Inside the Proton

J. Pretz
RWTH Aachen/ FZ Jülich

Jülich, July 2017

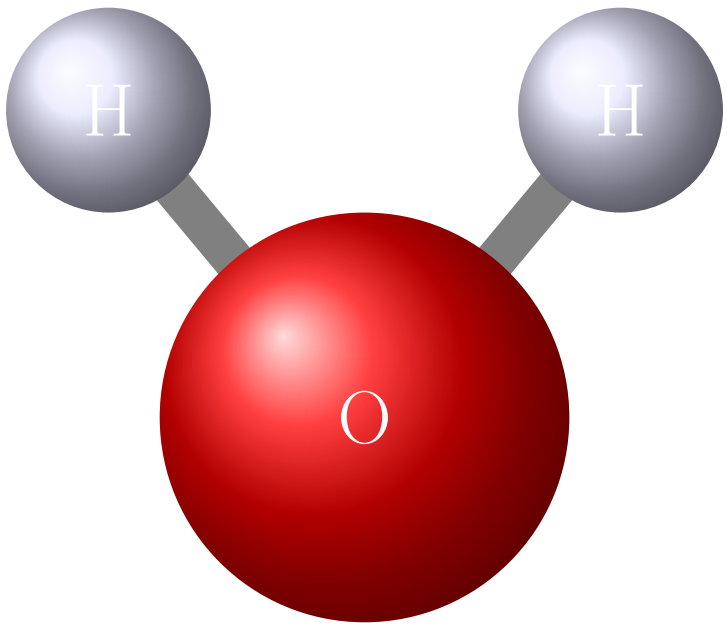
- **What is a proton?**
  Composition of matter
- **How does the inside of the proton look like?**
  Scattering experiments
- **Open Questions?**
  Current state of research

What is a proton?

Composition of Matter

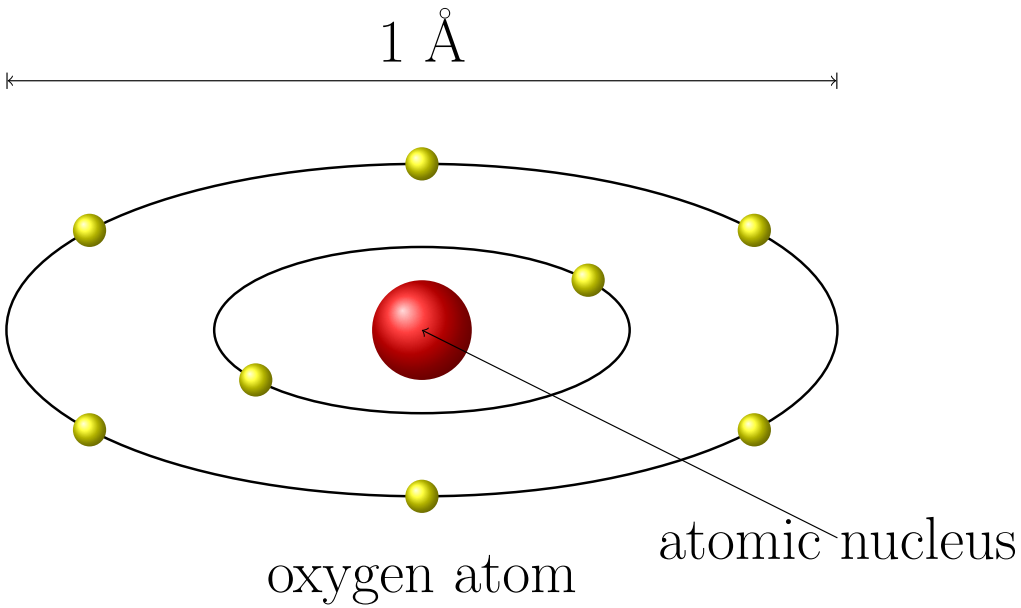
Composition of Matter

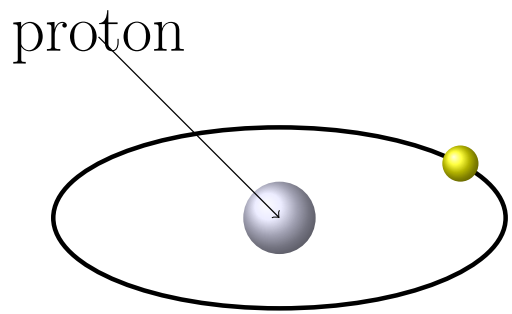
$$0,000.000.000.1\,\mathrm{m} = 10^{-10}\,\mathrm{m} = 1\text{Å}$$



water molecule

Composition of Matter





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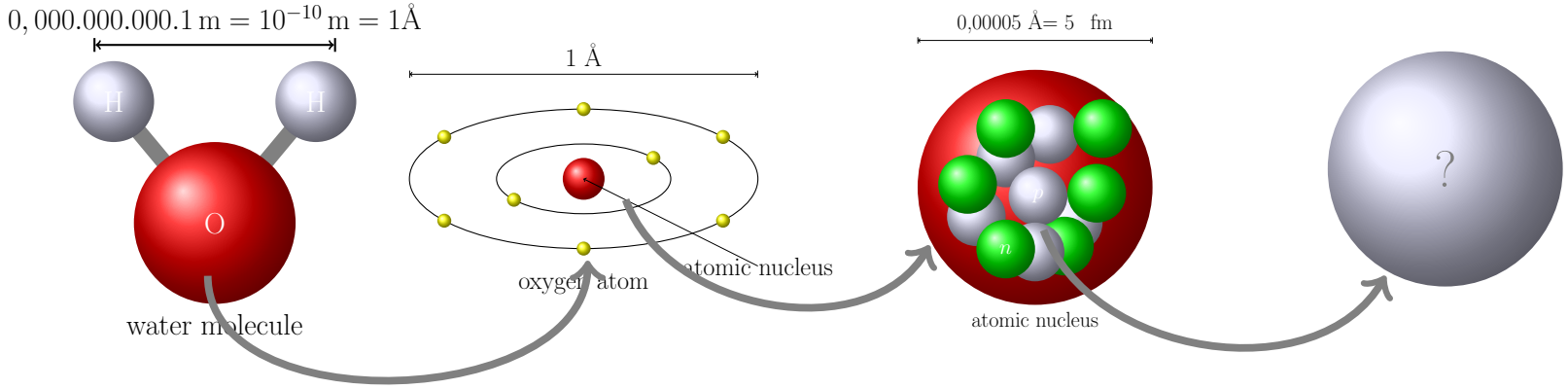


1Å= 100 00 fm

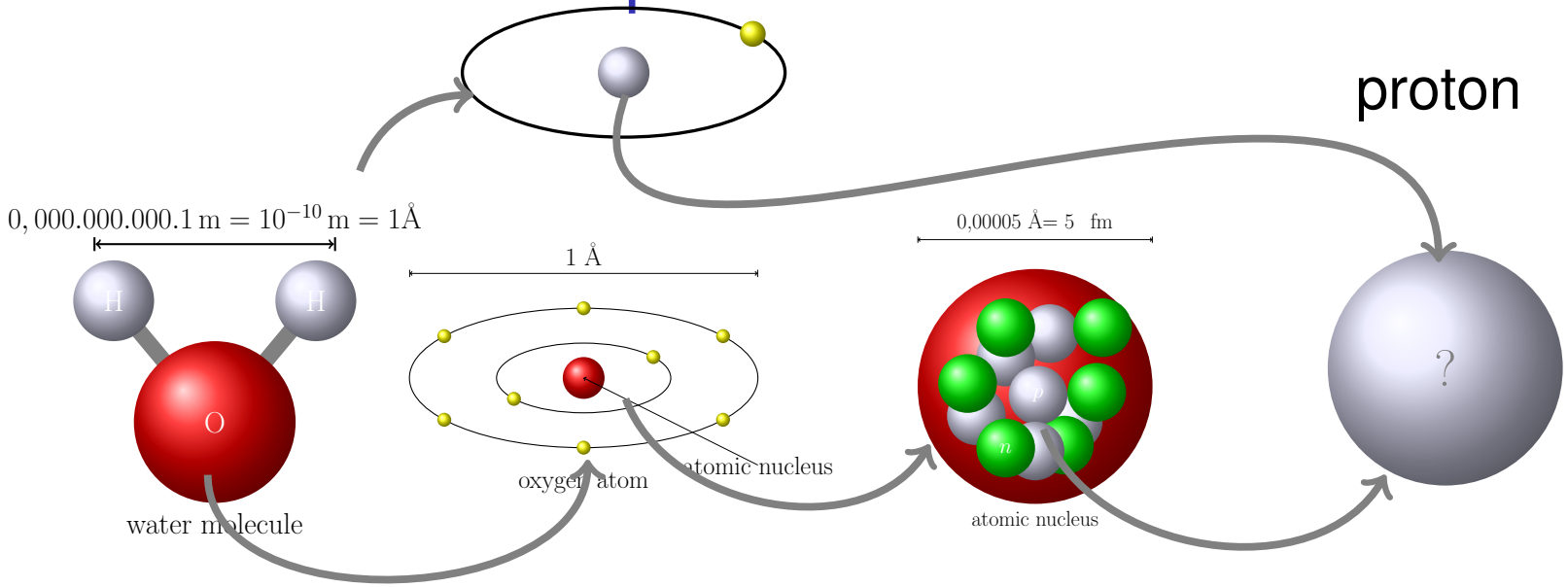
0,000.000.000.1 m

5 fm

1 fm

0,000.000.000.000.001 m

Composition of Matter



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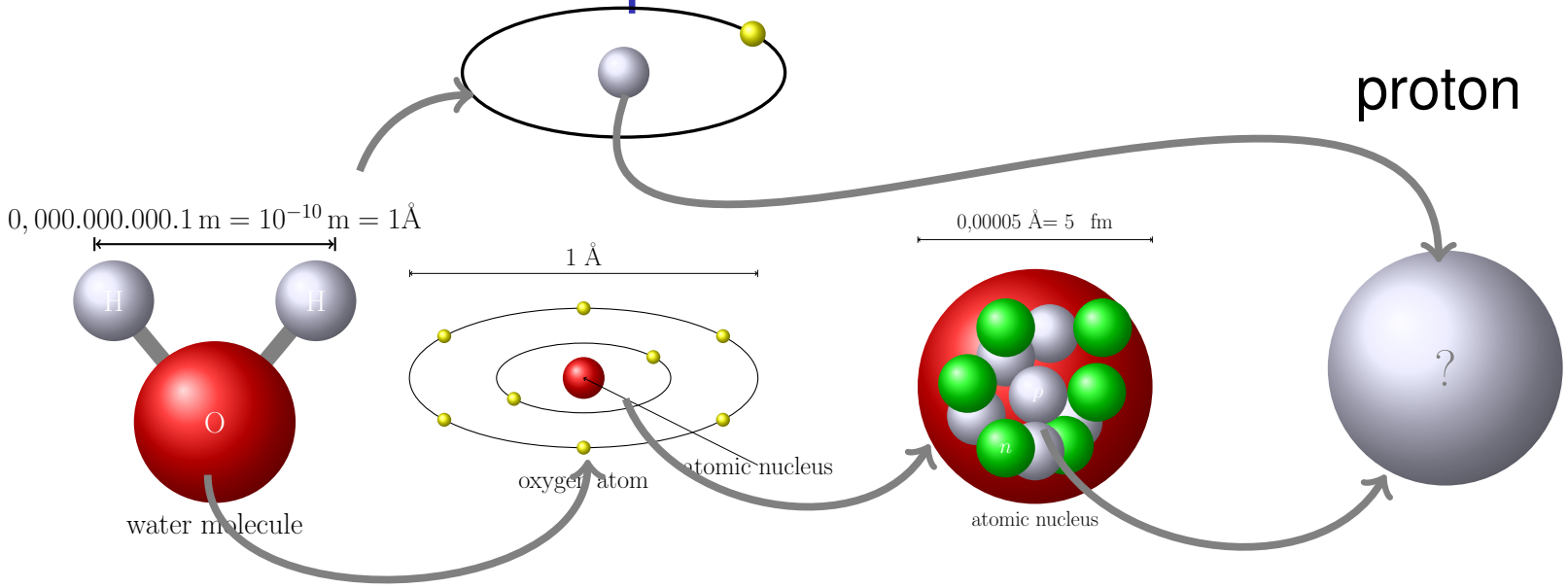

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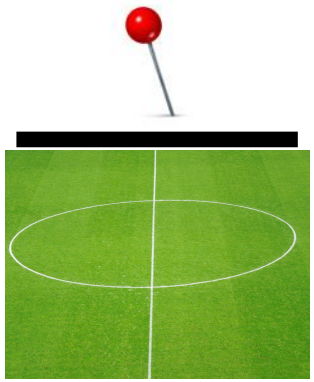
Proportions: $\dfrac{\text{nucleus}}{\text{shell}} \approx$



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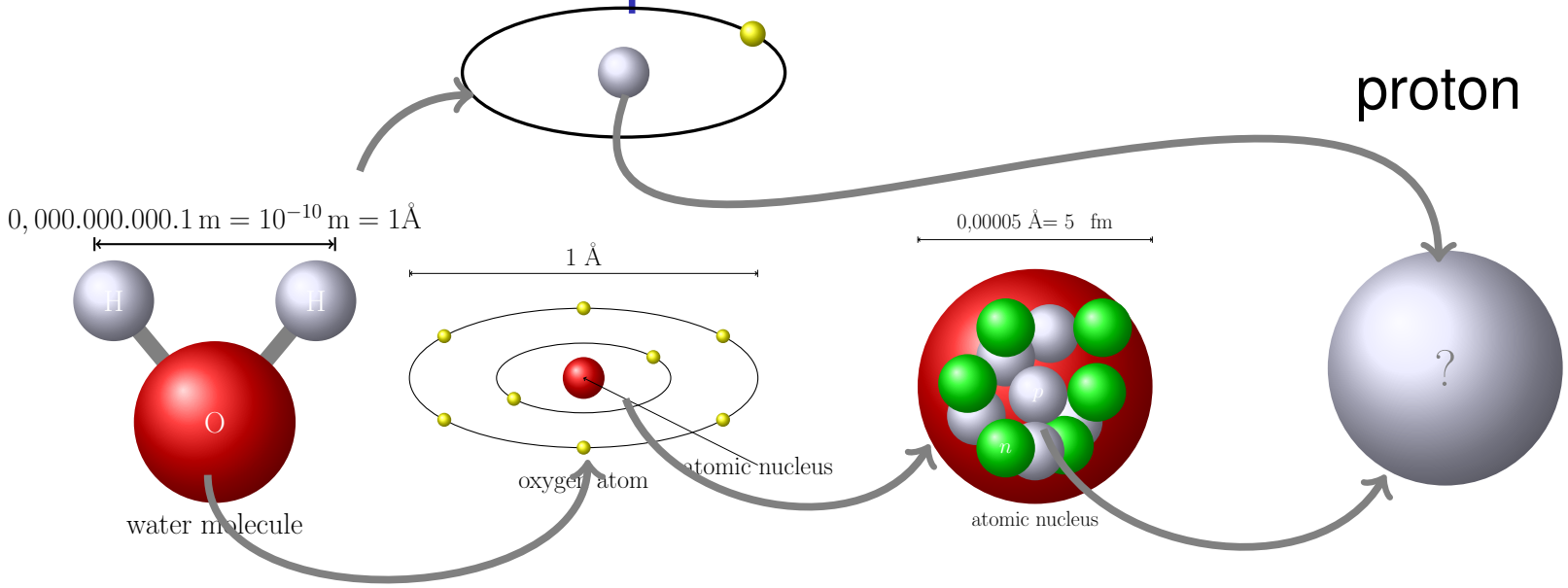

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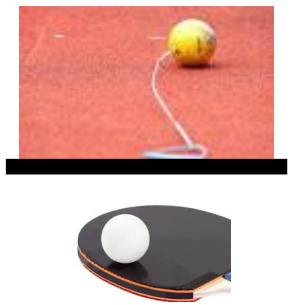
mass ratio: $\frac{\text{nucleus}}{\text{shell}} \approx$



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$4 \cdot 10^{24}$ protons

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- **Protons** are together with **neutrons** and **electrons** the building blocks of matter
- mass: $m = 1,7 \cdot 10^{-27}$ kg
- the proton has a positive electric charge
  charge: 1 elementary charge e,
  $e = 1.6 \cdot 10^{-19}$C

$4 \cdot 10^{24}$ protons

$5 \cdot 10^{22}$ e

How does the inside of the proton look like?

How can we learn something about the inside of an object?

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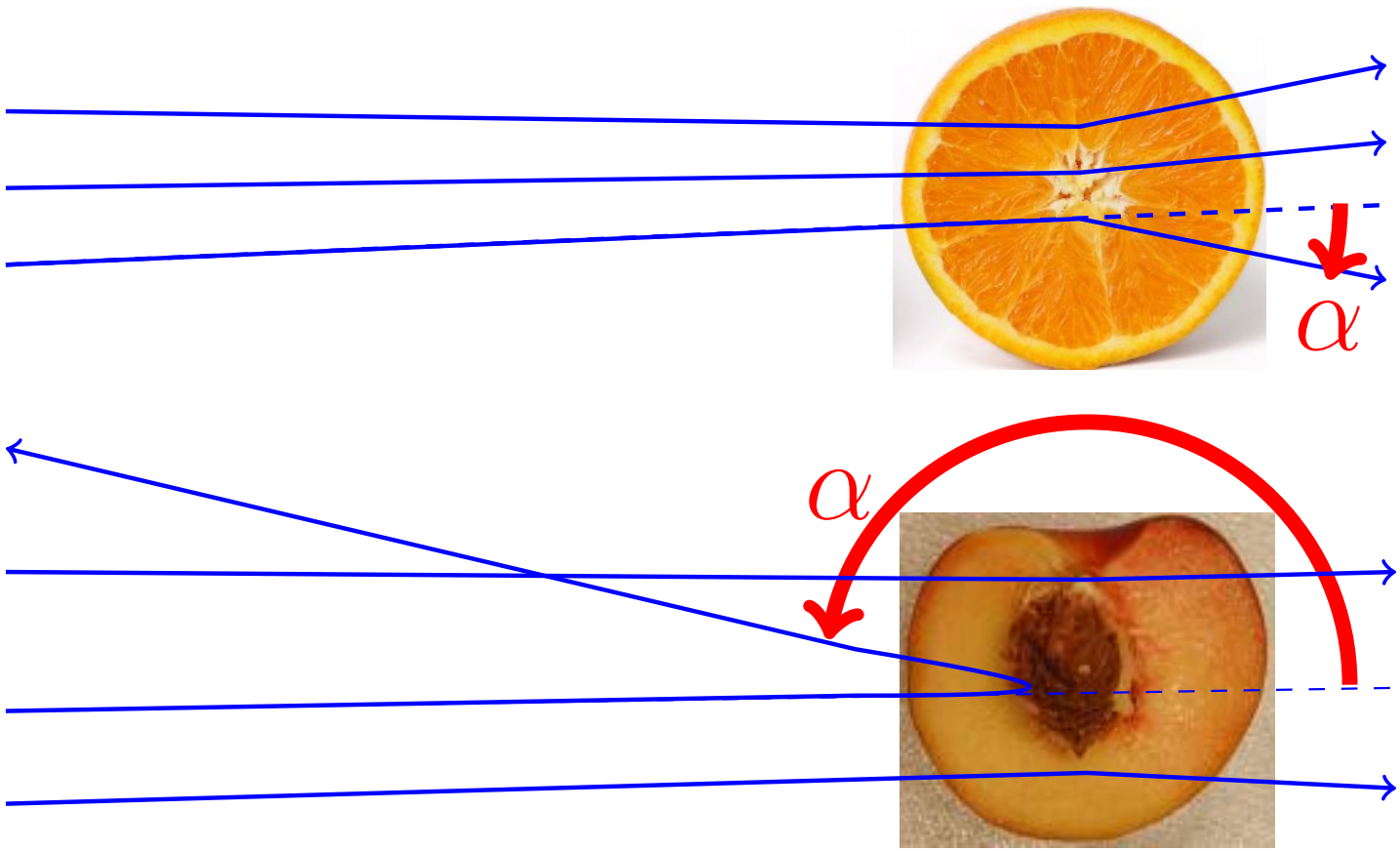
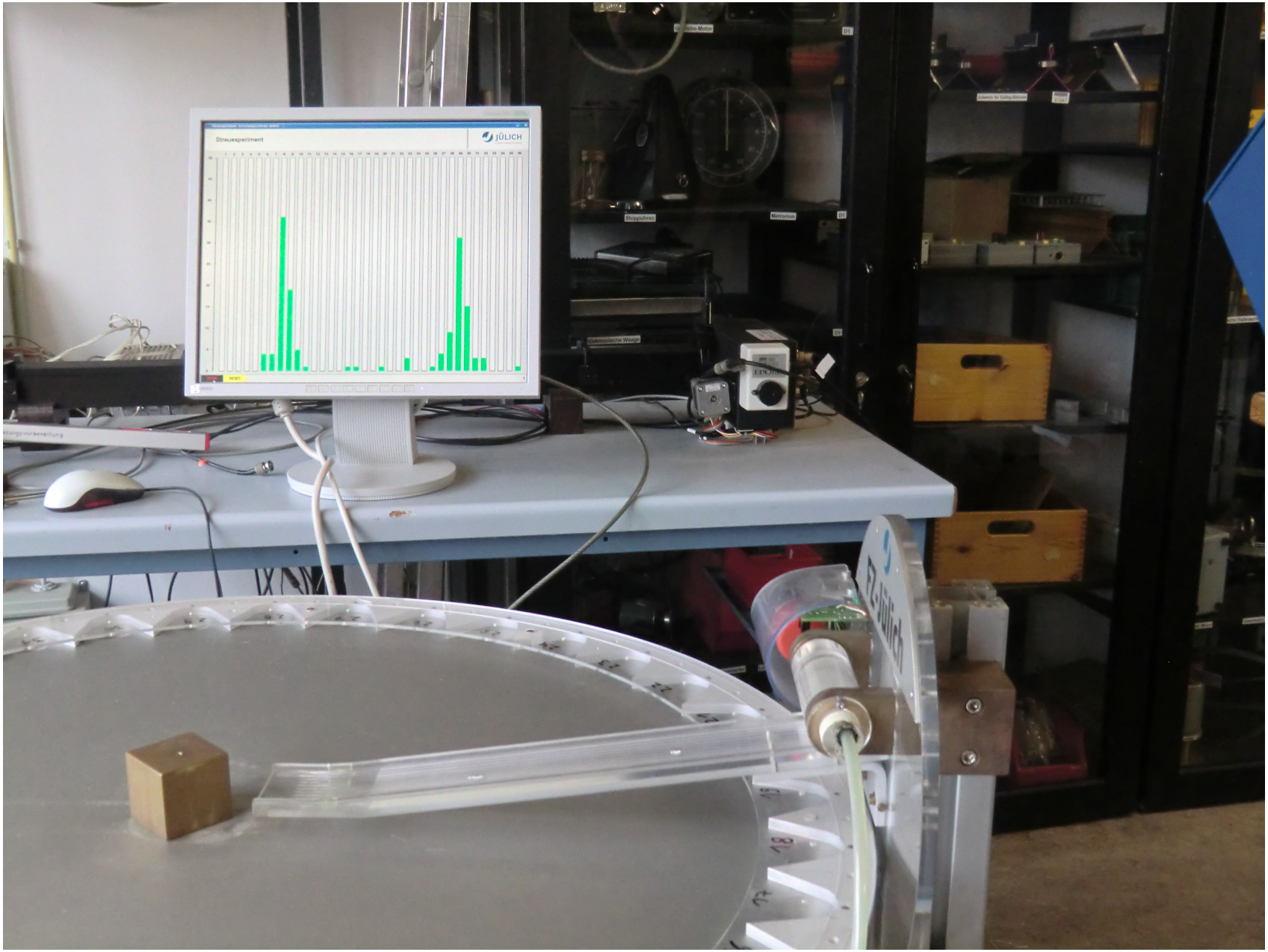
Principle of a scattering experiment

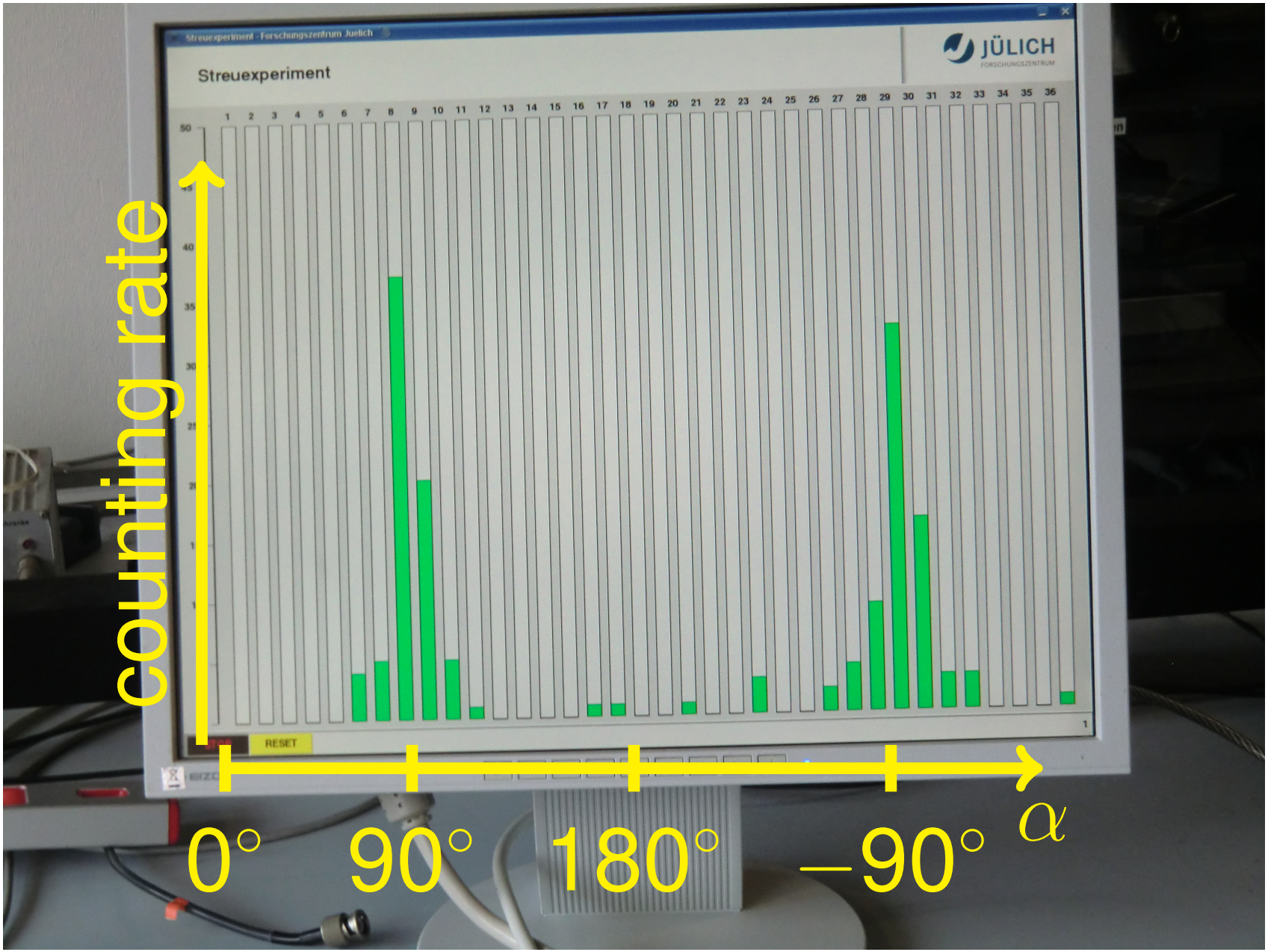


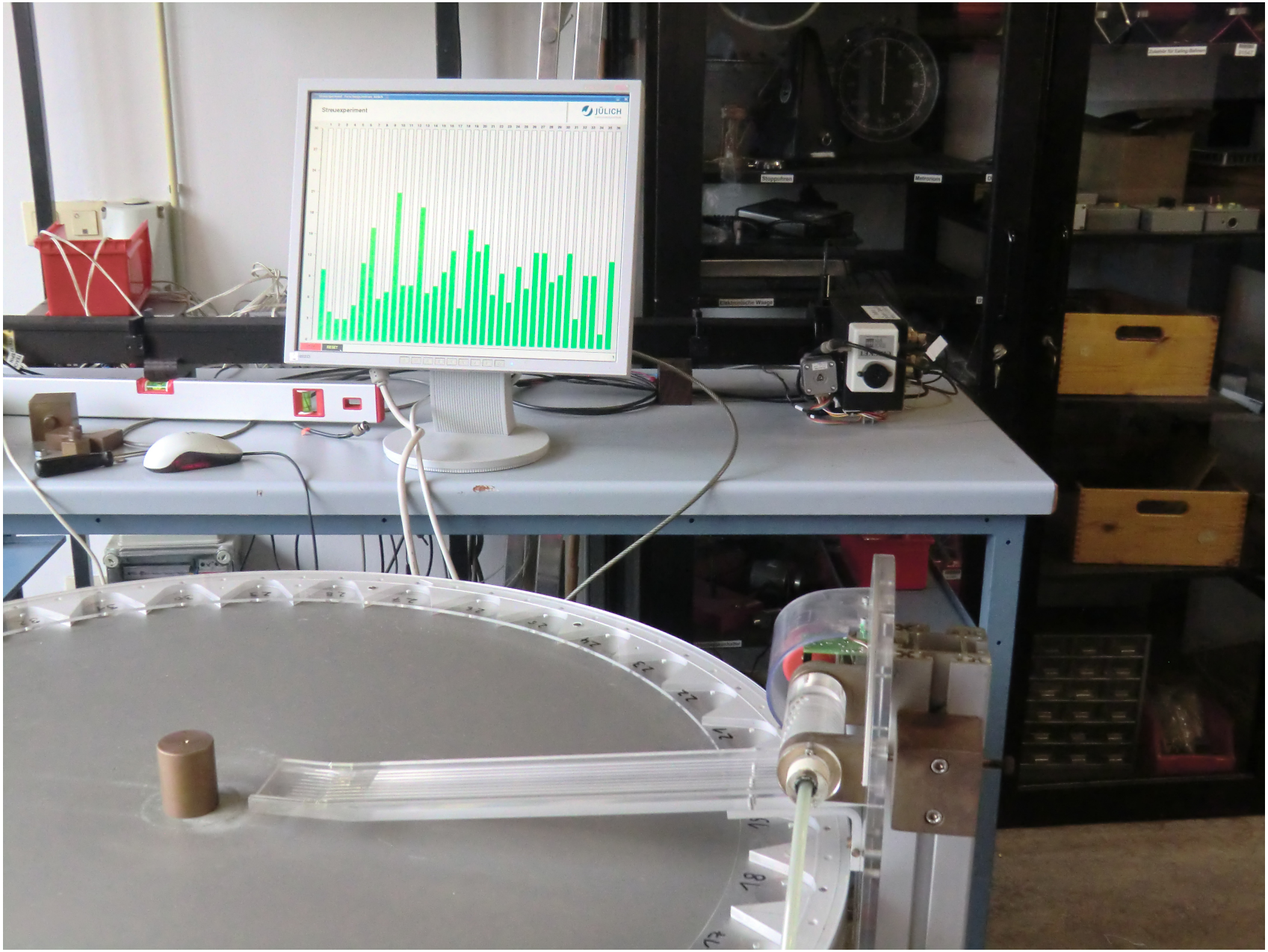
Principle of a scattering experiment

Shoot a projectile on the object under study.
Angular distribution of projectiles gives information about the inner structure of the object.

- Scattering experiments at particle accelerators are the main tool to study properties of particles and their interactions.


Streuexperiment
JÜLICH
FZ-Jülich


Streuexperiment - Forschungszentrum Juelich
Streuexperiment
JÜLICH
FORSCHUNGSZENTRUM
RESET
counting rate
0°
90°
180°
−90°
α


Streuexperiment
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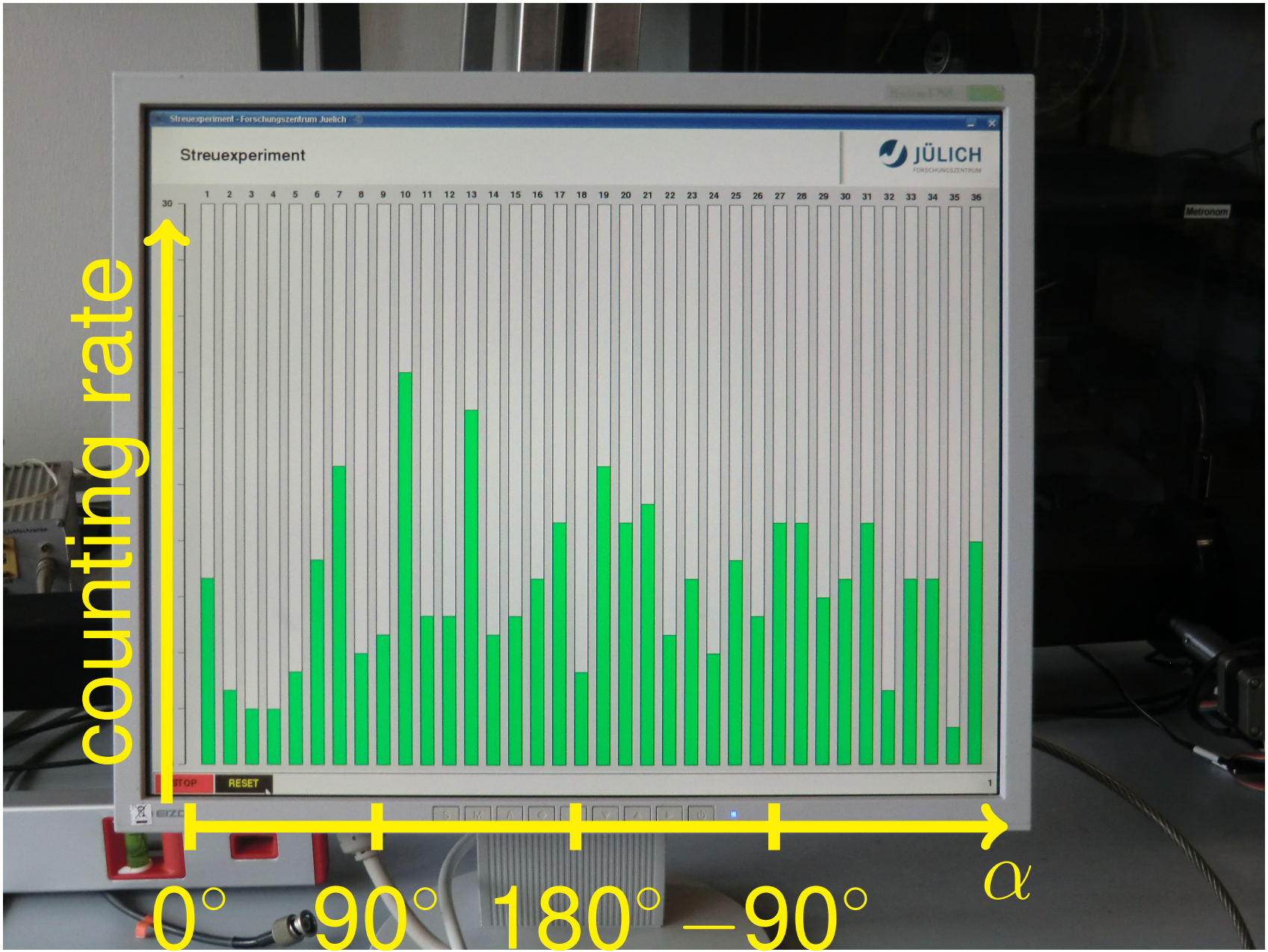
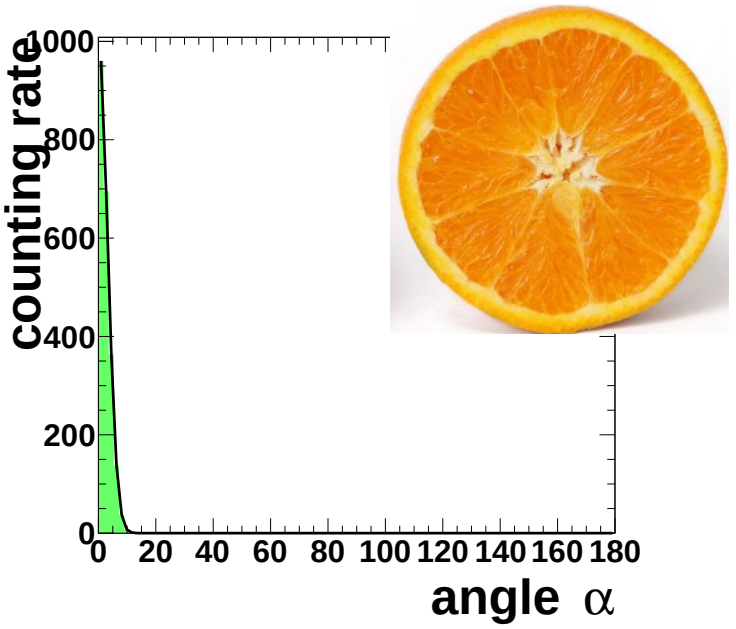
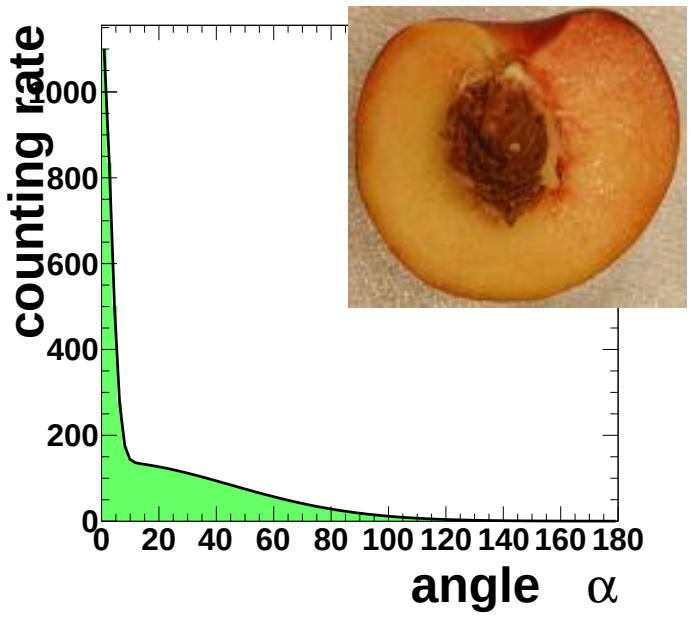
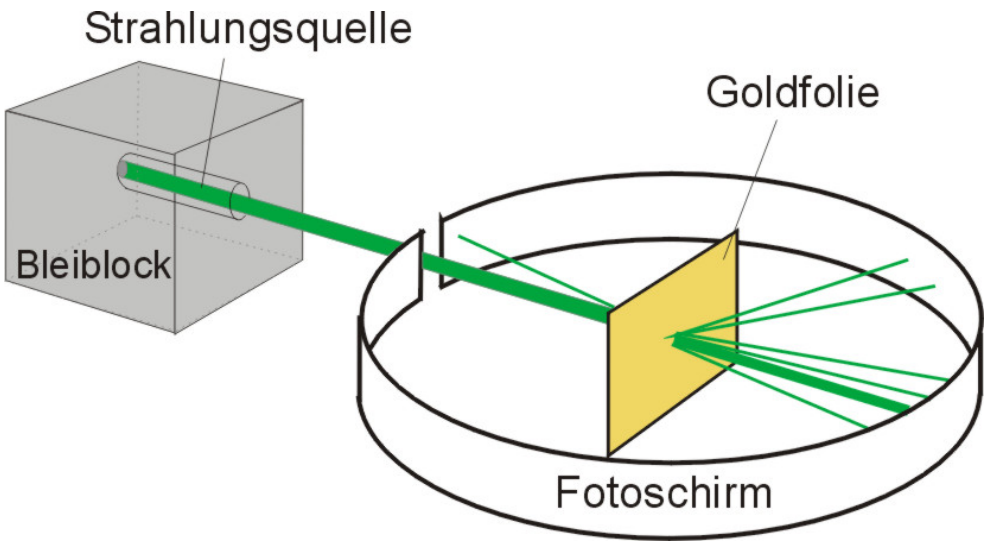

Streuexperiment - Forschungszentrum Juelich
Streuexperiment
JÜLICH
FORSCHUNGSZENTRUM
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30 31 32 33 34 35 36
30
STOP
RESET
counting rate
0°
90°
180°
−90°
α

Principle of a scattering experiment





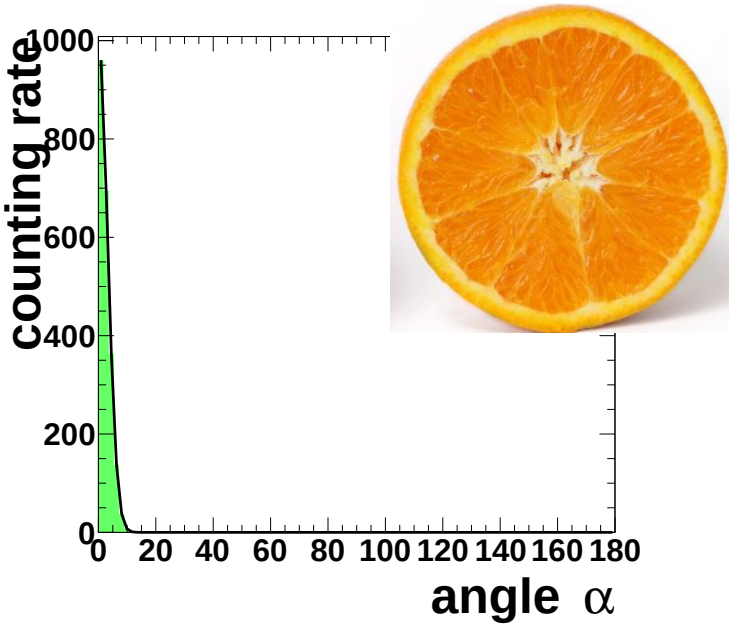
Principle of a scattering experiment

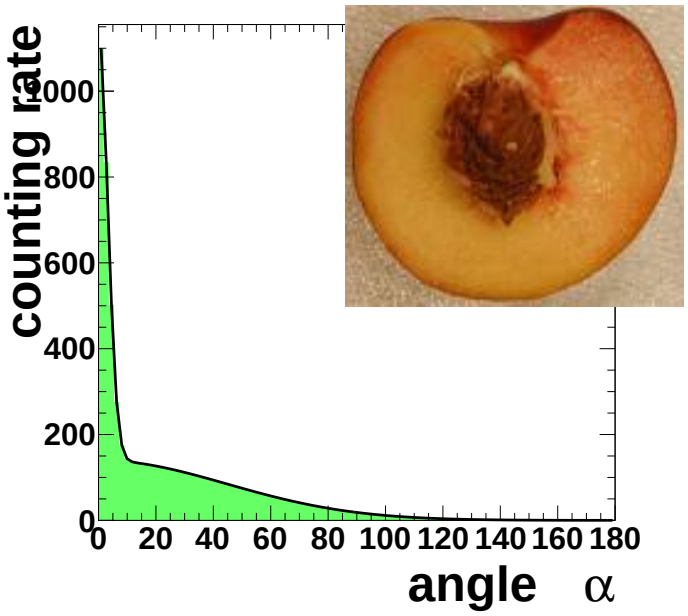


Ernest Rutherford
Noble prize 1908 (chemistry)

historical remark: Rutherford experiment (1911):
α-particle (Helium nucleus) on gold foil

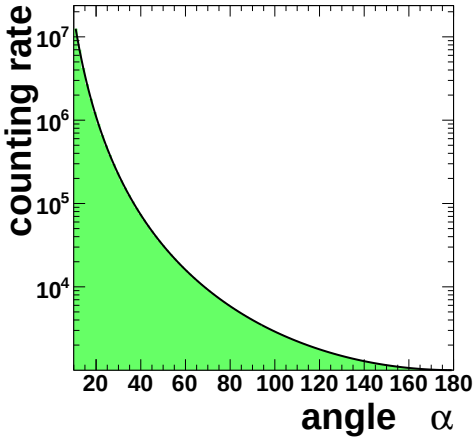
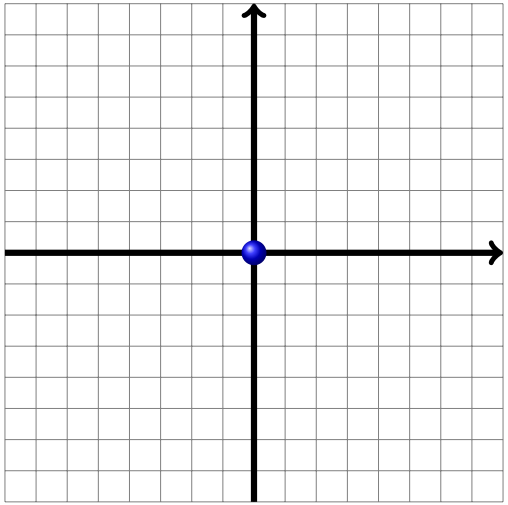
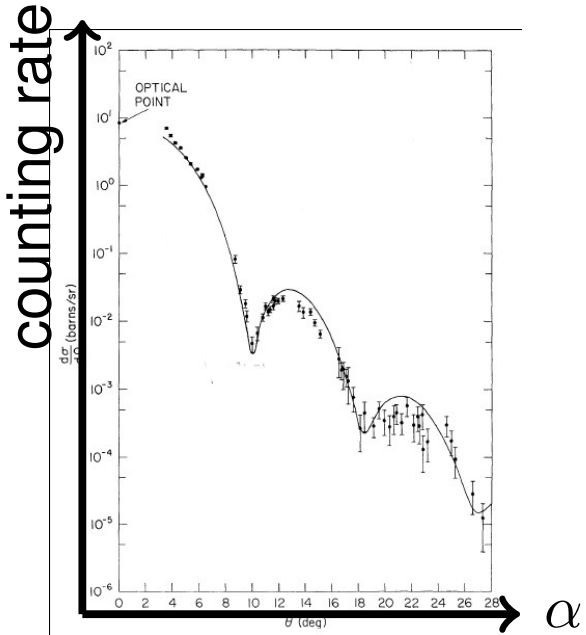
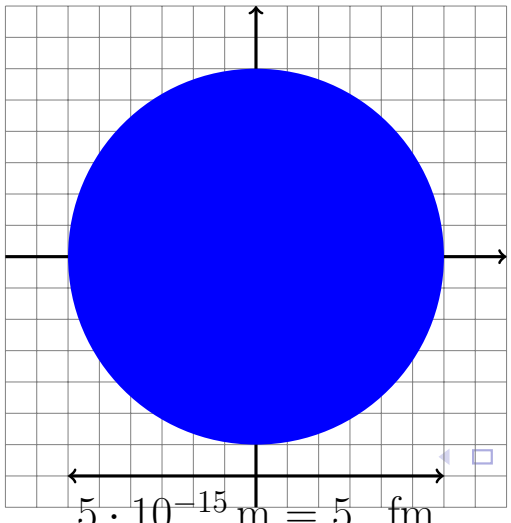
Principle of a scattering experiment

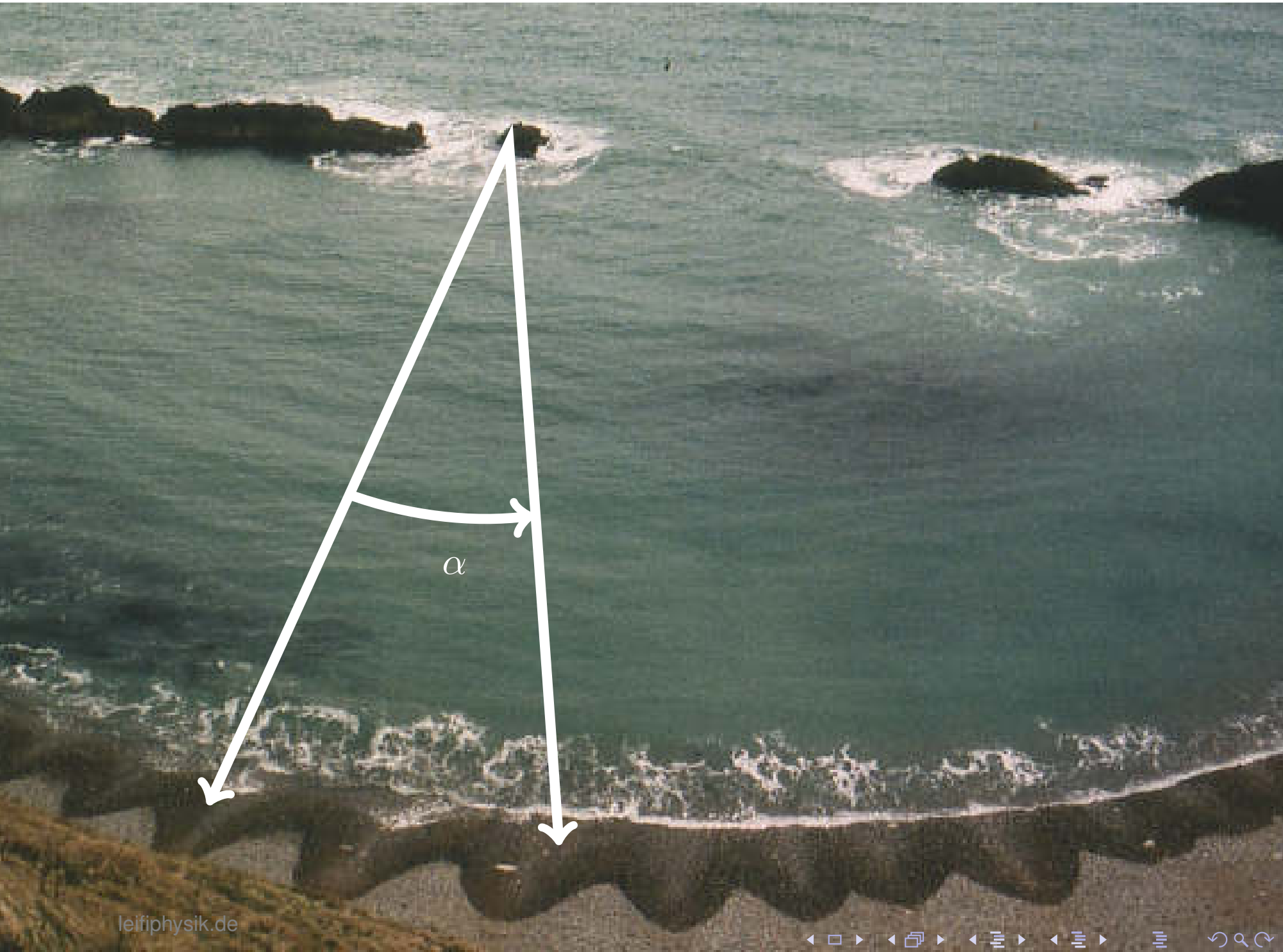


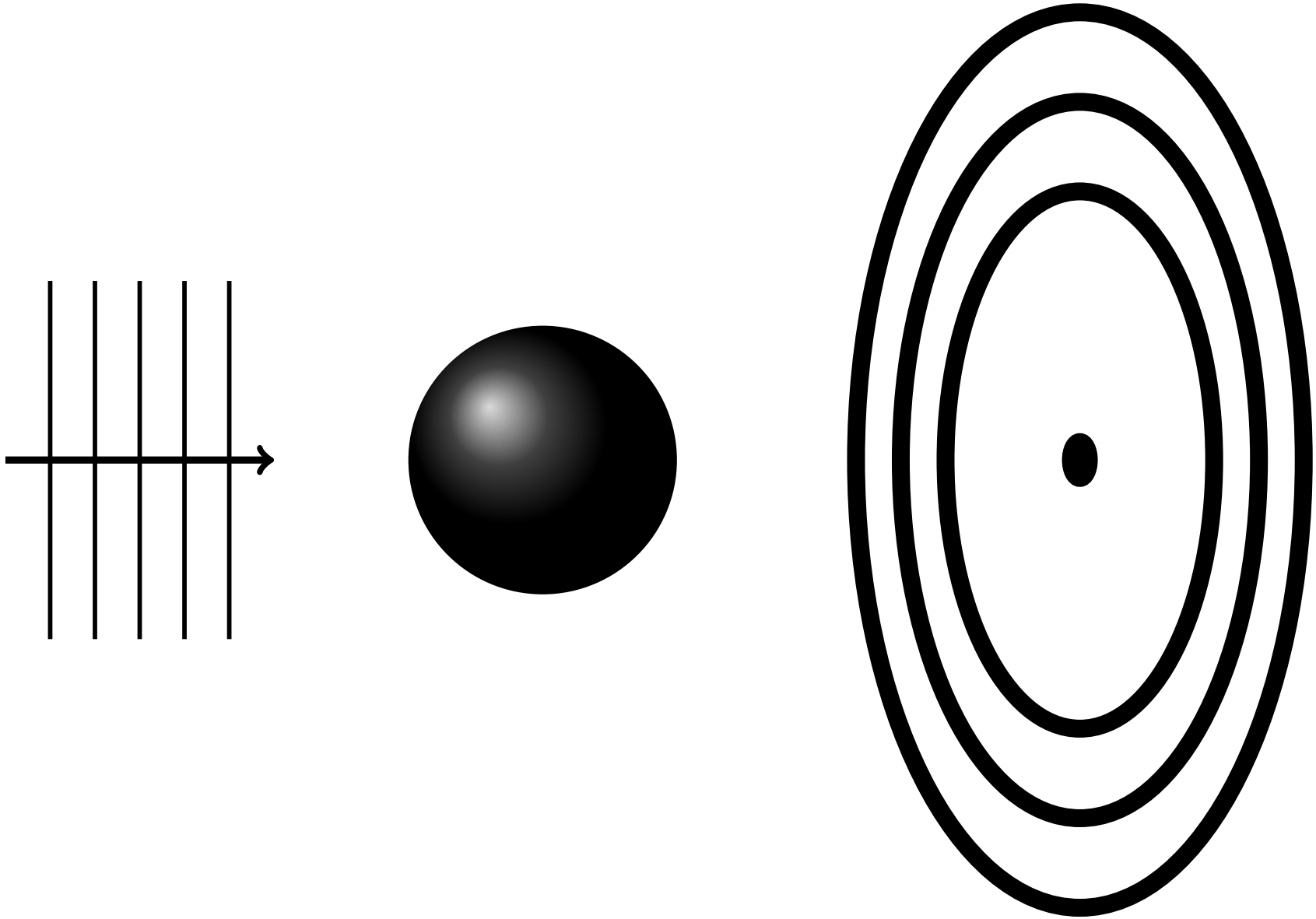


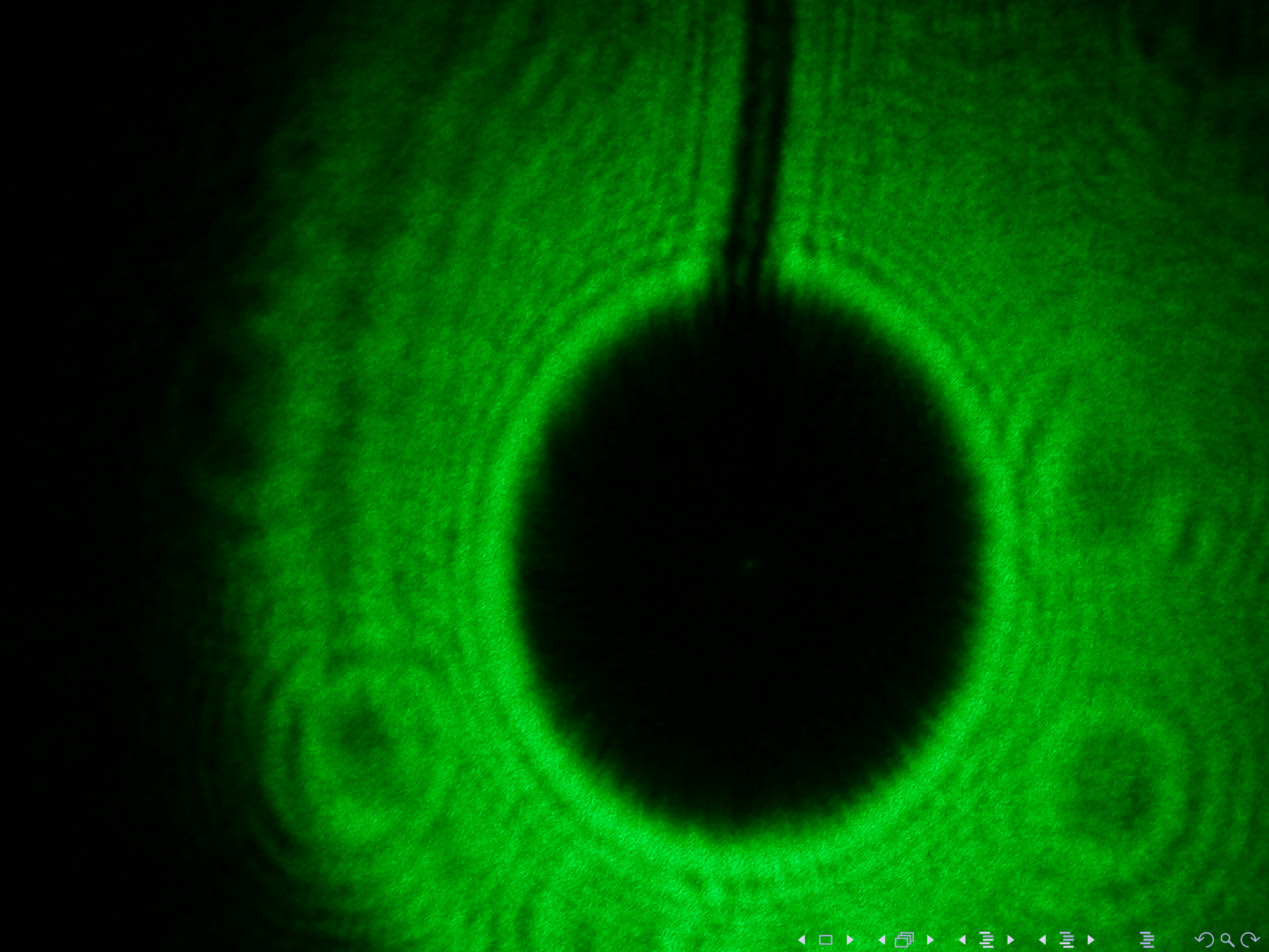
historical remark: Rutherford experiment (1911):
Atom looks more like a peach than an orange:
Shell is almost empty, mass is concentrated in center.

Examples

angular distribution	form	example
		electron
		nucleus

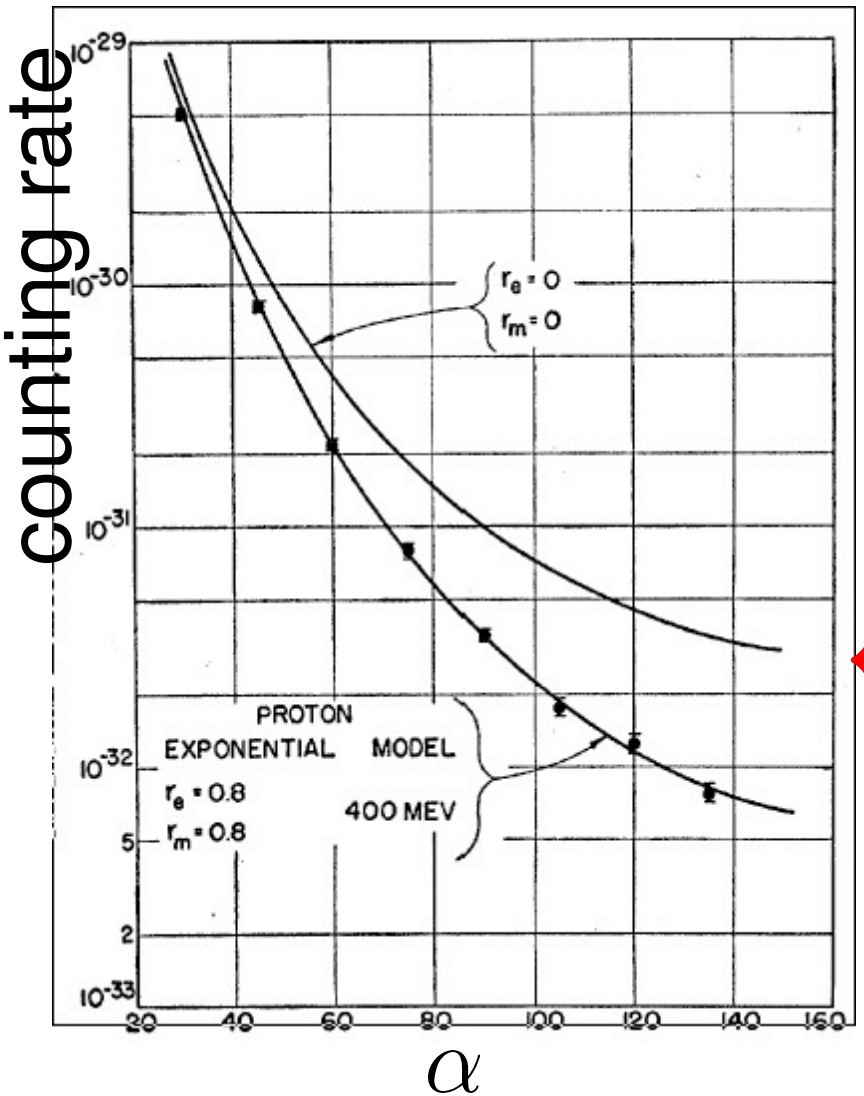

α





How does the angular distribution for the proton look like?

electron-proton-scattering



R. Hofstadter

Nobel prize 1961

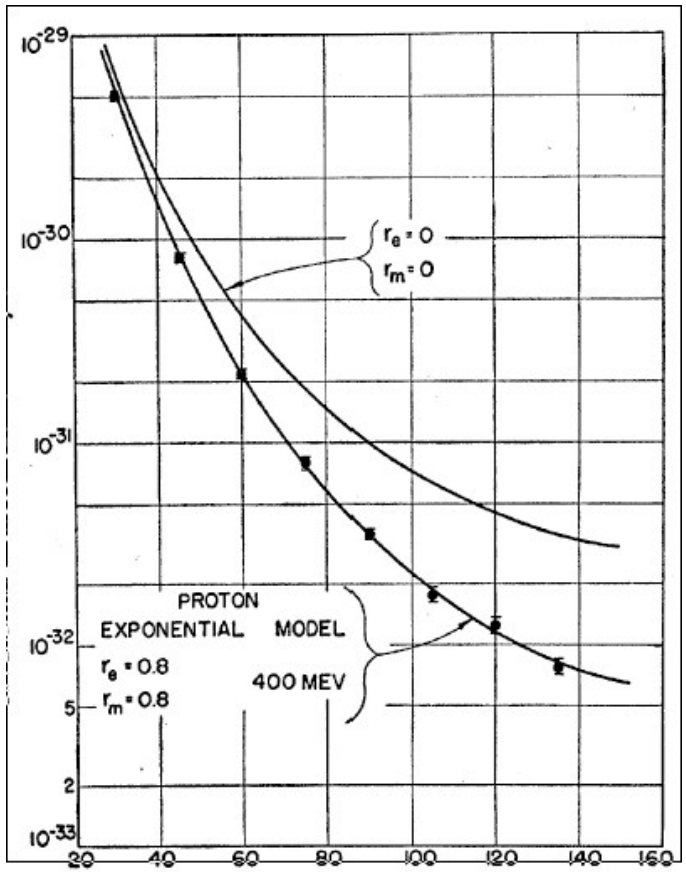
expectation for point-like particle

Spacial extension of protons

angular distribution

form

counting rate



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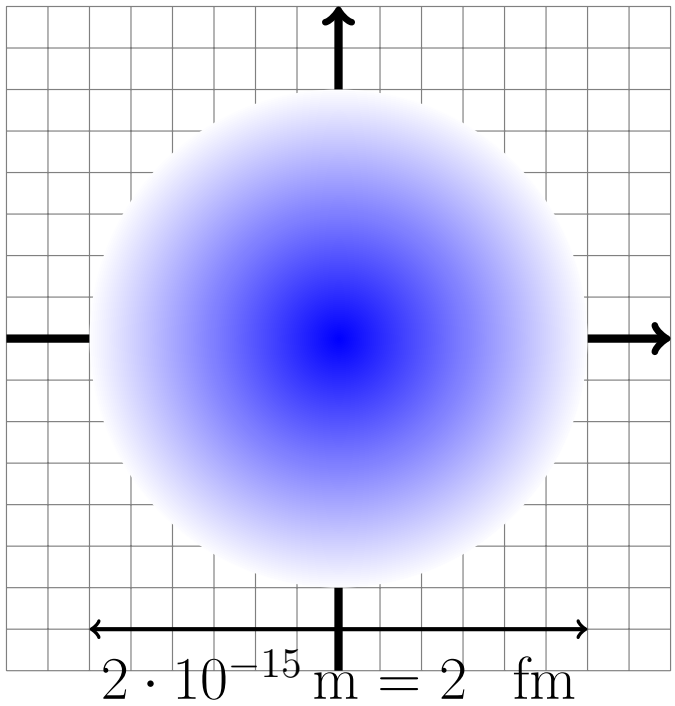
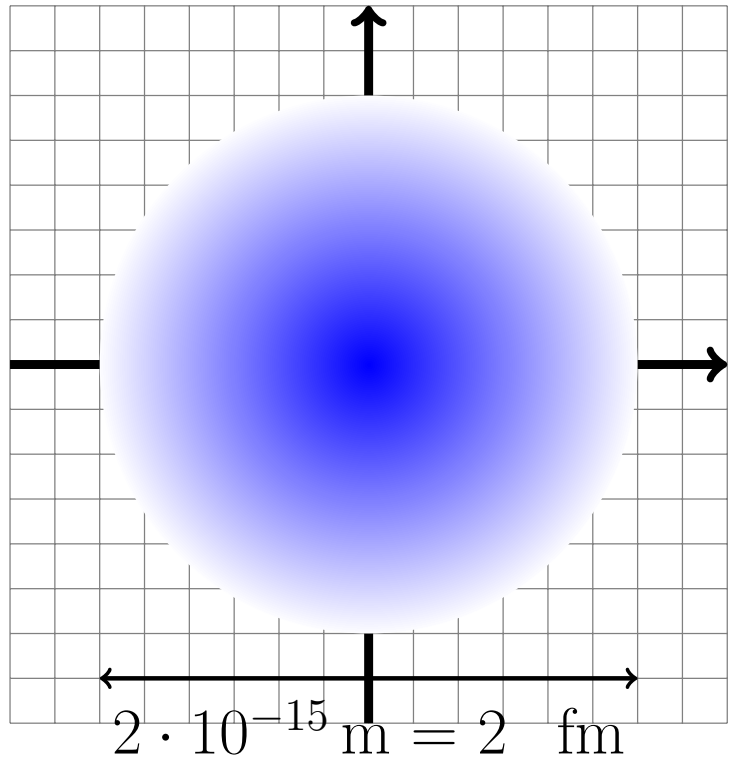


Spacial extension of protons

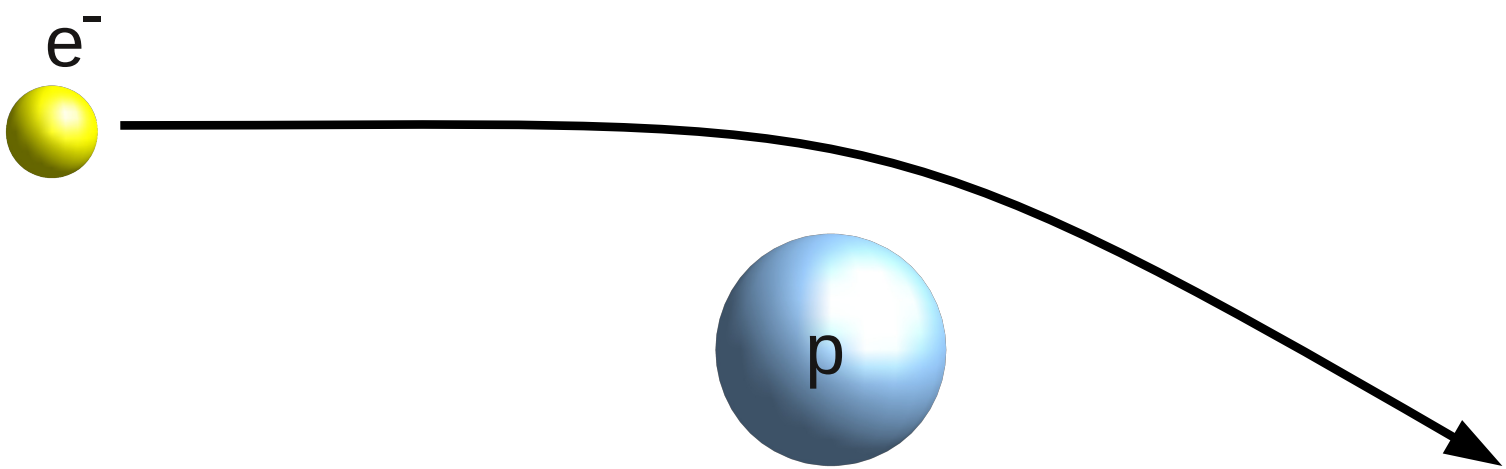
- proton has finite extension.
- radius $\approx 10^{-15}$ m = 1 fm
- edge is not clearly defined.
- more charge is concentrated in center



Elastic $\leftrightarrow$ inelastic scattering

up to now: **elastic scattering**:

$e^- + p \rightarrow e^- + p$



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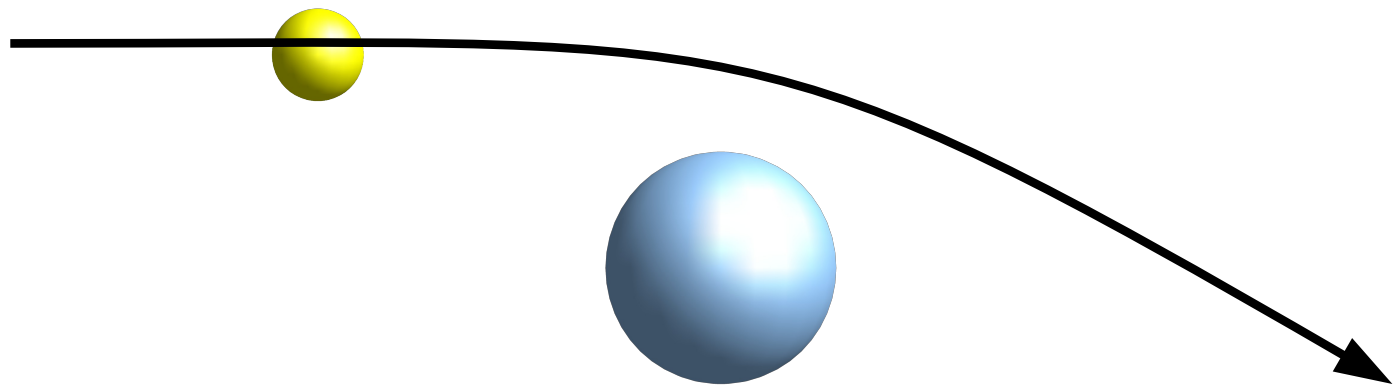

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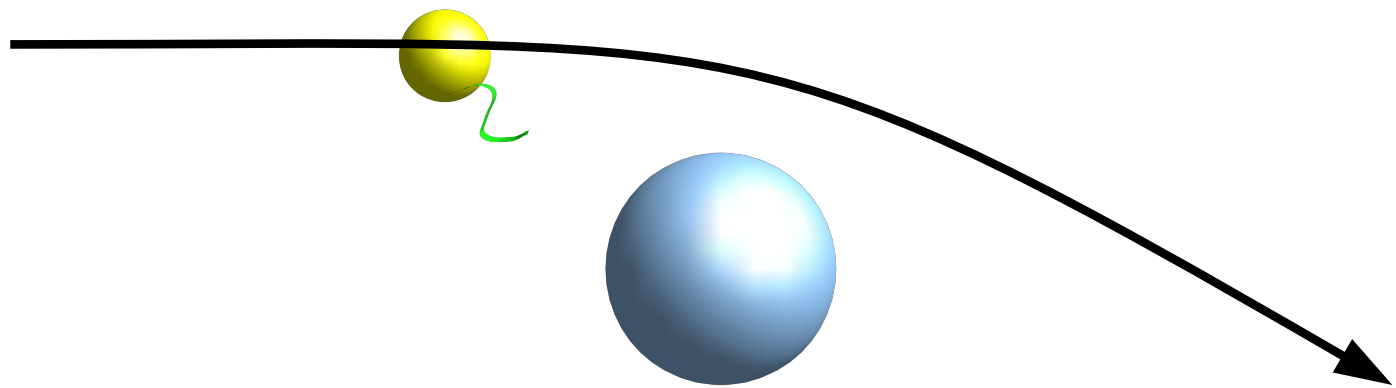

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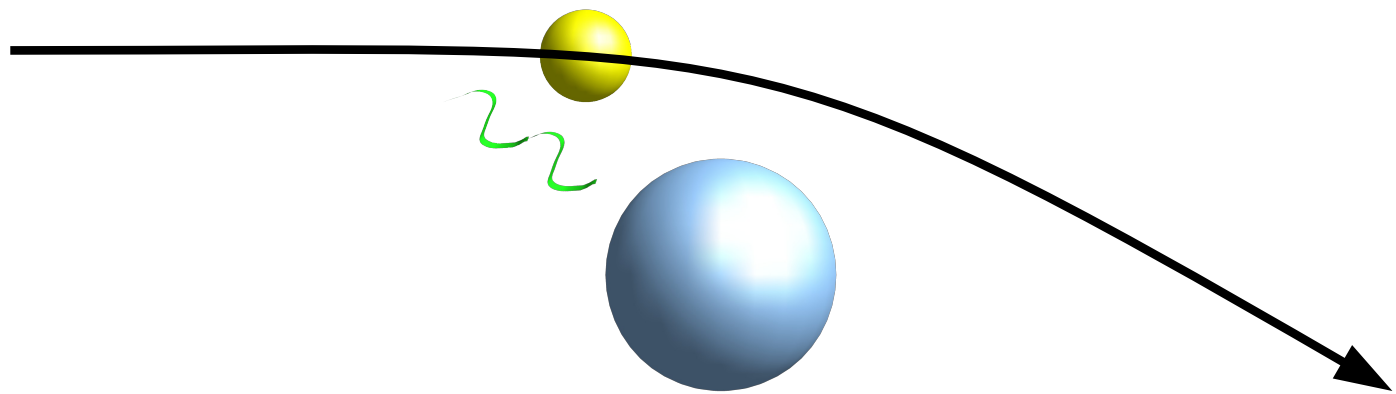

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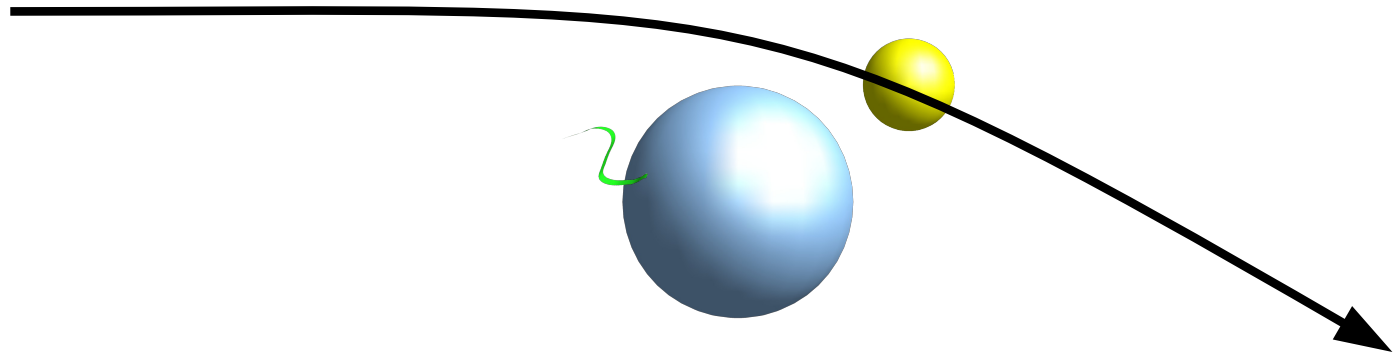

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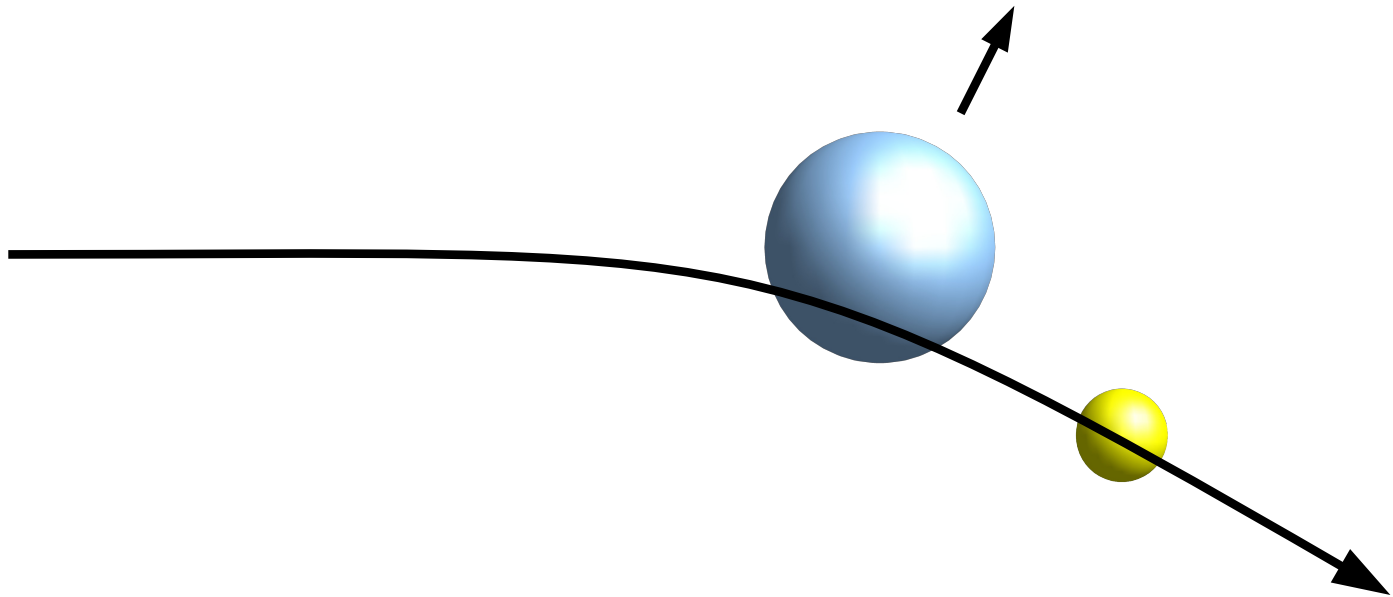

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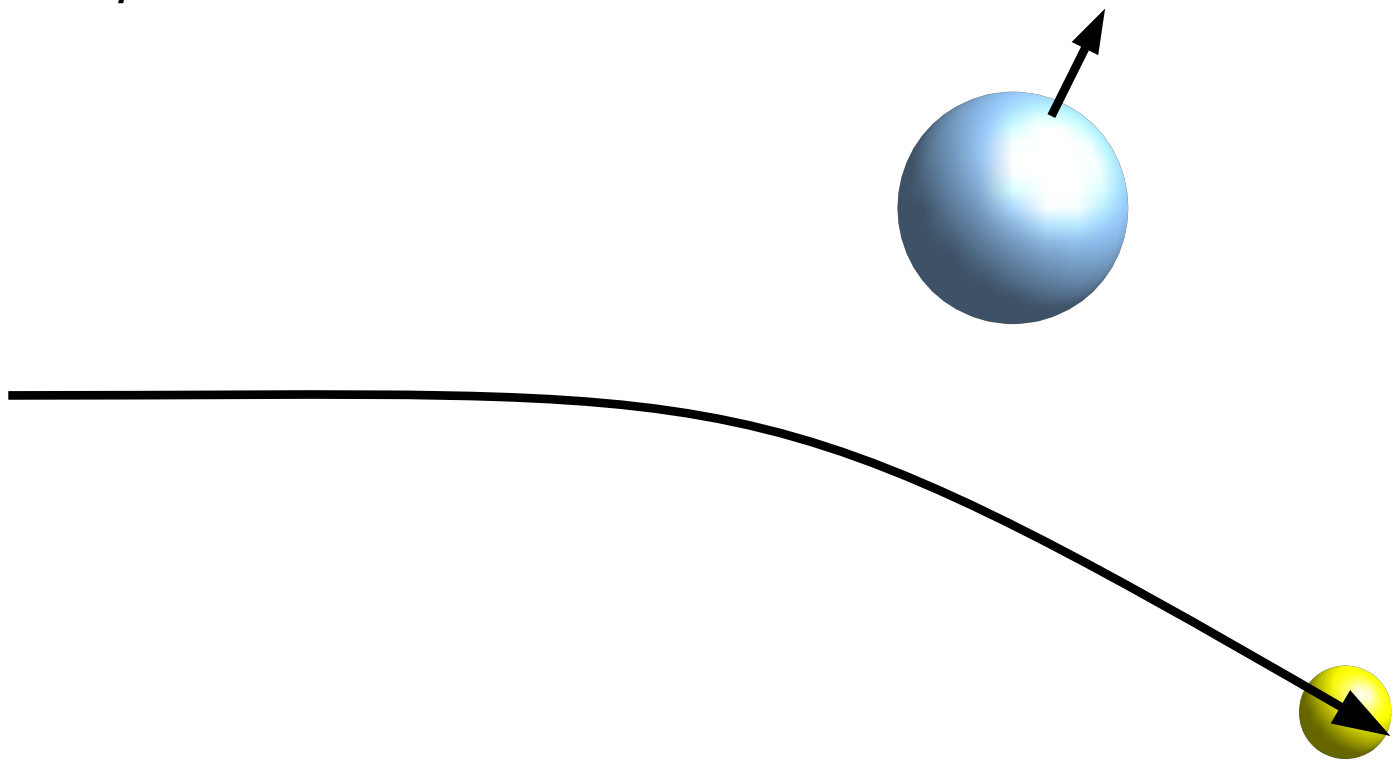

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What happens if protons are bombarded with electrons of higher energy?

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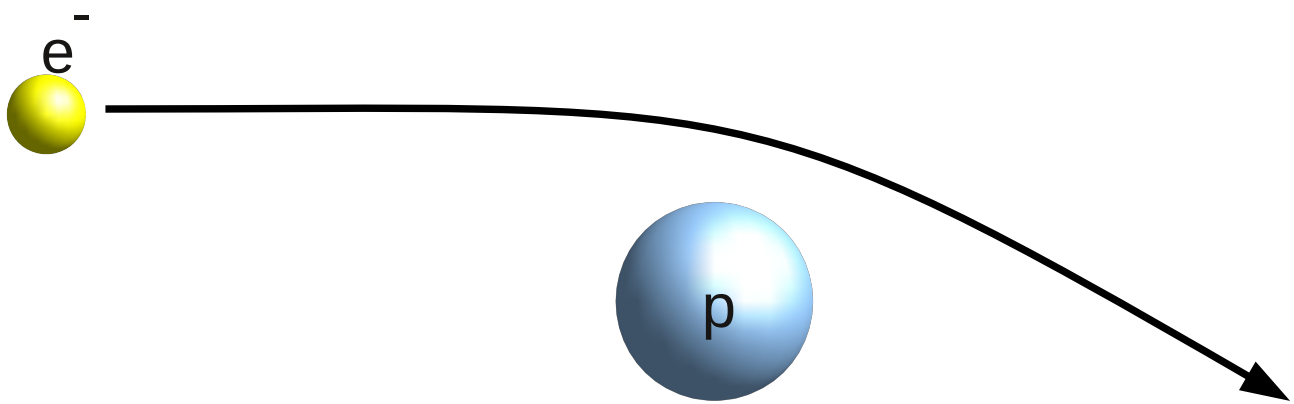
What happens if protons are bombarded with electrons of higher energy?

The proton breaks apart (**inelastic scattering**):

$e^- + p \rightarrow e^- + p_1 + p_2 + p_3 + \ldots$



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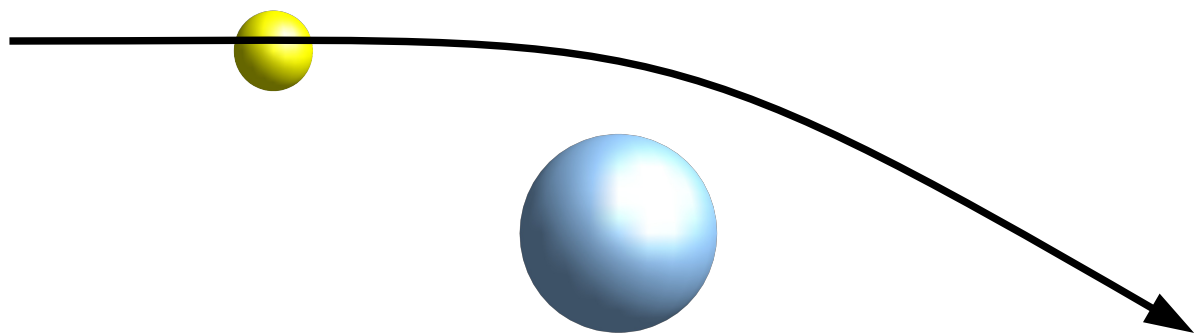

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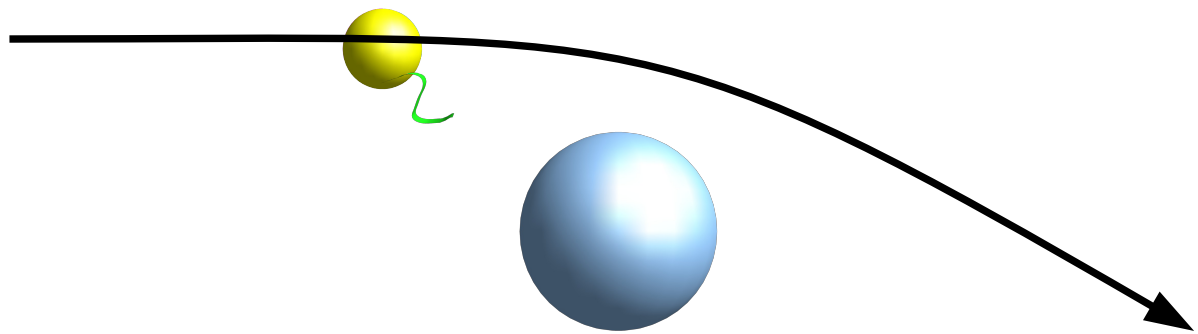

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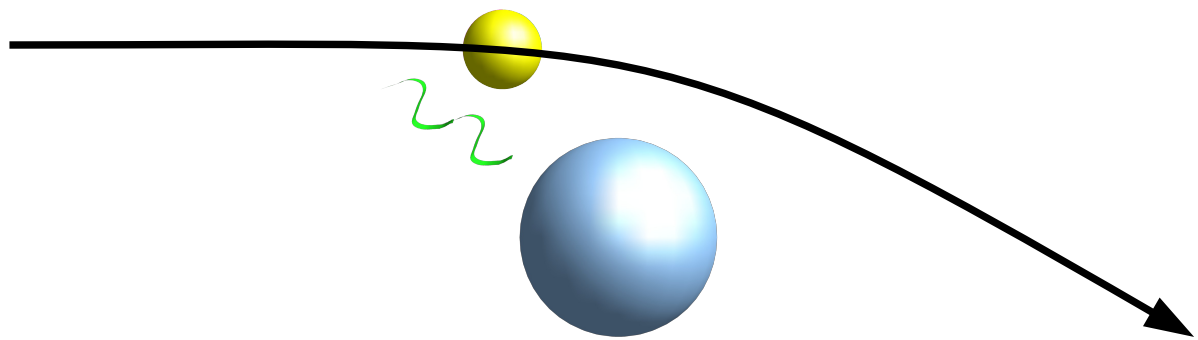

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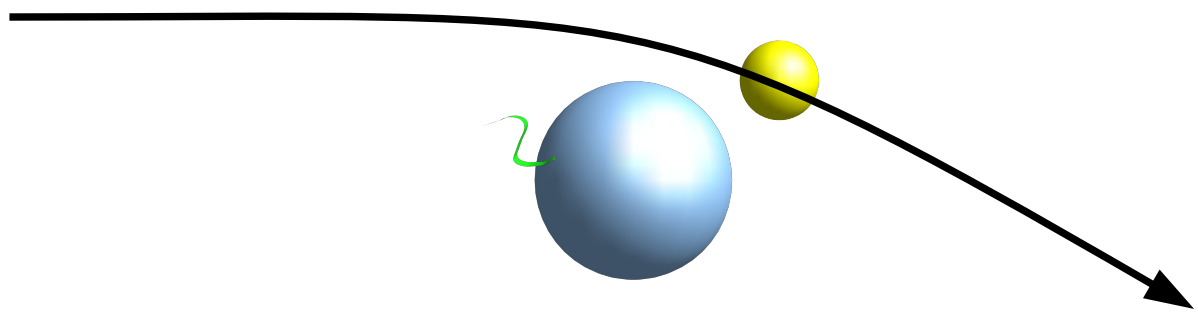

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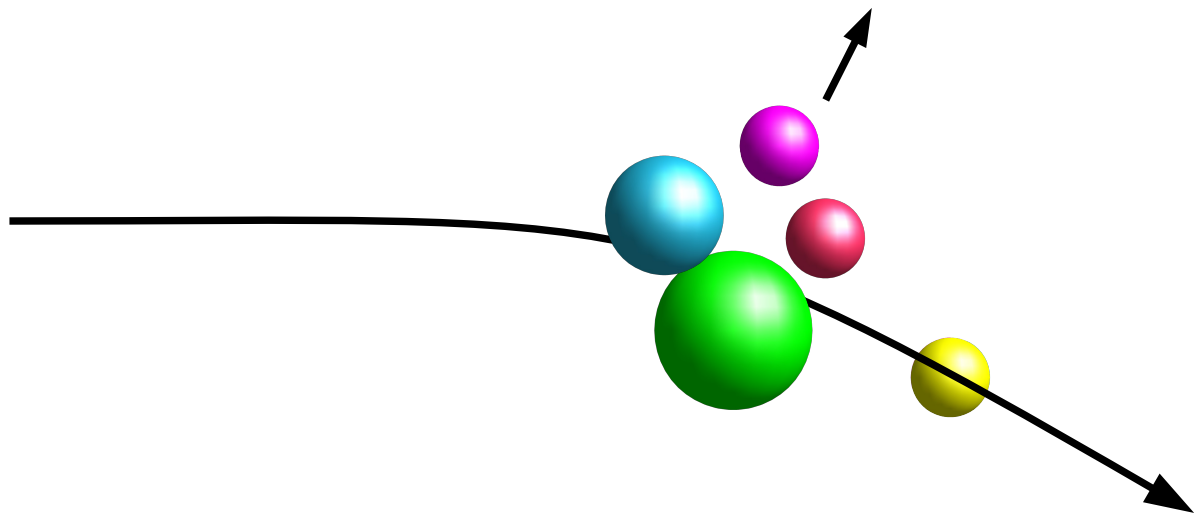

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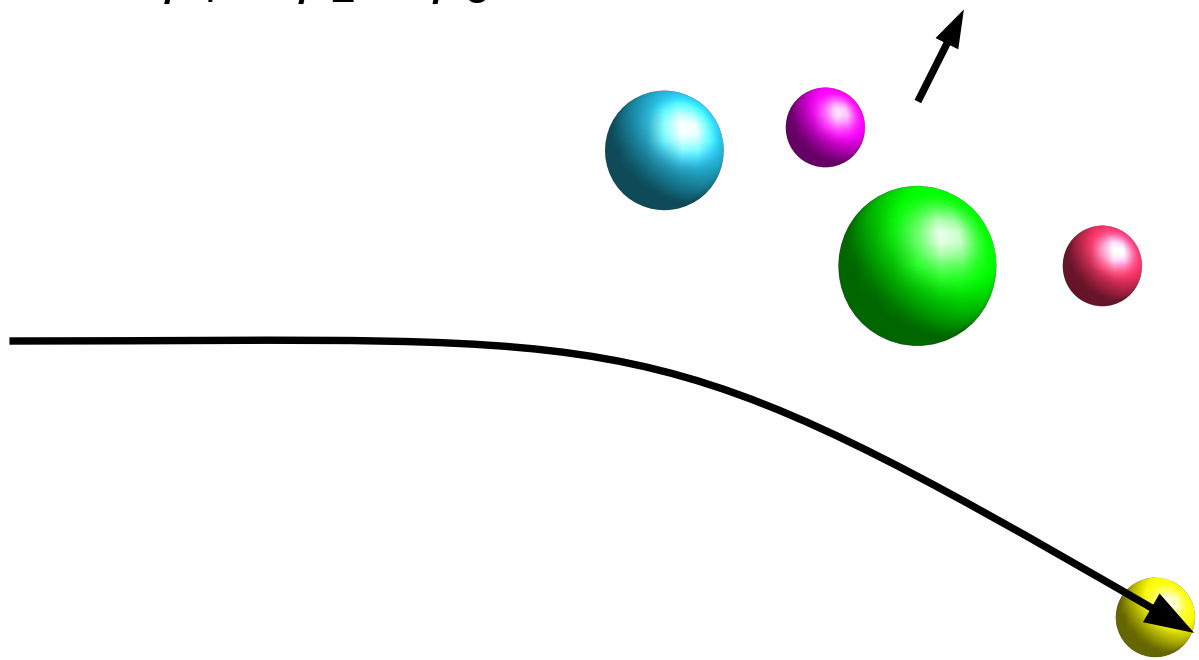
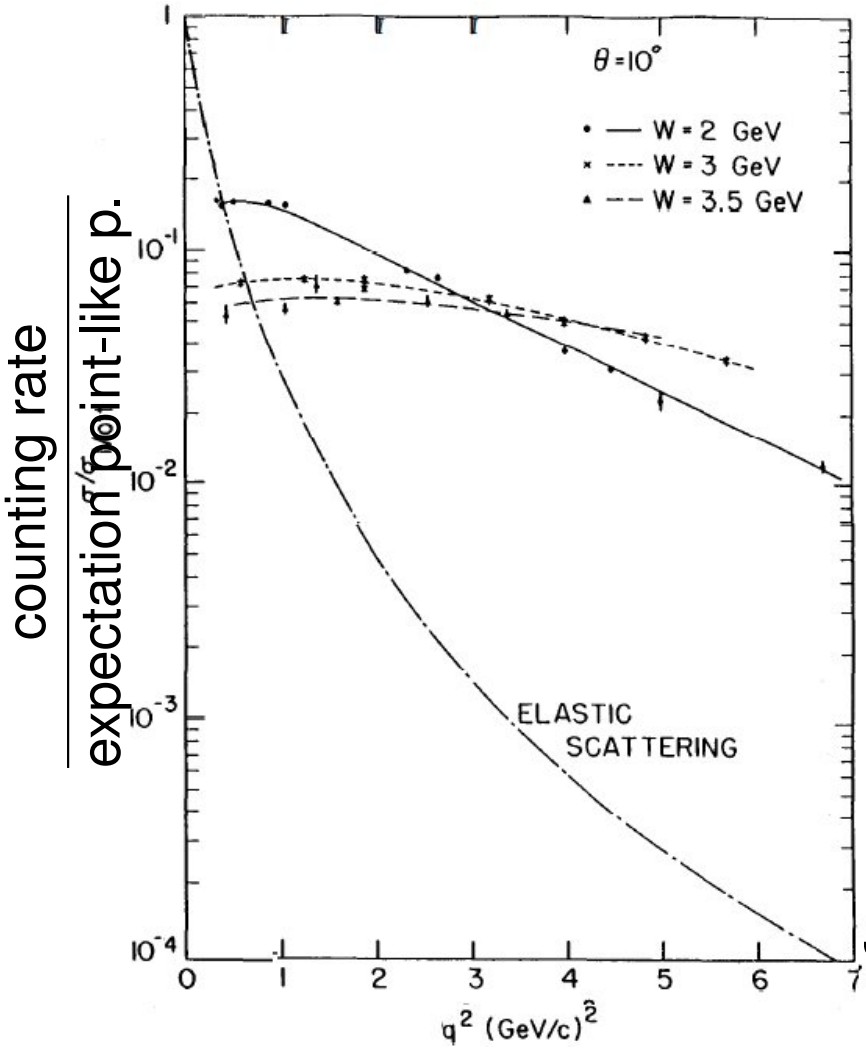
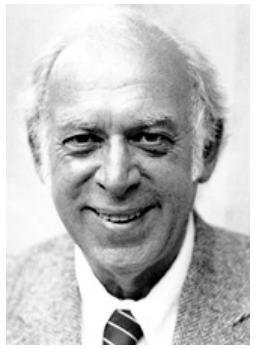
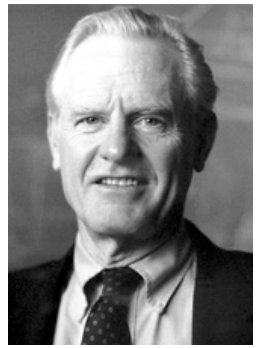


(Deep) inelastic scattering

$$\frac{\text{counting rate}}{\text{expectation point-like p.}} \approx \text{const.}$$

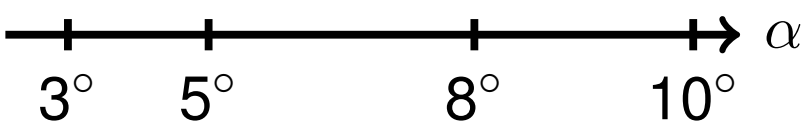


$\Rightarrow$ Indication for scattering off point-like particle inside proton!

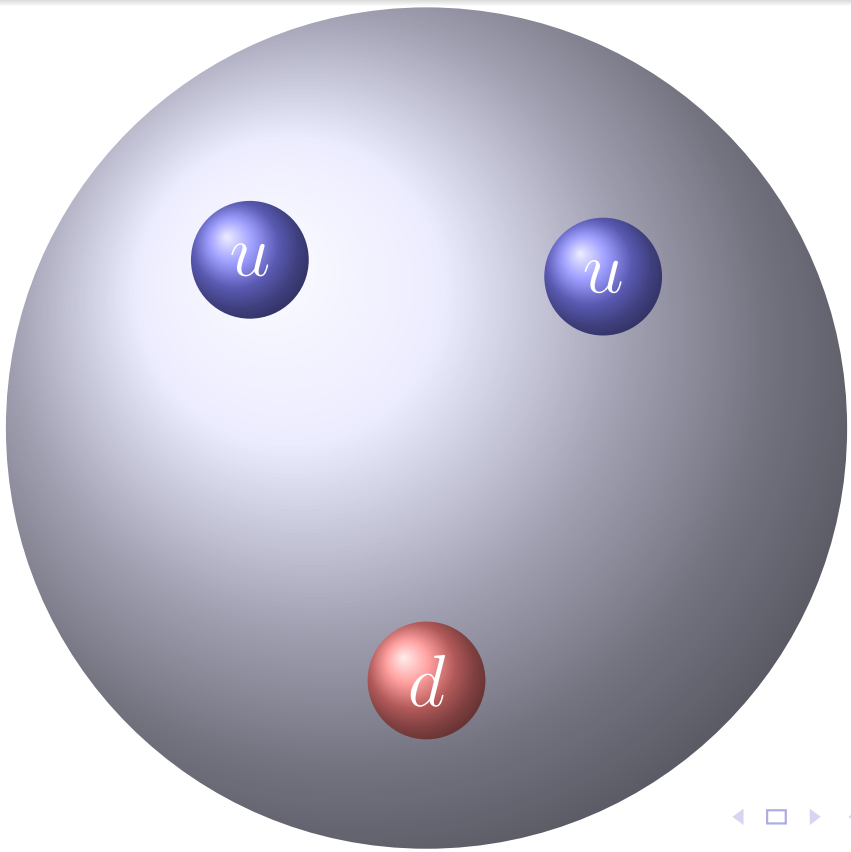

J. Friedman H. Kendall R. Taylor

Nobel prize 1990



Deep inelastic scattering

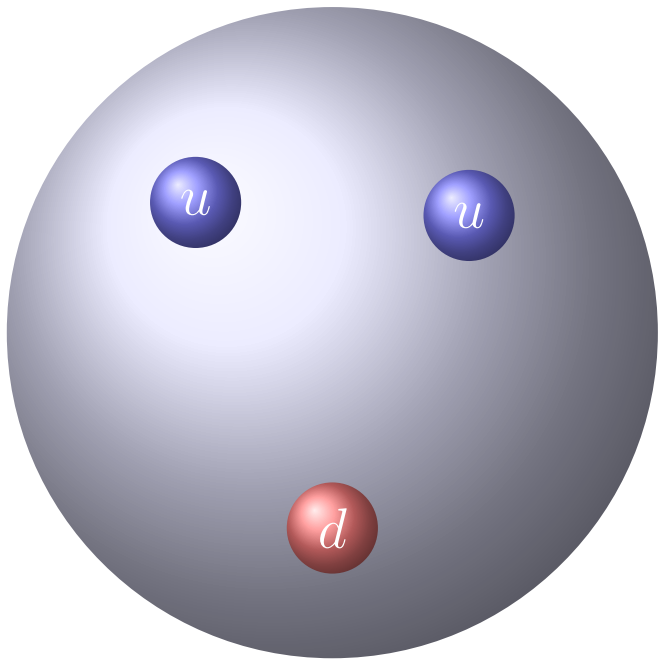
conclusion from observation $\left(\frac{\text{counting rate}}{\text{expectation point-like p.}} \approx \text{const.}\right)$:
deep inelastic scattering can be interpreted as elastic scattering on point-like particle (**quarks**) inside the proton.



Further experiments at even higher beam energies revealed the following picture of the proton:

- Scattering off proton can be interpreted as scattering off **quarks**. **Quarks** have charges which are multiples of 1/3 of the elementary charge e.

	up	down	strange
quark	u	d	s
charge/e	$2/3$	$-1/3$	$-1/3$
anti-quark	$\bar{u}$	$\bar{d}$	$\bar{s}$
charge/e	$-2/3$	$1/3$	$1/3$



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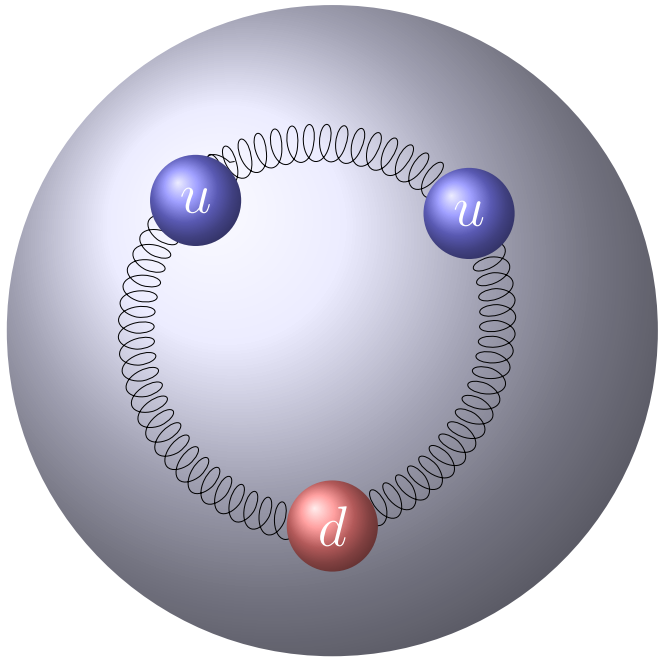
- **Quarks** are tight together by **gluons**



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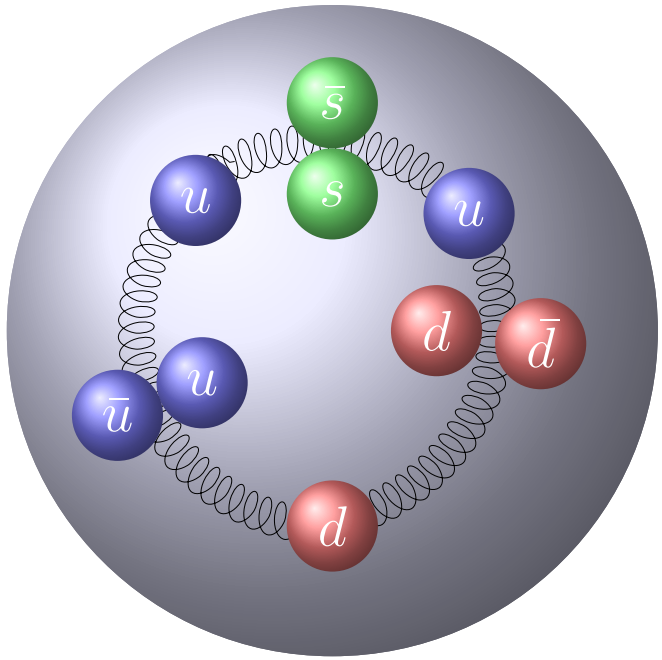
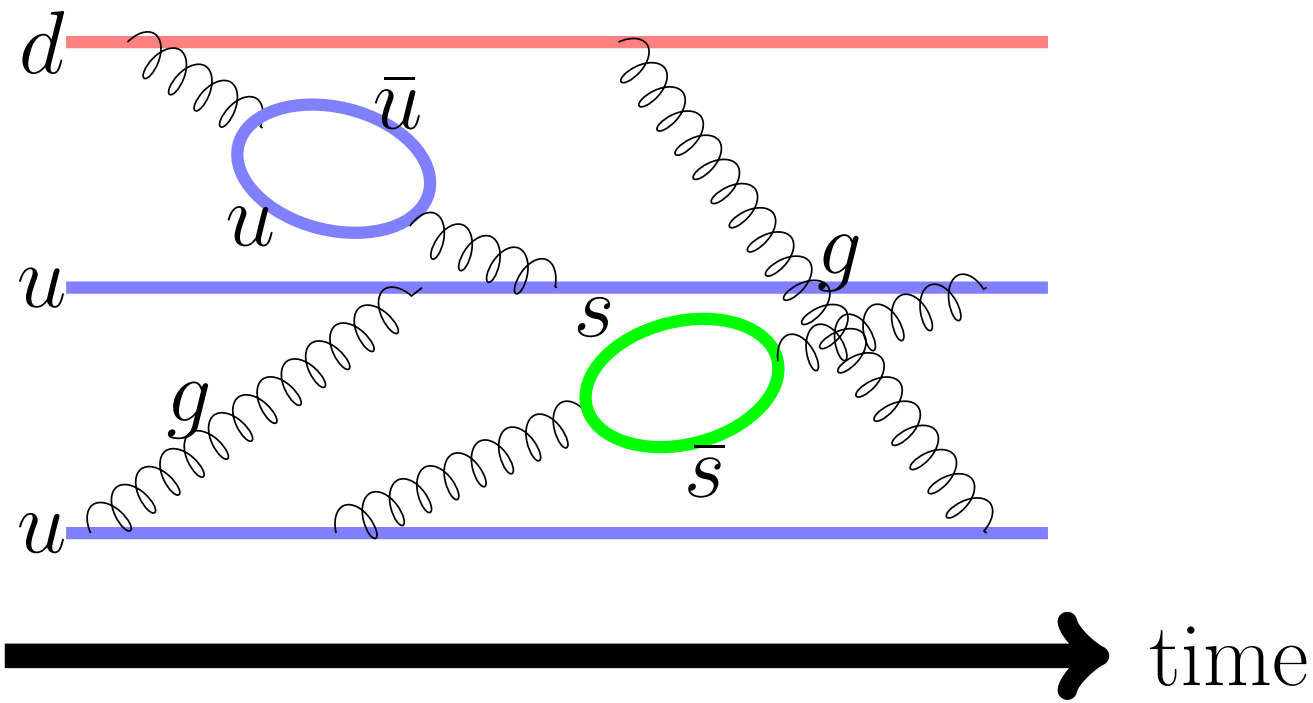
- **Quarks** are tight together by **gluons**
- **Gluons** can form **quark-antiquark-pairs**.

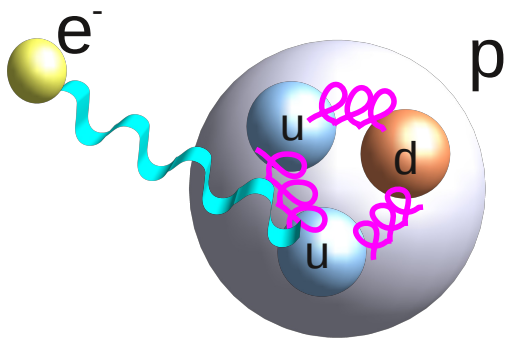


Dynamic picture of the proton



Scattering process in the Quark Model

$$e^- + p \rightarrow e^- + n + \pi^+ + \pi^+ + \pi^-$$



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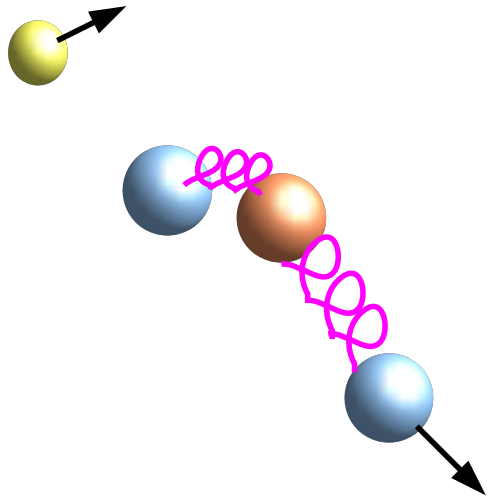

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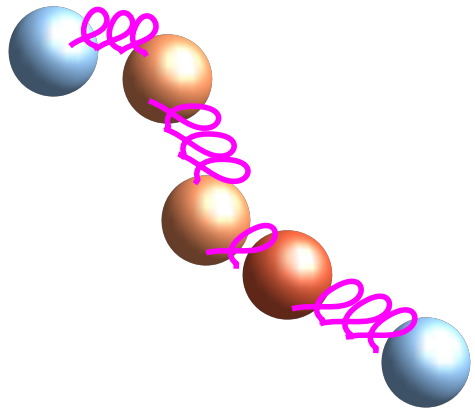

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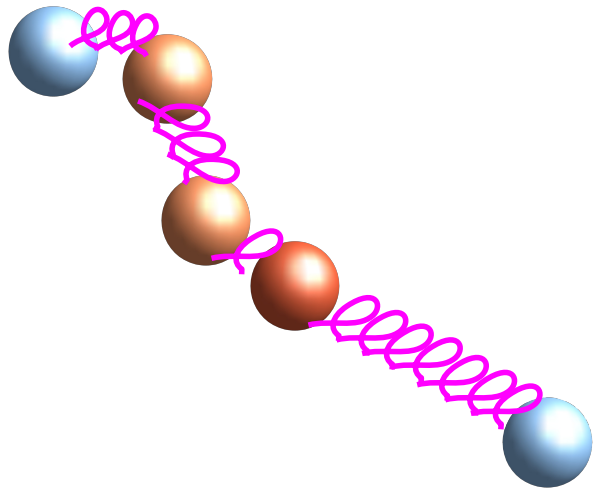

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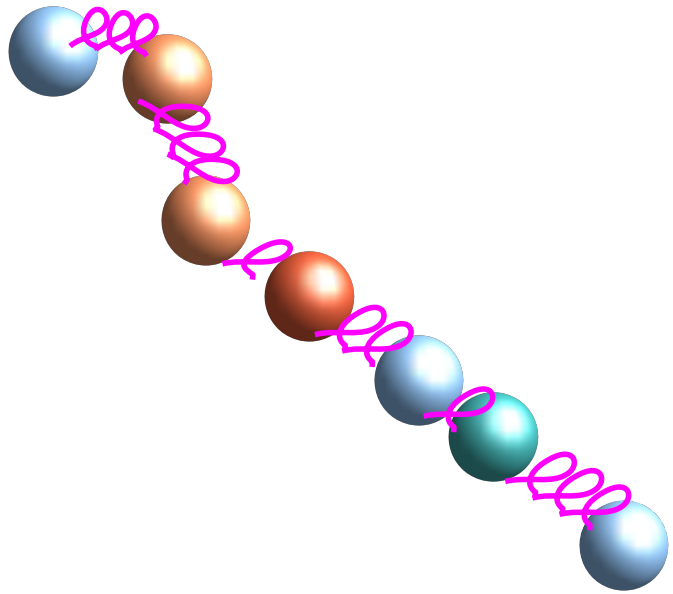

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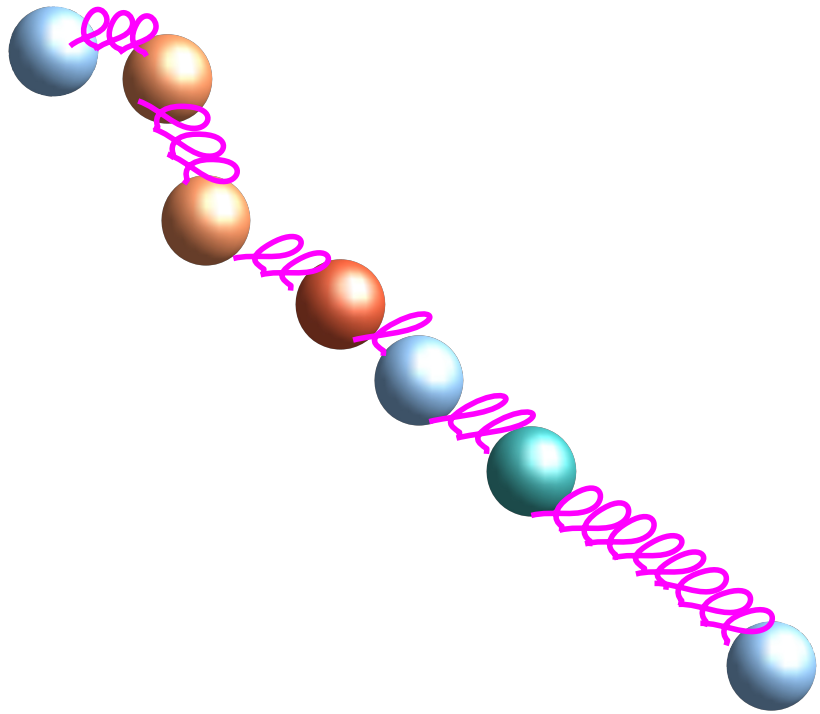

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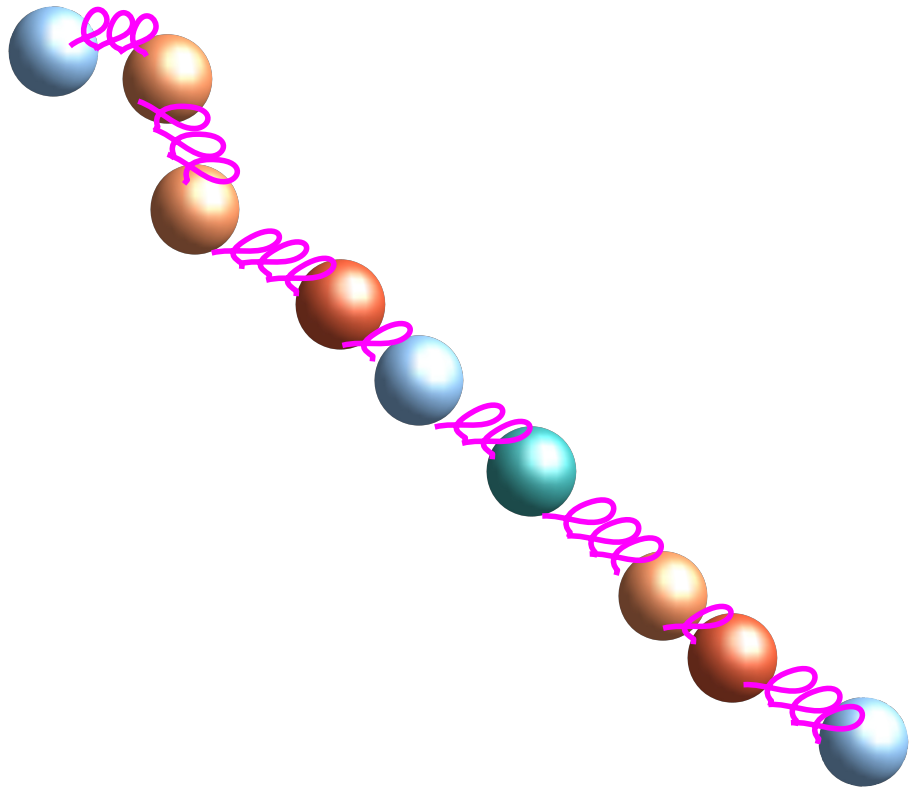

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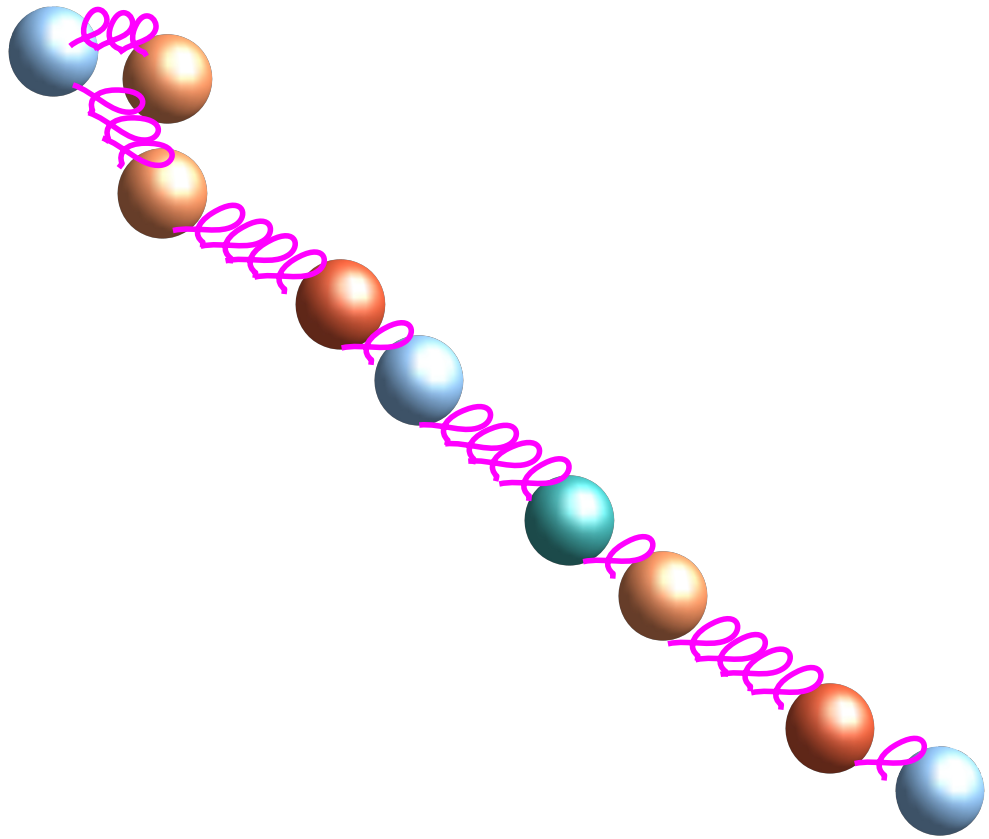

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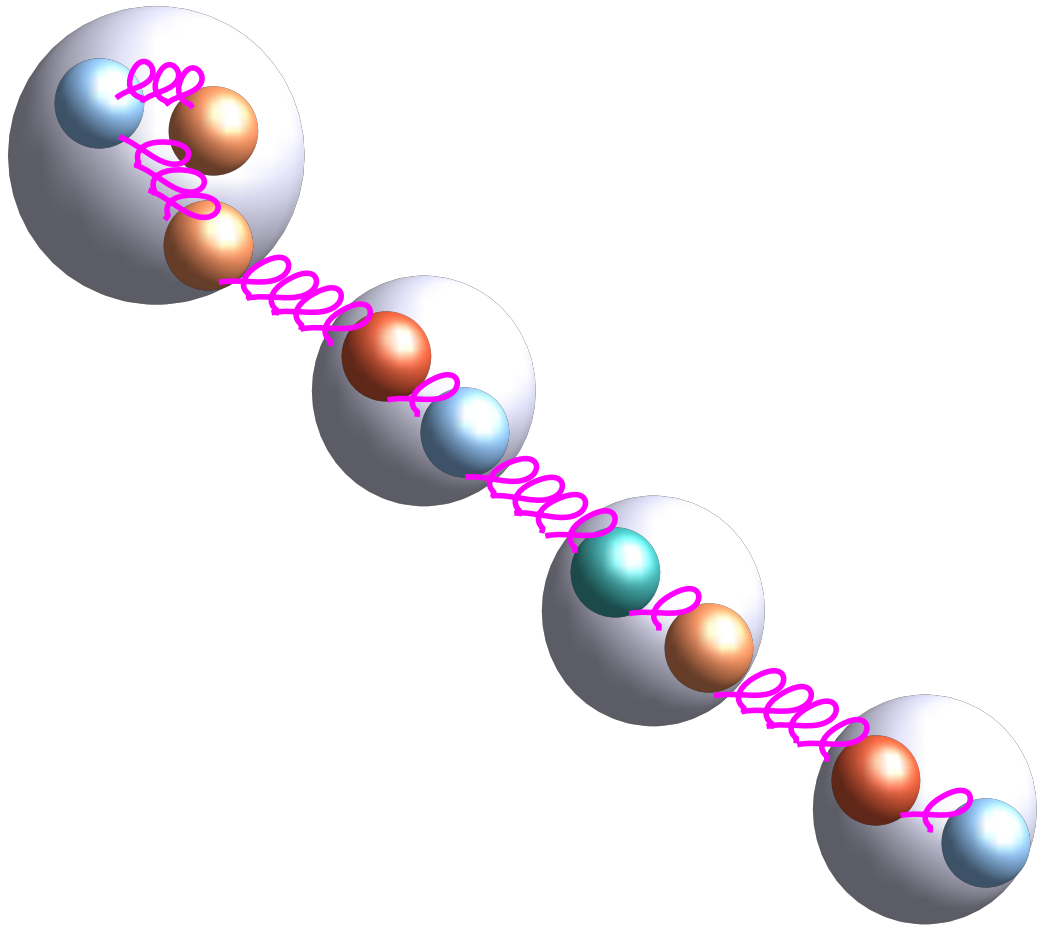

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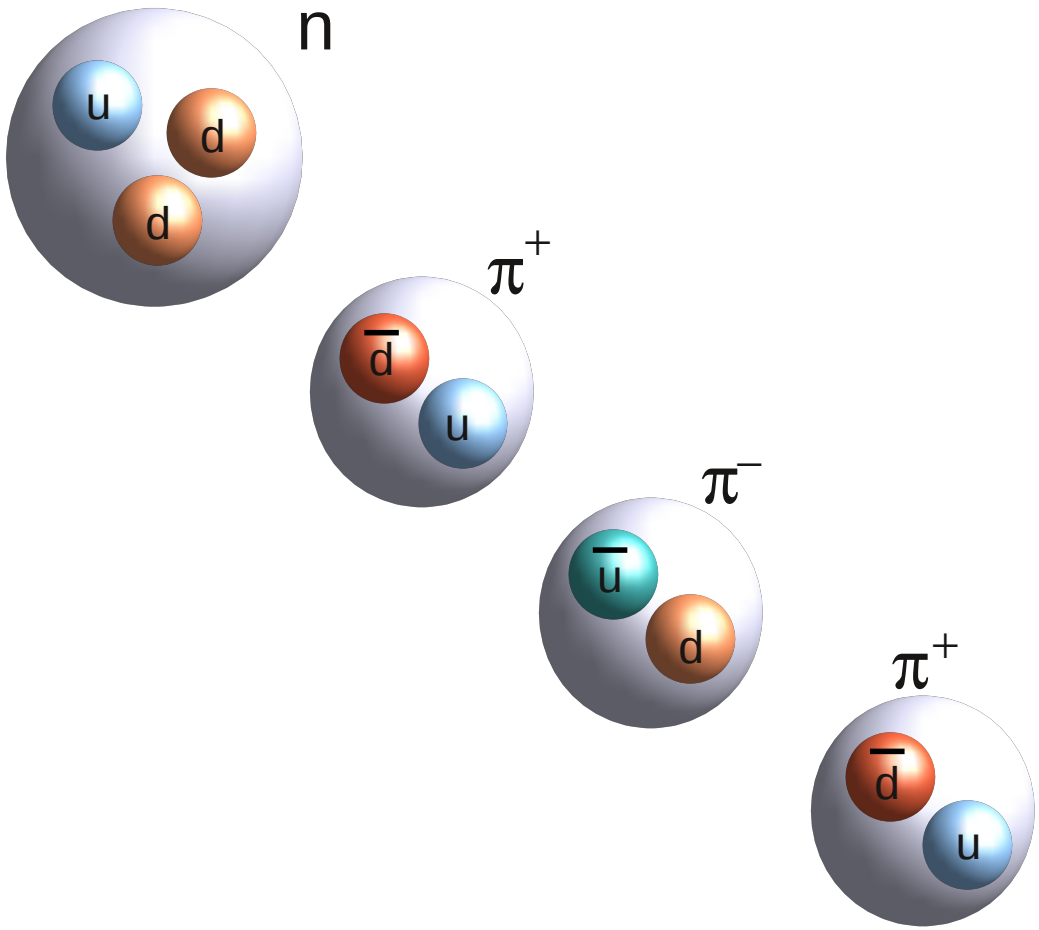
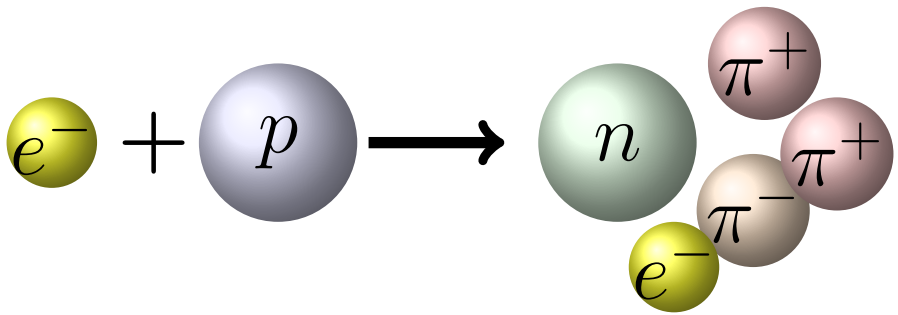


What is the proton made of?

$\Rightarrow$ clock consists of 4 gear-wheels, 9 screws, 3 springs, ...



proton does **not** simply consist of 1 neutron, two positively charged pions and a negatively charged pion

What is the proton made of?

- Bombarding the proton with high energy projectiles leads to the creation of new particles which are not part of the proton ($E = mc^2$)
- Although the question about the constituent parts of the proton is not easy to answer, physicists succeeded to describe scattering processes in detail.

  For the discovery of the higgs boson (Reaction at LHC: proton + proton $\rightarrow$ higgs boson + ...)
  the understanding of the proton is indispensable

Open questions?

Open questions?

- proton radius
- spin structure
- electric dipole moment

Spektrum
DER WISSENSCHAFT

ARTENBILDUNG
Buntbarsche: Evolution im Zeitraffer

APRIL 2014

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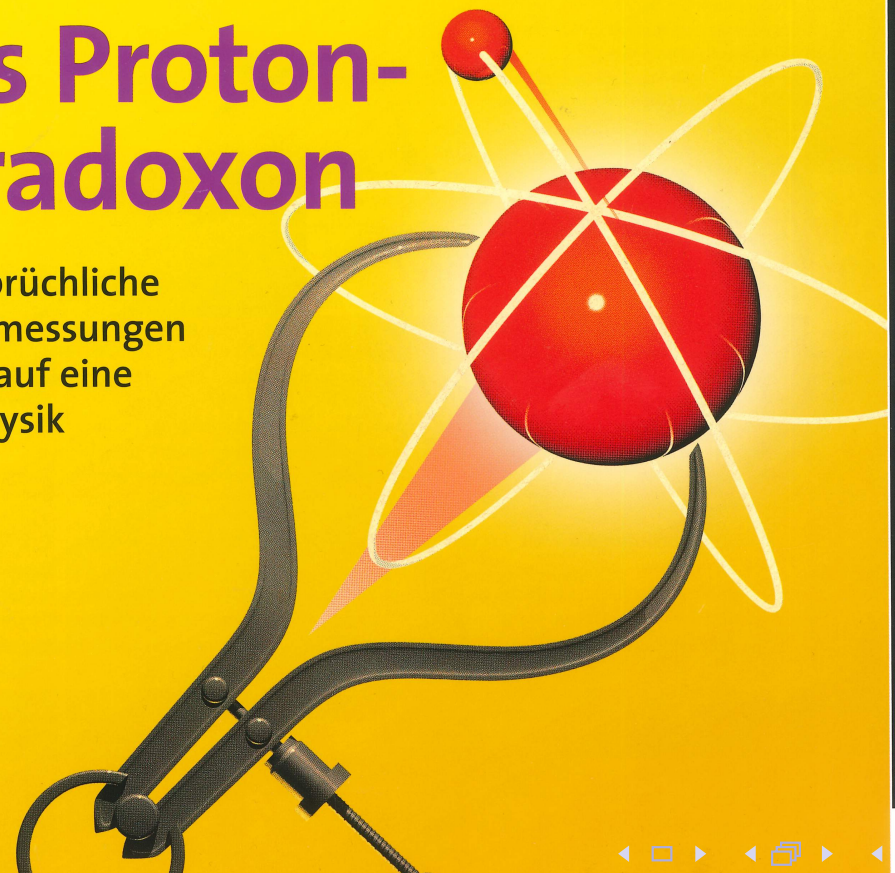
Ist die Natur digital oder analog?

KREBSTHERAPIE
Mit Stromstößen gegen Tumoren

ARCHÄOLOGIE
Die Erfindung der Landwirtschaft

Das Proton-Paradoxon

Widersprüchliche Größenmessungen deuten auf eine neue Physik



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Spin structure of proton

	proton
mass/kg	$1,7 \cdot 10^{-27}$
charge/e	+1

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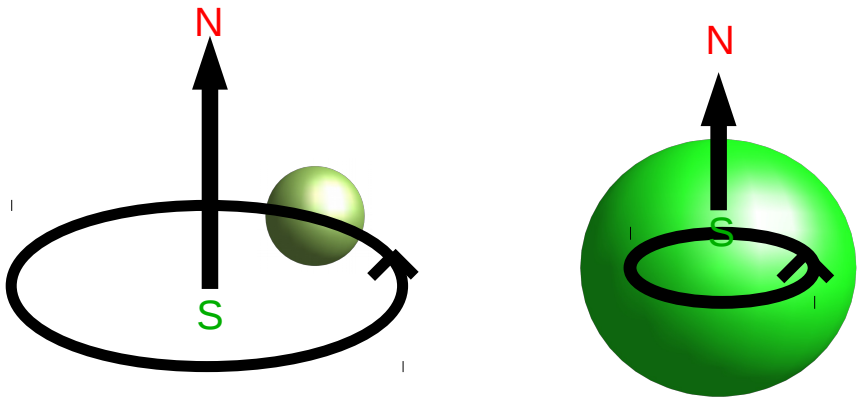
additional property for elementary particles:	
spin /$\hbar$	1/2

connected to spin is the magnetic moment μ.

$\hbar = \frac{h}{2\pi}$ Planck's constant

What is spin?

- In classical physics a magnetic field is always connected to an electric current, i.e. the movement of a charge particle
- A particle with spin causes a magnetic field even when it rests



orbital angular momentum

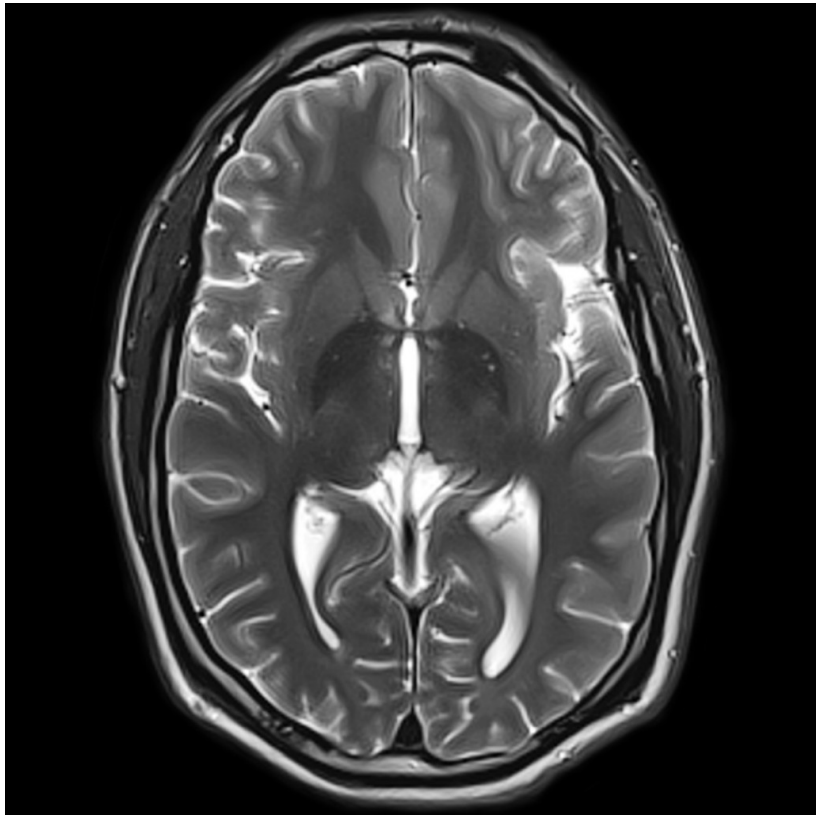
$n\,\hbar$

spin

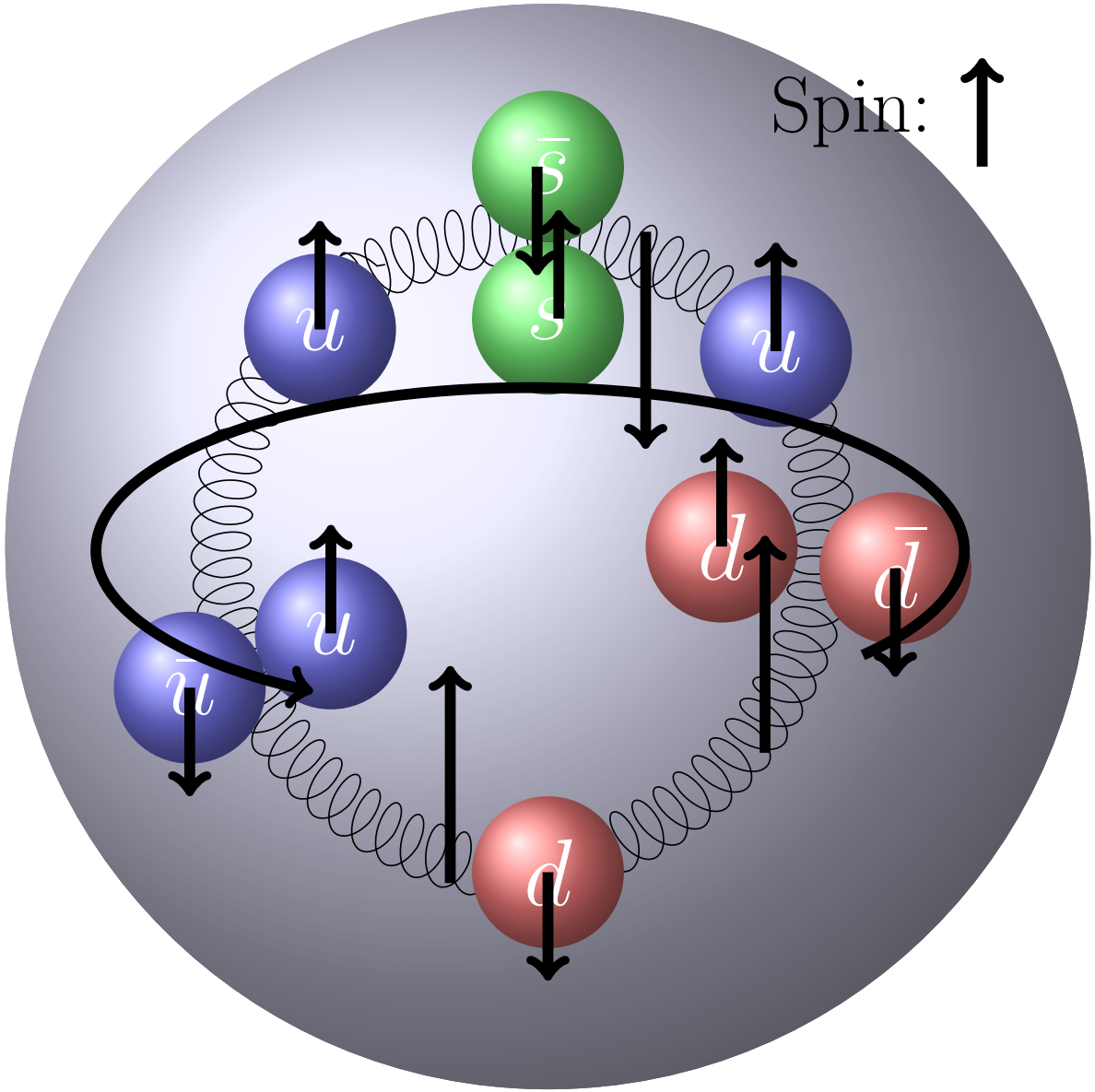
$n\,\frac{\hbar}{2}$

MRT – Magnetic Resonance Tomography

Make use of spin in medicine: Magnetic Resonance Tomography

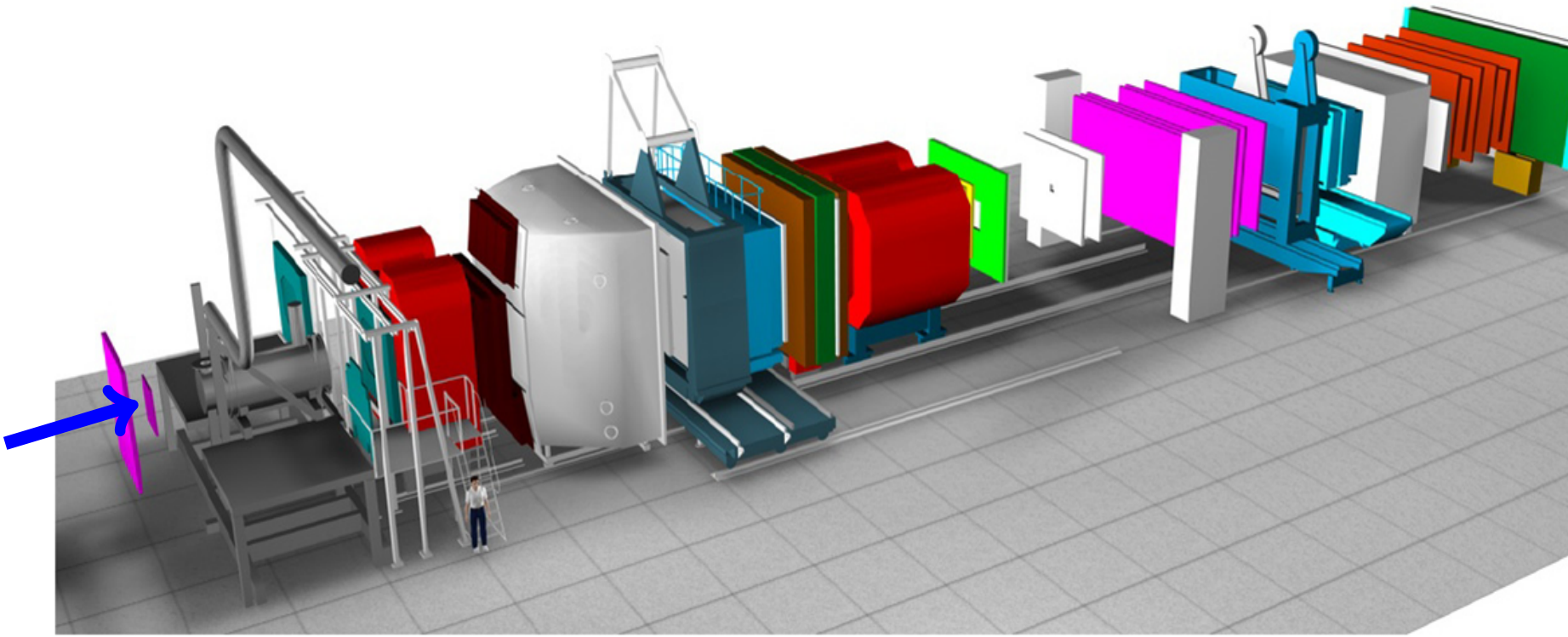


Proton Spin Puzzle



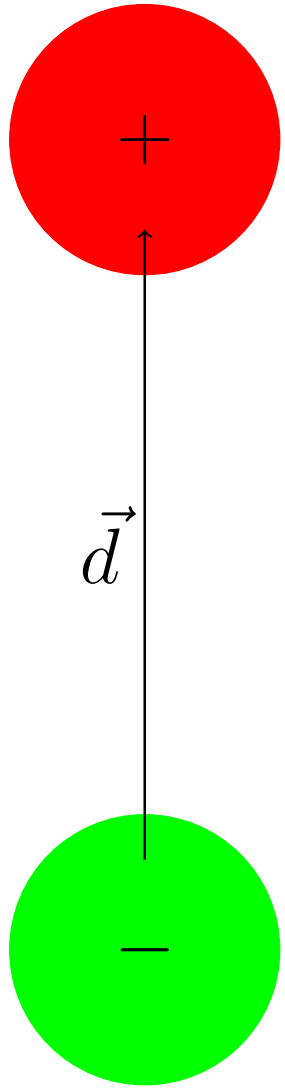
CERN

COMPASS Experiment at CERN



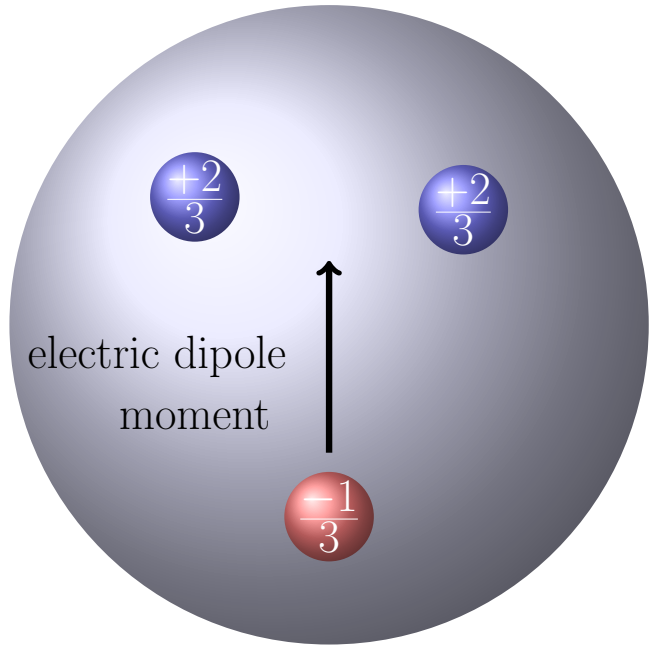
Electric Dipole Moments. . .

. . . occur when positive and negative charges are displaced from each other.



Electric Dipole Moments for elementary particles

- **Question:** Are positive and negative charges displaced inside the proton?
- If the proton had the size of the earth, one expects a separation of positive and negative charges corresponding to the thickness of a human hair.
- The existence of an electric dipole moment for elementary particles is closely connected to the question why matter is much more abundant in the universe than anti-matter.



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Summary

- What is a proton?
  Part of nucleus and, together with neutron and electron, a building block of matter

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  Part of nucleus and, together with neutron and electron, a building block of matter
- How does the inside of the proton look like?
  The proton has a complex dynamic structure of **quarks** and **gluons**
- Are there still open questions?
  Yes!