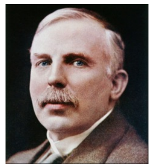
Pre-history of Deep-Inelastic Scattering

E. Tassi
Universita' della Calabria and INFN-Cosenza

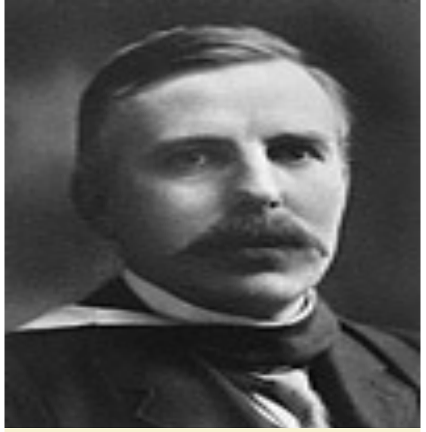
First European Summer School on the Physics of the Electron-Ion Collider
18-22 June 2023 – Corigliano-Rossano, Italy

Pre-History (1909-1960)

- Rutherford scattering
- Atomic nucleus
- Protons and neutrons
- Magnetic moments (p & n)
- Strong force
- Form factors





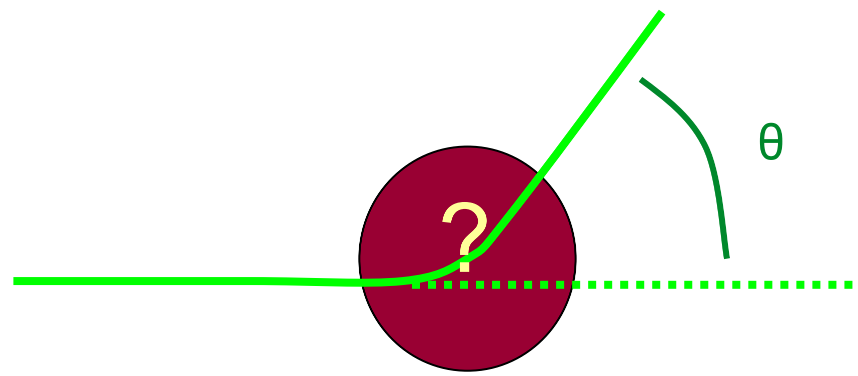


Nobel prize 1908

Rutherford Scattering

"The most famous fixed-target experiment of all time:"

Rutherford taught us the most important lesson:
the use of a scattering process to investigate the structure of matter



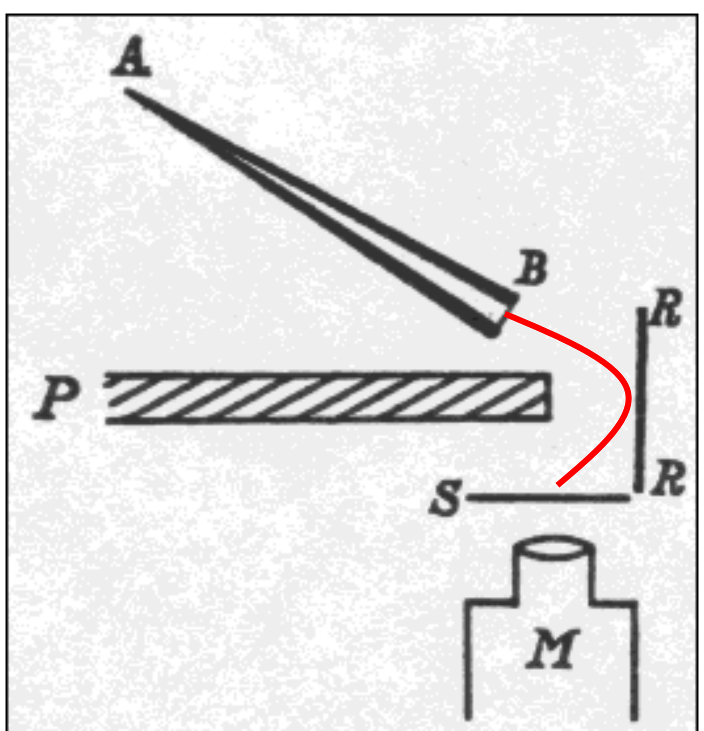


FIG. 1.

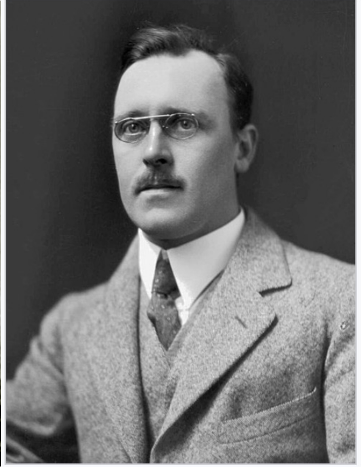
H. Geiger and E. Marsden observed the high-angle scattering ($\theta > 90^0$) alpha particles deflected by a thin gold foil.

Proc.Roy. Soc. A **82**, 495,1909

Rutherford interpreted the results as due to the scattering of alpha particles from a massive central charge

$$\sigma(\theta) = \frac{z^2 Z^2 e^4}{16E^2}\frac{1}{\sin^4\frac{1}{2}\theta}$$

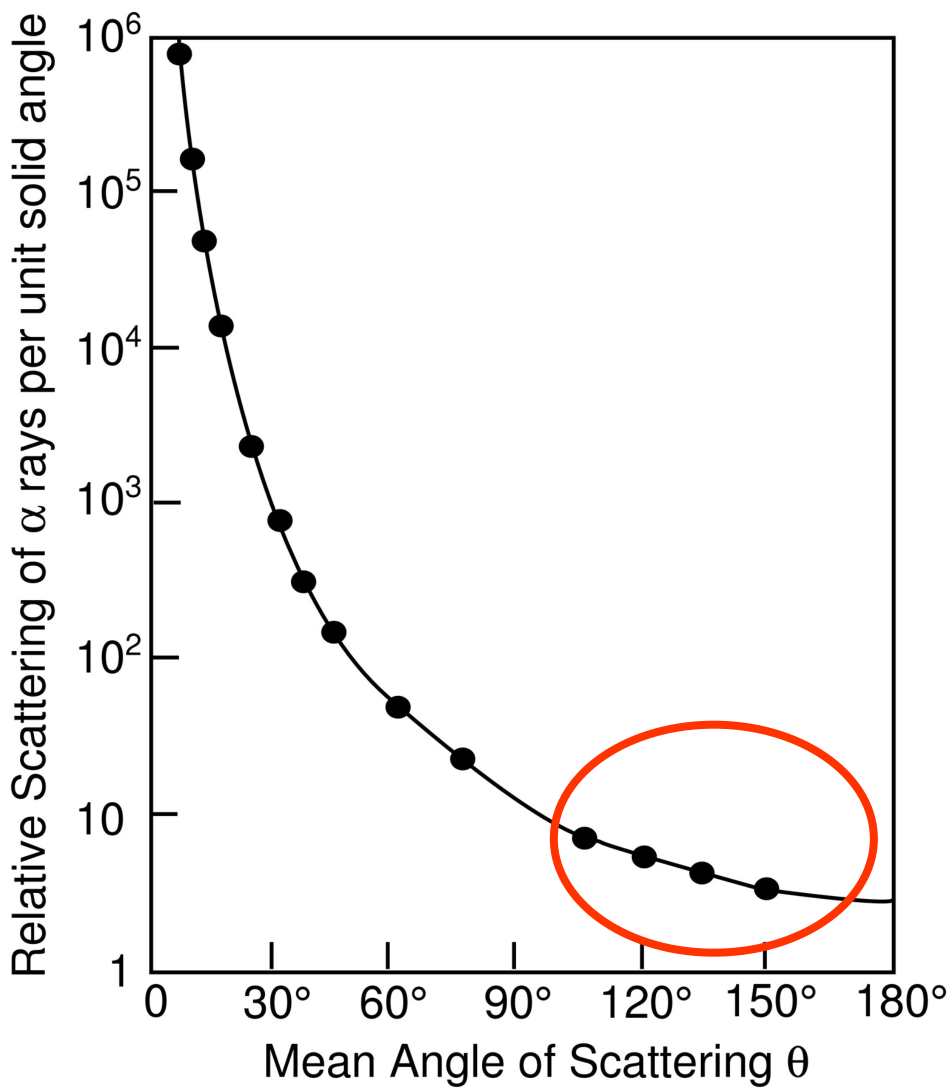
Phil. Mag. **21**,669,1911

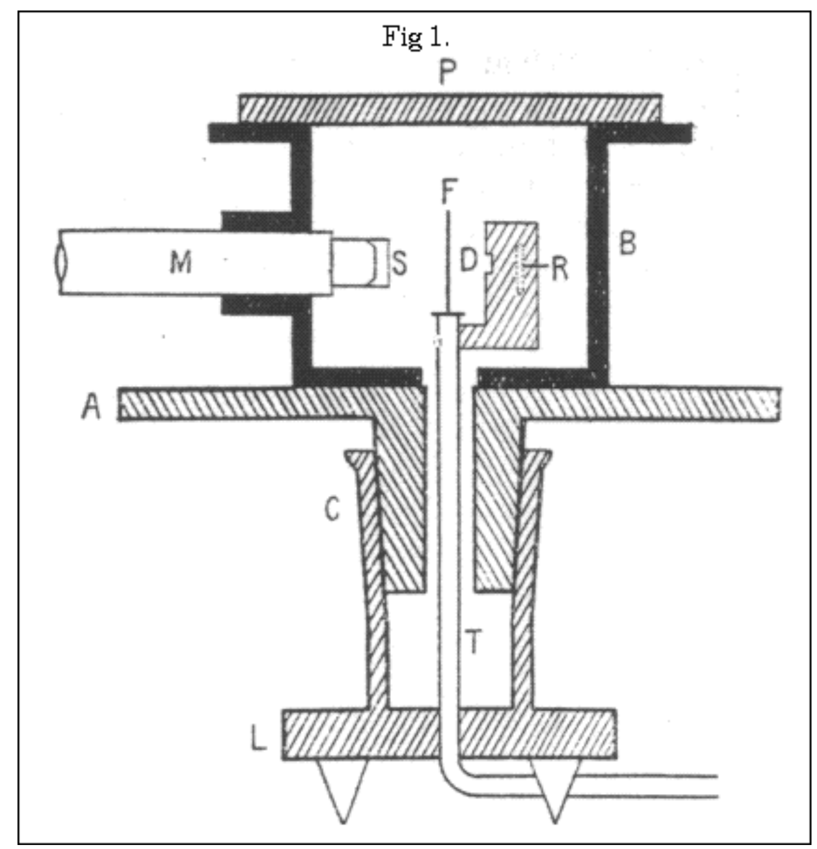


Rutherford Scattering

In 1913, Geiger and Marsden successfully verified (for high-Z nuclei) the predictions of Rutherford's theory.

Phil. Mag. **25**, 604,1913

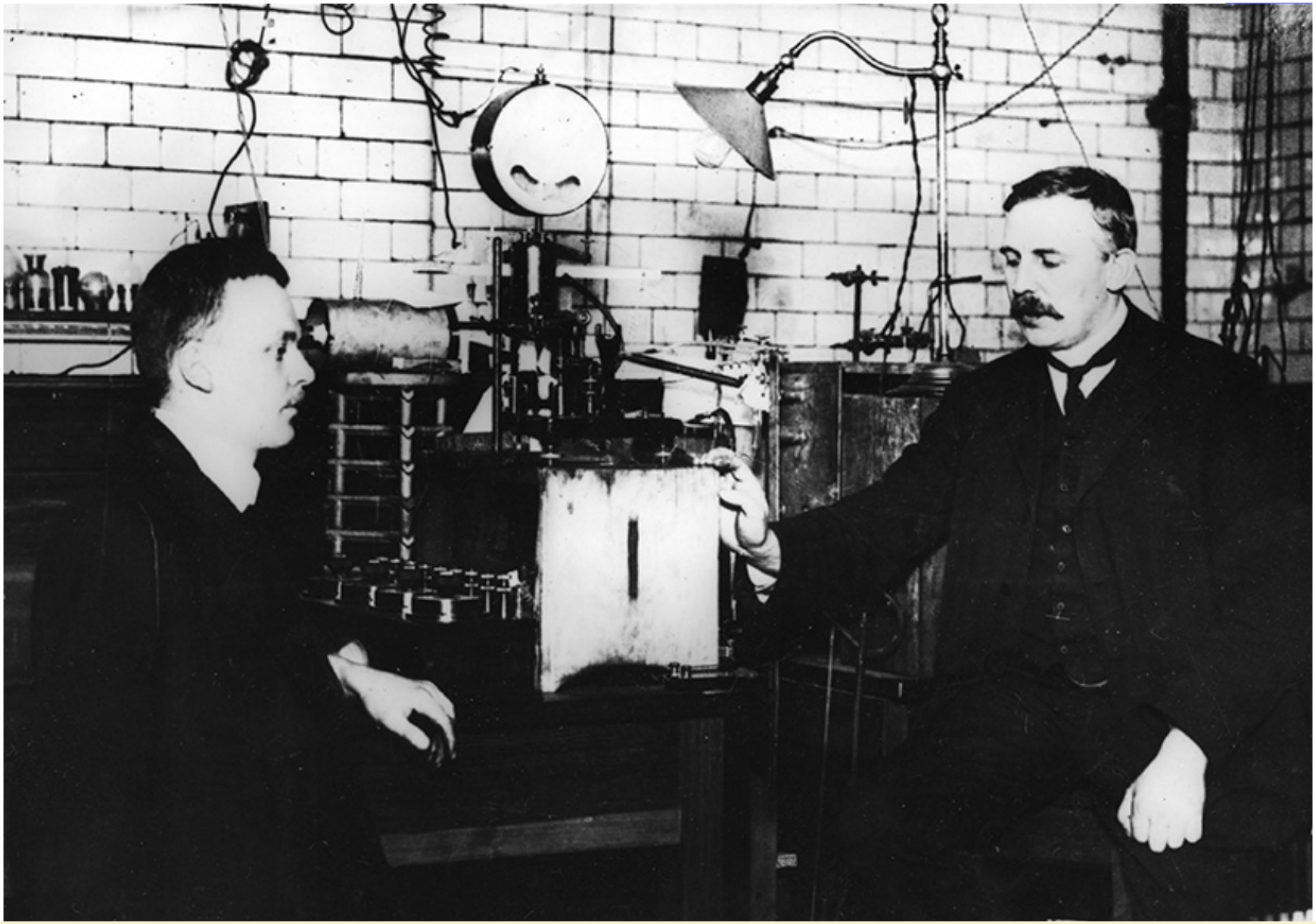




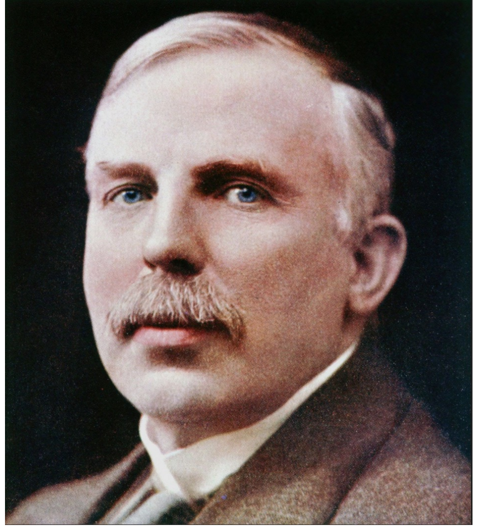
Discovery of the atomic nucleus

N.Bohr Old Quantum theory

Rutherford Scattering



"It was quite the most incredible event that has ever happened to me in my life. It was almost as incredible as if you fired a 15-inch shell at a piece of tissue paper and it came back and hit you."



Proton discovery

In 1917 Rutherford undertook a series of experiments on the collision of alpha particles with light atoms.

1919 – Proton discovery (“H-atom”)

First nuclear reactions

$$\alpha + {}^{14}C \rightarrow {}^{17}O + p$$

Phil. Mag. **37**, 581,1919

In 1921 Chadwick and Bieler obtained the first evidence of deviations from the law of Rutherford diffusion

$$\alpha + {}^{1}H \rightarrow {}^{1}H + \alpha$$

Phil. Mag. **42**, 923,1921

“The present experiments do not seem to throw any light on the nature of the law of variation of the forces at the seat of an electric charge, but merely show that the forces are of very great intensity…It is our task to find some field of force which will reproduce these effects.”

Chadwick, Bieler Phil. Mag. **42**, 923,1921

Nobel prize
1935

Neutron discovery

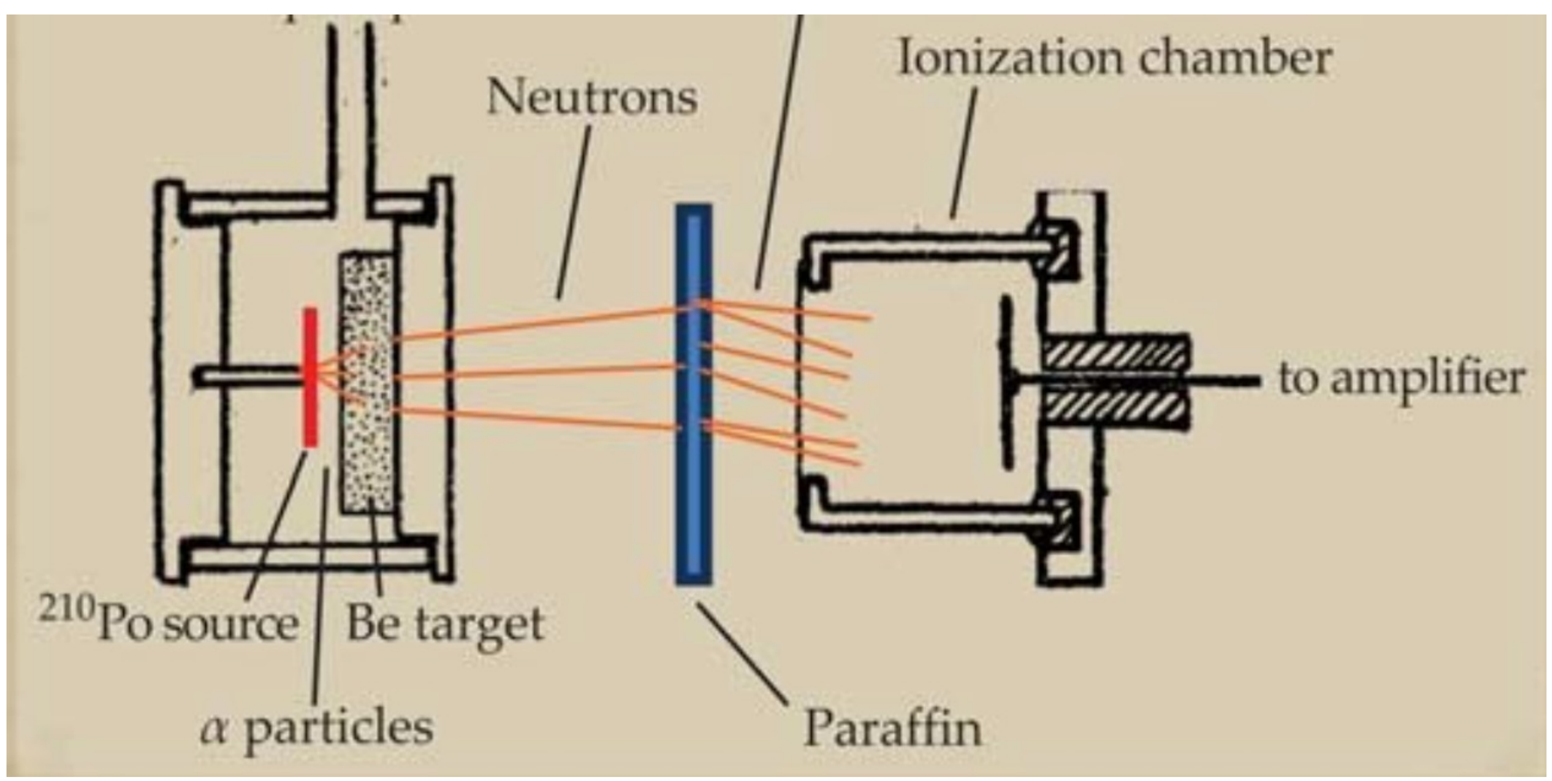
> "I think we shall have to make a real search for the neutron."
> Chadwick letter to Rutherford, 1924

In 1932, stimulated by earlier experiments by Bothe-Becker and in particular Joliot-Curie, J. Chadwick discovered the neutron

$$\alpha + {}^{9}Be \rightarrow {}^{12}C + n$$

Proc. Roy. Soc. A **136**, 692,1932

Nature **129**, 312,1932



Nobel prize 1935

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Discovery of β^{+} decay

Nobel prize 1935

$$\alpha + {}^{27}\mathrm{Al} \rightarrow {}^{30}\mathrm{P} + n$$
$$\searrow$$
$${}^{30}\mathrm{Si} + e^{+} + (\nu_e)$$

$$\alpha + {}^{10}\mathrm{Bi} \rightarrow {}^{13}\mathrm{N} + n$$
$$\searrow$$
$${}^{13}\mathrm{C} + e^{+} + (\nu_e)$$

Ernest Rutherford

"In our laboratory today we live in an atmosphere deemed with the flying fragments of exploding atoms and on this occasion I wish to say a few words on the methods and ideas employed to break up atoms and realize…the old dream of alchemists of transmutation of one element into another…"

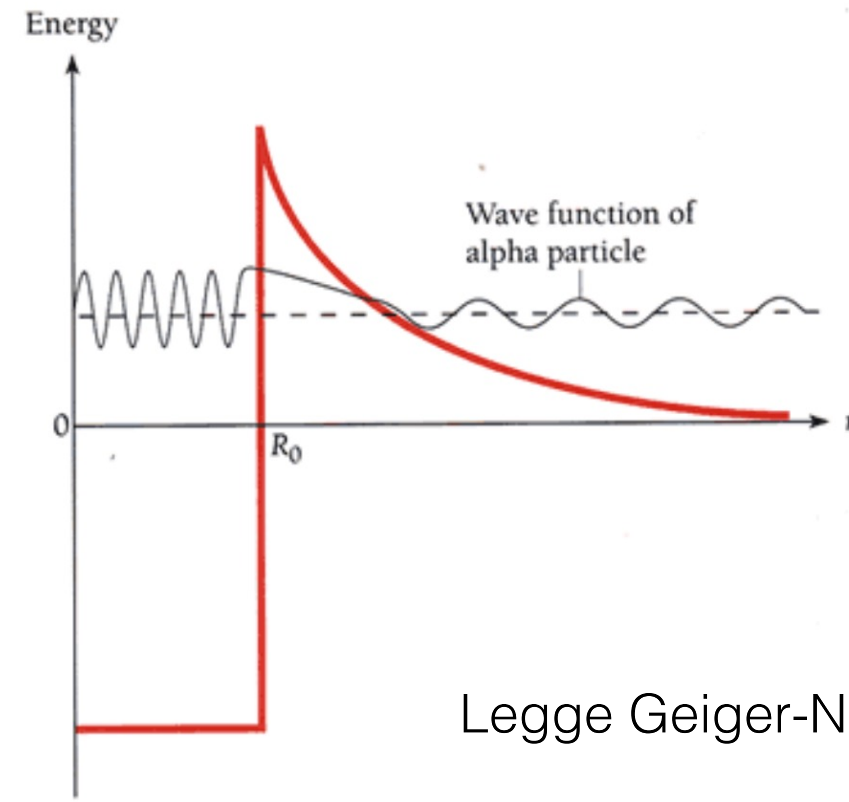
You tube Link. : https://www.youtube.com/watch?v=zBHD8ksx_Sg

Quantum Mechanics and QED

Quantum mechanics developed rapidly
in the period 1924-1927

Nuclear Physics:
- 1928: alpha decay theory
  (G. Gamow, R.W. Gurney &E.U. Condon)

Special Relativity:
- 1920-30 Binding energy - stability
  (B formula - Aston – Einstein $E_0=mc^2$)



Legge Geiger-Nuttal

Nobel prize 1933

1927-1930 A. P. Dirac lays the foundations of relativistic quantum mechanics and quantum electrodynamics (QED)

First steps towards quantum field theory

= > Spin and magnetic dipole moment of the electron :

$$\vec{\mu} = -\left(\frac{g\mu_B}{\hbar}\right)\vec{S} \quad \text{con} \quad \mu_B = \frac{e\hbar}{2m_e}$$

Magnetone di Bohr

Proton magnetic moment

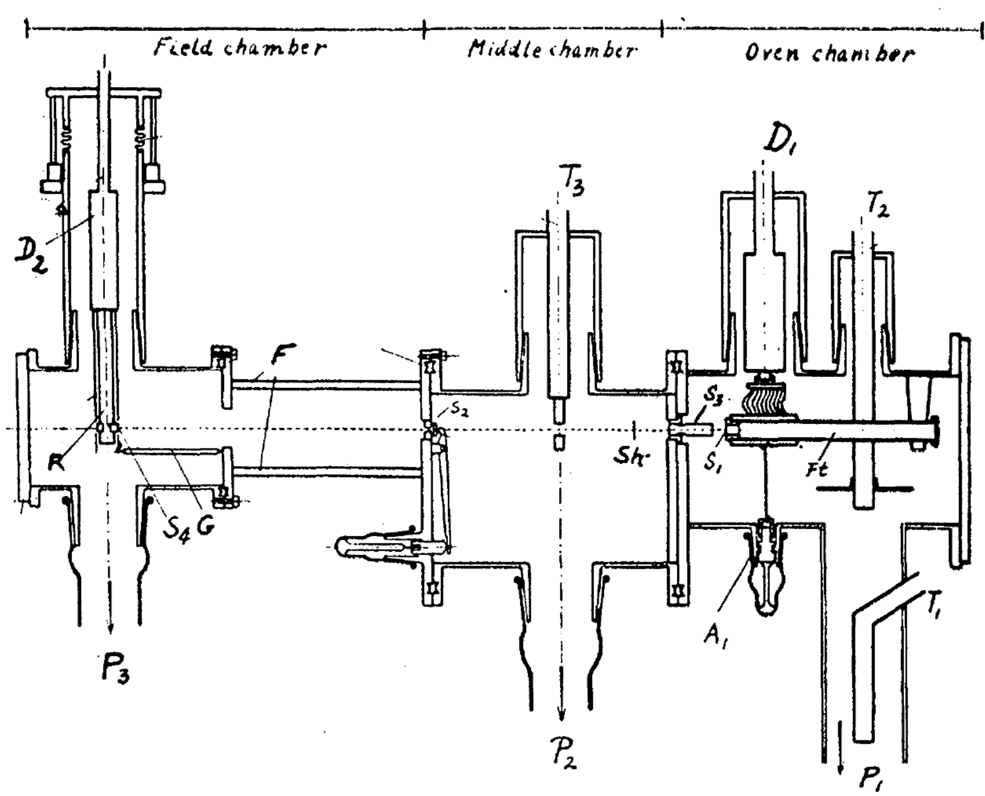
Nobel prize 1943

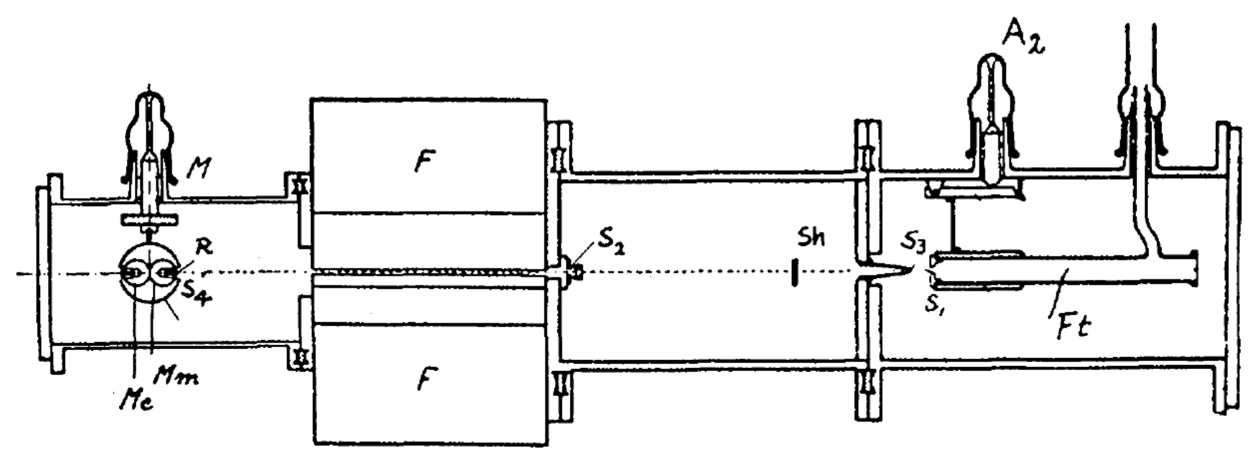
In 1933, O. Stern, I. Esterman and R. Frish presented the first determination of the proton's magnetic moment using the deflection in a B (non-homogeneous) field of a molecular beam (H_2).

$$\mu_p = 2.5\ \mu_N\ (\pm 10\%) \quad \text{con} \quad \mu_N = \frac{e\hbar}{2m_p}$$

Z. Phy. 85, 4,1933

Z. Phy. 85, 17,1933





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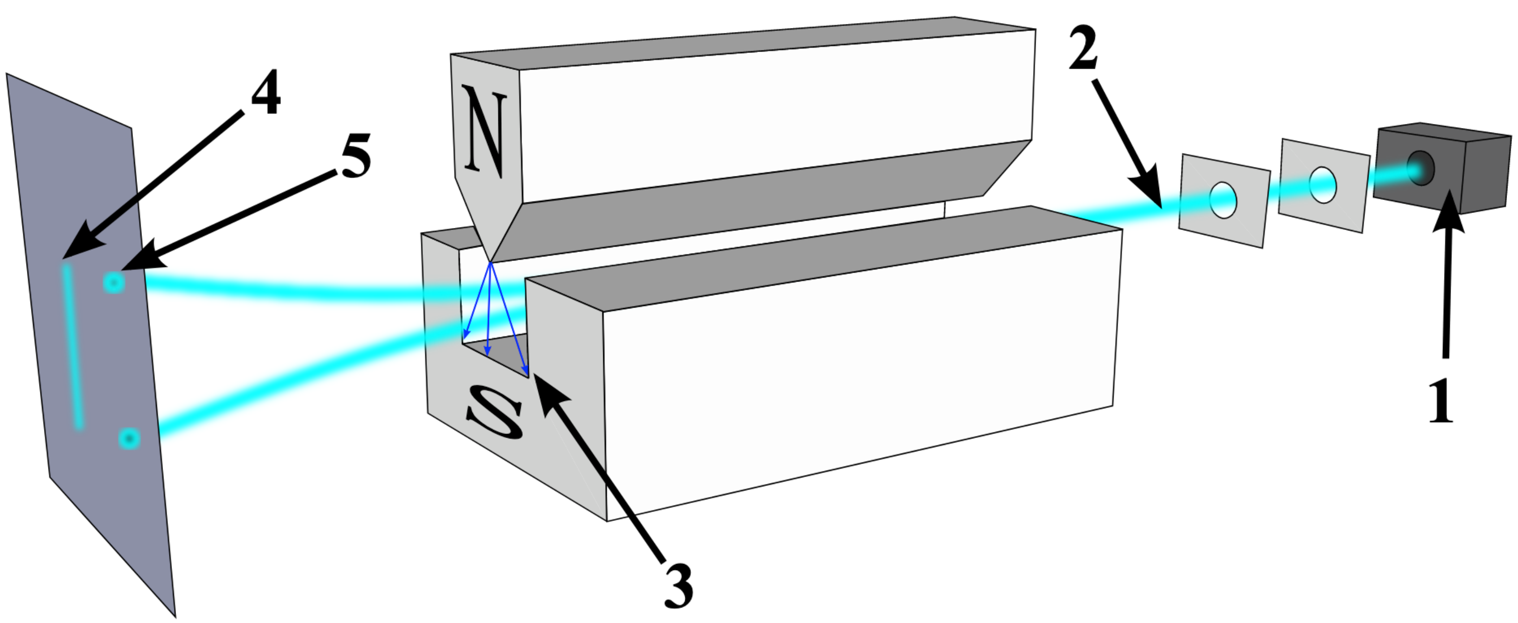
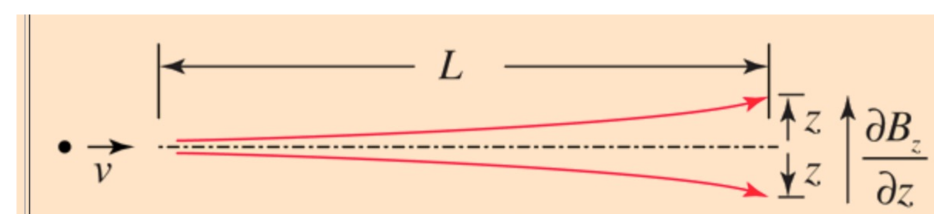


$$\vec{F}(\mathbf{r}) = \mu_k \vec{\nabla} B_k(\mathbf{r})$$



$$z = \frac{1}{2}at^2 = \frac{1}{2}\frac{F}{m}\left[\frac{L}{v}\right]^2 = \pm\frac{\mu_B L^2}{4KE}\frac{\partial B_z}{\partial z}$$

Proton and neutron magnetic moments

Nobel prize 1944

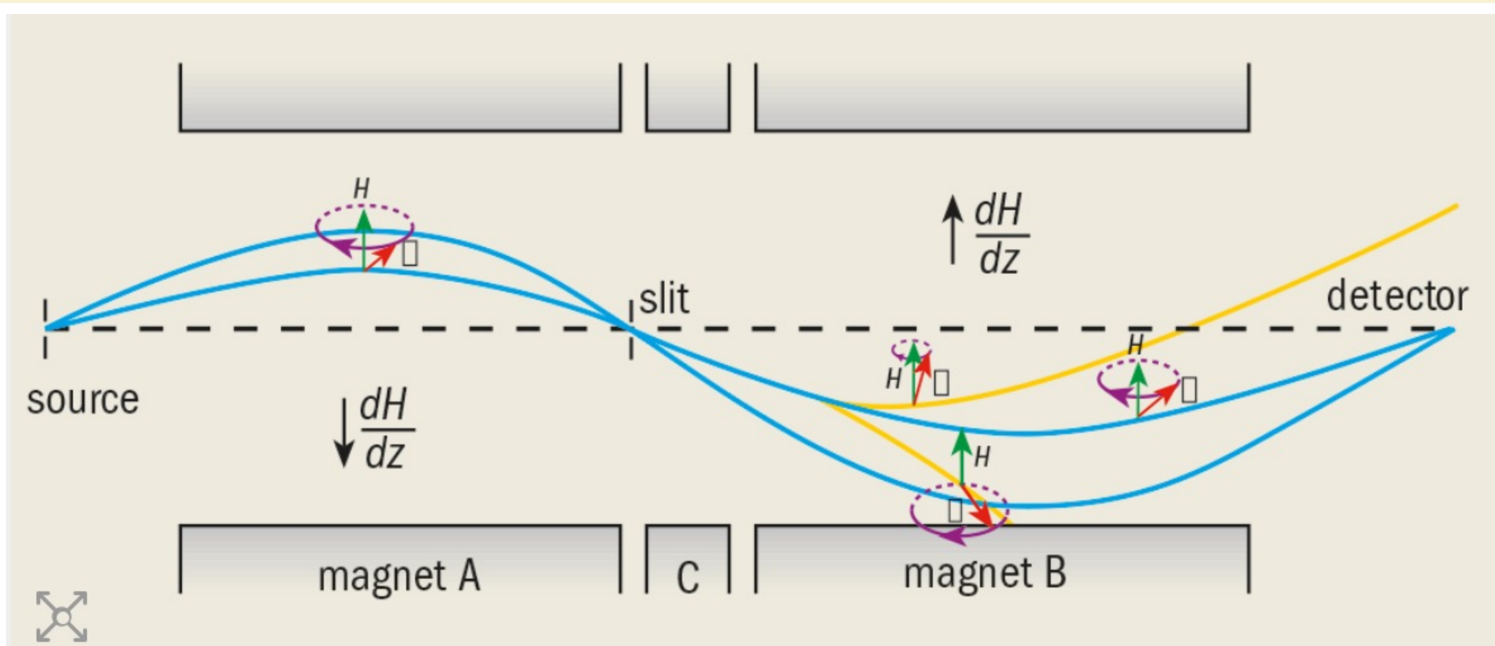
In 1939, I.I. Rabi et al. improved (with a new technique) the measurement of the magnetic moment of the proton and deuteron.

$$\mu_p = 2.785\mu_N \pm 0.02$$

$$\mu_D = 0.855\mu_N \pm 0.006 \; (\rightarrow \mu_n = -1.93\mu_N)$$

Phys. Rev. **56**, 728,1939

The proton and neutron are not elementary particles!



Nobel prize
1933

Nuclear force and Nuclear Physics

Z. Phys. **82** (1933) 137

1932-33: Heisenberg publishes three articles that mark the beginning of a theoretical study systematic study of the strong interaction
"*Über den Bau der Atomkern*" -> "nuclear exchange force" ("Platzwechsel")

1933-36 Important contributions by Maiorana, Breit, Wigner, Cassen & Condon

Z. Phys. **82** (1933) 137

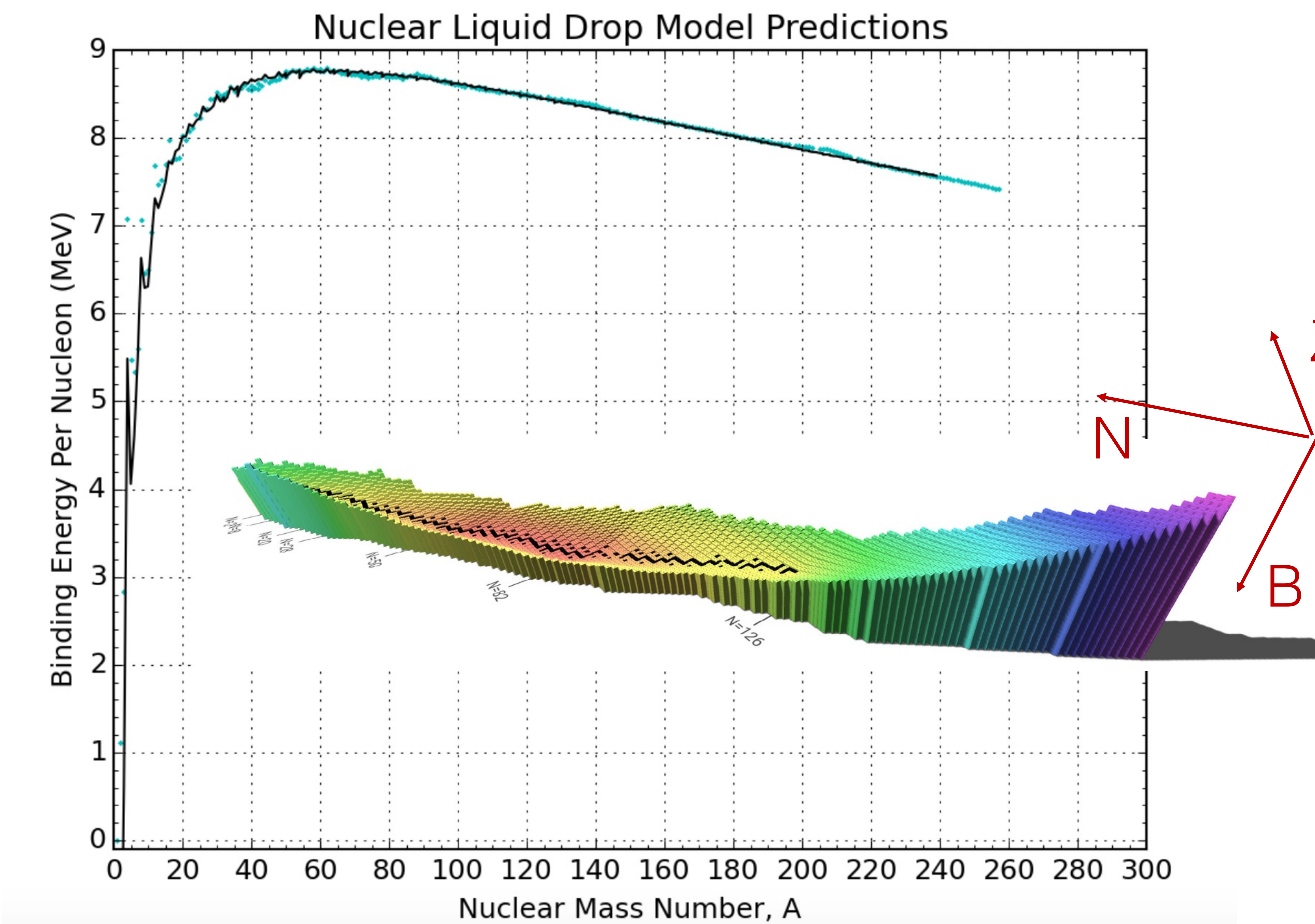
- Short range force ($< 10^{-15}$ m)
- Saturation (B ~ A)
- Charge independence (p-p, n-n e p-n)
- Isospin

Weizsäcker formula

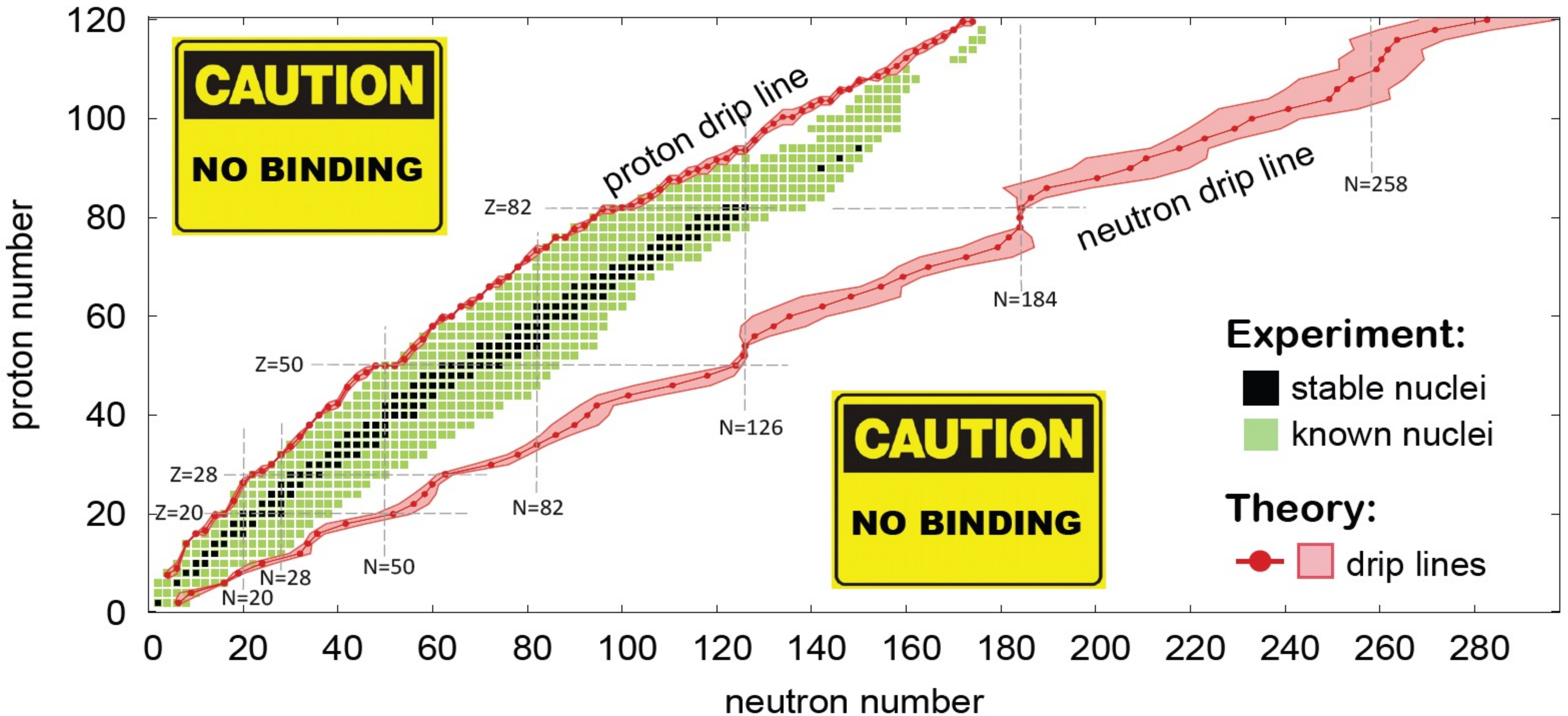
$$E = a_V A - a_S A^{2/3} - a_C \frac{Z(Z-1)}{A^{1/3}} - a_A \frac{(A-2Z)^2}{A} + \delta(A,Z)$$

Nuclear radius $R = r_0 A^{1/3}$

Nuclear Landscape



Nuclear Landscape



Nobel prize
1949

Yukawa

In 1935, Yukawa, to describe strong interactions, introduced an analogy between the electromagnetic force and the strong force. Proc. 17, 48 (1935)

Maxwell's Theory/QED

- Potential (Coulomb) $1/r$ (infinite range)
- Photons (massless)

Yukawa's "theory"

- Potential $\frac{e^{-\kappa r}}{r}$ (range) $1/\kappa$
- Mesons (mass m)

Estimate of the meson mass : $m \sim 200\ m_e$

The 'Yukawa meson' was initially identified with the muon ("μ meson") and later, also thanks to the fundamental work of Conversi-Pancini-Piccioni , with the pions $\pi^{\pm}, \pi^0$

Nobel prize
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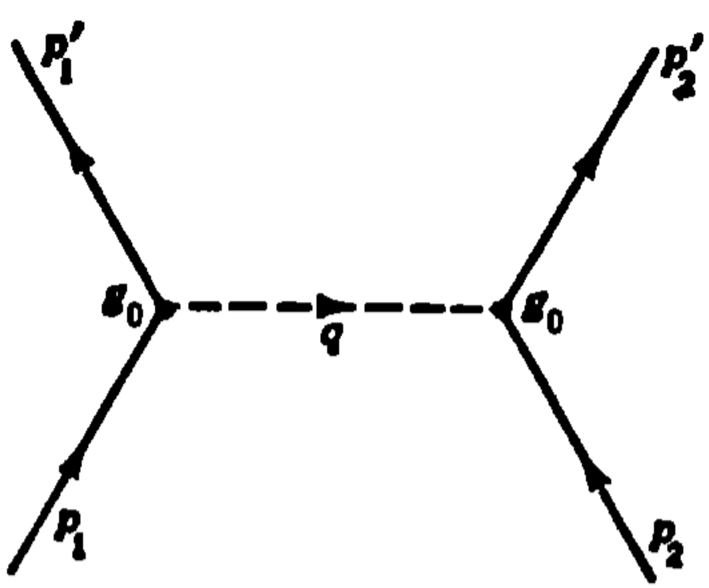


$$\mathcal{M} \sim \frac{g_0^2}{q^2 - \mu^2 + i\epsilon} \xrightarrow{\text{NR}} \frac{g_0^2}{|\mathbf{q}|^2 + \mu^2}$$

$$\frac{g_0^2}{|\mathbf{q}|^2 + \mu^2} \overset{\text{FT}}{\longleftrightarrow} V(r) \sim \ g_0^2 \frac{e^{-\mu r}}{r}$$

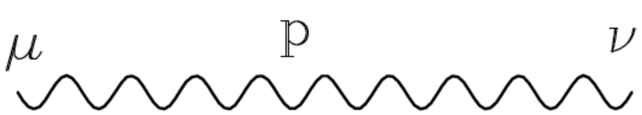
Nobel prize 1965

Quantum Electrodynamics

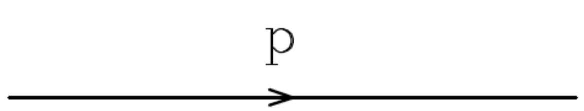
In the period 1947-1949, the renormalisation programme of Quantum Electrodynamics (Tomonaga, Schwinger, Feynman) was completed.

Feynman introduces a new language

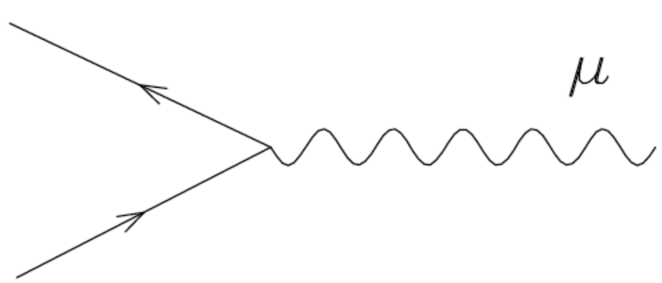
$$\mathcal{L} \;=\; \bar{\psi}(i\partial\!\!\!/ - m)\psi - e\bar{\psi}A\!\!\!/\psi - \frac{1}{4}F_{\mu\nu}F^{\mu\nu} \qquad F_{\mu\nu} = \partial_\mu A_\nu - \partial_\nu A_\mu$$



$$= \; -i\frac{g_{\mu\nu}}{p^2 + i\epsilon} \; \text{(Feynman gauge)}$$



$$= \; \frac{i}{p\!\!\!/ - m + i\epsilon} = i\frac{p\!\!\!/ + m}{p^2 - m^2 + i\epsilon}$$



$$= \; -ie\gamma_\mu Q$$

Spinors and pol. 4-vectors:

$$u, \bar{u}, v, \bar{v} \;\; \& \;\; \epsilon^\mu, {\epsilon^\mu}^*$$

Nobel prize 1965

Quantum Electrodynamics

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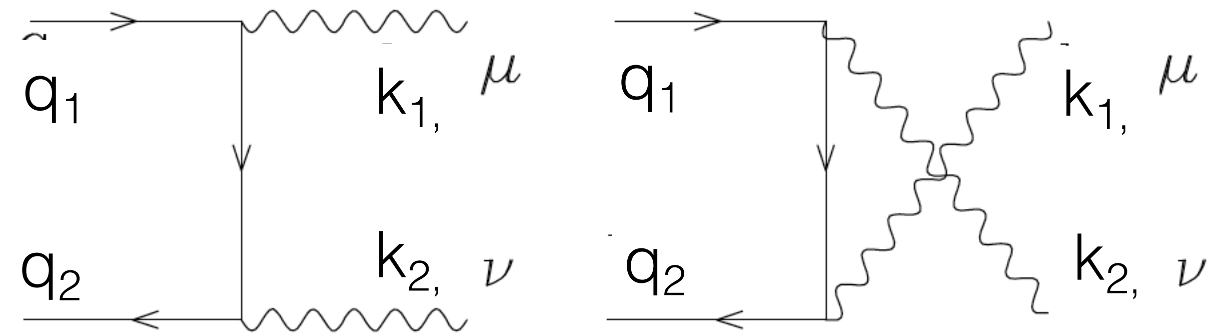
Example: $e^+e^- \rightarrow \gamma\gamma$



$$\mathcal{M} = \bar{v}(q_2, s_2)(-ie\gamma_\mu)\frac{i}{(\not{q}_1 - \not{k}_1 - m + i\epsilon)}(-ie\gamma_\nu)u(q_1, s_1)$$

$$\epsilon^{\nu *}(k_1, \lambda_1)\epsilon^{\mu *}(k_2, \lambda_2) +$$

$$+\bar{v}(q_2, s_2)(-ie\gamma_\nu)\frac{i}{(\not{q}_1 - \not{k}_2 - m + i\epsilon)}(-ie\gamma_\mu)u(q_1, s_1)$$

$$\epsilon^{\nu *}(k_1, \lambda_1)\epsilon^{\mu *}(k_2, \lambda_2)$$

$$\overline{\sum}|\mathcal{M}|^2 = 2e^4\left[\frac{(q_1k_2)}{(q_1k_1)} + \frac{(q_1k_1)}{(q_1k_2)} + 2m^2\left(\frac{1}{(q_1k_1)} + \frac{1}{(q_1k_2)}\right) + \right.$$

$$\left. -m^4\left(\frac{1}{(q_1k_1)} + \frac{1}{(q_1k_2)}\right)^2\right]$$

Perturbative meson field theory?

Based on the successes of QED, field theories based on scalar mediating particles (e.g. pions) were introduced.

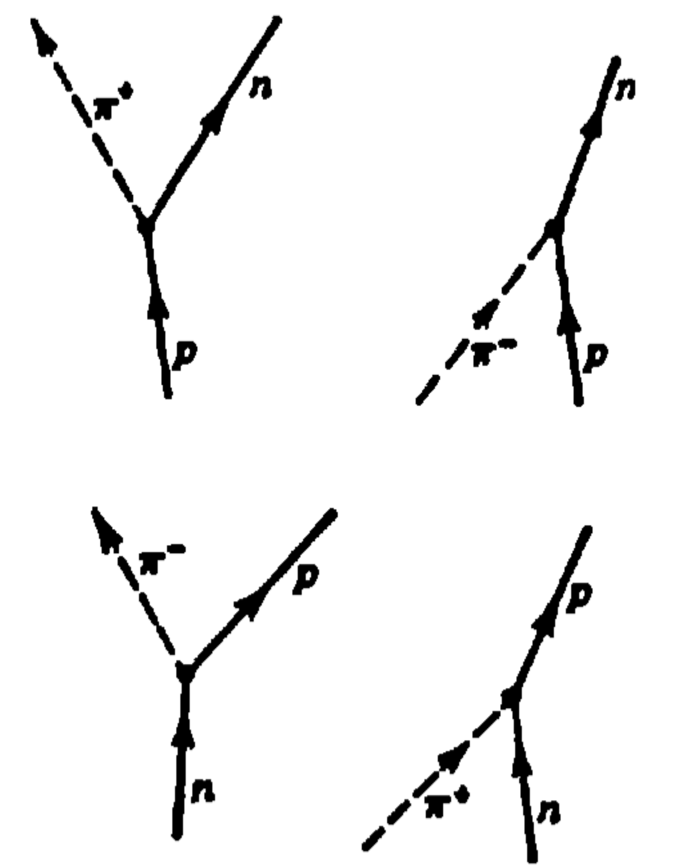
Pseudoscalar isotriplet with pseudoscalar coupling:

$$H_{int} = ig \int \big(\bar{\psi}(x)\vec{\tau}\gamma_5\psi(x) \cdot \vec{\pi}(x)\big) d\vec{x}$$

Creation and distruction operators of pions: $\pi^+ = \frac{\pi_1 + i\pi_2}{\sqrt{2}}, \quad \pi^- = \frac{\pi_1 - i\pi_2}{\sqrt{2}}, \quad \pi^0 = \pi_3$

Estimates obtained in the 1940s: $\frac{g^2}{\hbar c} \sim 15 - 40$

To be ccompared with: $\alpha = \frac{e^2}{\hbar c} \simeq \frac{1}{137}$



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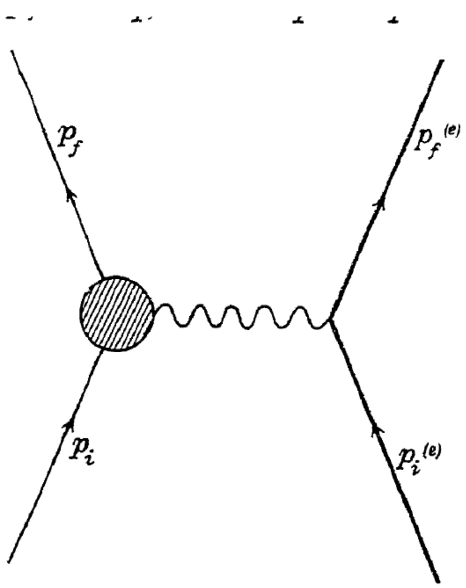
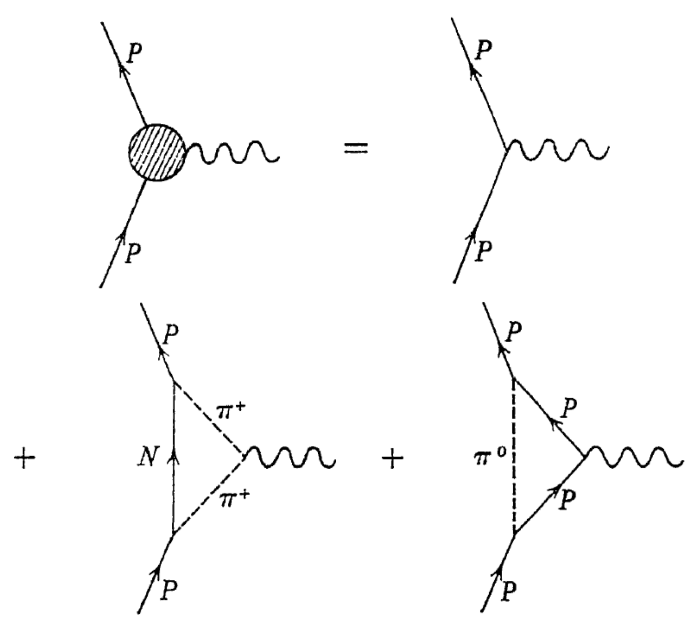




Proton magnetic moment: $\frac{g^2}{\hbar c} \simeq 52$

Neutron magnetic moment: $\frac{g^2}{\hbar c} \simeq 7$

Borowitz, Kohn – Phys.Rev. 76 818 (1949)

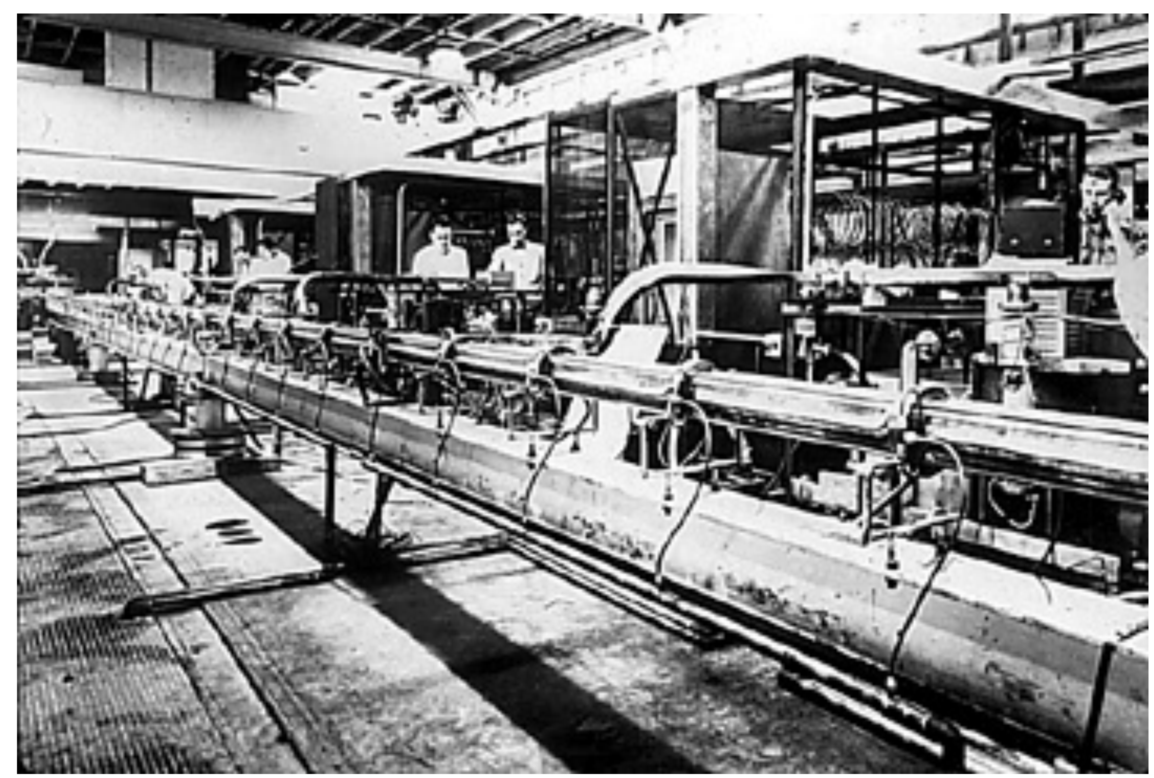
Linacs at the Stanford University

In the mid-1930s, the Varian brothers (research assistants at the microwave department of Stanford University) developed the 'klystron' using a special electromagnetic cavity (Rhumbatron) invented by W. Hansen.

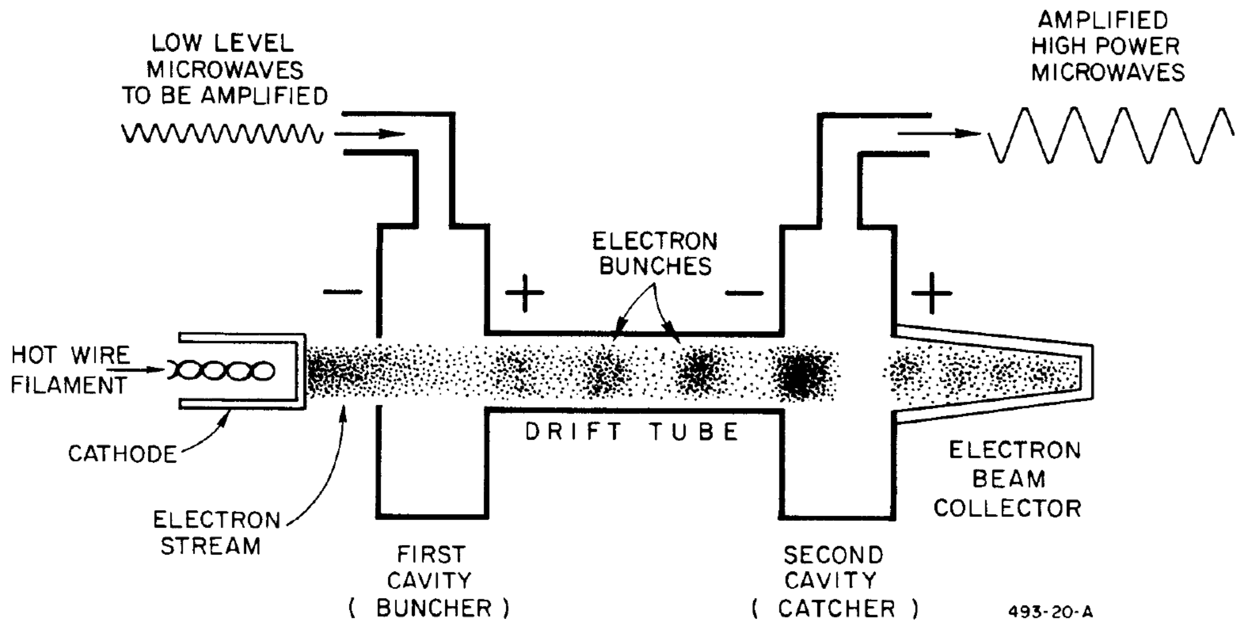
This device allowed Stanford's HEPL to play a leading role in the development of linear accelerators...

Under the direction of E. Ginzton HEPL began the construction of a series of 'small-scale' linacs (MARK I,II,III...).

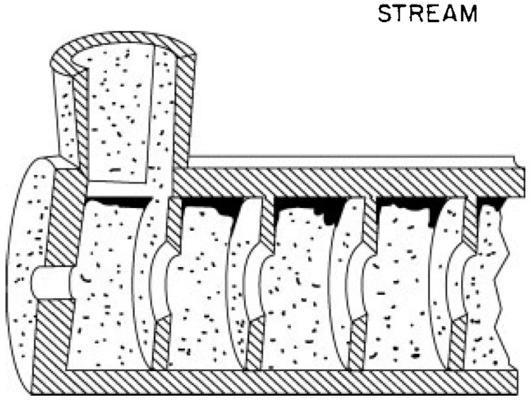
MARKIII was to be fundamental for the realisation of R. Hofstadter's experiments on e-N and e-p eastic scattering.

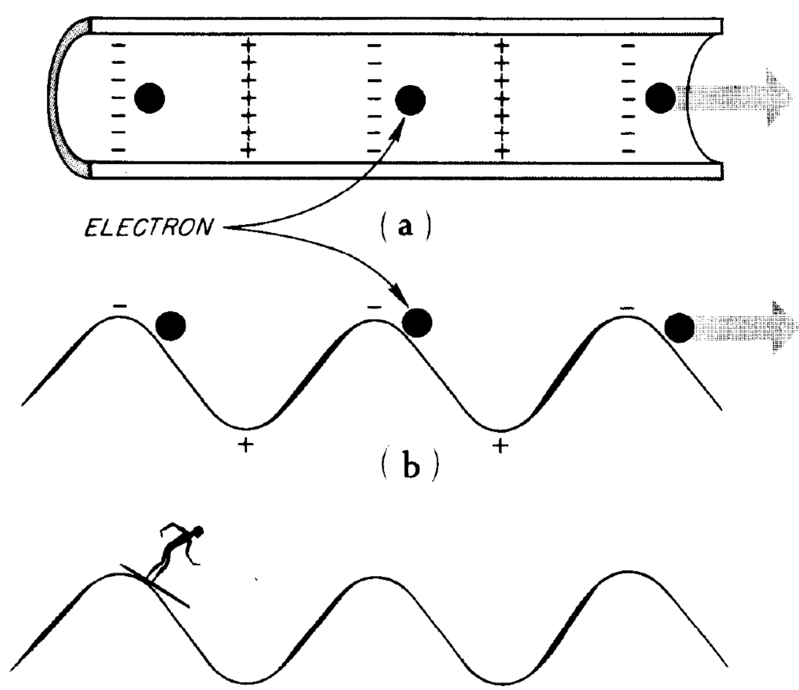


Klystron

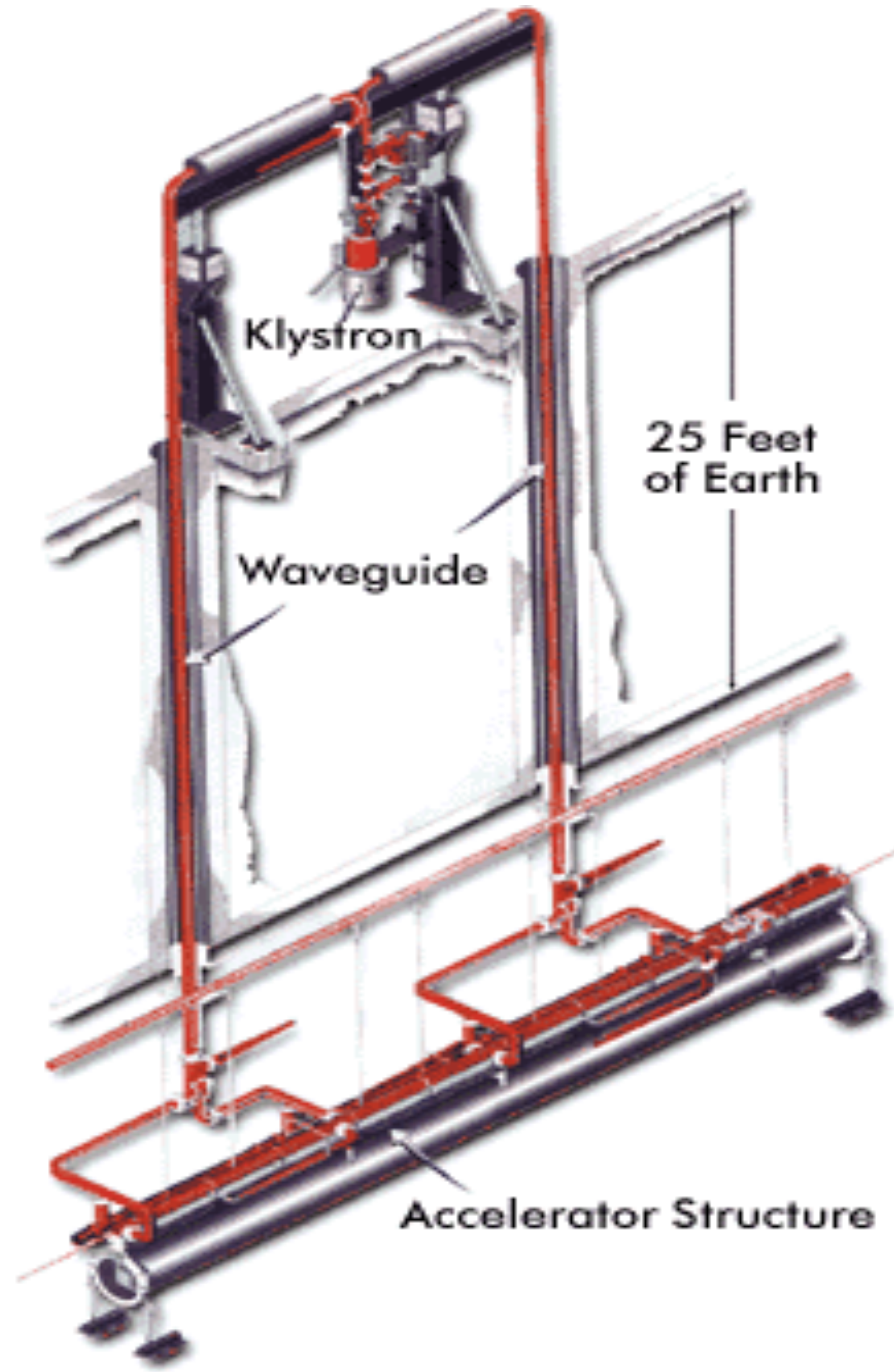


LOW LEVEL MICROWAVES TO BE AMPLIFIED
AMPLIFIED HIGH POWER MICROWAVES
ELECTRON BUNCHES
HOT WIRE FILAMENT
CATHODE
ELECTRON STREAM
DRIFT TUBE
ELECTRON BEAM COLLECTOR
FIRST CAVITY (BUNCHER)
SECOND CAVITY (CATCHER)
493-20-A





ELECTRON
(a)
(b)



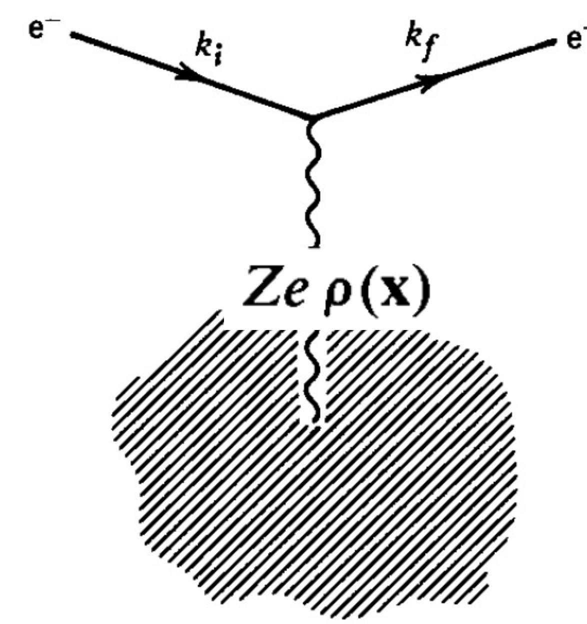
Klystron
25 Feet of Earth
Waveguide
Accelerator Structure

Nuclear Form Factor

Stimulated by accelerators technology advances and fully muture QED various theoreticians (Rose (48), Elton(50)) started to calculate cross sections for <u>elastic electron-Nucleus scattering</u>

$$\frac{d\sigma}{d\Omega} = \left(\frac{d\sigma}{d\Omega}\right)_{\text{Mott}} |F(\mathbf{q})|^2$$

$$F(\mathbf{q}) = \int \rho(\mathbf{x}) e^{i\mathbf{q}\cdot\mathbf{x}} \, d^3x$$



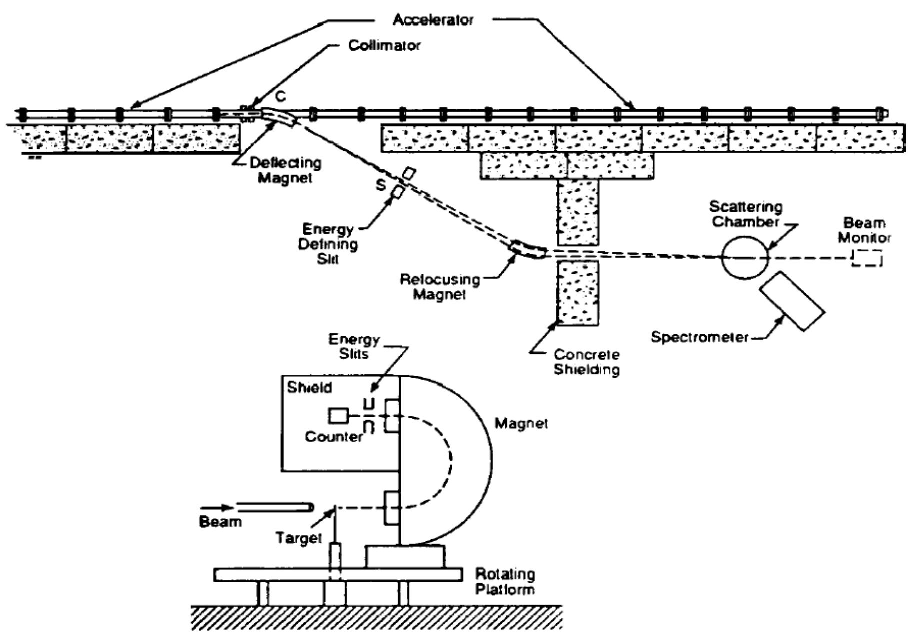
$$\left(\frac{d\sigma}{d\Omega}\right)_{\text{Mott}} = \frac{(Z\alpha)^2 E^2}{4k^4 \sin^4 \frac{\theta}{2}} \left(1 - v^2 \sin^2 \frac{\theta}{2}\right)$$

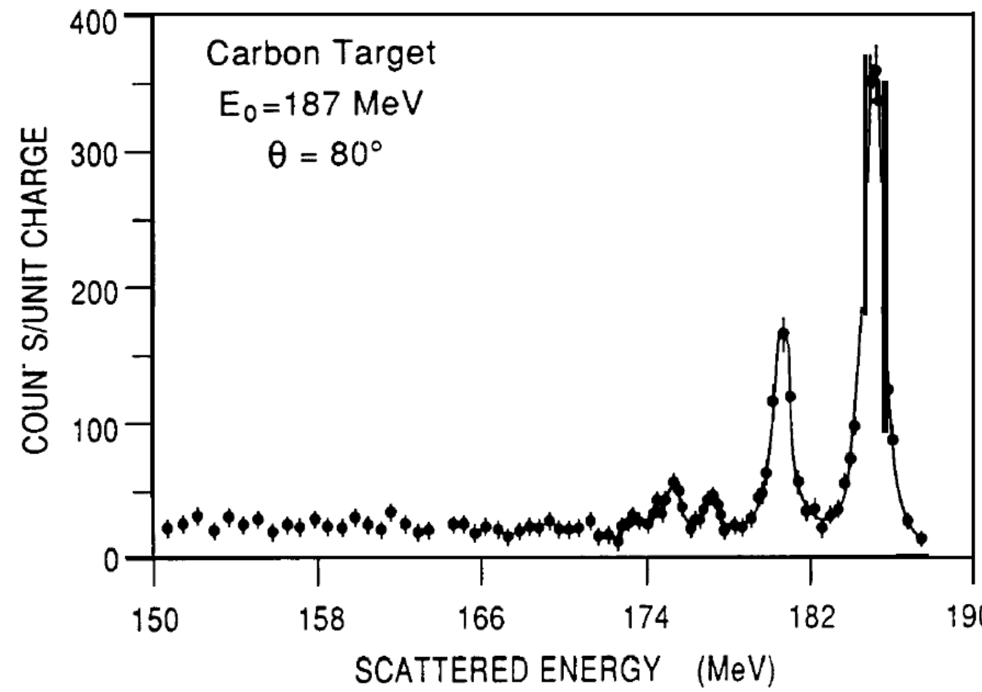
$$F(\mathbf{q}) = \int \left(1 + i\mathbf{q}\cdot\mathbf{x} - \frac{(\mathbf{q}\cdot\mathbf{x})^2}{2} + \cdots \right) \rho(\mathbf{x}) \, d^3x$$
$$= 1 - \frac{1}{6}|\mathbf{q}|^2 \langle r^2 \rangle + \cdots ,$$

$$r_{\text{m}}^2 = -6 \left. \frac{\mathrm{d}F(\mathbf{q})}{\mathrm{d}(|\mathbf{q}|^2)} \right|_{|\mathbf{q}|=0} .$$

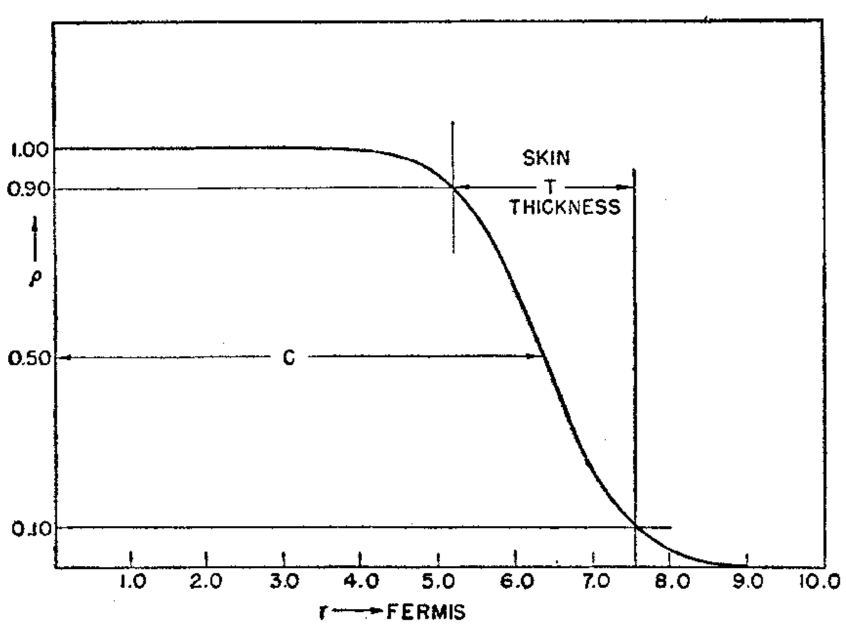
Nobel prize
1961

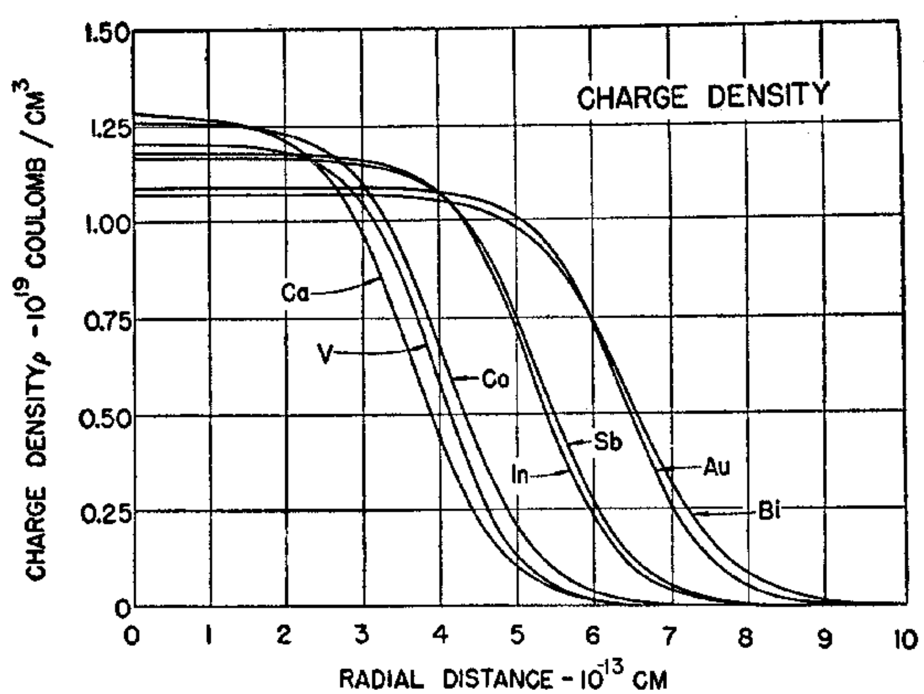
Nuclear Form Factor





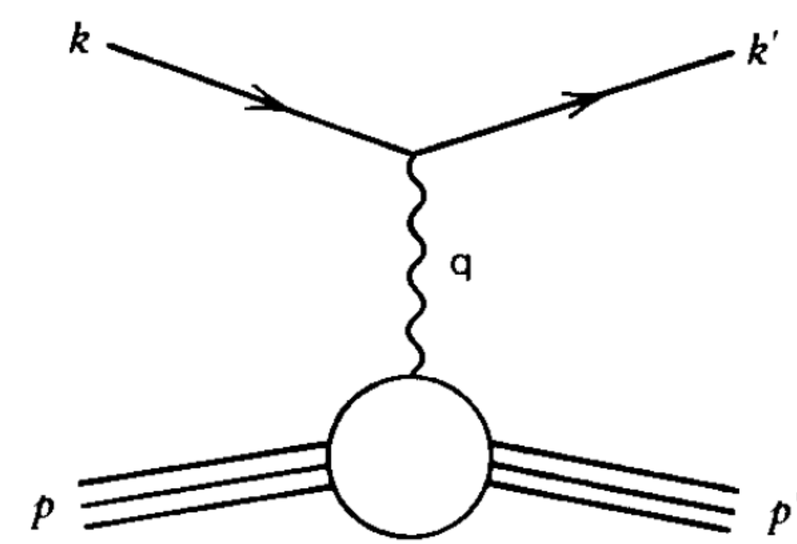
$$\rho(r) = \frac{\rho_1}{\exp[(r-c)/z_1]+1}.$$





Nucleon Form Factors

$$\frac{d\sigma}{d\Omega} = \frac{\alpha^2}{4E^2 \sin^4 \theta/2} \frac{\cos^2 \theta/2}{1 + (2E/M) \sin^2 \theta/2} \times \left\{ (F_1{}^p(t))^2 - \frac{t}{4M^2} \left(4M^2 (F_2{}^p(t))^2 + 2(F_1{}^p(t) + 2M\, F_2{}^p(t))^2 \tan^2 \frac{\theta}{2} \right) \right\}$$



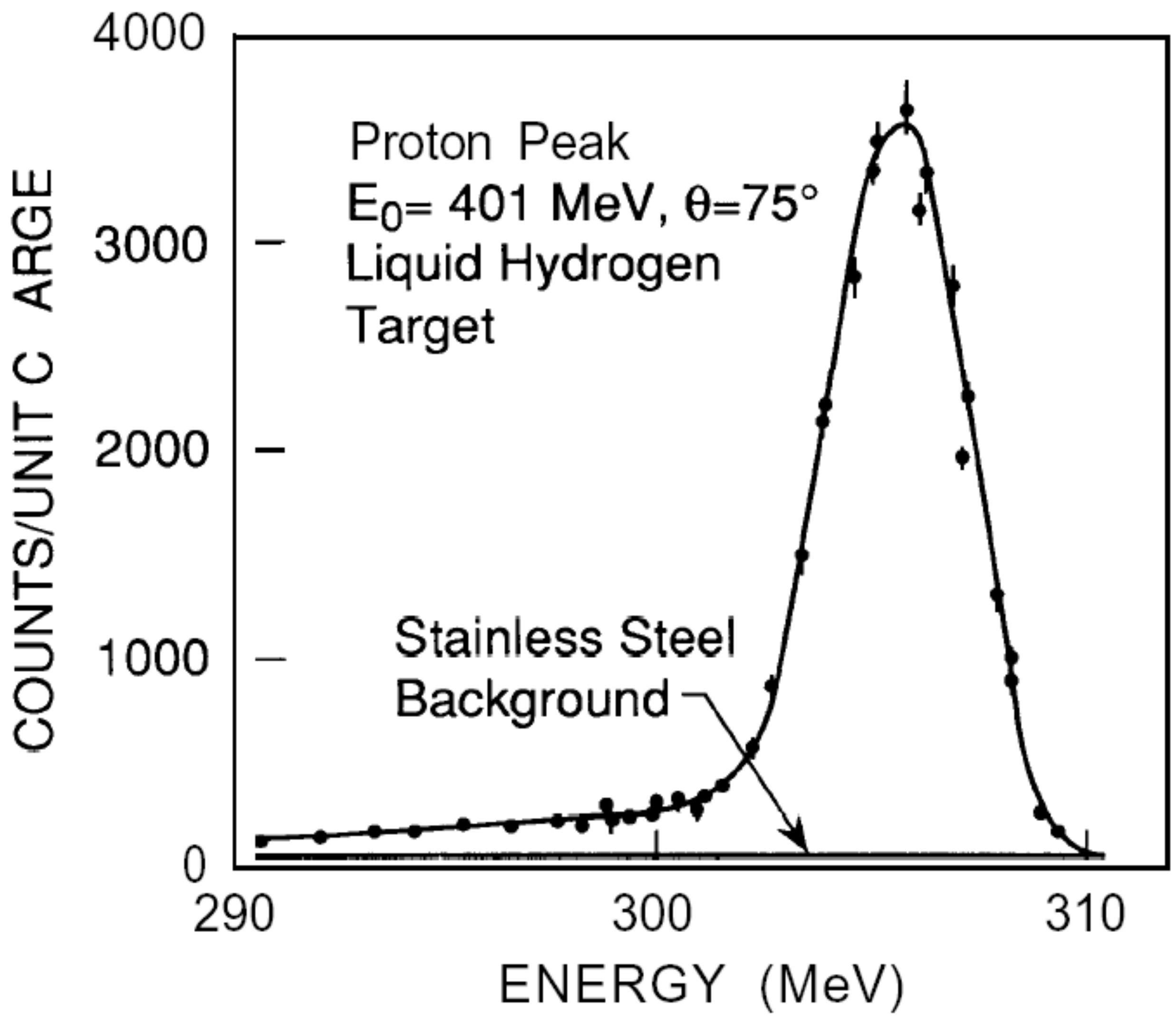
$$G_E{}^p(t) = F_1{}^p(t) + \frac{t}{2M} F_2{}^p(t)$$

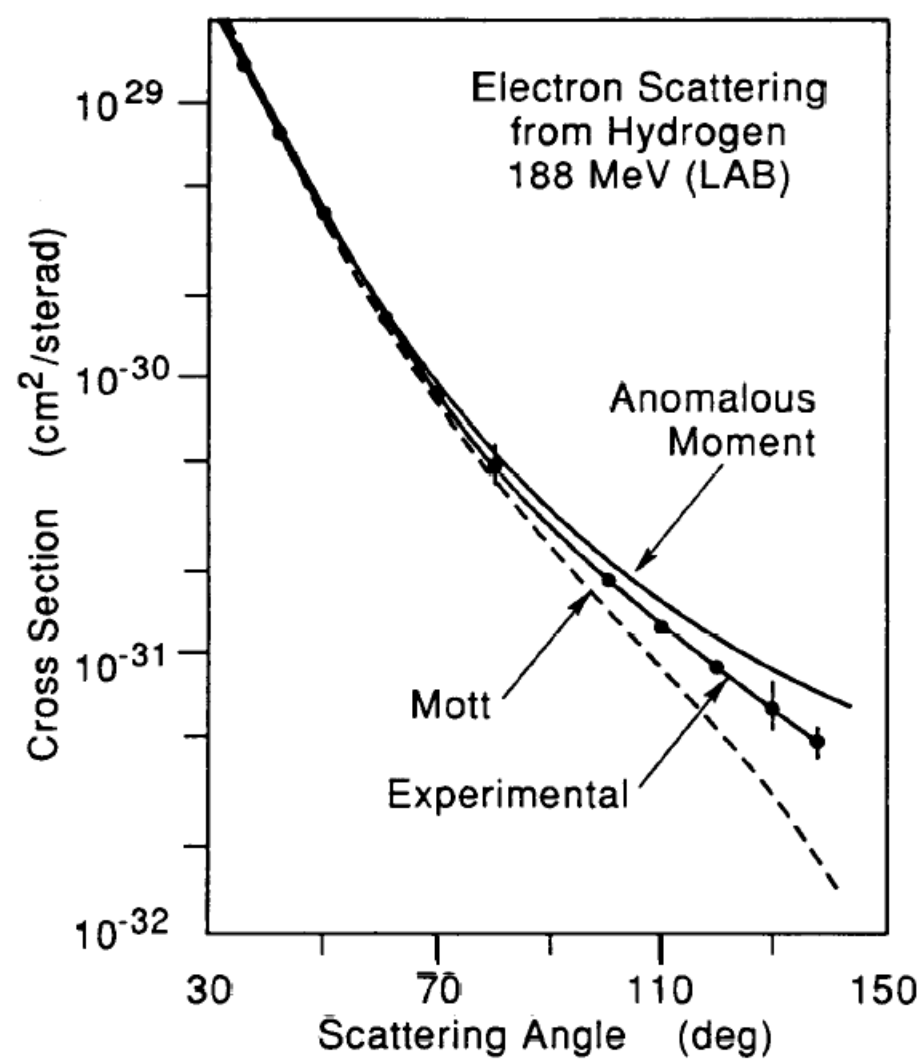
$$G_M{}^p(t) = F_1{}^p(t) + 2M\, F_2{}^p(t)$$

$$\frac{d\sigma}{d\Omega} = \left(\frac{d\sigma}{d\Omega}\right)_{\text{Mott}} \left\{ \frac{(G_E{}^p(t))^2 - \frac{t}{4M^2}(G_M{}^p(t))^2}{1 - t/4M^2} - \frac{t}{2M^2} (G_M{}^p(t))^2 \tan^2 \frac{\theta}{2} \right\}$$

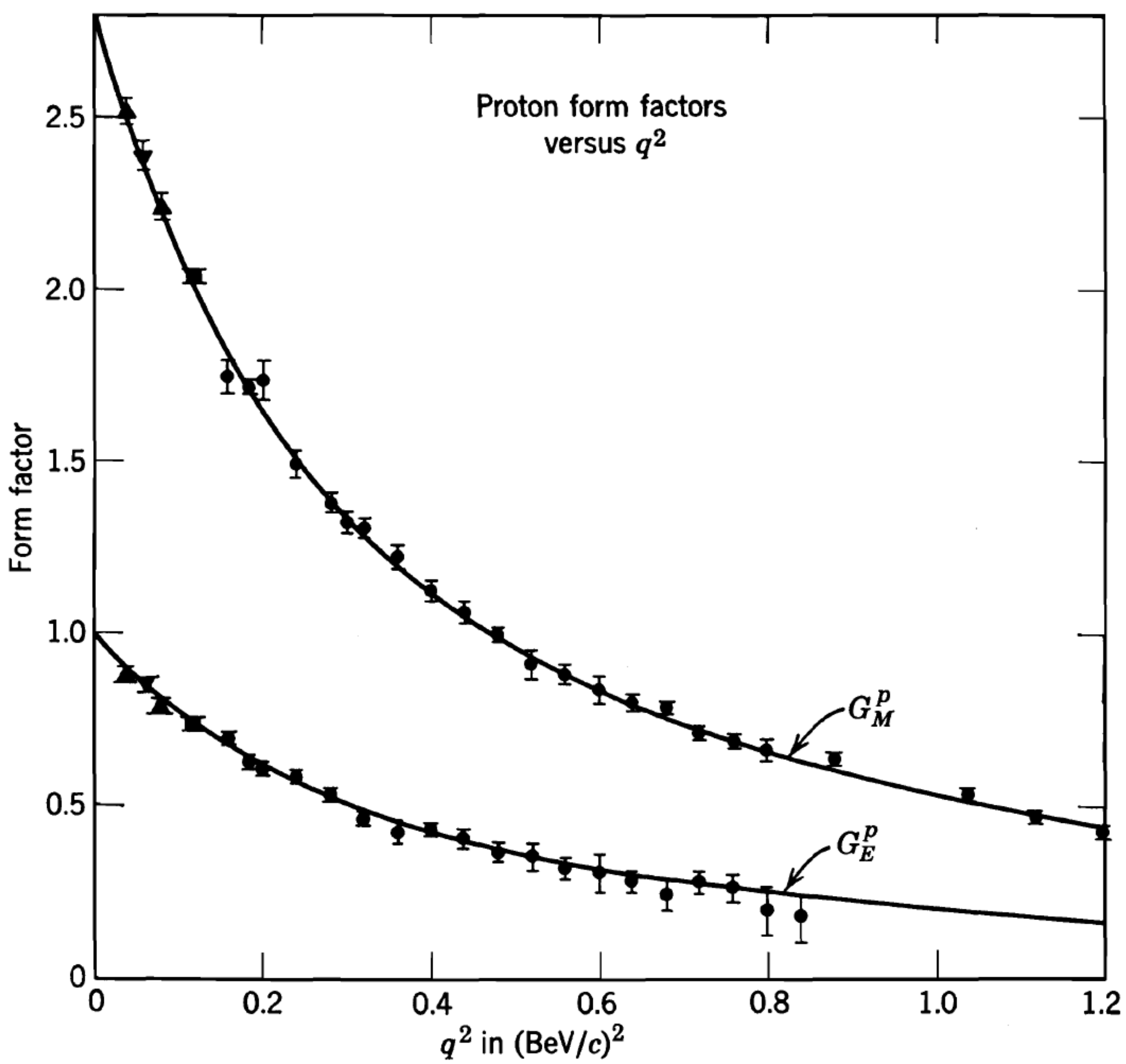
$$\left(\frac{d\sigma}{d\Omega}\right)_{\text{Mott}} = \frac{\alpha^2}{4E^2 \sin^4 \theta/2} \frac{\cos^2 \theta/2}{1 + (2E/M) \sin^2 \theta/2}$$

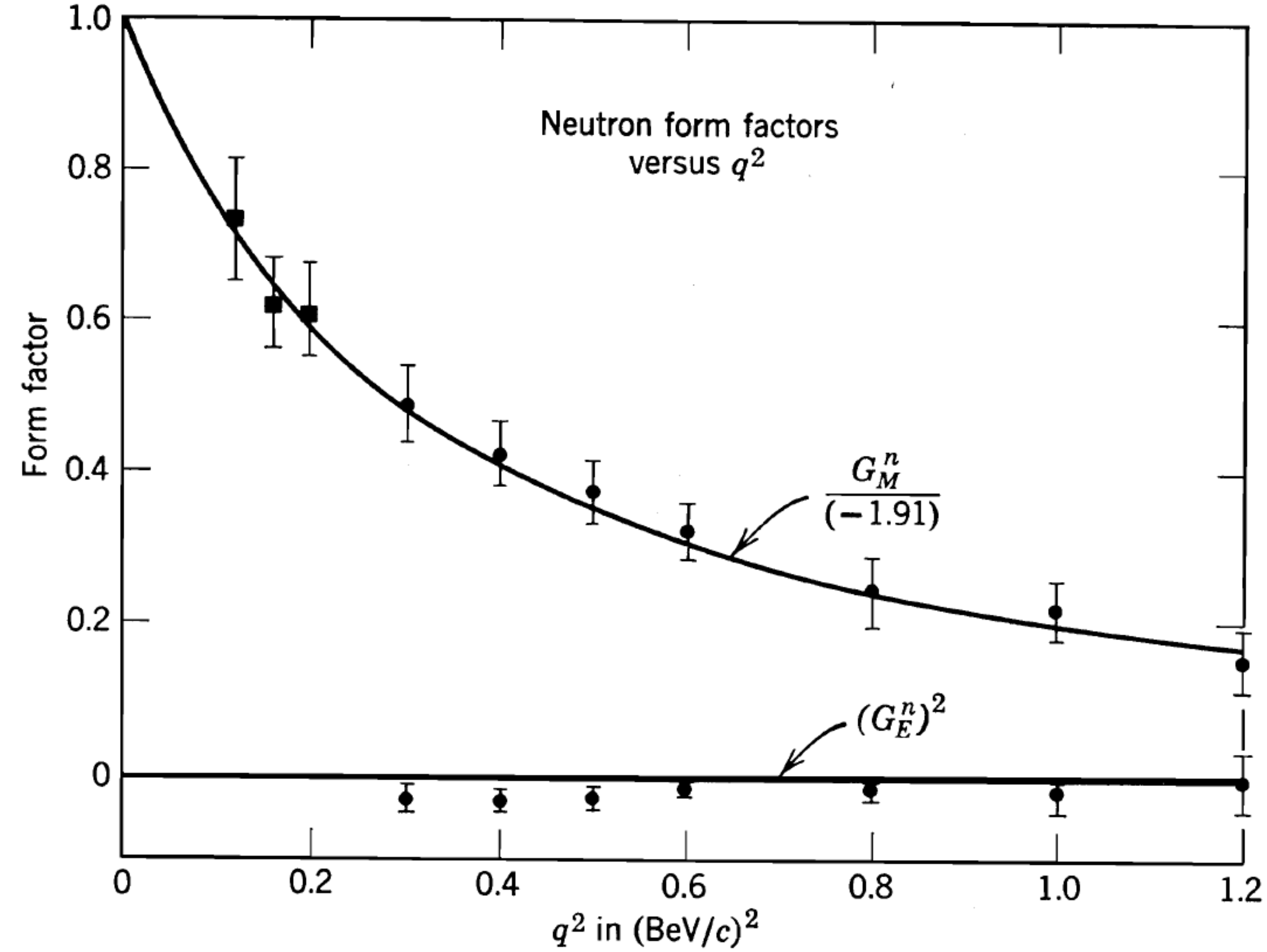
Nucleon Form Factors





Nucleon Form Factors





$$G_E^p(0) = 1$$
$$G_M^p(0) = 1 + \mu_p \cong 2.79$$

$$G_E^n(0) = 0$$
$$G_M^n(0) = \mu_n \cong -1.91$$


Nobel prize
1961

R. Hofstadter

"As we have seen, the proton and neutron, which were once thought to be elementary particles are now seen to be highly complex bodies. It is almost certain that physicists will subsequently investigate the constituent parts of the proton and neutron - the mesons of one sort or another. What will happen from that point on? One can only guess at future problems and future progress, but my personal conviction is that the search for ever-smaller and ever-more-fundamental particles will go on as Man retain the curiosity he has always demonstrated"

Nobel lecture 1961

Bibliography

Just an entry point (and references therein):