Outline: Antimatter

Lecturer: Hans-Jürgen Wollersheim

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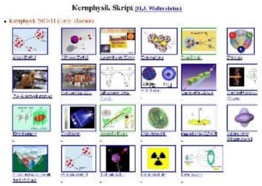
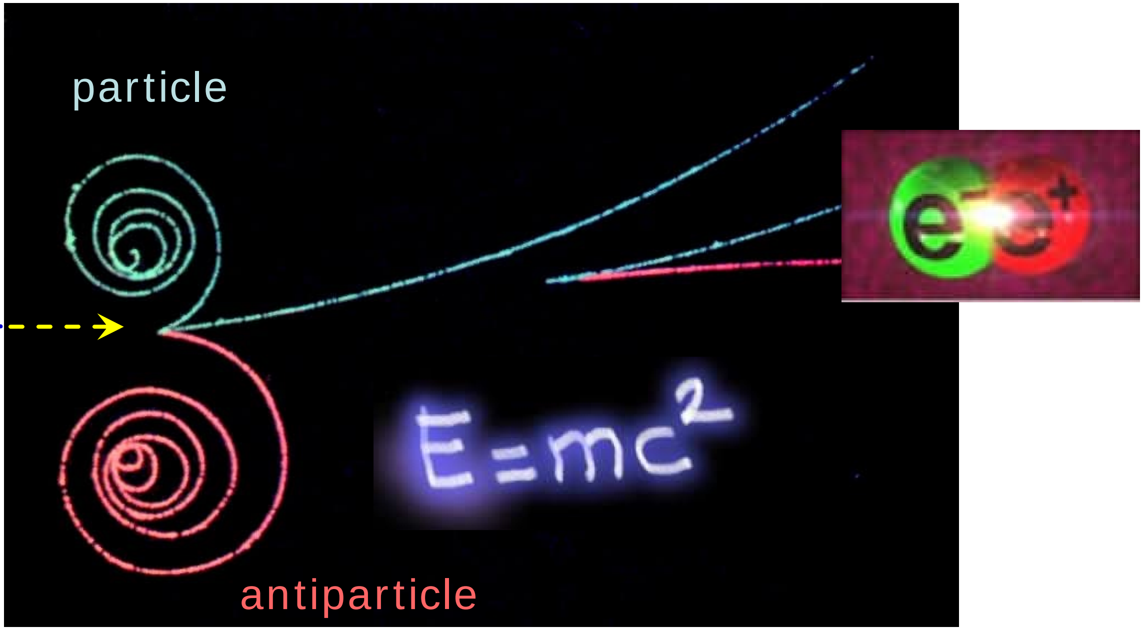
web-page: https://web-docs.gsi.de/~wolle/ and click on



Energy*



* gamma rays

1. History of Antimatter
2. Cosmology (**S**tandard **M**odel)
3. Matter-Antimatter asymmetry in particle physics
4. Neutrinoless double-beta decay

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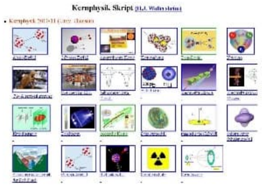
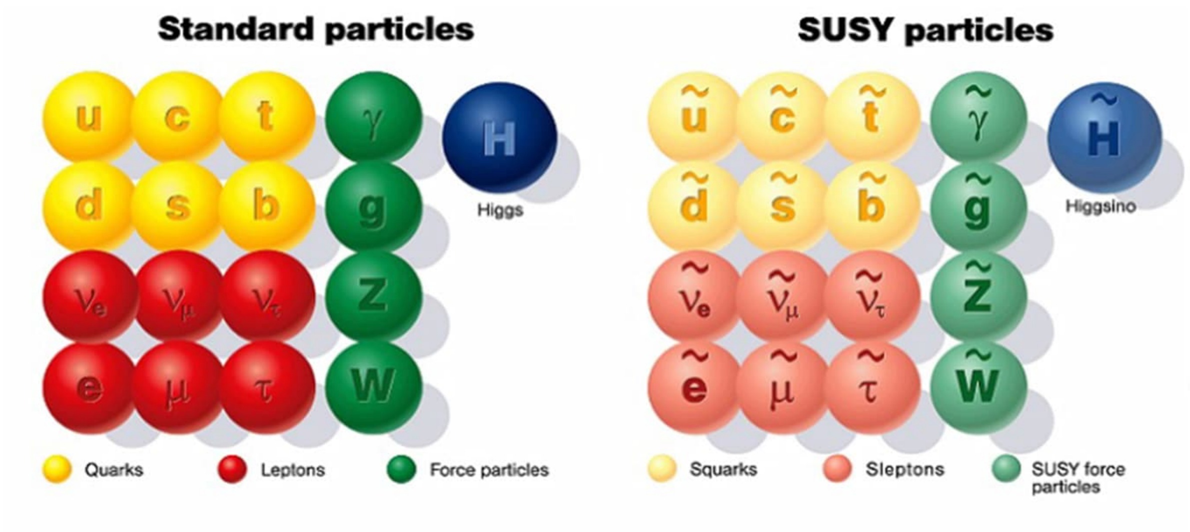
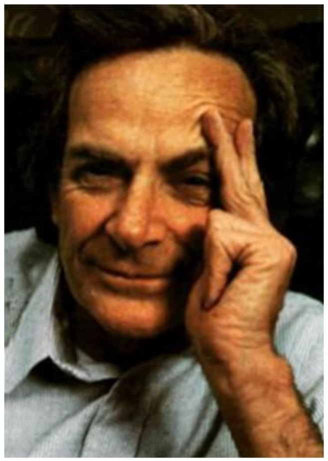


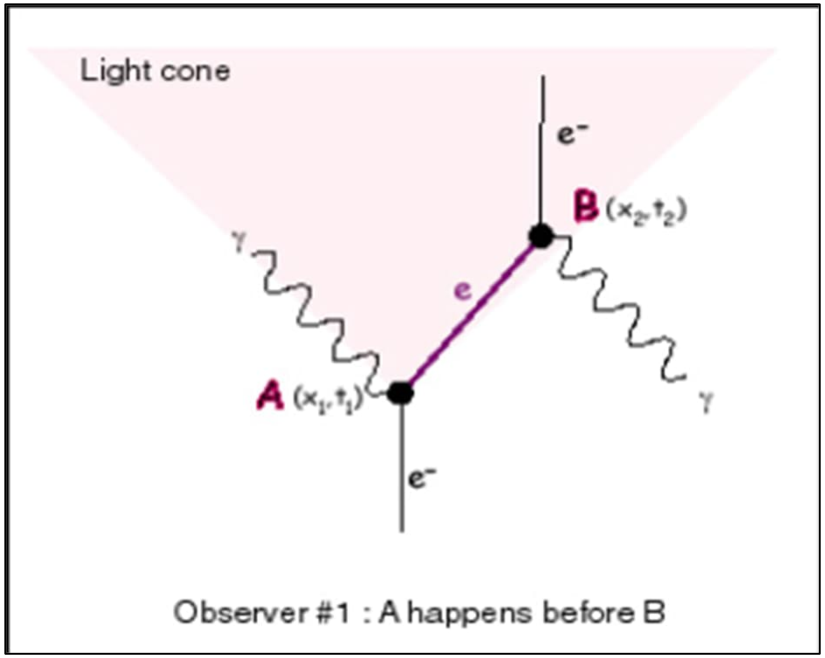


1. History of Antimatter
2. Cosmology
3. Matter-Antimatter Asymmetry
4. experiments

"Second quantization" – the electron (field) is no longer described by a wave function but an operator that creates and destroys particles. All energies are positive.



Richard Feynman



An electron can emit a photon at A, propagate a certain distance, and then absorb another photon at B.

REMINDER

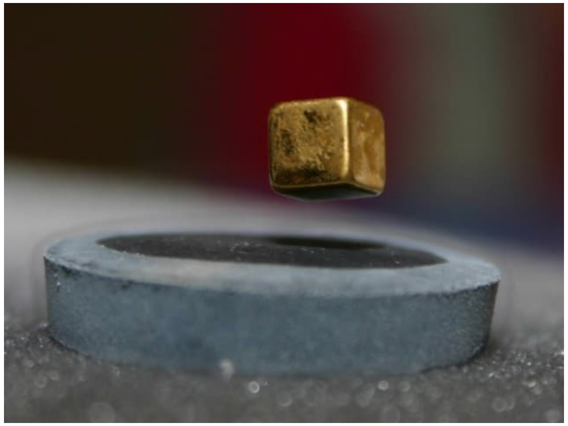
Fermions and Bosons

Fundamental characteristics of particles: ***Spin*** ("self angular momentum")

- Integer values (0, ±1, …) → ***Bosons***
- Half integer values (±1/2, ±3/2, …) → ***Fermions***

Satyendranath Bose

Bosons (Cooper pairs …) can be described by ***common wave function***
→ funny effects (super conductivity, super fluidity, …)



Enrico Fermi

Fermions (electrons or protons …) must be in different states
→ ***Pauli's exclusion principle*** (basis of all chemistry…)

Wolfgang Pauli

Matter Waves for Particles without Spin

REMINDER

	Non relativistic:	Relativistic:
Kinematics:	$E = \frac{\vec{p}^2}{2m}$	$E^2 = p^2c^2 + m^2c^4$
Quantum Mechanics:	$E \to i\hbar\frac{\partial}{\partial t}$ and $\vec{p} \to -i\hbar\vec{\nabla}$	$E \to i\frac{\partial}{\partial t}$ and $\vec{p} \to -i\vec{\nabla}$
Wave Equation:	$i\hbar\frac{\partial}{\partial t}\psi = \frac{-\hbar^2}{2m}\nabla^2\psi$	$-\frac{1}{c^2}\frac{\partial^2}{\partial t^2}\phi = -\nabla^2\phi + \frac{m^2c^2}{\hbar^2}\phi$

density: $\rho(x,t) = |\psi(x,t)|^2$

continuity equation: $\frac{\partial\rho}{\partial t} + \nabla\cdot j = 0$

Schrödinger equation: $\frac{\partial}{\partial t}\psi = \frac{i\hbar}{2m}\nabla^2\psi$

continuity equation: $\frac{\partial}{\partial t}(\psi^*\psi) = -\nabla\cdot\left[\frac{i\hbar}{2m}(\psi\nabla\psi^* - \psi^*\nabla\psi)\right]$

plane waves: $\psi = N\cdot e^{i(p\cdot x - E\cdot t)/\hbar}$ $\quad E = p^2/2m$

are solutions to the free Schrödinger equation

$p \to -p$ gives to same result

GSI

Matter Waves for Particles without Spin

REMINDER

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Wave Equation:	$i\hbar\frac{\partial}{\partial t}\psi = \frac{-\hbar^2}{2m}\nabla^2\psi$	$-\frac{1}{c^2}\frac{\partial^2}{\partial t^2}\phi = -\nabla^2\phi + \frac{m^2c^2}{\hbar^2}\phi$

Klein-Gordon equation

Unlike the Schrödinger equation, the Klein-Gordon equation does not contain factor ***i***. Consequently, it can have both real and complex solutions.

$$\left(\frac{1}{c^2}\frac{\partial^2}{\partial t^2} - \nabla^2 + m^2\right)\phi(x) = 0$$

plane waves:

$$\phi(x) = Ne^{i(p\cdot x - E\cdot t)} = e^{-ip_\mu\cdot x^\mu}$$

satisfies the dispersion relation
$E^2 = p^2 + m^2$

continuity equation:

$$\frac{\partial}{\partial t}i\left(\phi^*\frac{\partial\phi}{\partial t} - \phi\frac{\partial\phi^*}{\partial t}\right) = \nabla\cdot[i(\phi^*\nabla\phi - \phi\nabla\phi^*)]$$

The factor ***i*** is introduced to make the density real

$$\rho = 2|N|^2E \qquad j = 2|N|^2p$$

Matter Waves for Particles with Spin relativistic electron

Which equation describes a relativistic electron (c=1)?

$$E^2 = p^2 + m^2 \;\rightarrow$$

$$E = \pm(\alpha \cdot p) + \beta \cdot m$$

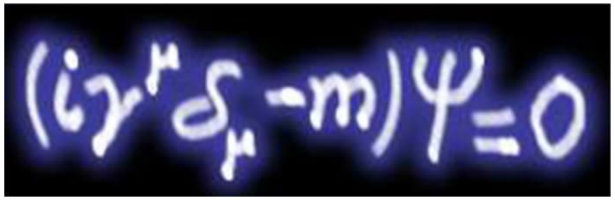
Dirac: Take the ‘square root’ – and deal with negative solution

Paul Dirac 1902-1984

Linear equation, based on relativistic energy-momentum conservation

$$i\frac{\partial}{\partial t}\Psi = -i\left(\alpha_x \frac{\delta}{\delta x}\Psi + \cdots\right) + \beta m \Psi$$

Solution: α, β are 4x4 matrices (called γ^{μ})
Ψ has 4 components (“spinor”)



What does Ψ stand for?

P. A. M. Dirac, Phys. Roy. Soc. A118 (1928) 351

Dirac equation – Four components?

Electron has spin ½ (two ways of alignment in a magnetic field).
Description by a two-component Pauli 'spinor' (spin-up and spin-down).

But: Ψ had two spin ½ particles!

$$\Psi_+ = \begin{pmatrix}1\\0\\0\\0\end{pmatrix} \; or \; \begin{pmatrix}0\\1\\0\\0\end{pmatrix} e^{-i\omega t}$$

$$\Psi_- = \begin{pmatrix}0\\0\\1\\0\end{pmatrix} \; or \; \begin{pmatrix}0\\0\\0\\1\end{pmatrix} e^{+i\omega t}$$

These are the two spin states of an electron with positive energy

These are the two spin states of something (similar) with 'negative' energy

For moving electrons, the upper and lower components mix.
The 'one-particle' wave function describes now a multi-particle wave function
Dirac 1929: 'negative' energy states with positive charge = proton **???**

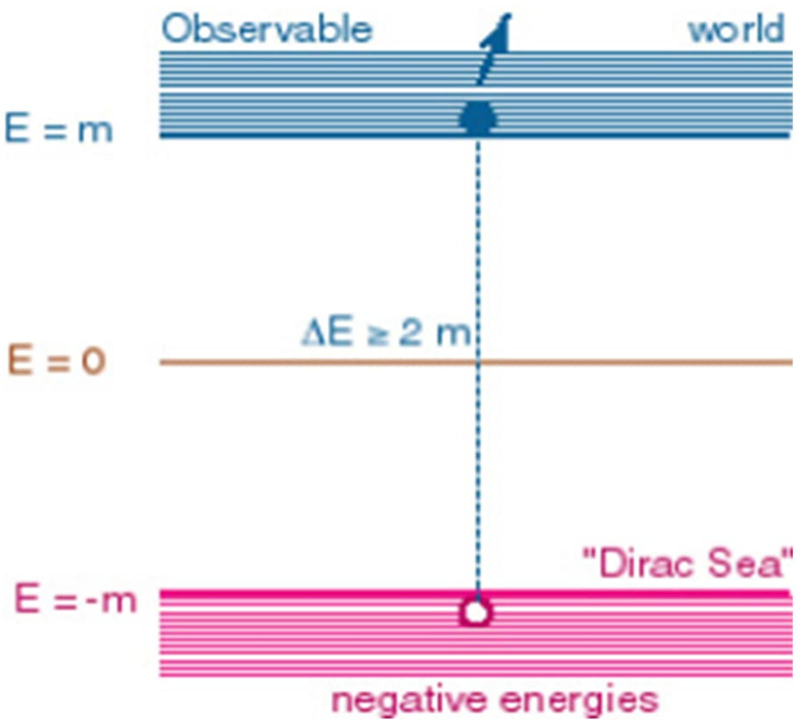
Dirac's interpretation: Holes in the vacuum

Dirac 1931: "Subsequent investigations, however, have shown that this particle necessarily has the same **mass of an electron** and also that, if it collides with an electron, the two will have a chance of annihilating one another …"

All positive energy states occupied by electrons. 'Pauli exclusion principle' prevents electrons to fall into the "Dirac sea" (otherwise $t_{trans} \sim 10^{-8}\ sec$)

Pair creation: By absorbing radiation ($E \geq 2m$)**,** an electron can be lifted from negative to positive energy state. The remaining hole (absence of negative charge) behaves like a positive electron – the positron.

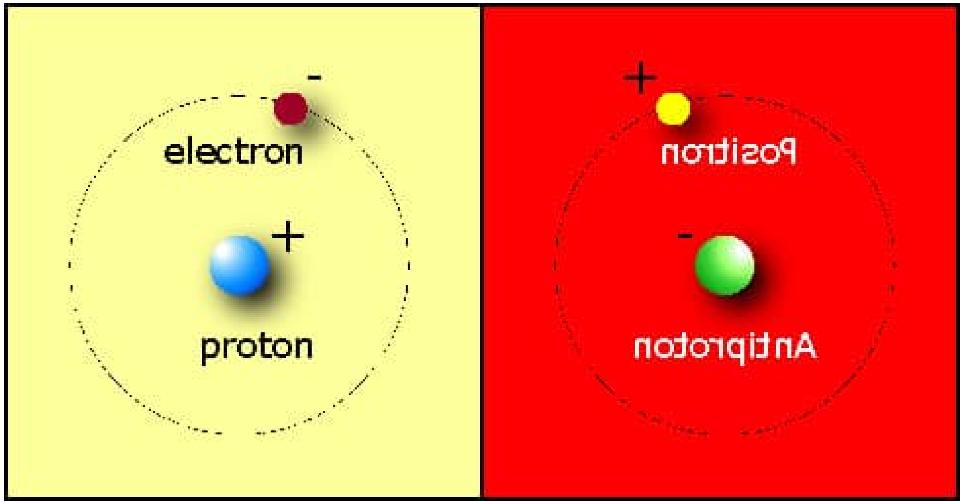
Vacuum had become very complicated
(infinite zero-point energy, infinite charge)



Is the Universe symmetric?

1933 Dirac (from his Nobel lecture)

"If we accept the view of complete symmetry between positive and negative electric charge so far as concerns the fundamental laws of Nature, we must regard it rather as an accident that the Earth (and presumably the whole solar system), ***contains a preponderance of negative electrons and positive protons.***



positronium lifetime: τ = 0.125 ns

Positron discovery (1932)

Carl Anderson

Anderson used cloud chamber in a 15 kG magnetic field

Cloud Chamber had two parts, separated by a 6 mm lead plate

Greater curvatures of lower track indicates that particles entered the chamber from below. This determines the positive charge of the particle.

From the track curvature and track length(= energy loss per cm) Anderson concluded that the positive charge of the particles is less than twice that of proton and the mass is less than twenty times the proton mass.

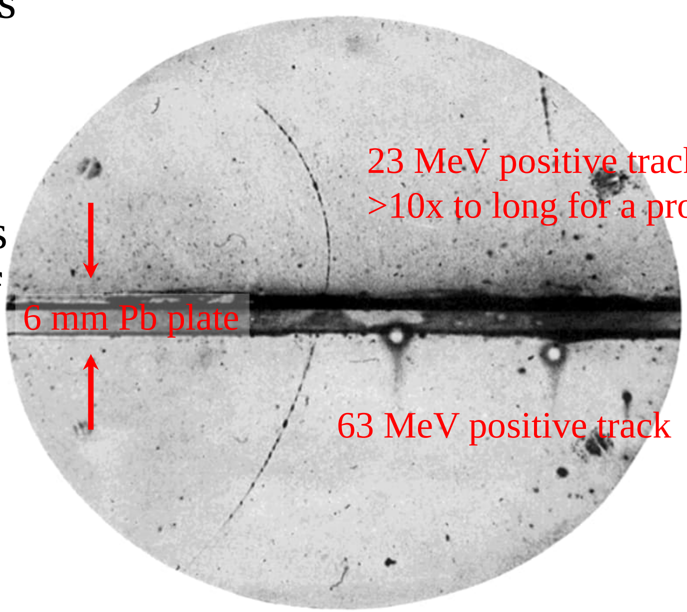
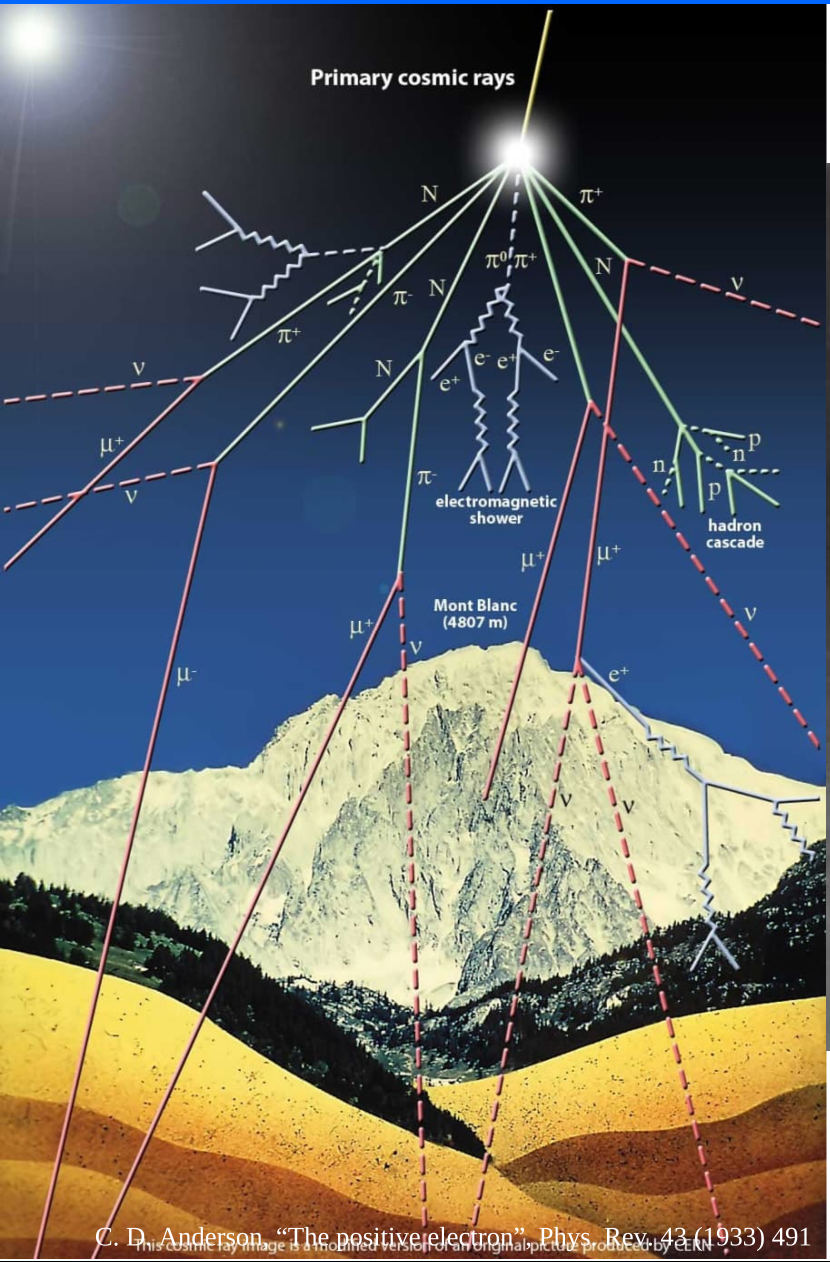


FIG. 1. A 63 million volt positron ($H\rho = 2.1 \times 10^5$ gauss-cm) passing through a 6 mm lead plate and emerging as a 23 million volt positron ($H\rho = 7.5 \times 10^4$ gauss-cm). The length of this latter path is at least ten times greater than the possible length of a proton path of this curvature.

C. D. Anderson, “The positive electron”, Phys. Rev. 43 (1933) 491

Positron discovery (1932)



C. D. Anderson, “The positive electron”, Phys. Rev. 43 (1933) 491

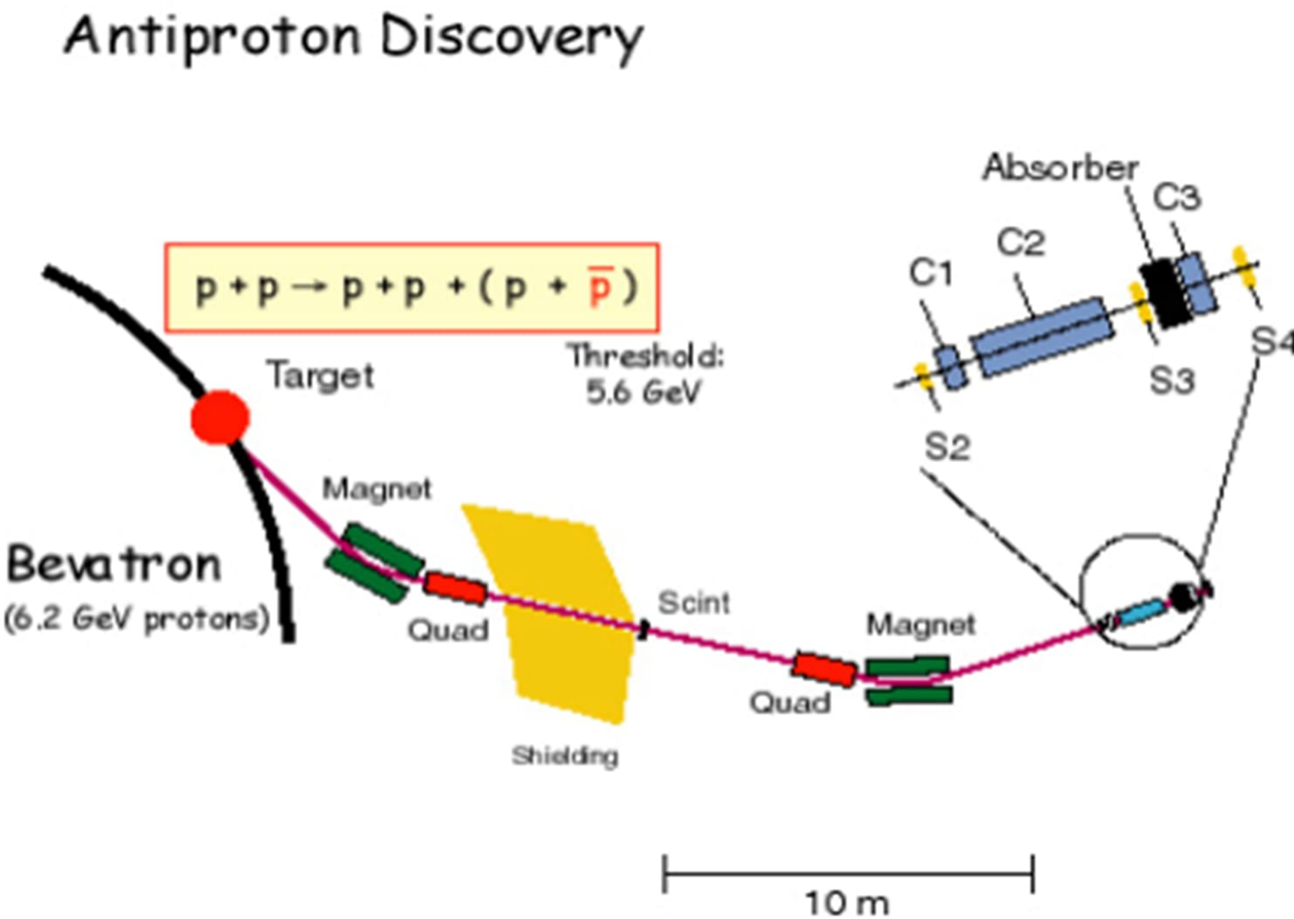
The 800 turns of 1 cm Cu tubing carried both an electrical current of up to 1600 A and cooling water, 150 liters per minute. A dc generator in the basement of the Aeronautics building at Caltech delivered up to 600 kW giving a strong magnetic field of up to 2.4 T.

Discovery of antiproton (1955)

In 1955, many prominent physicists remained doubtful if baryons would have antiparticles. After all, the magnetic moment of the proton ($g = 5.58 \neq 2$) seemed to indicate that the proton was **not** a Dirac particle. As an example, Maurice Goldhaber bet against the existence of the antiproton …

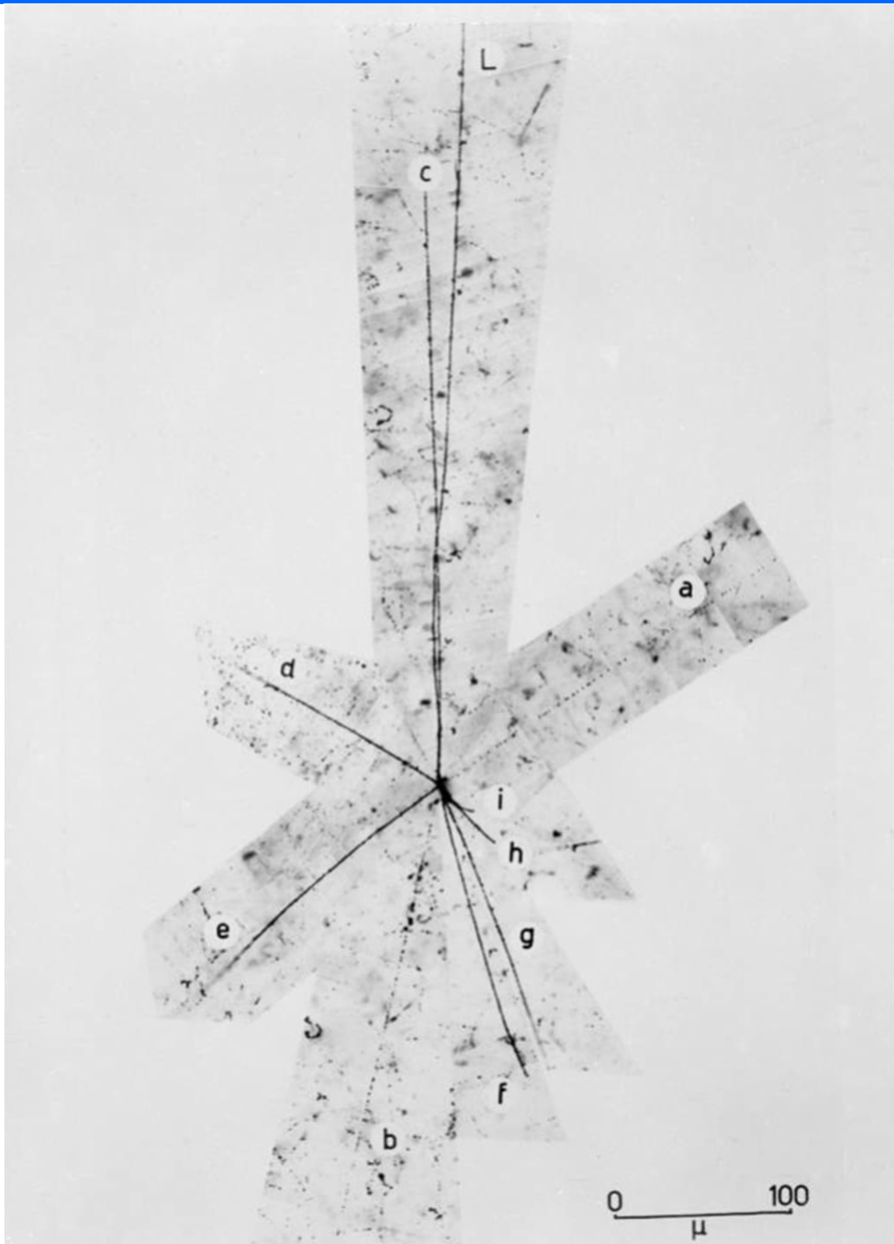
… and lost

(he gave Snyder 500 $ in November 1955)



The energy of the Bevatron at Berkeley had been designed for the production of the antiproton and as built by Ernest Lawrence and his team.

Discovery of antiproton (1955)



Antiproton annihilation

First symmetry test – mass, charge agreed to ~10%

Discovery of antiproton (1955)

Segrè

Chamberlain

PHYSICAL REVIEW

A journal of experimental and theoretical physics established by E. L. Nichols in 1893

SECOND SERIES, VOL. 100, NO. 3 NOVEMBER 1, 1955

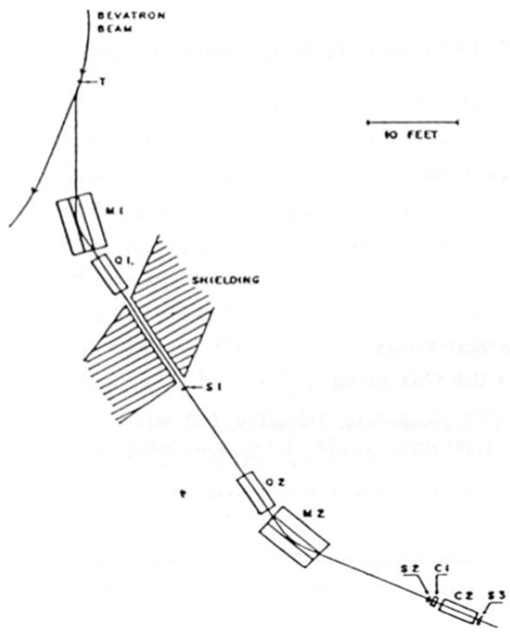
Observation of Antiprotons*

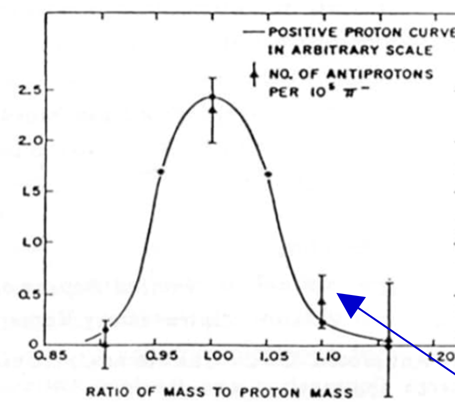
OWEN CHAMBERLAIN, EMILIO SEGRÈ, CLYDE WIEGAND,
AND THOMAS YPSILANTIS

Radiation Laboratory, Department of Physics, University of California, Berkeley, California

(Received October 24, 1955)

Nobel prize (1959)
for 50% of the collaboration





Tedious analysis …

Antineutron, Anti-Nuclei

Berkeley 1956: Discovery of **antineutron**
(Cork, Lambertson, Piccioni, Wenzel)

using the ‘antiproton beam’ and **charge-exchange reaction**

antiproton + proton → antineutron + neutron

The produced antineutron was recognizable by its annihilation properties, forming a star in the cloud chamber that is very similar to an antiproton star.

CERN 1965: Discovery of the **anti-deuteron**
(Massam, Muller, Righini, Schneegans, Zichichi)

The results reported imply the conclusion that a negative particle exists with mass equal to **1867±80 MeV**. The most simple interpretation of these data is to identify this particle with the anti-deuteron.

More Antimatter …

1932 Discovery of positron

1948 Discovery of positronium $\tau = 0.125$ ns

1955 Discovery of antiproton

1956 Discovery of antineutron

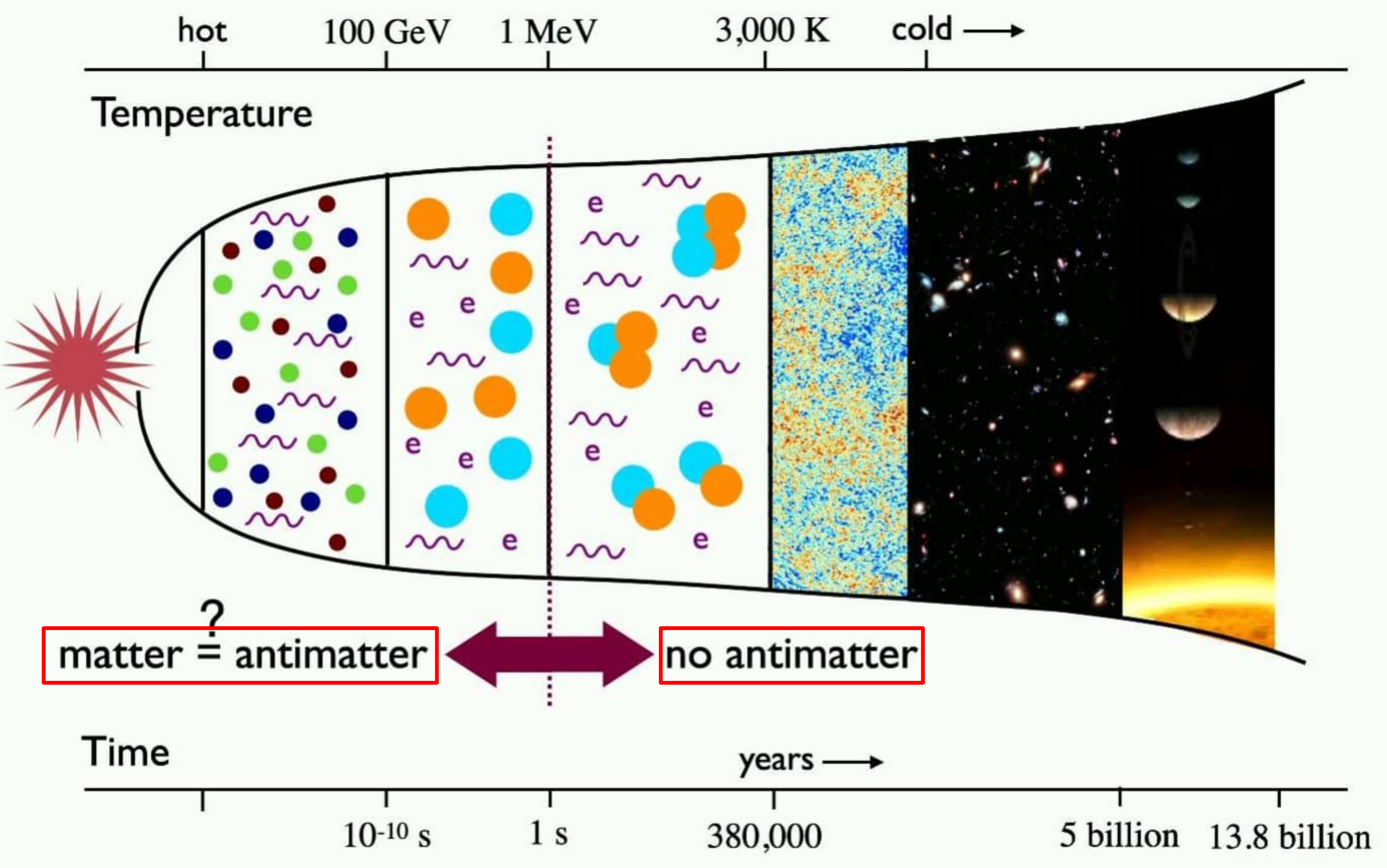
1965 Discovery of antideuteron

1970 Discovery of anti- ^{3}He

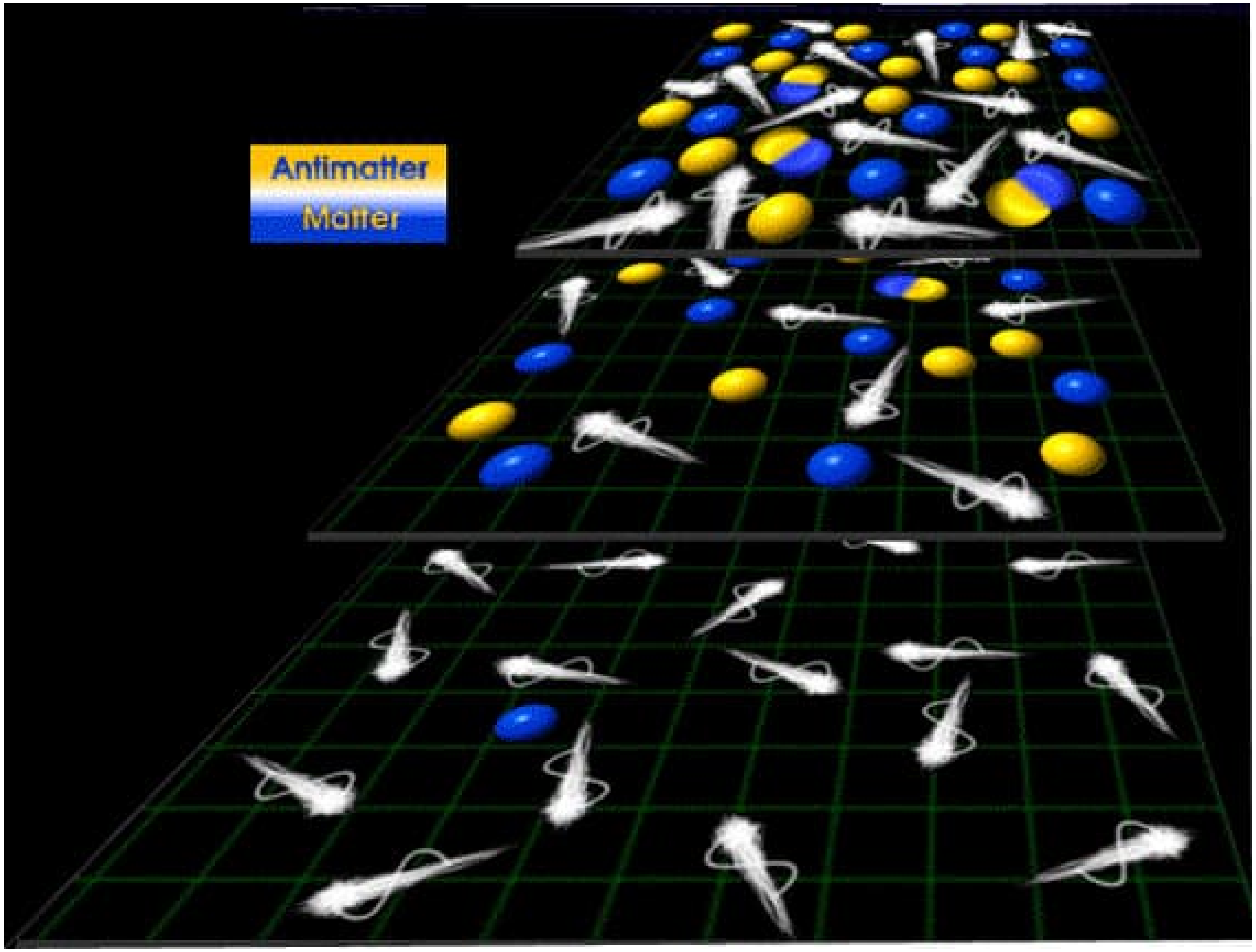
1978 Discovery of anti-tritium

1996 First creation of relativistic antihydrogen atoms

Matter-Antimatter Asymmetry in the Universe



Matter-Antimatter Asymmetry in the Universe

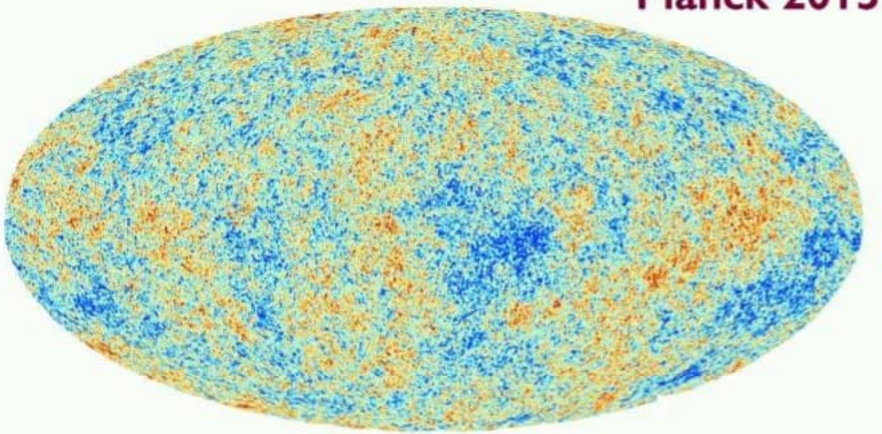


Without asymmetry – we would not be here!

Matter-Antimatter Asymmetry in the Universe

Cosmic Microwave Background

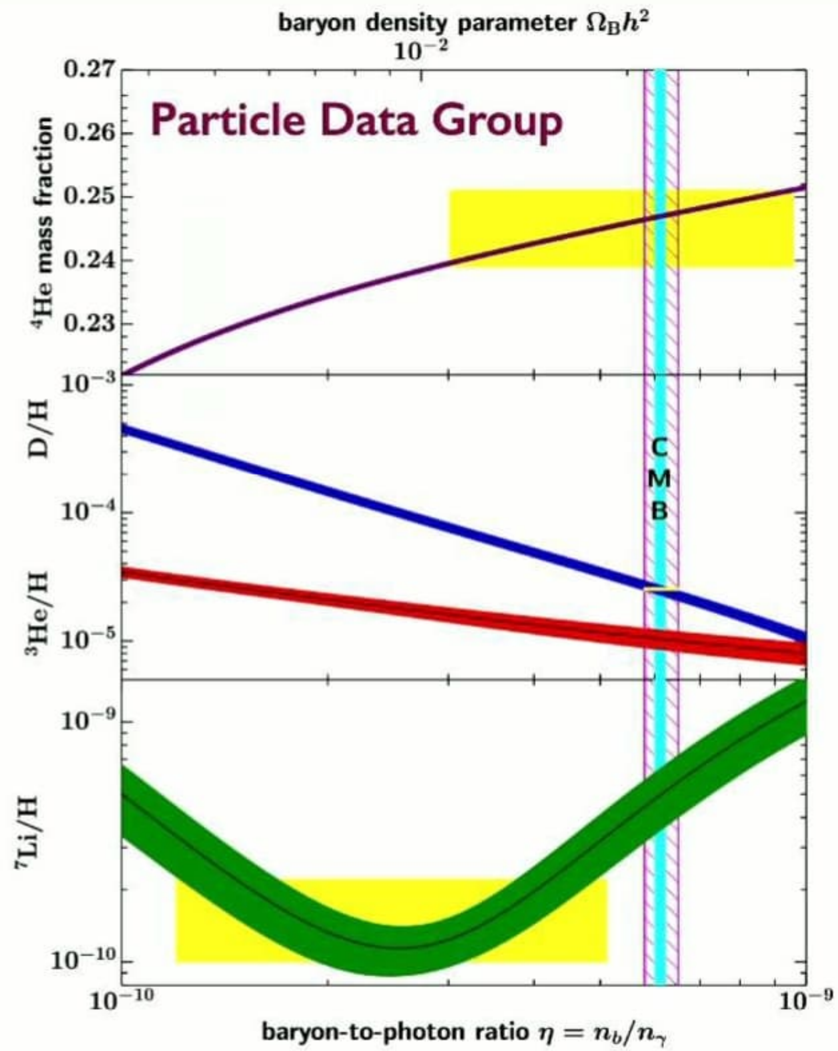
Planck 2015



Baryon-to-photon ratio:

$$\eta = \frac{n_B - n_{\bar{B}}}{n_\gamma} \simeq 6 \times 10^{-10}$$

Primordial light element abundances



Sacharow's Idea

Andrei D. Sacharow

Particles decay (a little) faster than antiparticles*

Small imbalance (1,000,000,001:1,000,000,000) occurs during cool-down of Universe

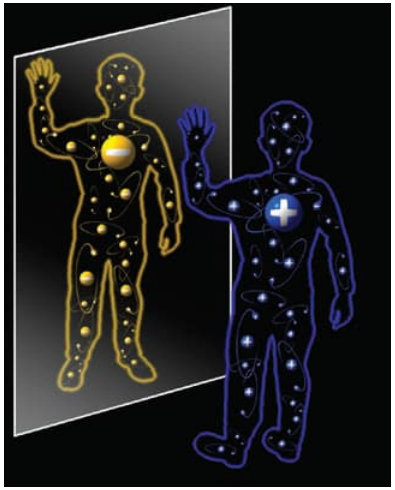
Most particle-antiparticle pairs annihilate to radiation

Galaxies, stars, planets, us = 'left-over'

*For experts: this is called 'CP violation'

1. Baryon number cannot be a conserved quantity
2. Charge and Charge-Parity (CP) symmetries must be violated
3. Out-of-equilibrium processes

Consequence: Proton is not stable!

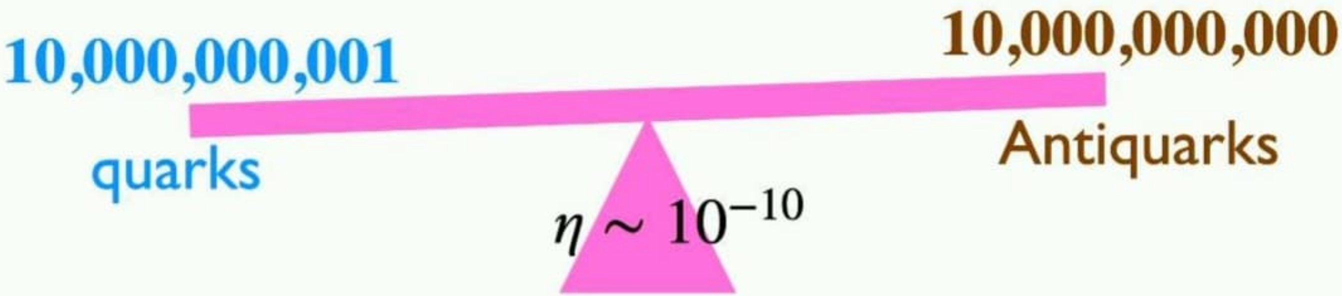


When we look at our image in a standard mirror, we are looking at the parity transformation of ourselves

CPT theorem: particles and antiparticles have the same mass, the same lifetime, but opposite charges (electric, baryonic, leptonic, etc.

Matter-Antimatter Asymmetry

How do we make sure there are more quarks than antiquarks in the early Universe?



Physics need to be a little bit different between matter and antimatter!

Andrei Sakharov
1921-1989

JETP Lett. 6 (1967) 4

Sakharov conditions

1. Baryon (matter) number cannot be a conserved quantity
2. Charge and Charge-Parity (CP) symmetries must be violated
3. Out-of-equilibrium processes

1964 (Cronin, Fitch, Christenson, Turlay)

In a small fraction of cases ($\sim 10^{-3}$), long lived K_L (a mixture of K^0 and $\overline{K}^0$ decays into pair of two pions, what is forbidden by CP-conservation

There are other manifestations of CP breaking. For example, if CP were exact symmetry, an equal number of K^0 and $\overline{K}^0$ would produce an equal number of electrons and positrons in the reaction

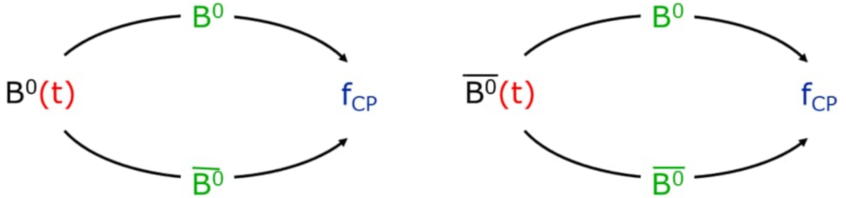
$$K^0 \rightarrow \pi^- e^+ \nu_e \qquad \overline{K}^0 \rightarrow \pi^+ e^- \bar{\nu}_e$$

However, this is not the case: the number of positrons is somewhat larger ($\sim 10^{-3}$) than the number of electrons.

Conclusion: there is indeed a tiny difference between particles and antiparticles, on the level of 10^{-3} (but not 100% asymmetry)

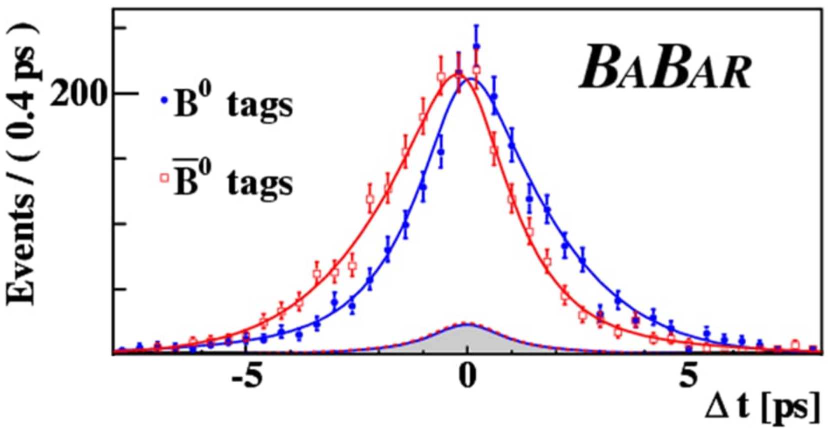
Measuring CP Violation with B^0s

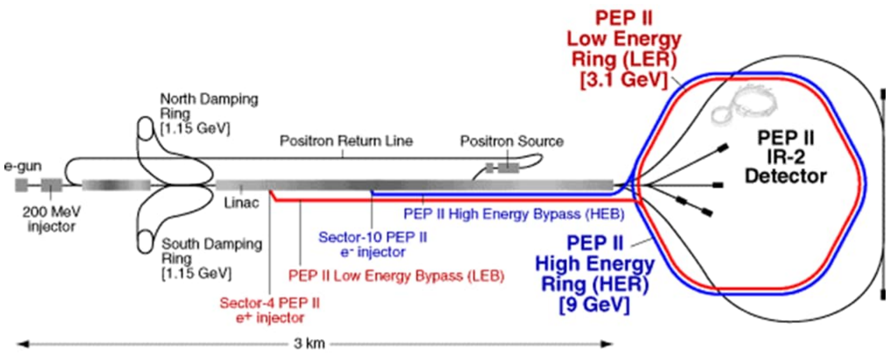
$$B^0 = \bar{b}d$$



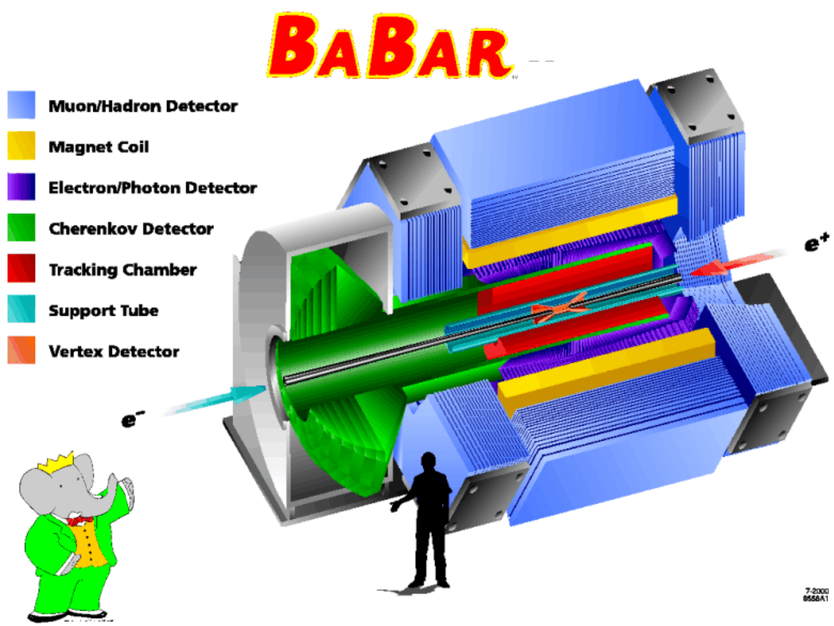
$$\overline{B^0} = b\bar{d}$$

Not equal –
CP Violation!



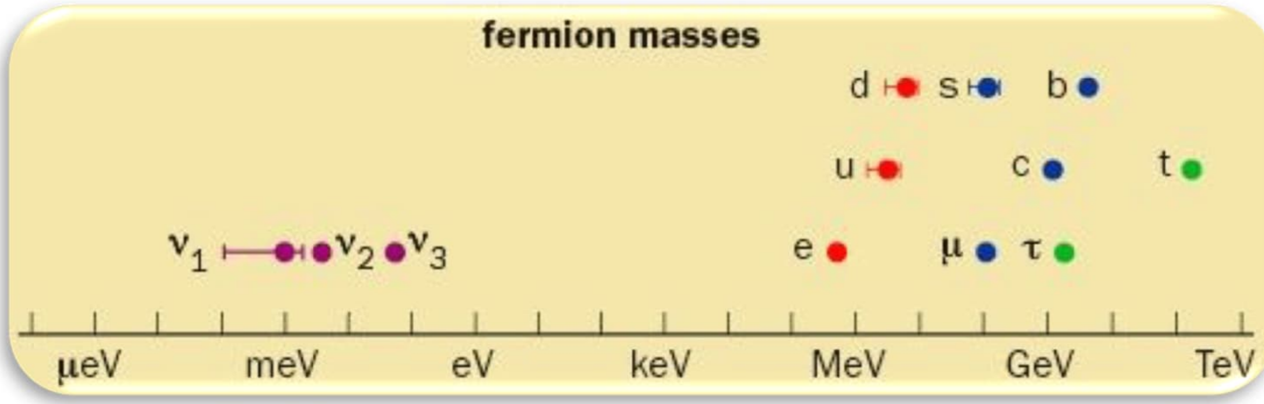


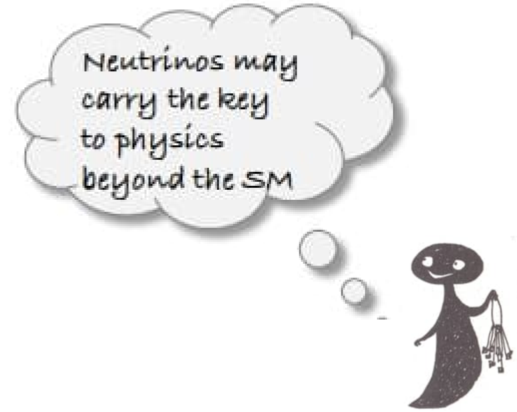
Stanford Linear Accelerator Center



B-meson

Why are neutrinos so interesting?





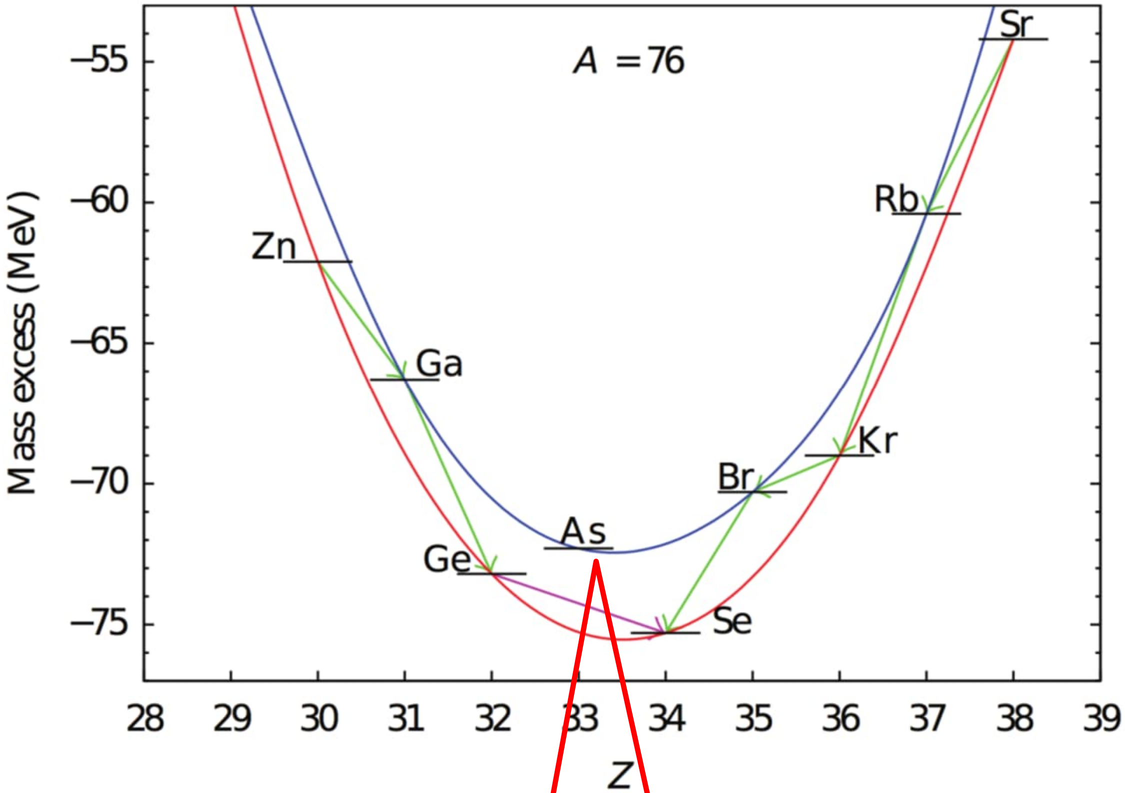
mass	< 0.120 eV/c^2
charge	0 e
spin	½ $\hbar$
chirality	left
interaction	weak and gravitation

❖ Particle/Nuclear Physics
- Fundamental questions about standard model
- Fundamental issues regarding interactions

❖ Cosmology
- Density 336 neutrinos per cubic centimeter
- Leptogenesis and matter-antimatter asymmetry

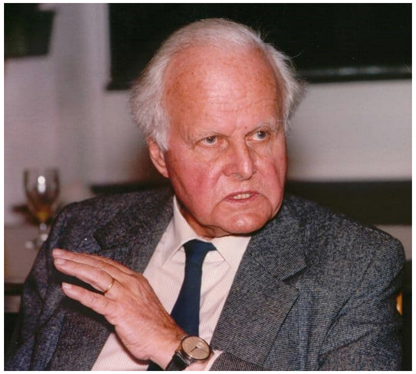
❖ Astrophysics
- Supernova explosions
- Solar burning

Two neutrino double beta decay



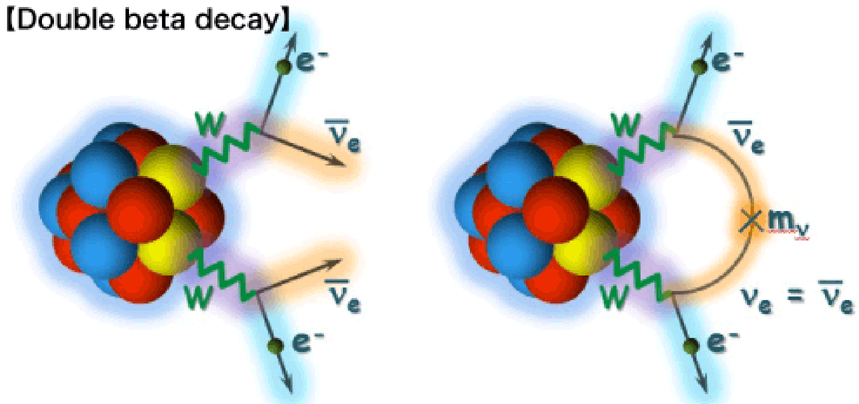
In some cases, the single beta decay is energetically forbidden.
Then the double beta decay becomes relevant

Isotope	$T_{1/2}$ (2ν) (y)
^{48}Ca	$(4.4 \pm 0.6)\cdot 10^{19}$
^{76}Ge	$(1.5 \pm 0.1)\cdot 10^{21}$
^{82}Se	$(0.92 \pm 0.07)\cdot 10^{20}$
^{96}Zr	$(2.3 \pm 0.2)\cdot 10^{19}$
^{100}Mo	$(7.1 \pm 0.4)\cdot 10^{18}$
^{116}Cd	$(2.8 \pm 0.2)\cdot 10^{19}$
^{128}Te	$(1.9 \pm 0.4)\cdot 10^{24}$
^{130}Te	$(1.5 \pm 0.1)\cdot 10^{20}$
^{150}Nd	$(8.2 \pm 0.9)\cdot 10^{18}$
^{238}U	$(2.0 \pm 0.6)\cdot 10^{21}$
^{136}Xe	$(2.1 \pm 0.2)\cdot 10^{22}$



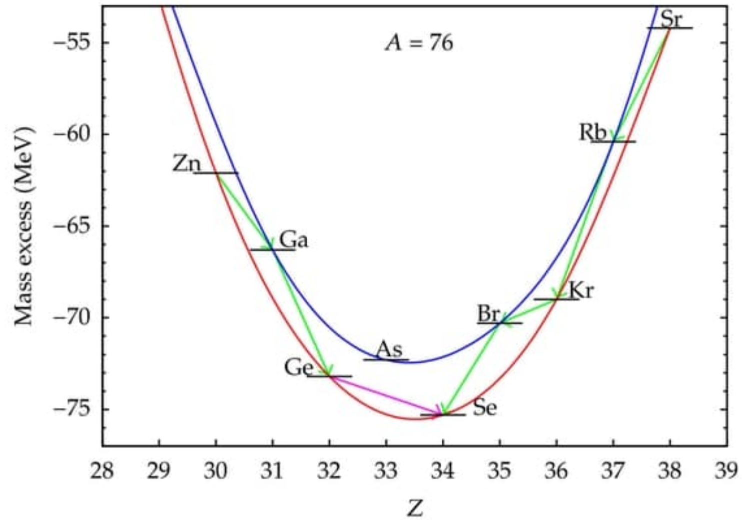
Carl von Weizäcker

Neutrinoless double-beta decay "forbidden" in SM



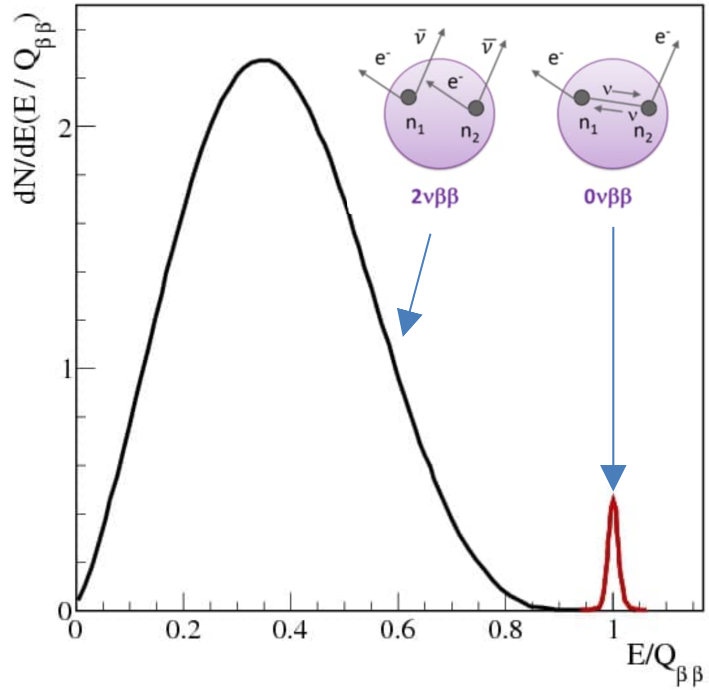
Double beta decay which emits anti-neutrinos

Neutrinoless double beta decay



Paul Dirac

Ettore Majorana



Fermions

particle-antiparticle pair

Neutral Particles

they are their own antiparticles
works for massless neutrinos

$$\nu = \bar{\nu}$$

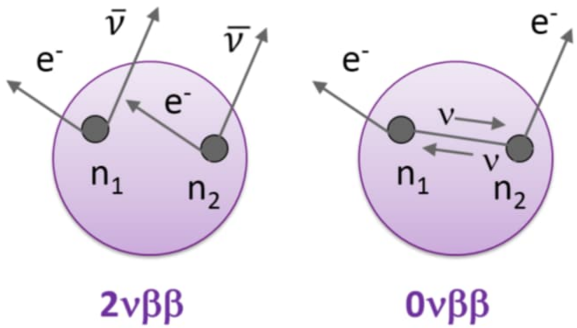
Which nuclei can decay via 0νββ ?

- Even-even nuclei
- Natural abundance is low (except ^{130}Te)
- Must use enriched material

Best lower limits on $T_{1/2}$:

$1.07 \cdot 10^{26}\ yr$ for ^{136}Xe
$0.9 \cdot 10^{26} yr$ for ^{76}Ge
$2.7 \cdot 10^{24} yr$ for ^{130}Te

Candidate*	Q [MeV]	Abund [%]
^{48}Ca -> ^{48}Ti	4.271	0.187
^{76}Ge -> ^{76}Se	2.040	7.8
^{82}Se -> ^{82}Kr	2.995	9.2
^{96}Zr -> ^{96}Mo	3.350	2.8
^{100}Mo -> ^{100}Ru	3.034	9.6
^{110}Pd -> ^{110}Cd	2.013	11.8
^{116}Cd -> ^{116}Sn	2.802	7.5
^{124}Sn -> ^{124}Te	2.228	5.64
^{130}Te -> ^{130}Xe	2.530	34.5
^{136}Xe -> ^{136}Ba	2.479	8.9
^{150}Nd -> ^{150}Sm	3.367	5.6



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

$$\nu_e + n \rightarrow p + e$$

Paul Dirac:

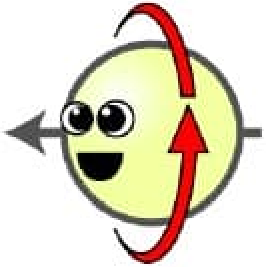
„The neutrino is **not identical** to the known antineutrino”

Ettore Majorana:

„The neutrino is **identical** to the known antineutrino”

Dirac versus Majorana

helicity:
projection of spin
onto momentum



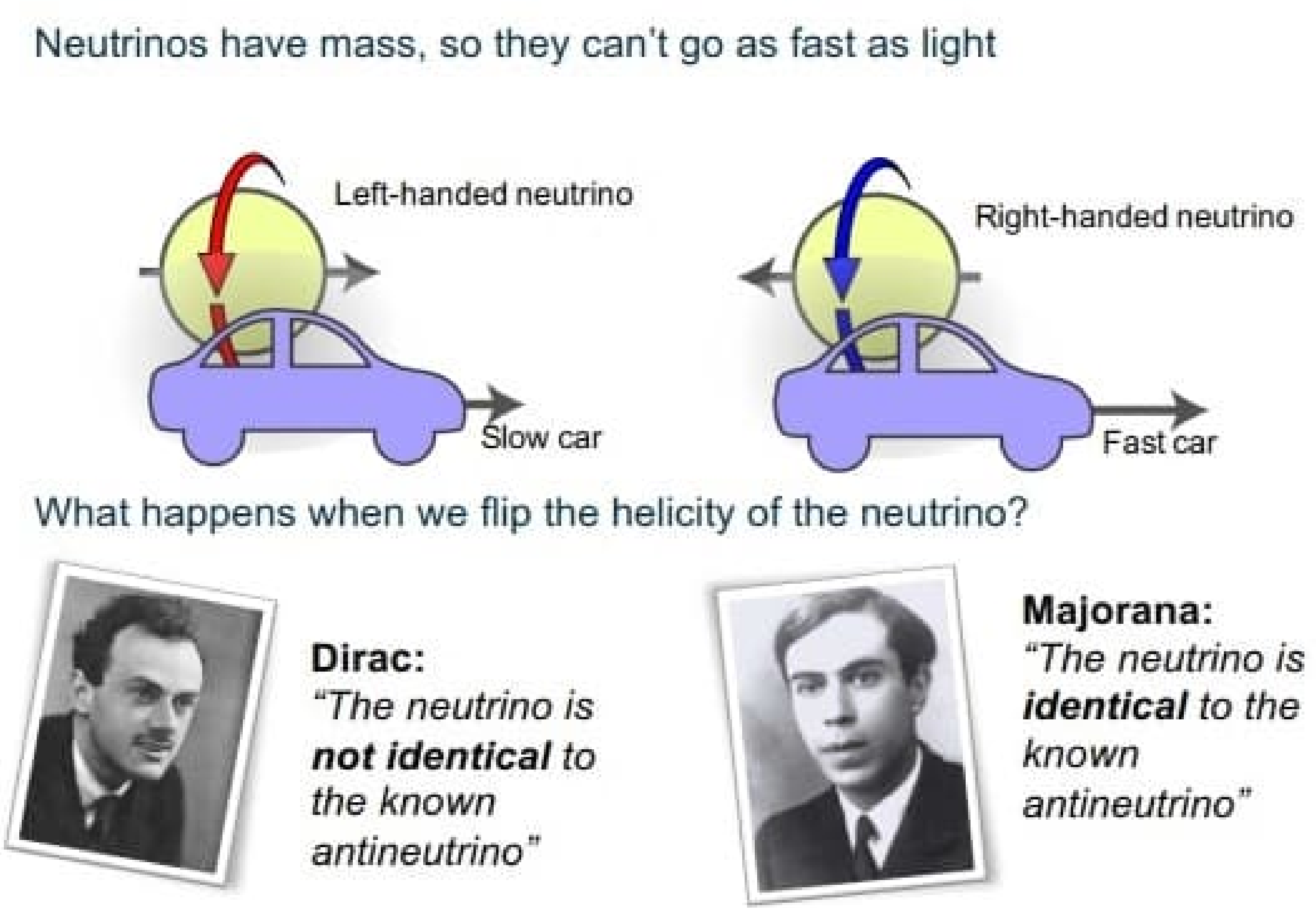
Experiments, so far, tell us:

- Neutrinos have left-handed helicity ⟶ $p \rightarrow n + e^{+} + \nu_e$
- Antineutrinos have right-handed helicity ⟶ $n \rightarrow p + e^{-} + \bar{\nu}_e$

Paul Dirac:
„Even if the neutrino flips its helicity it is still a fundamentally different particle. The reaction is not possible"

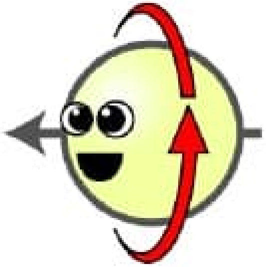
Ettore Majorana:
„Neutrino only has the wrong helicity, if it can flip the helicity this reaction should be possible"

Gedankenexperiment



Dirac versus Majorana

helicity:
projection of spin
onto momentum



Experiments, so far, tell us:

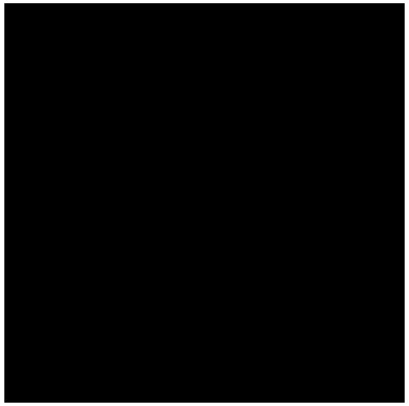
- Neutrinos have left-handed helicity → $p \to n + e^+ + \nu_e$
- Antineutrinos have right-handed helicity → $n \to p + e^- + \bar{\nu}_e$

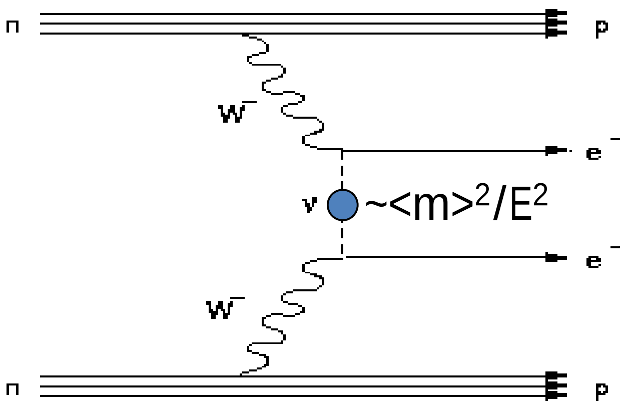
Dirac:
"There is a more fundamental difference between the two"

Majorana:
"That's the only difference"

Neutrinoless ββ-decay

If neutrino are massive and Majorana particles, due to m^2 $\overline{\psi}_R^C \psi_L$ term in Lagrangian one can observe $2\beta0\nu$





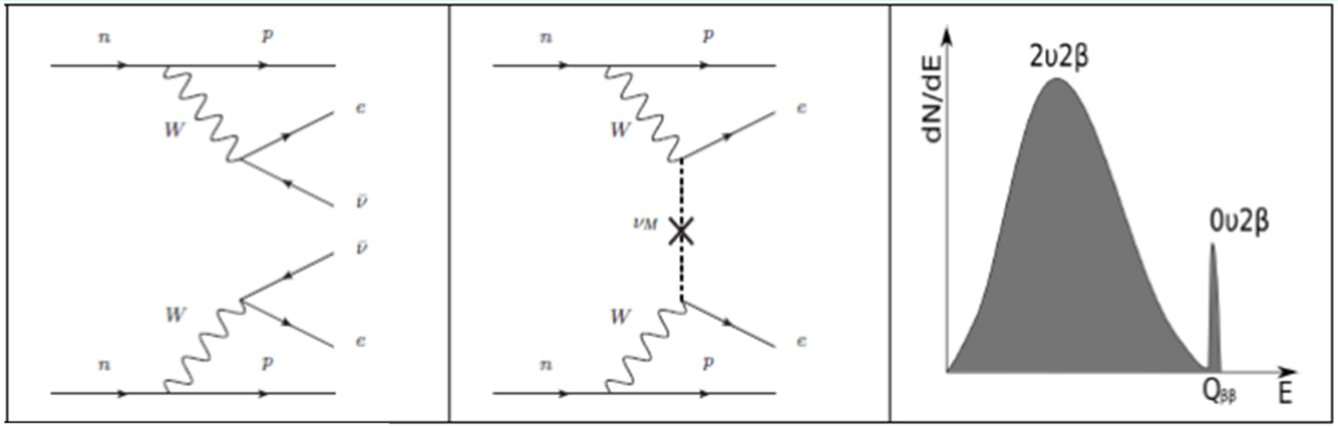
Golden plated channel:

a) 2 electrons

b) $E_{\beta 1} + E_{\beta 2} = Q_{\beta\beta}$

$(A,Z) \rightarrow (Z+2,A) + 2e^-$

Neutrinoless double-beta decay GERDA experiment



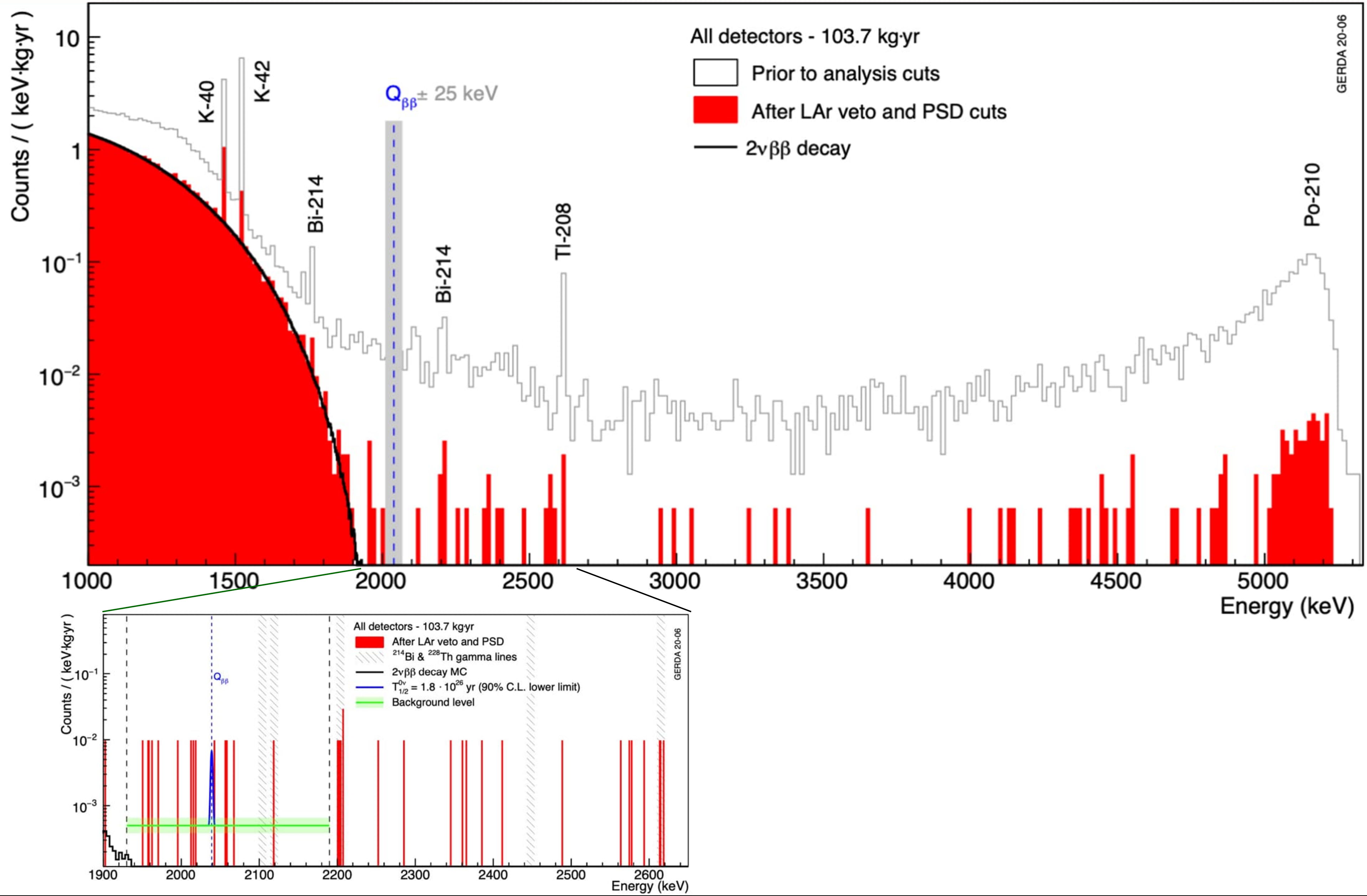
$Q_{\beta\beta} = 2039\ keV$

Located in Hall A at Laboratori Nazionali del Gran Sasso of INFN

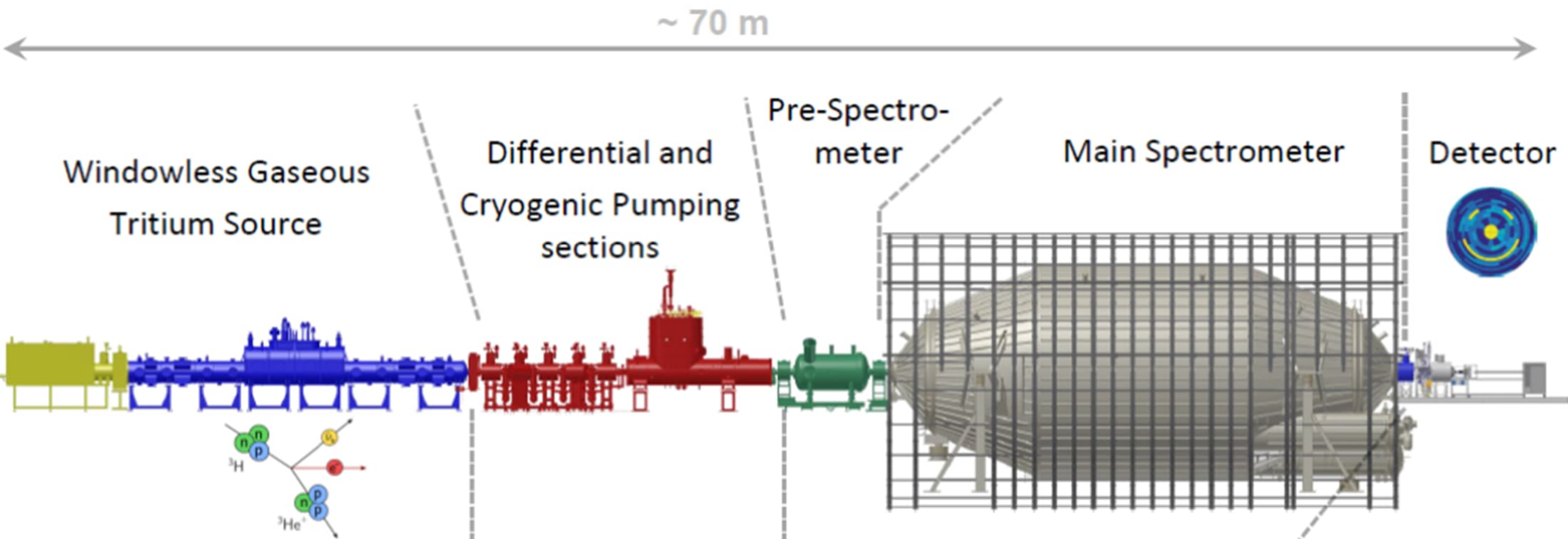
Array of bare Ge detectors 86% enriched in ^{76}Ge (~36 kg) directly inserted in liquid argon (LAr)

LEGEND 200 (kg)

Neutrinoless double-beta decay GERDA experiment



KATRIN = Karlsruhe Tritium Neutrino Experiment



- tritium β-decay
- decay rate: 10^{11} 1/s
- T_2 pressure: 10^{-3} to 10^{-6} mbar

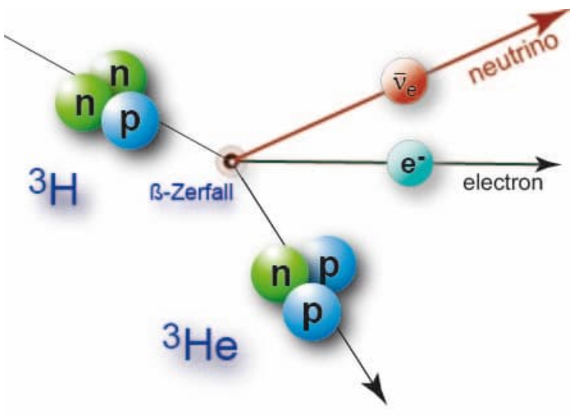
- β-electron transport
- tritium retention (factor > 10^{14})

- energy analysis of β-electrons
- resolution 0.93 eV @ 18.6 keV
- pressure < 10^{-10} mbar

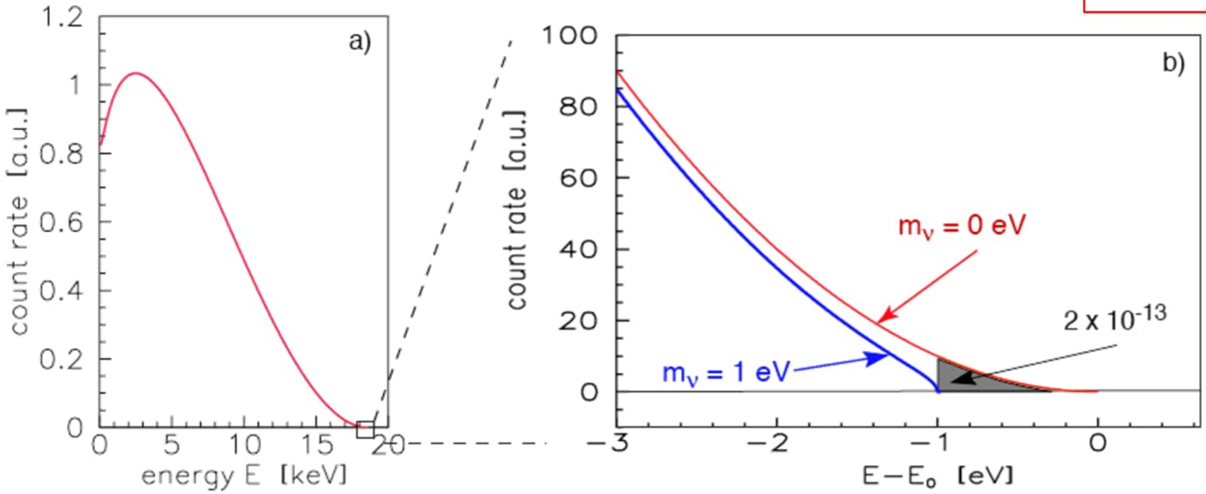
- counting of transmitted β-electrons

Goal: measure neutrino mass with sensitivity of 0.2 eV

KATRIN = Karlsruhe Tritium Neutrino Experiment



neutrino mass (2025) < 0,45 eV/c²



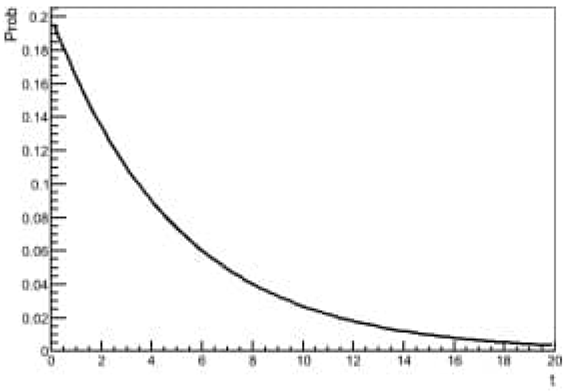
Appendix

How many 0νββ decays occur …

- for 1 t of Ge enriched to 86% ^{76}Ge
- in 1 year
- and if the half-life for 0νββ of ^{76}Ge was 10^{27} years

The probability to decay at time t is:

$$p(t) = \frac{1}{\tau} e^{-\left(1/_{\tau}\right)}$$



The probability to decay after a time period t_{exp} is

$$P\left(t_{exp}\right) = \int_{t=0}^{t=t_{exp}} \frac{1}{\tau} e^{-\left(t/_{\tau}\right)} dt$$

$$= 1 - e^{-\left(t_{exp}/_{\tau}\right)}$$

The number of decays for a given number N of isotopes is:

$$N_{decay} = N \cdot P\left(t_{exp}\right) = N \cdot \left(1 - e^{-\left(t/_{\tau}\right)}\right)$$

How many 0νββ decays occur …

$$N_{decay} = N \cdot \left(1 - e^{-\left(t_{exp}/\tau\right)}\right) = \frac{m_{tot}}{m_{iso}} \alpha \ln(2) \frac{t_{exp}}{T_{1/2}}$$

$$N = \frac{m_{tot}}{m_{iso}} \cdot \alpha$$

$$e^x \approx 1 + x$$

$$\tau = \frac{T_{1/2}}{\ln(2)}$$

N: number of isotopes
m_{tot}: total mass
m_{iso}: mass of atom
α: enrichment factor
t_{exp}: measurement time
$T_{1/2}$: half-life

How many 0νββ decays occur …

$$N_{decay} = N \cdot \left(1 - e^{-\left(t_{exp}/\tau\right)}\right) = \frac{m_{tot}}{m_{iso}} \alpha \ln(2) \frac{t_{exp}}{T_{1/2}}$$

$$= \frac{1000\ kg}{\frac{75.9}{6 \cdot 10^{23}}\ g} \cdot 0.86 \cdot \ln(2) \cdot \frac{1\ year}{10^{27}\ years} = \mathbf{5}$$

$$N_{background} = b \cdot \Delta E \cdot m_{tot} \cdot t_{exp}$$

N: number of isotopes
m_{tot}: total mass
m_{iso}: mass of atom
α: enrichment factor
t_{exp}: measurement time
$T_{1/2}$: half-life