Cosmology

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Abstract

An introduction to Cosmology, the attempt to describe the large-scale structure and order of the universe and its evolution. [1].

[1] For more see this. Lectures notes worked out at University of Silesia, Katowice, with support from the Foundation for Polish Science (FNP) and the University of Silesia, October 2009

Gravitation rules the Universe

This is an excursion into space–time (Geometry) and matter (Gravity) making up our Universe: what do we know about our Cosmos?, what is its history? what do we know about how it started and what is its future?

Universe: all physical experience accessible from large distances in space as far as empirically verifiable and/or what is able to explain or making plausible observed facts!

"Ill tell you what's behind the observable universe – lots and lots of unobservable universe."

Some peculiarities of Cosmology:
us, we will intercept one quarter as many photons, but the Sun's ANGULAR AREA against the sky background will also have now dropped to a quarter of what it was. So its areal intensity remains constant. With infinitely many stars, every element of the sky background should have a star, and the entire heavens should be at least as bright as an average star like the Sun.

(We say "at least as bright" because the stars of such a bright universe would begin to absorb heat from their neighbors, and precisely what happens when a star is heated is a technical matter for thermodynamic and nuclear theories. We don't expect such stars to cool down, but neither do we expect them to heat up indefinitely. Olbers' Paradox originated before physicists had developed the nuclear theory of how stars shine; thus, it was never concerned with how old the stars might be, and how the details of their energy transactions might affect their brightness.)

The fact that the night sky is not as bright as the Sun is called Olbers' paradox. It can be traced as far back as Kepler in 1610, and was rediscussed by Halley and Cheseaux in the eighteen century; but it was not popularized as a paradox until Olbers took up the issue in the nineteenth century.

There are many possible explanations which have been considered. Here are a few:

1. There's too much dust to see the distant stars.
2. The Universe has only a finite number of stars.
3. The distribution of stars is not uniform. So, for example, there could be an infinity of stars, but they hide behind one another so that only a finite angular area is subtended by them.
4. The Universe is expanding, so distant stars are red-shifted into obscurity.

5. The Universe is young. Distant light hasn't even reached us yet.

The first explanation is just plain wrong. In a black body, the dust will heat up too. It does act like a radiation shield, exponentially damping the distant starlight. But you can't put enough dust into the universe to get rid of enough starlight without also obscuring our own Sun. So this idea is bad.

The premise of the second explanation may technically be correct. But the number of stars, finite as it might be, is still large enough to light up the entire sky, i.e., the total amount of luminous matter in the Universe is too large to allow this escape. The number of stars is close enough to infinite for the purpose of lighting up the sky. The third explanation might be partially correct. We just don't know. If the stars are distributed fractally, then there could be large patches of empty space, and the sky could appear dark except in small areas.

But the final two possibilities are surely each correct and partly responsible. There are numerical arguments that suggest that the effect of the finite age of the Universe is the larger effect.

We live inside a spherical shell of ”Observable Universe” which has radius equal to the lifetime of the Universe. Objects more than about 13.7 thousand million years old (the latest figure) are too far away for their light ever to reach us.

Historically, after Hubble discovered that the Universe was expanding, but before the Big Bang was firmly established by the discovery of the cosmic background radiation, Olbers’ paradox was presented as proof of special relativity. You needed the red shift to get rid of the starlight. This effect certainly contributes, but the finite age of the Universe is the most important effect.

References: Ap. J. 367, 399 (1991). The author, Paul Wesson, is said to be on a personal crusade to end the confusion surrounding Olbers’ paradox.

Darkness at Night: A Riddle of the Universe, Edward Harrison, Harvard University Press, 1987

`Basis of modern Cosmology (theory of the universe) is Einstein's theory of gravity: general relativity (global) which is build on special relativity (local)`

And we will learn more precisely: why is it dark at night? or why is it sometimes so cold outside?

Some History (very sketchy)

We do not talk about the role of astrology/astronomy in ancient cultures like Egypt, Babylon, the Greek and Romans or India and China: but at all times people where fascinated and/or frightened about what is and what's happening out in sky. The periodic motions of sun and moon dictate our living and lead to the invention of the calendar and many other things at very early times of civilization. In Egypt already the role of stars as non–moving "fixed objects" (polar star) was recognized and played a role for the alignment of the pyramids. Much later: the quest of stellar system: How are stars arranged, and are they really fixed?

Existence of objects which are not stars: The first known representation of the Andromeda Nebula [only Hubble almost 1000 years later could proof it to be a Galaxy] (marked with the letter ”A”) by Persian astronomer Abd-al-Rahman Al Sufi in his ”Book of Fixed Stars” of 964 A.D. He called it the ”Little Cloud”.

❑ Natural perception: earth is in the center of the universe, everything rotates around us!

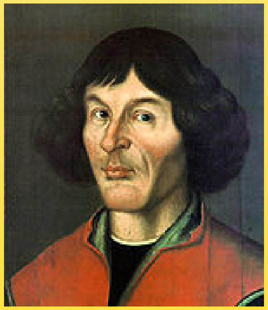
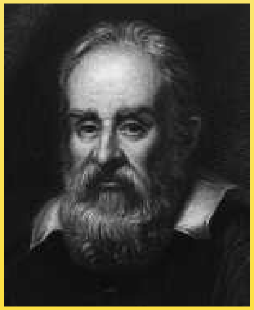
❑ In fact: earth a medium size planet circling around a medium size sun, which is located on the boarder of a medium size galaxy and which flies at a speed of a few 100 km/s heading somewhere in the universe, which contains billions of galaxies (see what Hubble Space Telescope sees: ✲≫).

- Cosmology is supposed to describe and explain the evolution of the universe (not its origin).

Modern Cosmology

Newton,	Copernicus,	Galilei,	Kepler
↓	↓	↓	↓
Gravity 1687	Heliocentric World	Telescope 1609	Planetary Motion

Heliocentric System / Quantitative Physics Laws

Heliocentric System: Aristarchus 280 B.C and others

Halley 1705: predicts comet to reappear 1758! (kind of black magic) Halley's Comet: 1531 (observed by Apianus) and 1607 (observed by Kepler) [first comet to be recognized as periodic (75-76 years)]

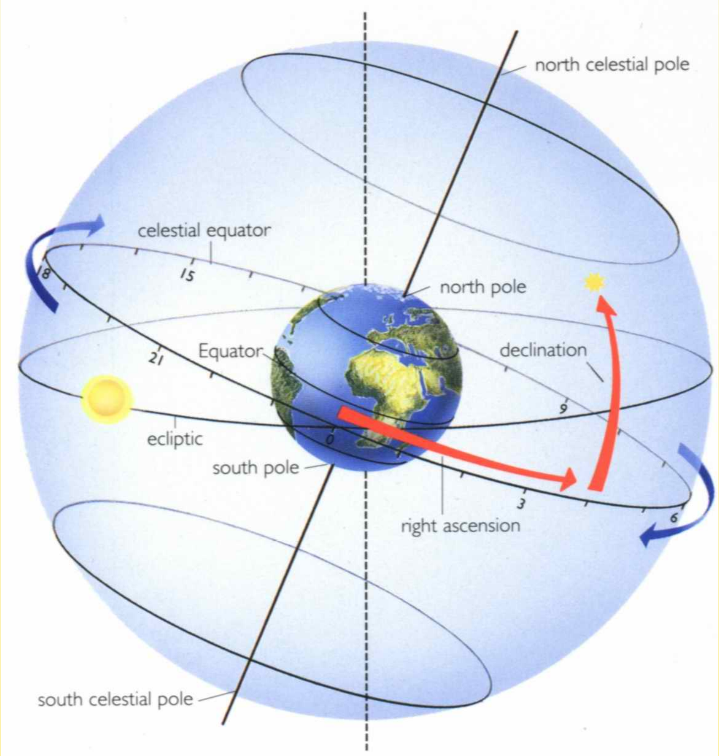
Geo- vs. Helio-centric system: what does it mean? In ancient times it was a matter of religion: we (“the pride of creation”) are sitting in the center? Where else? Today we would say: we just changed the reference frame and reality does not depend on the choice of the reference frame. However: motions of bodies in fact look very different in different frames. Planetary motions in the solar system look simpler and easier to understand in the heliocentric system. However, if you want to describe what happens in a Laboratory experiment likely the geocentric system looks more reasonable (at least if the experiment, at the level of precision attempted, is not affected by effects depending on the motion of the earth around the sun).

Remember Galileo Galilei:

”Und sie bewegt sich doch!” bzw. ”Und sie dreht sich doch!”

(Original lat.: ”Tamensi movetur!”, Original ital.: ”Eppur si muove!”)

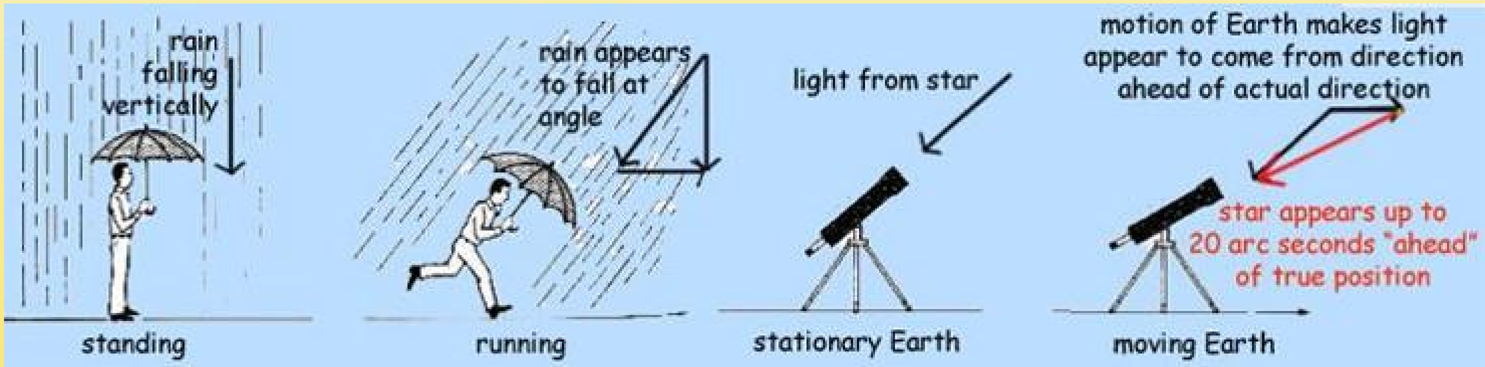
Der Legende nach soll Galilei diesen Satz beim Verlassen des Inquisitionsgerichts gemurmelt haben, nachdem er dem kopernikanischen Weltbild öffentlich abschwören musste. Eventuell könnte Giordano Bruno diesen Satz auf dem Scheiterhaufen gesprochen haben. [from Wikipedia]



Earth celestial coordinate system

By the way: much later Ernst Mach stressed the fact that physical laws take a particularly simple form in a frame which is attached to the "fixed star sky" [inertial frame] (Einstein's special relativity); Geometry attached to matter? Mach's principle. Einstein's general relativity: Duality between Matter and Geometry (Curvature).

Bradley 1725: aberration of star-light (by motion of earth), proves earth moves around the sun



Crucial point: finite speed of light (light needs time to reach us)!
Ole Rømer 1676, Fizeau 1849 ✲⋙. The maximum amount of the aberrational displacement of a star is approximately 20 arc seconds in right ascension or declination.

Stars are suns! Universe is “gas of suns”.

Cosmological Principle: (old)

The universe is homogeneous and isotropic in a 3–dimensional space, and was like that at all times and forever

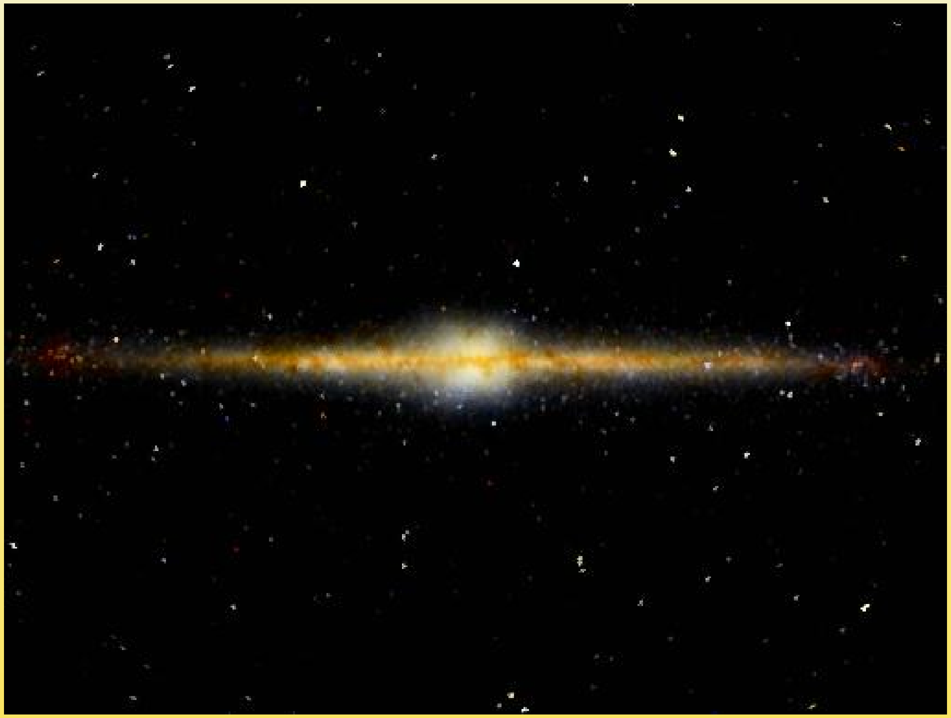
This is the homogeneous isotropic and static universe!

Note: Einstein had to change his general relativity theory by adding a cosmological constant to make such static universe consistent with mathematics. (the ”biggest blunder” in his life he later said)

Cosmology Events:

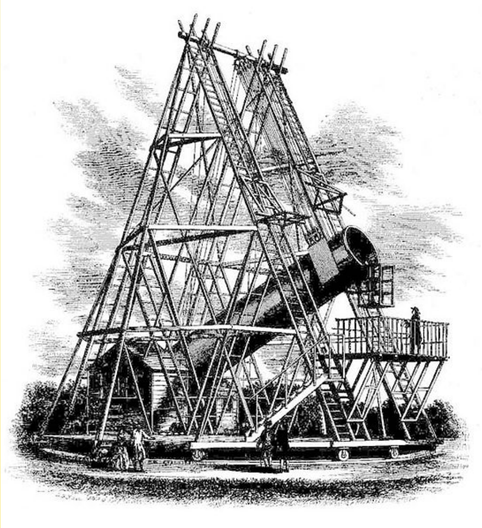
1750 Wight Milky-Way is a rotating disk of stars

The Milky Way is our own galaxy viewed from the inside. It is a vast collection of more than 200 billion stars, planets, nebulae, clusters, dust and gas. Our own sun and solar system are also part of the Milky Way galaxy.



Milky Way as seen by the COBE satellite in the infrared (IR).

1783	Mitchell existence of Black Holes
1785	Herschel "disk–shaped stars" nebulae (→ Galaxies)

⋮

$\boxed{1925}$ Hubble Andromeda nebulae is a Galaxy like the Milky-Way

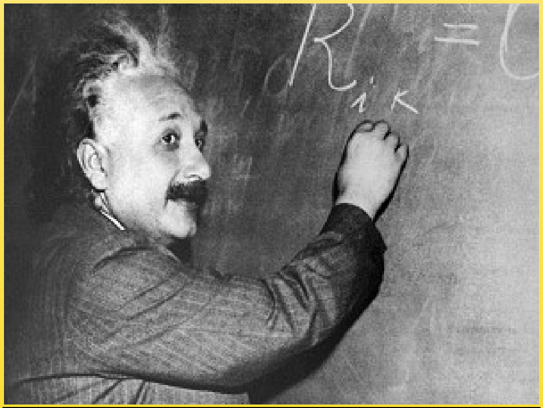
Events concerning Gravitation:

$\boxed{1687}$ Newton Newton's mechanics

1883 Mach Critics of Newton’s mechanics, Mach’s Principle

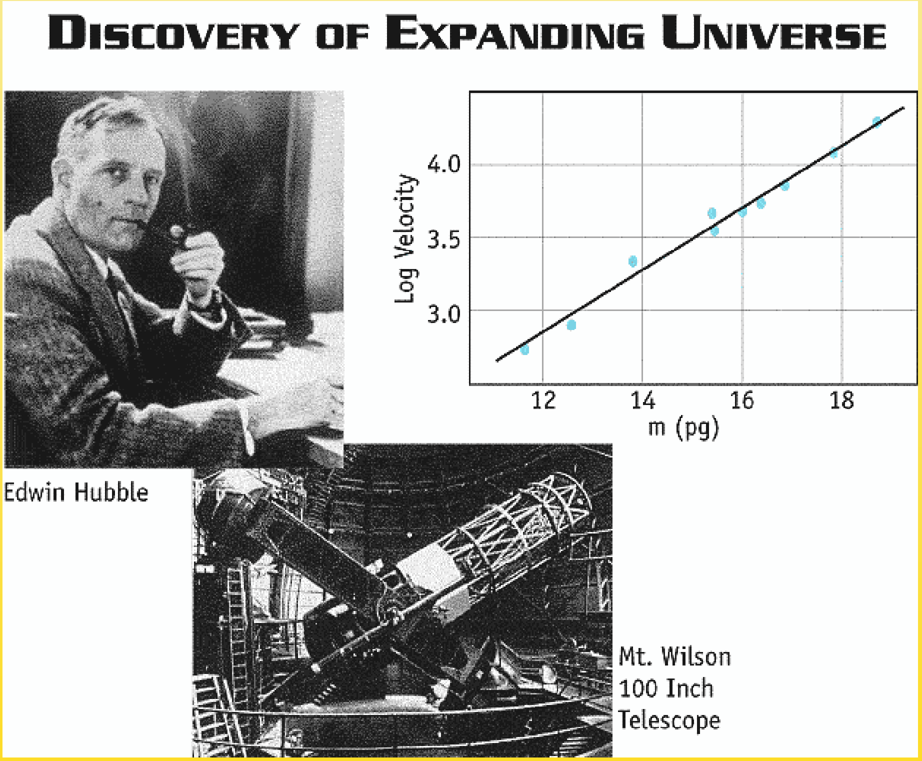
Fixed stars in the sky define a natural inertial frame!
How can matter (physics) know about frames (geometry)?
Mach: gravity and inertia both must have the same absolute reference frame, that of the ”fixed stars”

1916 Einstein Theory of Gravitation=General Relativity



Geometry ⇔ Matter

1917	Einstein Static Universe ⇔ GRT + cosmological constant
1922	Friedmann GRT = Evolution Cosmology
1929	Hubble Universal Expansion



Hubble constant H_0; $\boxed{v = H_0\, D}$

Hubble's Age of the Universe: $T_0 = D/v = H_0^{-1}$

The Age of the Universe

The age of the universe as a consequence of the cosmic evolution will be discussed later in several steps. Before the discovery of the universal expansion one actually could have neatly derived that the universe cannot have been since ever. This is possible with the help of

$\boxed{\text{Cosmochronology}}$

which is based on the existence of natural radioactivity of radioactive nuclei.

- Radioactive nuclei undergo radioactivity i.e. radioactive decay. They are unstable and thus have a finite lifetime.
- Stars exhibiting radioactive material cannot be arbitrarily old.
- This is a direct contradiction to an eternal static universe.

It is interesting to estimate the radioactive age of planets, stars and galaxies and to compare them with the Hubble-Age, the time elapsed since the expansion was ignited (at Big-Bang)

More later. Actually, for a long time 1929 to 1958 the Hubble age was lower than the age of the sun! Distance measurements were normalized wrongly.

The Earth in space

Study here what is our place in the universe and what surrounds us ✲⋙

Nuclear Physics

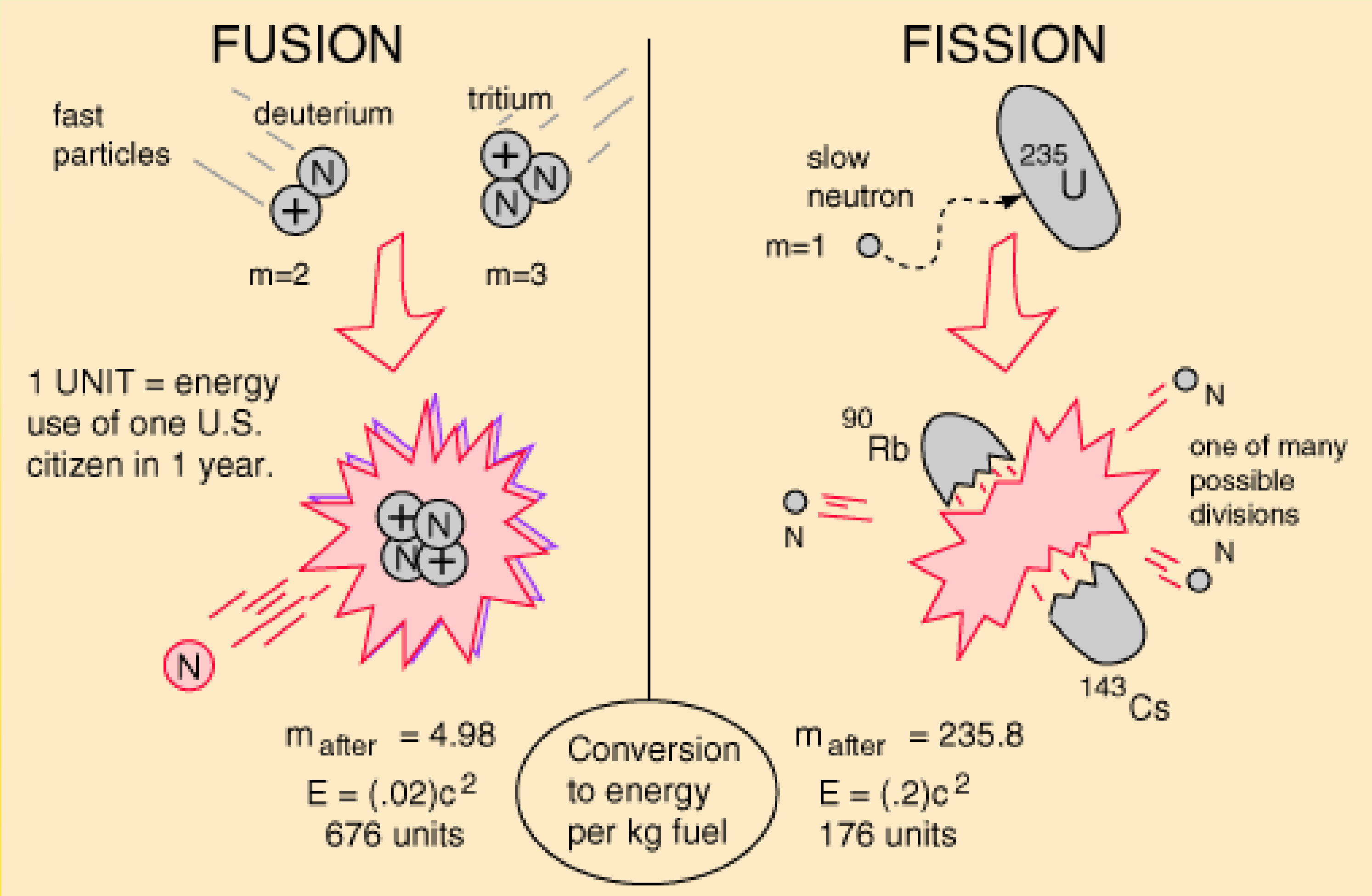
Nuclear Structure, the Weizsäcker Formula and all that: ✲⋙ Nuclear Binding Energy ✲⋙

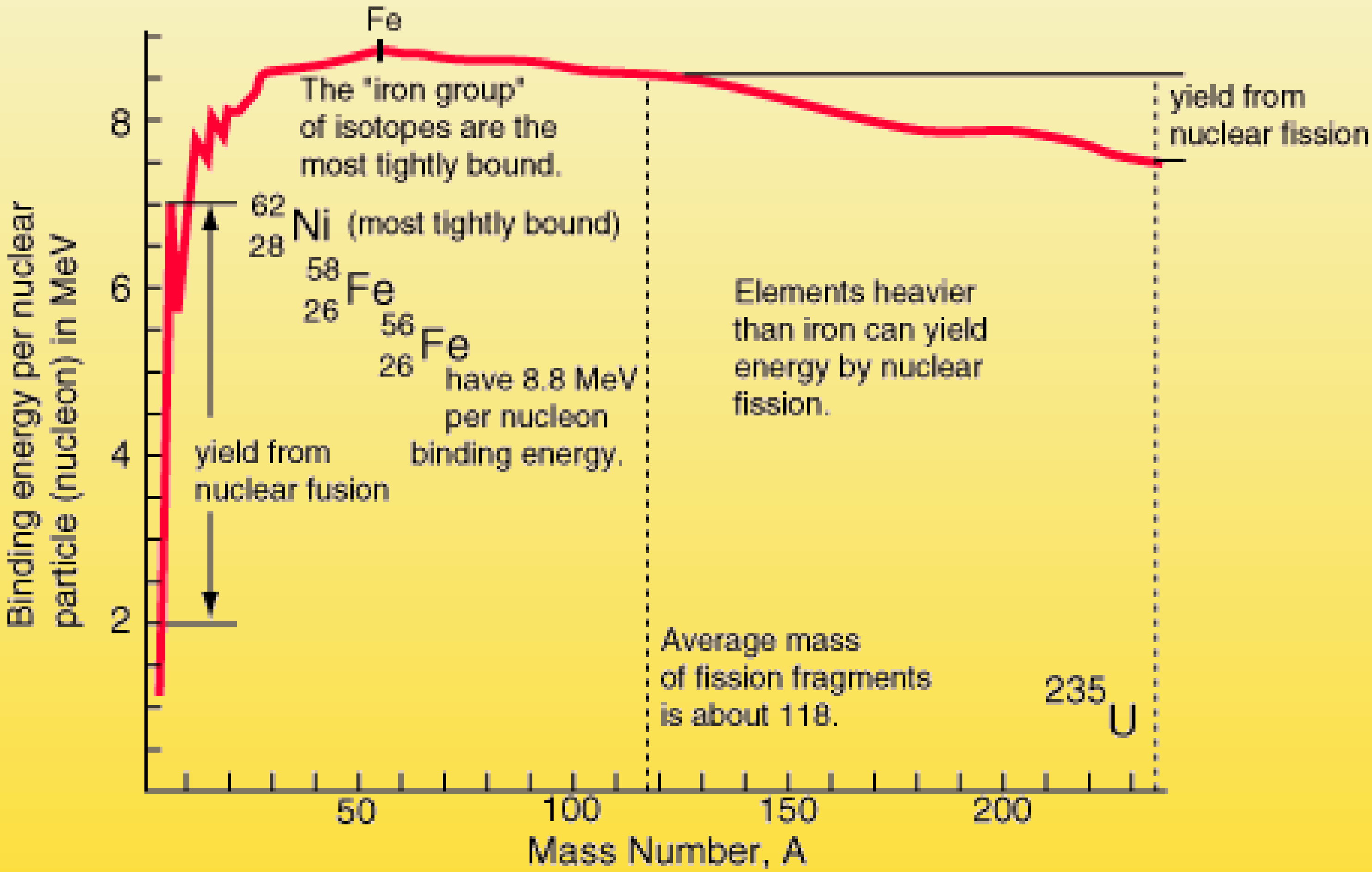
Atomic nucleus built from Z protons, N neutrons, atomic mass number $A = Z + N$ [denoted by ${}_Z X^A$, X chemical symbol of the element] has mass $M_{(Z,A)}$.

Binding energy is

$$B_{(Z,A)} = \left(M_{(Z,A)} - Z\, m_p - N\, m_n \right) c^2$$ Einstein 1905

the binding energy per nucleon is $B_{(Z,A)}/A$ and is largest for iron ${}_{26}Fe^{56}$. Heavier elements are obtained from lighter by fusion, lighter elements are obtained from heavier by fission.


FUSION
fast particles
deuterium
tritium
m=2
m=3
1 UNIT = energy use of one U.S. citizen in 1 year.
N
m after = 4.98
E = (.02)c 2
676 units
Conversion to energy per kg fuel
FISSION
slow neutron
m=1
235 U
90 Rb
N
one of many possible divisions
143 Cs
m after = 235.8
E = (.2)c 2
176 units


Fe
8
6
4
2
Binding energy per nuclear particle (nucleon) in MeV
The "iron group" of isotopes are the most tightly bound.
62
28
Ni (most tightly bound)
58
26
Fe
56
26
Fe
have 8.8 MeV per nucleon binding energy.
yield from nuclear fusion
Elements heavier than iron can yield energy by nuclear fission.
yield from nuclear fission
Average mass of fission fragments is about 118.
235
U
50
100
150
200
Mass Number, A

Link: topics: Radioactivity: ⋙ Nuclear Decay ⋙

Radioactivity (weak, strong or electromagnetic interaction process; α-,β-,γ-rays) is an intrinsic property of a specific species of nuclei characterized by a decay constant λ_i which only depends on the specific nucleus i, not on the number of nuclei. Given a sample of $N_{i\,0}$ nuclei (at time $t=0$), the number of decaying nuclei ΔN_i is proportional to the number of nuclei $N_i(t)$ at time t and the infinitesimal time interval Δt:

$$\Delta N_i = -\lambda\, N_i(t)\, \Delta t$$

which implies the exponential decay law

$$N_i(t) = N_{i\,0}\, \mathrm{e}^{-\lambda_i\, t}$$

Variants for given type i: $N = N_0\, 2^{-\frac{t}{T_{1/2}}} = N_0\, \mathrm{e}^{-\frac{\ln 2\, t}{T_{1/2}}} = N_0\, \mathrm{e}^{-\lambda\, t} = N_0\, \mathrm{e}^{-\frac{t}{\tau}}$

$T_{1/2}$ half-life; τ average lifetime [$\ln 2 \simeq 0.693 \cdots$] ➠ $\boxed{T_{1/2} = \frac{\ln 2}{\lambda} = \ln 2\, \tau}$

Note λ_i only depends on inner properties of a given nucleus (isotope), not on any external physical (temperature etc.) or chemical (density etc.) condition. ➠ Radioactive decay can be used as a clock .

Radioactive Dating, Age of the Earth

Radioactive Dating: ✲⋙

Earth, moon, meteorites: in rocks atoms of different type have crystallized at some time t_0. In general at the time of rock formation a rock sample exhibiting $N_P(t_0)$ parent atoms (decay constant λ_P) also contains some amount of the daughter atoms $N_D(t_0)$ (decay constant λ_D) into which the parent atoms decay. In decay the number of nuclei remains unchanged

$$N_P(t_1) + N_D(t_1) = N_P(t_0) + N_D(t_0)$$

with

$$N_i(t_1) = N_i(t_0)\,\mathrm{e}^{-\lambda_i\,(t_1-t_0)}\ ;\quad i = P, D$$

In general the initial ratio $N_D(t_0)/N_P(t_0)$ is unknown and we can not determine the time t_0 from the observed values of $N_P(t_1)$ and $N_D(t_1)$ at present time t_1. So additional information is needed in order to have a well posed problem.

In fact, usually there are other stable elements X around in the sample and one can look at ratios

$$\frac{N_P(t_1)+N_D(t_1)}{N_X(t_1)} = \frac{N_P(t_0)+N_D(t_0)}{N_X(t_0)}$$

which, assuming $N_X(t_1) = N_X(t_0)$ can be written as

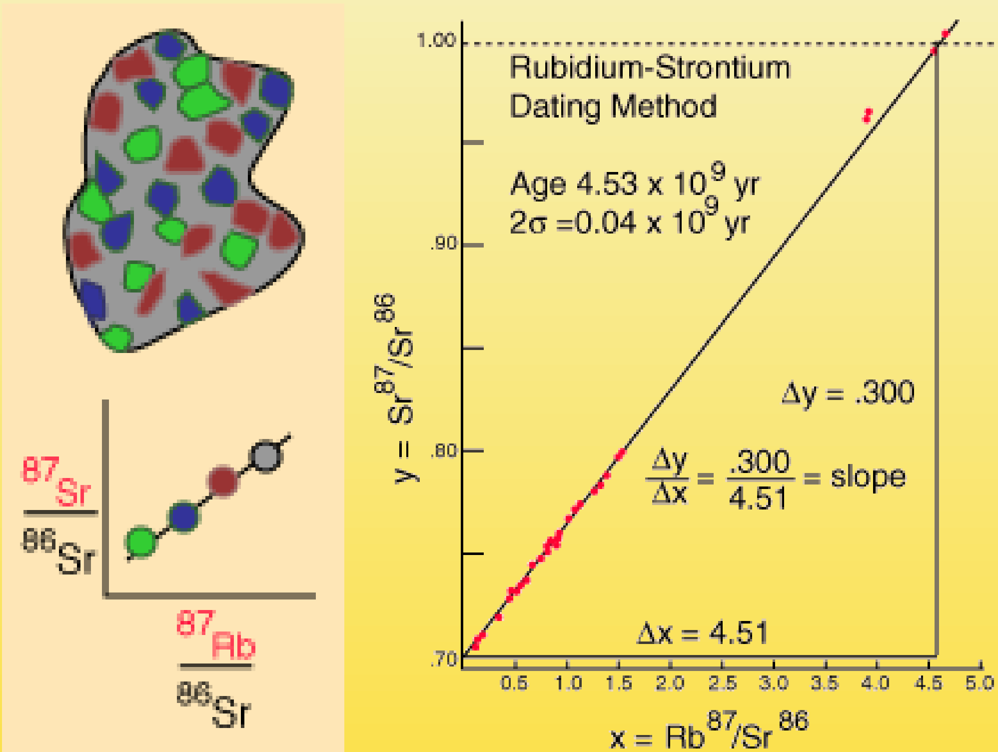
$$\frac{N_D(t_1)}{N_X(t_1)} = \frac{N_P(t_1)}{N_X(t_1)} \left[\mathrm{e}^{-\lambda_P (t_1 - t_0)} - 1 \right] + \frac{N_D(t_0)}{N_X(t_0)}$$

If the last ratio would be known, from the two ratios measured today (at t_1) we could determine the age $\Delta t = t_1 - t_0$. In general we do not know $N_D(t_0)/N_X(t_0)$, however.

The trick of radioactive dating works with the presumption

> all the minerals which crystallize together should show identical ages and identical isotopic ratios
> N_D/N_X

and plot $y = N_D(t_1)/N_X(t_1)$ against $x = N_P(t_1)/N_X(t_1)$ for different minerals in a crystalline sample. This yields plots like this:



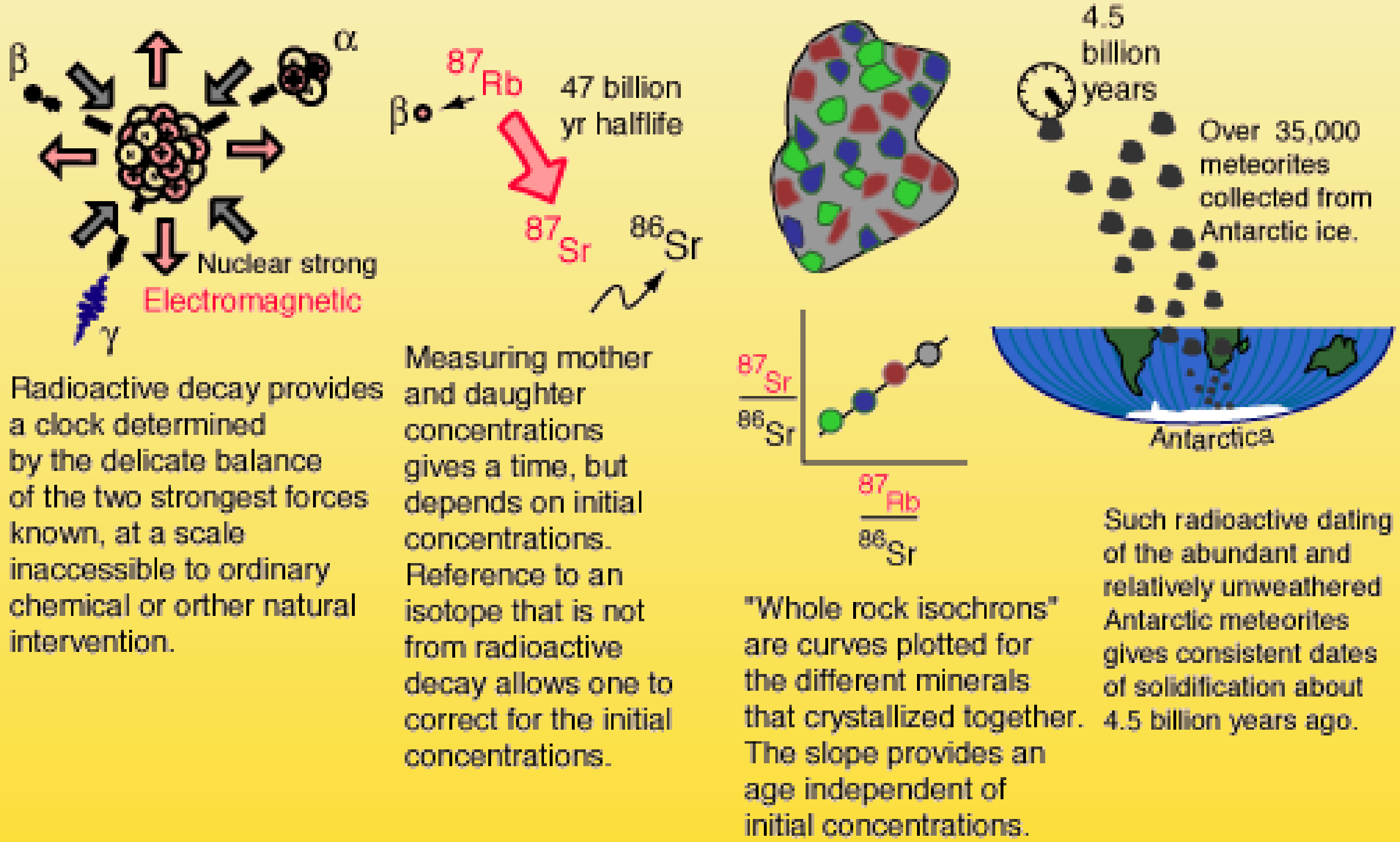
$$\Delta t = \frac{1}{\lambda} \ln \left[1 + \frac{\Delta y}{\Delta x} \right] = \text{ age}$$

$$T_{1/2} = 48.8\,\text{Gyr} \; ; \quad \frac{1}{\lambda} = \frac{T_{1/2}}{\ln 2}$$

$$\Rightarrow \Delta t = 4.53\,\text{Gyr}$$

This is the age of the earth! (used 1 Gyr = 10^9 yrs)

Summary of radioactive dating on earth:



Stars: consider the oldest stars iron series (metal) in star clusters (globular clusters). Material released in supernova explosion. What we find on earth for instance. Since the physics of such stars is quite well understood, one may estimate the isotopic ratio of Uranium isotopes at release time, which is found to be $K = {}^{235}\mathrm{U}/{}^{238}\mathrm{U} \sim 1.3 \pm 10\%$. On earth one finds $K_0 = 0.00723$[2].
What is the age of the Galaxy ?
Decay constants are: $\lambda^{238} = \ln 2/(4.46\ \mathrm{Gyr})\ , \quad \lambda^{235} = \ln 2/(0.7038\ \mathrm{Gyr})$

Radioactive decay law: $K = K_0\, \mathrm{e}^{(\lambda_{238}-\lambda_{235})\, t_\mathrm{G}}$ ➠ $t_\mathrm{G} \simeq 6.2$ Gyr

Note the age of the sun is $t_\odot \simeq 4.57$ Gyr $\sim$ age of the earth.

Radioactive dating is a science by itself. How reliable are assumptions to be made? Details more complicated, in general. Radioactive decay chains. Instability of decay products etc. Influense of volcanic activity ($\rightarrow$ zirkon samples). Lots of data and experience allow for reliable checks.

[2] In nature, uranium is found as uranium-238 (99.2742%) and uranium-235 (0.7204%). Uranium decays slowly by emitting an α-particle.

Played an important role in the development of modern cosmology (wrongly determined Hubble age).

Next ⊳⋙ lecture.

Exercise 2: background information on passage of radiation through matter.
Simple geometrical model for beam of particles/radiation hitting/passing a target.
Target particle density n, projectile versus target particle cross section σ; mean free path is

$$\ell = \frac{1}{\sigma\, n}$$

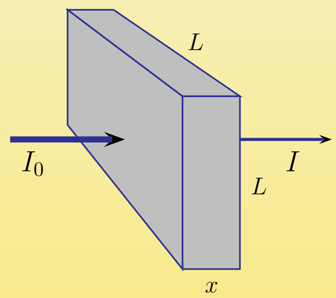
Recktangular target area $A = L^2$, thickness $\mathrm{d}x$; volume $\mathrm{d}V = L^2\,\mathrm{d}x$; particle number $\mathrm{d}N = n\,\mathrm{d}V$.

$$P(\text{ in d}x) = \frac{\text{Area of Atoms}}{\text{Area of Slab}} = \frac{\sigma\, n\, L^2\,\mathrm{d}x}{L^2} = n\,\sigma\,\mathrm{d}x$$

Geometrical interpretation of cross section: σ = Area of Atom $\equiv$ cross section
Particle beam of intensity I hitting target: drop in beam intensity:

$$\mathrm{d}I = -I\, n\,\sigma\,\mathrm{d}x \quad \text{or} \quad \frac{\mathrm{d}I}{\mathrm{d}x} = -I\, n\,\sigma \doteq -\frac{I}{\ell}$$

which is the Beer-Lambert law:



The solution is

$$I = I_0 \, \mathrm{e}^{-x/\ell}$$

Meaning of ℓ: mean free path, because it is the mean distance traveled by the beam particle before it get stopped. The probability that a particle is absorbed between x and $x + \mathrm{d}x$ is

$$\mathrm{d}P(x) = \frac{I(x) - I(x + \mathrm{d}x)}{I_0} = \frac{1}{\ell} \, \mathrm{e}^{-x/\ell} \, \mathrm{d}x \; ,$$

and thus

$$\langle x \rangle = \int_0^\infty x\,\mathrm{d}P(x) = \int_0^\infty \frac{x}{\ell}\,\mathrm{e}^{-x\ell}\,\mathrm{d}x = \ell$$

the fraction of particles that were not stopped (non-attenuated) by the absorber is called transmission

$$T \doteq \frac{I}{I_0} = \mathrm{e}^{-x/\ell} \quad \text{where} \quad x = \mathrm{d}x \;\; \text{thickness of the slab}$$

In statistical systems (kinetik theory) mean free path is $\ell = (n\sigma)^{-1}$ for large relative velocities between beam and target particles. In contrast, in a Maxwell gas $\ell = (\sqrt{2}n\sigma)^{-1}$ with $\ell = \frac{k_\mathrm{B}T}{\sqrt{2}\pi d^2 p}$, where p the pressure, T the temperature, d the diameter of a gas atom.