Beta decay

Coupling between nucleons and weak field

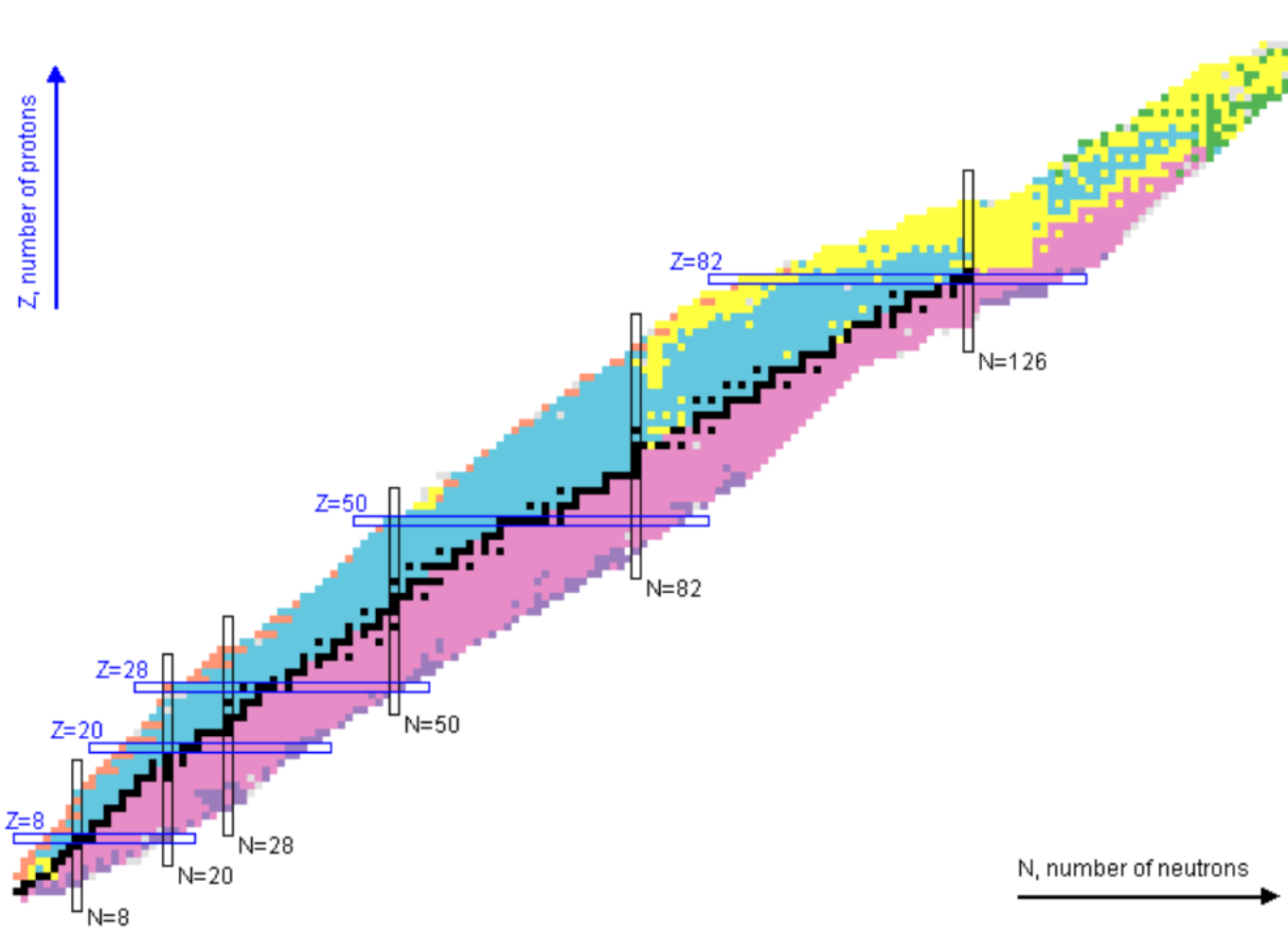
One of the puzzles in understanding beta-decay was the emission of particles (electron, positron, neutrino) that are not present in the atomic nucleus.

- 1899 Rutherford discovers beta radiation
- 1900 Becquerel suggests that beta particle is an electron
- 1901 Rutherford and Soddy discover that beta radioactivity involves transmutation
- 1911 Meitner and Hahn show that beta spectrum is continuous
- 1930 Pauli postulates neutrino
- 1931 Fermi names the new particle neutrino
- 1933 quantum theory of radiation developed
- 1934 Fermi theory of beta decay (based on relativistic formalism). The original Fermi's idea was that the weak force responsible for beta decay had essentially zero range.
- 1934 Wick develops theory of electron capture
- 1937 Electron capture observed by Alvarez
- 1956 Neutrino detected by Cowan and Reines
- 1957 Fall of parity conservation. Fermi theory revisited.
- 1961 Glashow, introduces neutral intermediate boson of weak interactions
- 1962 Three types on neutrino (Lederman, Schwartz and Steinberger)
- 1974 Pati-Salam GUT model
- 1984 GUT. Georgi and Glashow
- 1983 W and Z bosons discovered at CERN

Chart of Nuclides

Click on a nucleus for information

Color code	Half-life	Decay Mode	$Q_{\beta-}$	Q_{EC}	$Q_{\beta+}$	S_n	S_p	Q_α	S_{2n}	S_{2p}	$Q_{2\beta-}$	Q_{2EC}	Q_{ECp}
$Q_{\beta-n}$	BE/A	(BE-LDM Fit)/A	$E_{1st\ ex.\ st.}$	E_{2+}	E_{3-}	E_{4+}	E_{4+}/E_{2+}	β_2	$B(E2)_{42}/B(E2)_{20}$	σ(n,γ)	σ(n,F)	235U FY	239Pu FY



Tooltips
On
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Zoom	Uncertainty
1	NDS
2	Standard
3	Screen Size
4	
5	Narrow
6	
7	Wide

Nucleus

go

- Stable
- EC+β+
- β-
- α
- P
- N
- SF
- Unknown

Search options:

Levels and Gammas
Nuclear Wallet Cards
Decay Radiation

Help - Glossary

Dear radioactive ladies and gentlemen,

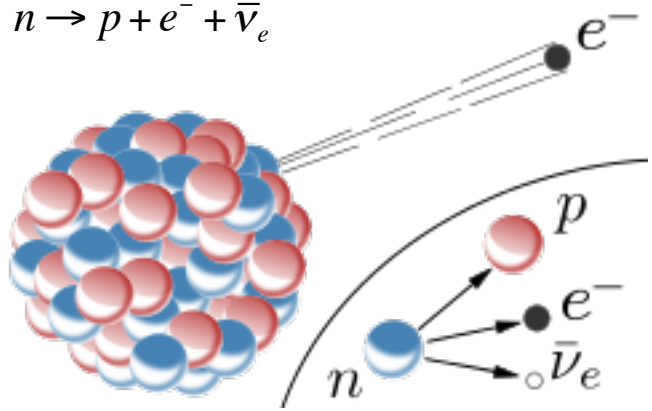
As the bearer of these lines [...] will explain more exactly, considering the 'false' statistics of N-14 and Li-6 nuclei, as well as the continuous β-spectrum, I have hit upon a desperate remedy to save the "exchange theorem" of statistics and the energy theorem. Namely [there is] the possibility that there could exist in the nuclei electrically neutral particles that I wish to call neutrons, which have spin 1/2 and obey the exclusion principle, and additionally differ from light quanta in that they do not travel with the velocity of light: The mass of the neutron must be of the same order of magnitude as the electron mass and, in any case, not larger than 0.01 proton mass. The continuous β-spectrum would then become understandable by the assumption that in β decay a neutron is emitted together with the electron, in such a way that the sum of the energies of neutron and electron is constant. […]
But I don't feel secure enough to publish anything about this idea, so I first turn confidently to you, dear radioactives, with a question as to the situation concerning experimental proof of such a neutron, if it has something like about 10 times the penetrating capacity of a γ ray.

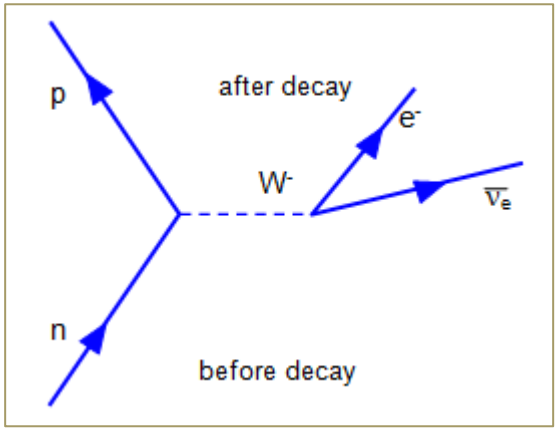
I admit that my remedy may appear to have a small a priori probability because neutrons, if they exist, would probably have long ago been seen. However, only those who wager can win, and the seriousness of the situation of the continuous β-spectrum can be made clear by the saying of my honored predecessor in office, Mr. Debye, [...] "One does best not to think about that at all, like the new taxes." [...] Therefore one should seriously discuss every way of rescue. Thus, dear radioactive people, scrutinize and judge. - Unfortunately, I cannot personally appear in Tübingen since I am indispensable here in Zürich because of a ball on the night from December 6 to 7.

With many greetings to you, also to Mr. Back, your devoted servant,

W. Pauli

$$n \rightarrow p + e^- + \bar{\nu}_e$$





The bilinear combinations ("currents") of the fermion fields are Lorentz *four-vectors*, similarly to the electromagnetic current (coupled to vector four-potential) familiar from QED:

$$\mathcal{L}_{\text{int}}^{(Fermi)} = -G\left(\bar{\psi}_p \gamma^\mu \psi_n\right)\left(\bar{\psi}_e \gamma^\mu \psi_\upsilon\right) + h.c.$$

Four-fermion Lagrangian

an annihilation operator for particle
or
a creation operator for antiparticle

Why is it called antineutrino?

Nuclear beta decay is one of the many facets of weak interaction. The basic reactions involving weak interactions in nuclei may be characterized by the decay of a neutron and a (bound) proton:

$$n \rightarrow p + e^- + \bar{\nu}_e$$

$$p_{bound} \rightarrow n + e^+ + \nu_e$$

A free proton cannot beta decay since a free neutron is more massive (939.566 MeV) than a free proton (938.272 MeV).

There are many other examples of weak decays:

a) semi-leptonic processes (both hadrons and leptons are involved)

$$\pi^+ \rightarrow \begin{matrix} \mu^+ + \nu_\mu \\ e^+ + \nu_e \end{matrix} \qquad \pi^- \rightarrow \begin{matrix} \mu^- + \bar{\nu}_\mu \\ e^- + \bar{\nu}_e \end{matrix}$$

b) purely-leptonic processes

$$\mu^- \rightarrow e^- + \bar{\nu}_e + \nu_\mu$$

The coupling constant (Fermi coupling constant): $G_F = 1.16639(2) \times 10^{-11} (\hbar c)^3 \mathrm{MeV}^{-2}$

Force carriers:

$$m_W c^2 = 80.36 \pm 0.12\,\mathrm{GeV}$$
$$m_Z c^2 = 91.187 \pm 0.07\,\mathrm{GeV}$$

interaction range is very short ~10^{-3} fm
(weak interactions can be considered as zero-range in nuclear physics!)

Beta decay: energy relations

atomic mass $$Mc^2 = M^{'}c^2 + Zm_e c^2 - \sum_{i=1}^{Z} B_{ei}$$

nuclear mass

electron binding energy

P(arent) D(aughter)

a) β⁻ decay

$$^{A}_{Z}X_N \rightarrow {}^{A}_{Z+1}X_{N-1} + e^- + \bar{\nu}_e$$

Nuclear recoil is very small

$$Q_{\beta^-} = T_{e^-} + T_{\bar{\nu}_e} = M^{'}_P c^2 - M^{'}_D c^2 - m_e c^2$$

In the following, we assume that the neutrino mass is ~zero and that the very small differences in electron binding energy between the parent and daughter atoms can be neglected. This gives:

$$Q_{\beta^-} = M_P c^2 - M_D c^2$$

Consequently, the β^- decay process is possible whenever $M_P > M_D$

b) β⁺ decay

$$^{A}_{Z}X_N \rightarrow {}^{A}_{Z-1}X_{N+1} + e^+ + \nu_e$$

$$Q_{\beta^+} = T_{e^+} + T_{\nu_e} = M^{'}_P c^2 - M^{'}_D c^2 - m_e c^2$$

$$= M_P c^2 - \left(M_D c^2 + 2m_e c^2\right)$$

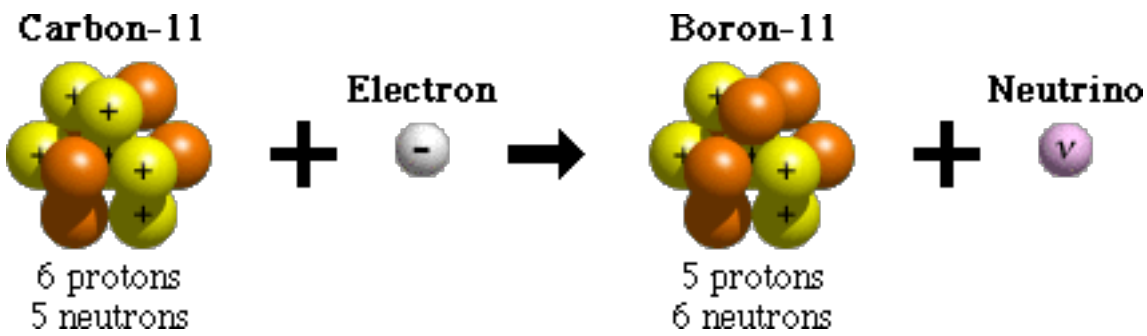
Consequently, the β^+ decay process has a *threshold* $2m_e c^2$

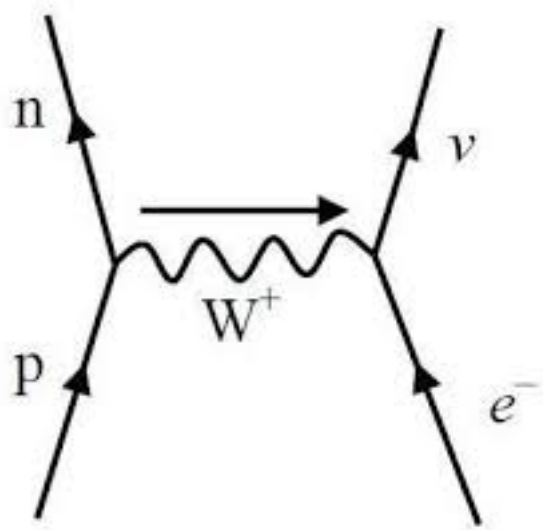
c) Electron capture (inverse beta decay)

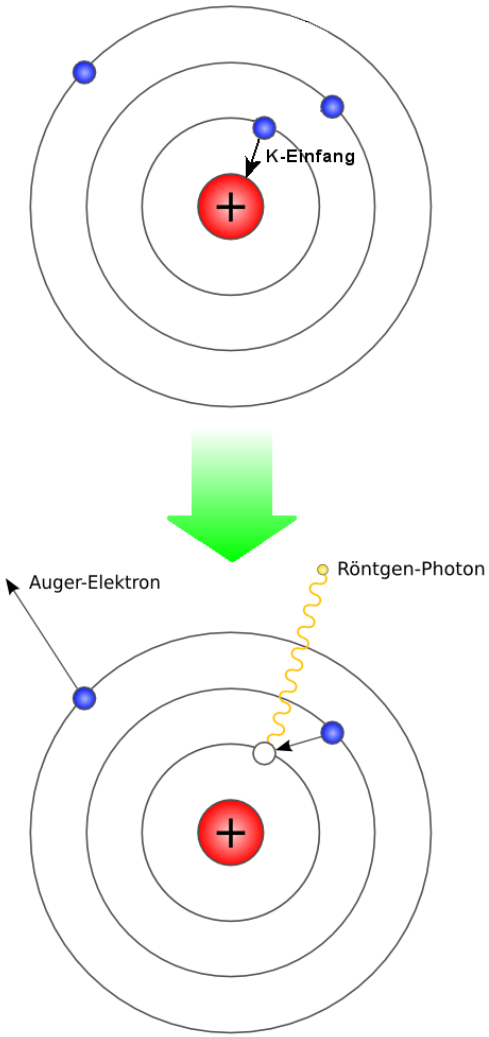
$$ {}^{A}_{Z}X_{N} + e^{-} \rightarrow {}^{A}_{Z-1}X_{N+1} + \nu_{e} $$

$$ Q_{EC} = M_{P}c^{2} - \left(M_{D}c^{2} - B_{en}\right) $$

Atomic electron is captured by a proton. This process leaves the atom in an excited state: a vacancy has been created! The vacancy is quickly filled by producing the characteristic X-ray cascade

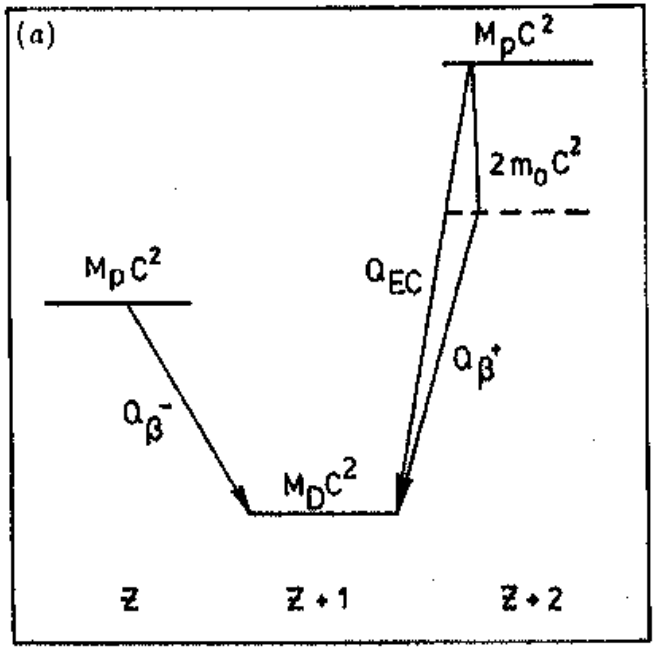


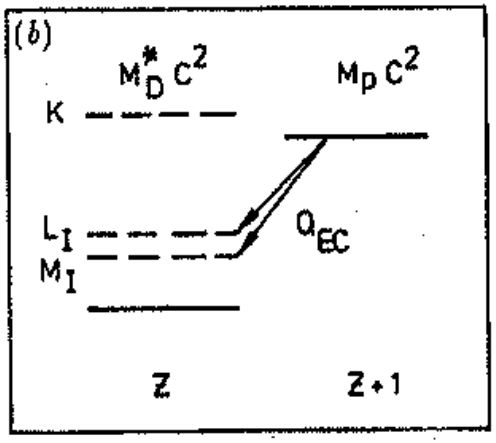




Decay	Type	Q (MeV)	T
$^{23}Ne \rightarrow {}^{23}Na + e^- + \bar{\nu}_e$	β^-	4.38	38 s
$^{99}Tc \rightarrow {}^{99}Ru + e^- + \bar{\nu}_e$	β^-	0.29	2.1×10^5 y
$^{25}Al \rightarrow {}^{25}Mg + e^+ + \nu_e$	β^+	3.26	7.2 s
$^{124}I \rightarrow {}^{124}Te + e^+ + \nu_e$	β^+	2.14	4.2 s
$^{15}O + e^- \rightarrow {}^{15}N + \nu_e$	EC	2.75	1.22 s
$^{41}Ca + e^- \rightarrow {}^{41}K + \nu_e$	EC	0.43	1.0×10^5 y

examples…





mass relationship in electron capture between the parent and daughter atom

energy relations in various beta decay processes

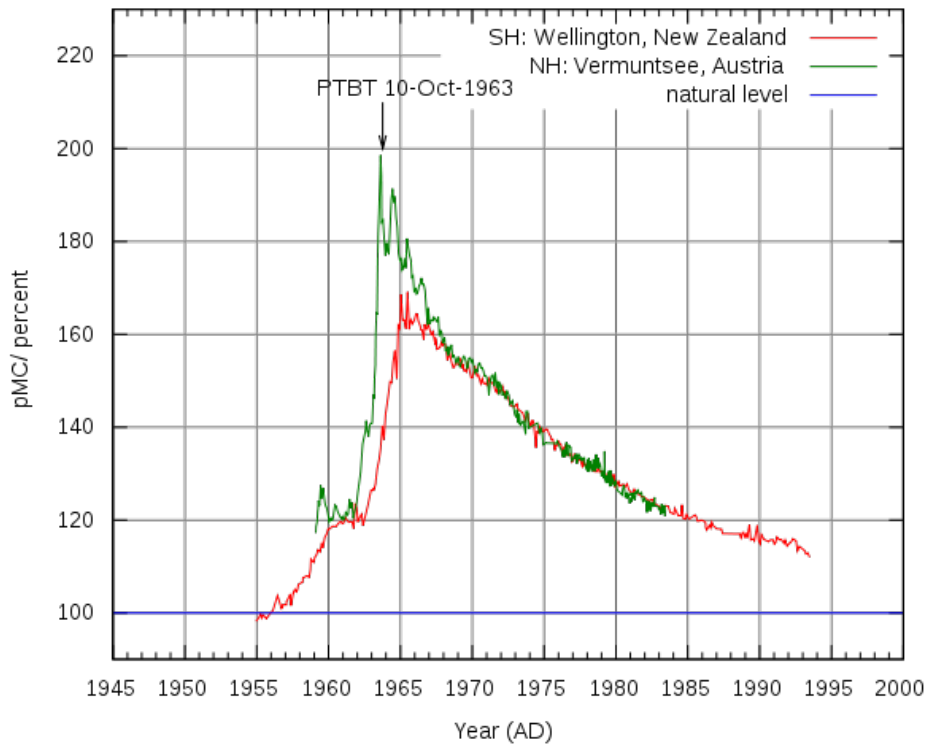
β^+ decay can occur when the mass of parent atom exceeds that of daughter atom by at least twice the mass of the electron

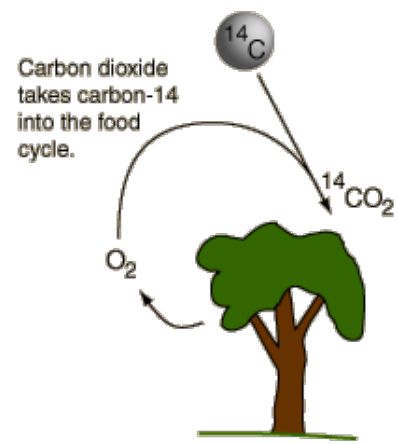
Radiocarbon dating

$$^{14}\mathrm{C} \rightarrow {}^{14}\mathrm{N} + e^- + \bar{\nu}_e$$

half-life of 5730 years

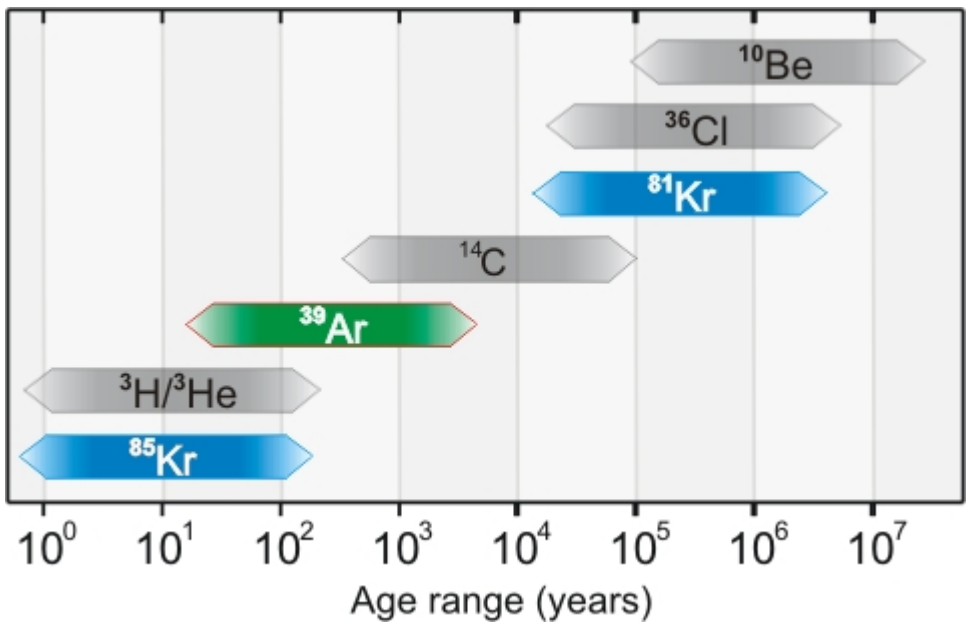
Radiocarbon dating is a radiometric dating method that uses ^{14}C to determine the age of carbonaceous materials up to about 60,000 years old. The technique was developed by Libby and his colleagues in 1949. In 1960, Libby was awarded the Nobel Prize in chemistry for this work. The level of ^{14}C in plants and animals when they die approximately equals the level of ^{14}C in the atmosphere at that time. However, it decreases thereafter from radioactive decay.





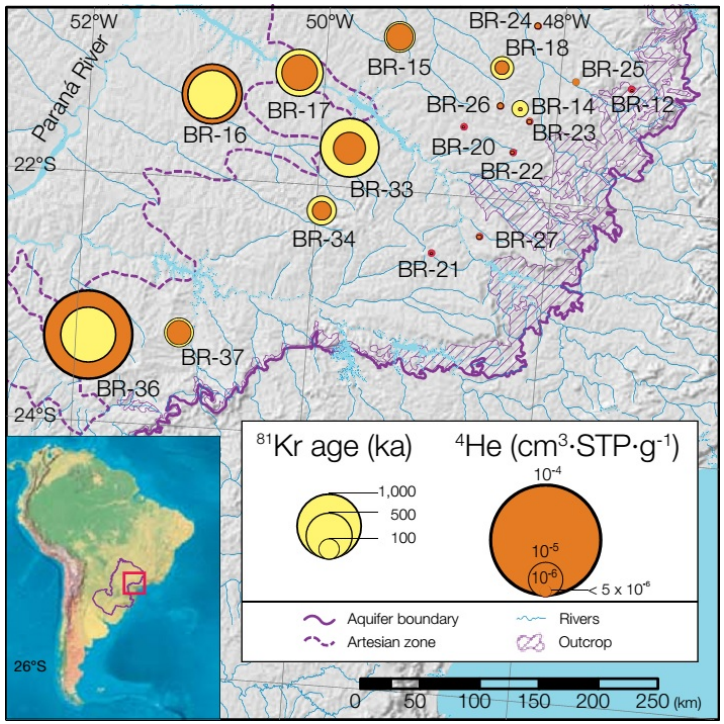
Atmospheric nuclear weapon tests almost doubled the concentration of ^{14}C in the Northern Hemisphere. The date that the Partial Test Ban Treaty (PTBT) went into effect is marked on the graph.

Radiokrypton dating



^{81}Kr half-life is $2.293 \cdot 10^5$y

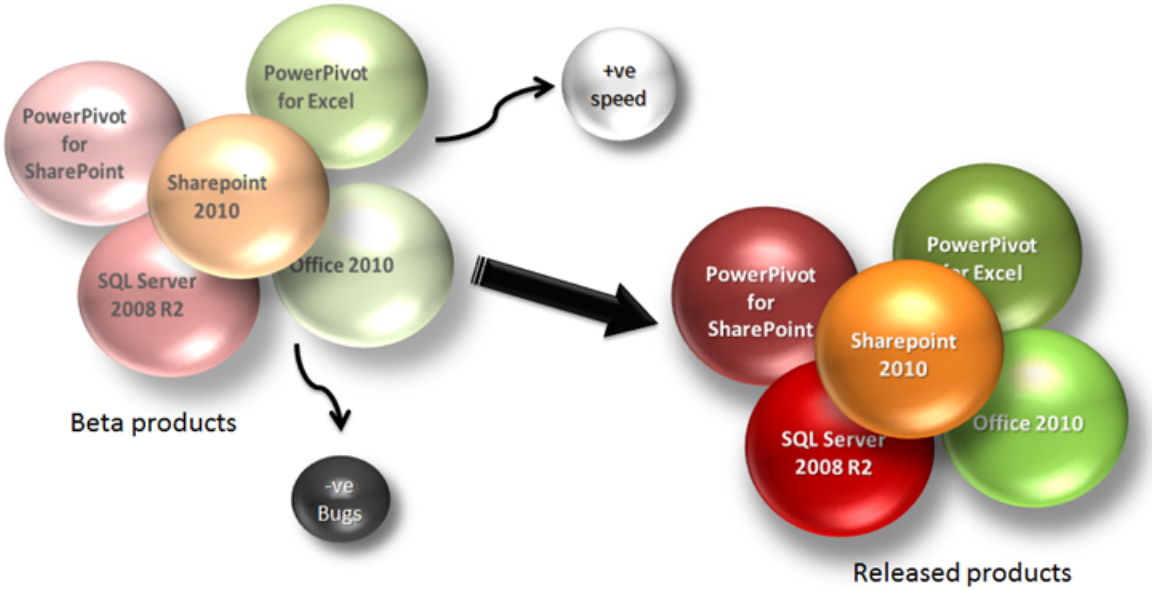
Guarani Aquifer, Brazil



https://www.phy.anl.gov/mep/atta/research/atta.html

Other applications ☺

http://blogs.technet.com/b/andrew/archive/2010/05/28/beta-decay.aspx



"I am pretty sure the term beta in software isn't related to atomic decay, but there are some similarities in that an atom that decays is unstable and decays after a period of time to something more stable e.g. Carbon14 to Nitrogen14. In the Microsoft world, the time to decay is usually 180 days (compared to a half life of 5,730 years for Carbon 14 to decay) and this results in fallout- the loss of bugs identified during the beat period, and some performance improvements and small enhancements leading to a very stable released product." (Andrew.Fryer)

Neutron beta decay

http://physics.aps.org/synopsis-for/10.1103/PhysRevLett.111.222501

Astrophysicists rely on a precise value of the free neutron lifetime to calculate the rate of nucleosynthesis during the big bang, while particle physicists use it to constrain fundamental parameters of the standard model. Yet measured lifetimes have varied by about a percent, depending on the experimental technique.

NIST: Phys. Rev. Lett. 111, 222501 (2013): T_n=(887.7±1.2[stat]±1.9[syst]) s

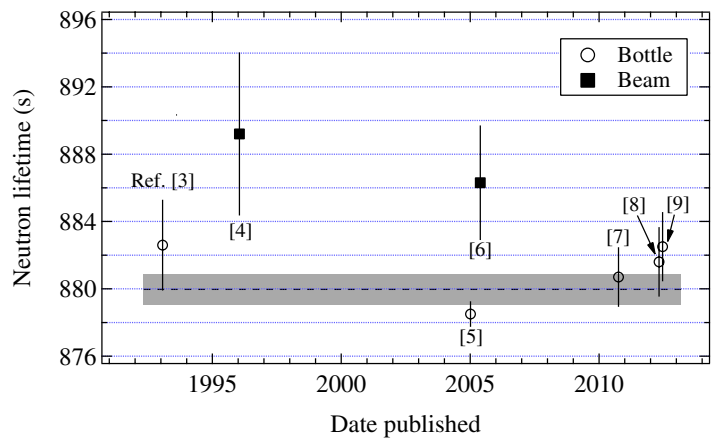


FIG. 1 (color online). The neutron lifetime measurements used in the 2013 PDG world average. The weighted mean and 1σ uncertainty (inflated by scale factor $\sqrt{\chi^2/\text{d.o.f.}} = 1.53$, following PDG procedures) of the data set is represented by the dashed line and shaded band.

Can proton beta-decay? Discuss.

Discuss beta decay of doubly-magic nuclei

- ^{48}Ni
- ^{78}Ni
- ^{100}Sn
- ^{132}Sn

Provide decay equations. Find Q-values.