opportunities for electron scattering with exotic nuclei

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Recent publications

" First Elastic Electron Scattering at the SCRIT Facility"

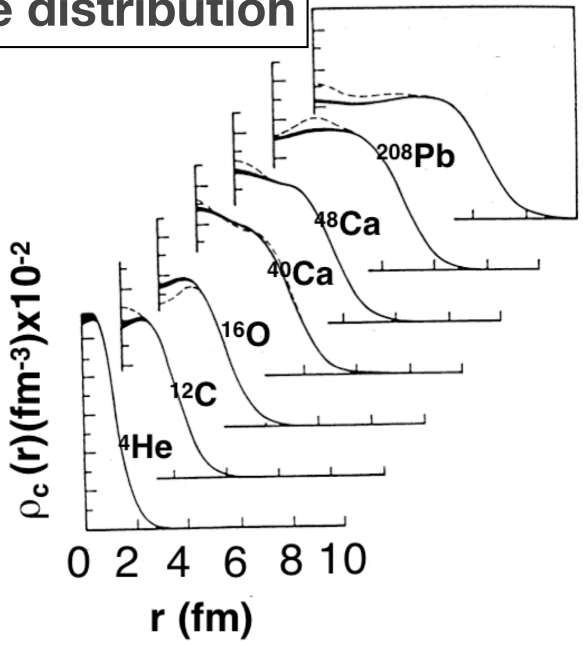
K. Tsukada *et al.* Phys. Rev. Lett. 118 (2017) 262501

" Prospects for Electron Scattering on Unstable Exotic Nuclei"

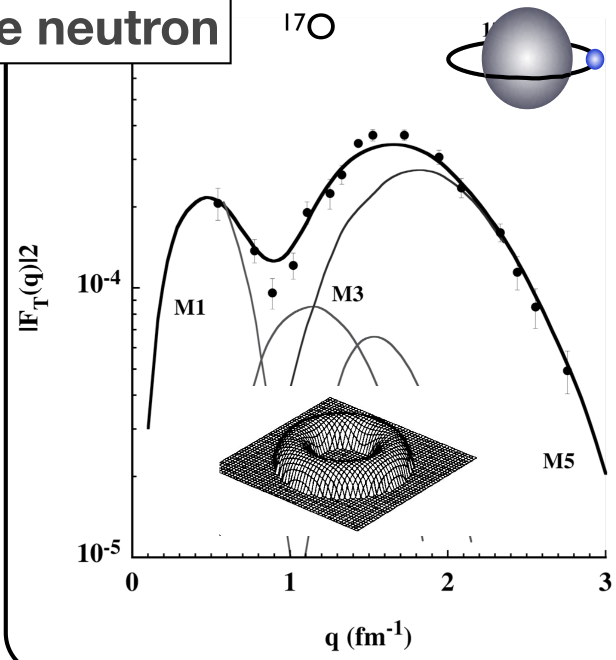
T. Suda and H. Simon, Prog. Part. Nucl. Phys. 96 (2017) 1-31.

Electron scattering for stable nuclei

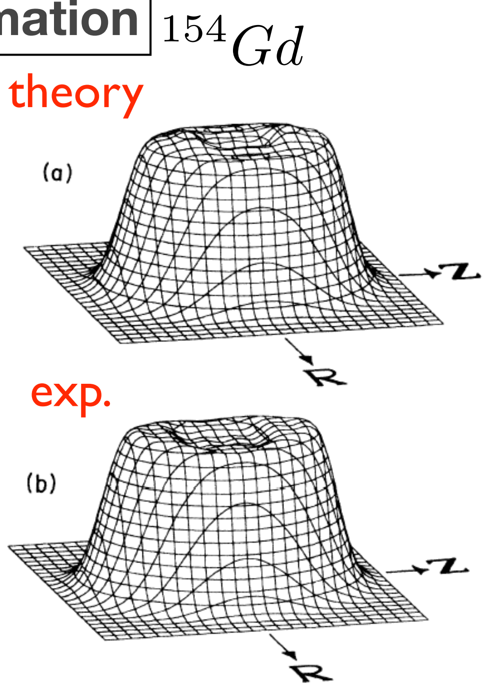
charge distribution



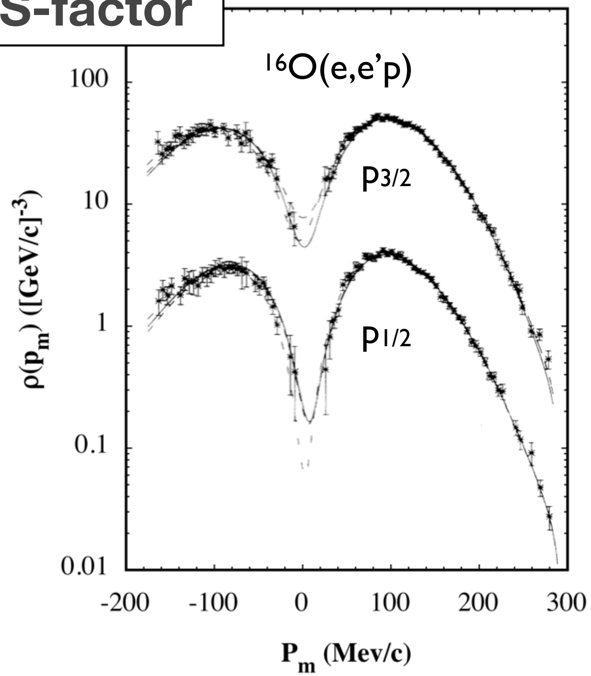
valence neutron



deformation



|Φ(p)|², S-factor

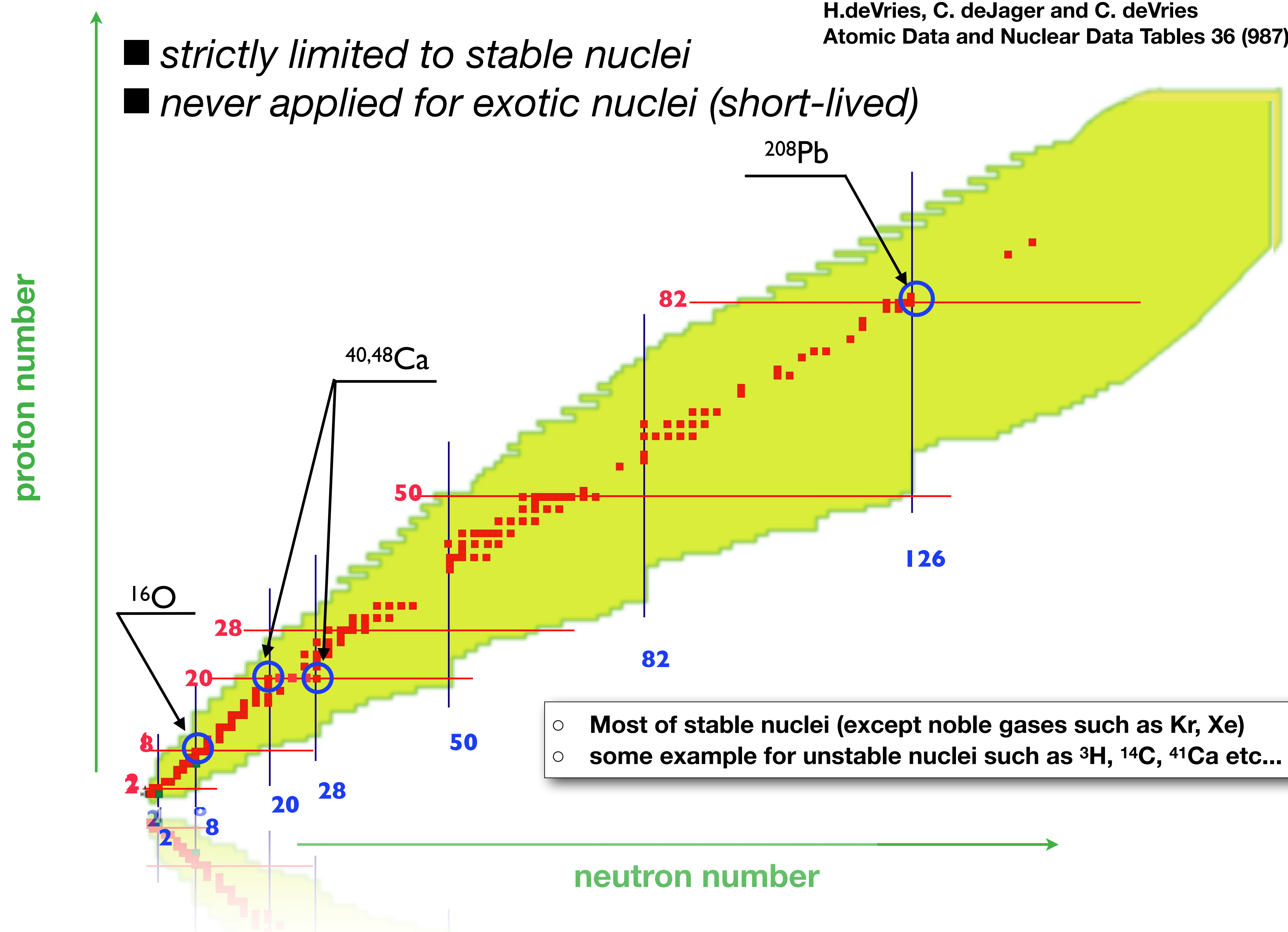


Nuclei studied by electron scattering

ECT* workshop 23-27, April, 2018
Exploring the role of electron-weak currents in atomic nuclei

H.deVries, C. deJager and C. deVries
Atomic Data and Nuclear Data Tables 36 (987)495

- *strictly limited to stable nuclei*
- *never applied for exotic nuclei (short-lived)*



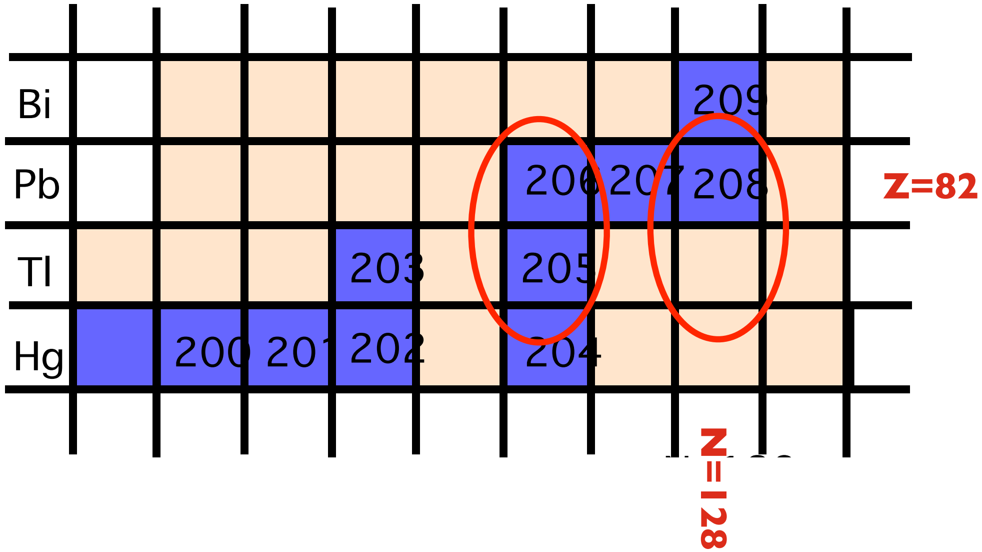
- Most of stable nuclei (except noble gases such as Kr, Xe)
- some example for unstable nuclei such as ^{3}H, ^{14}C, ^{41}Ca etc…

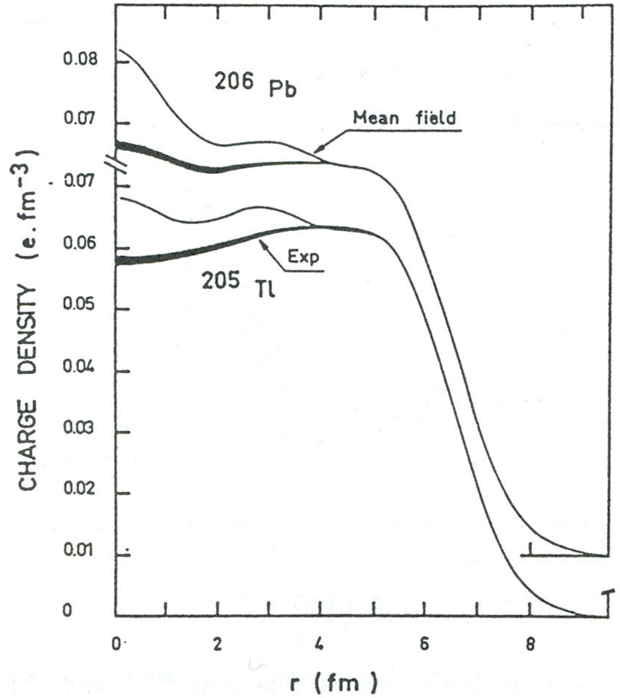
$3S_{1/2}$ protons and their spectroscopic factor

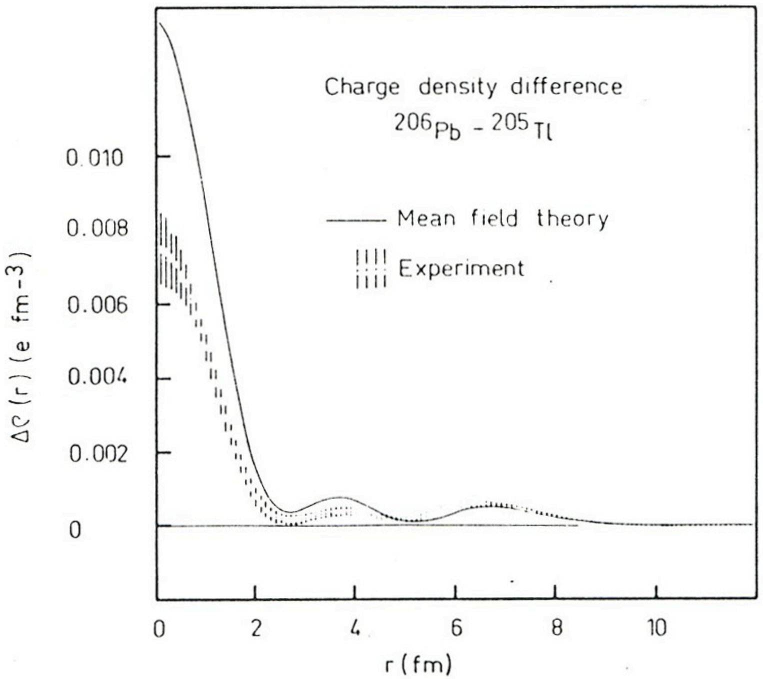
^{208}Pb - ^{207}Tl → ^{206}Pb - ^{205}Tl

unstable

$$|\psi_{3S_{1/2}}(r)|^2 = \rho_{Pb}(r) - \rho_{Tl}(r)$$
$$= \sum_{i=1}^{82} |\psi(r)|^2 - \sum_{i=1}^{81} |\psi(r)|^2$$
$$= \int e^{i\vec{q}\cdot\vec{r}} (|F_{Pb}(q)|^2 - |F_{Tl}(q)|^2) d^3q$$

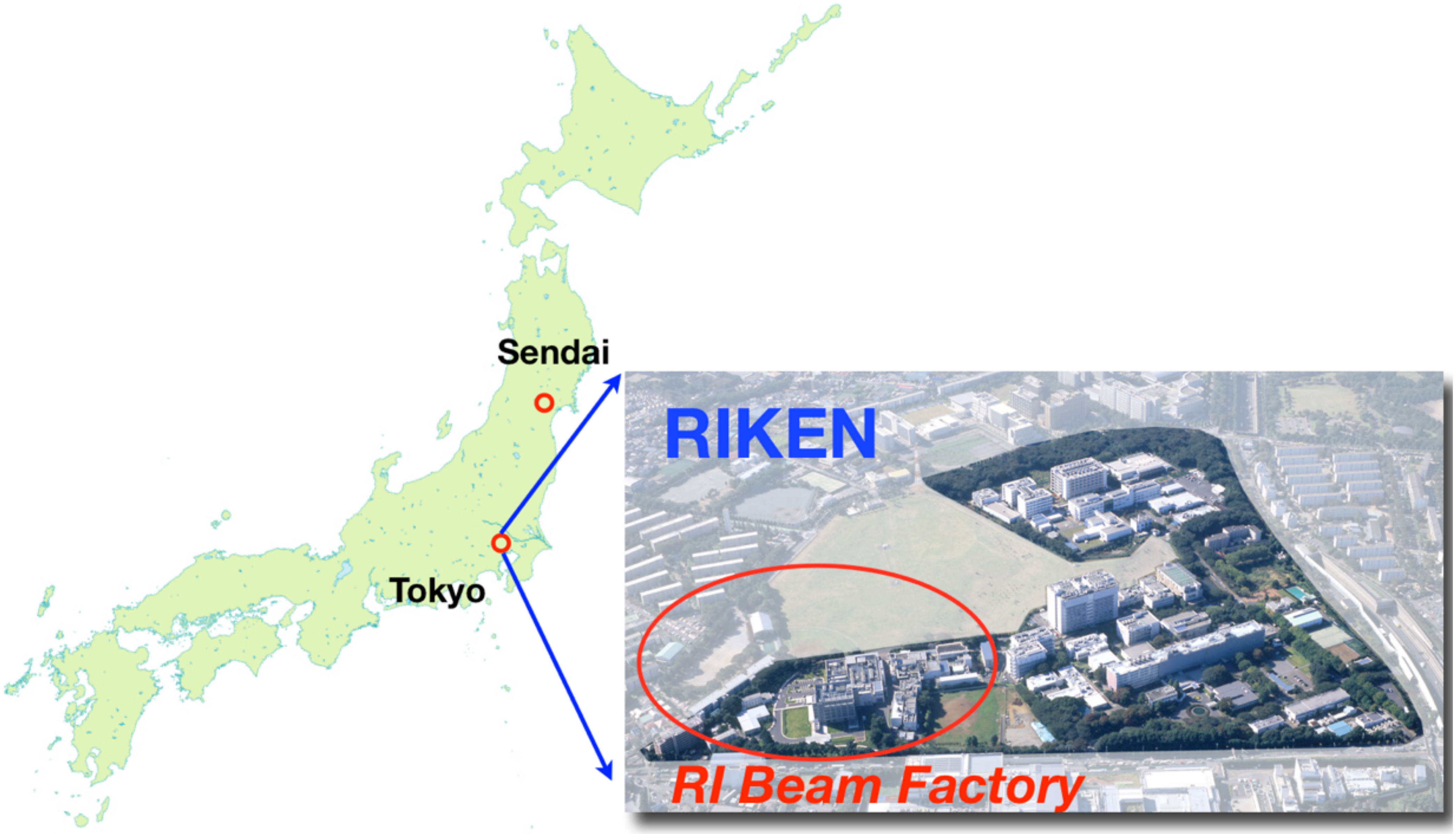






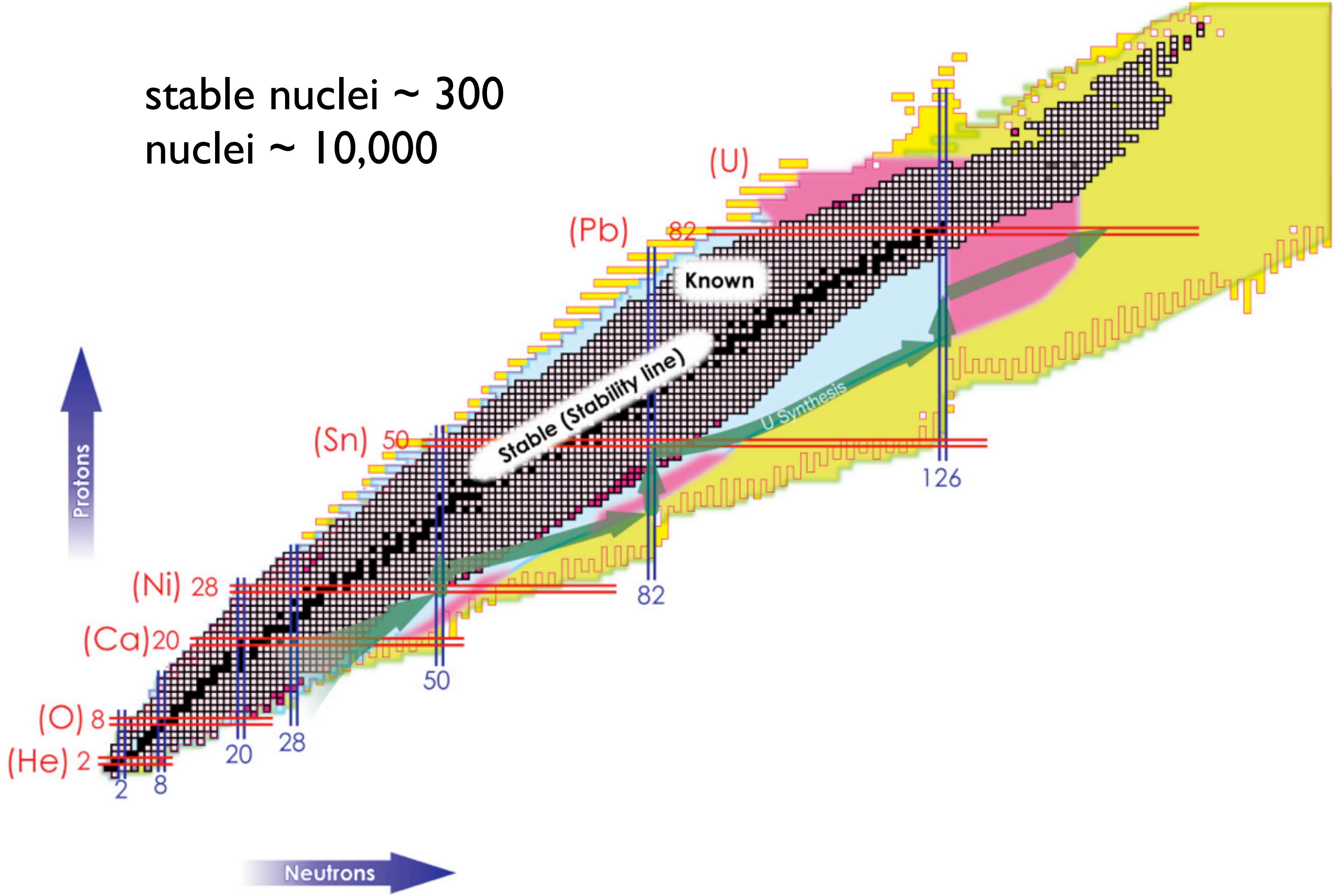
SCRIT electron scattering facility @ RIBF

world's first electron scattering facility dedicated for short-lived unstable nuclei

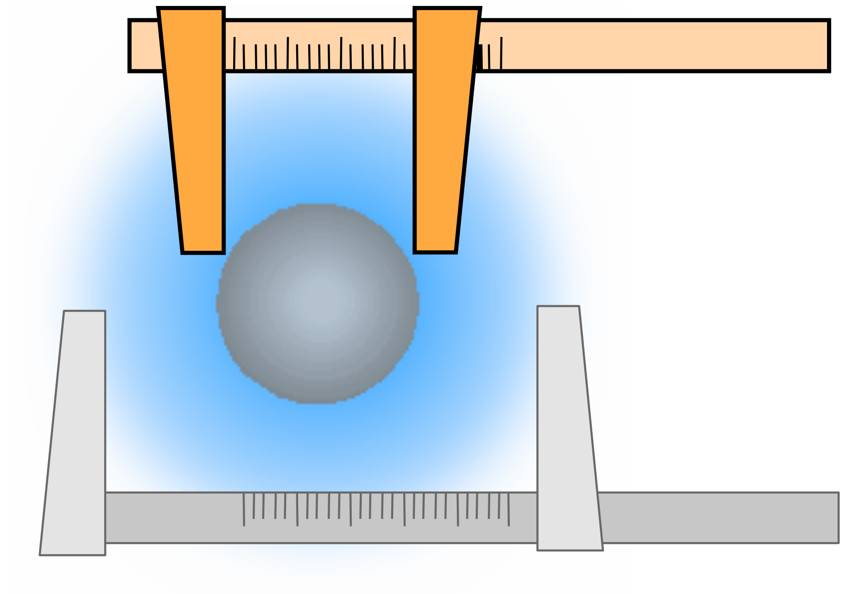


Nuclear Chart

stable nuclei ~ 300
nuclei ~ 10,000



size and shape of neutro- and proton-rich nuclei



$$< r_c^2 >= \int r^2 \rho_c(r)\ d\vec{r}$$

$$\rho_c(\vec{r}) = \sum_p \psi^*(\vec{r})\psi(\vec{r})$$

	size	shape
proton	isotope shift	electron scattering
matter	reaction cross section	proton scattering

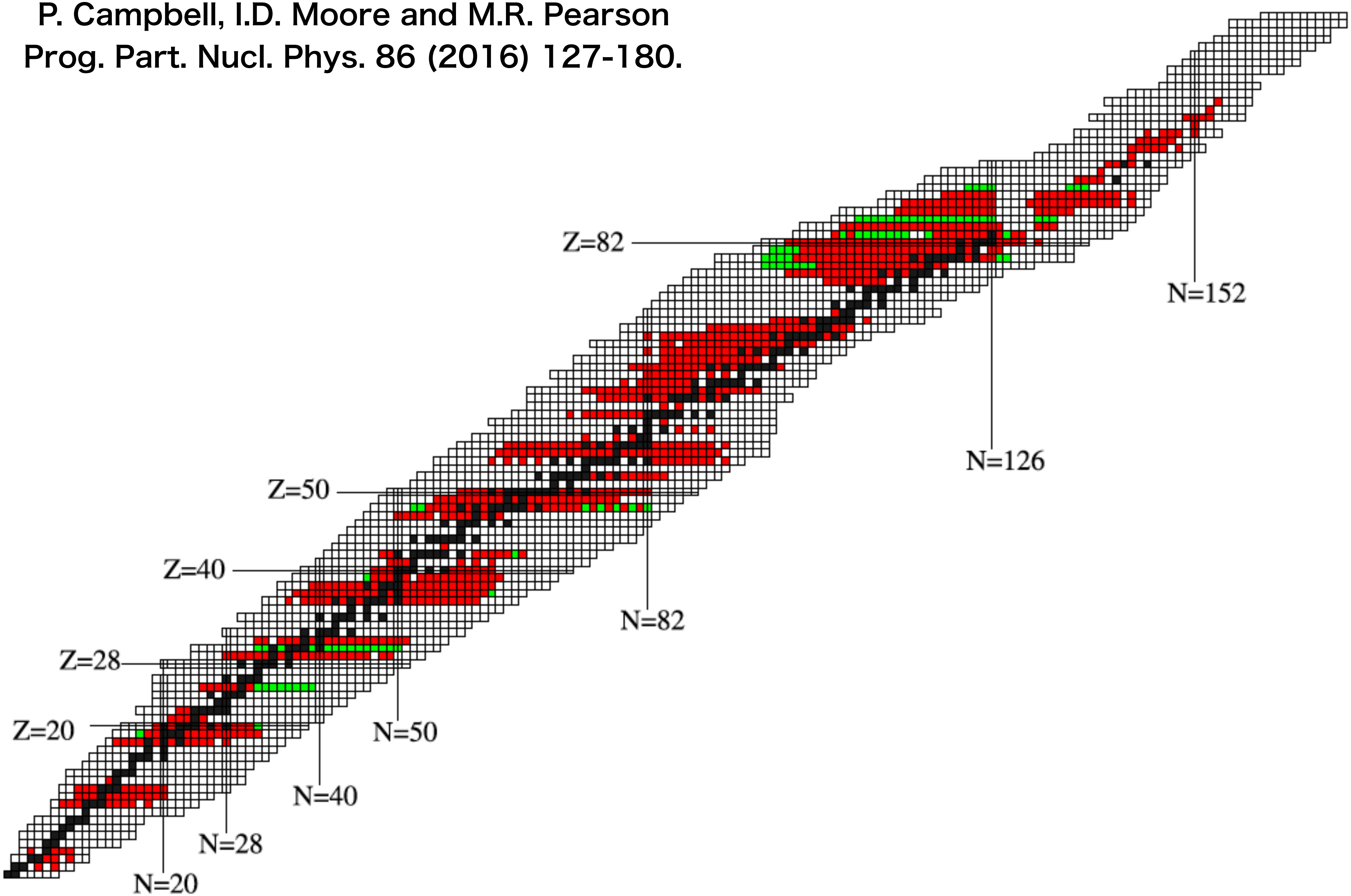
⇐ EM probe (proton row)

⇐ Hadronic probe (matter row)

(reaction mechanism ??)

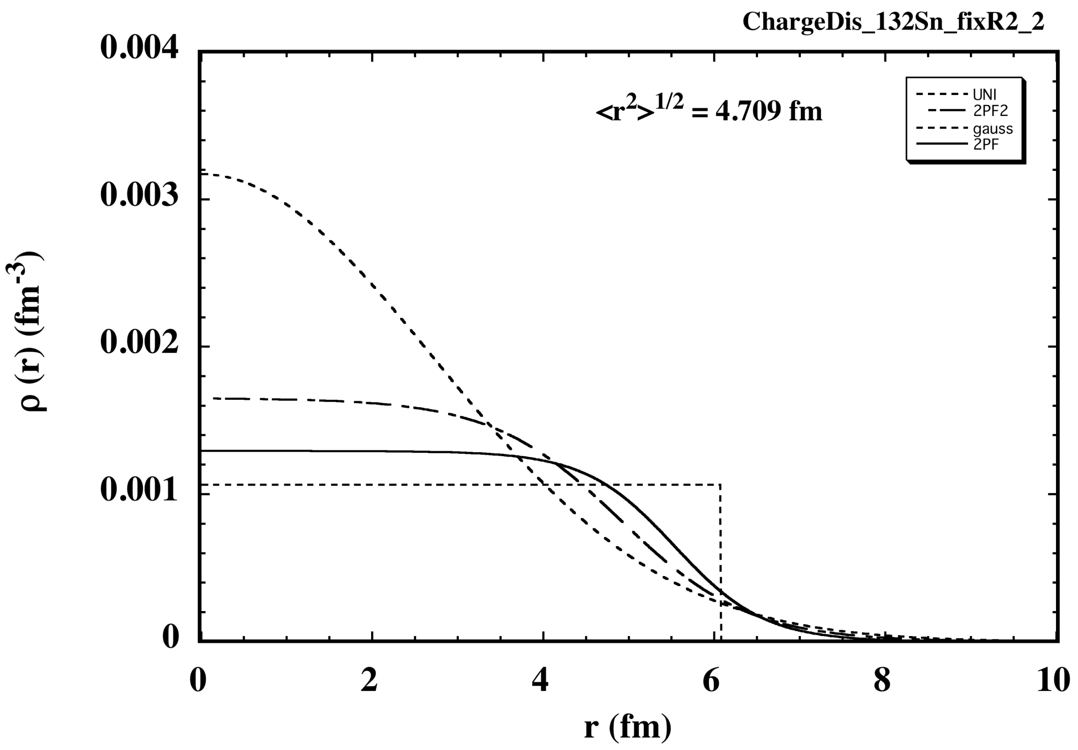
charge radii by isotope shifts

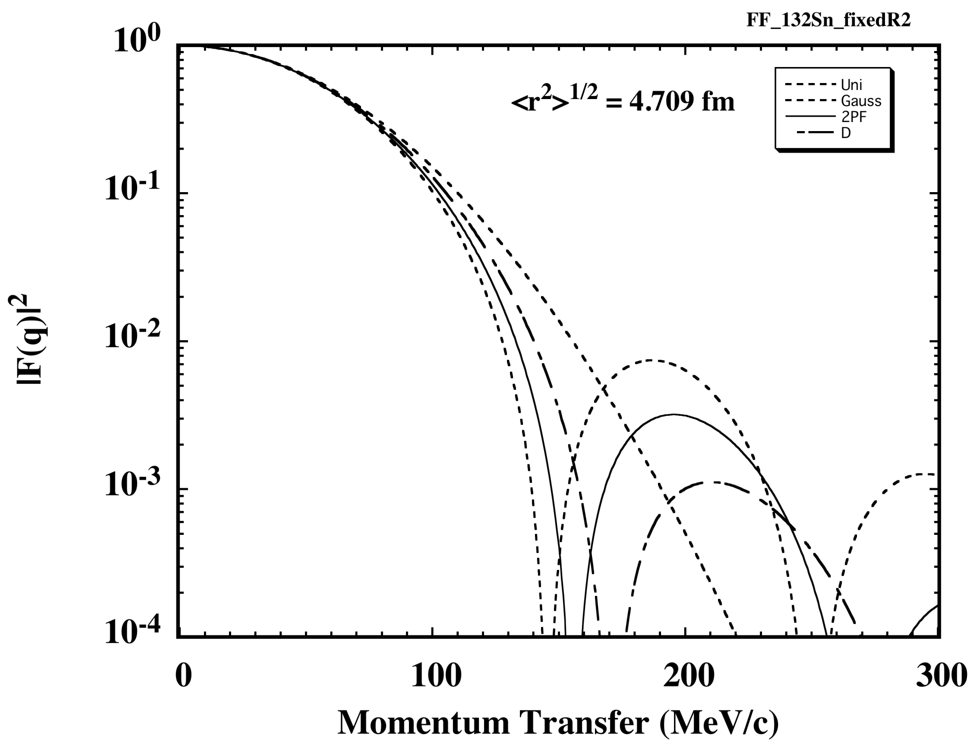
P. Campbell, I.D. Moore and M.R. Pearson
Prog. Part. Nucl. Phys. 86 (2016) 127-180.



Beyond charge radii (isotope shifts)

Density distributions having the same charge radius (4.709 fm)





e-scattering off short-lived exotic nuclei

"Hofstadter's experiments for exotic nuclei"

R. Hofstadter
1961 Nobel Prize

low production rate
short half lives ⇨ no "thick" target

expected low luminosity ⇨ elastic scattering (largest σ)

$$\frac{dN}{d\Omega} = L \frac{d\sigma}{d\Omega}$$

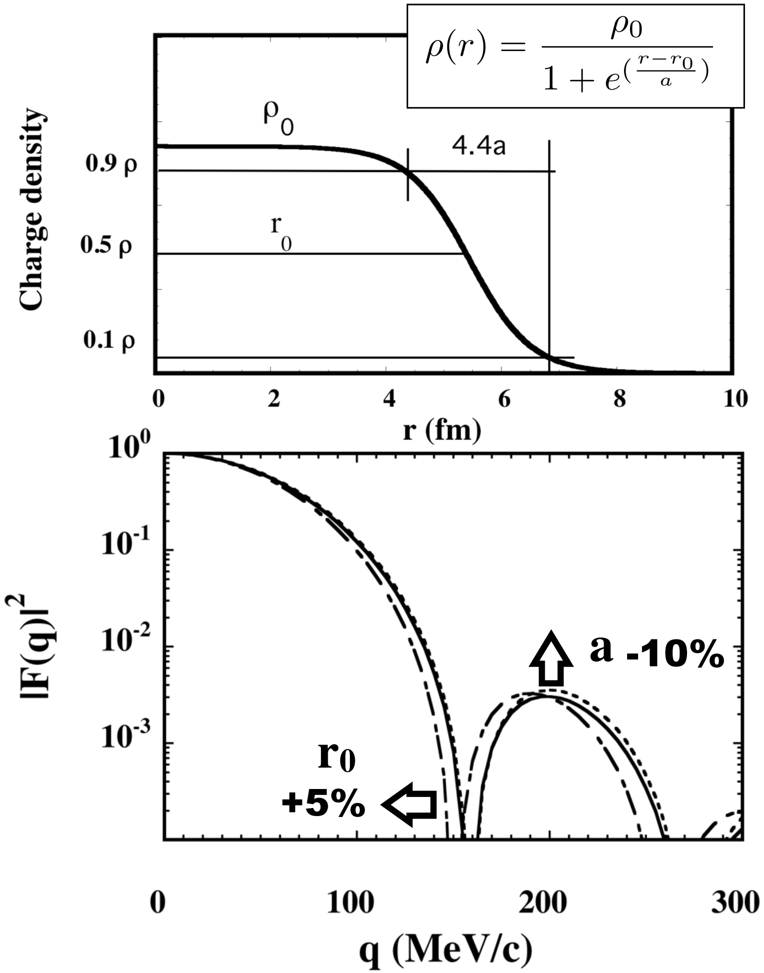
Elastic Scattering for spinless nuclei

PWIA

$$\frac{d\sigma}{d\Omega} = \frac{d\sigma_{\mathrm{Mott}}}{d\Omega}|F_c(q)|^2,$$

$$\frac{d\sigma_{\mathrm{Mott}}}{d\Omega} = \frac{z^2\alpha^2}{4e^2}\frac{\cos^2\theta}{\sin^4\theta}.$$

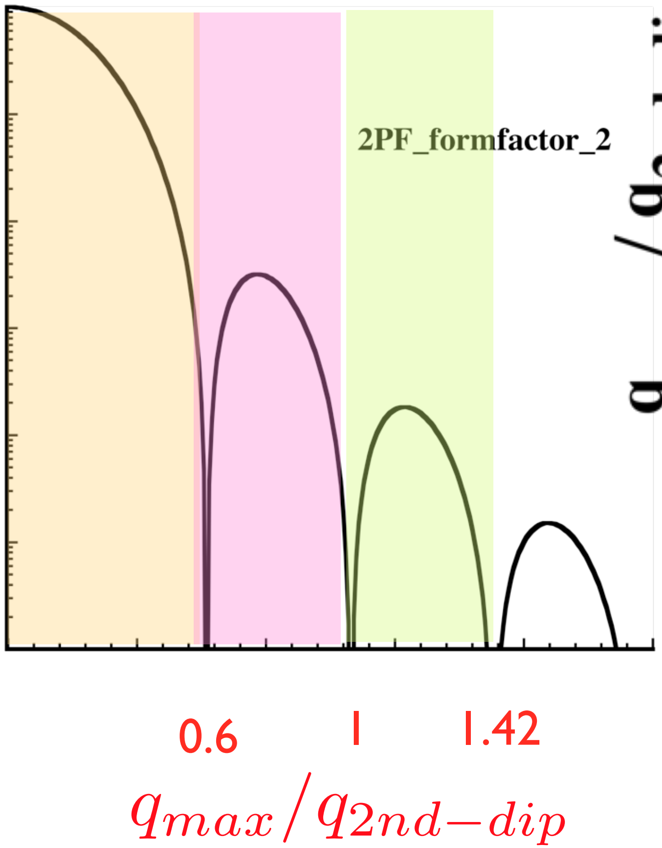
$$F_c(q) = \int \rho_c(\vec{r})e^{i\vec{q}\vec{r}}d\vec{r}$$

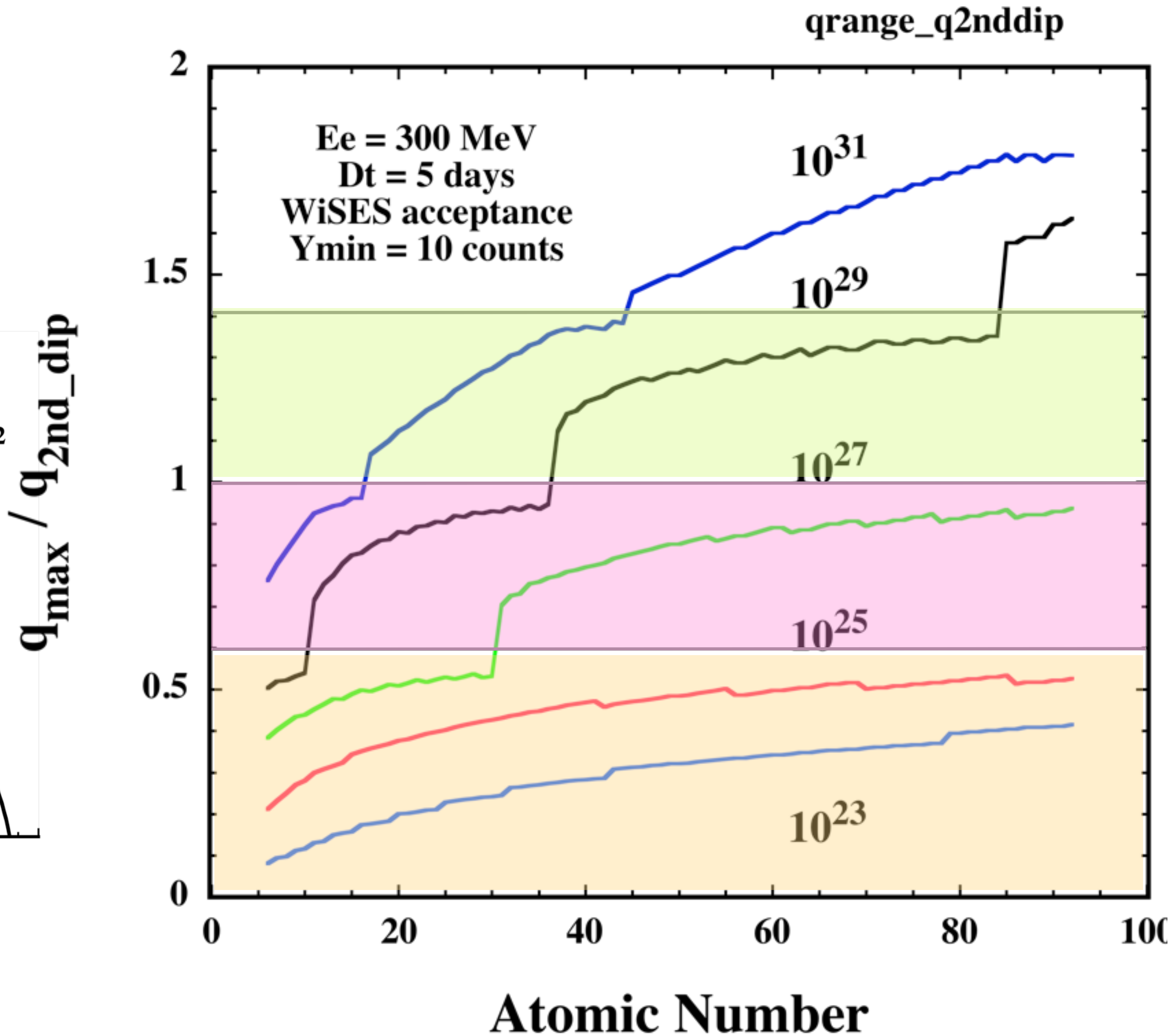


Accessible q-range for *L* and *Z*

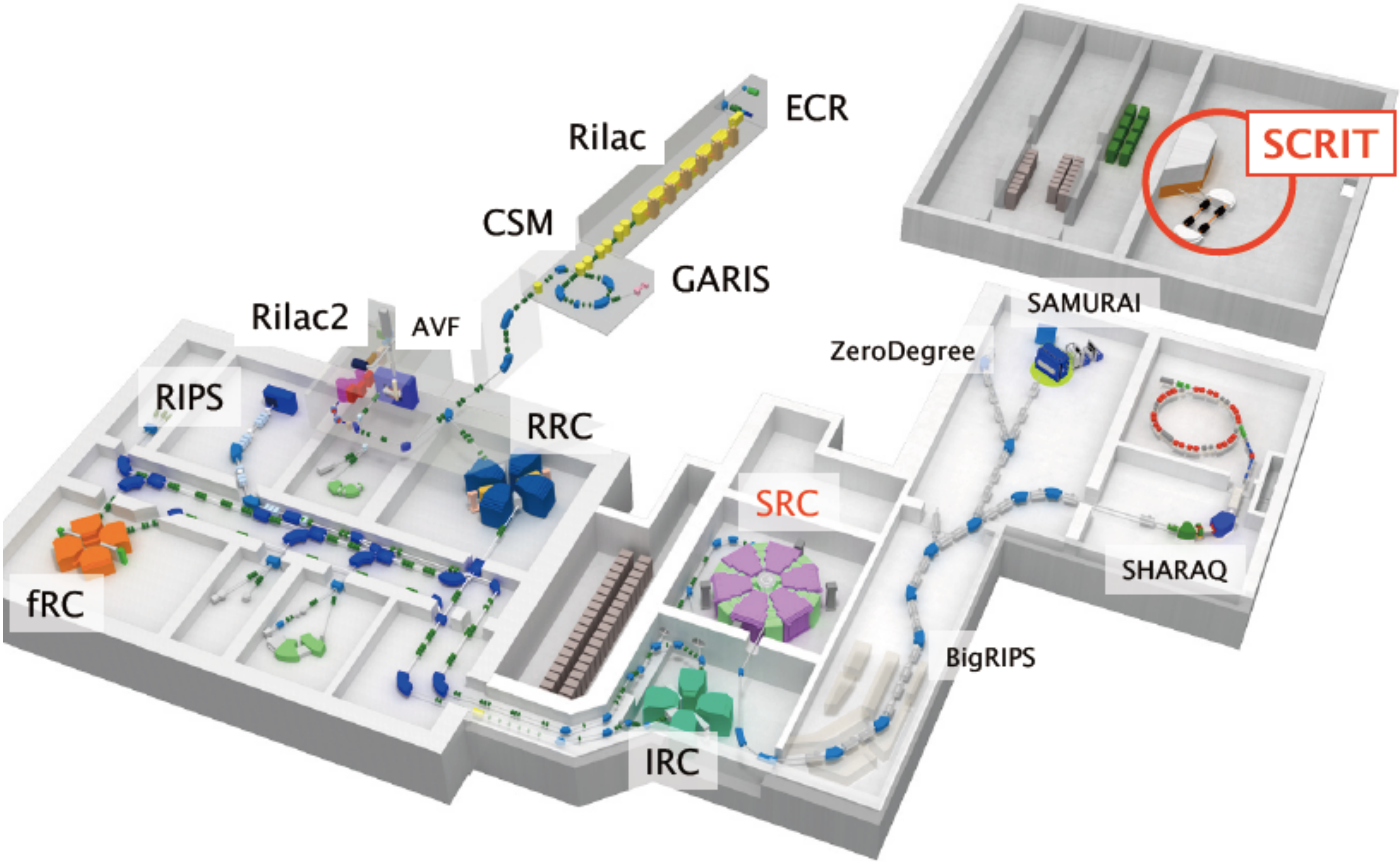
$$\sigma \propto Z^2$$

$$\sigma \propto 1/q^4$$



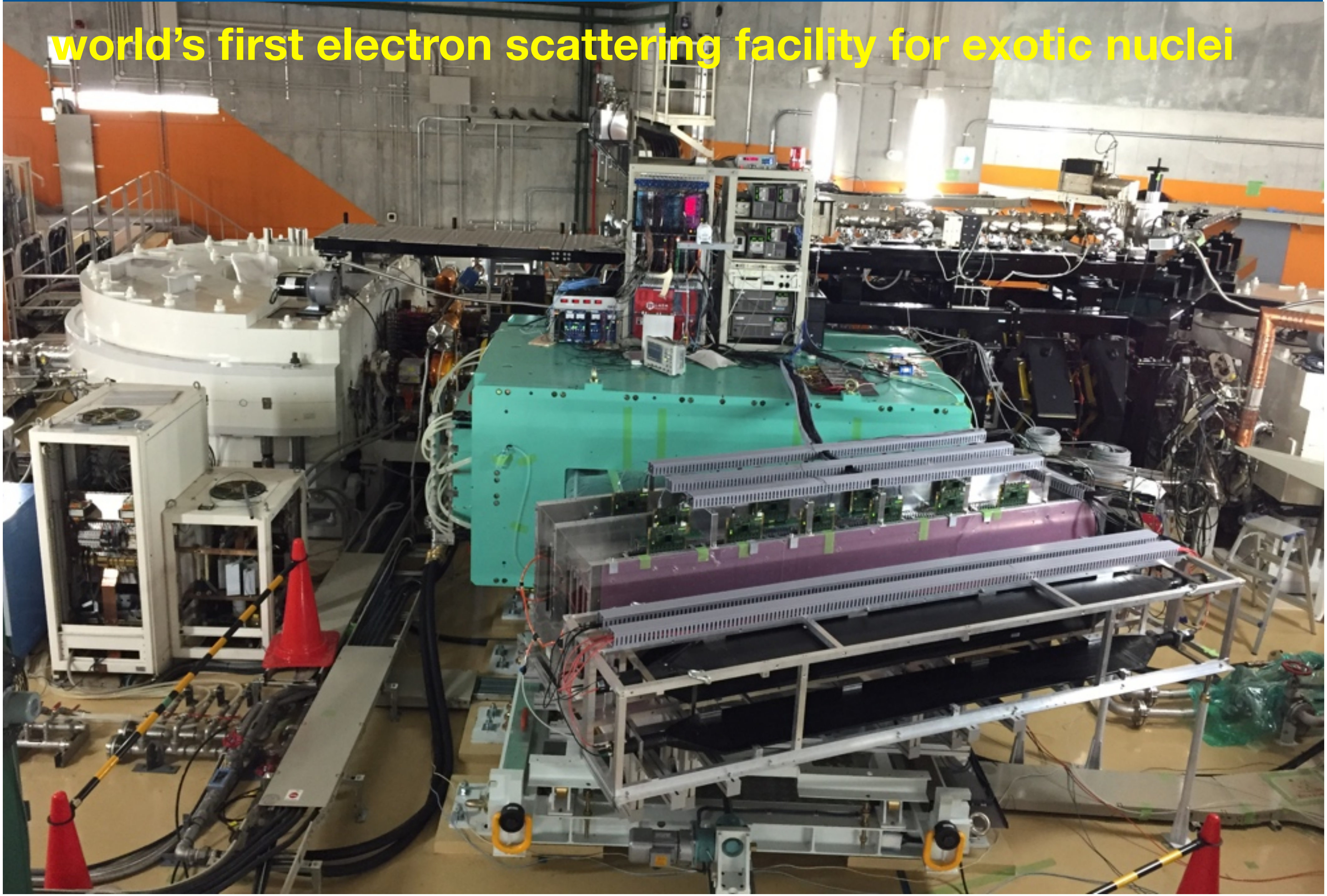


SCRIT electron scattering facility @ RIBF



RIKEN RI Beam Factory (Japan)

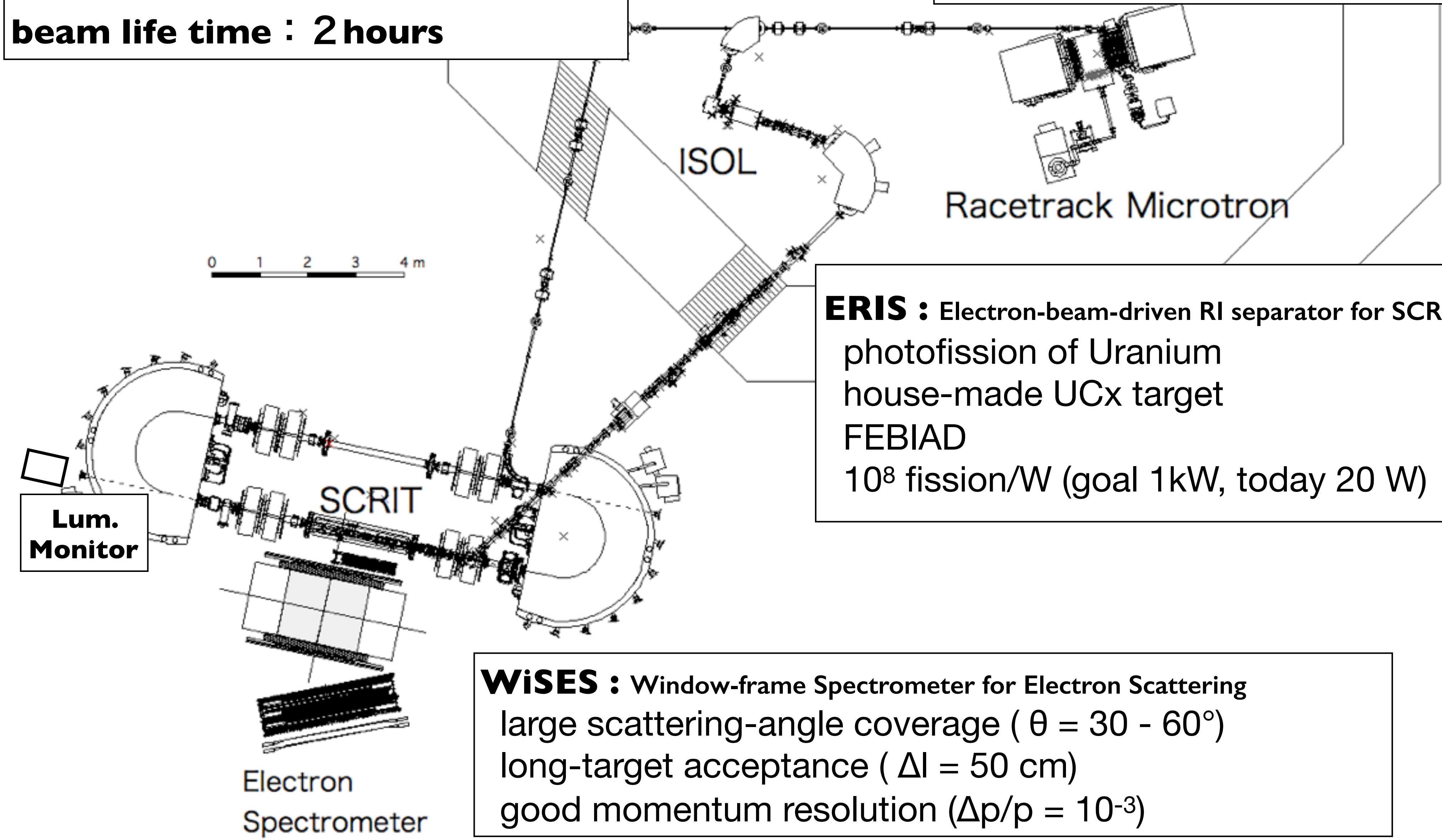
SCRIT facility in RIKEN/RI Beam Factory



SCRIT electron scattering facility

Electron energy : 150 - 700 MeV
stored current : 250 mA
beam life time : 2 hours

RTM : Race Track Microtron
injector + ISOL driver
150MeV/0.5 mA peak/2 μs pulse



ERIS : Electron-beam-driven RI separator for SCRIT
photofission of Uranium
house-made UCx target
FEBIAD
10^8 fission/W (goal 1kW, today 20 W)

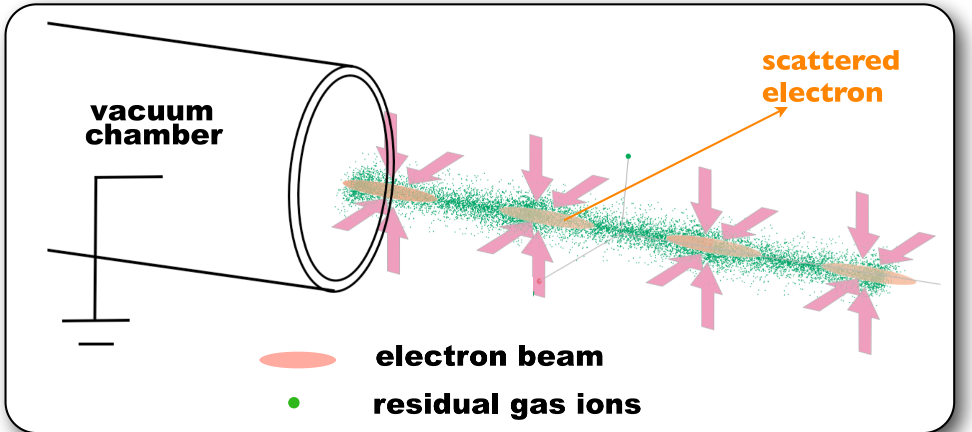
WiSES : Window-frame Spectrometer for Electron Scattering
large scattering-angle coverage (θ = 30 - 60°)
long-target acceptance (Δl = 50 cm)
good momentum resolution ($\Delta p/p = 10^{-3}$)

what is SCRIT (Self-Confining RI Target) ??

Idea

**Problematic ion trapping phenomena
@
electron storage ring**

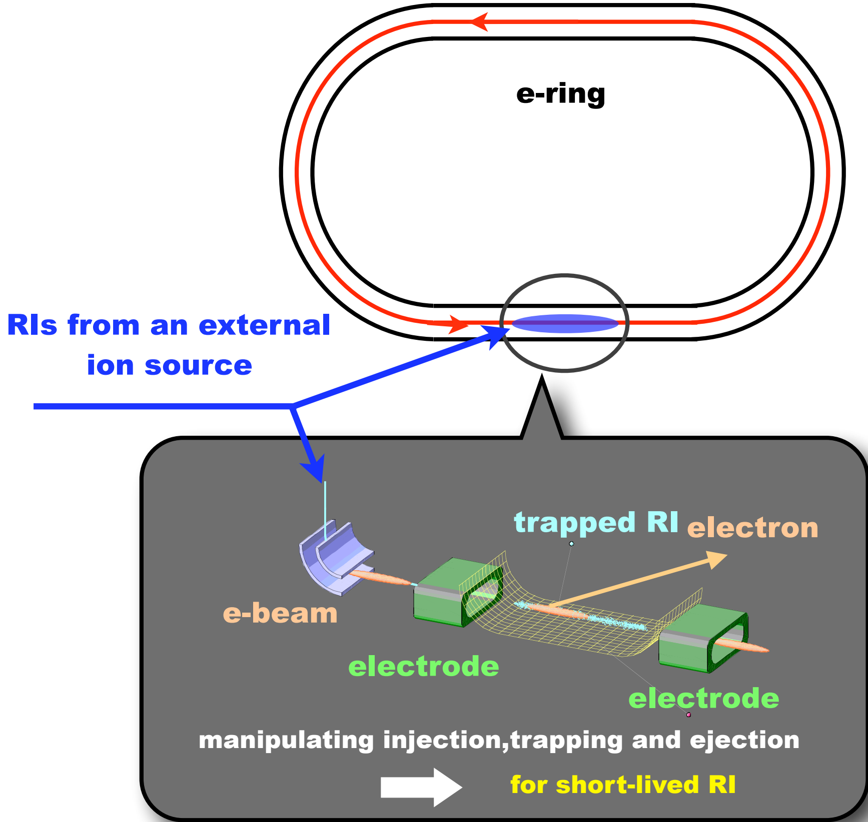
ionized residual gases are trapped by the circulating electron beam



ill problem of e-storage ring

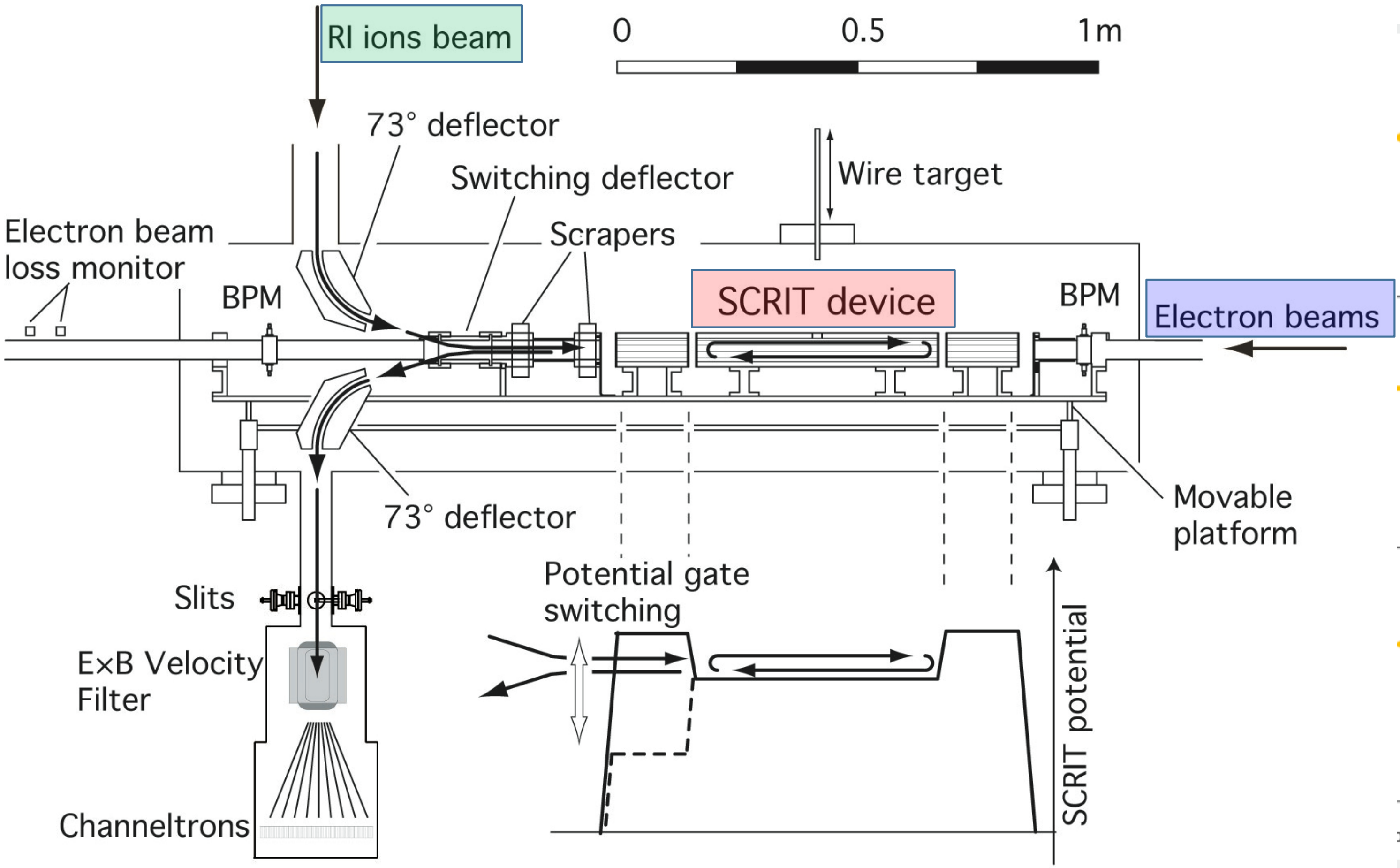
new ion trap for e-RI scattering

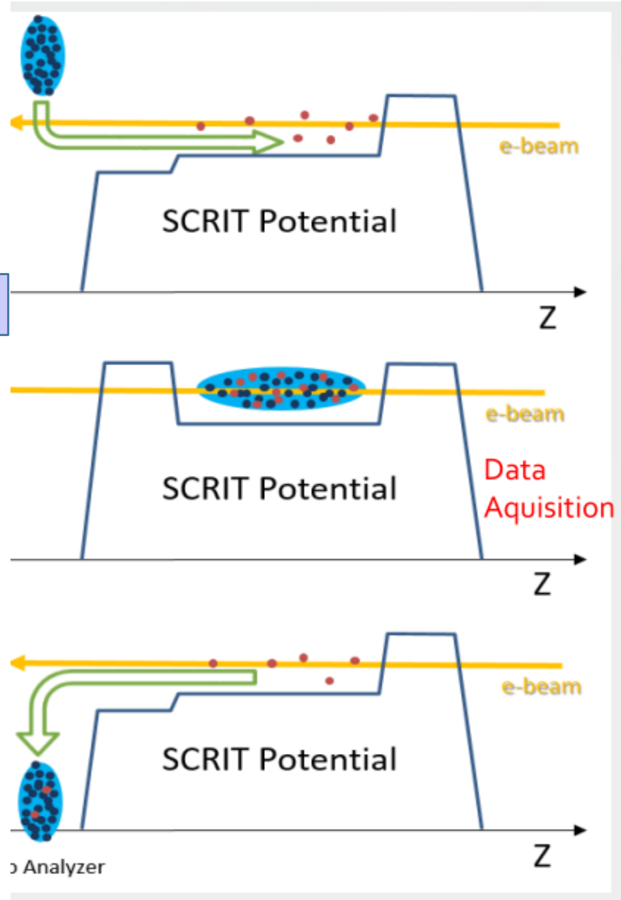
**trapping RIs on electron beam
(automatic e-scattering off trapped RIs)**

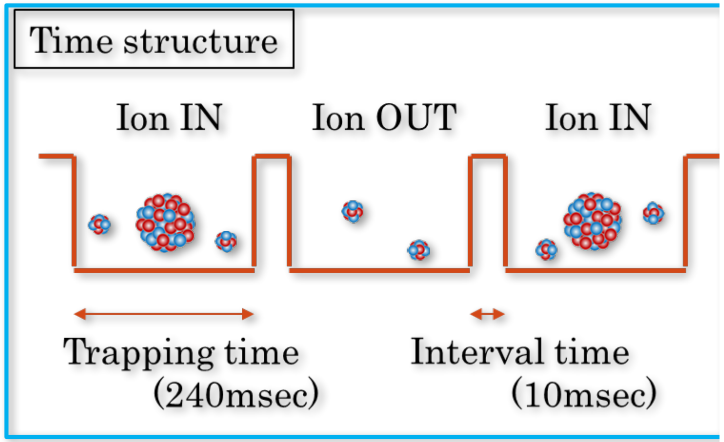


Nucl. Instrum. Methods A532 (2004) 216.
Phys. Rev. Lett. 100 (2008) 164801.
Pays. Rev. Lett. 102 (2009) 102501.

SCRIT device



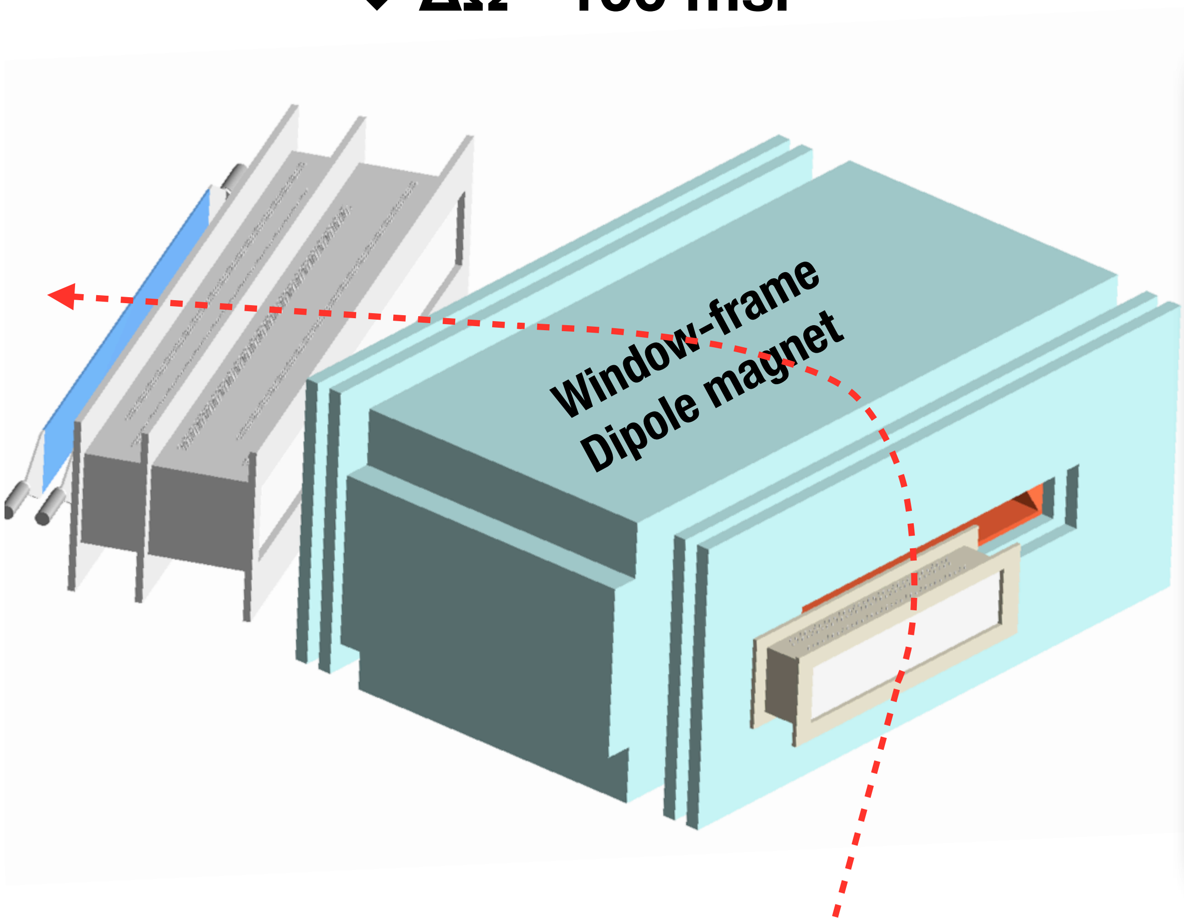


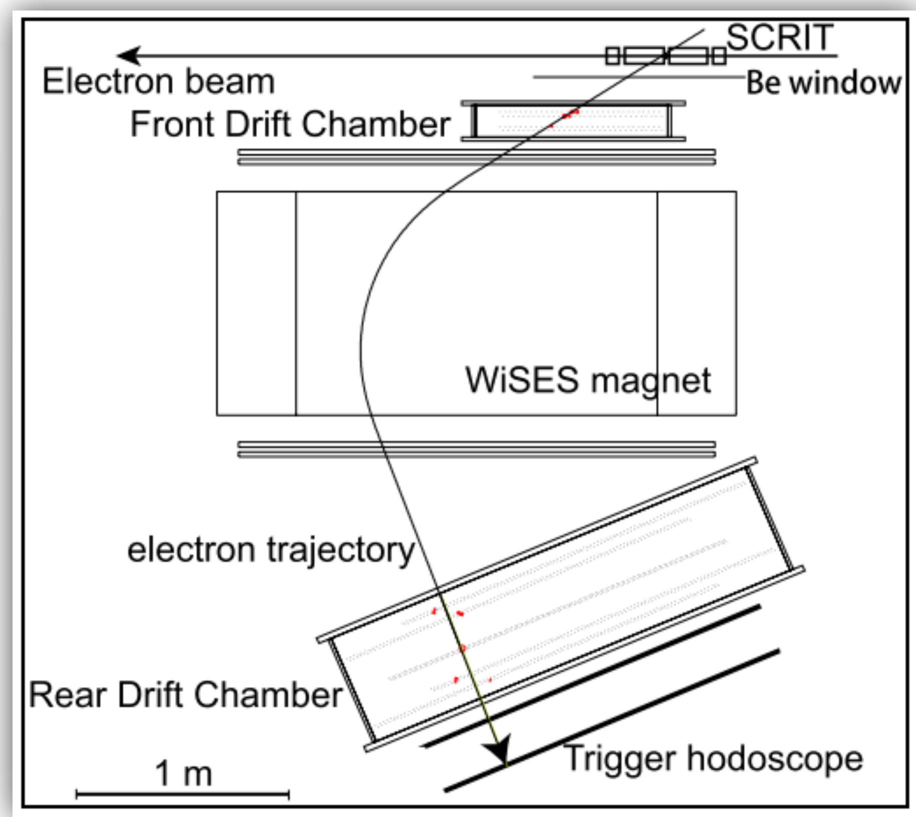


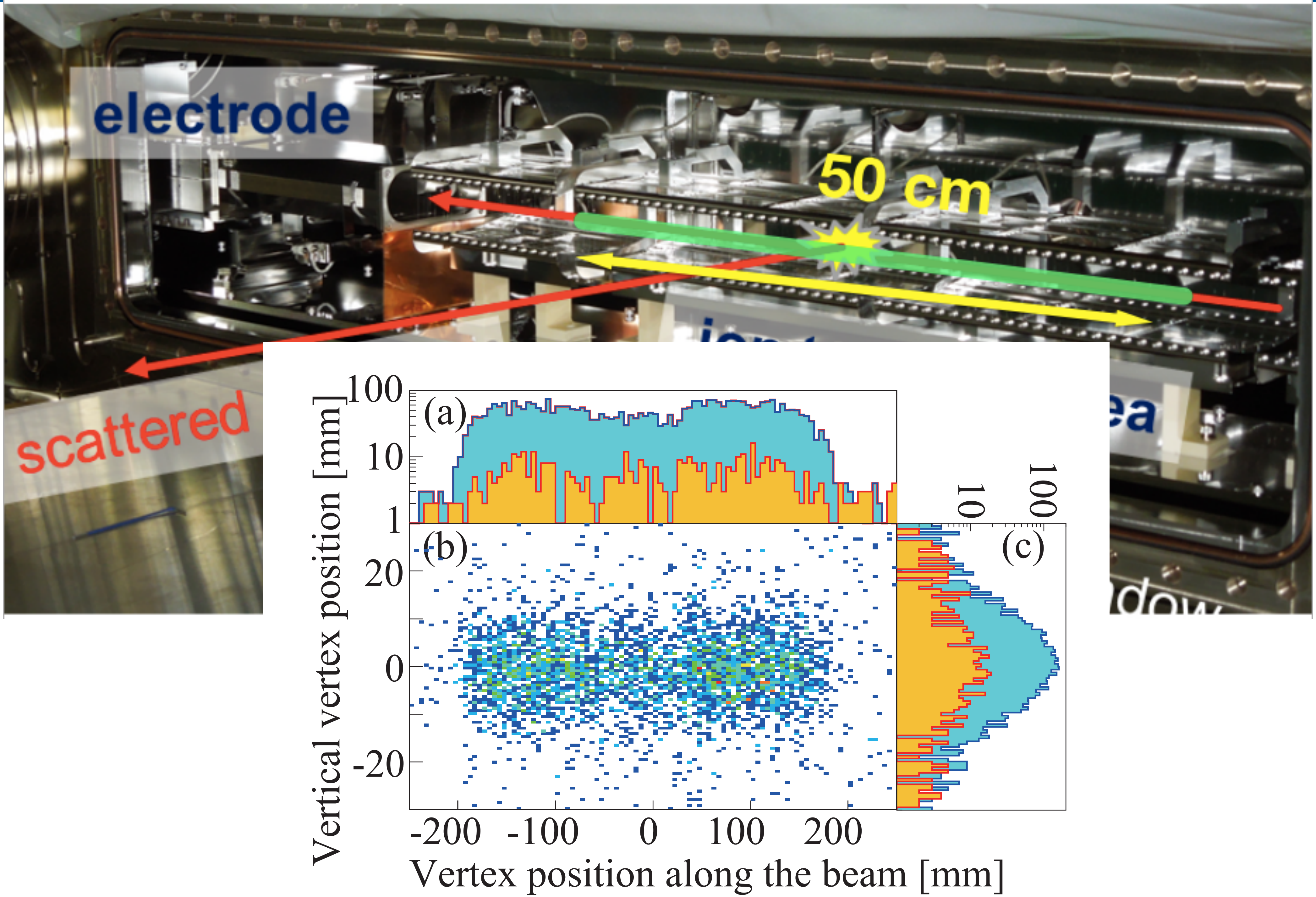
WiSES (Window-frame Spectrometer for Electron Scattering)

- long target acceptance (50cm)
- wide scattering angle coverage

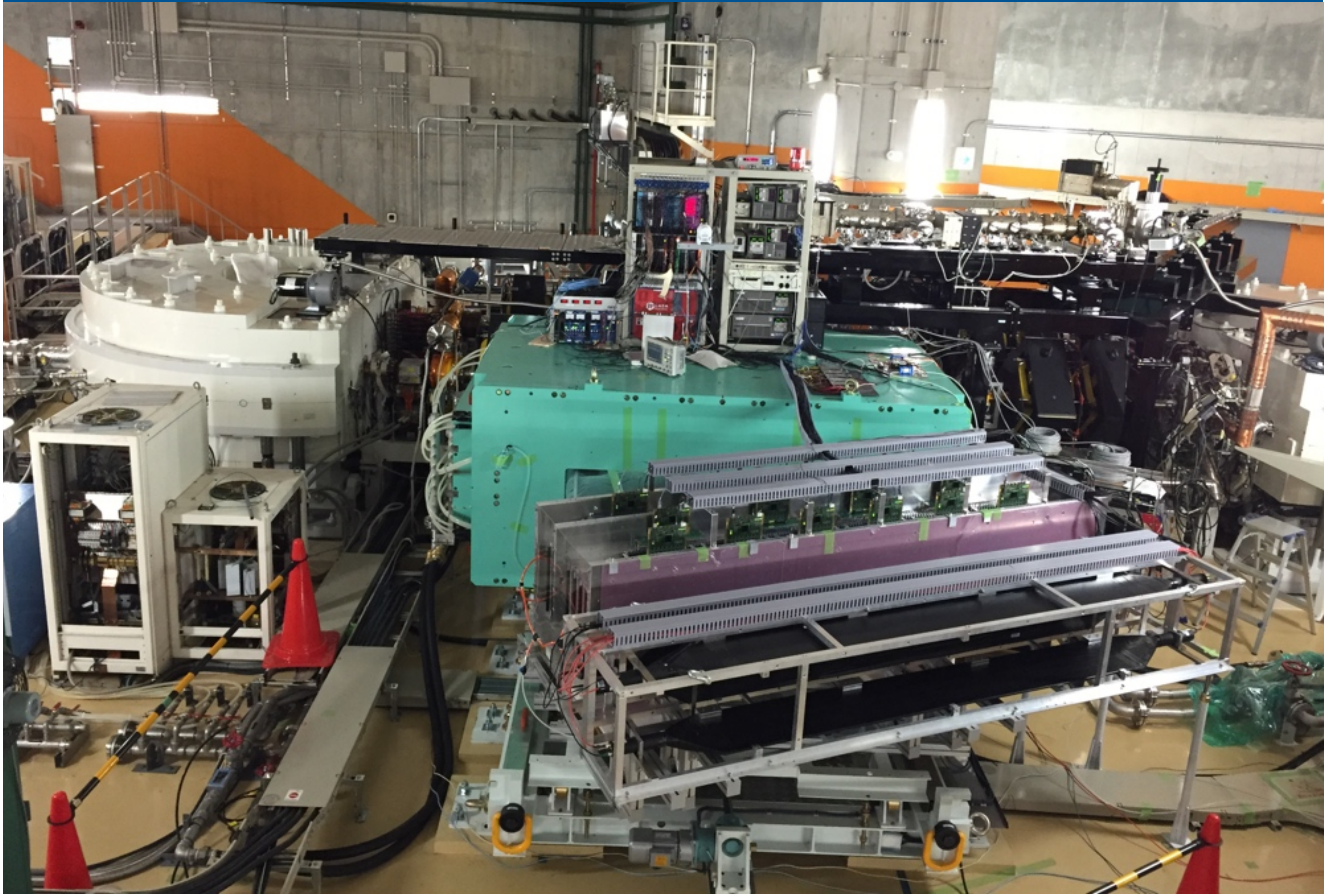
- $\Delta p/p \leq 10^{-3}$ (ΔE<300keV@300MeV)
- Bmax = 0.8 T
- $\Delta\theta = 30^\circ$ ($45\pm15^\circ$)
- $\Delta\Omega \sim$ 100 msr





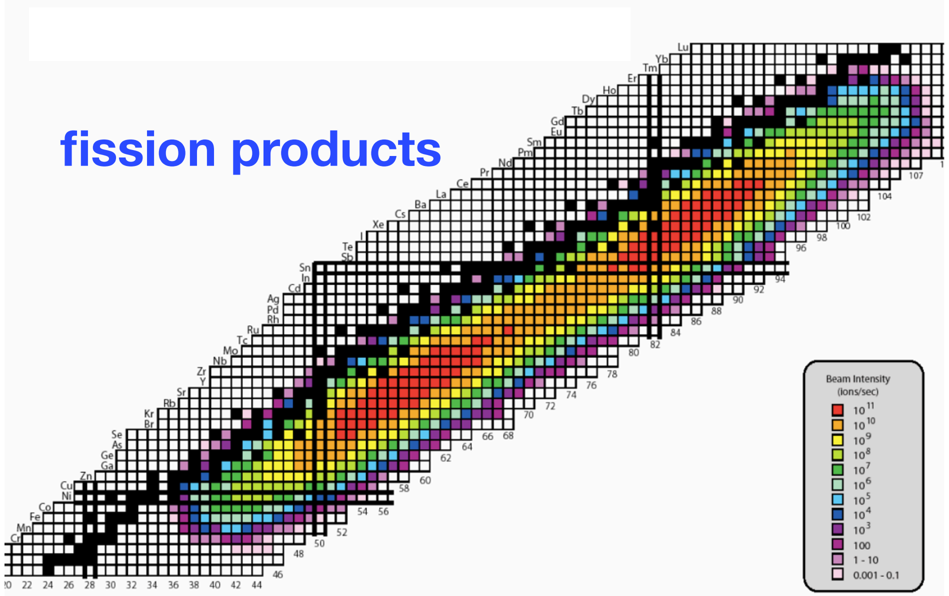

electrode
50 cm
scattered
(a)
(b)
(c)
100
10
1
20
0
-20
Vertical vertex position [mm]
-200
-100
0
100
200
Vertex position along the beam [mm]

SCRIT facility in RIKEN/RI Beam Factory

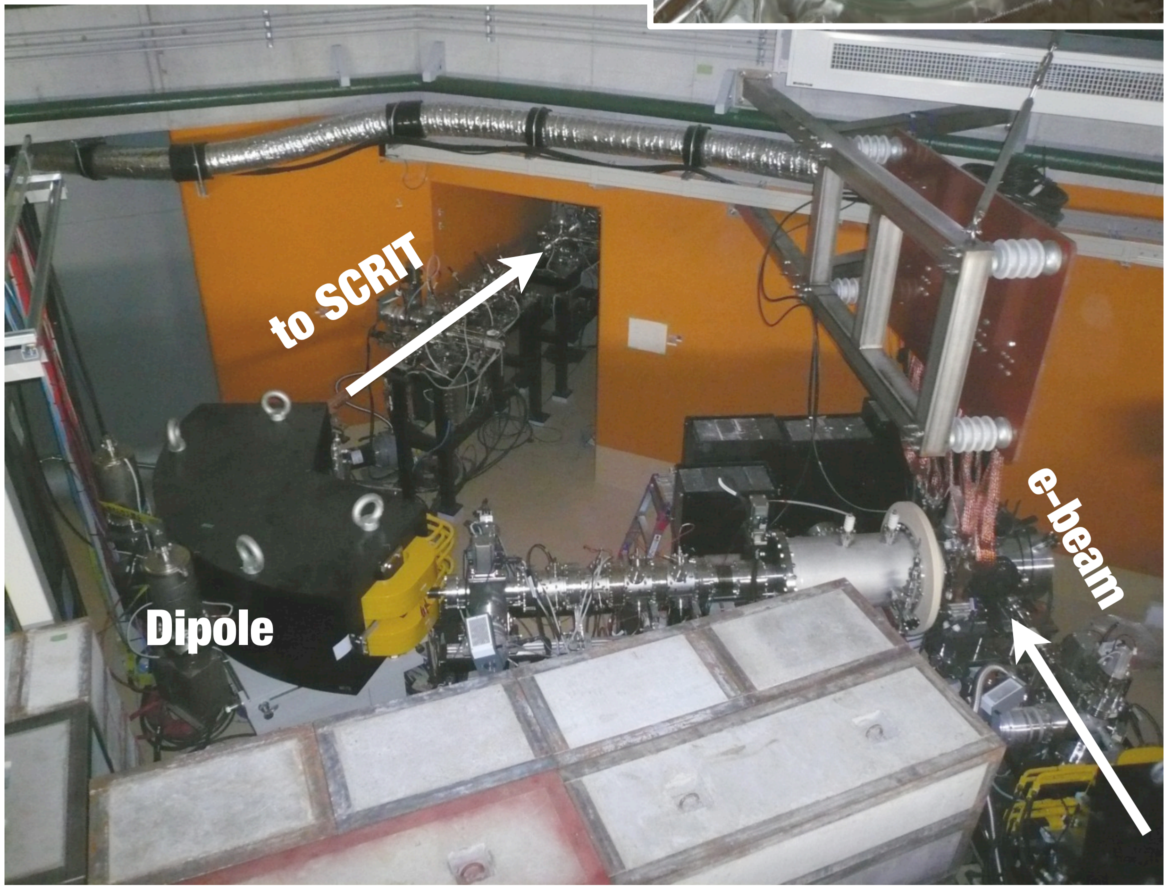


ERIS (Electron-beam-driven RI separator for SCRIT)

Reaction : photo- (electro-) fission of ^{238}U.
Target : house-made UCx
Driver : Race Track Microtron
(Ee=150 MeV)
Ion Source : FEBIAD type



T. Ohnishi et al.
NIM B317 (2013) 357.



Production Rate

$N_{fission}$ ~ 10^8 /watt

$N_{^{132}Sn}$ ~ 10^6 / watt * 1% ($\varepsilon_{trans.}$)

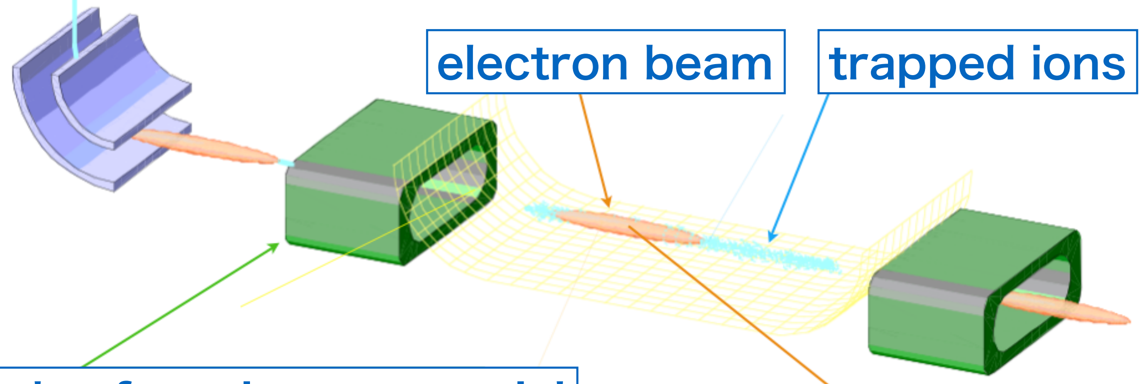
beam power : ~ 50W as of today

~ 1 kW the goal

Luminosities

~10^8 ions are trapped on e-beam (~ 1 mm^2)

N_t ~10^8 /mm^2 => 10^{10} /cm^2

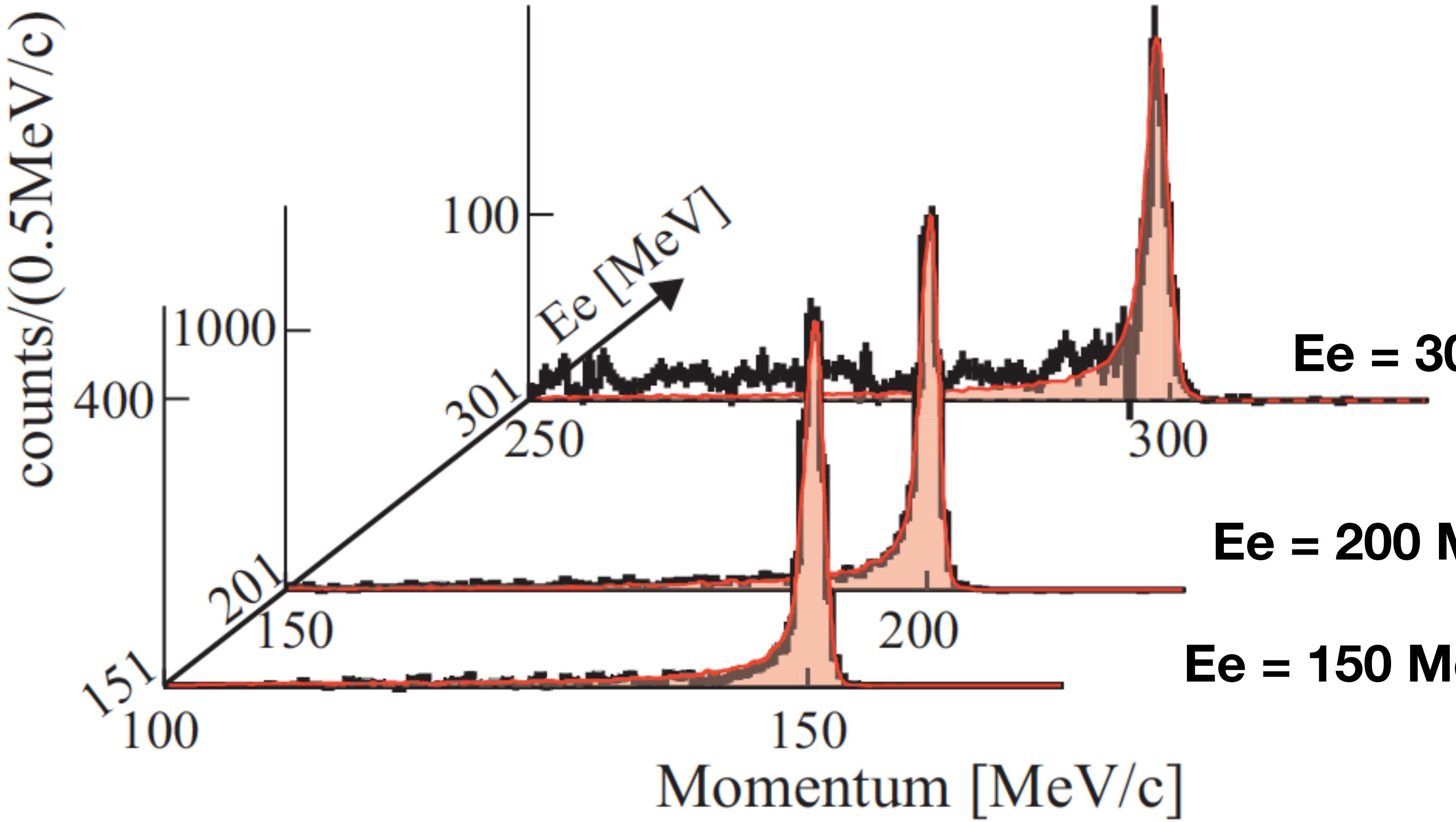


	Ee	N_{beam}	ρ · t	L
Hofstadter's era (1950s)	150 MeV	~ 1nA (~10^9 /s)	~10^{19} /cm^2	~10^{28} /cm^2/s
JLAB	6 GeV	~100μA (~10^{14} /s)	~10^{22} /cm2	~10^{36} /cm^2/s
SCRIT	**150 - 300 MeV**	**~200 mA (~10^{18} /s)**	**~ 10^{10} /cm^2**	**~10^{27} /cm^2/s**

First physics run $^{132}Xe(e,e')$

Ee = 150, 200 and 300 MeV
θ = 30 - 60 deg.
=> q = 80 - 300 MeV

$N_{trapped}$ ~ 10^8 @ Ie = 250 mA
=> L ~ 10^{27} /cm²/s
a week measurement

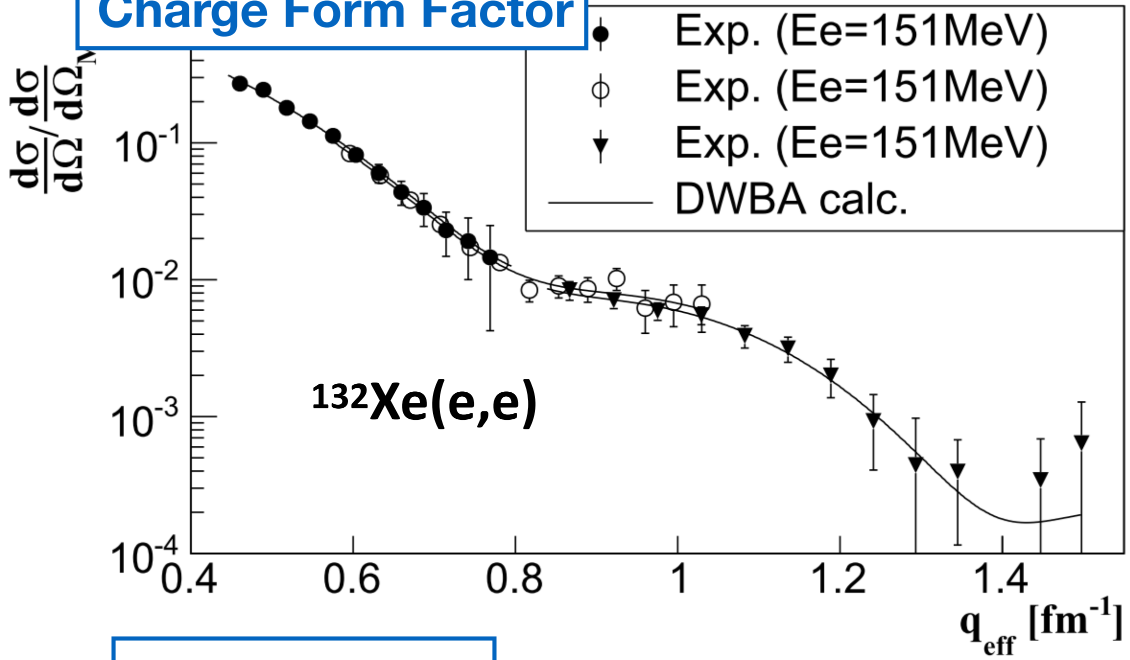


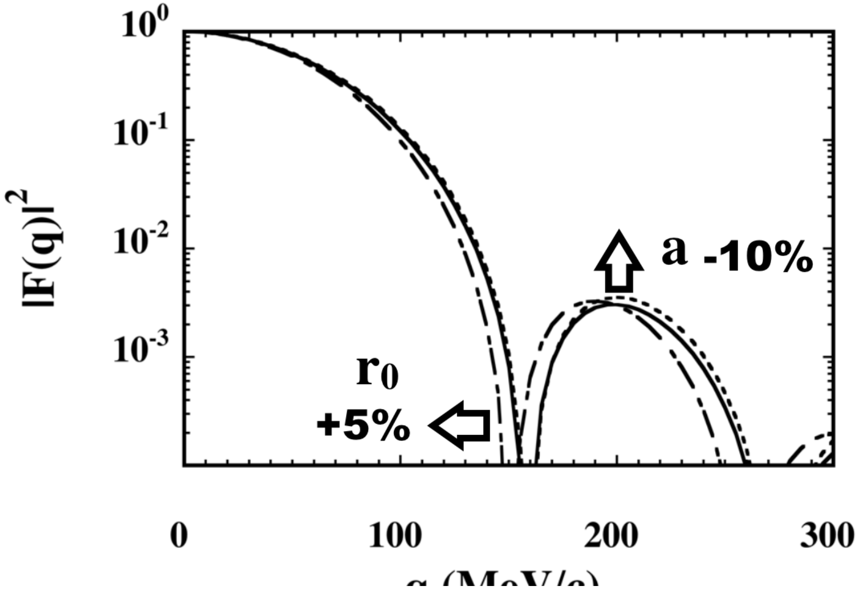
K. Tsukada *et al.* Phys. Rev. Lett. 118 (2017) 262501

First experiment ($^{132}Xe(e,e')$)

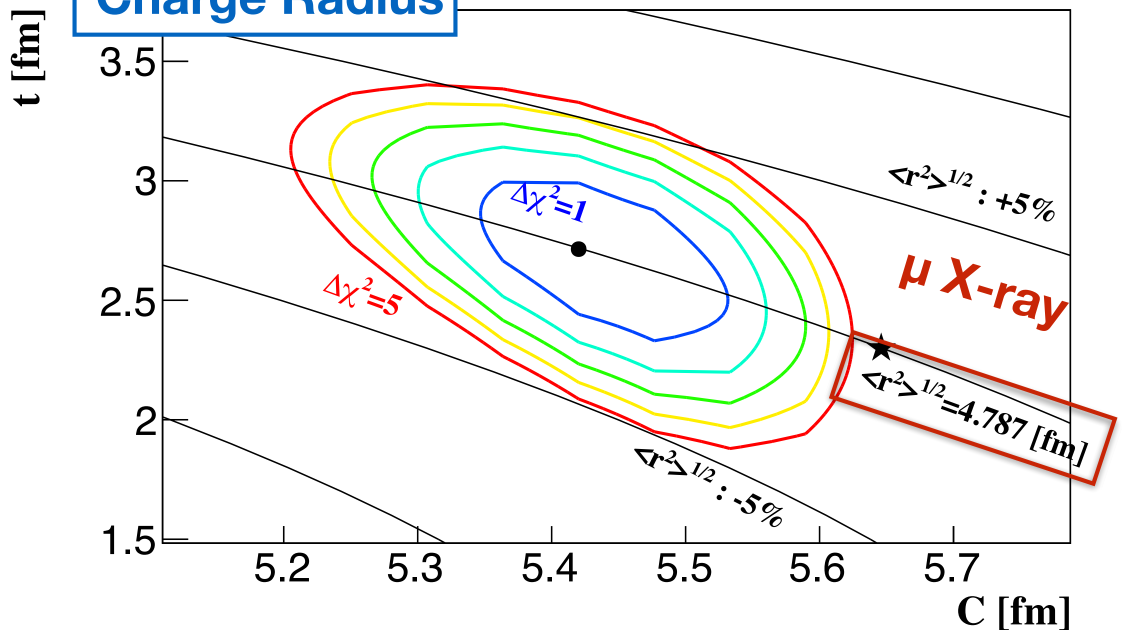
using ~10^8 target nuclei

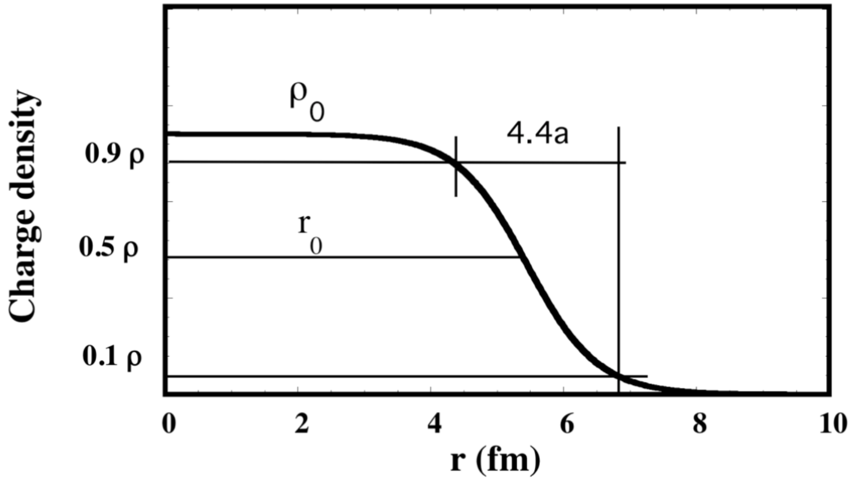
Charge Form Factor





Charge Radius





K. Tsukada *et al.* Phys. Rev. Lett. 118 (2017) 262501

Toward e+RI exp. at SCRIT facility

First physics run with 10^8 ions with stable atom

Luminosity : ~ 10^{27} /cm^2/s

^{132}Xe charge density distribution

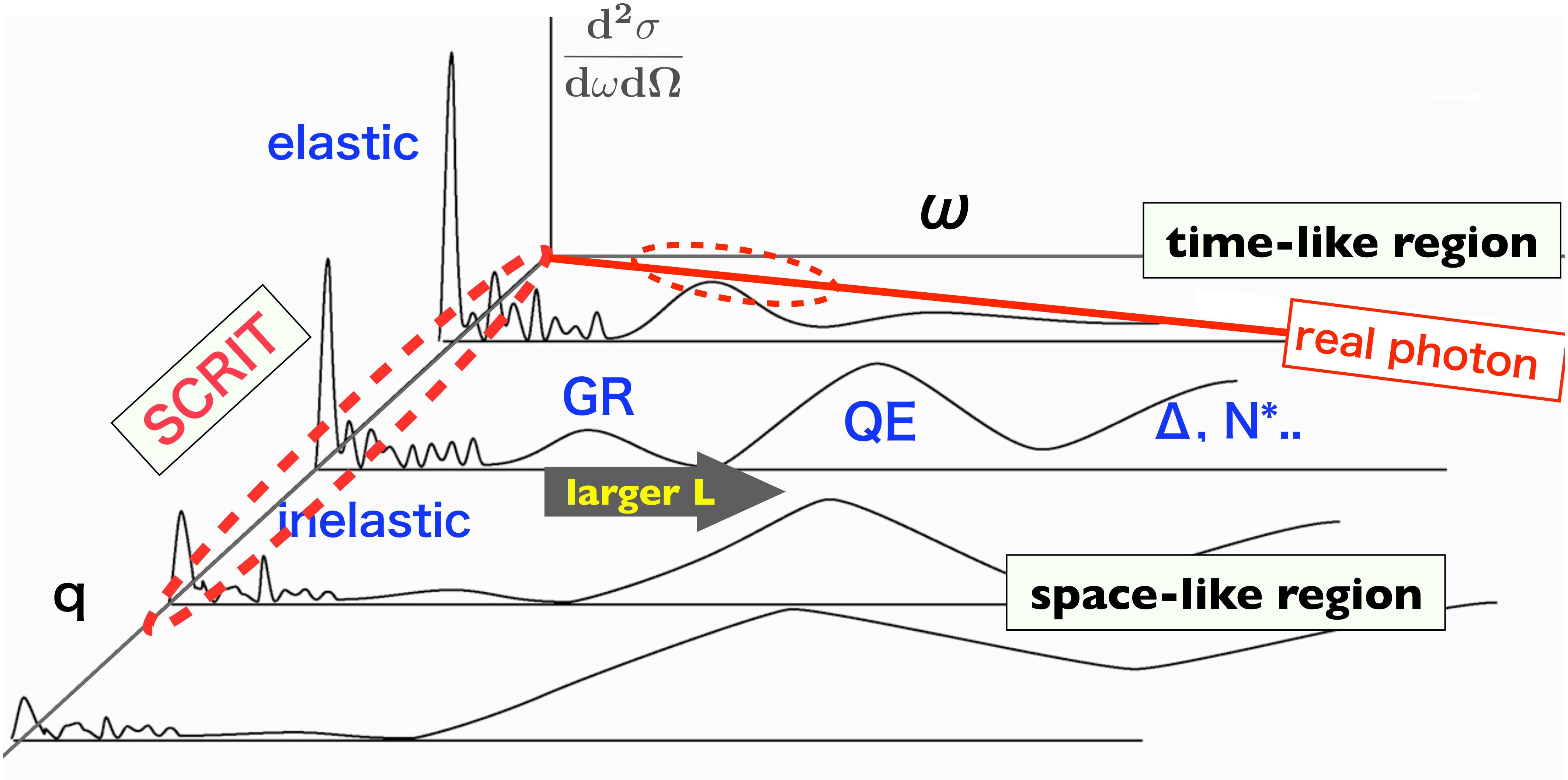
PRL 118 (2017) 262501
PPNP 96 (2017) 1-31.

Toward unstable nuclei

e-beam power is not enough to reach 10^{27} /cm^2/s

need to increase beam power for ISOL up to 1 kW

(ω, q) responses of atomic nuclei



ω = q : Photo-nuclear reaction

ω ~ 0 MeV : Charge Radii, Electromagnetic moments

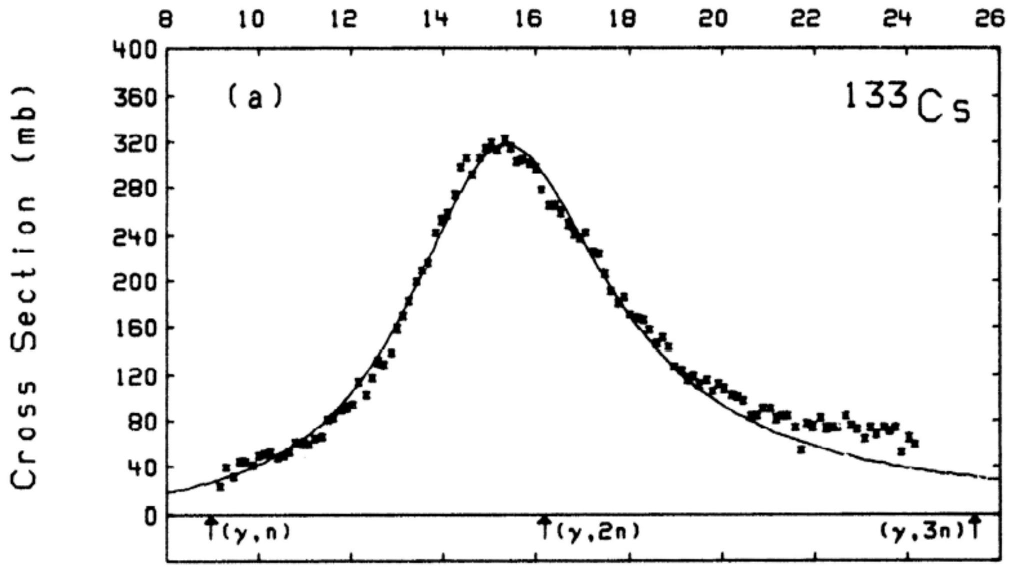
ω ~ a few MeV : B(EL) （ex, CoulX）

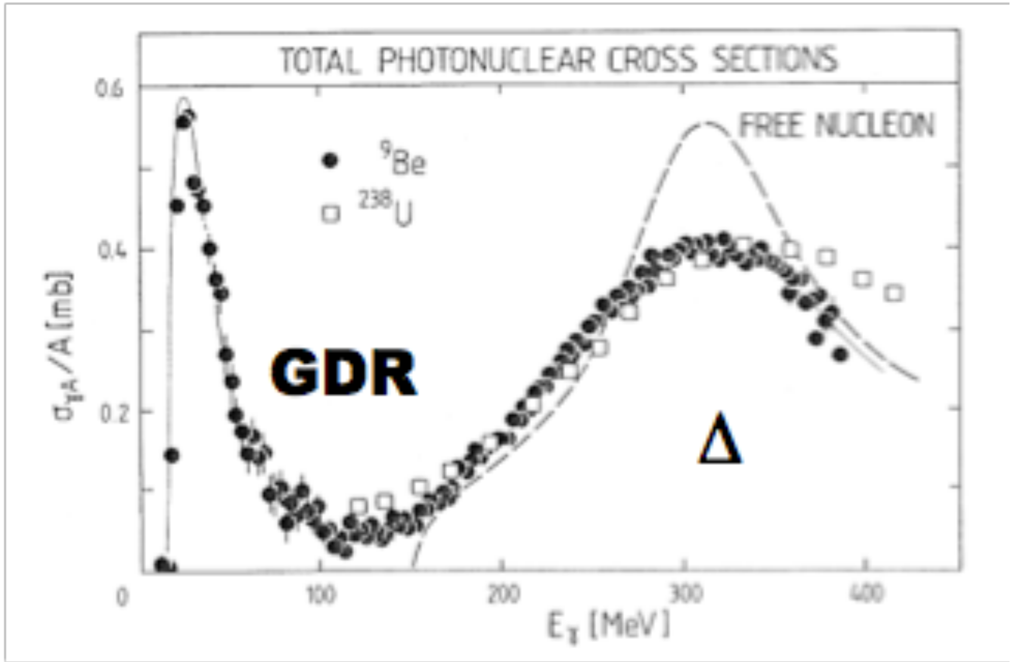
ω ~ a few 10 MeV : GDR （@ SCRIT facility）

Additional Research Opportunity

Photonuclear reaction of exotic nuclei
at
the SCRIT electron scattering facility

Total Photoabsorption Cross Section





1) Response functions (operators : well-known)

2) Sum Rules

TRK sum rule

$$\int_0^\infty \sigma(E_\gamma) dE_\gamma = \frac{2\pi^2 e^2 \hbar}{M}\frac{NZ}{A}(1+\kappa) = 60\frac{NZ}{A}(1+\kappa) MeV \cdot mb$$

Bremmstrahlung sum rule

$$\int_0^\infty \frac{\sigma(E_\gamma)}{E_\gamma} dE_\gamma = \frac{4\pi^2 e^2}{3\hbar}\frac{NZ}{A-1} < r^2 >$$

Migdal sum rule

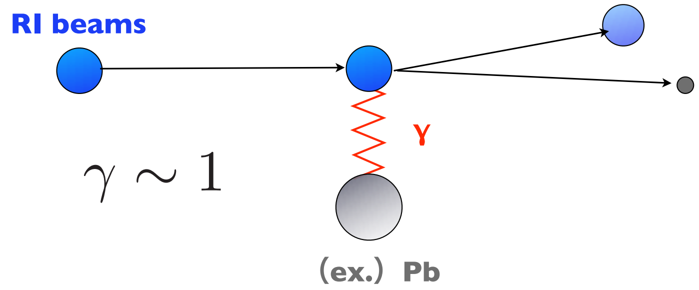
$$\int_0^\infty \frac{\sigma(E_\gamma)}{E_\gamma^2} dE_\gamma = \frac{2\pi^2}{\hbar} P$$

P : polarizability

photonuclear reaction for exotic nuclei

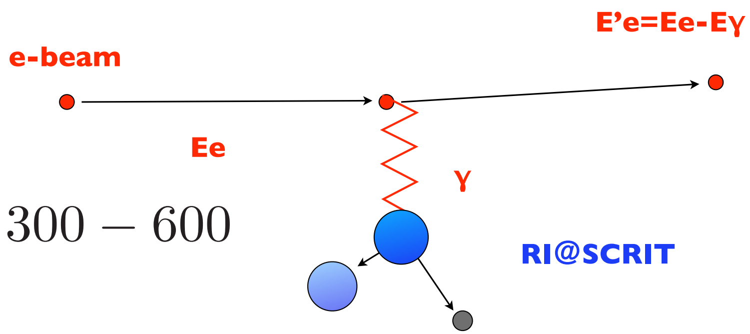
so far

only way : Coulomb excitation in heavy ion reaction



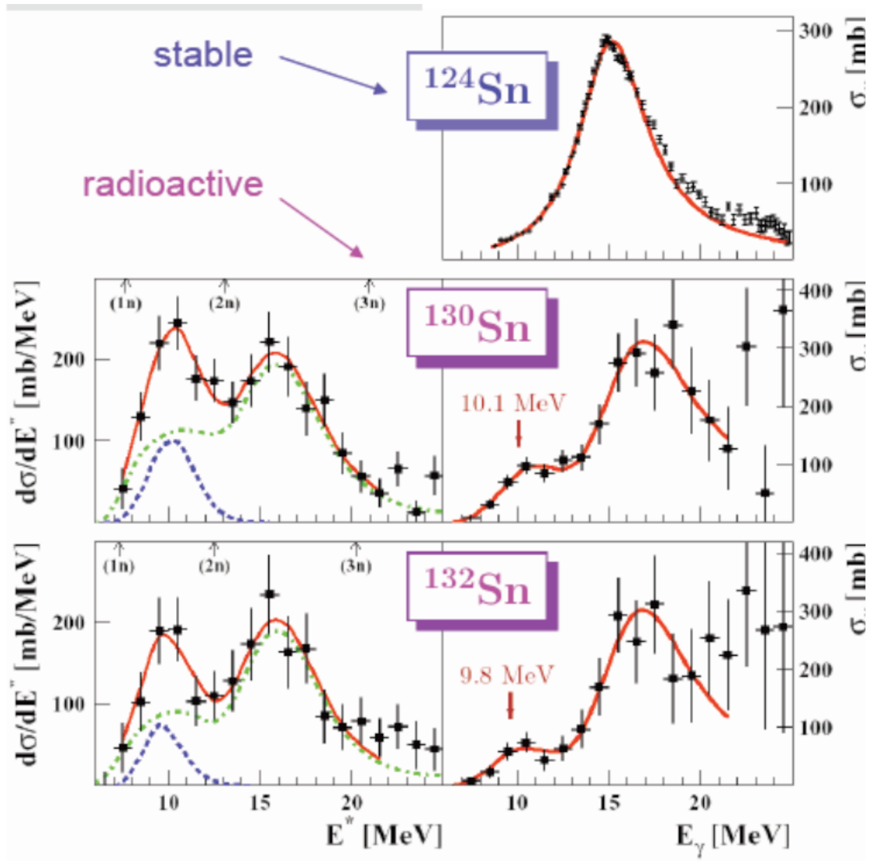
$$\gamma \sim 1$$

SCRIT facility



$$\gamma \sim 300 - 600$$

^{132}Sn+Pb -> ^{131}Sn + n + X @ GSI



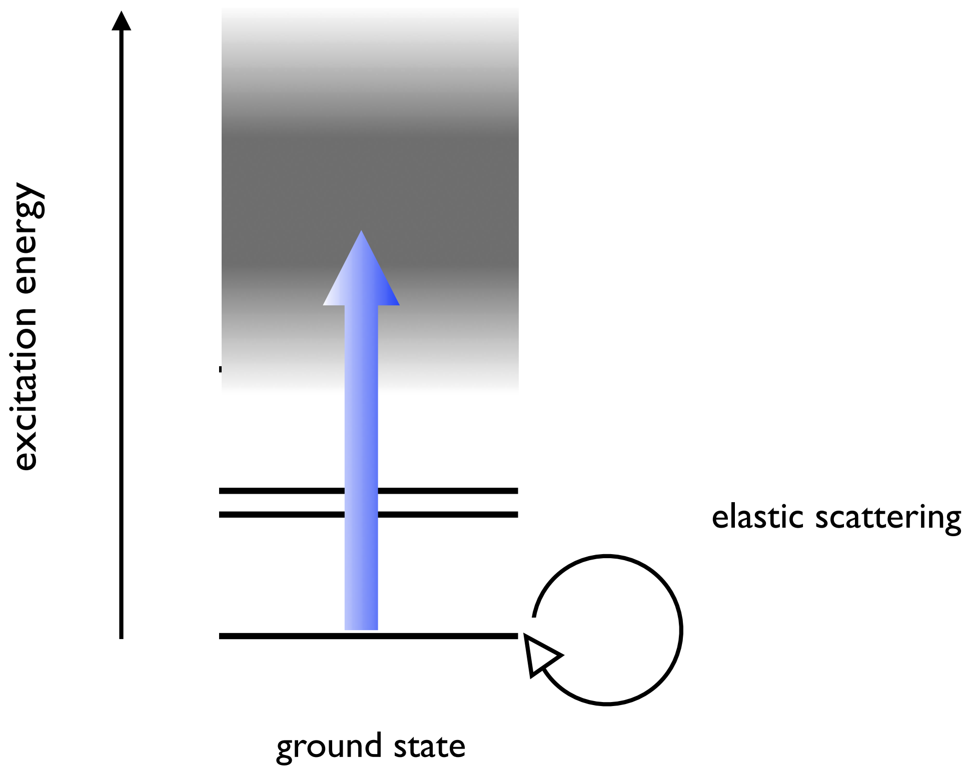
purely EM probe
  well under control
  negligible multi-stop

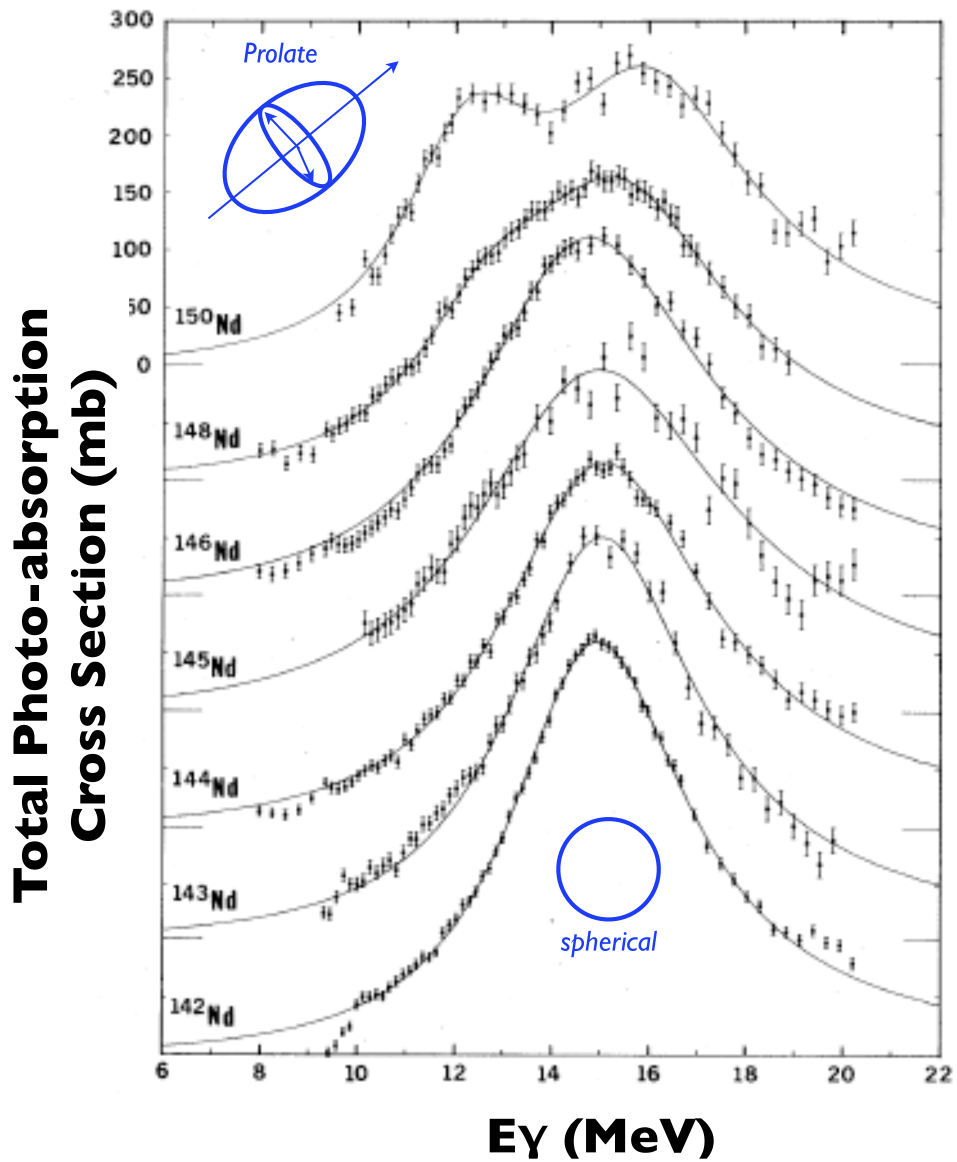
ultra-forward
  electron scattering

Virtual Photon flux

$$\frac{d^2\sigma}{dE_e d\Omega} = \sum \frac{d^2 N_e^{EL}(E, E_\gamma, \theta)}{dE_\gamma d\Omega} \cdot \sigma_\gamma^{EL}(E_\gamma)$$

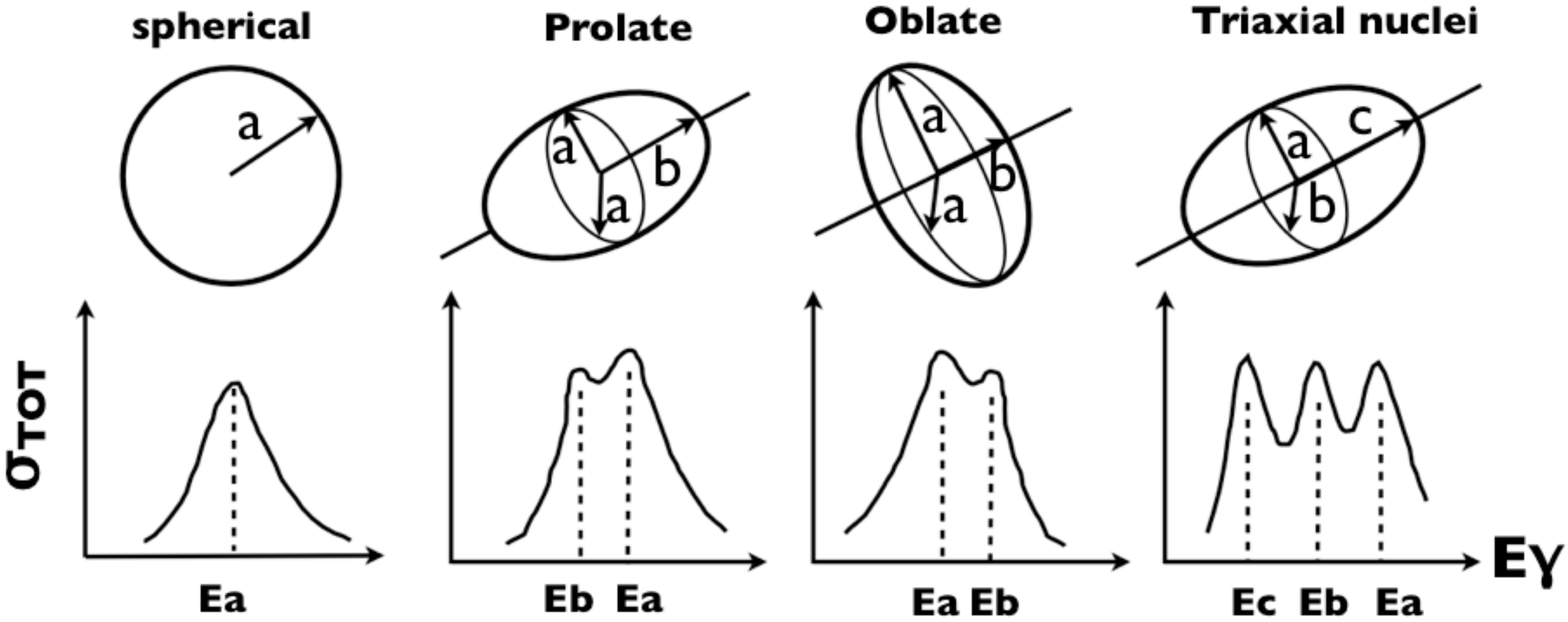
σTOT in GDR region



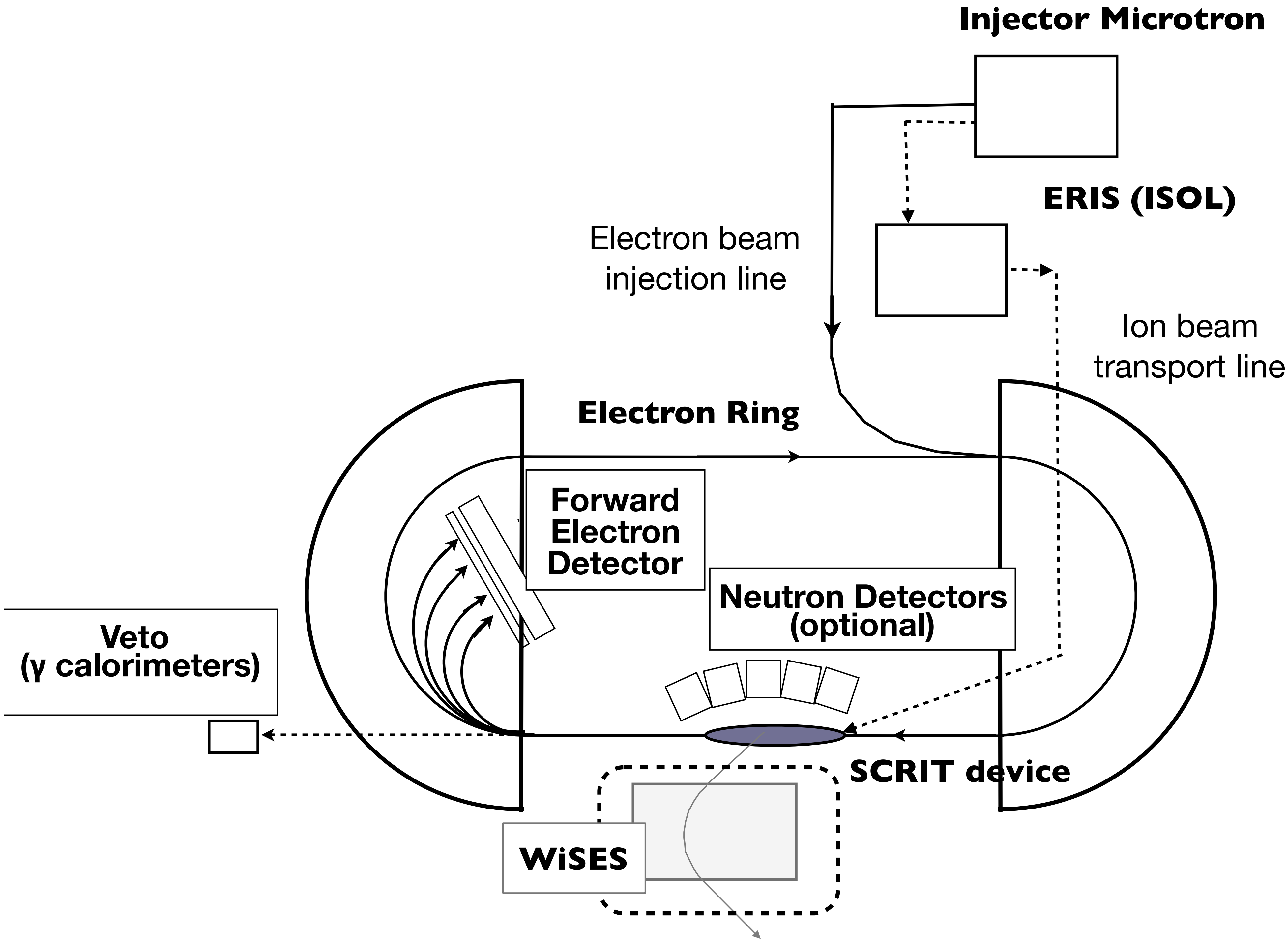


B. L. Berman and S. C. Fultz, Rev. of Mod. Phys. 47 (1975) 713

photo-nuclear responses of exotic nuclei



R. Bergere :Lecture Note in Physics, 61 (1971) 84

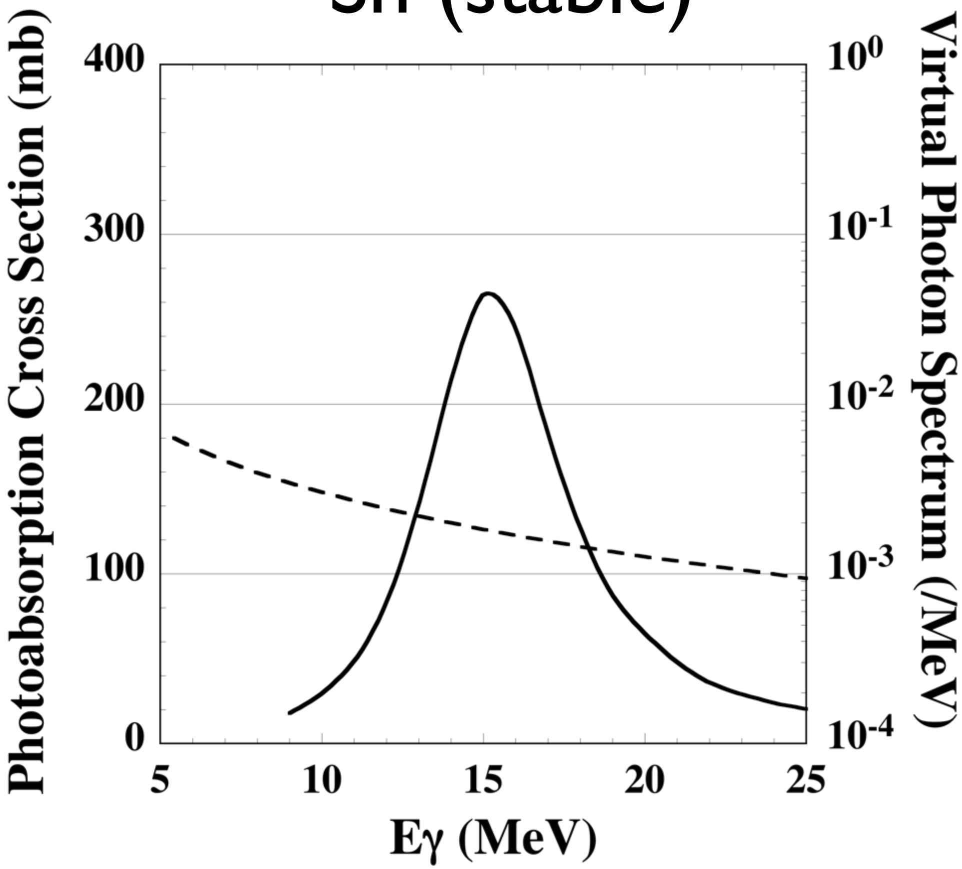

Injector Microtron
ERIS (ISOL)
Electron beam
injection line
Ion beam
transport line
Electron Ring
Forward
Electron
Detector
Neutron Detectors
(optional)
Veto
(γ calorimeters)
SCRIT device
WiSES

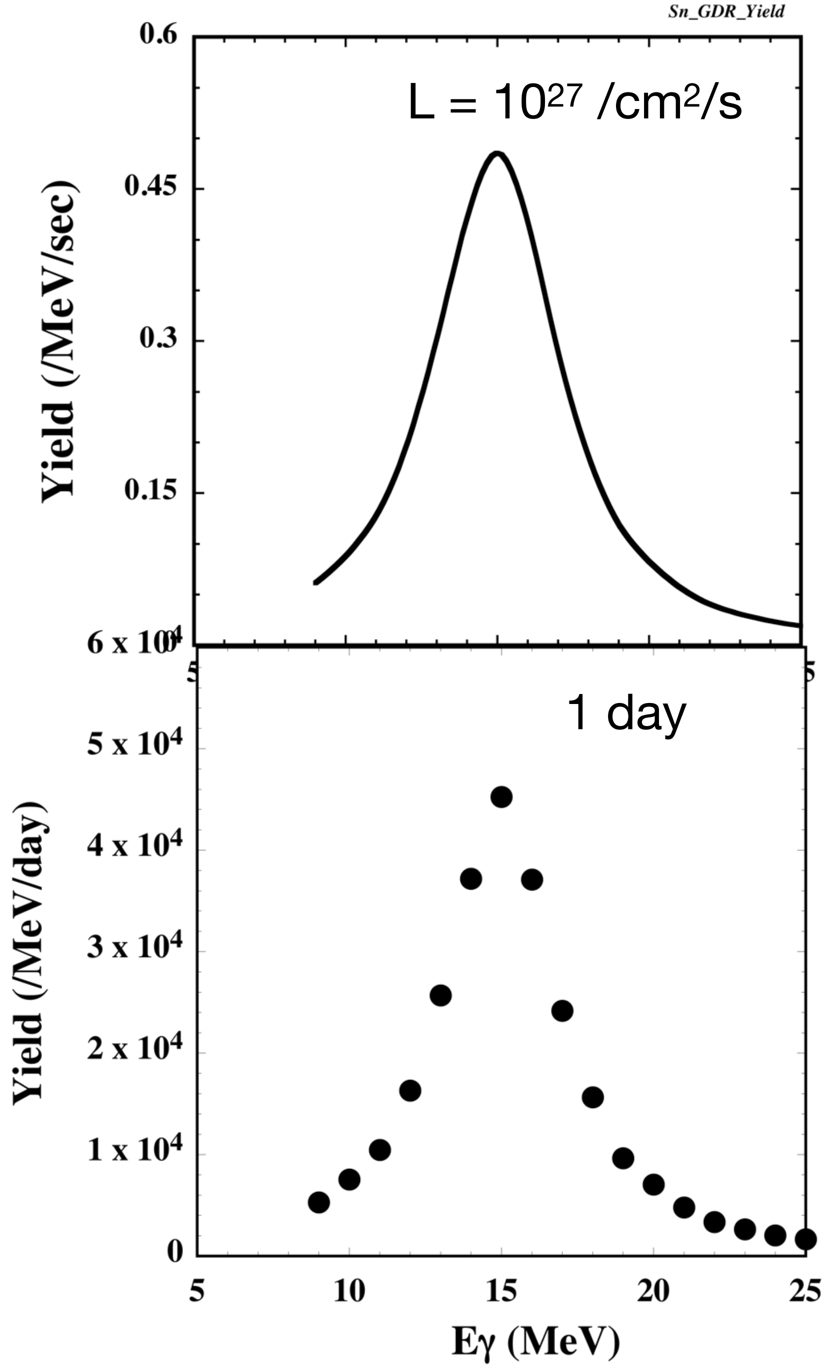
Expected reaction rate for $L = 10^{27}$ /cm²/s

virtual photon theory

$$\frac{dN}{dE_\gamma} = L \cdot \int d\Omega \frac{d^2 N_e^{E1}(E, E_\gamma, \theta)}{dE_\gamma d\Omega} \cdot \sigma_\gamma^{E1}(E_\gamma)$$

^{120}Sn (stable)





P. Durgapal and D.S. Onley
Comp. Phys. Comm. 32 (1984) 291

ECT* workshop in 16-20 July

ECT* workshop 23-27, April, 2018
Exploring the role of electron-weak currents in atomic nuclei

ECT* workshop on e-scattering for exotic nuclei

“Probing exotic structure of short-lived nuclei by electron scattering”

Organizers : *T. Suda (Tohoku), H. Simon (GSI),*
T. Otsuka (RIKEN/Tokyo), C. Barbieri (Surry)

Castello di Trento (Trint), watercolor 19.8 x 27.7, painted by A. Dürer on his way back from Venice (1495). British Museum, London

2018 PROGRAMME OF ACTIVITIES

05-09 March — **Recent Advances and Challenges in the Description of Nuclear Reactions at the Limit of Stability**
Organisers: P. Capel (*Université Libre de Bruxelles*), A. M. Moro (*University of Sevilla*), J. Casal (*ECT*, Trento*), J. A. Lay (*University of Sevilla*)

26-30 March — **Determination of the Absolute Electron (Anti)-Neutrino Mass**
Organisers: K. Valerius (*KIT, Karlsruhe*), L. Gastaldo (*Heidelberg University*)

09-13 April — **Spontaneous and Induced Fission of Very Heavy and Super-Heavy Nuclei**
Organisers: E. Vardaci (*University of Napoli*), N. Carjan (*JINR, Dubna, NIPNE-HH, Bucarest*), Y. Oganessian (*JINR, Dubna*)

16-20 April — **Exposing Novel Quark and Gluon Effects in Nuclei**
Organisers: I. Cloët (*ANL, Lemont*), R. Dupré (*CNRS-IN2P3, Orsay*), S. Riordan (*ANL, Lemont*)

09-13 July — **Modeling Neutrino-Nucleus Interactions**
Organisers: F. Sanchez (*Barcelona Institute of Science and Technology*), U. Mosel (*Giessen University*), M. Barbaro (*Turin University*), N. Jachowicz (*Ghent University*), D. Harris (*FNAL*)

16-20 July — **Probing Exotic Structure of Short-lived Nuclei by Electron Scattering**
Organisers: T. Suda (*Tohoku University*), H. Simon (*GSI, Darmstadt*), T. Otsuka (*RIKEN, Wako*), C. Barbieri (*University of Surrey*)

03-07 September — **Quantum Gravity meets Lattice QFT**
Organisers: A. Schäfer (*Regensburg University*), N. Bodendorfer (*Regensburg University*), K. Giesel (*University of Erlangen*), M. Hanada (*Kyoto University, Livermore, Stanford University*), M. Panero (*Turin University*), Y. Laffe (*Seattle University*)

10-14 September — **Mapping Parton Distribution Amplitudes and Functions**

Summary

e-scattering off exotic nuclei @ SCRIT (RIKEN)

1. SCRIT electron scattering facility started its operation.

   world's first (and only) electron scattering facility for short-lived nuclei

2. Final commissioning experiment for stable ^{132}Xe (e,e') completed:

   L ~ 10^{27} /cm^2/s with ~10^8 ions on e-beam

   $d\sigma/d\Omega$ @ $q \leq 1.5$ fm^{-1}

3. next : e+RI (^{138}Xe, ^{132}Sn) scattering @ L > 10^{26} /cm^2/s

   ISOL (γ+U) : towards higher beam power (20 W ---> 1 kW) : ~10^{11} fission/s

   under budget request

4. Future perspectives

   Total photo-absorption cross section of exotic nuclei

   covering the whole GDR region