Experiments
Hyrogen, Dirac theory

Lecture 2

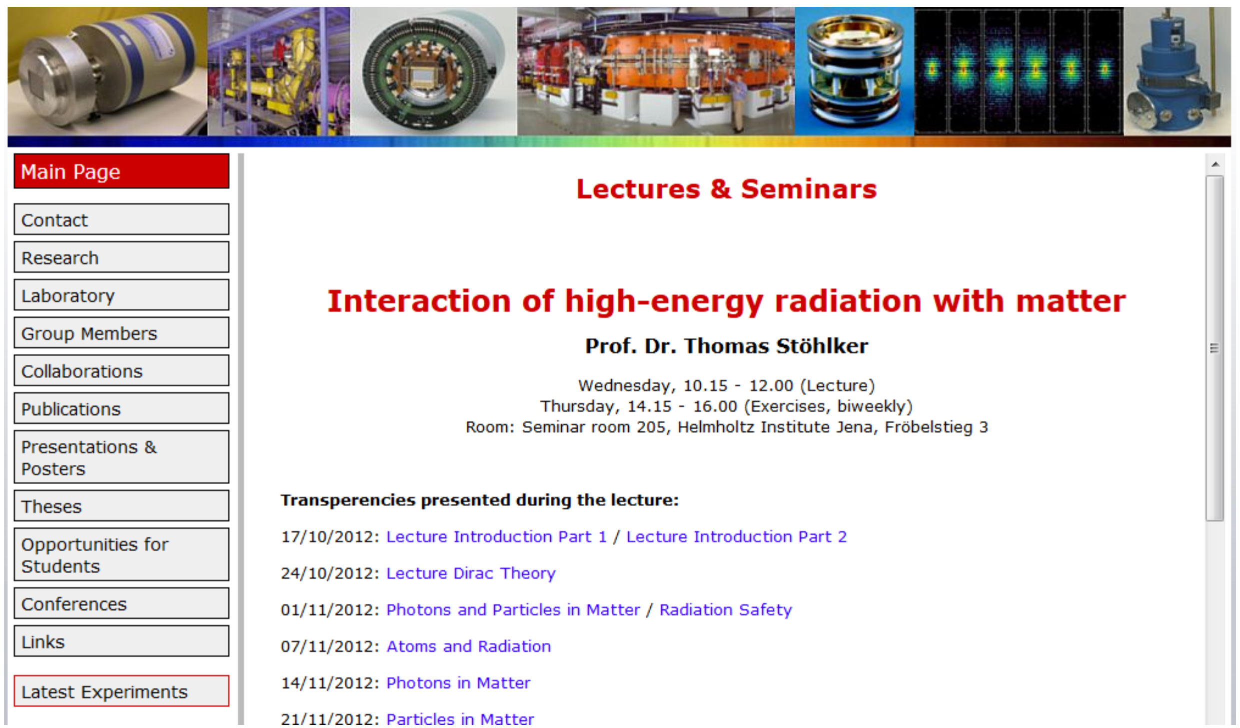
April 22nd 2014

Lectures in Internet

Find zipped .PPT & .PDF files with the lectures at:

http://web-docs.gsi.de/~stoe_exp/lectures/lectures.php

(password: dirac2015)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Lectures & Seminars

Interaction of high-energy radiation with matter

Prof. Dr. Thomas Stöhlker

Wednesday, 10.15 - 12.00 (Lecture)
Thursday, 14.15 - 16.00 (Exercises, biweekly)
Room: Seminar room 205, Helmholtz Institute Jena, Fröbelstieg 3

Transperencies presented during the lecture:

17/10/2012: Lecture Introduction Part 1 / Lecture Introduction Part 2

24/10/2012: Lecture Dirac Theory

01/11/2012: Photons and Particles in Matter / Radiation Safety

07/11/2012: Atoms and Radiation

14/11/2012: Photons in Matter

21/11/2012: Particles in Matter

Preliminary plan of the lectures

- 1 15.04.2015 Preliminary Discussion / Introduction

- 2 22.04.2015 Experiments (discovery of the positron, formation of antihydrogen, ...)
- 3 29.04.2015 Experiments (Lamb shift, hyperfine structure, quasimolecules and MO spectra)
- 4 06.05.2015 Theory (from Schrödinger to Dirac equation, solutions with negative energy)
- 5 13.05.2015 Theory (photon, quantum field theory (just few words), Feynman diagrams, QED corrections)

- 6 20.05.2015 Theory (matrix elements and their evaluation, radiative decay and absorption)
- 7 27.05.2015 Experiment (photoionization, radiative recombination, ATI, HHG...)

- 8 03.06.2015 Theory (single and multiple scattering, energy loss mechanisms, channeling regime)
- 9 10.06.2015 Experiment (Kamiokande, cancer therapy, ….)

- 10 17.06.2015 Experiment (Auger decay, dielectronic recombination, double ionization)
- 11 24.06.2015 Theory (interelectronic interactions, extension of Dirac (and Schrödinger) theory for the description of many-electron systems, approximate methods)

- 12 01.07.2015 Theory (atomic-physics tests of the Standard Model, search for a new physics)
- 13 08.07.2015 Experiment (Atomic physics PNC experiments (Cs,...), heavy ion PV research)

General

http://hyperphysics.phy-astr.gsu.edu/hbase/hframe.html

NIST Physical Reference Data - X-Ray and Gamma-Ray Data

http://physics.nist.gov/PhysRefData/contents-xray.html

Fundamental Physical Constants

http://physics.nist.gov/PhysRefData/contents-constants.html

Atomic Spectroscopic Data

http://physics.nist.gov/PhysRefData/contents-atomic.html

X-Ray World Wide Web Server

X-ray Emission Lines http://xray.uu.se/hypertext/XREmission.html

Electron Binding Energies http://xray.uu.se/hypertext/EBindEnergies.html

Berkeley National Laboratory

Table of Isotopes http://ie.lbl.gov/education/isotopes.htm

Atomic Data http://ie.lbl.gov/atomic/atom.htm

Elemental Physical Properties http://ie.lbl.gov/elem/elem.htm (pdf download possible)

CODATA Internationally recommended values of the Fundamental Physical Constants

http://physics.nist.gov/cuu/Constants/index.html

Institute of Chemistry, Free University Berlin

Fundamental Physical Constants http://www.chemie.fu-berlin.de/chemistry/general/constants_en.html

Conversion of Units http://www.chemie.fu-berlin.de/chemistry/general/units_en.html

Periodic tables (professional edition)

http://www.webelements.com/

Korea Atomic Energy Research Institute

Table of Nuclides http://atom.kaeri.re.kr/ton/nuc6.html

Center for Synchrotron Radiation Research and Instrumentation, Chicago, United States

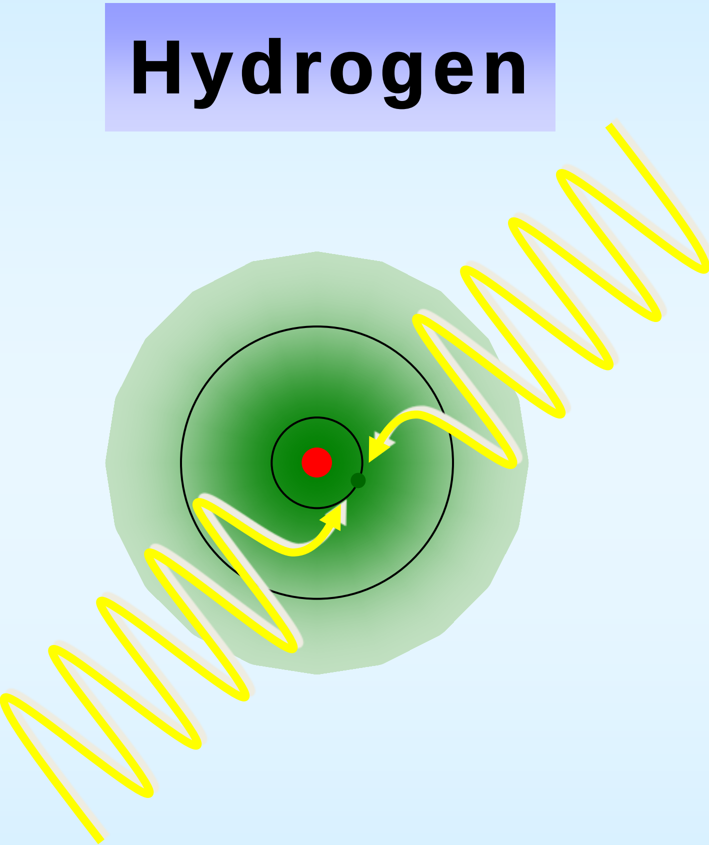
Periodic Table of Elements - X-ray properties

http://www.csrri.iit.edu/periodic-table.html

Contents

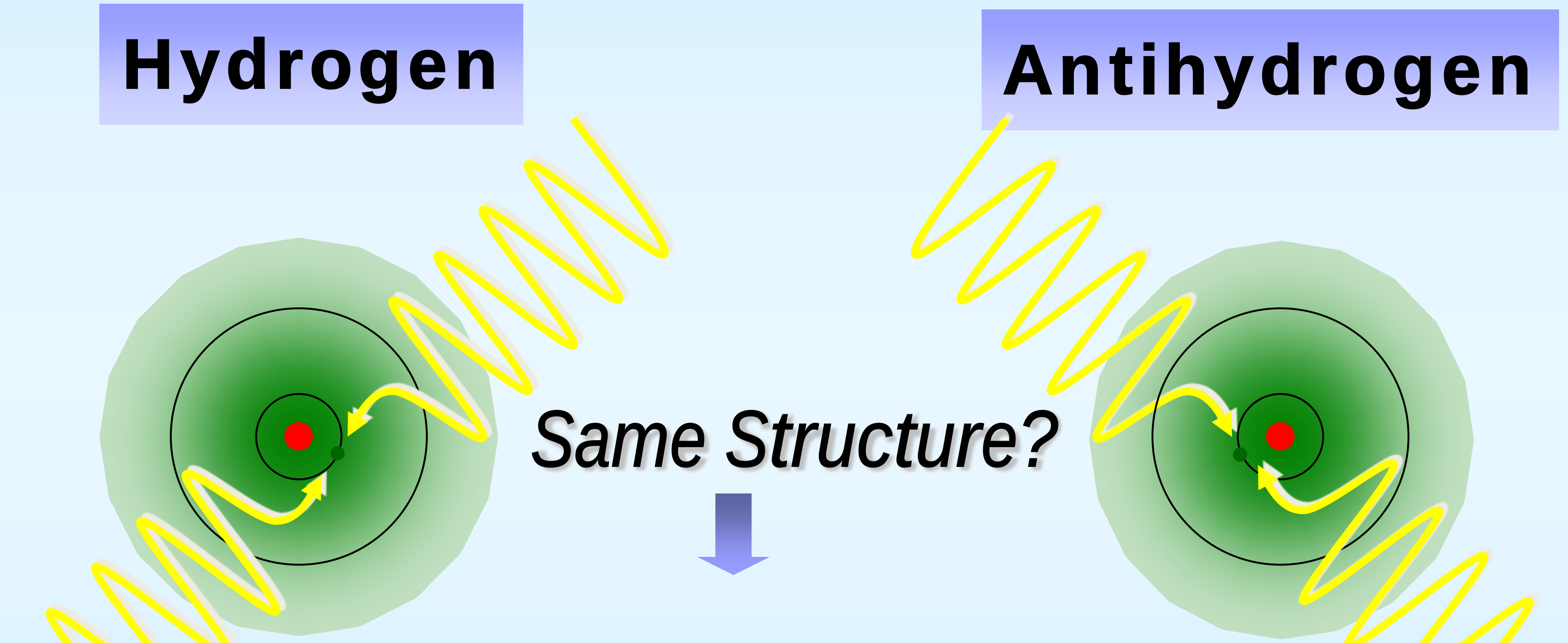
- Summary: The hydrogen atom in a non-relativistic view
- Stern-Gerlach Experiment – The Spin of the electron
- Dirac – The effect of relativity on the atomic structure
- Cosmic Rays
- The discovery of the positron
- First production of antihydrogen
- Positron-Emissions-Tomographie (PET)

Hydrogen atom



$$\Delta E / E \approx 10^{-14}$$

Ultracold & Trapped $\bar{p}$

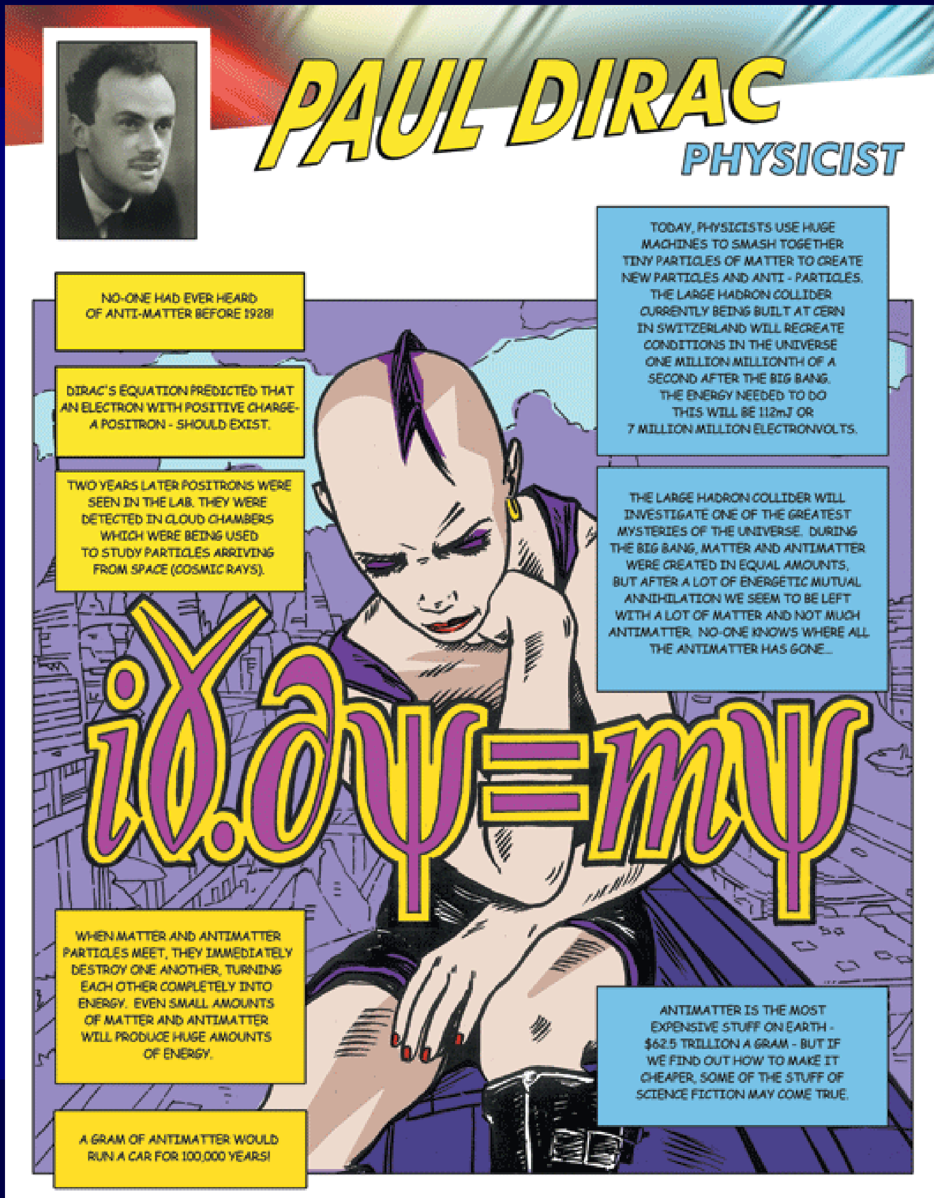


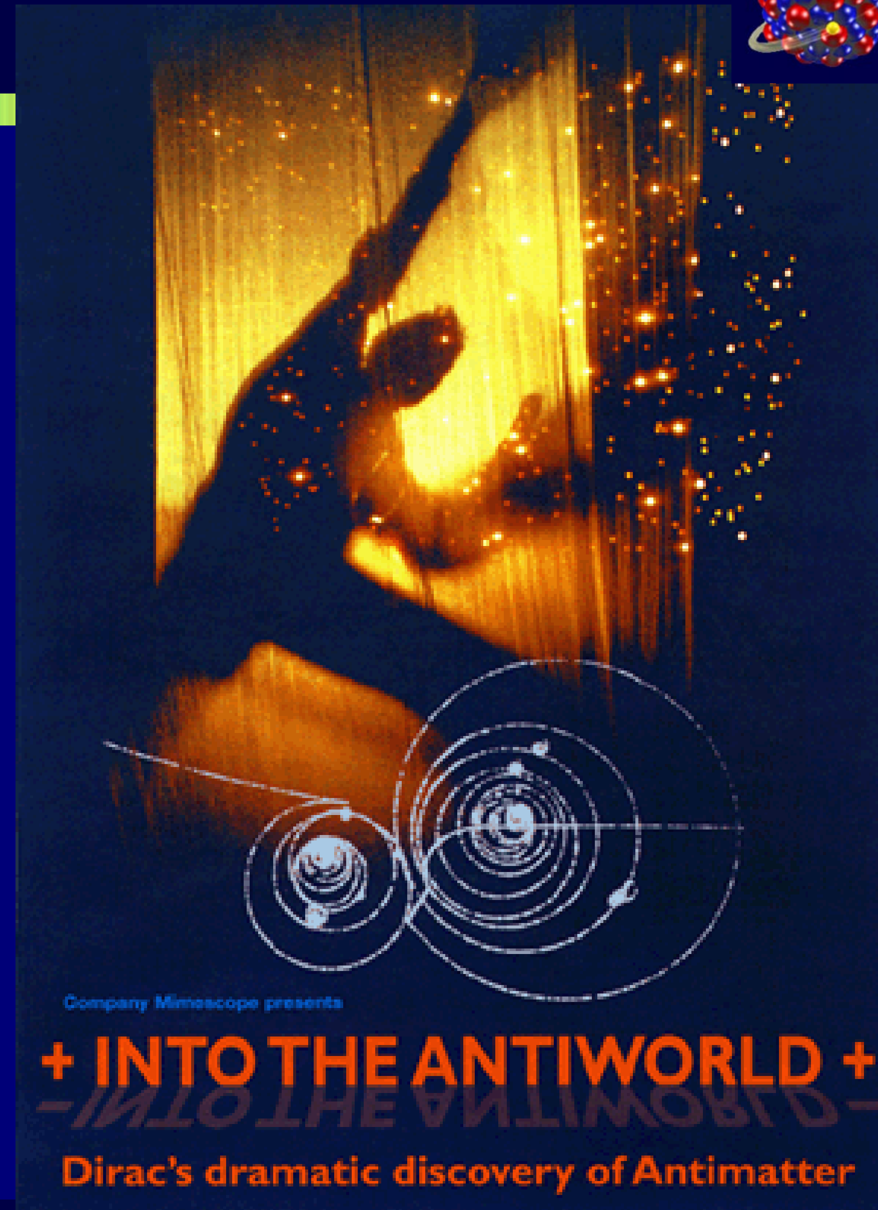
CPT Invariance

$$\Delta E / E \approx 10^{-14}$$

- …d at CERN
- in flight: 1996
- in traps: 2002


DER SPIEGEL
DAS TOR ZU EINER
ANDEREN WELT
Physiker
entschlüsseln
das Geheimnis der
Anti-Materie


PAUL DIRAC
PHYSICIST
NO-ONE HAD EVER HEARD OF ANTI-MATTER BEFORE 1928!
DIRAC'S EQUATION PREDICTED THAT AN ELECTRON WITH POSITIVE CHARGE- A POSITRON - SHOULD EXIST.
TWO YEARS LATER POSITRONS WERE SEEN IN THE LAB. THEY WERE DETECTED IN CLOUD CHAMBERS WHICH WERE BEING USED TO STUDY PARTICLES ARRIVING FROM SPACE (COSMIC RAYS).
$i\gamma.\partial\psi=m\psi$
TODAY, PHYSICISTS USE HUGE MACHINES TO SMASH TOGETHER TINY PARTICLES OF MATTER TO CREATE NEW PARTICLES AND ANTI - PARTICLES. THE LARGE HADRON COLLIDER CURRENTLY BEING BUILT AT CERN IN SWITZERLAND WILL RECREATE CONDITIONS IN THE UNIVERSE ONE MILLION MILLIONTH OF A SECOND AFTER THE BIG BANG. THE ENERGY NEEDED TO DO THIS WILL BE 112mJ OR 7 MILLION MILLION ELECTRONVOLTS.
THE LARGE HADRON COLLIDER WILL INVESTIGATE ONE OF THE GREATEST MYSTERIES OF THE UNIVERSE. DURING THE BIG BANG, MATTER AND ANTIMATTER WERE CREATED IN EQUAL AMOUNTS, BUT AFTER A LOT OF ENERGETIC MUTUAL ANNIHILATION WE SEEM TO BE LEFT WITH A LOT OF MATTER AND NOT MUCH ANTIMATTER. NO-ONE KNOWS WHERE ALL THE ANTIMATTER HAS GONE...
WHEN MATTER AND ANTIMATTER PARTICLES MEET, THEY IMMEDIATELY DESTROY ONE ANOTHER, TURNING EACH OTHER COMPLETELY INTO ENERGY. EVEN SMALL AMOUNTS OF MATTER AND ANTIMATTER WILL PRODUCE HUGE AMOUNTS OF ENERGY.
A GRAM OF ANTIMATTER WOULD RUN A CAR FOR 100,000 YEARS!
ANTIMATTER IS THE MOST EXPENSIVE STUFF ON EARTH - $62.5 TRILLION A GRAM - BUT IF WE FIND OUT HOW TO MAKE IT CHEAPER, SOME OF THE STUFF OF SCIENCE FICTION MAY COME TRUE.


Company Mimescope presents
+ INTO THE ANTIWORLD +
Dirac's dramatic discovery of Antimatter

elprize.org/nobel_prizes/physics/laureates/1933/

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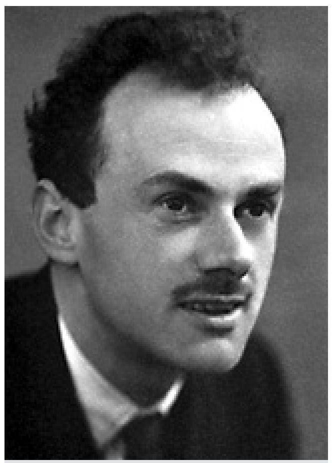
The Nobel Prize in Physics 1933

"for the discovery of new productive forms of atomic theory"



Erwin Schrödinger

1/2 of the prize

Austria

Berlin University
Berlin, Germany

b. 1887
d. 1961

Paul Adrien Maurice Dirac

1/2 of the prize

United Kingdom

University of Cambridge
Cambridge, United Kingdom

b. 1902
d. 1984

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Paul A.M. Dirac

Biography
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Documentary
Banquet Speech
Other Resources

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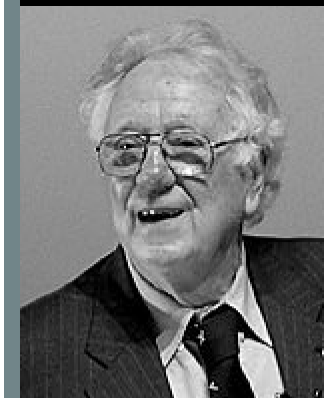
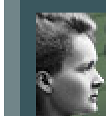
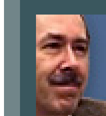


Nobel Lecture by Oliver Smithies



All Physics Nobel Laureates



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Internet

The Nobel Prize in Physics 1936

"for his discovery of cosmic radiation"

"for his discovery of the positron"

Victor Franz Hess

Carl David Anderson

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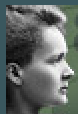

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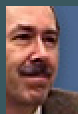

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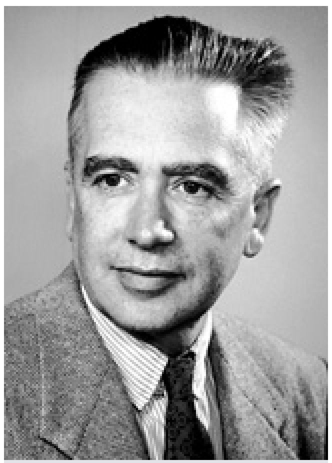
The Nobel Prize in Physics 1959

"for their discovery of the antiproton"



Emilio Gino Segrè

1/2 of the prize

USA

University of California
Berkeley, CA, USA

b. 1905
(in Tivoli, Italy)
d. 1989

Owen Chamberlain

1/2 of the prize

USA

University of California
Berkeley, CA, USA

b. 1920
d. 2006

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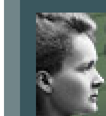
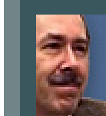
Documentary about Doris Lessing


All Physics Nobel Laureates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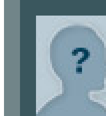
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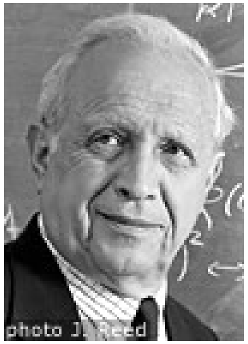
The Nobel Prize in Physics 2005

"for his contribution to the quantum theory of optical coherence"

"for their contributions to the development of laser-based precision spectroscopy, including the optical frequency comb technique"



Roy J. Glauber

1/2 of the prize

USA

Harvard University
Cambridge, MA, USA

b. 1925

John L. Hall

1/4 of the prize

USA

University of Colorado, JILA;
National Institute of Standards and Technology
Boulder, CO, USA

b. 1934

Theodor W. Hänsch

1/4 of the prize

Germany

Max-Planck-Institut für Quantenoptik
Garching, Germany;
Ludwig-Maximilians-Universität
Munich, Germany

b. 1941

http://nobelprize.org/physics/laureates/2005/index.html

The Spectrum of Hydrogen

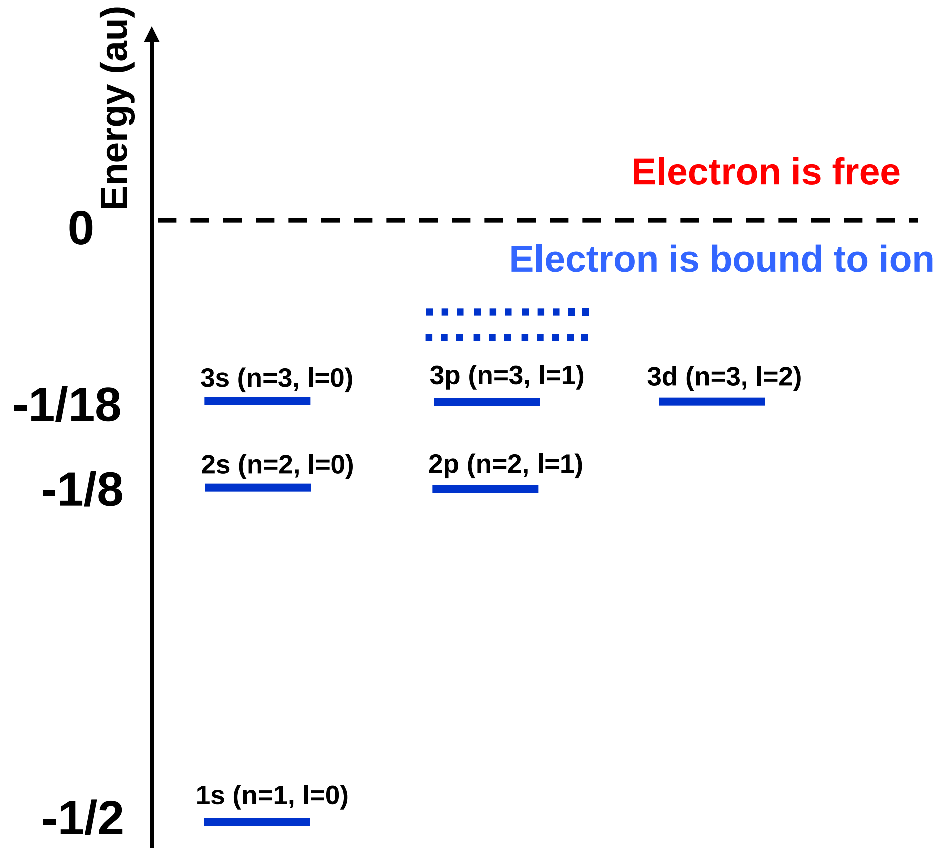
- One needs three quantum numbers to define the state of hydrogen (hudrogen-like) atom:
  - n = 1, 2, 3… (principal)
  - l = 0, … n-1 (orbital)
  - m = -l, …. +l (magnetic)

$$\psi(\mathbf{r}) = \psi(r,\theta,\varphi) = R_{nl}(r)Y_{lm}(\theta,\varphi)$$

- The energy depends only on the principal quantum number:

$$E_n = -\frac{Z^2}{2n^2}$$

- i.e. in nonrelativistic theory the states are degenerate (l, m)!



How to remove degeneracy?
We have to break the symmetry of the system!

Hydrogen

Energy eigenvalue of the hydrogen atom

$$E_n = -\frac{me^4}{32\pi^2\varepsilon_0^2\hbar^2 n^2} = \frac{-13.6}{n^2}\,\mathrm{eV}$$

Schrödinger equation $U \propto -\frac{1}{r}$

$$-\frac{\hbar^2}{2m}\left(\frac{\partial^2}{\partial x^2} + \frac{\partial^2}{\partial y^2} + \frac{\partial^2}{\partial z^2}\right)\psi_{nlm} + U\psi_{nlm} = E_n\psi_{nlm}$$

The solution (energy) for a central Coulomb-potential only depends on the quantum number n, but not on l or m. States with the same n are degenerated, what means they have the same energy.

(In many-electron atoms the degeneracy disappears because of a non-central Coulomb-potential.)

Atomic Units

for electrons $$m_e = 1 \quad \Rightarrow \quad v = p$$

scaling properties $$r = \frac{n^2}{Z} \qquad v = \frac{Z}{n} \qquad E = \frac{1}{2} Z^2$$

fine-structure constant $$c = \frac{1}{\alpha} = 137.036$$

$$\alpha = \left(\frac{e^2}{\hbar \cdot c} \right)_{gauss} ; \alpha = \left(\frac{e^2}{4\pi \cdot \varepsilon_o \cdot \hbar \cdot c} \right)_{SI}$$

$$\alpha = 1/137.03599911(46)$$

Atomic Units

Atomic Units		SI-Units
$\hbar = 1$	atomic Planck constant	$1.05 * 10^{-34}$ Js
$m_e = 1$	atomic mass unit	$9.1 * 10^{-31}$ kg
$e = 1$	atomic charge unit	$1.6 * 10^{-19}$ C
$4\pi\varepsilon_0 = 1$	dielectric constant	

The Bohr-radius defines the atomic length unit

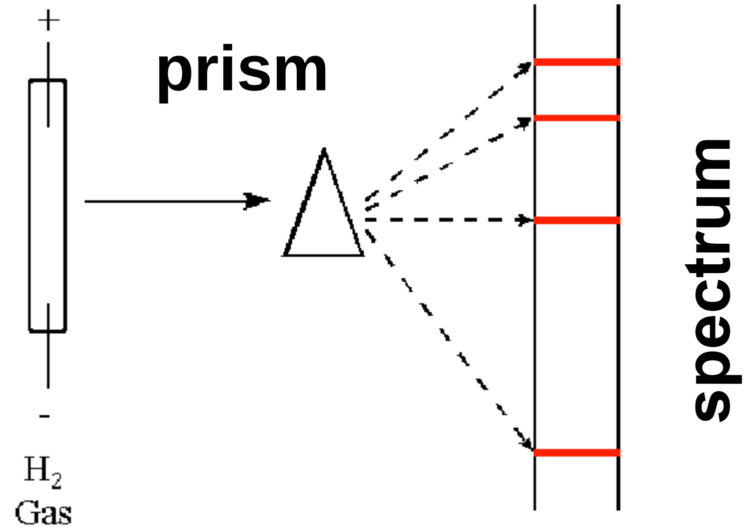
$a_0 = 0{,}53 \cdot 10^{-8}$ cm : 1 a.u.

The atomic energy unit is 27.21 eV and is called Hartree

For the ionization-energy of the hydrogen atom follows

1/2 Hartree = 13.6 eV = 1 Rydberg

The hydrogen spectrum



Balmer-spectrum

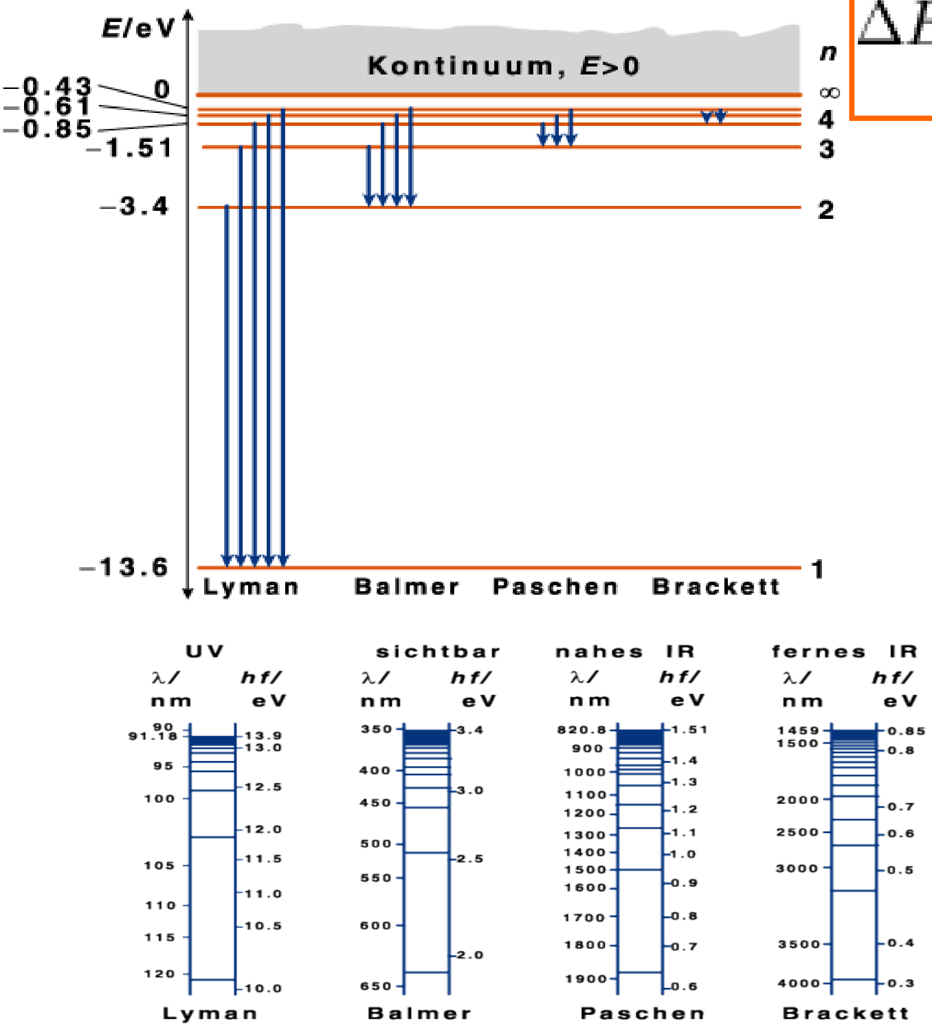
A lot of stars have spectra which are identical to the absorption spectrum of hydrogen. In 1885 Balmer developed an empirical formula to calculate the frequency of these lines

$$\nu_m = R\left(\frac{1}{4} - \frac{1}{m^2}\right) \qquad \lambda_m = \frac{c}{\nu_m} \tag{1}$$

where m $\geq$ 3 and R are constants (Rydberg-frequency). This formula describes for m=3, 4, ... a continuous serial of lines of the frequencies ν_m (resp. the wavelengths λ_m) known as Balmer-series. In general these lines are described in the following way:

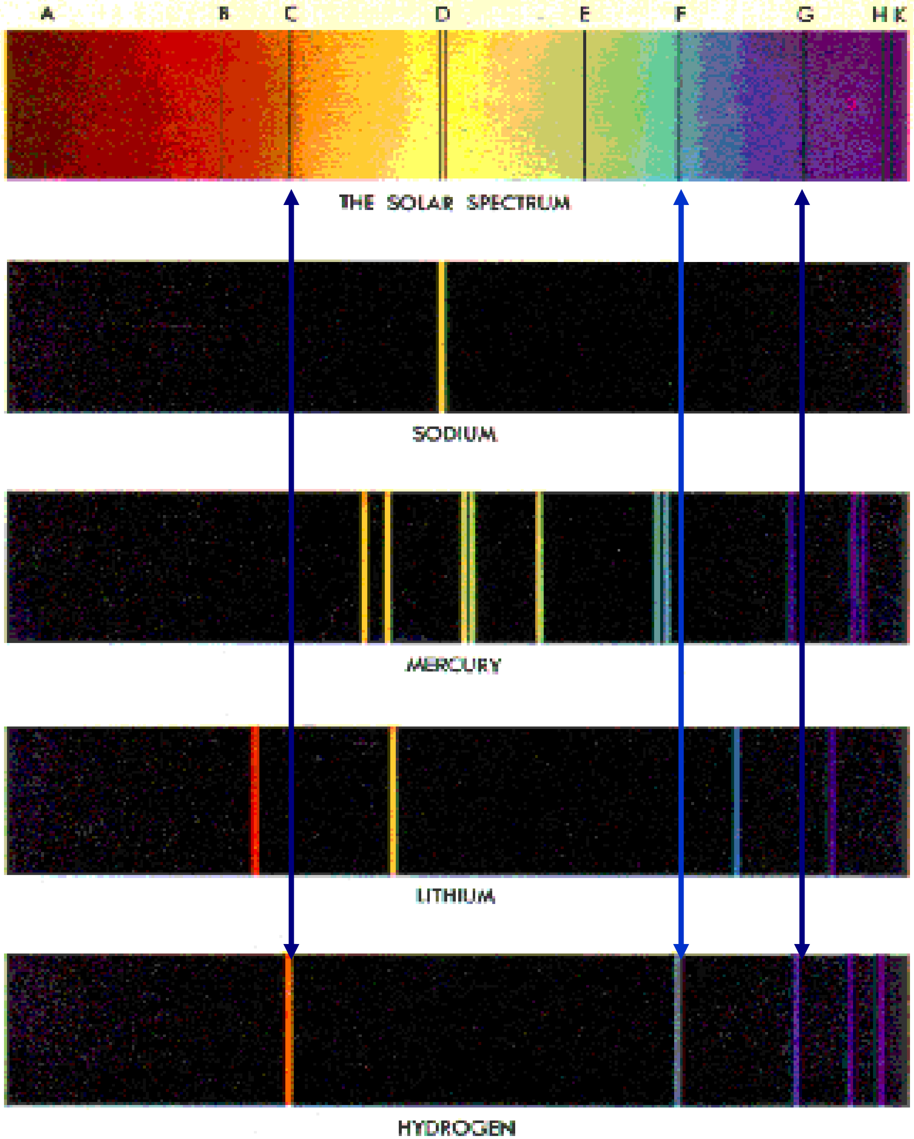
H_α (m=3), H_β (m=4), ...

The spectrum of atomic hydrogen



$$\Delta E = E_i - E_j = \frac{-e^4 m_e}{32\pi^2 \varepsilon_0^2 \hbar^2}\left(\frac{1}{i^2} - \frac{1}{j^2}\right).$$

For the ground state of hydrogen (n=1) the eigenvalue is ***-13.6 eV***. The excitation-energies can be calculated as differences between the energy levels by using the **Rydberg-formula.**



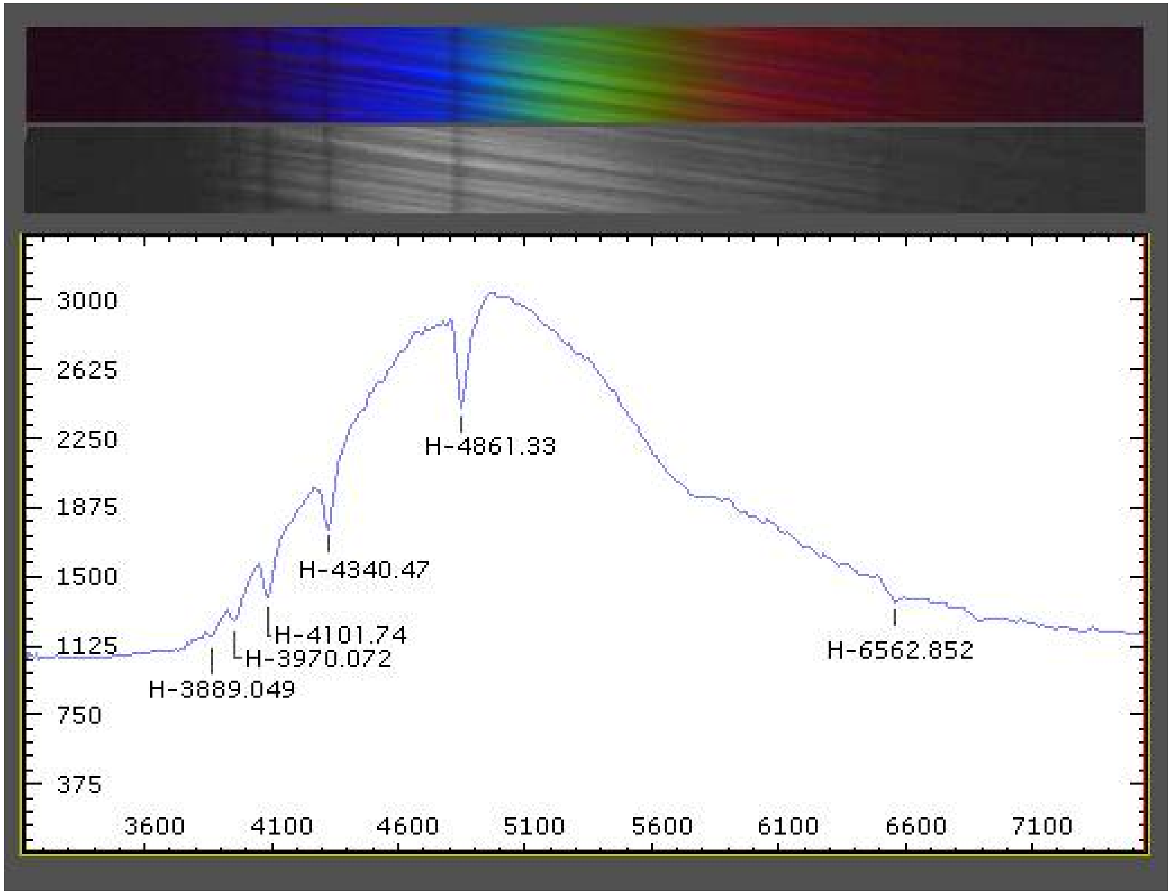
sodium

mercury

lithium

hydrogen

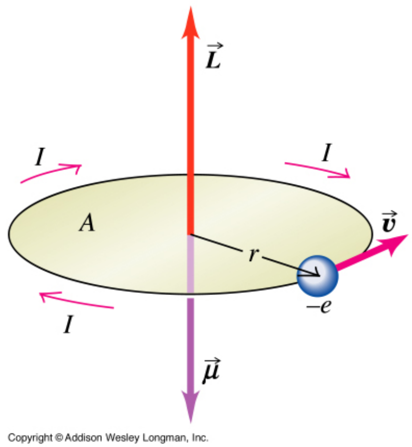
solar spectrum **(top) with absorption-lines of sodium (D) und hydrogen, in comparison to calibration lines of some elements**



Spectrum of Sirius depending on the wavelenght [in A = 10^{-8} cm]
with a multitude of hydrogen (H) –absorption lines from the Balmer-series.

Magnetic moments

Orbital magnetic dipole moment



In classical electrodynamics:

$$|\mu| = \boldsymbol{I} \cdot \boldsymbol{A}$$

current — vector area of the current loop

$$|\mu| = \boldsymbol{I} \cdot \boldsymbol{A} = \frac{q}{T}\pi r^2 = \frac{qv}{2\pi r}\pi r^2 = \frac{q}{2m} mvr = \frac{q}{2m} L$$

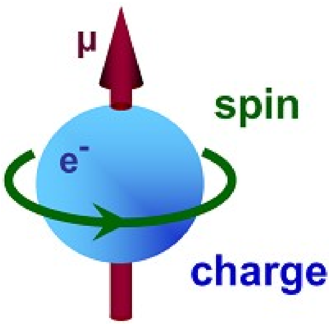
In quantum mechanics, for electron: q=-e

$$\hat{\boldsymbol{\mu}}_l = -\mu_0 \hat{\mathbf{L}} / \hbar, \qquad \mu_0 = \frac{e\hbar}{2m_e}$$

Bohr magneton

Spin magnetic moment

classical picture



$$\hat{\boldsymbol{\mu}}_s = -g_s \mu_0 \hat{\mathbf{S}} / \hbar$$

Gyromagnetic rato

Stern-Gerlach-experiment

The z-component of the angular momentum

(Stern-Gerlach experiment 1922)

example: d-state with n=3

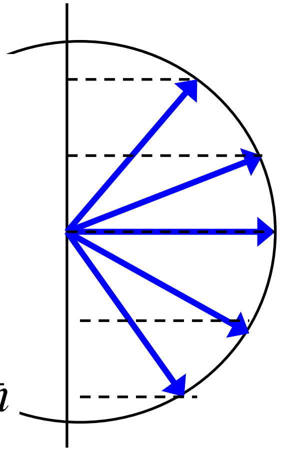
$L_z = 2\hbar$

$L_z = \hbar$

$L_z = 0$

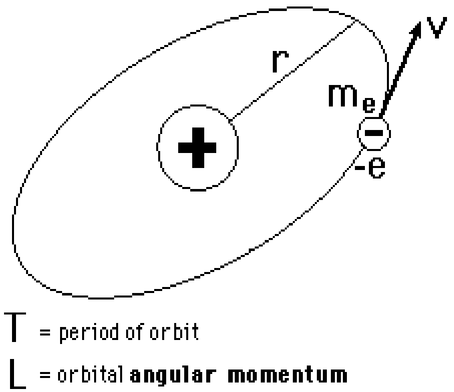
$L_z = -\hbar$

$L_z = -2\hbar$



$$\vec{\mu} = \frac{\mathrm{e}}{2\mathrm{m}}\left(\mathrm{m}\vec{\mathrm{v}} \times \vec{\mathrm{r}}\right) = \mathrm{e}/2\mathrm{m} \cdot \vec{\mathrm{L}}$$

Magnetic moment = current x area



In a magnetic field $\vec{B} = B_z \cdot \vec{e}$ is the ***magnetic* energy** of an electron

$$E = \vec{\mu} \cdot \vec{B} = -\mu_z B_z = -\frac{e}{2m} L_z B_z$$

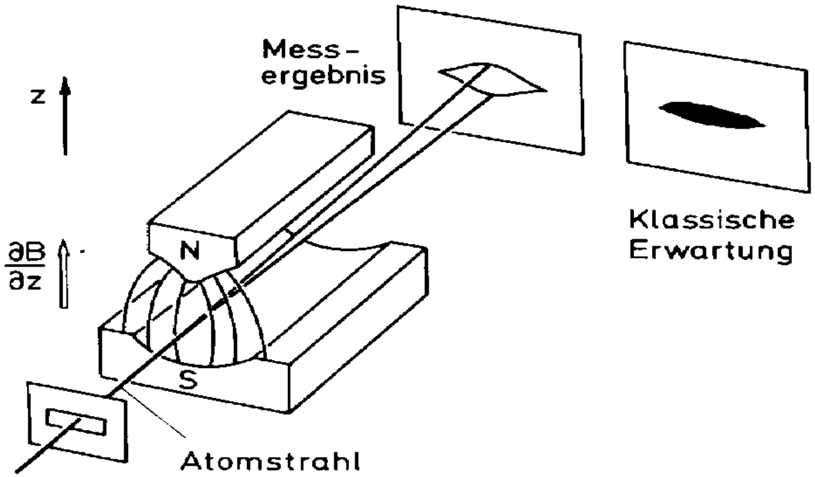
Is **B_z inhomogeneous** ($\partial/\partial z\, B_z \neq 0$), the electron feels a force proportional to L_z

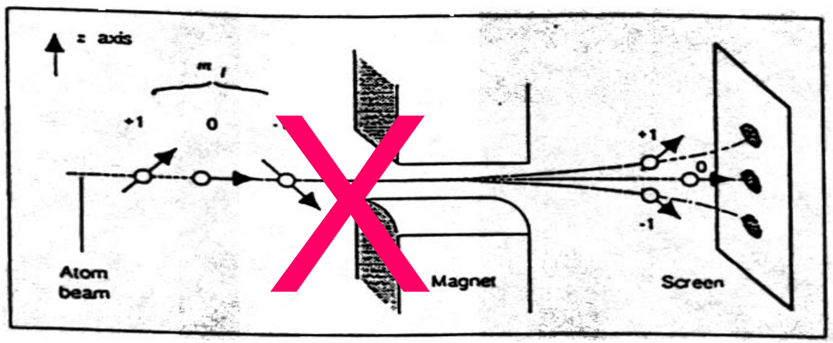
$$F_z \propto -L_z \frac{\partial}{\partial z} B_z$$

Stern-Gerlach Experiment

Stern and Gerlach used silver atoms (Ag, Z=47)
electron configuration: ${}_{36}Kr + 4\,d^{10} + 5s^{1}$; accordingly one valence electron in the 5s-shell

$$F_z \propto -L_z \partial / \partial z B_z$$

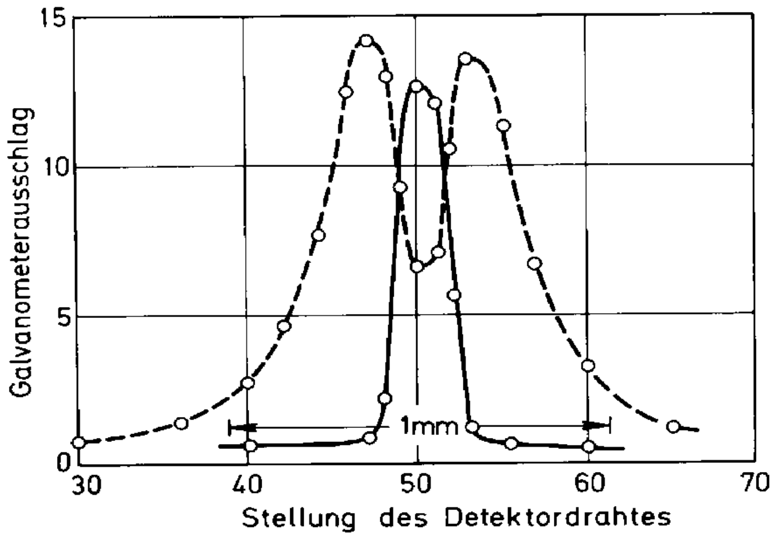




Stern-Gerlach-experiment: In an inhomogeneous magnetic field a beam of silver atoms is diverted and splitted into two beam parts. The magnetic field possesses a gradient of 10 T/cm and a length of 10 cm.

Stern and Gerlach assumed L=1 for the electron and therefore expected a splitting into three parts with

m_z= -1, 0, 1



Observed intensity of the silver atom beam as a function of the distance to the beam axis:
with (dashed line) and without (solid line) magnetic field

Only two lines were observed !!!

⬇

existance of a quantization direction

⬇

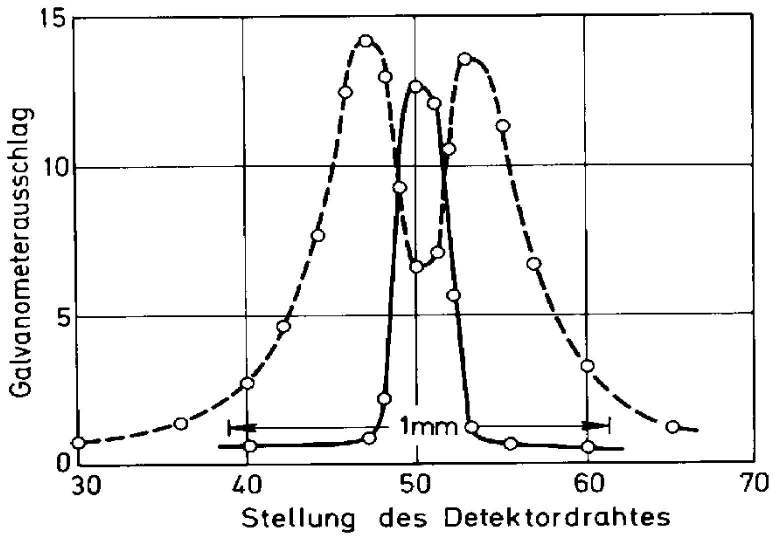
Contrary to the expectation, an even splitting was observed

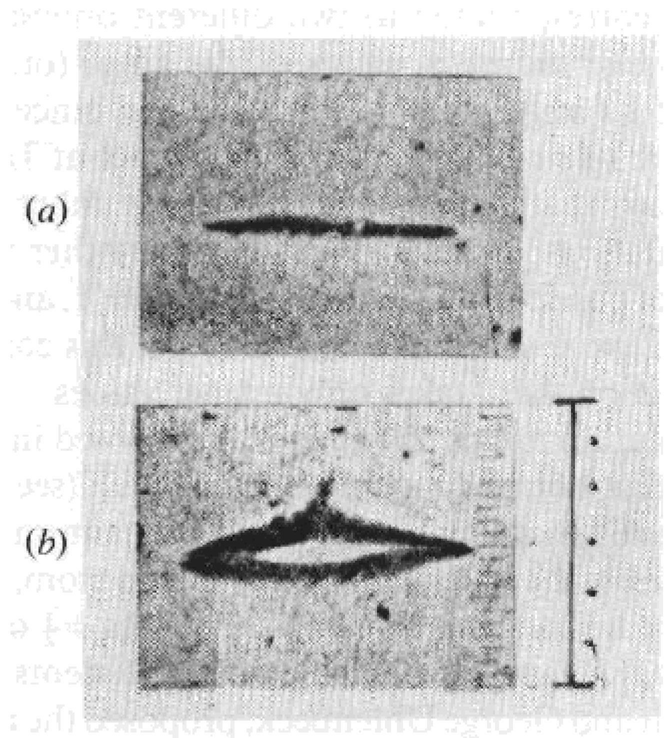
From today's point of view it is known that the assumption **L = 1** for the valence electron in the silver atom was wrong. The 47th electron occupies the 5s -shell and therefore L = 0.
Assuming this, a **single spot** would have been expected instead of **two**!
In 1925 Goudsmit, Uhlenbeck and **Pauli** found the solution to this problem by postulating the
'***exclusion principle'***

Besides the known quantum numbers n, l, m there must be a fourth quantum number

no two electrons of one atom are equal in all four quantum numbers

Stern-Gerlach Experiment: The experimental result





DIRAC theory
(relativistic formulation of quantum mechanics)

Schrödinger's wave function (1926) was the first 'highlight" of the new quantum mechanics. But there was still a problem: the **theory of special relativity** was **not** included.

Hamilton-operator of a free electron according to Dirac

$$\mathrm{H} = \alpha \cdot \mathrm{p} + \beta m_e$$

with the operators α and β (4 x 4 matrix).
The corresponding eigenvalue-equation is:

$$\mathrm{H}|\Psi> = E|\Psi>$$

with the two solutions

$$\mathrm{E} = +\mathrm{c}\sqrt{(\mathrm{p}^2 + \mathrm{m}^2\mathrm{c}^2)}$$

$$\mathrm{E} = -\mathrm{c}\sqrt{(\mathrm{p}^2 + \mathrm{m}^2\mathrm{c}^2)}$$

Unexpected Antiparticles (Dirac)

1928

Since half the solutions must be rejected as referring to the charge $+e$ on the electron, the correct number will be left to account for duplexity phenomena.

1930

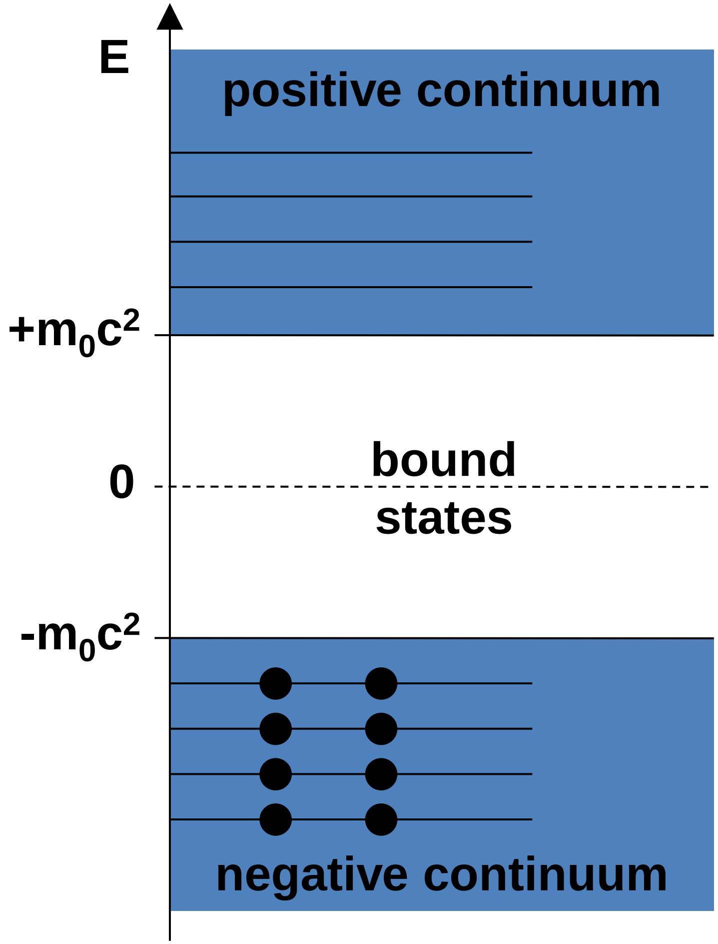
would fill it, and will thus correspond to its possessing a charge $+e$. We are therefore led to the assumption that *the holes in the distribution of negative-energy electrons are the protons*. When an electron of positive energy drops into

1931

nearly all, of the negative-energy states for electrons are occupied. A hole, if there were one, would be a new kind of particle, unknown to experimental physics, having the same mass and opposite charge to an electron. We may call such a particle an anti-electron. We should not expect to find any of

Presumably the protons will have their own negative-energy states, all of which normally are occupied, an unoccupied one appearing as an anti-proton.

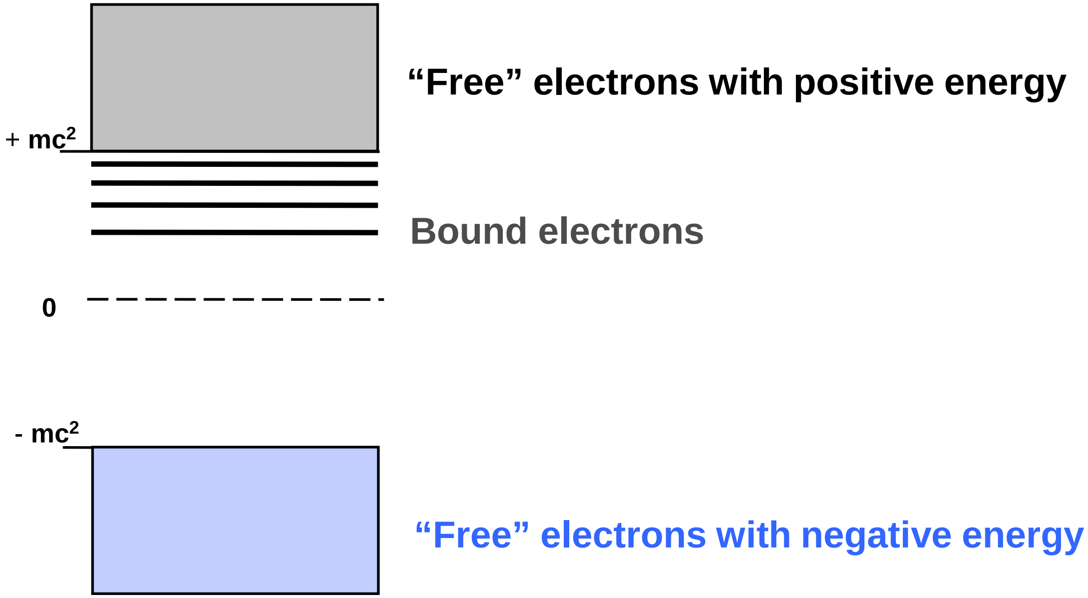
Prediction of anti-matter



Dirac, Anderson, the Positron and the anti-matter. In his famous equation Paul Dirac combined (**1929**) the fundamental equation of quantum mechanics, the Schrödinger-equation with the theory of special relativity. He did not discard the negative energy –solutions of his equation as unphysical but interpreted them as states of the anti-particle of the electron (positron, having the same mass but opposite charge). In **1932** Carl Anderson discovered the positron the first time in the cosmic radiation. This was the proof of the existence of 'anti-matter', with incalculable consequences for the future of physics.

Energy spectrum of the Dirac particle

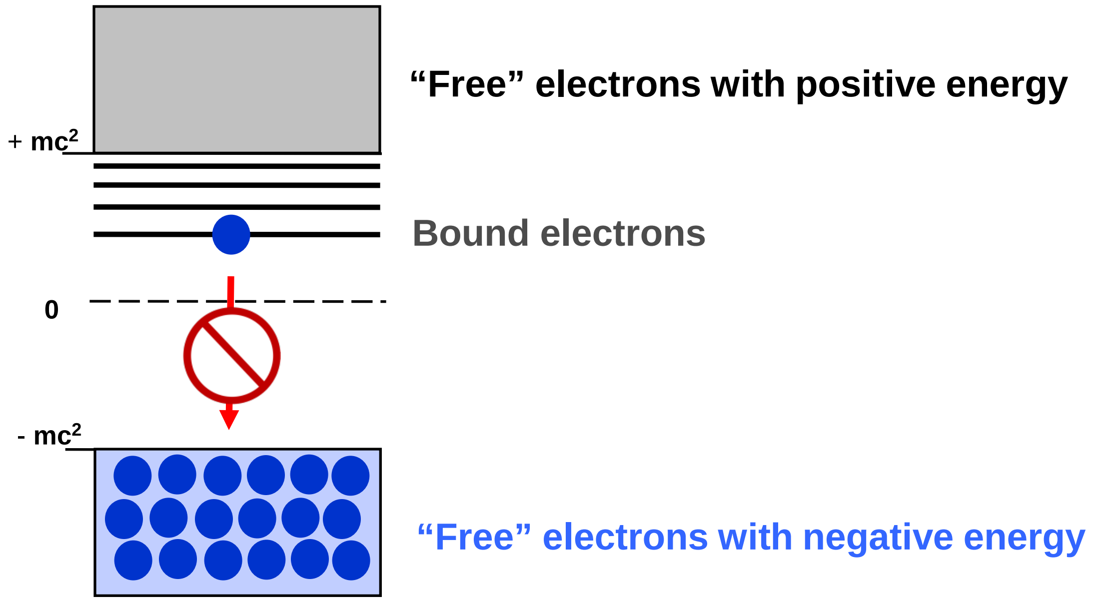
- **For the free particles we found:** $E_{\pm}(p) = \pm\sqrt{(m_e c^2)^2 + (pc)^2}$
  - **Energy of positive energy particles:** $E_{+}(p) > m_e c^2$
  - **Energy of negative energy particles:** $E_{-}(p) < -m_e c^2$



Where is the problem here?

Dirac sea

- **In 1930 Paul Dirac have proposed a theoretical model of the vacuum as an infinite sea of particles possessing negative energy.**



- **Since all the states in Dirac sea are occupied “our” electron can not go down from the domain of positive energies. (Pauli principle.)**

Cosmic Rays and the Discovery of Positrons

The Nobel Prize in Physics 1936
Victor F. Hess, Carl D. Anderson

The Nobel Prize in Physics 1936

Victor F. Hess

Carl D. Anderson

Victor Franz Hess

Carl David Anderson

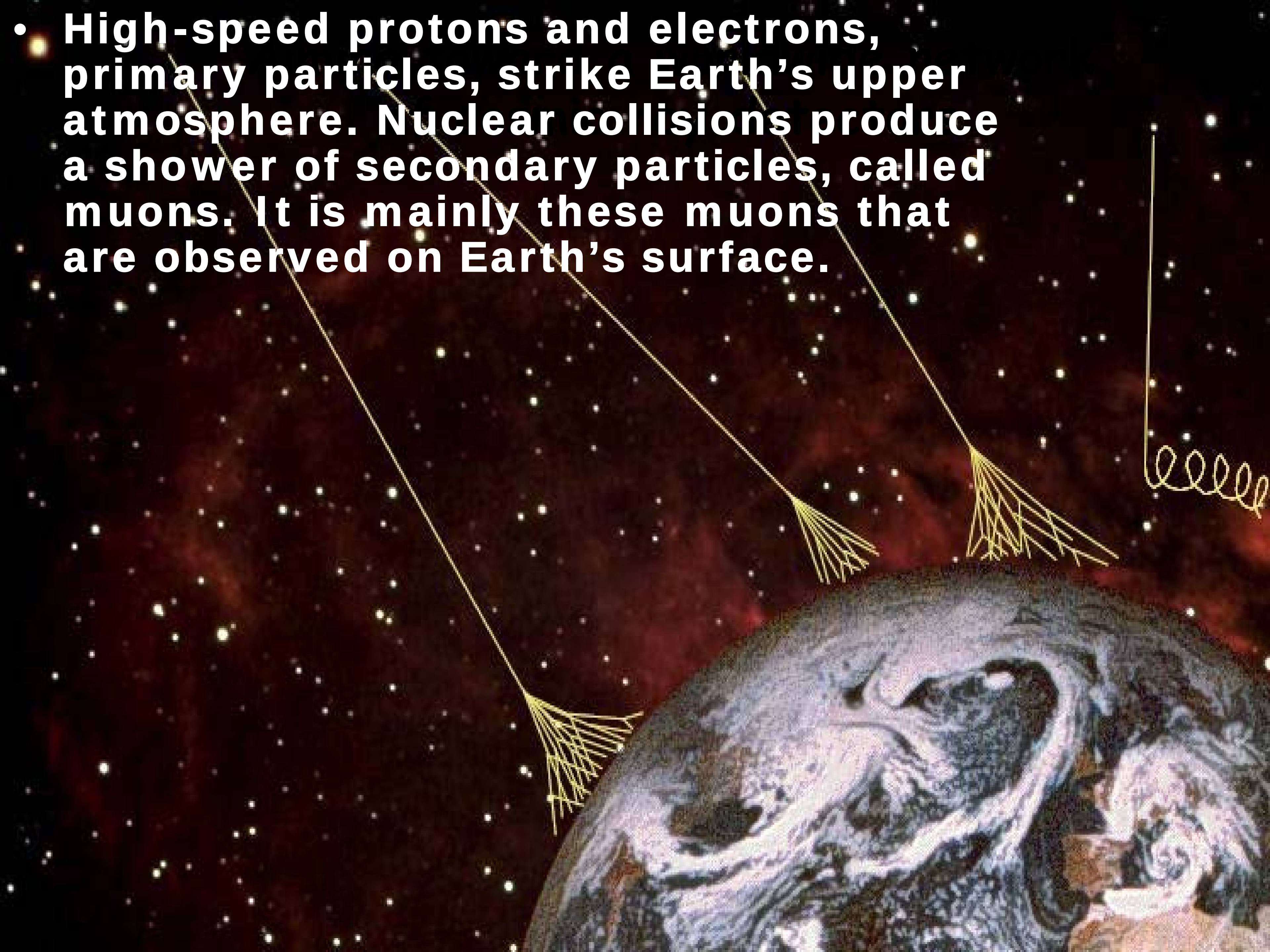
The Nobel Prize in Physics 1936 was divided equally between Victor Franz Hess *"for his discovery of cosmic radiation"* and Carl David Anderson *"for his discovery of the positron"*.

Origin of Cosmic Rays

- **The Sun**
  (mostly low energy)
- **Supernovae**
- **Gamma Ray Bursts**

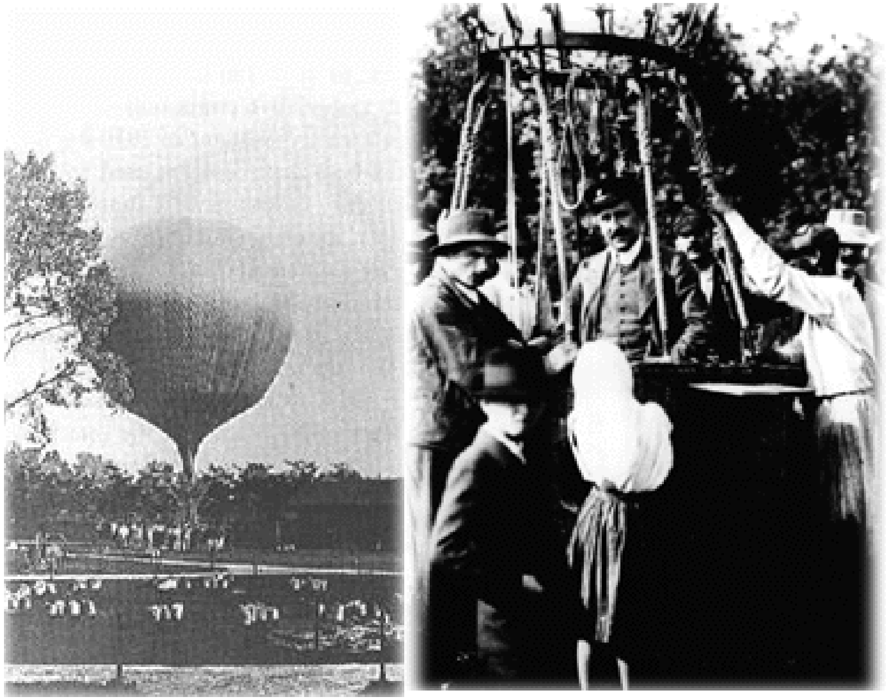
Extra-solar cosmic rays also known as **Galactic Cosmic Rays**, originate and are accelerated to nearly the speed of light by supernovae explosions.

- **High-speed protons and electrons, primary particles, strike Earth’s upper atmosphere. Nuclear collisions produce a shower of secondary particles, called muons. It is mainly these muons that are observed on Earth’s surface.**



Discovery of Cosmic Rays

- From 1911 to 1913 Victor Hess measured radiation levels at various altitudes (up to 4500 m) in the Earth's atmosphere.
- Radiation levels increased with altitude!
- This radiation was called "*Cosmic Radiation*" later became "*Cosmic Rays*".
- Nobel Award in 1936.



http://hires.physics.utah.edu/reading/intro.html

Discovery of Cosmic Rays

wird sie aber gewiß gerne übernehmen; er hat auch einige meiner früheren Blitzaufnahmen übernommen.

Aus der Abteilung für Geophysik, Meteorologie und Erdmagnetismus:

Viktor F. Hess (Wien), Über Beobachtungen der durchdringenden Strahlung bei sieben Freiballonfahrten.

ser Behandlung zeigte Apparat 1 eine normale Ionisation von ca. 16 Ionen, Apparat 2 eine solche von ca. 11 Ionen pro ccm und Sek. Die Firma Günther & Tegetmeyer in Braunschweig hat an den Apparaten noch eine weitere wesentliche Verbesserung angebracht: bisher erfolgte die Scharfeinstellung auf die Fäden durch alleiniges Verschieben des Okulars, was mit nicht unbeträchtlichen Änderungen der Vergrößerung verbunden war und bei wiederholter Einstellung Ablesungsdifferenzen bis zu 0,5 be-

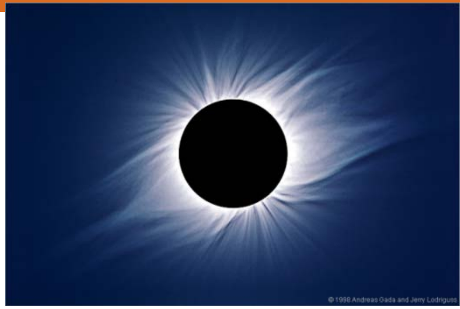
7. Fahrt (7. August 1912).

Ballon: „Böhmen" (1680 cbm Wasserstoff).
Meteorolog. Beobachter: E. Wolf.

Führer: Hauptmann W. Hoffory.
Luftelektr. Beobachter: V. F. Hess.

Nr.	Zeit	Mittlere Höhe		Beobachtete Strahlung				Temp.	Relat. Feucht. Proz.
		absolut m	relativ m	Apparat 1 q_1	Apparat 2 q_2	Apparat 3 q_3	Apparat 3 reduz. q_3		
1	15^h 15—16^h 15	156	0	17,3	12,9	—	—	—	—
2	16^h 15—17^h 15	156	0	15,9	11,0	18,4	18,4	1½ Tag vor dem Aufstiege (in Wien)	
3	17^h 15—18^h 15	156	0	15,8	11,2	17,5	17,5		
4	6^h 45—7^h 45	1700	1400	15,8	14,4	21,1	25,3	+6,4°	60
5	7^h 45—8^h 45	2750	2500	17,3	12,3	22,5	31,2	+1,4°	41
6	8^h 45—9^h 45	3850	3600	19,8	16,5	21,8	35,2	—6,8°	64
7	9^h 45—10^h 45	4800	4700	40,7	31,8			—9,8°	40
		(4400—5350)				—	—		
8	10^h 45—11^h 15	4400	4200	28,1	22,7	—	—	—	—
9	11^h 15—11^h 45	1300	1200	(9,7)	11,5	—	—	—	—
10	11^h 45—12^h 10	250	150	11,9	10,7	—	—	+16,0°	68
11	12^h 25—13^h 12	140	0	15,0	11,6	—	—	(nach der Landung in Pieskow, Brandenburg)	

Discovery



1086 Hess, Durchdringende Strahlung bei sieben Freiballonfahrten. Physik. Zeitschr. XIII, 1912.

waren nicht möglich, da der Ballon infolge der Abkühlung des Gases zum Niedergehen gezwungen wurde.

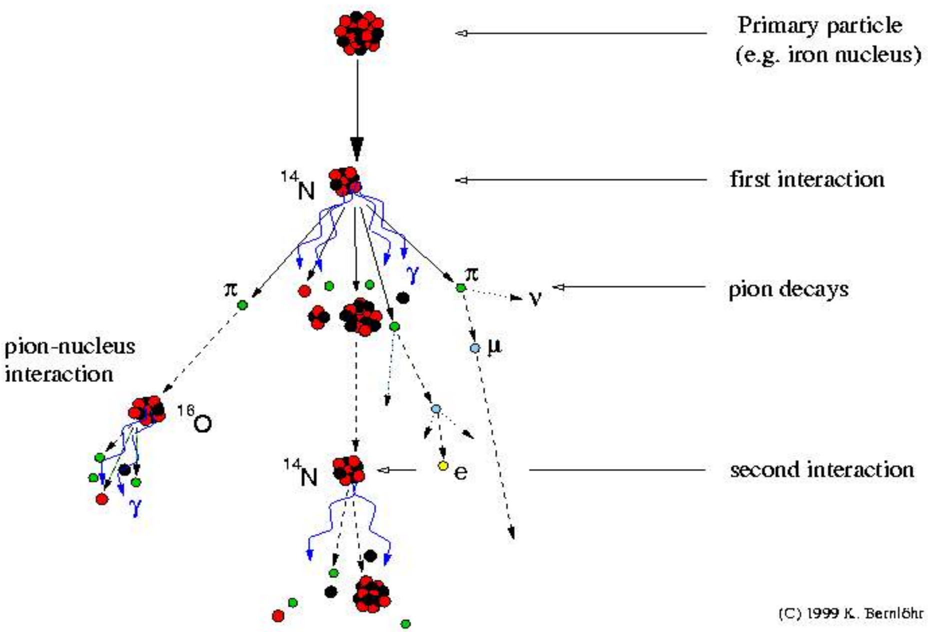
Es wurde also eine Vergrößerung der Strahlung in ca. 2000 m gefunden. Da kein Einfluß der Verfinsterung auf die durchdringende Strahlung zu bemerken war, werden wir schließen dürfen, daß selbst, wenn ein Teil der Strahlung kosmischen Ursprungs sein sollte, er kaum von der Sonne ausgeht, wenigstens solange man eine direkte, geradlinig sich ausbreitende γ-Strahlung im Auge hat. Diese Anschauung wird noch dadurch bekräftigt, daß ich bei den späteren Fahrten im Ballon nie einen ausgeprägten Unterschied der Strahlung bei Tag und bei Nacht gefunden habe.

Hess determined that “essentially, the sun could not be the source of cosmic rays, at least as far as the undeflected (by the solar eclipse) rays were concerned.”

Production of Positrons in the Atmosphere

Cascades

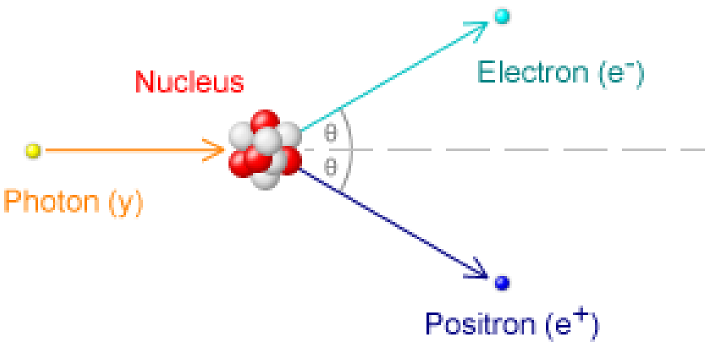
Development of cosmic-ray air showers



$$\pi^+ \rightarrow \mu^+ + \nu_\mu$$
$$\pi^- \rightarrow \mu^- + \overline{\nu}_\mu$$

$$\mu^+ \rightarrow e^+ + \nu_e + \nu_\mu$$
$$\mu^- \rightarrow e^- + \nu_e + \nu_\mu$$

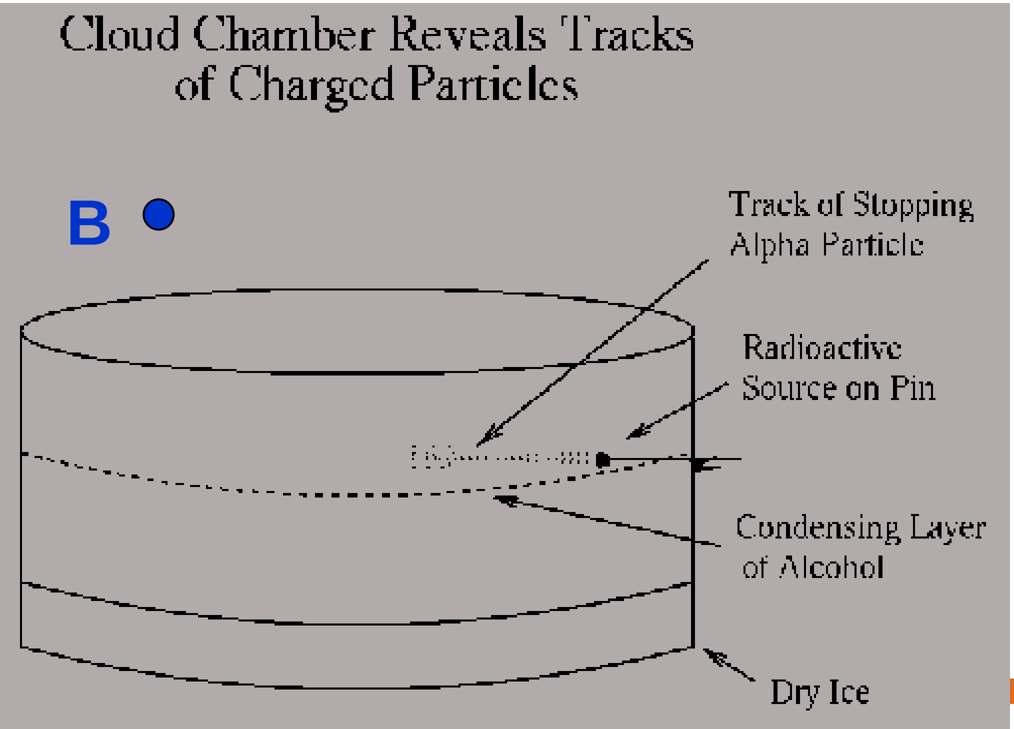
Direct Production by Gammas



Discovery of the positron (Carl David Anderson 1905 – 1991)

Detector (cloud chamber: Wilson 1910)

Cloud chamber is filled with over-saturated watersteam, which condensates along the track of an energetic, ionizing particle. In addition a strong **magnetic field B** is applied to the cloud chamber. A **charged particle** will be forced on a **circular,** in general case an **ellipsoidal track** by the B field which crosses the interaction plane perpendicularly.



Charged particle in magnetic field:
(momentum **mv** and **B** are perpendicular)

$$\frac{mv^2}{r} = qvB$$

$$\Rightarrow rB = B\rho = \frac{mv}{q}$$

$B\rho$ magnetic ridigity

detector in magnetic field: particles are moving on a circular track

Issues to be considered by the experiment

1. What can be used as a **source for positrons**?

2. How is it possible to determine the **signature of the charge**?
   (Did the particle come from the 'top' or from 'bottom'?)

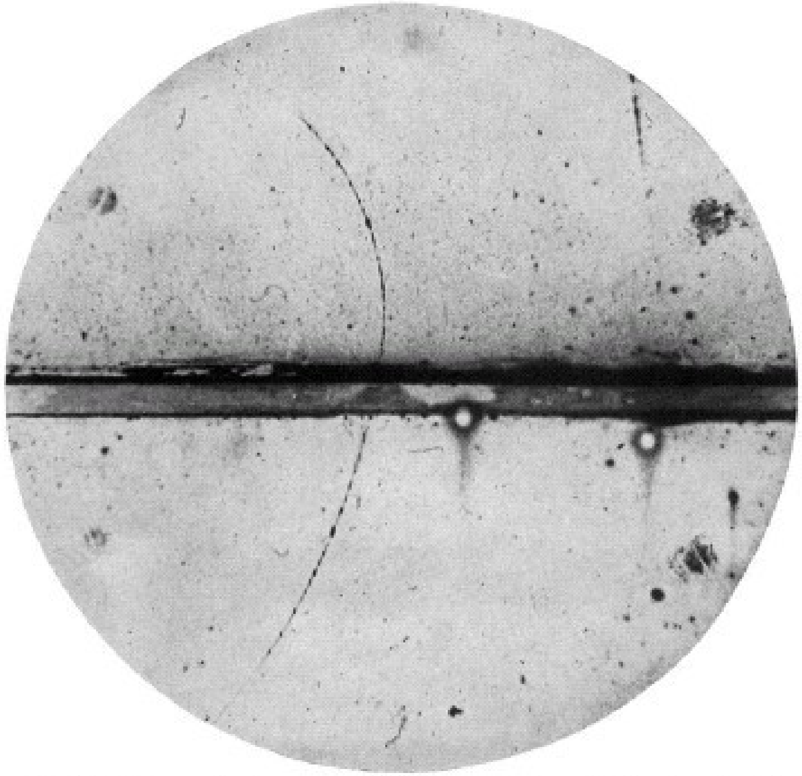
3. How can the 'new' **positron** with electron mass $\mathbf{m_e}$ and positive charge $\mathbf{q = + e}$ be distinguished from a p**roton** in case, only momentum-measurement is possible?

Solutions:

1. Cosmic radiation

2. Cloud chamber: separated by a lead-plate of 6mm thickness, which extenuates the energy of the cosmic particle. As a result, the radius of curvature has to be smaller before passing the plate then afterwards. This gives the incoming-direction.

3. for protons and positrons with given momentum **mv** the range of coverage in the cloud chamber differs a lot!



The first confirmation of a positron

Cloud chamber photograph by Andersen

- Phys. Rev. 43, 491 (1933)
- Nobel prize 1936 together with Victor Hess !

The first **'fingerprint' of anti-matter**. Anderson discovers the trace of a positron in his cloud chamber (in the middle one can see a lead-plate of 6mm thickness).

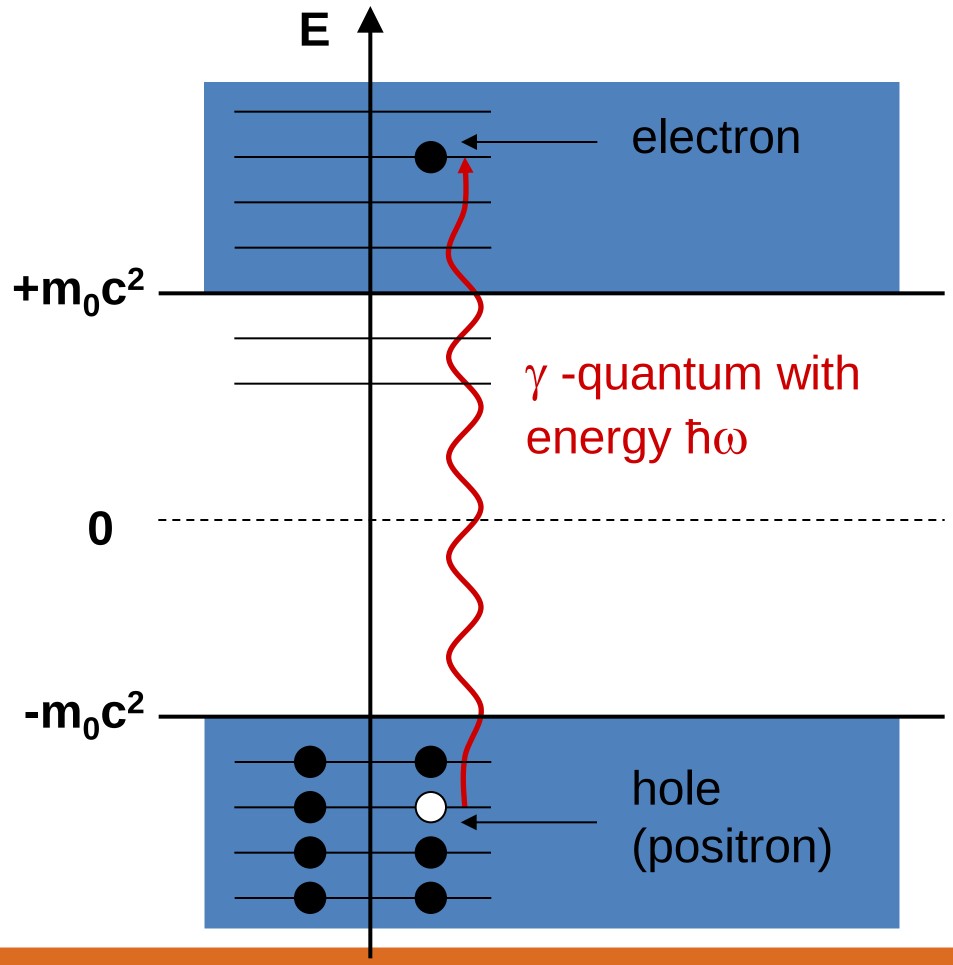
1. The **upper** part of the bending gives information about the **incoming-direction.**

2. The **lower** part gives the **positive charge** of the particle by its bending-direction.

3. By analyzing the **radius of curvature** before and after the transition the momentum can be estimated

Electron-positron pair production

In order to produce electron-positron pairs we would need:
at least two times the rest mass of the elecreon !!!



- energy of about

$$\hbar\omega \approx mc^2 \approx 1MeV$$

to induce pair production

In case a whole in the negative continuum excits, an electron will immediately fill the vacancy and two 511 keV quanta are emitted.

Application in tomography

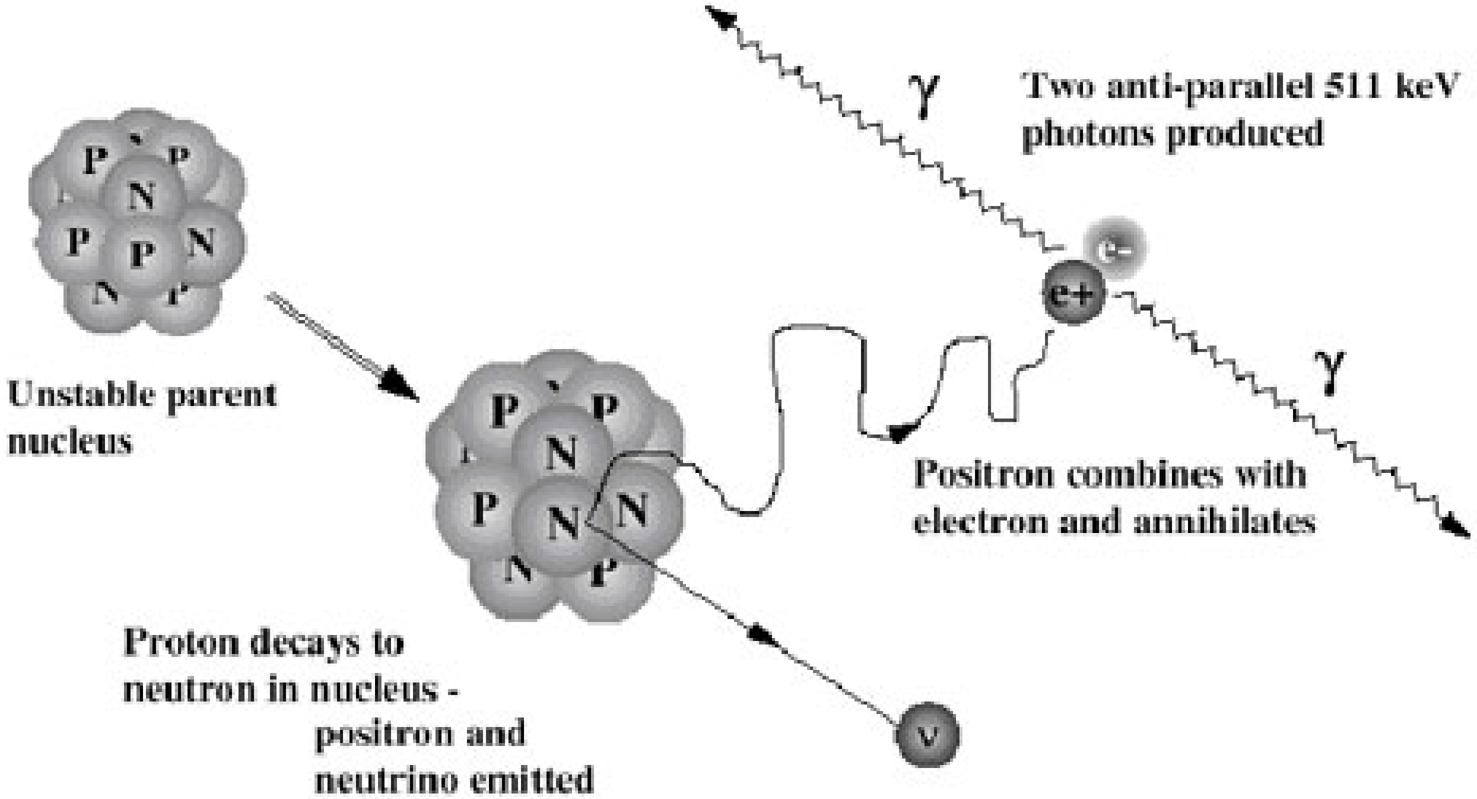
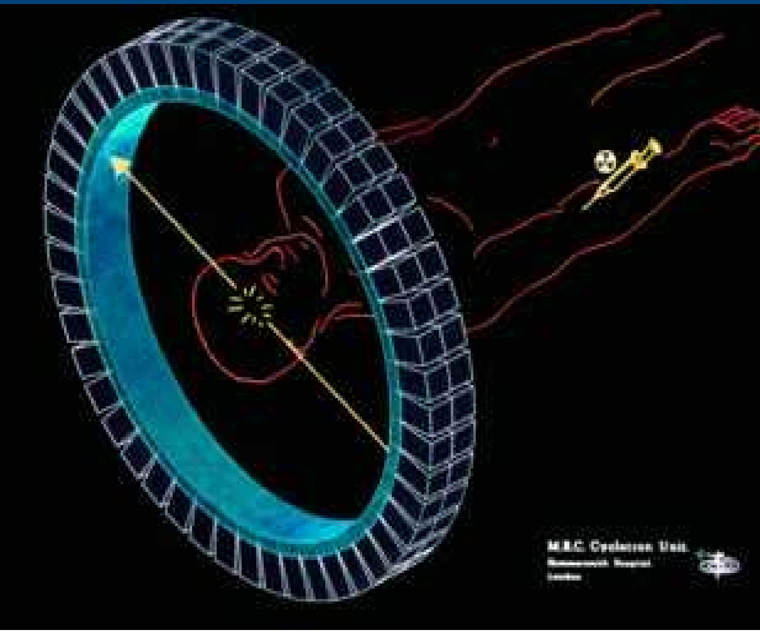
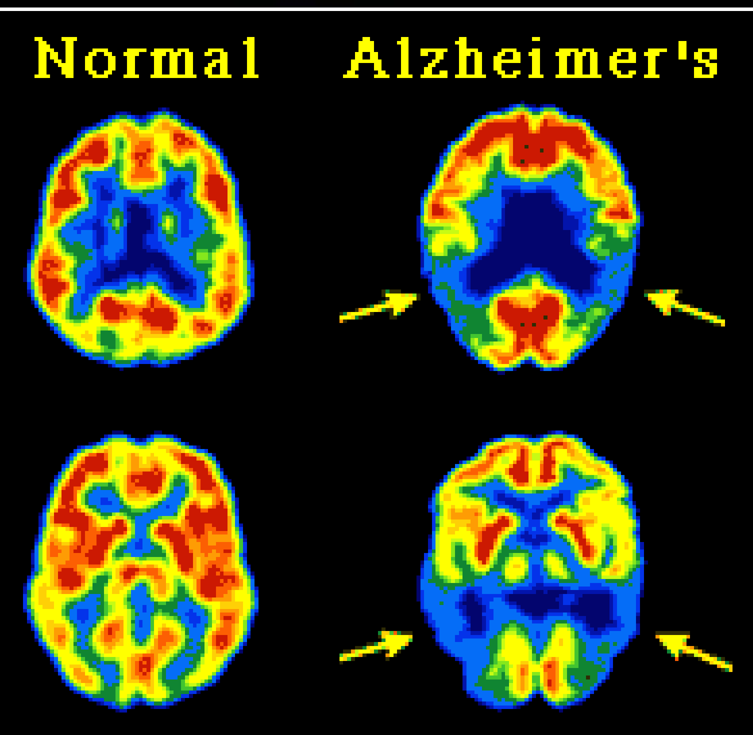


Figure 1.1. Positron emission and annihilation.

Production of a positron during β+ decay and annihilation afterwards



Positron emission tomography (**PET**):
β+ -active C-, O-, or Fluor-nuclei are injected into the brain. There the local brain activity can be measured by detecting the collinear 511 keV photons of the **electron-positron elimination-radiation**



PET - camera made of segmented (position sensitive) γ-detectors

Brain activity measured with PET

Matter ⇔ Energy $E=mc^2$

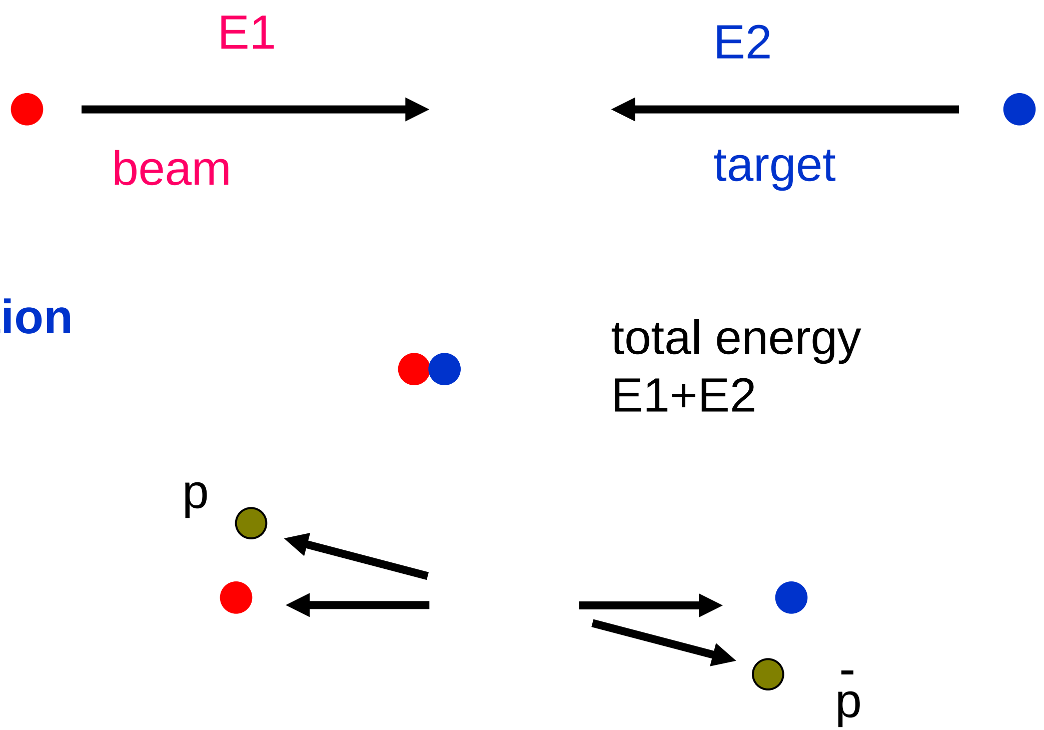
Collision processes of high-energetic particles (cm system), particle production (antiproton production)

$$p + p \Rightarrow p + p + (p + \bar{p})$$

i) Initial

ii) interaction

iii) final

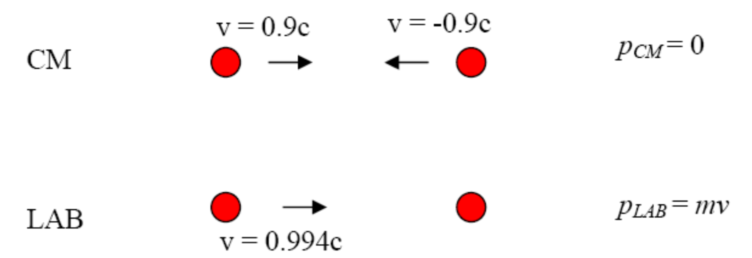


(total momentum $p_1 + p_2 = 0$)

total energy E1+E2

Total energy: $E1 + E2 = mc^2 > 4\, m_0\, c^2$

Threshold !!!



The same collision as viewed in the CM and LAB frames.

$$E^2 = \left(m_0c^2\right)^2 + c^2p^2$$

$$m \cdot c^2 = \sqrt{E^2 - \vec{p}^2 \cdot c^2}$$

Comparing the center of mass energy with the lab energy at these high energies,

$$E_{lab} = (m + m_0)c^2$$

$$E_{cm}{}^2 - c^2p_{cm}{}^2 = E_{lab}{}^2 - c^2p_{lab}{}^2$$

$$E_{cm}{}^2 = E_{lab}{}^2 - c^2p_{lab}{}^2; \quad \text{but } p_{cm} = 0$$

$$E_{cm}{}^2 = m^2c^4 + 2mc^2m_0c^2 + m_0^2c^4 - p_{lab}^2c^2; \qquad p_{lab} \approx mc$$

$$E_{cm}{}^2 = m_0c^2\left(2mc^2 + m_0c^2\right)$$

$$E_{cm}{}^2 = 2m_0c^2mc^2\,; m >> m_0$$

$$E_{cm} \approx \sqrt{2m_0c^2E_{lab}}$$

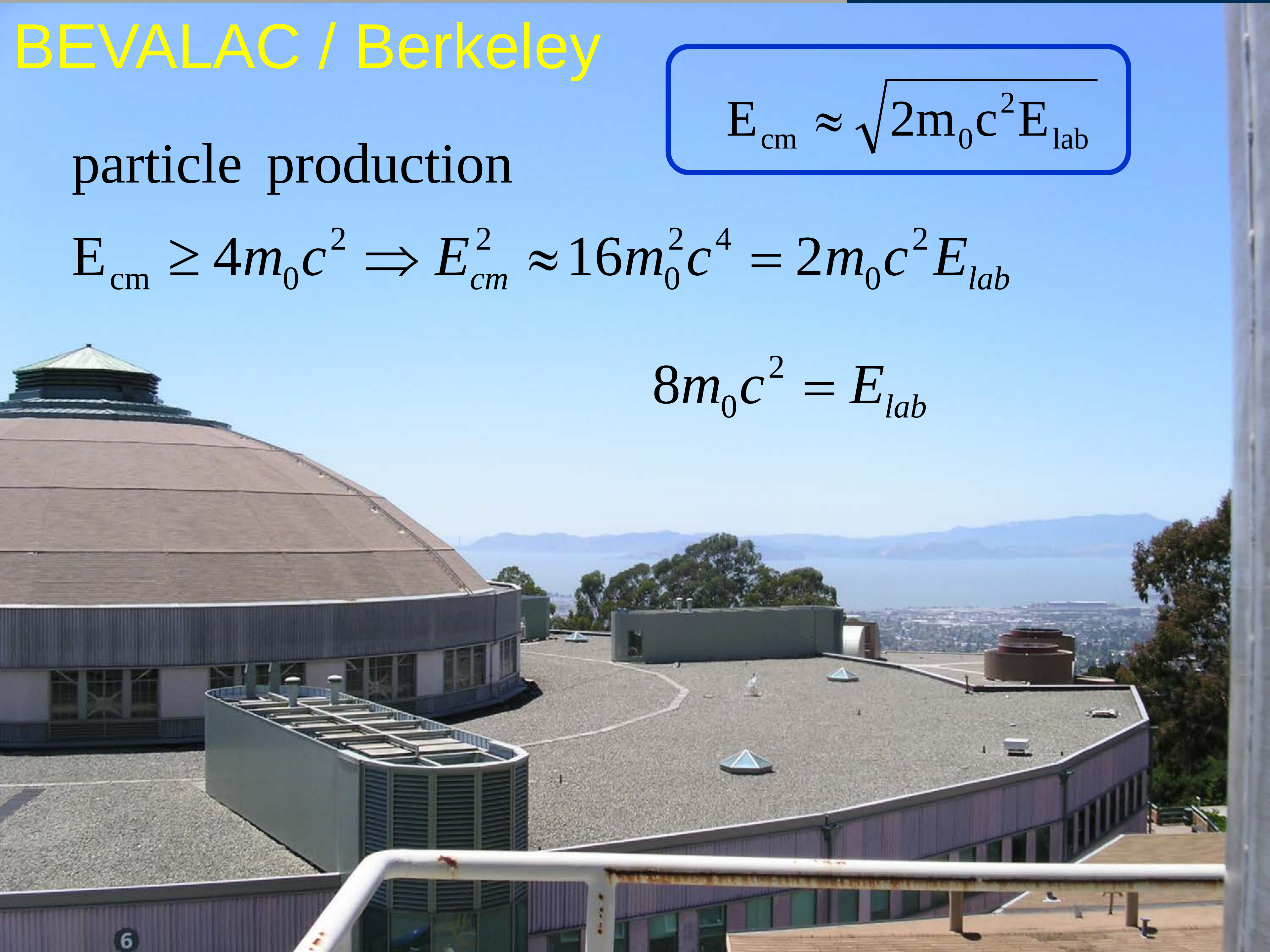
BEVALAC / Berkeley

$$E_{cm} \approx \sqrt{2m_0c^2E_{lab}}$$

particle production

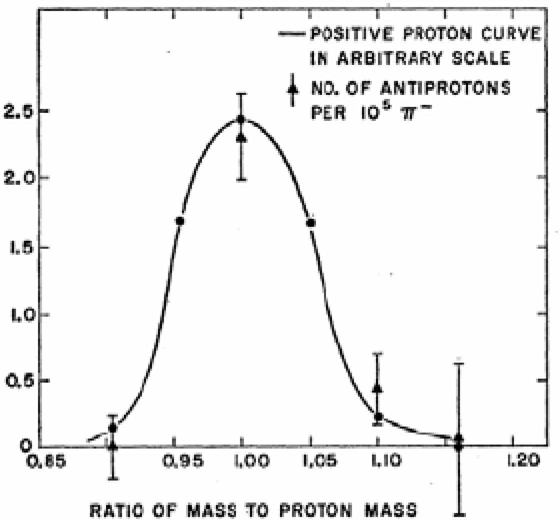
$$E_{cm} \geq 4m_0c^2 \Rightarrow E_{cm}^2 \approx 16m_0^2c^4 = 2m_0c^2E_{lab}$$

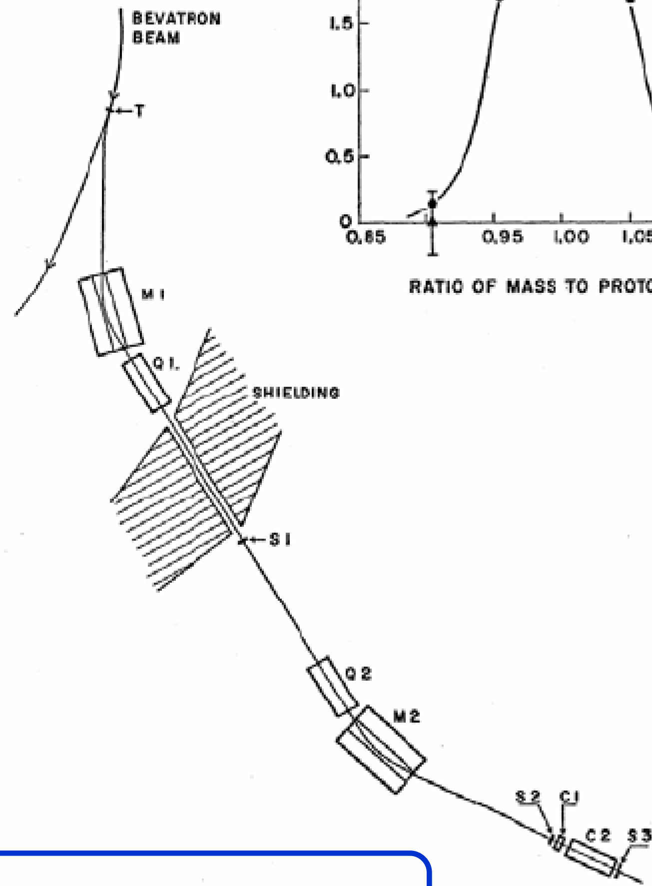
$$8m_0c^2 = E_{lab}$$



Discovery of the Antiproton

- *Bevatron 5.6 GeV*
  - Just at threshold!
- *Discrimination against π⁻: measure*
  - Momentum
    - Magnets: 1.19 GeV
  - Velocity
    - TOF 51 vs. 40 ns
  - Cerenkov counter veto
- *60 events in 1955*
- *$\Delta m/m_p \sim 5\%$*

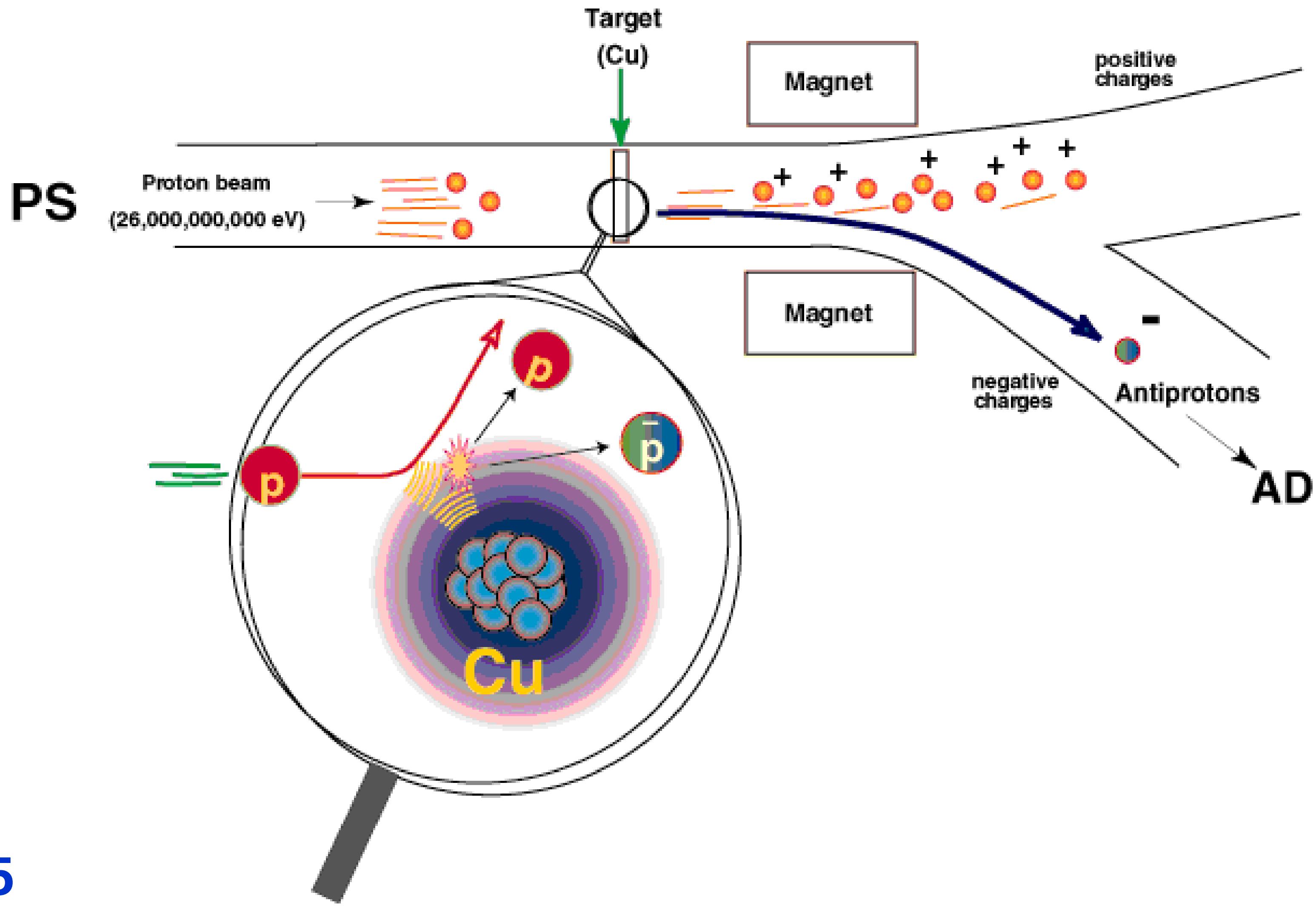




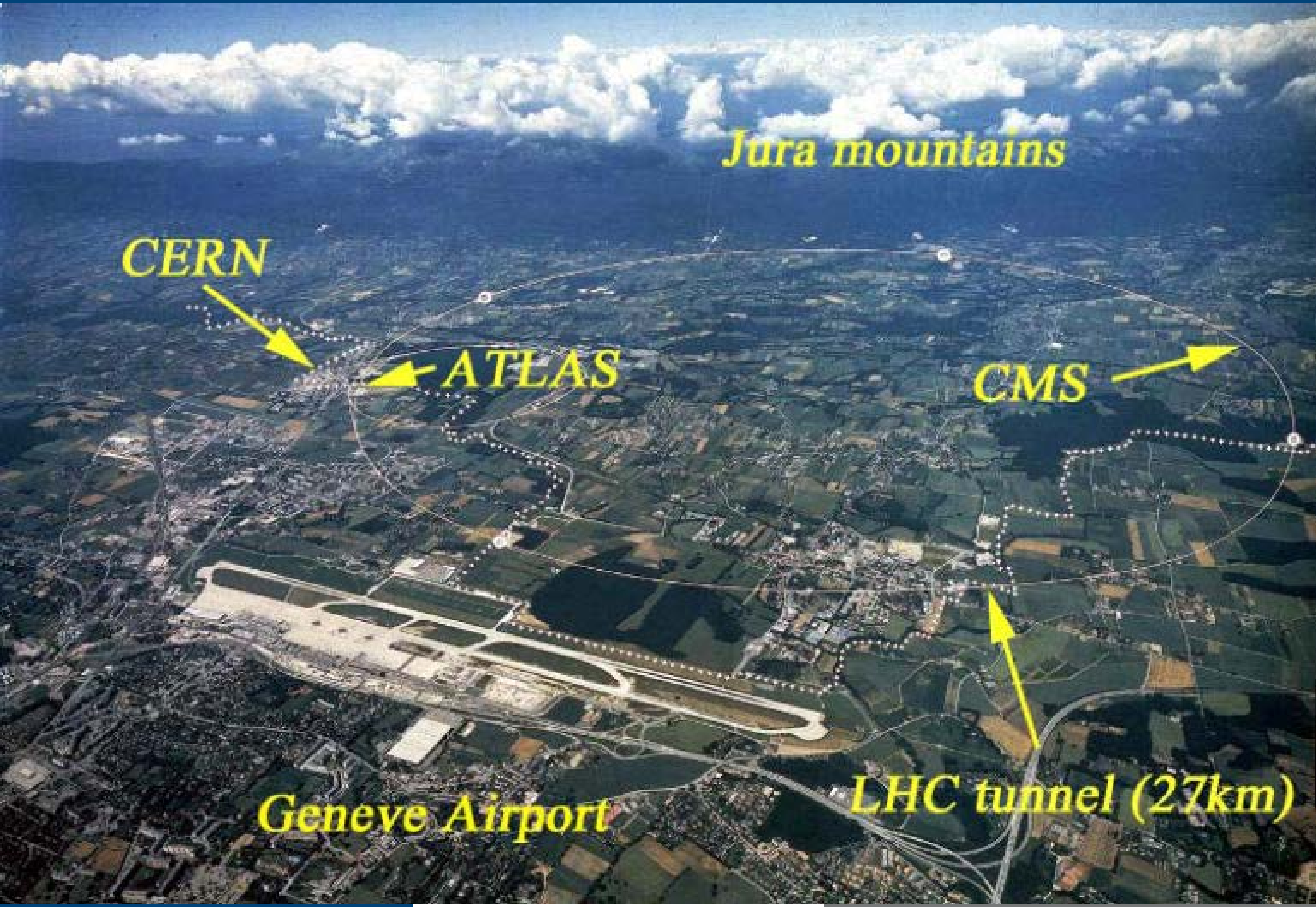
- O. Chamberlain, E. Segre, C. Wiegand, T. Ypsilantis, Phys. Rev. 100, 947 (1955)
- *Nobelprize Chamberlain & Segre 1959*

p + p => p + p + (p + p)

Principle of Antiproton Production



1995


Jura mountains
CERN
ATLAS
CMS
Geneve Airport
LHC tunnel (27km)

1. Consider the process of electron-positron pair production in the field of bare uranium nucleus (Z=92). Estimate the minimal energy needed for such a process assuming that the electron is created in the ground, 1s, state of the resulting hydrogen-like ion. Give the result in eV.
2. The (classical) velocity of the electron in the groud state of hydrogen atom and moving around the nucleus is, according to Bohr model, v = 0.007*c where c is the speed of light. Estimate the velocity of electron moving in the field of uranium nucleus (Z=92).
3. Consider boron-like magnesium-ion Mg^{7+} (nuclear charge Z=12, number of electrons N=5) in which one of electrons is in the Rydberg state with n=50. Find ionization energy for the outer (Rydberg) electron.
4. Assume that you are observing radiative decay between 4d and 3p states of atomic hydrogen. How many lines in the spectrum will you observe if you place the atoms in a magnetic field?