Welcome back to 8.033!

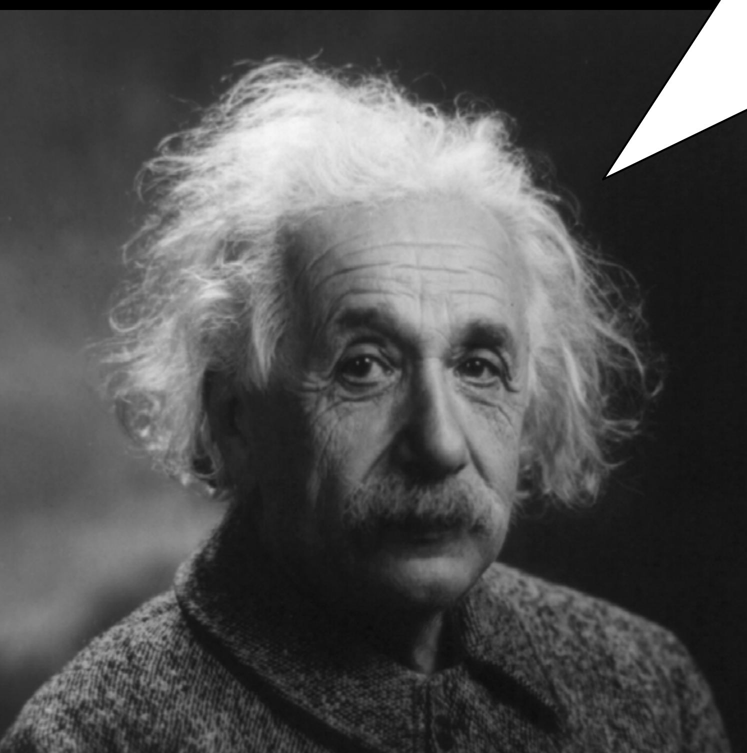


Image courtesy of Wikipedia.

Relativistic dynamics summary:

Dynamics toolbox: formula summary

- Mass-energy unification:

$$E = mc^2 = m_0\gamma c^2$$

- Momentum 4-vector:

$$\mathbf{P} \equiv m_0\mathbf{U} = \begin{pmatrix} p_x \\ p_y \\ p_z \\ E/c \end{pmatrix}$$

- Energy formula:

$$E = \sqrt{(m_0c^2)^2 + (cp)^2}$$

- Velocity formula:

$$\beta = \frac{cp}{E}$$

MIT Course 8.033, Fall 2006, Lecture 12

Max Tegmark

Today's topics:

- Atomic, nuclear & particle physics
- Parallel & transverse acceleration & force
- Particle accelerators

FOCUS OF PARTICLE PHYSICS COMPONENT OF 8.033:

1) Give you basic overview of atomic, nuclear & particle physics so that you can
    1) Better see the big picture
    2) Get more out of popular talks and articles
    3) Pass the "cocktail party test"
2) Apply two core relativity results:
    1) Mass-energy unification
    2) Energy-momentum conservation

Atomic physics

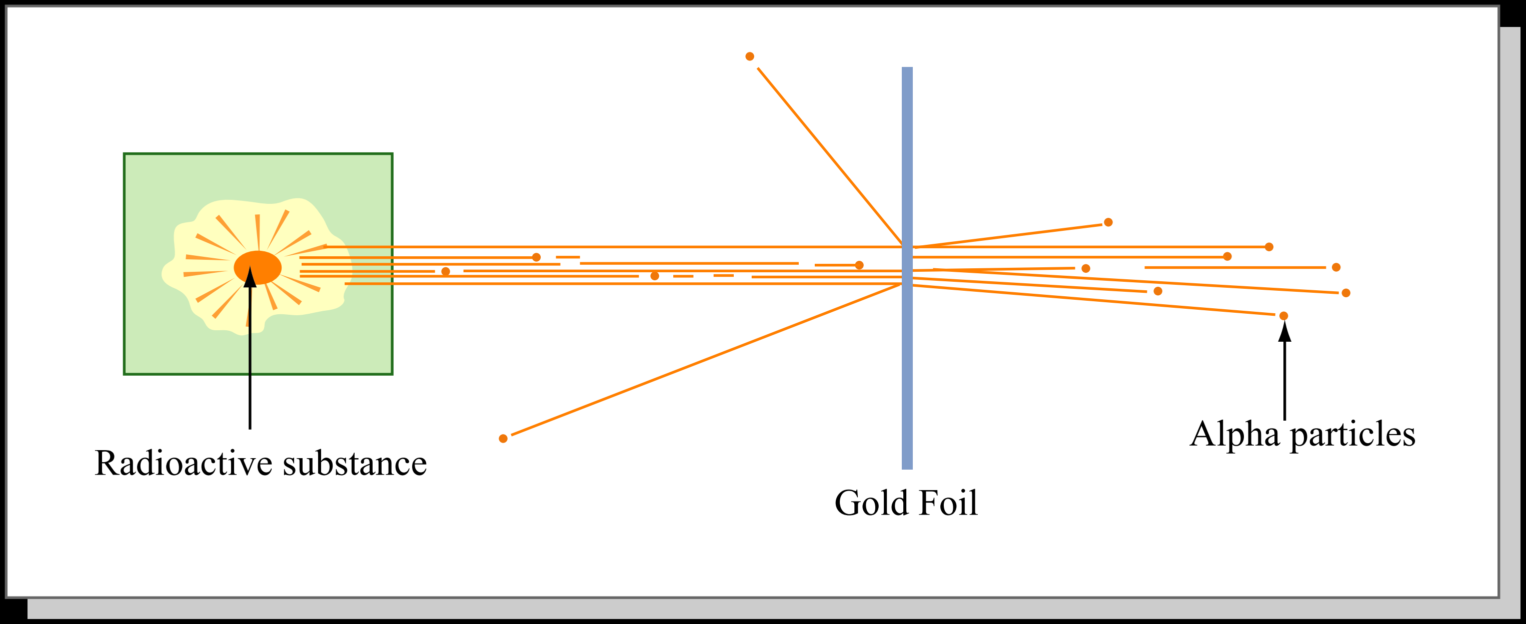


Figure by MIT OCW.

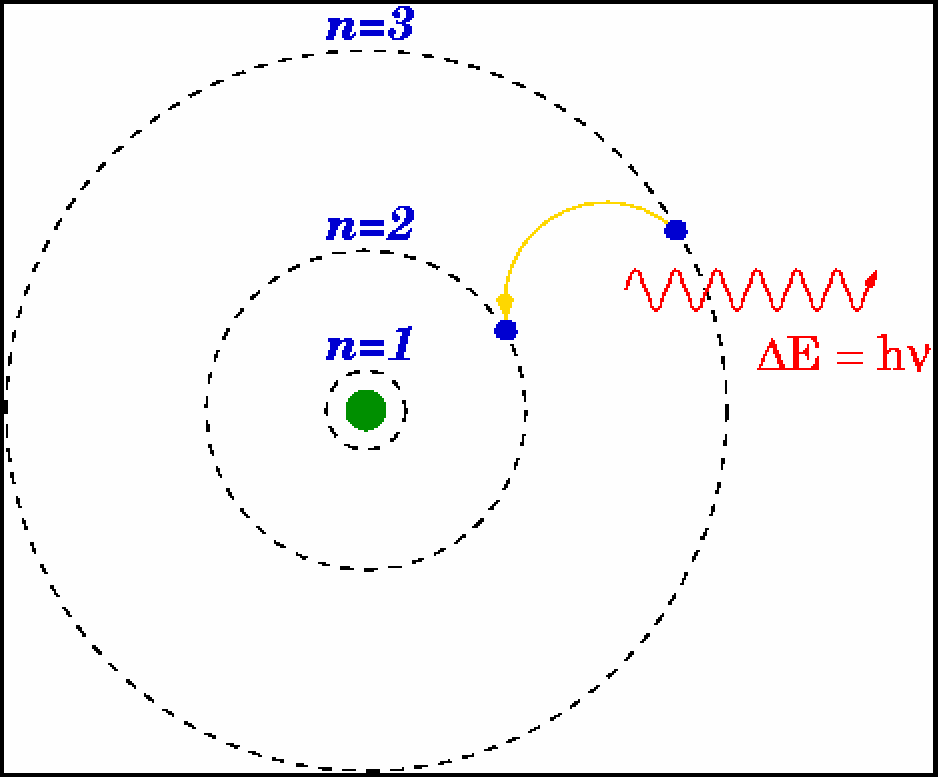


Image courtesy of Wikipedia.

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
87 Fr	88 Ra	103 Lr	104 Rf	105 Db	106 Sg	107 Bh	108 Hs	109 Mt	110 Uun	111 Uuu	112 Uub						
			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	

#118 just confirmed! → ◆

Spectral line
experiment

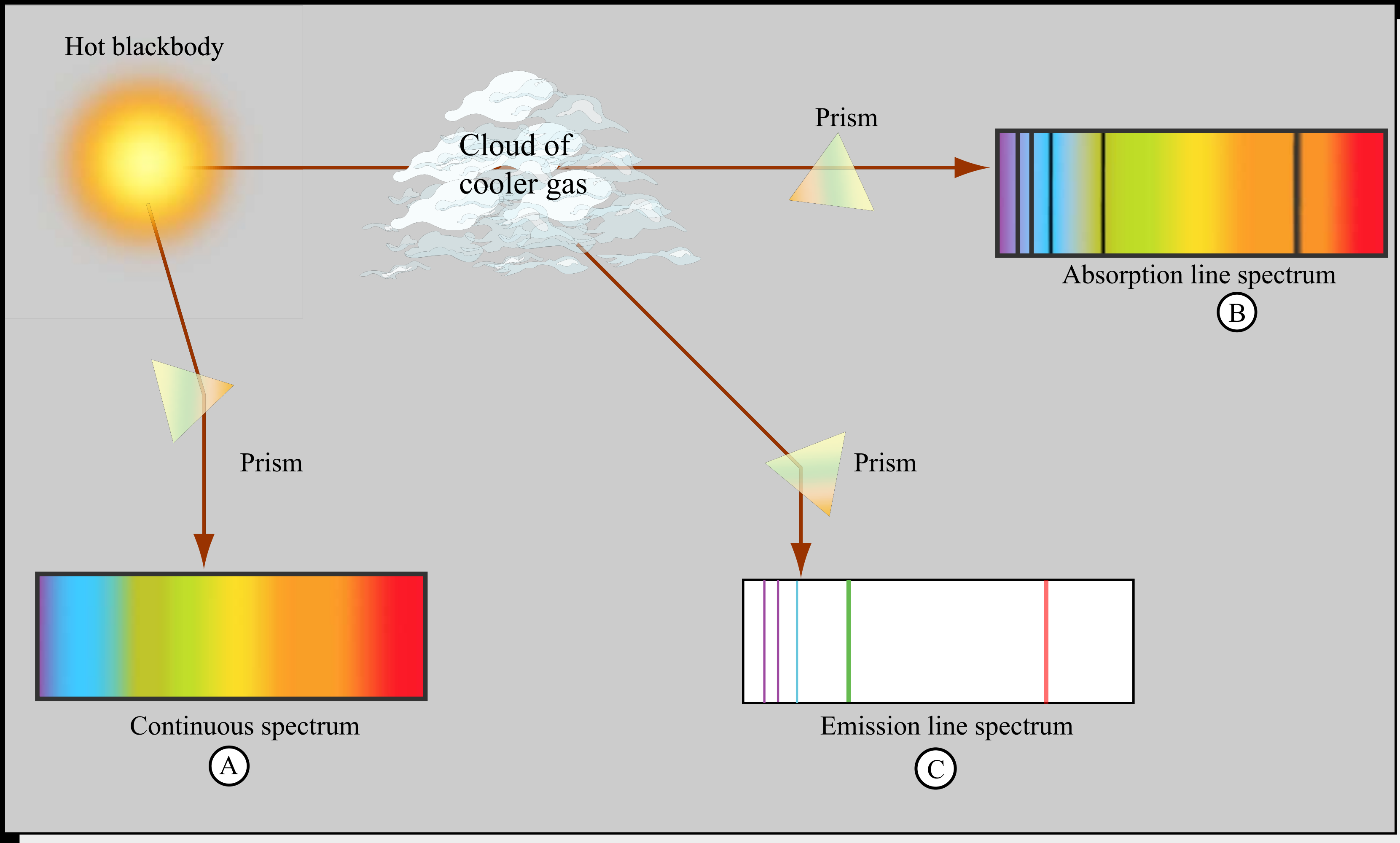


Figure by MIT OCW.

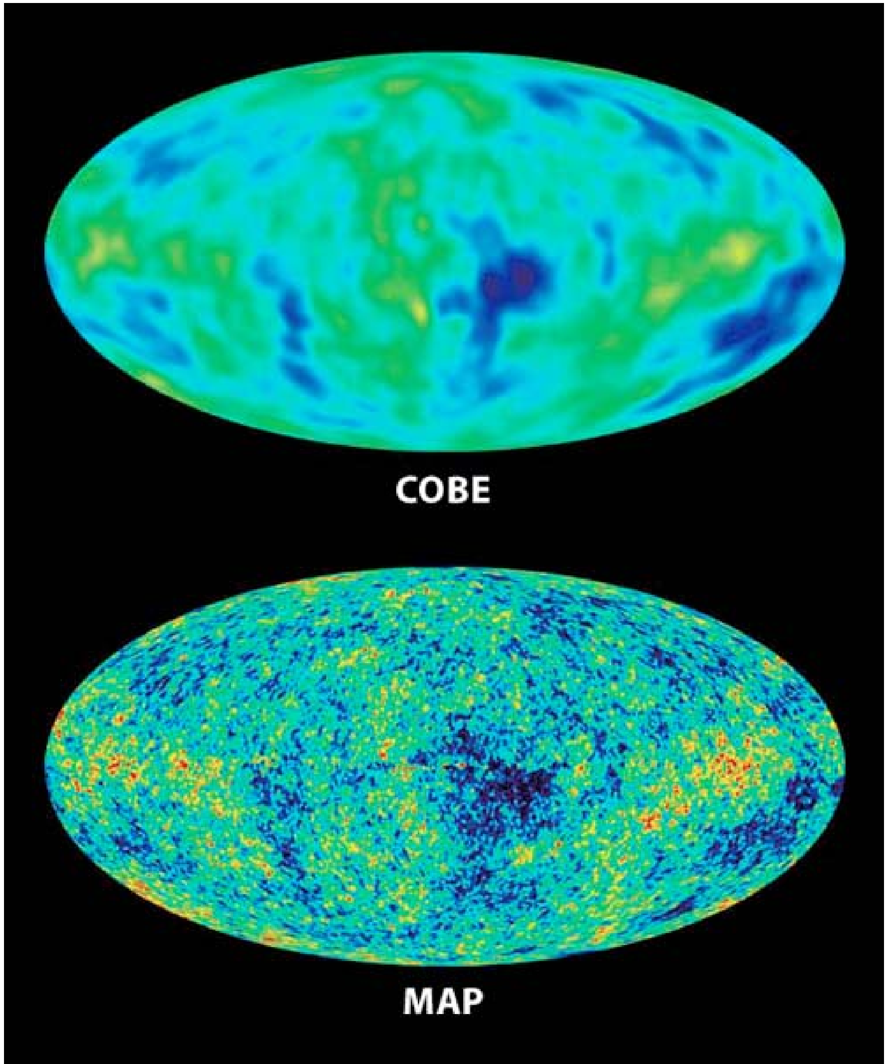


Image courtesy of NASA.

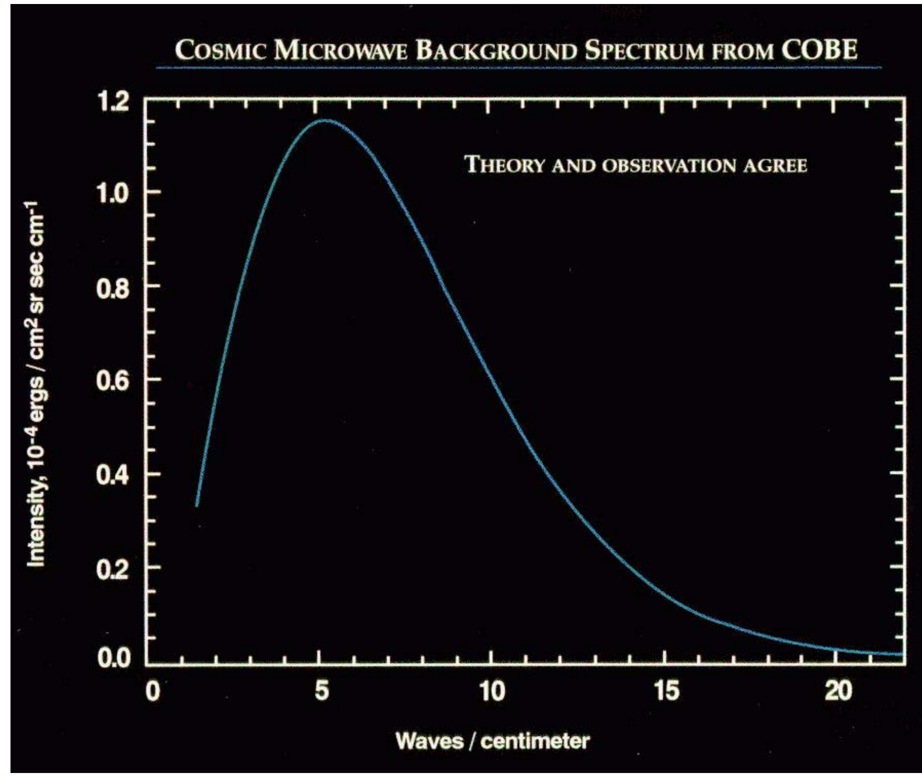


Image courtesy of NASA.

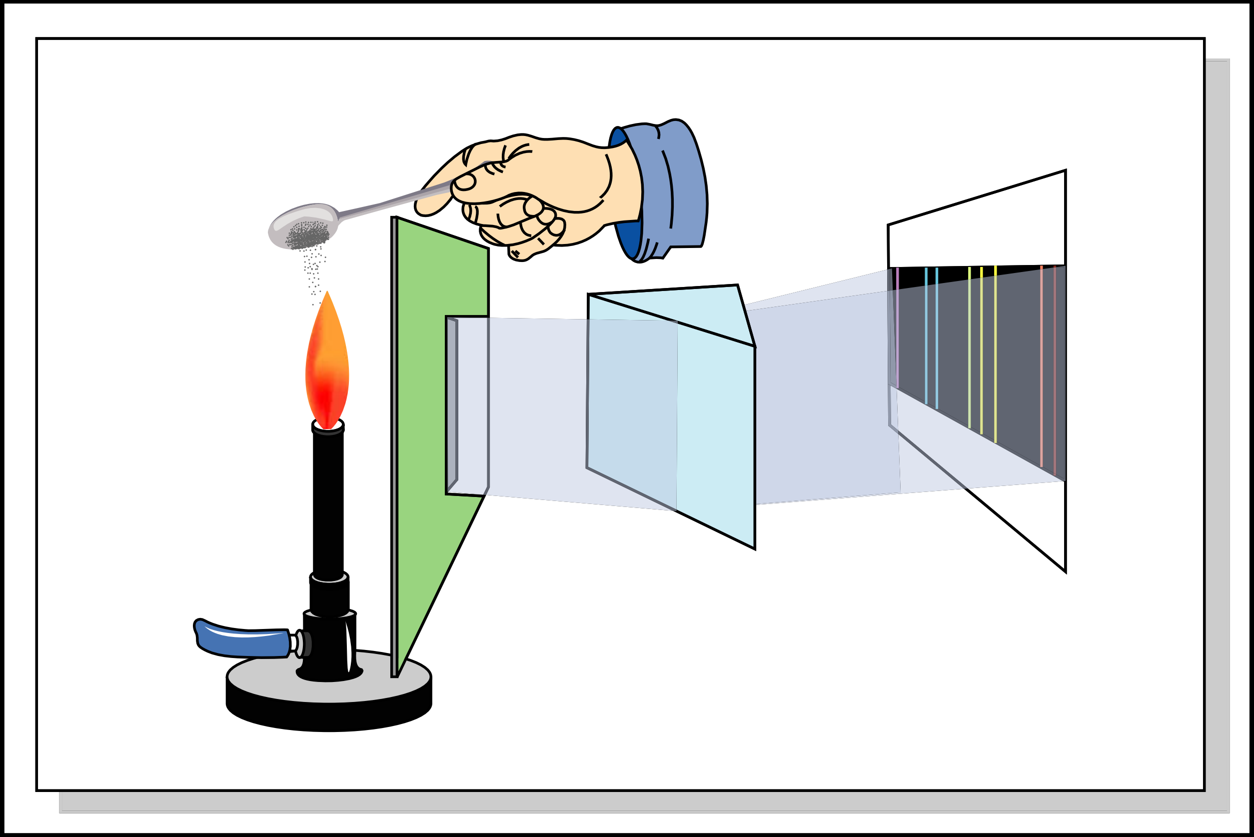


Figure by MIT OCW.

Emission spectrum of hydrogen:

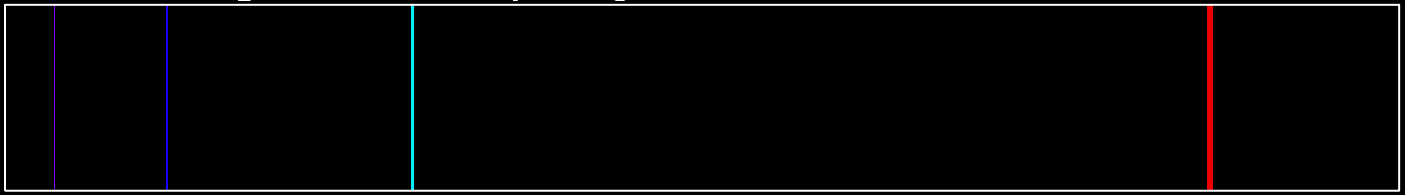


Image courtesy of Wikipedia.

Emission spectrum of iron:

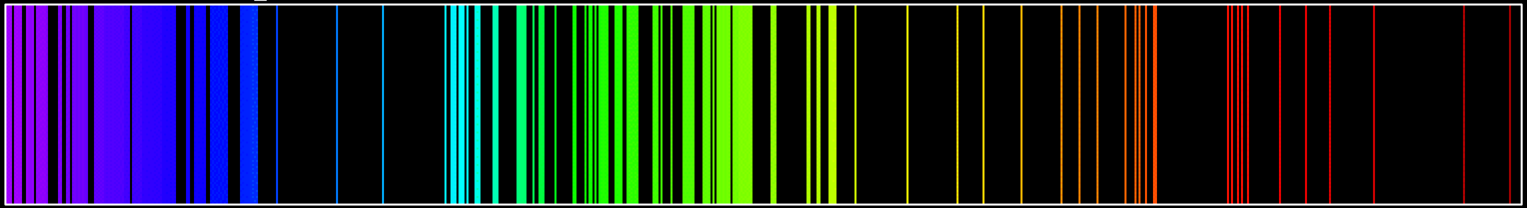


Image courtesy of Wikipedia.

How do we know what stars are made of?

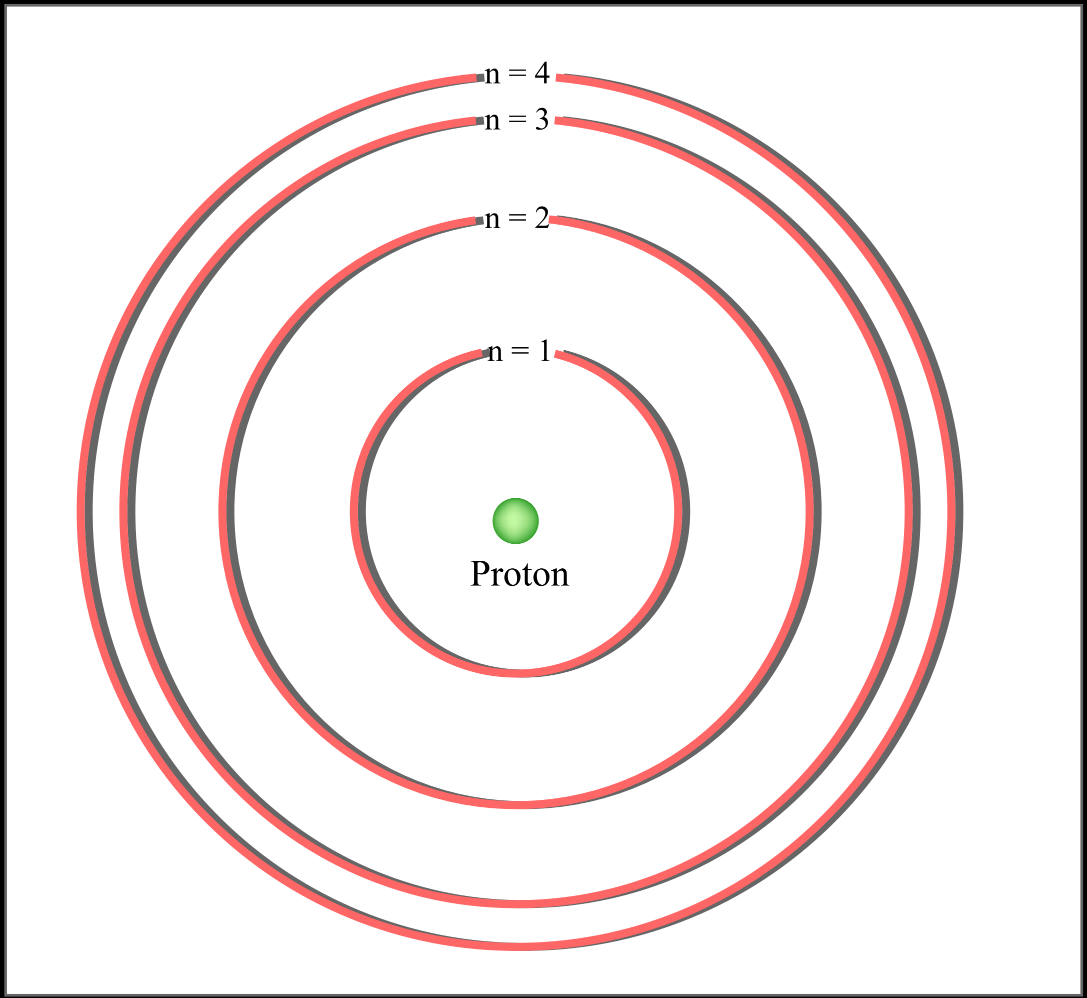


Figure by MIT OCW.

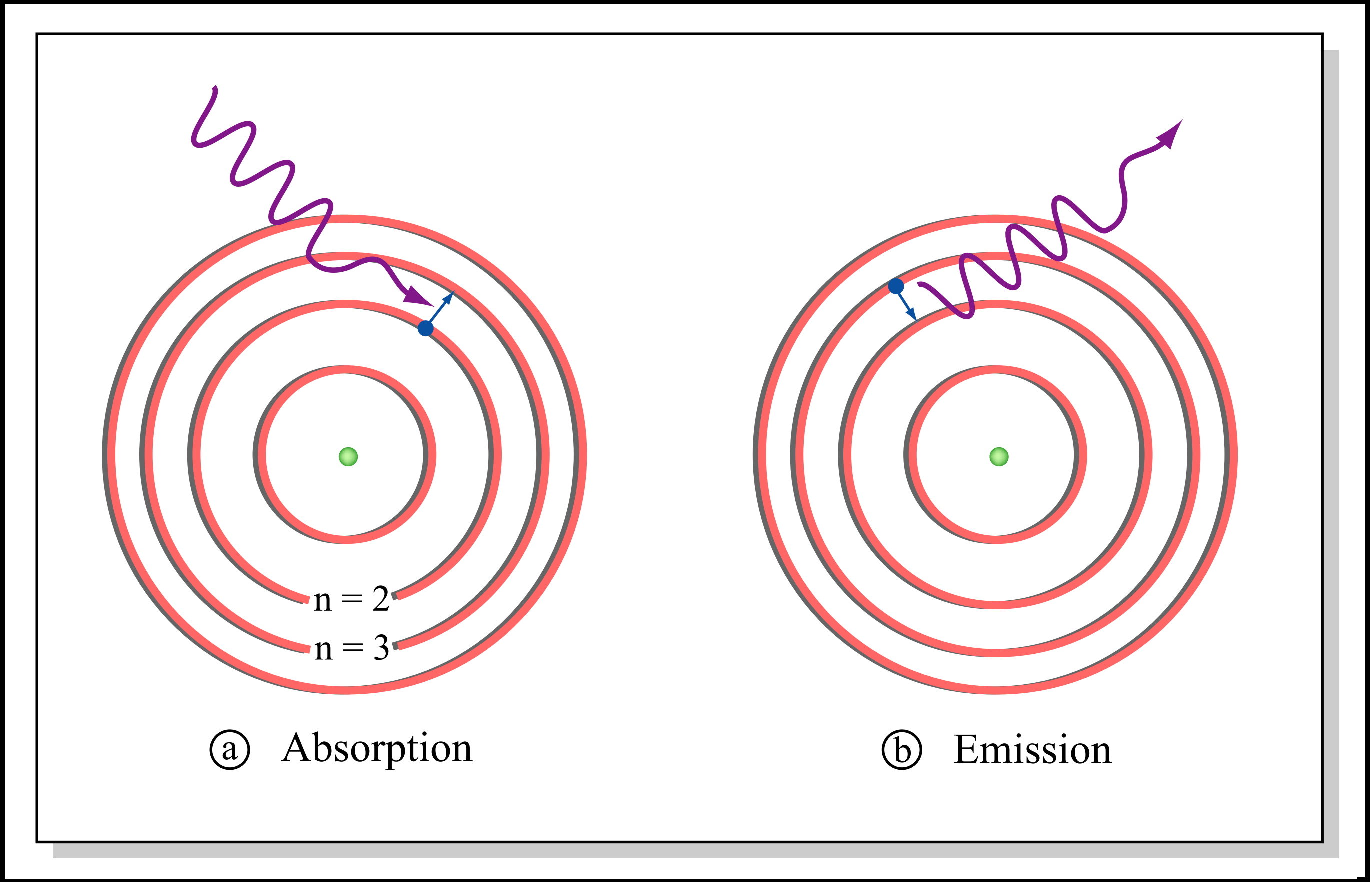


Figure by MIT OCW.

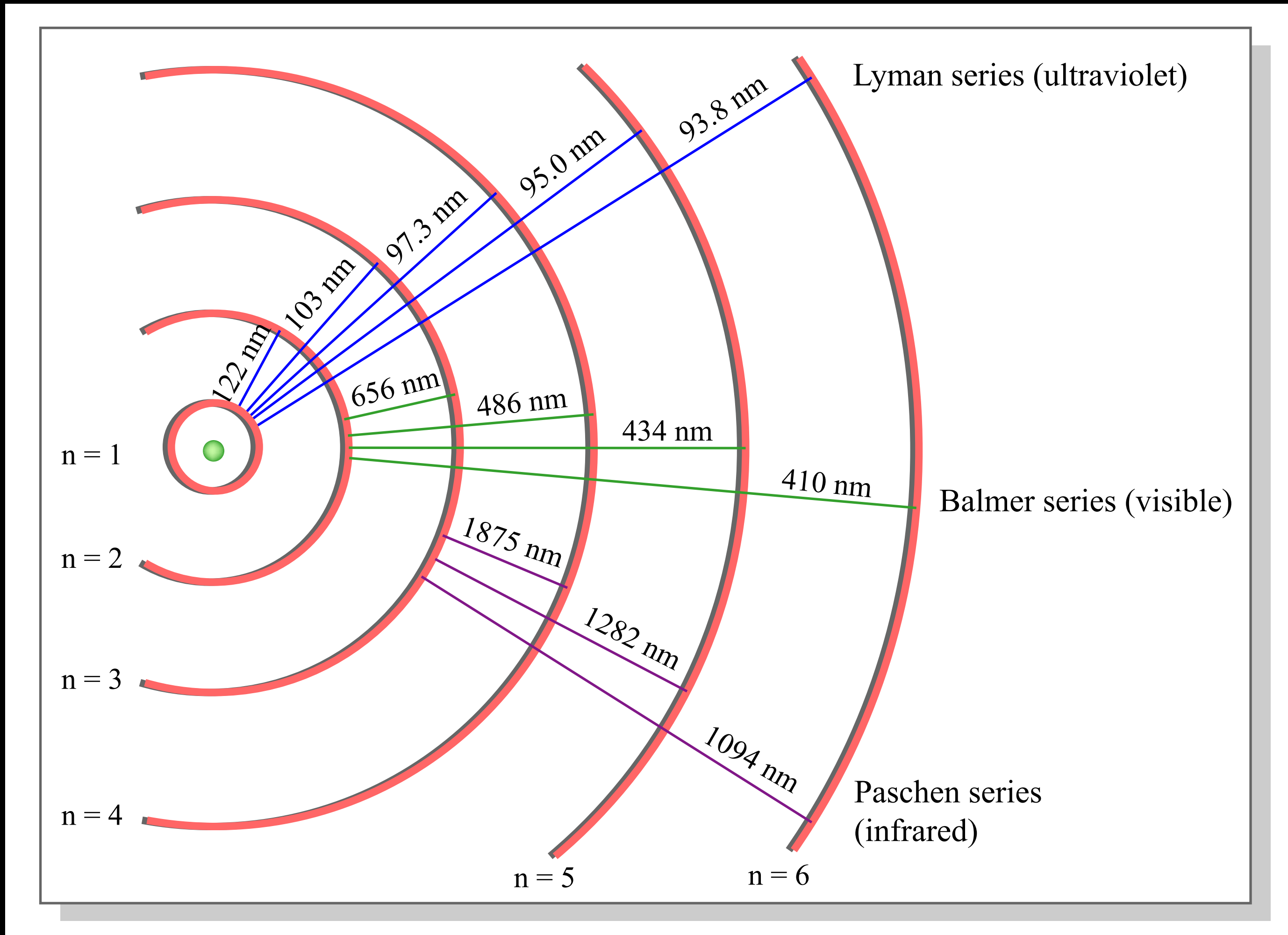


Figure by MIT OCW.

Photons

Photoelectric effect

- Einstein's model was that
  - the photon carries energy $h\nu$
  - a certain work W_e is required to liberate an electron from the metal

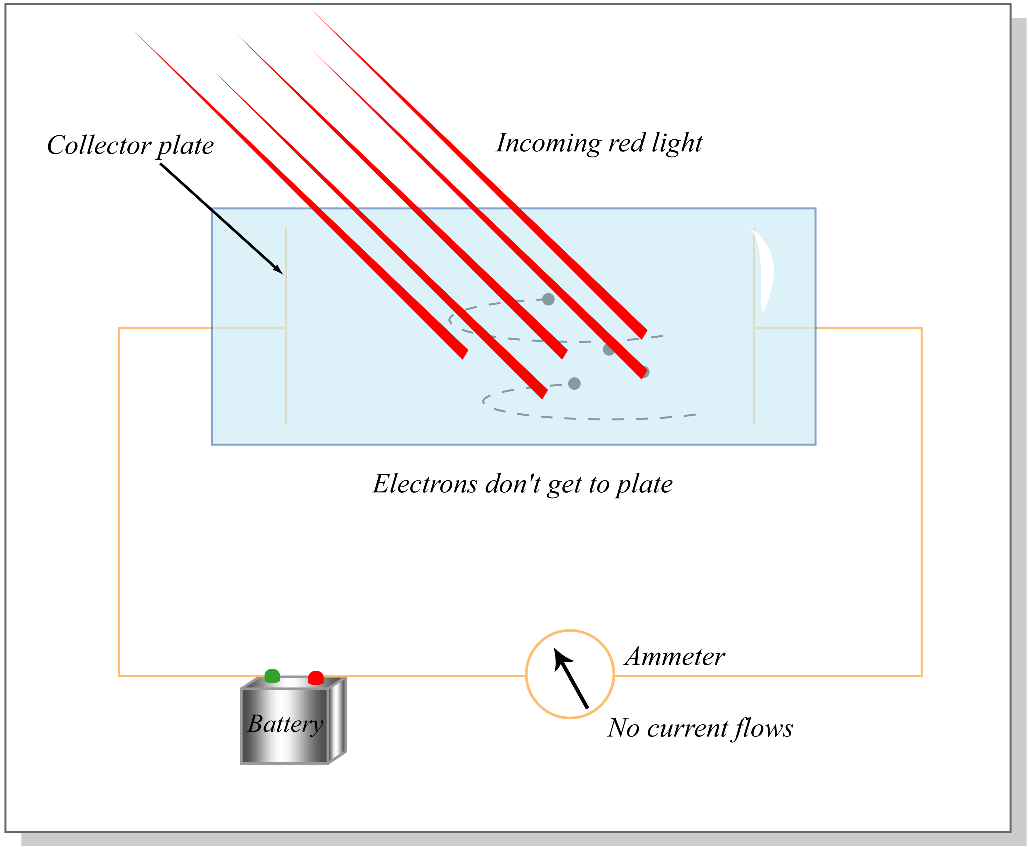


Figure by MIT OCW.

Photoelectric effect

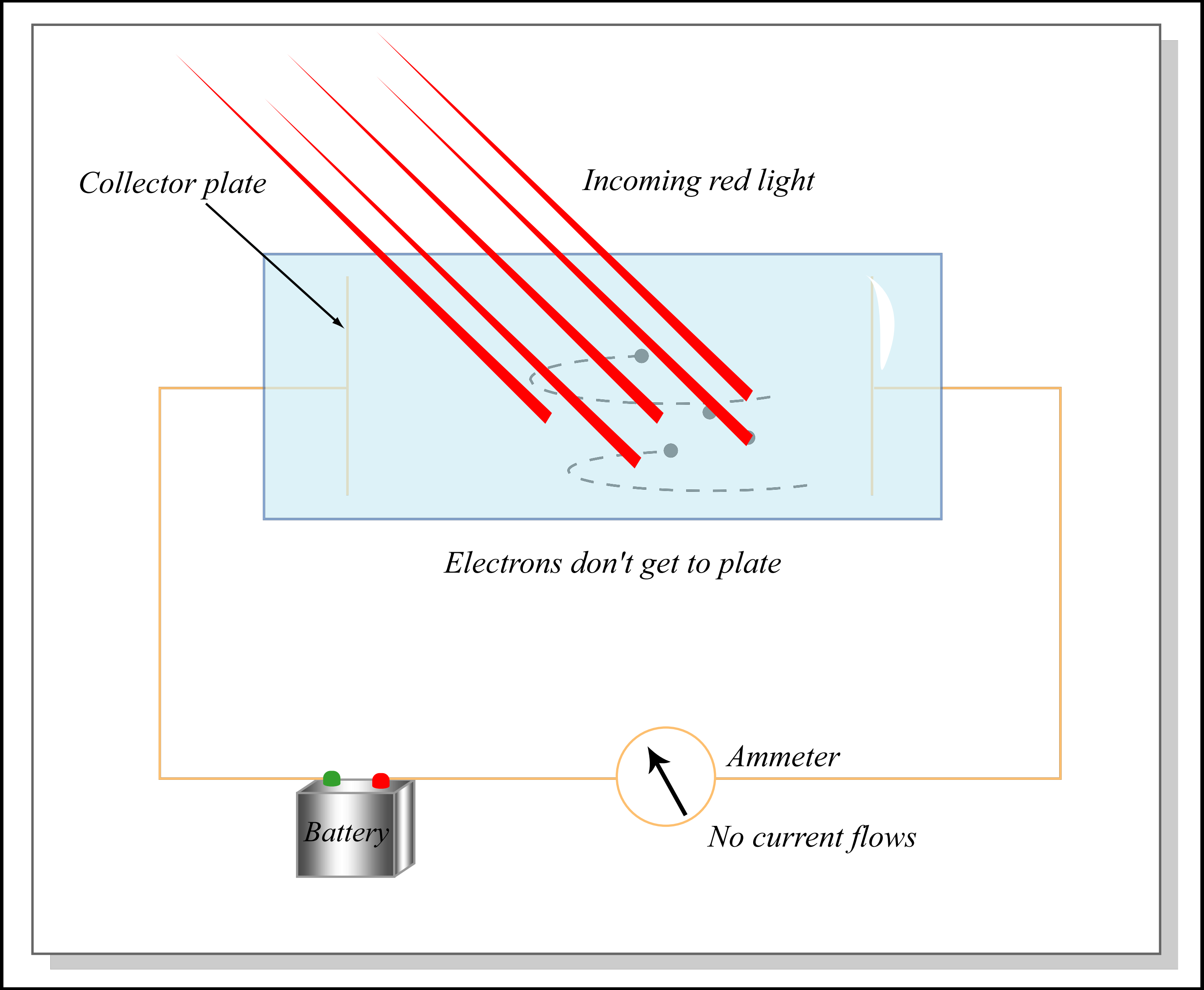


Figure by MIT OCW.

Photoelectric effect

Lenard 1902

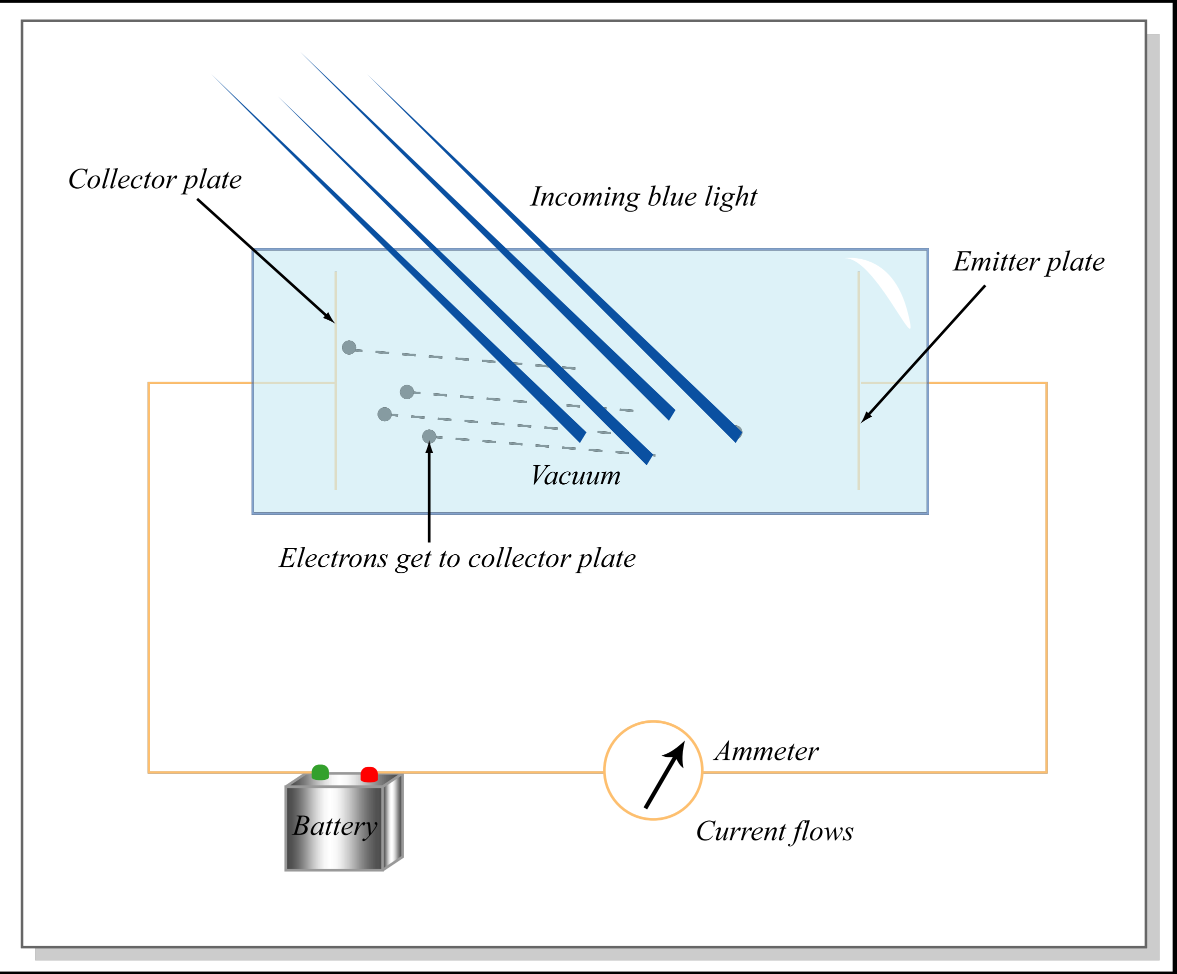
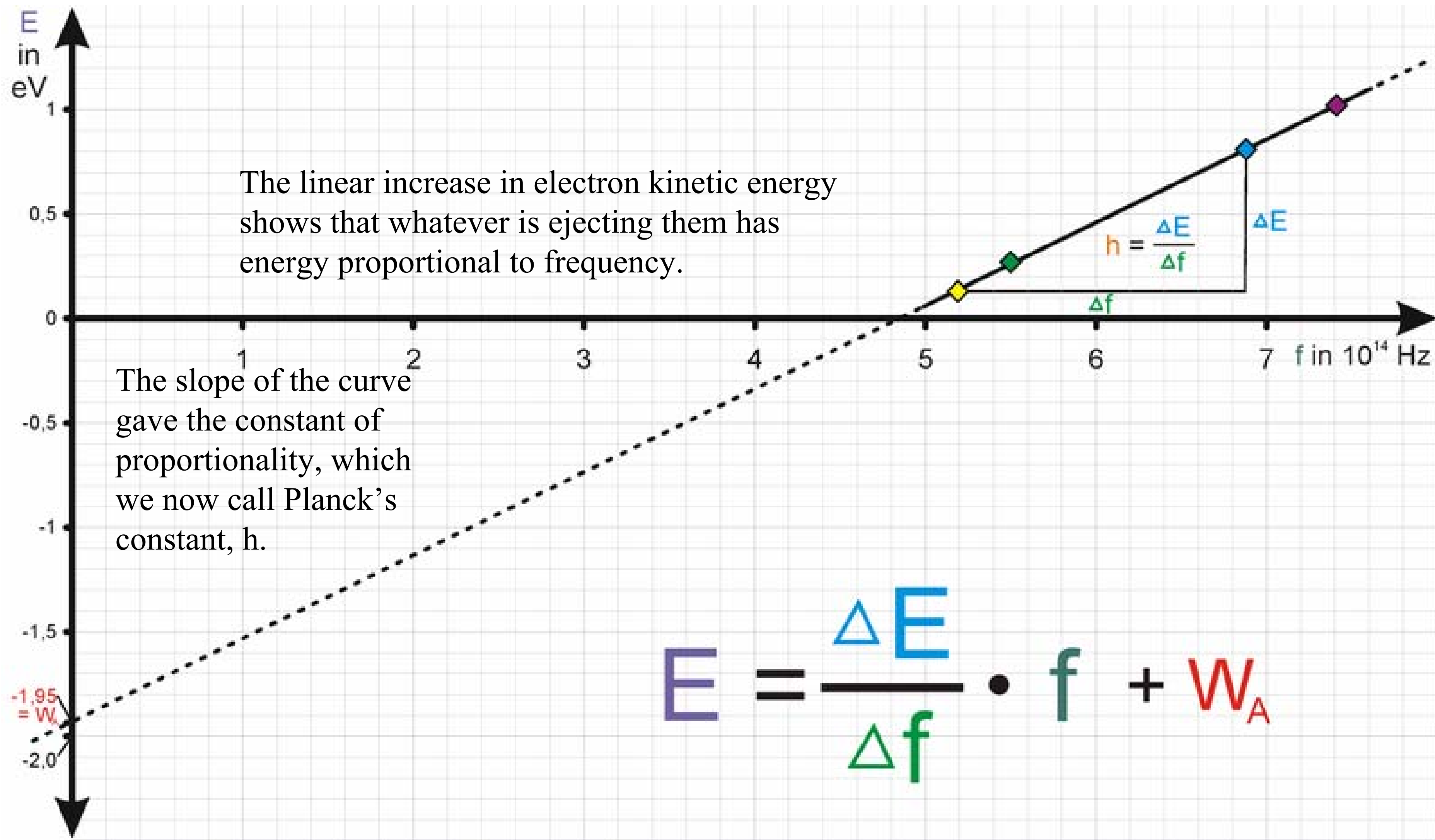


Figure by MIT OCW.

Photoelectric effect

- Einstein's model was that
  - the photon carries energy $h\nu$
  - a certain work W_e is required to liberate an electron from the metal
- This explained both of Lenard's 1902 observations:
  - light with frequency $h\nu < W_e$ liberates no electrons at all
  - light with frequency $h\nu > W_e$ liberates electrons with kinetic energy $h\nu - W_e$.
  - increasing the *intensity* of the light (the photon flux) didn't affect the existence of liberated electrons or their kinetic energy
- Bottom line: we can treat the photon as just another particle.



The linear increase in electron kinetic energy shows that whatever is ejecting them has energy proportional to frequency.

The slope of the curve gave the constant of proportionality, which we now call Planck's constant, h.

Image courtesy of Wikipedia.

(PS6, problem 6)

Working with photons: (PS6, problem 4)

- Photon 4-vector:

$$\mathbf{P} = \hbar \begin{pmatrix} \mathbf{k} \\ k \end{pmatrix},$$

  where $k = \omega/c$.

- So $p = E/c$ for photons.

- Comparing $\mathbf{P}$ with the wave 4-vector $\mathbf{K}$ shows that

$$\mathbf{P} = \hbar\mathbf{K}.$$

  This relation in fact holds for *all* particles, even massive ones — as you'll see when you get to wave-particle duality in quantum mechanics. If you take a field theory course, you'll see this pop right out of the so-called Klein-Gordon equation.

- Doppler effect is just special case of $\mathbf{P}$-transformation for zero rest mass — show on PS6.

Nuclear physics

Nuclear physics terminology

- The *atomic number* Z of a nucleus is its number of protons.
- The *atomic weight* A of a nucleus is its number of nucleons (protons + neutrons).
- Z determines the name of the element (its order in the periodic table).
- Nuclei with same Z and different A are said to be different *isotopes* of the same element.
- Notation example: Fe^{56} means $Z = 26$ (iron) and $A = 56$.
- The *mass excess* for a nucleus is $m_0 - A$ amu, *i.e.*, its rest mass minus the number of nucleons times amu.
- By this definition, the mass excess of C^{12} is zero.

(PS6, problem 1)

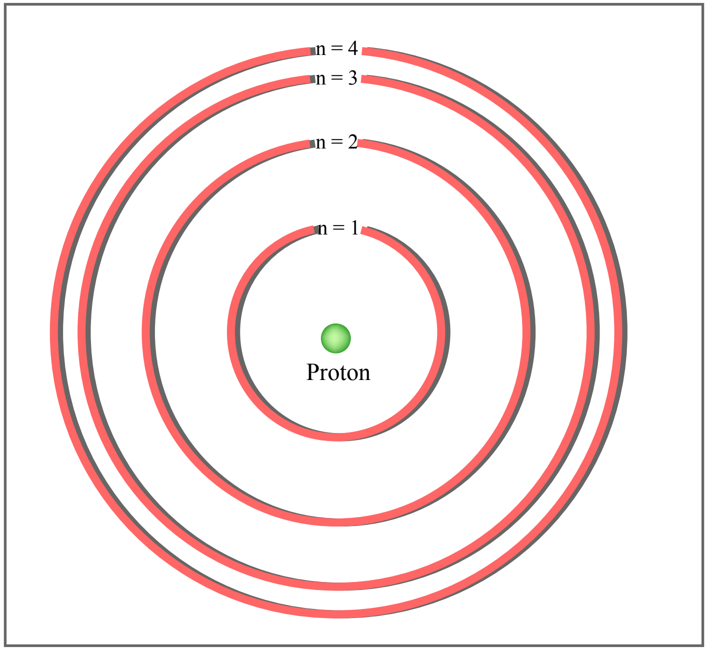


Figure by MIT OCW.

Rest mass and binding energy

- The rest energy of an object is its energy in the frame where it has zero momentum.
- This rest energy is the sum of *all* energy contributions, both positive (like rest masses and kinetic energies of its constituent particles) and negative (like potential energy from force holding constituents together).
- The *binding energy* of a nucleus is rest energy of its neutrons and protons free minus rest energy of the nucleus.

- m_n ≈ 939.6 MeV (udd)
- m_p ≈ 938.3 MeV (uud)
- $m_u \approx 4$ MeV
- $m_d \approx 7$ MeV
- Electromagnetic ≈ 1.7 MeV
- So mostly glue!

- Electric repulsion between protons *increases* mass of nucleus.
- Attraction between nucleons (strong force) *decreases* mass of nucleus.
- Only nuclei whose (Z, A) give positive binding energy can exist
- Semi-empirical relationship (von Weizsäcker 1935):

$$\frac{E_{\text{binding}}}{c^2} \approx \left[15.8A - 18.3A^{2/3} - 0.714\frac{Z^2}{A^{1/3}} - 23.2\frac{(A-2Z)^2}{A} + (-1)^Z\frac{12}{A^{1/2}}\right] \text{MeV}$$

  The last term is omitted if A is an odd number.
- Much work remains to be done in this field!

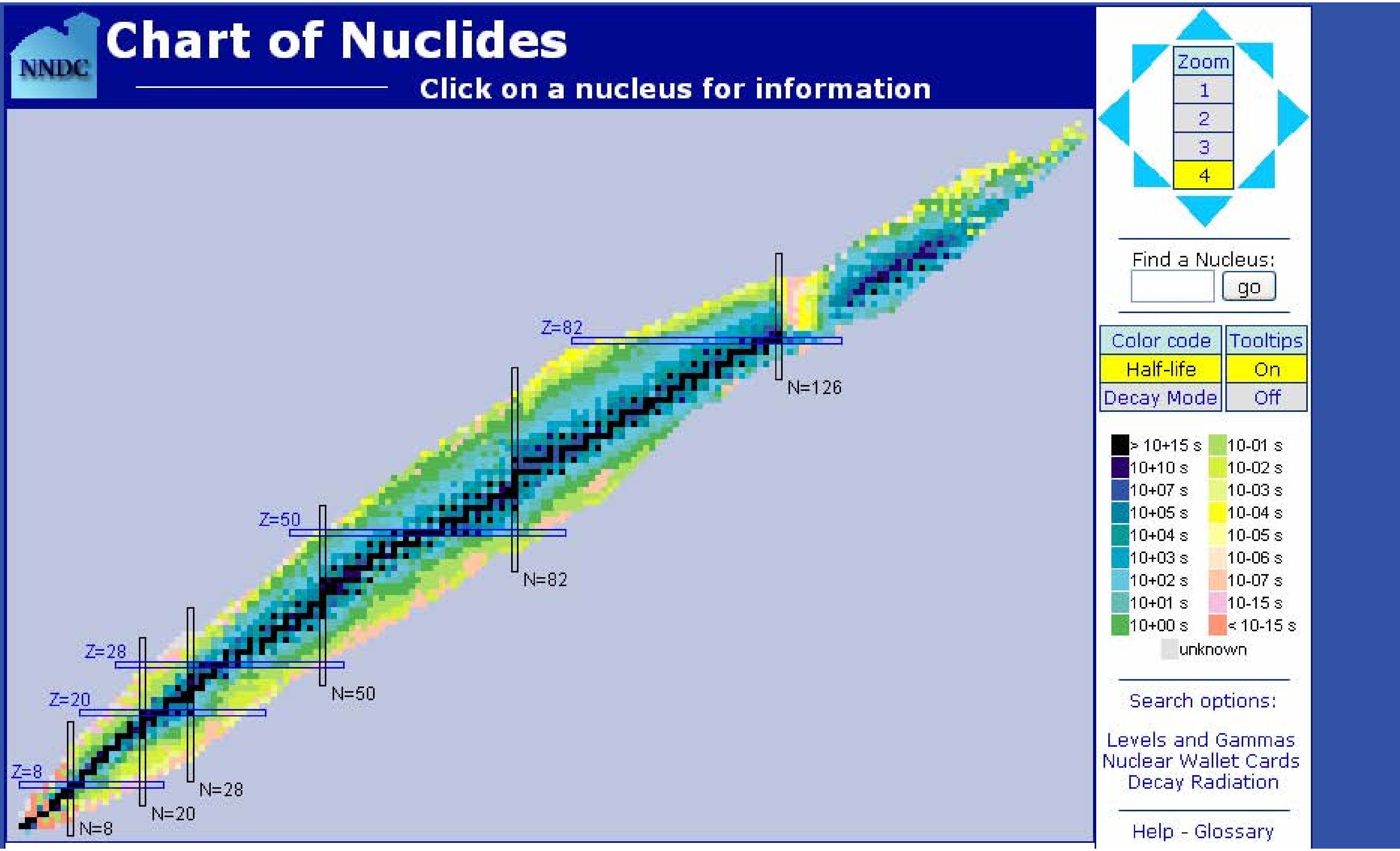


Image courtesy of the National Nuclear Data Center.

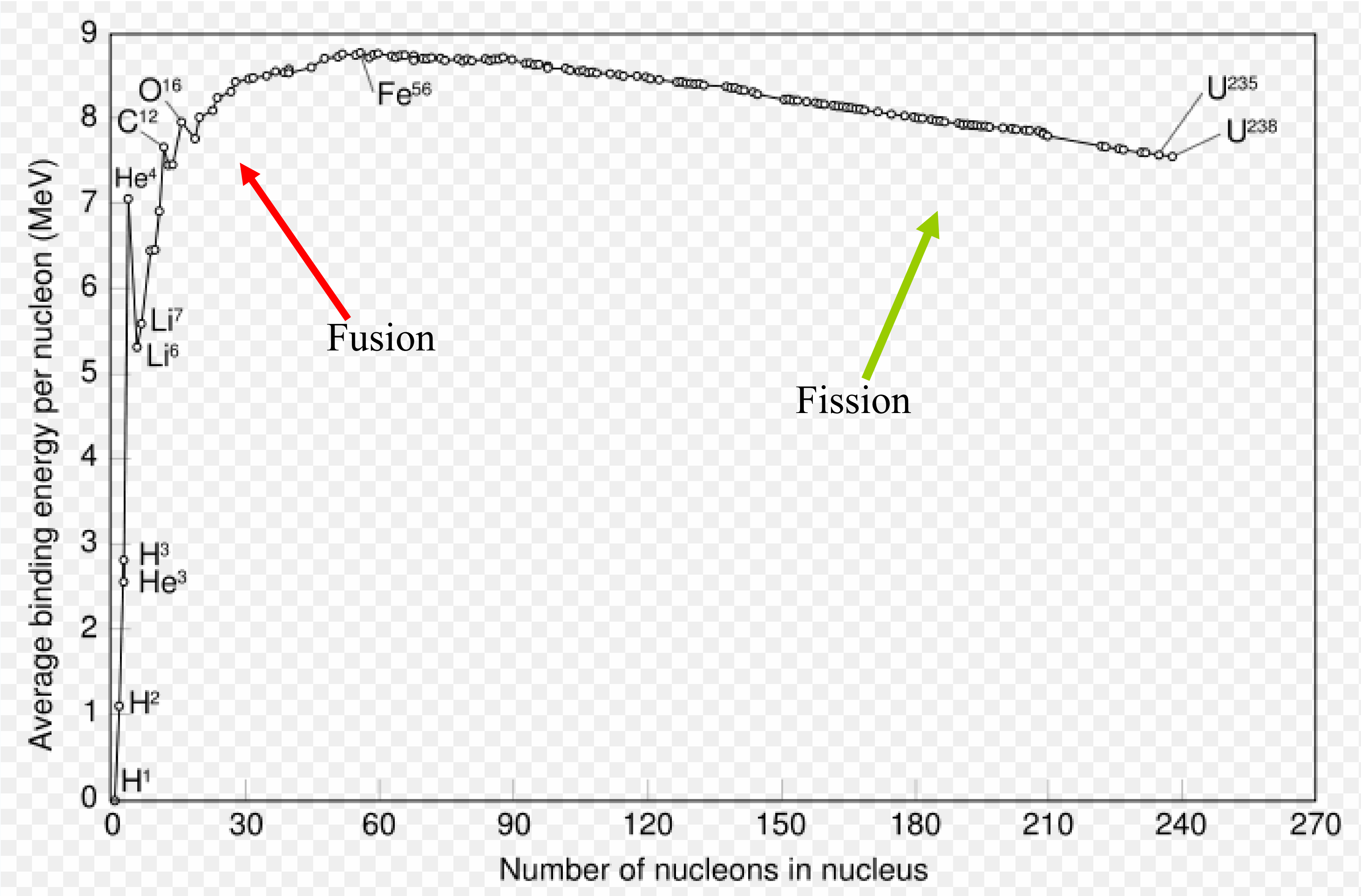


Image courtesy of Wikipedia.

Brought to you by
Tom Lehrer

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
87 Fr	88 Ra	103 Lr	104 Rf	105 Db	106 Sg	107 Bh	108 Hs	109 Mt	110 Uun	111 Uuu	112 Uub						

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