Physics of the XXth century
Part 2

Physics of atomic nuclei
and
elementary particles

Selected events in the development of nuclear physics

1912 Hess – cosmic radiation
1913 Soddy - isotopes
1913 Van den Broek – atomic number = nuclear charge Z
1914-1932 various electron-proton models of atomic nuclei
1914 Chadwick – continuous energy spectrum of β rays
1919 Rutherford: $\alpha + {}^{14}N \rightarrow {}^{1}H + {}^{17}O$ (later interpretation)
1930 Pauli - hypothesis of the neutrino
1932 Anderson - positron
1932 Chadwick - neutron
1932 Iwanienko, Heisenberg - proton-neutron model of atomic nuclei
1932 Lawrence - cyclotron 1 MeV
1932 Cockcroft i Walton: $p + {}^{7}Li \rightarrow \alpha + \alpha$
1934 Iréne and Frederick Joliot-Curie - artificial radioactivity
1934 Fermi - theory of β decay
1934 Fermi et al. – radioactivity induced by neutrons
1935 Yukawa – proposed existence of ”mesons”
1936 Anderson i Neddermeyer – ”meson” (μ)
1938 Hahn i Strassmann – spontaneous fission of uranium

Radioactive series

uranium → uranium X → ?

thorium → thorium X → thorium emanation →

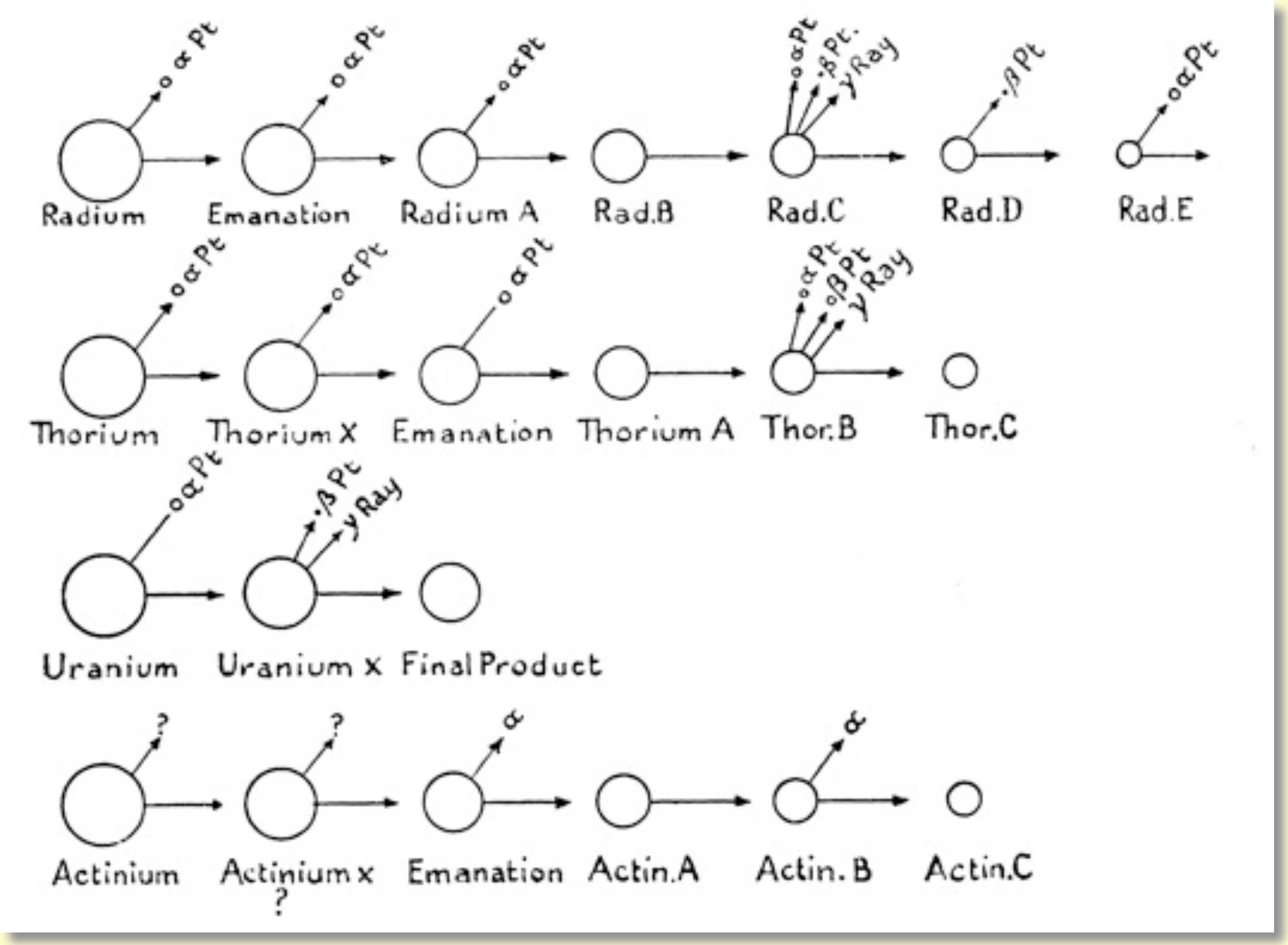
thorium I → thorium II → ?

radium → radium emanation → radium I → radium II

→ radium III → ?

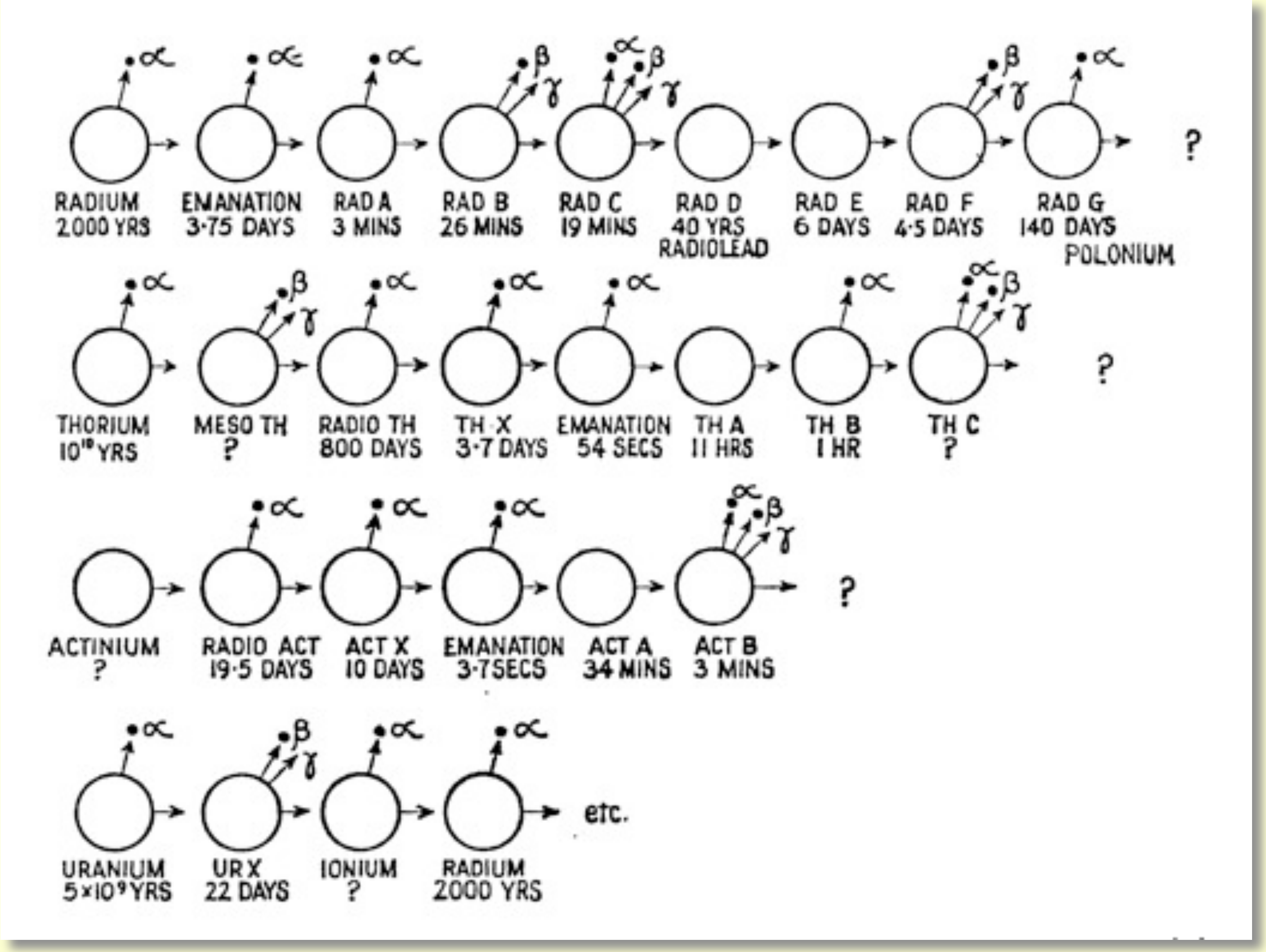
Rutherford and Soddy (1902)

Radioactive series

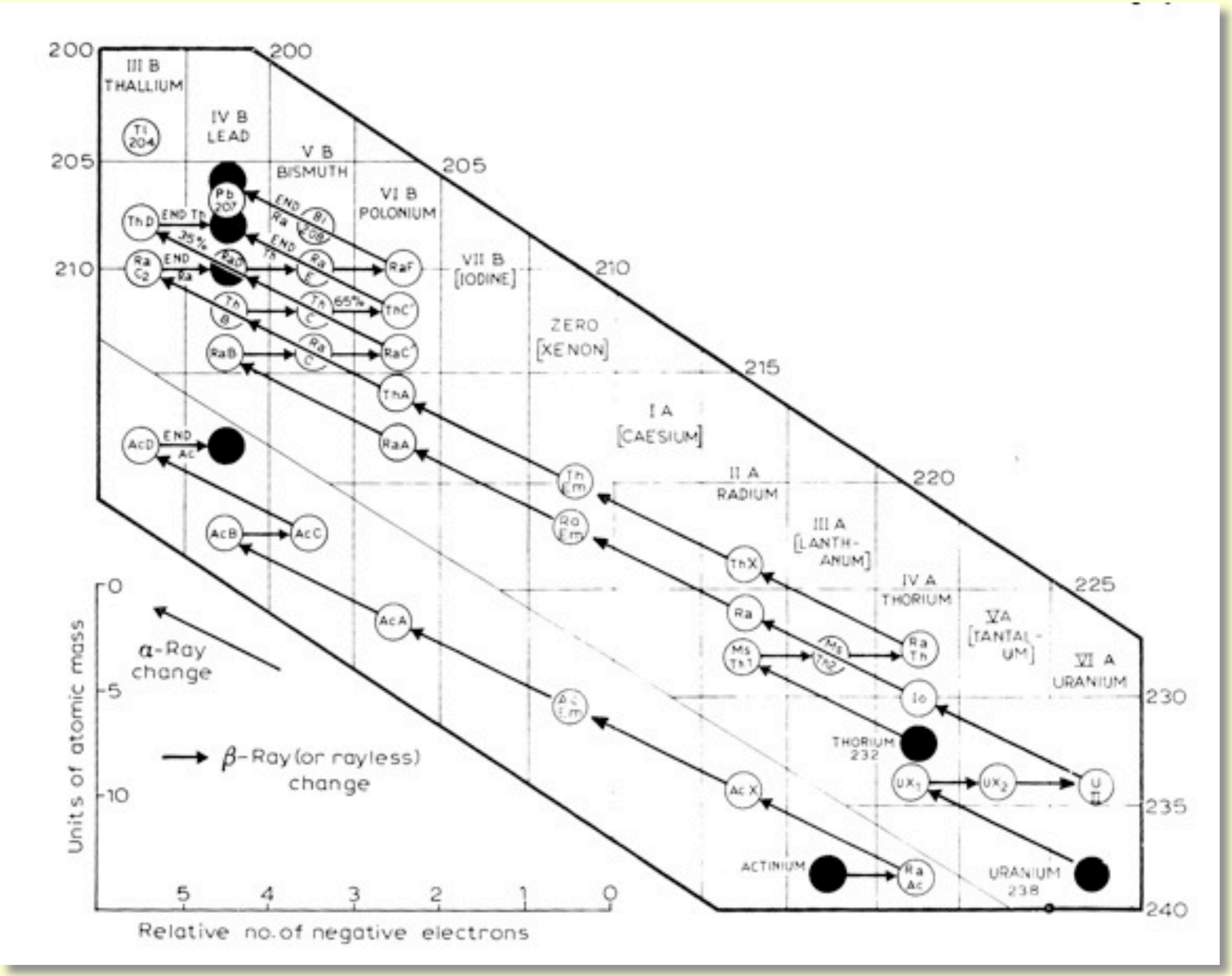


Rutherford (1904)

Radioactive series



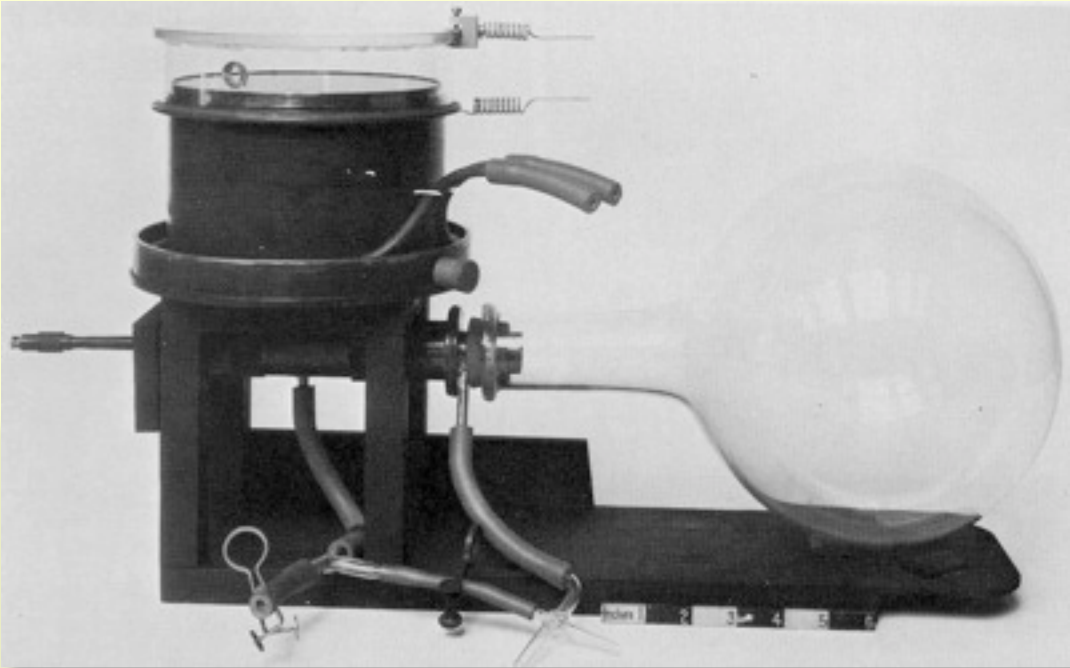
Rutherford (1908)



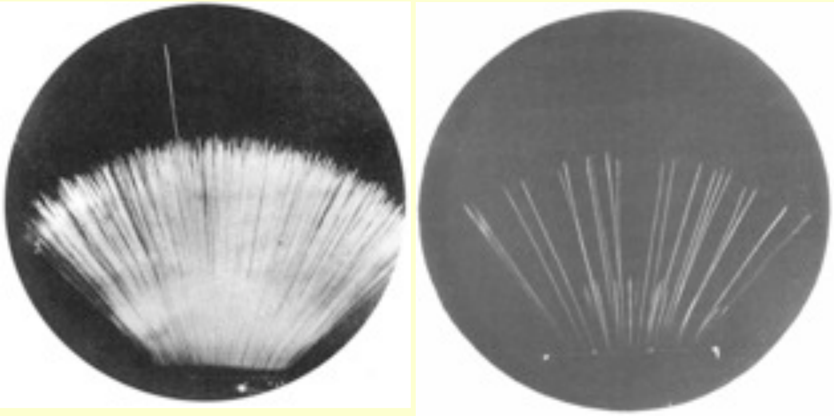
200
205
210
215
220
225
230
235
240
III B THALLIUM
IV B LEAD
V B BISMUTH
VI B POLONIUM
VII B [IODINE]
ZERO [XENON]
I A [CAESIUM]
II A RADIUM
III A [LANTHANUM]
IV A THORIUM
VA [TANTALUM]
VI A URANIUM
Tl 204
Pb 207
Bi 208
ThD
RaC2
RaD
RaE
RaF
ThB
ThC
ThC'
RaB
RaC
RaC'
ThA
RaA
AcD
AcB
AcC
AcA
Th Em
Ra Em
Ac Em
ThX
Ra
MsTh1
MsTh2
RaTh
Io
UX1
UX2
U II
AcX
RaAc
THORIUM 232
ACTINIUM
URANIUM 238
END Th
END Ra
END Ac
35%
65%
α-Ray change
β-Ray (or rayless) change
Units of atomic mass
Relative no. of negative electrons

Soddy (1913)

Charles T. R. Wilson (1869-1959)



The first Wilson’s chamber

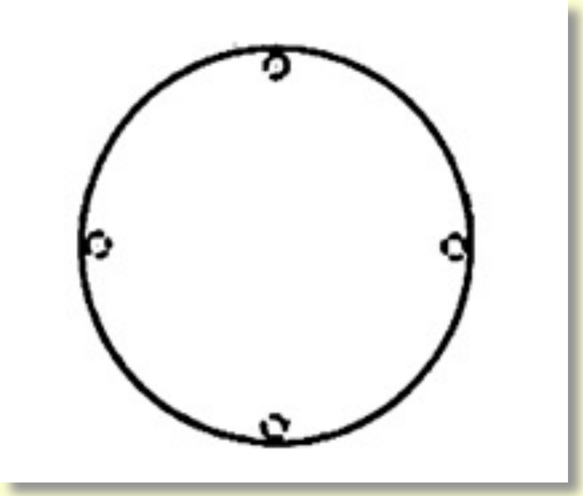


Tracks of α particles from a radioactive sample

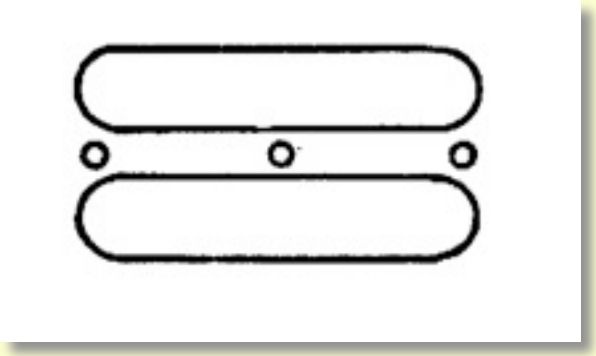
”The exceedingly small dimensions found for the hydrogen nucleus add weight to the suggestion that the hydrogen nucleus is the positive electron, and its mass is entirely electromagnetic in origin. According to the electromagnetic theory, the electrical mass of a charged body, supposed spherical, is $2e^2/3a$ where e is the charge and a the radius. The hydrogen nucleus consequently must have a radius about 1/1830 of the electron if its mass is to be explained in this way. There is no experimental evidence at present contrary to such an assumption. The helium nucleus has a mass nearly four times that of hydrogen. If one supposes that the positive electron, i.e. the hydrogen atom, is a unit of which all atoms are composed, it is to be anticipated that the helium atom contains four positive electrons and two negative.”

Ernest Rutherford, *The Structure of the Atom*, Phil. Mag. 27, 488 (1914)

A model of the alpha particle
by William D. Harkins (1920)



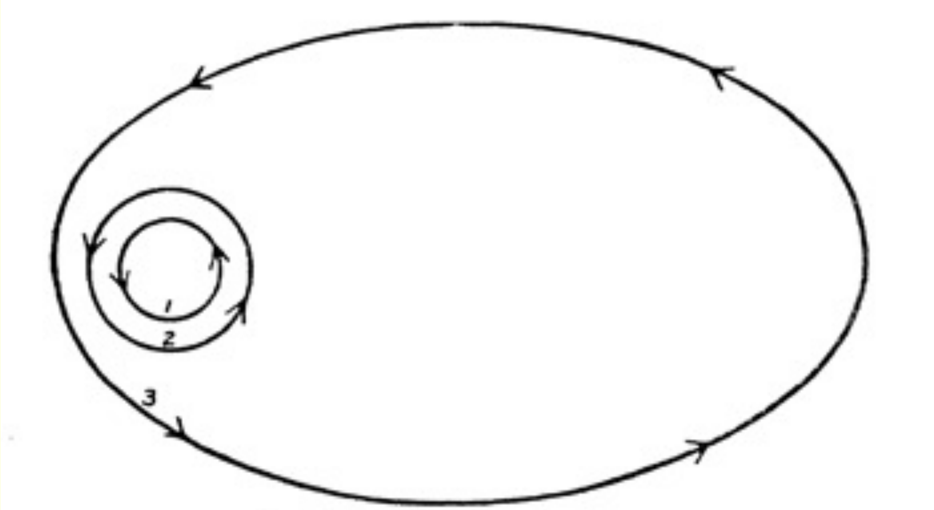
top view



side view

"The helium nucleus is assumed to consist of two negative electrons which have the form of rings, or discs, or spheres flattened into ellipsoids. The rings or discs lie with their greatest dimension perpendicular to the axis of the nucleus, and far from each other relative to their dimensions, between the two discs near their edges are the positive electrons in a symmetrical arrangement, that is at the corners of a square."

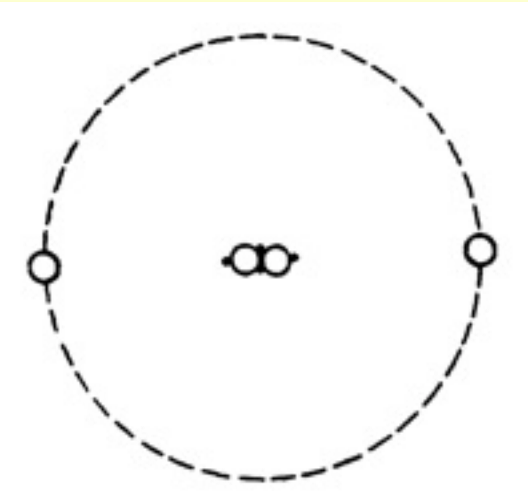
Phys. Rev. 15, 73 (1920)



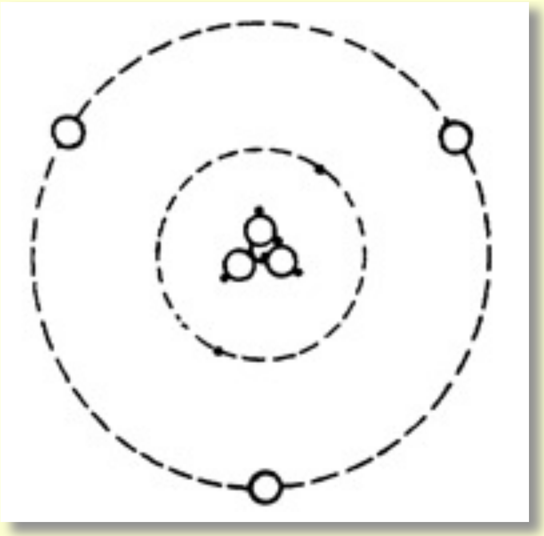
Alfred W. Stewart,
Phil. Mag. 36, 326 (1918)

"At the centre of the structure is a group of negative electrons travelling in closed orbits which, for the sake of clearness, may be assumed to be circular. Closely surrounding this negative group lies another series of orbits occupied by positive electrons which, in some cases, are associated with negative electrons in a manner to be dealt with later. These orbits are assumed to be circular also; their extreme diameter may be taken, according to Rutherford's view, as not being greater than 10^{-12} cm.; and, as in the Rutherford atom, the mass of the system is assumed to be concentrated in this portion. Further still from the centre, other electrons move in orbits of an elliptical character, the ellipses being much elongated, so that the electrons travel in paths like those of comets in the solar system...."

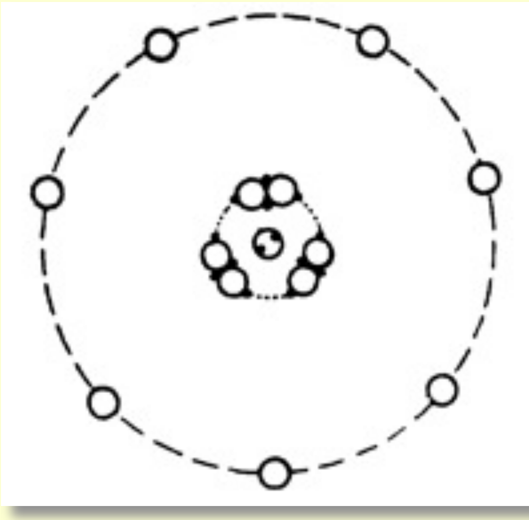
E. Gehrcke, *Ber. Deut. Phys. Ges.* 17, 779 (1919)



He



Li

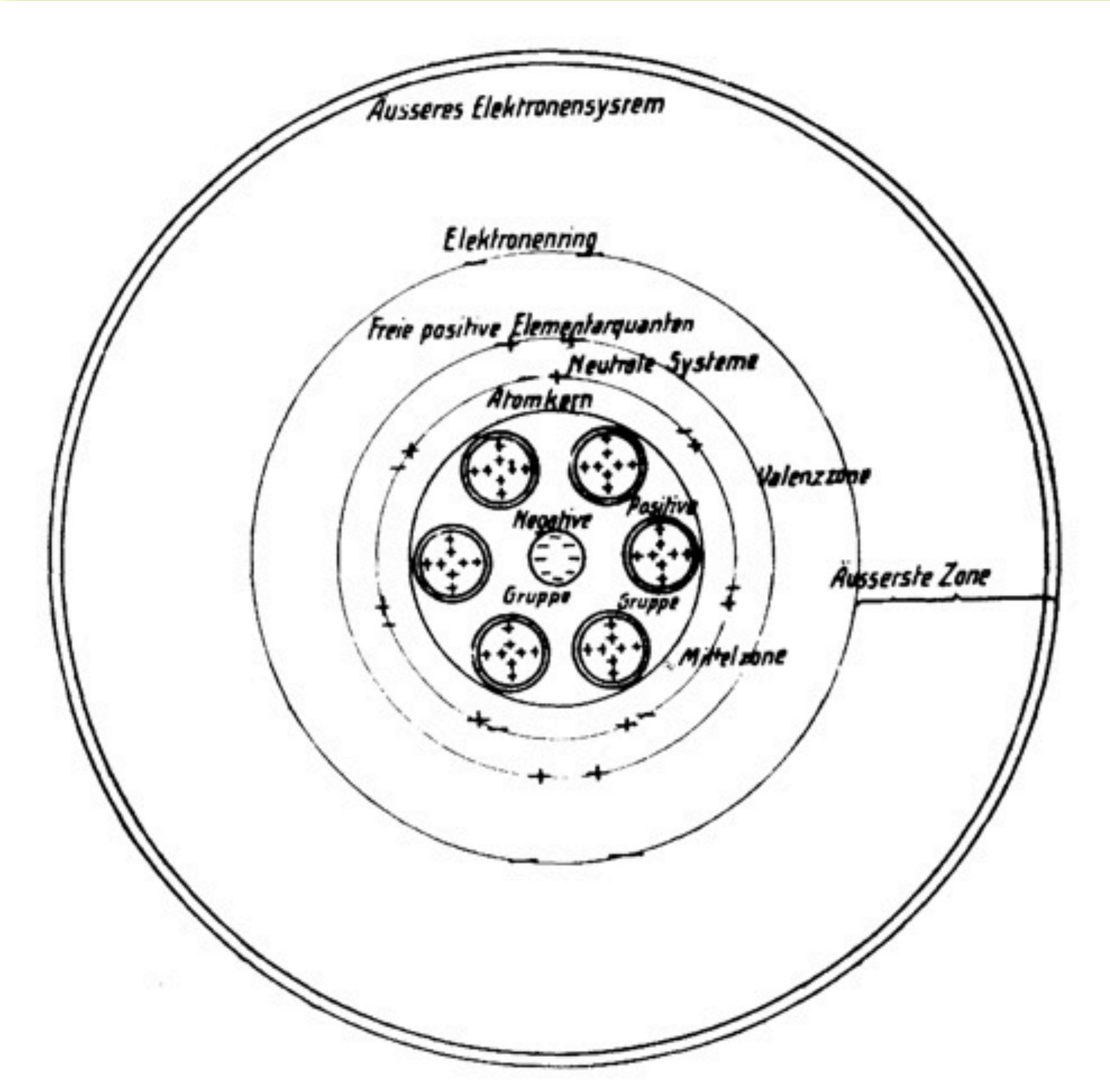


N

”Onion-like” structure of the nuclei of heavier atoms, e.g.

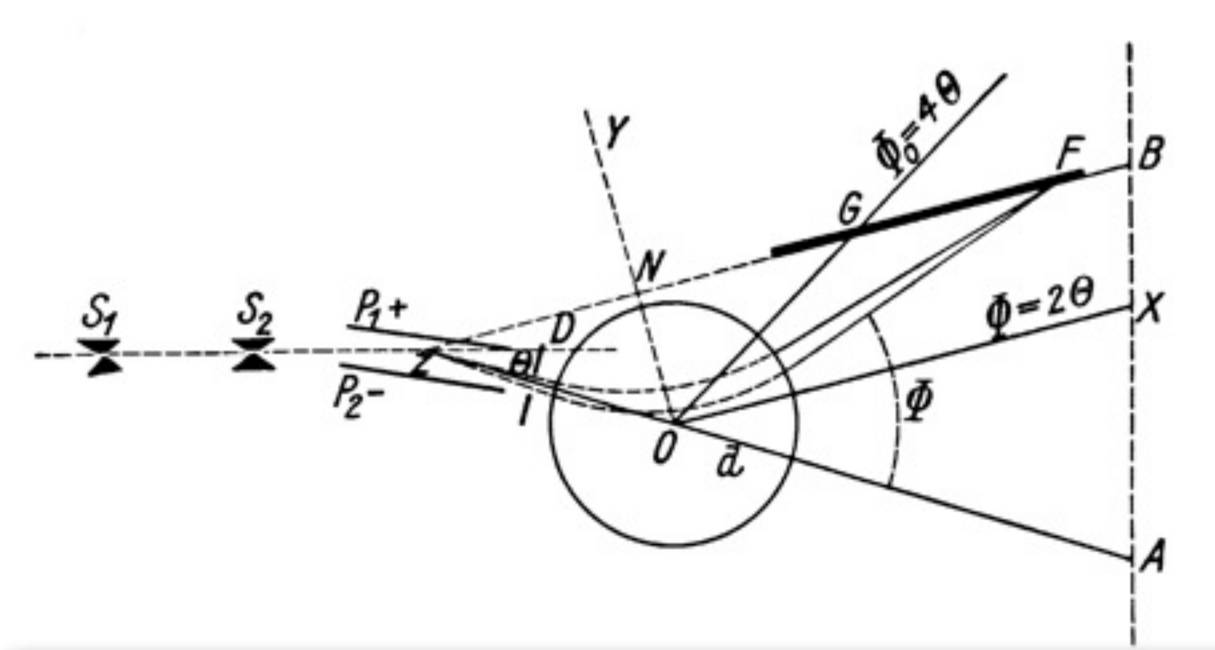
Nucleus of Na = nucleus of Li and ring of 4 α particles
Nucleus of Cu = nucleus of Na and ring of 10 α particles and 2 nuclear electrons
Nucleus of Ag = nucleus of Cu and ring of 11 α particles and 4 nuclear electrons
etc.

Sitz. Heidel. Akad. Wiss. 1-23 (1920)

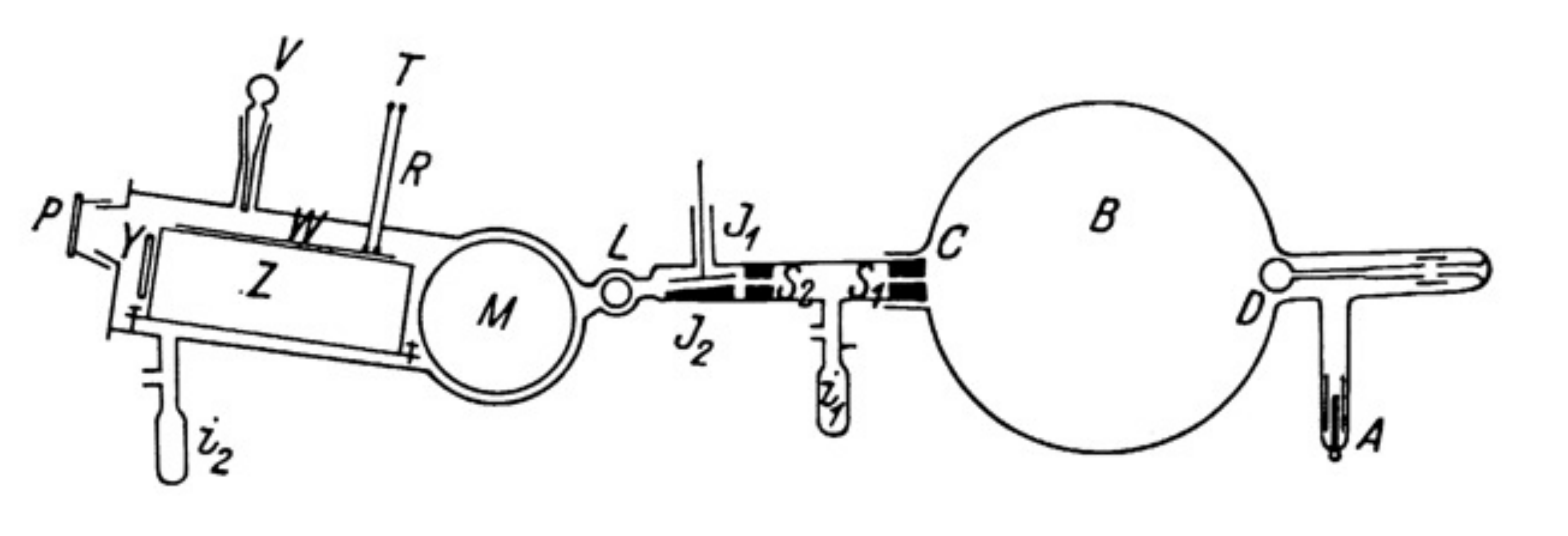


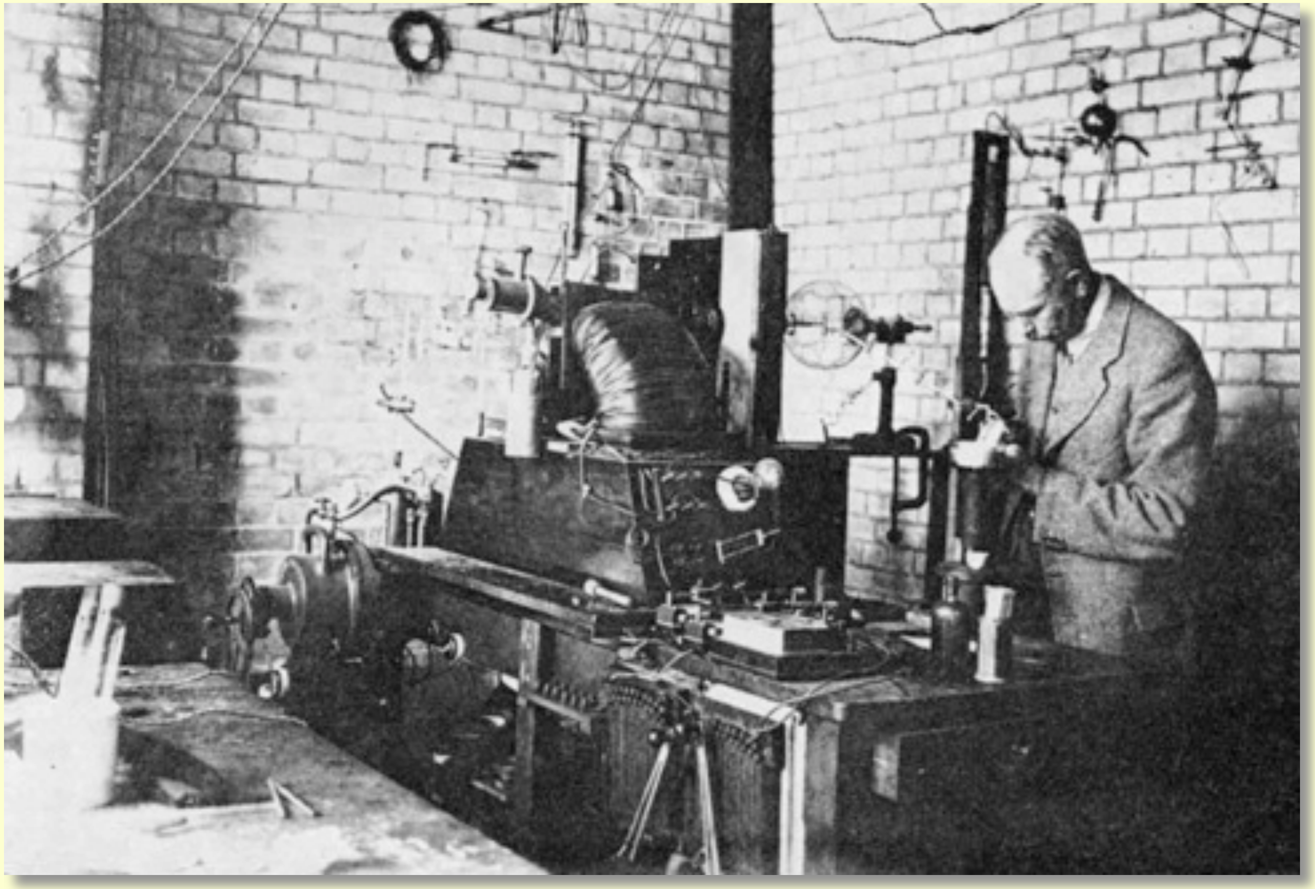
Atomic model for Z = 44, A = 118 by Emil Kohlweiler Z. Phys. Chemie **93**, 1 (1918)

Study of isotopes



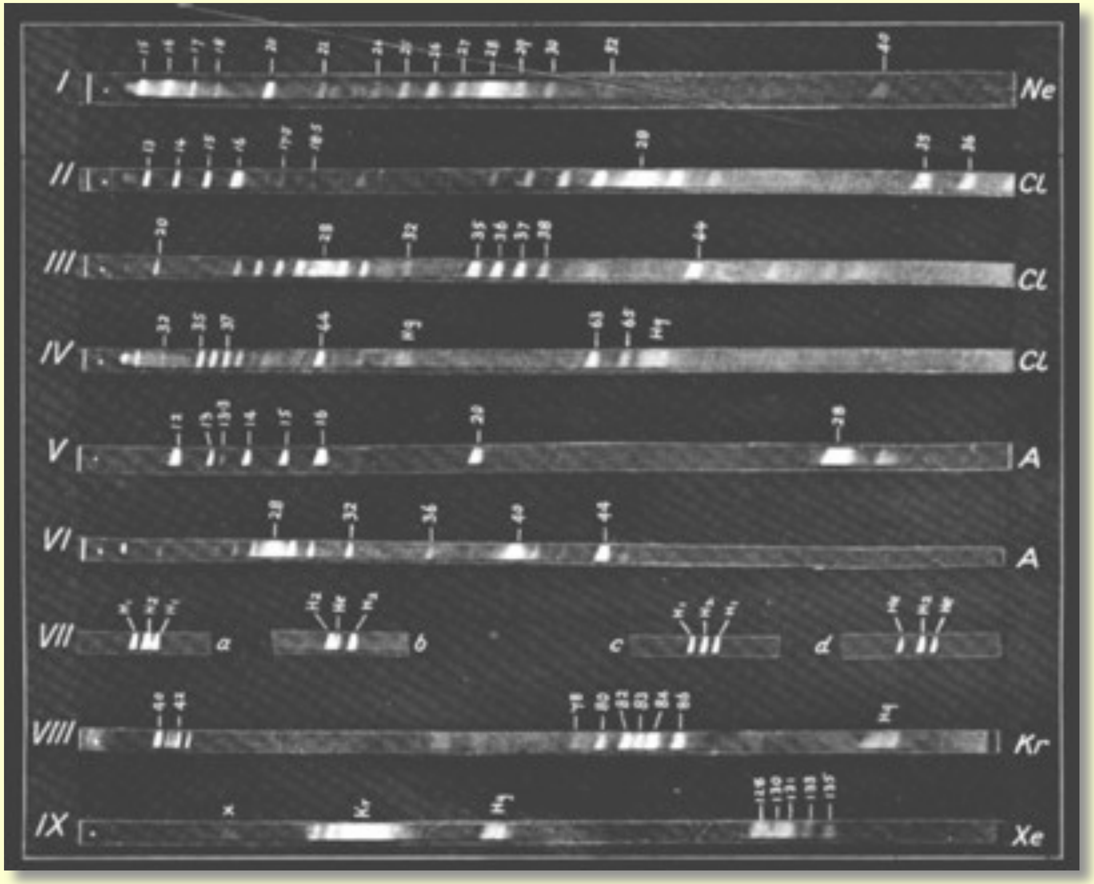
Scheme of Aston’s mass spectrometer

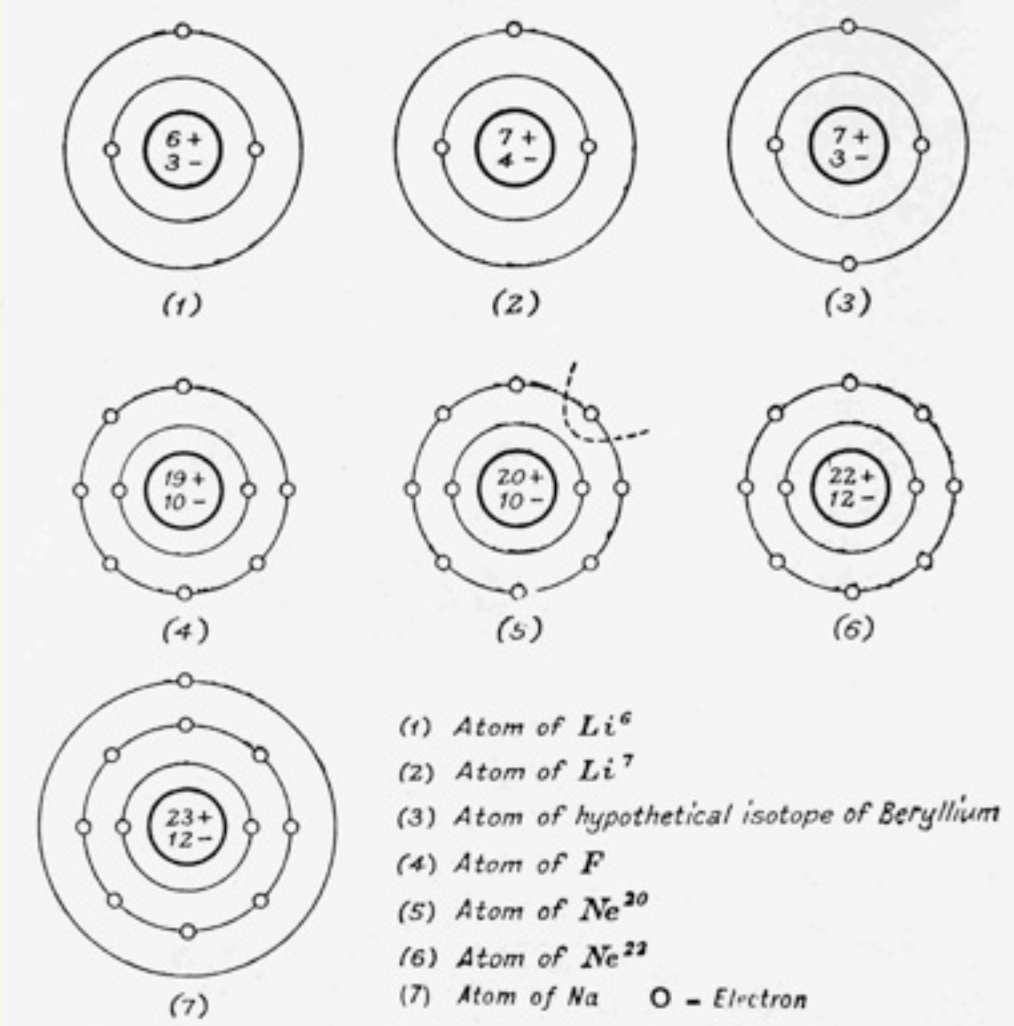




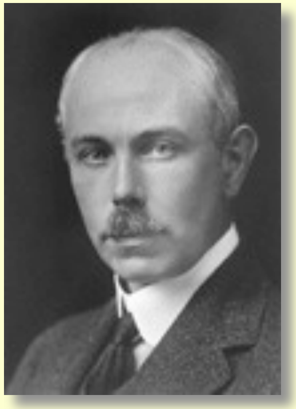
Aston at his mass spectrometer (1920)

Aston’s results (May 1920)

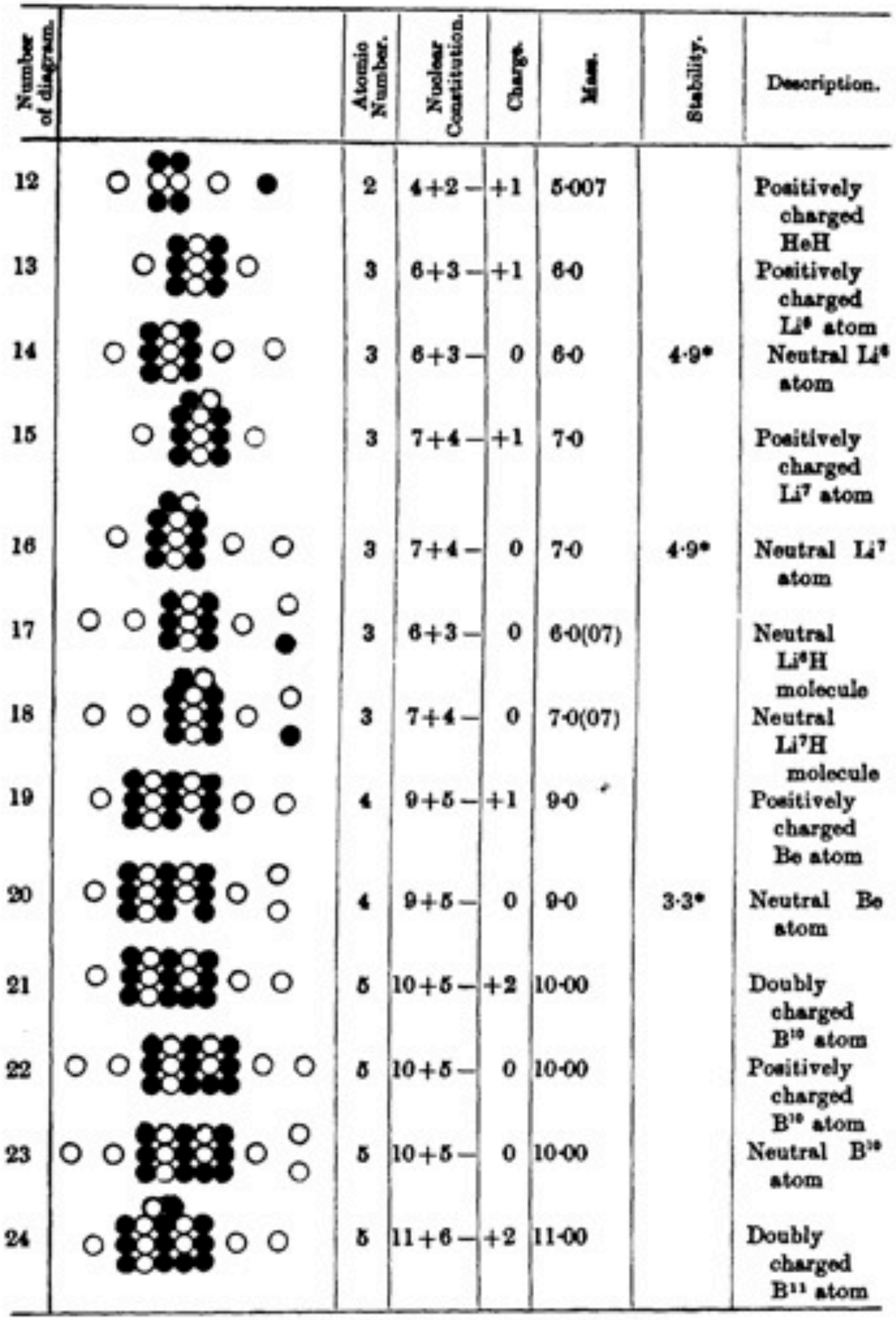




Aston, *Isotopes* (1922)



Francis Aston
(1877-1945)



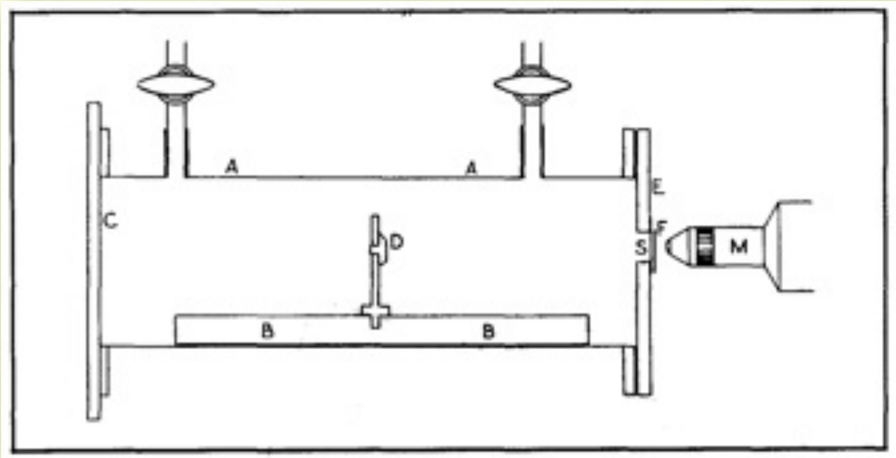
Number of diagram.		Atomic Number.	Nuclear Constitution.	Charge.	Mass.	Stability.	Description.
12		2	4+2 –	+1	5·007		Positively charged HeH
13		3	6+3 –	+1	6·0		Positively charged Li^6 atom
14		3	6+3 –	0	6·0	4·9*	Neutral Li^6 atom
15		3	7+4 –	+1	7·0		Positively charged Li^7 atom
16		3	7+4 –	0	7·0	4·9*	Neutral Li^7 atom
17		3	6+3 –	0	6·0(07)		Neutral Li^6H molecule
18		3	7+4 –	0	7·0(07)		Neutral Li^7H molecule
19		4	9+5 –	+1	9·0		Positively charged Be atom
20		4	9+5 –	0	9·0	3·3*	Neutral Be atom
21		5	10+5 –	+2	10·00		Doubly charged B^{10} atom
22		5	10+5 –	0	10·00		Positively charged B^{10} atom
23		5	10+5 –	0	10·00		Neutral B^{10} atom
24		5	11+6 –	+2	11·00		Doubly charged B^{11} atom

* Calculated from frequency of radiation.

Aston’s diagrams for the nuclei of various isotopes between Z = 2 and Z = 5.
The ”nuclear constitution” of each is shown by the tightly packed protons (dark dots) and the ”nuclear” electrons (open circles)

Isotopes (1922)

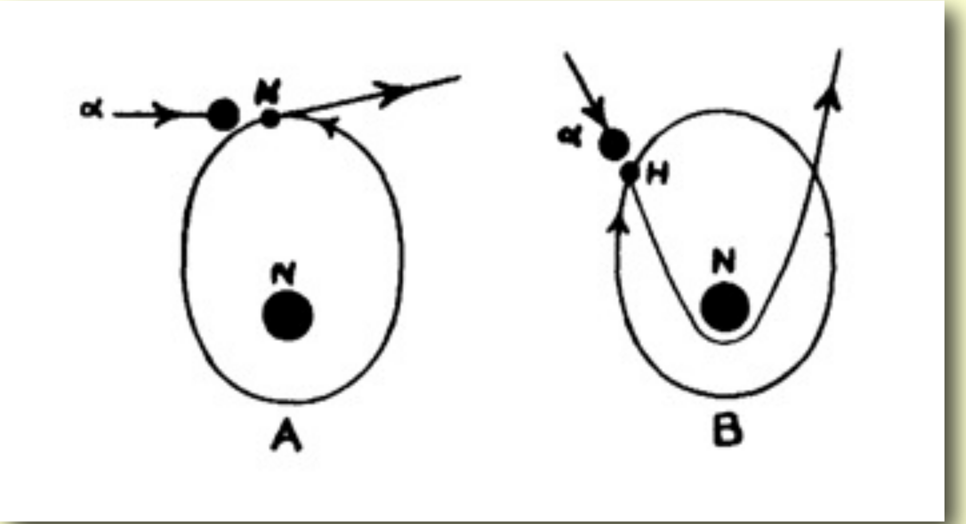
Ernest Rutherford 1919



First nuclear reaction observed

”It is difficult to avoid the conclusion that the long-range atoms arising from collision of α particles with nitrogen are not nitrogen atoms but probably atoms of hydrogen, or atoms of mass 2...We must conclude that the nitrogen atom is disintegrated under the close collision with a swift α particle, and that the hydrogen atom which is liberated formed a constituent part of the nitrogen nucleus...”

Collision of α Particles with Light Atoms (Part IV), Phil. Mag. **37**, 581 (1919)



Rutherford's model

"We should anticipate from radioactive data that the nitrogen nucleus consists of three helium nuclei of atomic mass 4 and either two hydrogen nuclei or one of mass 2. If the H nuclei were outriders of the main system of mass 12, the number of close collisions with the bound H nuclei would be less than if the latter were free, for the α particle in a collision comes under the combined field of the H nucleus and of the central mass...The general results indicate that the H nuclei... are distant about twice the diameter of the electron (7×10^{-13} cm) from the centre of the main atom."

The initial interpretation: $\alpha + {}^{14}N \rightarrow \alpha + H + {}^{13}C$.

Collision of α Particles with Light Atoms (Part IV), Phil. Mag. **37**, 581 (1919)

The final interpretation $\alpha + {}^{14}N \rightarrow H + {}^{17}O$ was accepted only after Blackett's photographs (1924)

”We should expect the H nucleus to be the simplest of all and, if it be the positive electron, it may have exceedingly small dimensions compared with the negative electron...
In considering the possible constitution of the elements, it is natural to suppose that they are built up ultimately of hydrogen nuclei and electrons. On this view the helium nucleus is composed of four hydrogen nuclei and two negative electrons with a resultant charge of two....
We have shown that atoms of mass about 3 carrying two positive charges are liberated by α-particles both from nitrogen and oxygen, and it is natural to suppose that these atoms are independent units in the structure of gases... We have seen that so far the nuclei of three light atoms have been recognised experimentally as probable units of atomic structure, viz.

$$\overset{+}{H_1}, \quad \overset{++}{X_3}, \quad \overset{++}{He_4}$$

where the subscript represents the mass of the element.”

Ernest Rutherford, Bakerian Lecture: *Nuclear Constitution of Atoms* (1920)

”The expulsion of an H atom carrying one charge from nitrogen should lower the mass by 1 and the nuclear charge by 1. The residual nucleus should thus have a nuclear charge 6 and mass 13, and should be an isotope of carbon. If negative electron is released at the same time, the residual atom becomes an isotope of nitrogen.
The expulsion of a mass 3 carrying two charges from nitrogen, probably quite independent of the release of the H atom, lowers the nuclear charge by 2 and the mass by 3. The residual atom should thus be an isotope of boron of nuclear charge 5 and mass 11. If an electron escapes as well, there remains an isotope of carbon of mass 11...
The data at present available are quite insufficient to distinguish between these alternatives...”

Rutherford, Bakerian Lecture: *Nuclear Constitution of Atoms* (June 3, 1920)

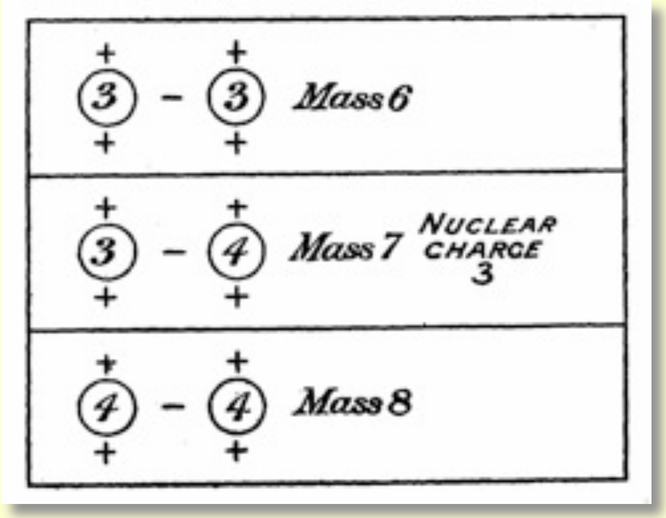
In modern notation:

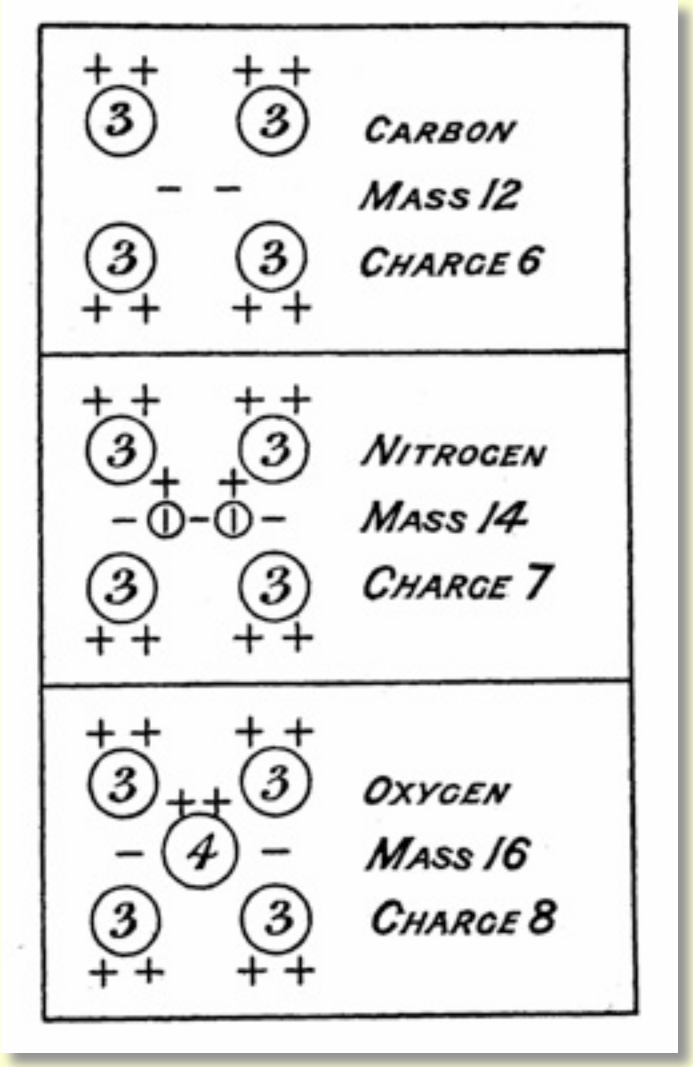
$$^{4}\mathrm{He} + {}^{14}\mathrm{N} \rightarrow {}^{4}\mathrm{He} + {}^{1}\mathrm{H} + {}^{13}\mathrm{C}$$

$$^{4}\mathrm{He} + {}^{14}\mathrm{N} \rightarrow {}^{4}\mathrm{He} + {}^{1}\mathrm{H} + {}^{13}\mathrm{N} + e^{-}$$

$$^{4}\mathrm{He} + {}^{14}\mathrm{N} \rightarrow {}^{4}\mathrm{He} + {}^{3}\mathrm{X} + {}^{11}\mathrm{B}$$

$$^{4}\mathrm{He} + {}^{14}\mathrm{N} \rightarrow {}^{4}\mathrm{He} + {}^{3}\mathrm{X} + {}^{11}\mathrm{C} + e^{-}$$





Rutherford's models for three isotopes of lithium and for ^{12}C, ^{14}N, and ^{16}O. The building blocks are the hydrogen nuclei, alpha particles and X_3^{++} particles

Bakerian lecture (1920)

P. M. S. Blackett

Ejection of Protons from Nitrogen Nuclei - Photographed by the Wilson Method
Proc. Roy. Soc. **107**, 349 (1925)

23000 photographs
ca. 420 000 tracks of α particles

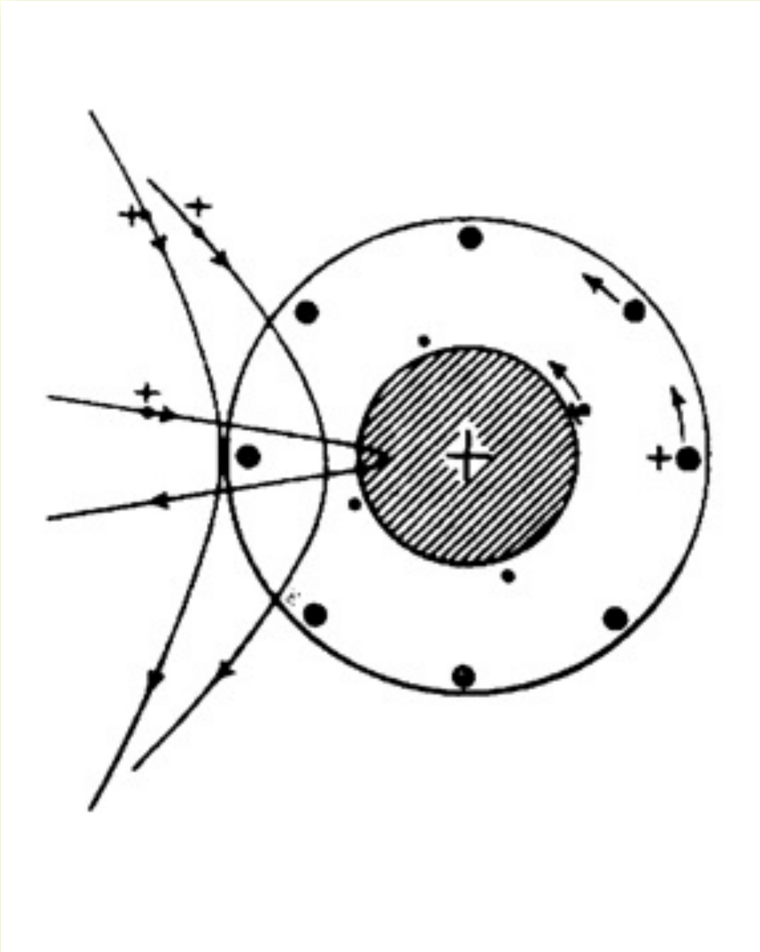
Eight ”forks” undoubtedly representing the ejection of a proton from the nitrogen nucleus

$$^{14}N + {}^{4}He \rightarrow {}^{17}O + {}^{1}H$$

Rutherford commenting on Blackett's results:

"...The fine track of the proton was clearly visible, also that of the recoiling nucleus, but there was no sign of a third track to be expected if the α particle escaped after the collision...
In 1923 Prof. W. D. Harkins and R. W. Ryan (Journ. Amer. Chem. Soc. **45**, 2095)...recorded a photograph of a collision in which the α ray track broke into three distinct branches - indicating a disintegration in which two high speed particles appear in addition to the recoiling nucleus. My attention has recently been directed to another interesting photograph recorded by M. Akiyama (Jap. Journ. Phys. **2**, 272, 1923), which also shows three branches... It is, of course, difficult to reconcile these photographs with the eight obtained by Blackett in which no third branch has been noted... It is obvious that there is still much work to be done to clear up these difficulties..."

Nature **115,** 493 (1925)



An extension (1925) of Rutherford's nuclear model included "satellites" (negative electrons and positive protons), which formed closely spaced "neutral doublets". The new model used to explain why uranium freely emits relatively low energy α particles (of range 2.7 cm), while α particles of higher energy (of range 6.7 cm) are scattered away. The emission of low energy α particles was explained as due to the break up of closely spaced "satellites".

In 1927 Rutherford extended the model quantitatively by showing that a number of gamma-ray lines could be interpreted as arising from transitions of such "satellites". He did not give up this model even after Gamow's quantum theory of α decay (1928).

The nucleus has a form of a circular disc, made up of concentric rings. Positively charged H and He particles describe circular orbits around the midpoint of the atom as centre. Around each positive charge revolve the negative electrons.

H. T. Wolff, Ann. d. Phys. 60, 685 (1919)

The nucleus of helium is assumed to consist of four protons in a circle and two electrons on the axis. To explain the observed stability of α particles it is necessary to assume that Coulomb's law is not obeyed.

Y. Takahashi, Phys. Math. Soc. Japan, Proc. 5, 137 (1923)

The protons in an atomic nucleus lie in two zones, an inner one solid and spherical and in which each proton is accompanied by a single electron, and an outer spherical shell in which the protons form pairs, each pair with one electron.

S. Ono, Phys. Math. Soc. Japan, Proc. 8, 76 (1926)

The nucleus is a system of differently charged concentric spheres, some positive and others negative.

G. I. Pokrowski, Ann.d. Phys. 9, 505 (1931)

"The nitrogen catastrophe"

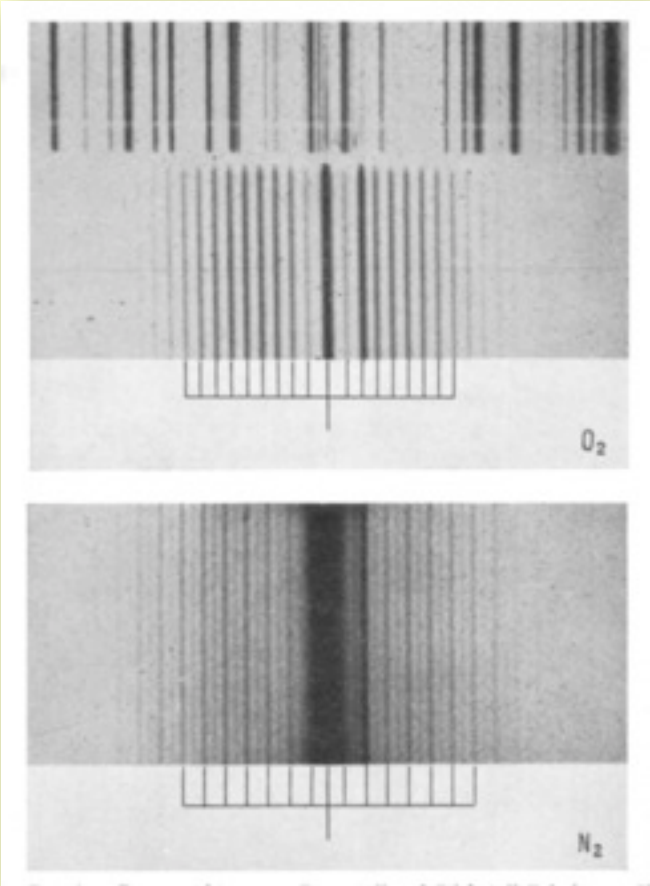
proton-electron model of atomic nuclei

mass of the ^{14}N nucleus $\cong$ 14 proton masses
charge of the ^{14}N nucleus = 7 proton charges

Hence the ^{14}N nucleus was believed to be built of 14 protons and 7 electrons, a total of 21 particles. The odd number of spin 1/2 particles ought to produce a half-integer total spin

”The nitrogen catastrophe”

Raman band spectra for O_2 and N_2 proving that both nuclei obey the Bose statistics
F. Rasetti, Z.Phys. 61, 600 (1930)

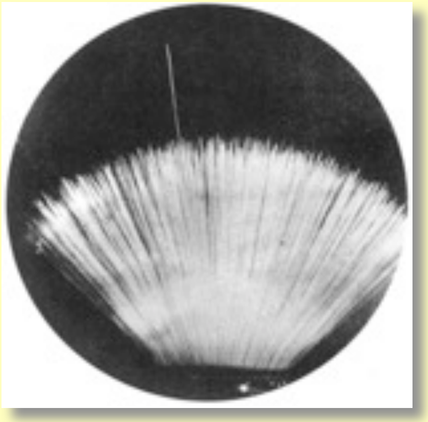


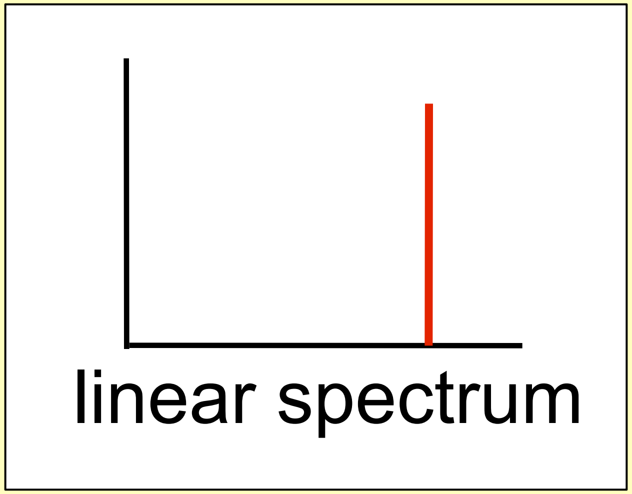
”One is therefore probably required to assume that in the nucleus the protons and electrons do not maintain their identity in the same way as in the case when they are outside the nucleus.”

R. de Kronig (1928)

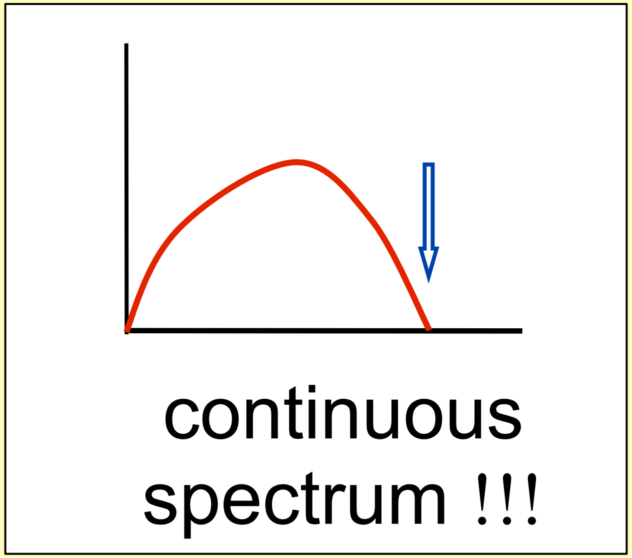
Mystery of the energy spectrum of β rays

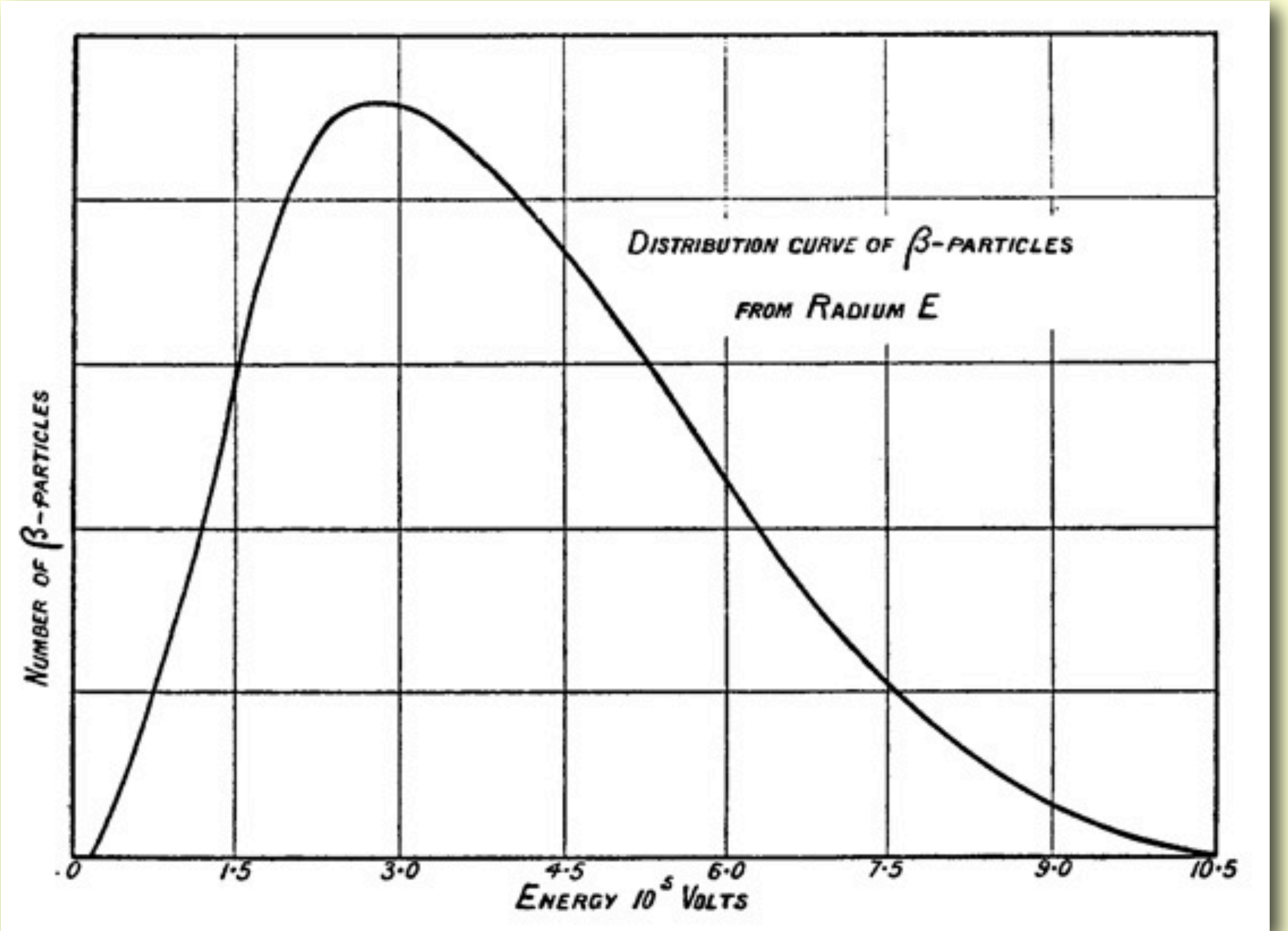
$$^{238}U \rightarrow {}^{234}Th + \alpha$$





$$^{234}Th \rightarrow {}^{234}Pa + \beta$$





C. D. Ellis and W. D. Wooster, Proc. Roy. Soc. **A117**, 109 (1927)

1930 Pauli - neutrino hypothesis

1930 Bothe-Becker experiment

1932 Urey - deuterium

1932 Chadwick - neutron

1932 Anderson - positron

1932 Iwanenko, Heisenberg - proton-neutron nuclear model

1932 Lawrence - 1 MeV cyclotron

1932 Cockroft & Walton: $p + {}^{7}Li \rightarrow \alpha + \alpha$

Pauli’s letter to Hans Geiger and Lise Meitner participating in a physics conference in Tübingen, December 4, 1930

”I have come upon a desperate way out regarding the 'wrong' statistics of the N-14 and the Li-6 nuclei, as well as to the continuous β-spectrum, in order to save the alternation law of 'statistics' and the energy law. To wit, the possibility that there could exist in the nuclei electrically neutral particles which I shall call neutrons, which have spin 1/2 and satisfy the exclusion principle, and which are further distinct from light quanta in that they do not move with light velocity. The mass of the neutrons should be of the same order of magnitude as the electron mass, and, in any case, not larger than 0.01 times the proton mass. The continuous β-spectrum should then become understandable from the assumption that in β decay a neutron is emitted along with the electron, in such a way that the sum of the energies of the neutron and the electron is constant.”

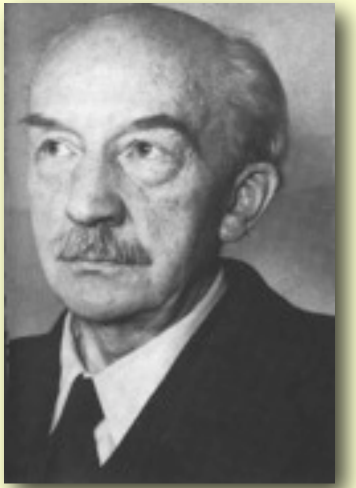
Pauli's letter to Hans Geiger and Lise Meitner participating in a physics conference in Tübingen, December 4, 1930 (cont.)

”For the time being I dare not publish anything about the idea and address myself confidentially first to you, dear radioactive ones, with the question how it would be with the experimental proof of such a neutron, if it were to have the penetrating power equal to or about ten times larger than a γ-ray. I admit that my way out may not seem very probable a priori since one would probably have seen the neutrons a long time ago if they exist. But only he who dares wins...
Thus, dear radioactive ones, examine and judge.
Unfortunately I cannot appear personally in Tubingen since a ball which takes place in Zurich the night of the sixth to the seventh of December makes my presence here indispensable...”

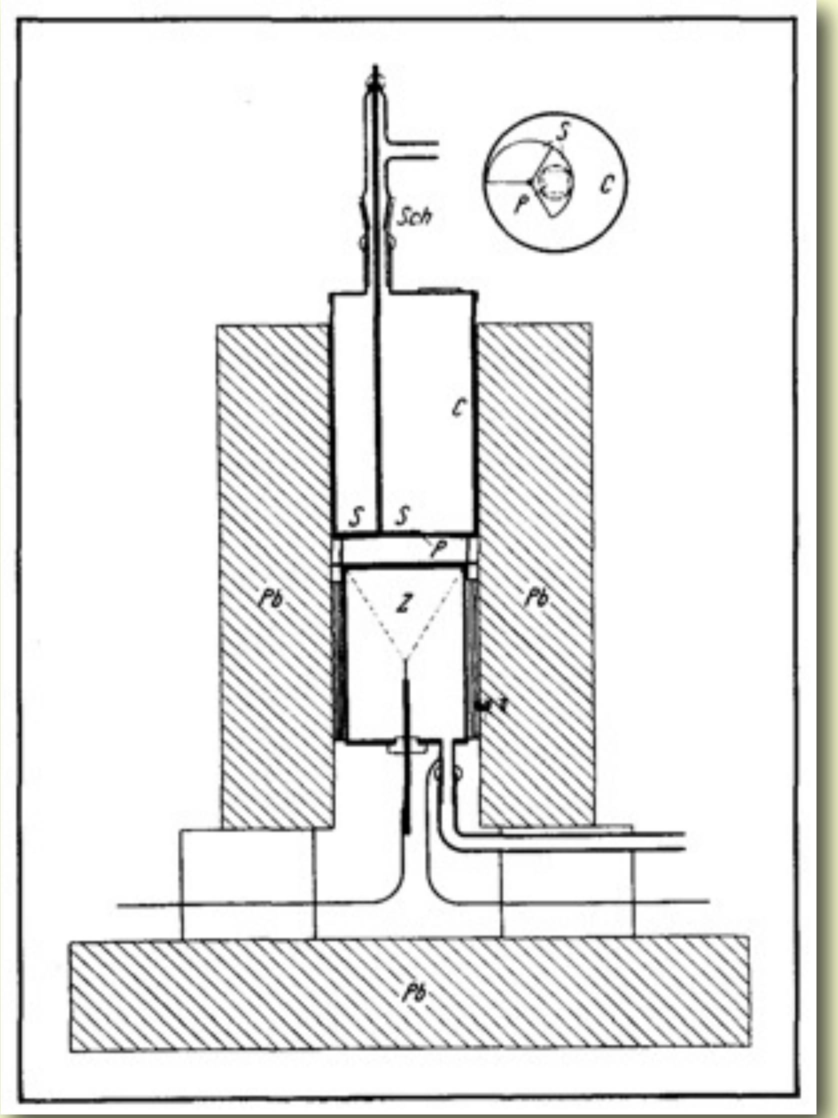
(After the discovery of the neutron by Chadwick in 1932 Fermi proposed to call Pauli's hypothetical particle a ”neutrino”)

Bothe-Becker experiment (1930)

"Beryllium radiation", more penetrating than ordinary γ-rays, produced by exposing beryllium to α particles from Ra [Z.Phys. **66**, 289, 310 (1930)]



Walther Bothe



Letters to the Editor

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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 $(\text{cm.})^{-1}$. 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 $3{\cdot}2 \times 10^9$ 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.

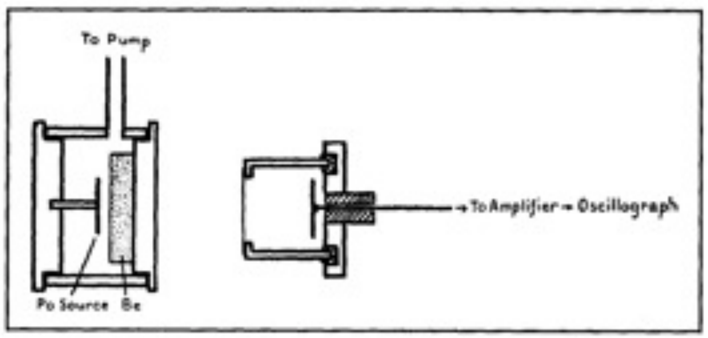
If it be supposed that the radiation consists of quanta, then the capture of the α-particle by the Be^9 nucleus will form a C^{13} nucleus. The mass defect of C^{13} is known with sufficient accuracy to show that the energy of the quantum emitted in this process cannot be greater than about 14×10^6 volts. 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,
Cambridge, Feb. 17.

James Chadwick
(1891-1974)



Experimental scheme

$$ {}^{4}_{2}He + {}^{9}_{4}Be = {}^{12}_{6}C + {}^{1}_{0}n $$

THE NEUTRON

By R. M. Langer and N. Rosen
Massachusetts Institute of Technology

(Received May 12, 1931)

Abstract

The writers point out that the postulation of the existence of the "neutron," a combination of an electron and a proton, of small size and low energy would be very useful in explaining a number of atomic and cosmic phenomena. They find that a mathematical treatment based on existing theory leads to indications of such a state but no definite proof.

I. Introduction

IT IS an attractive speculation to try to describe a process by which the various elements could be formed. In the present state of atomic theory it is really an anomaly that there are elements other than hydrogen; for no one has hitherto attempted to show that quantum systems could exist with the dimensions and energies appropriate to nuclei or constituents of nuclei. Our purpose here is to indicate how such systems may exist on the basis of wave-mechanics, and thus offer a way of describing the process of building up of the heavier elements.

The present article is devoted to a discussion of a combination of an electron and a proton of low energy and very small size which we shall speak of as the "neutron." Such a particle, if it exists, must have a mass but slightly smaller than that of a hydrogen, a diameter of 10^{-12} to 10^{-15} cm, and energy of the order of magnitude of m_0c^2 ($15m_0c^2$ is an upper limit; m_0 = electron mass) less than that of hydrogen in order to account for observed phenomena. It seems proper to begin by pointing out reasons for the assumption of the existence of a neutron and to show how it might help to explain certain phenomena.

Discussion on the Structure of Atomic Nuclei, April 28, 1932

Rutherford: ”...It is generally supposed that the nucleus of a heavy element consists mainly of α-particles with an admixture of a few free protons and electrons, but the exact division between these constituents is unknown... It appears as if the electron within the nucleus behaves quite differently from the electron in the outer atom... it now seems clear that the nuclear γ-rays are due to the transition of an α-particle between energy levels in an excited nucleus...
The idea of the possible existence of ”neutrons”, that is, of a close combination of a proton and an electron to form a unit of mass nearly 1 and zero charge is not new...”

Discussion on the Structure of Atomic Nuclei, April 28, 1932

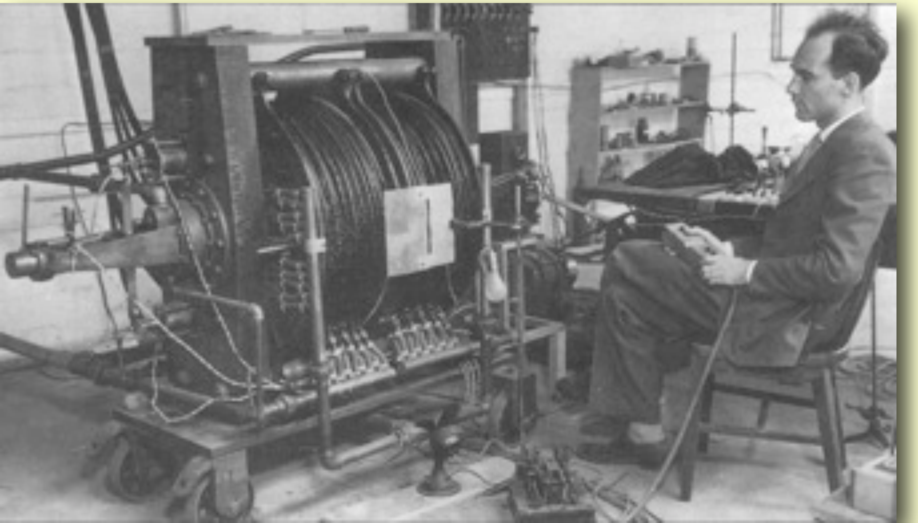
Chadwick: ”The neutron may be pictured as a small dipole, or perhaps better, as a proton embedded in an electron. On either view the ‘radius’ of the neutron will be between 10^{-13} cm. and 10^{-12} cm....”

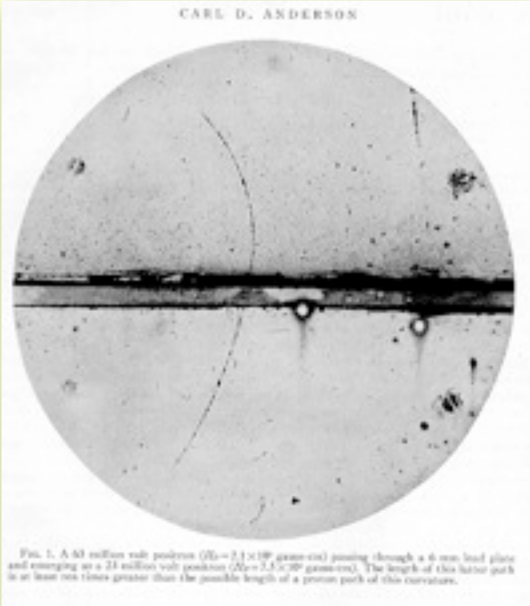
Ellis: ”It must not be forgotten that there are other particles in the nucleus besides α-particles and electrons. Fowler has suggested that the presence of protons may be responsible for certain peculiarities of the spectrum, and recent work shows that we may even have to consider neutrons of one or more kinds...”

Lindemann: ”We must examine how the neutron fits into the scheme of modern physics. From the point of view of the classical quantum theory, it is difficult to see how it can exist...”

The discovery of the positron

Carl Anderson at his instruments (1932)





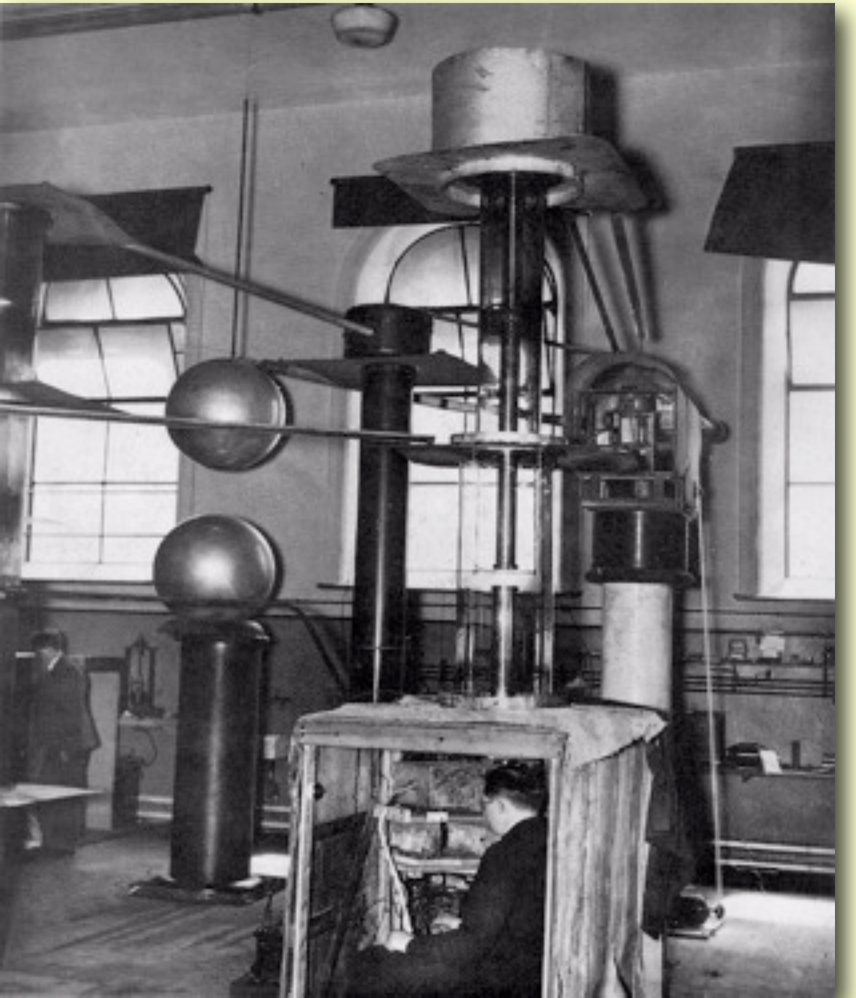
Pair production (I. & F. Joliot-Curie)

”It has often been stated in the literature that the discovery of the positron was a consequence of its theoretical prediction by Dirac, but this is not true. The discovery of the positron was wholly accidental. Despite the fact that Dirac’s relativistic theory of the electron was an adequate theory of the positron, and despite the fact that the existence of this theory was well known to nearly all physicists, it played no part whatsoever in the discovery of the positron.”

Carl Anderson

$$p + {}^{7}Li \rightarrow \alpha + \alpha$$

First nuclear reaction obtained with the use of accelerators



John Cockroft (1897-1967)

Ernest Walton (1903-1995)

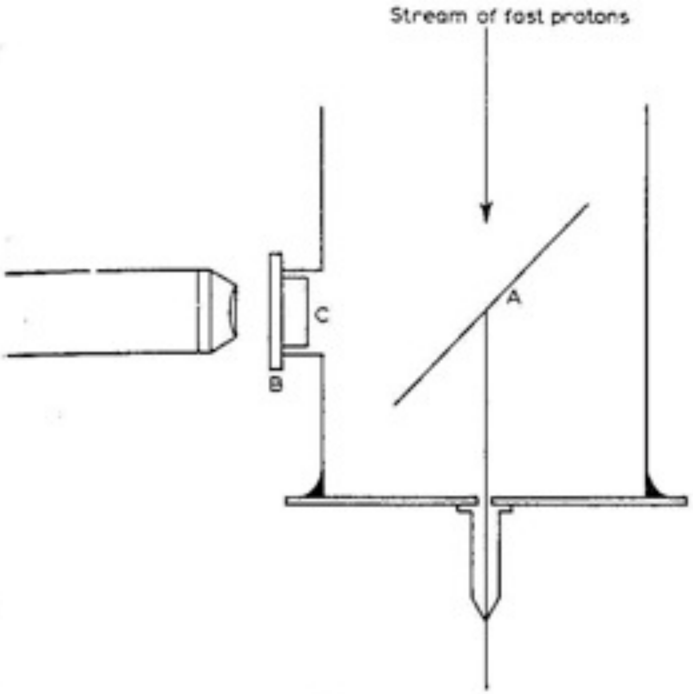


Fig. 2.

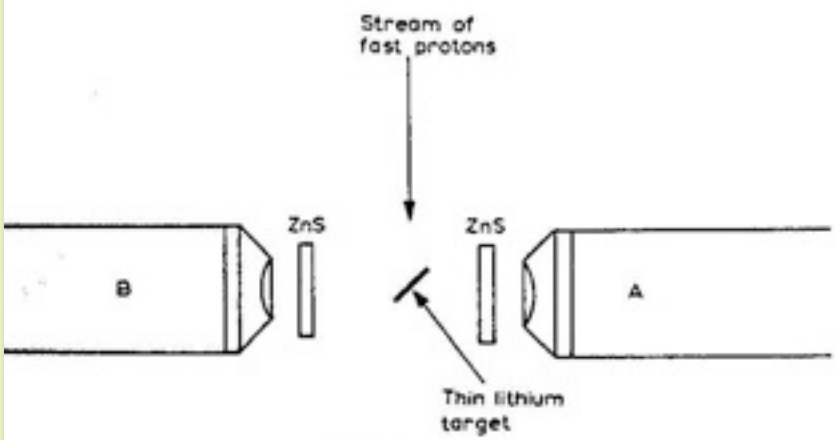
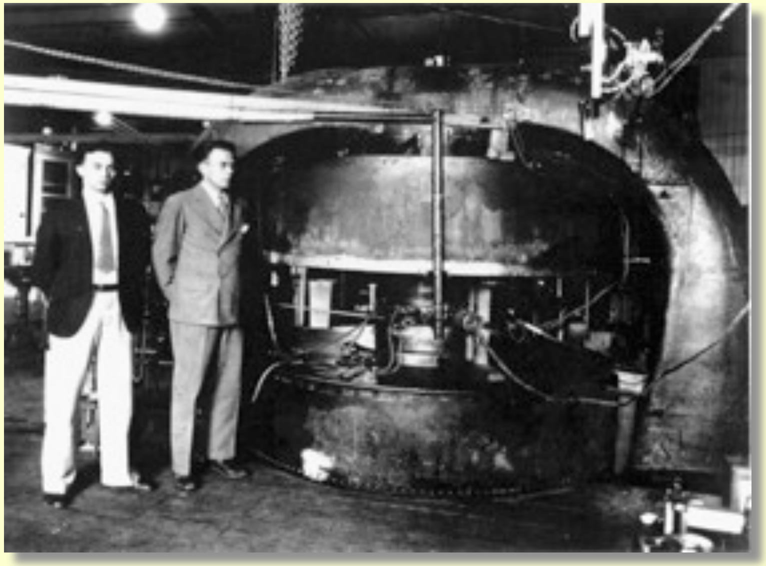


Fig. 3.

The scheme of the Cockroft-Walton experiment

Robert Van de Graaf with one of his first accelerators

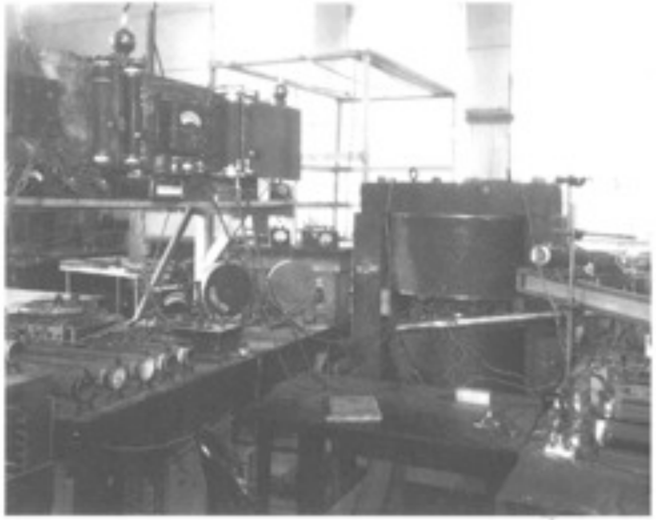
Ernest Lawrence (1901-1958) discoverer of the cyclotron



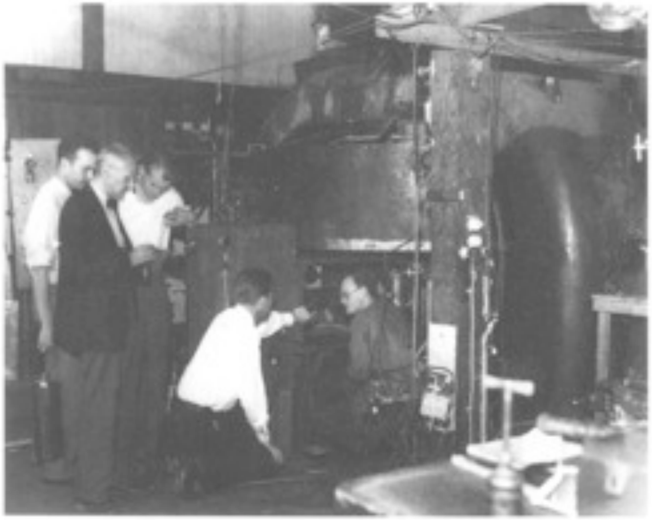
Lawrence and Livingston
at the cyclotron

Lawrence's cyclotrons

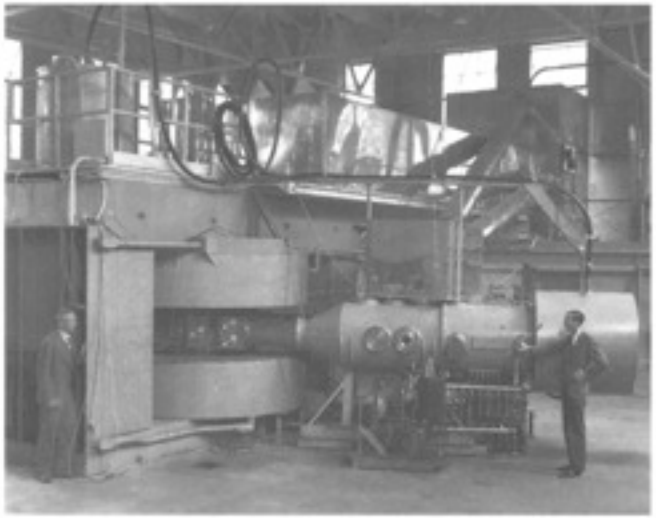
28 cm
I 1932



69 cm
XII
1932



1.5 m
X 1939



4.7 m
1957

Solvay Conference 1933

Irène i Frédéric Joliot-Curie

Discovery of artificial radioactivity

Artificial Production of a New Kind of Radio-Element

By F. Joliot and I. Curie, Institut du Radium, Paris

SOME months ago we discovered that certain light elements emit positrons under the action of α-particles[1]. Our latest experiments have shown a very striking fact: when an aluminium foil is irradiated on a polonium preparation, the emission of positrons does not cease immediately, when the active preparation is removed. The foil remains radioactive and the emission of radiation decays exponentially as for an ordinary radio-element. We observed the same phenomenon with boron and magnesium[2]. The half life period of the activity is 14 min. for boron, 2 min. 30 sec. for magnesium, 3 min. 15 sec. for aluminium.

We have observed no similar effect with hydrogen, lithium, beryllium, carbon, nitrogen, oxygen, fluorine, sodium, silicon, or phosphorus. Perhaps in some cases the life period is too short for easy observation.

The transmutation of beryllium, magnesium, and aluminium α-particles has given birth to new radio-elements emitting positrons. These radio-elements may be regarded as a known nucleus formed in a particular state of excitation; but it is much more probable that they are unknown isotopes which are always unstable.

For example, we propose for boron the following nuclear reaction:

$$ {}_5B^{10} + {}_2He^4 = {}_7N^{13} + {}_0n^1 $$

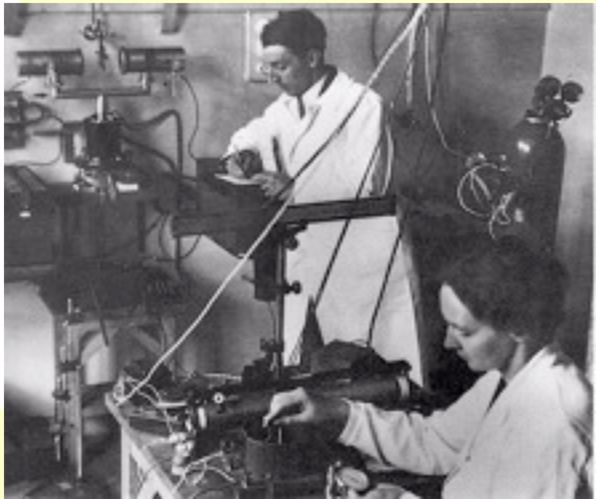
${}_7N^{13}$ being the radioactive nucleus that disintegrates with emission of positrons, giving a stable nucleus ${}_6C^{13}$. In the case of aluminium and magnesium, the radioactive nuclei would be ${}_{15}P^{30}$ and ${}_{14}Si^{27}$ respectively.

The positrons of aluminium seem to form a continuous spectrum similar to the β-ray spectrum. The maximum energy is about 3×10^6 e.v. As in the case of the continuous spectrum of β-rays, it will be perhaps necessary to admit the simultaneous emission of a neutrino (or of an antineutrino of Louis de Broglie) in order to satisfy the principle of the conservation of energy and of the conservation of the spin in the transmutation.

The transmutations that give birth to the new radio-elements are produced in the proportion of 10^{-7} or 10^{-6} of the number of α-particles, as for other transmutations. With a strong polonium preparation of 100 millicuries, one gets only about 100,000 atoms of the radioactive elements. Yet it is possible to determine their chemical properties, detecting their radiation with a counter or an ionisation chamber. Of course, the chemical reactions must be completed in a few minutes, before the activity has disappeared.

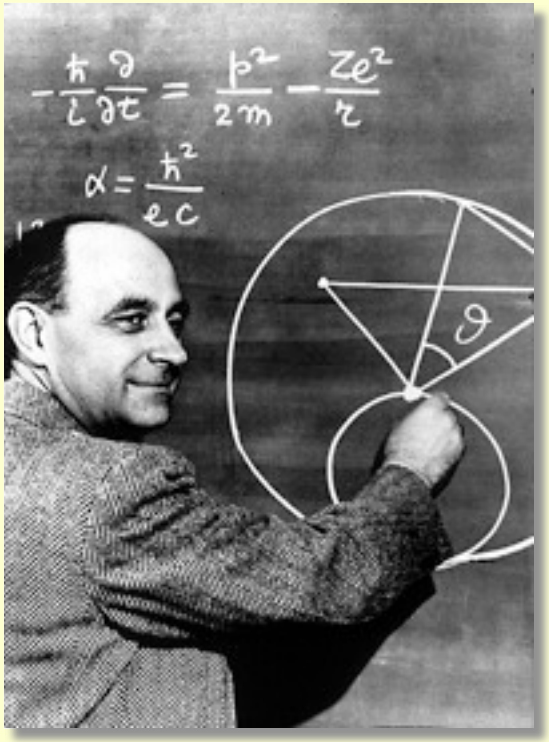
We have irradiated the compound boron nitride (BN). By heating boron nitride with caustic soda, gaseous ammonia is produced. The activity separates from the boron and is carried away with the ammonia. This agrees very well with the hypothesis that the radioactive nucleus is in this case an isotope of nitrogen.

When irradiated aluminium is dissolved in



The first theory of β decay (including the hypothetical neutrino) was proposed by Fermi. His paper, rejected from *Nature*, was published first in Italian and few weeks later as "*Versuch einer Theorie der β-Strahlen*", Z.f. Physik **88**, 161 (1934)

Radioactivity induced by slow neutrons was discovered by Fermi and his group (Amaldi, D'Agostino, Rasetti, Segré), Proc. Roy.Soc. 146, 483 (1934)



Enrico Fermi
(1901-1954)

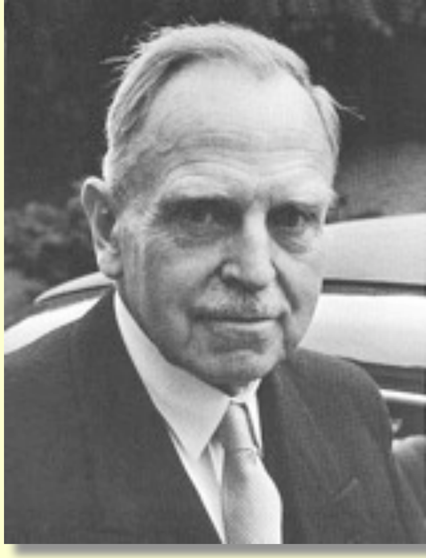
1934  Fermi et al. concluded that they observed transuranic elements:
^{93}Au (Ausonium) and ^{94}Hs (Hesperium)

1934  Fermi’s conclusion criticised by Ida Noddack

1938  Iréne Curie and Pavel Savitch announced discovery of transuranium elements in the reaction n + U → transuranium

1938  On 22 December Hahn and Strassmann announced that uranium bombarded with neutrons gives barium

1939   In January Otto Frisch and Lise Meitner published their opinion that uranium bombarded with neutrons undergoes fission



Otto Hahn

”As chemists we must on grounds of shortly stated experimental results, change the names in the above scheme, and instead of Ra, Ac, Th, use the symbols Ba, La, Ce. As ‘nuclear chemists’ closely related to physics in a certain way, we cannot yet decide to make the jump contradicting all previous experience in nuclear physics.”
Naturwissenschaften **27**, 11 (1939)

Fritz Strassmann

denn andere Elemente als Radium oder Barium kommen nicht in Frage.

Schließlich haben wir auch einen Indikatorversuch mit unserem rein abgeschiedenen „Ac II" (H.Z. rund 2,5 Stunden) und dem reinen Actiniumisotop $MsTh_2$ gemacht. Wenn unsere „Ra-Isotope" kein Radium sind, dann sind die „Ac-Isotope" auch kein Actinium, sondern sollten Lanthan sein. Nach dem Vorgehen von Mme CURIE[1] haben wir eine Fraktionierung von Lanthanoxalat, das die beiden aktiven Substanzen enthielt, aus salpetersaurer Lösung vorgenommen. Das $MsTh_2$ fand sich, wie von Mme CURIE angegeben, in den Endfraktionen stark angereichert. Bei unserem „Ac II" war von einer Anreicherung am Ende nichts zu merken. In Übereinstimmung mit CURIE und SAVITCH[2] über ihren allerdings nicht einheitlichen 3,5-Stunden-Körper finden wir also, daß das aus unserem aktiven Erdalkalimetall durch β-Strahlenemission entstehende Erdmetall kein Actinium ist. Den von CURIE und SAVITCH angegebenen Befund, daß sie die Aktivität im Lanthan anreicherten, der also gegen eine Gleichheit mit Lanthan spricht, wollen wir noch genauer experimentell prüfen, da bei dem dort vorliegendem Gemisch eine Anreicherung vorgetäuscht sein könnte.

Ob die aus den „Ac-La-Präparaten" entstehenden, als „Thor" bezeichneten Endglieder unserer Reihen sich als Cer herausstellen, wurde noch nicht geprüft.

Was die „Trans-Urane" anbelangt, so sind diese Elemente ihren niedrigeren Homologen Rhenium, Osmium, Iridium, Platin zwar chemisch verwandt, mit ihnen aber nicht gleich. Ob sie etwa mit den noch niedrigeren Homologen Masurium, Ruthenium, Rhodium, Palladium chemisch gleich sind, wurde noch nicht geprüft. Daran konnte man früher ja nicht denken. Die Summe der Massenzahlen Ba + Ma, also z. B. 138 + 101, ergibt 239!

Als Chemiker müßten wir aus den kurz dargelegten Versuchen das oben gebrachte Schema eigentlich umbenennen und statt Ra, Ac, Th die Symbole Ba, La, Ce einsetzen. Als der Physik in gewisser Weise nahestehende „Kernchemiker" können wir uns zu diesem, allen bisherigen Erfahrungen der Kernphysik widersprechenden, Sprung noch nicht entschließen. Es könnten doch noch vielleicht eine Reihe seltsamer Zufälle unsere Ergebnisse vorgetäuscht haben.

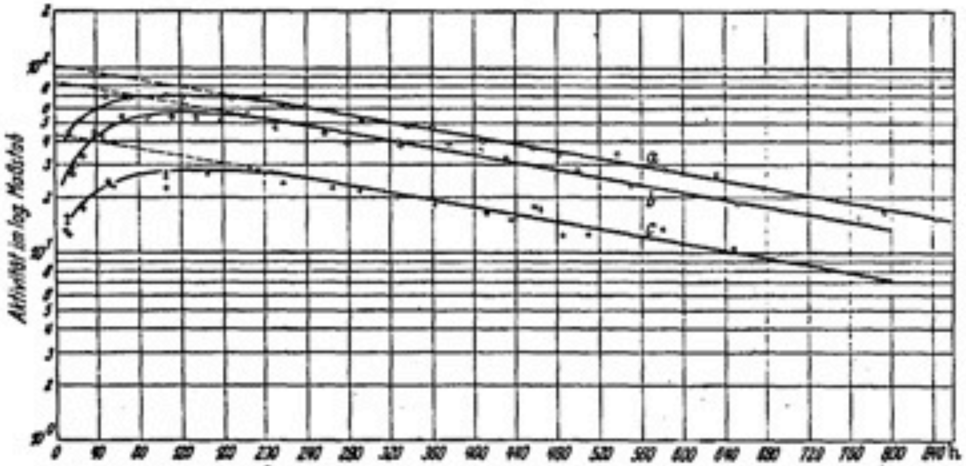


Fig. 4. Bestimmung der Halbwertszeit von Ra IV bei verschiedener Bestrahlungszeit und -art.

a = Ra IV [∾4 Tage bestrahlt] } verstärkt,
b = Ra IV [∾2,6 „ „] } ←——→ Ra-Abtrennung 15 Std. nach Ende der Bestrahlung.
c = Ra IV [∾2,6 „ „] unverstärkt,

a H.Z. = ∾311 Stunden, b H.Z. = ∾310 Stunden, c H.Z. = ∾300 Stunden.

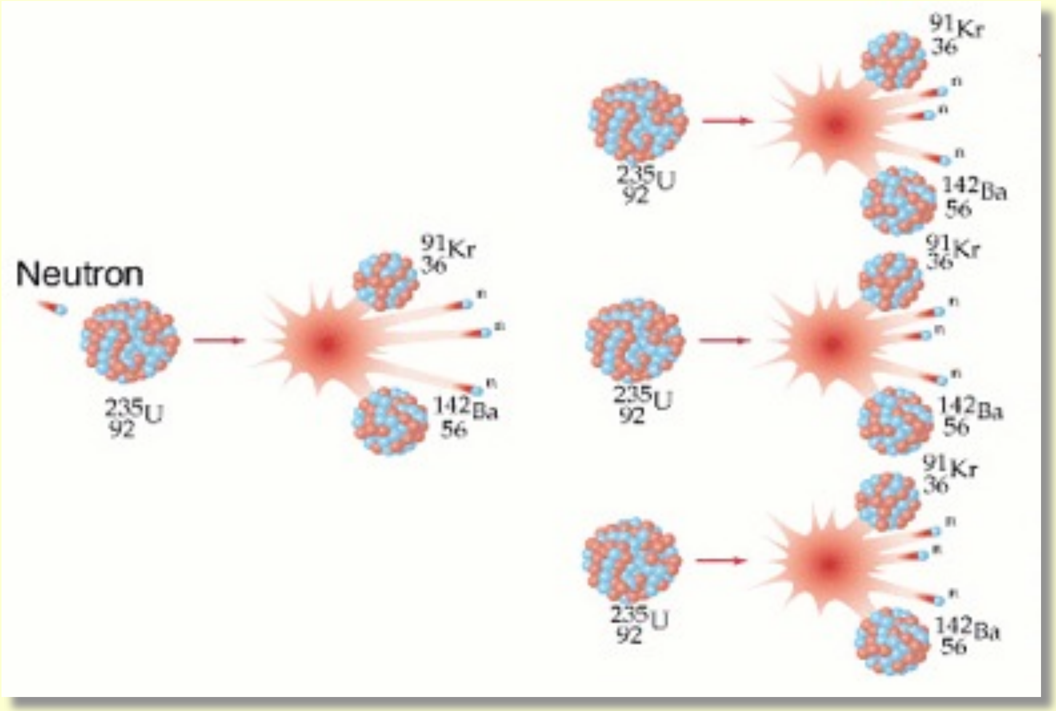
Es ist beabsichtigt, weitere Indikatorenversuche mit den neuen Umwandlungsprodukten durchzuführen. Insbesondere soll auch eine gemeinsame Fraktionierung der aus Thor durch Bestrahlen mit schnellen Neutronen entstehenden, von MEITNER, STRASSMANN und HAHN[1] untersuchten Radiumisotope mit unseren aus dem Uran entstandenen Erdalkalimetallen versucht werden. An Stellen, denen starke künstliche Strahlenquellen zur Verfügung stehen, könnte dies allerdings wesentlich leichter geschehen.

Zum Schlusse danken wir Frl. CL. LIEBER und Frl. I. BOHNE für ihre wirksame Hilfe bei den sehr zahlreichen Fällungen und Messungen.

[1] Mme PIERRE CURIE, J. Chim. physique etc. 27, 1 (1930).
[2] I. CURIE u. P. SAVITCH, C. r. Acad. Sci. Paris 206, 1643 (1938).

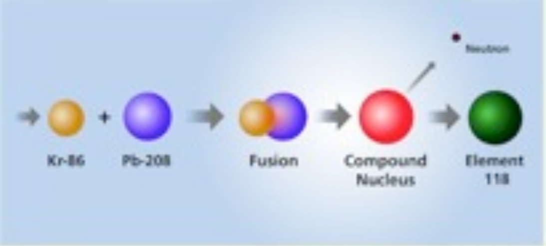
[1] L. MEITNER, F. STRASSMANN u. O. HAHN, l. c.

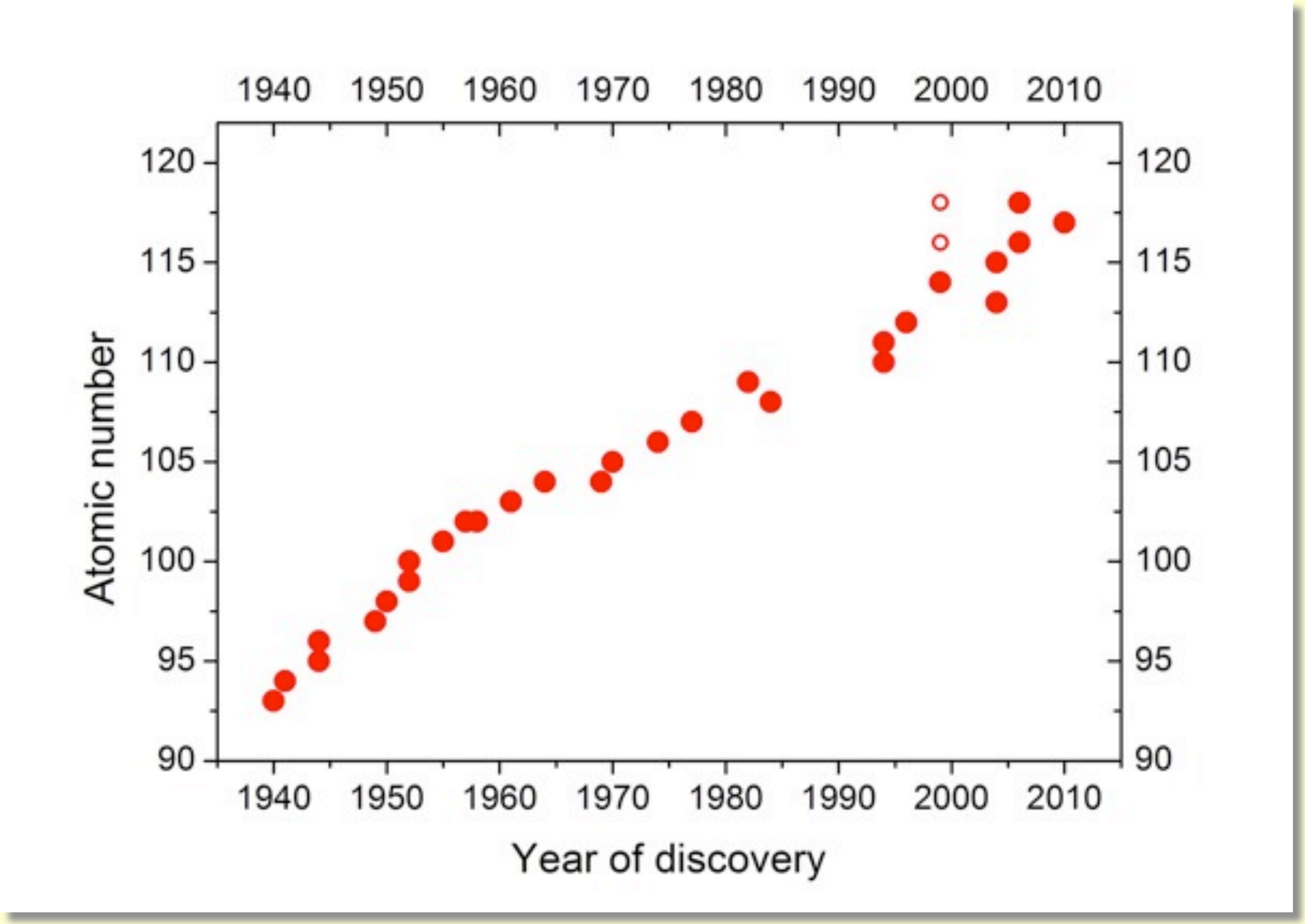
Otto Hahn
and
Fritz Strassmann



Neutron
$^{235}_{92}U$
$^{91}_{36}Kr$
$^{142}_{56}Ba$
n

Transuranium elements

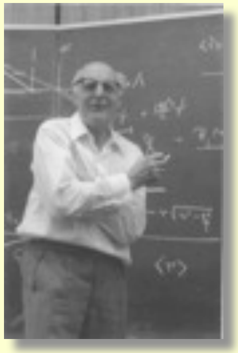




Nuclear models

1939 Liquid drop model (Niels Bohr and John Archibald Wheeler

1949 Shell model (Maria Goeppert-Mayer and Hans Jensen (also Otto Haxel and Hans Suess)



1950 Collective model (Aage Bohr, Ben Mottelson and James Rainwater)

Cosmic radiation

- Discovered in August 1912 by Hess in a balloon flight up to above 5000 m
- Confirmed 1913-1919 by Kohlhörster in balloon flights up to above 9000 m
- Treated initially as ”*Ultragammastrahlung*” until the results of coincidence methods (Bothe & Kohlhörster, 1929; Rossi, 1929), the discovery of ”east-west asymmetry”, and the cloud chamber photographs of ”showers” (Blackett & Occhialini, 1933)

Victor Hess
(1883-1964)

Hess landing in 1912

Cosmic ”shower” registered by Blackett and Occhialini

Carriers of nuclear force proposed

Hideki Yukawa
(1907-1981)

”*On the interaction of elementary particles*”, Proc. Phys.-Mat. Soc. Japan **14**, 48 (1935)

Particles with mass about 200 times larger than electron mass postulated to explain interaction of nucleons in the nucleus

Discovery of ”mesons”

C. D. Anderson, S. H. Neddermeyer, Phys. Rev. 51, 884 (1937)
J. C. Street, E. C. Stevenson, Phys. Rev. 51, 1005 (1937)
reported discovery in cosmic rays of a particle with mass equal to about 200 electron masses

”It seems highly probable that Street and Stevenson and Anderson and Neddermeyer have actually discovered a new elementary particle which has been predicted by theory.”
E. C. G. Stueckelberg, Phys. Rev. 52, 41 (1937)

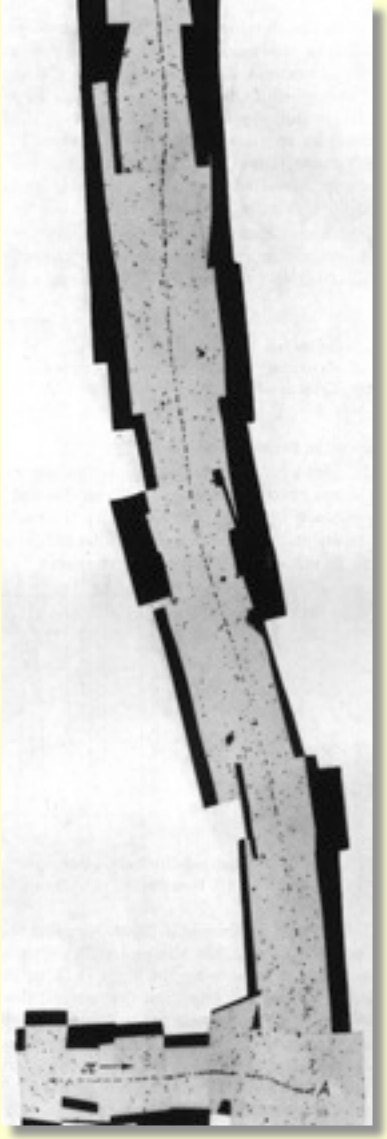
{proposed names: barytron, yukon, mesotron, then finally meson}

However, it was soon found that the cosmic ray ”mesons” interact with air at least 100 times weaker than needed for a Yukawa particle. Tomonaga and Araki (1940), Sakata and Inoue (1943), Marshack and Bethe (1947) postulated existence of two mesons

The discovery of pions

Conversi, Pancini and Piccioni found that the positive mesons coming to rest in iron undergo spontaneous decay while the negative are captured by the iron nuclei much before they have time to decay
Phys. Rev. **71**, 209 (1947)

Cecil Powell
(1903-1969)



First $\pi \rightarrow \mu$ decay

C.M.G. Lattes, H. Muirhead, G. P. S. Occhialini, C. F. Powell, "*Processes involving charged mesons*", Nature **159**, 694, May 24 (1947)

"There is, therefore, good evidence for the production a single homogeneous group of secondary mesons, constant in mass and kinetic energy. This strongly suggests a fundamental process, and not one involving an interaction of a primary meson with a particular type of nucleus in the emulsion. It is convenient to refer to this process in what follows as the μ-decay. We represent the primary mesons by the symbol π, and the secondary by μ."

C.M.G. Lattes, G. P. S. Occhialini, C. F. Powell,
Nature **160**, 454, Oct. 4 (1947)

Development of particle physics after 1947

Quantum electrodynamics

In 1947 Willis Lamb and Robert Retherford discovered separation of $2S_{1/2}$ and $2P_{1/2}$ hydrogen levels (supposed to have the same energy in the Dirac's theory.
In 1948-1951 Schwinger, Feynman and Tomonaga independently developed new QED formalism, by introducing renormalization procedure to avoid divergences.

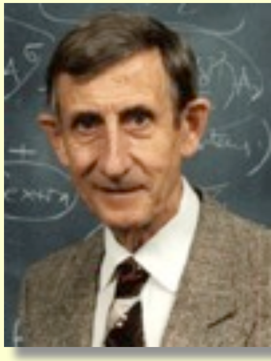
Willis Lamb

Richard Feynman

Julian Schwinger

Sin-Itiro Tomonaga

Dyson proved that the three approaches to QED were equivalent



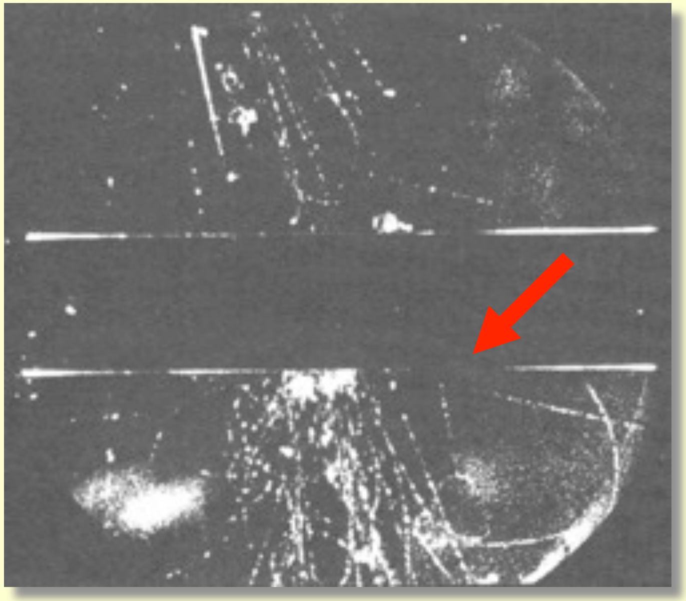
Freeman Dyson

A surprising discovery in 1947

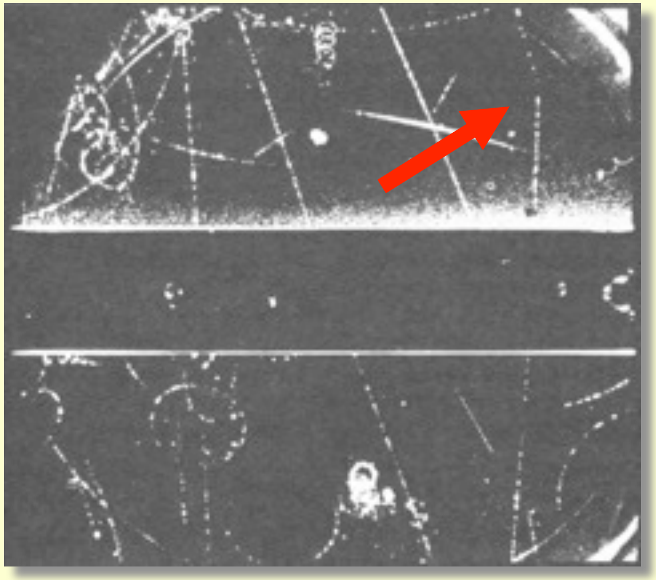
In December 1947
Rochester and Butler
in Manchester reported the
first "V particles", which
soon were found to be
produced only in pairs
Nature 160, 855 (1947)

George Rochester

Clifford Butler

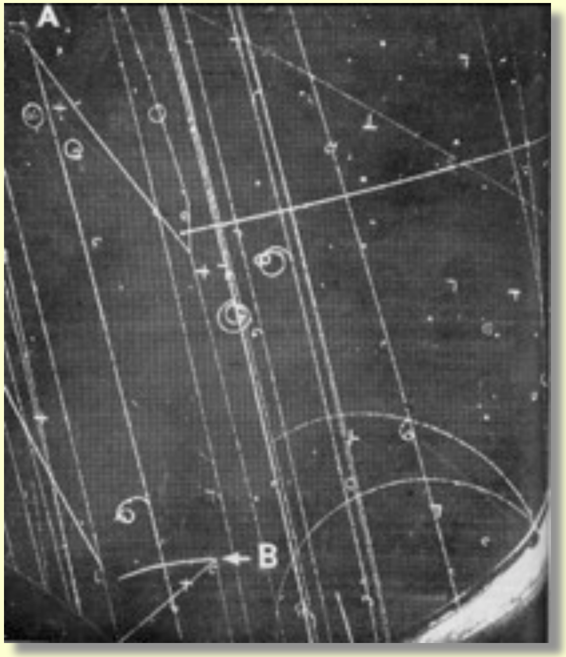


Neutral V particle



Charged V particle

V particles at once showed unusual properties



- They were copiously produced in high energy collisions (with cross section of a few percent of that for pion production)
- Thus, if the same mechanism was responsible for their production and decay, their lifetime should be of the order of 10^{-21} s.
- The observed lifetime was $\geq 10^{-10}$ s.

In order to explain associated production of V particles Gell-Mann, and independently Nishijima, proposed a new quantum number called (by Gell-Mann) ”strangeness” (1953)

Murray Gell-Mann

”The interpretation of the new particles as displaced charge multiplets”
– Gell-Mann’s paper at the 1955 Pisa Conference presented his scheme in a final form. New quantum number ‘strangeness’ was oficially introduced (but used in talks since September 1953)

Kazuhiko Nishijima

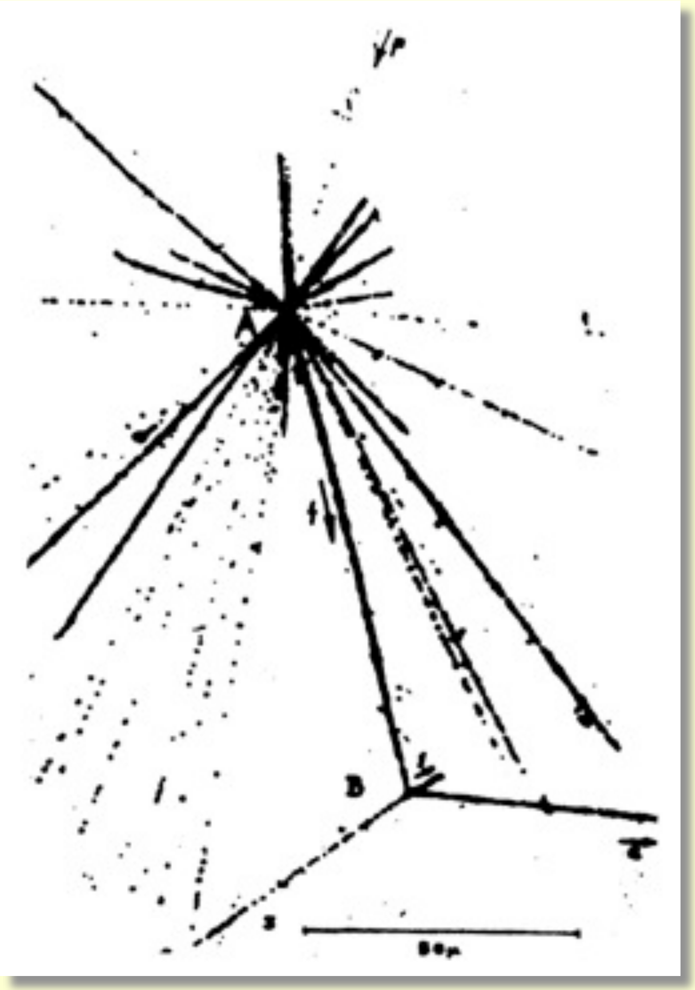
In Japan Nishijima proceeded along similar lines as Gell-Mann and also presented his results in the years 1953-1955; but his papers published in Japanese *Progress in Theoretical Physics* had less impact than Gell-Mann’s

Gell-Mann

"Strange particles...were not considered respectable, especially among the theorists. I am told… that when he wrote his excellent paper on the decay of the tau particle into three pions Dalitz was warned that it might adversely affect his career, because he would be known as the sort of person who worked on that kind of things."

"Pion physics was indeed the central topic for theoretical physics in the mid 1950s, and that was what the young theoretician was expected to work on. The strange particles were considered generally to be an obscure and uncertain area of phenomena, as some kind of dirt effect which could not have much role to play in the nuclear forces, whose comprehension was considered to be the purpose of our research."

Dalitz



First hypernucleus found in 1952 by Marian Danysz and Jerzy Pniewski

Proliferation of strange particles

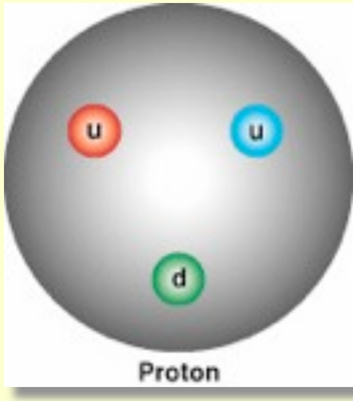
K^0 K^+ K^- Λ Σ^+ Σ^0 Σ^- Ξ^0 Ξ^- Ω^- (weakly decaying)
and numerous ”resonances” (strongly decaying)

1956 Shoichi Sakata model

1961 Murray Gell-Mann; Yuval Ne’eman - SU(3) group symmetry model ”The Eightfold Way”

1964 Murray Gell-Mann (quarks); George Zweig (aces)

1964-65 Oscar Greenberg, Yoichiro Nambu, Moo-Young Han - coloured quarks



A SCHEMATIC MODEL OF BARYONS AND MESONS *

M. GELL-MANN
California Institute of Technology, Pasadena, California

Received 4 January 1964

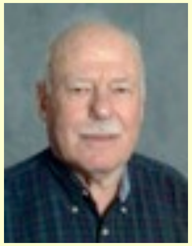
If we assume that the strong interactions of baryons and mesons are correctly described in terms of the broken "eightfold way" [1-3], we are tempted to look for some fundamental explanation of the situation. A highly promised approach is the purely dynamical "bootstrap" model for all the strongly interacting particles within which one may try to derive isotopic spin and strangeness conservation and broken eightfold symmetry from self-consistency alone [4]. Of course, with only strong interactions, the orientation of the asymmetry in the unitary space cannot be specified; one hopes that in some way the selection of specific components of the F-spin by electromagnetism and the weak interactions determines the choice of isotopic spin and hypercharge directions.

Even if we consider the scattering amplitudes of strongly interacting particles on the mass shell only and treat the matrix elements of the weak, electromagnetic, and gravitational interactions by means

ber $n_t - n_{\bar{t}}$ would be zero for all known baryons and mesons. The most interesting example of such a model is one in which the triplet has spin $\frac{1}{2}$ and $z = -1$, so that the four particles d^-, s^-, u^0 and b^0 exhibit a parallel with the leptons.

A simpler and more elegant scheme can be constructed if we allow non-integral values for the charges. We can dispense entirely with the basic baryon b if we assign to the triplet t the following properties: spin $\frac{1}{2}$, $z = -\frac{1}{3}$, and baryon number $\frac{1}{3}$. We then refer to the members $u^{\frac{2}{3}}$, $d^{-\frac{1}{3}}$, and $s^{-\frac{1}{3}}$ of the triplet as "quarks" [6] q and the members of the anti-triplet as anti-quarks $\bar{q}$. Baryons can now be constructed from quarks by using the combinations $(q\,q\,q)$, $(q\,q\,q\,q\,\bar{q})$, etc., while mesons are made out of $(q\,\bar{q})$, $(q\,q\,\bar{q}\,\bar{q})$, etc. It is assuming that the lowest baryon configuration $(q\,q\,q)$ gives just the representations **1**, **8**, and **10** that have been observed, while the lowest meson configuration $(q\,\bar{q})$ similarly gives just **1** and **8**.

“The paper proposing the existence of quarks was accepted by *Physics Letters* only because it had Gell-Mann’s name on it. The editor said, ‘The paper looks crazy but if I accept it and it is nonsense, everyone will blame Gell-Mann and not *Physics Letters*. If I reject it and it turns out to be right, I will be ridiculed’ ”



Harry Lipkin (1997)

“The establishment prejudice against quarks even created serious difficulties for obtaining appointments and promotions for young people in our group. Deans and committees were influenced by pejorative comments in letters from well-known physicists about people who rush into print with such garbage.”

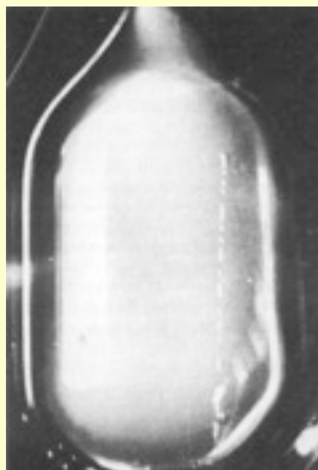
Harry Lipkin (1997)

On quarks in 1970

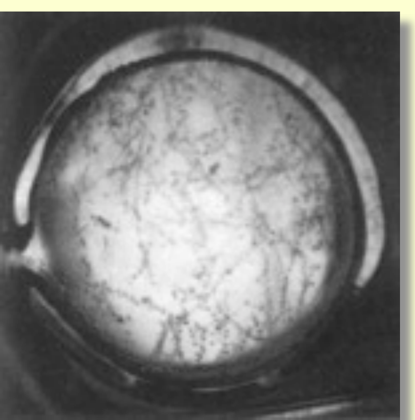
„The [quark] model came after the use of SU(3) and SU(6) groups. For the applicability of these groups **it is of course not necessary at all that quarks or the quark model should exist. Nor can one with absolute certainty say that quarks cannot exist. From the way they make up the hadrons it is seen that it would be highly unusual, if the quarks actually did exist.**"

A. Barut, Rapporteur's talk at the XVth International Conference on High Energy Physics, Kiev, 1970,

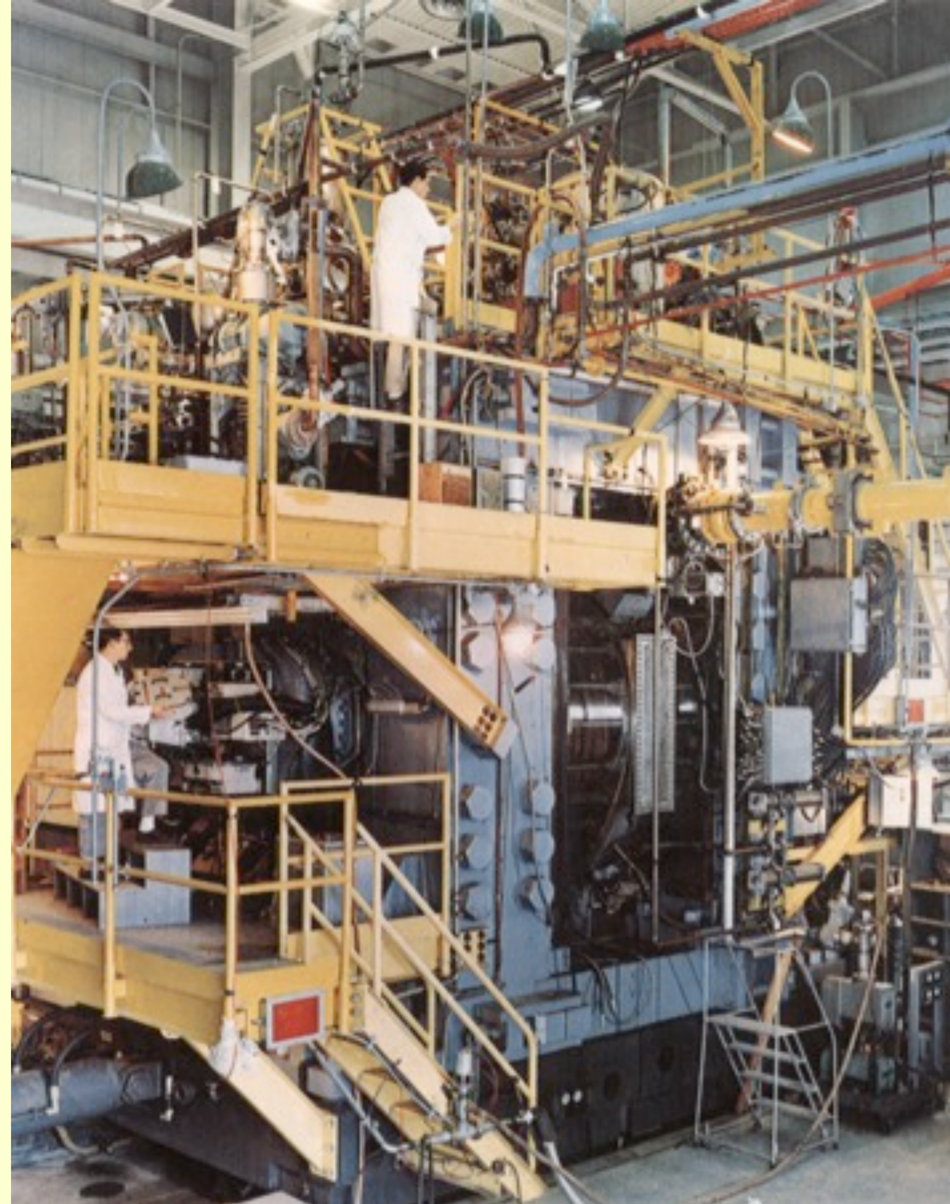
Donald
Glaser



Glaser's first
bubble
chamber

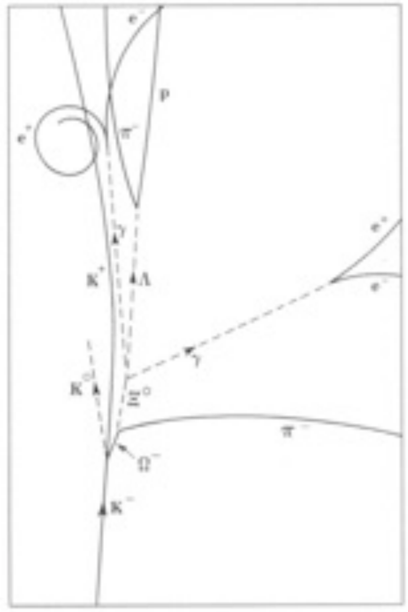


Tracks in 3.5 cm
hydrogen
bubble chamber
1954



80 inch BNL hydrogen
bubble chamber 1965

The Ω^- hyperon



A spectacular confirmation of Gell-Mann's prediction

PHYSICAL REVIEW VOLUME 104, NUMBER 1 OCTOBER 1, 1956

Question of Parity Conservation in Weak Interactions*

T. D. LEE, *Columbia University, New York, New York*

AND

C. N. YANG,† *Brookhaven National Laboratory, Upton, New York*

(Received June 22, 1956)

The question of parity conservation in β decays and in hyperon and meson decays is examined. Possible experiments are suggested which might test parity conservation in these interactions.

RECENT experimental data indicate closely identical masses[1] and lifetimes[2] of the $\theta^+(\equiv K_{\pi 2}^+)$ and the $\tau^+(\equiv K_{\pi 3}^+)$ mesons. On the other hand, analyses[3] of the decay products of τ^+ strongly suggest on the grounds of angular momentum and parity conservation that the τ^+ and θ^+ are not the same particle. This poses a rather puzzling situation that has been extensively discussed.[4]

One way out of the difficulty is to assume that parity is not strictly conserved, so that θ^+ and τ^+ are two different decay modes of the same particle, which necessarily has a single mass value and a single lifetime. We wish to analyze this possibility in the present paper against the background of the existing experimental evidence of parity conservation. It will become clear

PRESENT EXPERIMENTAL LIMIT ON PARITY NONCONSERVATION

If parity is not strictly conserved, all atomic and nuclear states become mixtures consisting mainly of the state they are usually assigned, together with small percentages of states possessing the opposite parity. The fractional weight of the latter will be called $\mathfrak{F}^2$. It is a quantity that characterizes the degree of violation of parity conservation.

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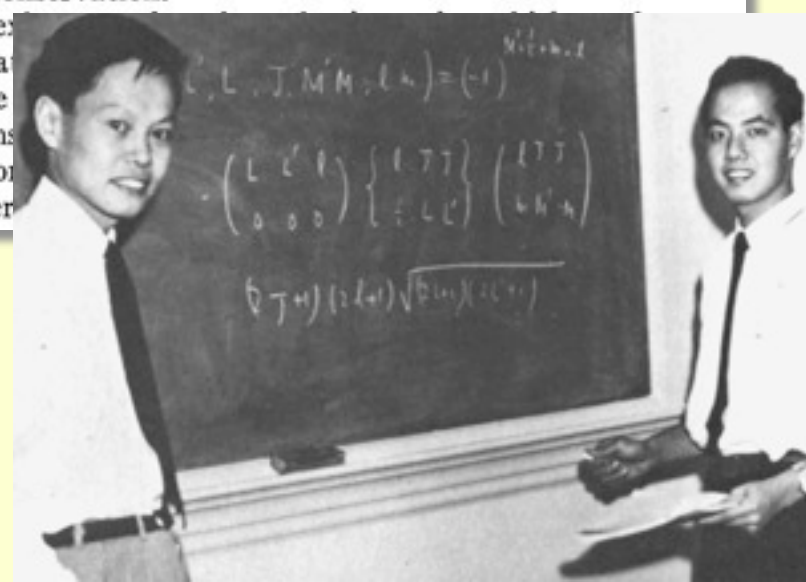
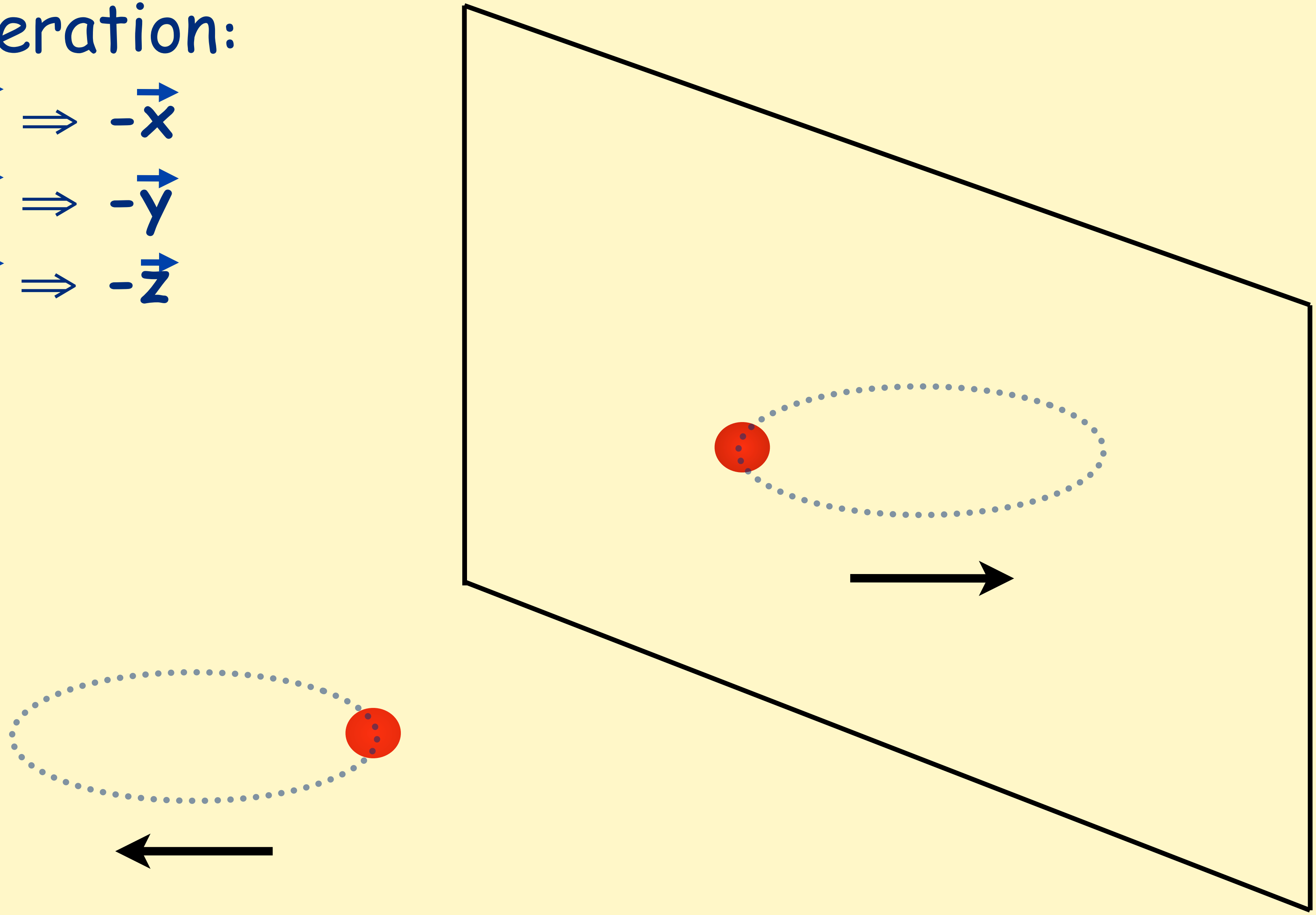
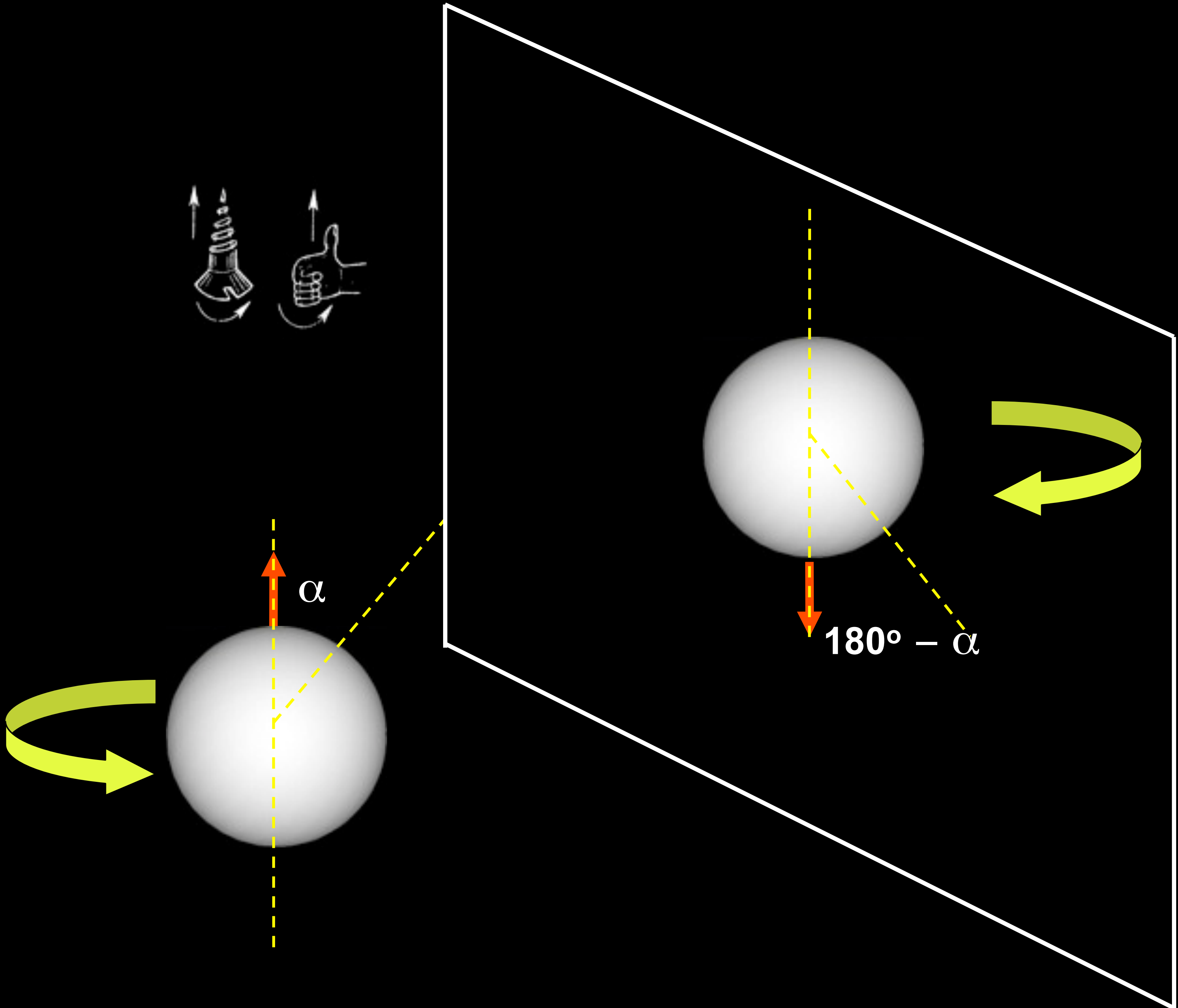


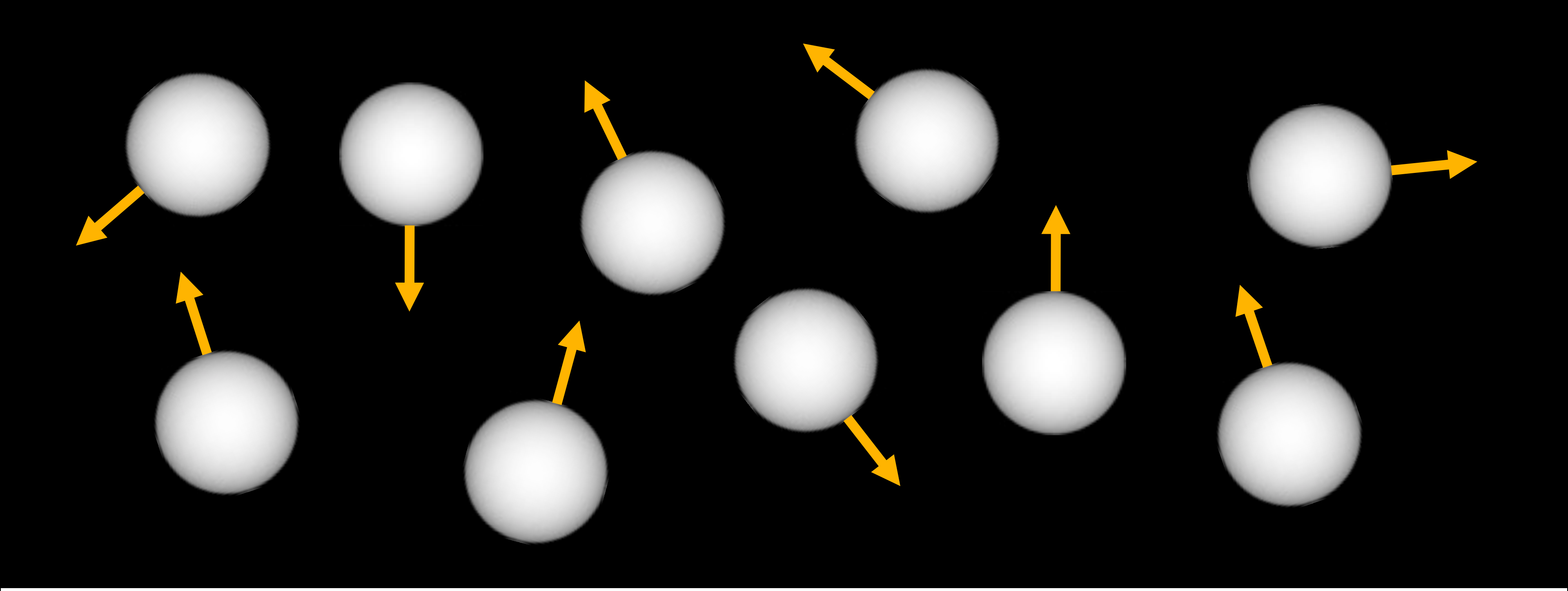
P operation:

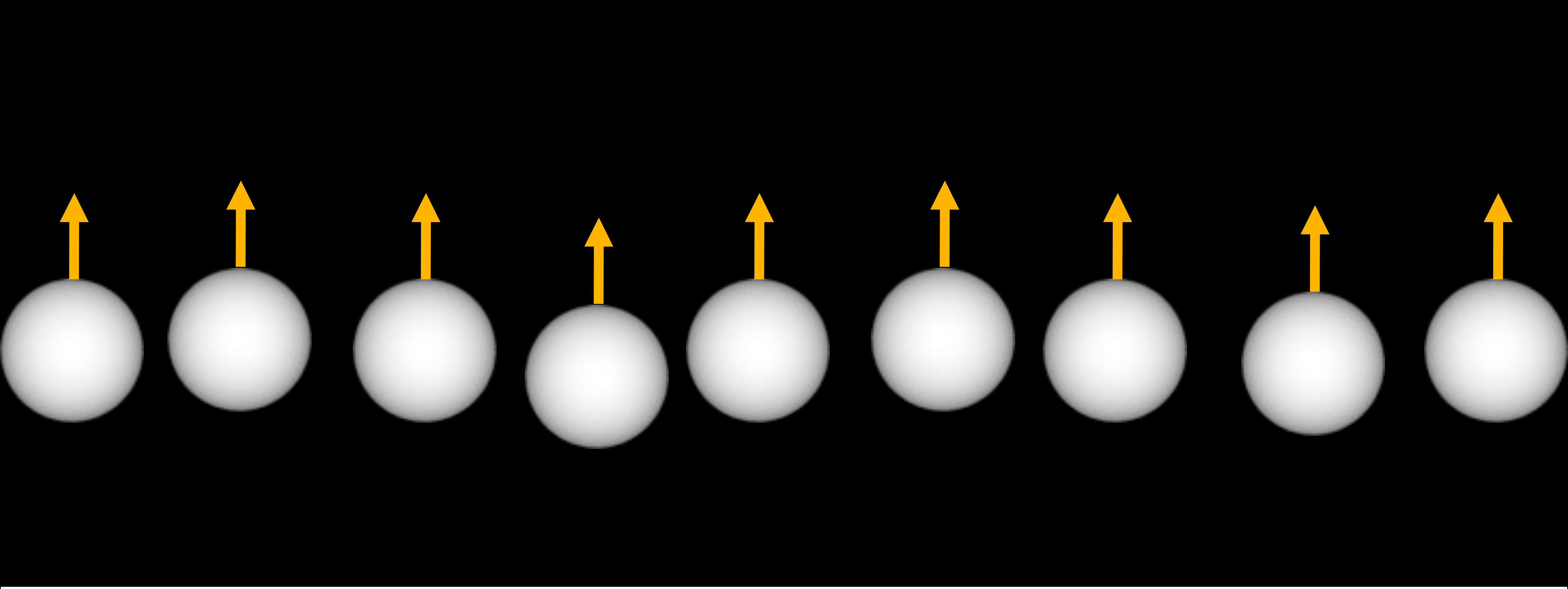
$$\vec{x} \Rightarrow -\vec{x}$$
$$\vec{y} \Rightarrow -\vec{y}$$
$$\vec{z} \Rightarrow -\vec{z}$$



Reflection in a mirror reverses the direction of rotation


α
180° – α





- Minimize thermal motion
- Polarize nuclei
- Cool by adiabatic demagnetization

It took experimenters several months to discover that in radioactive decay emission of electrons at angles α and $(180^{o} - \alpha)$ is <u>different</u>.

Therefore, parity is not conserved in weak interactions !!!

New York Herald Tribune
January 16, 1957

Special press conference
in Columbia University
on January 15,1957,
when articles of two
experimental groups were
submitted to *Physical Review*

Physics 'Principle' Wrong, Mirror Reflection Not True

Experimenters Demolish 'Law' After 30 Years

By Earl Ubell

Nine men and a woman shattered one of the solid pillars of the science of physics yesterday.

They announced at Columbia University that with two experiments they had destroyed one of the most cherished physical laws, one that had stood unmolested for three decades.

Likened by one scientist to Einstein's discovery of the theory of relativity, the achievement opens the way to a whole new set of explanations of the atom, the world and the cosmos.

The scientists, in what was called the most important development in physics in ten years, left in tatters the so-called "principle of parity," which had as high a standing as the law of conservation of mass and energy.

Landmark Demolished

Physicists had used this principle as a searchlight into the tangled jungle of the atom. It enabled them to manipulate their equations with carefree abandon to predict atomic behavior. All the experiments had supported its truth. Now it is gone.

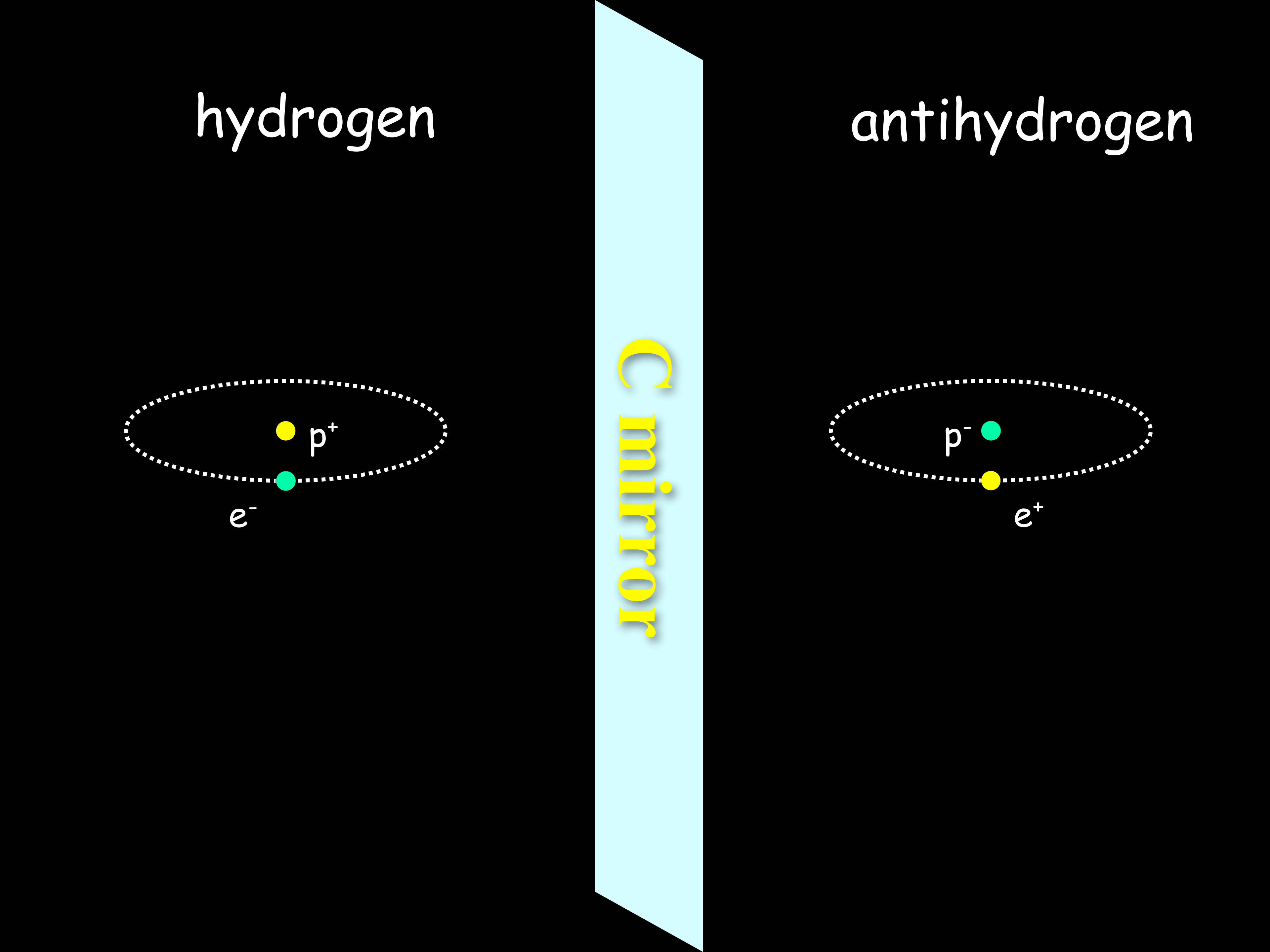
The principle of parity told physicists what had been "obvious to common sense" for a long time: that phenomena of nature look the same whether observed directly or through a mirror, except that right and left are reversed. This makes it

Herald Tribune photo by Ira Rosenberg

Associate Prof. Chien Shiung Wu at Columbia yesterday.

atomic particle, a so-called k-meson, which is torn loose from the heart of an atom by

The other test involved Columbia's 385,000,000-volt cyclotron at Nevis, N. Y. This


hydrogen
antihydrogen
C mirror
p+
e−
p−
e+

For seven years 1957-1964 physicists were convinced that CP conservation was the correct answer

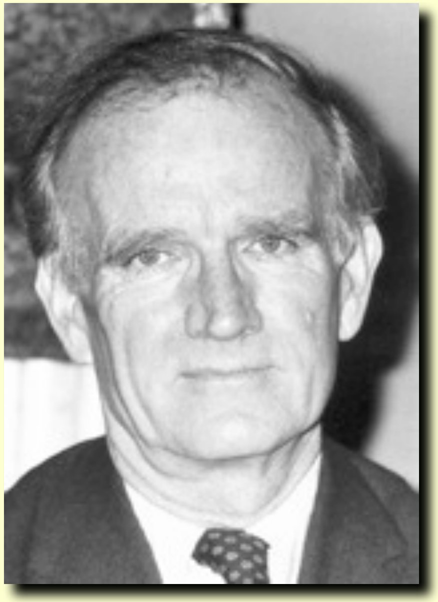
The discovery of CP non-conservation took everybody by surprise

Non-conservation of CP discovered !

In decays of neutral K-mesons positive electrons are emitted **more often** than negative electrons

$$\frac{(K_L^0 \rightarrow \pi^- e^+ \nu)}{(K_L^0 \rightarrow \pi^+ e^- \overline{\nu})} \cong 1{,}0067$$

James W. Cronin



Val L. Fitch

Nobel Prize in Physics (1980) ”for the discovery of violations of fundamental symmetry principles in the decay of neutral K mesons”

Non-conservation of CP

↓

The **absolute difference** between matter and antimatter was discovered

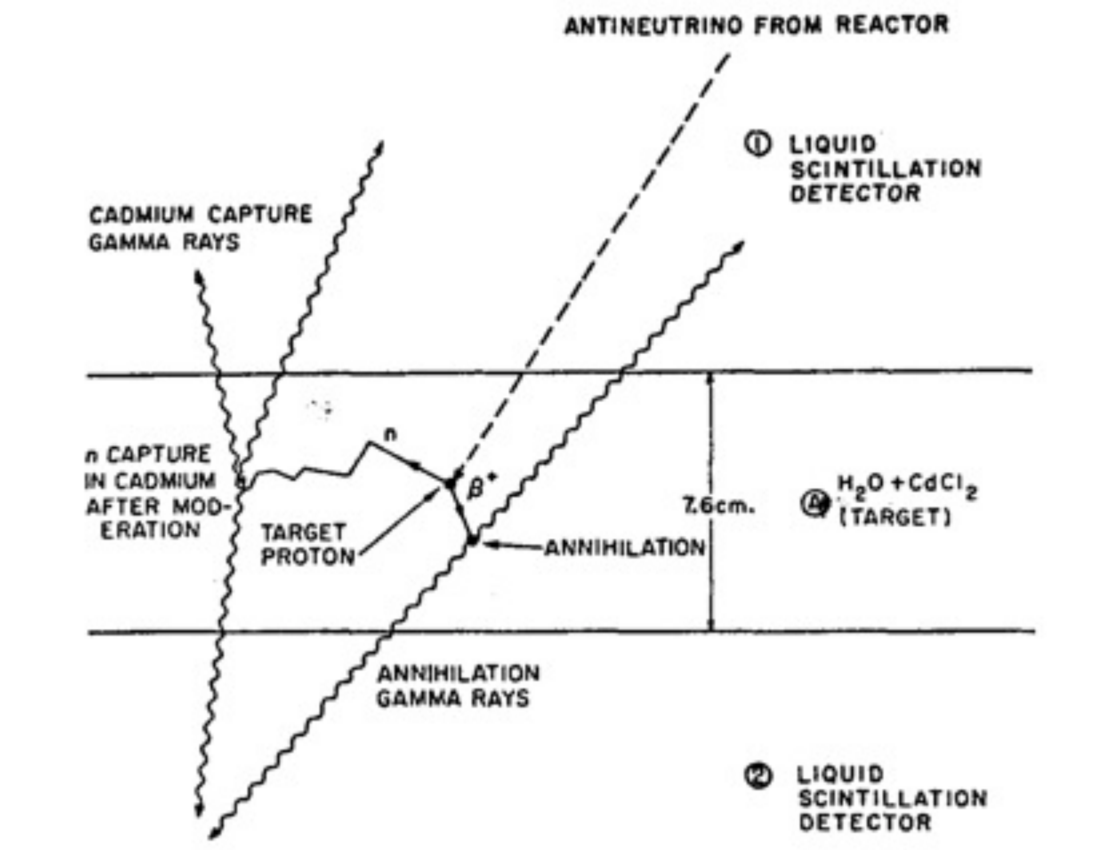
The neutrino

"There is practically no possible way of observing the neutrino"
Bethe and Peierls, Nature, April 1934

The Reines-Cowan experiment at Savannah River reactor

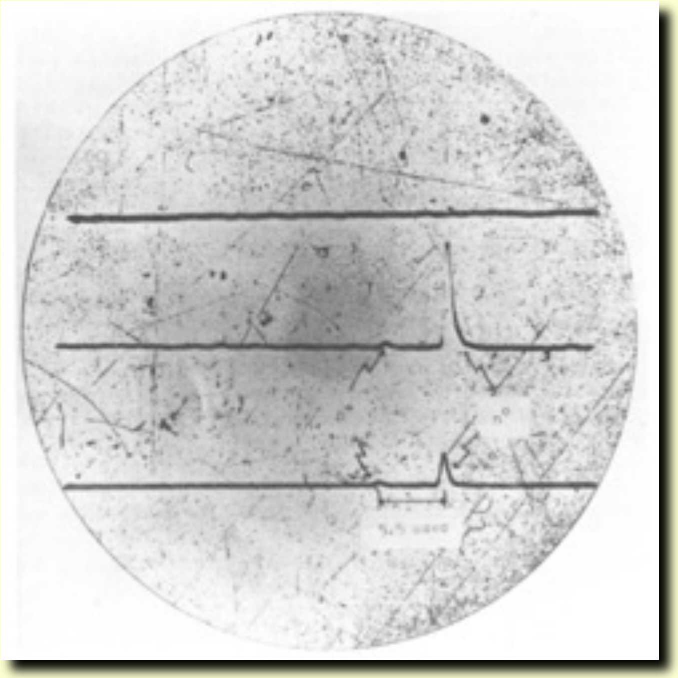
Fred Reines and Clyde Cowan

The 4500 litre tank
with liquid scintillator



Scheme of antineutrino detection experiment.

The Reines - Cowan experiment



The detection signal of inverse β- decay

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

Reines and Cowan telegram
to Pauli on 14 June, 1956

WESTERN UNION

To Professor W. Pauli 14 June 1956
Zurich University
Switzerland

We are happy to inform you that we have definitely detected neutrinos from fission fragments by observing inverse beta decay of protons. Observed cross section agrees well with expected six times ten to minus forty-four square centimeters.

Frederick Reines Clyde Cowan
Box 1663 Los Alamos, New Mex

"We are happy to inform you that we have definitely detected neutrinos from fission fragments by observing inverse beta decay of protons. Observed cross section agrees well with expected six times ten to minus forty-four square centimeters."

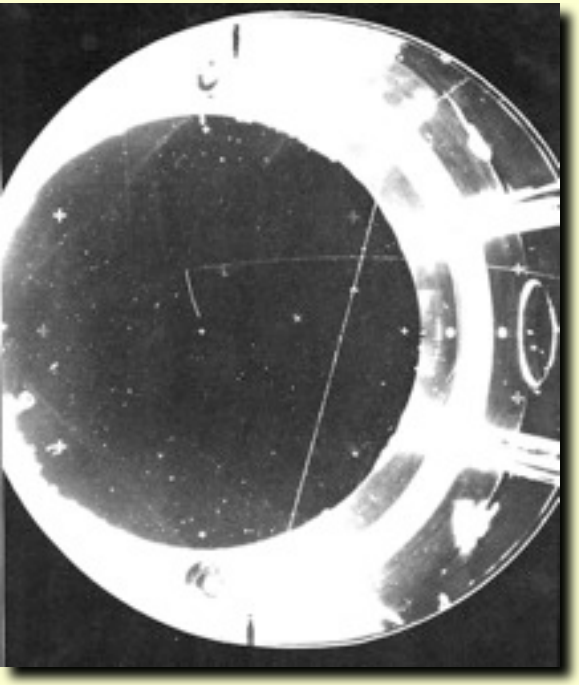
Discovery of the second neutrino (1962)

Lack of the decay $\mu \rightarrow e + \gamma$ allowed by other conservation laws suggested two neutrinos

Leon Lederman

Melvin Schwartz

Jack Steinberger

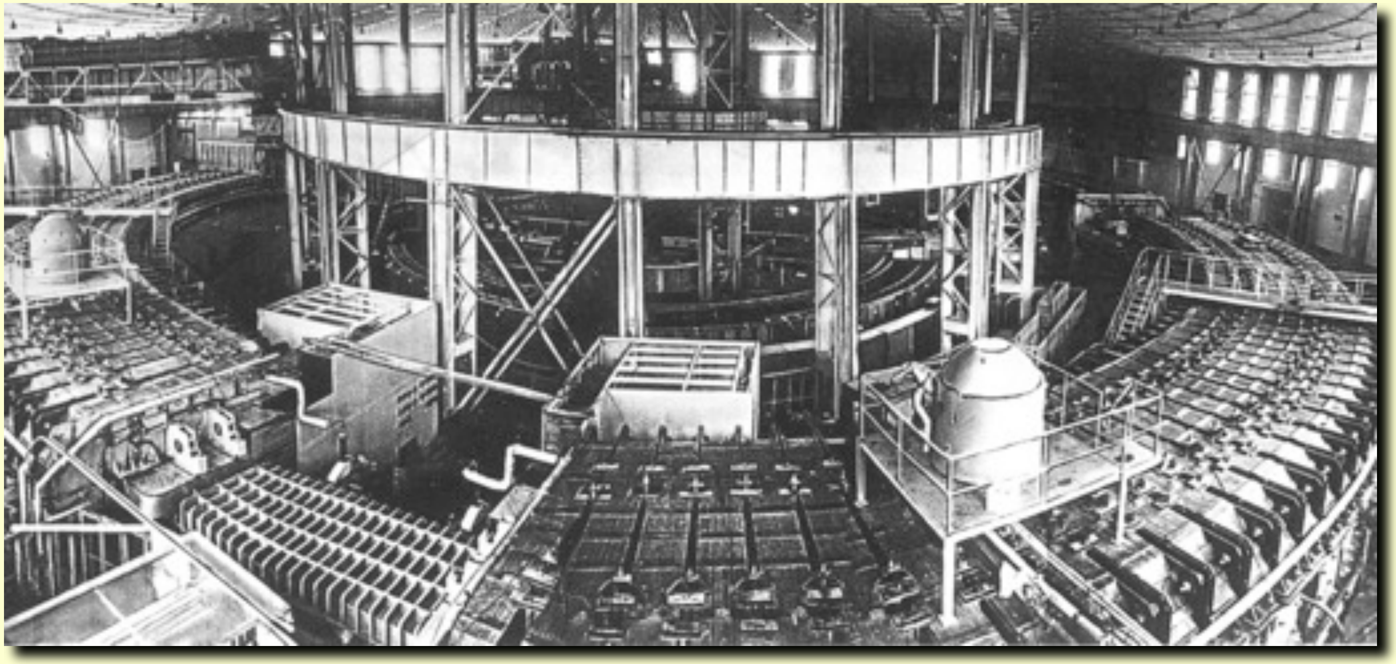


Neutrino from pion decay <u>different</u> from neutrino from nuclear beta decay

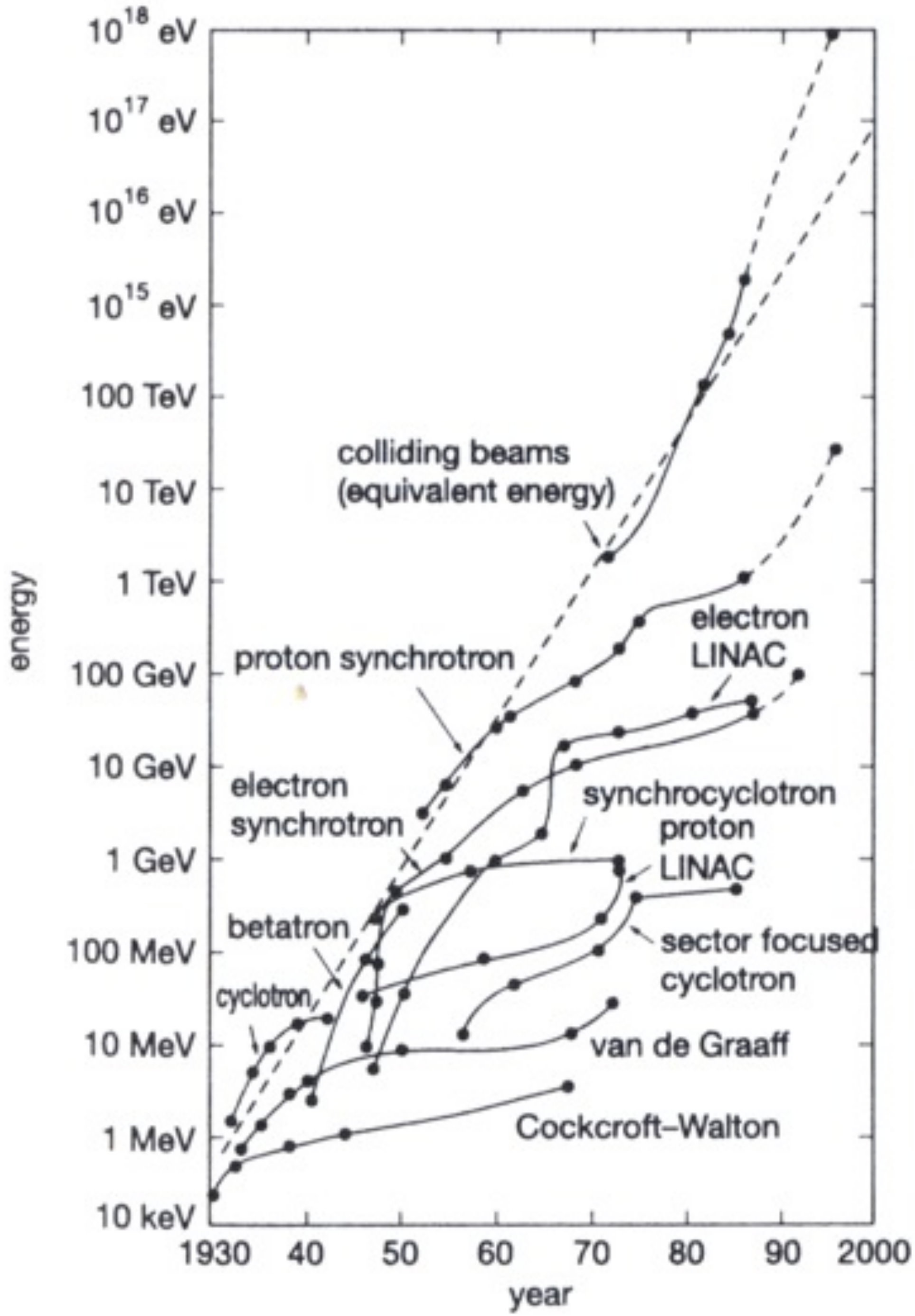
Proton synchrotrons

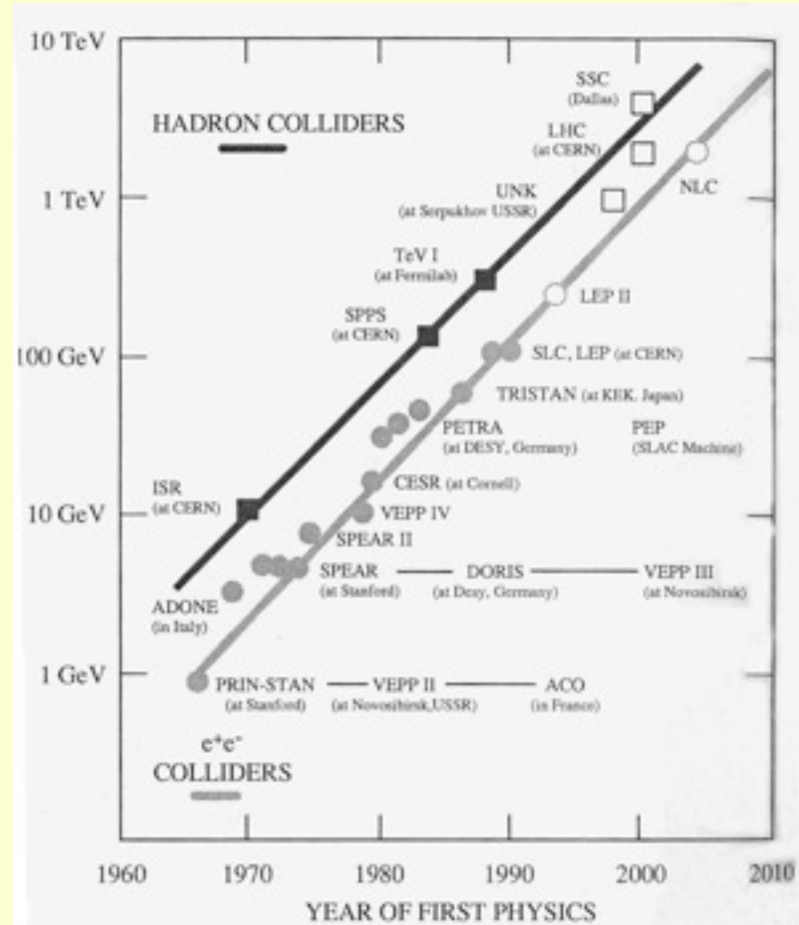
Cosmotron (3 GeV)
in BNL 1952

Bevatron (6 GeV)
in LBL 1954

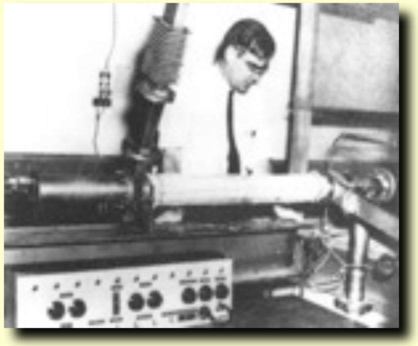


10 GeV proton synchrotron in Dubna
weak focusing, magnet of 36,000 tonnes





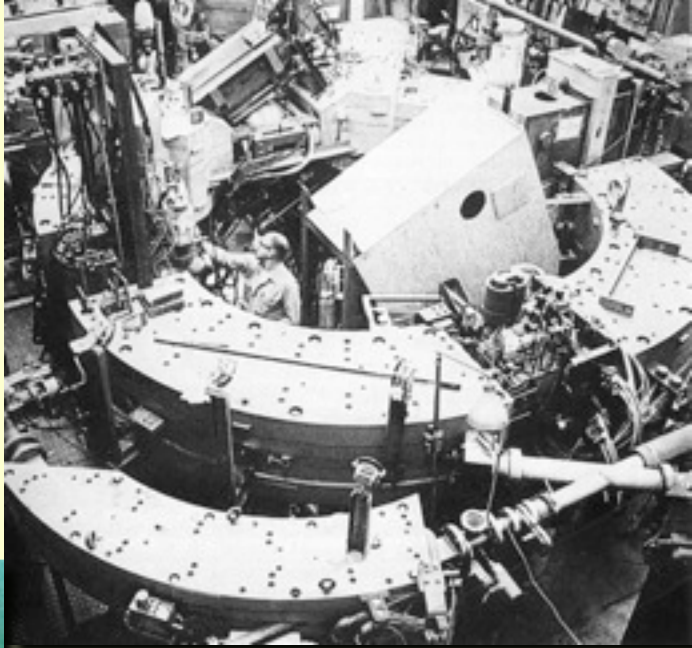
Livingston’s plot

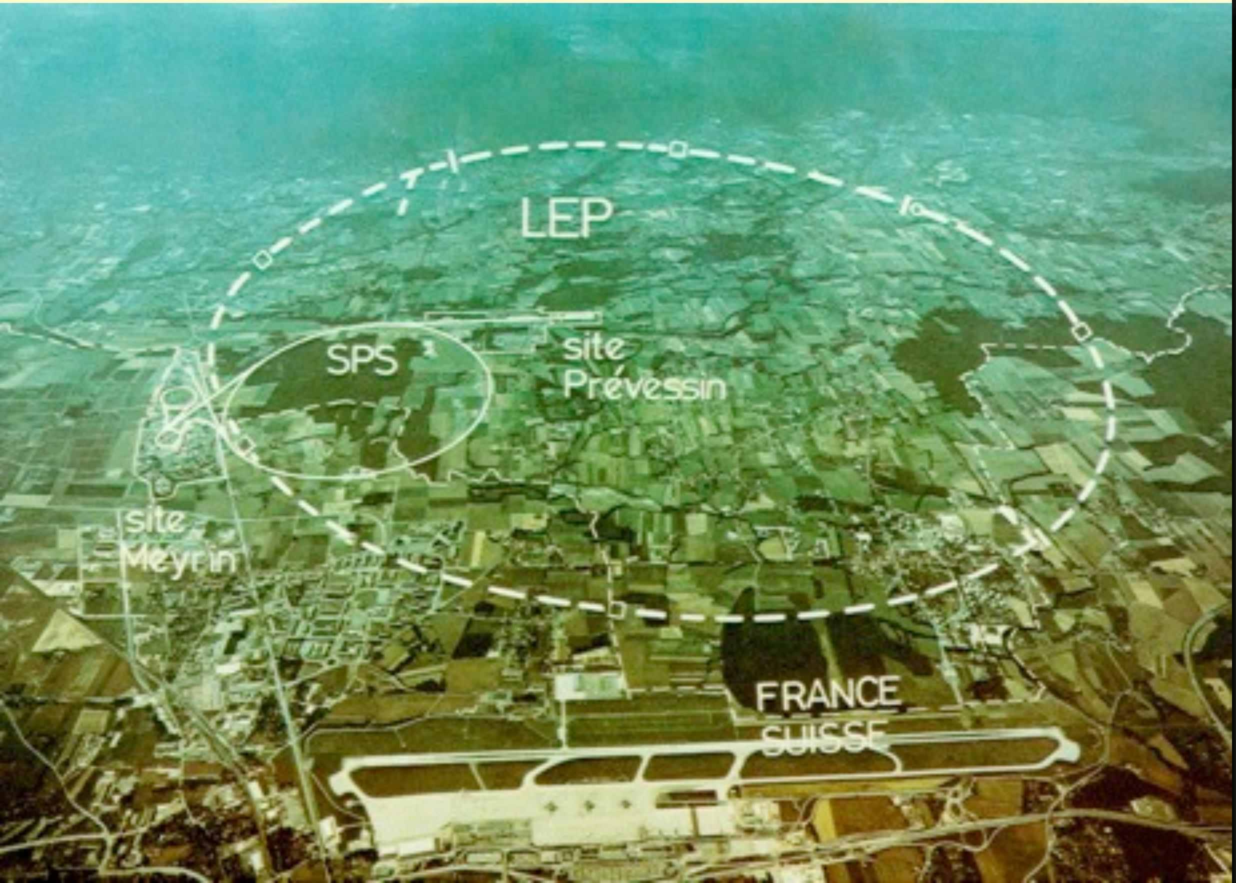


The first linear electron accelerator built by William Hansen at Stanford in 1947 (length 3.6 m, energy 6 GeV)

3 km linear accelerator at SLAC (energy 30 GeV)

First storage ring for electrons
(colliding beams accelerator)
at Stanford
Princeton-Stanford team (1965)





European Laboratory of Particle Physics (CERN)

Observation of Antiprotons*

Owen Chamberlain, Emilio Segrè, Clyde Wiegand, and Thomas Ypsilantis

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

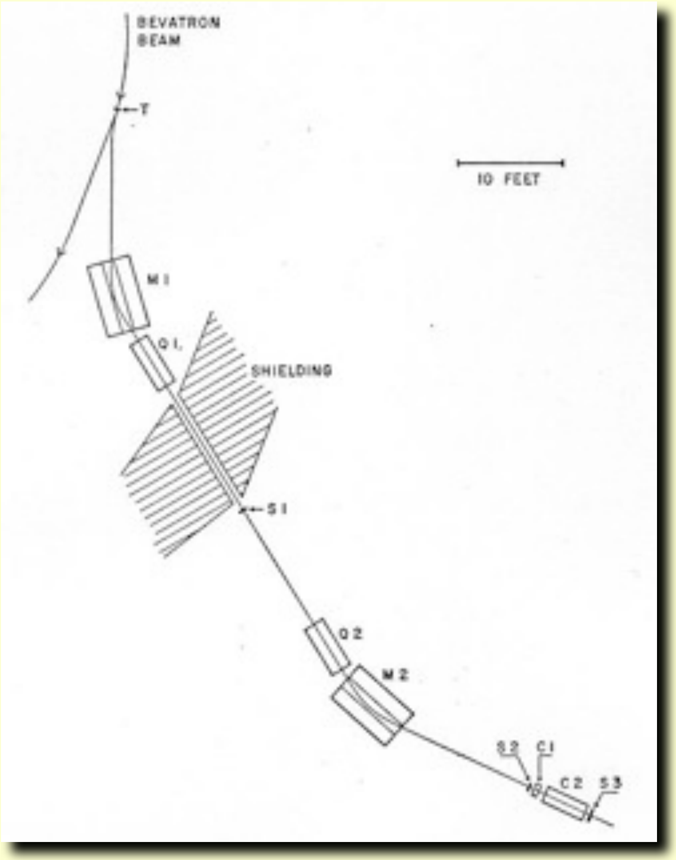
(Received October 24, 1955)

ONE of the striking features of Dirac's theory of the electron was the appearance of solutions to his equations which required the existence of an antiparticle, later identified as the positron.

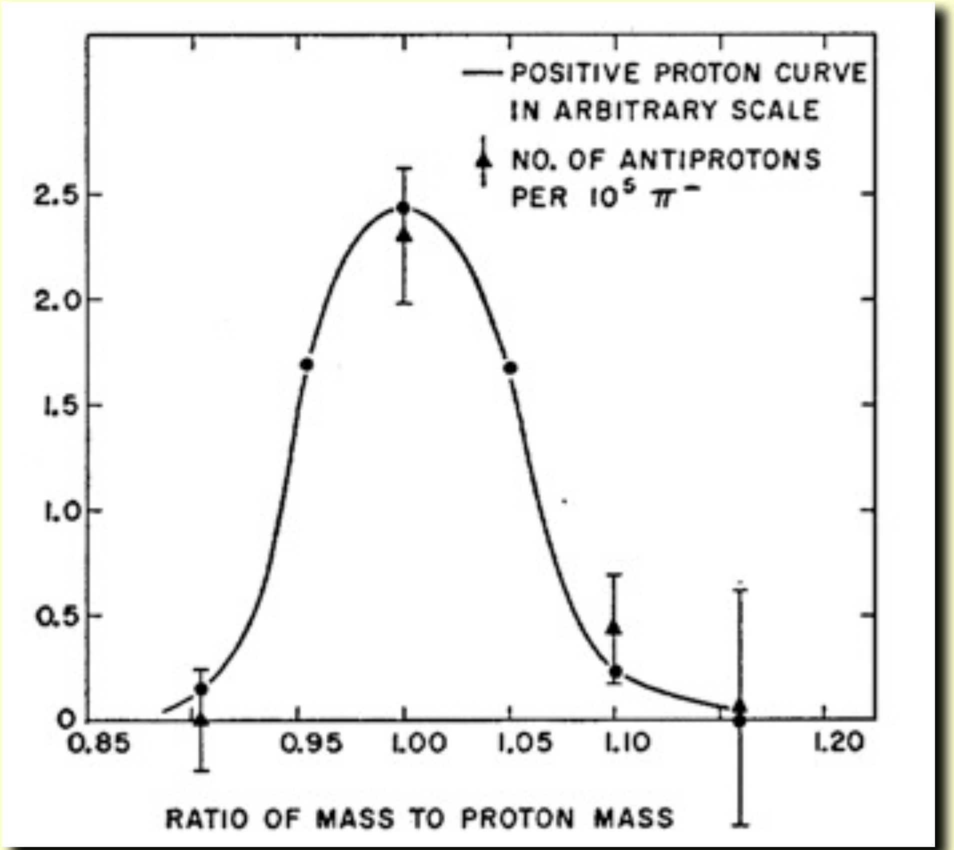
The extension of the Dirac theory to the proton requires the existence of an antiproton, a particle which bears to the proton the same relationship as the positron to the electron. However, until experimental proof of the existence of the antiproton was obtained, it might be questioned whether a proton is a Dirac particle in the same sense as is the electron. For instance, the anomalous magnetic moment of the proton indicates that the simple Dirac equation does not give a complete description of the proton.

The experimental demonstration of the existence of antiprotons was thus one of the objects considered in the planning of the Bevatron. The minimum laboratory kinetic energy for the formation of an antiproton in a nucleon-nucleon collision is 5.6 Bev. If the target nucleon is in a nucleus and has some momentum, the

The discoverers of the antiproton

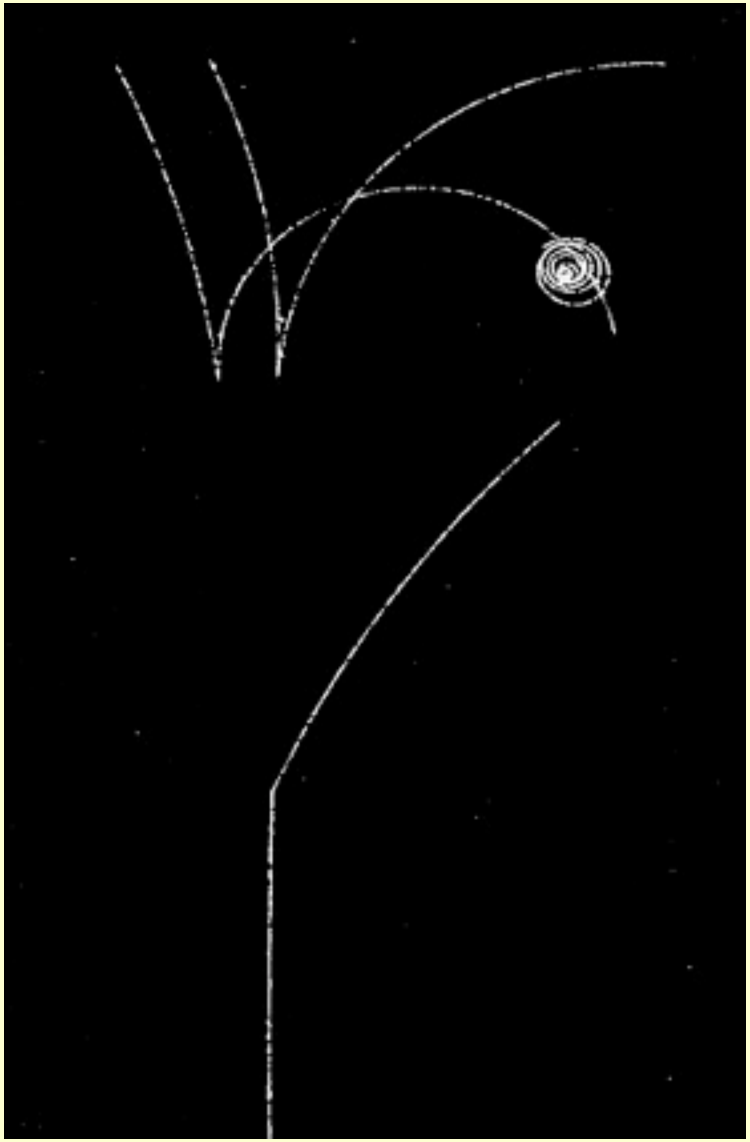


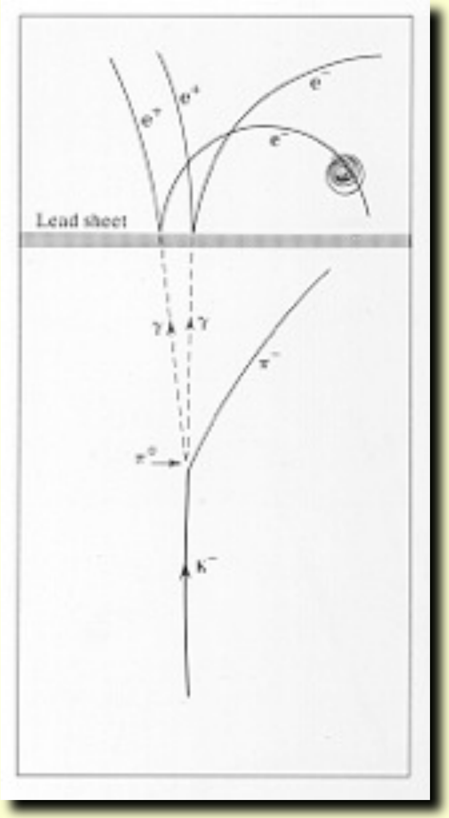
Beam and detectors



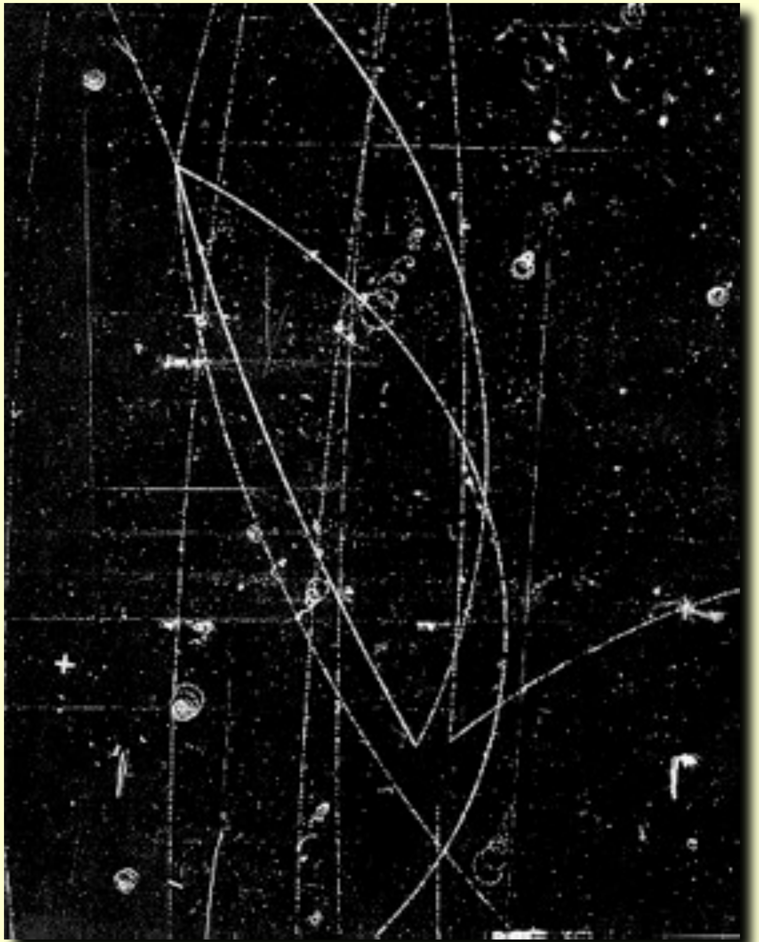
Measurement of antiproton mass

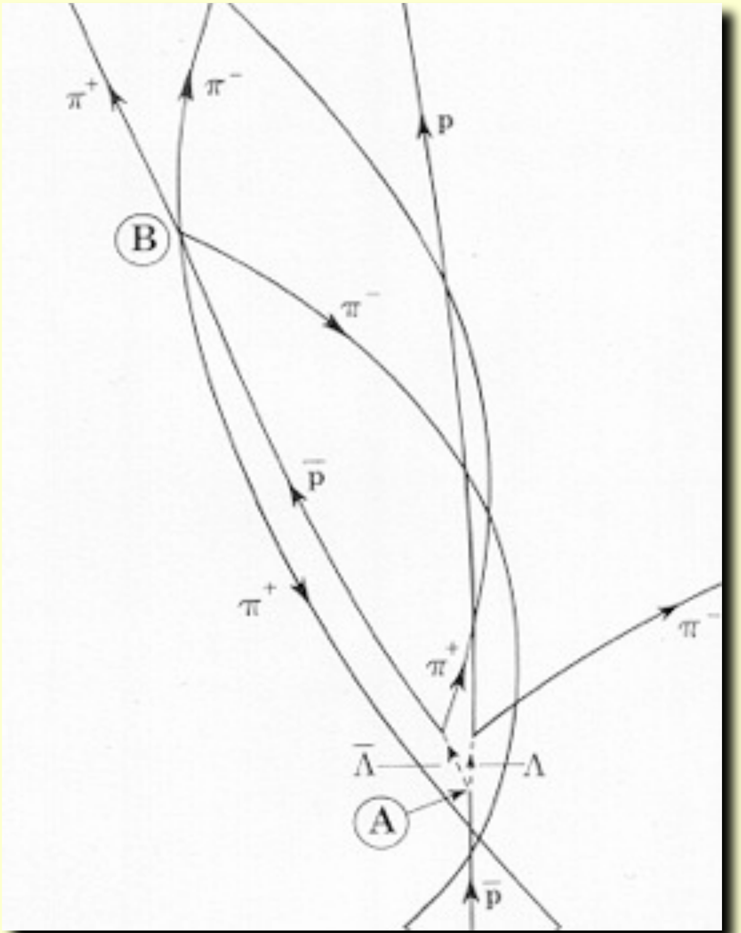
Electron-positron pair production





$$\bar{p} + p \rightarrow \bar{\Lambda} + \Lambda$$





Production of antihydrogen

G. Baur [a], G. Boero [b], S. Brauksiepe [a], A. Buzzo [b], W. Eyrich [c], R. Geyer [a], D. Grzonka [a], J. Hauffe [c], K. Kilian [a], M. LoVetere [b], M. Macri [b], M. Moosburger [c], R. Nellen [a], W. Oelert [a], S. Passaggio [b], A. Pozzo [b], K. Röhrich [a], K. Sachs [a], G. Schepers [e], T. Sefzick [a], R.S. Simon [d], R. Stratmann [d], F. Stinzing [c], M. Wolke [a]

[a] *IKP: Forschungszentrum Jülich GmbH, Germany*
[b] *Genoa University and INFN, Italy*
[c] *PI, Universität Erlangen–Nürnberg, Germany*
[d] *GSI Darmstadt, Germany*
[e] *IKP, Universität Münster, Germany*

Received 8 December 1995; revised manuscript received 21 December 1995
Editor: L. Montanet

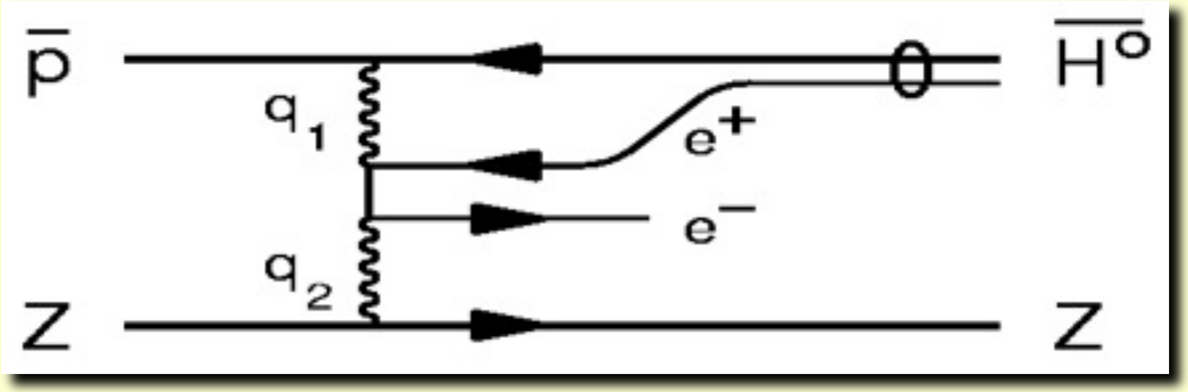
Abstract

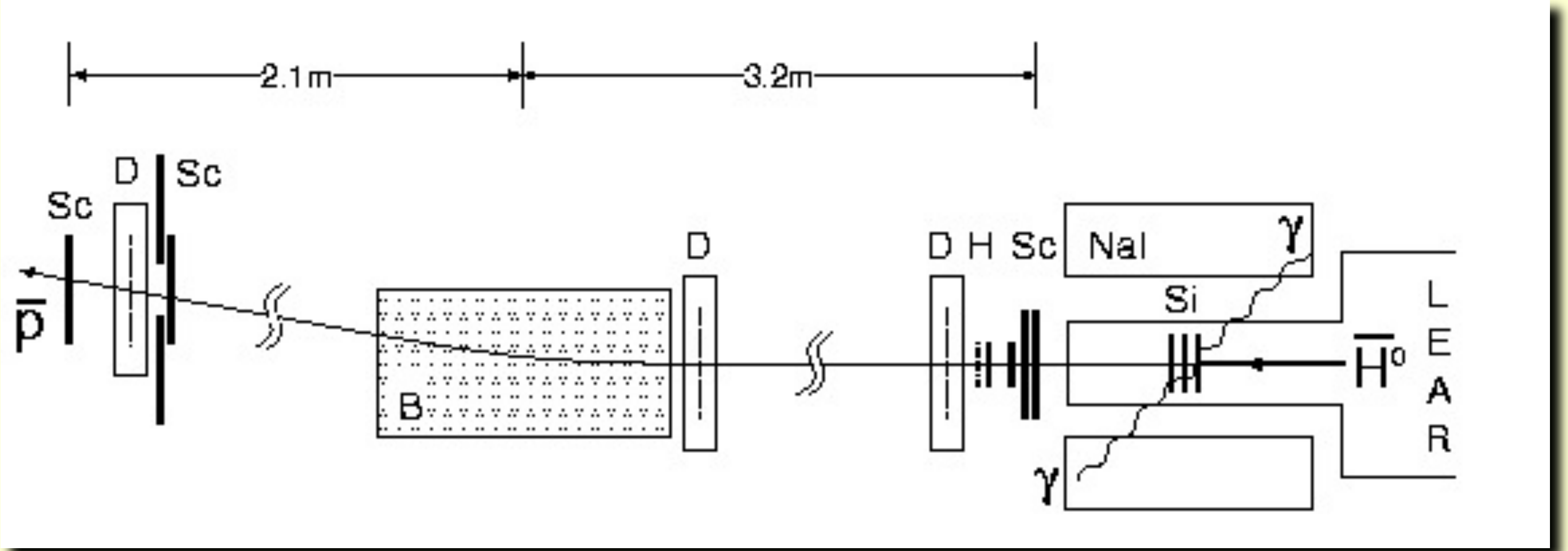
Results are presented for a measurement for the production of the antihydrogen atom $\overline{H}^0 \equiv \bar{p}e^+$, the simplest atomic bound state of antimatter.

A method has been used by the PS210 collaboration at LEAR which assumes that the production of $\overline{H}^0$ is predominantly mediated by the e^+e^--pair creation via the two-photon mechanism in the antiproton–nucleus interaction. Neutral $\overline{H}^0$ atoms are identified by a unique sequence of characteristics. In principle $\overline{H}^0$ is well suited for investigations of fundamental CPT violation studies under different forces, however, in our investigations we concentrate on the production of this antimatter object, since so far it has never been observed before.

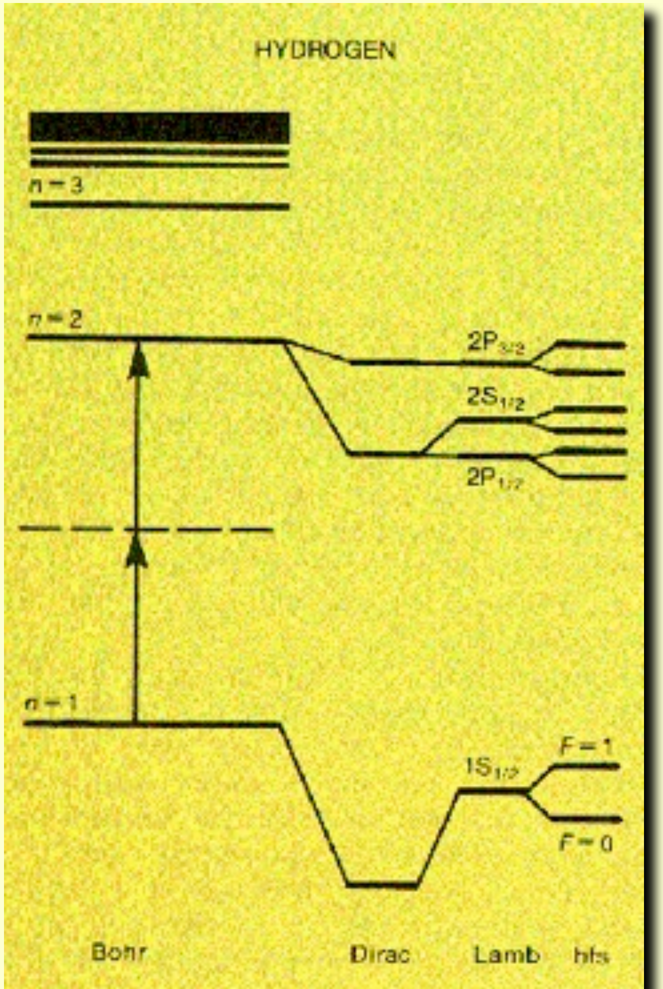
The production of 11 antihydrogen atoms is reported including possibly 2 ± 1 background signals, the observed yield agrees with theoretical predictions.

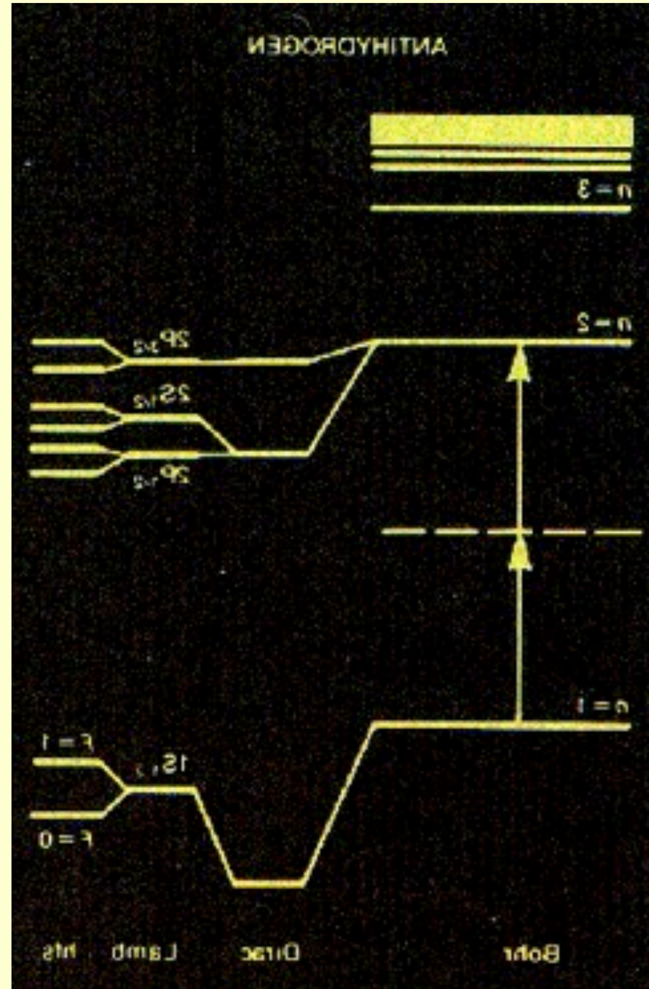
Production of antihydrogen at CERN





Energy levels of hydrogen and antihydrogen





Some milestones in the path to the Standard Model

1954 Yang-Mills gauge-invariant field theory
1956 Discovery of parity violation
1962 Discovery of the second neutrino
1964 Quark model (Gell-Mann, Zweig)
1964-65 Greenberg, Han and Nambu - colour
1964 Higgs mechanism of mass generation
1964 Discovery of the CP violation at BNL
1967 Glashow, Salam and Weinberg electroweak theory
1970 Glashow-Iliopoulos-Maiani - GIM mechanism
1971 ‘t Hooft - renormalizability of gauge theories
1973 Gell-Mann and Fritzsch - chromodynamics
1973 Gross and Wilczek, Politzer - asymptotic freedom
1973 Detection of neutral currents at CERN
1974 Discovery of the *c* quark at BNL and Stanford
1975 Discovery of the third lepton τ at Stanford
1977 Discovery of the *b* quark at FNAL
1979 Discovery of gluons at DESY
1982 Observation of the $W^{\pm}$ boson at CERN*
1983 Observation of the Z^{o} boson at CERN*
1995 Observation of the *t* quark at FNAL*
2012 Discovery of the „Higgs boson” at CERN

* There were earlier ‘discoveries’ of vector bosons and the *t* quark

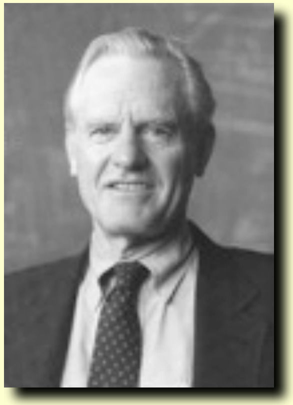
Structure of nucleons

Robert Hofstadter (1954)
measured the charge radius of protons,
neutrons and nuclei

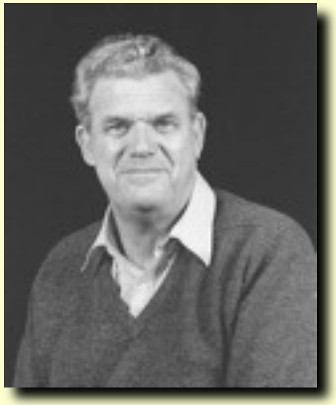
Experiments of deep inelastic scattering of electrons on protons inaugurated at SLAC in1967

Wolfgang Panofsky during the Heidelberg conference (1967):
”One has the impression that nature is trying to tell us something simple that nobody is seeing”

Jerome
Friedman



Henry
Kendall

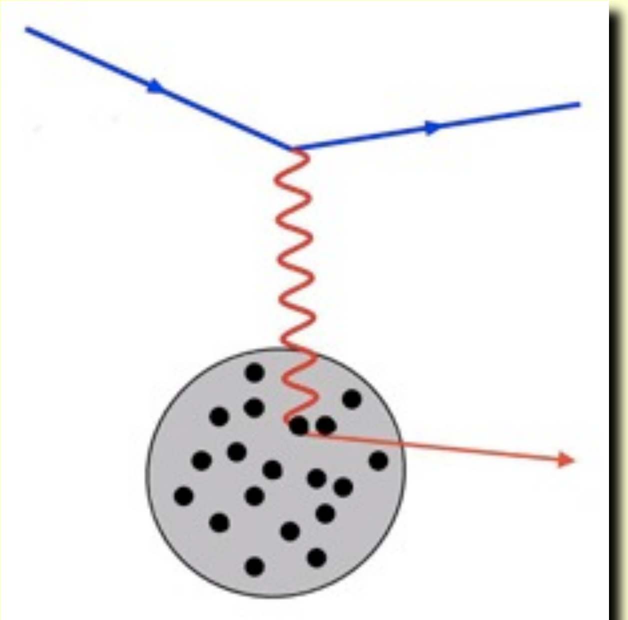


Richard
Taylor

Discovery of the parton structure of nucleons

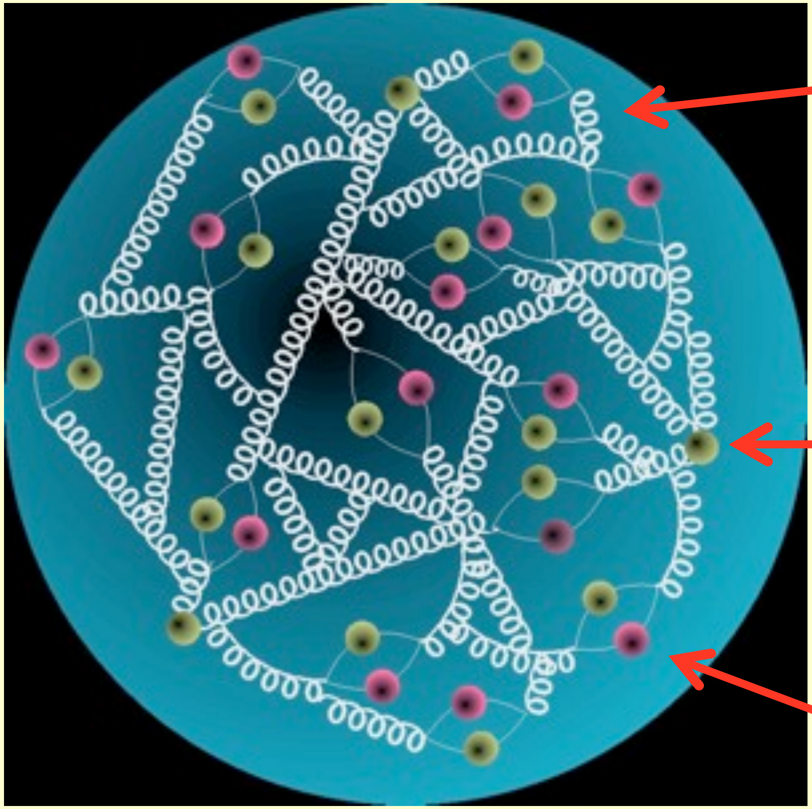
Feynman's parton model

In interactions at very high energies
the proton may be treated as a collection
of non-interacting point particles (partons)



DIS – deep inelastic scattering

”True” picture of the proton



gluon

valence quark

quark-antiquark pair

The unification of electromagnetic and weak interactions

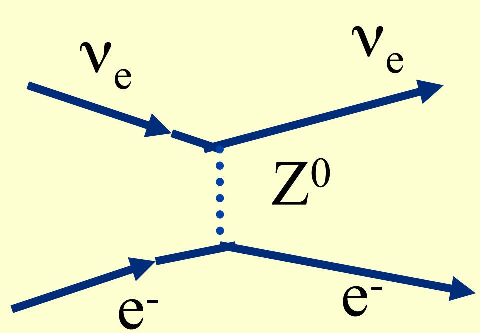
Sheldon Glashow

Abdus Salam

Steven Weinberg

Electroweak interactions are mediated by four intermediate vector bosons: W^+, W^-, Z^o, γ (1967)

Experimental confirmation: discovery of neutral weak currents at CERN by the Gargamelle Collaboration (1973)



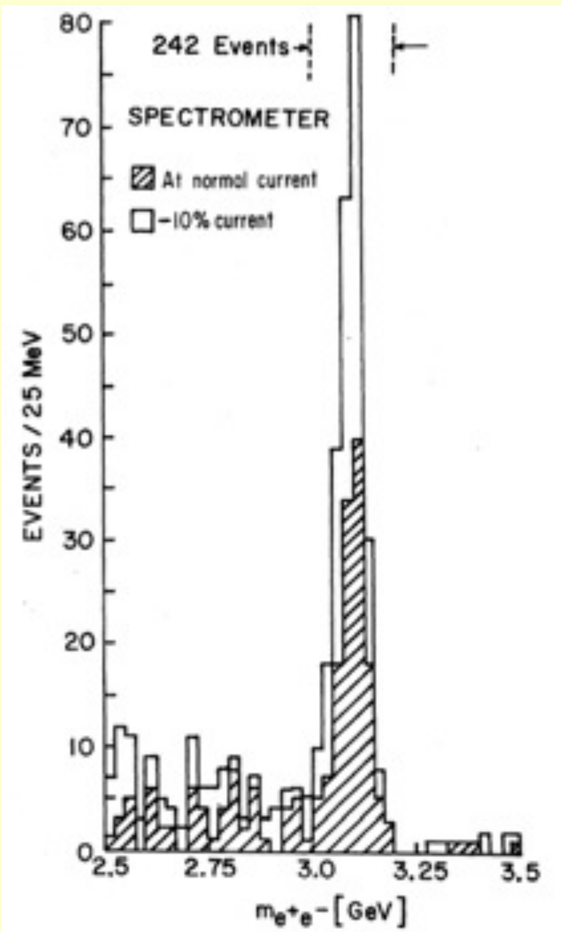
The first NC event

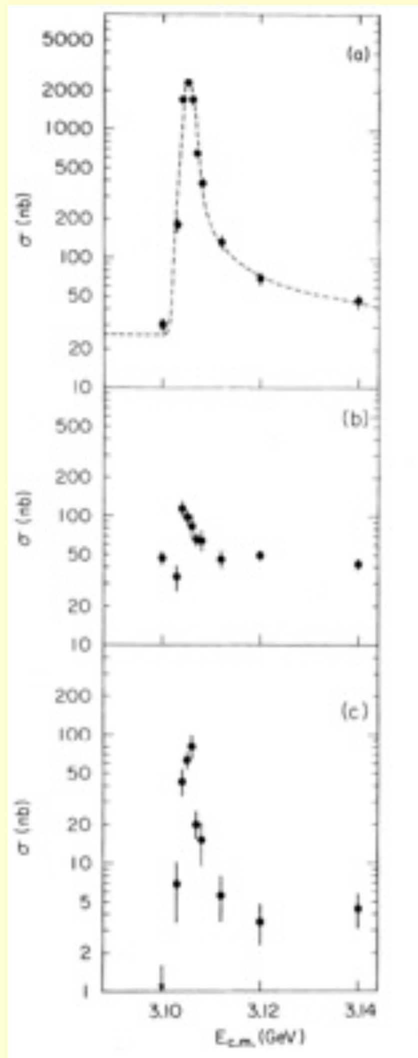
The second generation of quarks and leptons

The ”November revolution” of 1974

Discovery of *J/ψ* particle by teams led by Richter and Ting confirmed the existence of the fourth quark c predicted in 1964 and 1970

BNL





SLAC

Burton Richter

Samuel Ting

The third generation of quarks and leptons

The third generation of quarks
predicted by Kobayashi and Maskawa
(1973)

Makoto
Kobayashi

Toshihide
Maskawa

Martin Perl

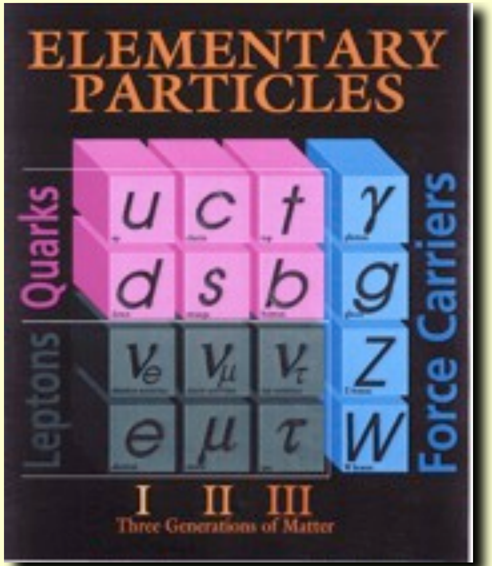
The third lepton τ
discovered by Perl
(1975)

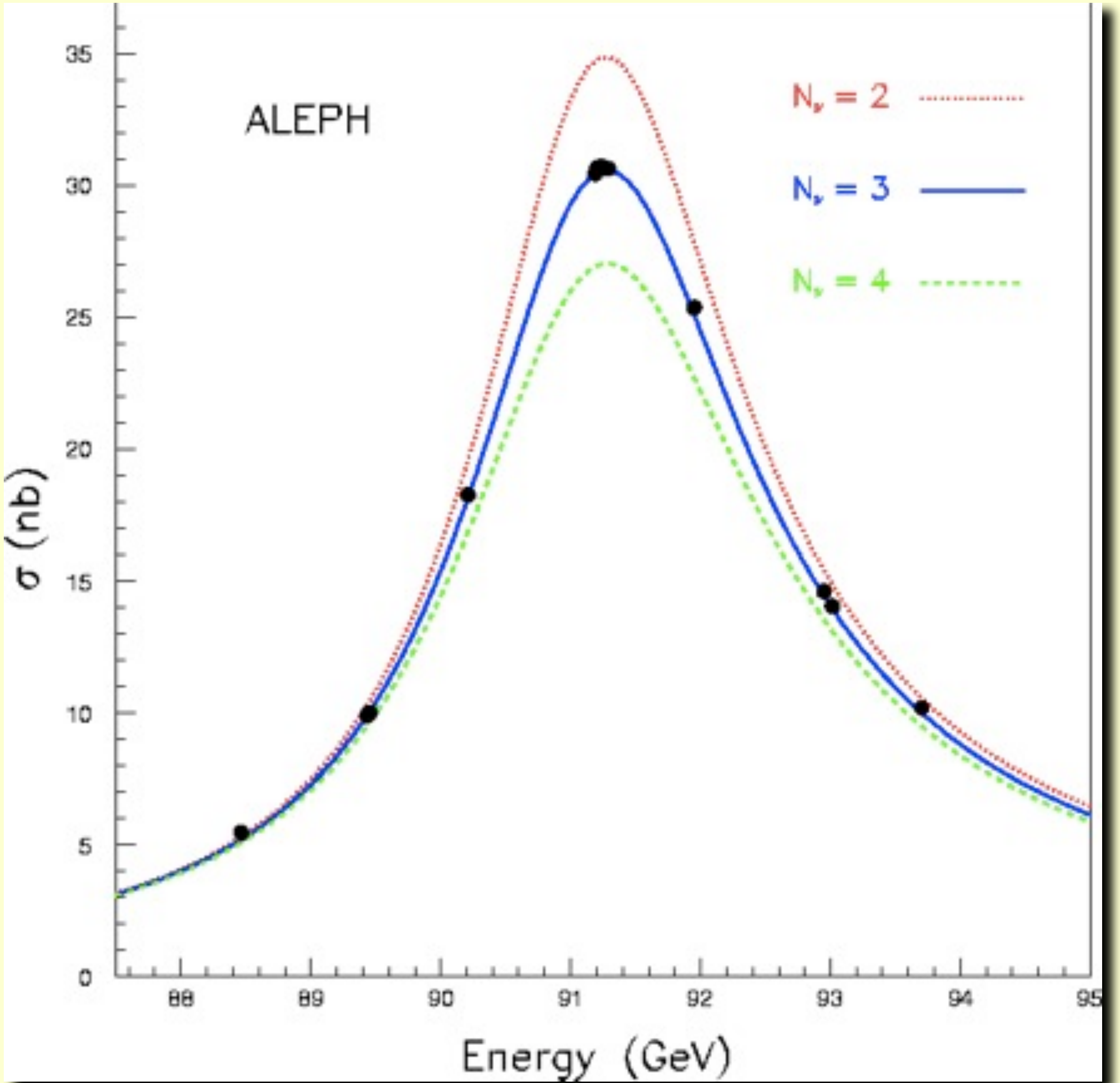
The fifth quark *b*
discovered by
Lederman
(1977)

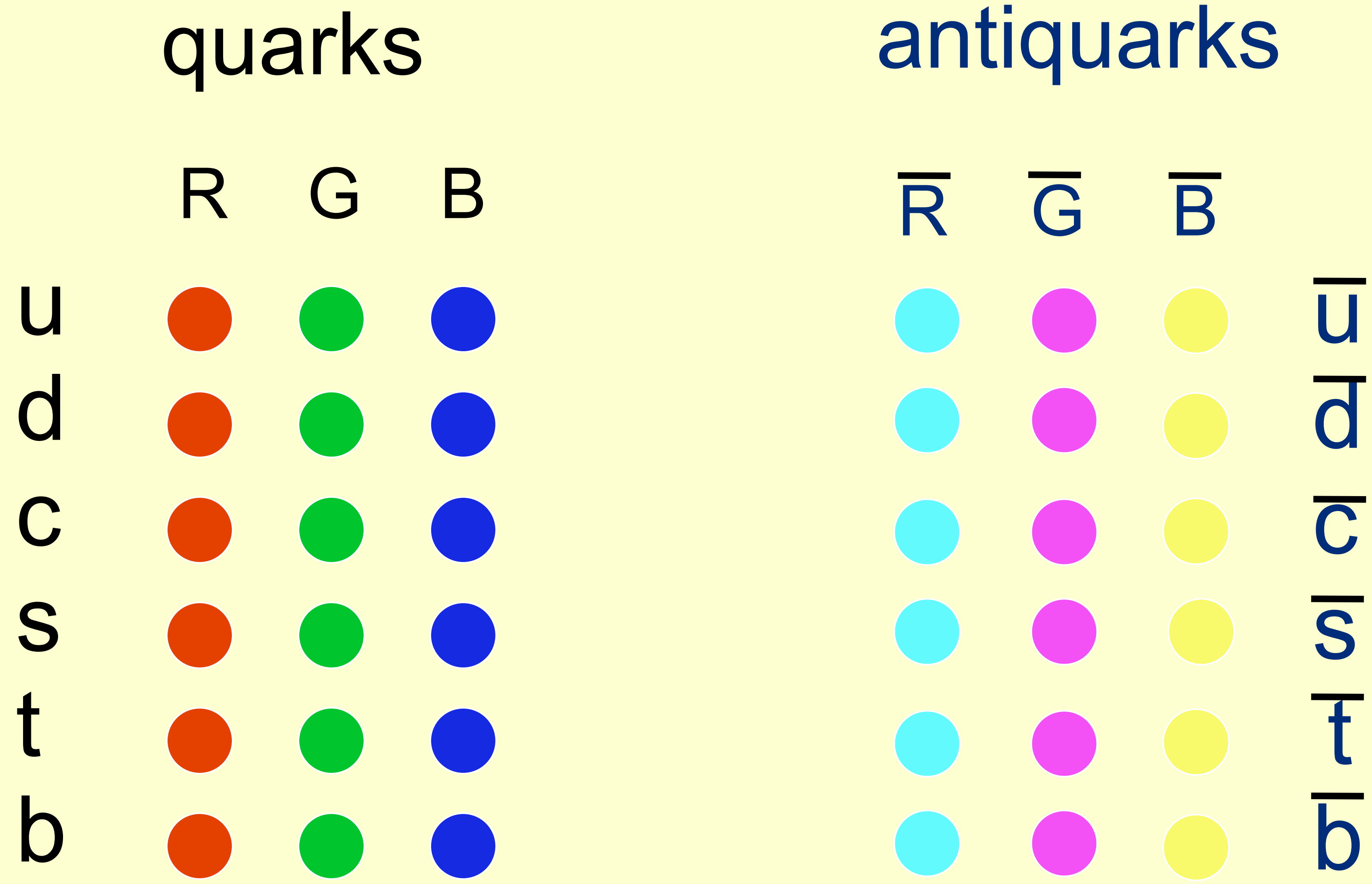
Leon Lederman

The sixth quark *t* discovered in 1995 (CDF, D0) in Fermilab
The third neutrino observed in 2000 (DONUT) in Fermilab

In 1989 four LEP experiments at CERN established that there are only three generations of quarks and leptons






quarks
antiquarks
R
G
B
$\bar{R}$
$\bar{G}$
$\bar{B}$
u
d
c
s
t
b
$\bar{u}$
$\bar{d}$
$\bar{c}$
$\bar{s}$
$\bar{t}$
$\bar{b}$

Elementary particles

(1938)	(~ 1970)		(now)	
e^-	e^-	1897	e^-	1897
p	p	1911 - 1919	e^+	1932
γ	γ	1923 (1905)	μ^-, μ^+	1937
e^+	e^+	1932	τ^-, τ^+	1975
n	n	1932	ν_e	1956 (1930)
d	$\mu^\pm$	1937	ν_μ	1962
α	$\pi^\pm$	1947	ν_τ	2000 (1975)
	$K^0, K^\pm$	1947		
	π^0	1949	u,d,s	1964
	Λ	1951	c	1974 (1964)
	Δ	1952 - 1953	b	1977
	Σ, Ξ	1952 - 1959	t	1995
	p^-	1955		
	ν_e	1956 (1930)	γ	1923 (1905)
	ν_μ	1962	$W^\pm$	1983 (1967)
	Ω	1964	Z	1983 (1967)
			g	1979 (1973)
			H	2012 (1964)

End of the road?

"This could be the discovery of the century. Depending, of course, on how far down it goes."

The cartoon shown by Weisskopf at the conclusion of the 1962 ICHEP in Geneva is still timely