Towards e^- scattering on exotic nuclei

F. Flavigny (LPC Caen)

on behalf of the working group

Outline

Why using electrons to probe (exotic) nuclei ?

- The e^- probe for nuclei
- Ilustration of past achievements and link with new physics cases
  - Elastic → Bubble nuclei
  - Inelastic → N=50 physics / Shape coexistence
  - Quasi-free → Short range correlations
  - And much more

How to perform e^--RI collisions?

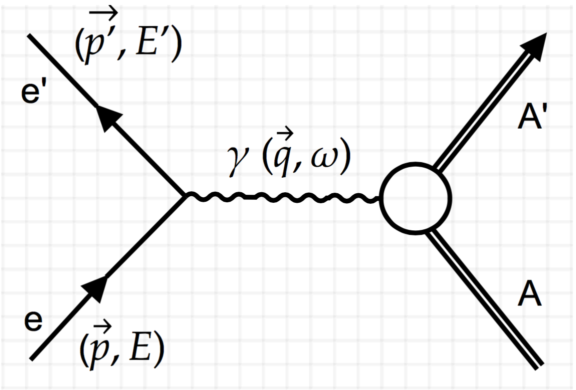
- Luminosity requirements
- Techniques:
  - Trap (SCRIT)
  - Collider (ELISE)
- Existing (pre)design study (ETIC)

The electromagnetic probe for nuclei/hadrons

- EM interaction well-known and weak

  → e^- penetrate deeply without absorption

- Single Virtual-photon exchange (good approx.)
  - Momentum transfer q = 1/λ
    E_e=500 MeV – λ ~ 0.5 fm scale



Integrated quantities → (e^- scattering microscope) → Spatially dependant quantities

Examples:

$$< r^2 > = \left[\int_0^\infty \rho(r)\, r^2\, dr \right]^2$$

$$B(EL) = \left[\frac{J_f}{J_i} \int_0^\infty \rho_L(r)\, r^{L+2}\, dr \right]^2$$

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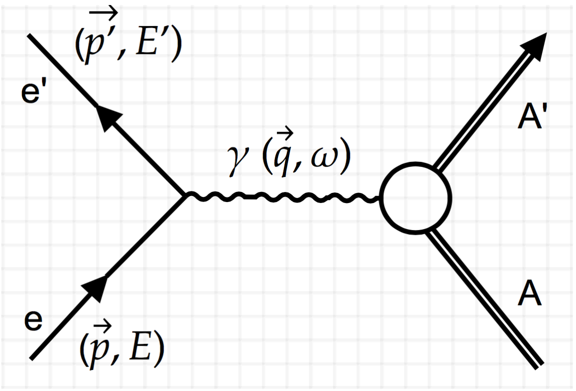

$$\frac{d\sigma}{d\Omega\, dE} = \frac{4\pi}{M_T}\, \sigma_{Mott} \left[\left(\frac{q_\lambda^2}{q^2}\right)^2 S_L(q,\omega) + \left(\frac{1}{2}\frac{q_\lambda^2}{q^2} + tan^2\frac{\theta}{2}\right) S_T(q,\omega) \right]$$

Nuclear response surfaces
or
Dynamic structure functions

$$\begin{cases} \omega \rightarrow Exc.\ Energy \\ q \rightarrow r \end{cases}$$

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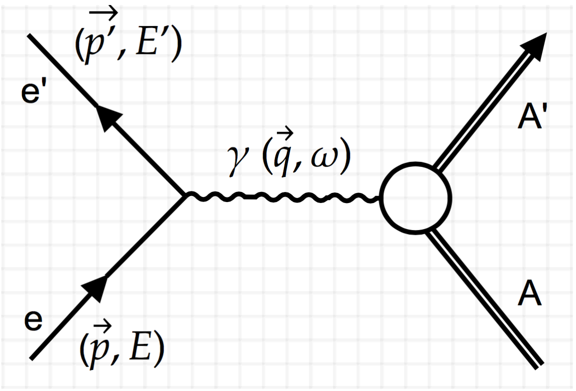

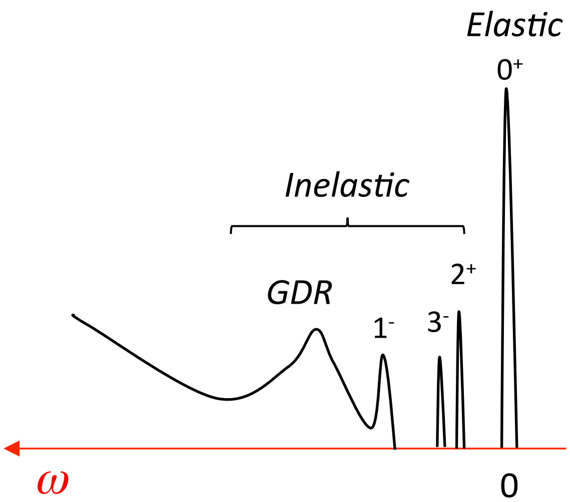

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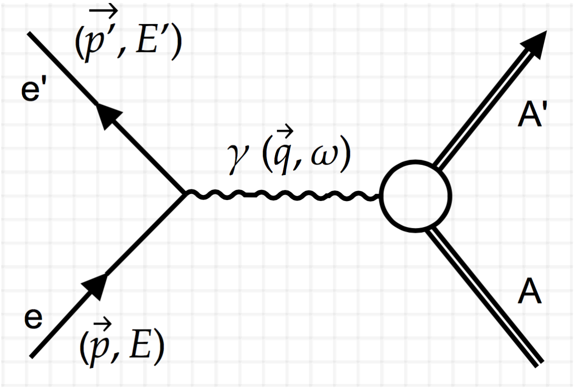
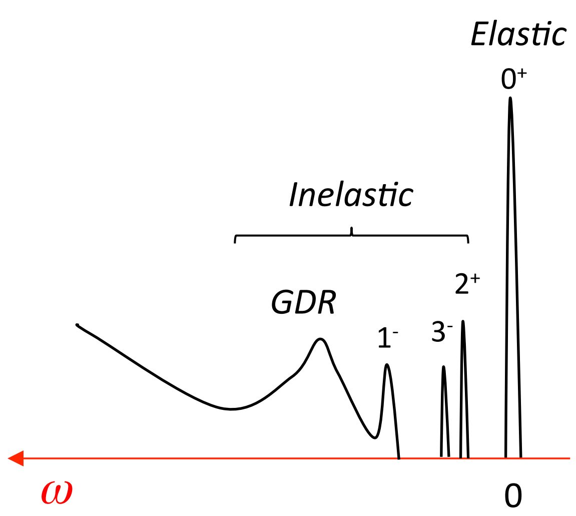
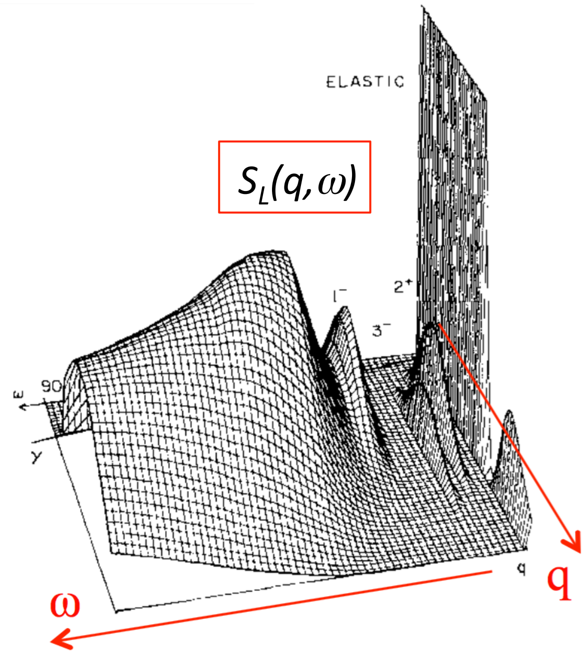






[Donelly and Walecka, ARNPS 25, 329 (1975)]

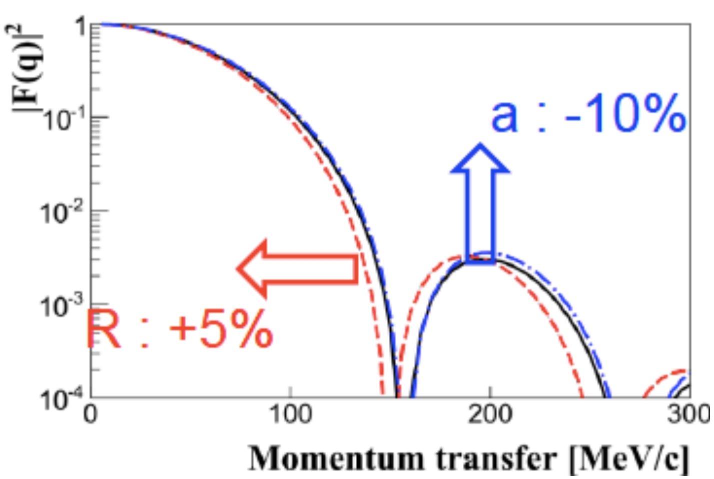
Elastic scattering

For ($\omega=0$) and $J^{\pi}=0^{+}$ states:

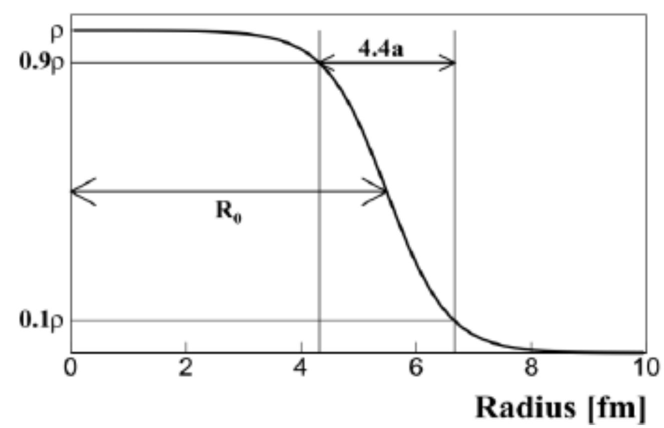
$$\left(\frac{d\sigma}{d\Omega}\right)_{eA\rightarrow eA} = \left(\frac{d\sigma}{d\Omega}\right)_{Mott} |F_c(\vec{q})|^2 \qquad F_c(\vec{q}) = \frac{1}{(2\pi)^{3/2}} \int \rho_c(\vec{r})\, e^{i\vec{q}.\vec{r}}\, d^3r$$

$\rho_c(r)$ → **Tool to probe several basic features of nuclear structure**

- Nuclear saturation, extension, binding and surface tension
- Oscillations --> shell structure and many-body correlations



$$\rho_C = \rho/(1 + e^{(r-R)/a})$$



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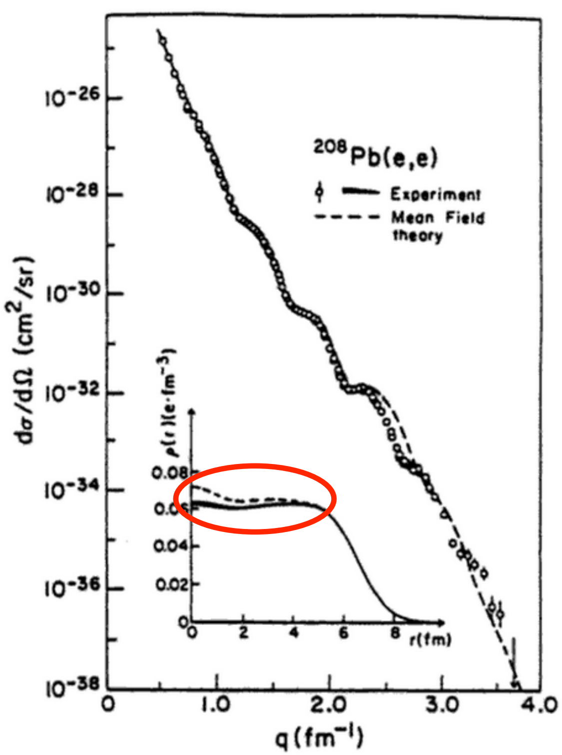
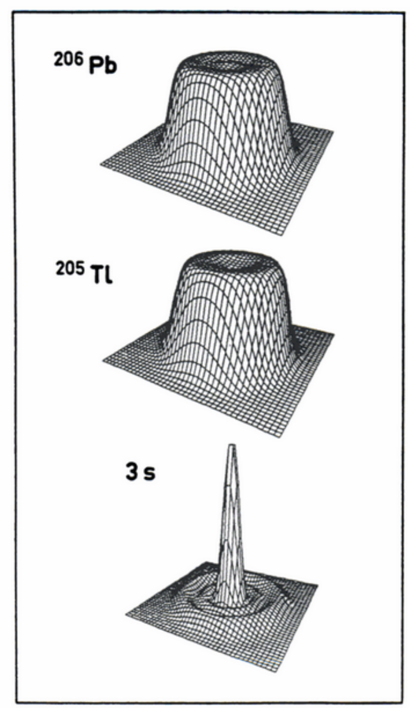


B. Frois and Papanicolas
Ann. Rev. Nucl. Part. Sci 37 (1987)

Dechargé and Gogny
PRC 81 (1980)

Cavedon, Frois, Goutte et al.
PRL 49 (1982)

etc…



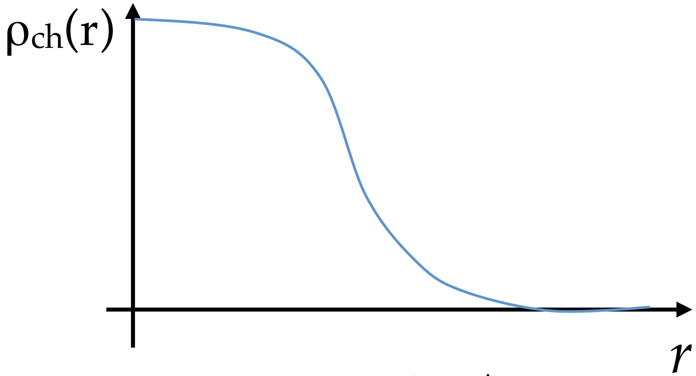
[B. Frois et al, Modern Topics in Electron Scattering (1991)]

Elastic scattering : Bubble nuclei

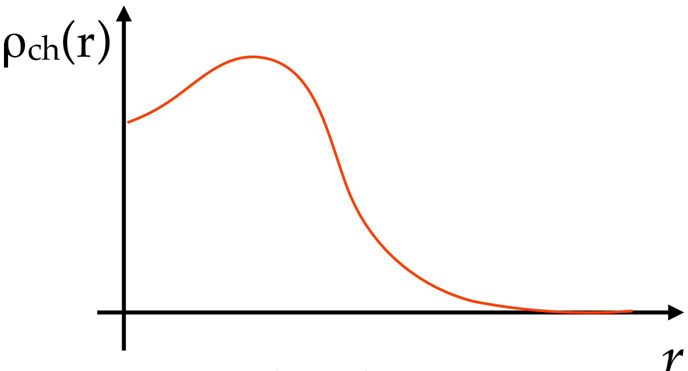
Prediction

Central depletion of $\rho_{ch}(r)$

[Dechargé et al. 2003, Bender & Heenen 2013]
[Khan et al. 2008, Grasso et al. 2009,…]



« conventional »



« (semi)-bubble »

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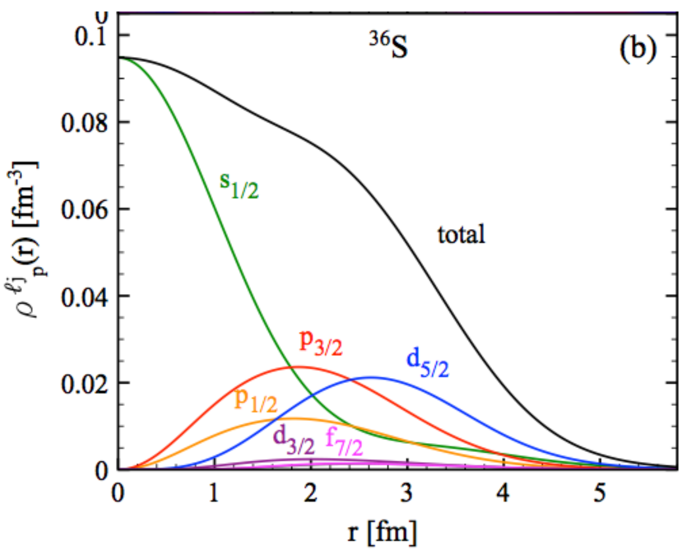
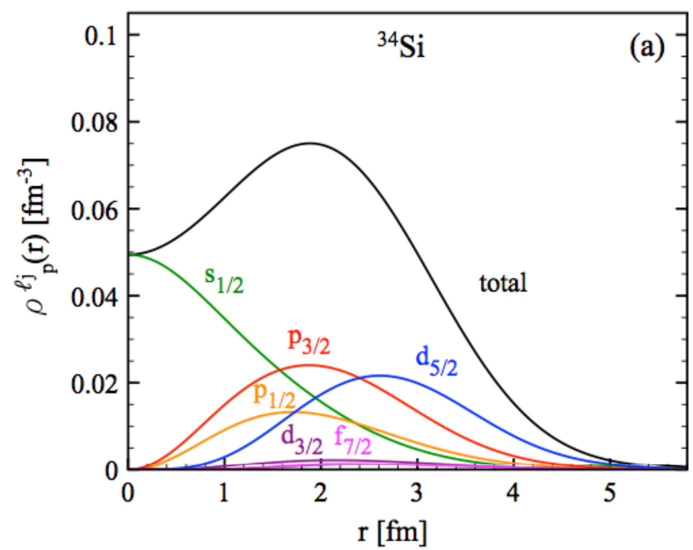
Interpretation

QM effect

$\ell = 0$ orbitals radially peaked at $r = 0$
$\ell \neq 0$ orbitals suppressed at small r



(-2p)
in $s_{1/2}$ orbital



Figures from [T. Duguet, V. Somà et al., PRC 95 (2017) 034319]

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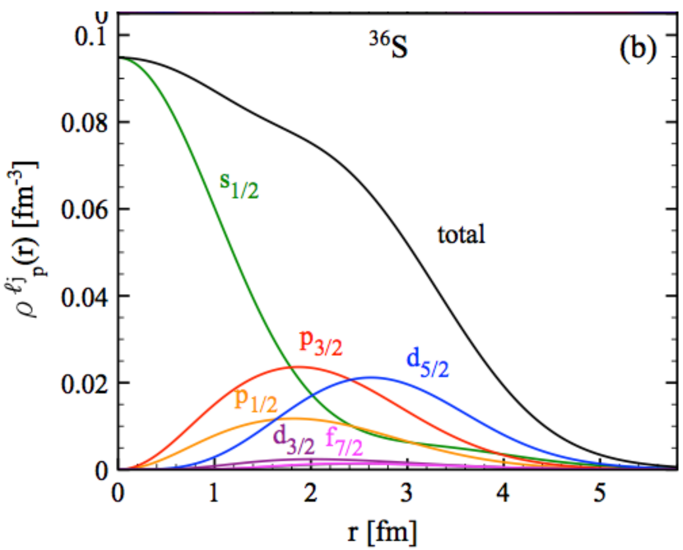
Consequence

Spin-Orbit interaction

$$V_q^{so}(\vec{r},\vec{p}) = \frac{1}{2}\left[W_1 \nabla\rho_q(\vec{r}) + W_2 \nabla\rho_{\bar{q}}(\vec{r})\right]\sigma \wedge \vec{p}$$



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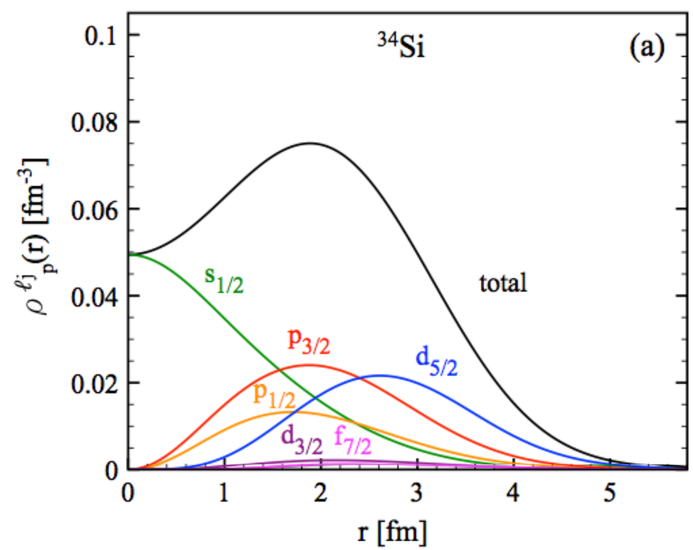

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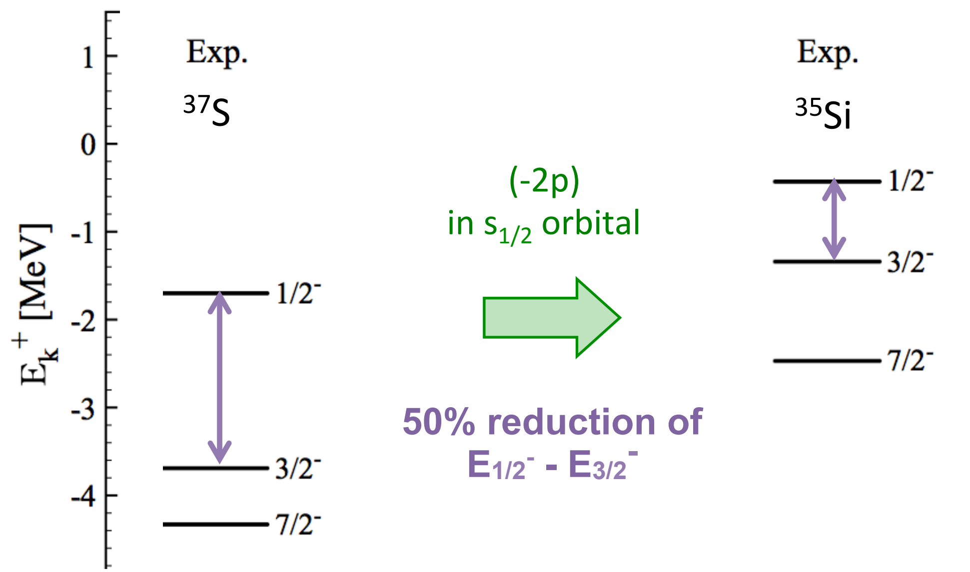
Indirect/model dependent signature

One-neutron addition



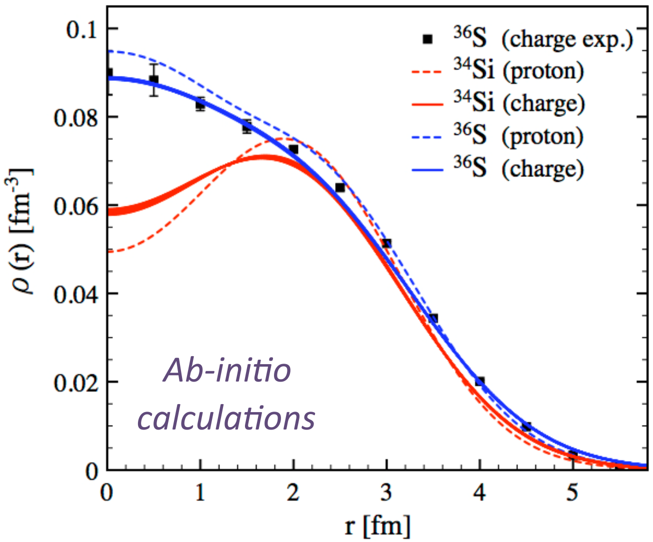
Exp. data: [Thorn *et al.* 1984] [Eckle *et al.* 1989] [Burgunder *et al.* 2014]

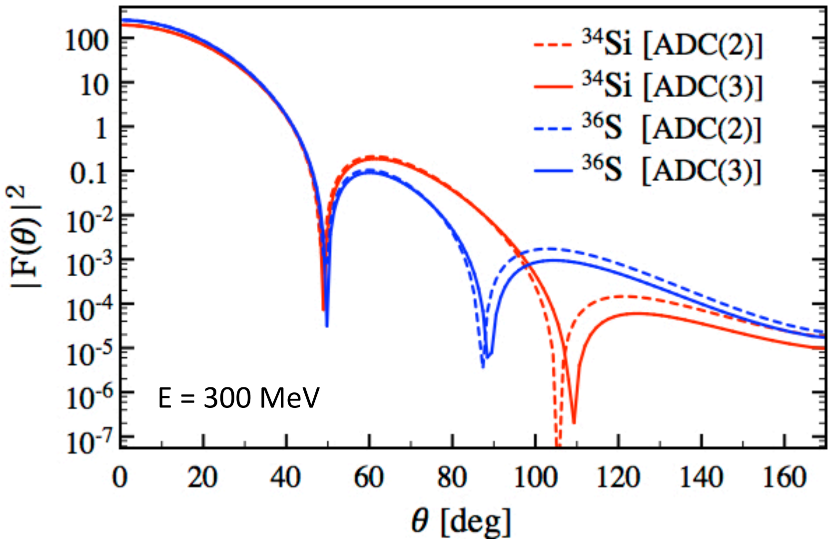
Elastic scattering : Bubble nuclei

Prediction	Interpretation	Consequence
Central depletion of $\rho_{ch}(r)$ [Dechargé et al. 2003, Bender & Heenen 2013] [Khan et al. 2008, Grasso et al. 2009,...]	**QM effect** $\ell = 0$ orbitals radially peaked at $r = 0$ $\ell \neq 0$ orbitals suppressed at small r	**Spin-Orbit interaction** $V_q^{so}(\vec{r},\vec{p}) = \frac{1}{2}\left[W_1 \nabla\rho_q(\vec{r}) + W_2 \nabla\rho_{\bar{q}}(\vec{r})\right]\sigma \wedge \vec{p}$

Direct/Unambiguous signature of central depletion

[T. Duguet, V. Somà et al., PRC 95 (2017) 034319]



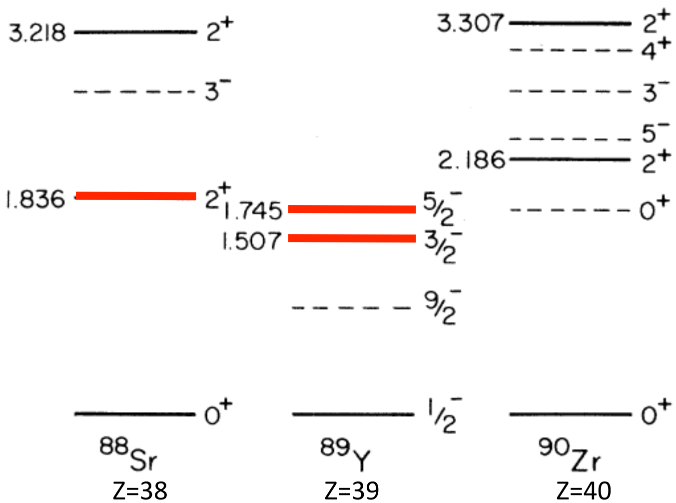


Clear differences in $|F(\theta)|^2$ for $\theta > 50°$

Inelastic scattering : Collectivity & Conf. Mixing

Transition charge densities in N=50 isotones

[Schwenker et al., PRL 50, 17 (1983)]



Initial interpretation:

- Weak-coupling: **[^{88}Sr; 2+]⊗ π 2p$_{1/2}$**
- Similar shapes/conf. for 2^{+} states

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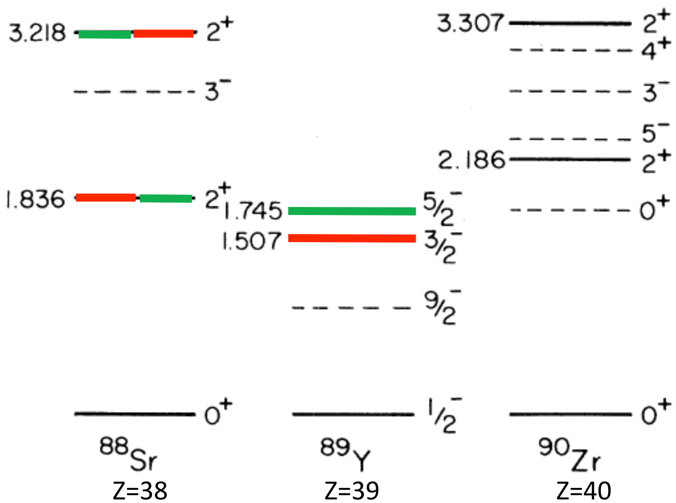

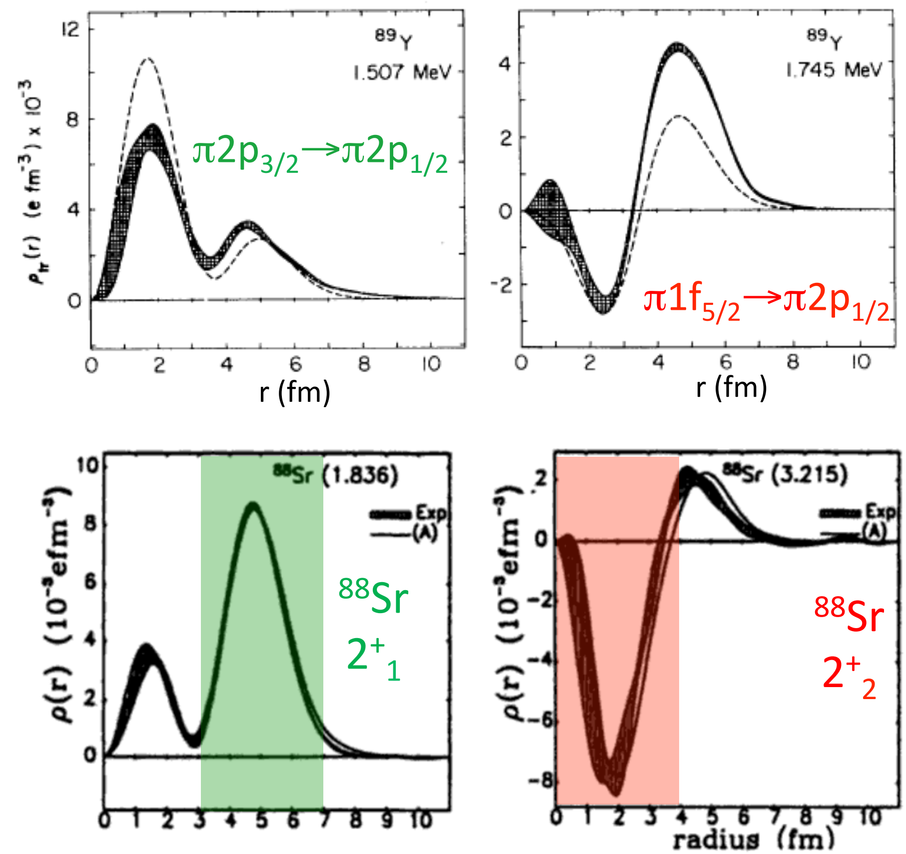

surface oscillation

nuclear interior solicited

After (e,e') precise study of π conf.:

- Orth. Comb: $[2p_{3/2}^{-1}2p_{1/2}]_{2+}$ & $[1f_{5/2}^{-1}2p_{1/2}]_{2+}$
- Localization of nucleons inv. in collectivity

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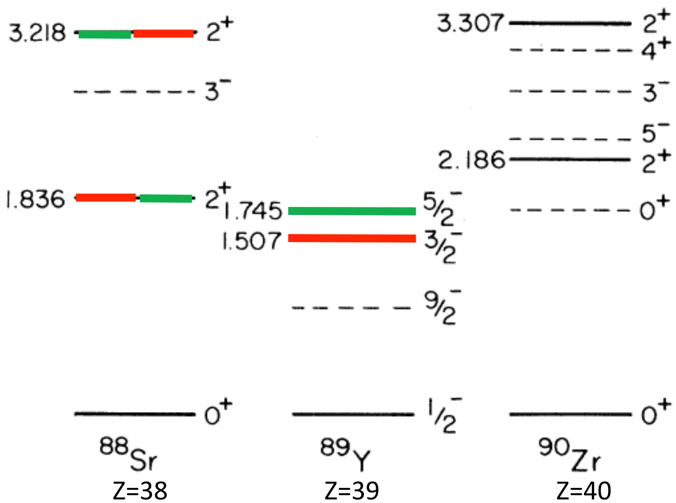

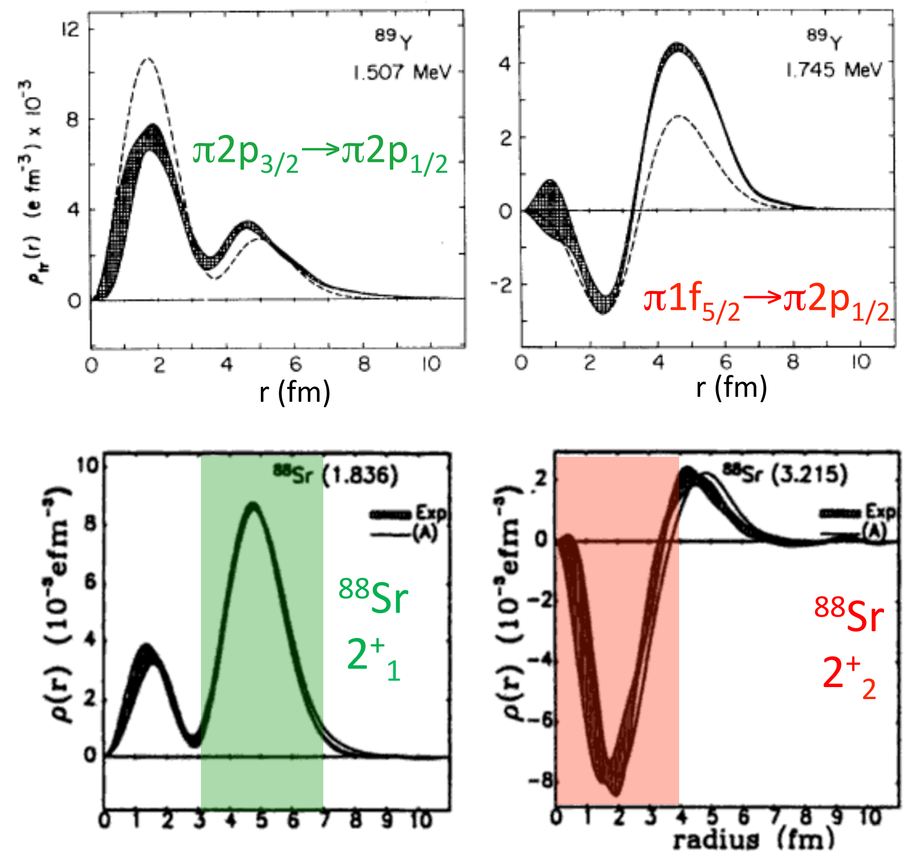

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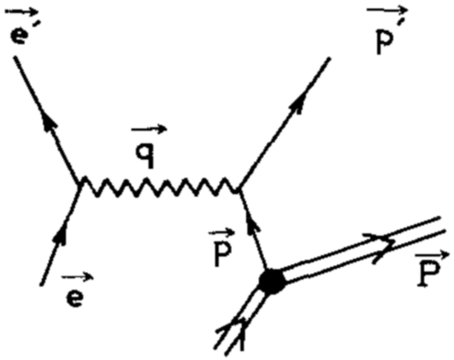
- Localization of nucleons inv. in collectivity

Tool to probe collectivity precisely → Shape coex/transition region, island of inv., etc)

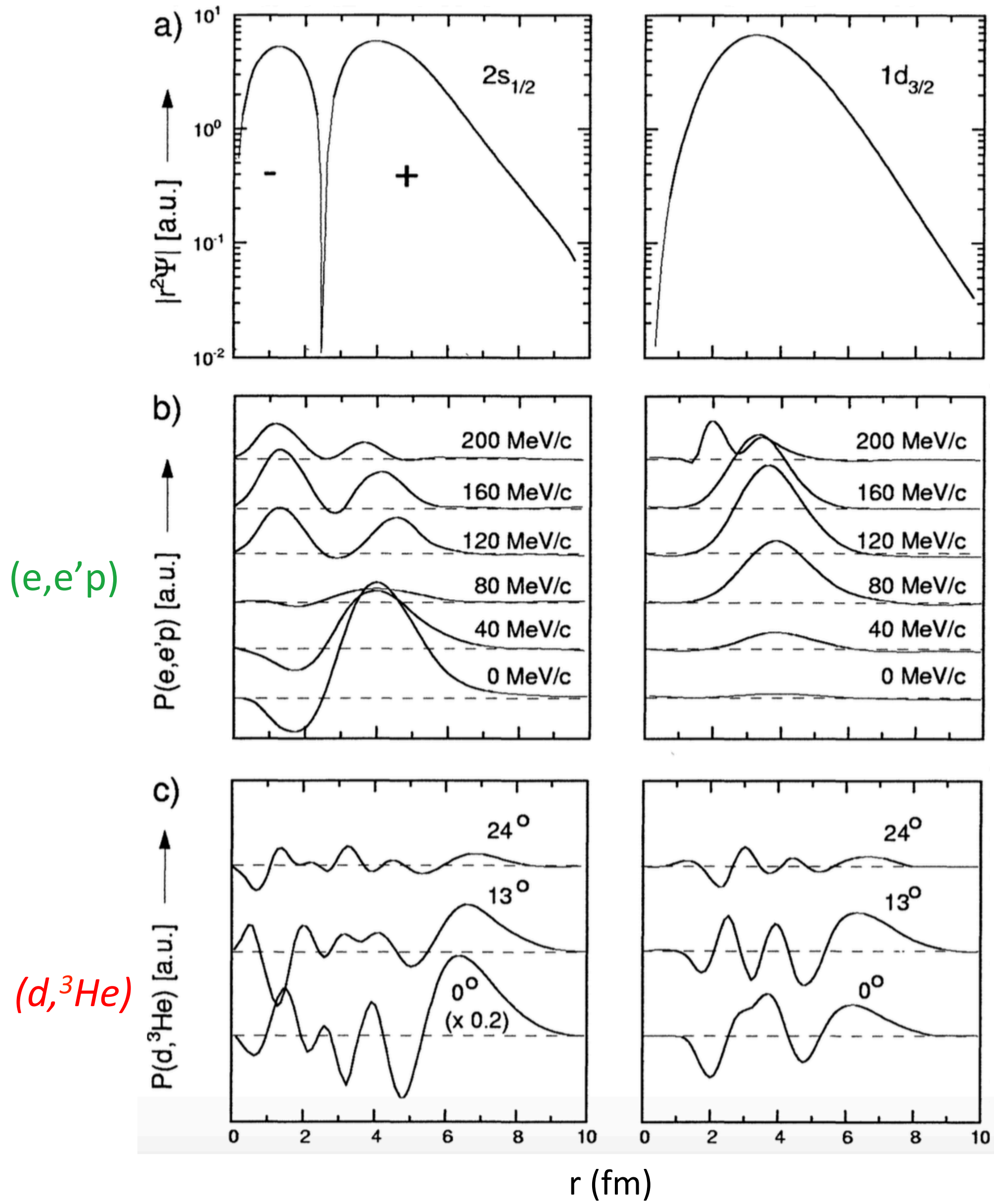
(e,e'p) Quasi-free scattering



Information on:

- Nuclear (hole) spectral function
  - (s.p. energies, mom. dis, Spec. Fac.)
  - in medium modification of nuc. prop.
  - access to deeply-bound states

[Kramer et al., NPA 679, 267 (2001)]



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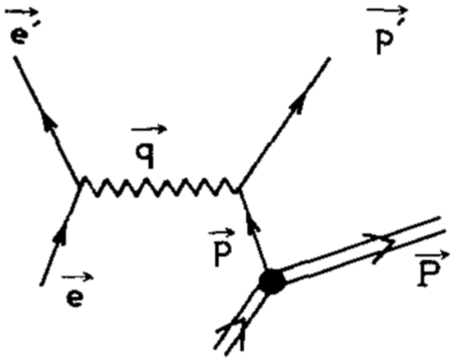

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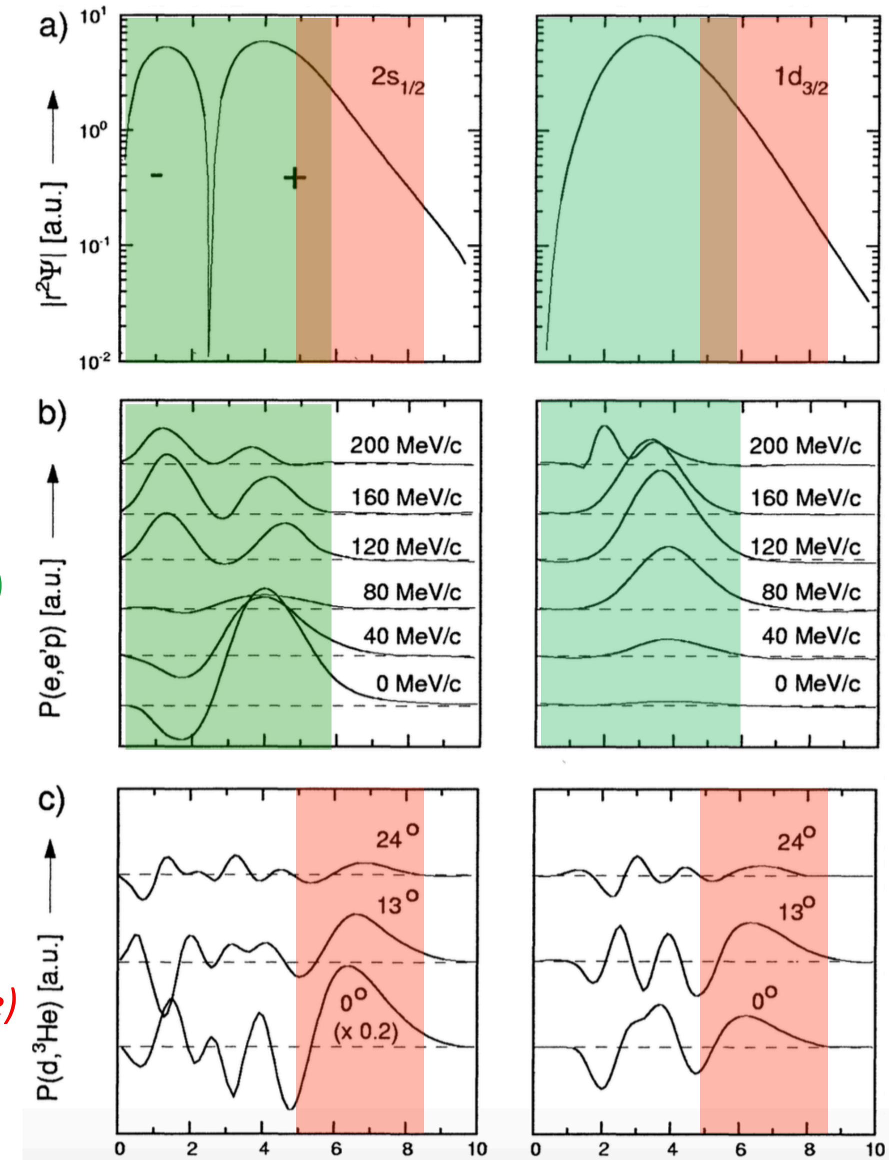

(e,e'p)

(d,^{3}He)

r (fm)

Information on:

- Nuclear (hole) spectral function
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  - access to deeply-bound states

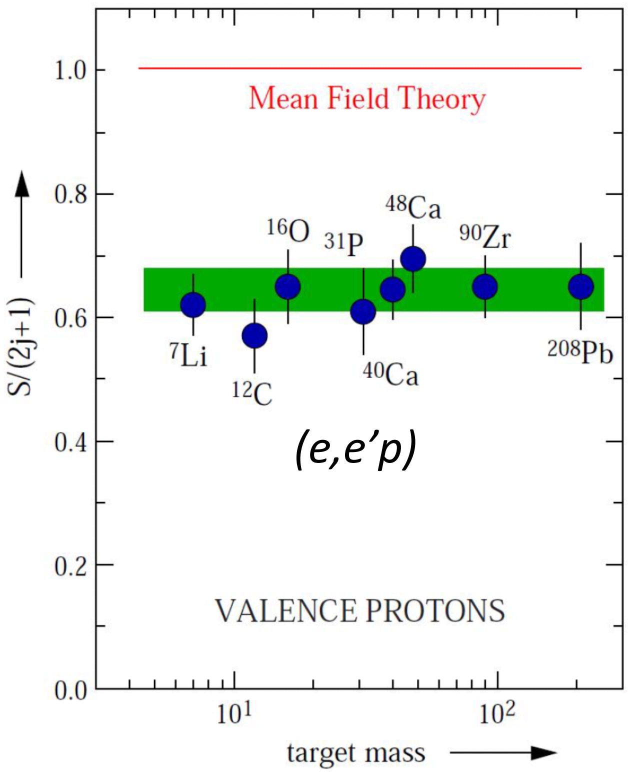
→ **Better sensitivity to details of s.p. w.f**

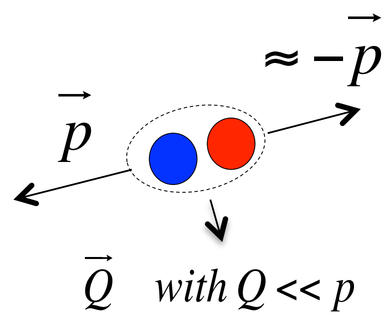
… not only asymptotic tail

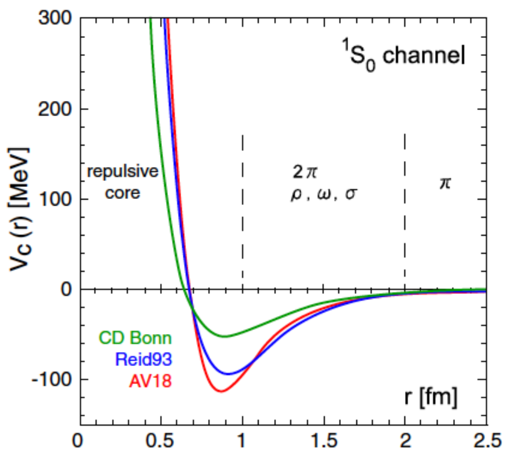
$$P(r) = \frac{1}{\Delta r}(\sigma_{r-\Delta r/2} - \sigma_{r+\Delta r/2})$$

(e,e'p) Quasi-free scattering : Short Range Correlations

[Dickhoff and Barbieri, PPNP **52** 377 (2004)]







- Repulsive hard-core + tensor → **high-mom. correlations**
- Stable nuclei:
  - **20% of nucleons** are concerned
  - with **90% of neutron-proton pairs**

*[Subedi et al., Science **320** (2008)]*

How does these correlations evolve for exotic nuclei with asymetric n/p ratios?

Intermediate conclusion

And much more to look at… | **Complementarity/Link with**

- Halo nuclei , clustering, etc. — *[O.Sorlin et al.]*
- **Fission** studies (precise control of E*) — *[B. Jurado et al]*
- Collectivity / Photonuclear reactions (PDR, GDR, etc..) — *[G. Duchêne et al.]*

  +Scattering on **Magnetic currents** — *[F. Gulminelli et al.]*

  [A. Lopez-Martens et al.]
- Better controlled mechanisms (ideal coulex, controlled FSI) — *[A. Matta et al.]*
- **Solid Theoretical** support (Structure and Reaction) — *[F. Nowacki et al.]*

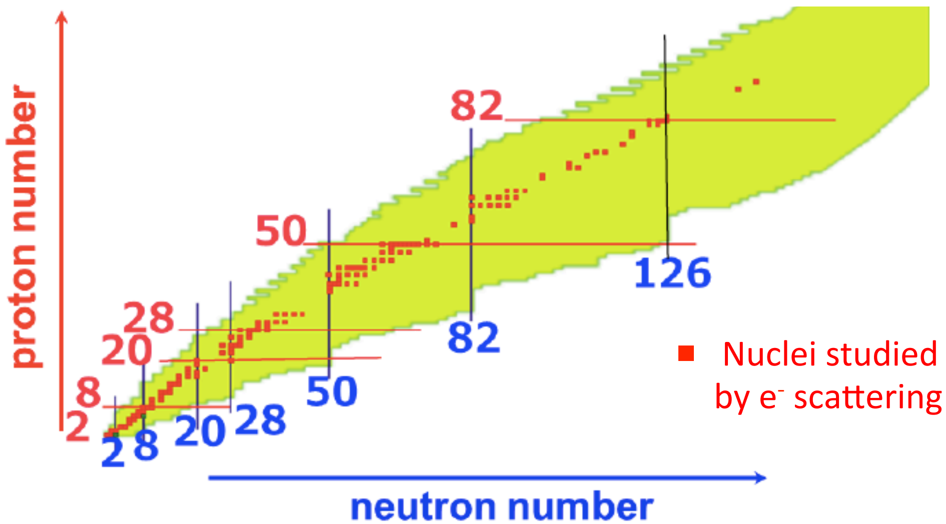
  [M. Grasso et al.]

  [M. Bender et al.]

- Polarised e^- beam applications
- **Hadron physics** at low Q^2 — Other GTs
- R&D on medical applications with HI e- beam

1. **Vast** physics program spanning **most of the interests** of our community
2. ..and **extendable** to interest of other communities
3. Based on very **solid grounds** (theoretical and experimental)

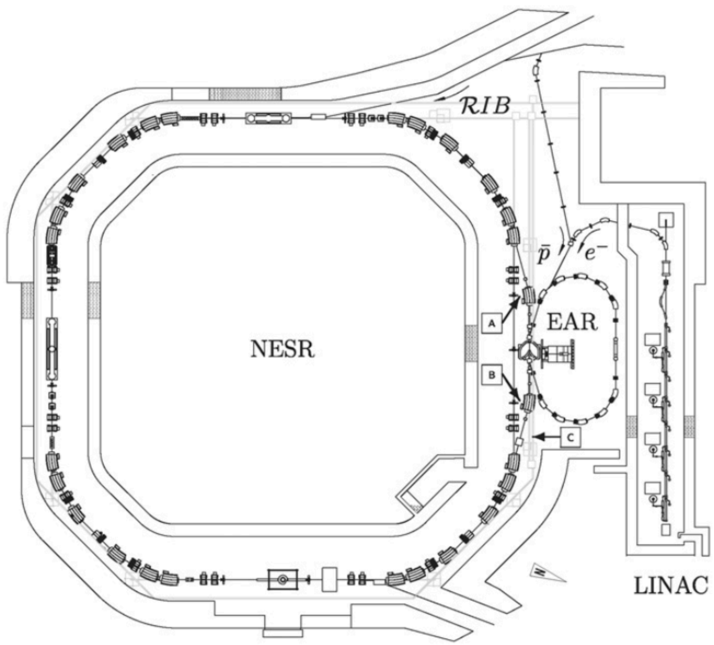
Context and Luminosity requirements



Reaction	Deduced quantity	Target Nuclei	Luminosity [$cm^{-2}s^{-1}$]
Elastic scattering at small q	r.m.s. charge radii	Light Medium	10^{24}
First minimum in elastic form factor	Density distribution with 2 parameters	Light Medium Heavy	10^{28} 10^{26} 10^{24}
Second minimum in elastic form factor	Density distribution with 3 parameters	Medium Heavy	10^{29} 10^{26}
Inelastic scattering Pygmy/Giant resonances	Position, width, strength, decays	Medium Heavy	10^{28} 10^{28}
Quasi-free scattering	SF, spectral strength	Light	10^{29}

Required luminosities for different electron scattering studies, adapted from [Antonov et al., NIMA 637, 60 (2011)]

ELISE project @ FAIR



A. Antonov et al., NIMA **637** 60 (2011)

e^-RIB Collider configuration

NESR (0.74 GeV/nucleon**) + EAR** (0.5 GeV)

→ Targeted luminosity ~ **10^{28} ($cm^{-2}s^{-1}$)**

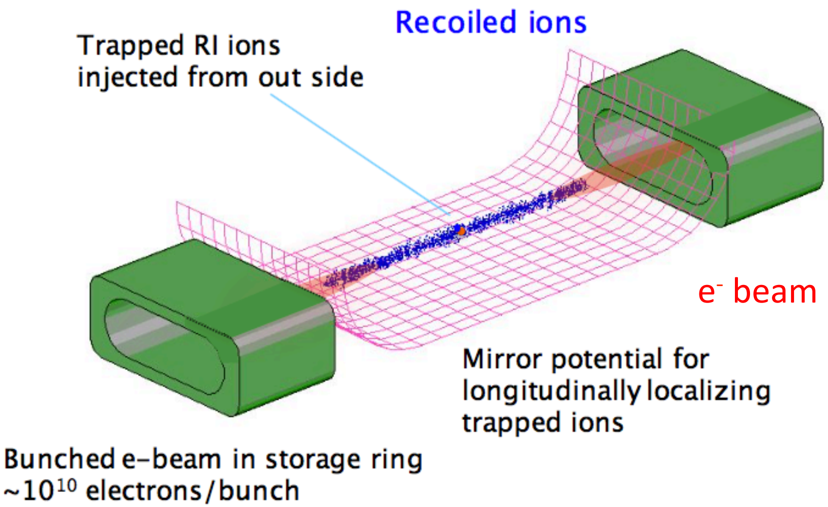
Excluded from funded part of FAIR modularized start version (module 4)

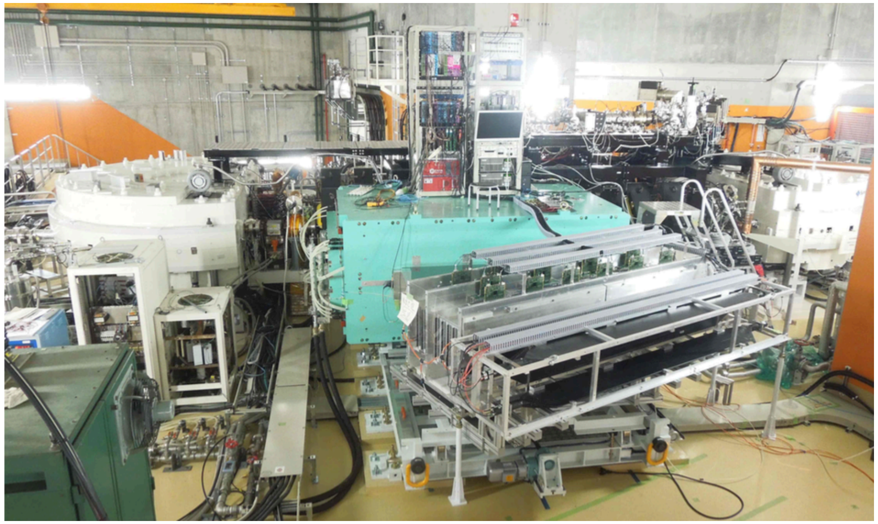
✓ **Variety of RIB** from fragmentation
✓ Target and scattered particle detectable
✓ Narrow interaction region / good overlap

X **Pre-cooling** before NESR (1.5 s)
X Requires very-high res. Spectrometer

X Not FAIR priority – Very long term
X Requires **Full FAIR operation** – Limited BT

SCRIT (Self-Containing RI Target) @ RIKEN





- **Pioneering** proof-of-concept
- ~ 2-3 Phys. + 2-3 tech/Eng. (~3 FTE)
- Recycling of an existing (small) ring + ISOL source
- **Achieved luminosity** is ~ **$3x10^{27}$ $cm^{-2}s^{-1}$** - stable Xe
- e^- beam properties ⟷ Ion-trapping properties

Wakasugi et al., NIMA 532, 216 (2004)
Wakasugi et al., PRL 100, 164801 (2008)
Suda et al, PRL 102, 102501 (2009)
Wakasugi et al., NIMB 317, 668 (2013)
Tsukada et al., PRL 118, 262501 (2017)

French initiatives

ETIC@GANIL

[A.Obertelli, A. Corsi et al., CEA-SPhN]

First conceptual design study in 2015 (GANIL 2025)

- SCRIT-like design — adapted to GANIL (ISOL+continuous)
- Targeted luminosity ~ **10^{29} ($cm^{-2}s^{-1}$)** — to cover most of scattering processes
  (I_e = 100-200 mA; N_{trap} = 10^6 pps; $\sigma_x\sigma_y$ = 10^{-10-} m^2)

Solutions: Synchrotron or Energy Recovery Linac (ERL) – **no showstopper**

- ERL more advantageous but more recent → Requires **R&D and Demonstrator**

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PERLE@IJCLAB

[PERLE CDR, JPG 45 (2018) 065003.]

ERL demonstrator for LHeC

- « A facility to develop energy recovery , multi-turn, large current, large energy »
- **Direct overlap with nuclear physics requirements**
- Combination with ALTO-like RIB source → First physics program (reduced luminosity)

French initiatives

ETIC@GANIL

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- « A facility to develop energy recovery , multi-turn, large current, large energy »
- **Direct overlap with nuclear physics requirements**
- Combination with ALTO-like RIB source → First physics program (reduced luminosity)

Opportunity of synergy with particle physics and between national facilities

Conclusion: e^- scattering on exotic nuclei

- **Physics Case ?**

  YES – Looks vast, extendable

- **Challenging/Difficult ?**

  YES - No pain No gain

- **Plan/Strategy/Synergies ?**

  YES – preliminary but not insane

Need more work

...help welcome

Workshop in 2020 (ESNT)