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Highlights from the electron scattering experiments at Accélérateur Linéaire de Saclay

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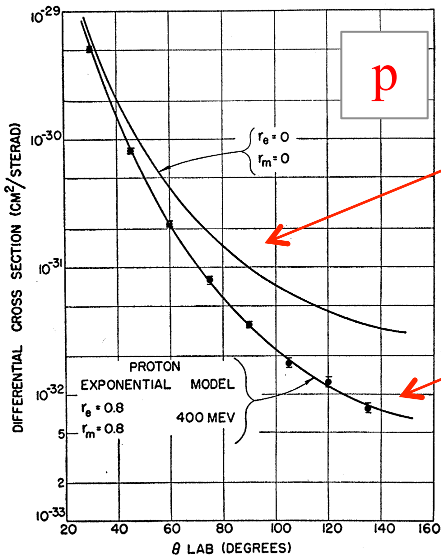
Electron scattering on nuclei – a glimpse of history

- 1951, Illinois Betatron: E = 15.7 MeV

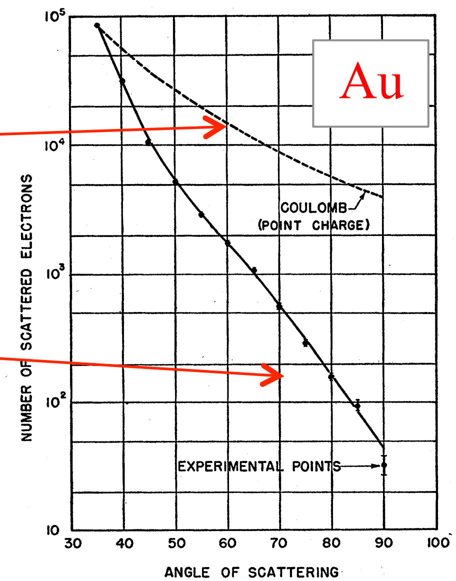
Lyman, Hansen and Scott, Phys. Rev. 84, 626 (1951)

- 1953 – mid 60's, Stanford, E = 100 – 500 MeV



POINT CHARGE calculation

DATA



R. Hofstadter, Rev. Mod. Phys. 28, 214 (1956)

- 1961: R. Hofstadter – Nobel prize

"for his pioneering study of electron scattering in atomic nuclei and ... … the structure of the nucleons"

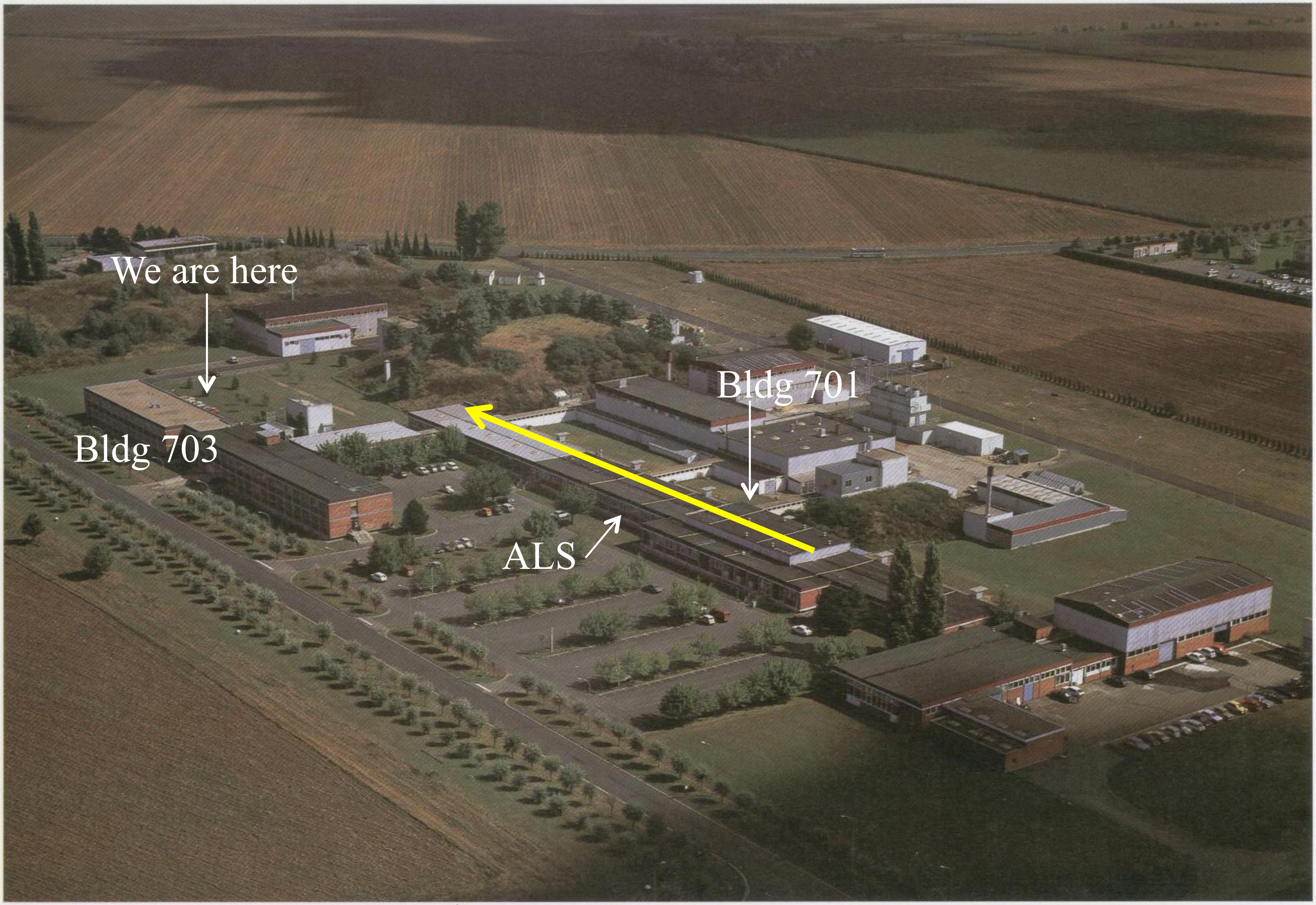
Followed by machines at Darmstadt, Mainz, Tohoku, Kharkov, Bates, Saclay

ALS (Accélérateur Linéaire de Saclay)

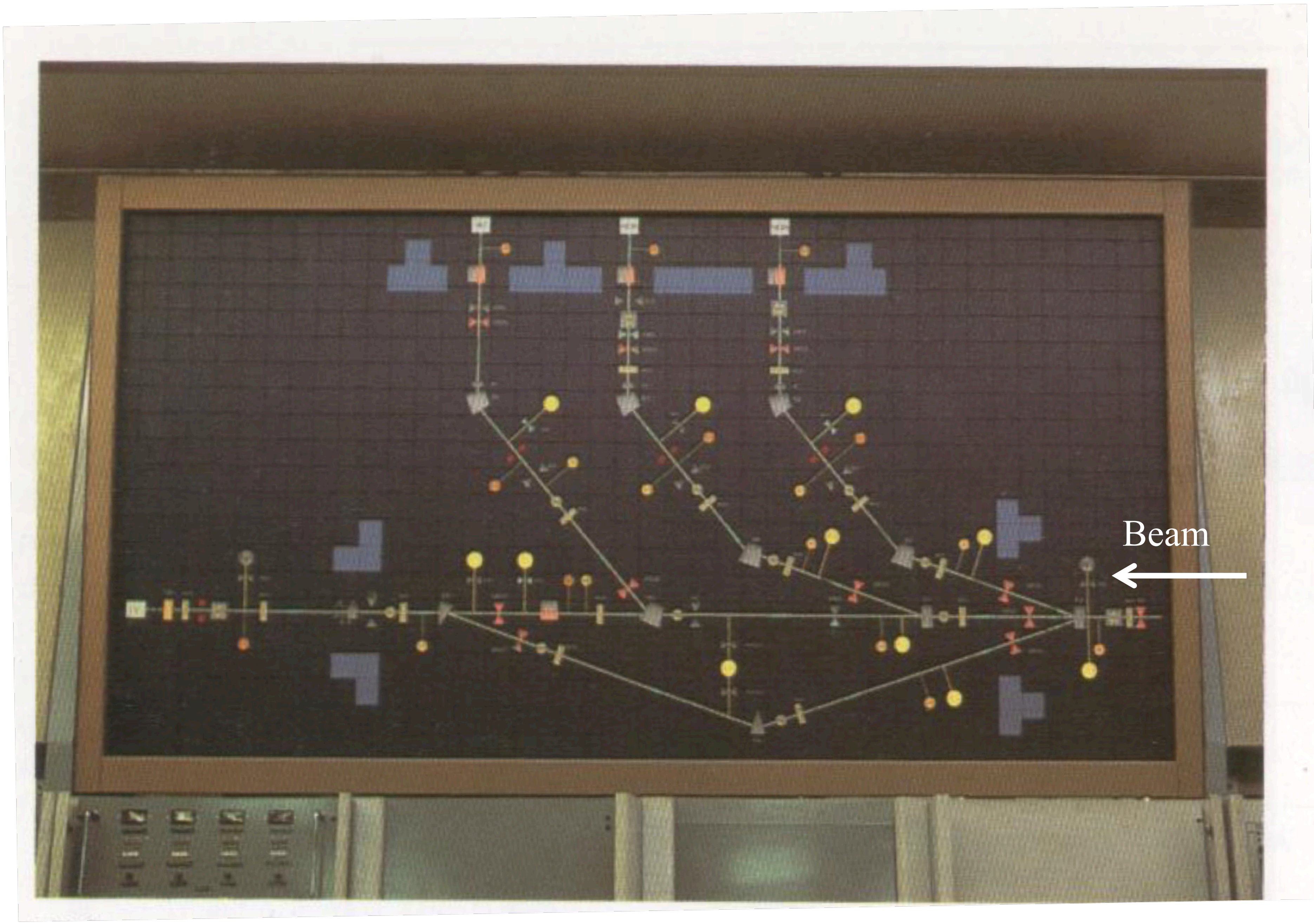
- ALS:
  - Original idea by Christophe Tzara, 1959.
  - First beam in 1970.

- Main characteristics:
  - Length: 200 m, underground tunnel
  - Energy: 150 to 700 MeV
  - Duty cycle: 1% to 2% (compare to 10^{-3} or 10^{-4} for older machines)
  - Pulse length: 1 µs to 20 µsec, usually 10 µs or 20 µs.
  - Rate: 500 Hz to 3000 Hz
  - Peak current: up to 60 mA (at 420 MeV)
  - Mean current: up to >100 µA, usually 20-30 µA
  - Positron beam: up to 0.1 µA

High energy and duty cycle machine + high-resolution, low-bgnd detection system


We are here
Bldg 701
Bldg 703
ALS

Accelerator tunnel


Beam

Experiments at ALS

- Electron scattering on nucleon and heavy nuclei
  - elastic (e,e)
  - inelastic (e,e')
- Coincidence experiments
  - (e,e'p) studies
- Photonuclear experiments
  - (γ,p), (γ,π)
  - $(\gamma,p\pi)$, etc…
- Secondary beams
  - pion beam
  - muon studies

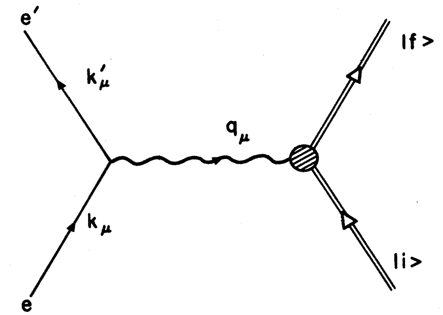
This talk: a selection of (e,e), (e,e') and (e,e'p) experiments

Summary of this talk

1. Nuclear charge distributions
2. The HE1 experimental hall
3. Single-particle valence nucleon orbits
4. Few-nucleon system studies
5. Transition charge densities
6. Quasi-elastic response functions

Electron scattering

- Main characteristics:
  - EM interaction is weak ($\alpha = 1/137$)
  - One photon exchange is a good approximation
  - Vary the 3-transfer q and the energy ω independently
    - Momentum transfer: $= q_\mu^2 = 4ee'\sin^2(\theta/2);\ q_\mu = (\omega, q);\ \omega = e - e'$
  - For a given ω, map-out the Fourier transform of charge (transition) density
  - Same q_μ^2 : vary separately energy and scattering angle
  - Distance scale : nucleus is probed with a wavelength $\lambda \sim 1/q$
    - for q values of about 2-3 fm^{-1}, probe distances smaller than 1 fm.



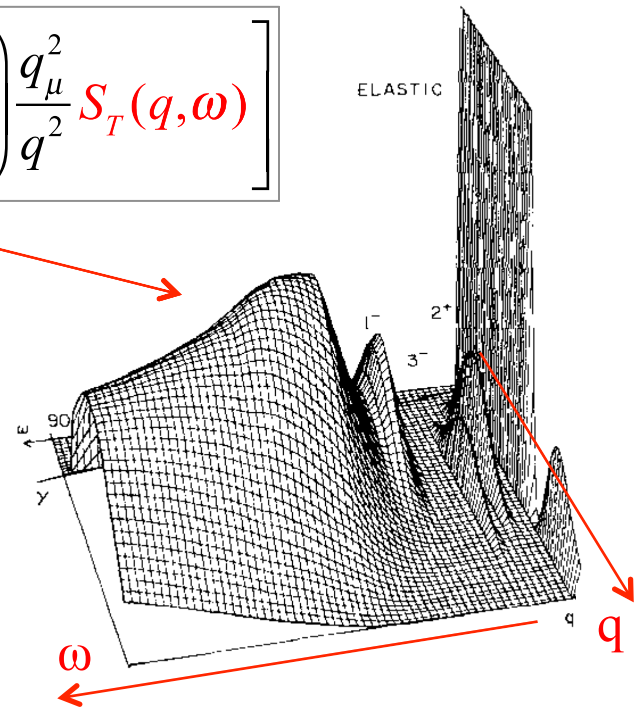
Electron scattering provides a microscope to probe the spatial structure of nuclei

Electron scattering on a spin J_0 nucleus

- General case

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)

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

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

- Elastic scattering on a $J_0 = 0$ nucleus:

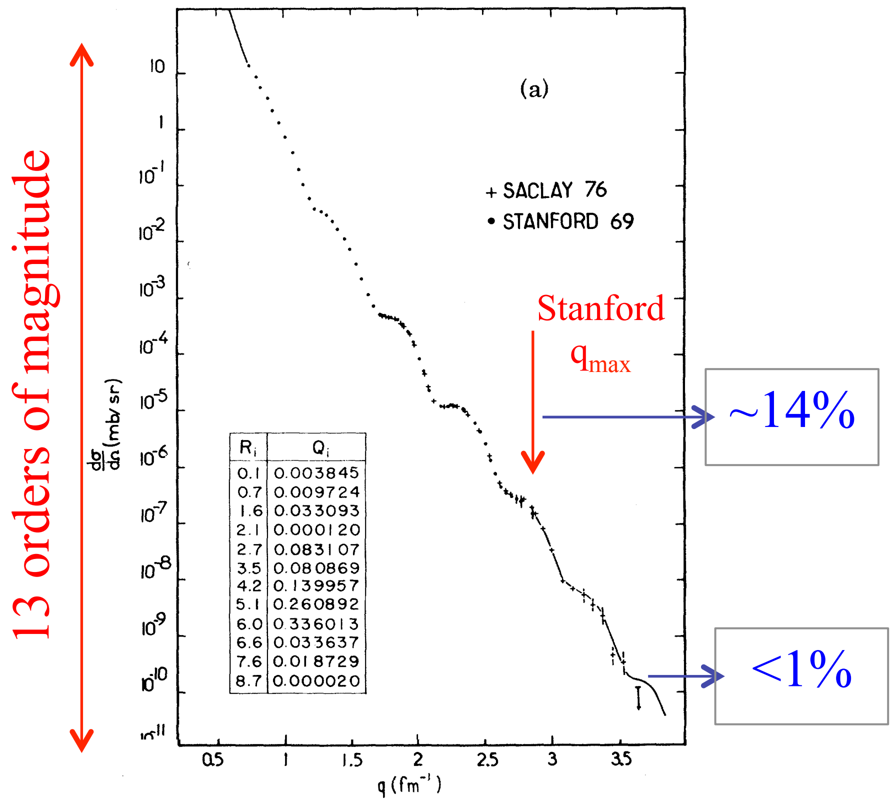
$$F_{ch}(q) \propto \int_0^\infty \rho(r)\frac{\sin(qr)}{qr}r^2\,dr$$

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

Nuclear charge distributions

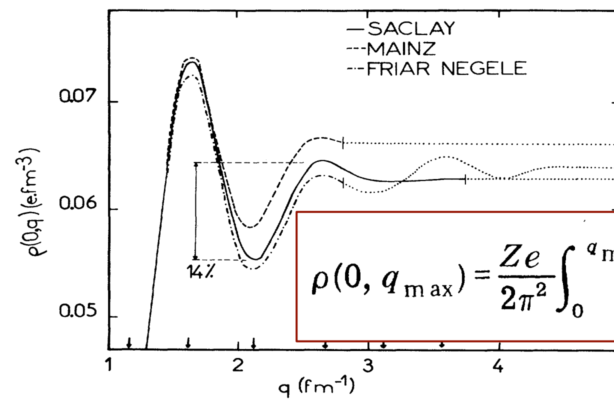
- Cross section for (e,e') on ^{208}Pb

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



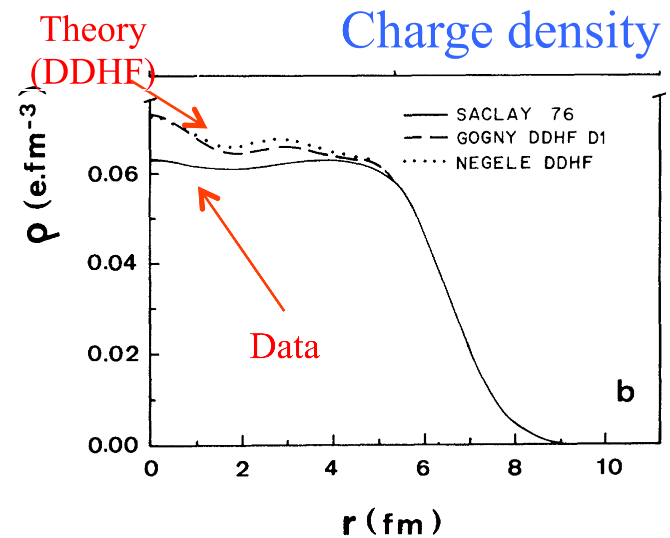
R_i	Q_i
0.1	0.003845
0.7	0.009724
1.6	0.033093
2.1	0.000120
2.7	0.083107
3.5	0.080869
4.2	0.139957
5.1	0.260892
6.0	0.336013
6.6	0.033637
7.6	0.018729
8.7	0.000020

Error estimate



$$\rho(0, q_{max}) = \frac{Ze}{2\pi^2}\int_0^{q_{max}} F(q) q^2 \, dq,$$

Charge density

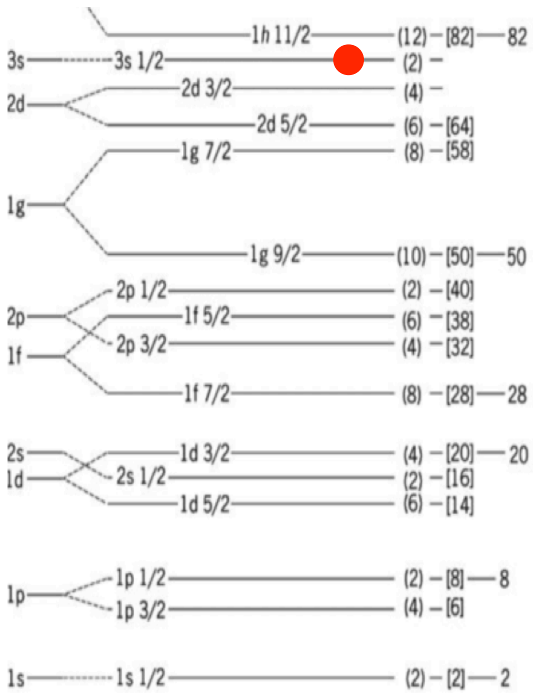


Very precise determination of the charge density down to r = 0 fm
Some difference between data and mean-field theory below r = 4 fm

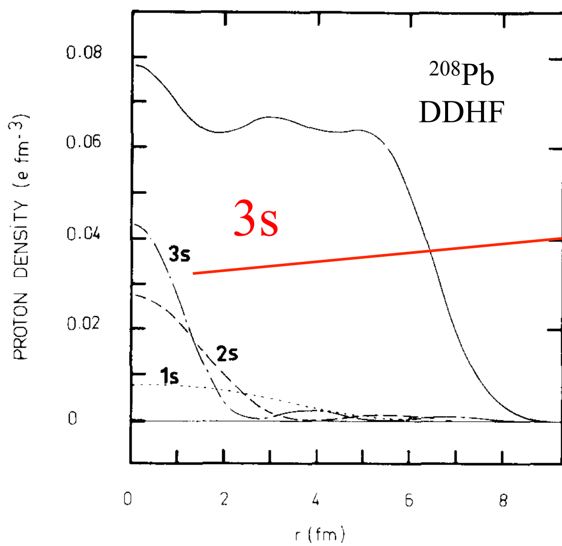
What about the 3s proton orbit?

- Charge density difference ^{206}Pb – ^{205}Tl (or ratio ^{205}Tl/^{206}Pb)
  - ^{206}Pb: and ^{205}Tl: differ by one 3s proton

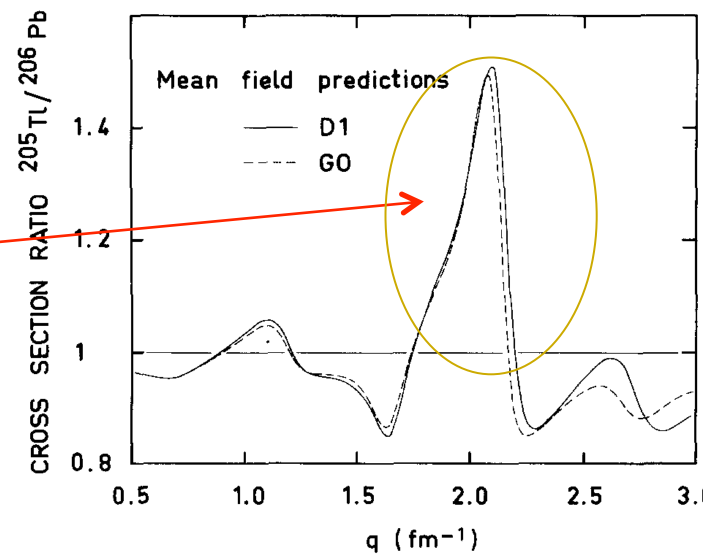
Cavedon et al., PRL 49, 978 (1982)



Predicted 3s charge densities



Predicted cross section ratio (DDHF)

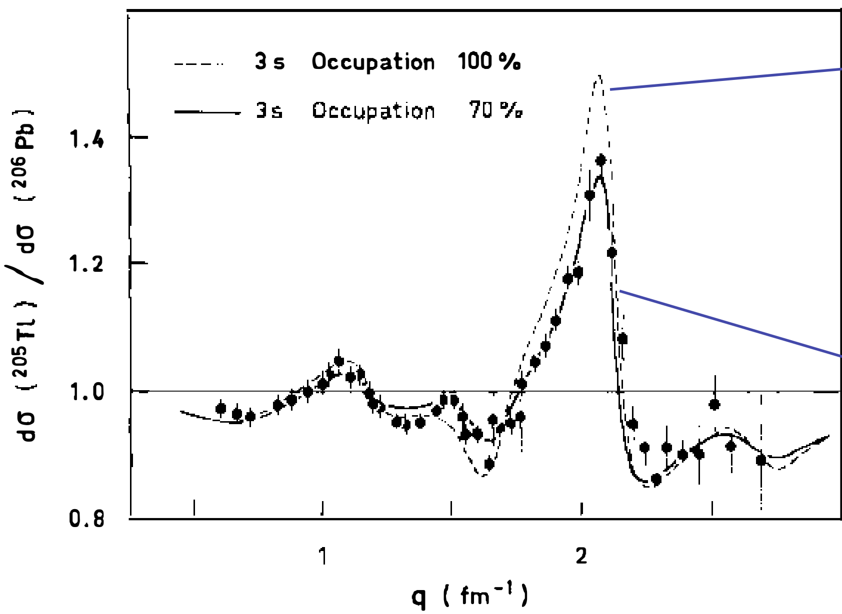


Charge density difference : mainly in the center of the nucleus
The 3s difference in ρ(r) result in a large peak around q = 2 fm^{-1}

What about the 3s proton orbit?

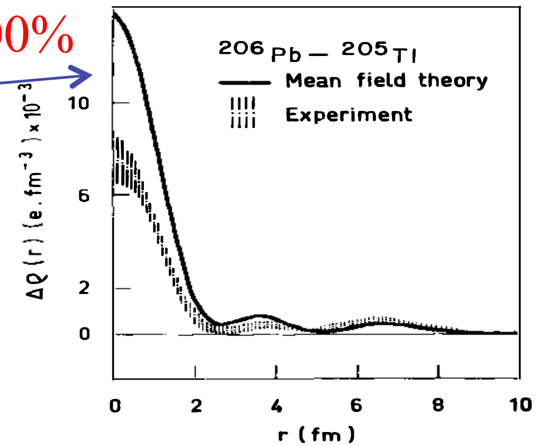
Cavedon et al., PRL 49, 978 (1982)

Experimental cross section ratio

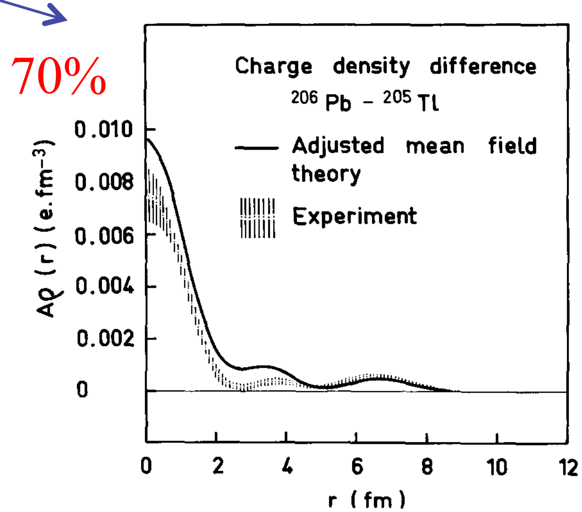


Density differences

3s = 100%



3s = 70%



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 larger than predicted

Charge density distributions for doubly-closed shell nuclei

Frois and Papanicolas, ARNPS 37, 133 (1987)

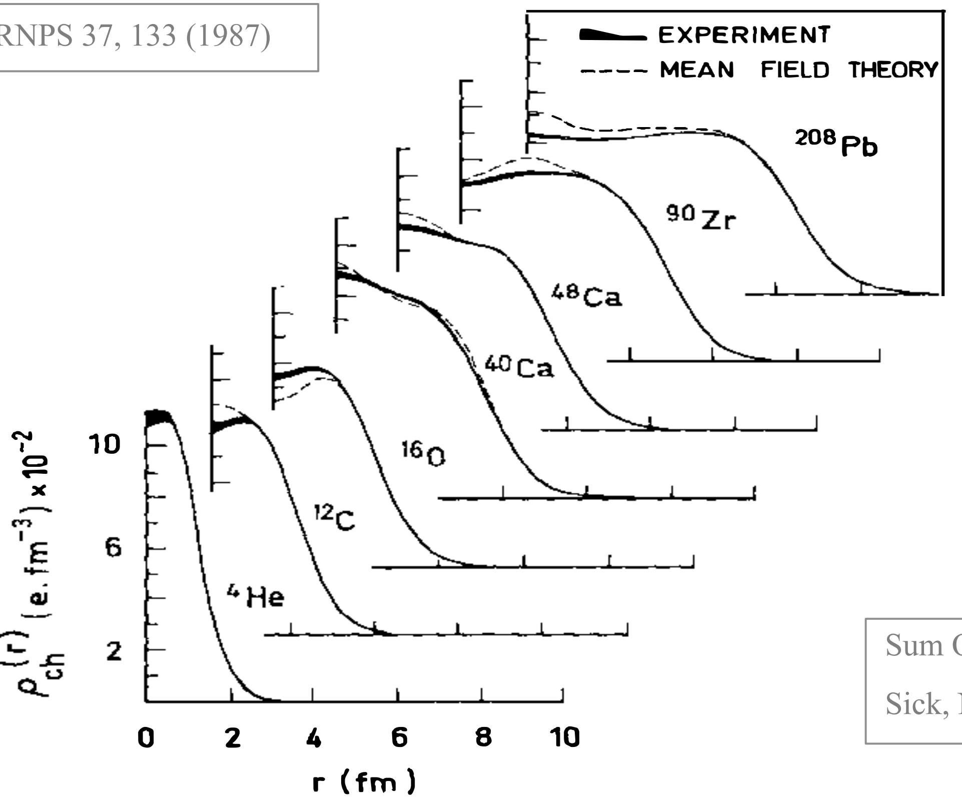


Figure 8 Charge density distributions of doubly closed-shell nuclei. The thickness of the solid line depicts the experimental uncertainty. The mean field calculations are from (53).

Sum Of Gaussians expansion:

Sick, Nucl. Phys. A218, 509 (1974)

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

Electron scattering – main corrections to the raw data

- Coulomb corrections
  - Electron wave function is distorted in the field of the nucleus
  - Approximation: effective momentum transfer: $q_{eff} = q(1 + f_{\lambda} \frac{Z\alpha}{E R_{eq}})$
  - Tools: Phase shift analysis (elastic charge) or DWBA
- Dispersion corrections
  - Intermediate excitation with exchange of two photons
  - small, up to few %; in diffraction minima only
- Radiative corrections
  - Radiation of real and virtual photons before or during the interaction
  - Important (up to 25-30% for elastic scattering) -- well known

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

The "fathers" of HE1:

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

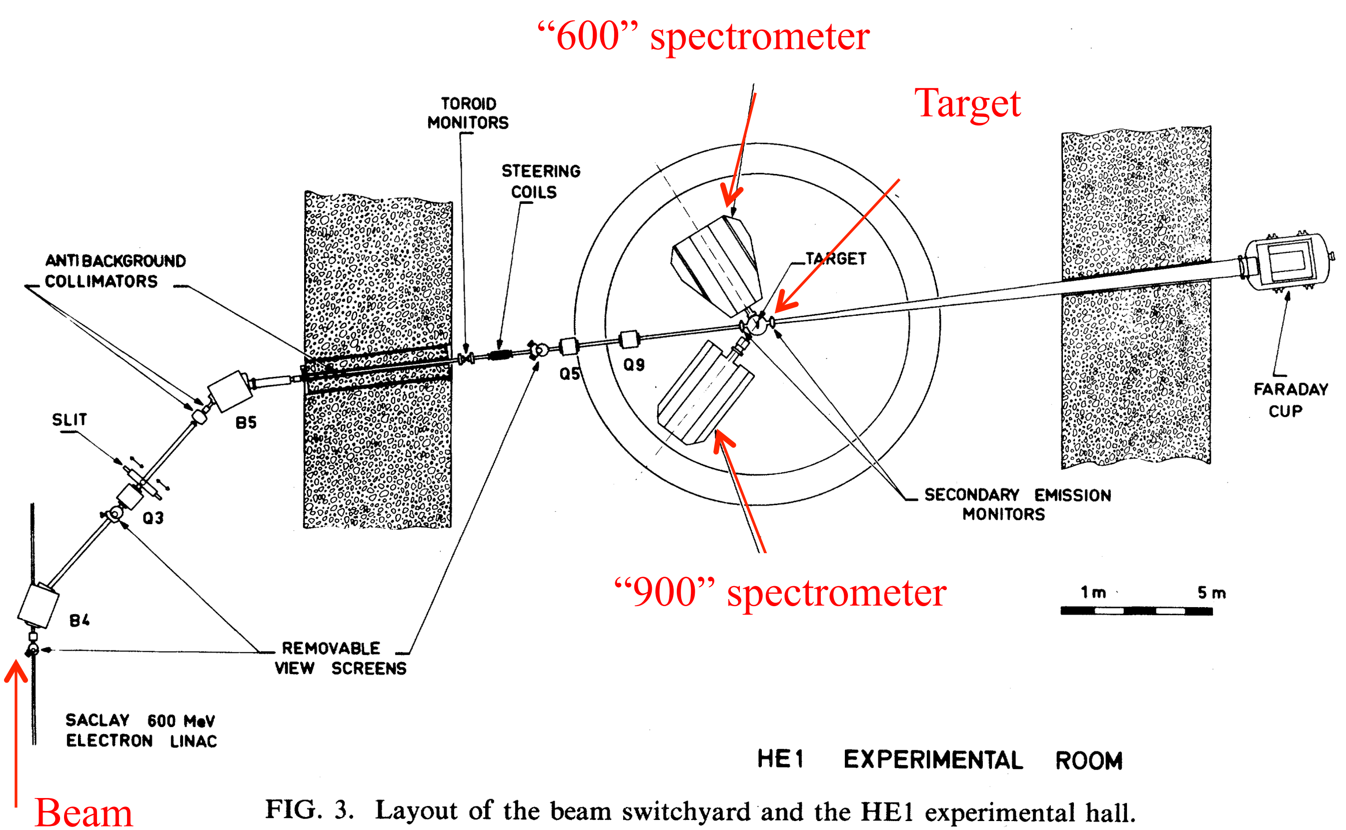


FIG. 3. Layout of the beam switchyard and the HE1 experimental hall.

Philippe Leconte

Jean Mougey

HE1 experimental room – "600" and "900" magnets

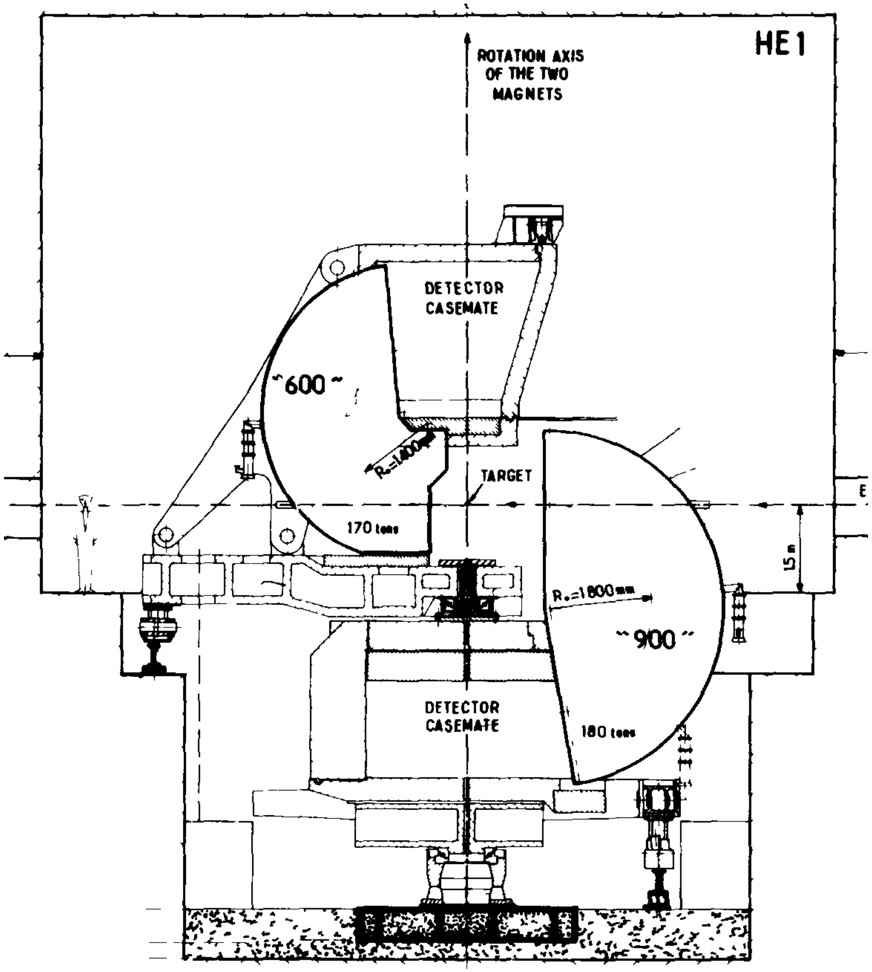


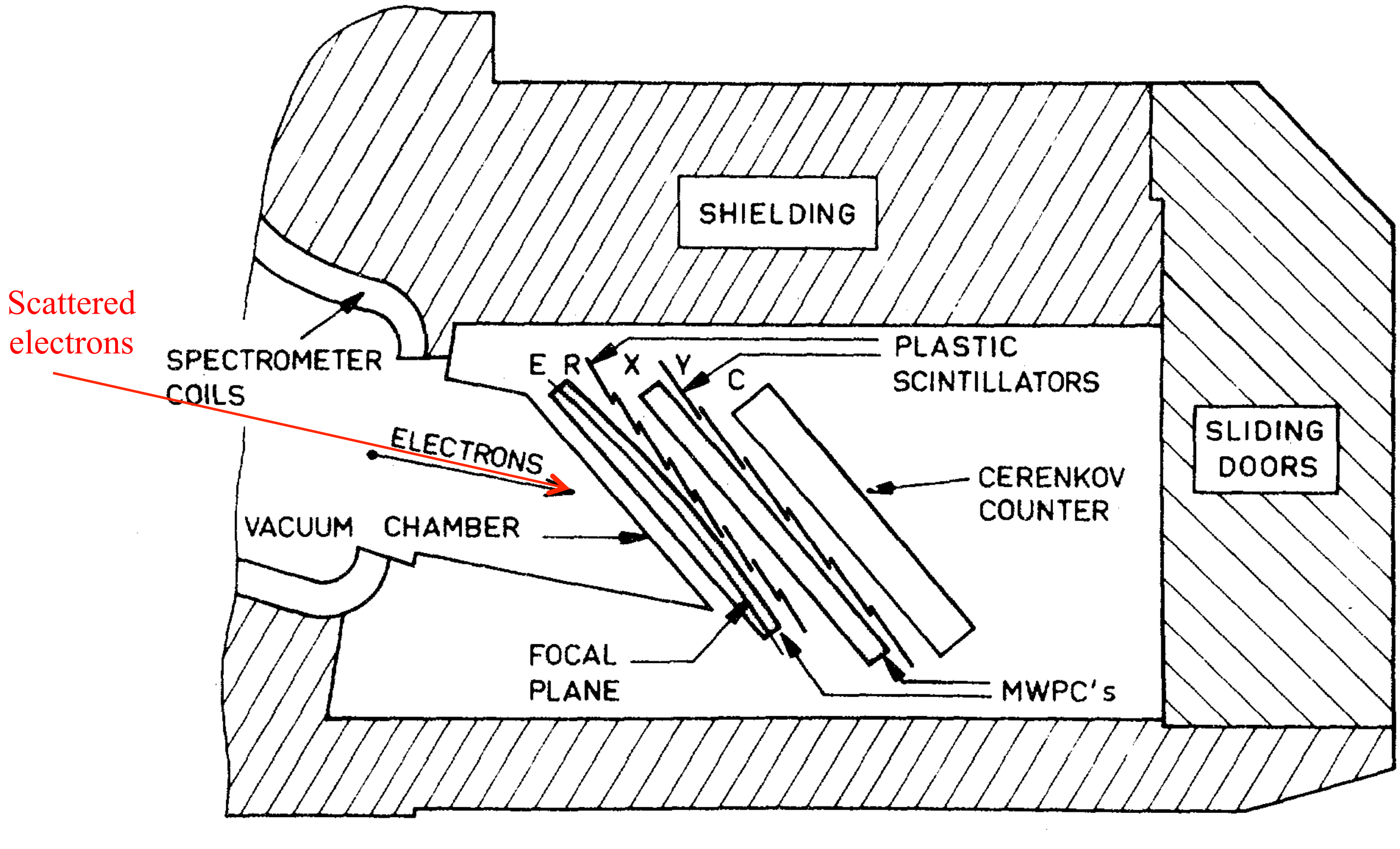
TABLE 1

Spectrometer characteristics

	"600"	"900"
Radius (cm)[a]	140	180
Bending angle [a]	153°	169° 42′
Gap (cm)[a]	8	12
Shape of pole extremities		
entrance	Plane, non rotated	Curved $R = 147$ cm
exit	Plane, rotated by 22°	
Maximum rigidity (MeV c^{-1})	630	900
Corresponding field (T)	1 5	1 67
Corresponding current (A)	565	625
Corresponding electric power (kW)	100	220
Field indices	$n = \frac{1}{2}\ \beta = \frac{3}{8}$	$n = \frac{1}{2}\ \beta = \frac{1}{6}$
Object distance (cm)[a]	70	147
Image distance (cm)[a]	140	147
Focusing	Single	Double
Focal plane angle	33° 30′	39° 11′
Momentum acceptance	+10%, −30%	±5%
Maximum solid angle (msr)	6 7	5 6
Dispersion (cm/%)	6 7	11 0
Momentum resolution	4×10^{-4}	$1\ 5 \times 10^{-4}$

Total weight: about 1000 tons

Detector casemate



Example:

36 hours with not a single count in the elastic peak region

Good shielding: mandatory for low cross-section measurements

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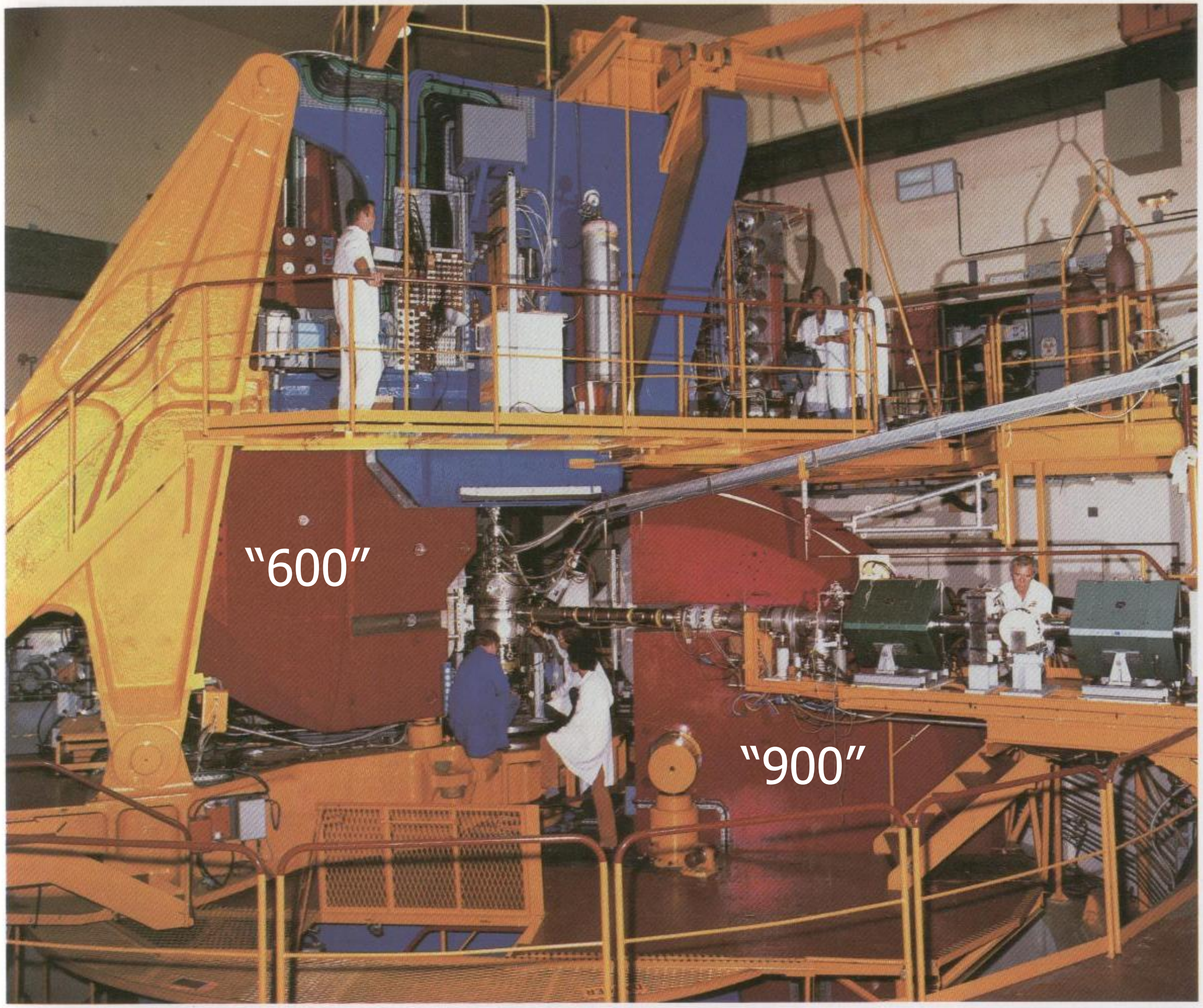
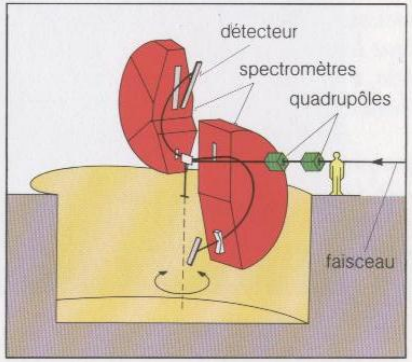


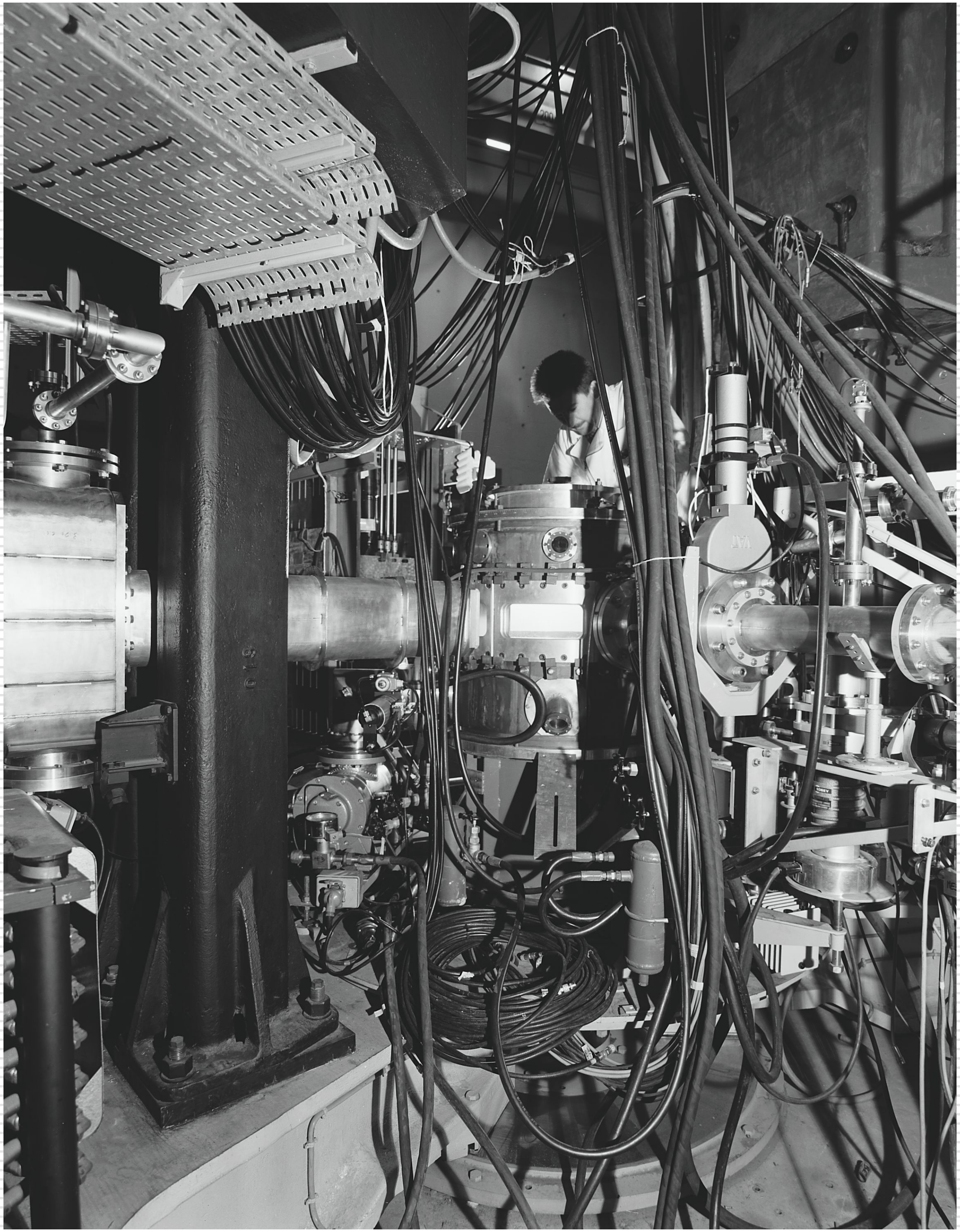
Ensemble des deux spectromètres utilisés pour la diffusion d'électrons.

Certaines expériences exigent que l'on soit capable de distinguer des processus qui donnent lieu à émission de particules dont la quantité de mouvement est très voisine. Seul un instrument capable de séparer des valeurs très proches permet une observation fine. Les spectromètres conçus à l'ALS ont des performances qui en font l'un des meilleurs appareillages sur le plan mondial.

La salle HE1, en particulier, possède un ensemble de deux gigantesques aimants, le tout pesant environ 1 000 tonnes, capables de distinguer l'énergie des particules au dix millième près.



Éclaté schématique de l'ensemble des deux spectromètres.



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Nice atmosphere…

"Magnetic" electron scattering

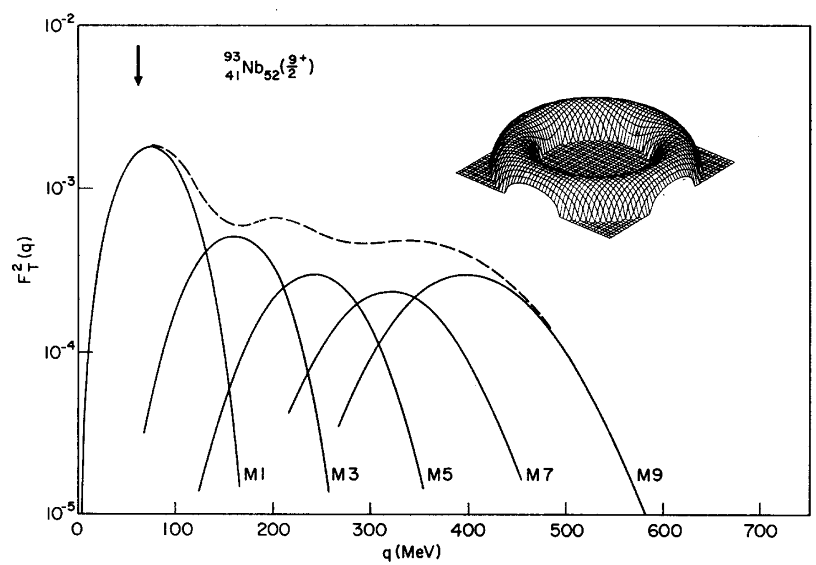
- Magnetic (on the magnetization distribution) electron scattering
  - On $J_0 \neq 0$ nuclei

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

- Magnetic (odd) multipoles
  - M1, M3, … MΛ ($\Lambda = 2J_0$)
  - example: ^{93}Nb ($1g_{9/2}$)

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

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



Donnelly and Walecka, Nucl. Phys. A201, 81 (1973).
Donnelly and Sick, Rev. Mod. Phys. 56, 461 (1984).

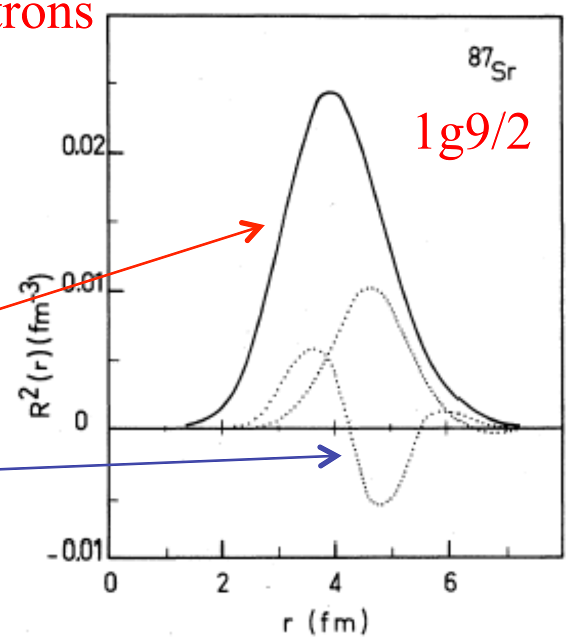
Valence proton and neutrons distributions

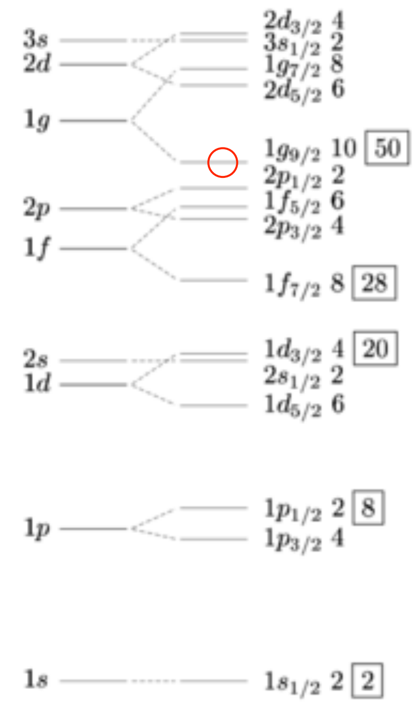
- Simplification for “stretched” spin configurations: $J_0 = l + \frac{1}{2}$
  - Spin: highest one of all filled shells
  - Multipole $\Lambda = 2J_0$: only intrinsic magnetization
  - No conf. mixing from other nucleons
  - Valid for protons and neutrons

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

- Example: ^{87}Sr

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





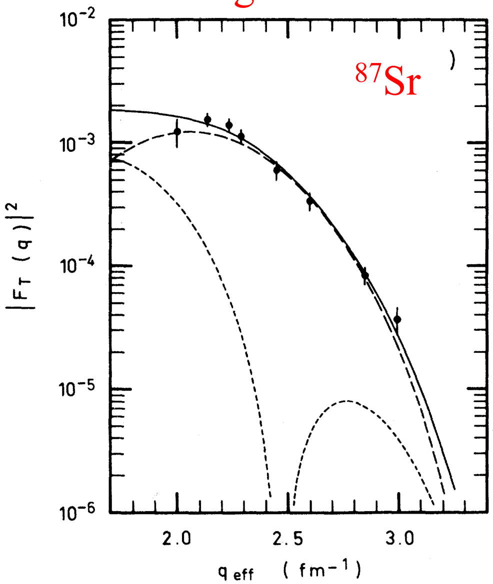
A clean way to measure the entire shape of the valence nucleons

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

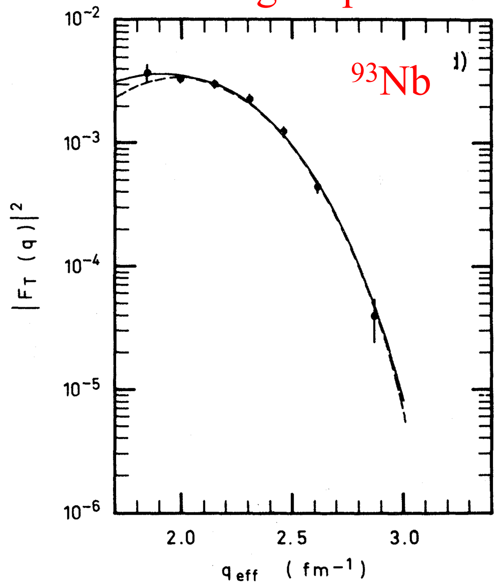
Sick at al., PRL 38,1259 (1977).

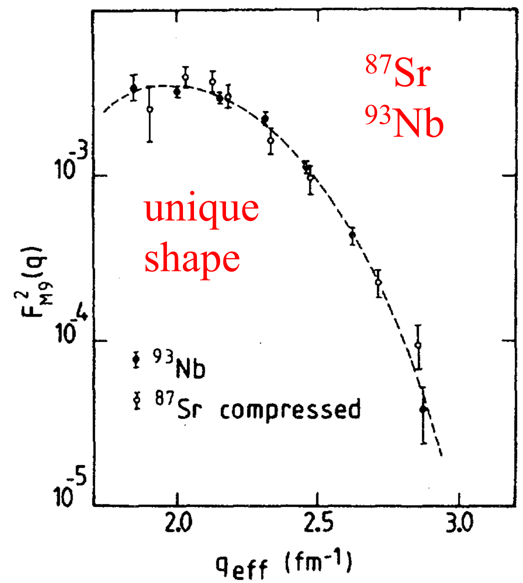
Platchkov at al., Phys. Rev. C25, 2318 (1982).

g9/2 neutron



g9/2 proton





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

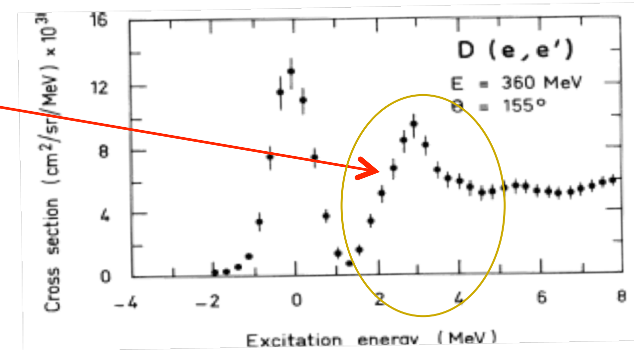
		Valence radius (fm)			
Nucleus	Orbit	DDHFB	WS	WS + MEC	
^{87}Sr	$1g^{n}_{9/2}$	4.832	4.756(72)	4.823(76)	neutron N = 49
^{93}Nb	$1g^{p}_{9/2}$	4.931	4.897(58)	4.946(64)	proton Z = 41

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

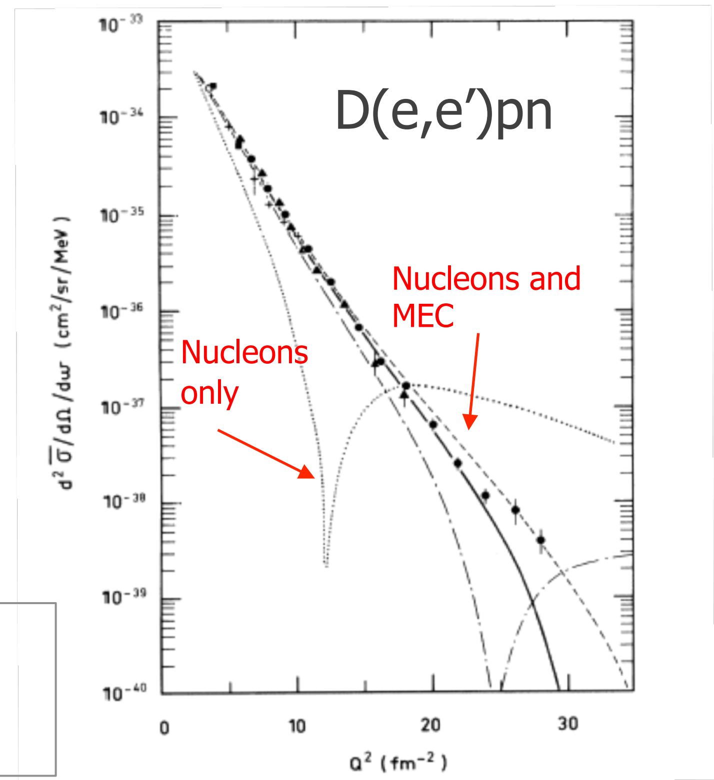
Evidence for meson-exchange currents in the deuteron

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

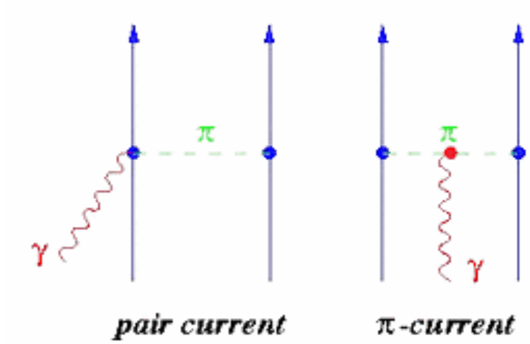
Bernheim et al., PRL 46, 402 (1981)
Auffret et al., PRL 55, 1352 (1985)



- Deuteron: $^3S_1$ and $^3D_1$ (~5%) states
- Two transitions: $^3S_1 \rightarrow {}^1S_0$ and $^3D_1 \rightarrow {}^1S_0$
- Destructive interference around 12 fm^{-2}



- Meson exchange contributions



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

The deuteron form factor A(Q²)

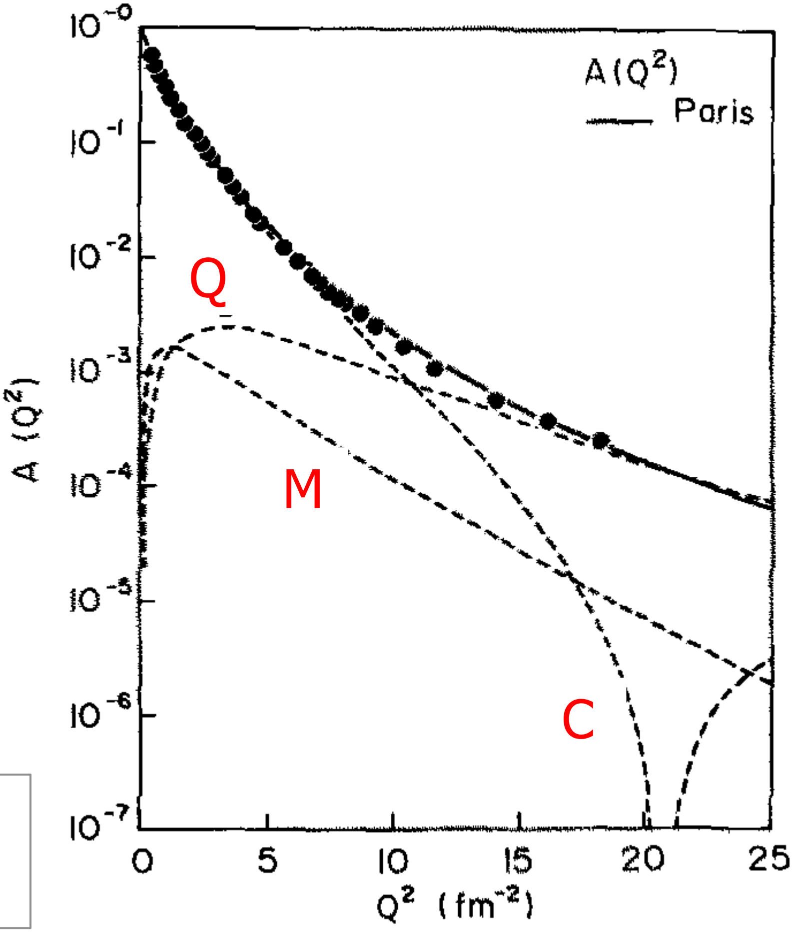
- Cross section:

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

- Form factors (deuteron spin = 1)

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

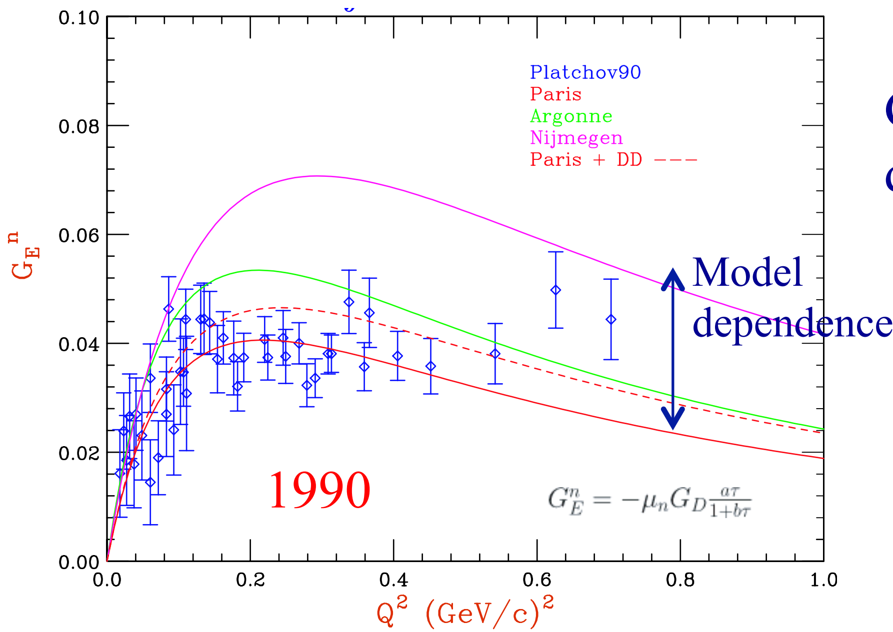
- Dependent on:
  - N-N potential
  - Neutron FF
  - Meson-exchange currents, Rel effects



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

The neutron electric form factor, G_E^n

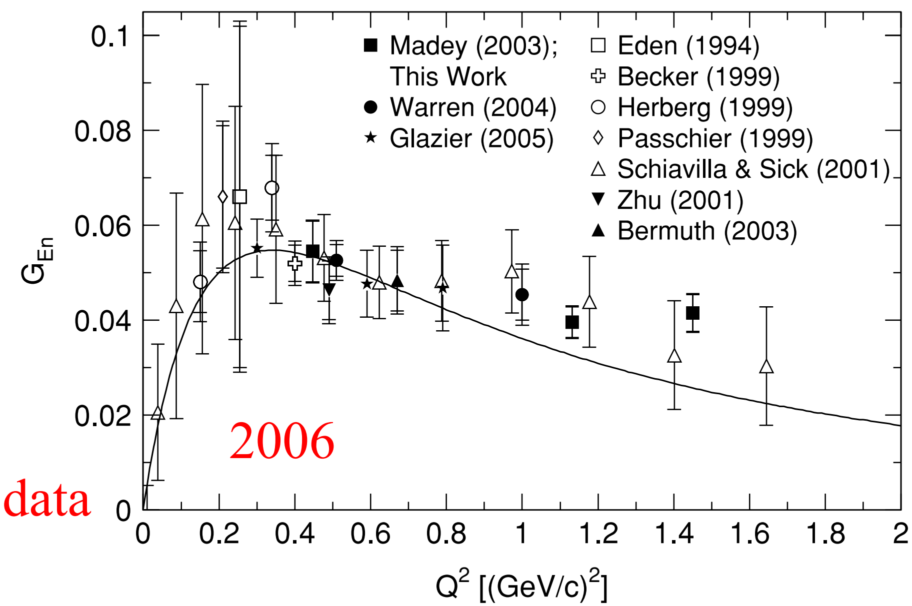
Platchkov et al., Nucl. Phys. A510, 740 (1990)



Saclay data

G_{en} as determined from elastic electron-deuteron scattering (~280 citations)

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

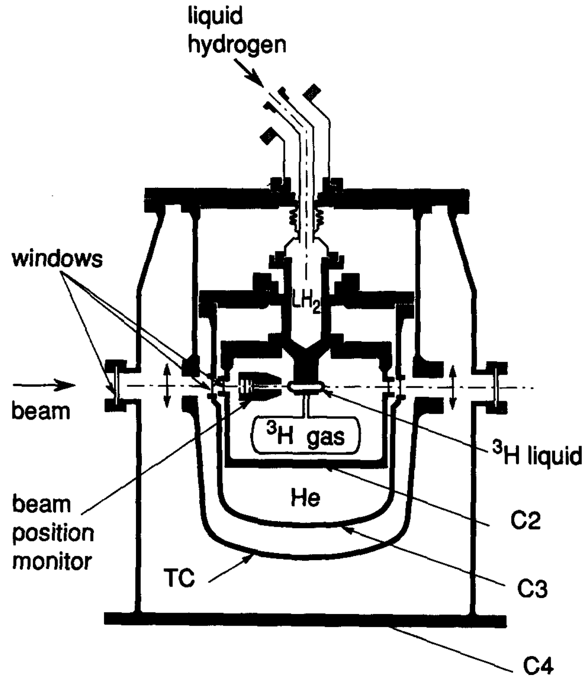


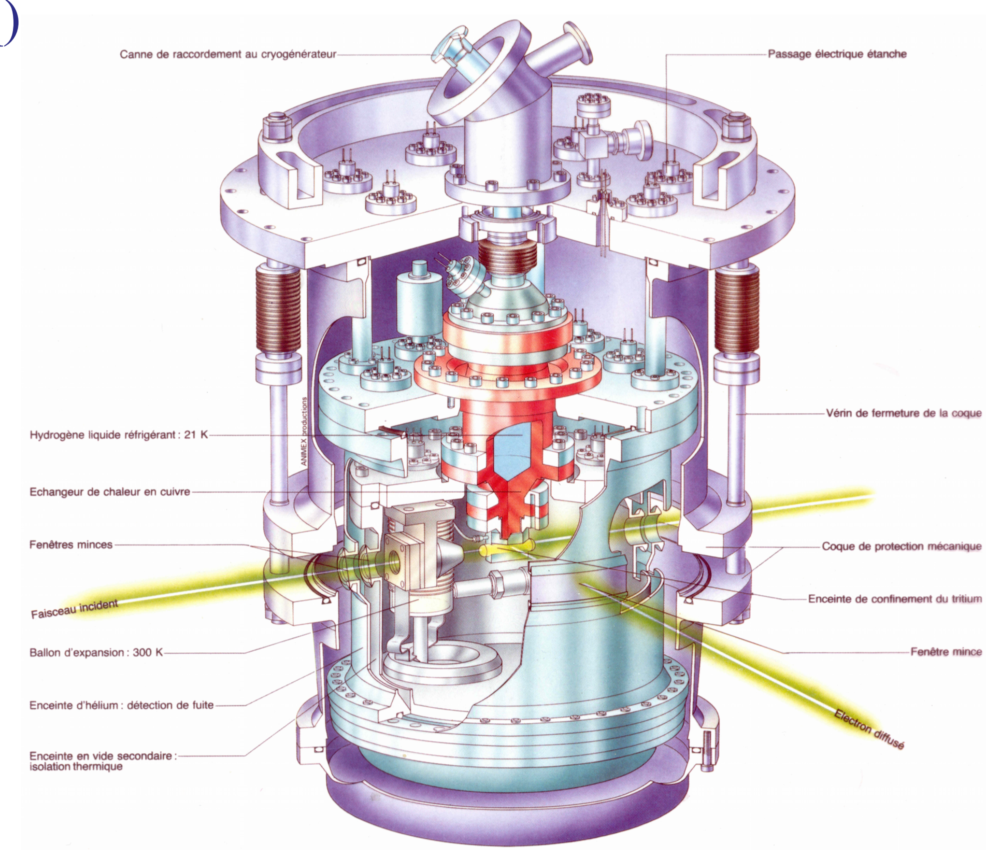
JLab and Mainz polarization data

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)
  - Target length: 5 cm





Three-nucleon system – form factor measurements

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

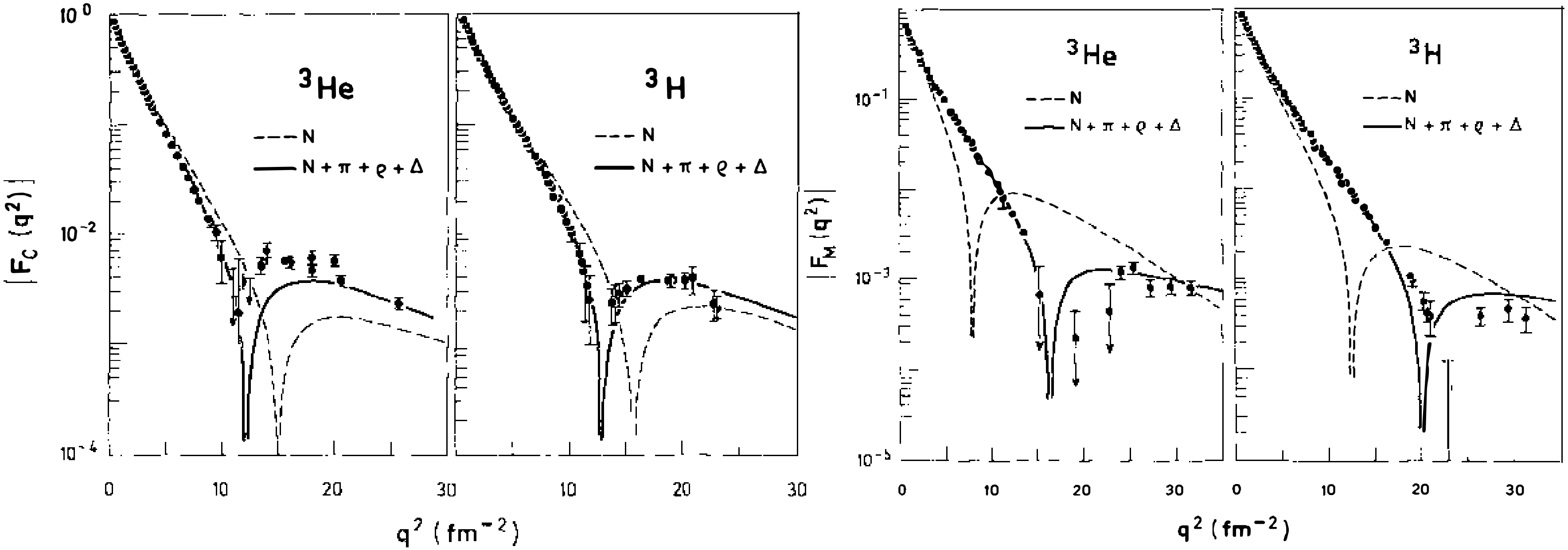
Amroun et al., PRL 69, 253 (1992)

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

Cavedon et al. PRL 49, 986 (1982)

Charge form factors

Magnetic form factors



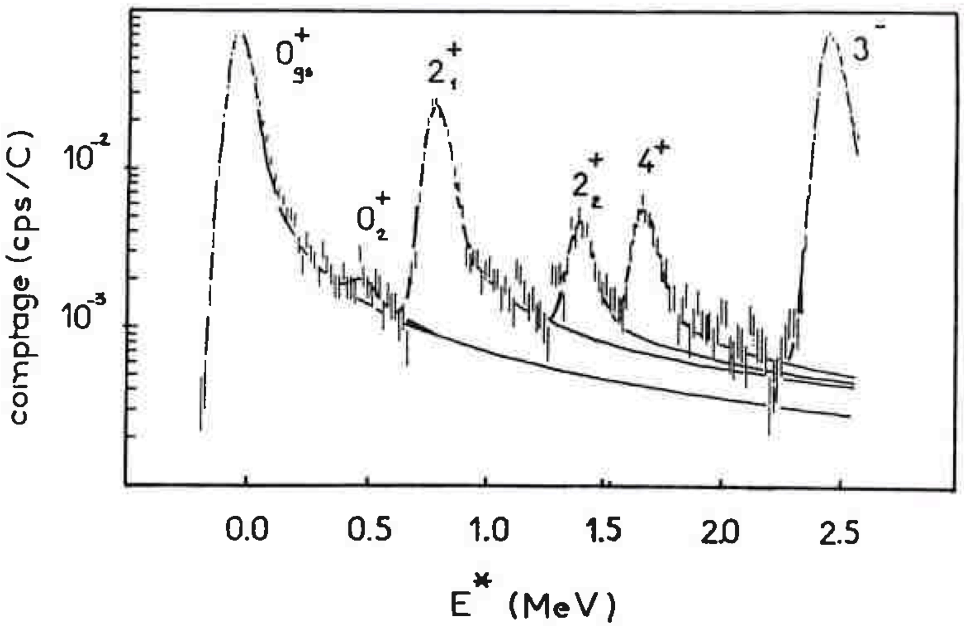
Meson-exchange currents are mandatory for a good description, particularly for magnetic form factors

Three-body forces have a minor effect

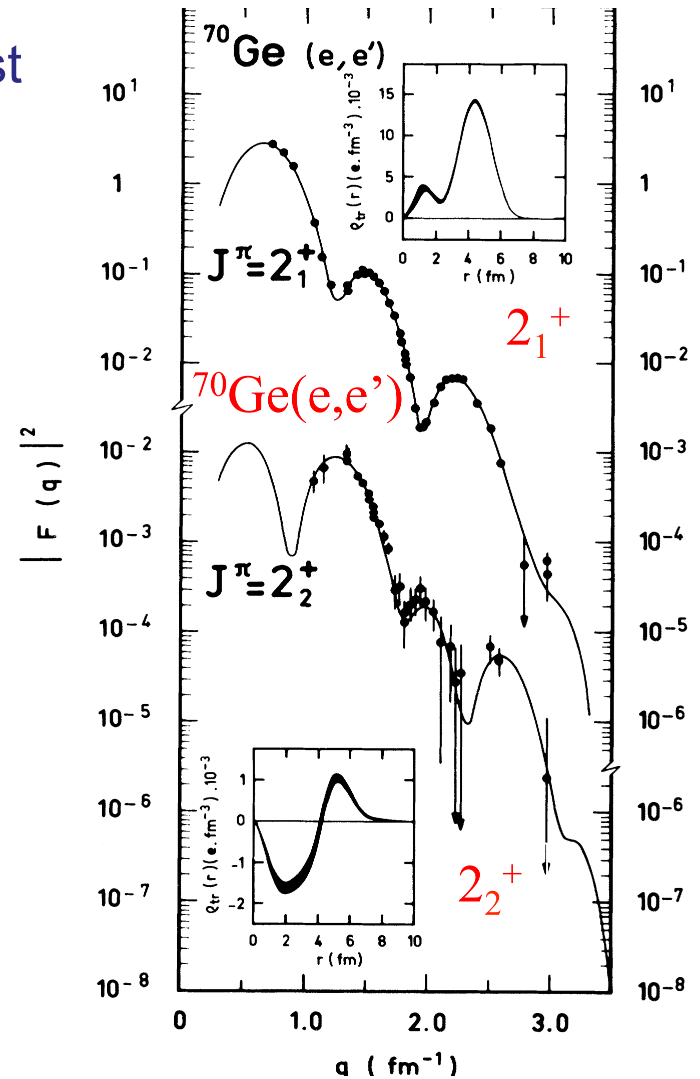
Configuration mixing in ^{70,72,74,76}Ge isotopes

- Inelastic (e,e') scattering
  - Transition charge densities of the first 2^+ states in ^{70,72,74,76}Ge isotopes
  - (p,t) and (t,p) reactions: hints for configuration mixing

Electron scattering spectrum



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

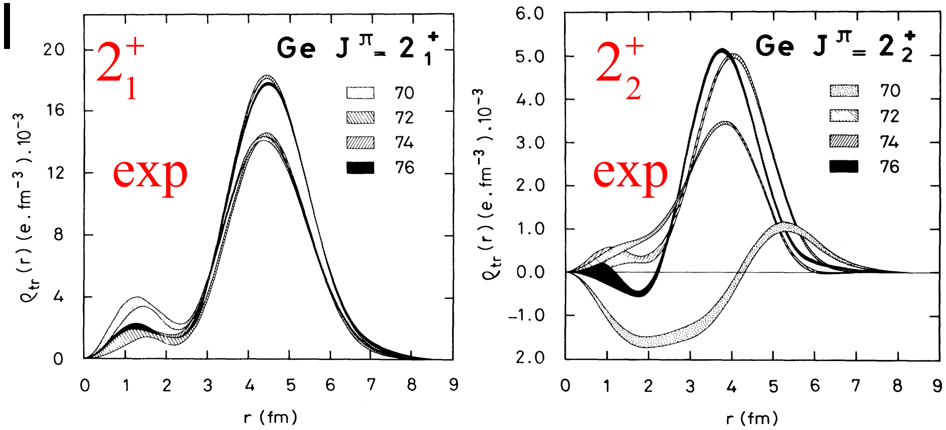


Configuration mixing in Ge isotopes – exp / th

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

- Interacting Boson Model

A. Arima F. Iachello



  - Combines single-particle and collective motions
  - Allows for configuration mixing

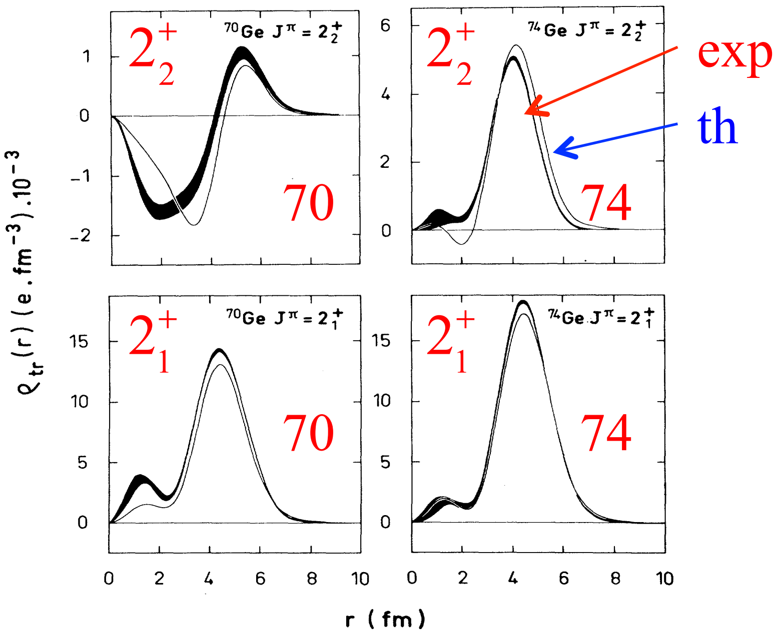


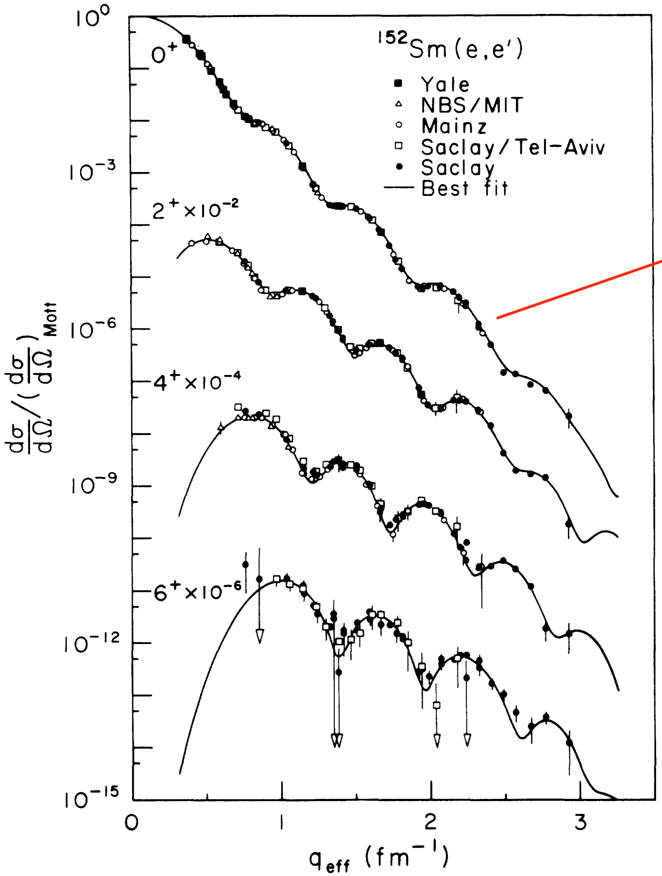
FIG. 3. Comparison between the predicted (thin line) and experimental (thick line) transition densities.

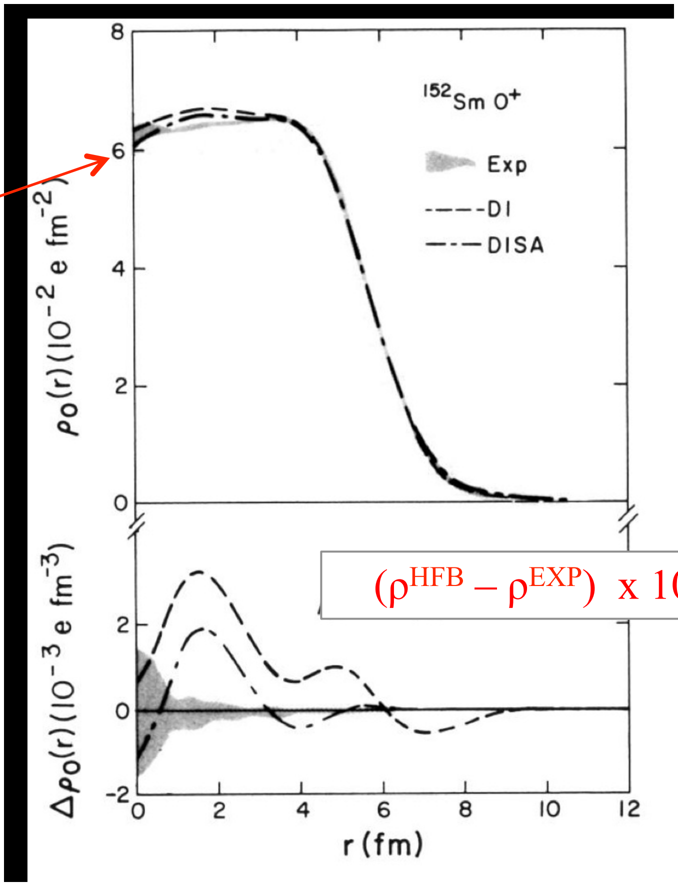
Precise determination of the 2^+ transition densities
Evidence for the coexistence of two configurations, in agreement w/ IBM-2

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

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

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



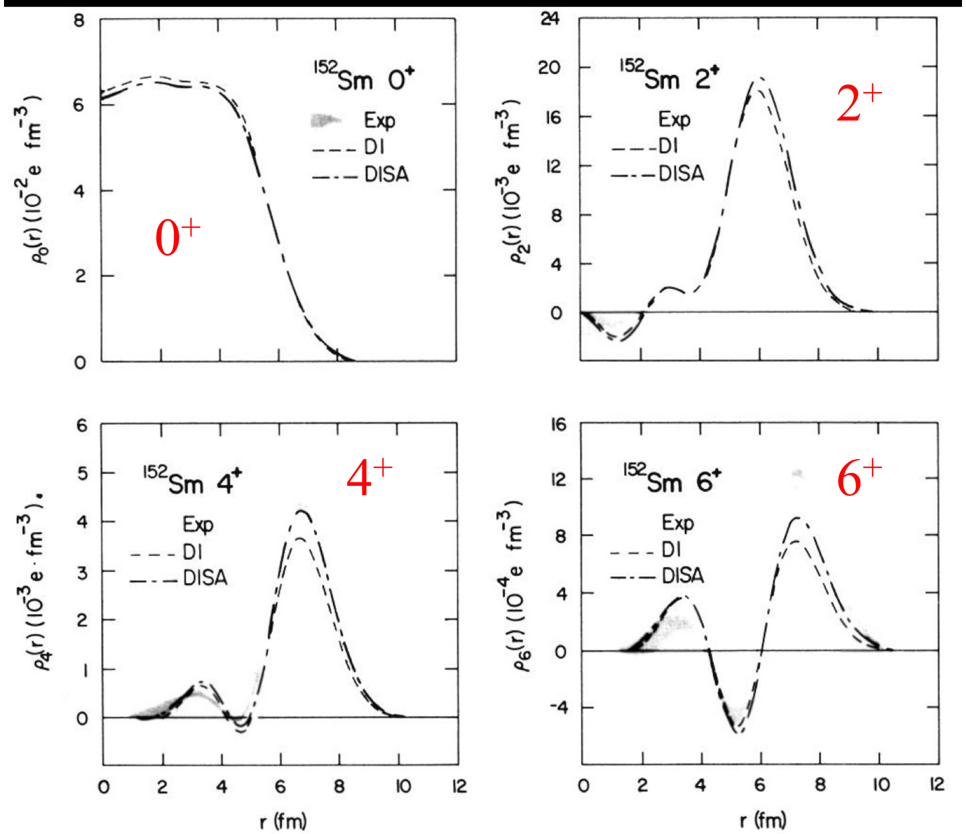


$(\rho^{HFB} - \rho^{EXP})$ x 10

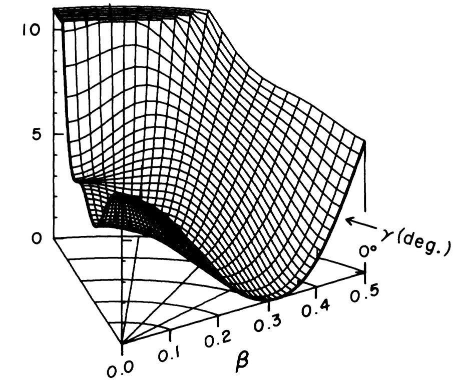
Comparison with a triaxial DD HFB calculation

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

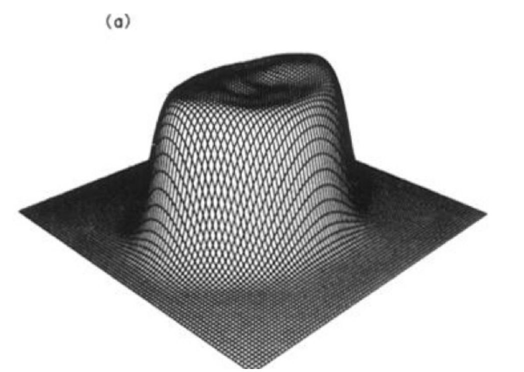
- Comparison with triaxial mean-field HFB calculation
  - two versions of the D1 Gogny force



Phan et al.,
Phys. Rev. C38,
1173 (1988)



(β,γ) potential energy surface



Exp. intrinsic charge density
Fourier-Bessel Analysis

The ground-state rotational band of 152Sm is well described by triaxial HFB calculation

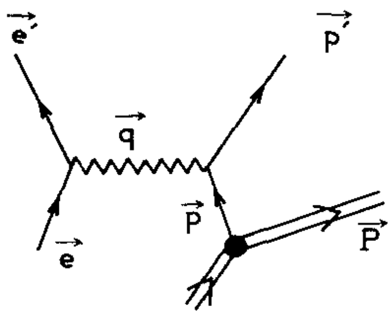
“Quasi-elastic” electron scattering

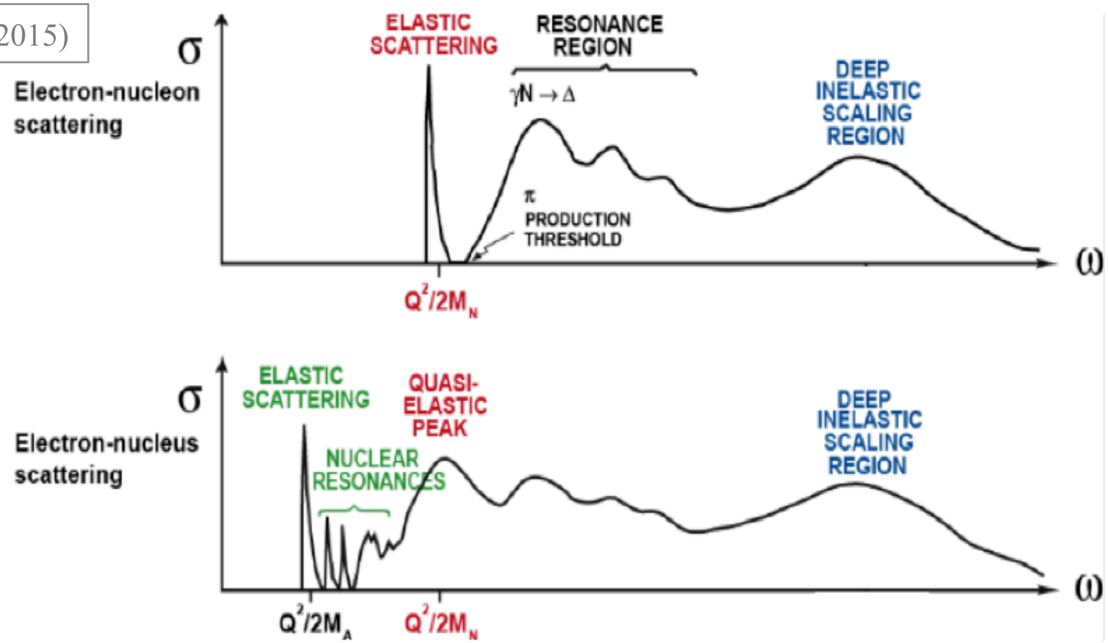
- Quasi-elastic peak

  Response functions: S_L, S_T

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

Fig. from G.T. Garvey et al., Phys. Rep. 580(2015)



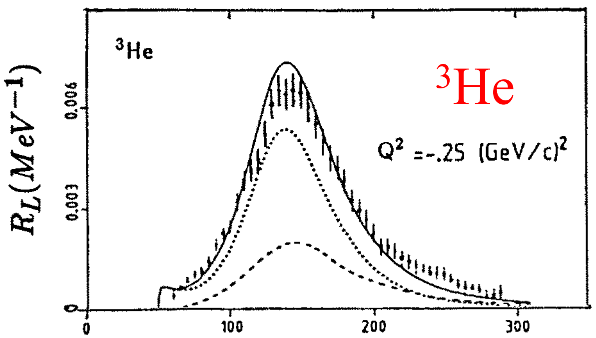


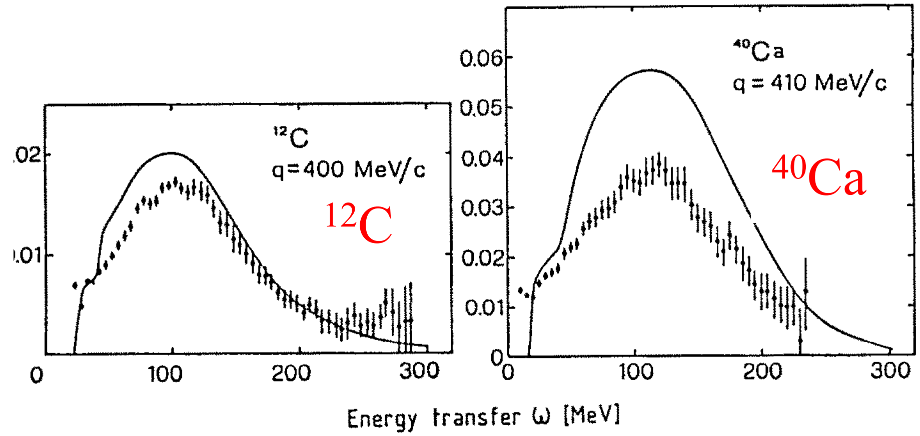
- Motivations
  - scattering from quasi-”free” nucleons inside the nucleus
  - probe the nucleon momentum distribution

Are nucleon properties modified in nuclear medium?

Longitudinal response functions in (e,e'): ^{3}He, ^{12}C, ^{40}Ca

- 1983: Quenching of S_L in nuclei



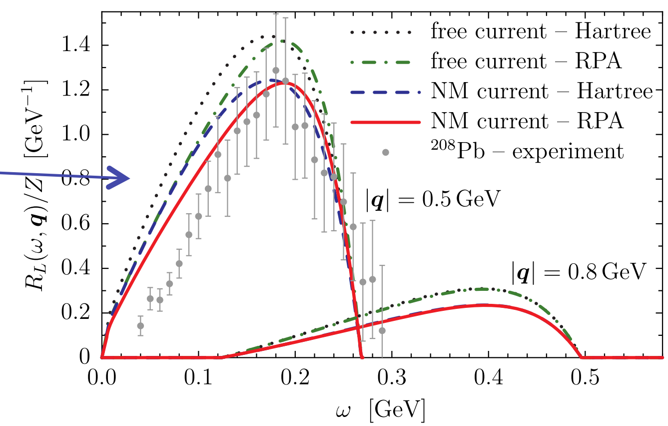


Meziani et al., PRL 52, 2130 (1984).
Meziani et al., PRL 54, 1223 (1985).

Suppression was related to the EMC effect

Cloet, Bentz and Thomas, PRL 116, 2016.

- 2016: still a fundamental issue
  - Chiral effective quark theory based on NJL model that "explains" EMC



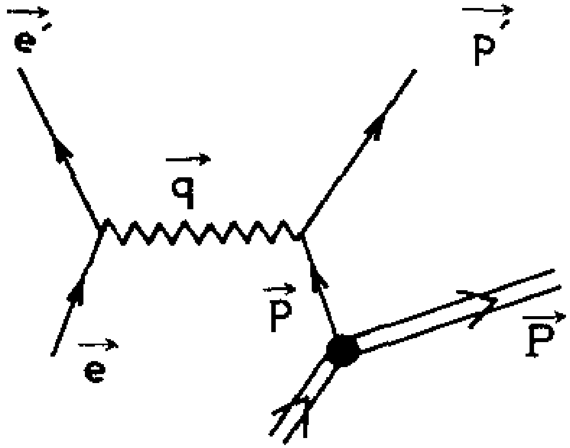
Nuclear matter effect: significant suppression (up to 30%)

Coincidence experiments (e,e'p)

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

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

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

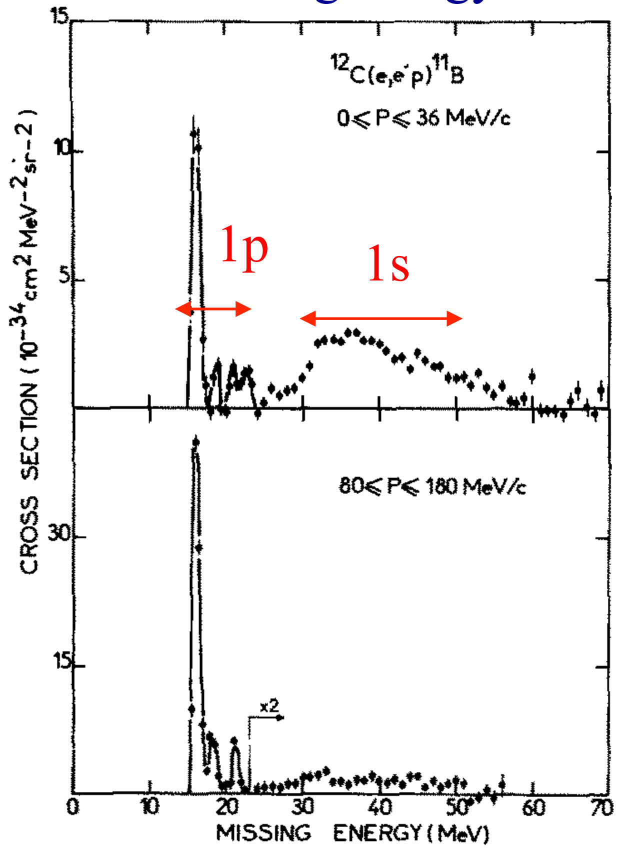


- Information on:
  - nuclear spectral function : momentum and energy distributions
  - probe individual shells; access also to deeply-bound states

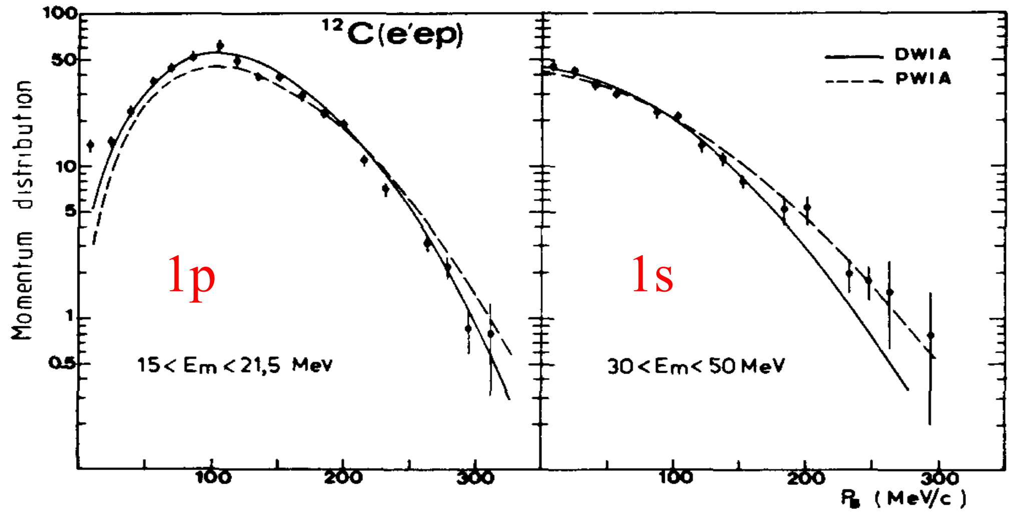
Examples of (e,e'p) experiments

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

Missing energy



Momentum distributions

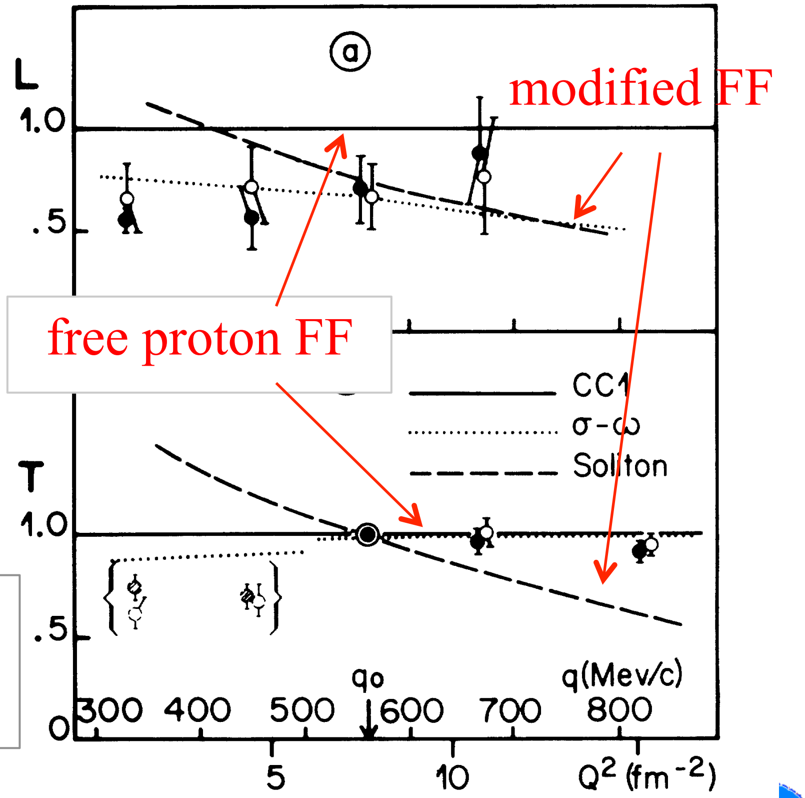


Access to: single-particle energy and momentum distributions, occupation probabilities, bound nucleon properties

Bound proton form factor measurements

- Question: 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

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



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

Summary: (my) extrapolations from ALS to ETIC ?

- 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, mandatory if low cross section measurements
- Coincidence experiments?
  - Large energy and momentum acceptances
  - Good energy and momentum resolutions

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