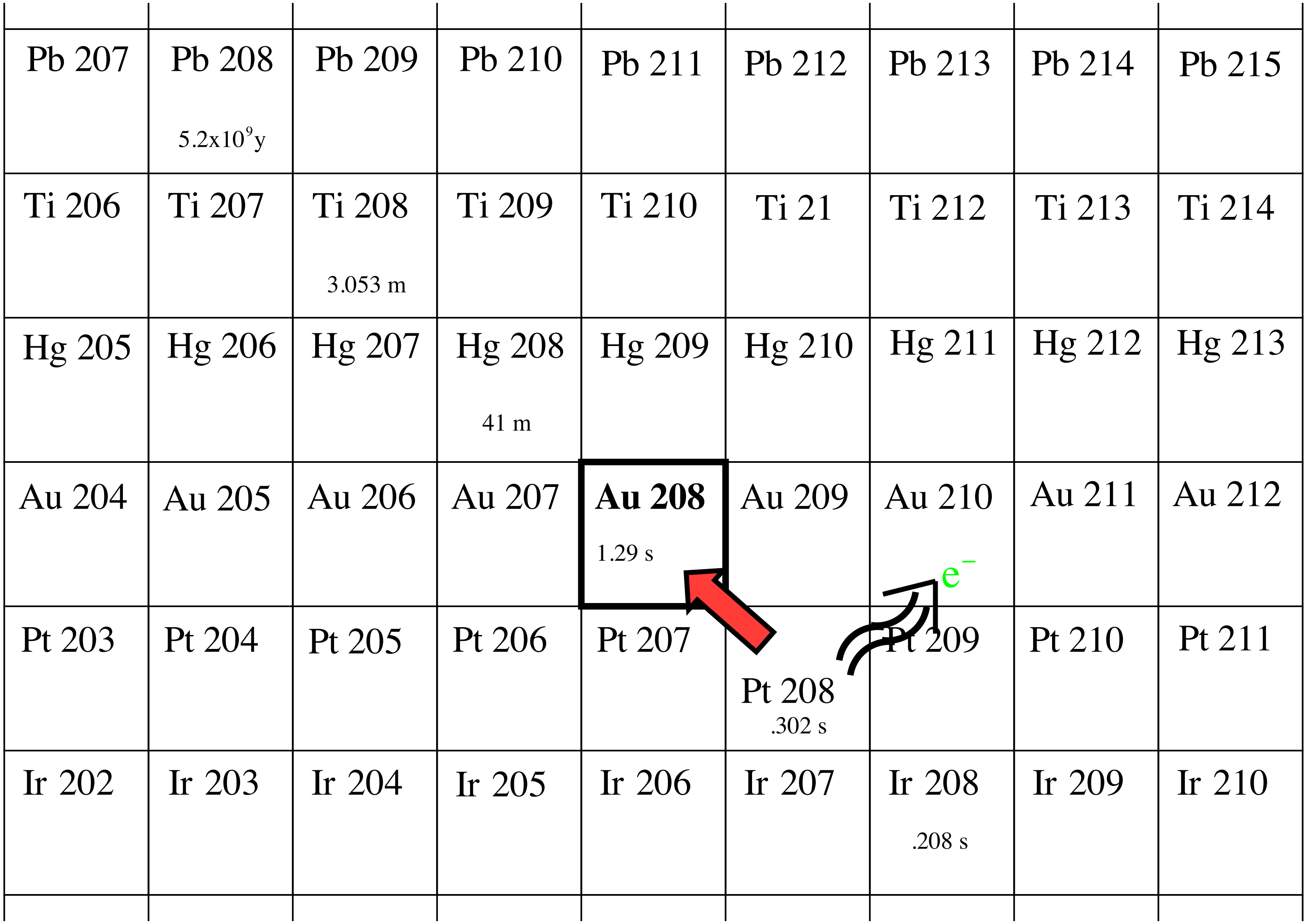
Pb 207	Pb 208 5.2x10^9y	Pb 209	Pb 210	Pb 211	Pb 212	Pb 213	Pb 214	Pb 215
Ti 206	Ti 207	Ti 208 3.053 m	Ti 209	Ti 210	Ti 21	Ti 212	Ti 213	Ti 214
Hg 205	Hg 206	Hg 207	Hg 208 41 m	Hg 209	Hg 210	Hg 211	Hg 212	Hg 213
Au 204	Au 205	Au 206	Au 207	Au 208 1.29 s	Au 209	Au 210	Au 211	Au 212
Pt 203	Pt 204	Pt 205	Pt 206	Pt 207	Pt 208 .302 s	Pt 209	Pt 210	Pt 211
Ir 202	Ir 203	Ir 204	Ir 205	Ir 206	Ir 207	Ir **208** .208 s	Ir 209	Ir 210

After .208 seconds, the iridium will beta decay into platnum 208 with one less neutron, jumping as shown on the neutron chart below.



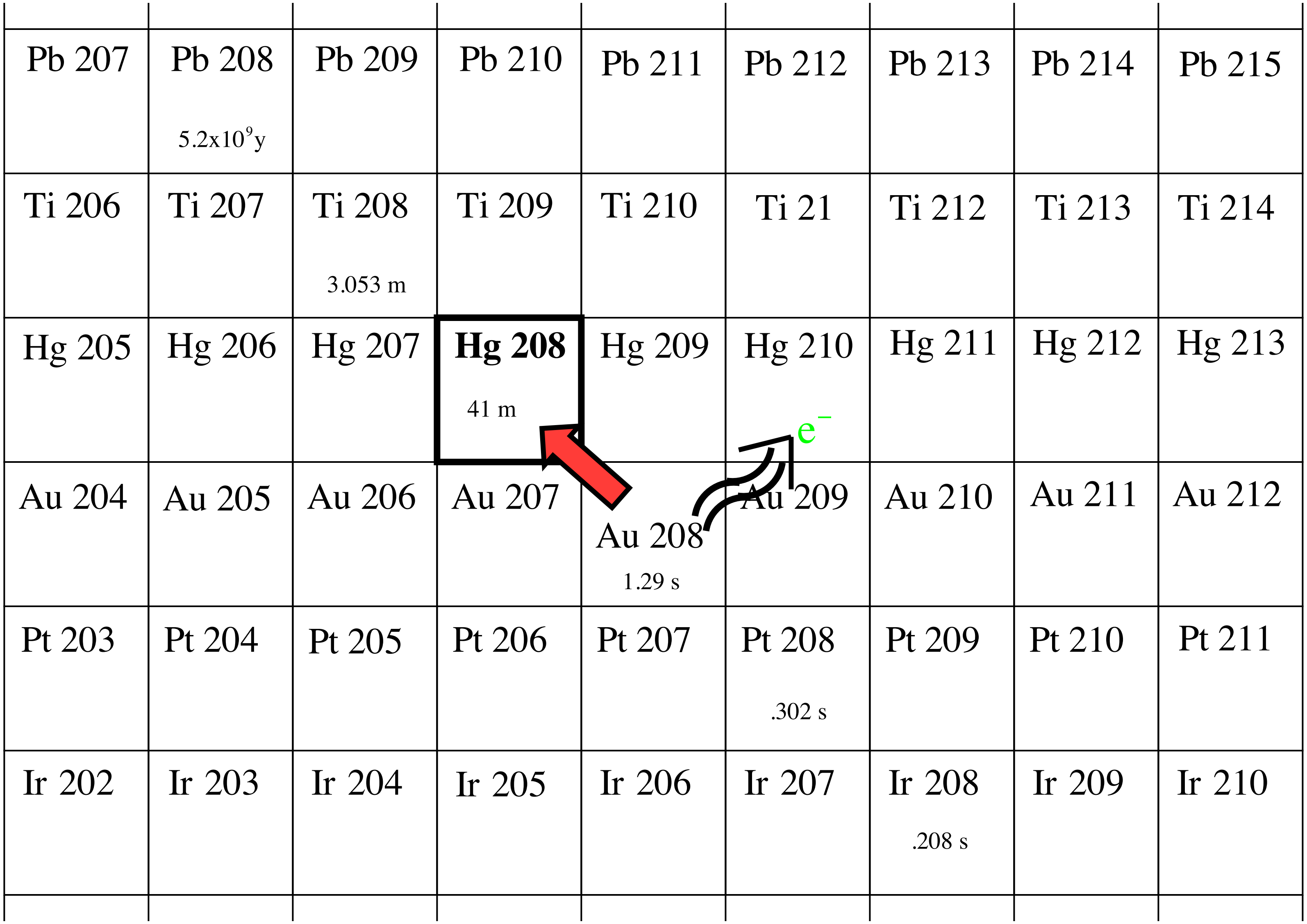
Pb 207	Pb 208 5.2x10^{9}y	Pb 209	Pb 210	Pb 211	Pb 212	Pb 213	Pb 214	Pb 215
Ti 206	Ti 207	Ti 208 3.053 m	Ti 209	Ti 210	Ti 21	Ti 212	Ti 213	Ti 214
Hg 205	Hg 206	Hg 207	Hg 208 41 m	Hg 209	Hg 210	Hg 211	Hg 212	Hg 213
Au 204	Au 205	Au 206	Au 207	Au 208 1.29 s	Au 209	Au 210	Au 211	Au 212
Pt 203	Pt 204	Pt 205	Pt 206	Pt 207	**Pt 208** .302 s	Pt 209	Pt 210	Pt 211
Ir 202	Ir 203	Ir 204	Ir 205	Ir 206	Ir 207	Ir 208 .208 s	Ir 209	Ir 210

After .302 seconds, the platnum will beta decay into gold 208 with one less neutron, jumping as shown on the neutron chart below.



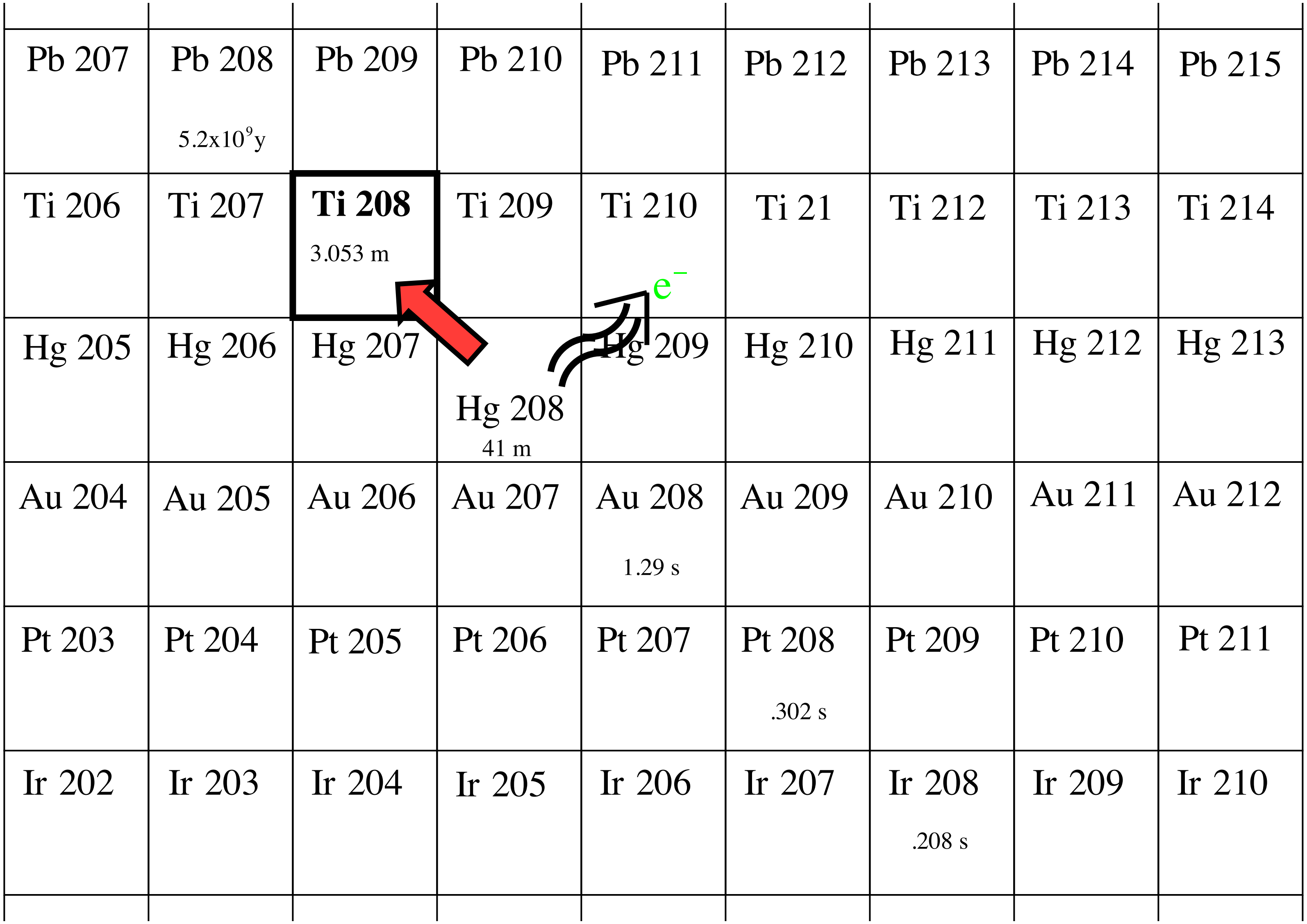
Pb 207	Pb 208 $5.2x10^9$y	Pb 209	Pb 210	Pb 211	Pb 212	Pb 213	Pb 214	Pb 215
Ti 206	Ti 207	Ti 208 3.053 m	Ti 209	Ti 210	Ti 21	Ti 212	Ti 213	Ti 214
Hg 205	Hg 206	Hg 207	Hg 208 41 m	Hg 209	Hg 210	Hg 211	Hg 212	Hg 213
Au 204	Au 205	Au 206	Au 207	**Au 208** 1.29 s	Au 209	Au 210	Au 211	Au 212
Pt 203	Pt 204	Pt 205	Pt 206	Pt 207	Pt 208 .302 s	Pt 209	Pt 210	Pt 211
Ir 202	Ir 203	Ir 204	Ir 205	Ir 206	Ir 207	Ir 208 .208 s	Ir 209	Ir 210

After 1.29 seconds, the gold will beta decay into mercury 208 with one less neutron, jumping as shown on the neutron chart below.



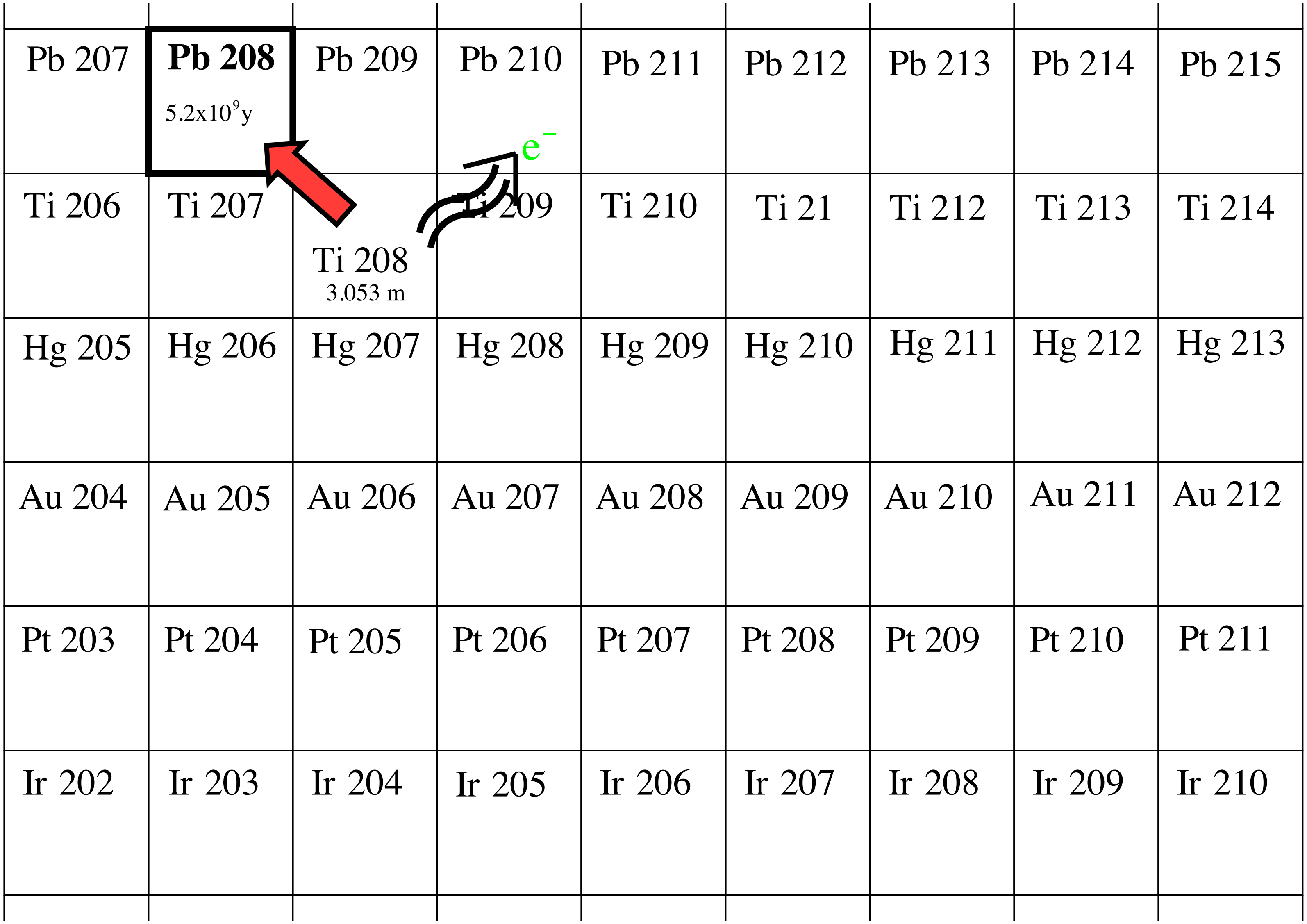
Pb 207	Pb 208 5.2x10^9y	Pb 209	Pb 210	Pb 211	Pb 212	Pb 213	Pb 214	Pb 215
Ti 206	Ti 207	Ti 208 3.053 m	Ti 209	Ti 210	Ti 21	Ti 212	Ti 213	Ti 214
Hg 205	Hg 206	Hg 207	**Hg 208** 41 m	Hg 209	Hg 210	Hg 211	Hg 212	Hg 213
Au 204	Au 205	Au 206	Au 207	Au 208 1.29 s	Au 209	Au 210	Au 211	Au 212
Pt 203	Pt 204	Pt 205	Pt 206	Pt 207	Pt 208 .302 s	Pt 209	Pt 210	Pt 211
Ir 202	Ir 203	Ir 204	Ir 205	Ir 206	Ir 207	Ir 208 .208 s	Ir 209	Ir 210

After 41 minutes, the mercury will beta decay into titanium 208 with one less neutron, jumping as shown on the neutron chart below.



Pb 207	Pb 208 5.2x10^{9}y	Pb 209	Pb 210	Pb 211	Pb 212	Pb 213	Pb 214	Pb 215
Ti 206	Ti 207	**Ti 208** 3.053 m	Ti 209	Ti 210	Ti 21	Ti 212	Ti 213	Ti 214
Hg 205	Hg 206	Hg 207	Hg 208 41 m	Hg 209	Hg 210	Hg 211	Hg 212	Hg 213
Au 204	Au 205	Au 206	Au 207	Au 208 1.29 s	Au 209	Au 210	Au 211	Au 212
Pt 203	Pt 204	Pt 205	Pt 206	Pt 207	Pt 208 .302 s	Pt 209	Pt 210	Pt 211
Ir 202	Ir 203	Ir 204	Ir 205	Ir 206	Ir 207	Ir 208 .208 s	Ir 209	Ir 210

After 3.053 minutes, the titanium will beta decay into lead 208 with one less neutron, jumping as shown on the neutron chart below. As lead 208 has a half life of 52,000,000 years, this is a stable atom and we’ve just created a “bigger” atom from a “smaller” atom without using fusion.



Pb 207	**Pb 208** $5.2\text{x}10^{9}$y	Pb 209	Pb 210	Pb 211	Pb 212	Pb 213	Pb 214	Pb 215
Ti 206	Ti 207	Ti 208 3.053 m	Ti 209	Ti 210	Ti 21	Ti 212	Ti 213	Ti 214
Hg 205	Hg 206	Hg 207	Hg 208	Hg 209	Hg 210	Hg 211	Hg 212	Hg 213
Au 204	Au 205	Au 206	Au 207	Au 208	Au 209	Au 210	Au 211	Au 212
Pt 203	Pt 204	Pt 205	Pt 206	Pt 207	Pt 208	Pt 209	Pt 210	Pt 211
Ir 202	Ir 203	Ir 204	Ir 205	Ir 206	Ir 207	Ir 208	Ir 209	Ir 210