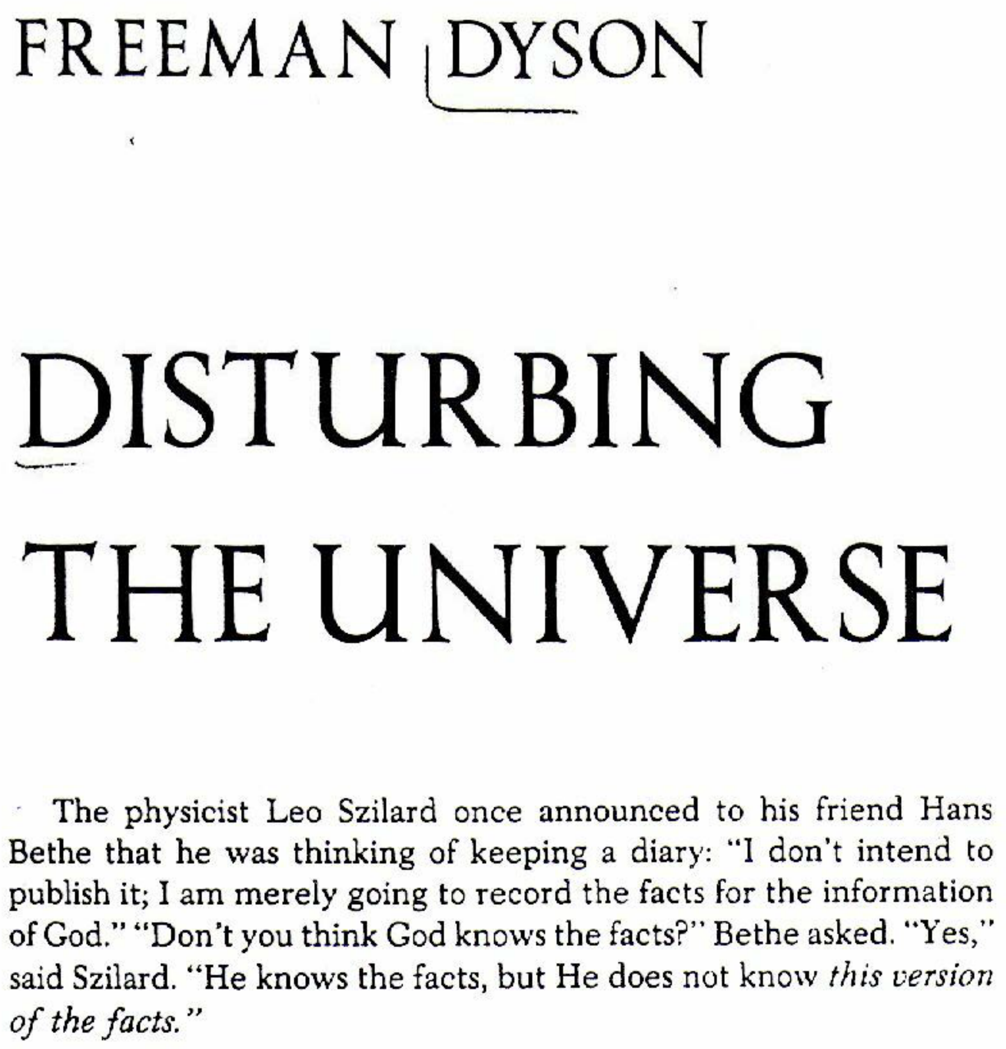
PREHISTORY

Warning! Ettől az előadástól nem leszel okosabb, talán olyan kiváncsi leszel vagy úgy feldühödsz, hogy elkezded olvasni a komoly tudományos irományokat:

DiLella, Bruning,Dissertori,Ullaland stb, akiktől én is loptam és megtalálhatók a web-n a következő helyeken:



FREEMAN DYSON

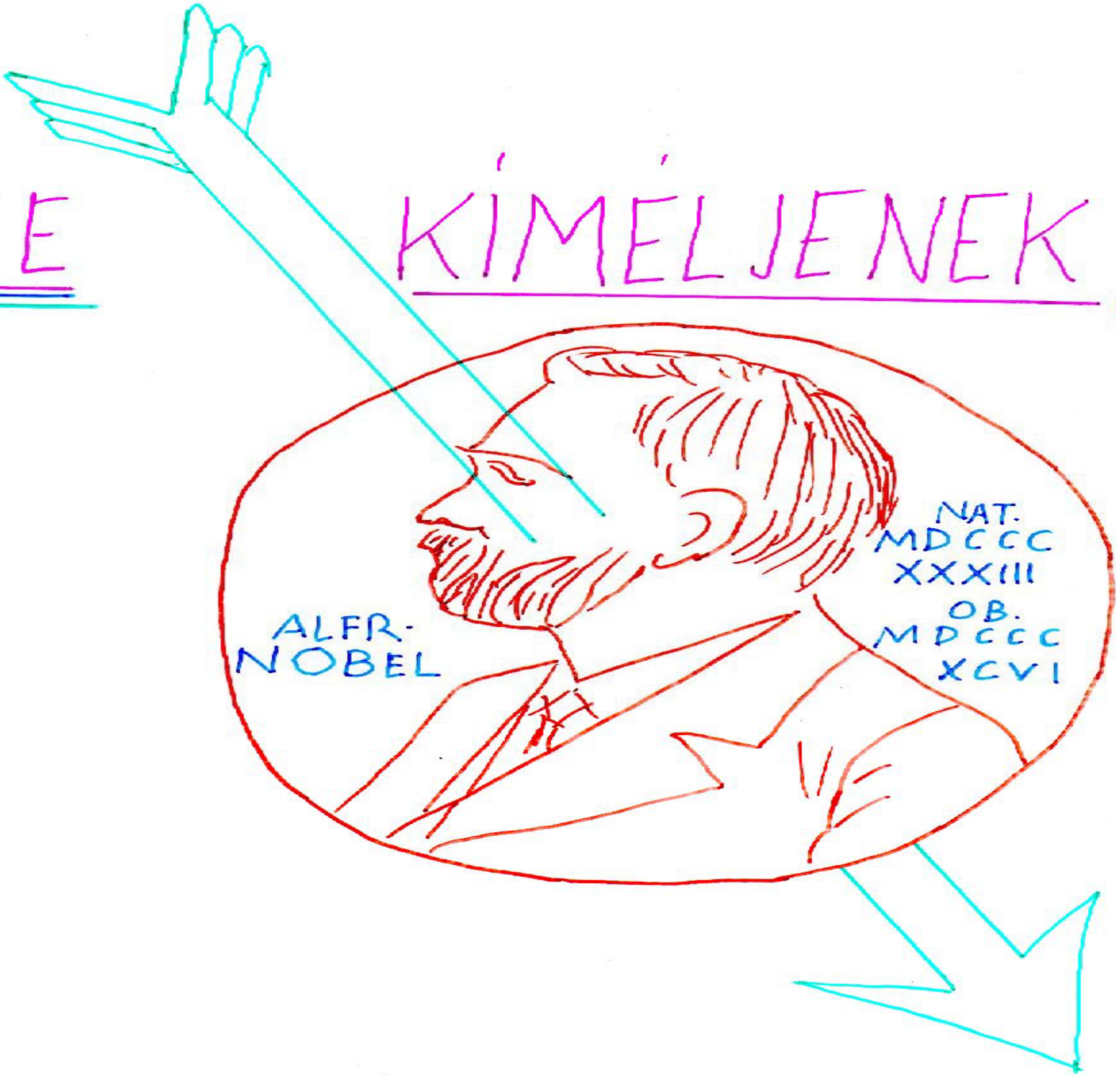
DISTURBING THE UNIVERSE

The physicist Leo Szilard once announced to his friend Hans Bethe that he was thinking of keeping a diary: "I don't intend to publish it; I am merely going to record the facts for the information of God." "Don't you think God knows the facts?" Bethe asked. "Yes," said Szilard. "He knows the facts, but He does not know *this version of the facts.*"

-A naplót nem szándékozom publikálni, csak rögzíteni akarom a tényeket Isten számára.
-Nem gondolod, hogy Isten úgyis tudja a tényeket?
-Igen, valóban tudja a tényeket, de vajon tudatában van-e a tények **ezen** verziójának is?

KALANDOROK*

NE KÍMÉLJENEK!



* KUTATÓK

THE PITFALLS of MENTAL EVOLUTION

We are in the habit of visualizing man's political and social history
as a wild *zigzag* which alternates between **progress and disaster**
but
the history of science as steady cumulative process where each epoch adds some new item of knowledge to the legacy of past, making the *temple of science grow* brick by brick to ever greater height.

The fact is that this progress was **neither** 'continuous' **nor** 'organic': occasional leaps and bounds alternating with delusional pursuits, *culs-de-sac*,regressions,periods of blindness and amnesia. (A. Koestler)

A legdrámaibb példa a szellemi **ALVAJÁRÁS**ra a heliocentrikus világkép viharos története a görögöktől Newtonig, amelyben kulcsszerepet a *főalvajárók*: **Kopernikusz, Galilei és Kepler** játszottak.

A *részecske fizika* története is tele van hasonló minidrámákkal.

De az igazi nagy kérdésekről és válaszokról fogalmunk sincs ma sem.

Az IGAZI KALANDOK csak most kezdődnek !!!!!!

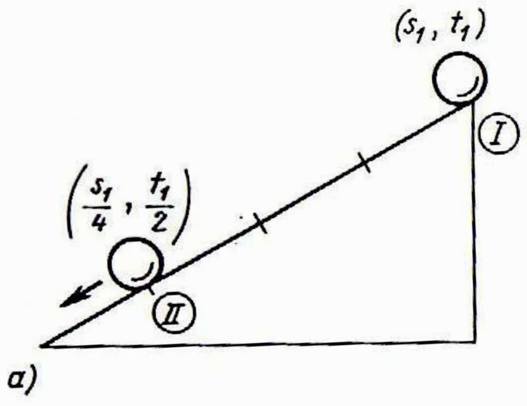
A zseni nem mászott fel a pisai ferde toronyba, hanem a gravitációt ferdítette el:

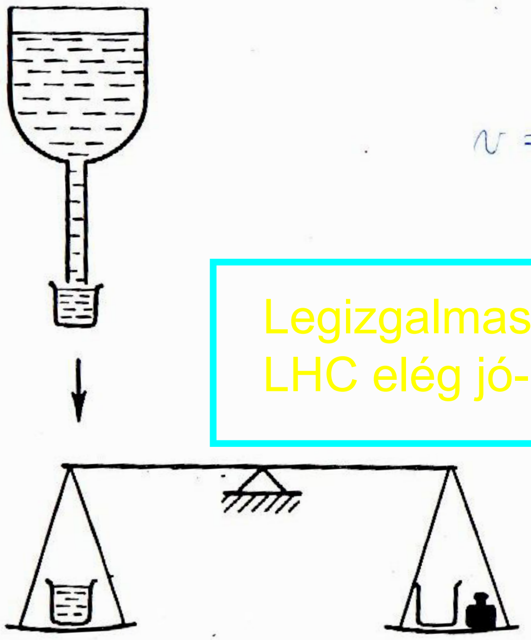
3.3—6 *idézet*

Egy körülbelül tíz méter hosszú, fél méter széles és három hüvelyk vastag deszka keskenyebbik oldalába egy hornyot vájtunk, egy hüvelyknél kissé szélesebbet . . . nagyon simára készítettük . . . és benne egy nagyon kemény, kerek és sima fémgolyót engedtünk gurulni. Miután az említett lejtőt ferdén elhelyeztük, miközben az egyik végét két-három méterrel a vízszintes fölé emeltük, legurultattuk a golyót a horonyban, és megfigyeltük azt az időt, a mindjárt ismertetendő módon, amennyire a golyónak a lefutáshoz szüksége volt, miközben ugyanezt a megfigyelést újra és újra megismételve elvégeztük, hogy biztosak legyünk az idő mérését illetően: a legkisebb különbséget sem találtuk, még egy pulzusidő tizedét sem. Majd ugyanazon golyót a horony negyed hosszúságú részén futtattuk végig, és amikor az időt megmértük, mindig pontosan az előző idő felét kaptuk.

És ami az idő mérését illeti: felakasztottunk egy tekintélyes vödröt vízzel tele, jó magasra, amelynek aljából, egy nyíláson keresztül, a víz vékony fonál alakjában folydogált, ezt a vizet fogtuk fel egy kis edényben, amíg a golyó a lejtőt vagy annak egy részét befutotta. Időről időre megmértük ezen kis vízmennyiségeket, melyeket így gyűjtöttünk, egy igen pontos mérlegen. Ezek súlyának különbsége és viszonya pontosan az idők különbségét és viszonyát adta; és ezt oly pontossággal, hogy — bármennyiszer is ismételtük meg a kísérletet, soha nem tértek el egymástól.

GALILEI: *Discorsi* ford.Simonyi Károly





$$\frac{s_i}{t_i^2} = const = \left(\frac{a}{2}\right)$$

$v = a \cdot s$?

$v = a \cdot t$?

Legizgalmasabb kérdés: Vajon az LHC elég jó-e látni a gravitációt ???

A gravitációs kölcsönhatás csatolási állandójának első hiteles mérése

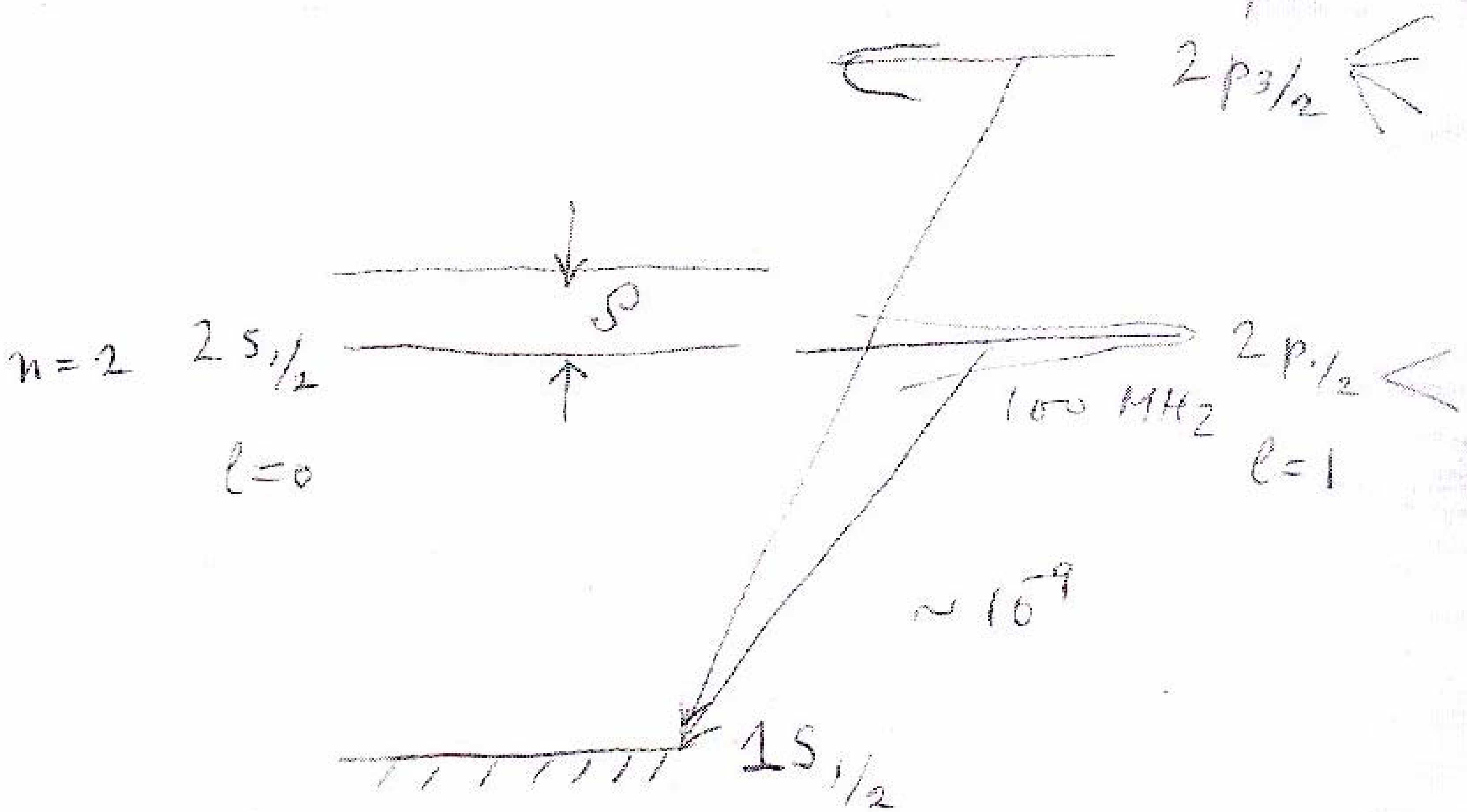
kis hibával: g = 5 m/sec2

MIND OVER MATTER:
THE INTELLECTUAL CONTENT OF EXPERIMENTAL PHYSICS

V.L. Telegdi*
California Institute of Technology, Pasadena, CA91125

According to my experience, the most brilliant physics students at any university want to become theoreticians, and this on both sides of the Atlantic ocean. It is rare that a person of the intellectual power of, say , a Gell-Mann or a Cabibbo decides to embark on a career in experimental physics. It is obvious that this fact entails a serious loss for physics, since physics is primarily a natural science. I have often asked myself about the reasons for this regrettable situation; once these are established, perhaps remedies could be suggested.

I have come up with two reasons. The first of these is the style in which physics is taught essentially everywhere. There are two models, A and B, both of which fail to convey to the students the intellectual content of important experiments. Following model A, the student is told that some great genius, identified by name, predicted a remarkable dependence y(x) of one observable upon another. That dependence was then subsequently brilliantly confirmed by experiment - by some unspecified person. In model B, one presents an observed dependence y(x) that constituted, at its time, a great puzzle. Again, a great genius (name given) came along and presented a theory which fitted the observations perfectly. In either model, the intellectual accomplishment of the experimentalist is generally not conveyed to the students. I shall illustrate this by two examples: (1) in Okun's masterful book "Leptons and Quarks", experiments are rarely described - although the authors are given - their results are merely quoted, as "one finds....". (2) I once gave a course "Great Experiments in Modern Physics" at MIT. It was attended by young students and ... senior theorists. Many of the latter learned for the first time how Willis Lamb had actually determined "his" shift, how many brilliant insights he had had to have to achieve his goals.


2p3/2
S
n = 2
2s1/2
2p1/2
100 MHz
l=0
l=1
~10^-9
1s1/2

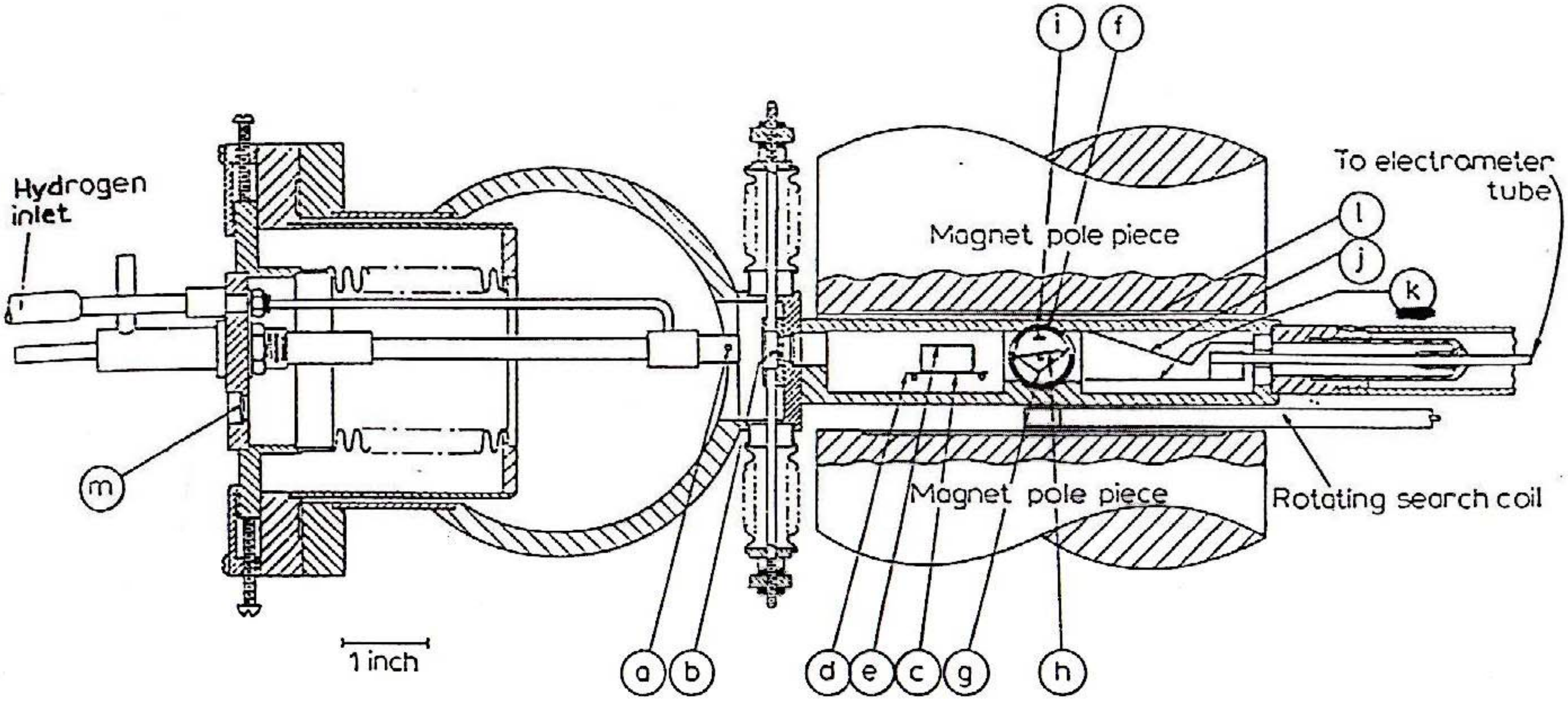


Fig. 3. Cross section of second apparatus: (*a*) tungsten oven of hydrogen dissociator, (*b*) movable slits, (*c*) electron bombarder cathode, (*d*) grid, (*e*) anode, (*f*) transmission line, (*g*) slots for passage of metastable atoms through interaction space, (*h*) plate attached to center conductor of r-f transmission line, (*i*) d.c. quenching electrode, (*j*) target for metastable atoms, (*k*) collector for electrons ejected from target, (*l*) pole face of magnet, (*m*) window for observation of tungsten oven temperature.

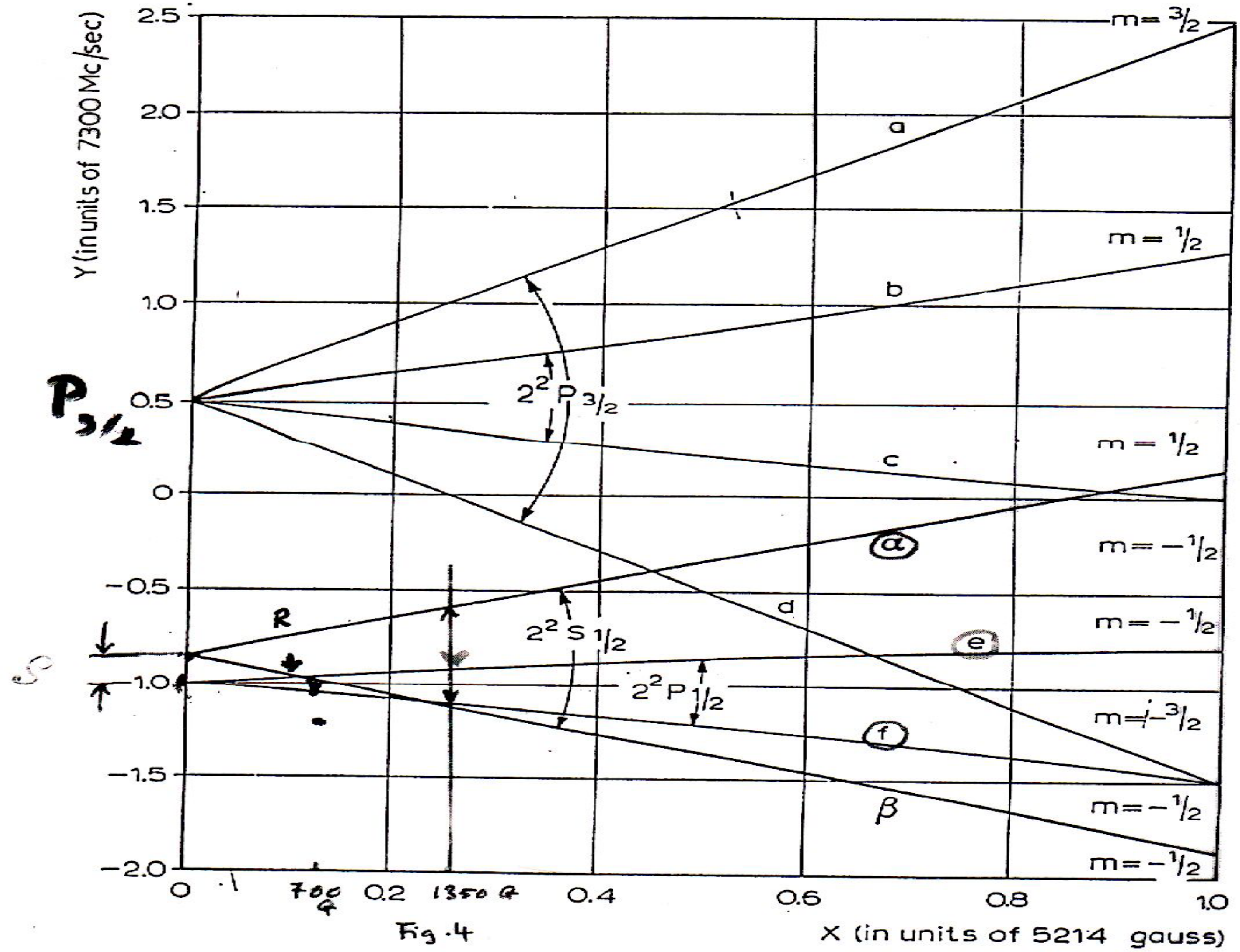

Y (in units of 7300 Mc/sec)
2.5
2.0
1.5
1.0
0.5
0
−0.5
−1.0
−1.5
−2.0
$P_{3/2}$
S
m = 3/2
a
m = 1/2
b
$2^2P_{3/2}$
m = 1/2
c
m = −1/2
α
m = −1/2
d
R
$2^2S_{1/2}$
e
$2^2P_{1/2}$
m = −3/2
f
m = −1/2
β
m = −1/2
0
·1
700 G
0.2
1350 G
0.4
0.6
0.8
1.0
X (in units of 5214 gauss)

Fig. 4

Találós kérdés:

A Lamb-shift eredménye, hogy az S pálya energiája magasabb mint a P-é.

Miért olyan fontos, hogy magasabb???

Mi az üzenete a Lamb-shiftnek az LHC részére?

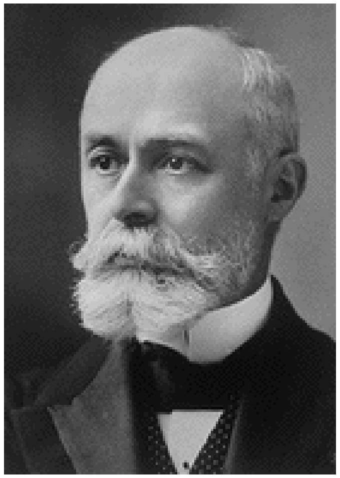
Hullámfügvény maximuma, ahol a proton felforralja a vákuumot.

Newton óta kérdés a színpad és a szereplők viszonya: részecskék vs vákuum

Bohr-Rutherford: Kvantummechanika   Lamb-shift:Kvantumtérelmélet

1896: Discovery of natural radioactivity

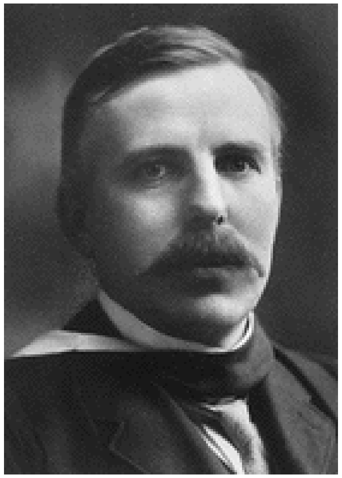
(Henri Becquerel)



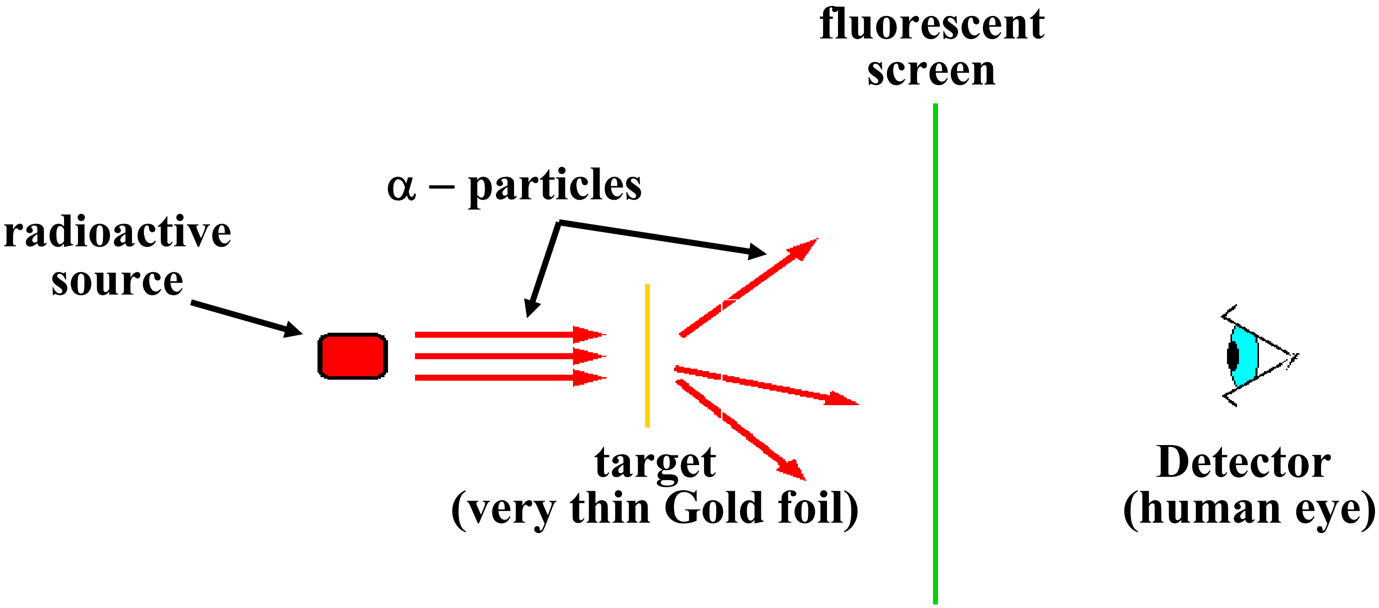
Henri Becquerel

1909 – 13: Rutherford's scattering experiments

Discovery of the atomic nucleus



Ernest Rutherford

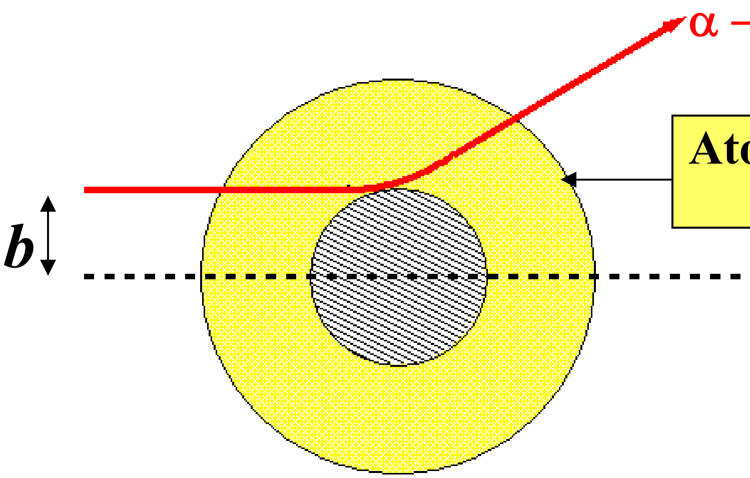


α – particles : nuclei of Helium atoms spontaneously emitted by heavy radioactive isotopes

Typical α – particle velocity $\approx 0.05\ c$ (c : speed of light)

Expectations for α – atom scattering

α – atom scattering at low energies is dominated by Coulomb interaction



α – particle

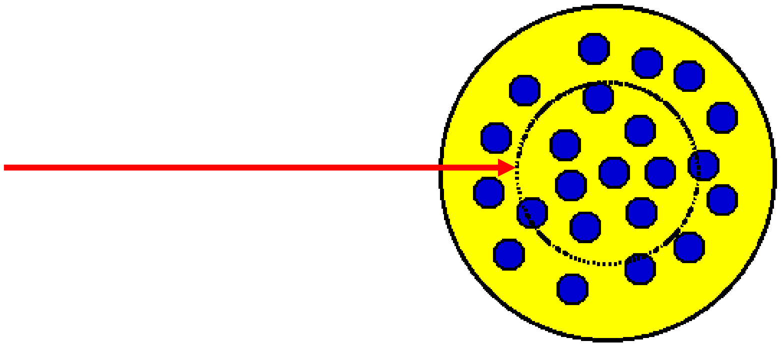
Atom: spherical distribution of electric charges

impact parameter

b

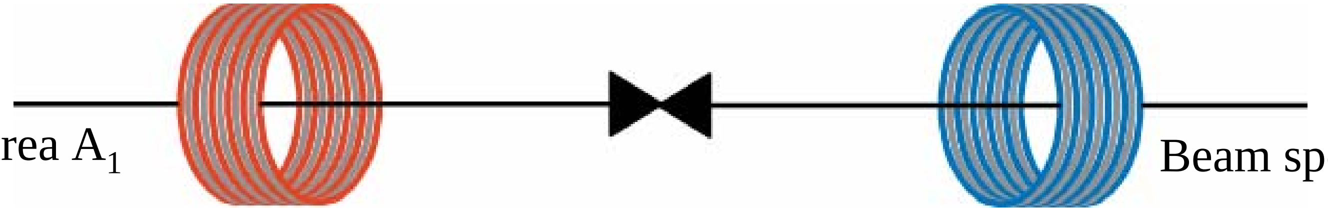
α – particles with impact parameter = *b* "see" only electric charge within sphere of radius = *b* (Gauss theorem for forces proportional to r^{-2})

For Thomson's atomic model the electric charge "seen" by the α – particle is zero, independent of impact parameter



$\Rightarrow$ no significant scattering at large angles is expected

Cross section σ or the differential cross section $d\sigma/d\Omega$ is an expression of the probability of interactions.



Beam spot area A_1

$\Phi_1=N_1/t$

Beam spot area A_2

$\Phi_2=N_2/t$

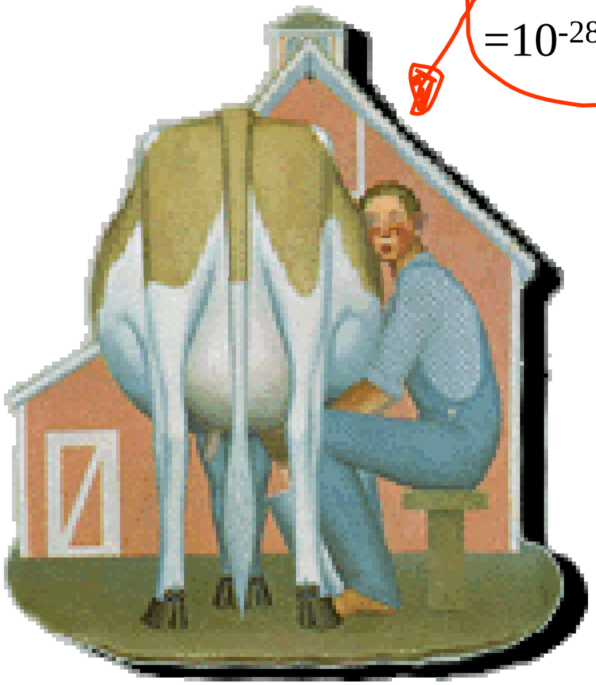
The interaction rate, R_{int}, is then given as:

$$R_{\text{int}} \propto \frac{N_1 N_2}{A\cdot t}$$

$$= \sigma \mathcal{L}$$

σ has the dimension area.
1 barn = 10^{-24} cm^2

$=10^{-28}$ m^2



Grant Wood, Fruits of Iowa: Boy Milking Cow, 1932

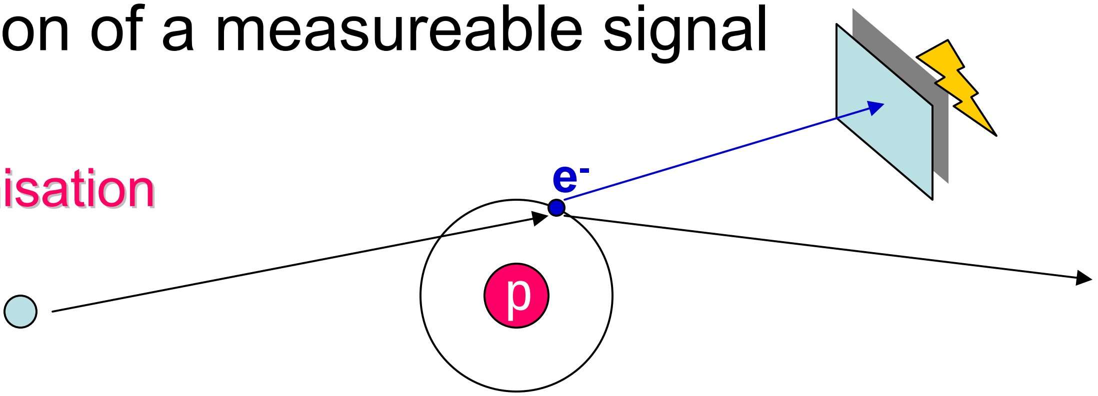
The luminosity, $\mathcal{L}$, is given in cm^{-2}s^{-1}

Miért csűr (barn) a hatáskeresztmetszet egysége?

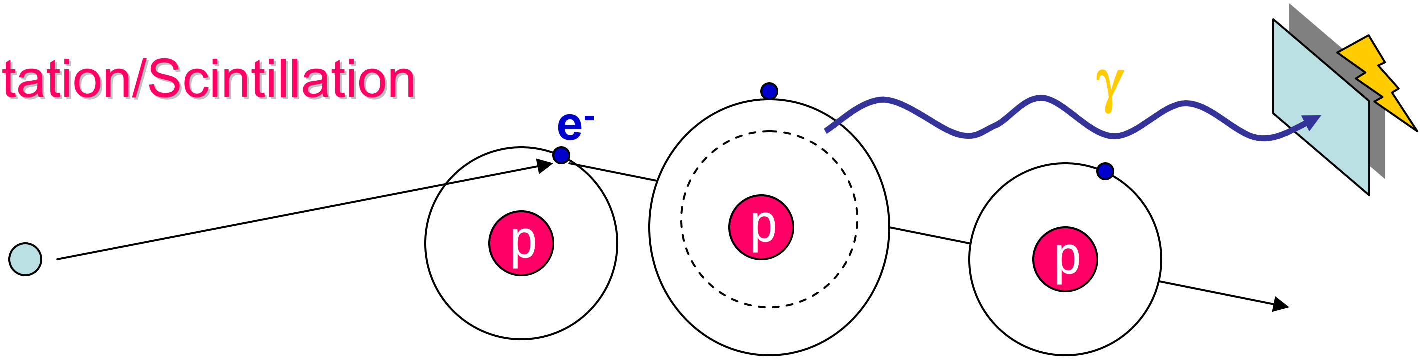
from C. Joram, SSL 2003

Principles of a measurement

- Measurement occurs via the interaction of a particle with the detector(material)
  - creation of a measureable signal
    - Ionisation



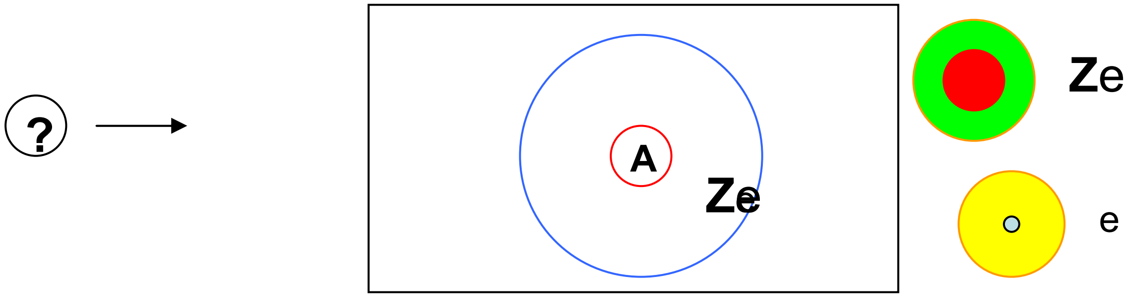
- Excitation/Scintillation



- Change of the particle trajectory
  - curving in a magnetic field, energy loss
  - scattering, change of direction, absorption

See Dissertori handout !!!!!

Észlelendő RÉSZECSKE **Észlelő KÖZEG** **Közeg TÍPUSAi**

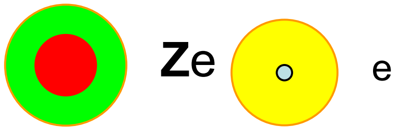


Hadron-anyag
Mag Coulomb-tér

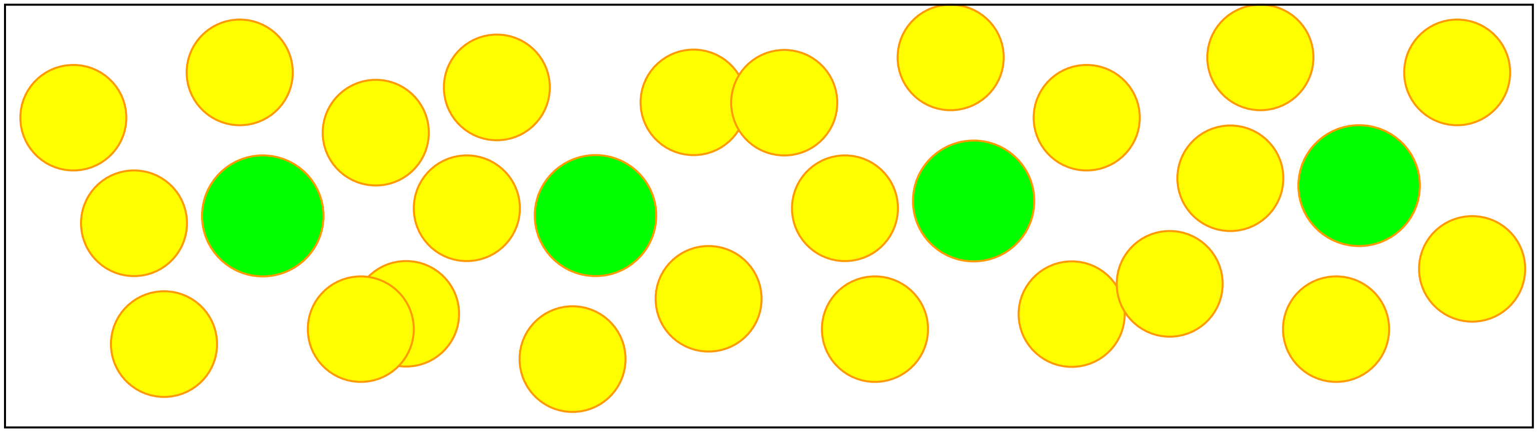
e Coulomb-tér

Mit látnak az egyes részecskék? Vannak erős (S), gyenge(W) és foton(EM) szeműek.

HADRON:	töltött (S, EM, W)	semleges (S, W)
LEPTON:	töltött (EM, W)	semleges (W)
FOTON (EM)		

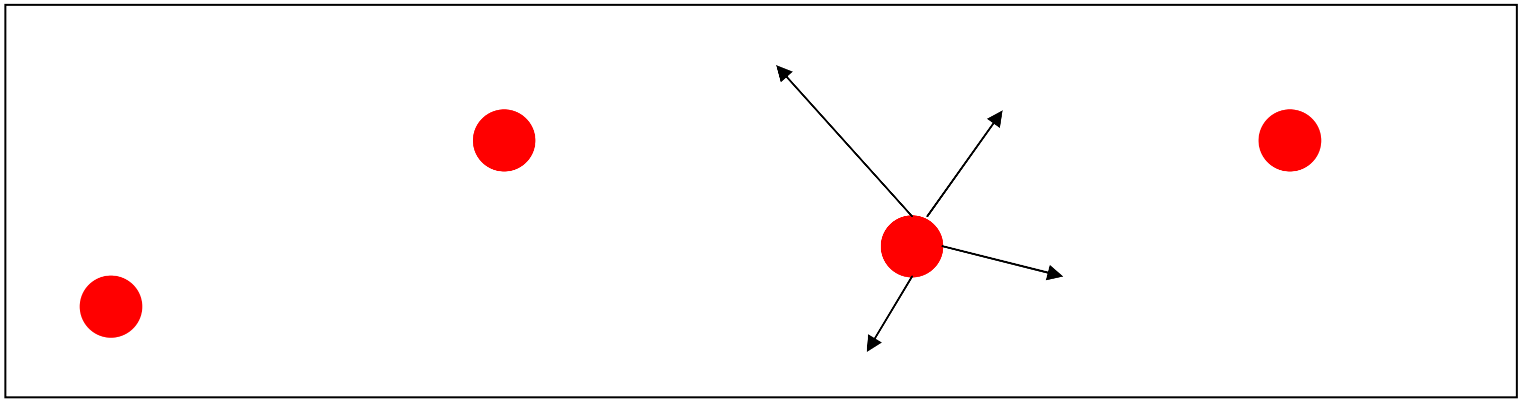


Coulomb-anyag

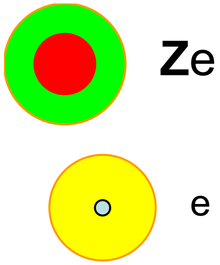


Minden **töltött** részecske érzi ezt: gerjeszt, ionizál vagy elektron-lyuk párt kelt (C,TRD)

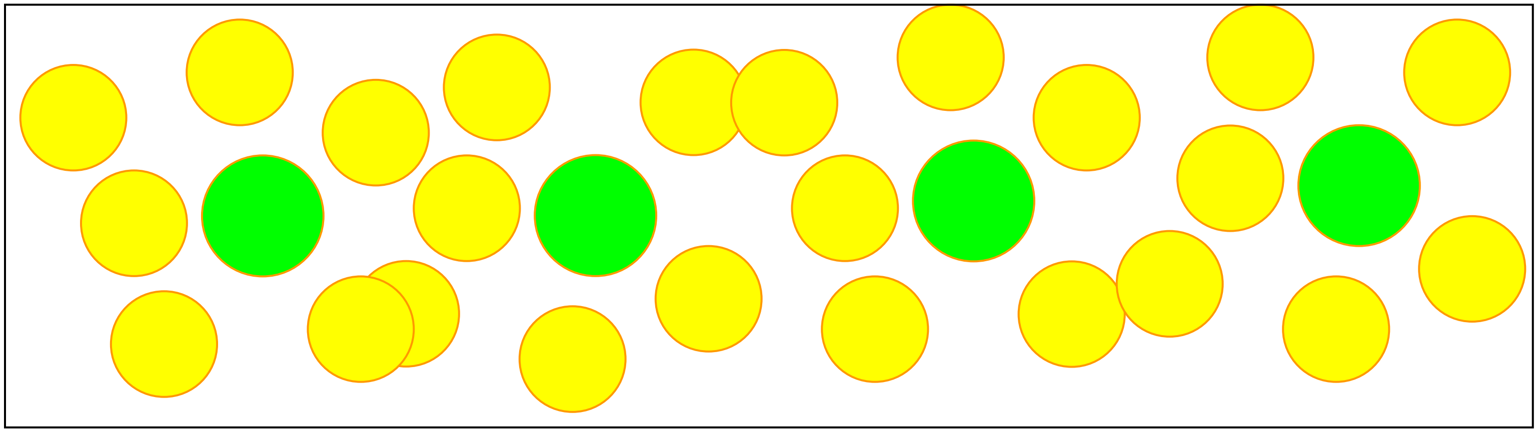
Hadron-anyag



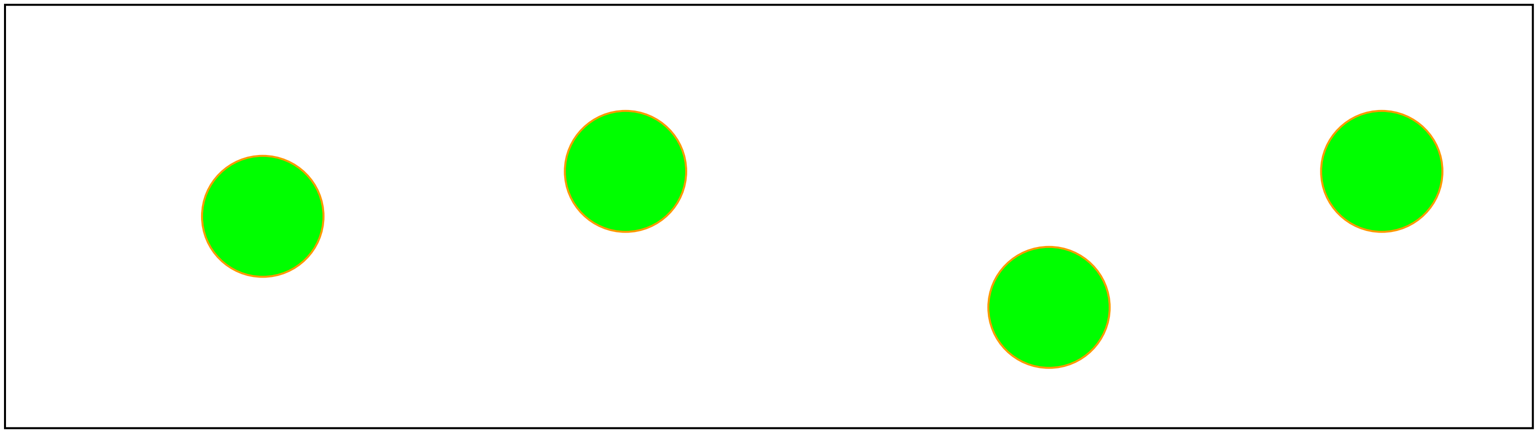
Minden hadron (neutron is) látja, ritkán van ütközés, de akkor nagyot durran.



Coulomb-anyag



Nukleáris Coulomb-anyag



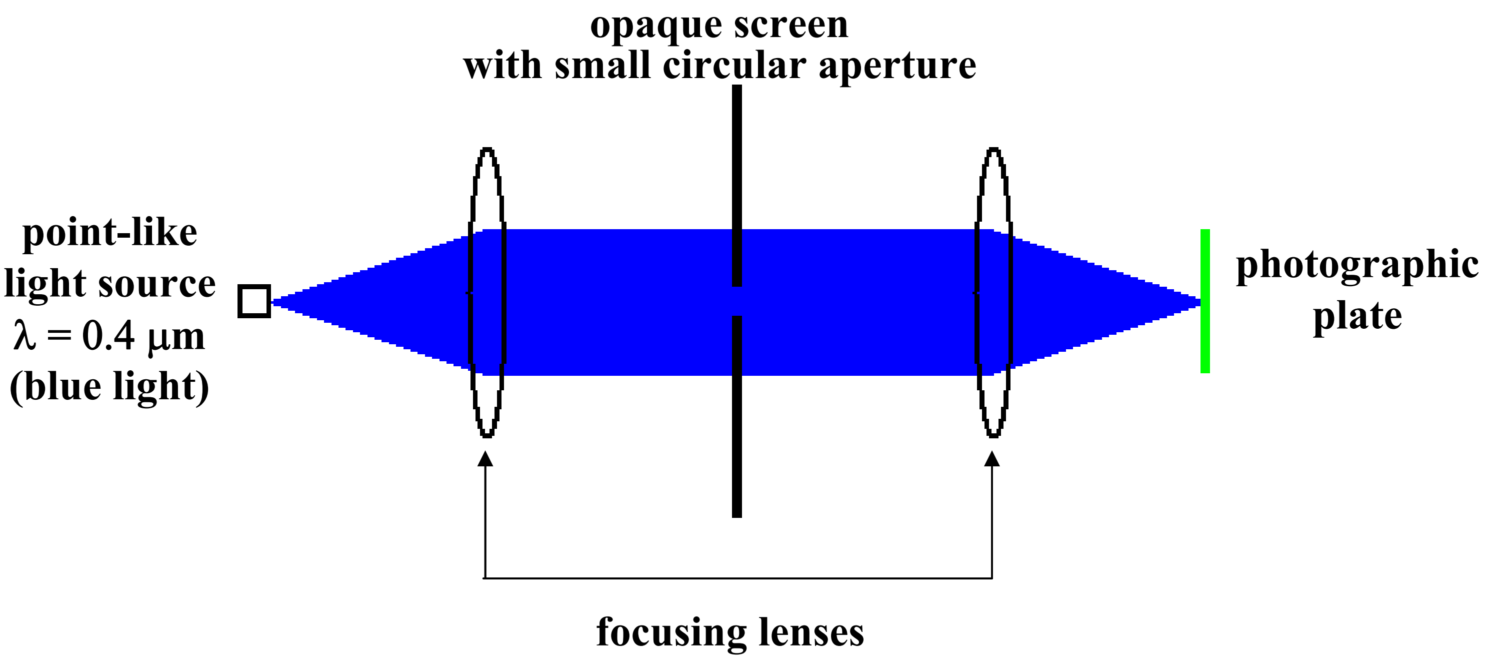
A rendkívüli kis tömegű FOTON és ELEKTRON különlegesen intenzíven kölcsönhat a magok erős (ha Z nagy!) Cb-terével: Párkeltés illetve Bremsstrahlung (fékezési sugárzás)

Two questions:

- Why did Rutherford need α – particles to discover the atomic nucleus?
- Why do we need huge accelerators to study particle physics today?

Answer to both questions from basic principles of Quantum Mechanics

Observation of very small objects using visible light



1924: De Broglie's principle

Louis de Broglie

Not only light, but also matter particles possess both the properties of waves and particles

Relation between wavelength and momentum:

$$\boxed{\lambda = \frac{h}{p}}$$

h: Planck constant

$p = m\,\mathrm{v}$: particle momentum

Hypothesis soon confirmed by the observation of diffraction pattern in the scattering of electrons from crystals, confirming the wave behaviour of electrons (Davisson and Germer, 1927)

Wavelength of the α – particles used by Rutherford in the discovery of the atomic nucleus:

$$\lambda = \frac{h}{m_\alpha \mathrm{v}} \approx \frac{6.626\times 10^{-34}\ \mathrm{J\,s}}{(\underset{\substack{\uparrow\\ \text{α–particle}\\ \text{mass}}}{6.6\times 10^{-27}}\ \mathrm{kg})\times(\underset{\substack{\uparrow\\ 0.05\ c}}{1.5\times 10^{7}}\ \mathrm{m\ s^{-1}})} \approx 6.7\times 10^{-15}\ \mathrm{m} = 6.7\times \underset{\substack{\uparrow\\ \sim\ \text{resolving power}\\ \text{of Rutherford's}\\ \text{experiment}}}{10^{-13}}\ \mathrm{cm}$$

Typical tools to study objects of very small dimensions

		Resolving power
Optical microscopes	Visible light	$\sim 10^{-4}$ cm
Electron microscopes	Low energy electrons	$\sim 10^{-7}$ cm
Radioactive sources	α–particles	$\sim 10^{-12}$ cm
Accelerators	High energy electrons, protons	$\sim 10^{-16}$ cm

Bohr-Rutherford: SZÉP ÚJ VILÁG

kb 1OO elem helyett: KETTŐ építőkő !!!!!

Ilyen **egyszerű** még sose volt a világ.

DE a fránya kísérleti fizikusok tovább matattak...

ujabb és ujabb *kísérleti technikákat* vezettek be....

A NEUTRON FELFEDEZÉSE

Rutherford $\begin{cases} \text{1911-ben publikálta a kicsi atommag létét} \\ \text{1920-ban javasolta a neutron létezését.} \end{cases}$

De "MINDENKI" azt, hitte : ATOMMAG = A*proton + (A-Z)*elektro

ELVI PROBLÉMÁK

1. Ha "e" a magon belül van, akkor :

$$\Delta p \cdot \Delta x \approx \hbar \rightarrow c \cdot \Delta p \cdot \Delta x = \hbar c = 200 \text{ MeV-fermi}$$

$$\Delta p = \frac{200 \text{ MeV-fermi}}{\text{fermi}} \cdot \frac{1}{c} = 200 \text{ MeV}/c \quad \begin{cases} m_e \sim 0.5 \text{ MeV}/c^2 & \gamma \approx 40 \\ m_p \sim 1000 \text{ MeV}/c^2 & \gamma \approx \end{cases}$$

2. Bose vs Fermi statisztika: N_7^{14} mag

14 proton + 7 elektron = Fermion (feles-spin)

7 proton + 7 neutron = Boson (egész-spin)

Mérés : spin = 1

KISÉRLETI FÉLREÉRTELMEZÉSEK

1. Bothe - Becher $He_2^4 + Be_4^9 \xrightarrow{?} C_6^{13} + \gamma$

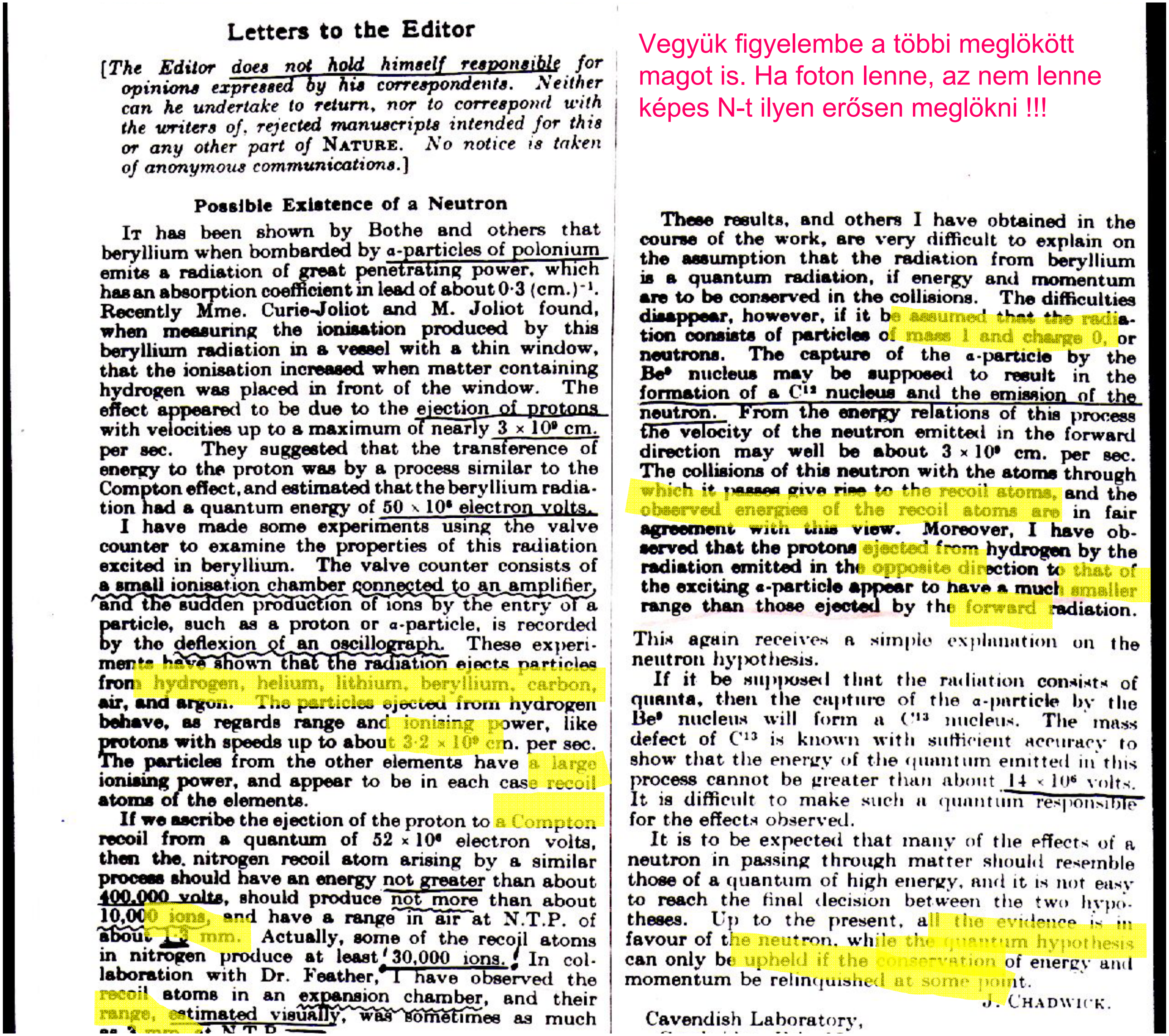
Észlelték az "áthatoló sugárzást", de azt gondolták X-su

2. Joliot + Curie : ez a sugárzás protonokat lök ki paraffinból, de azt hitték, hogy COMPTON-effektus (1931)

MEGVILÁGOSODÁS

$E_\gamma \geq 50 \text{ MeV}$ kellene! $He_2^4 + Be_4^9 \rightarrow C_6^{12} + n_0^1$!

ERŐS ÉS GYENGE FELFEDEZÉSE!!



Letters to the Editor

[The Editor does not hold himself responsible for opinions expressed by his correspondents. Neither can he undertake to return, nor to correspond with the writers of, rejected manuscripts intended for this or any other part of NATURE. *No notice is taken of anonymous communications.]*

Possible Existence of a Neutron

IT has been shown by Bothe and others that beryllium when bombarded by α-particles of polonium emits a radiation of great penetrating power, which has an absorption coefficient in lead of about 0·3 (cm.)$^{-1}$. Recently Mme. Curie-Joliot and M. Joliot found, when measuring the ionisation produced by this beryllium radiation in a vessel with a thin window, that the ionisation increased when matter containing hydrogen was placed in front of the window. The effect appeared to be due to the ejection of protons with velocities up to a maximum of nearly 3 × 10^9 cm. per sec. They suggested that the transference of energy to the proton was by a process similar to the Compton effect, and estimated that the beryllium radiation had a quantum energy of 50 × 10^6 electron volts.

I have made some experiments using the valve counter to examine the properties of this radiation excited in beryllium. The valve counter consists of a small ionisation chamber connected to an amplifier, and the sudden production of ions by the entry of a particle, such as a proton or α-particle, is recorded by the deflexion of an oscillograph. These experiments have shown that the radiation ejects particles from hydrogen, helium, lithium, beryllium, carbon, air, and argon. The particles ejected from hydrogen behave, as regards range and ionising power, like protons with speeds up to about 3·2 × 10^9 cm. per sec. The particles from the other elements have a large ionising power, and appear to be in each case recoil atoms of the elements.

If we ascribe the ejection of the proton to a Compton recoil from a quantum of 52 × 10^6 electron volts, then the nitrogen recoil atom arising by a similar process should have an energy not greater than about 400,000 volts, should produce not more than about 10,000 ions, and have a range in air at N.T.P. of about 1·3 mm. Actually, some of the recoil atoms in nitrogen produce at least 30,000 ions. In collaboration with Dr. Feather, I have observed the recoil atoms in an expansion chamber, and their range, estimated visually, was sometimes as much as 3 mm. at N.T.P.

These results, and others I have obtained in the course of the work, are very difficult to explain on the assumption that the radiation from beryllium is a quantum radiation, if energy and momentum are to be conserved in the collisions. The difficulties disappear, however, if it be assumed that the radiation consists of particles of mass 1 and charge 0, or neutrons. The capture of the α-particle by the Be^9 nucleus may be supposed to result in the formation of a C^{12} nucleus and the emission of the neutron. From the energy relations of this process the velocity of the neutron emitted in the forward direction may well be about 3 × 10^9 cm. per sec. The collisions of this neutron with the atoms through which it passes give rise to the recoil atoms, and the observed energies of the recoil atoms are in fair agreement with this view. Moreover, I have observed that the protons ejected from hydrogen by the radiation emitted in the opposite direction to that of the exciting α-particle appear to have a much smaller range than those ejected by the forward radiation. This again receives a simple explanation on the neutron hypothesis.

If it be supposed that the radiation consists of quanta, then the capture of the α-particle by the Be^9 nucleus will form a C^{13} nucleus. The mass defect of C^{13} is known with sufficient accuracy to show that the energy of the quantum emitted in this process cannot be greater than about 14 × 10^6 volts. It is difficult to make such a quantum responsible for the effects observed.

It is to be expected that many of the effects of a neutron in passing through matter should resemble those of a quantum of high energy, and it is not easy to reach the final decision between the two hypotheses. Up to the present, all the evidence is in favour of the neutron, while the quantum hypothesis can only be upheld if the conservation of energy and momentum be relinquished at some point.

J. CHADWICK.

Cavendish Laboratory,

Vegyük figyelembe a többi meglökött magot is. Ha foton lenne, az nem lenne képes N-t ilyen erősen meglökni !!!

Basic principles of particle detection

<u>Passage of charged particles through matter</u>

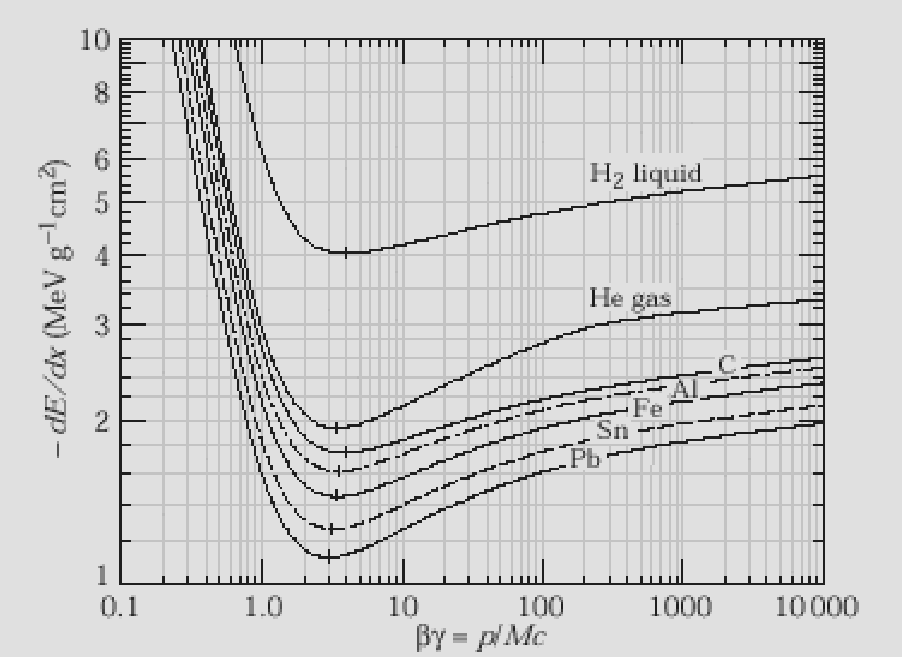
Interaction with atomic electrons → **ionization**
(neutral atom → ion$^+$ + free electron)

→ **excitation of atomic energy levels**
(de-excitation → photon emission)

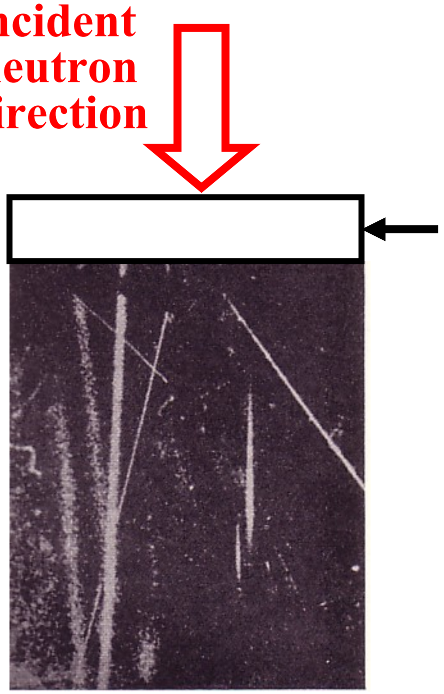
Ionization + excitation of atomic energy levels → energy loss

Mean energy loss rate – *dE /dx*

- **proportional to (electric charge)^2 of incident particle**
- **for a given material, function only of incident particle velocity**
- **typical value at minimum:**
  $-dE/dx = 1 - 2$ MeV /(g cm^{-2})



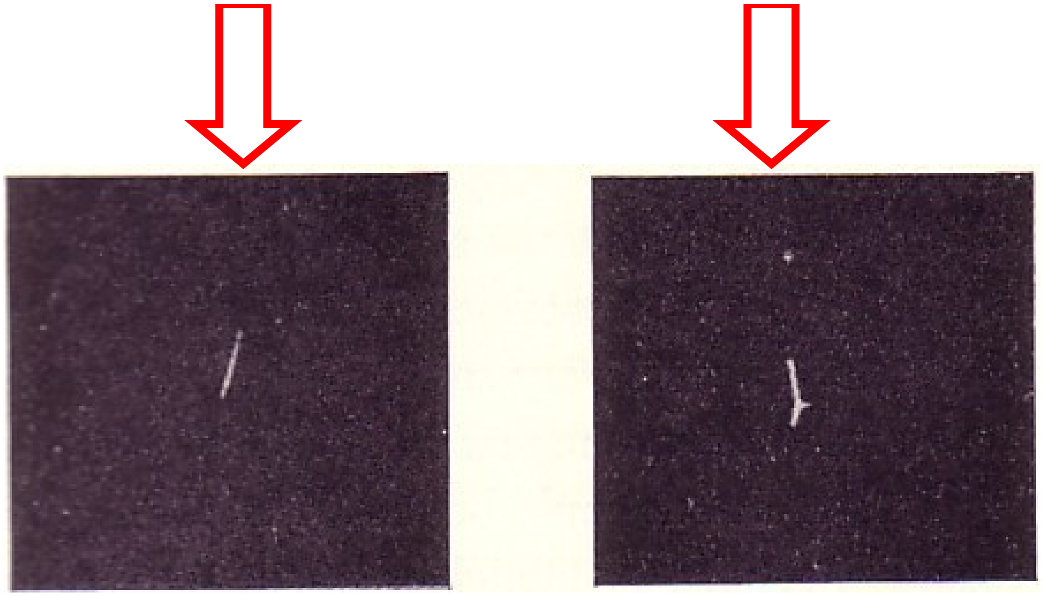
<u>NOTE</u>: traversed thickness (*dx*) is given in g /cm^2 to be independent of material density (for variable density materials, such as gases) – multiply *dE /dx* by density (g/cm^3) to obtain *dE /dx* in MeV/cm



Incident neutron direction

Plate containing free hydrogen (paraffin wax)

proton tracks ejected from paraffin wax



Recoiling Nitrogen nuclei

Assume that incident neutral radiation consists of particles of mass m moving with velocities $v < V_{max}$

Determine max. velocity of recoil protons (U_p) and Nitrogen nuclei (U_N) from max. observed range

$$U_p = \frac{2m}{m + m_p} V_{max} \qquad U_N = \frac{2m}{m + m_N} V_{max}$$

From non-relativistic energy-momentum conservation
m_p: proton mass; m_N: Nitrogen nucleus mass

$$\Rightarrow \quad \frac{U_p}{U_N} = \frac{m + m_N}{m + m_p}$$

From measured ratio U_p / U_N and known values of m_p, m_N determine neutron mass: $m \equiv m_n \approx m_p$

Present mass values : $m_p = 938.272\ \text{MeV}/c^2$; $m_n = 939.565\ \text{MeV}/c^2$

ANTIMATTER

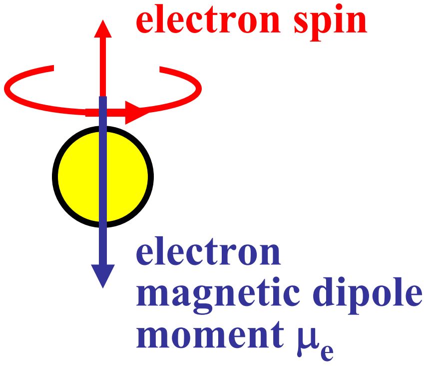
Discovered "theoretically" by P.A.M. Dirac (1928)

P.A.M. Dirac

Dirac's equation: a relativistic wave equation for the electron

Two surprising results:

- Motion of an electron in an electromagnetic field:
  presence of a term describing (for slow electrons) the
  potential energy of a magnetic dipole moment in a magnetic field
  ⇒ existence of an intrinsic electron magnetic dipole moment opposite to spin



$$\mu_e = \frac{e\hbar}{2m_e} \approx 5.79 \times 10^{-5}\ [\text{eV/T}]$$

- For each solution of Dirac's equation with electron energy $E > 0$
  there is another solution with $E < 0$
  What is the physical meaning of these "negative energy" solutions ?

Experimental confirmation of antimatter

(C.D. Anderson, 1932)


Carl D. Anderson

Detector: a Wilson cloud – chamber (visual detector based on a gas volume containing vapour close to saturation) in a magnetic field, exposed to cosmic rays

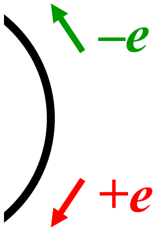
Measure particle momentum and sign of electric charge from magnetic curvature

Lorentz force $\vec{f} = e\vec{v} \times \vec{B}$ ⇒ **projection of the particle trajectory in a plane perpendicular to $\vec{B}$ is a circle**

Circle radius for electric charge $|e|$: $$R\,[\mathrm{m}] = \frac{10\, p_\perp [\mathrm{GeV/c}]}{3B\,[\mathrm{T}]}$$

$p_\perp$: momentum component perpendicular to magnetic field direction

NOTE: impossible to distinguish between positively and negatively charged particles going in opposite directio



$\Rightarrow$ **need an independent determination of the particle direction of motion**

The Positive Electron

Carl D. Anderson, *California Institute of Technology, Pasadena, California*

(Received February 28, 1933)

Out of a group of 1300 photographs of cosmic ray tracks in a vertical Wilson chamber 15 tracks were of positive particles which could not have a mass as great as that of the proton. From an examination of the energy loss and ionization produced it is concluded that the charge is less than twice, and is probably exactly equal to, that of the proton. If these particles carry unit positive charge the curvatures and ionizations produced require the mass to be less than twenty times the electron mass. These particles will be called positrons. Because they occur in groups associated with other tracks it is concluded that they must be secondary particles ejected from atomic nuclei.

Editor

On August 2, 1932, during the course of photographing cosmic-ray tracks produced in a vertical Wilson chamber (magnetic field of 15,000 gauss) designed in the summer of 1930 by Professor R. A. Millikan and the writer, the tracks shown in Fig. 1 were obtained, which seemed to be interpretable only on the basis of the existence in this case of a particle carrying a positive charge but having a mass of the same order of magnitude as that normally possessed by a free negative electron. Later study of the photograph by a whole group of men of the Norman Bridge Laboratory only tended to strengthen this view. The reason that this interpretation seemed so inevitable is that the track appearing on the upper half of the figure cannot possibly have a mass as large as that of a proton for as soon as the mass is fixed the energy is at once fixed by the curvature. The energy of a proton of that curvature comes out 300,000 volts, but a proton of that energy according to well established and universally accepted determinations[1] has a total range of about 5 mm in air while that portion of the range actually visible in this case exceeds 5 cm without a noticeable change in curvature. The only escape from this conclusion would be to assume that at exactly the same instant (and the sharpness of the tracks determines that instant to within about a fiftieth of a second) two independent electrons happened to produce two tracks so placed as to give the impression of a single particle shooting through the lead plate. This assumption was dismissed on a probability basis, since a sharp track of this order of curvature under the experimental conditions prevailing occurred in the chamber only once in some 500 exposures, and since there was practically no chance at all that two such tracks should line up in this way. We also discarded as completely untenable the assumption of an electron of 20 million volts entering the lead on one side and coming out with an energy of 60 million volts on the other side. A fourth possibility is that a photon, entering the lead from above, knocked out of the nucleus of a lead atom two particles, one of which shot upward and the other downward. But in this case the upward moving one would be a positive of small mass so that either of the two possibilities leads to the existence of the positive electron.

1

20
↓
60

In the course of the next few weeks other photographs were obtained which could be interpreted logically only on the positive-electron basis, and a brief report was then published[2] with due reserve in interpretation in view of the importance and striking nature of the announcement.

MAGNITUDE OF CHARGE AND MASS

It is possible with the present experimental data only to assign rather wide limits to the magnitude of the charge and mass of the particle. The specific ionization was not in these cases measured, but it appears very probable, from a knowledge of the experimental conditions and by comparison with many other photographs of high- and low-speed electrons taken under the same conditions, that the charge cannot differ in magnitude from that of an electron by an amount as great as a factor of two. Furthermore, if the photograph is taken to represent a positive particle penetrating the 6 mm lead plate, then the energy lost, calculated for unit charge, is approximately 38 million electron-volts, this value being practically independent of the proper mass of the particle as long as it is not too many times larger than that of a free negative electron. This value of 63 million volts per cm energy-loss for the positive particle it was considered legitimate to compare with the measured mean of approximately 35 million volts[3] for negative electrons of 200–300 million volts energy since the rate of energy-loss for particles of small mass is expected to change only very slowly over an energy range extending from several million to several hundred million volts. Allowance being made for experimental uncertainties, an upper limit to the rate of loss of energy for the positive particle can then be set at less than four times that for an electron, thus fixing, by the usual relation between rate of ionization and

$p\,[\mathrm{GeV}/c] = 0.3\,B\,[\mathrm{T}]\,\rho\,[\mathrm{m}]$

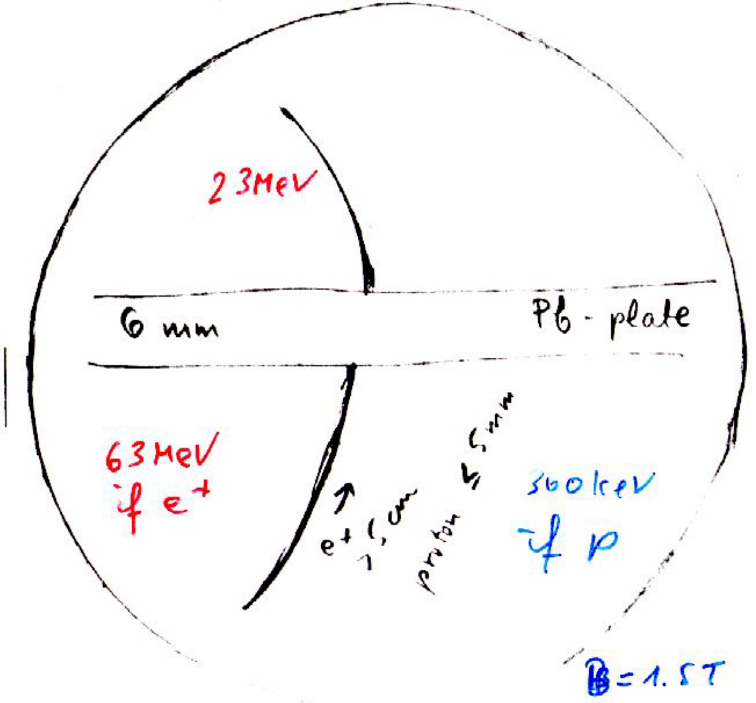


Fig. 1. A 63 million volt positron ($H\rho = 2.1 \times 10^5$ gauss-cm) passing through a 6 mm lead plate and emerging as a 23 million volt positron ($H\rho = 7.5 \times 10^4$ gauss-cm). The length of this latter path is at least ten times greater than the possible length of a proton path of this curvature.

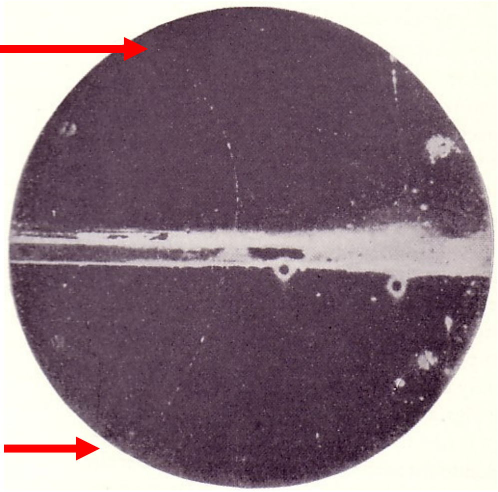
---

[1] Rutherford, Chadwick and Ellis, *Radiations from Radioactive Substances*, p. 294. Assuming $R \propto v^3$ and using data there given the range of a 300,000 volt proton in air S.T.P. is about 5 mm.

[2] C. D. Anderson, Science **76**, 238 (1932).

[3] C. D. Anderson, Phys. Rev. **43**, 381A (1933).

First experimental observation of a positron



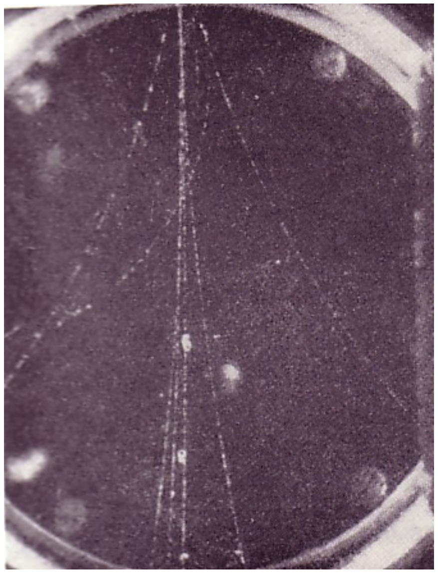
23 MeV positron

6 mm thick Pb plate

63 MeV positron

direction of high-energy photon

Production of an electron-positron pair by a high-energy photon in a Pb plate



Cosmic-ray “shower” containing several $e^+ e^-$ pairs

1937: Theory of nuclear forces (H. Yukawa)

Hideki Yukawa

Existence of a new light particle ("meson") as the carrier of nuclear forces

Relation between interaction radius and meson mass *m*:

$$R_{\text{int}} = \frac{\hbar}{mc} \Rightarrow mc^2 \approx 200 \text{ MeV for } R_{\text{int}} \approx 10^{-13} \text{ cm}$$

Yukawa's meson initially identified with the muon – in this case μ^- stopping in matter should be immediately absorbed by nuclei ⇒ nuclear breakup
(not true for stopping μ^+ because of Coulomb repulsion - μ^+ never come close enough to nuclei, while μ^- form "muonic" atoms)

Experiment of Conversi, Pancini, Piccioni (Rome, 1945):

study of μ^- stopping in matter using μ^- magnetic selection in the cosmic rays

In light material ($Z \leq 10$) the μ^- decays mainly to electron (just as μ^+)
In heavier material, the μ^- disappears partly by decaying to electron, and partly by nuclear capture (process later understood as $\mu^- + p \rightarrow n + \nu$).
However, the rate of nuclear captures is consistent with the weak interaction.

⇒ **the muon is not Yukawa's meson**

"μ" vs "π"

1935 YUKAWA: $M_Y \sim 100$ MeV/c^2

Közvetíti az erős és gyenge(!) kölcsönhatás, mint γ

1937 ANDERSON – NEDDERMEYER

STREET – STEVENSON

Kozmikus sugárzás 2-komponens
- shower
- penetrating ~ 130 Me

1942 Bomlás-idő $\tau = 2.3 \pm 0.2\,\mu s$ (Rossi, Nereson)

$\mu \rightarrow e + ??$ "KÉSLELTETT" koincidencia

1940 TOMONAGA-ARAKI: M_Y^+-t a mag taszítja anyagban lelassul és késve bomlik ($> 10^{-6}$ s)

M_Y^--t kis sugarú körpályán befogja a gyors magerők megeszik ($\sim 10^{-23}$ s).

Kozmikus sugárzás föld színén: főleg μ (10^{-6} s), π (10^{-8} s)

1945/46 CONVERSI, PANCINI, PICCIONI: előszűrés mágnessel

Vasban + decay ; − eltűnik (nincs késleltett koinc.)

De C-ben − bomlás is! [A muon befogva is tovább élhet!?]

1947 jan. Perkins: Emulzióban π felrobbant egy magot

1947 LATTES, OCCHIALINI, POWELL: Emulzió 5500 m Andok ; 2800 m Pireneusok

$\pi \rightarrow \mu \rightarrow e$ lánc

LEWIS, OPPENHEIMER, WOUTHUYSEN javasolja, hogy a shower komponens forrása a neutral Yukawa meson.

1938 N. KEMMER: isospin (n,p) (π^+, π^0, π^-)

1950 STEINBERGER, PANOFSKY, STELLER: $\pi^0 \rightarrow 2\gamma$

1947: **Discovery of the π - meson**(the “real” Yukawa particle)

Observation of the $\pi^+ \rightarrow \mu^+ \rightarrow e^+$ decay chain in nuclear emulsion exposed to cosmic rays at high altitudes

Nuclear emulsion: a detector sensitive to ionization with ~1 μm space resolution (AgBr microcrystals suspended in gelatin)

In all events the muon has a fixed kinetic energy (4.1 MeV, corresponding to a range of ~ 600 μm in nuclear emulsion) ⇒ two-body decay

$m_\pi = 139.57\ \mathrm{MeV}/c^2$ **; spin = 0**

Dominant decay mode: $\pi^+ \rightarrow \mu^+ + \nu$

(and $\pi^- \rightarrow \mu^- + \overline{\nu}$ **)**

Mean life at rest: $\tau_\pi = 2.6 \times 10^{-8}$ **s = 26 ns**

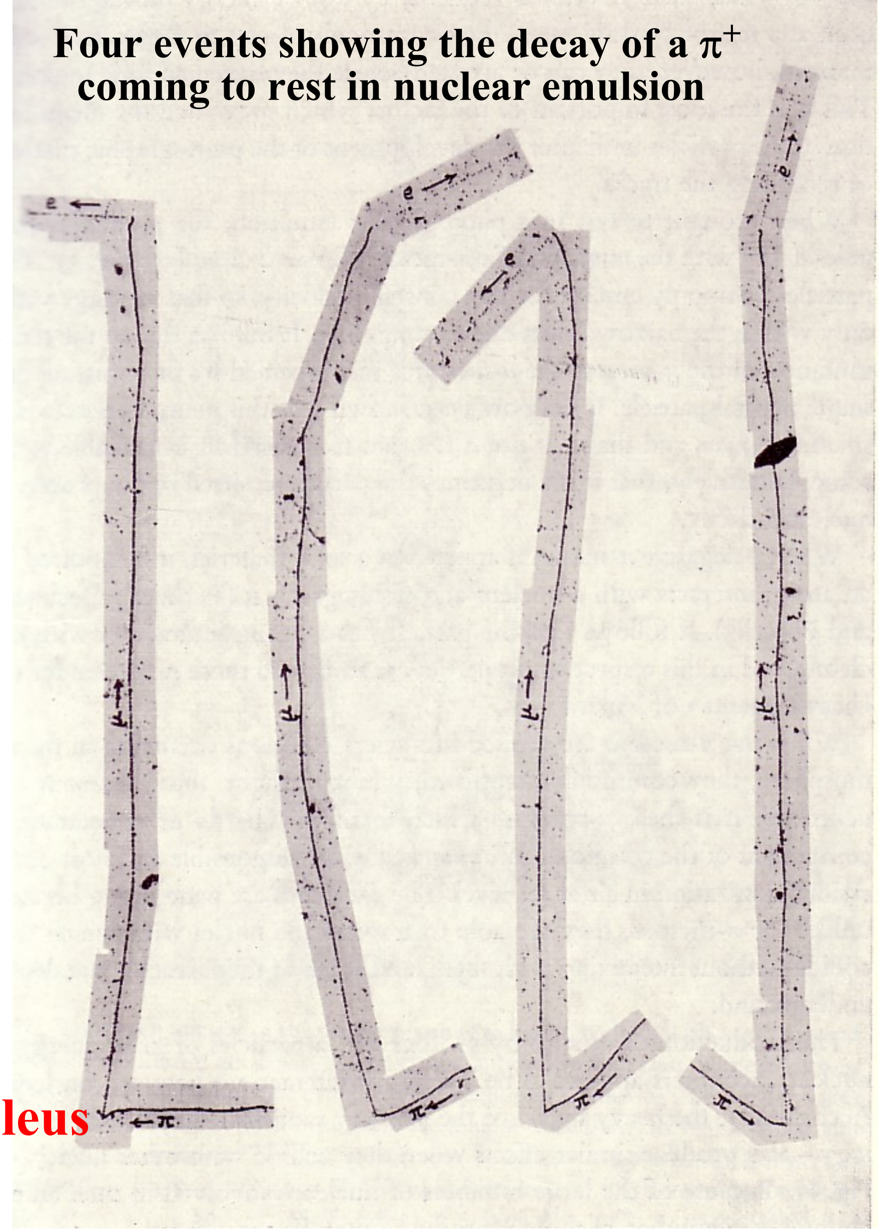
π^- at rest undergoes nuclear capture, as expected for the Yukawa particle

A neutral π – meson (π°) also exists:

m (π°) = 134. 98 MeV /c^2

Decay: $\pi^\circ \rightarrow \gamma + \gamma$ **, mean life = 8.4×10^{-17} s**

π – mesons are the most copiously produced particles in proton – proton and proton – nucleus collisions at high energies



Four events showing the decay of a π$^+$ coming to rest in nuclear emulsion

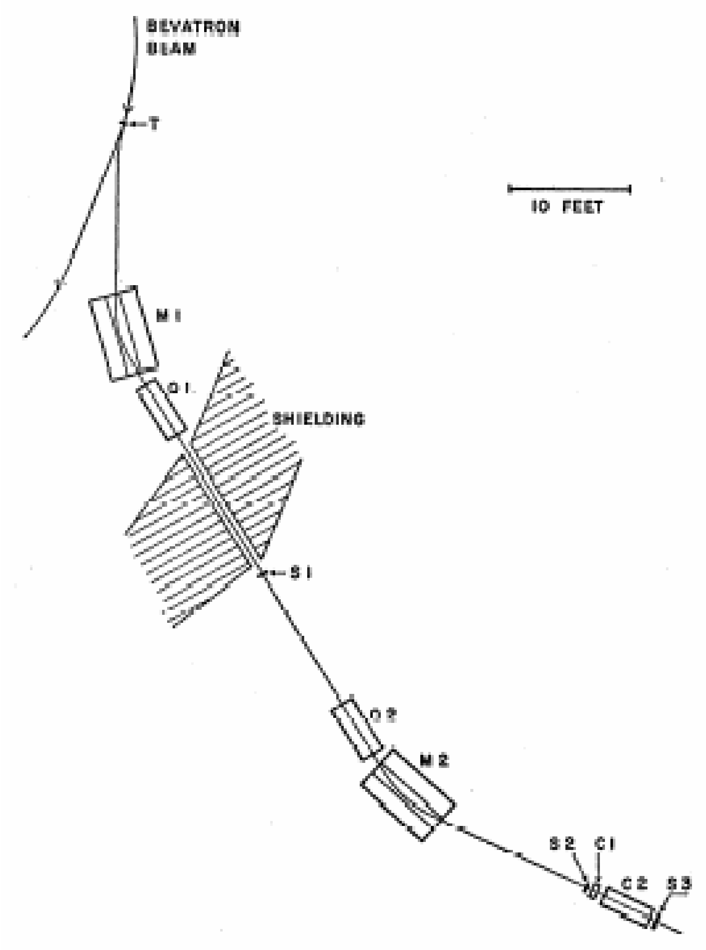
Antiproton discovery (1955)

Threshold energy for antiproton ($\bar{p}$) production in proton – proton collisions

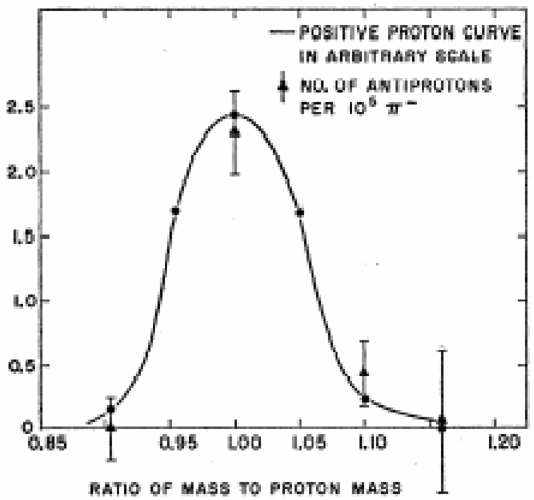
Baryon number conservation $\Rightarrow$ simultaneous production of $\bar{p}$ and p (or $\bar{p}$ and n)

Example: $p + p \rightarrow p + p + \bar{p} + p$ **Threshold energy ~ 6 GeV**

"Bevatron": 6 GeV proton synchrotron in Berkeley



- **build a beam line for 1.19 GeV/c momentum**
- **select negatively charged particles (mostly π^-)**
- **reject fast π^- by Čerenkov effect: light emission in transparent medium if particle velocity v > *c* / *n* (*n*: refraction index) – antiprotons have v < *c* / *n* $\Rightarrow$ no Čerenkov light**
- **measure time of flight between counters S_1 and S_2 (12 m path): 40 ns for π^-, 51 ns for antiprotons**



For fixed momentum, time of flight gives particle velocity, hence particle mass

Eddig előfordult kísérleti technikák

Szórás

Ionizáció (Bethe-Bloch) ionizációs kamra, ködkamra, emulzió
dE/dx , Range

Fluoreszcencia , szcintillátor

Cserenkov-sugárzás

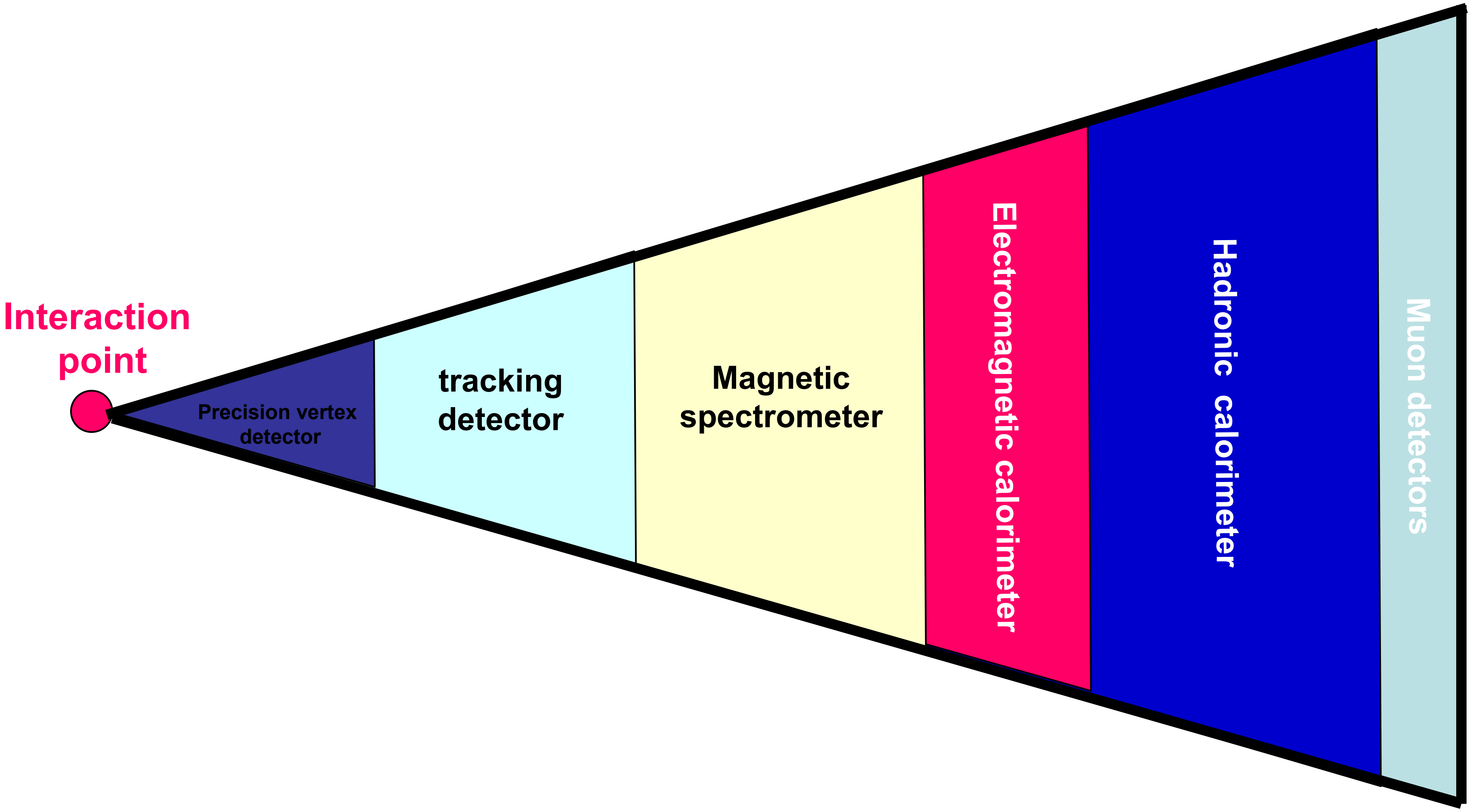
Momentum mérés mágneses térben

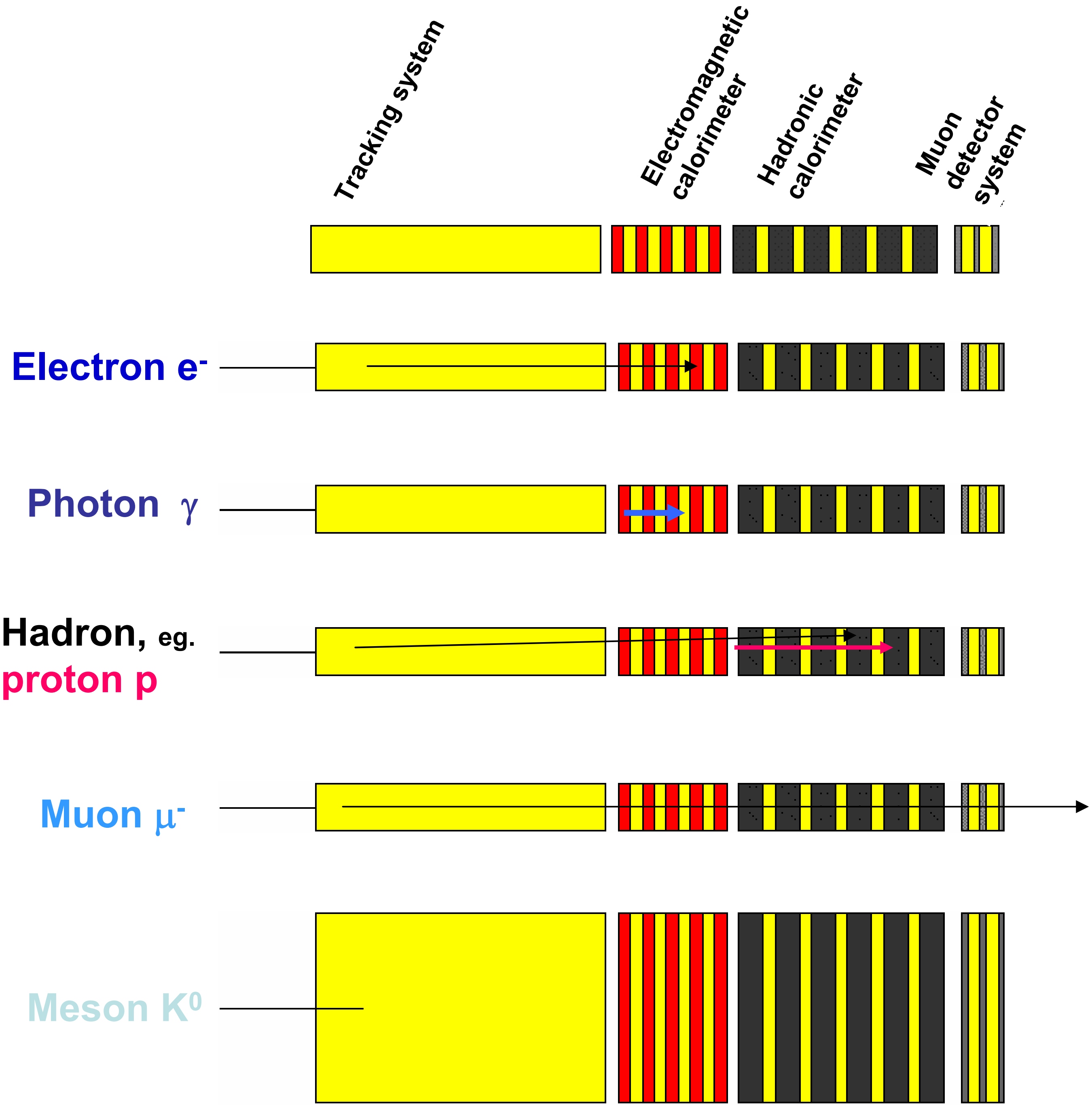
Time-of-Flight (TOF) repülési idő spektrométer

Diffrakció kristályrácson

Typical detector concept

- Combine different detector types/technologies into one large detector system





Tracking system

Electromagnetic calorimeter

Hadronic calorimeter

Muon detector system

Electron e^-

Photon γ

Hadron, eg. proton p

Muon μ^-

Meson K^0

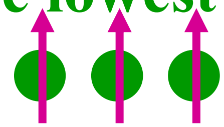
Prediction and discovery of the Ω^- particle

A success of the static quark model

The "decuplet" of spin $\frac{3}{2}$ baryons

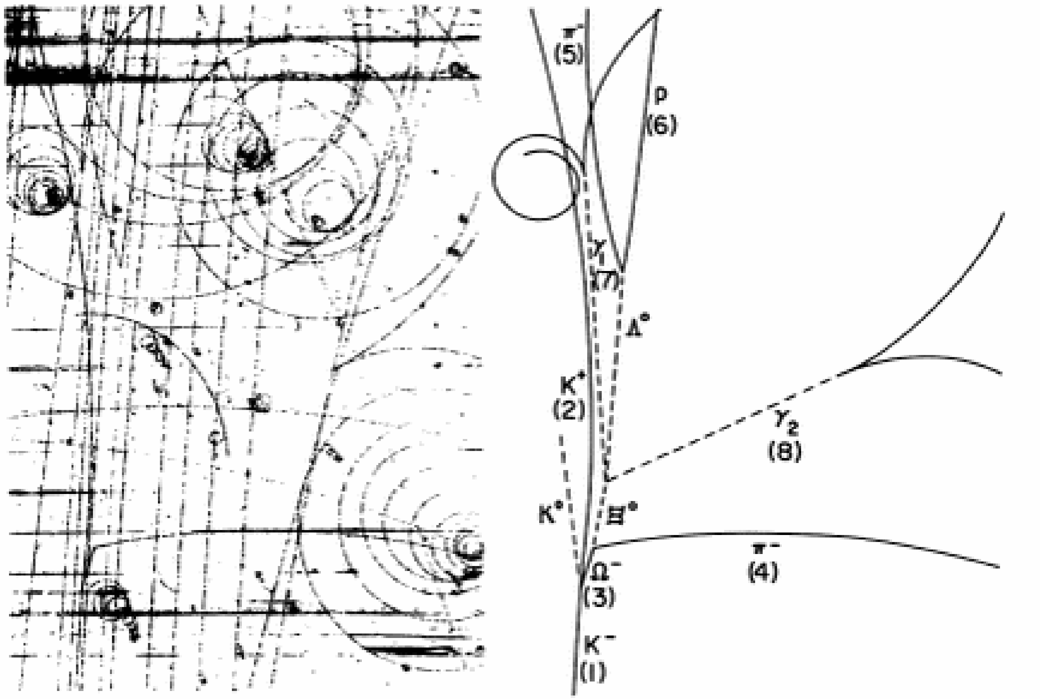
Strangeness					Mass (MeV/c^2)
0	N^{*++} *uuu*	N^{*+} *uud*	N^{*0} *udd*	N^{*-} *ddd*	1232
–1	Σ^{*+} *suu*	Σ^{*0} *sud*	Σ^{*-} *sdd*		1384
–2	Ξ^{*0} *ssu*	Ξ^{*-} *ssd*			1533
–3	Ω^- *sss*				1672 (predicted)

Ω^-: the bound state of three *s* – quarks with the lowest mass with total angular momentum = 3/ 2 ⇒



Pauli's exclusion principle requires that the three quarks cannot be identical

The first Ω^- event (observed in the 2 m liquid hydrogen bubble chamber at BNL using a 5 GeV/c K^- beam from the 30 GeV AGS)



Chain of events in the picture:

$K^- + p \rightarrow \Omega^- + K^+ + K^\circ$
(strangeness conserving)

$\Omega^- \rightarrow \Xi^\circ + \pi^-$
($\Delta S = 1$ weak decay)

$\Xi^\circ \rightarrow \pi^\circ + \Lambda$
($\Delta S = 1$ weak decay)

$\Lambda \rightarrow \pi^- + p$
($\Delta S = 1$ weak decay)

$\pi^\circ \rightarrow \gamma + \gamma$ (electromagnetic decay)
with both γ – rays converting to an e^+e^- in liquid hydrogen
(very lucky event, because the mean free path for $\gamma \rightarrow e^+e^-$ in liquid hydrogen is ~10 m)

Ω^- mass measured from this event = 1686 ± 12 MeV/c^2

The Uncertainty Principle


Werner Heisenberg

CLASSICAL MECHANICS

Position and momentum of a particle can be measured independently and simultaneously with arbitrary precision

QUANTUM MECHANICS

Measurement perturbs the particle state ⇒ position and momentum measurements are correlated:

$$\boxed{\Delta x \Delta p_x \approx \hbar}$$

(also for *y* and *z* components)

Numerical example:

$$\Delta p_x = 100\ \mathrm{MeV/c} \Longrightarrow \Delta x \approx 1.97 \times 10^{-13}\ \mathrm{cm}$$

Quite a few people concluded correctly that there was as much intellectual content in the Lamb experiment as in the QED explanation of it (This example is marred by the fact the Lamb was actually an accomplished theorist!).

A second, altogether different reason derives from what I might call the "theory of the father image": In practice, all our physics courses are theoretical, whether the title of the course says so or not. The theorists teaching theory mostly know what they are talking about, and the experimentalist frequently do not. So the student (who though he may himself not understand the subject, still infallibly catches the lack of understanding of the lecturer!) says to himself: "I do not want to become like him (insert name of experimentalist) but like him (insert name of theorist)". //

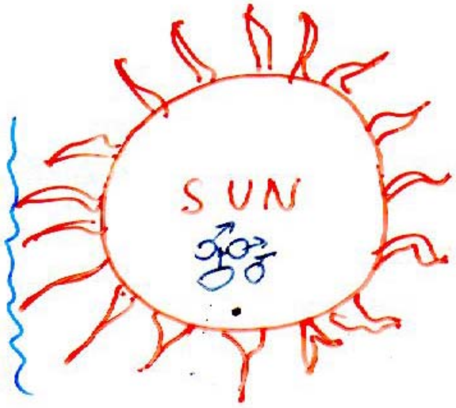
What can we do to remedy this situation? Two things: First, we must postpone the difference in training of future experimentalists and theorists as far as possible. The difference is one of technique and not one of intellectual competence. Second, we must teach courses in which brilliant experiments of great significance are analyzed in some detail.

I shall, in what follows, describe some experiments which fall into this category, of course more briefly that one would do so in a curricular lecture. I have avoided experiments which are (and should be) generally known, hoping to offer you some pleasant surprises. I shall discuss four experiments in chronological order.

(STAR) ASTRONOMY : CSILLAGÁSZAT

OUTSIDE OBSERVATION

LÁTSZAT



ν

The surface is visible only

NUCLEAR PHYSICS : MAGFIZIKA

DEEP UNDERSTANDING

VALÓSÁG

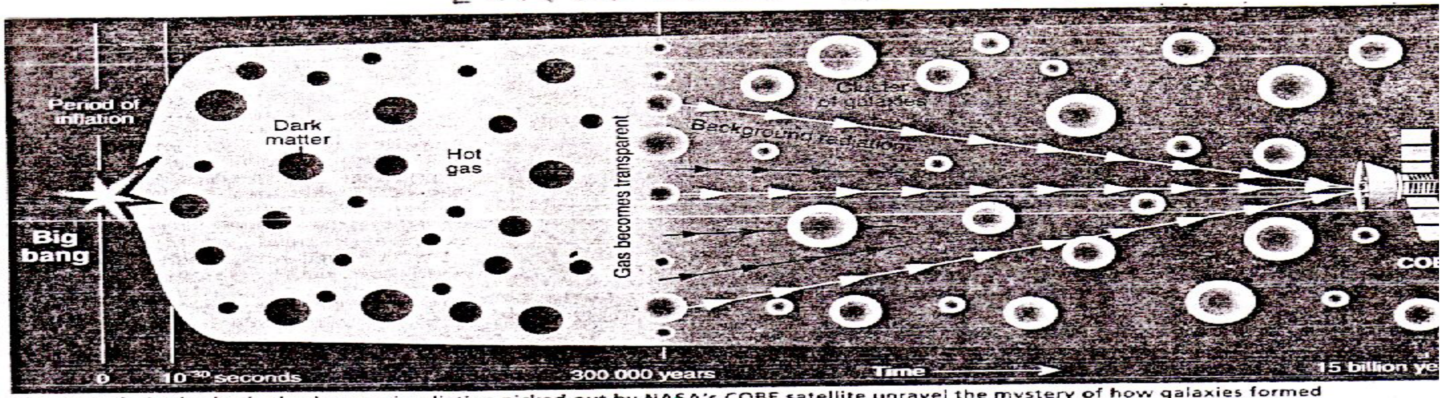
What is happening INSIDE the stars

- Nuclear fusion

ν - detectors "see" the center of the stars

NEW SCIENTIST THIS WE

EXPERIMENTAL COSMOLOGY



Time travel: ripples in the background radiation picked out by NASA's COBE satellite unravel the mystery of how galaxies formed

HIGH ENERGY PARTICLE PHYS

RECREATES: !!
WHAT IS HAPPENING AT

T ~ μs

HIGGS
Quark-Gluon-Plasma
GUT ?
DARK MATTER?

QUARK-FIZIKA

VALÓSÁG

SPACE ASTRONOMY

VISIBILITY only after

T > 300 000 yers

GALAXIS-ÁSZAT

LÁTSZAT

Electron, proton spin = ½ħ (measured)
Nitrogen nucleus (*A* = 14, *Z* = 7): 14 protons + 7 electrons = 21 spin ½ particles
TOTAL SPIN MUST HAVE HALF-INTEGER VALUE
Measured spin = 1

DISCOVERY OF THE NEUTRON (Chadwick, 1932)

James Chadwick

Neutron: a particle with mass ≈ proton mass
but with zero electric charge

Solution to the nuclear structure problem:

Nucleus with atomic number *Z* and mass number *A*:
a bound system of *Z* protons and (*A* – *Z*) neutrons

Nitrogen anomaly: no problem if neutron spin = ½ħ
Nitrogen nucleus (A = 14, Z = 7): 7 protons, 7 neutrons = 14 spin ½ particles
⇒ **total spin has integer value**

Neutron source in Chadwick's experiments: a ^{210}Po radioactive source (5 MeV α – particles) mixed with Beryllium powder ⇒ emission of electrically neutral radiation capable of traversing several centimetres of Pb:

$$\underset{\substack{\uparrow \\ \alpha\text{ - particle}}}{{}^{4}\mathrm{He}_2} + {}^{9}\mathrm{Be}_4 \rightarrow {}^{12}\mathrm{C}_6 + \text{neutron}$$

First (wrong) ideas about nuclear structure

(before 1932)

Observations

- **Mass values of light nuclei $\approx$ multiples of proton mass (to few %) (proton $\equiv$ nucleus of the hydrogen atom)**
- **β decay: spontaneous emission of electrons by some radioactive nuclei**

Hypothesis: the atomic nucleus is a system of protons and electrons strongly bound together

Nucleus of the atom with atomic number Z and mass number A:

a bound system of A protons and $(A-Z)$ electrons

Total electric charge of the nucleus = $[A-(A-Z)]e = Z\,e$

Problem with this model: the "Nitrogen anomaly"

Spin of the Nitrogen nucleus = 1

Spin: intrinsic angular momentum of a particle (or system of particles)

In Quantum Mechanics only integer or half-integer multiples of $\hbar \equiv (h / 2\pi)$ are possible:

- **integer values for orbital angular momentum** (e.g., for the motion of atomic electrons around the nucleus)
- **both integer and half-integer values for spin**

Generic solutions of Dirac's equation: complex wave functions $\Psi(\vec{r}, t)$

In the presence of an electromagnetic field, for each negative-energy solution the complex conjugate wave function Ψ^* is a positive-energy solution of Dirac's equation for an electron with opposite electric charge (+*e*)

Dirac's assumptions:

- **nearly all electron negative-energy states are occupied and are not observable.**
- **electron transitions from a positive-energy to an occupied negative-energy state are forbidden by Pauli's exclusion principle.**
- **electron transitions from a positive-energy state to an empty negative-energy state are allowed ⇒ electron disappearance. To conserve electric charge, a positive electron (positron) must disappear ⇒ e^+e^- annihilation.**
- **electron transitions from a negative-energy state to an empty positive-energy state are also allowed ⇒ electron appearance. To conserve electric charge, a positron must appear ⇒ creation of an e^+e^- pair.**

⇒ empty electron negative–energy states describe positive energy states of the positron

Dirac's perfect vacuum: a region where all positive-energy states are empty and all negative-energy states are full.

Positron magnetic dipole moment = μ_e but oriented parallel to positron spin