Lecture 4

- Nuclear burning
- Helium production
- Comment on faint Sun paradox
- # of neutrinos
- Center to limb variation

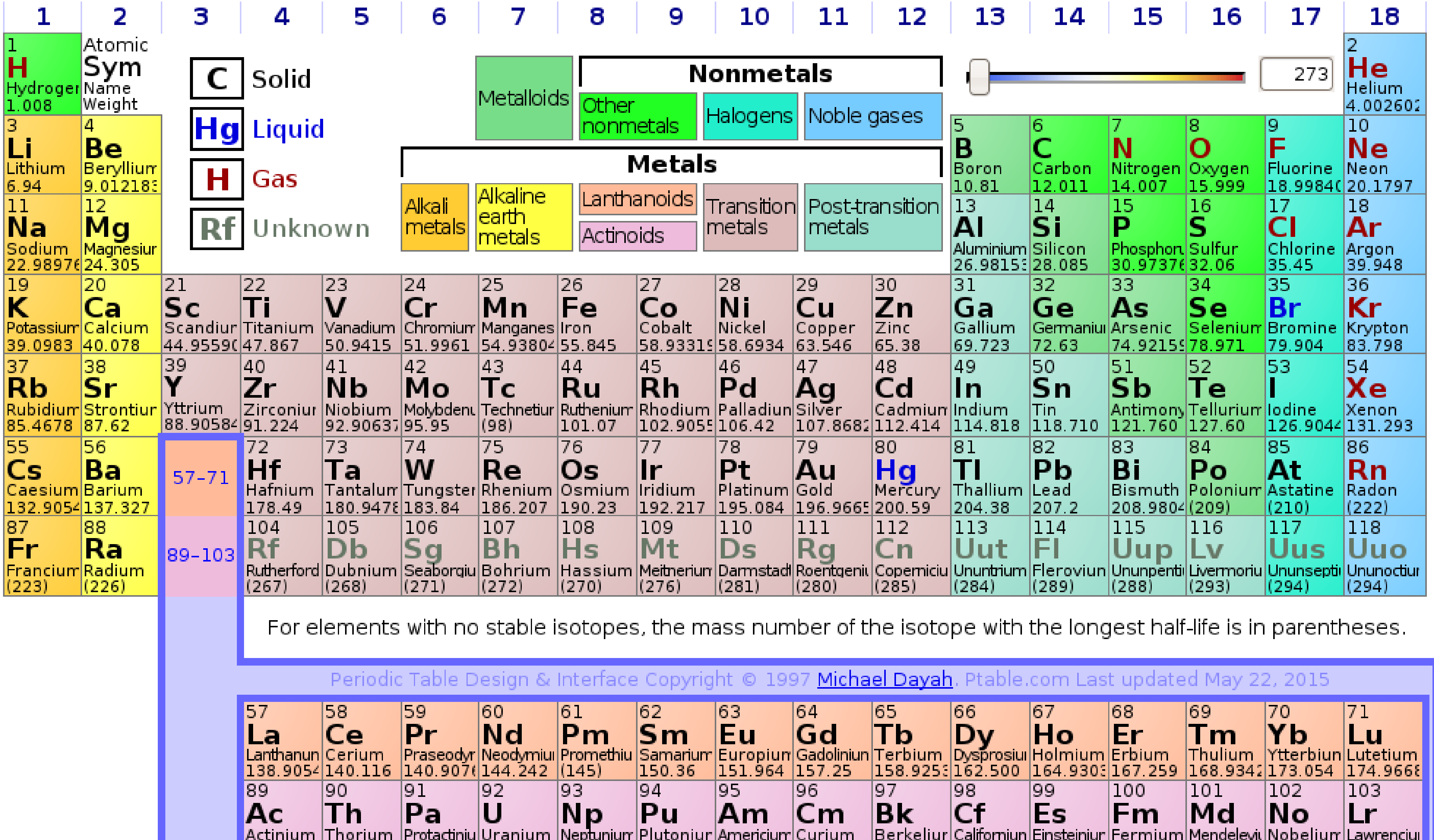
Summary of previous lecture

- About solar interior
  - Tricks to “look” deeper
  - Change of L with Y
  - Faint Sun paradox
- Radiation transport
  - Effective (Rosseland) opacity

Periodic table

1.008*4=4.032
-4.003
=0.029

Mass deficit



	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
1	1 **H** Hydroger 1.008	Atomic **Sym** Name Weight																2 **He** Helium 4.002602
2	3 **Li** Lithium 6.94	4 **Be** Berylliur 9.012183											5 **B** Boron 10.81	6 **C** Carbon 12.011	7 **N** Nitrogen 14.007	8 **O** Oxygen 15.999	9 **F** Fluorine 18.99840	10 **Ne** Neon 20.1797
3	11 **Na** Sodium 22.98976	12 **Mg** Magnesiur 24.305											13 **Al** Aluminium 26.98153	14 **Si** Silicon 28.085	15 **P** Phosphoru 30.97376	16 **S** Sulfur 32.06	17 **Cl** Chlorine 35.45	18 **Ar** Argon 39.948
4	19 **K** Potassiur 39.0983	20 **Ca** Calcium 40.078	21 **Sc** Scandiur 44.9559	22 **Ti** Titanium 47.867	23 **V** Vanadium 50.9415	24 **Cr** Chromiur 51.9961	25 **Mn** Manganes 54.93804	26 **Fe** Iron 55.845	27 **Co** Cobalt 58.93319	28 **Ni** Nickel 58.6934	29 **Cu** Copper 63.546	30 **Zn** Zinc 65.38	31 **Ga** Gallium 69.723	32 **Ge** Germaniu 72.63	33 **As** Arsenic 74.92159	34 **Se** Seleniur 78.971	35 **Br** Bromine 79.904	36 **Kr** Krypton 83.798
5	37 **Rb** Rubidiur 85.4678	38 **Sr** Strontiur 87.62	39 **Y** Yttrium 88.90584	40 **Zr** Zirconiur 91.224	41 **Nb** Niobium 92.90637	42 **Mo** Molybdenu 95.95	43 **Tc** Technetiur (98)	44 **Ru** Rutheniur 101.07	45 **Rh** Rhodium 102.9055	46 **Pd** Palladiun 106.42	47 **Ag** Silver 107.8682	48 **Cd** Cadmiur 112.414	49 **In** Indium 114.818	50 **Sn** Tin 118.710	51 **Sb** Antimony 121.760	52 **Te** Telluriur 127.60	53 **I** Iodine 126.9044	54 **Xe** Xenon 131.293
6	55 **Cs** Caesium 132.9054	56 **Ba** Barium 137.327	57-71	72 **Hf** Hafnium 178.49	73 **Ta** Tantalur 180.9478	74 **W** Tungster 183.84	75 **Re** Rhenium 186.207	76 **Os** Osmium 190.23	77 **Ir** Iridium 192.217	78 **Pt** Platinum 195.084	79 **Au** Gold 196.9665	80 **Hg** Mercury 200.59	81 **Tl** Thallium 204.38	82 **Pb** Lead 207.2	83 **Bi** Bismuth 208.9804	84 **Po** Poloniur (209)	85 **At** Astatine (210)	86 **Rn** Radon (222)
7	87 **Fr** Franciur (223)	88 **Ra** Radium (226)	89-103	104 **Rf** Rutherford (267)	105 **Db** Dubnium (268)	106 **Sg** Seaborgiu (271)	107 **Bh** Bohrium (272)	108 **Hs** Hassium (270)	109 **Mt** Meitneriur (276)	110 **Ds** Darmstadt (281)	111 **Rg** Roentgeniu (280)	112 **Cn** Coperniciu (285)	113 **Uut** Ununtrium (284)	114 **Fl** Fleroviun (289)	115 **Uup** Ununpenti (288)	116 **Lv** Livermoriu (293)	117 **Uus** Ununsepti (294)	118 **Uuo** Ununoctiur (294)

C Solid
Hg Liquid
H Gas
Rf Unknown

Metalloids
Nonmetals: Other nonmetals, Halogens, Noble gases
Metals: Alkali metals, Alkaline earth metals, Lanthanoids, Actinoids, Transition metals, Post-transition metals

273

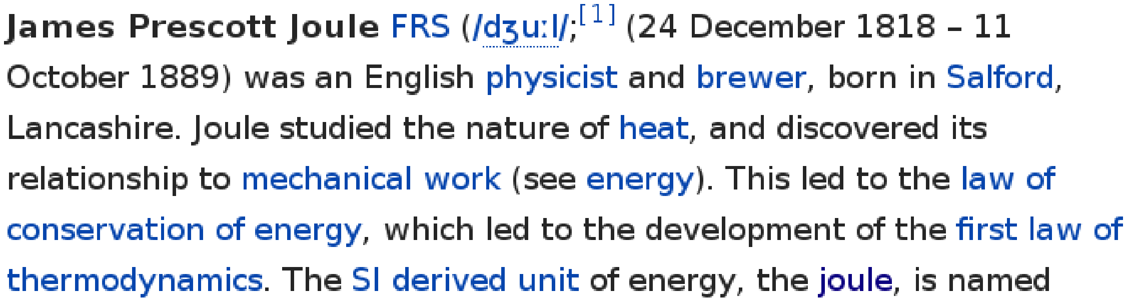
For elements with no stable isotopes, the mass number of the isotope with the longest half-life is in parentheses.

57 **La** Lanthanun 138.9054	58 **Ce** Cerium 140.116	59 **Pr** Praseodyr 140.9076	60 **Nd** Neodymiu 144.242	61 **Pm** Promethiu (145)	62 **Sm** Samariur 150.36	63 **Eu** Europiur 151.964	64 **Gd** Gadoliniun 157.25	65 **Tb** Terbium 158.9253	66 **Dy** Dysprosiu 162.500	67 **Ho** Holmium 164.9303	68 **Er** Erbium 167.259	69 **Tm** Thulium 168.9342	70 **Yb** Ytterbiun 173.054	71 **Lu** Lutetium 174.9668
89 **Ac** Actinium	90 **Th** Thorium	91 **Pa** Protactiniu	92 **U** Uranium	93 **Np** Neptuniur	94 **Pu** Plutoniur	95 **Am** Americiur	96 **Cm** Curium	97 **Bk** Berkeliur	98 **Cf** Californiun	99 **Es** Einsteiniur	100 **Fm** Fermium	101 **Md** Mendelevi	102 **No** Nobeliur	103 **Lr** Lawrenciu

Energy release

Energy release when one ^{4}He atom is produced

$$0.029 \times 1.66 \times 10^{-27}\ \text{kg} * c^2 = 4.33 \times 10^{-12}\ \text{J}$$



James Prescott Joule FRS (/dʒuːl/;[1] (24 December 1818 – 11 October 1889) was an English physicist and brewer, born in Salford, Lancashire. Joule studied the nature of heat, and discovered its relationship to mechanical work (see energy). This led to the law of conservation of energy, which led to the development of the first law of thermodynamics. The SI derived unit of energy, the joule, is named

$$1\ \text{eV} = 1.6 \times 10^{-19}\ \text{J}$$

$$27/4\ \text{MeV/nucleon} = 4 \times 6.8\ \text{MeV/nucleon}$$

Rate of burning

Energy release when one ^{4}He atom is produced

$0.029 \times 1.66 \times 10^{-27}$ kg $* c^2 = 4.33 \times 10^{-12}$ J

Helium production during life time

$t = 5 \times 10^9$ yr $* 3 \times 10^7$ s/yr $= 1.5 \times 10^{17}$ s

$E = Lt = 3.8 \times 10^{26} * 1.5 \times 10^{17}$ J $= 5.8 \times 10^{43}$ J

Number of helium produced during the Sun’s life time

$5.8 \times 10^{43} / 4.3 \times 10^{-12} = 1.3 \times 10^{55}$

$4 * 1.66 \times 10^{-27}$ kg $* 1.3 \times 10^{55} = 0.9 \times 10^{29}$ kg

Fractional increase

$$\Delta Y = 0.044$$

Remember: L dependence on Y

$$\ln L = \ln L_\odot + a(Y_0 - Y_{0\odot}) + b(\alpha - \alpha_\odot)$$

$$\ln r = \ln r_\odot + c(Y_0 - Y_{0\odot}) + d(\alpha - \alpha_\odot)\ ,$$

R and *L* grow (faint sun paradox)

$$a \equiv \frac{\partial \ln L}{\partial Y_0} = 8.6 \qquad b \equiv \frac{\partial \ln L}{\partial \alpha} = 0.04$$

$$c \equiv \frac{\partial \ln r}{\partial Y_0} = 2.1 \qquad d \equiv \frac{\partial \ln r}{\partial \alpha} = -0.13$$

L/L_0=exp(8.6*ΔY)=exp(8.6*0.044)=1.46

Google for “Effective Temperature”

$$T_{\mathrm{eff}}^{\mathrm{Earth}} = T_{\mathrm{eff}}^{\mathrm{Sun}} \left(\frac{R_{\mathrm{Sun}}}{2D} \right)^{1/2} (1 - A)^{1/4} \leq 279\,\mathrm{K}$$

Earth radius does not enter

A. The Earth itself cools

B. The Earth is much cooler than the Sun

C. The Earth can be considered a point mass

Rate of burning

Energy release when one ^{4}He atom is produced

$0.029 \times 1.66 \times 10^{-27}$ kg $* c^2 = 4.33 \times 10^{-12}$ J

1 eV $= 1.6 \times 10^{-19}$ J

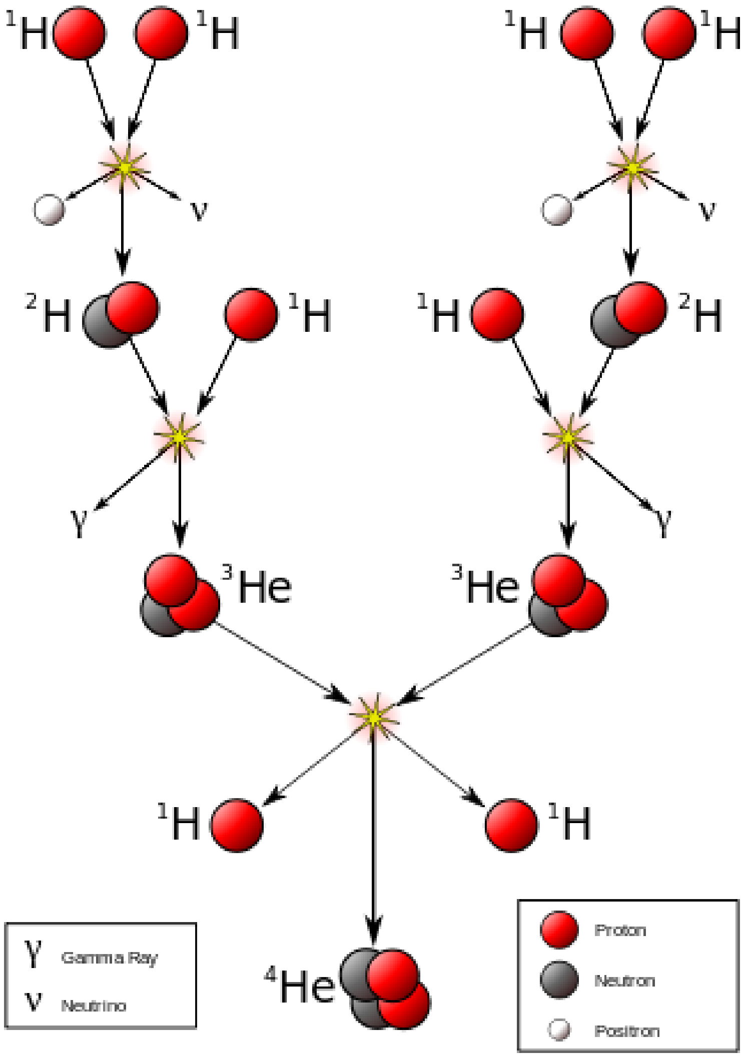
27/4 MeV/nucleon = 4 x 6.8 MeV/nucleon

Compare with accretion power

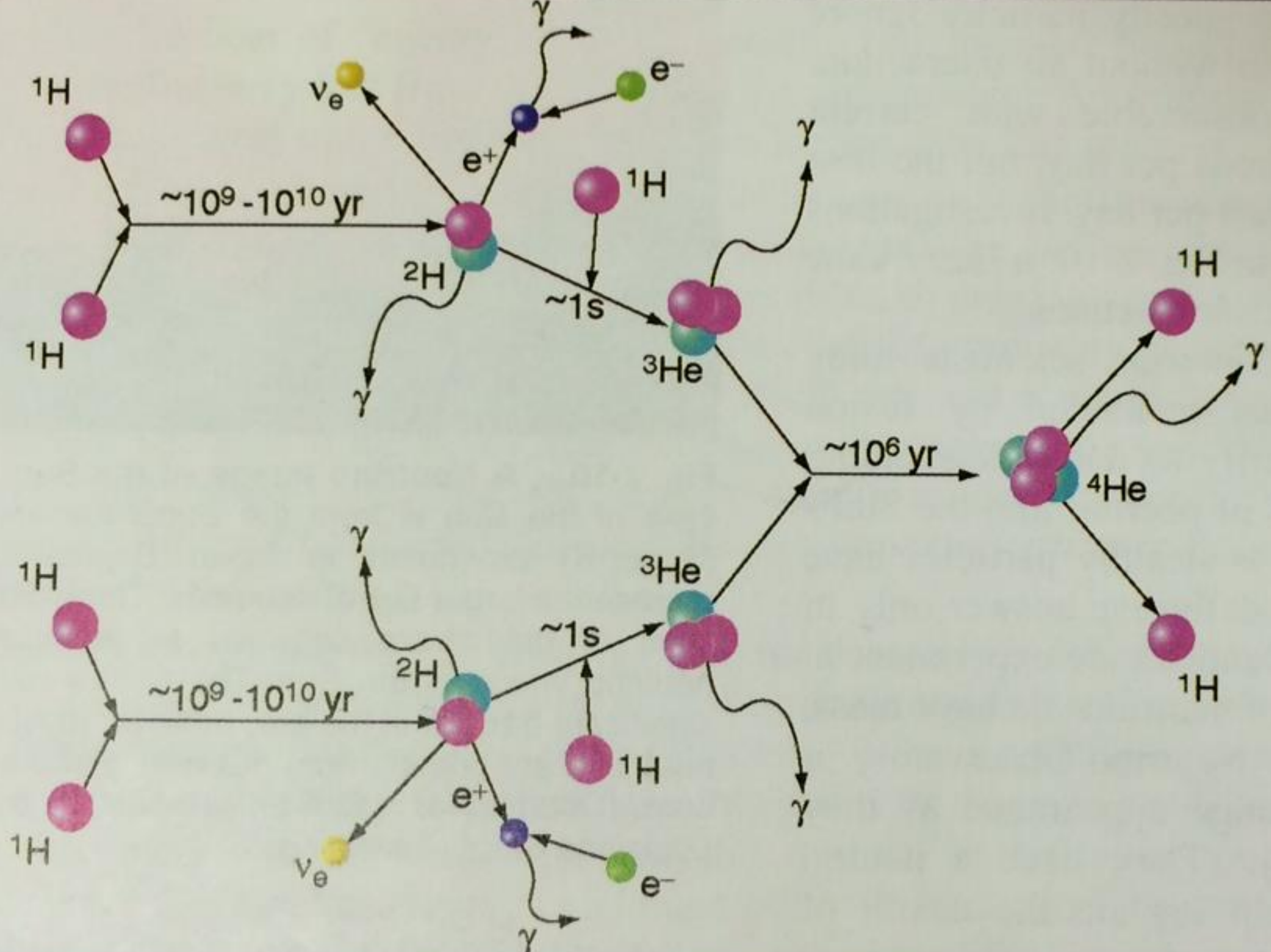
Compute # of neutrinos

$$2e^- + 4p \rightarrow {}^4\text{He} + 2\nu_e + 26.73\ \text{MeV}$$

2 neutrinos per Helium atom



- 1^{st} reaction 10^9-10^{10} yr
- This is the most important reaction among 2 other ones
- There is also the CNO cycle, which also produces 2 neutrinos
- CNO important at hi T
- See Stix Sect. 2.3.5 and Knipp Box 2.2, p.59


γ
e⁻
νe
¹H
e⁺
¹H
~10⁹ -10¹⁰ yr
²H
~1s
γ
¹H
¹H
³He
γ
γ
~10⁶ yr
⁴He
γ
¹H
³He
²H
~1s
~10⁹ -10¹⁰ yr
¹H
¹H
e⁺
¹H
γ
νe
e⁻
¹H
γ

Rate of neutrinos

A. 1 neutrino/cm^2/s
B. 10^5 neutrino/cm^2/s
C. 10^{10} neutrino/cm^2/s
D. 10^{15} neutrino/cm^2/s
E. 10^{20} neutrino/cm^2/s

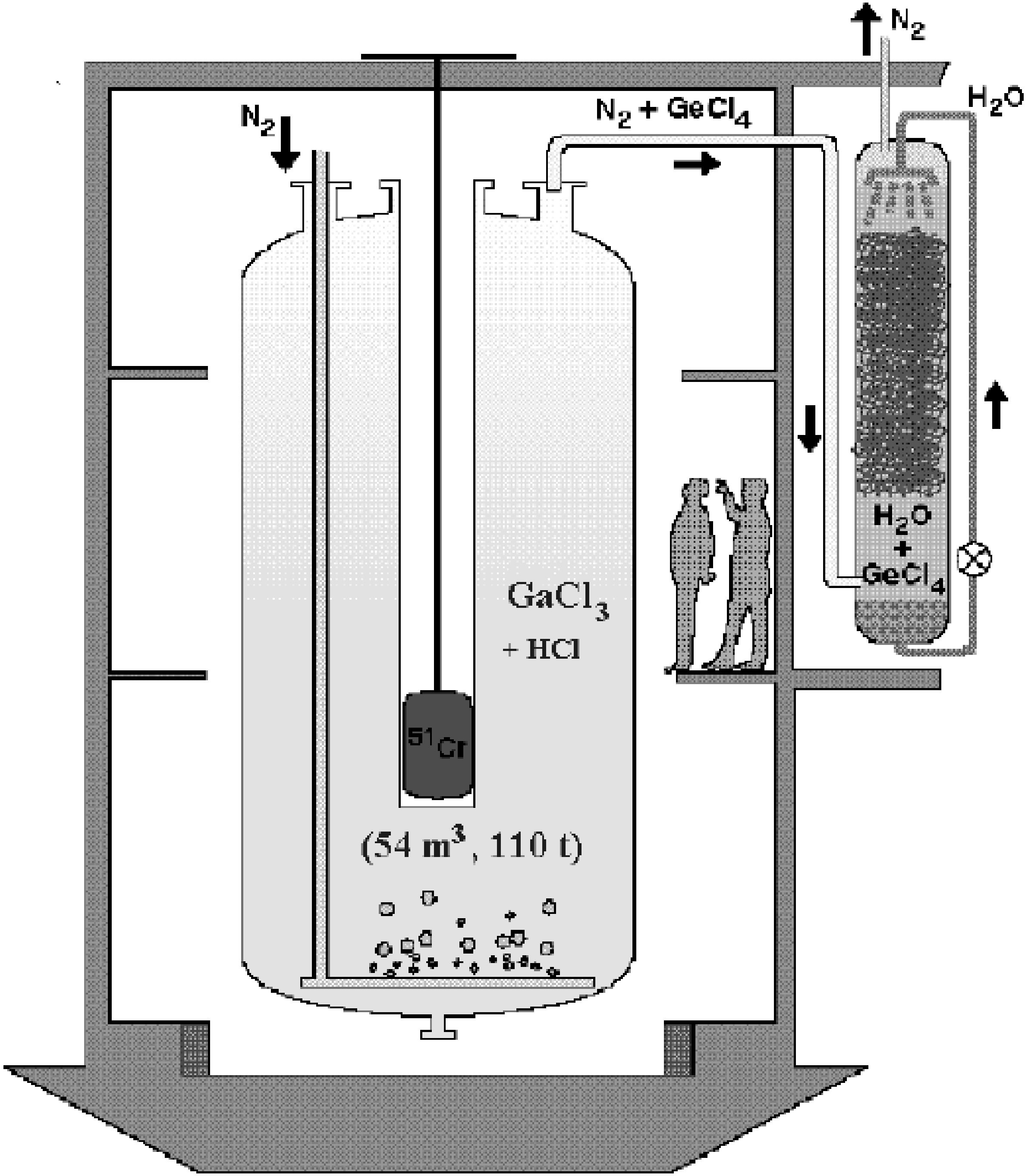


Fig. 3.45. The ^{71}Ga neutrino detector of the GALLEX experiment in the Gran Sasso Underground Laboratory, Italy. The picture shows the ^{51}Cr calibration source in the central shaft. Courtesy MPI für Kernphysik, Heidelberg

Neutrino detection

- ^{37}Cl and ^{71}Ga have large cross-section
  - Homestake mine (S Dakota) and Gran Sasso
- $\nu + {}^{71}\mathrm{Ga} \rightarrow {}^{71}\mathrm{Ge} + e^{-}$
  - Germanium chemically extracted
  - its decay (11.4 half time) was measured with counters
- Super Kamiokande and Ice Cube work with Cherenkov radiation of leptons moving faster than light in water