PHYS 250

Lecture 3.2

More Atoms

Plus Nuclei

Today

Administrivia

Review

Things I should have done Monday

We need more than Bohr to explain atoms & the Periodic Table

A bit of Nuclear Physics

Administrivia

There will be a WebWork posted tonight, and a worksheet on Friday.

Midterm is Wednesday June 4 at 5-6 PM. On paper, in this room.
Midterm covers through today's material, and related homework and worksheet.

I will post some old midterms, and solutions.

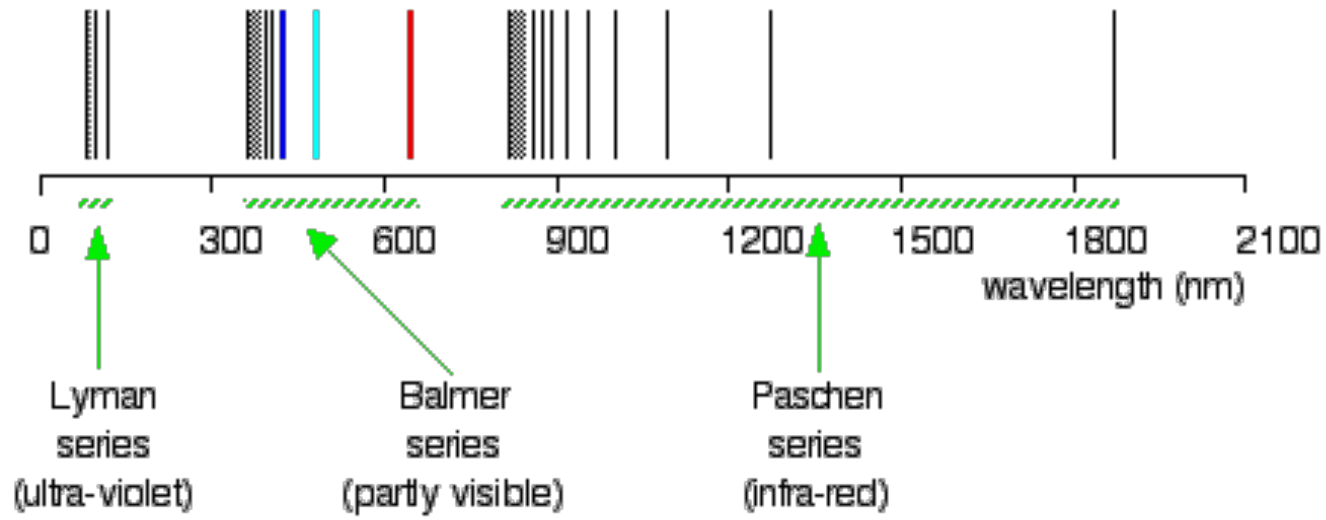
You may bring one page (both sides) of notes / formulas.
A team note sheet is allowed.

Any calculator is allowed, but no wireless devices.

Review 1

Diffraction grating with spacing d: $d\sin\theta = n\lambda$, with $n = 0, \pm 1, \pm 2$, etc.

Hydrogen spectral lines:



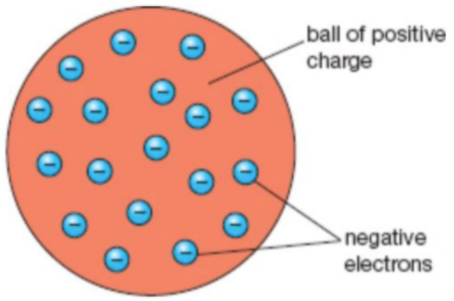
Rydberg formula: $\dfrac{1}{\lambda} = RZ^2\left(\dfrac{1}{n_1^2} - \dfrac{1}{n_2^2}\right)$ with $n_2 > n_1$, $\quad R = \dfrac{1}{91.13\text{ nm}}$

Energy form: $E_{\text{photon}} = 13.6\text{ eV}\cdot Z^2 \cdot \left(\dfrac{1}{n_1^2} - \dfrac{1}{n_2^2}\right)$

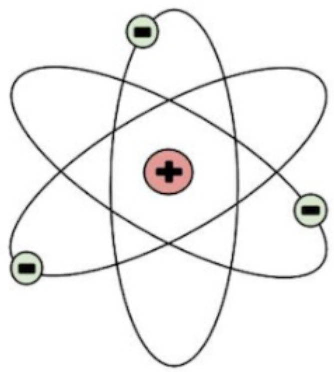
These work very well for atoms with only a single electron, and fairly well (using $Z = 1$) for some lines in "alkali" metals with a single outer electron.

Review 2

JJ Thomson "discovered" the electron,
measured its charge to mass ratio,
and proposed the "Plum-Pudding" atom.



Rutherford et al. "discovered" the nucleus
by alpha-particle scattering, and proposed
electrons orbited the heavy nucleus.



Classical circular orbit with Coulomb force:

$$E = -\frac{1}{2}\frac{Zq^2}{4\pi\varepsilon_0}\frac{1}{r} = -\frac{m}{2}\left[\frac{Zq^2}{4\pi\varepsilon_0}\right]^2\frac{1}{L^2} \qquad L = mvr$$

Rutherford atoms wouldn't be identical, and would decay in picoseconds.

Review 3

Bohr model: Angular momentum is quantized: $L = \frac{h}{2\pi} = n\hbar$ with $n = 1, 2, 3$ etc.

$$\hbar = \frac{h}{2\pi} = 1.055 \times 10^{-34} \text{ J-s} \qquad \hbar c = \frac{1240 \text{ eV-nm}}{2\pi} = 197.4 \text{ eV-nm}$$

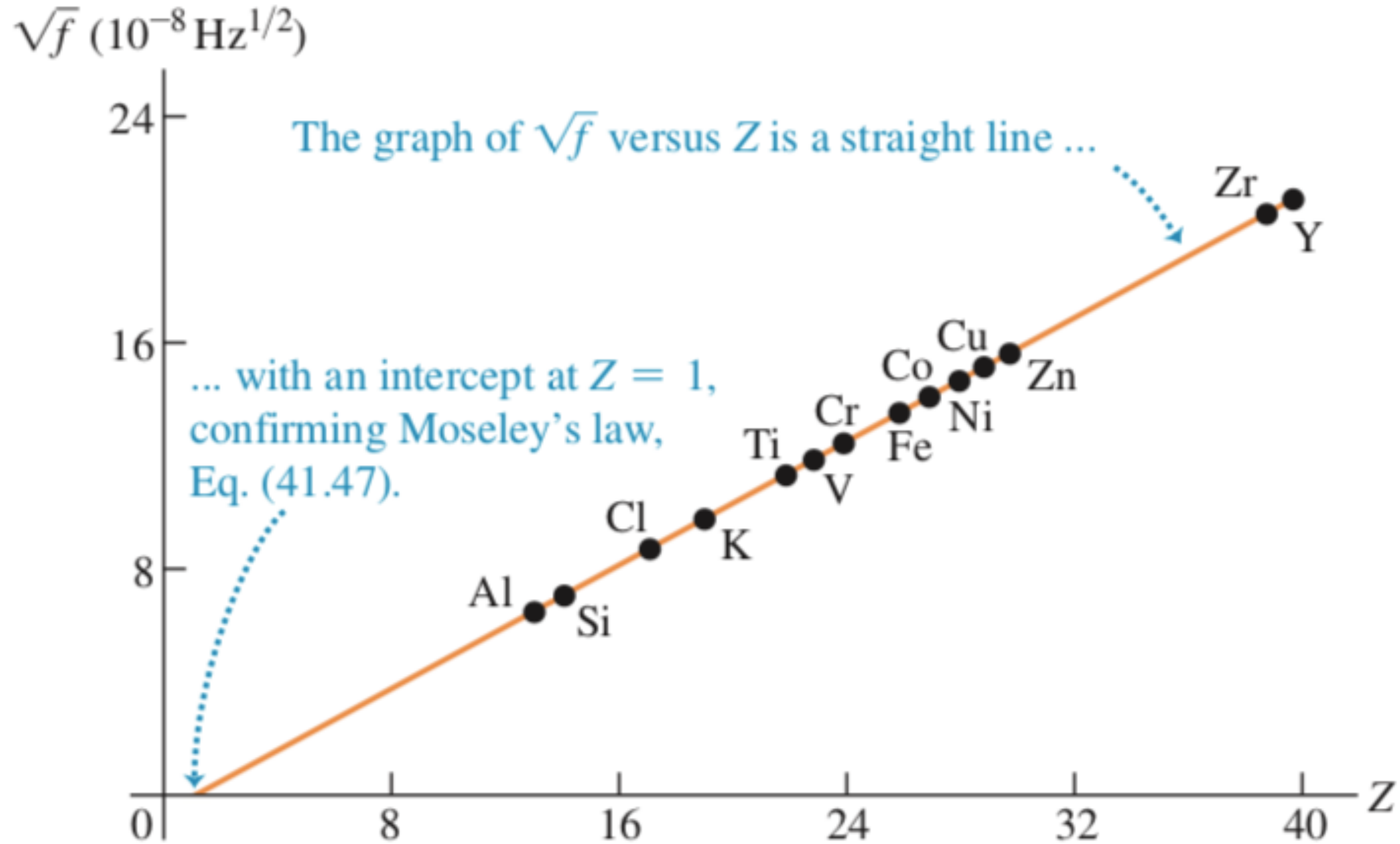
$$E_n = -\frac{m}{2}\left[\frac{q^2}{4\pi\varepsilon_0\hbar}\right]^2 \frac{Z^2}{n^2} = -13.6 \text{ eV} \cdot \frac{Z^2}{n^2} \qquad r_n = \frac{\hbar^2}{m}\frac{4\pi\varepsilon_0}{q^2}\frac{n^2}{Z} = 52.97 \text{ pm} \cdot \frac{n^2}{Z}$$

Bohr <u>predicts</u> predicts definite energies with differences agreeing with Rydberg, predicts lowest energy state has a standard size, in agreement with experiment.

Predicts hydrogen atoms are flat not spherical, and wrong magnetic moment.

Review 4

Moseley Plot of $\sqrt{f} = \sqrt{c/\lambda}$ vs Z for Kα X-rays



Moseley's Law for Kα X-rays:

$$E = 13.6 \cdot \left(\frac{1}{1^2} - \frac{1}{2^2}\right) \cdot (Z-1)^2$$

$$= 10.2 \text{ eV} \cdot (Z-1)^2$$

For Kβ, it's $E = 13.6 \cdot \left(\frac{1}{1^2} - \frac{1}{3^2}\right) \cdot (Z-1)^2 = 12.1 \text{ eV} \cdot (Z-1)^2$

For Lα, it's $E = 13.6 \cdot \left(\frac{1}{2^2} - \frac{1}{3^2}\right) \cdot (Z-7.4)^2 = 1.89 \text{ eV} \cdot (Z-7.4)^2$

One "screening" electron for the K-lines, 7.4 for the L-lines.

Review 5

Photon wavelength-momentum relation: $E = pc = \frac{hc}{\lambda} \rightarrow \lambda = \frac{hc}{pc} = \frac{h}{p}$

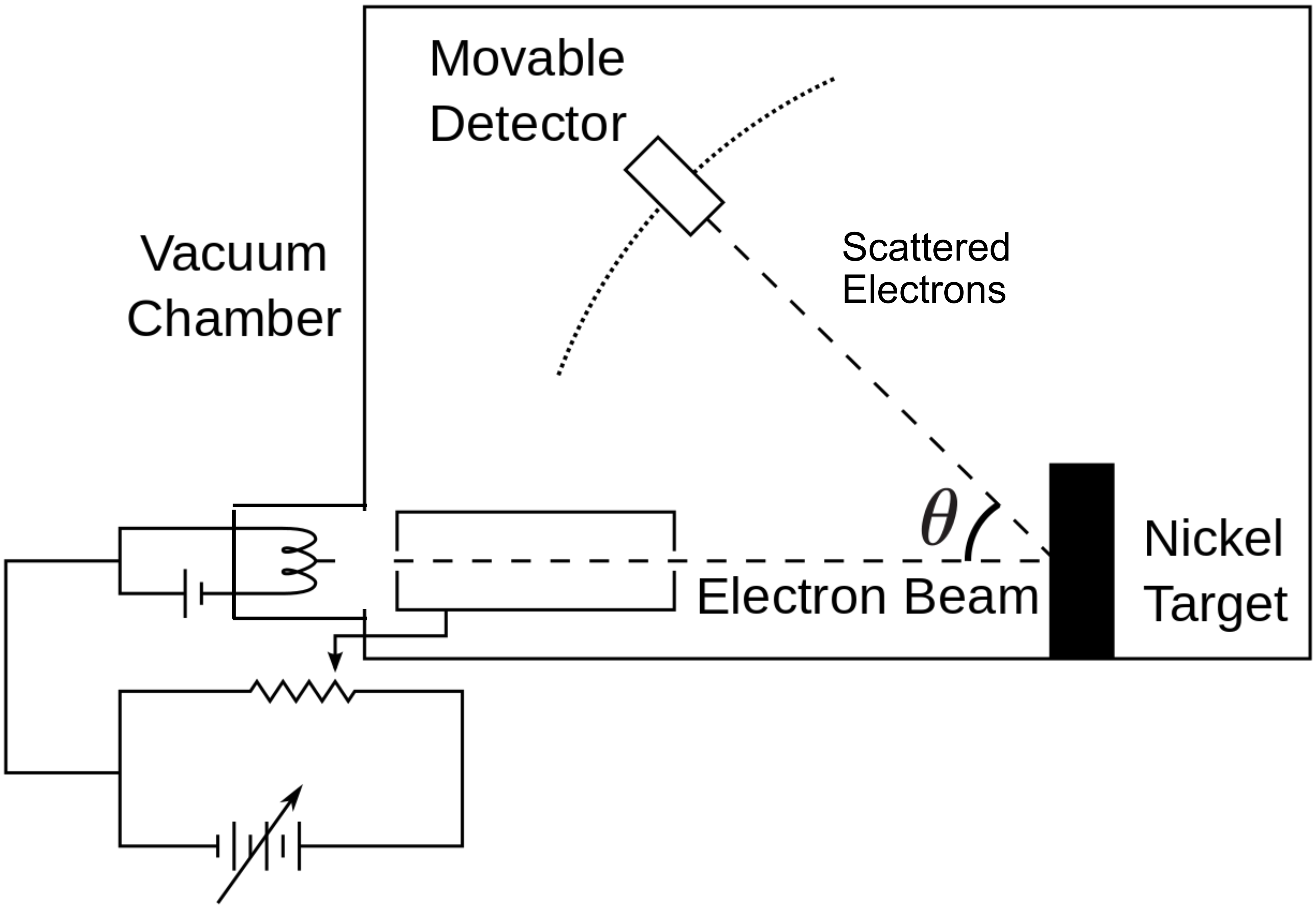
de Broglie Hypothesis: $\lambda = \frac{h}{p}$ for electrons (and atoms), not just photons.

Requiring an integer number of de Broglie wavelengths around a Bohr orbit predicts $L = n\frac{h}{2\pi} = n\hbar$, explaining the 2π needed to get the energies right.

$$E_{\text{kinetic}} = \frac{1}{2}mv^2 = \frac{p^2}{2m} \rightarrow p = \sqrt{2mE_{\text{kinetic}}} \quad \rightarrow \quad \lambda = \frac{hc}{\sqrt{2mc^2 E_{\text{kinetic}}}} = \frac{1.227\ \sqrt{\text{eV}} \cdot \text{nm}}{\sqrt{E_{\text{eV}}}}$$

Davisson-Germer Experiment

In 1927, Clinton Davisson & Lester Germer were studying the scattering of electrons from nickel electrodes in vacuum tubes at Bell Labs.



Results

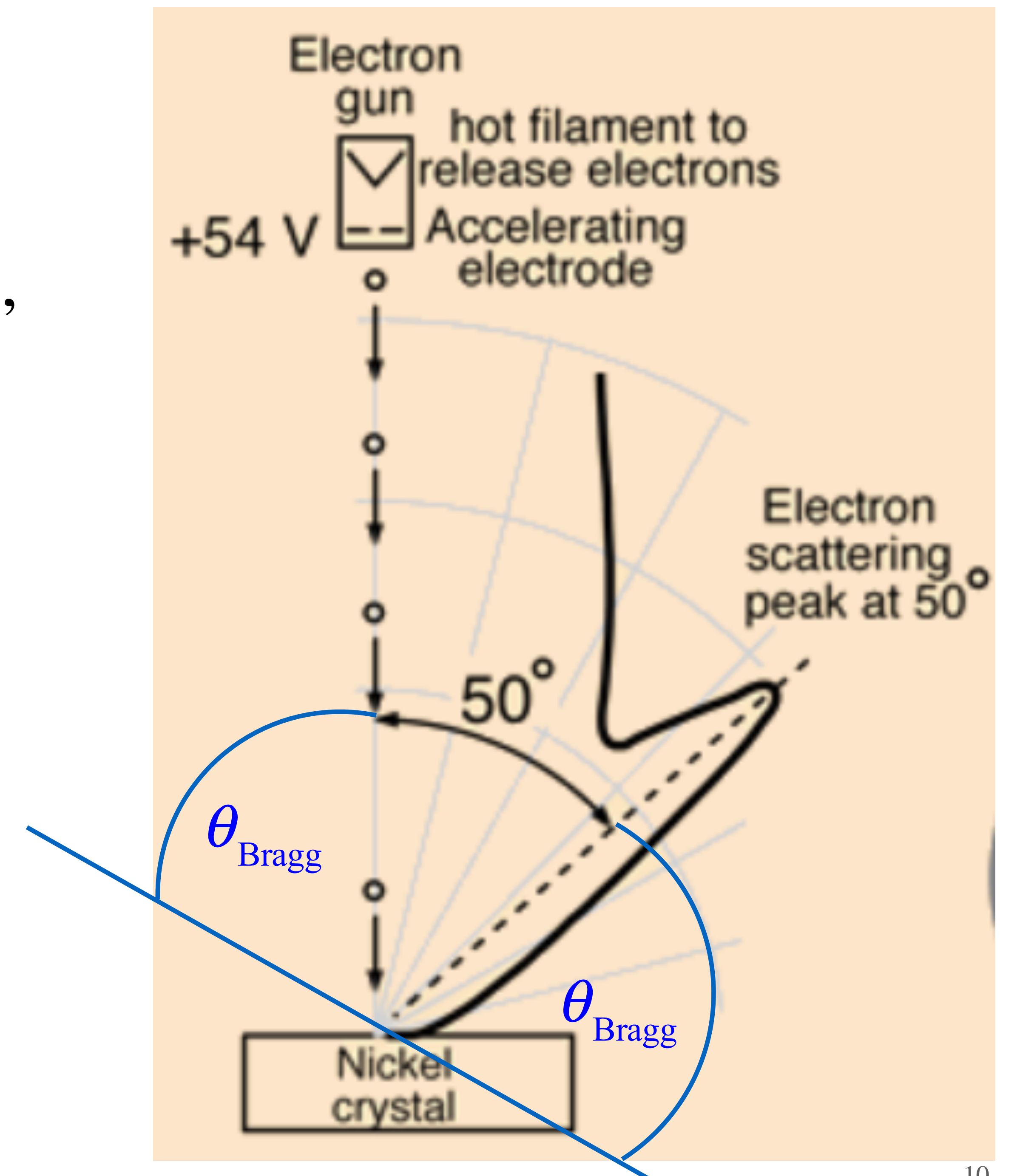
Usually at large θ, there were few scattered electrons.

One time they contaminated their nickel target,
and to clean it, they baked it
in a high temperature oven.

After that, the data looked quite different.
There was a large peak at 50° scattering angle,
with a 54 Volt electron beam.

This corresponds to a Bragg angle of

$$\theta_{\text{Bragg}} = \frac{180° - 50°}{2} = 65°$$



Interpretation

de Broglie predicts $\lambda = \dfrac{1.227\ \sqrt{\text{eV}} \cdot \text{nm}}{\sqrt{54\ \text{eV}}} = 0.167\ \text{nm} = 167\ \text{pm}$

The d value for nickel was known to be 91 pm from X-ray diffraction.

Bragg then predicts $\lambda = 2d\sin\theta = 2 \cdot 91\ \text{pm} \cdot \sin 65° = 165\ \text{pm}$

Davisson & Germer had (accidentally) verified that electrons diffract like waves, just as de Broglie's picture predicted!

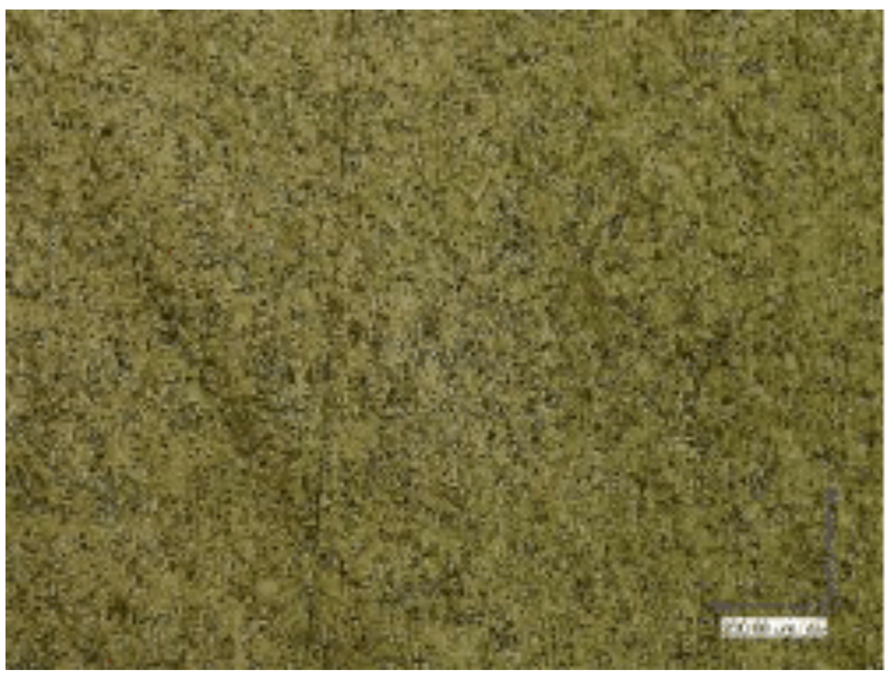
Why Baking the Nickel Mattered

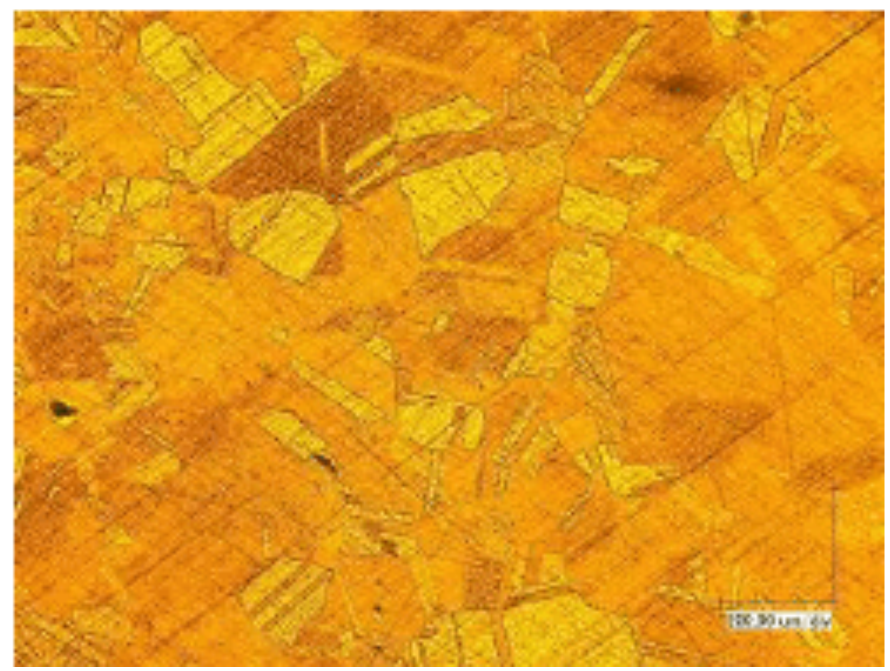
Nickel, like most metals, is made of small crystals that are randomly oriented. So the crystal planes are randomly oriented, and it's hard to see diffraction.

When D&G heated their nickel crystal to clean off the contamination, it cooled slowly in the vacuum.

The micro-crystals merged into larger ones. Here's an example from copper:

Normal

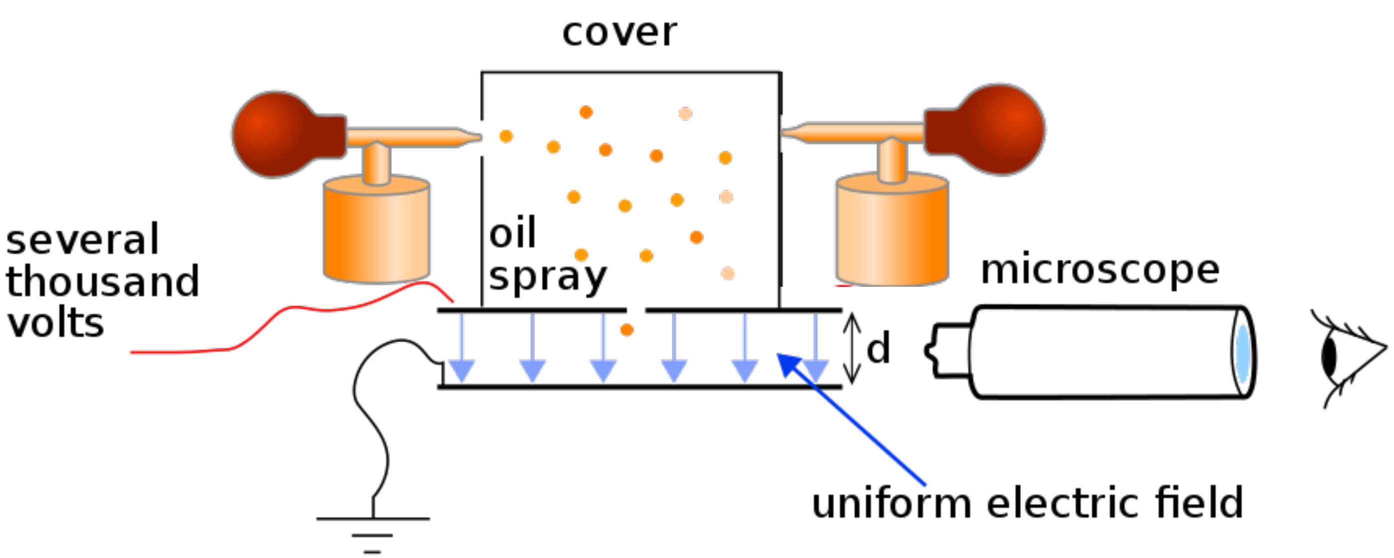




Annealed

The Charge of the Electron

Robert Millikan's oil-drop experiment measured the charge of the electron.



He measured the mass of tiny oil drops by how fast they fell, combined with the known viscosity of air.

A drop typically had a net charge of plus or minus a few electrons.
He then adjusted an electric field until $Eq = mg$, levitating the drop, and allowing q to be calculated.

Millikan found that the charge was always a multiple of 1.59×10^{-19} Coulombs, within 1% of the current value of 1.602×10^{-19}.

The Relative Weights of Atoms

Chemists in the 1800s knew (most) molecular formulas under the assumption that a given volume of any gas has the same number of molecules (Gay-Lussac).

(This is implied by the success of the kinetic theory of gases).

They knew many <u>relative</u> atomic weights of light atoms by weighing how many grams of X combined with how many grams of Y, plus the molecular formula.

The specific heat (Joules/degree/mole) is close to the same for all metals (Dulong & Petit), which gives <u>relative</u> atomic weights from specific heat/gram.

Electrochemistry (how much gas is electrolyzed, or grams of metal plated, per Coulomb of charge), combined with knowledge or guesses of ionization states, gives absolute charge-to-mass ratios, and <u>relative</u> atomic weights.

But there wasn't any <u>absolute</u> knowledge of atomic weights.

Absolute Atomic Weights & Avogadro

Combining Thomson's electron charge-to-mass ratio and Millikan's charge gives the absolute mass of the electron.

Combining Millikan's electron charge with electrochemical charge-to-mass ratios of atoms gives absolute atomic weights.

Combining absolute atomic weights with known masses of known volumes of gas gives the number of atoms in the gas, equivalent to Avogadro's Number.

Of course, if Avogadro's number had been known, the mass of a gas volume would have given the absolute atomic weight without charge-to-mass etc.

(The ideal gas law is $PV = n_{\text{moles}}RT$ with measured $R = 8.315\ \text{J / mole-K}$.
Kinetic theory of gases predicts $PV = n_{\text{moles}}k_B N_A T$, so $R = k_B N_A$.
where k_B is Boltzman's constant and N_A is Avogadro's Number.
When Planck's fit gave a value for k_B , that would have allowed Avogadro's number to be calculated from R).

Multiple Electrons ?

Once there is an electron orbiting a proton, the net charge is zero, so we wouldn't expect a second electron to be able to orbit.

(Actually, there is something called H^-, which is a proton with 2 electrons. It's uncommon in chemistry, but the TRIUMF cyclotron actually accelerates H^- rather than protons. After acceleration, they strip off both electrons in a metal foil. The resulting proton bends in the opposite direction in the magnetic field, so it's easier to extract the proton beam).

Two electrons could orbit Helium. Unlike Hydrogen, it doesn't form chemical bonds. (The Bohr model basically can't explain chemical bonds).

Three electrons could orbit Lithium.
It forms chemical bonds rather similar to Hydrogen.

Multiple Electrons 2

Moseley's Law $E_{K\alpha} = 13.6 \text{ eV} \cdot \left(\frac{1}{1^2} - \frac{1}{2^2} \right) \cdot (Z-1)^2$ works for all atoms.

The implies one electron is knocked out of the n = 1 orbit,
and an electron from the n = 2 orbit falls into its place.

The Z – 1 factor implies that one electron remains in the n = 1 orbit,
meaning that there were <u>two</u> electrons originally in the n = 1 orbit.

There must be some extra rule that allows 2 electrons be in the n = 1 orbit,
but a third electron must be in n = 2.

Moseley's Law $E_{L\alpha} = 13.6 \text{ eV} \left[\frac{1}{2^2} - \frac{1}{3^2} \right] (Z-7.4)^2 = 1.889 \text{ eV} \cdot (Z-7.4)^2$

for n = 3 to n = 2 transitions implies that there are about 7.4 electrons
"screening" the n = 3 electrons from the nucleus. Another rule?

Pauli Exclusion Principle

There can only be two electrons in a given "state."

Not predicted by either Bohr or Schrodinger.

The "wavefunction" for identical particles 1 and 2 is $\psi\left(\vec{x}_1, s_1, \vec{x}_2, s_2\right)$,
and $1 \leftrightarrow 2$ must either do nothing, or flip the sign of the function.

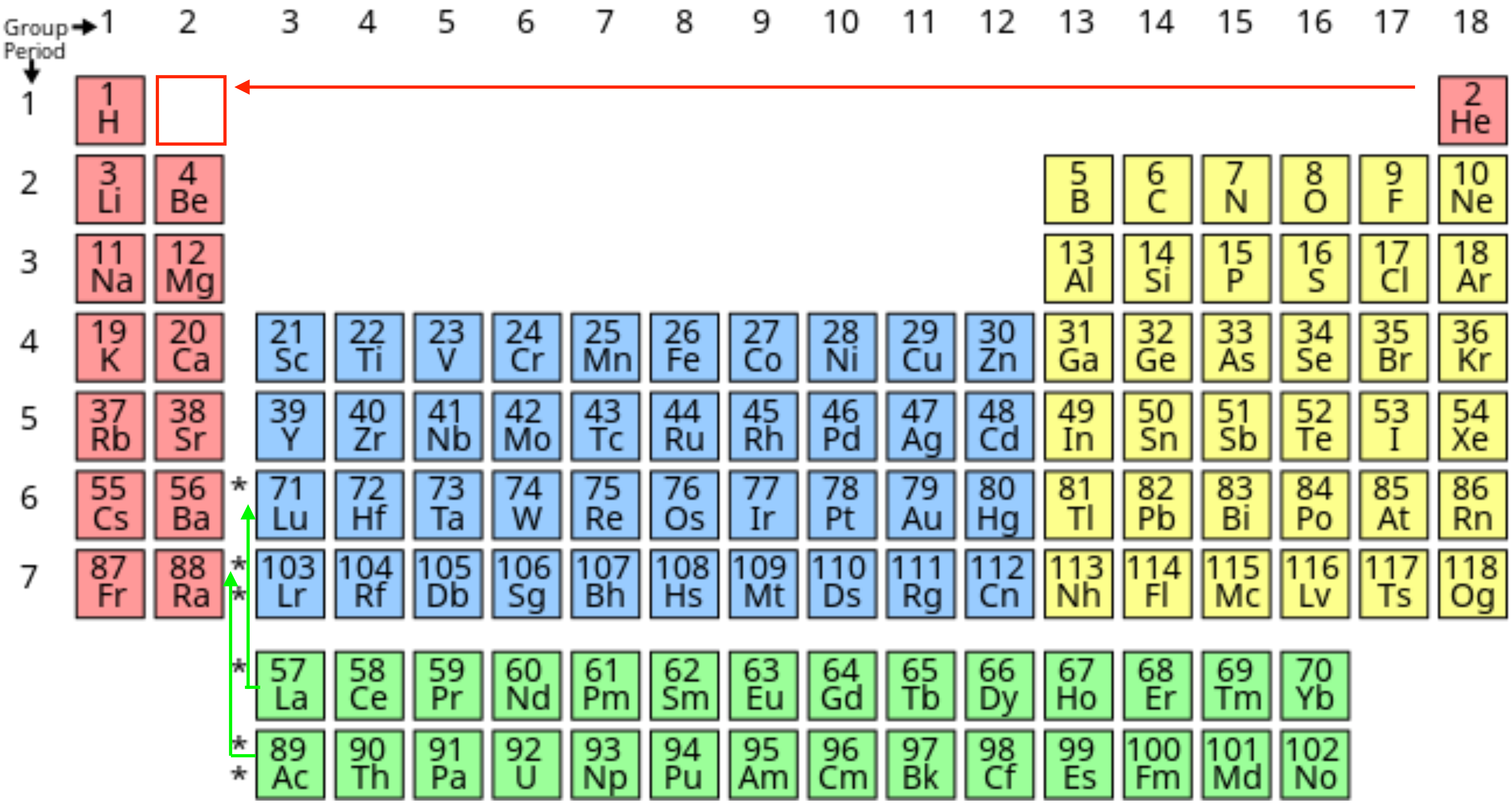
The relativistic Dirac Equation predicts electrons come in 2 "spin" states.

Quantum field theory says for such particles, the sign must flip.

If the particles have different $\vec{x}$ dependence (different "orbits")
or different s-values (different "spins"), everything is fine.

But if they have the same $\vec{x}$ dependence and the same s-values,
then flipping $1 \leftrightarrow 2$ does nothing, but it's supposed to flip the sign.
The only possibility is that $\psi = 0$, meaning zero probability of that happening.

Periodic Table



What makes the pattern of 2, then 2+6, twice, then 2+10+6, twice, then 2+14+10+6, twice?

Angular Momentum States

The Bohr model says angular momentum is $L = n\hbar$,
but says the smallest value is $\ell = 1$.

Schrodinger also says $L = \ell\hbar$, but it allows $\ell = 0$.
(I'm using ℓ rather than *n* here to avoid a future confusion).
Pauli allows 2 electrons in the $\ell = 0$ "state."

Schrodinger also allows a higher-energy $\ell = 0$ "state,"
and Pauli allows 2 electrons in that "state."

Schrodinger says that for $\ell = 1$, there are 3 "states" $m = -1, 0, +1$.
These states have higher energy than the $\ell = 0$ "state," but a coincidence
of the Hydrogen potential makes them the same as the higher $\ell = 0$ "state."
Pauli then allows 6 electrons in those "states."

This explains the 2, 2 + 6 pattern in the top rows of the Periodic Table.

Angular Momentum States 2

Schrodinger says the next "states" up in energy are a higher single $\ell = 0$ state,
a triple $\ell = 1$ state, and an $\ell = 2$ state with $m = -2, -1, 0, +1, +2$.

Pauli allows 2 + 6 + 10 electrons in these.

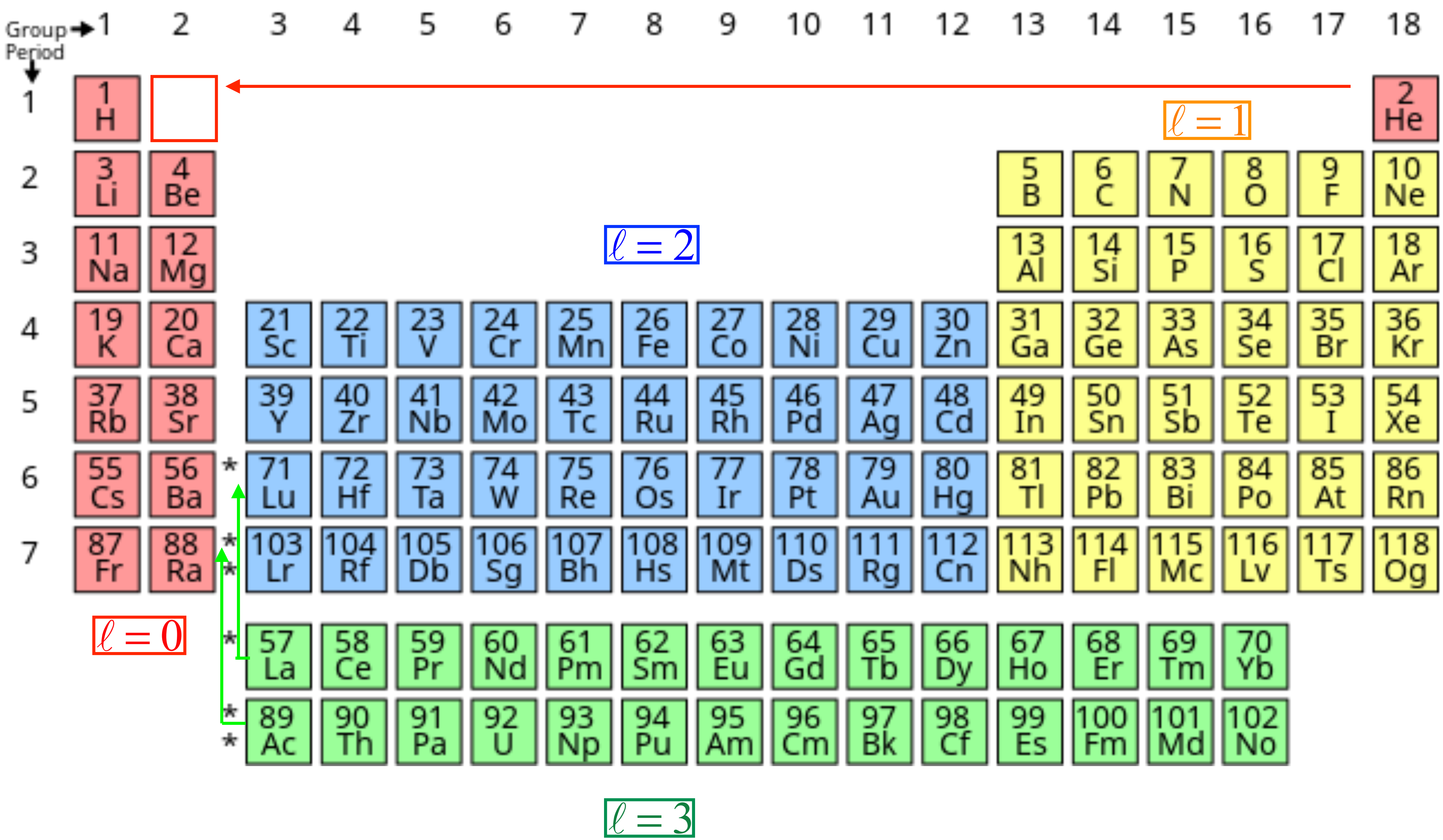
The next "states" up are a single $\ell = 0$ state, a triple $\ell = 1$ state,
a quintuple $\ell = 2$ state, and an $\ell = 3$ state with $m = -3, -2, -1, 0, +1, +2, +3$

Pauli allows 2 + 6 + 10 +14 electrons in these.

For Hydrogen, or any single-electron atom, these levels all have the same energy.

But with "screening" from inner electrons, they aren't all the same energy.
So which "states" get filled first gets kind of jumbled.

Periodic Table



The Sizes of Atoms

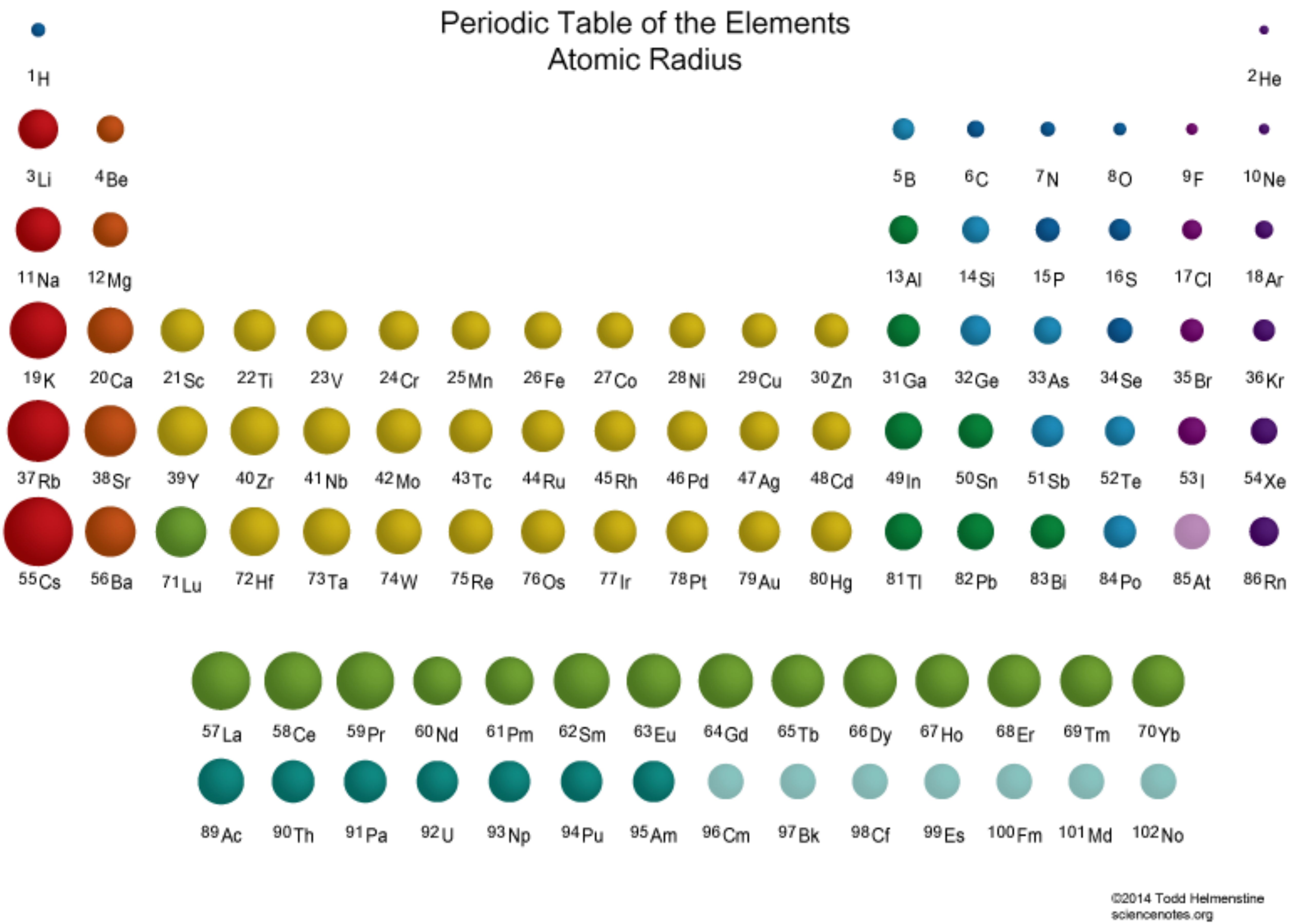
The Bohr Model radius is $r = 52.97 \text{ pm } \dfrac{n^2}{Z}$.

If all the electrons in an atom are in the $n = 1$ orbit,
high-Z atoms would be very small.

The sizes of atoms can be estimated by Bragg diffraction in crystals,
and other more modern methods.

Hydrogen is the Born Model size, Helium is a bit smaller as expected,
but high-Z elements are not smaller, they are larger, and all about the same size.

(The first-column elements with one outer electron are particularly big).


Periodic Table of the Elements
Atomic Radius
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 71 Lu 72 Hf 73 Ta 74 W 75 Re 76 Os 77 Ir 78 Pt 79 Au 80 Hg 81 Tl 82 Pb 83 Bi 84 Po 85 At 86 Rn
57 La 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
89 Ac 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
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Atomic Weight Mysteries

The atomic number Z is the charge of the nucleus, in units of the electron charge. Moseley showed how to measure Z for any element.

Most elements other than Hydrogen have an atomic weight quite close to Z times the Hydrogen weight, but times two.

But some elements violated the $2Z$ rule rather badly.

The natural assumption was that there were $2Z$ hydrogen nuclei (protons) in the nucleus of other atoms, but one was neutralized by an electron.

But if that was possible, why didn't Hydrogen neutralize itself that way?

When "intrinsic spin" of electrons and protons and nuclei was better understood, it became clear that could not be the explanation.

Mass Spectrometer and Isotopes

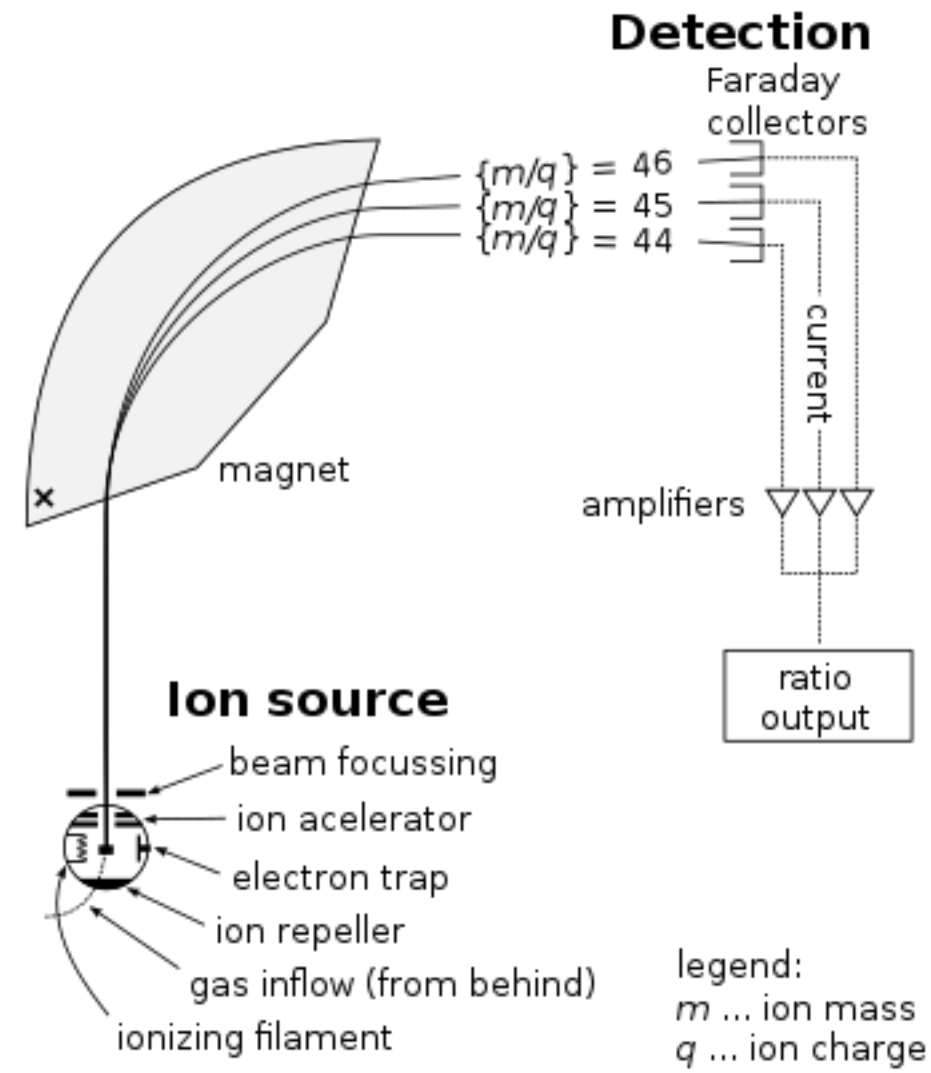
A mass spectrometer accelerates charged atoms (or molecules) to an energy given by a voltage.

All the ions have the same kinetic energy, but their velocity depends on their mass.

In a magnetic field, the radius of curvature depends on the mass times velocity.

So different masses have different radii.

For almost all elements, there are several different masses for the same Z value.



Atoms with different masses for the same Z are called <u>isotopes</u>.

But this doesn't explain where the extra mass is coming from.

Types of Radioactivity

The first types of radioactivity discovered were called Alpha and Beta.

Alpha rays could be stopped by a few cm of air, or a sheet of paper.

Beta rays could go ~ a meter in air, but could be stopped by a thin metal sheet.

Gamma rays were much more penetrating (which made them harder to detect, so they were discovered later.

The energies of these rays was of order MeV.

Alpha rays are Helium nuclei. Beta rays are electrons.
Gamma rays are photons, essentially X-rays but higher energy.

A New Type of Radioactivity

In 1930, Walther Bothe and Herbert Becker found that when Alpha rays from Polonium (which have particularly high energy) hit Lithium or Beryllium, a new kind of radiation was produced.

It was not deflected by electric or magnetic fields, like Gamma rays, but it was far more penetrating than Gamma rays.

In 1932, Frederic Joliot and Irene Joliet-Curie found that the new radiation could knock protons out of paraffin (rich in hydrogen), with energy 5 MeV.

Theoretically, photons could produce 5 MeV recoil protons, but the photons would need to be over 50 MeV to do that, far higher than the Polonium Alphas.

But if the radiation was a neutral particle with a mass comparable to a proton, it would only need to have an energy of about 5 MeV, consistent with Polonium.

The Neutron

Eventually it was accepted that the new radiation was a neutral particle with a mass comparable to the proton. Which could solve the M ~ 2Z problem.

The energetic Alpha from Polonium could penetrate the Coulomb repulsion of Lithium or Beryllium, and cause a nuclear reaction releasing a Neutron.

It was unclear if the Neutron was a mini-Hydrogen state of proton and electron, or a completely new particle.

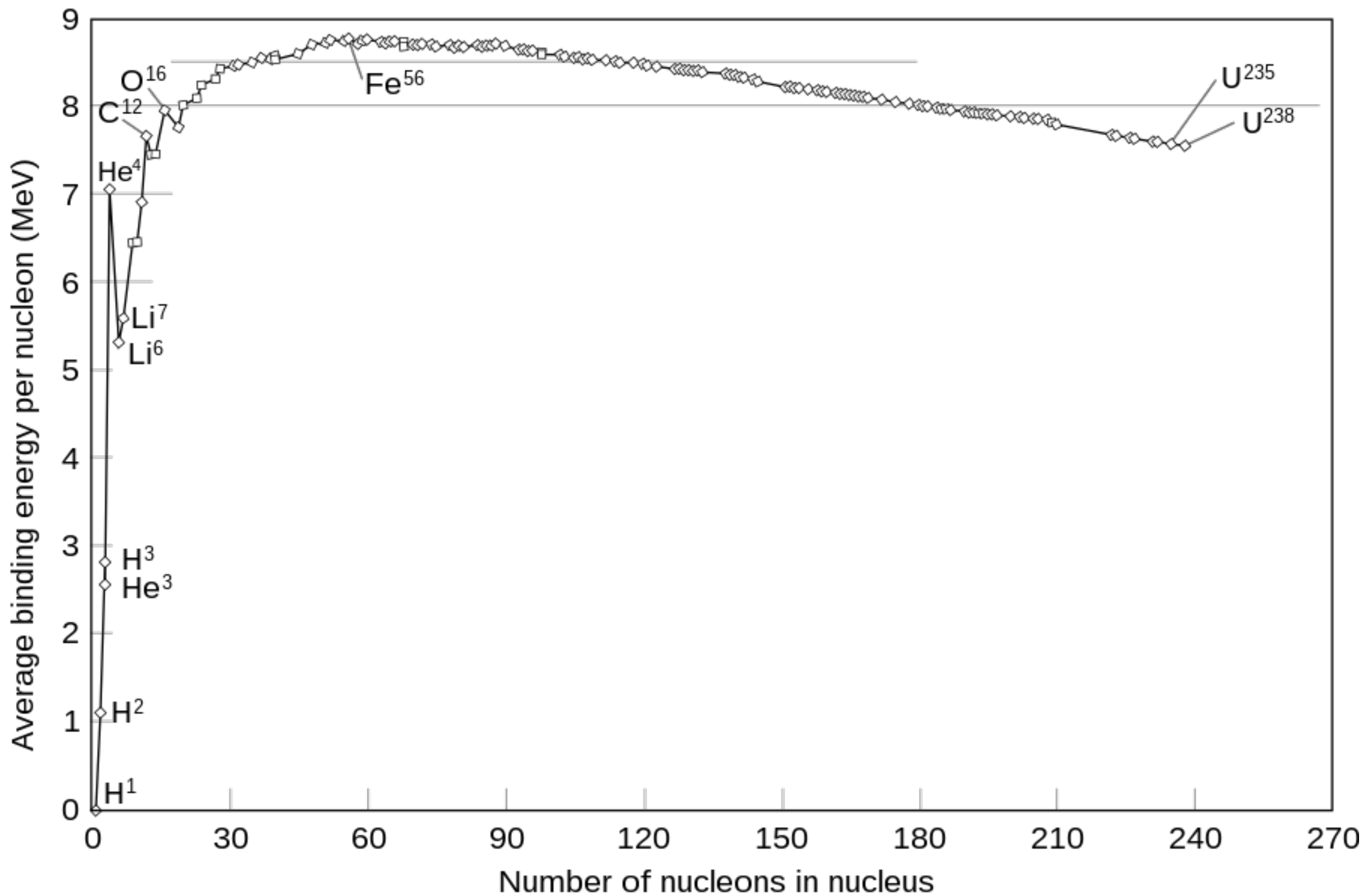
This was resolved by using a Gamma ray of known energy to break up Deuterium into a proton and a neutron, and measuring the energy of the proton.

The result was that the neutron mass was slightly <u>larger</u> than the mass of a proton plus and electron. So it could not be a bound state.

That also implies that the neutron can decay into a proton, electron (plus anti-neutrino, postulated later): $n^0 \rightarrow p^+ + e^- + \bar{\nu}_e^0 + 0.783\ \text{MeV}$

Nuclear Binding Energies

With the determination of the Neutron mass, and the recognition of isotopes, it was possible to compare the mass-spectrometer measurements of mass to the sum of Proton, Neutron, and Electron masses, in terms of $E = mc^2$



For most elements, the binding energy is about 8 MeV per Proton or Neutron.

Compared to the few eV per atom in chemical bonds, that's gigantic !

Nuclear Mysteries

Most big nuclei have close to equal numbers of protons and neutrons.

But why?

It's tempting to explain that by thinking that Neutrons attract Protons, but Neutrons repel Neutrons, and Protons repel Protons.

Also, free Neutrons decay with a $1/e$ lifetime of about 15 minutes, or half-life of about 10 minutes.

Why don't the Neutrons decay in nuclei?

Simple but Smart Questions

Do a Proton and a Neutron attract each other?

We do see Deuterium, with the chemistry of Hydrogen, but mass of 2.

Do two Protons bind to each other?

That would chemically be Helium, but with mass 2 not 4. We don’t see that.

Maybe the Protons repel each other?

But we <u>do</u> see inert Helium with mass 3, meaning 2 Protons plus one Neutron.

We also see Hydrogen with mass 3 (Tritium), one Proton plus 2 Neutrons.

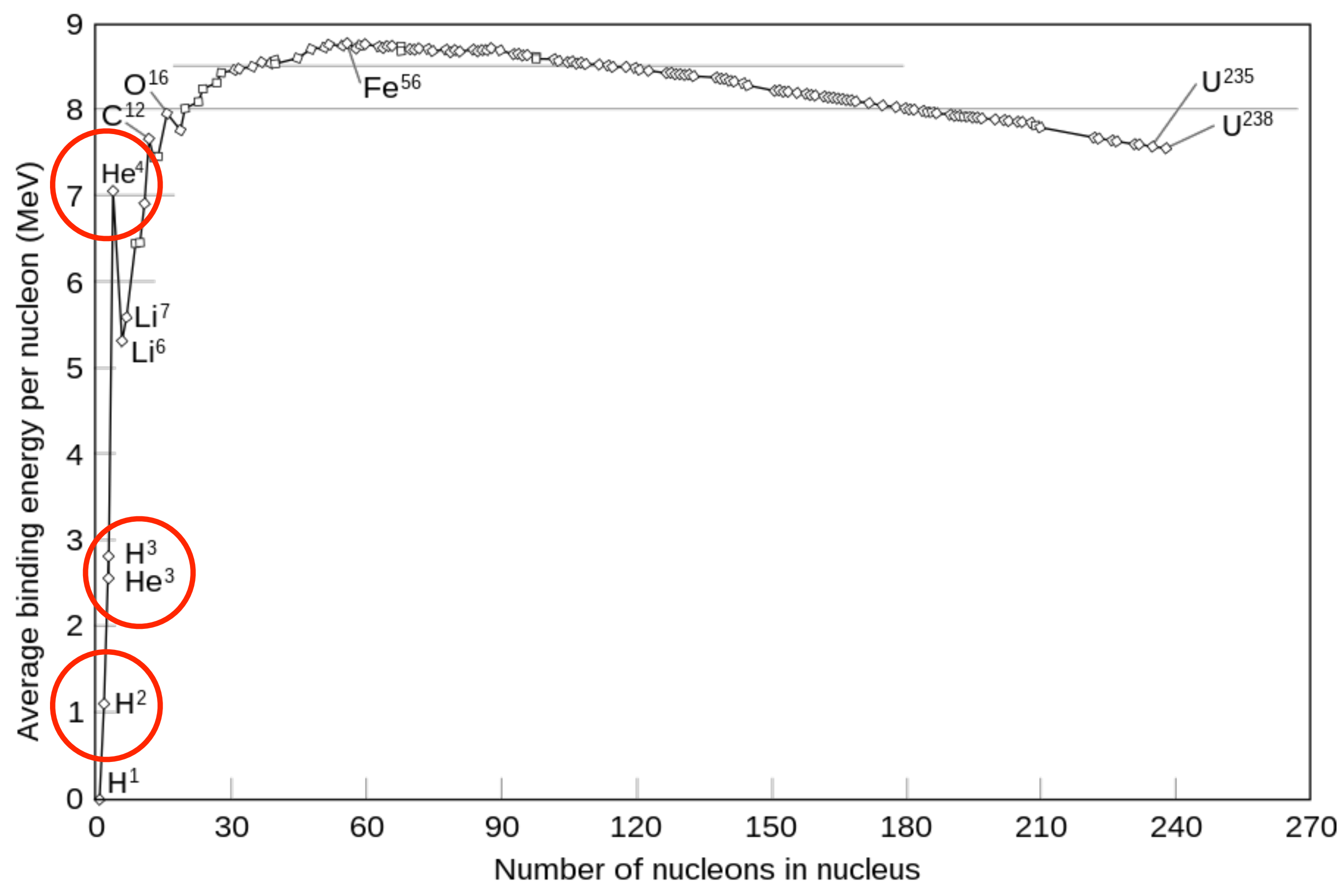
It would be hard to detect a bound state of 2 Neutrons, but it’s not seen.

Nuclear Binding Energies 2

In Deuterium, there is one "pair," and the nucleons attract each other with energy a bit more than 1 MeV.

In both Tritium and Helium-3, there are 3 "pairs," and the attraction is almost 3 MeV per nucleon.

In Helium-4, there are 6 "pairs," and the attraction is 7 MeV per nucleon.



But the increase in binding energy per nucleon seems to "saturate" beyond that.

Neutron-Proton Attraction?

It looks much more like Protons attract both Neutrons and Protons equally, and Neutrons attract both Protons and Neutrons equally.

But, the attraction depends on the relative "spin" (both $\pm$ 1/2) of the particles.

The attraction is only strong enough to bind them if the "spins" are aligned.
If the spins are opposite, it's not strong enough.

But Pauli says two Protons, or two Neutrons, <u>can't</u> have spins aligned.

But one Proton and one Neutron, with spins aligned, <u>can</u> bind.
That's Deuterium. It has total spin 1/2 + 1/2 = 1.

Why Don’t the Neutrons Decay?

In Tritium (one Proton, 2 Neutrons), one Neutron <u>does</u> decay.

The mean lifetime is 12.3 years, much longer for than a free Neutron.

But still a pain for nuclear weapons designers…

In Helium-3 (two Protons, one Neutron), the Neutron <u>doesn’t</u> decay.

That would result in a nucleus with 3 Protons and no Neutrons.

The lowest “orbit” can hold 2 protons (but they could not be in the favorable spin-aligned configuration). The third proton has to go into a higher energy “orbit.”

The resulting nucleus would have higher mass than Helium-3, so the decay is impossible.

Why Don't the Neutrons Decay 2

In big nuclei, Pauli exclusion requires most Protons and Neutrons
to be in high energy states."

If a Neutron decays, it turns into a Proton. Pauli prevents the Proton from going into a low-energy state, because those states are occupied already.

The Proton usually has to go into an empty state with higher energy.

If that extra energy is larger than the Neutron-Proton mass difference, the Neutron can't decay.

If there are too many Neutrons, then some Neutrons are in high energy states, with empty lower-energy Proton states available. In that case, Neutrons will decay until the number of Neutrons and Protons is close to equal.

Proton to Neutron Decay

If there are too many Protons in a nucleus, some Protons must be in high-energy states, and there are empty Neutron states with lower energy.

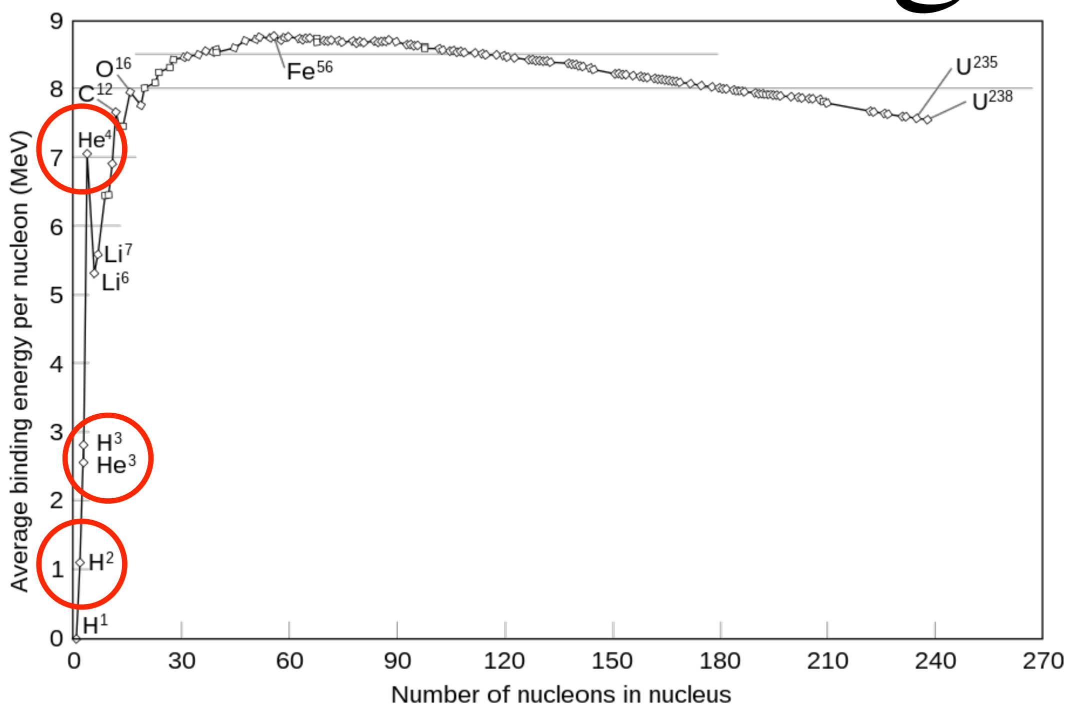
A Proton can emit an anti-electron (plus neutrino) and become a Neutron, which can move into an empty state with lower energy.

Even though a Proton has a lower mass than a Neutron, so a free proton can't decay into a Neutron, it <u>can</u> happen in a very proton-rich nucleus.

This actually has some uses. There is a medical research and diagnostic technique called Positron Emission Tomagraphy. The anti-electron can annihilate with an electron to make two Gamma-rays that go in opposite directions. Detecting both of them determines a line. Detecting many such lines determines a location in space. Some positron-emitting isotopes are selectively taken up in the body. So the regions they are taken up can be identified.

Nuclear Force is Short-Range

Deuterium has 1 pair,
Tritium and Helium-3 have 3 pairs,
and Helium-4 has 6 pairs.



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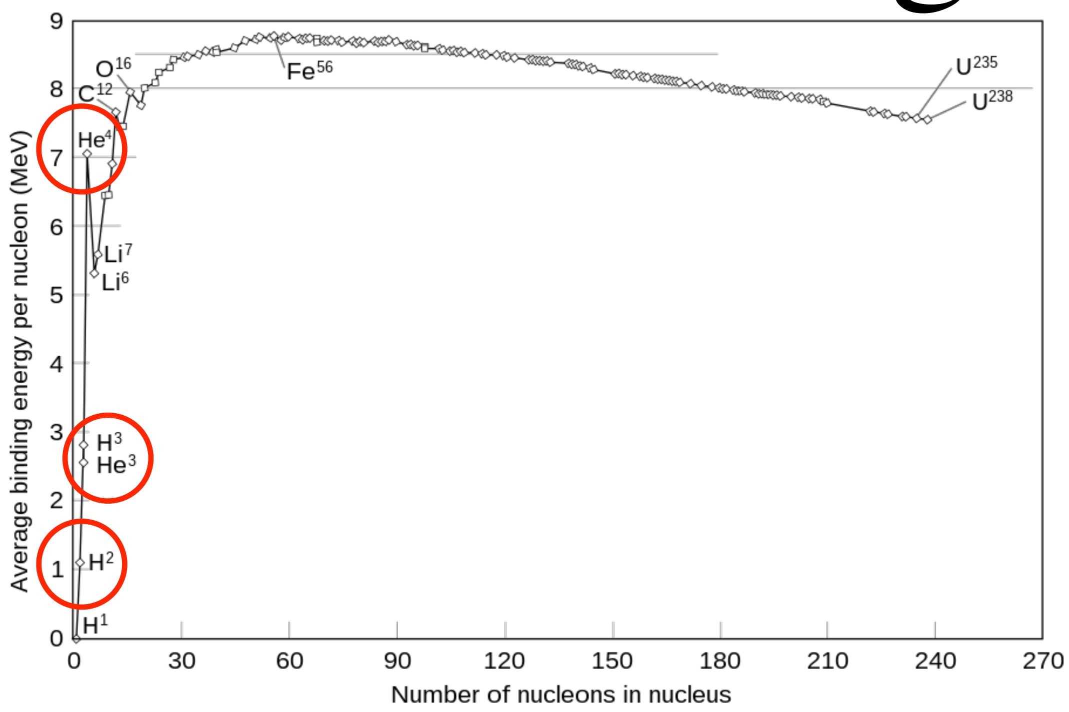
So the binding energy
seems to be proportional to pairs.



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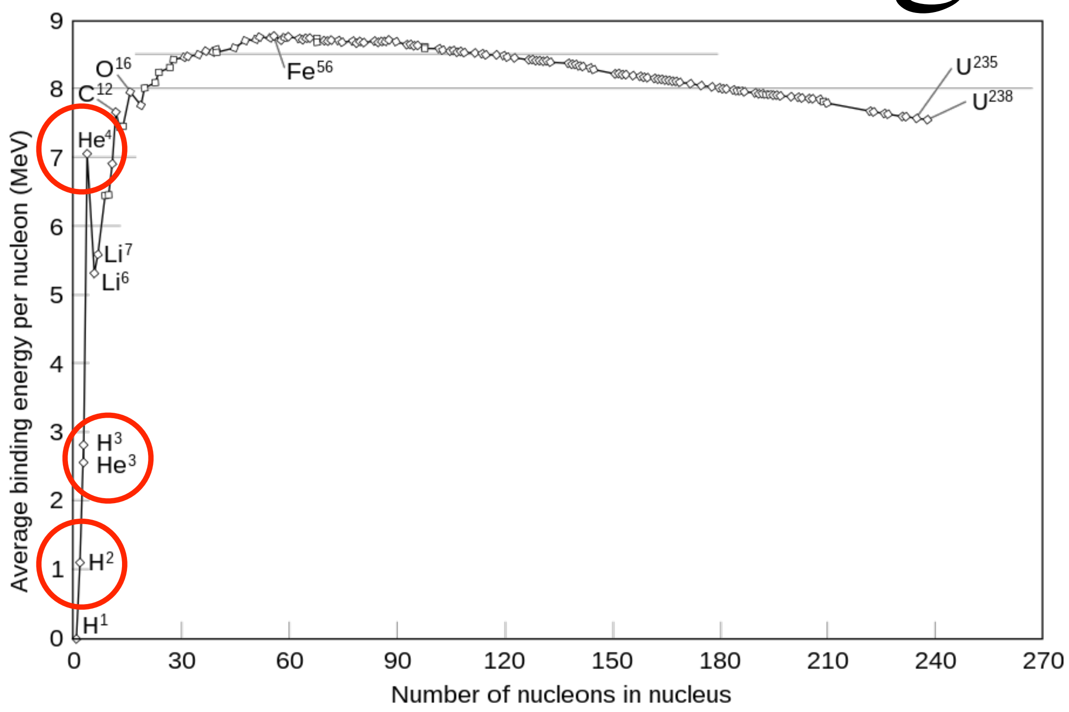

But bigger nuclei would have quadratically more pairs,
but the binding energy per nucleon doesn't go up much.

Nuclear Force is Short-Range

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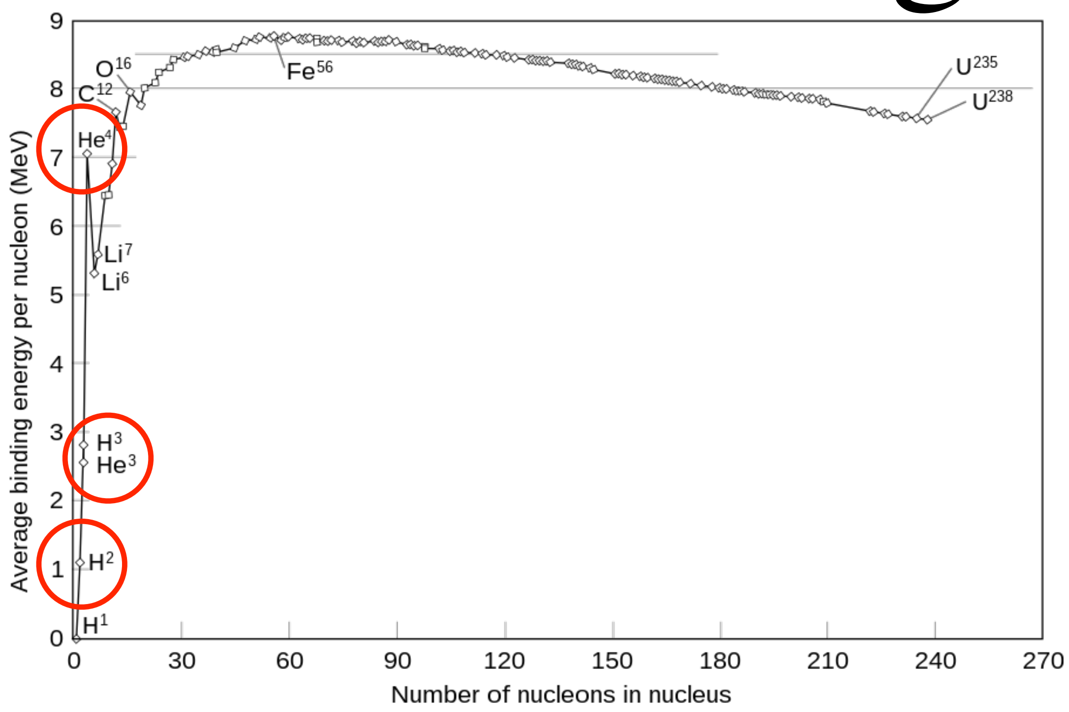

But bigger nuclei would have quadratically more pairs,
but the binding energy per nucleon doesn't go up much.

It must be that the nuclear force is basically "nearest-neighbor."

Nuclear Force is Short-Range

Deuterium has 1 pair,
Tritium and Helium-3 have 3 pairs,
and Helium-4 has 6 pairs.

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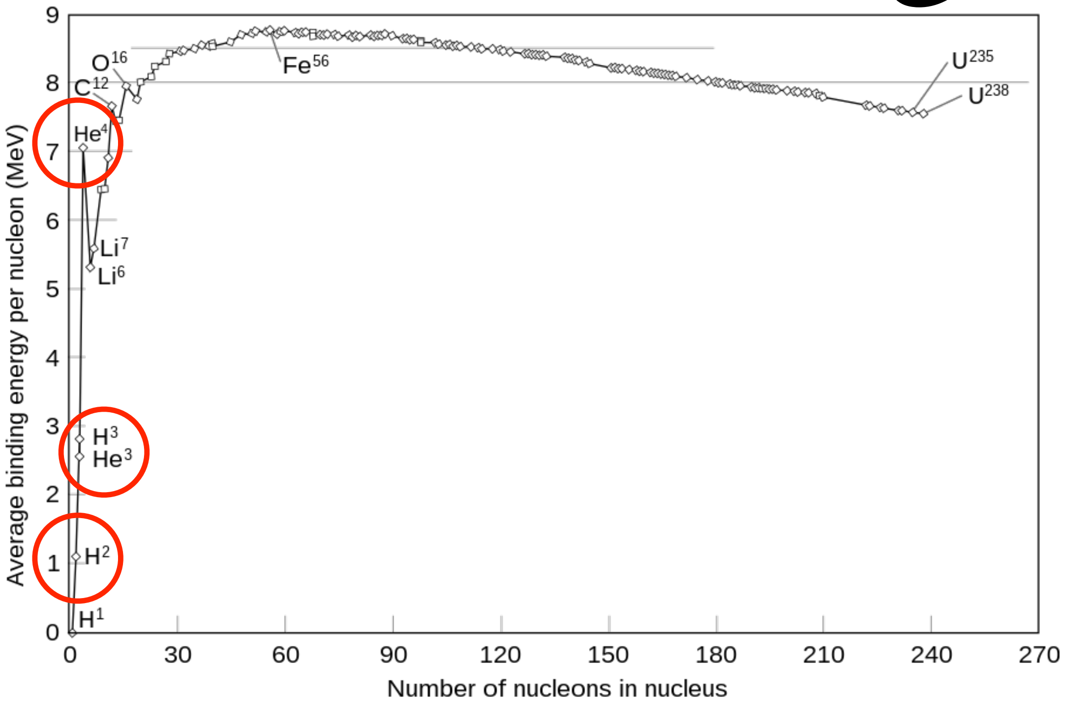

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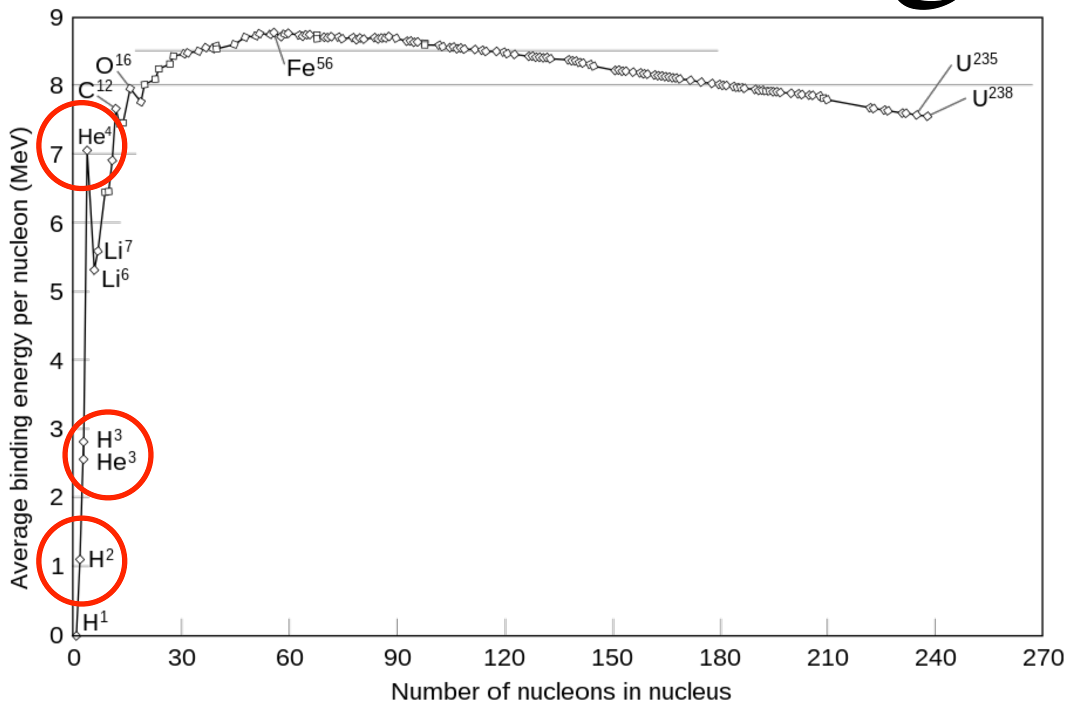

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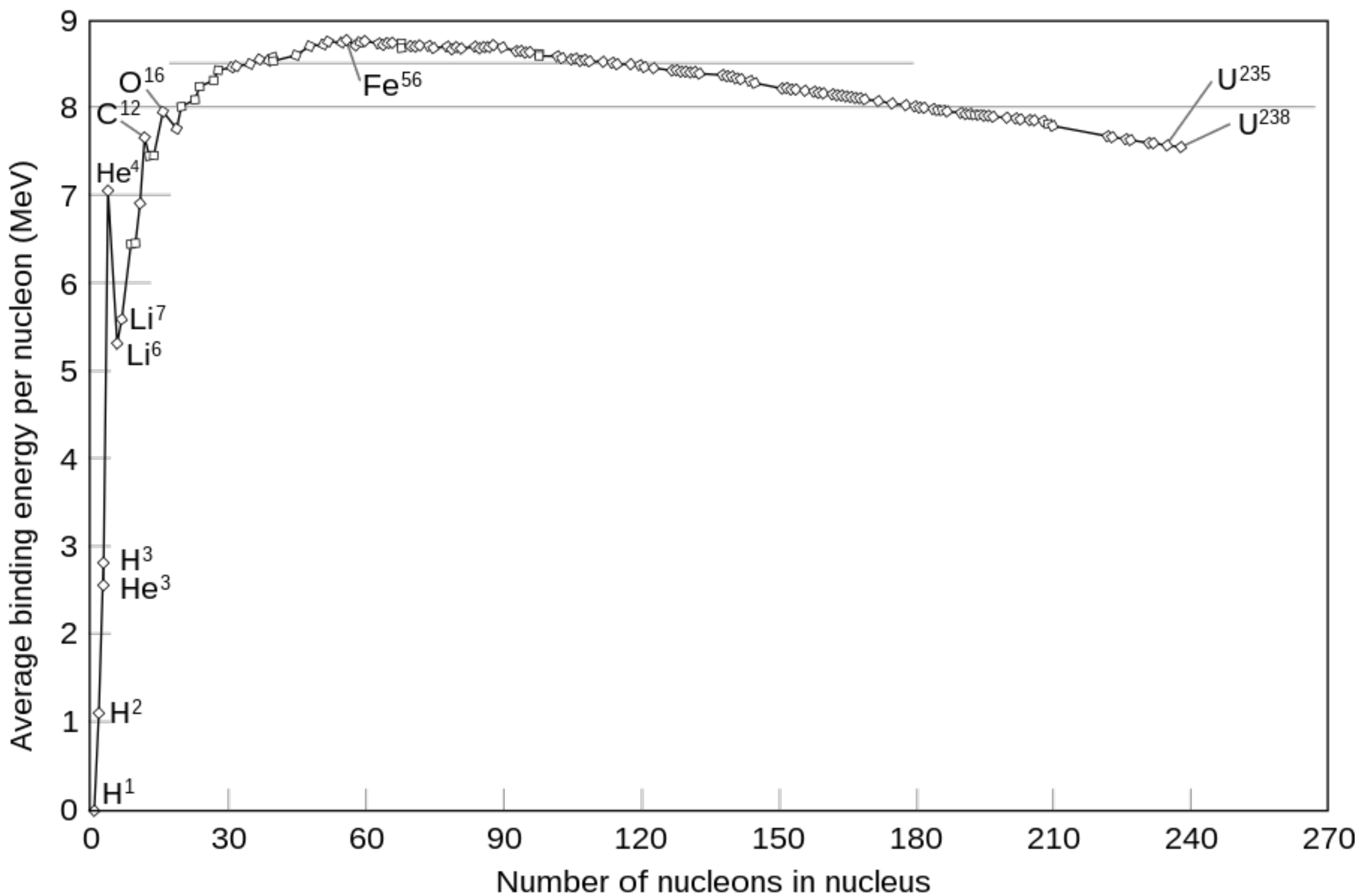
in the lowest energy state, and in contact with each other.

In larger nuclei, the extra nucleons have to be moving around
in higher energy states, thus farther apart, and the attraction is much weaker.

Fusion, Decay, and Fission

The steep positive slope on the left is due to strong attraction between protons and neutrons. Fusing them together releases energy. Stars and H-bombs.

The negative slope beyond Iron is due to the electrostatic repulsion of Protons. Breaking a big nucleus up into smaller pieces releases energy. Radioactive decay and fission-bombs.



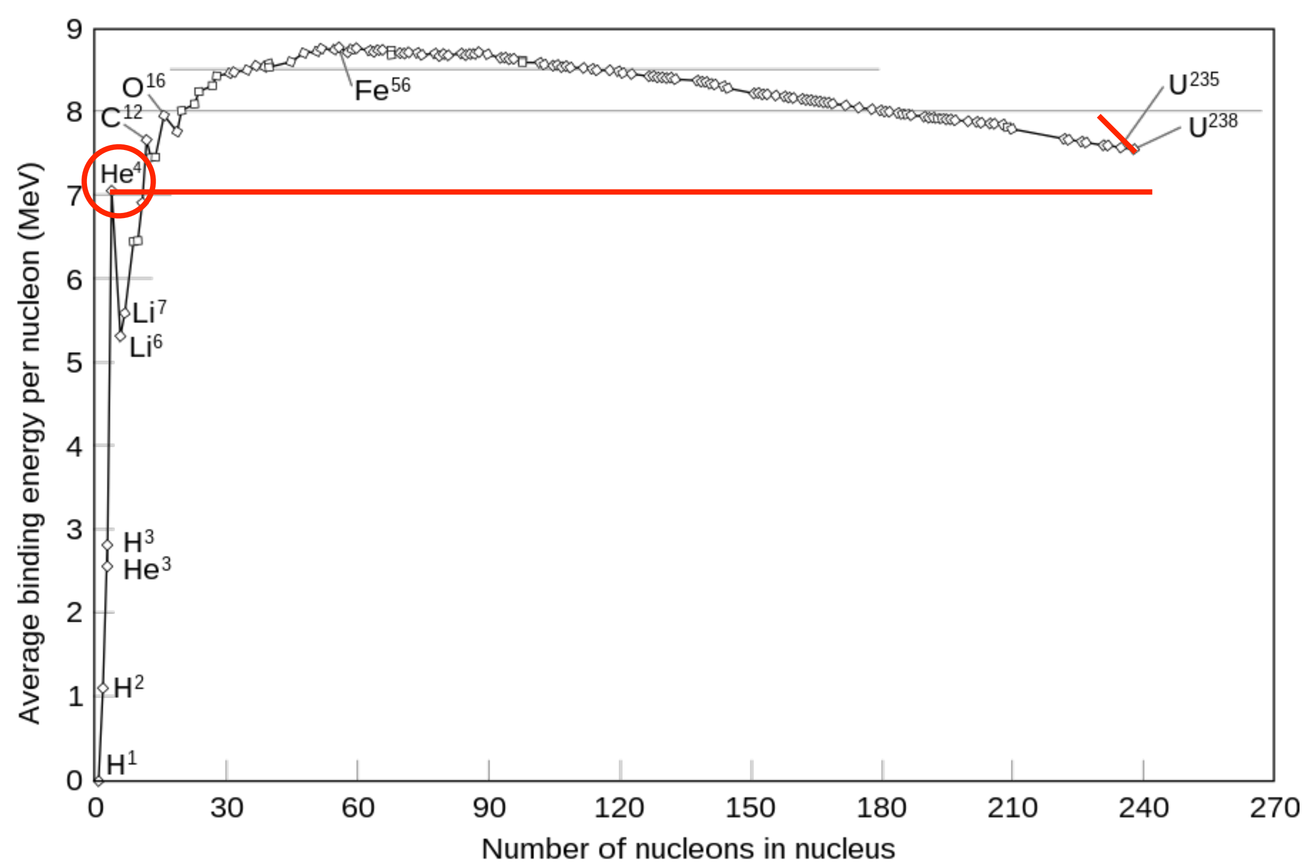
Alpha Decay

Ejecting a single proton or neutron from any nucleus is a net energy loser.

But the standard graph is just for stable proton-neutron combinations.
There are other unstable combinations, so actually the graph is fuzzy.

Ejecting 2 protons and 2 neutrons bound into Helium simultaneously
can be a net energy gain by reducing the proton repulsion. That's Alpha decay.

The Alpha energy is always exactly the same for a given decay.



Beta Decay

An Alpha decay reduces the number of Protons by 2,
and the number of Neutrons by two.

Typically, that leaves the nucleus with more Neutrons than it “needs.”

So a Neutron typically decays into a Proton, Electron, and Anti-Neutrino.

Because the final state is an Electron, Neutrino, and recoil Nucleus,
the energy of the Electron does not have a predictable value
(although the distribution of energies <u>is</u> predictable).

The Beta decay increases the number of Protons by 1.
That may allow a subsequent Alpha decay.

Or there may be a second Beta decay, making another Alpha decay more likely.

Gamma Decay

Gamma rays are emitted when a nucleus goes from a higher energy state to a lower energy state. It's much like photon emission from an atom.

Usually Gamma rays are emitted very quickly.

But some Alpha or Beta transitions have a long lifetime, and leave the nucleus in an excited state, and a Gamma ray is emitted soon thereafter.

So some Gamma rays are emitted with a very long half-life.

An example is Potassium-40. It has a half-life of 1.25 billion years.

But about 11% of its decays result in Argon-40 in an excited state, which almost instantly emits a 1.5 MeV Gamma ray.

Fission

Basically any nucleus can "capture" either a Proton or a Neutron and become a heavier nucleus.

Since there is electrostatic repulsion, a Proton would need to have a high energy to approach close enough to be captured.

But a Neutron is neutral, so it can "sneak" into any nucleus.

Electrostatic repulsion of protons makes large nuclei unstable.

If you hit a large nucleus with an energetic Neutron, it will "fission" or split in two. This releases the electrostatic repulsion energy of about 200 MeV per nucleus!

It also releases about 2 extra Neutrons, making a chain-reaction possible.

Fission 2

For U-238, it takes a high-energy Neutron to cause fission.

And while the fission does produce several extra Neutrons,
most don't have enough energy to cause another U-238 fission.

So a chain-reaction is impossible with U-238.

A quirk of the nuclear force makes U-235 actually "suck in"
even a low-energy Neutron strongly enough to fission it.

So a chain-reaction <u>is</u> possible with U-235.

But natural Uranium is only about 0.7% U-235,
and the U-238 absorbs too many Neutrons for a chain-reaction.

So a chain-reaction can't happen in pure natural Uranium.

Fission 3

If you remove most of the U-238 from natural Uranium,
a fast fission chain-reaction is possible. A fission bomb.

On average, a Neutron from a fission travels a few centimeters
before causing another fission. So you need a lump of U-235 that is
more than a few centimeters in radius for the reaction to work. Critical mass.

But you need to assemble the critical mass only when you are at the target!

If the Neutrons are slowed down, U-238 absorbs fewer, and U-235 absorbs more,
and the reaction is possible even with a fair amount of U-238 around.

The Hydrogen in ordinary water is good at slowing down Neutrons.
But it also captures some of them. So you have to enrich to about 3% U-235.
That's standard for ordinary water-cooled power reactors.

Heavy water, with Deuterium instead of Hydrogen, doesn't absorb many
Neutrons. So a CANDU reactor with heavy water can run with natural Uranium.

Plutonium

When a U-238 nucleus captures a Neutron, it becomes U-239.

It has too many Neutrons, so one decays into a Proton, giving Neptunium-239.

That still has too many Neutrons, so one decays, giving Plutonium-239.

That is the same as adding 2 Protons and 2 Neutrons to U-235,
which gives Pu-239 fission properties like U-235, but better (for bombs).

Bomb-builders love Pu-239. And they love CANDU reactors,
because they make Plutonium from natural Uranium…

U-239 can also capture a second neutron, and you end up with some Pu-240.

Unfortunately for bomb-builders, Pu-240 has a high rate of <u>spontaneous</u> fission,
so it makes neutrons continuously.

And those cause a bomb to start fissioning when it's only partly assembled.

Fusion

Stars shine by fusing Hydrogen into Helium. But that requires Neutrons too.

It turns out that two Protons can collide and fuse into Deuterium, while simultaneously emitting an anti-Electron and a Neutrino. This releases about 1 MeV, although the Neutrino energy just escapes.

It's a very uncommon reaction. If it were common, stars would burn up fast!

When a Proton hits the Deuterium, it can form Helium-3. This releases about 6 MeV as Gamma rays that turn into heat.

When two Helium-3 nuclei collide, they can fuse into Helium-4 plus two left-over Protons.

Fusion 2

Because the Proton + Proton to Deuterium reaction is so slow,
hydrogen bombs use a different reaction.

Deuterium + Tritium produces Helium-4 plus a Neutron plus 14 MeV.

Deuterium can be refined from seawater, but Tritium is not found in nature.

It's manufactured inside the H-bomb during the explosion
by Lithium-6 + Neutron producing Helium-4 plus Tritium.

The "fuel" for an H-bomb is the chemical Lithium-6 Deuteride.

The reactions require high temperatures and pressures,
which are created by a fission bomb "trigger."

Fusion 3

The Deuterium + Tritium reaction can also be produced outside of a bomb.

Deuterium and Tritium plasma can be confined in a magnetic field, and fusion has been observed in those conditions (by detecting neutrons).

The resulting Neutron can be used to breed Tritium out of Lithium. But it also damages the reactor walls and makes them radioactive.

But after many decades of work, it has not been possible to stabilize the plasma enough to make a workable power reactor. It may be close, but not cheap!

Deuterium + Helium-3 also works, and makes a Proton instead of a Neutron. In principle, the Proton energy can be turned directly into electricity, instead of just heat. And it doesn't make the walls radioactive.

Helium-3 is very rare on Earth. Maybe mine it on the Moon? More practically, just breed a lot of Tritium and let it decay…

For Next Time

Midterm is Wednesday June 4 at 5-6 PM. On paper, in this room.
Midterm covers through today's material, plus homework and worksheet.

Any calculator is allowed, but no wireless devices.

You may bring one page (both sides) of notes / formulas.
A team note sheet is allowed.

We will start Schrodinger Equation on Monday.
Read Y&F Chapter 40.1-4, 42.3-7, 39.4