Irfu
Institut de recherche
sur les lois fondamentales
de l'Univers

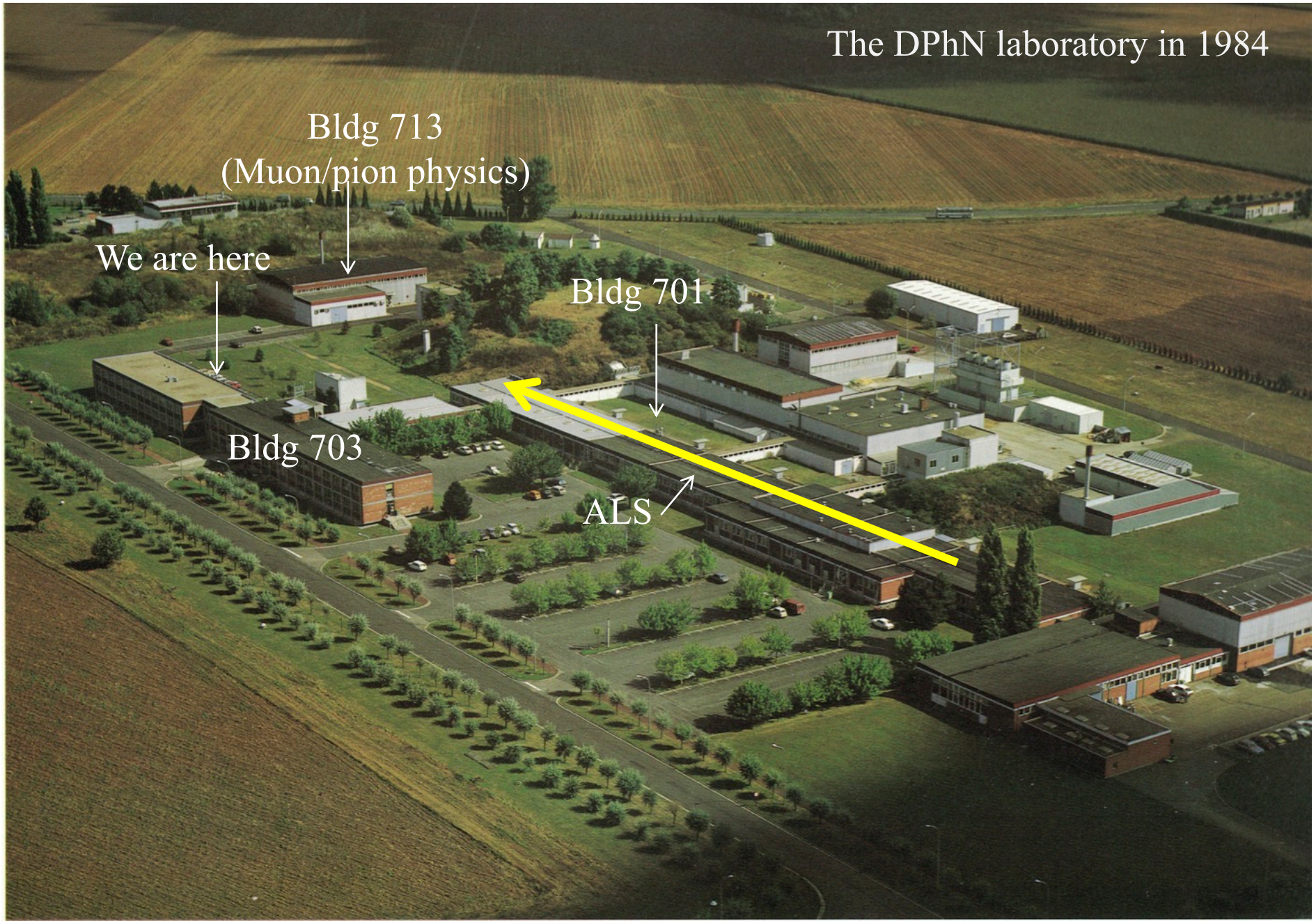
Irfu - CEA Saclay
Institut de recherche
sur les lois fondamentales
de l'Univers

Electron scattering at Orme des Merisiers

Selected results from ALS (**A**ccélérateur **L**inéaire de **S**aclay)

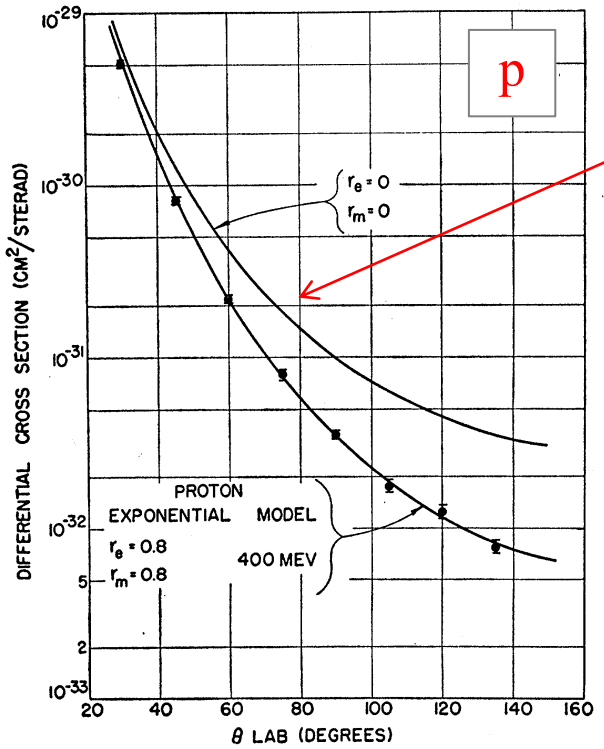
Stephane Platchkov

Paris-Saclay University, CEA/IRFU, France

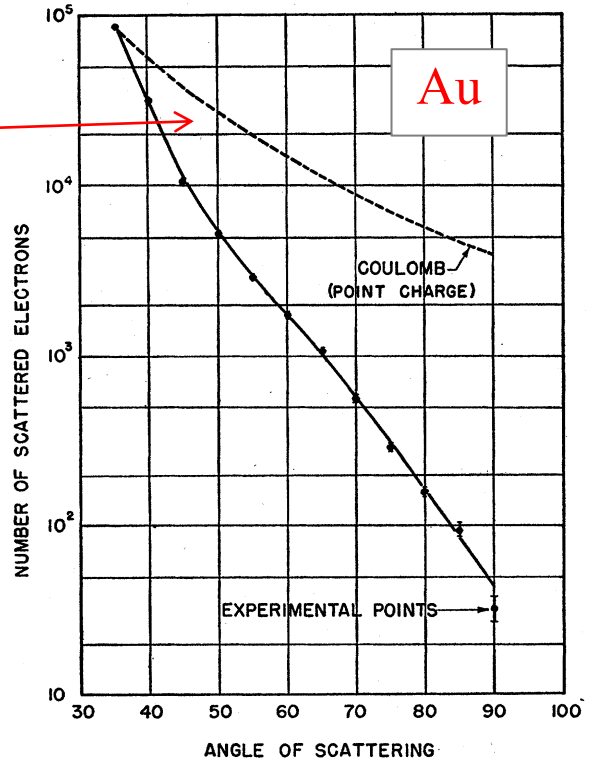

The DPhN laboratory in 1984
Bldg 713
(Muon/pion physics)
We are here
Bldg 701
Bldg 703
ALS

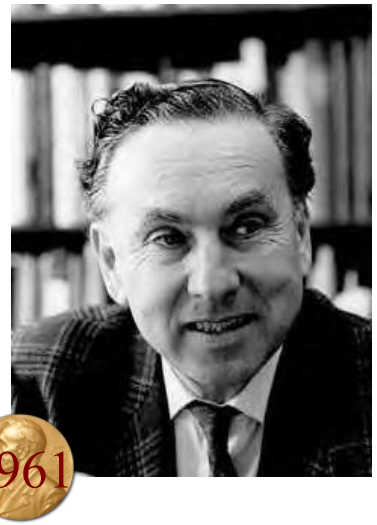
Electron scattering on nuclei – a glimpse of history

- 1951, Illinois Betatron: E = 15.7 MeV = => $R_A \sim 10^{-13} A^{1/3}$
- 1953 – mid 60's, Stanford, E = 100 – 500 MeV



POINT CHARGE calculation





R. Hofstadter (1915-1990)

- Followed by: Darmstadt, Mainz, Tohoku, Kharkov, MIT-Bates, Amsterdam, Saclay

ALS: Accélérateur Linéaire (d'électrons) de Saclay

- History
  - 1959: Original idea, proposed by Christophe Tzara
  - 1964: Project funded by the CEA
  - 1965: Construction begins
  - 1969: First beam on target (4 years!)

Christophe Tzara
(1927-2018)
ALS lead scientist
Chef de service
Physics "guru" until
~1987

Le Monde — Publié le 21 février 1969 à 00h00

Un nouvel accélérateur linéaire à électrons a été inauguré à Saclay par le ministre de la recherche

M. Galley, minisire de la recherche et des questions atomiques et spatiales, a inauguré mercredi un accélérateur de particules construit par le CEA, dans une annexe du contre d'éludés nucléaires de Saclay, l'Orme-des-Merisiers. Celle nouvelle machine, que l'on désigne sous le nom d'A.L.S. (Accélérateur linéaire de Saclay), doit permettre de conférer à des électrons une énergie de 600 millions d'électrons-volts (MeV) ; il permet des éludes nouvelles sur la

ALS: Accélérateur Linéaire (d'électrons) de Saclay

- Main linac characteristics
  - Length: 200 m
  - Energy: 150 to 700 MeV
  - Duty cycle: 1-2% (compare to 10^{-3} or 10^{-4} for older machines)
  - Pulse length: 10 μs
  - Rate: 1000 or 2000 p/s
  - Peak current: 60 mA
  - Mean current: up to 100 μA
- Detection systems
  - + High resolution: ~10^{-4}
  - + Lowest possible background

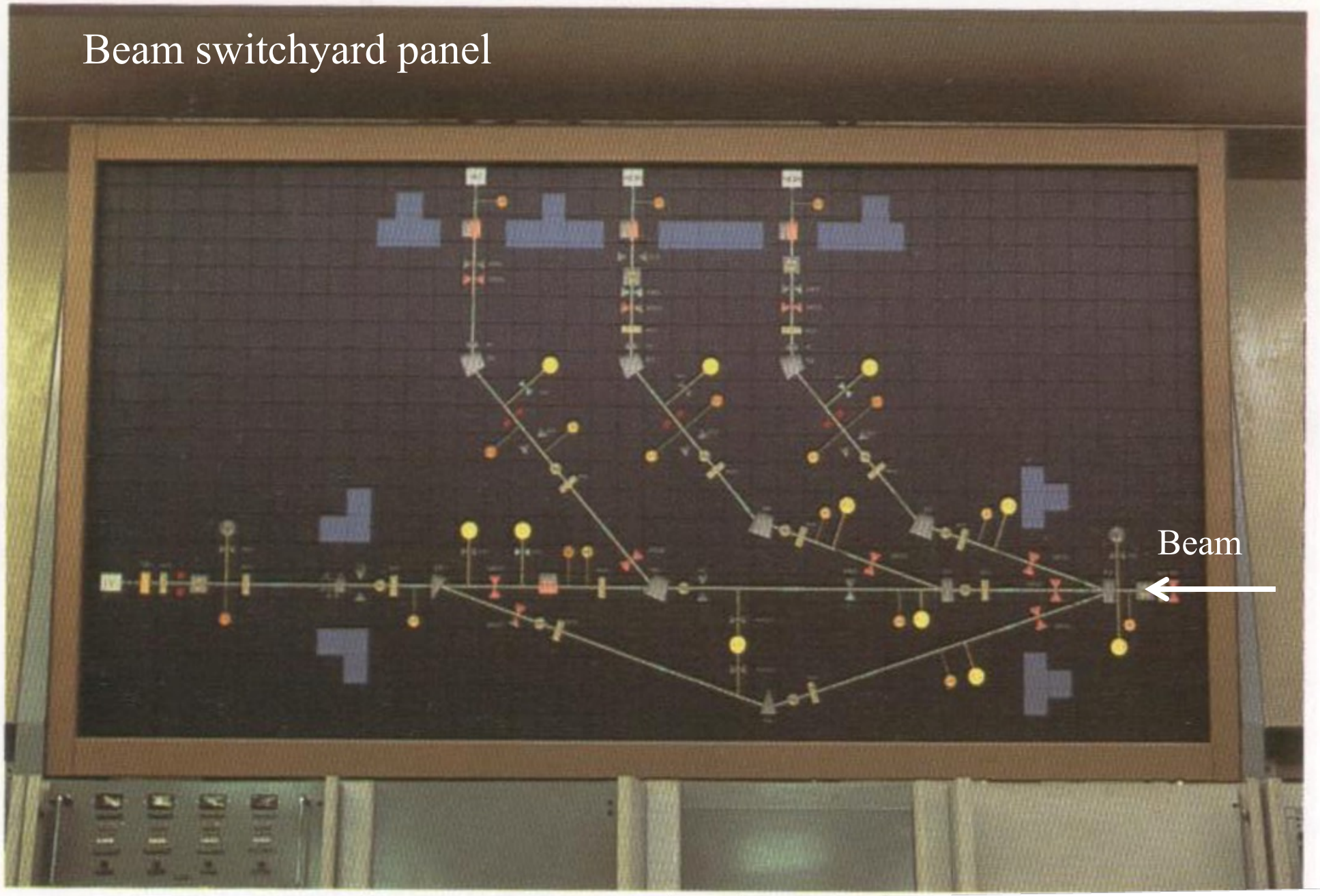
Albert Messiah
(1921-2013)
CEA director of
DPhN: 1965-1972
Physics: 1972-1982

talk at HEP Conference Columbia U., (USA) 1969:
...
§to be able to perform precision experiments with real or virtual photons of energy-momentum ranging from 100 to 500 MeV or more. This leads one to energies ranging up to 500 MeV, say, for the primary electron beam, together with order of magnitude improvements in the other beam characteristics, notably in intensity and duty cycle.

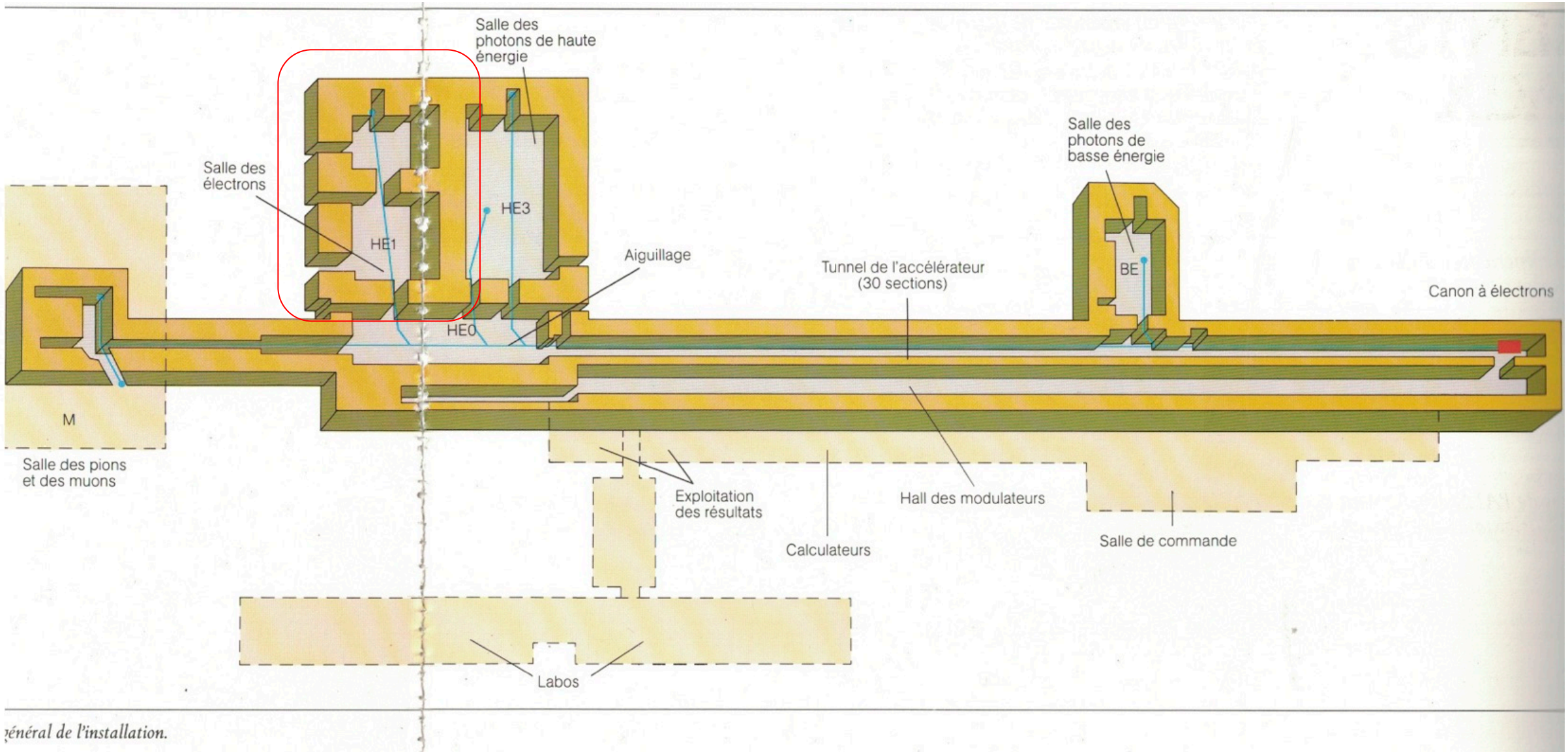
Accelerator tunnel

Main Control room

Beam switchyard panel



Simplified view of the laboratory (top view)

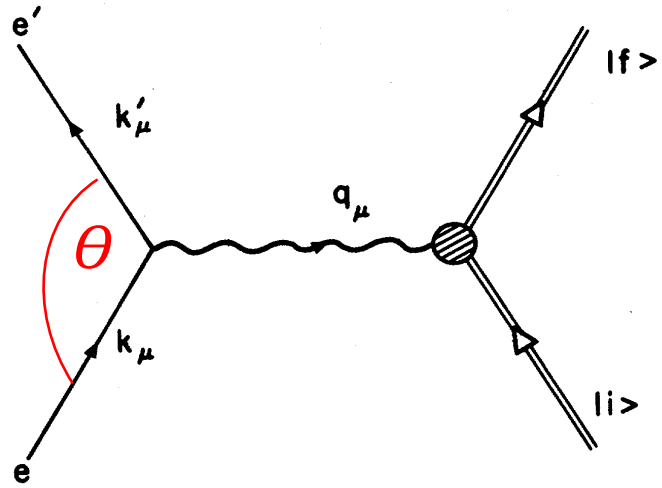


général de l'installation.

Electron scattering

- Main advantages:
  - EM interaction is weak ($\alpha = 1/137$)
  - EM interaction is known (QED)
  - One photon exchange is a very good approximation
  - Vary the 3-transfer q and the energy ω independently
  - Vary the polarization of the virtual photon

  + …



$$= q_\mu^2 = 4ee'\sin^2(\theta/2);\ \mathrm{q}_\mu = (\omega, q);\ \omega = e - e'$$

- Distance scale : nucleus is probed with a wavelength $\lambda \sim 1/q$
  - for q values of about 2-3 fm^{-1} (~0.5 GeV/c) probe distances smaller than 1 fm.

(nuclear physics: from 5-6 fm to 0.1 fm)

A microscope to probe the spatial structure of nuclei

Elastic electron scattering: basic reminders

- Point nucleus with charge Z, no spin (Mott, 1932):

$$\sigma_{Mott}(\theta) = \left(\frac{Ze^2}{2E}\right)^2 \frac{cos^2(\theta/2}{sin^2(\theta/2)}$$

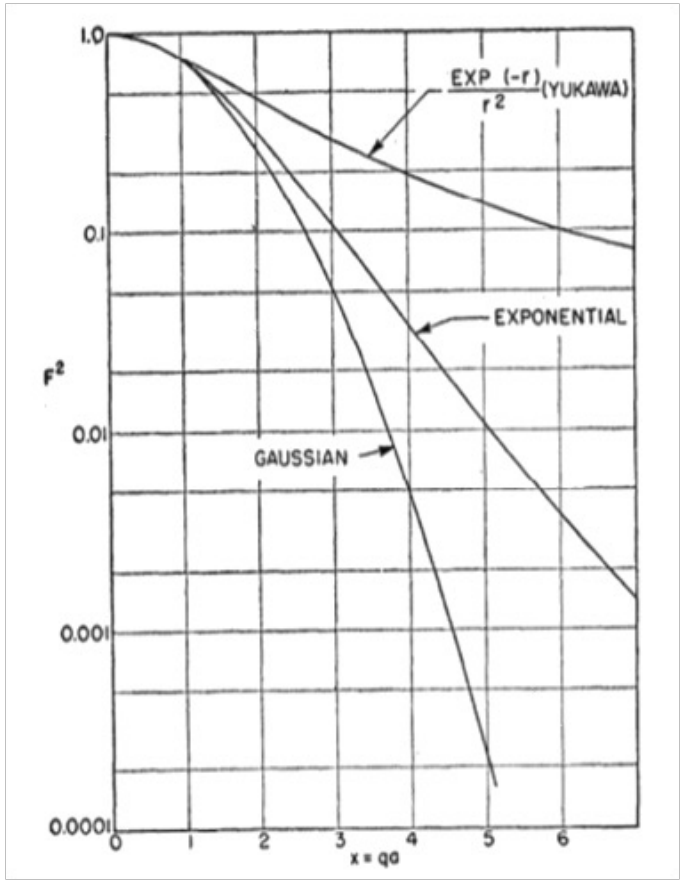
sir N.F. Mott (1905-1996)

- Finite size nucleus

$$\sigma_0 = \sigma_{Mott}(\theta).F_{ch}^2(q)$$

- Form factor $F_{ch}(q)$: (r = radius)

$$F_{ch}(q) \propto \int_0^\infty \rho(r) \frac{\sin(qr)}{qr} r^2 \, dr$$

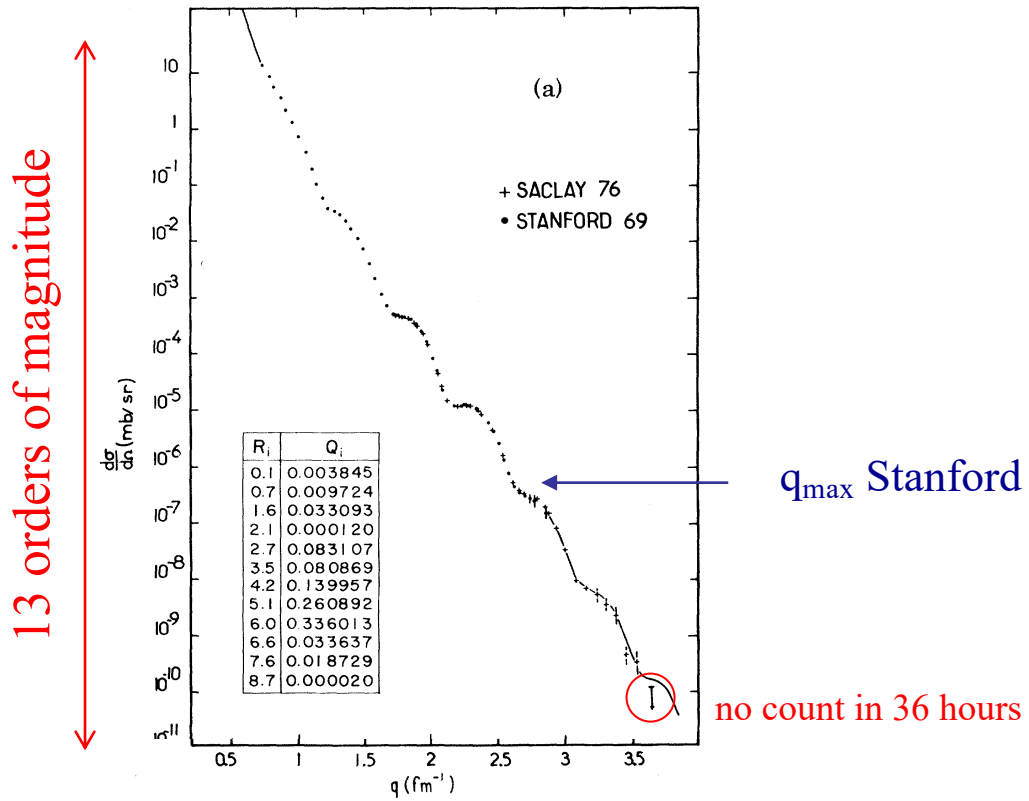


Possible models for $\rho_{ch}(r)$ (Hoftsadter, 1956)

The charge form factor is a Fourier transform of the nuclear charge distribution

Nuclear charge distributions

- Cross section for (e,e') on ^{208}Pb

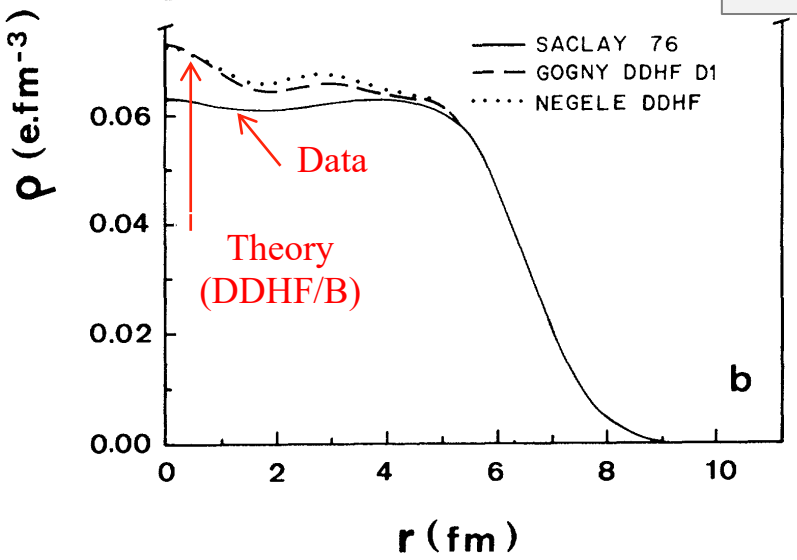


R_i	Q_i
0.1	0.003845
0.7	0.009724
1.6	0.033093
2.1	0.000120
2.7	0.083107
3.5	0.080869
4.2	0.139957
5.1	0.260892
6.0	0.336013
6.6	0.033637
7.6	0.018729
8.7	0.000020

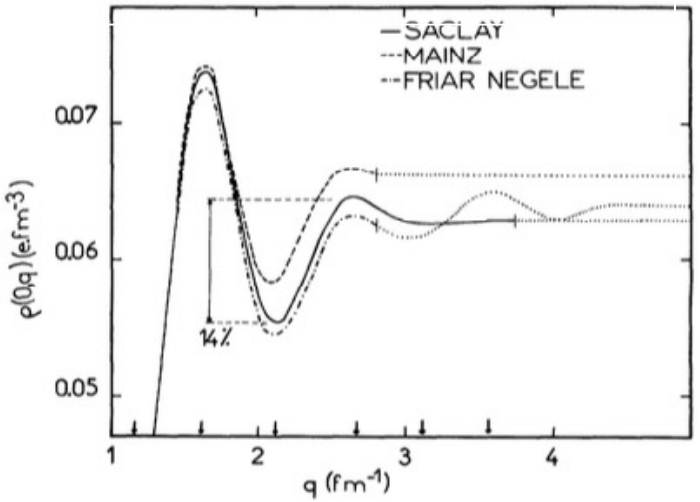
Precise determination of the charge density down to r = 0 fm

Charge density

Frois et al., PRL 38, 152 (1977)

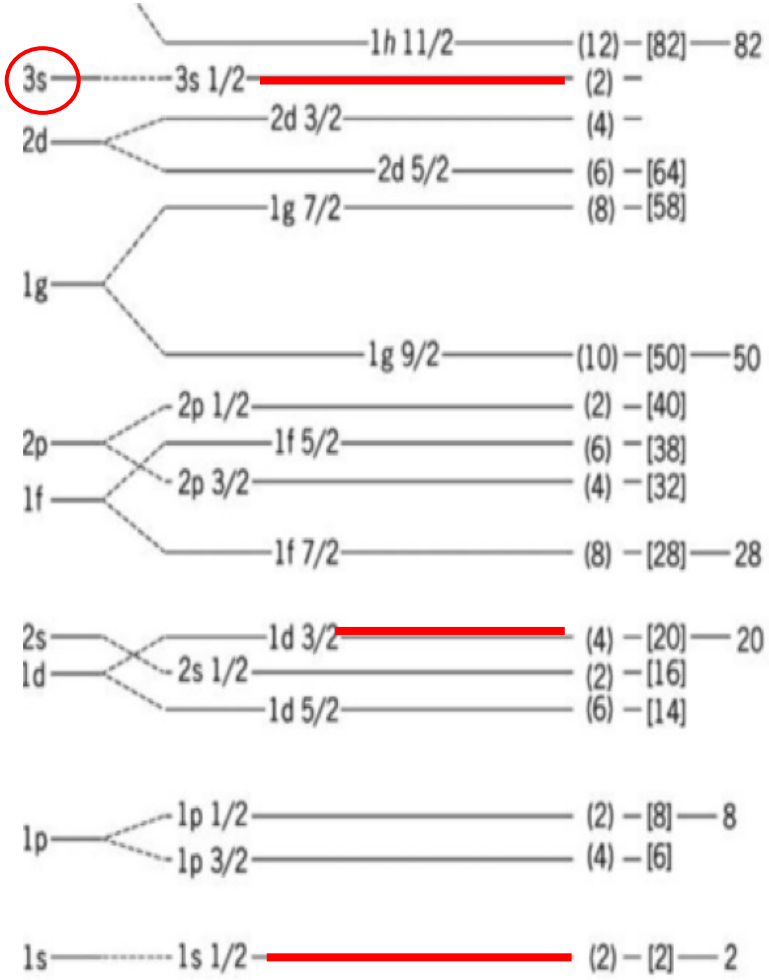


Error estimates vs q (fm^{-1})

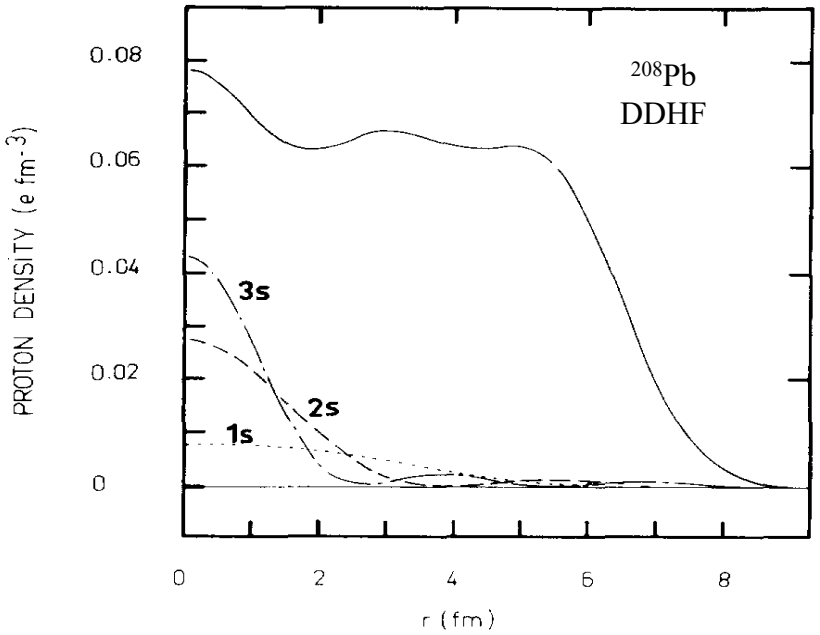


Where is the difference coming from?

- Nuclear shell model near ^{208}Pb



Predicted 1s, 2s and 3s charge densities

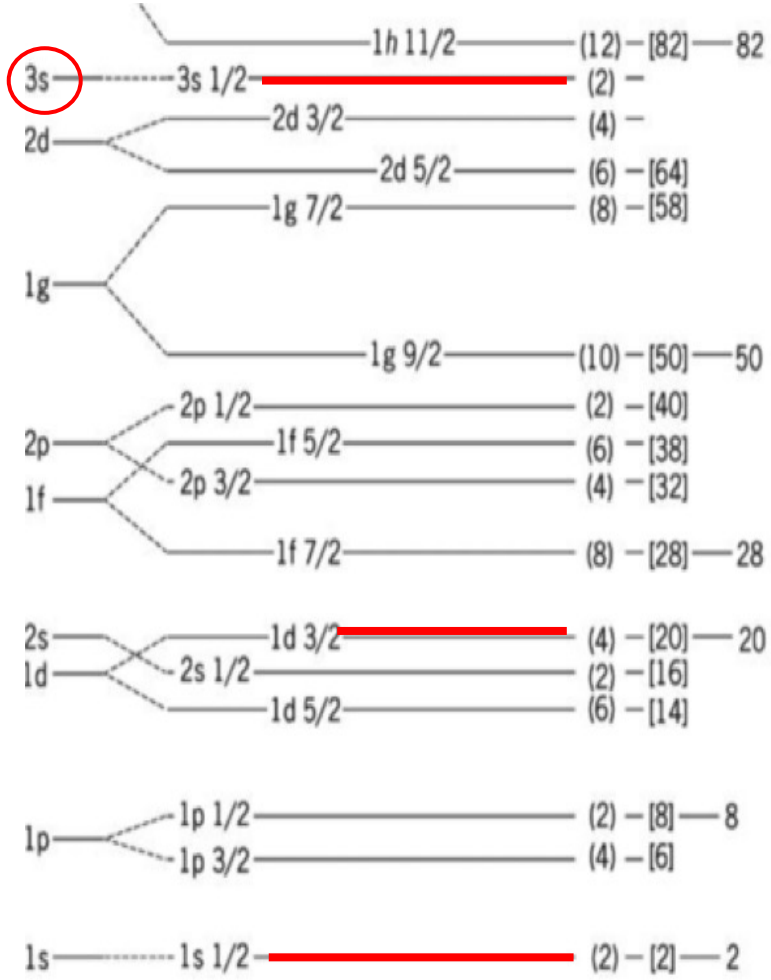


Should we trust the shell model in the nuclear interior?
=> Need a measurement of the most inner, 3s, orbit

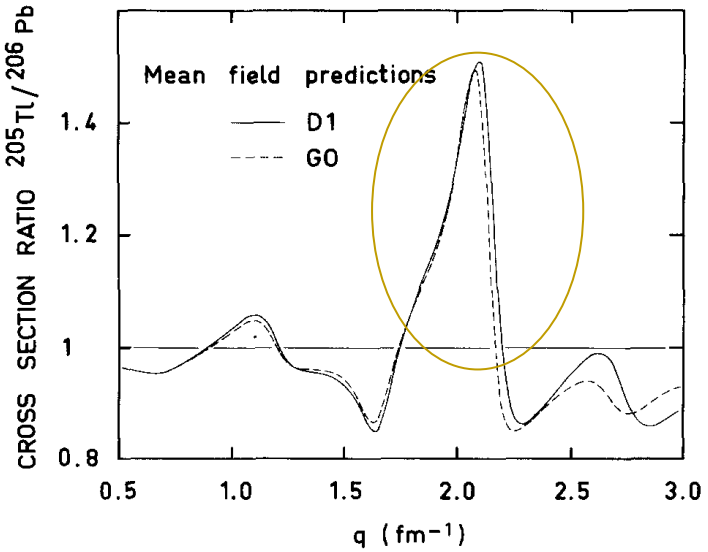
Isolate the 3s proton orbit

- Charge densities of ^{206}Pb and ^{205}Tl: differ by one 3s proton

Cavedon et al.,
PRL 49, 978 (1982)



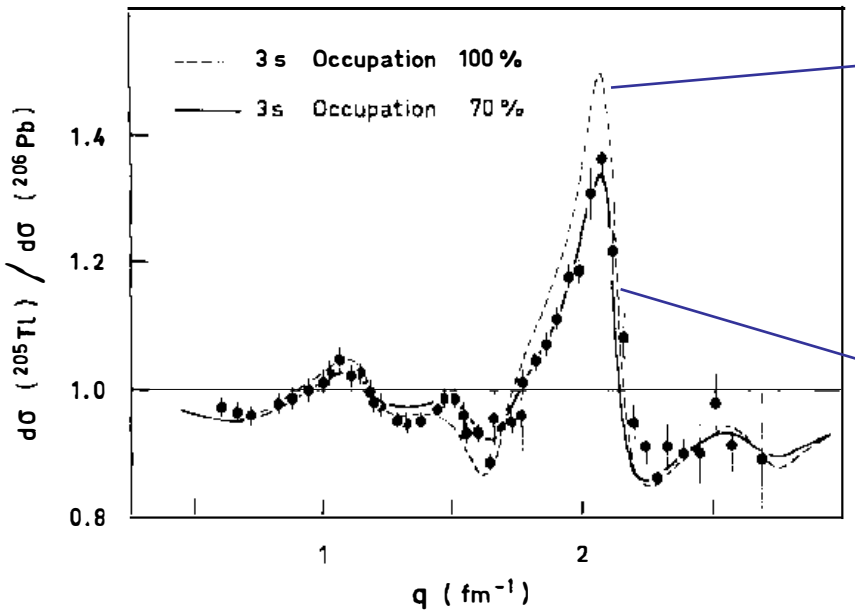
Predicted ^{205}Tl/^{206}Pb cross section ratio (DDHF)



The 3s difference in ρ(r) results in a large peak around q = 2 fm^{-1}

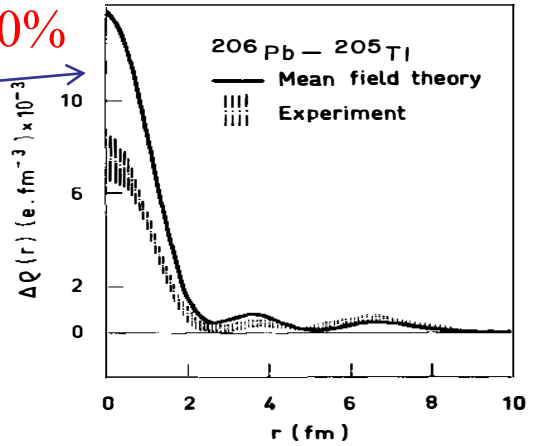
What about the 3s proton orbit?

Experimental $^{205}Tl/^{206}Pb$ cross section ratio (DDHF)

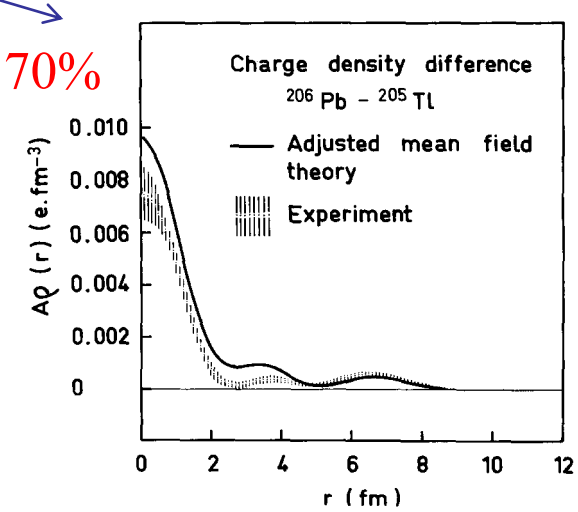


Density differences

3s = 100%



3s = 70%



Cavedon et al., PRL 49, 978 (1982)

1/ Shell model concept is valid in the nuclear interior
2/ Shape of the 3s orbit is well described in DDHF(B).
3/ Configuration mixing is about 30%

Charge density distributions for doubly-closed shell nuclei

Frois and Papanicolas, ARNPS 37, 133 (1987)

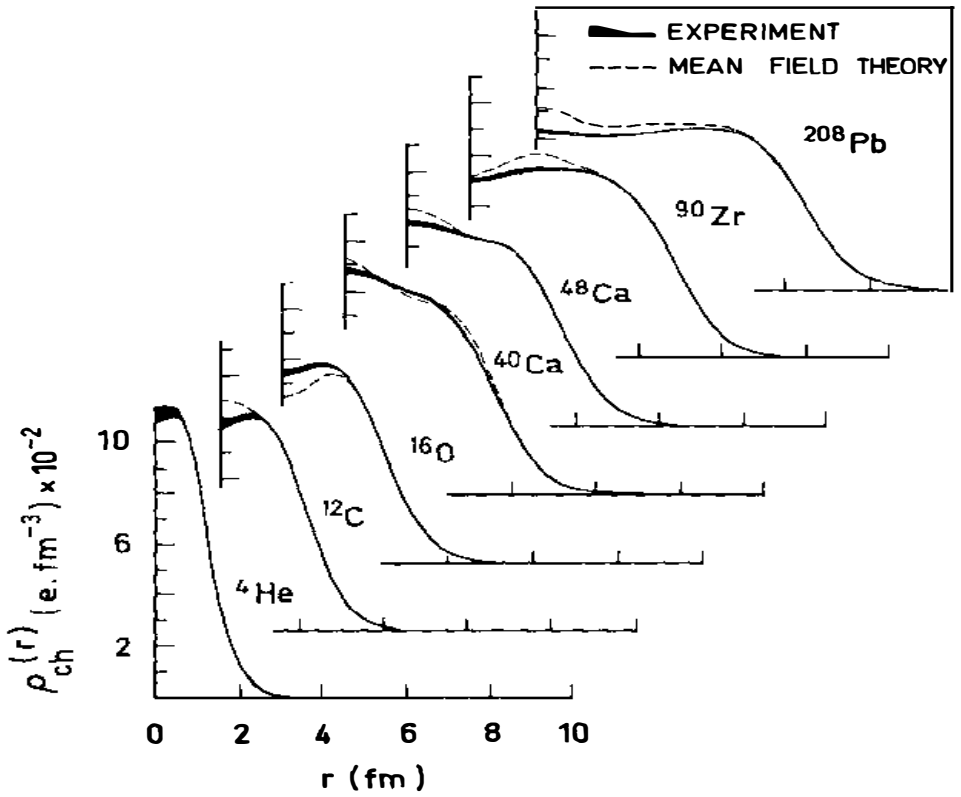


Figure 8 Charge density distributions of doubly closed-shell nuclei. The thickness of the solid line depicts the experimental uncertainty. The mean field calculations are from (53).

Overall good agreement between mean-field theory and data
No specific trend as a function of A

ALS: HE1 experimental hall: (e,e') and (e,e'p)

P. Leconte et al.,
NIM 169, 401 (1980)

TOP VIEW

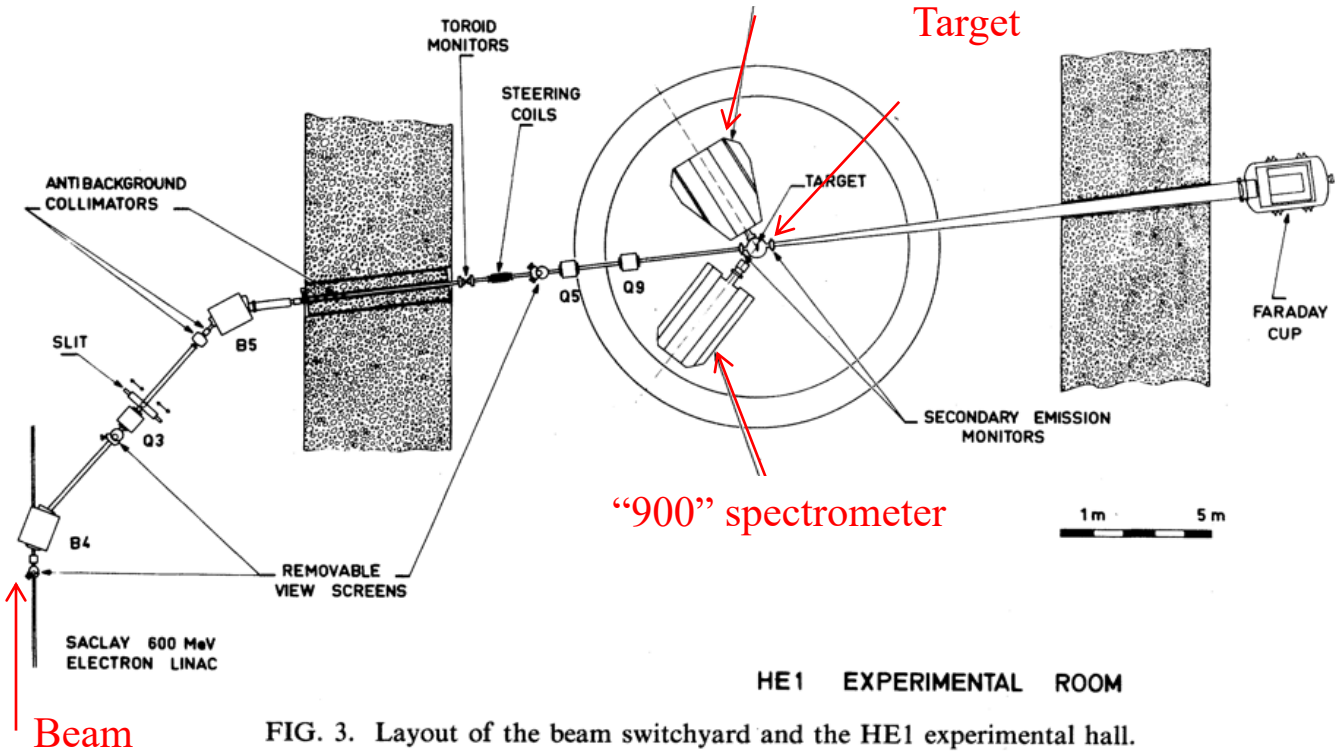
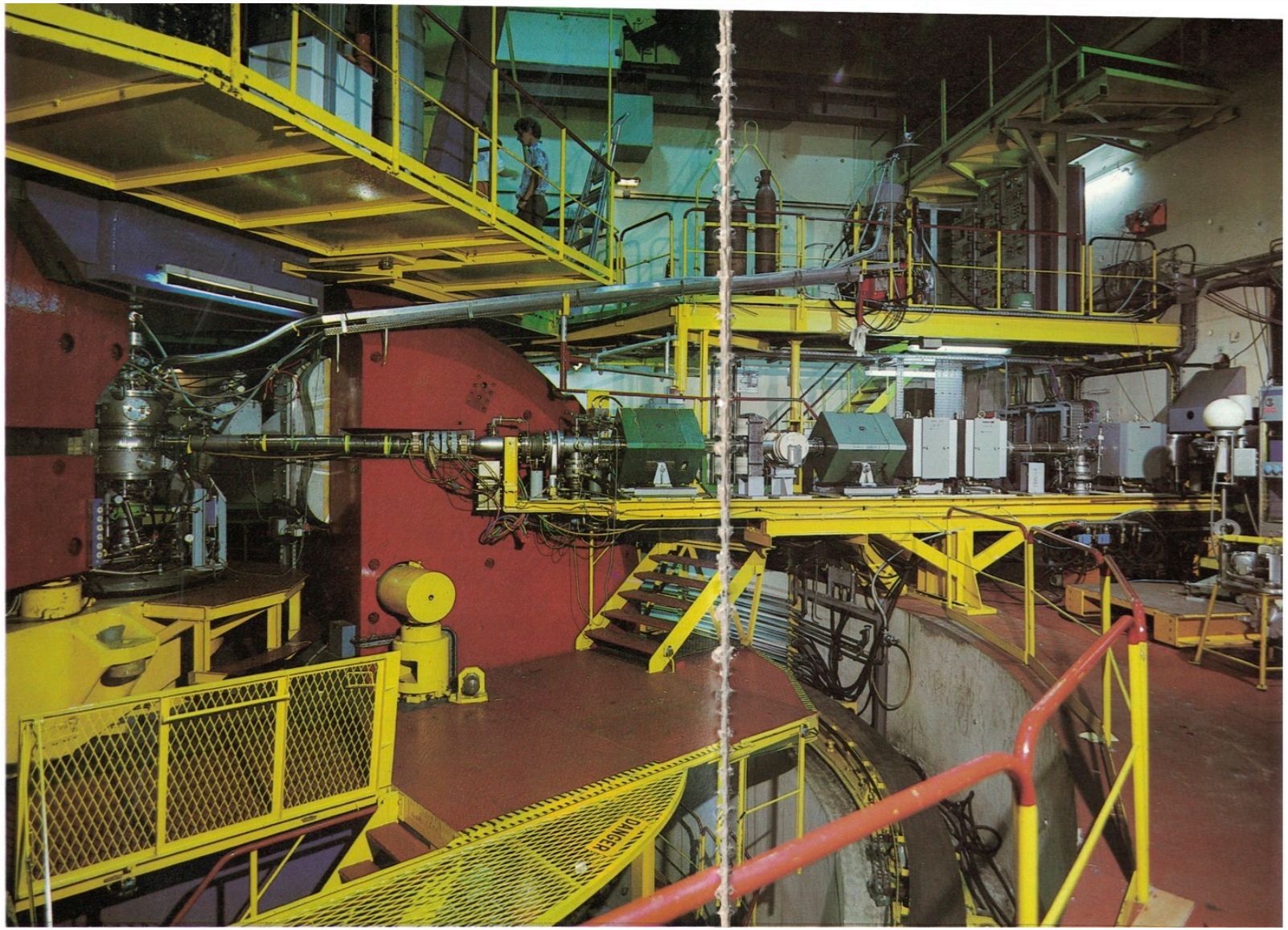


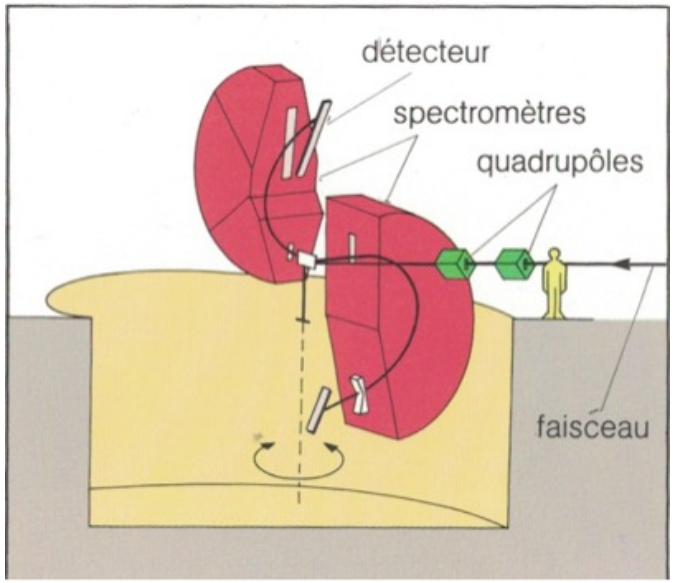
FIG. 3. Layout of the beam switchyard and the HE1 experimental hall.

The fathers of the HE1 experimental hall

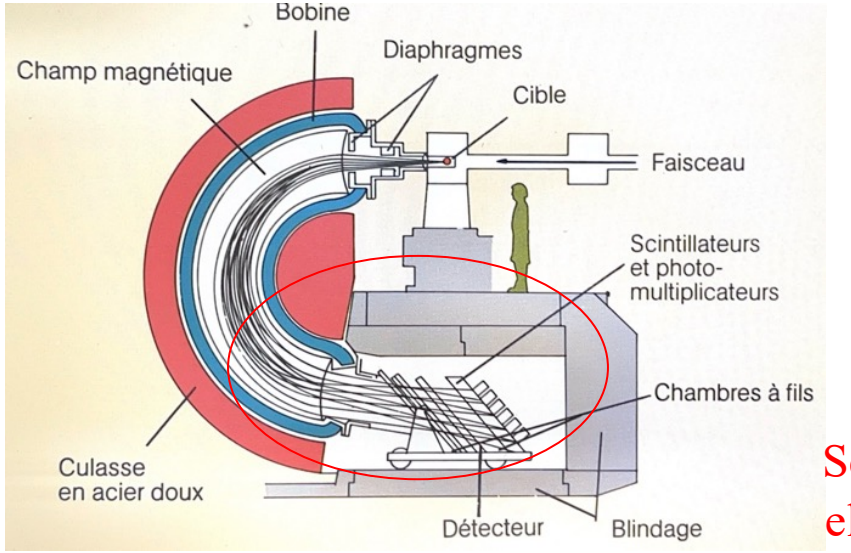
Philippe Leconte

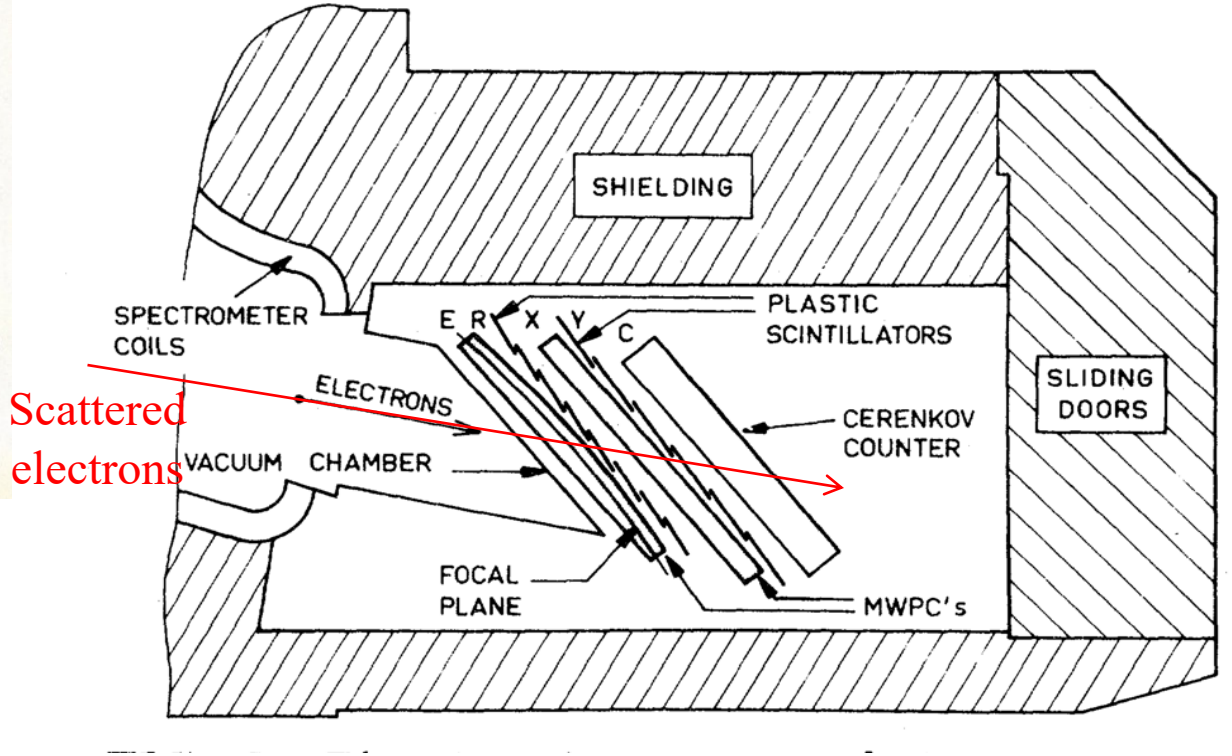
Jean Mougey




détecteur
spectromètres
quadrupôles
faisceau

Detector casemate





Scattered electrons

Example for ^{208}Pb:

36 hours without a single count in the elastic peak region

Excellent shielding: mandatory for low cross-section measurements

Electron scattering: a spin J_0 nucleus

- General case (elastic or inelastic)

Donnelly and Walecka, ARNPS, 329 (1975)

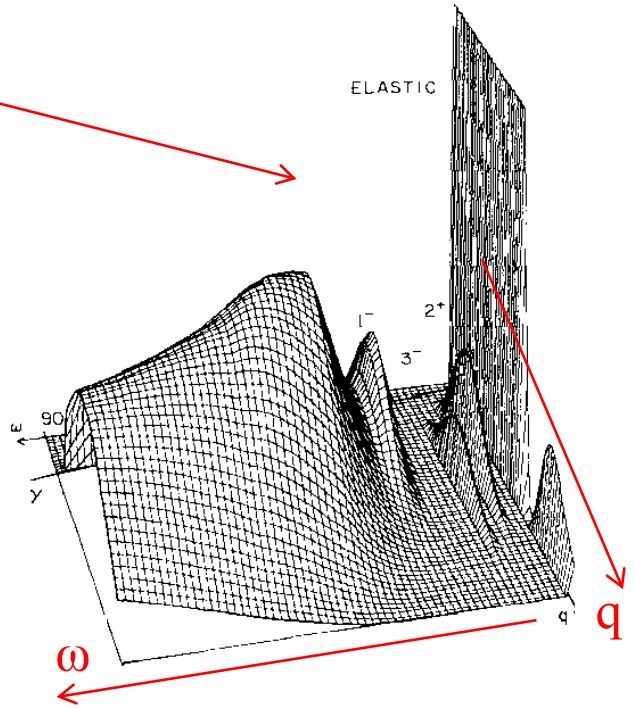
$$\frac{d\sigma}{d\Omega dE} = \frac{4\pi}{M}\sigma_{Mott}\eta^{-1}\left[\frac{q_\mu^2}{q^2}S_L(q,\omega) + \left(\frac{1}{2}\frac{q_\mu^2}{q^2} + \tan^2\frac{\theta}{2}\right)\frac{q_\mu^2}{q^2}S_T(q,\omega)\right]$$

- For elastic scattering : (ω=0)

$$\frac{d\sigma}{d\Omega}(q) = \sigma_{Mott}\eta^{-1}\left[F_L^2(q) + \left(\frac{1}{2} + \tan^2\frac{\theta}{2}\right)F_T^2(q)\right]$$

$$F_L^2(q) = \sum_{J=0}^{2J_0} F_{CJ}^2(q) = \frac{4\pi}{2J_0+1}\sum_{even\ J}\left|\left\langle \psi_A \middle\| M_J^{Coul}(q) \middle\| \psi_A \right\rangle\right|$$

$$F_T^2(q) = \sum_{J=0}^{2J_0} F_{MJ}^2(q) = \frac{4\pi}{2J_0+1}\sum_{J=0}^{2J_0}\left|\left\langle \psi_A \middle\| \hat{T}_J^M(q) \middle\| \psi_A \right\rangle\right|$$



Radial extension of an individual nucleon orbit?

Donnelly and Walecka,
Nucl. Phys. A201, 81 (1973).

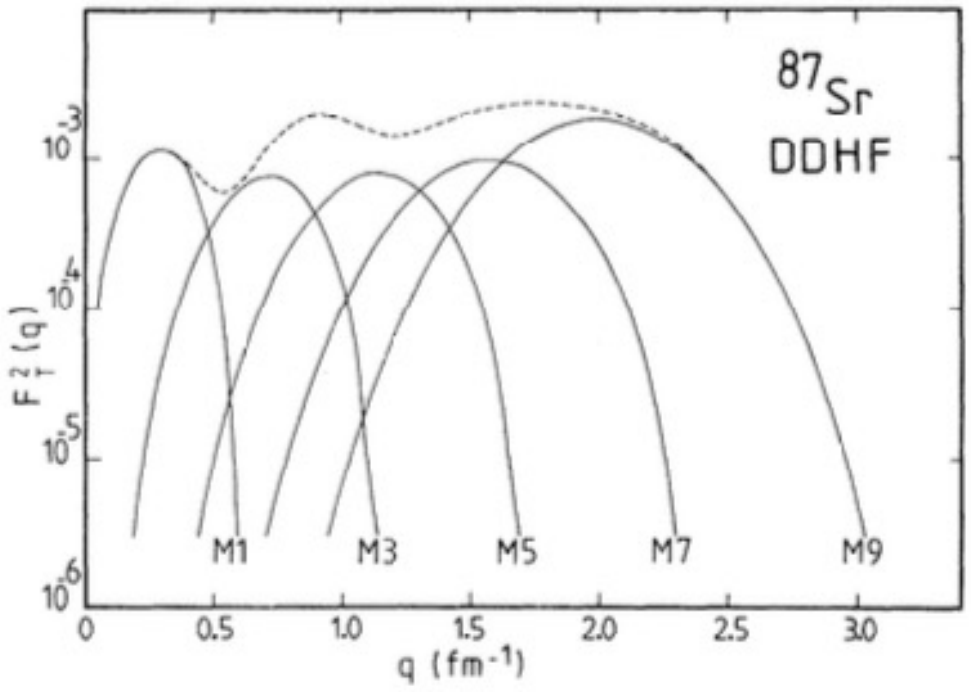
- Magnetic (on the magnetization distribution) electron scattering
  - On $J_0 \neq 0$ nuclei

$$\frac{d\sigma}{d\Omega}(q) = \sigma_{Mott}\eta^{-1}\left[F_L^2(q) + \left(\frac{1}{2} + \tan^2\frac{\theta}{2}\right)F_T^2(q)\right]$$

- Magnetic (odd) multipoles
  - M1, M3, … MΛ ($\Lambda = 2J_0$)
  - example: $^{87}Sr_{38}$ (neutron $1g_{9/2}$)

$$F_T^2(q) = \sum_{J=0}^{2J_0} F_{MJ}^2(q) = \frac{4\pi}{2J_0+1}\sum_{J=0}^{2J_0}\left|\left\langle \psi_A \left\| \hat{T}_J^M(q) \right\| \psi_A \right\rangle\right|$$

- Properties of multipoles
  - MJ: peak at different q values
  - M1 – M7: config. mixing
  - M9: easy to isolate at high q



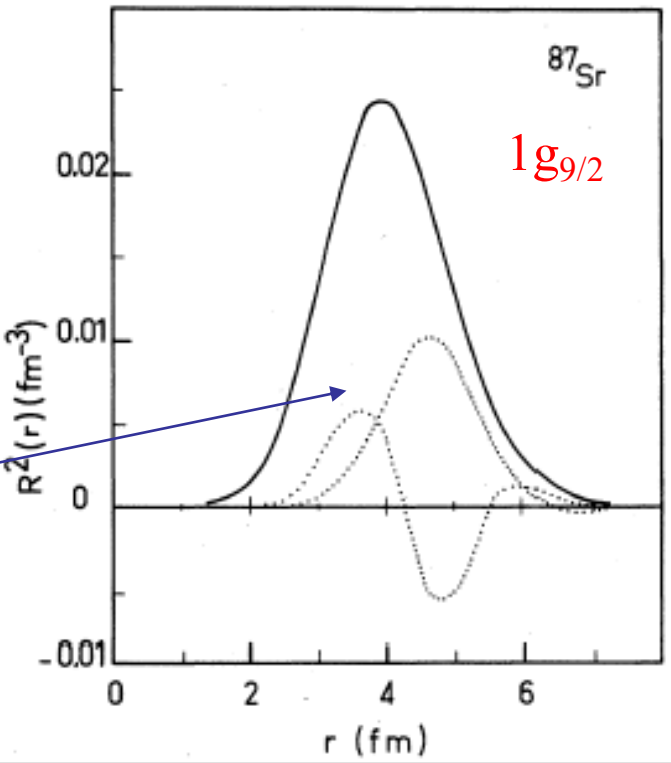
Valence proton and neutron radial distributions

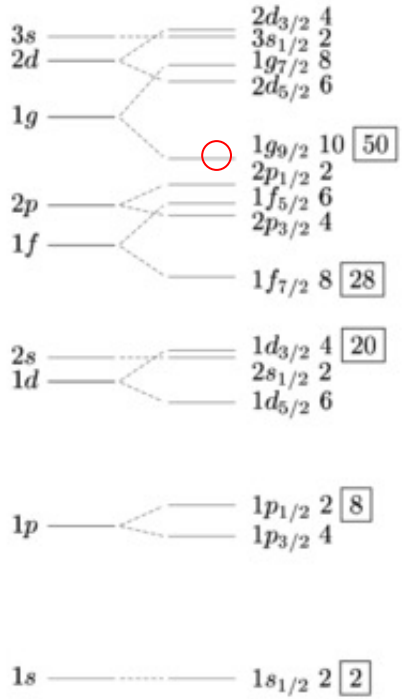
- Simplification for "stretched" spin configurations: $J_0 = l + \frac{1}{2}$
  - Spin: highest one of all filled shells
  - Multipole $\Lambda = 2J_0$: only intrinsic magnetization
  - No conf. mixing from other nucleons
  - Valid for protons and neutrons

$$F_{M\Lambda}(q) = C_\Lambda \alpha_\Lambda \mu \int_0^\infty R^2(r) j_{\Lambda-1}(qr) r^2 \, dr$$

- Example: ^{87}Sr

$$F_{M9}(q) \propto \int_0^\infty R^2(r) j_8(qr) r^2 \, dr$$



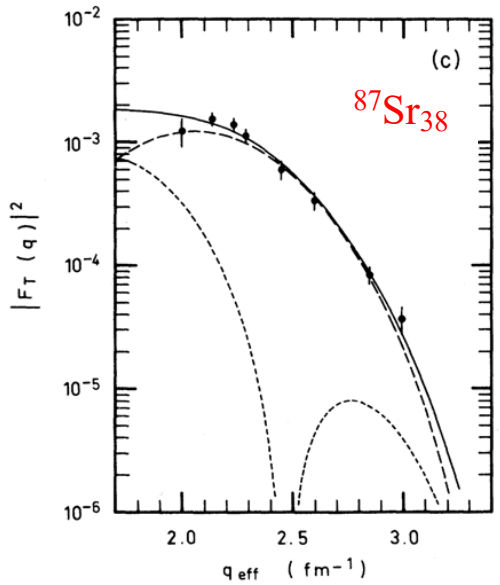


A clean way to measure both the radius and the shape of the valence nucleons

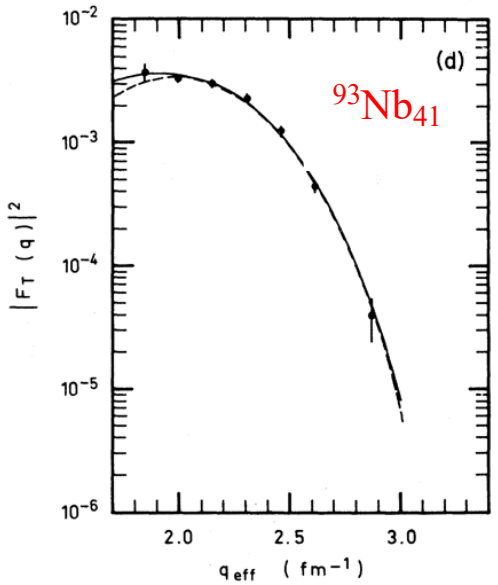
Valence neutrons and protons : ^{87}Sr and ^{93}Nb

Sick at al., PRL 38,1259 (1977).

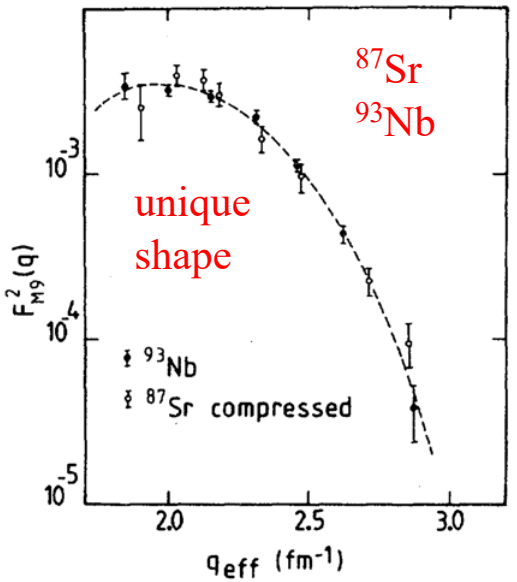
g9/2 neutron



g9/2 proton



Platchkov at al., Phys. Rev. C25, 2318 (1982).



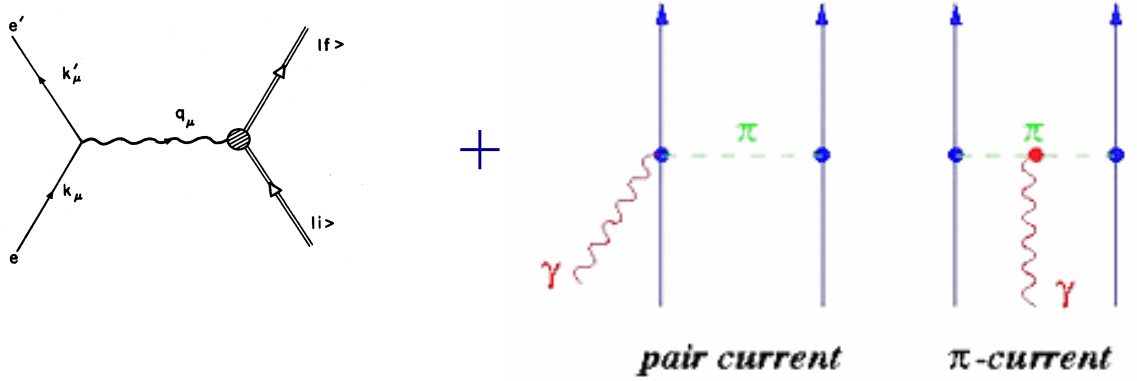
- Radii of the $1g_{9/2}$ orbit

Nucleus	Orbit	Valence radius (fm) DDHFB	WS	WS + MEC	
^{87}Sr	$1g^n_{9/2}$	4.832	4.756(72)	4.823(76)	neutron N = 49
^{93}Nb	$1g^p_{9/2}$	4.931	4.897(58)	4.946(64)	proton Z = 41

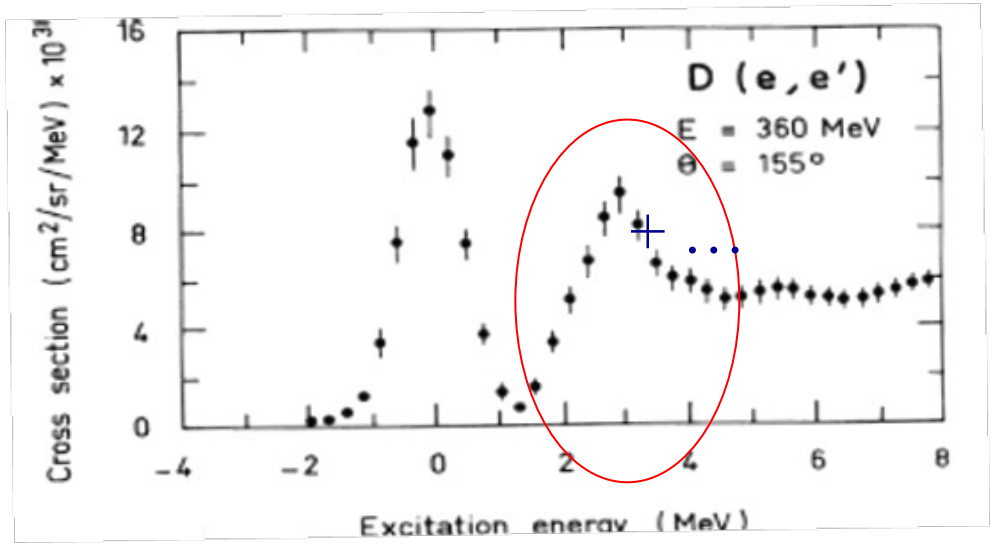
Proton and neutron $1g_{9/2}$ orbits have the same shape
The neutron radius looks slightly smaller (2.5% ± 2%): no neutron halo

Evidence for meson-exchange currents

- Meson exchange contributions



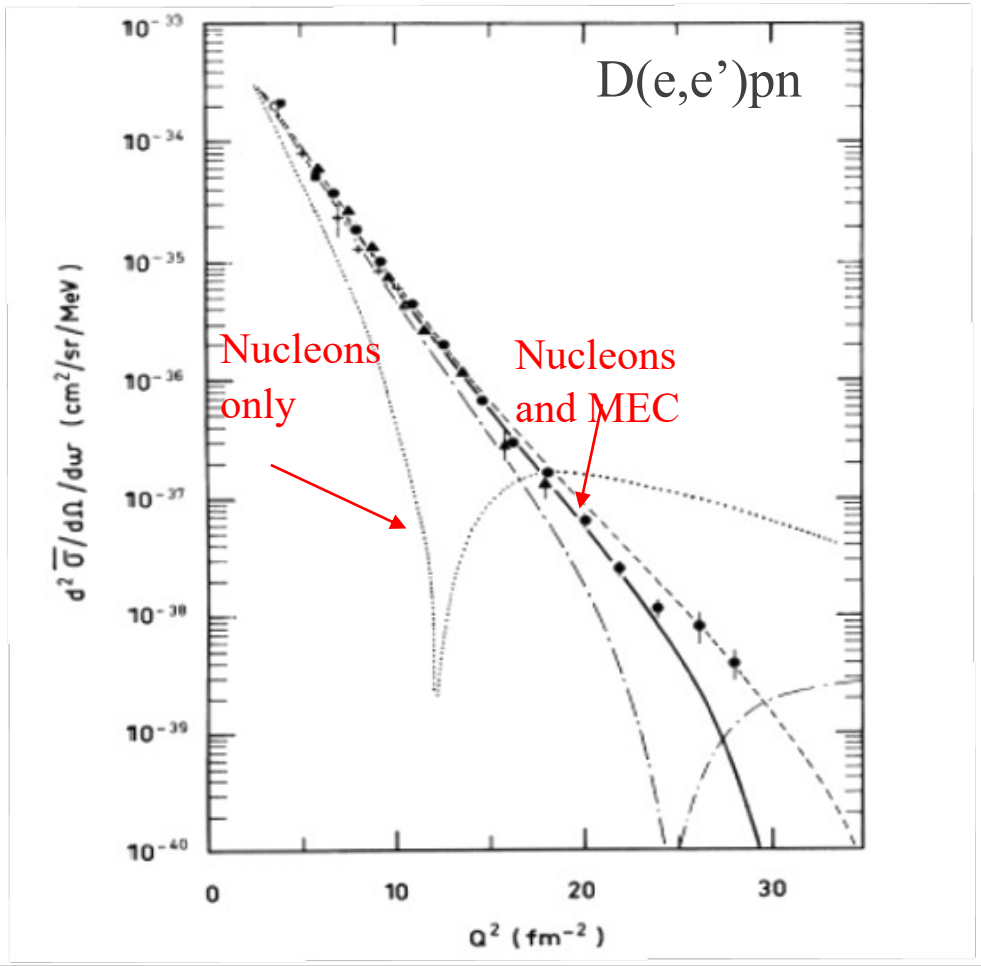
- => Electro-disintegration at threshold d(e,e')pn
  - Deuteron binding energy: 2.2 MeV
  - Threshold = cross section near 2.2 MeV ($^1S_0$)
  - Deuteron: $^3S_1$ (95%) and $^3D_1$ (~5%) states
  - Two transitions: $^3S_1 \rightarrow {}^1S_0$ and $^3D_1 \rightarrow {}^1S_0$



Evidence for meson-exchange currents in the deuteron

- Electro-disintegration at threshold d(e,e')pn

Bernheim et al., PRL 46, 402 (1981)
Auffret et al., PRL 55, 1352 (1985)



Nucleon + meson theory provides good explanation of the data (up to $q^2 = 28$ fm^{-2})

The neutron electric charge distribution?

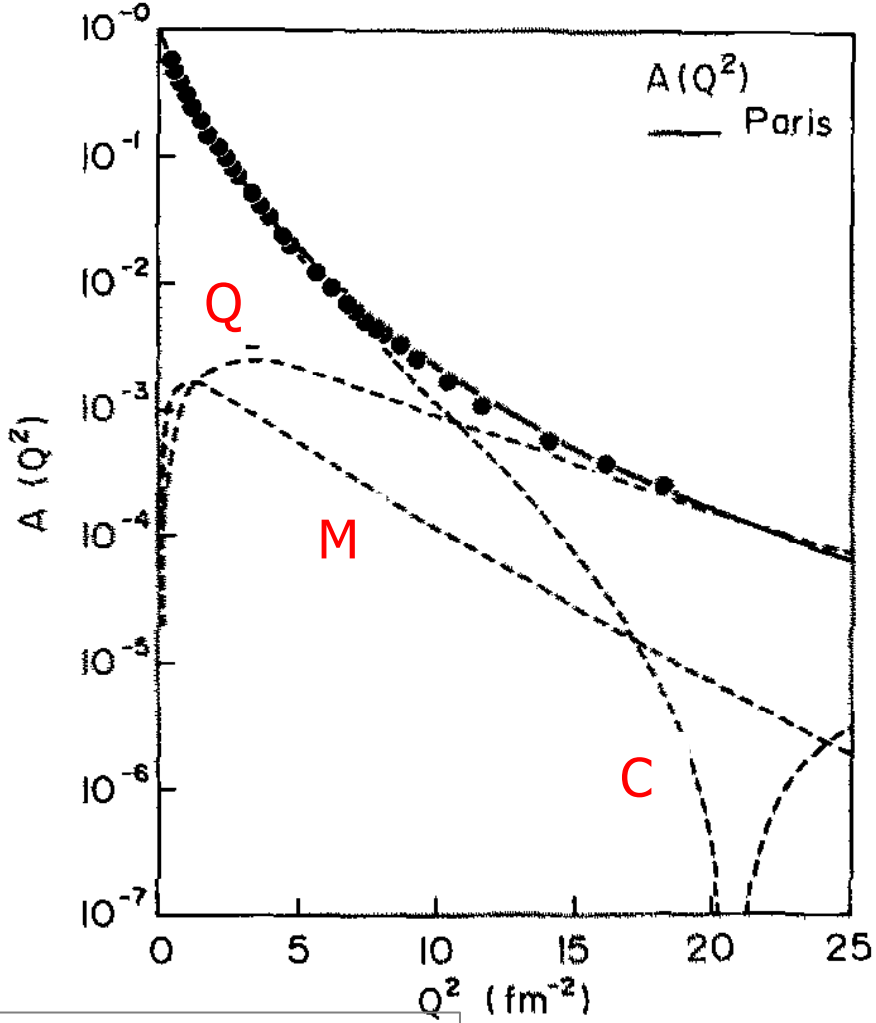
- e^- + d elastic cross section:

$$\frac{d\sigma}{d\Omega} = \sigma_M \left[A(Q^2) + B(Q^2)\tan^2\left(\frac{\theta}{2}\right) \right]$$

- Form factors (deuteron spin = 1)

$$A(Q^2) = F_C^2(Q^2) + \frac{8}{9}\tau^2 F_Q^2(Q^2) + \frac{2}{3}\tau F_M^2(Q^2)$$

- Depends on:
  - N-N potential
  - Neutron form factor
  - + Meson-exchange currents, Rel effects

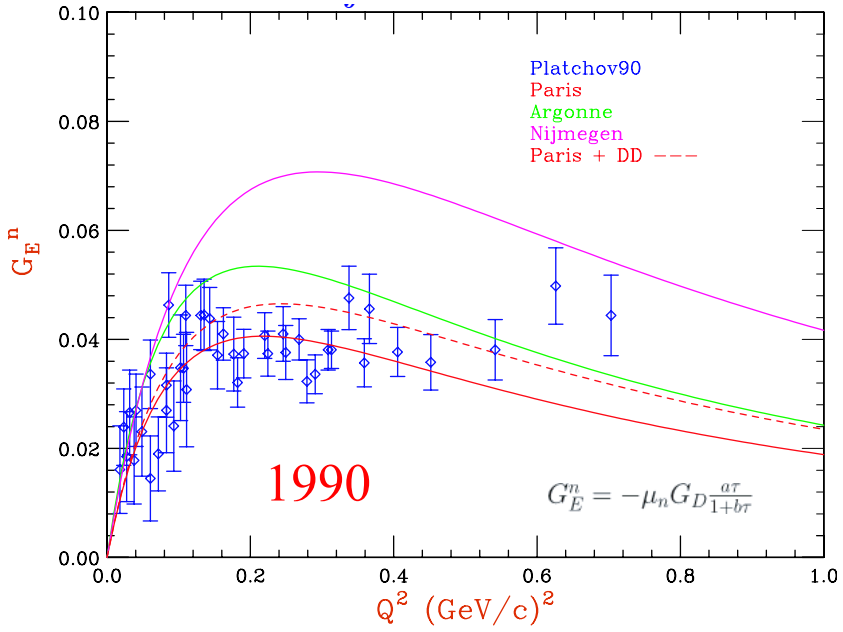


Allows a model-dependent determination of the neutron electric form factor

The neutron electric form factor, G_E^n

G_{en} as determined from elastic electron-deuteron scattering

Platchkov et al., Nucl. Phys. A510, 740 (1990)



The neutron electric form factor, G_E^n

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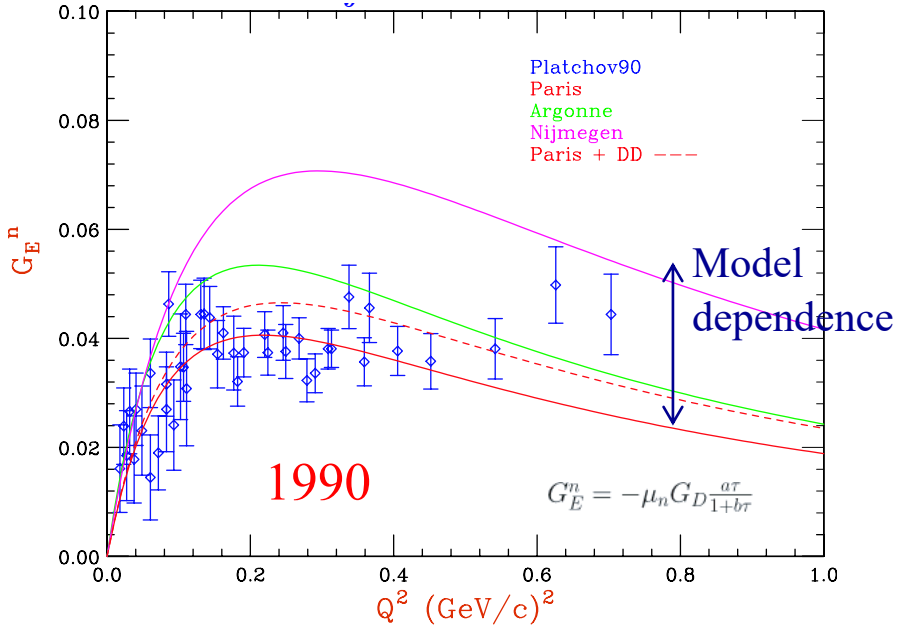
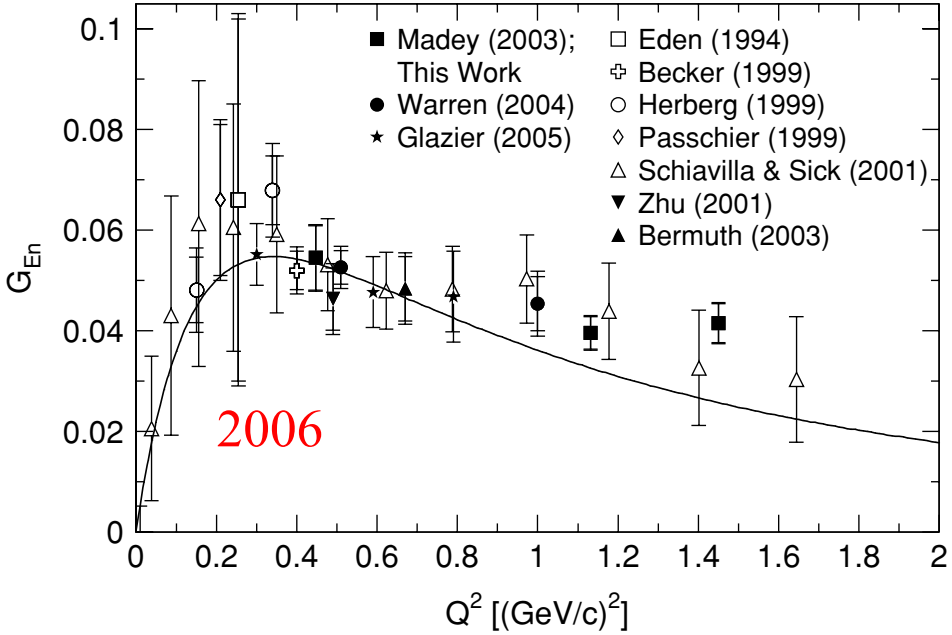
Platchkov et al., Nucl. Phys. A510, 740 (1990)



G_{en} from JLab and Mainz polarization data

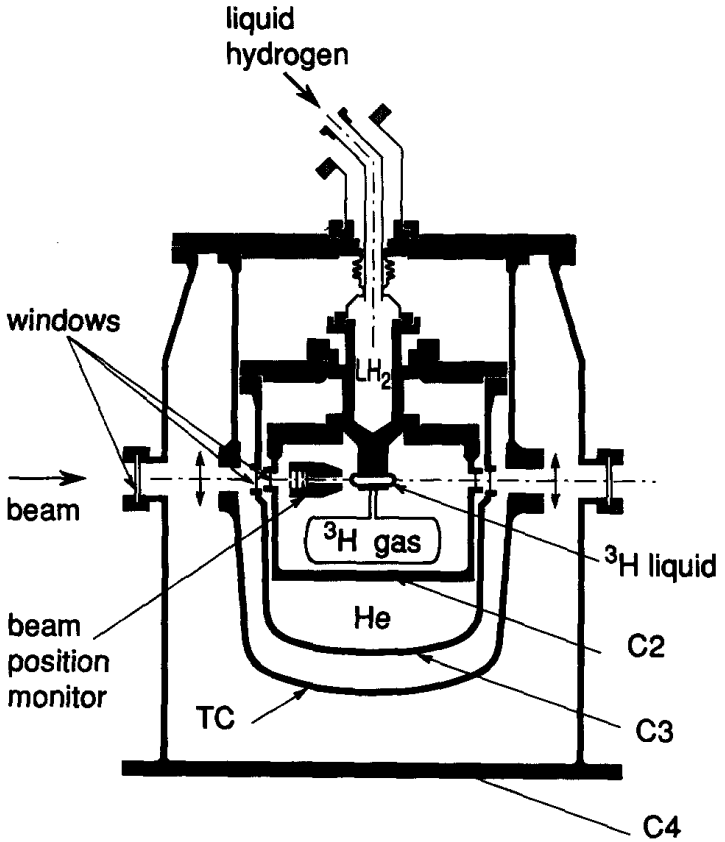
Plaster et al., Phys. Rev. C73, 025205 (2006)

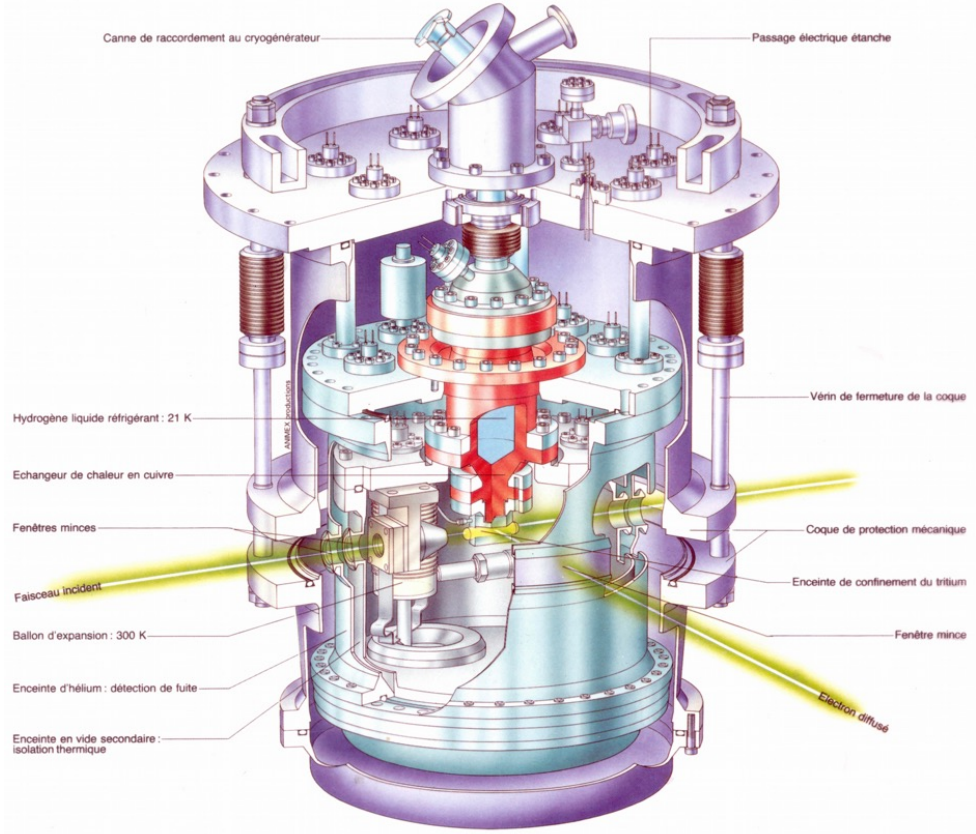


Three-nucleon system: ^{3}He and ^{3}H

Juster et al., PRL 55, 461 (1985)

- Saclay tritium target (1985):
  - Sealed target, P = 3 bars, cooled by liquid hydrogen at 20 K
  - Safety: 4 containers with many sensors, two independent computers
  - Activity: 10 kCi (3.7×10^{14} Bq)





Three-nucleon system – form factor measurements

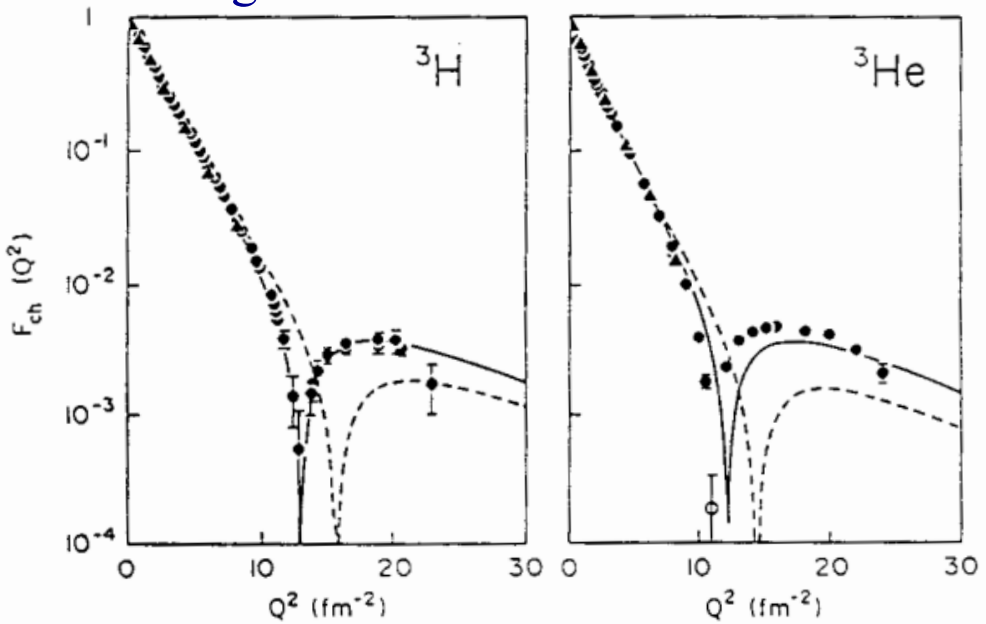
Cavedon et al. PRL 49, 986 (1982)

Juster et al., PRL 55, 2261 (1985)

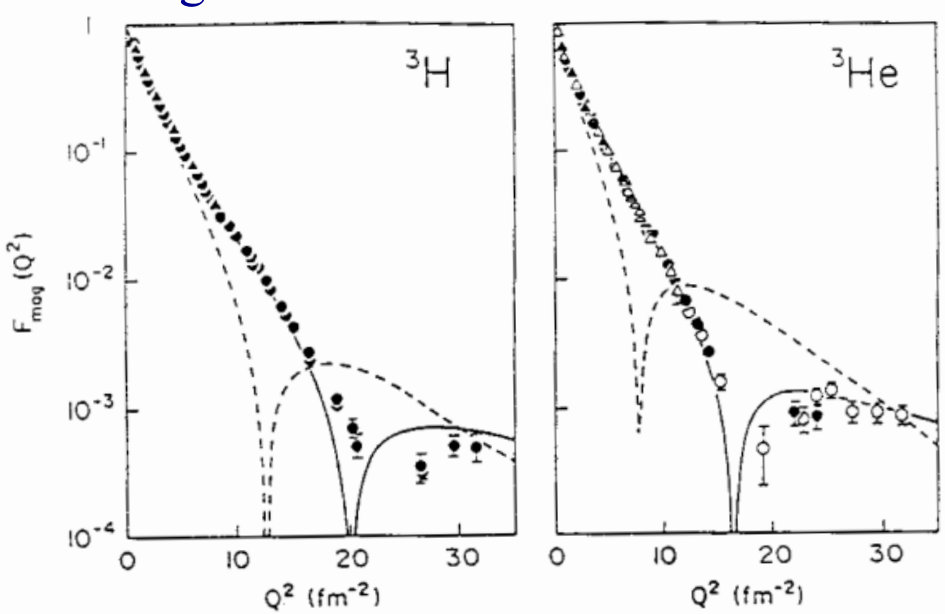
Amroun et al., PRL 69, 253 (1992)

Amroun et al., Nucl. Phys. A579, 596 (1994)

Charge form factors



Magnetic form factors

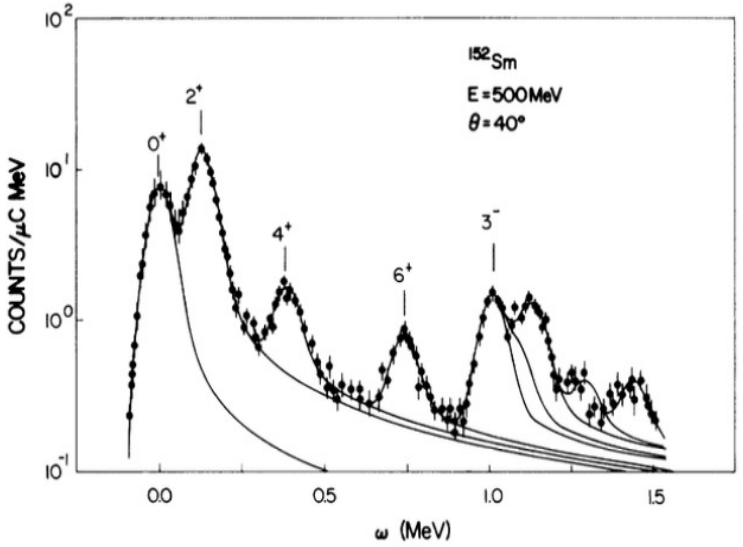


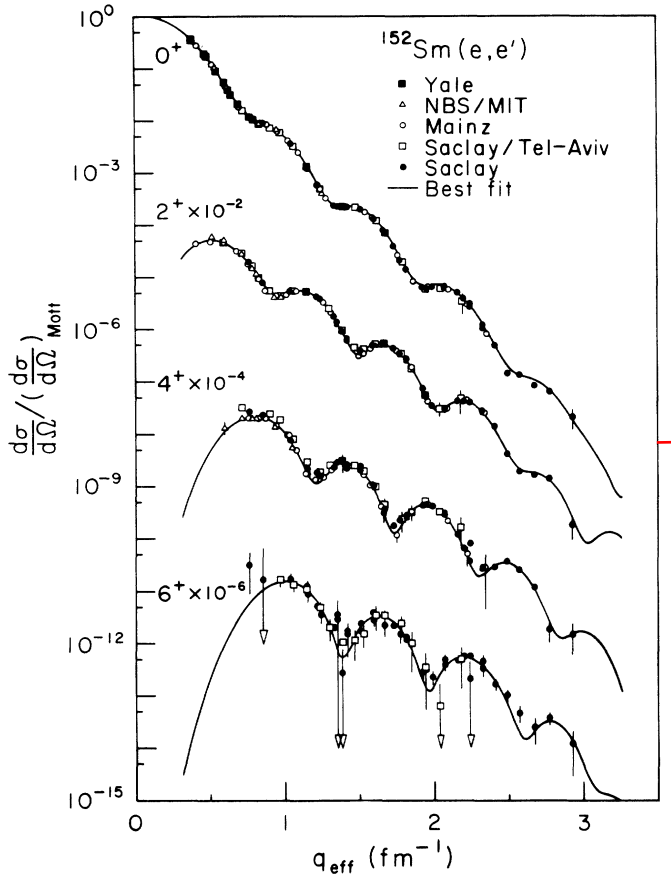
Meson-exchange currents are mandatory for a good description
Three-body force has a minor effect

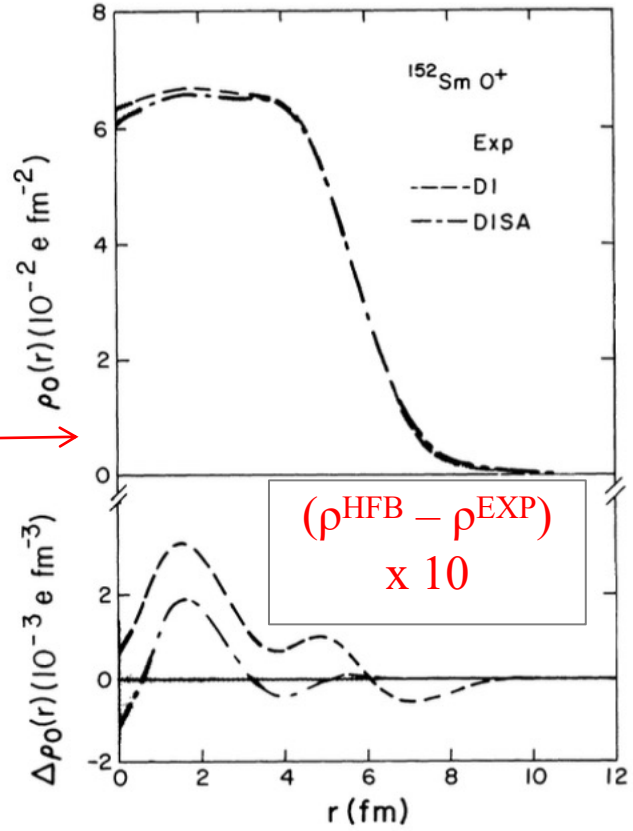
Inelastic (e,e') scattering from ^{152}Sm

- Transition charge densities for 0^+, 2^+, 4^+, 6^+

Phan et al., PR C38, 1173 (1988)







Comparison with a triaxial DD-HFB calculation

Ground state and transitional charge densities of ^{152}Sm

- Comparison with a triaxial mean-field HFB calculation
  (two versions of the effective Gogny force: D1 and D1SA)

Phan et al., PR C38, 1173 (1988)

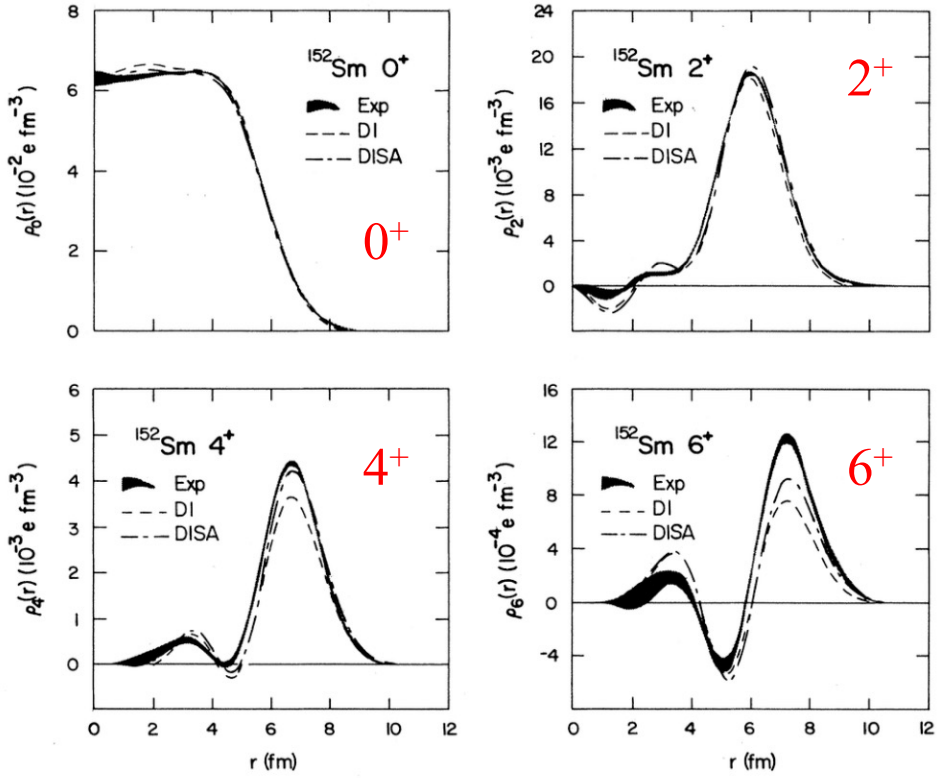
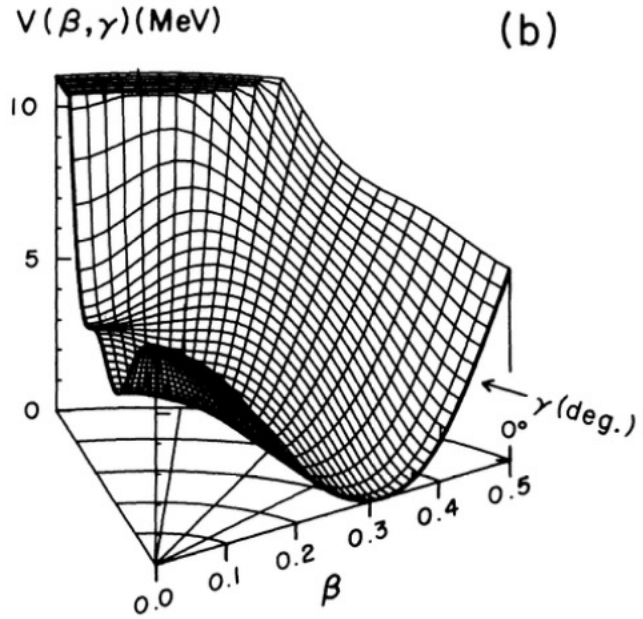


FIG. 8. The experimentally determined ground state and transition charge densities for the first four states of the ground state rotational band. Also shown are the theoretical predictions obtained using the *D*1 (— — —) and *D*1*SA* (—·—·—) effective interactions.



Potential energy surface of ^{152}Sm

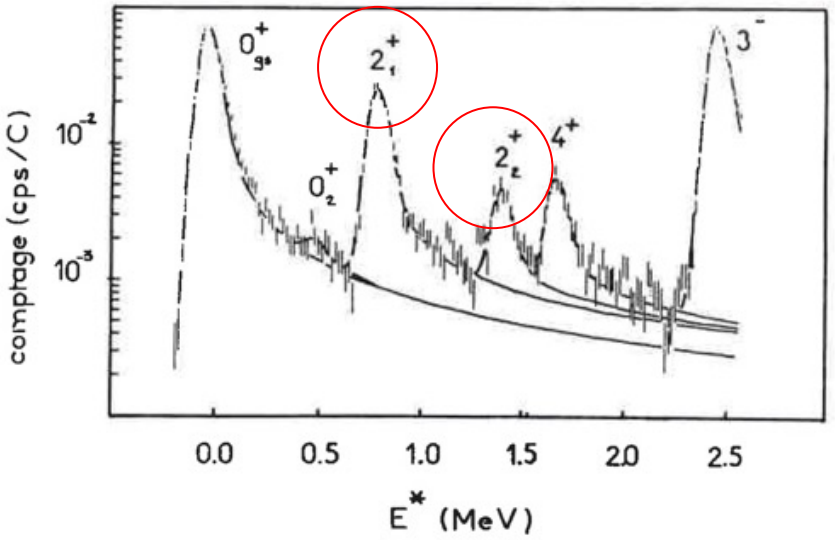
The ground-state rotational band of ^{152}Sm is well described by a HFB calculation

A configuration mixing in ^{70,72,74,76}Ge isotopes?

- Two-nucleon transfer reactions: strange behavior around $^{72\text{-}70}$Ge?

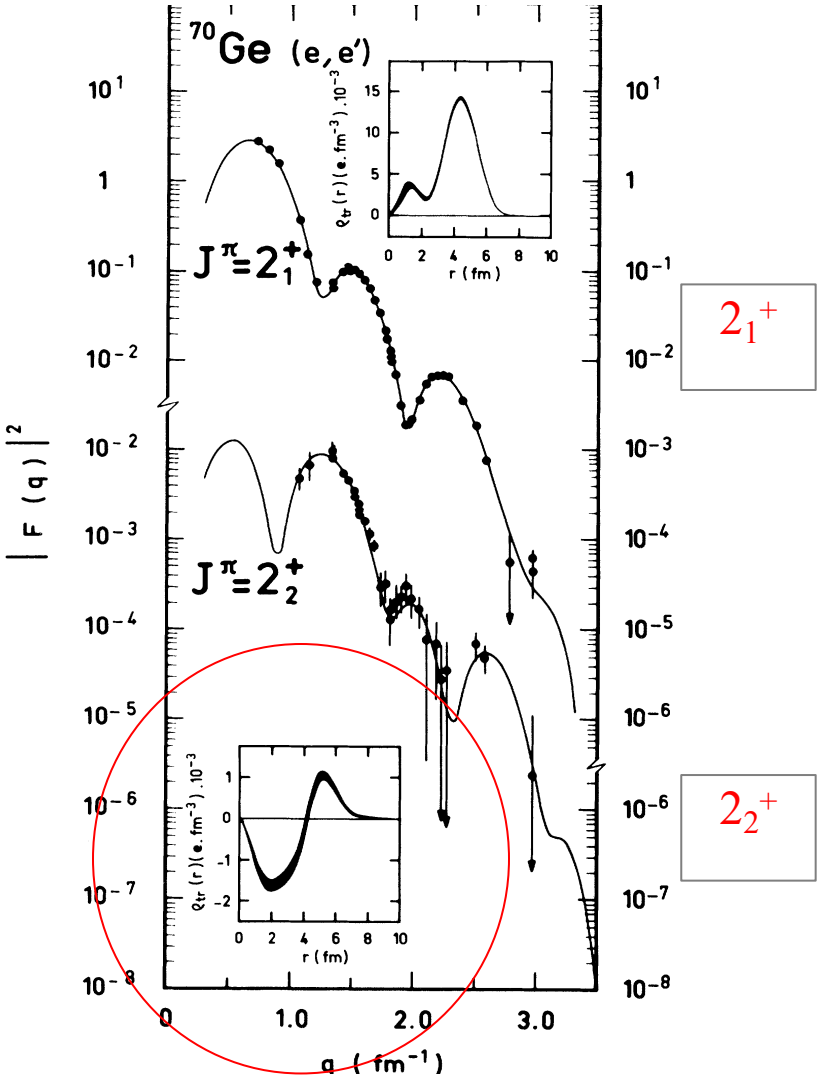
=> (e,e'): Measure the transition charge densities of the first 2^+ states in the ^{70,72,74,76}Ge isotopes

Electron scattering spectrum



Why such a sudden change for ^{70}Ge ?

Bazantay et al., PRL 54, 643 (1985)

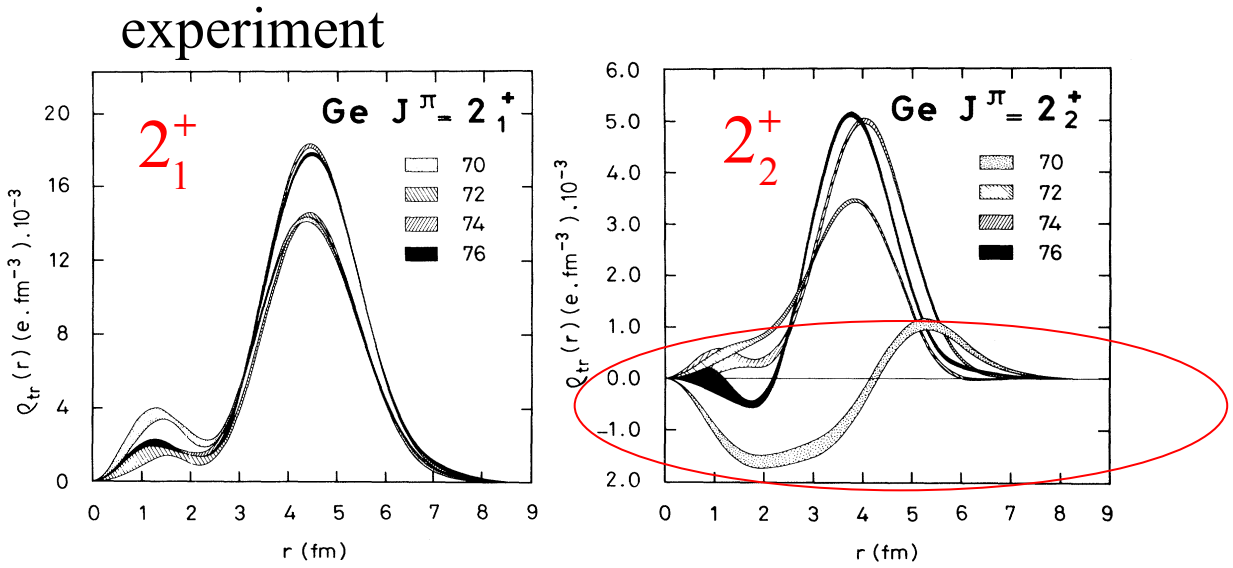


2_1^+

2_2^+

Configuration mixing in Ge isotopes – exp / th

- Interacting Boson Model: neutron and proton boson pairs
  - Combines single-particle and collective motions
  - Allows for configuration mixing



Bazantay et al., PRL 54, 643

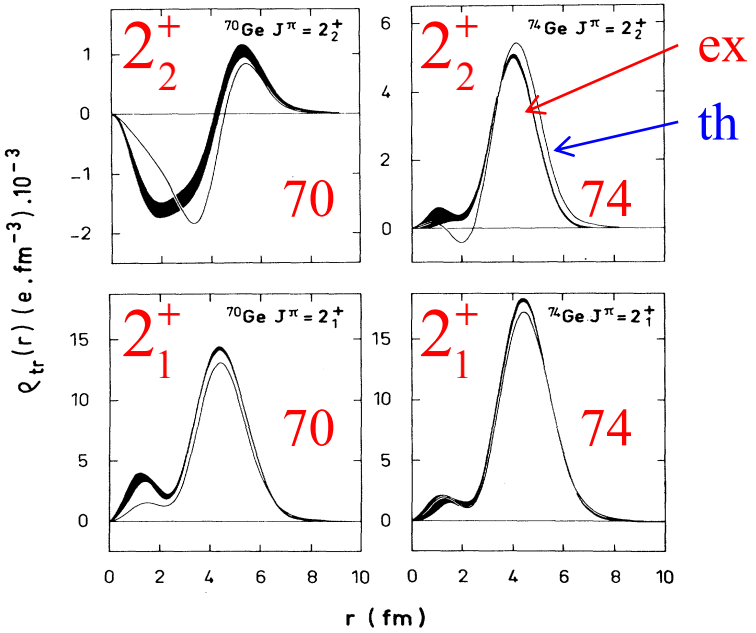


FIG. 3. Comparison between the predicted (thin line) and experimental (thick line) transition densities.

Evidence for the coexistence of two configurations; Agreement with with IBM-2, only for different configurations in ^{68,70}Ge vs ^{72,74,76}Ge

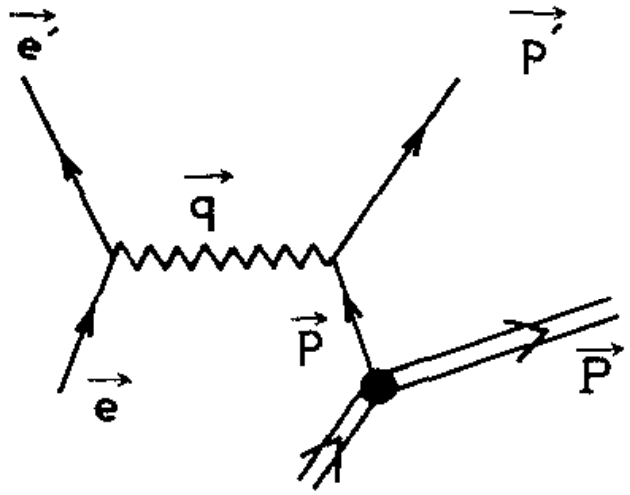
Nice atmosphere…

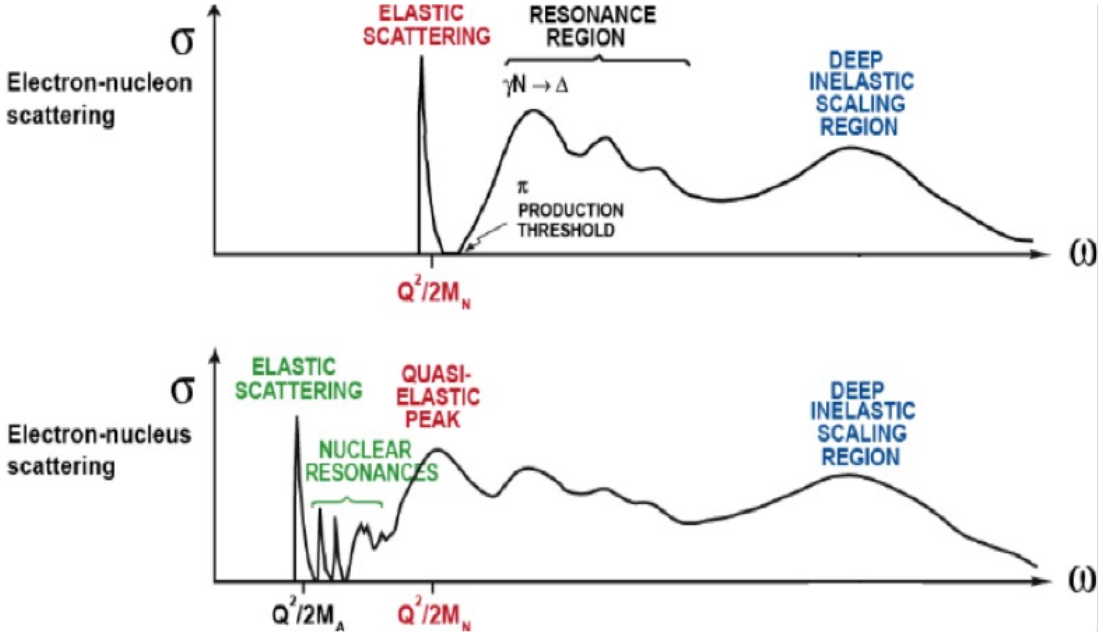
“Quasi-elastic” electron scattering

- Quasi-elastic peak

$$\frac{d\sigma}{d\Omega dE} = \frac{4\pi}{M}\sigma_{Mott}\eta^{-1}\left[\frac{q_\mu^2}{q^2}\,R_L(q,\omega) + \left(\frac{1}{2}\frac{q_\mu^2}{q^2} + \tan^2\frac{\theta}{2}\right)\frac{q_\mu^2}{q^2}\,R_T(q,\omega)\right]$$

esponse functions: R_L, R_T





- Motivations
  - scattering from quasi-”free” nucleons inside the nucleus
  - probe the nucleon momentum distribution

Are nucleon properties modified in nuclear medium?

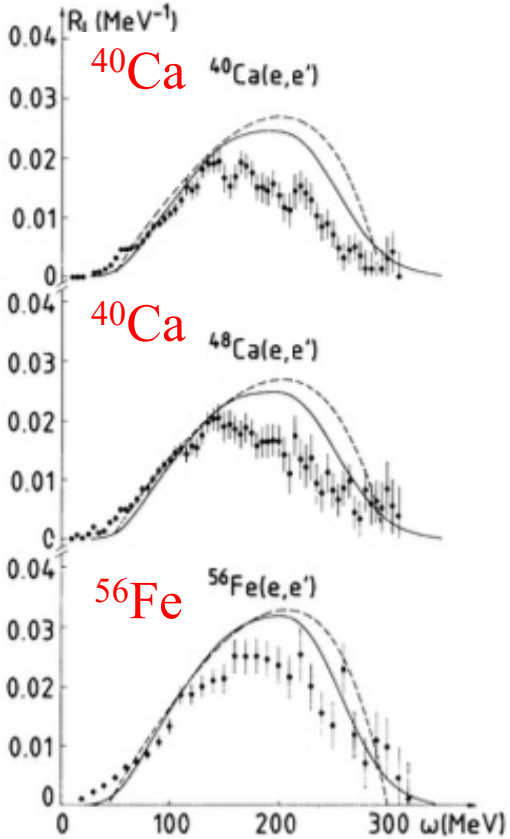
Longitudinal response function and Coulomb Sum Rule

- Coulomb Sum Rule

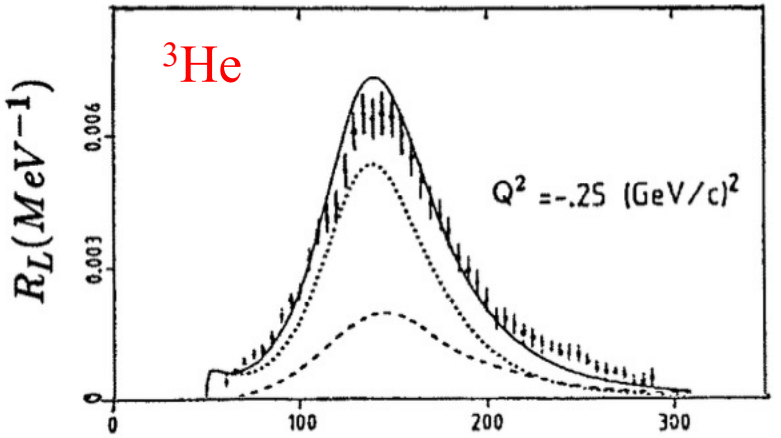
Meziani et al., PRL 52, 2130 (1984).
Meziani et al., PRL 54, 1223 (1985).

Marchand et al., PL 153B, 29 (1985)

$$S_L(q) = \frac{1}{Z} \int_{0+}^{\infty} \frac{R_L(q,\omega)}{\tilde{G}_E^2} d\omega$$



quenching!



no quenching

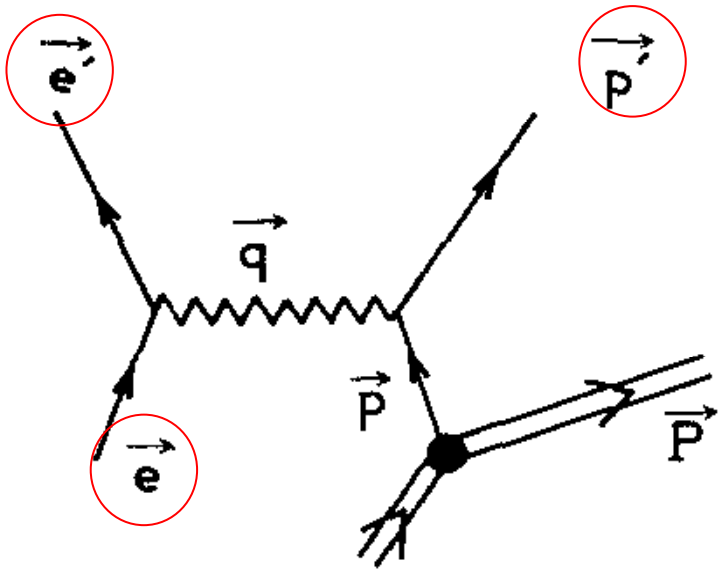
Nuclear matter effect: significant quenching (up to 30%)

Coincidence experiments (e,e'p)

- Kinematics - coincidence experiment:
  - initial proton momentum
  - proton removal energy

$$\vec{p} = -\vec{p}_B = \vec{e}' + \vec{p}' - \vec{e}$$

$$E = e - e' - T' - p^2 / 2M_{A-1}$$



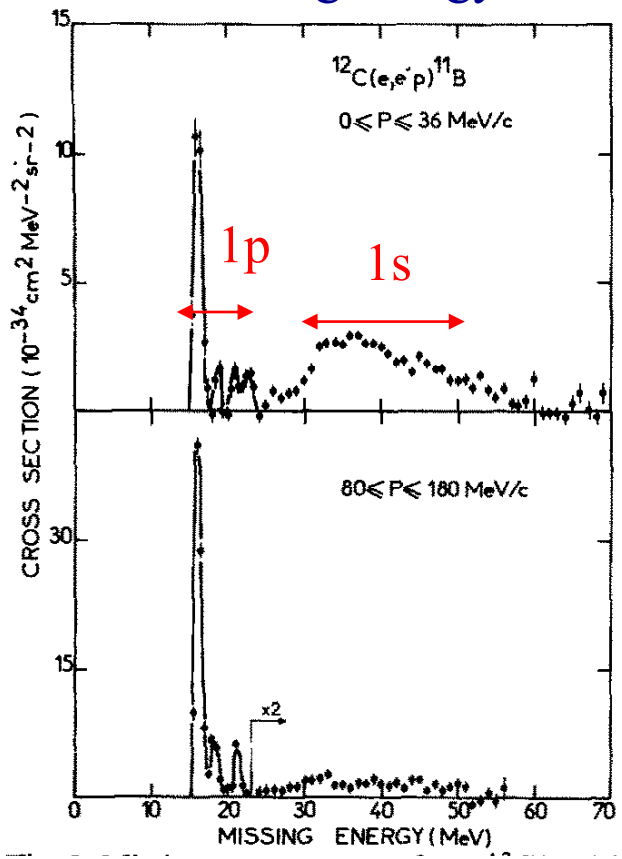
$$\sigma(e,e'p) = \frac{d^6\sigma}{de'\,d\Omega_{e'}\,dp'\,d\Omega_{p'}} = K\left(\frac{d\sigma}{d\Omega}\right)_p S(\vec{p},E)$$

- Information on:
  - nuclear spectral function : momentum and energy distributions
  - probe individual shells; access also to deeply-bound states

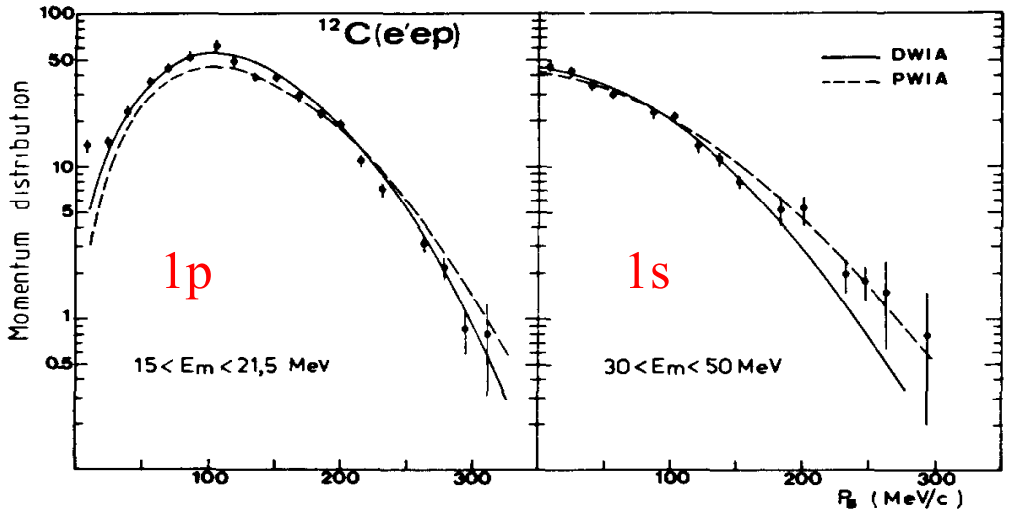
Examples of (e,e'p) experiments

Mougey et al., Nucl. Phys. A262,461 (1976).

Missing energy



Momentum distributions



Access to: single-particle energy and momentum distributions, occupation probabilities, bound nucleon properties

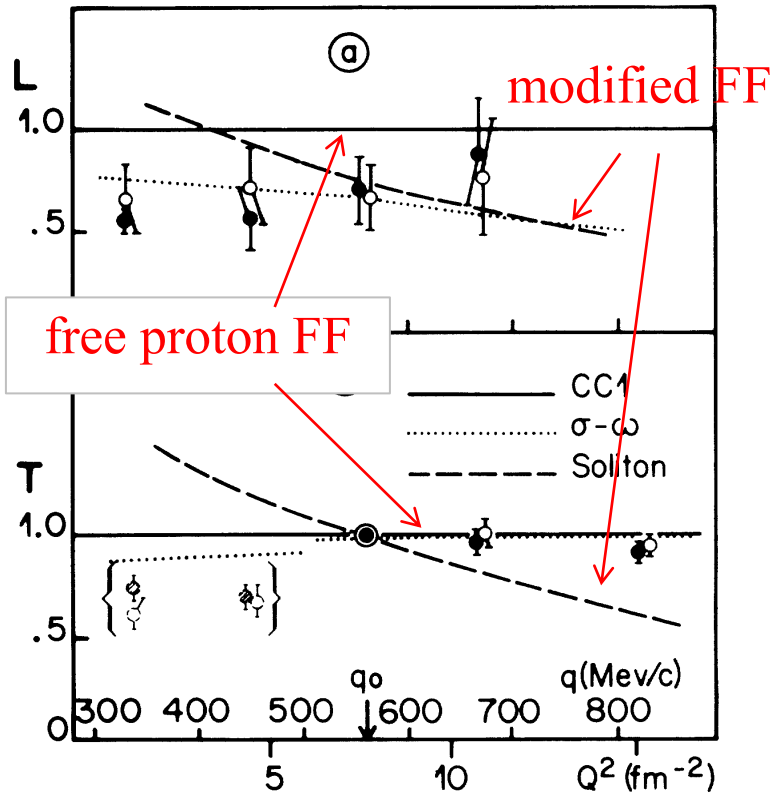
Bound proton form factor measurements

Reffay et al., PRL. 60,776 (1988).

- Are nucleon properties modified in the nuclear medium?
  - in PWIA:

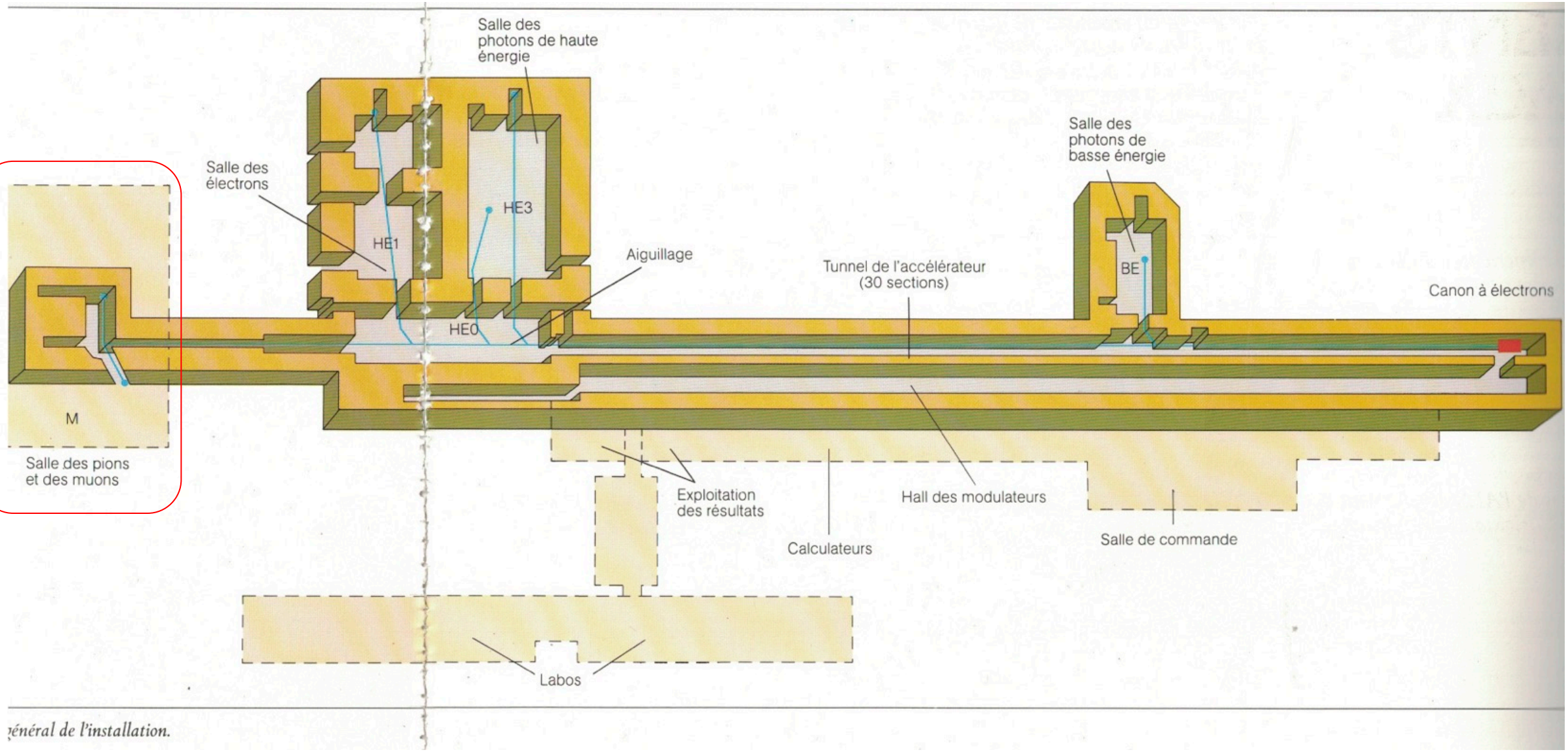
$$\sigma(e,e'p) = \frac{d^6\sigma}{de'd\Omega_{e'}dp'd\Omega_{p'}} = K\left(\frac{d\sigma}{d\Omega}\right)_p S(\vec{p},E)$$

- Goal:
  - study bound σ_{ep} q-dependence
  - separate L and T contributions
  - compare to DWBA calculations



No modification of the bound proton FF
L-response quenching R ~ 65%

Overview of the laboratory (top view)



général de l'installation.

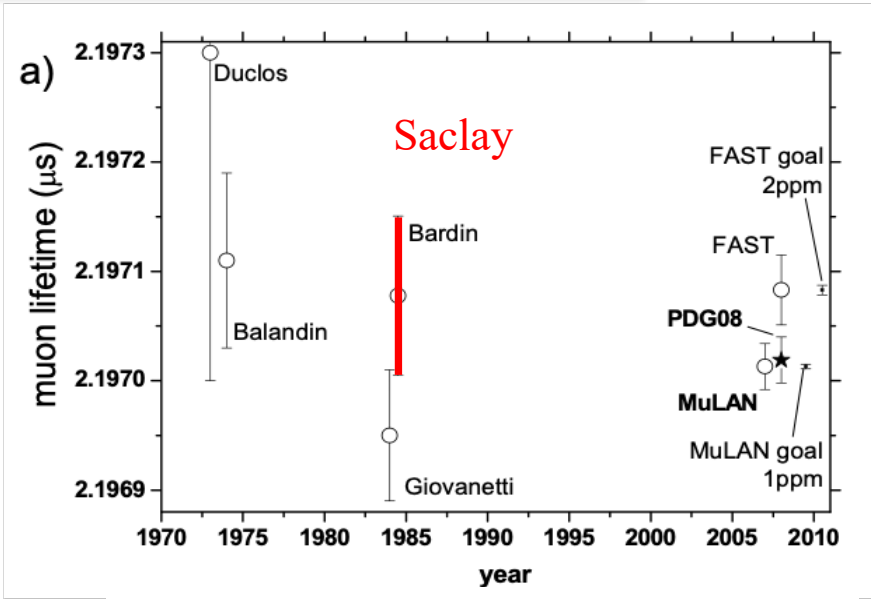
SM basic parameters: μ lifetime, capture rate and weak ps coupling

- Muon lifetime measurements
  - Stop the muons n a ultrapure "protium" target
  - Physics results (errors of ~3.10^{-5})

$$\tau_{\mu^-} = 2194.903 \pm 0.066 \text{ ns}$$

$$\tau_{\mu^+} = 2197.148 \pm 0.066 \text{ ns}$$

Bardin et al;, Nucl.Phys. A352 (1981) 365.

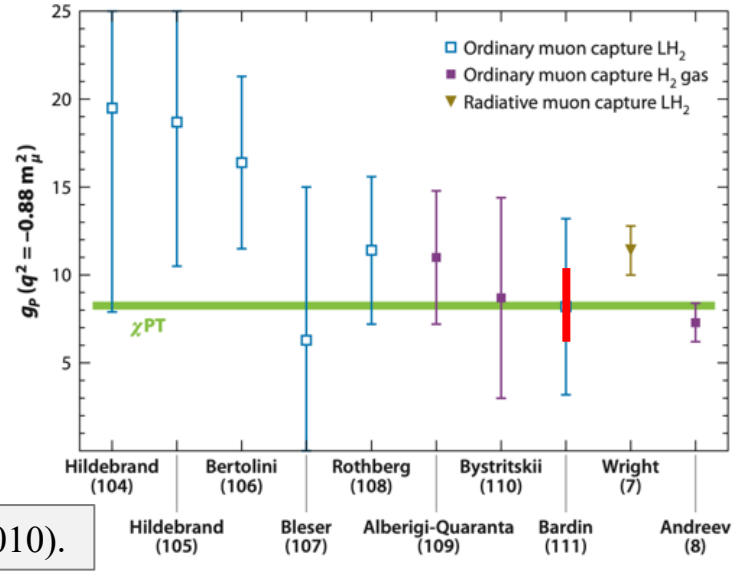


- Muon capture rate $(\mu^- + p \rightarrow n + \nu_\mu)$
  - Related to the EW coupling constants g_A, g_p

=> Determine the ps coupling constant g_p:

  - Saclay 1981: $g_p = 8.70 \pm 1.90$

Bardin et al., Phys.Lett.104B (1981) 320.



Kammel, ARNPS 60 (2010).

From ALS to e – RI collisions (eRIB) ?

- Electron machine
  - Beam energy: between 100 and ~500 MeV
  - Electron currents: >> 100 mA
  - Duty cycle: >1% OK; coincidence: 100%
  - Luminosity: higher $\mathcal{L}$ => larger q, access to more processes…
- Detection system
  - Resolution: 100 keV or better
  - Angular range: high enough (25° – 155°?)
  - Background : low bgnd is mandatory (good shielding)
- Coincidence experiments?
  - Large energy and momentum acceptances
  - Good energy and momentum resolutions

From ALS to e – RI collisions (eRIB) ?

- Results from SCRIT (Aug. 30, 2023)

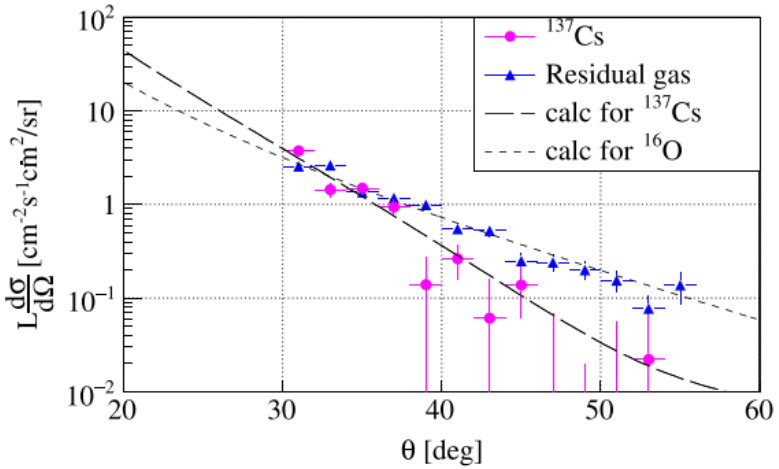
PHYSICAL REVIEW LETTERS **131,** 092502 (2023)

Editors' Suggestion | Featured in Physics

First Observation of Electron Scattering from Online-Produced Radioactive Target

K. Tsukada,[1,2] Y. Abe,[2] A. Enokizono,[2,3] T. Goke,[4] M. Hara,[2] Y. Honda,[2,4] T. Hori,[2] S. Ichikawa,[2,*] Y. Ito,[1] K. Kurita,[3] C. Legris,[4] Y. Maehara,[1] T. Ohnishi,[2] R. Ogawara,[1,2] T. Suda,[2,4] T. Tamae,[4] M. Wakasugi,[1,2] M. Watanabe,[2] and H. Wauke[2,4]

E = 150 MeV, $\mathscr{L}$ = ~0.9.10^{26}



- eRIB project in France
  - Radioactive nuclei: ~10^8/s
  - Beam energy: between 100 and ~500 MeV
  - Electron currents: >> 100 mA (synchrotron ? microtron + storage ring?)
  - Luminosity: higher $\mathcal{L}$ => larger q, access to more processes…
  - Resolution: 100 keV or better
  - Angular range: large enough (25° – 155°) to separate L and T
  - Background : low, mandatory if low cross section measurements

Summary

- ALS (1969 – 1992): a world-class facility – produced a number of “textbook” results
  - Electron scattering on nucleon and heavy nuclei
    - Charge and magnetization densities, transition densities, deformation studies, sum rules
  - Coincidence (e,e’p) experiments
    - Limits of the independent-particle picture, spectral functions,
  - Photonuclear experiments
    - (γ,p), (γ,π), (γ,pπ), etc…
  - Secondary beams
    - Pion studies, Muon lifetime and capture rates
- Future: eRIB ?
  - Similar studies on exotic nuclei…