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Study of quantum electrodynamics and chromodynamics in atomic bound systems

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Exotic atomic systems

- Simple atomic systems

→ accurate theoretical predictions

→ simple spectra

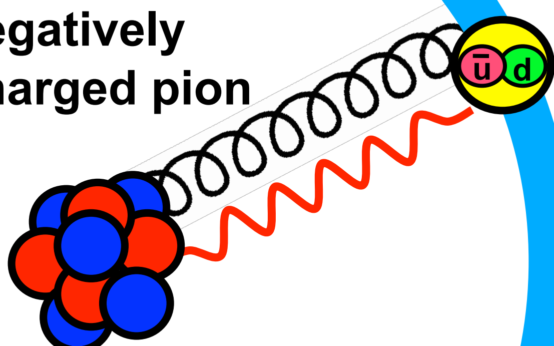
➔ accurate test of fundamental interactions:

Quantum Electrodynamics (in strong filed)

and Chromidynamics (at low energy)

Pionic atoms

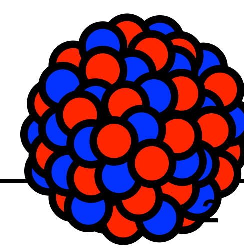
Atoms with a negatively charged pion



Highly charged ions

One-, two- three-electron atoms

Z >>1



Summary

- Introduction
  - Test of QED in strong field
  - Study of strong interaction force at low energy
- Heavy highly charged ions
  - Production
  - Lamb shift measurement
  - Vacuum decay experiment
- Pionic atoms
  - Production
  - Pionic hydrogen and deuterium spectroscopy
  - Pion mass measurement
- Conclusions and outlooks

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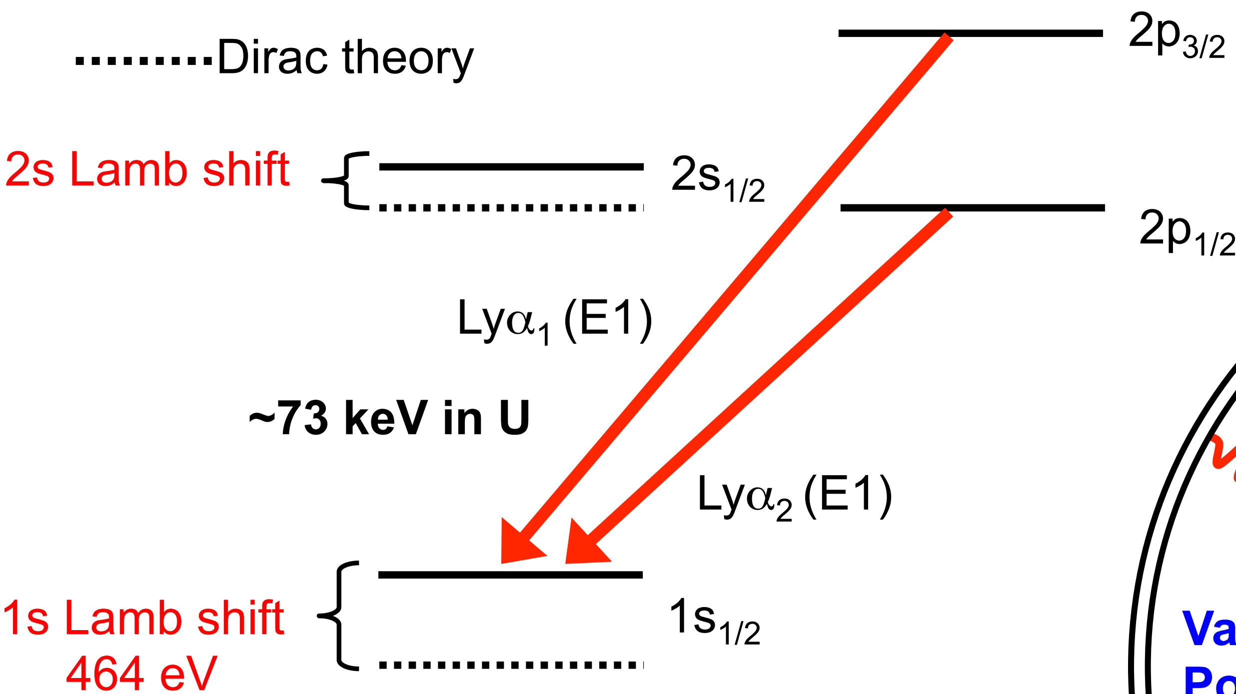
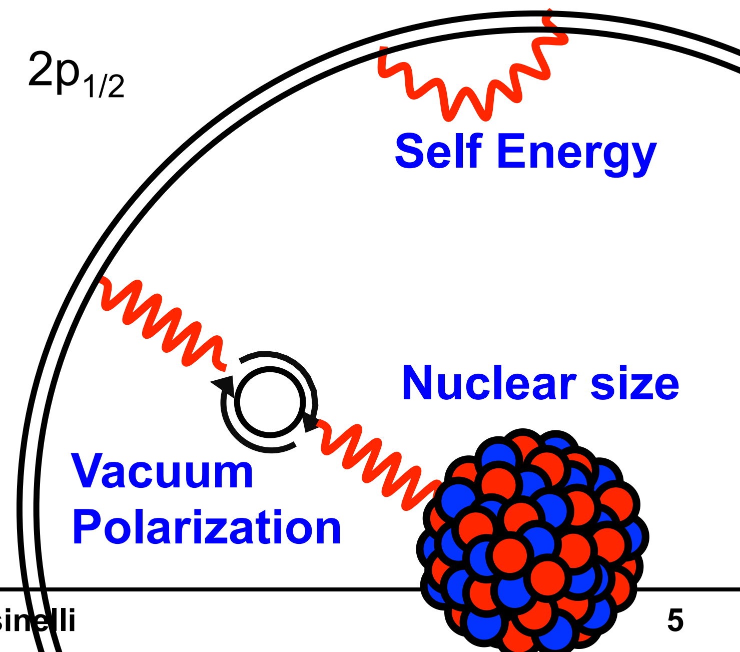
Highly charged ions

Dirac equation (spin-1/2 particles) ➔

$$E^{nj} = \frac{mc^2}{\sqrt{1 + \frac{(Z\alpha)^2}{\left[n - j - 1/2 + \sqrt{(j+1/2)^2 - (Z\alpha)^2}\right]^2}}}$$

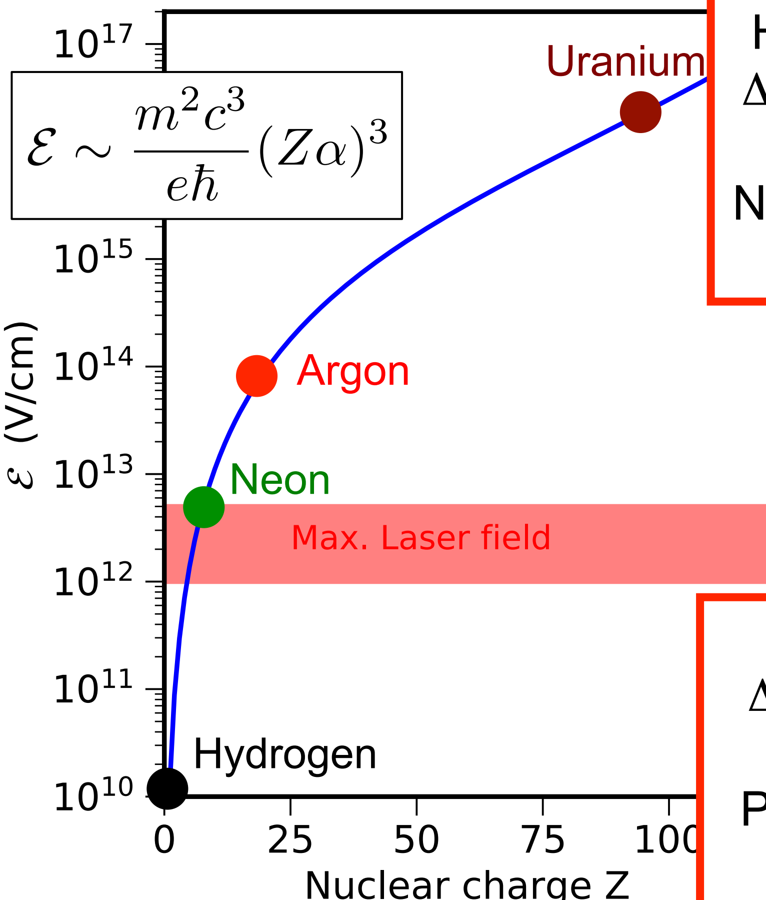
- Simple atomic systems
  → accurate theoretical predictions
  → simple spectra





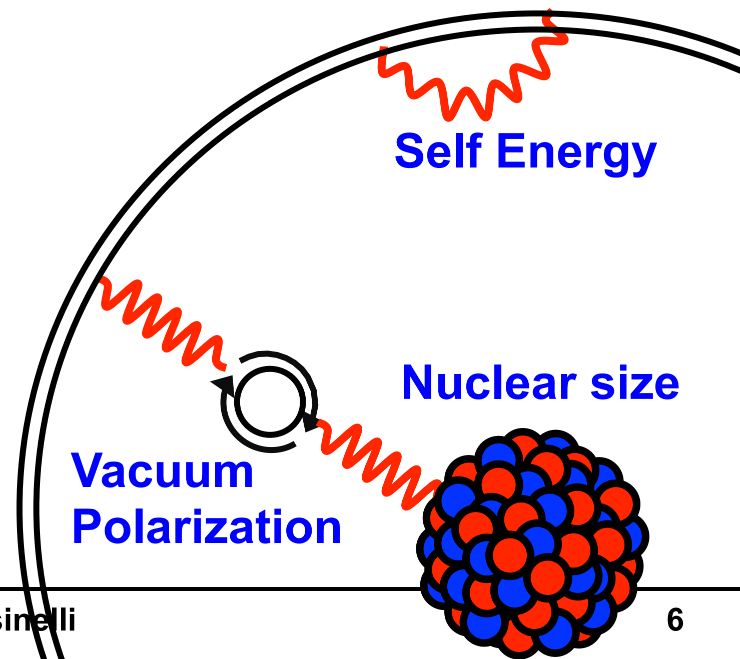
Few electrons heavy charged ions

- Simple atomic systems
  - → accurate theoretical predictions
  - → simple spectra
- Strong electric field
  - → Quantum Electrodynamic effects enhanced
  - → Large perturbation during collisions with other atoms



H-like Uranium
$\Delta E_{QED} \approx 500$ eV
$Z \cdot \alpha \approx 1$
Non perturbative in $Z\alpha$

Hydrogen
$\Delta E_{QED} \approx 10^{-6}$ eV
$Z \cdot \alpha \approx 10^{-2}$
Perturbative in α and $Z\alpha$

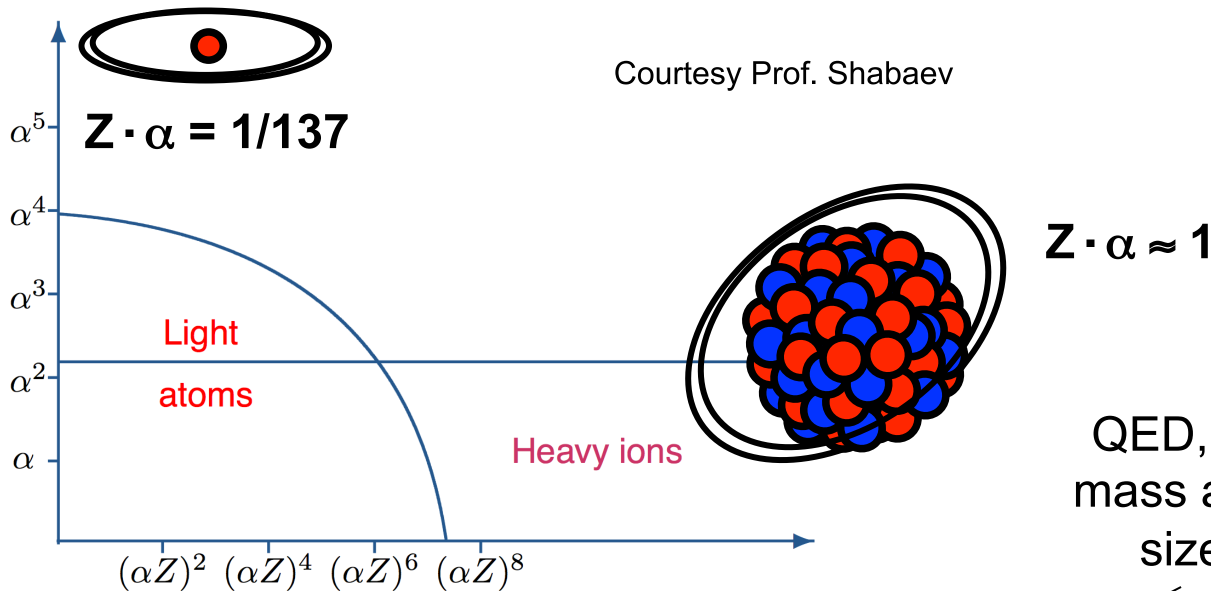


Tests of QED calculations at strong-coupling regime

α and Zα expansion

$$E^{nj} = mc^2 - mc^2\frac{(Z\alpha)^2}{2n^2} + mc^2(Z\alpha)^4\left[a(n,j) + \alpha b(n,j) + \alpha^2 c(n,j) + \ldots\right] + \\ + mc^2(Z\alpha)^6\left[a'(n,j) + \alpha b'(n,j) + \alpha^2 c'(n,j) + \ldots\right] + \ldots$$

M.I. Eides *et al.*, Phys. Rep. **342**, 63-261 (2001)
P.J. Mohr *et al.*, Rev. Mod. Phys. **88**, 035009 (2016).



Dirac eq.

QED, reduced mass and finite size contrib.

α expansion, all-order in Zα

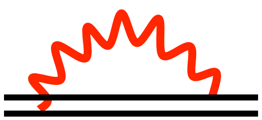
$$E^{nj} = \frac{mc^2}{\sqrt{1 + \frac{(Z\alpha)^2}{\left[n - j - 1/2 + \sqrt{(j+1/2)^2 - (Z\alpha)^2}\right]^2}}} + \alpha F(Z\alpha) + \alpha^2 G(Z\alpha) + \ldots$$

Non-perturbative bound system QED

First order in α

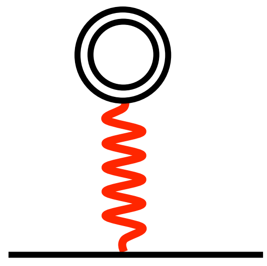
Self- energy

P.J. Mohr, Annals of Physics **88**, 26-51 (**1974**)



Vacuum polarization

N.L. Manakov *et al.*, Sov. Phys. JETP **68**, 673-679 (**1989**)
G. Soff *et al.*, Phys. Rev. A **38**, 5066-5075 (**1988**)



(Free particle QED renormalization in 1940-50)

Dirac eq. (**1928**)

$$E^{nj} = \frac{mc^2}{\sqrt{1 + \frac{(Z\alpha)^2}{\left[n - j - 1/2 + \sqrt{(j+1/2)^2 - (Z\alpha)^2}\right]^2}}} + \alpha F(Z\alpha) + \alpha^2 G(Z\alpha) + \ldots$$

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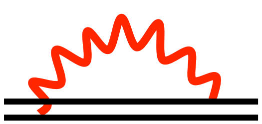

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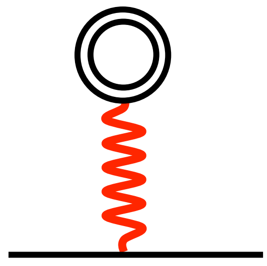
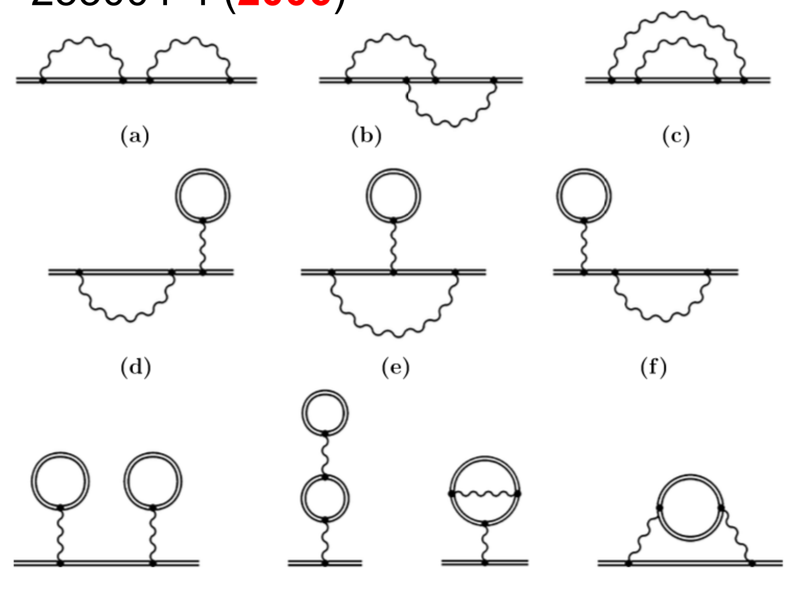


Second order in α

V.A. Yerokhin *et al.*, Phys. Rev. Lett. **97**, 253004-4 (**2006**)



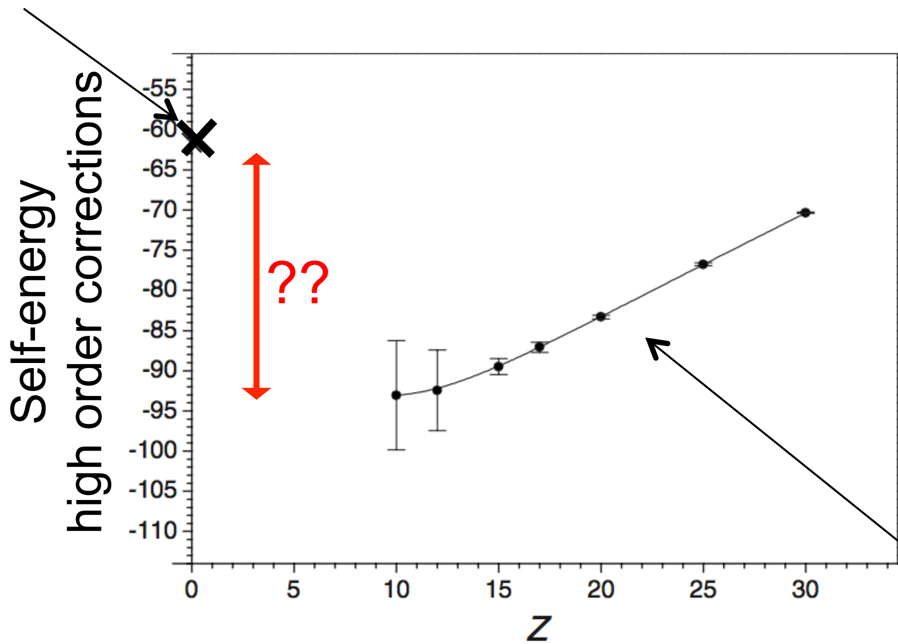
Dirac eq. (**1928**)

$$E^{nj} = \frac{mc^2}{\sqrt{1 + \frac{(Z\alpha)^2}{\left[n - j - 1/2 + \sqrt{(j+1/2)^2 - (Z\alpha)^2}\right]^2}}} + \alpha F(Z\alpha) + \alpha^2 G(Z\alpha) + \ldots$$

Self-energy predictions

α and Zα expansion

$$E^{nj} = mc^2 - mc^2\frac{(Z\alpha)^2}{2n^2} + mc^2(Z\alpha)^4\left[a(n,j) + \alpha b(n,j) + \alpha^2 c(n,j) + \ldots\right] + \\ + mc^2(Z\alpha)^6\left[a'(n,j) + \alpha b'(n,j) + \alpha^2 c'(n,j) + \ldots\right] + \ldots$$



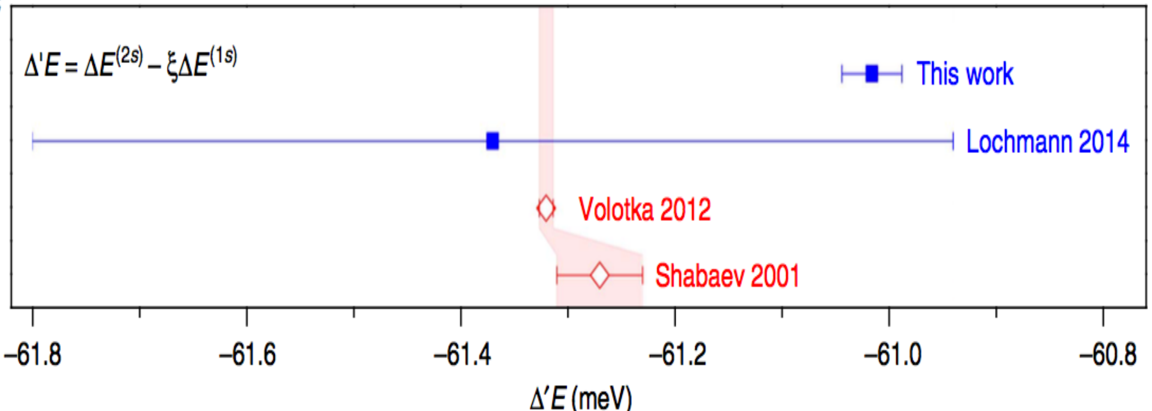
V.A. Yerokhin, Phys. Rev. A **80**, 040501 (2009)

α expansion, all-order in Zα

$$E^{nj} = \frac{mc^2}{\sqrt{1 + \frac{(Z\alpha)^2}{\left[n - j - 1/2 + \sqrt{(j+1/2)^2 - (Z\alpha)^2}\right]^2}}} + \alpha F(Z\alpha) + \alpha^2 G(Z\alpha) + \ldots$$

Quantum electrodynamics tests in atomic systems: open questions

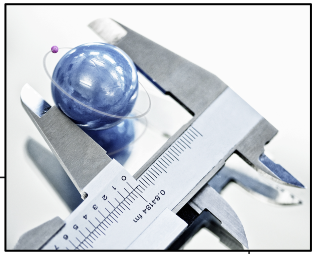
Hyperfine structure of H- and Li-like Bismuth



J. Ullmann *et al.*, Nat. Commun. **8**, 15484 (2017)

Laser spectroscopy of stored heavy ions

Proton radius puzzle

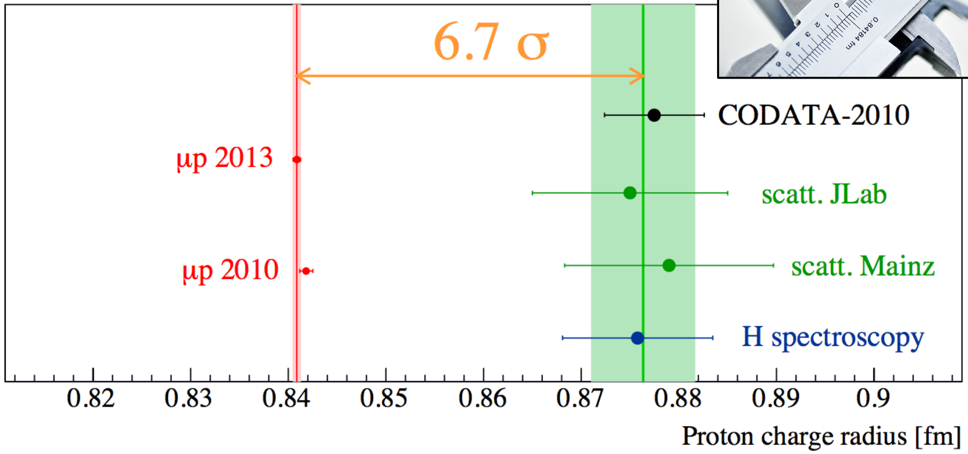


Strong disagreement between **hydrogen** and **muonic hydrogen** spectroscopy

$m_\mu = 200\, m_e$

$$\mathcal{E} \sim \frac{m^2 c^3}{e\hbar}(Z\alpha)^3$$

$$r_n \sim \frac{\hbar n^2}{mcZ\alpha}$$



A. Antognini *et al.*, Science **339**, 417-420 (2013)
R. Pohl *et al.*, Nature **466**, 213-216 (2010)

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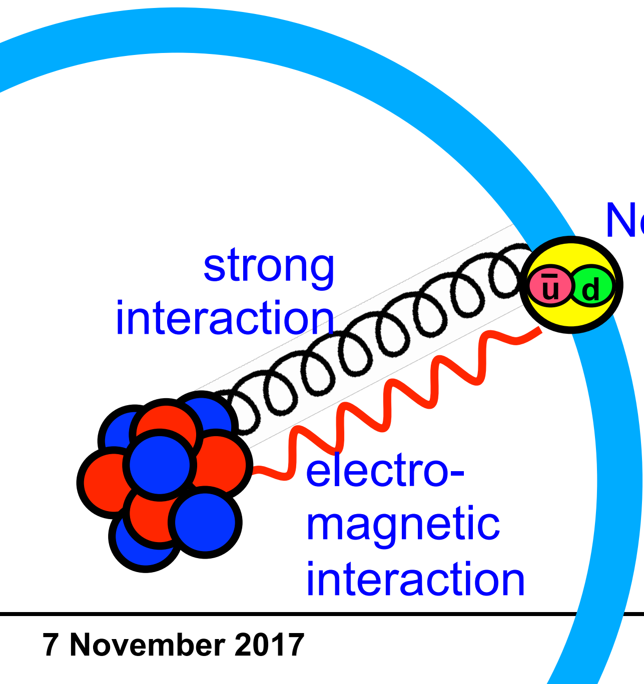
Pionic atoms

FAQ: What is a pion?



Negative charged pion

- m_π = 254 m_e
- lifetime=26 ns

Hydrogen-like atoms

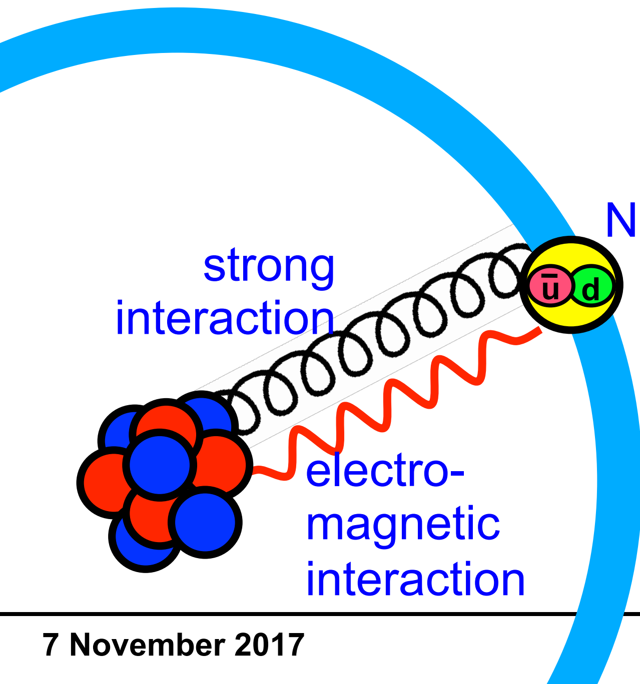
Pionic atoms

- Simple atomic systems
  → accurate theoretical predictions
  → simple spectra
- Strong electric field
  → Quantum Electrodynamic effects enhanced
- Presence of strong interaction
- Small Bohr radius

$$E^{nl} = \frac{mc^2}{\sqrt{1 + \frac{(Z\alpha)^2}{\left[n - l - 1/2 + \sqrt{(l+1/2)^2 - (Z\alpha)^2}\right]^2}}}$$

$$\mathcal{E} \sim \frac{m^2 c^3}{e\hbar}(Z\alpha)^3$$

$$r_n \sim \frac{\hbar n^2}{mcZ\alpha}$$



Negative charged pion

- $m_\pi = 254\ m_e$
- lifetime=26 ns

Hydrogen-like atoms

Pionic atoms

- Electromagnetic interaction → bound system

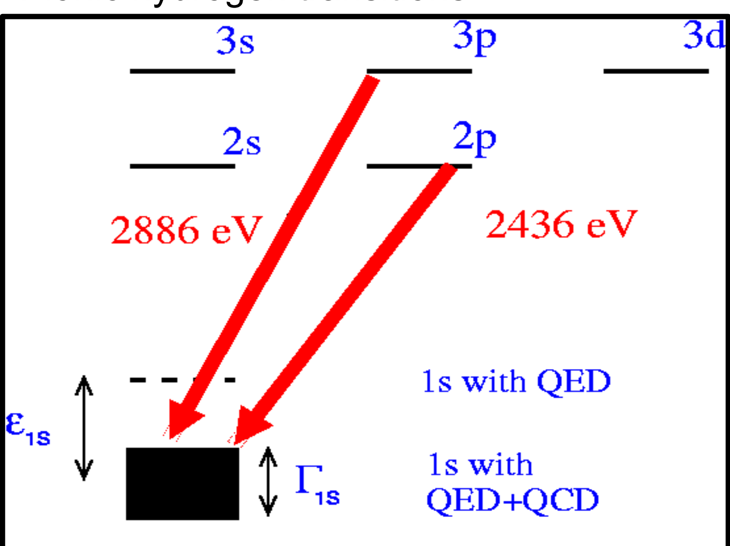
$$E_n = mc^2 \frac{(Z\alpha)^2}{2n^2} + \mathcal{O}\left[(Z\alpha)^4\right]$$

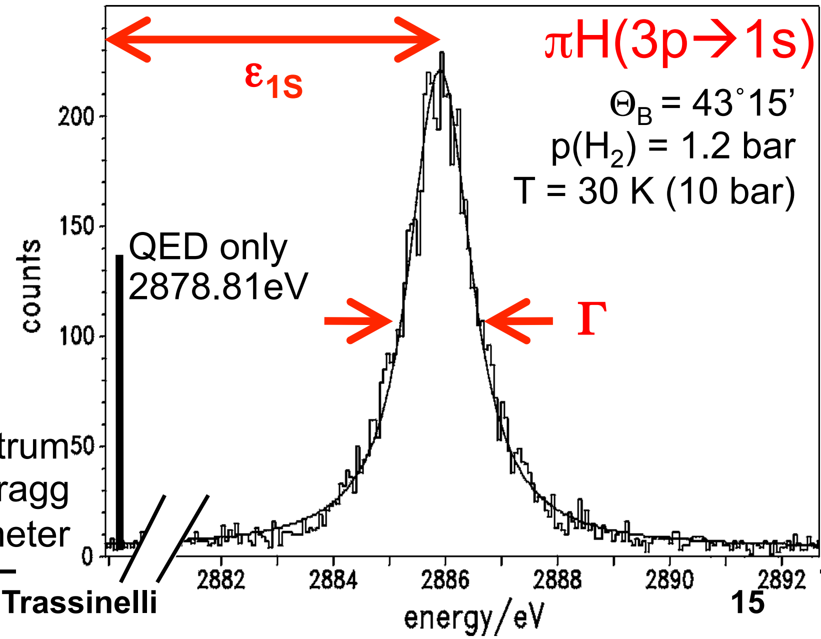
- **Strong interaction!!**

    Attraction or repulsion → shift of the energy transition ε

    Reaction with the nucleus → ground state instable
    - lifetime of the atom not infinite
    - non-zero linewidth Γ of the atomic transitions

Pionic hydrogen transitions





Experimental spectrum obtained with a Bragg spectrometer

Strong interaction Lagrangians

High energy - - - - - - - - - - - Low energy

Quantum ChromoDynamics Lagrangian

$$\mathcal{L}_{\rm QCD} = \bar{\psi}_i \left(i\gamma^\mu (D_\mu)_{ij} - m\,\delta_{ij} \right) \psi_j - \frac{1}{4} G^a_{\mu\nu} G^{\mu\nu}_a$$

$$= \bar{\psi}_i (i\gamma^\mu \partial_\mu - m)\psi_i - g G^a_\mu \bar{\psi}_i \gamma^\mu T^a_{ij} \psi_j - \frac{1}{4} G^a_{\mu\nu} G^{\mu\nu}_a \,,$$

Chiral perturbation theory Lagrangian (4th order dev.)

$$\mathcal{L}_{\rm eff} = \mathcal{L}_\pi^{(p^2)} + \mathcal{L}_\pi^{(e^2)} + \mathcal{L}_\pi^{(e^2 p^2)} + \mathcal{L}_{\rm N}^{(p)} + \mathcal{L}_{\rm N}^{(p^2)} + \mathcal{L}_{\rm N}^{(p^3)} + \mathcal{L}_{\rm N}^{(e^2)} + \mathcal{L}_{\rm N}^{(e^2 p)} + \mathcal{L}_\gamma ,$$

$$\mathcal{L}_\pi^{(p^2)} + \mathcal{L}_\pi^{(e^2)} + \mathcal{L}_\gamma = \frac{F^2}{4} \langle d^\mu U^\dagger d_\mu U + \chi^\dagger U + U^\dagger \chi \rangle + Z F^4 \langle Q U Q U^\dagger \rangle - \frac{1}{4} F_{\mu\nu} F^{\mu\nu} - \frac{1}{2} (\partial_\mu A^\mu)^2 ,$$

$$= F^2 \{ \langle d^\mu U^\dagger d_\mu U \rangle (k_1 \langle Q^2 \rangle + k_2 \langle Q U Q U^\dagger \rangle) + k_4 \langle d^\mu U^\dagger Q U \rangle \langle d_\mu U Q U^\dagger \rangle + k_3 (\langle d^\mu U^\dagger Q U \rangle \langle d_\mu U^\dagger Q U \rangle + \langle d^\mu U Q U^\dagger \rangle \langle d_\mu U Q U^\dagger \rangle) \} ,$$

$$\bar{\Psi} \left\{ i\not{D} - m + \frac{1}{2} g \not{u} \gamma_5 \right\} \Psi ,$$

$$\bar{\Psi} \left\{ c_1 \langle \chi_+ \rangle - \frac{c_2}{4m^2} \langle u_\mu u_\nu \rangle D^\mu D^\nu + \text{h.c.} + \frac{c_3}{2} \langle u_\mu u^\mu \rangle + \frac{i}{4} c_4 \sigma^{\mu\nu} [u_\mu, u_\nu] + c_5 \hat{\chi}_+ \right\} \Psi ,$$

$$\frac{i}{2m} \bar{\Psi} \{ d_5 [\chi_-, u_\mu] D^\mu \} \Psi + \text{h.c.} ,$$

$$F^2 \bar{\Psi} \{ f_1 \langle \hat{Q}_+^2 - Q_-^2 \rangle + f_2 \langle Q_+ \rangle \hat{Q}_+ \} \Psi ,$$

$$\frac{F^2}{2} \bar{\Psi} \{ g_1 \langle Q_+^2 - Q_-^2 \rangle \gamma^\mu \gamma_5 u_\mu + g_2 \langle Q_+ \rangle^2 \gamma^\mu \gamma_5 u_\mu \} \Psi$$

$$+ \frac{i F^2}{2m} \bar{\Psi} \{ g_6 \langle Q_+ \rangle \langle Q_- u_\mu \rangle D^\mu + g_7 \langle Q_+ u_\mu \rangle Q_- D^\mu + g_8 \langle Q_- u_\mu \rangle Q_+ D^\mu \} \Psi + \text{h.c.} ,$$

V. Baru *et al.*, Nucl. Phys. A **872**, 69-116 (2011)

Nucleon propagator in ChPT with pion and other propagator contributions
J. Gasser *et al.*, Nuclear Physics B **307**, 779 (1988)

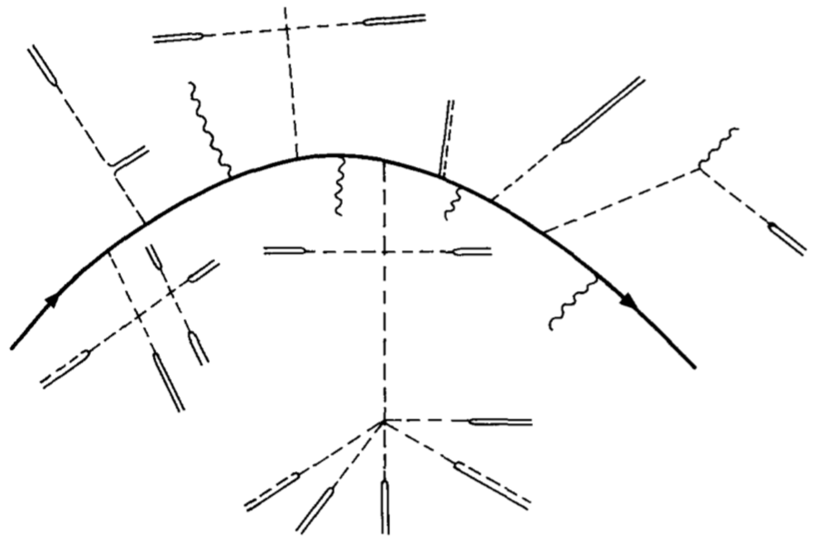


Fig. 1. A typical term in the expansion (3.7) of the nucleon propagator. ——→—— nucleon; - - - pions; ∿∿ vector current; ═ ═ axial vector current; –⊏ pseudoscalar density; ══ scalar density.

Strong interaction Lagrangians

High energy - - - - - - - - - - - Low energy

Quantum ChromoDynamics Lagrangian

$$\mathcal{L}_{\mathrm{QCD}} = \bar{\psi}_i \left(i\gamma^\mu (D_\mu)_{ij} - m\,\delta_{ij}\right)\psi_j - \frac{1}{4}G^a_{\mu\nu}G^{\mu\nu}_a$$
$$= \bar{\psi}_i(i\gamma^\mu\partial_\mu - m)\psi_i - gG^a_\mu\bar{\psi}_i\gamma^\mu T^a_{ij}\psi_j - \frac{1}{4}G^a_{\mu\nu}G^{\mu\nu}_a\,,$$

1 coupling constant

Chiral perturbation theory Lagrangian (4th order dev.)

$$\mathcal{L}_{\mathrm{eff}} = \mathcal{L}_\pi^{(p^2)} + \mathcal{L}_\pi^{(e^2)} + \mathcal{L}_\pi^{(e^2p^2)} + \mathcal{L}_{\mathrm{N}}^{(p)} + \mathcal{L}_{\mathrm{N}}^{(p^2)} + \mathcal{L}_{\mathrm{N}}^{(p^3)} + \mathcal{L}_{\mathrm{N}}^{(e^2)} + \mathcal{L}_{\mathrm{N}}^{(e^2p)} + \mathcal{L}_\gamma,$$

$$\mathcal{L}_\pi^{(p^2)} + \mathcal{L}_\pi^{(e^2)} + \mathcal{L}_\gamma = \frac{F^2}{4}\langle d^\mu U^\dagger d_\mu U + \chi^\dagger U + U^\dagger\chi\rangle + ZF^4\langle QUQU^\dagger\rangle - \frac{1}{4}F_{\mu\nu}F^{\mu\nu} - \frac{1}{2}(\partial_\mu A^\mu)^2,$$

$$\mathcal{L}_\pi^{(e^2p^2)} = F^2\{\langle d^\mu U^\dagger d_\mu U\rangle(k_1\langle Q^2\rangle + k_2\langle QUQU^\dagger\rangle) + k_4\langle d^\mu U^\dagger QU\rangle\langle d_\mu UQU^\dagger\rangle + k_3(\langle d^\mu U^\dagger QU\rangle\langle d_\mu U^\dagger QU\rangle + \langle d^\mu UQU^\dagger\rangle\langle d_\mu UQU^\dagger\rangle)\},$$

$$\mathcal{L}_{\mathrm{N}}^{(p)} = \bar{\Psi}\left\{i\not{D} - m + \frac{1}{2}g\not{u}\gamma_5\right\}\Psi,$$

$$\mathcal{L}_{\mathrm{N}}^{(p^2)} = \bar{\Psi}\left\{c_1\langle\chi_+\rangle - \frac{c_2}{4m^2}\langle u_\mu u_\nu\rangle D^\mu D^\nu + \text{h.c.} + \frac{c_3}{2}\langle u_\mu u^\mu\rangle + \frac{i}{4}c_4\sigma^{\mu\nu}[u_\mu, u_\nu] + c_5\tilde{\chi}_+\right\}\Psi,$$

$$\mathcal{L}_{\mathrm{N}}^{(p^3)} = \frac{i}{2m}\bar{\Psi}\{d_5[\chi_-, u_\mu]D^\mu\}\Psi + \text{h.c.},$$

$$\mathcal{L}_{\mathrm{N}}^{(e^2)} = F^2\bar{\Psi}\{f_1\langle\hat{Q}_+^2 - Q_-^2\rangle + f_2\langle Q_+\rangle\hat{Q}_+\}\Psi,$$

$$\mathcal{L}_{\mathrm{N}}^{(e^2p)} = \frac{F^2}{2}\bar{\Psi}\{g_1\langle\hat{Q}_+^2 - Q_-^2\rangle\gamma^\mu\gamma_5 u_\mu + g_2\langle Q_+\rangle^2\gamma^\mu\gamma_5 u_\mu\}\Psi + \frac{iF^2}{2m}\bar{\Psi}\{g_6\langle Q_+\rangle\langle Q_- u_\mu\rangle D^\mu + g_7\langle Q_+ u_\mu\rangle Q_- D^\mu + g_8\langle Q_- u_\mu\rangle Q_+ D^\mu\}\Psi + \text{h.c.},$$

18 and more low energy coupling constants (LEC) (depending on the expansion order)

V. Baru *et al.*, Nucl. Phys. A **872**, 69-116 (2011)

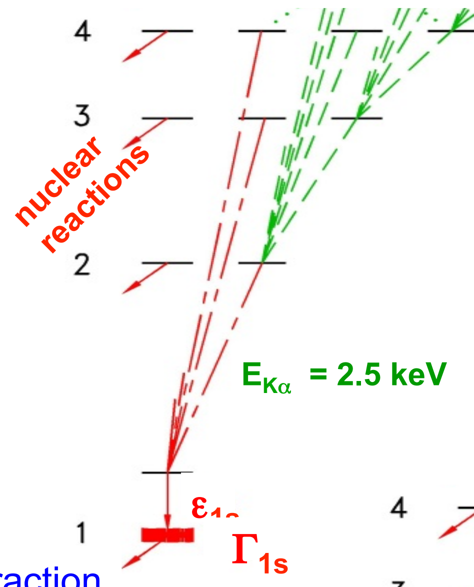
Need of experimental experiment to measure the LECs and test the theory!!

Strong interaction in simple bound systems

Shift and width related to the pion-nucleus scattering length and cross sections

πH
$$\begin{cases} \epsilon_{1s}^{\pi H} \propto a_{\pi^- p \to \pi^- p} + corr. \\ \Gamma_{1s}^{\pi H} \propto (a_{\pi^- p \to \pi^0 n})^2 + corr. \end{cases}$$

πH transitions

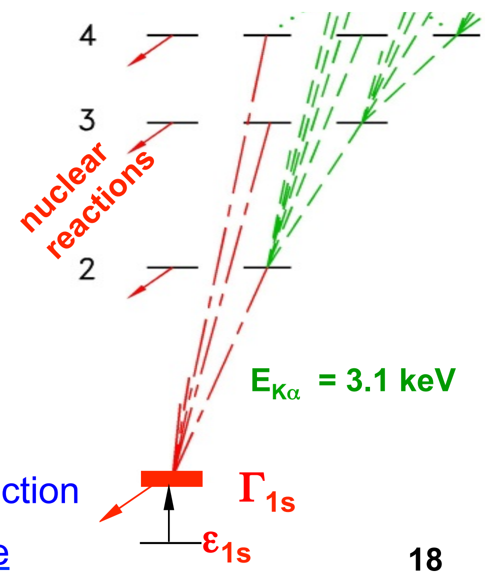


strong interaction

attractive

πD
$$\begin{cases} \epsilon_{1s}^{\pi D} \propto a_{\pi^- p \to \pi^- p} + a_{\pi^- n \to \pi^- n} + corr. \\ \Gamma_{1s}^{\pi D} \propto \Im m(a_{\pi d \to \pi d}) \end{cases}$$

πD transitions



strong interaction

repulsive

Strong interaction in simple bound systems

Shift and width related to the pion-nucleus scattering length and cross sections

πH

$$\epsilon_{1s}^{\pi H} \propto a_{\pi^- p \to \pi^- p} + corr.$$

$$\Gamma_{1s}^{\pi H} \propto (a_{\pi^- p \to \pi^0 n})^2 + corr.$$

πD

$$\epsilon_{1s}^{\pi D} \propto a_{\pi^- p \to \pi^- p} + a_{\pi^- n \to \pi^- n} + corr.$$

$$\Gamma_{1s}^{\pi D} \propto \Im m(a_{\pi d \to \pi d})$$

→ Basic pion-nucleon interaction properties

→ Pion production cross section from p–p collisions

Highly charged ions and pionic atoms

- Simple atomic systems

$$E_n = mc^2 \frac{(Z\alpha)^2}{2n^2} + \mathcal{O}\left[(Z\alpha)^4\right]$$

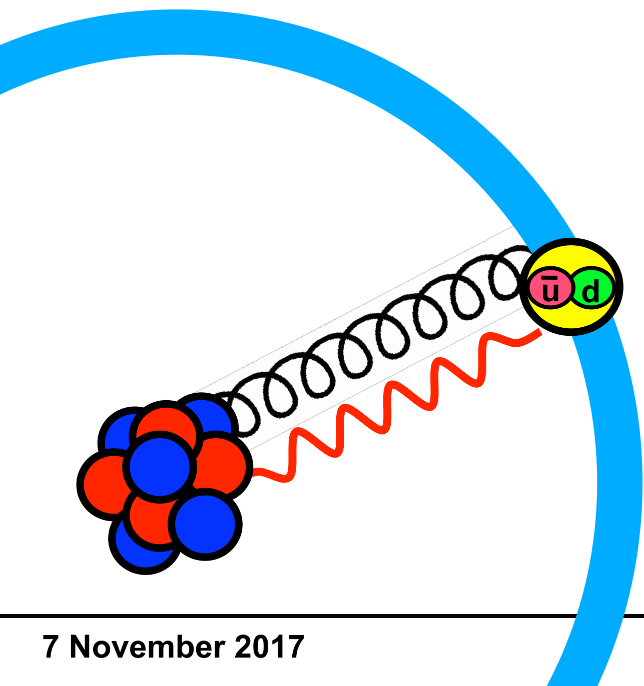
⇨ X-ray spectroscopy

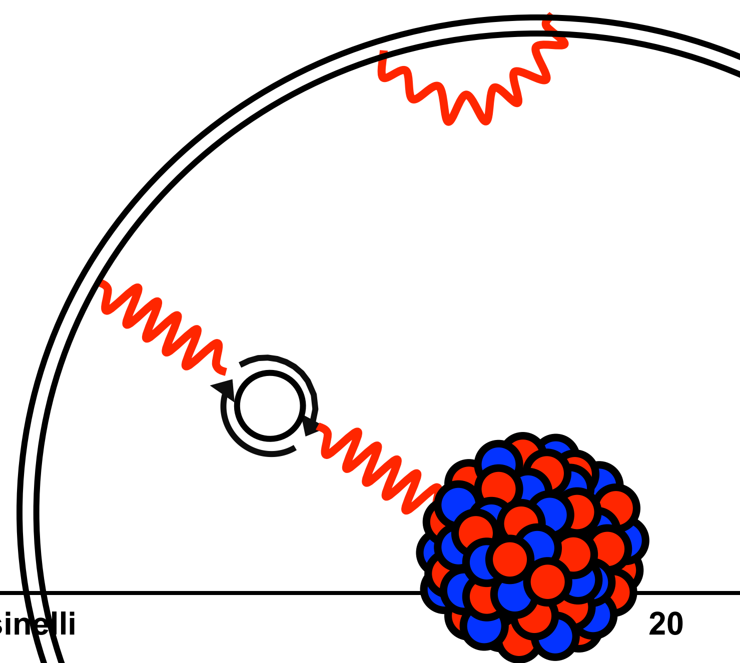
- Strong electric field

$$\mathcal{E} \sim \frac{m^2 c^3}{e\hbar}(Z\alpha)^3$$

- Small Bohr radius

$$r_n \sim \frac{\hbar n^2}{mcZ\alpha}$$





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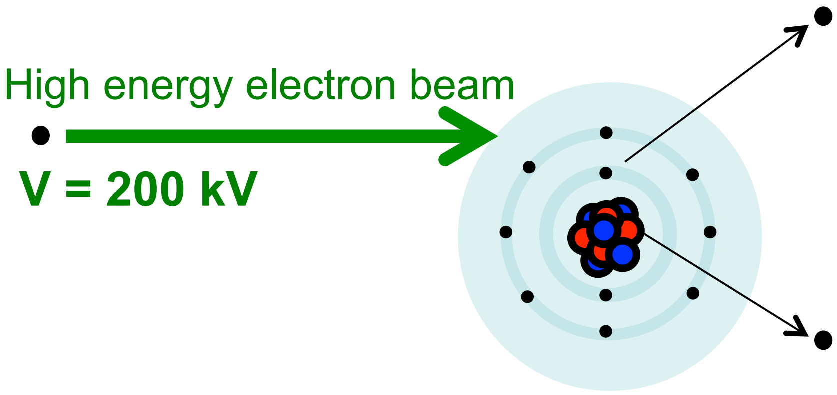
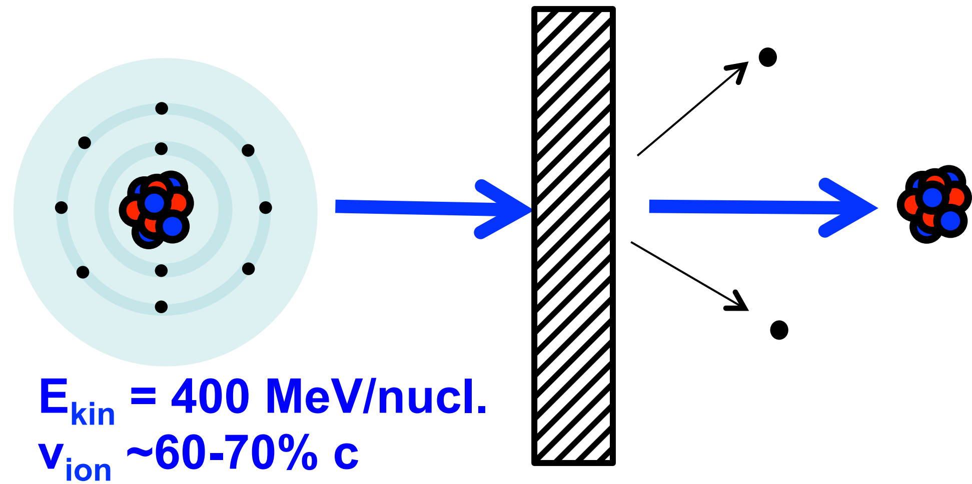
Highly charged ion production and studies

Electron impact and trapping



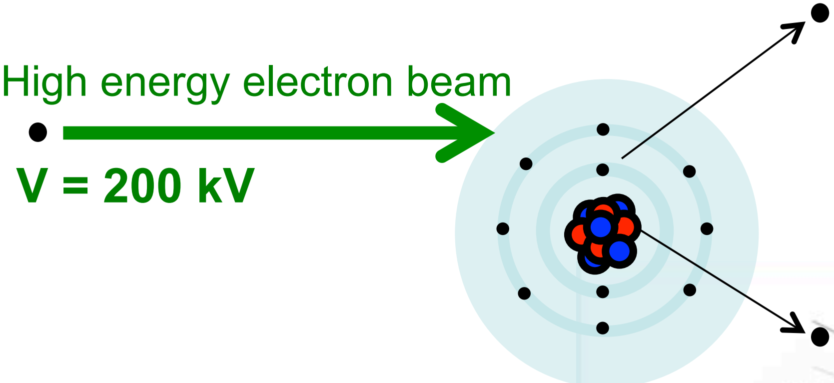
Acceleration and stripping



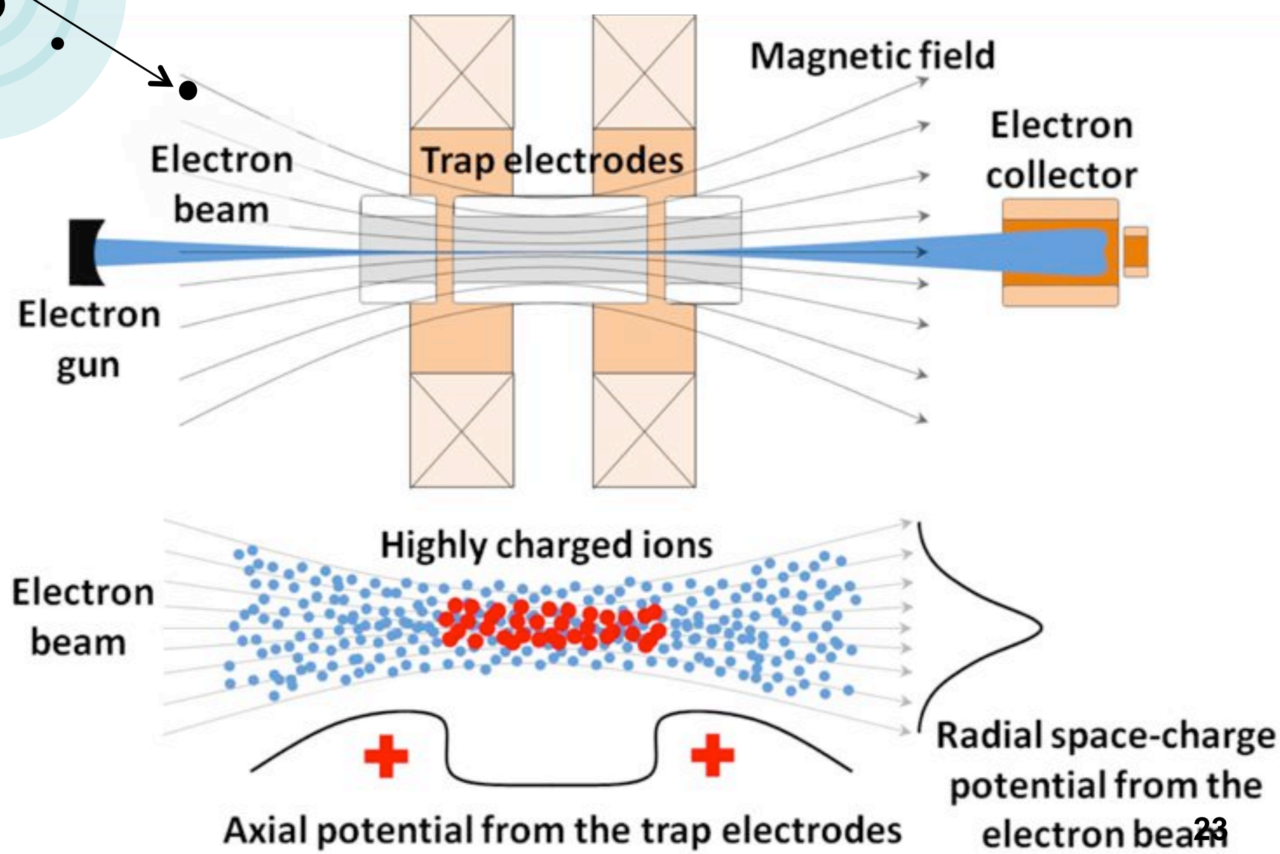
Electron impact and trapping

High energy electron beam

V = 200 kV

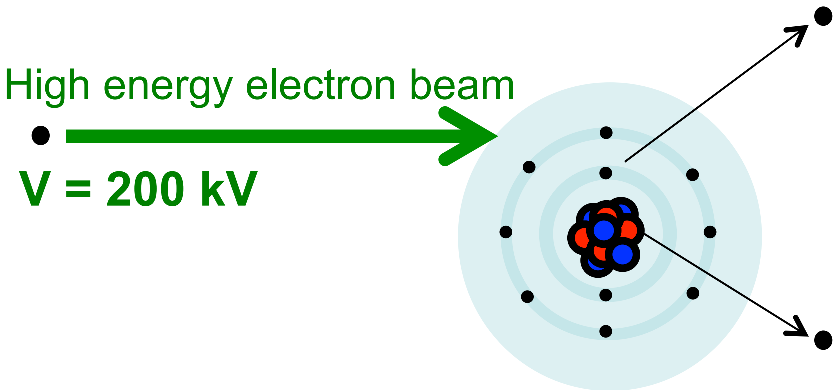


Electron Beam Ion Trap (EBIT) principle

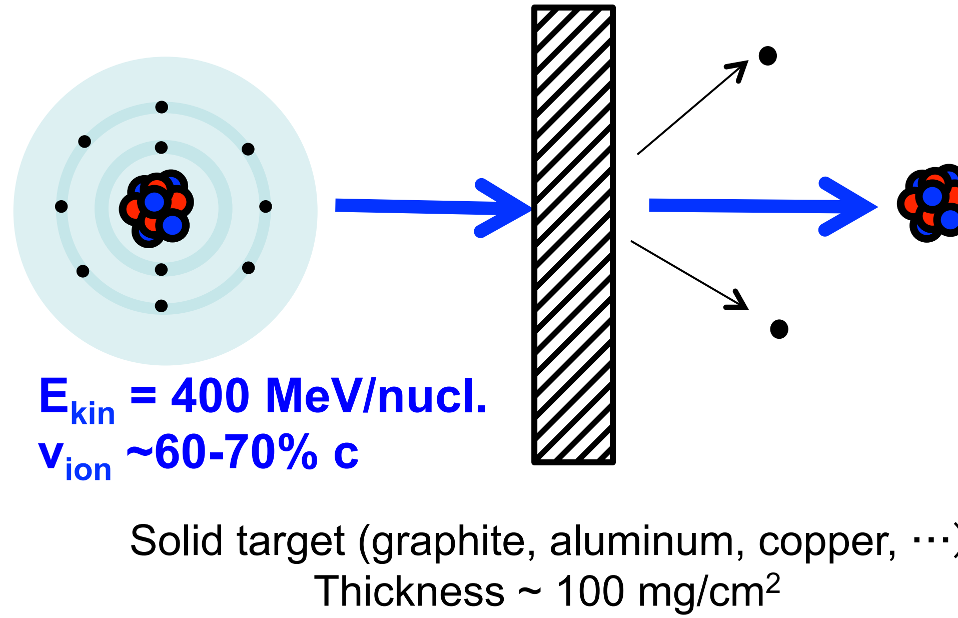


Highly charged ion production and studies

Electron impact and trapping



Acceleration and stripping

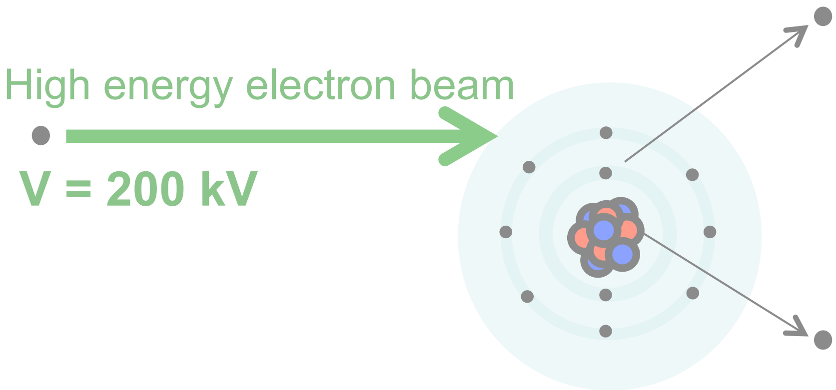


- **Max Planch Inst., Heidelberg, Germany**
- **NIST, Gaithersburg, USA**
- **⋯**

- **GSI, Darmstadt, Germany**
- **IMP, Lanzhou, China**
- **⋯**

Highly charged ion production and studies

Electron impact and trapping



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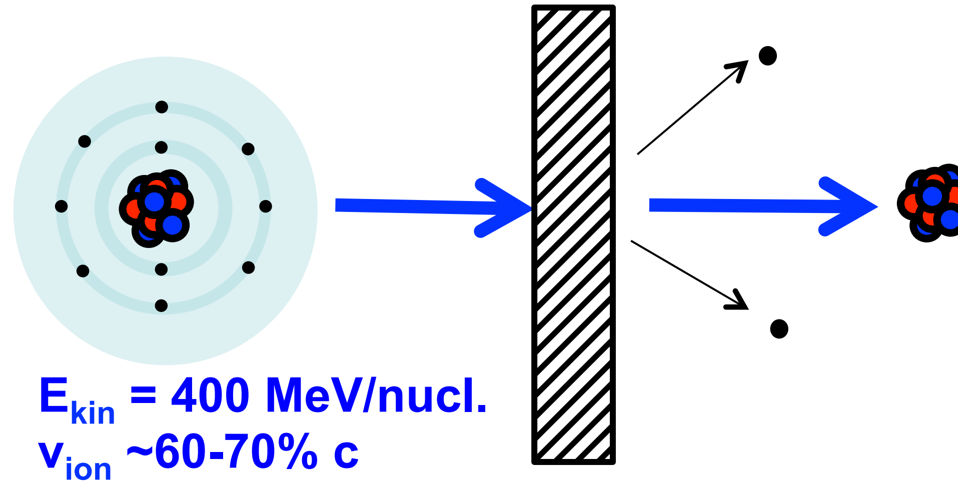
- …

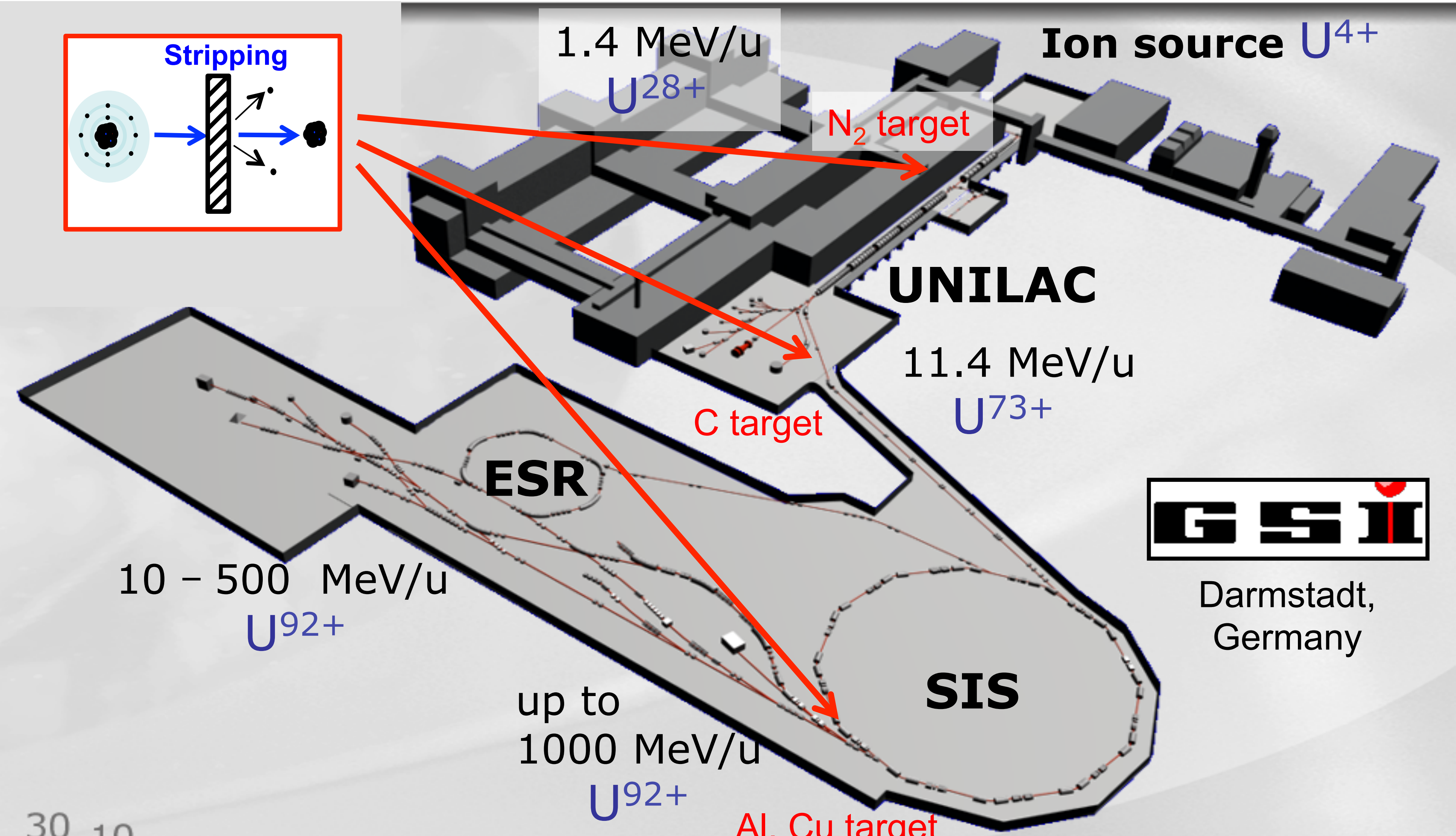
Acceleration and stripping



Solid target (graphite, aluminum, copper, …)
Thickness ~ 100 mg/cm²

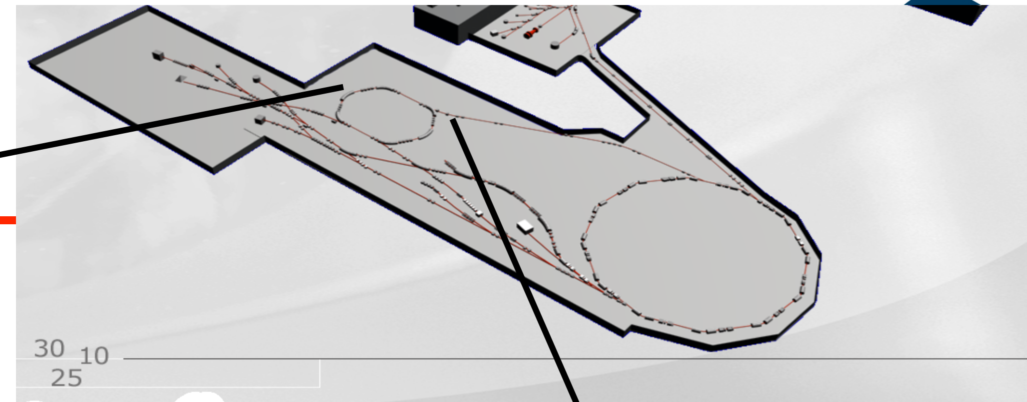
- **GSI, Darmstadt, Germany**
- IMP, Lanzhou, China
- …

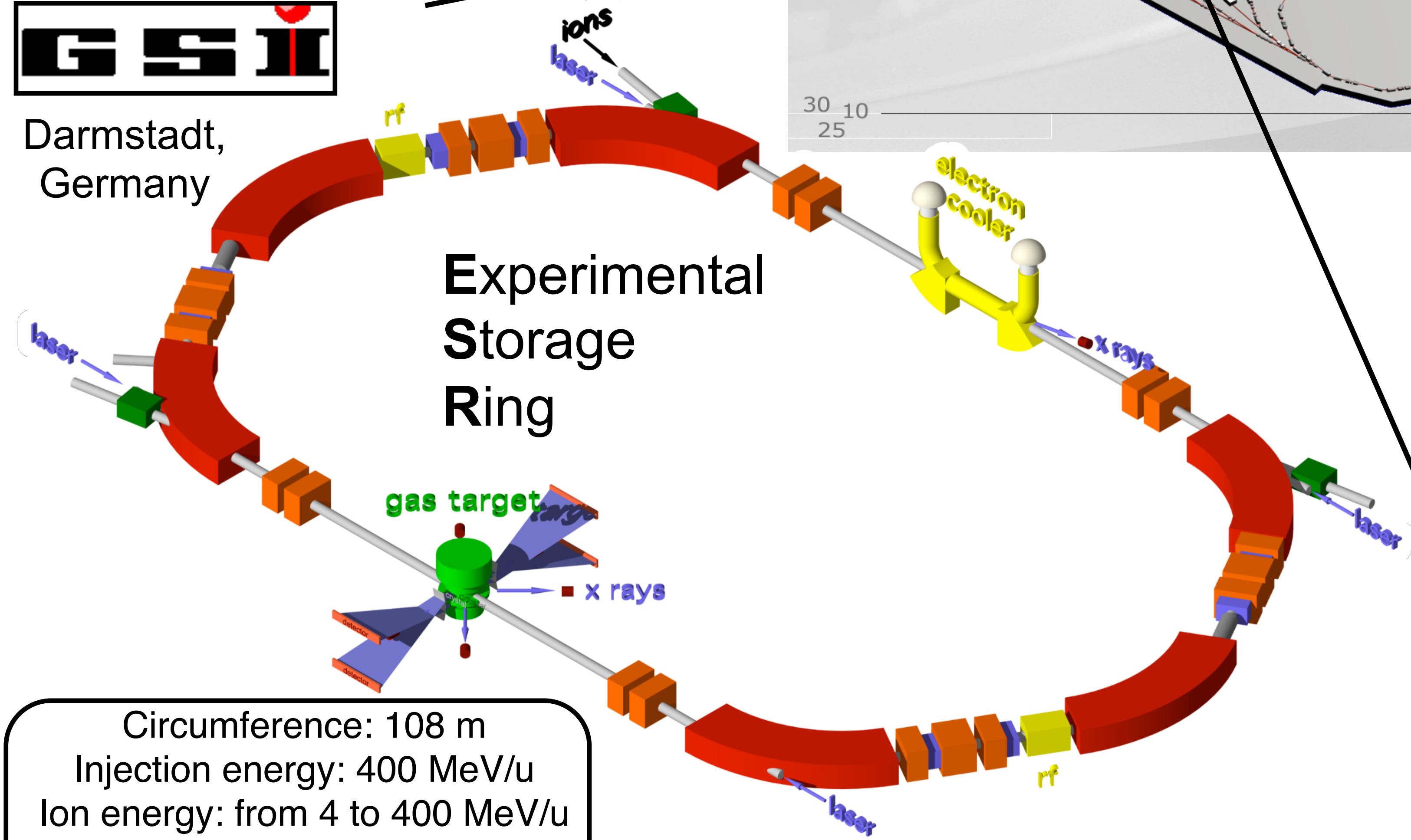
Highly charged ion production



ESR storage ring at GSI

Darmstadt, Germany

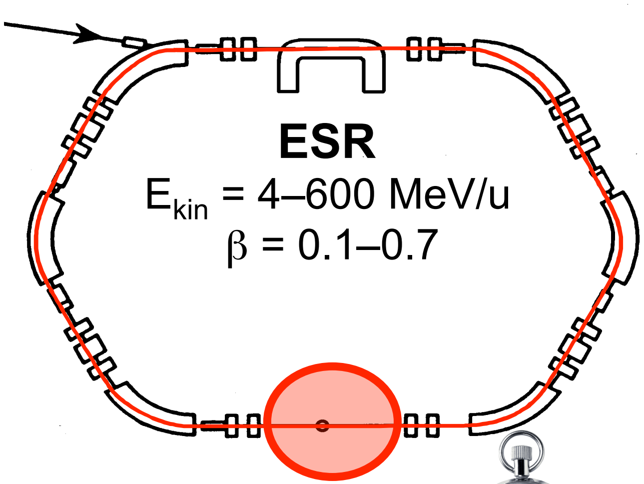




Experimental
Storage
Ring

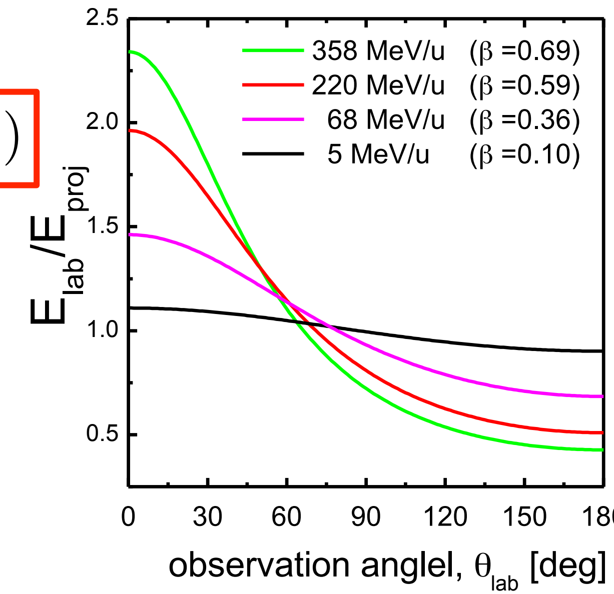
Circumference: 108 m
Injection energy: 400 MeV/u
Ion energy: from 4 to 400 MeV/u
Revolution frequency: 1 Mhz
Stored ions: ~10^8
Pressure = $10^{-10\text{–}11}$ mbar

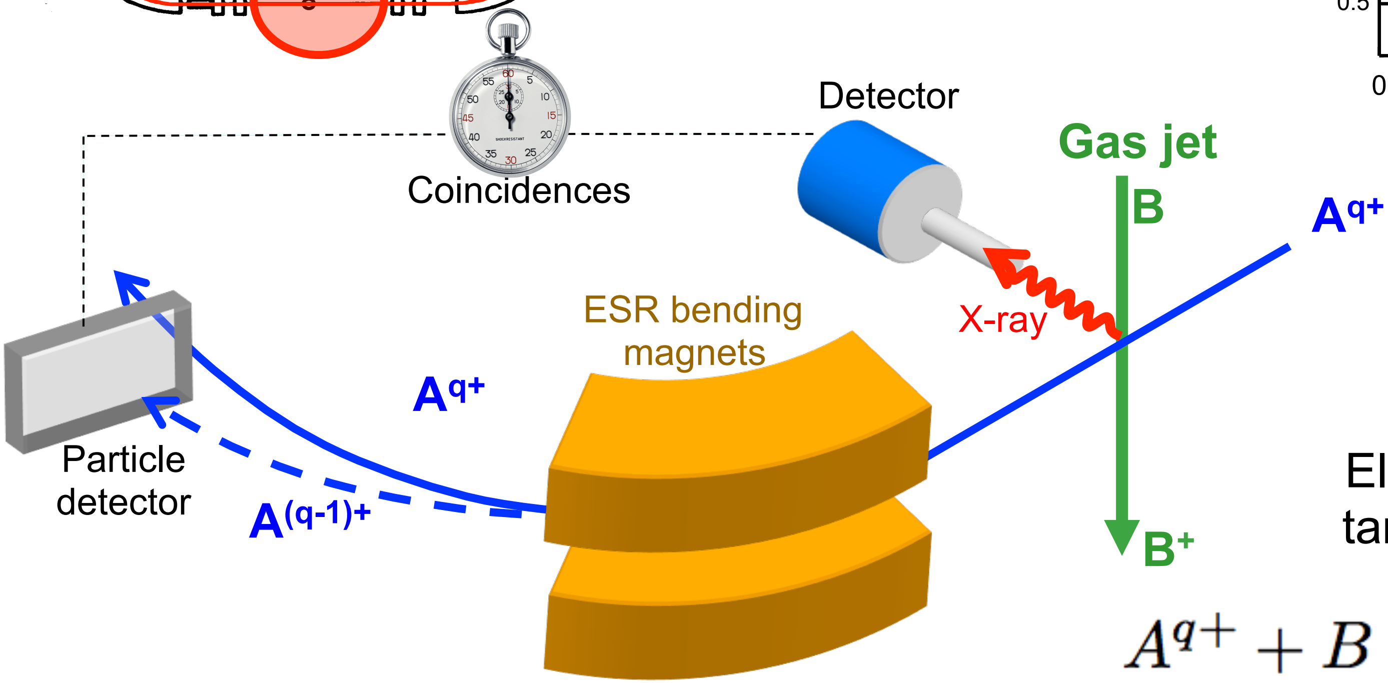
Experiments at the gas jet-target



Relativistic Doppler shift

$$E_{\rm ion} = E_{\rm lab}\gamma(1-\beta\cos\theta)$$



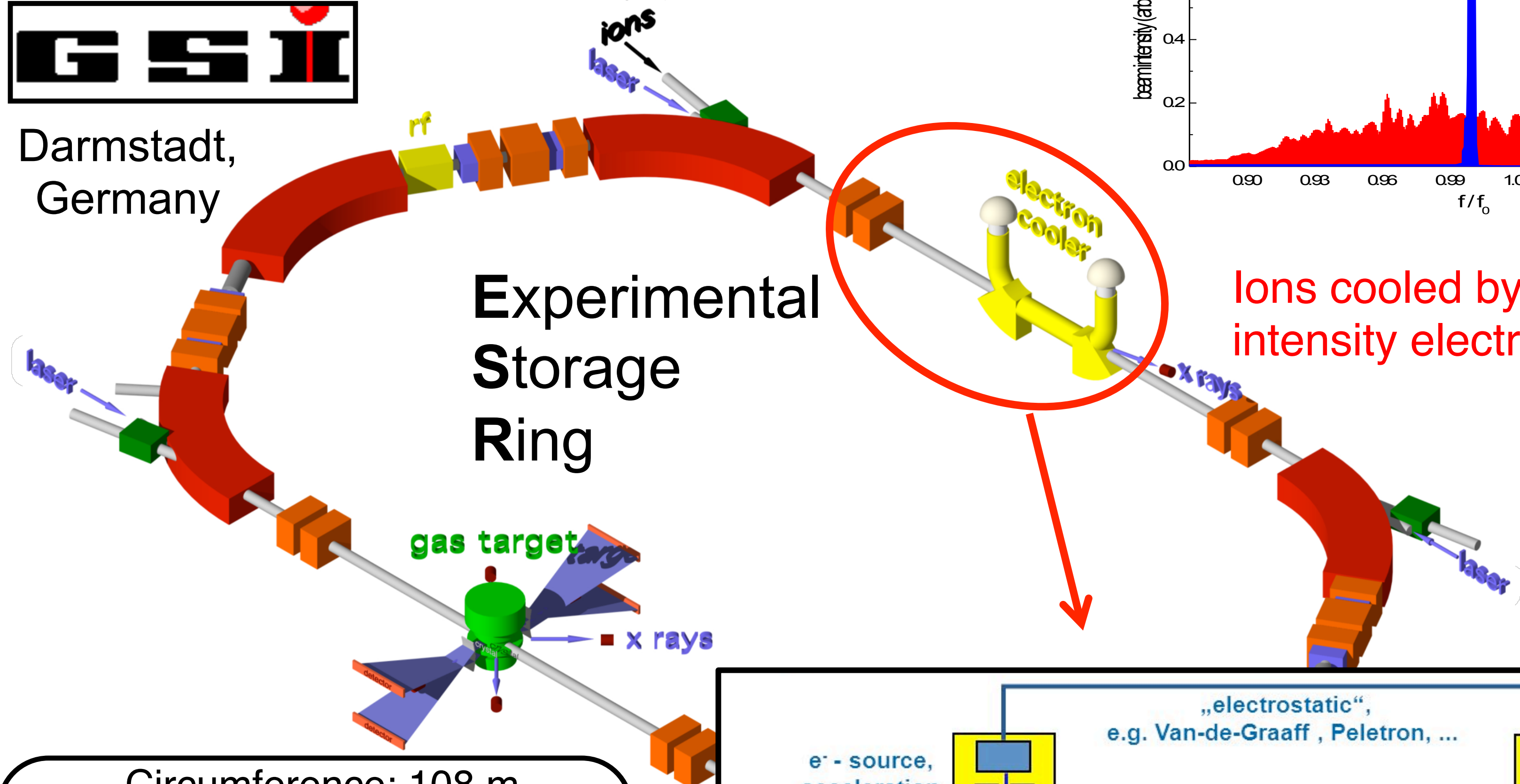


Electron transfer from the target atom to the fast ion

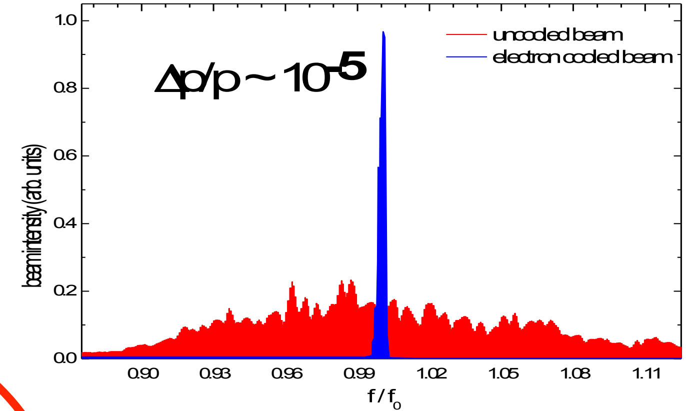
$$A^{q+} + B \rightarrow A^{(q-1)+} + B^{+}$$

ESR storage ring at GSI

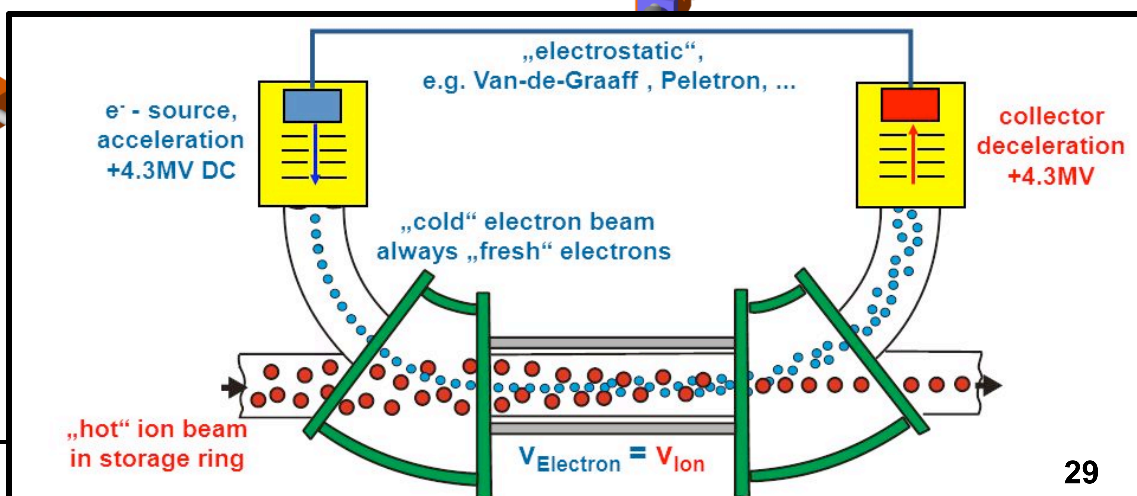
Darmstadt, Germany



Experimental
Storage
Ring

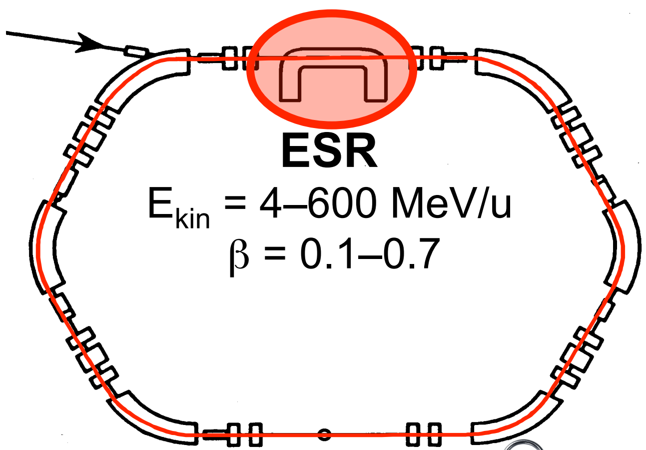


Ions cooled by an high intensity electron beam



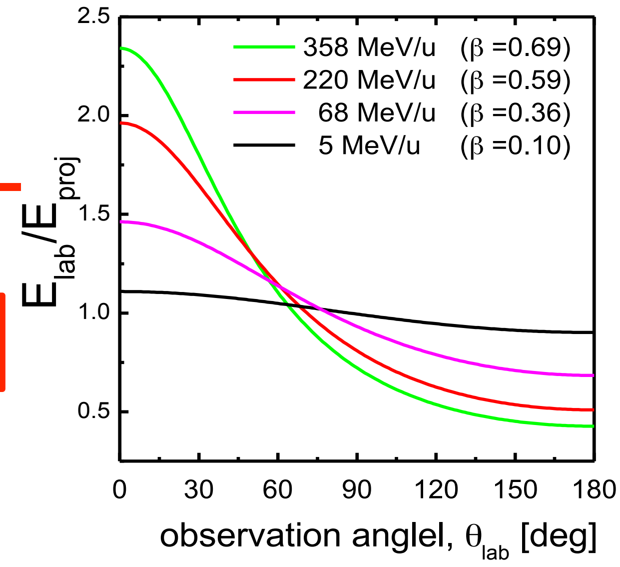
Circumference: 108 m
Injection energy: 400 MeV/u
Ion energy: from 4 to 400 MeV/u
Revolution frequency: 1 Mhz
Stored ions: ~10^8
Pressure = 10^{-10-11} mbar

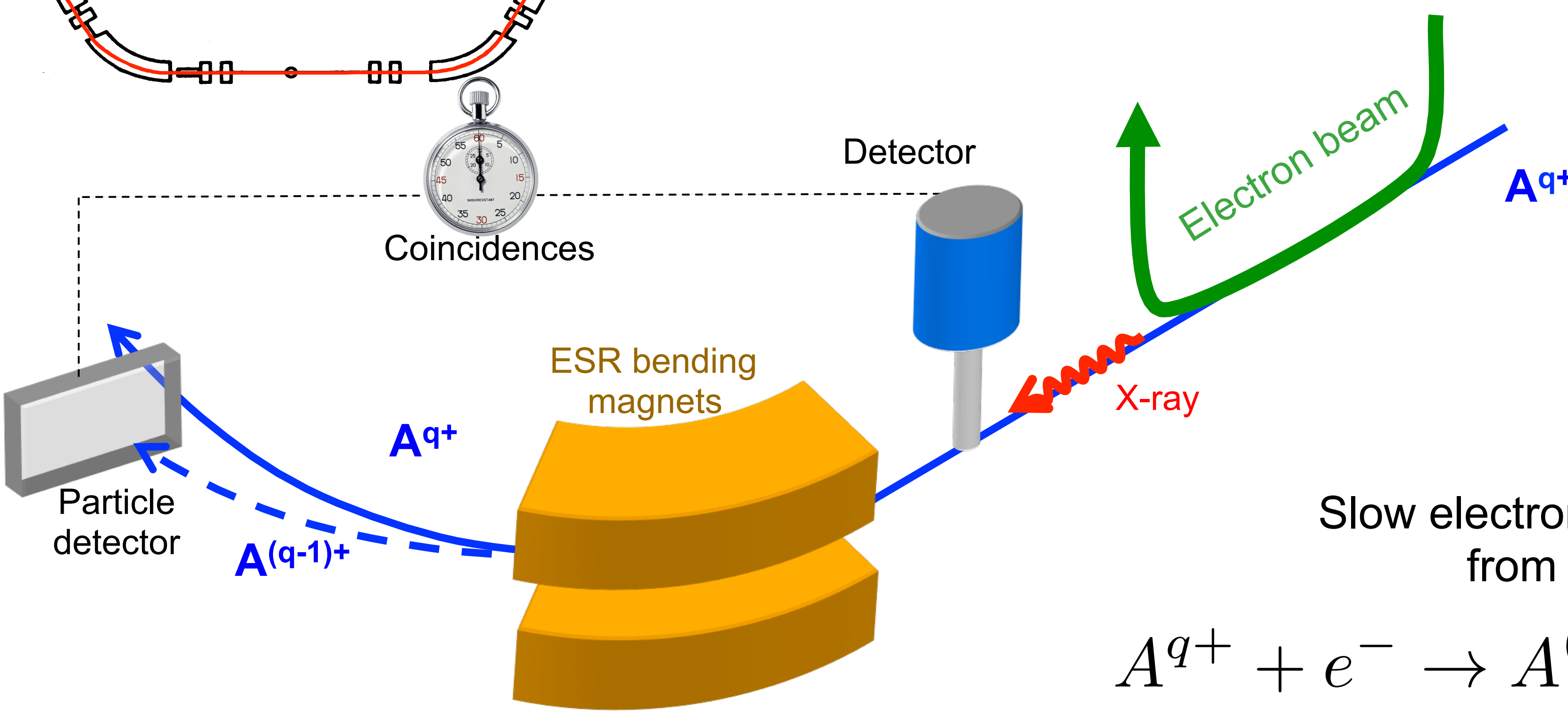
Experiments at e-cooler



Relativistic Doppler shift

$$E_{\text{ion}} = E_{\text{lab}}\gamma(1-\beta\cos\theta)$$





Slow electron captured from thefast ion

$$A^{q+} + e^- \rightarrow A^{(q-1)+}$$

Summary

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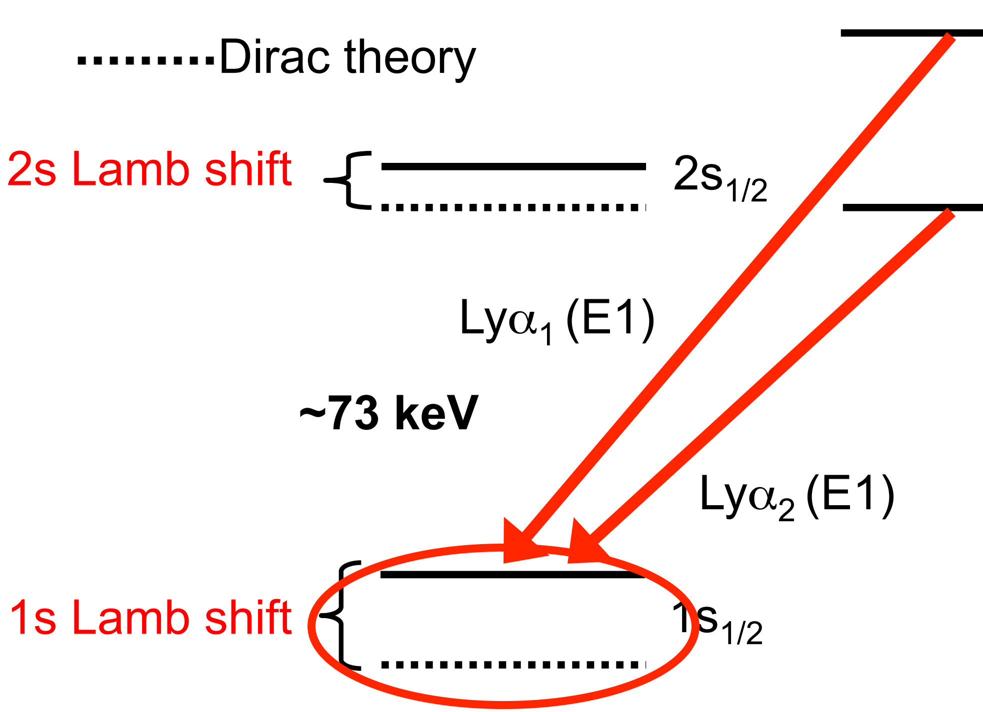
Lamb shift of H-like Uranium

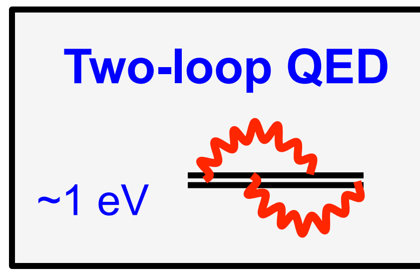


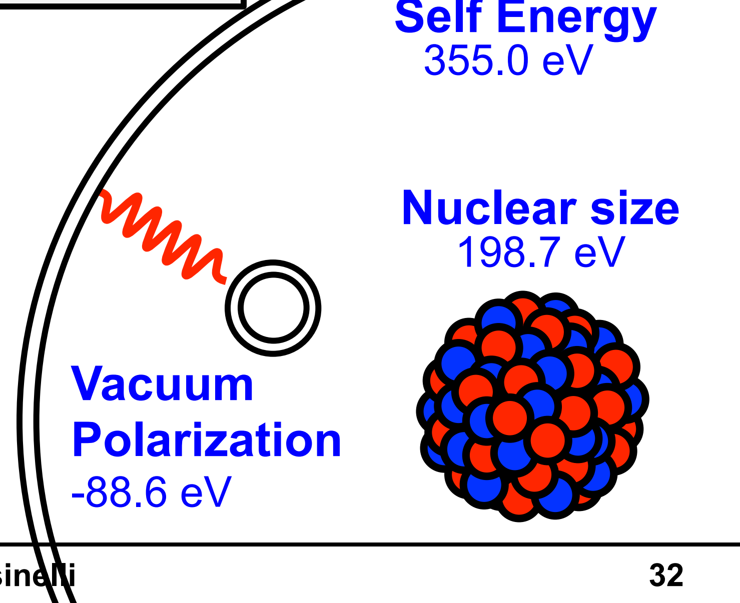
QED corrections

$$\Delta E \sim Z^4/n^3$$

Z: nuclear charge
n: principal quantum number

Important for s-states

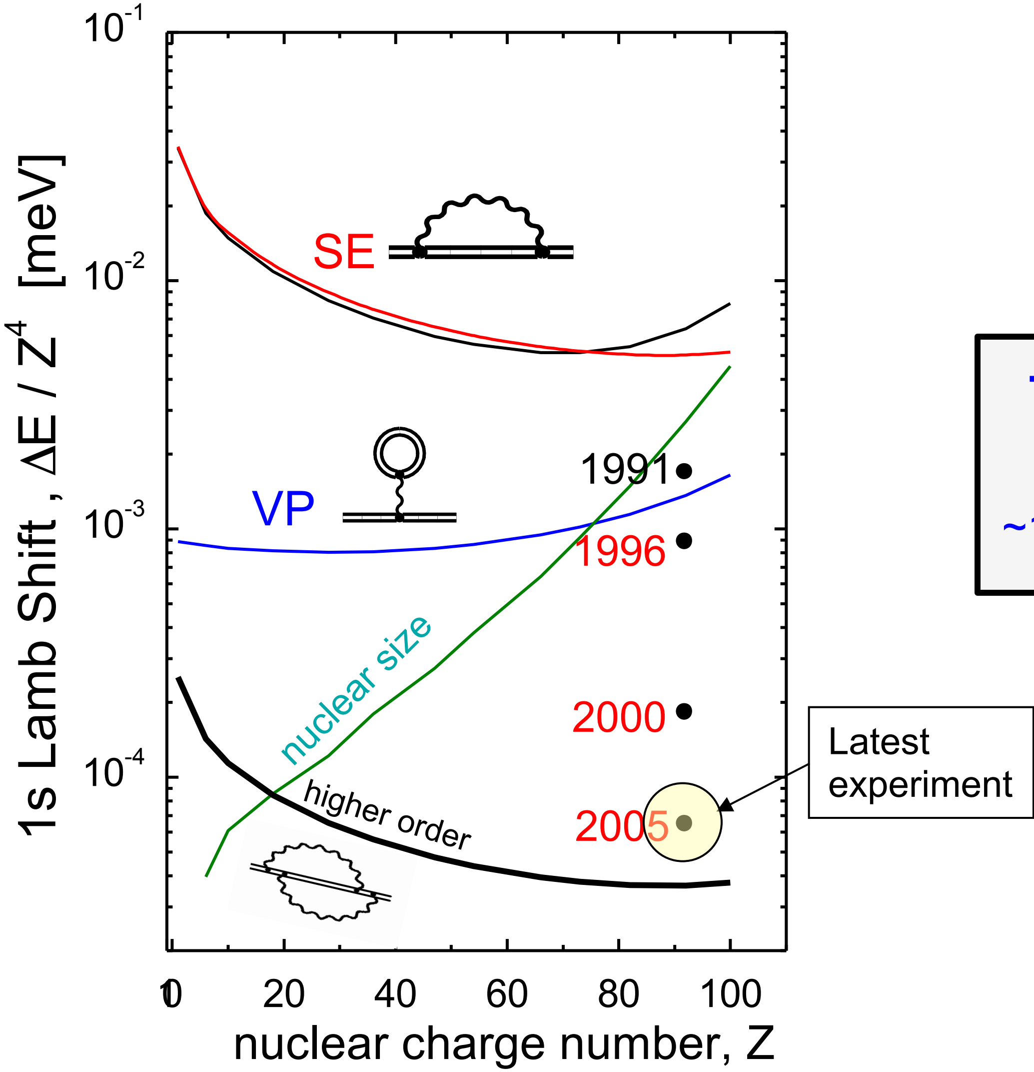




Theory: 463.8 ± 0.5 eV

V.A. Yerokhin *et al.*, J. Phys. Chem. Ref. Data **44**, 033103 (2015).

Lamb shift of H-like Uranium



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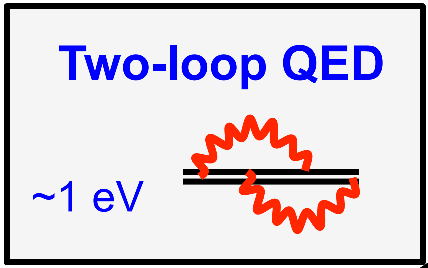
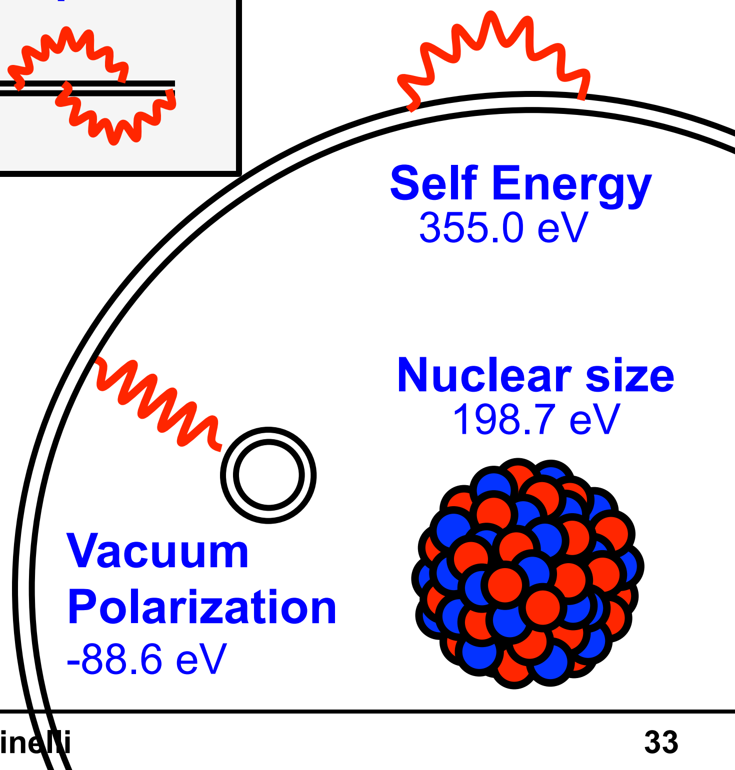
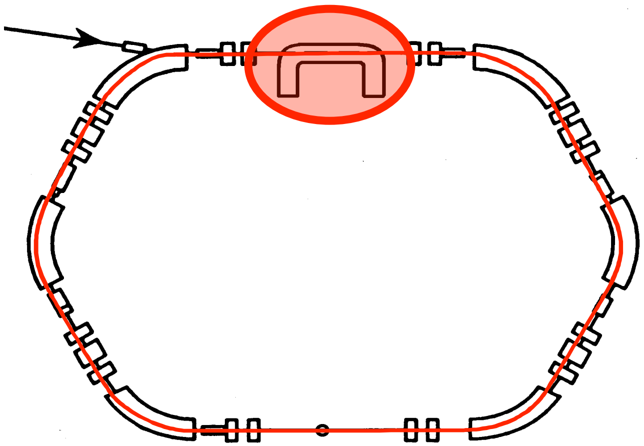
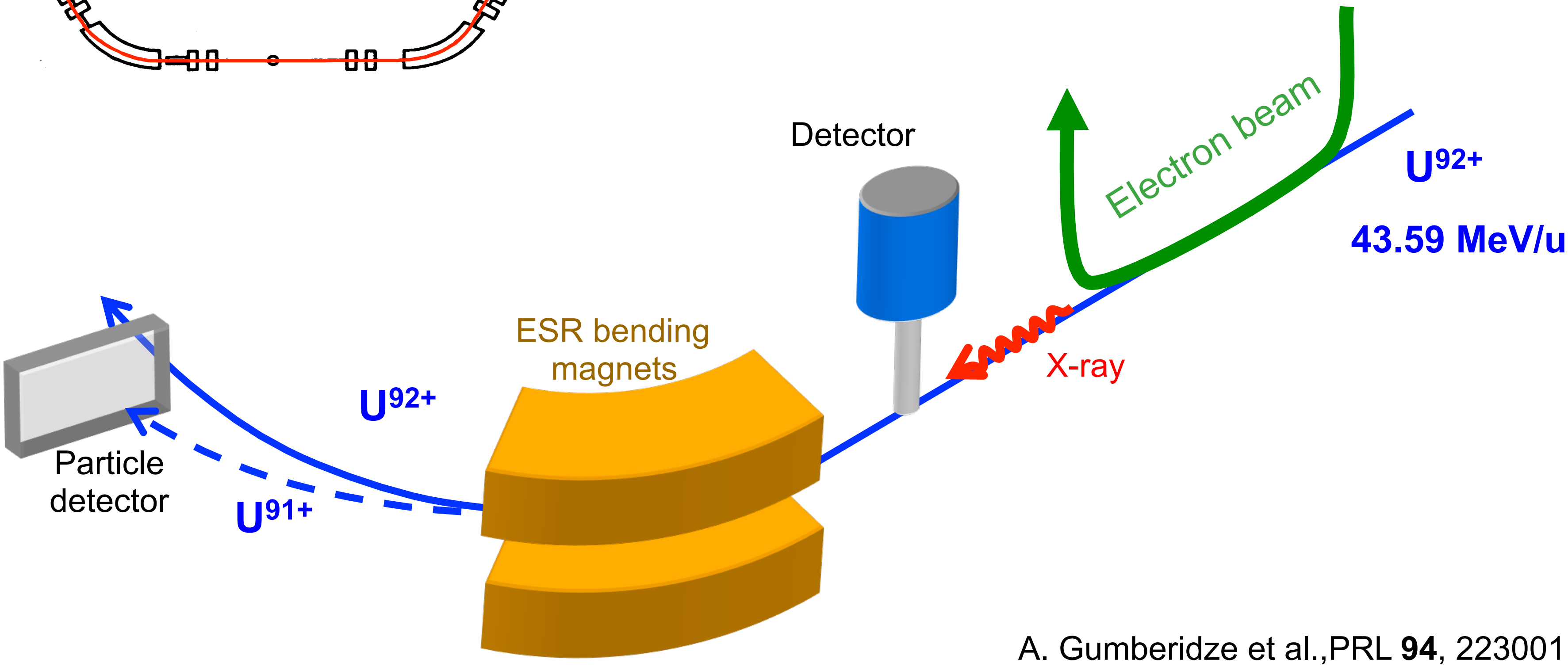




Lamb shift of H-like Uranium

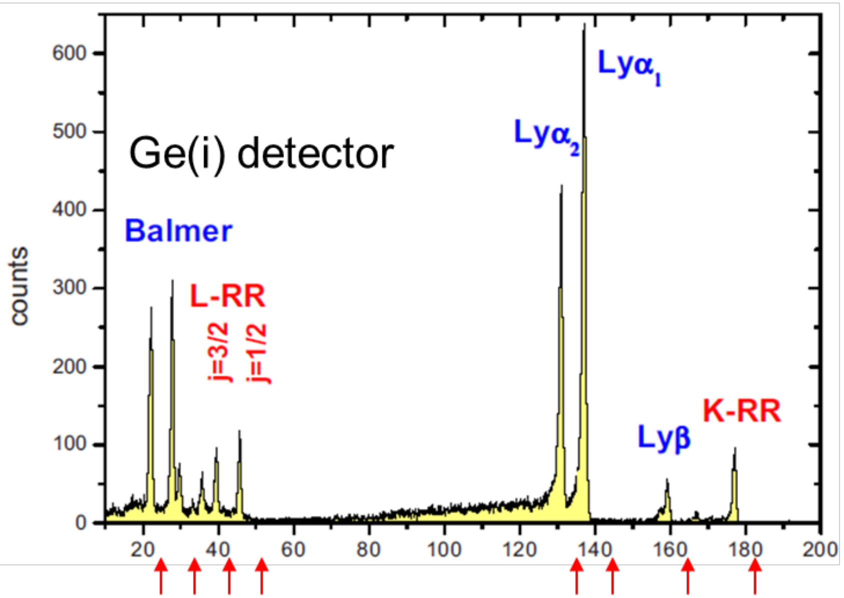




A. Gumberidze et al.,PRL **94**, 223001 (2005)

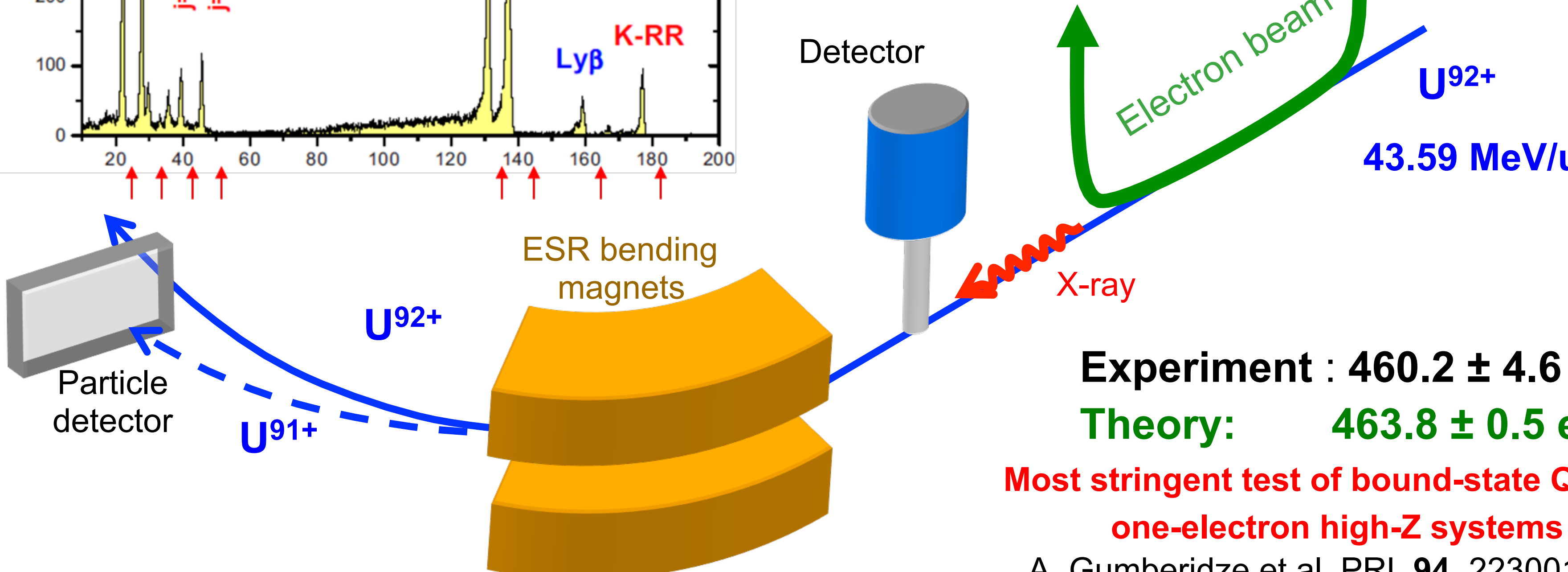
Lamb shift of H-like Uranium

Many lines providing intrinsic energy calibration and redundant data.



- **decelerated ions**
- **close to 0-deg observation geometry**
- **standard germanium detector**

$$E_{\text{ion}} = E_{\text{lab}}\gamma(1-\beta\cos\theta)$$



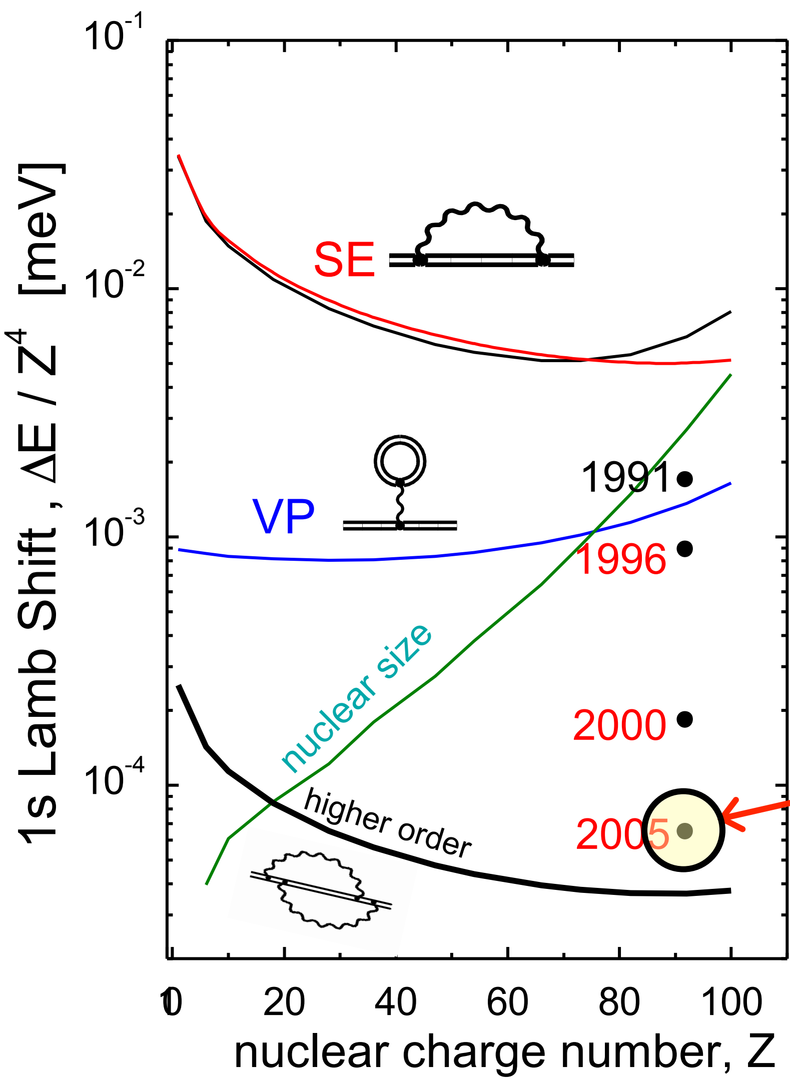
Experiment : **460.2 ± 4.6 eV**

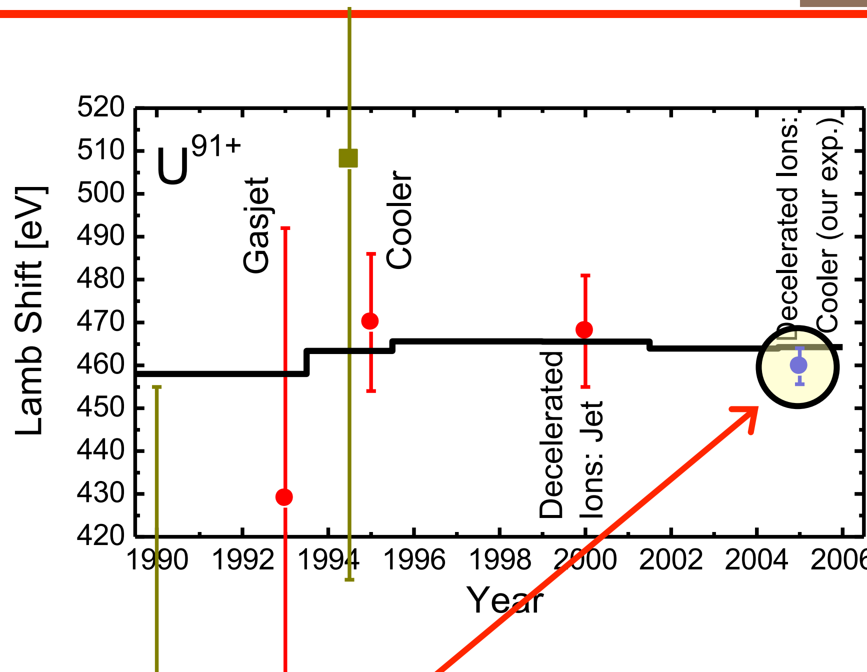
Theory: 463.8 ± 0.5 eV

Most stringent test of bound-state QED for one-electron high-Z systems

A. Gumberidze et al.,PRL **94**, 223001 (2005)

Lamb shift of H-like Uranium





Latest experiment

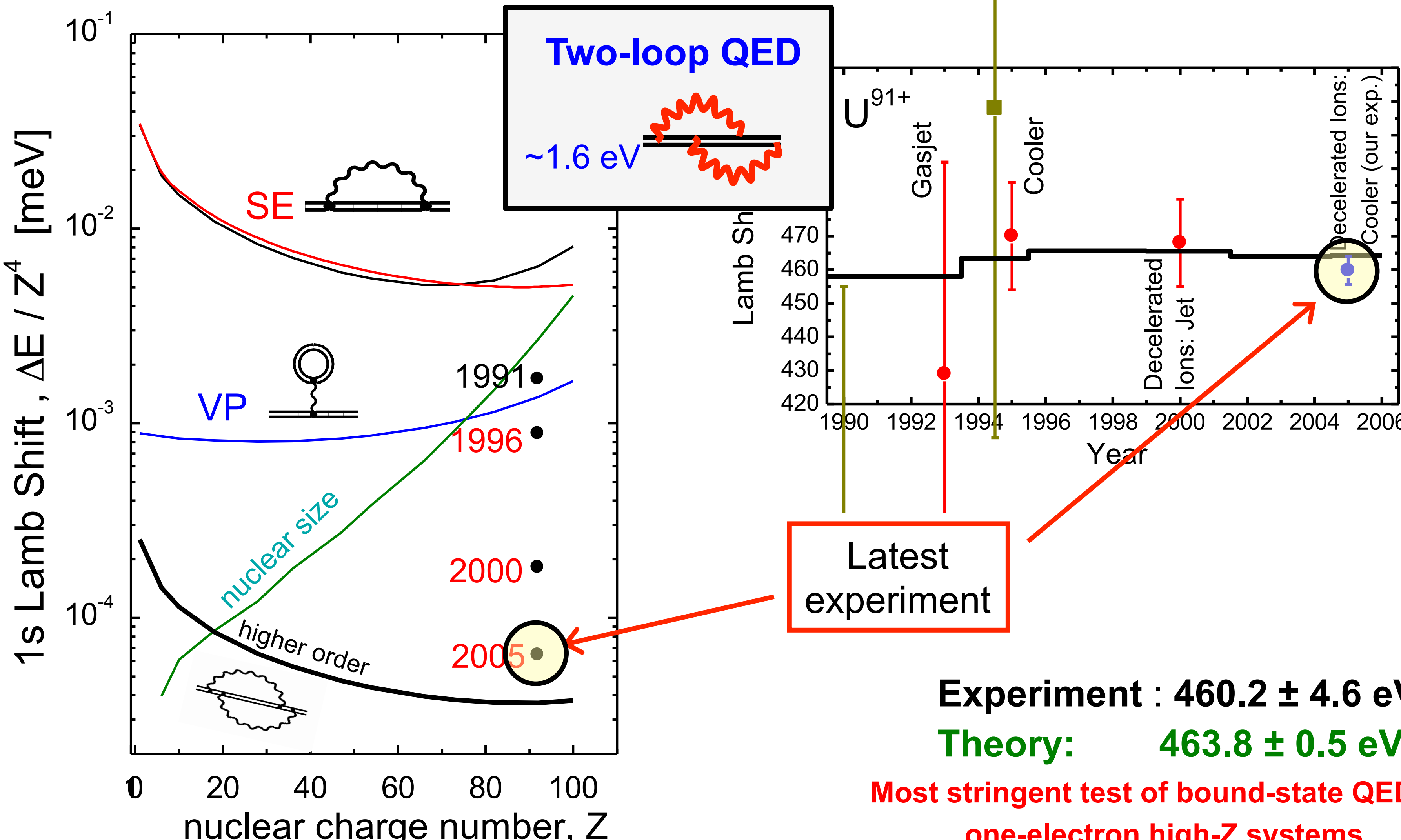
Experiment : **460.2 ± 4.6 eV**

Theory: 463.8 ± 0.5 eV

Most stringent test of bound-state QED for one-electron high-Z systems

A. Gumberidze et al.,PRL **94**, 223001 (2005)

Lamb shift of H-like Uranium



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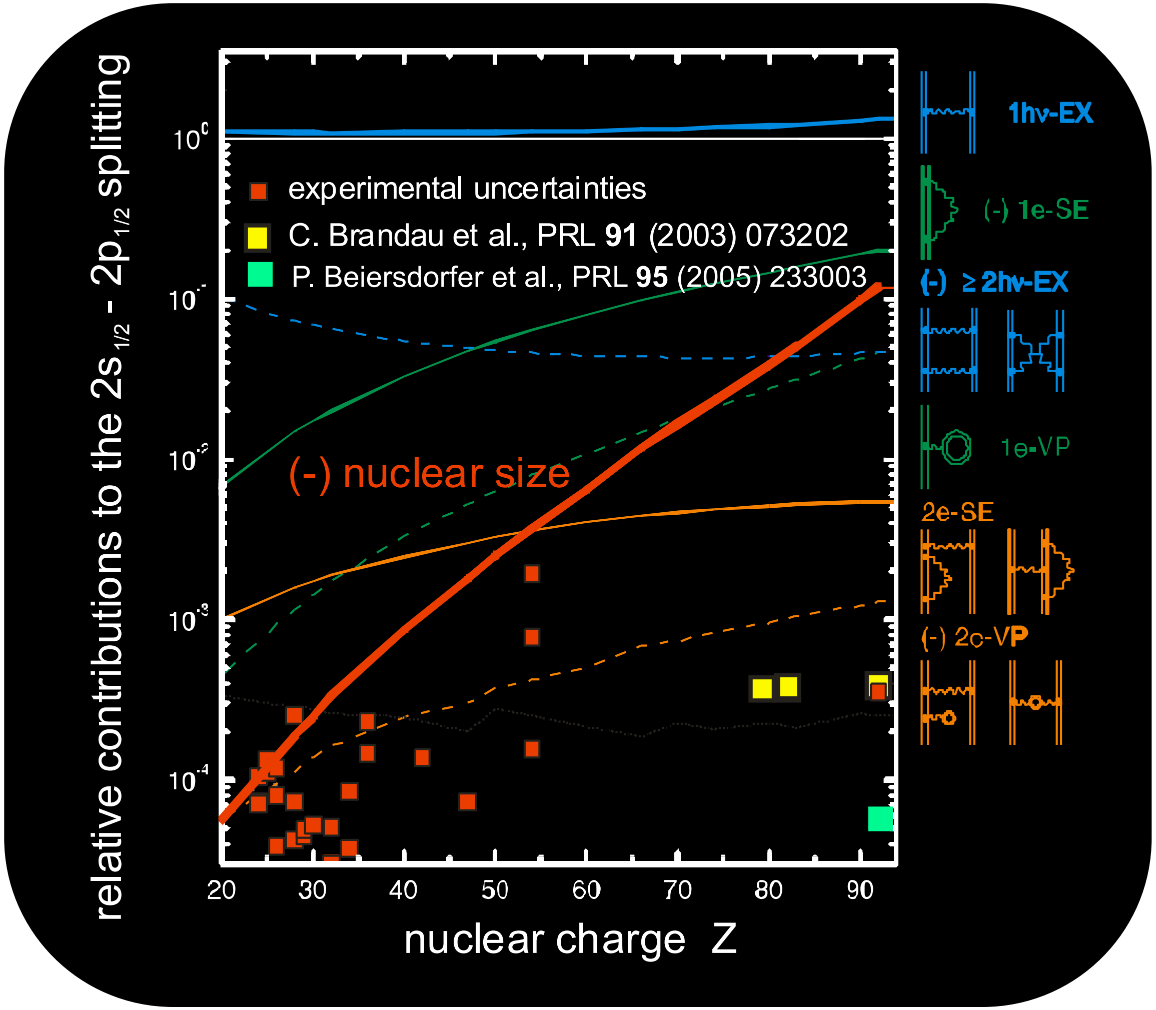
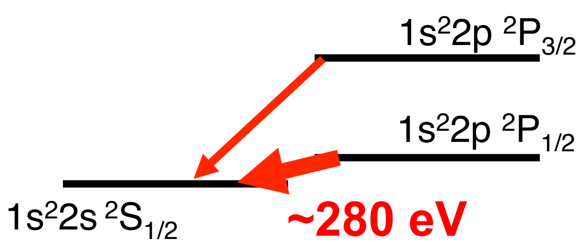
Most stringent test of bound-state QED for one-electron high-Z systems

A. Gumberidze et al.,PRL **94**, 223001 (2005)

Most precise spectroscopy tests in Li-like systems



Li-like Uranium (3 el.)



XUV spectroscopy

Detailed knowledge about the nucleus is vital for strong field QED studies (nuclear size but also nuclear structure ⇒ nuclear polarization)

Summary

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  - **Vacuum decay experiment**
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  - Pionic hydrogen and deuterium spectroscopy
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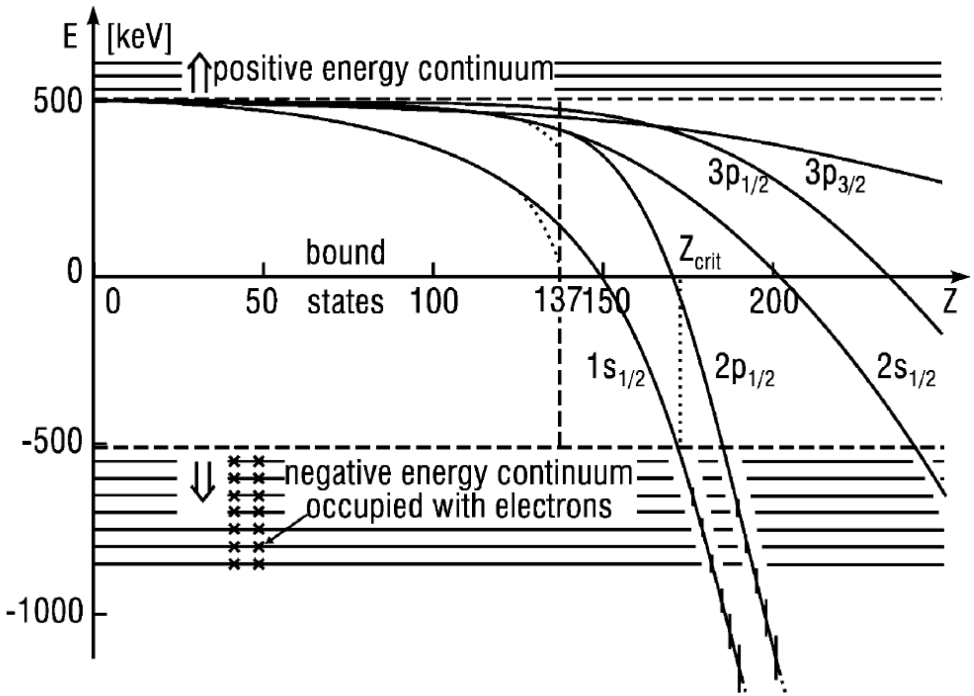
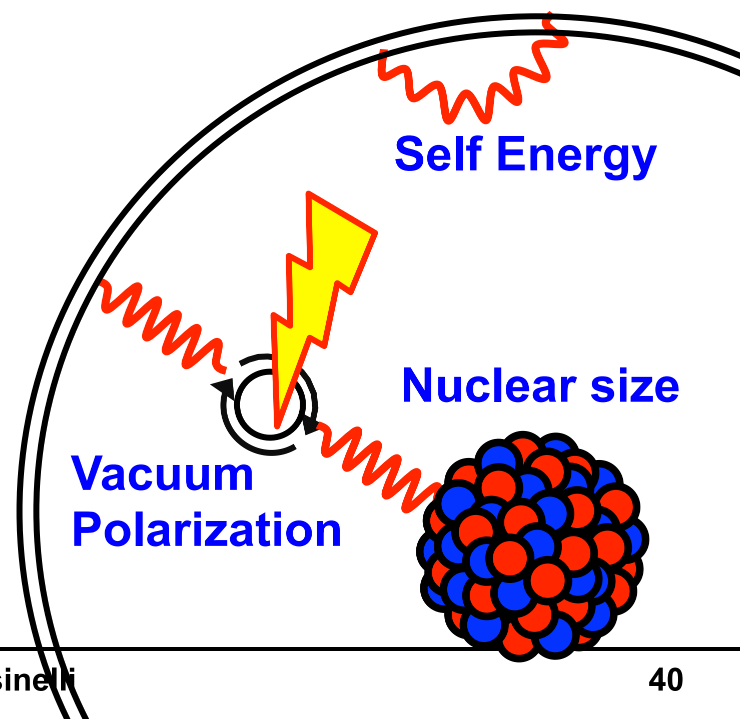
Supercritical fields

Dirac equation: $E_{1s} = mc^2\sqrt{1-(Z\alpha)^2}$

Z > 1/α = 137 → electron/positron pair creation

Finite nucleus size → Z_{crit} = 173





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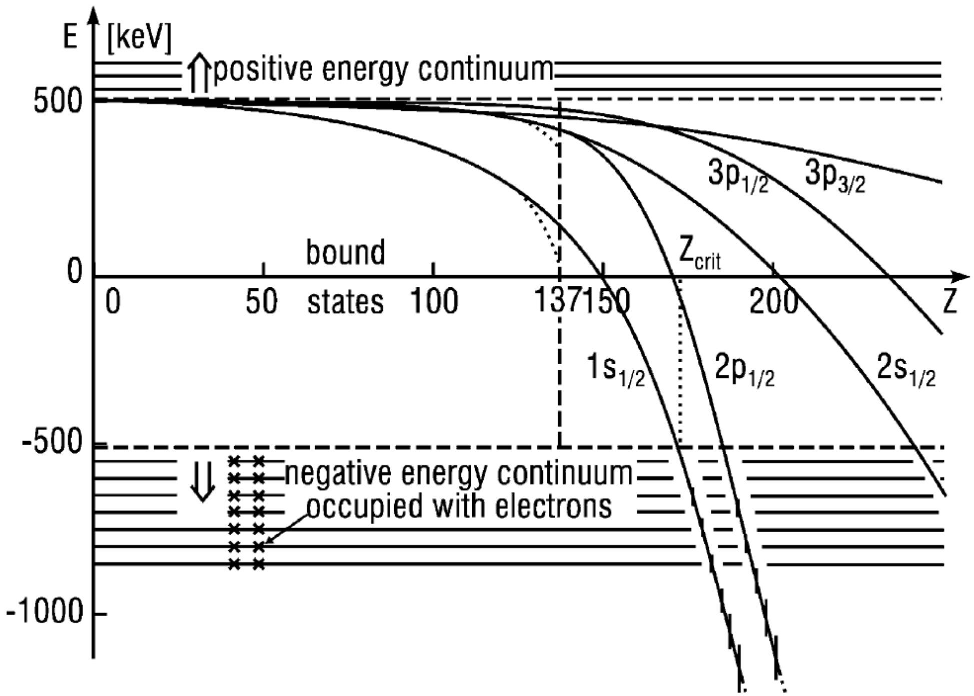
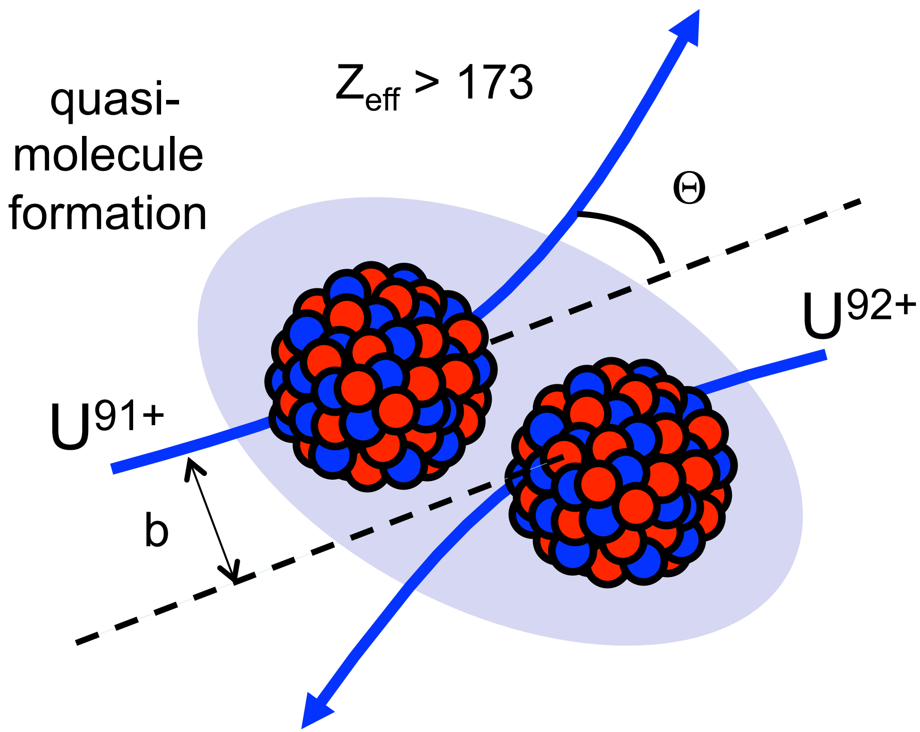
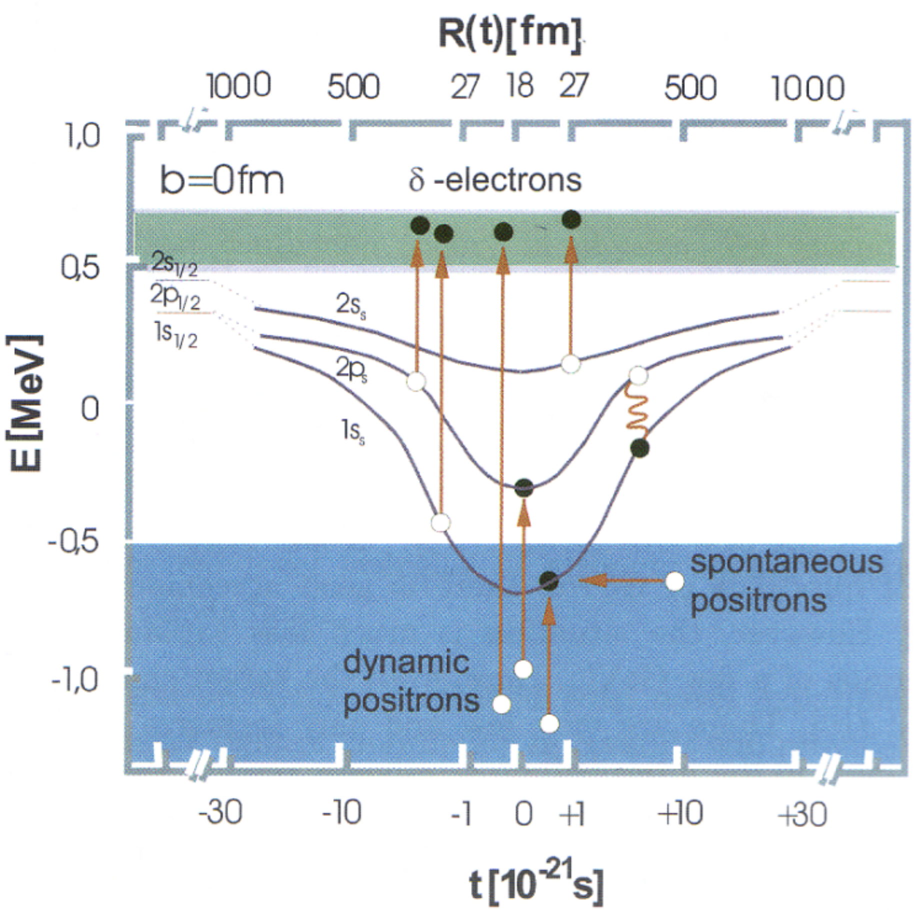
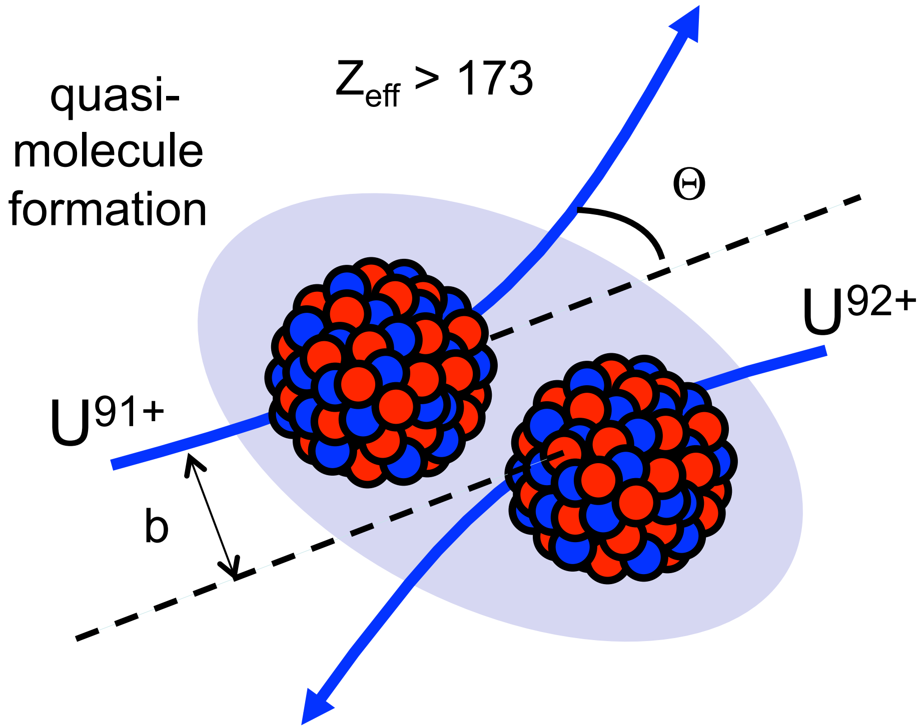




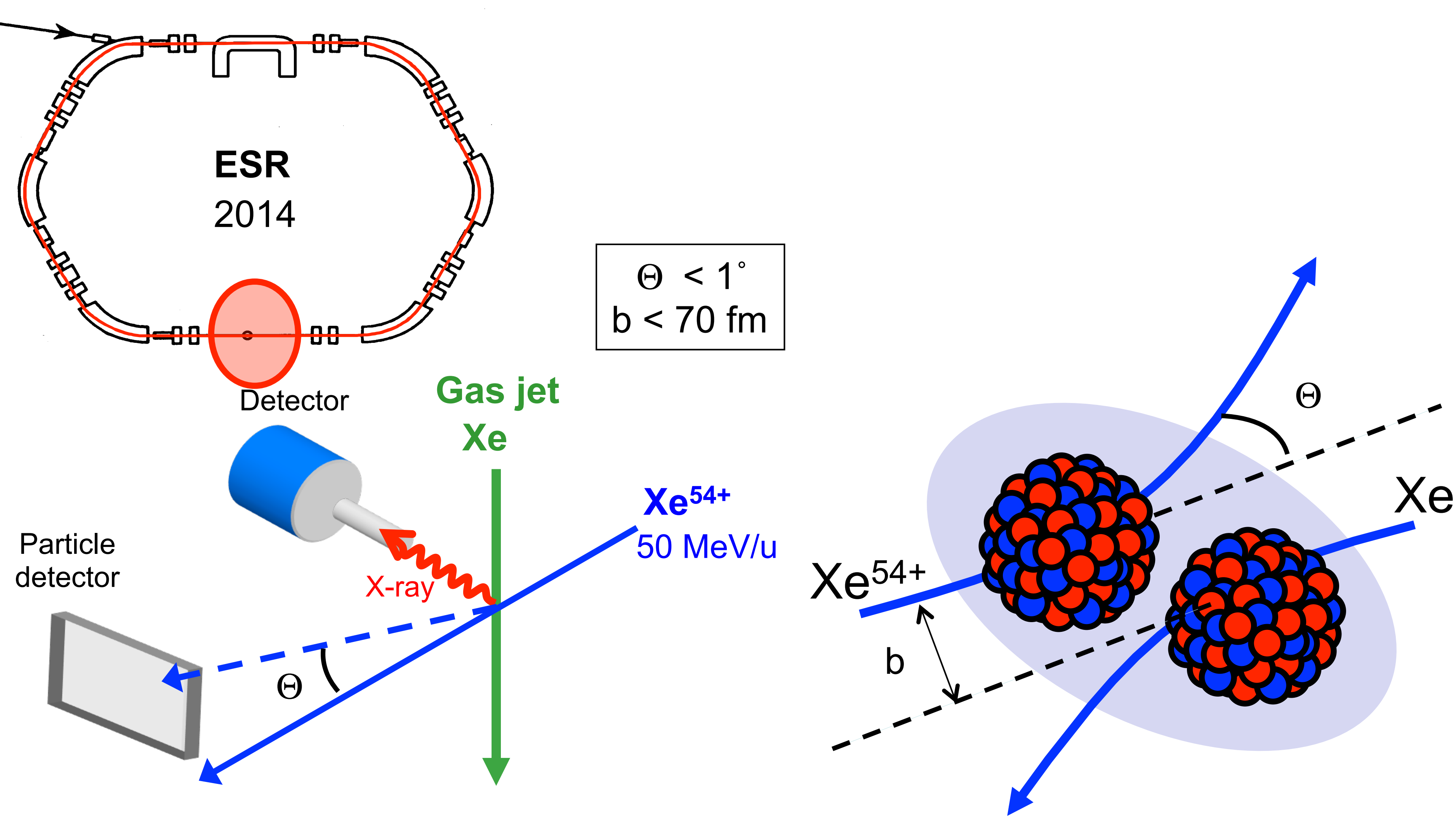
Supercritical Fields:
formation of super heavy quasi-molecules



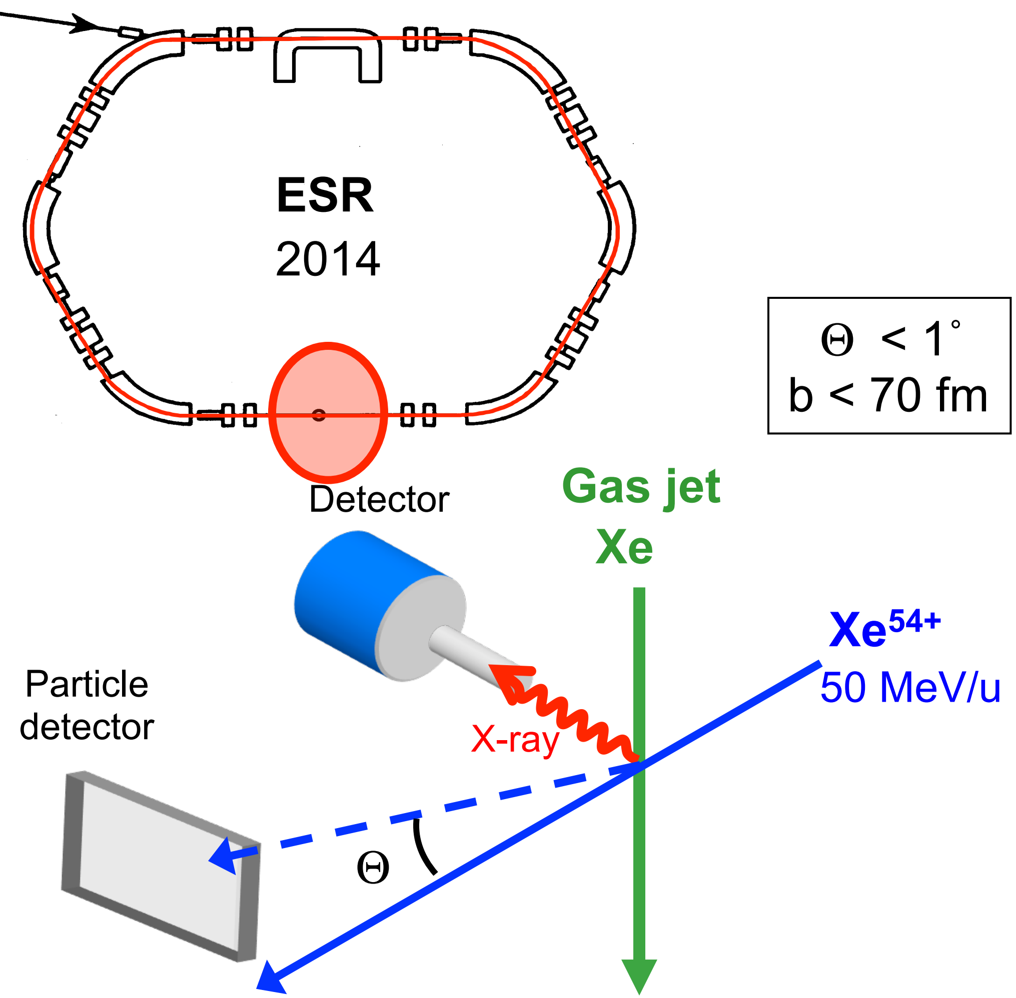
Slow ion – ion collision
~ 5 MeV/u



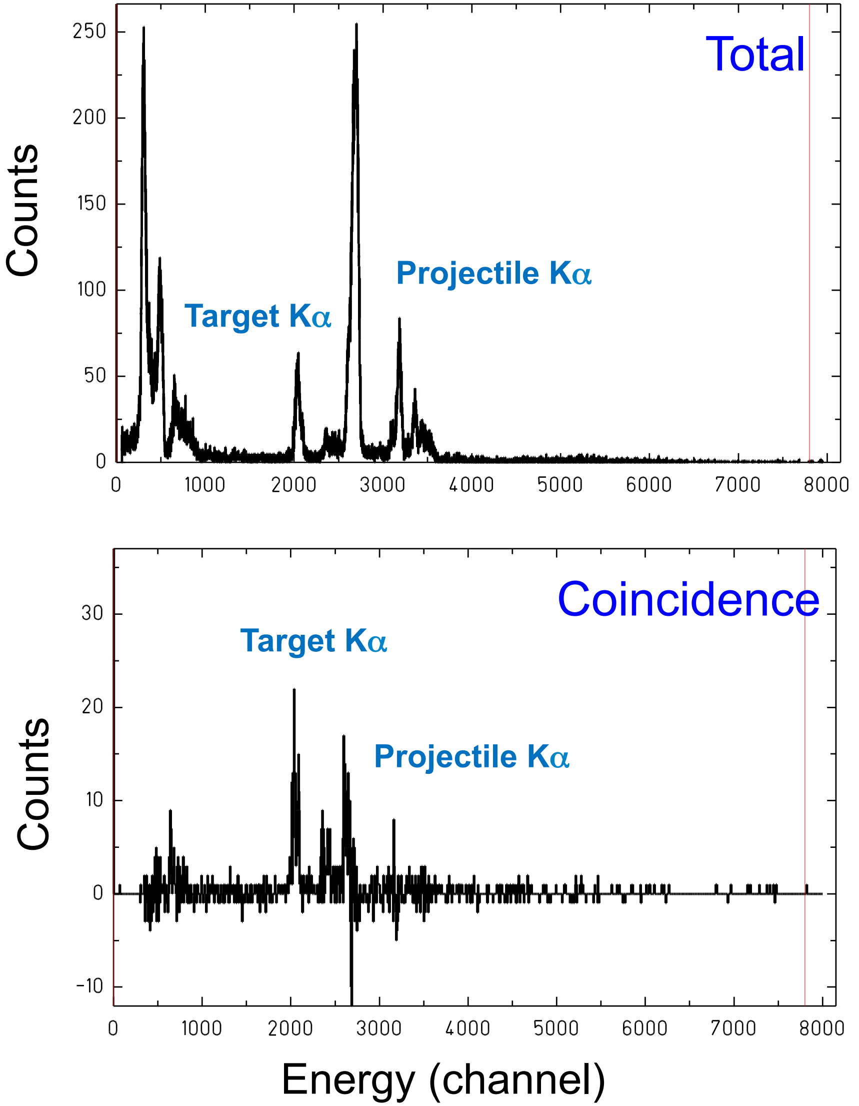
First steps to supercritical fields



First steps to supercritical fields



Θ < 1°
b < 70 fm



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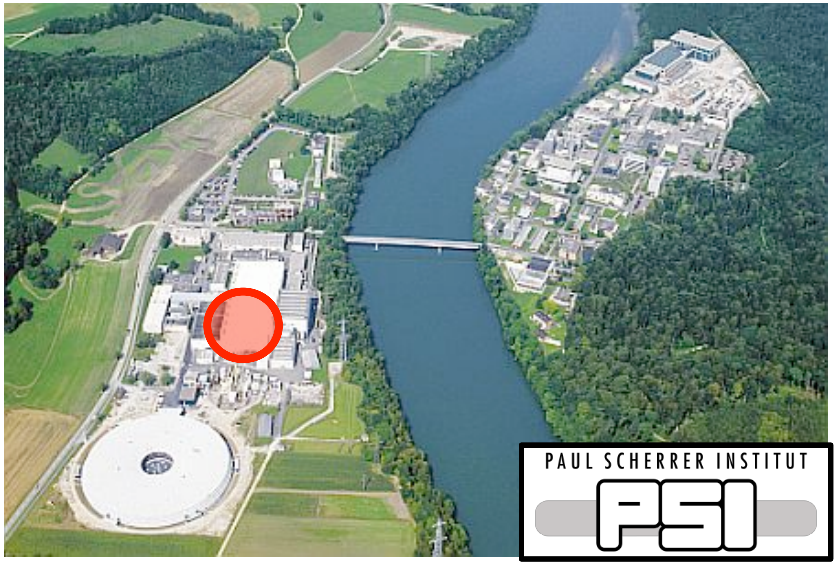
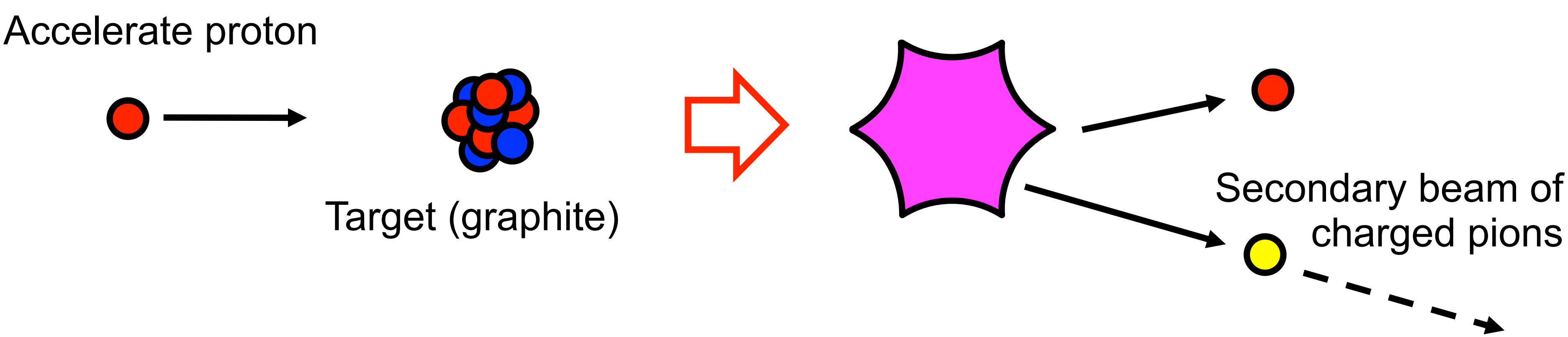
Pion beam production



Production at the Paul Scherrer Institut (Villigen, Switzerland)

- Proton beam : E_{kin}=590 MeV/c, I=1.9 mA
- Graphite target

- 10^8 pions/sec, E_{kin}=110 MeV/c

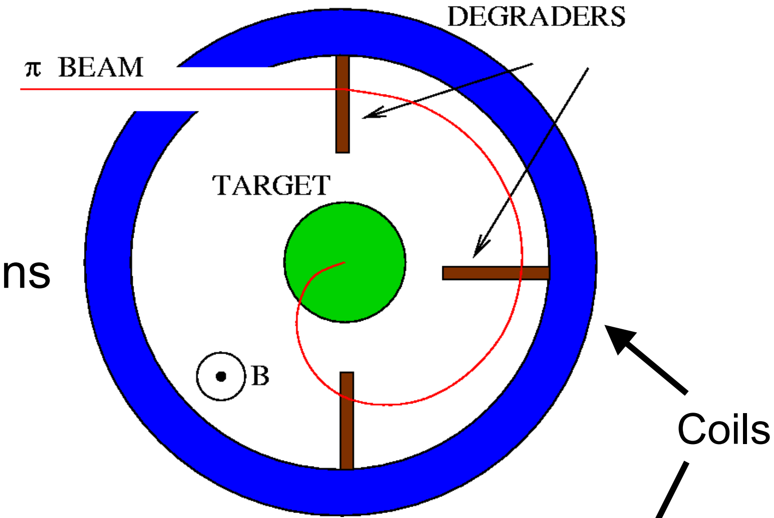


Pionic and muonic atoms production

- Cyclotron trap to stop the pions:
  - strong magnetic field (B_{max}=3.5 Tesla)
  - plastic degraders (energy loss)

- Gaseous target:
  - T: from 14 K to room temperature
  - effective pressure: from ~0 to 40 bars

τ_{π^-}= 26 ns

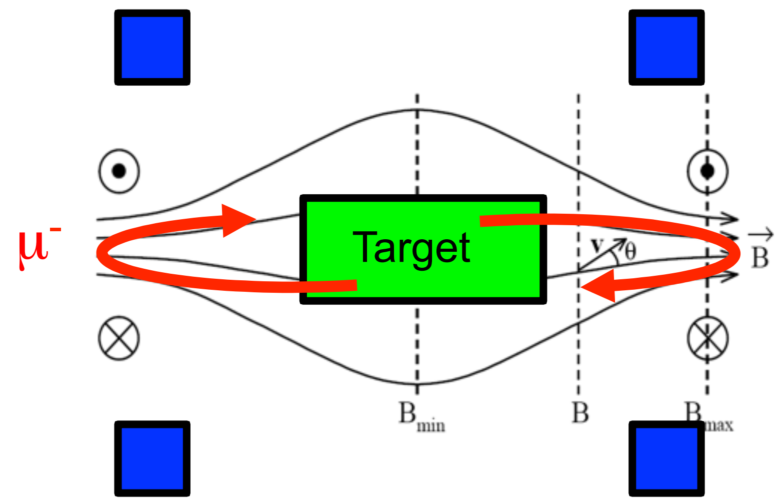


⇩

0.5% (per bar) of the incoming pions are stopped inside the target

- Production and trapping of the muons

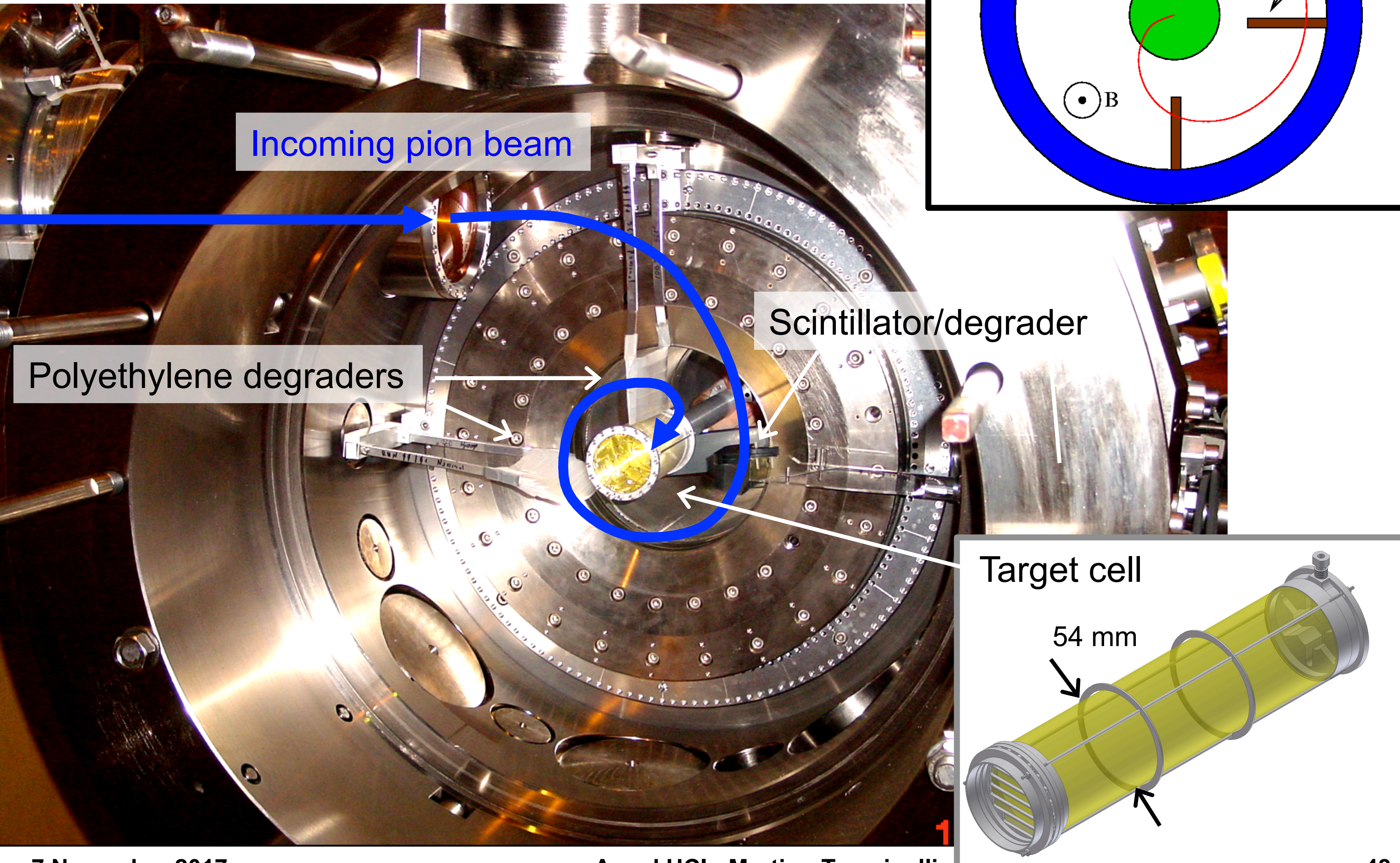
$$\pi^- \rightarrow \mu^- + \bar{\nu}_\mu$$

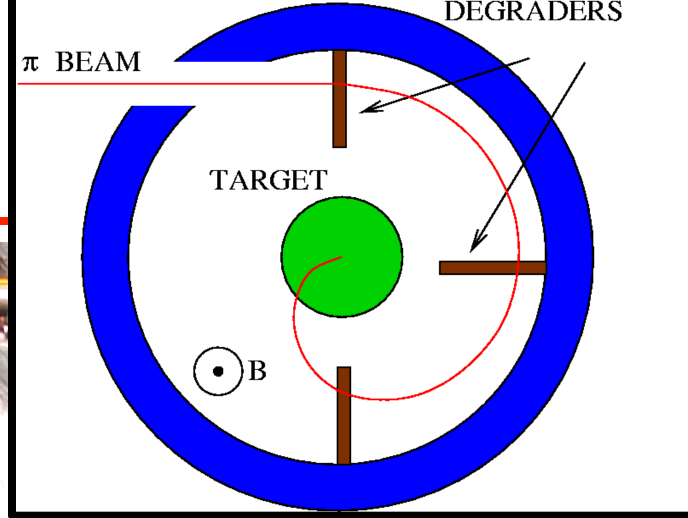


⇩

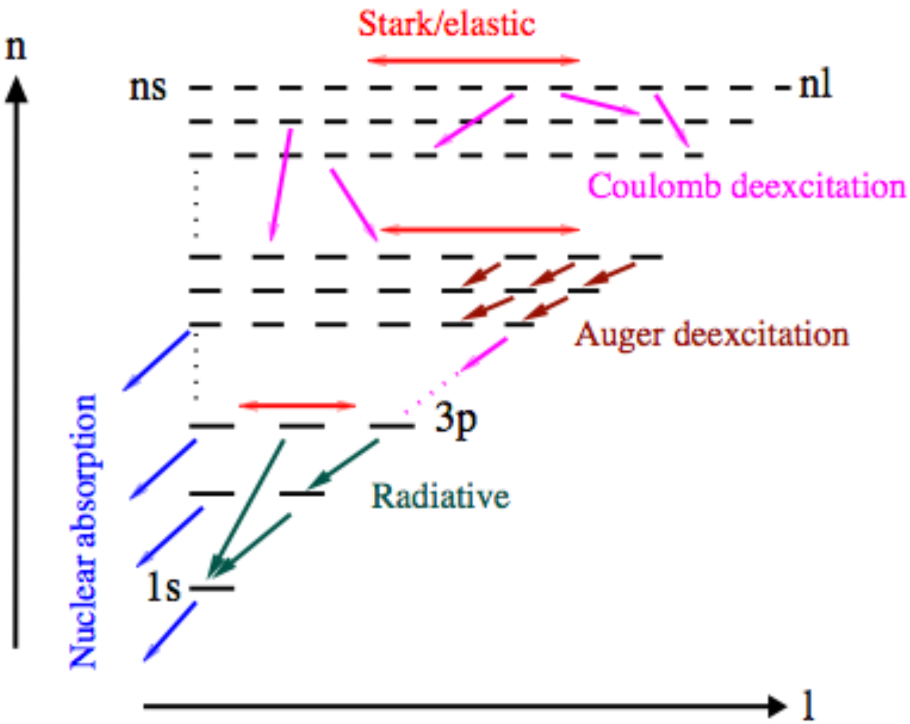
Formation of muonic and pionic atoms

Cyclotron trap





Exotic atoms formation



- Deceleration and stop particle in target
  E_{kin}~10 eV

- Capture at radii of outmost electrons

$$n_\pi = n_{el}\sqrt{\frac{m_\pi}{m_{el}}} \approx 16 \quad \text{in the case of } \pi H$$

Highly excited state!

- De-excitation by competing Auger and X-ray emission

$$\Gamma_{\text{Auger}} \propto \frac{1}{\sqrt{2\Delta E + 38eV}}$$

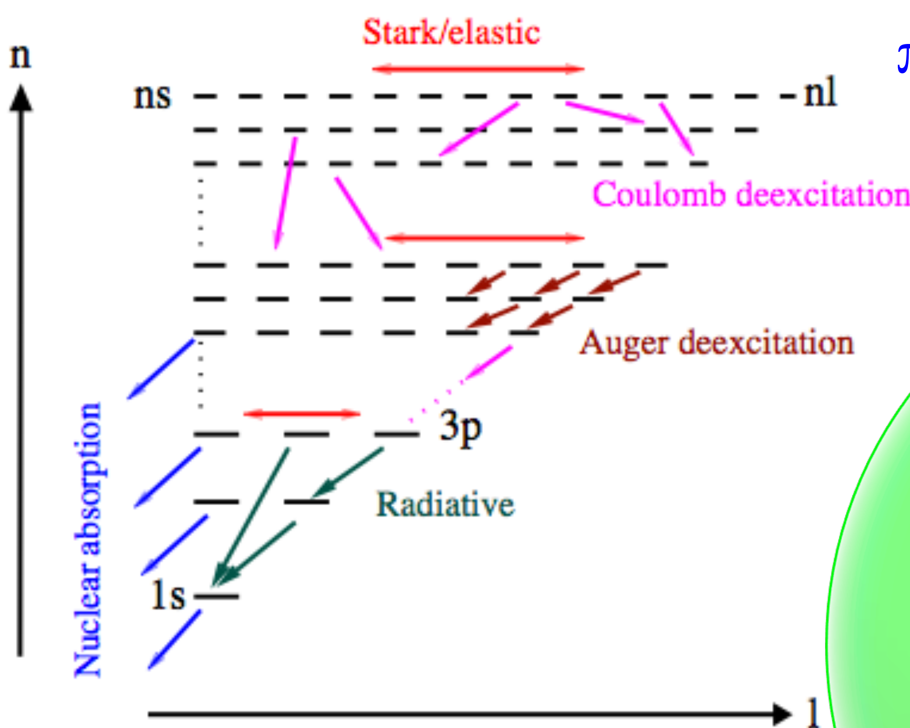
Dominates for large n

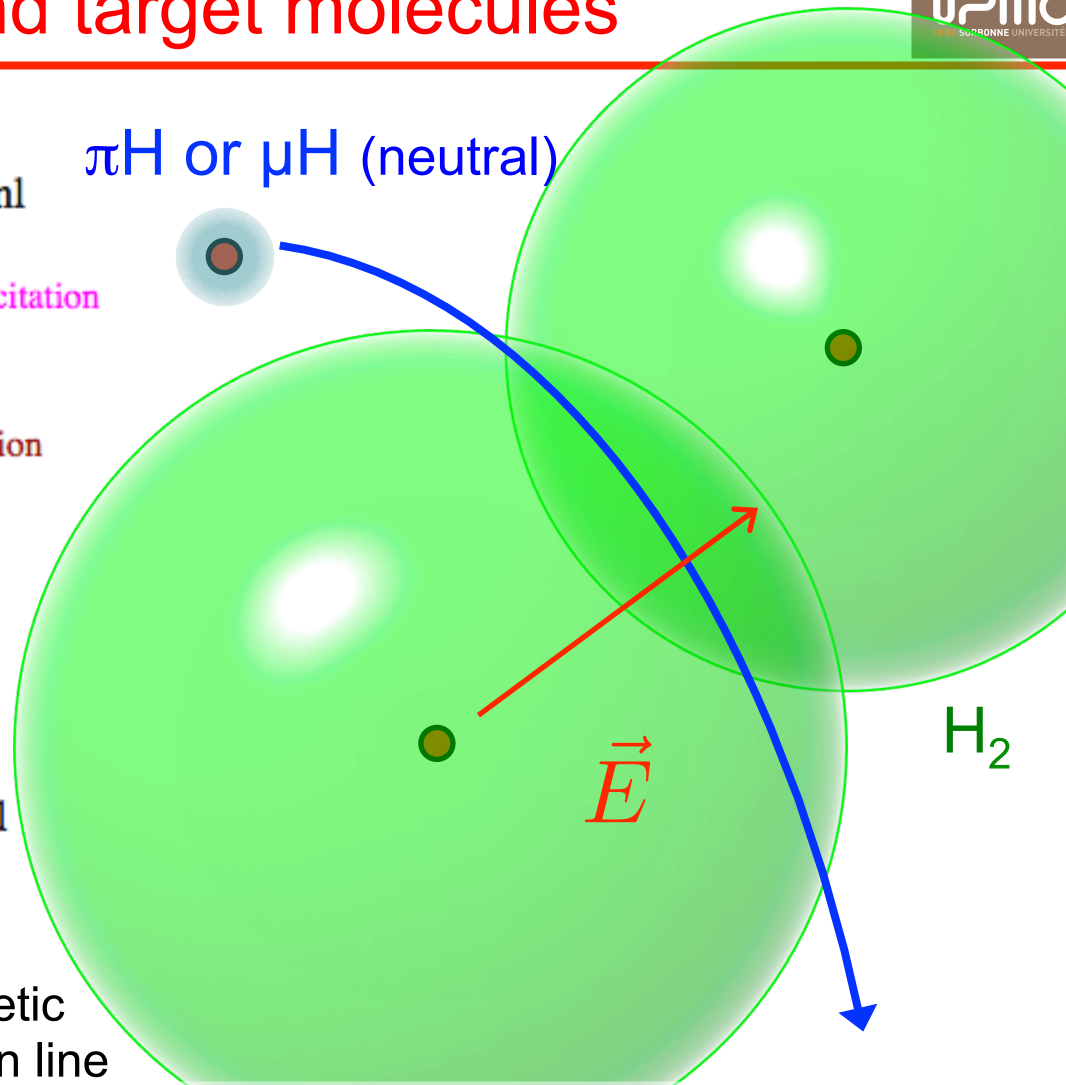
$$\Gamma_{\text{rad}} \propto \Delta E^3$$

Dominates for small n

Low Z + dilute targets => no electrons remaining!!

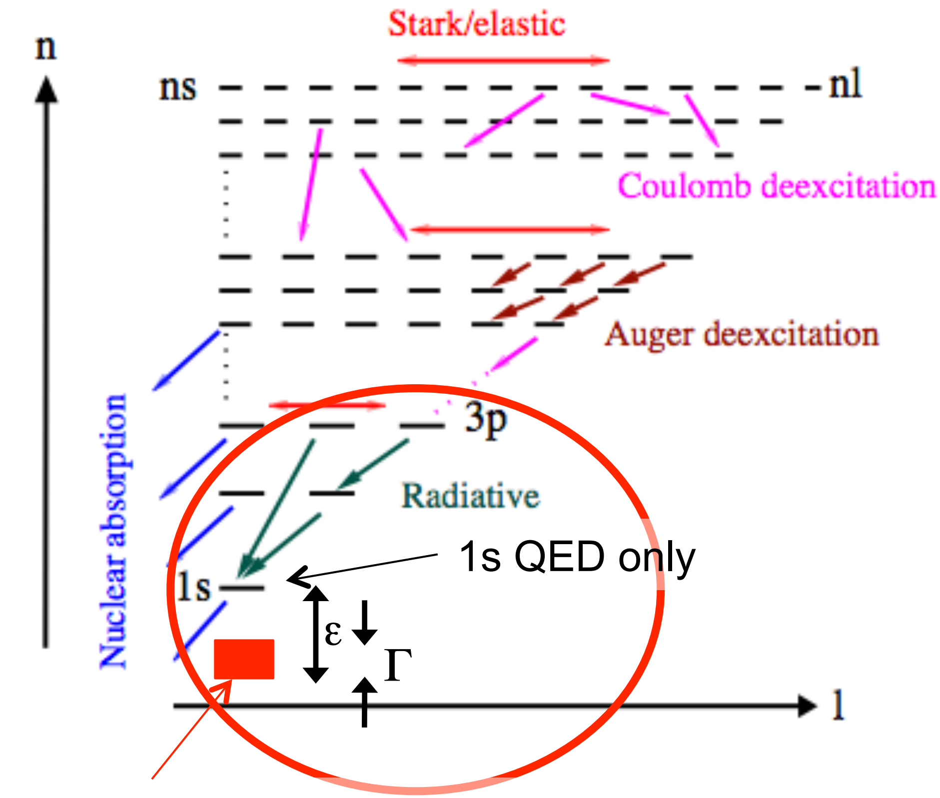
Transitions induced by collisions between exotic hydrogen and target molecules

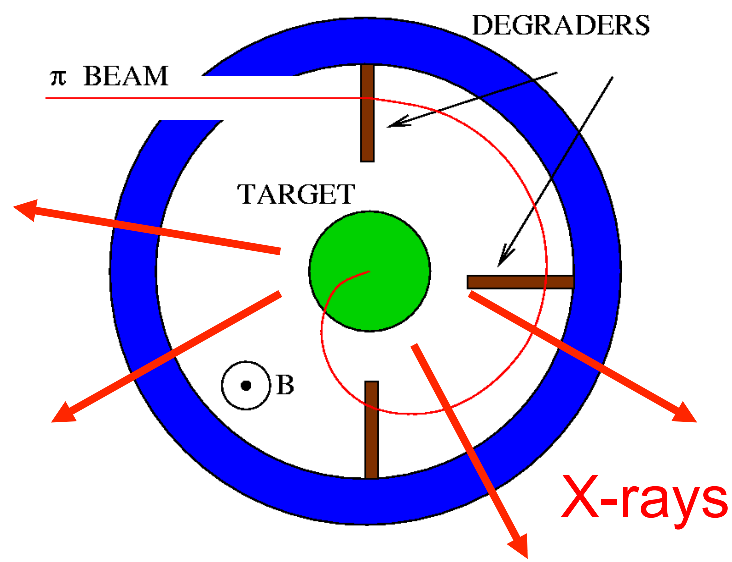




- Stark mixing
- Coulomb de-excitation → gain of kinetic energy → Doppler shift of the transition line
- Molecular formation

Dependency on the target density!!



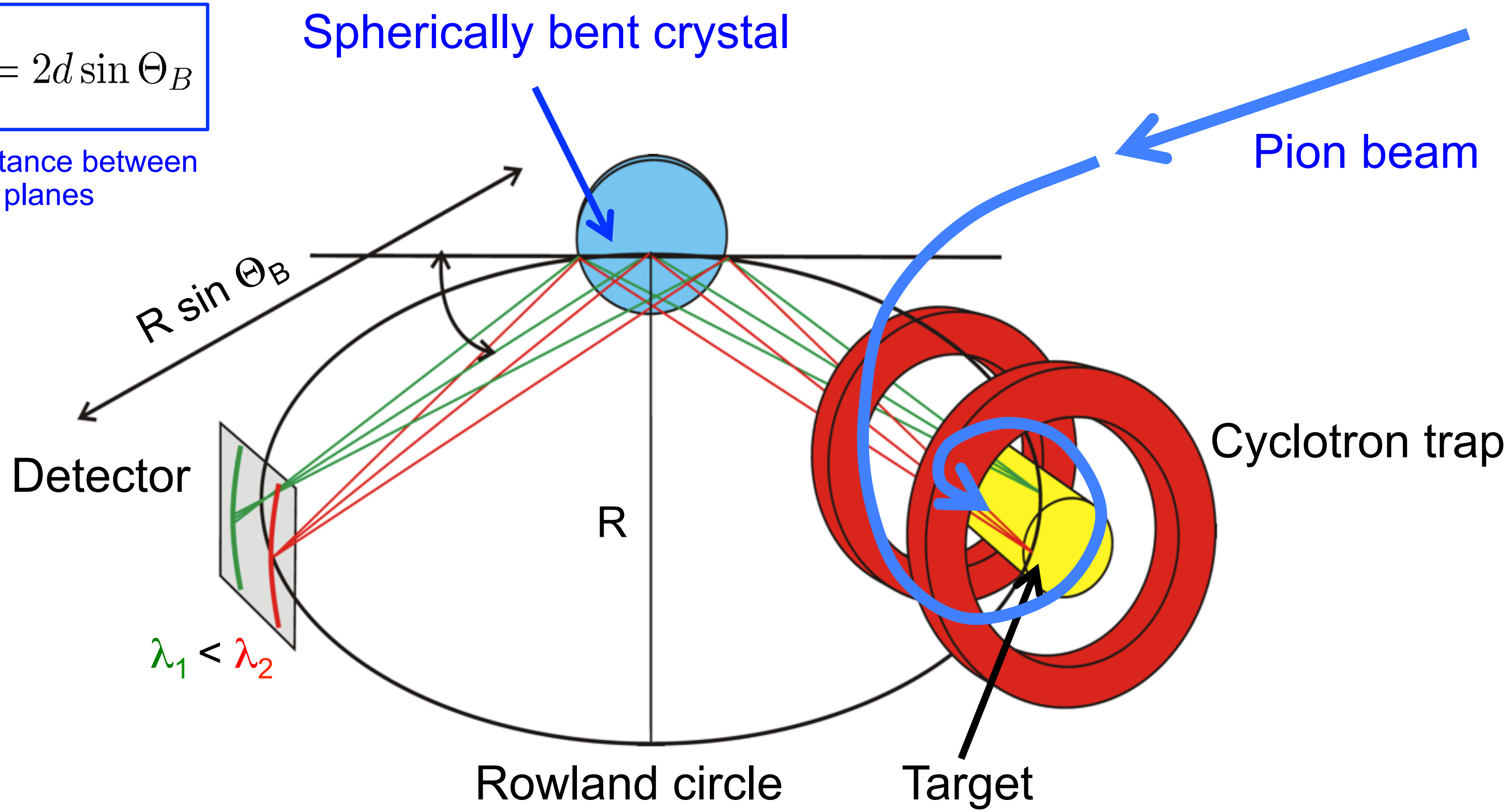


High power resolution for 2-4 keV X-ray required ⇨ Bragg crystal spectroscopy

Johann-type Bragg spectrometer

$$\frac{h\,c}{E} = 2d\sin\Theta_B$$

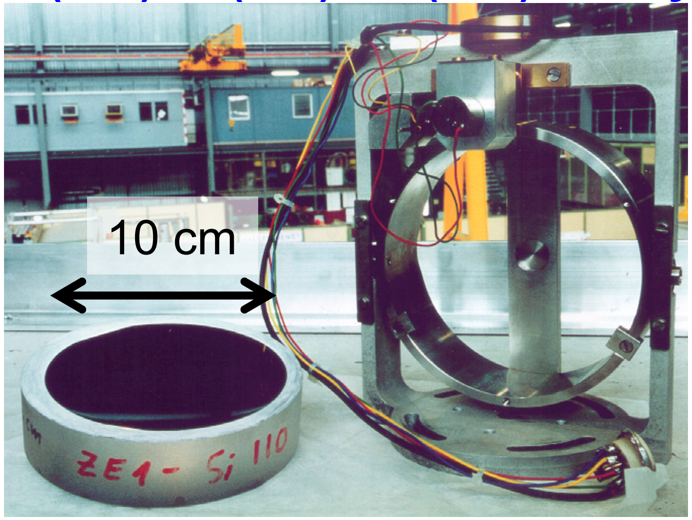
d = distance between crystal planes



[1] H.H. Johann, Zeitschrift für Physik **69**, 185 (1931)
[2] J. Eggs *et al.*, Zeitschrift für angewandte Physik **20**, 118 (1965)
[3] D. Gotta, Progress in Particle and Nuclear Physics **52**, 133 (2004)
[4] D. Gotta *et al.*, Spectrochim. Acta, Part B **120**, 9 (2016)

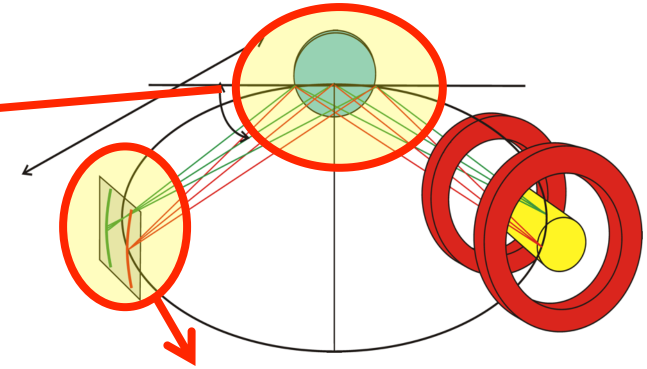
Diffraction crystal and position sensitive detector

Si(110), Si(111), Qz(100), … crystal [1]



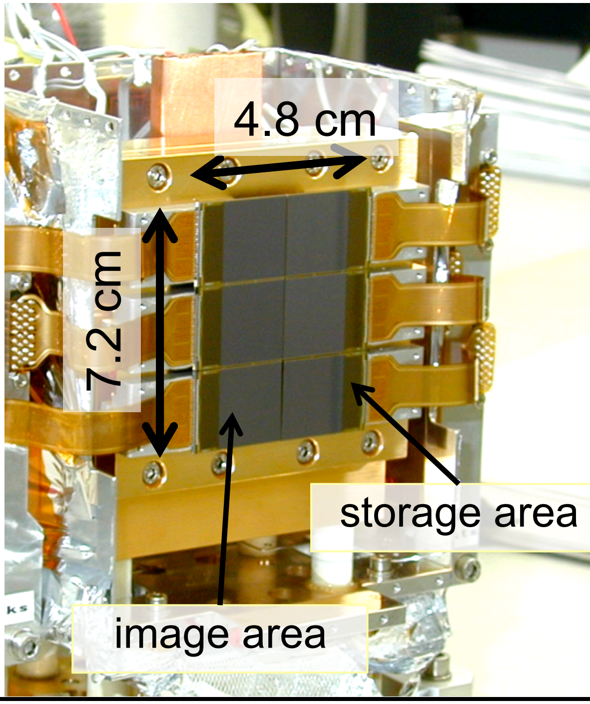
Radius of curvature: ~ 3 m
Diameter: 10 cm
Thickness: 290 µm
Support: polished quartz lens

Produced by Zeiss (Oberkochen, Germany)



2 × 3 X-ray CCD array with frame buffer [2,3]

Total transmission: ~5 10^{-8}



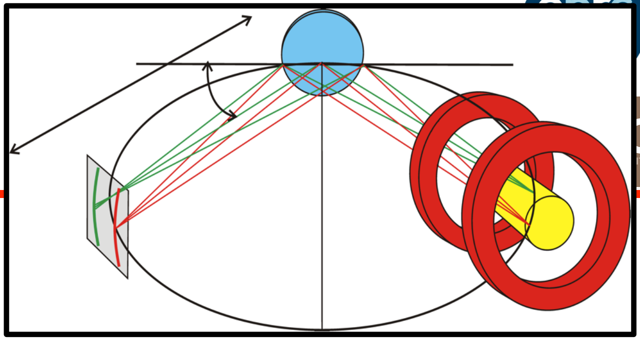
pixel size 40 µm × 40 µm
600 × 600 pixels per chip
frame transfer ≈ 10 ms

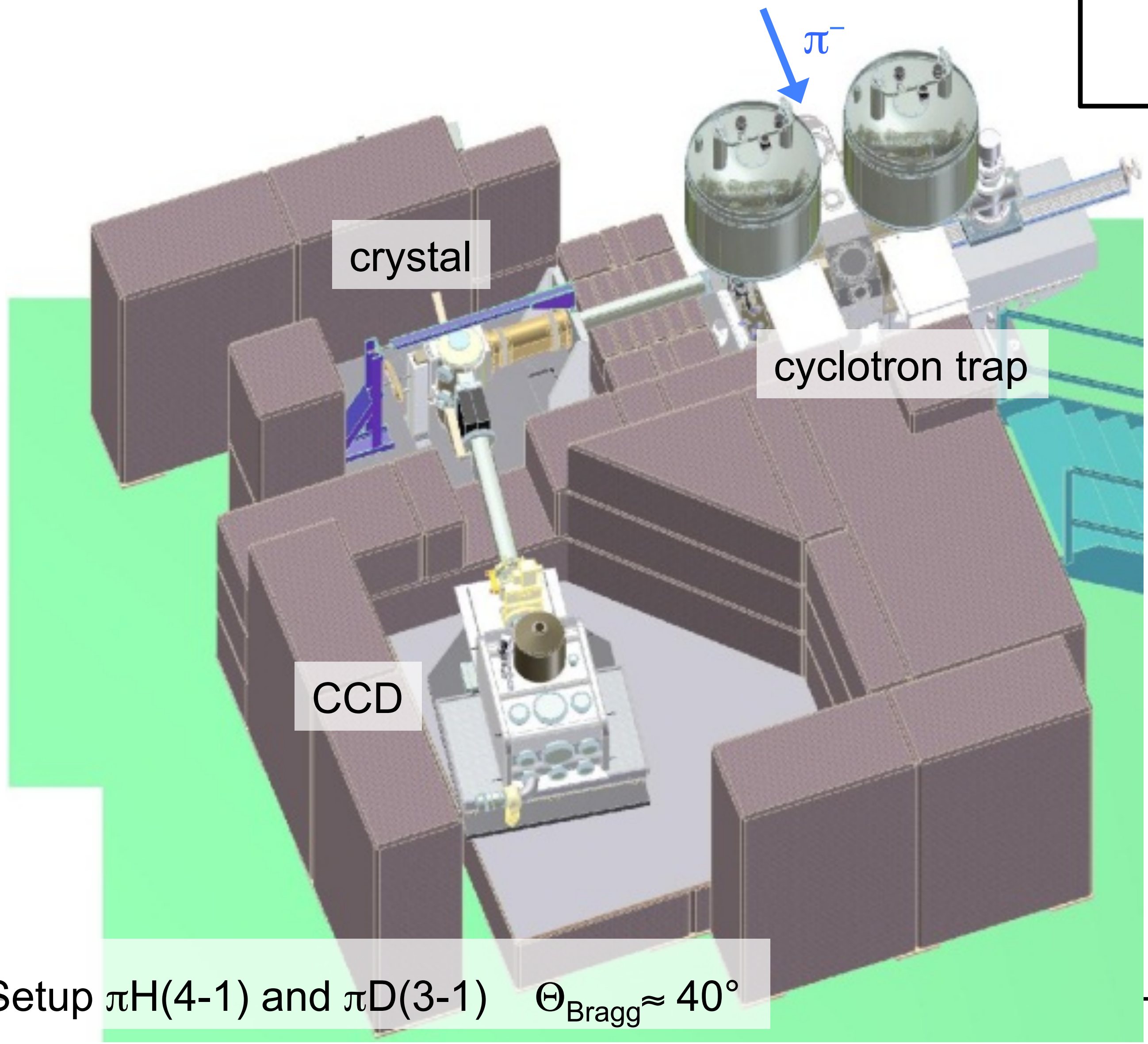
data processing ~24 s
operates at – 100°C

$\Delta E \approx$ 150 eV @ 4 keV
Efficiency ≈ 90%

[1] D.S. Covita *et al.*, Rev. Sci. Instum. **79**, 033102-3 (2008)
[2] N. Nelms *et al.*, Nucl. Instrum. Methods A **484**, 419 (2002)
[3] P. Indelicato *et al.*, Rev. Sci. Instum. **77**, 043107 (2006)

Typical set-up at PSI

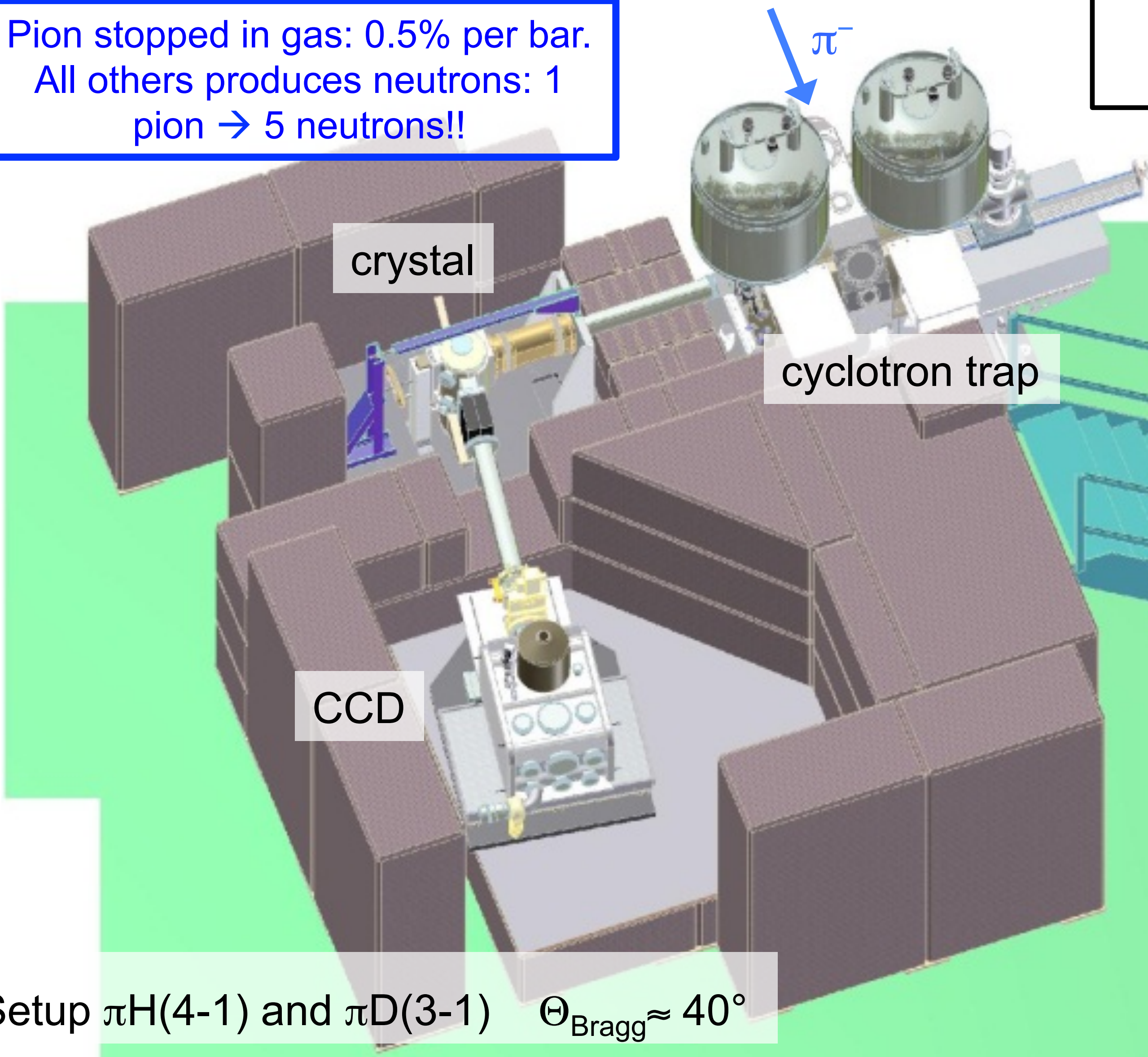




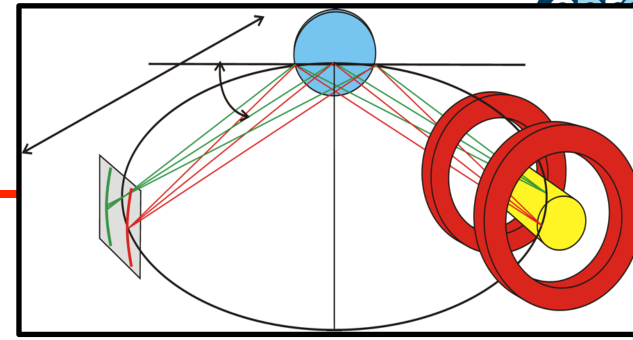
Setup $\pi H(4\text{-}1)$ and $\pi D(3\text{-}1)$ $\Theta_{Bragg} \approx 40°$

Typical set-up at PSI

Pion stopped in gas: 0.5% per bar.
All others produces neutrons: 1 pion → 5 neutrons!!



Setup πH(4-1) and πD(3-1) $\Theta_{Bragg} \approx 40°$



huge background on the CCD

⇩

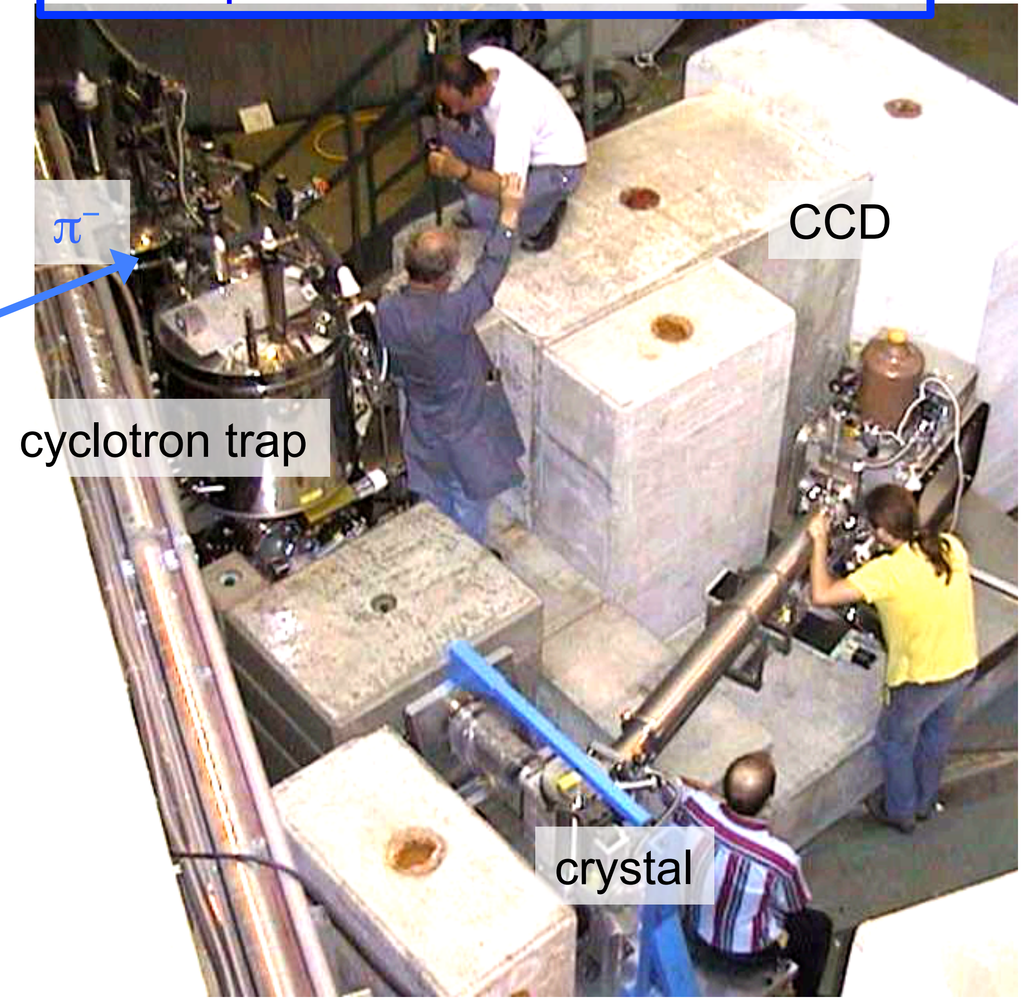
heavy concrete

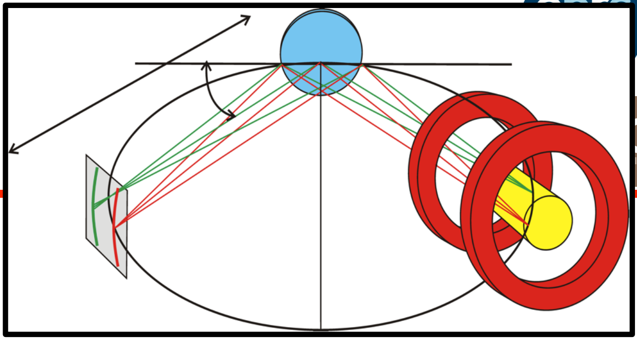
⇩

peak-to-background reduced by a factor of 10

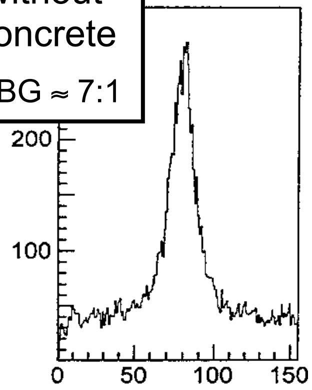
Typical set-up at PSI

Pion stops in gas: few % all others:
1 pion makes 5 neutrons!!

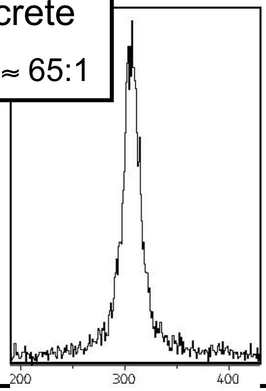




without concrete
P/BG ≈ 7:1



with concrete
P/BG ≈ 65:1



huge background on the CCD

⇩

heavy concrete

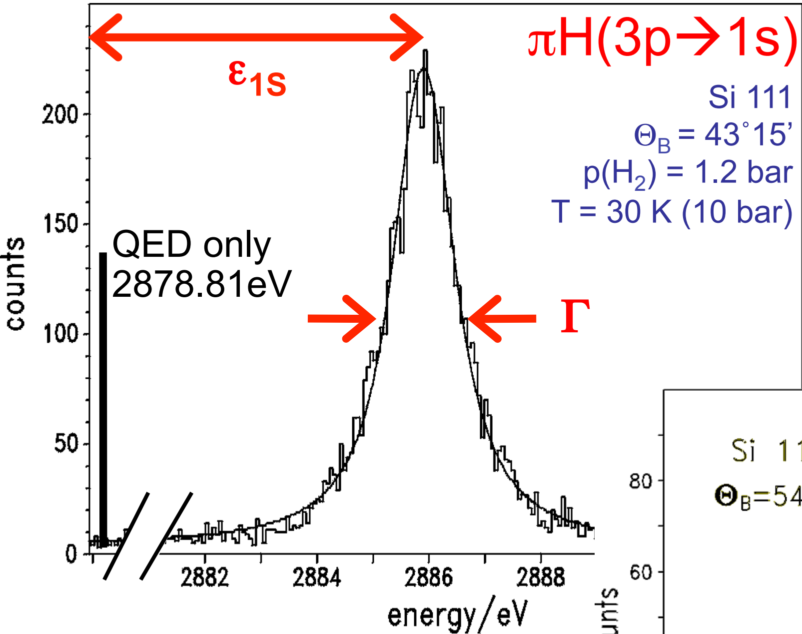
⇩

peak-to-background reduced by a factor of 10

Summary

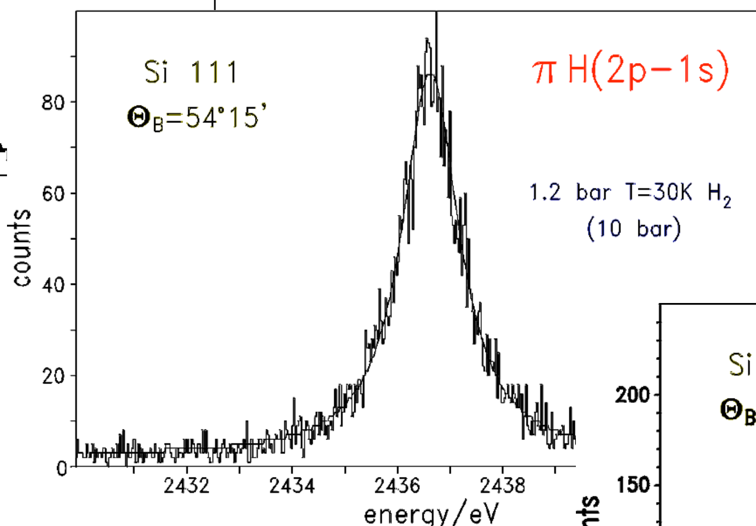
- Introduction
  - Test of QED in strong field
  - Study of strong interaction force at low energy
- Heavy highly charged ions
  - Production
  - Lamb shift measurement
  - Vacuum decay experiment
- Pionic atoms
  - Production
  - **Pionic hydrogen and deuterium spectroscopy**
  - Pion mass measurement
- Conclusions and outlooks

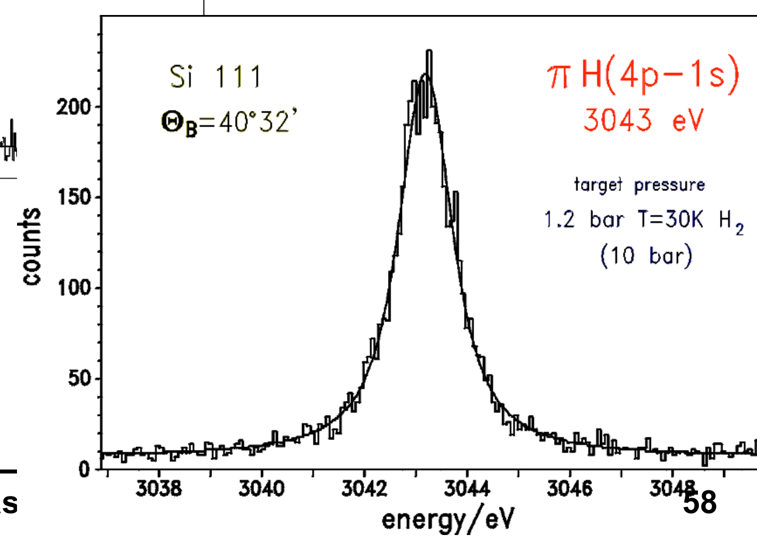
Pionic hydrogen results



Independent measurement:

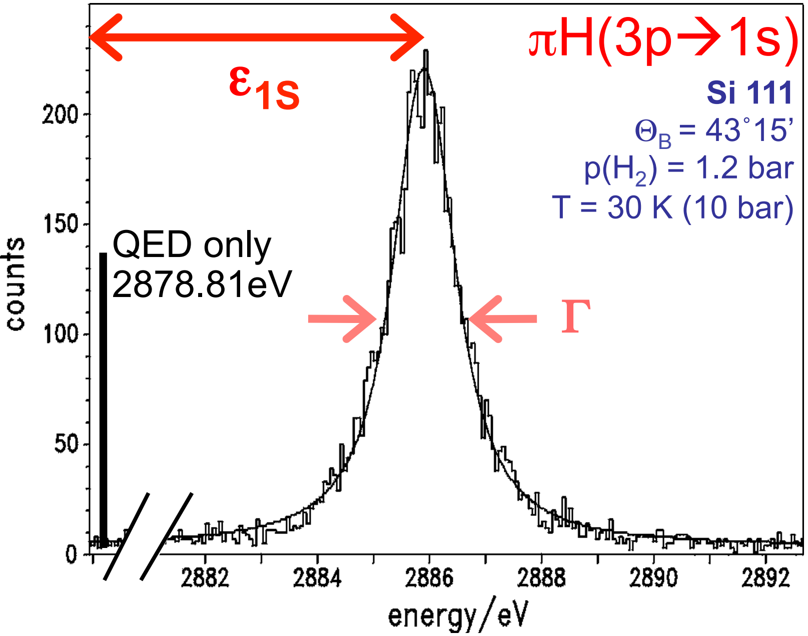
- Different transitions
- Different energy calibration
- Different crystals
- **Different target densities**





Several weeks of data acquisition for each spectrum

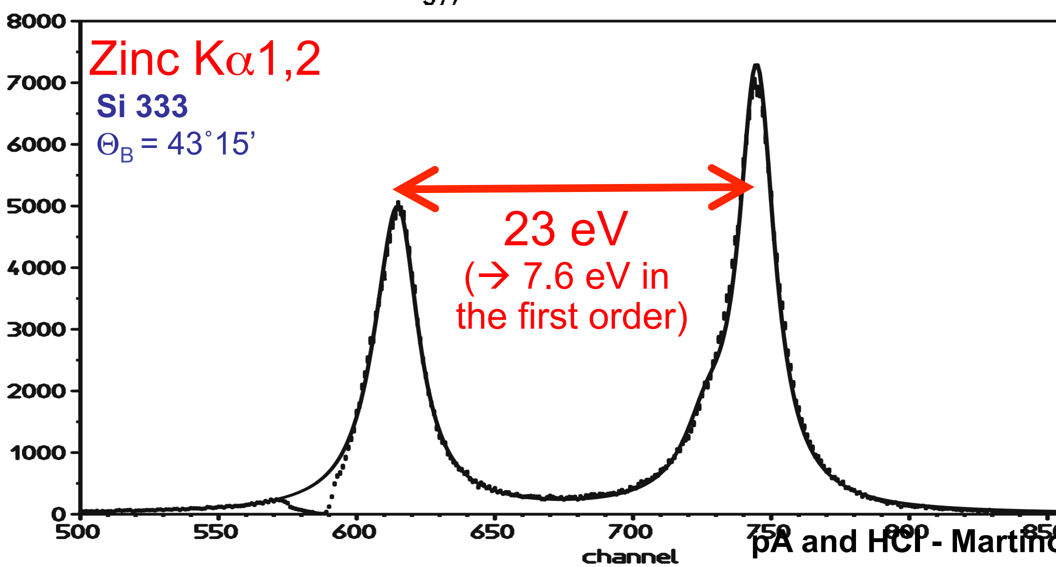
Pionic hydrogen shift measurement

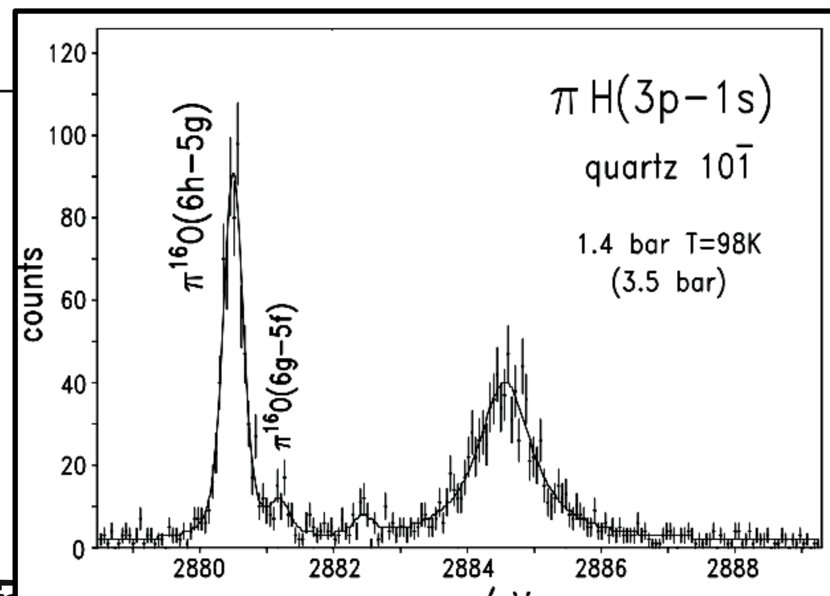


Calibrations

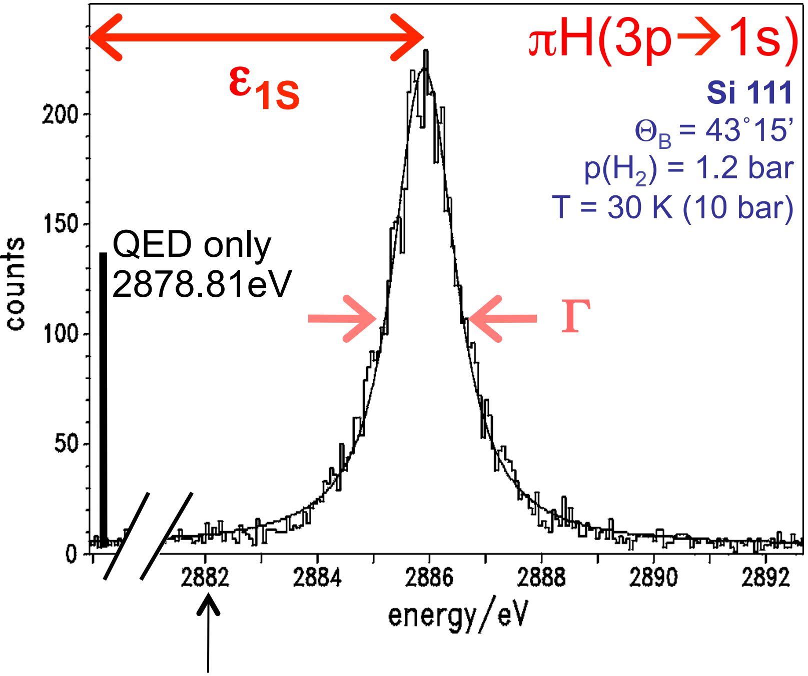
- Kα fluorescence from selected target (different reflection order)
- from other exotic atom transitions (where strong interaction effects are negligible)

smaller systematic errors from crystal spectrometer aberrations and possible chemical shifts and pion mass accuracy

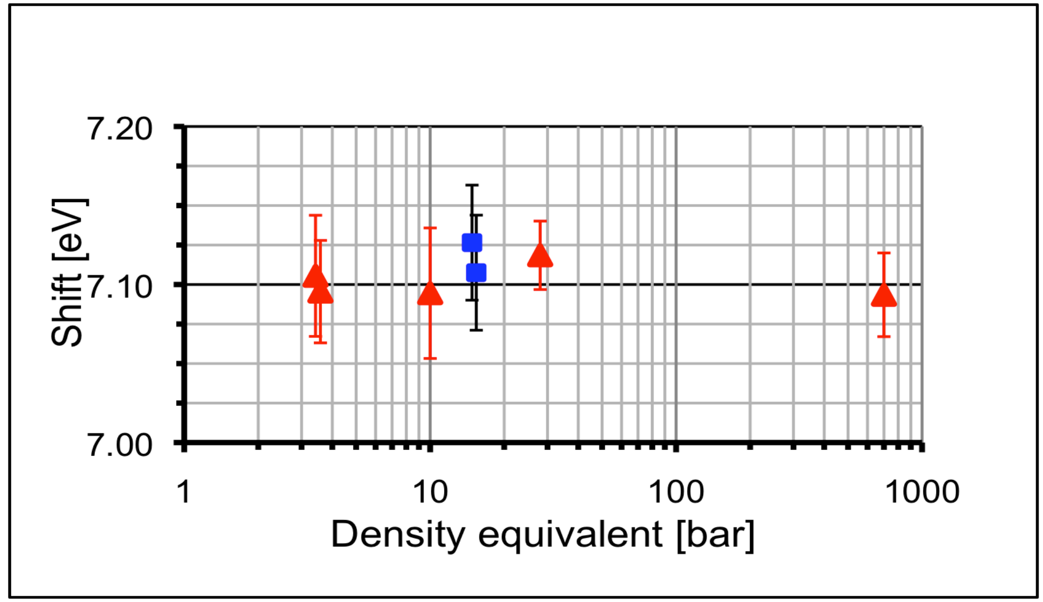




Pionic hydrogen shift measurement



Satellite position



ETHZ-PSI previous experiment – Ar Kα
H.-Ch.Schröder et al. Eur. Phys.J.C 1 **473** (2001)

ε_{1s} = + 7.0869 ± 0.0071 ± 0.0064 eV (± 0.13%) [1]

(attractive force)

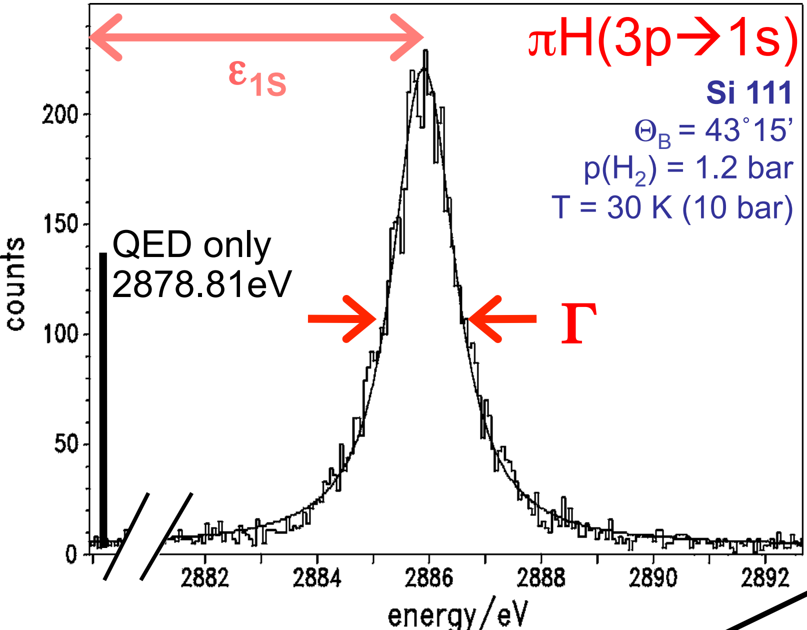
0.001 eV from QED predictions [4]
→ **from the pion mass**

Results

- No satellite from molecular X-ray detected (theoretical predictions [2] not confirmed)
- New value for the strong interaction shift in πH [3] (more 3 times smaller uncertainty)

[1] M. Hennebach *et al.*, Eur. Phys. J. A **50**, 1-10 (2014)
[2] S.Kilic et al., Phys. Rev. A **70** 042506 (2004)
[3] D. Gotta, et al., Lect. Notes Phys. **745** 165 (2008)
[4] Schlesser et al., Phys. Rev. C **84**, 015211 (2011)

Pionic hydrogen width measurement



Much more complex!!

$$\Gamma_{exp} = \Gamma_{crystal} \otimes \Gamma_{Doppler} \otimes \Gamma_{1s}$$

from the strong interaction (goal!)

from the fast movement of the ions

from the response function of the instrument

Characterization of the spectrometer [1,2]

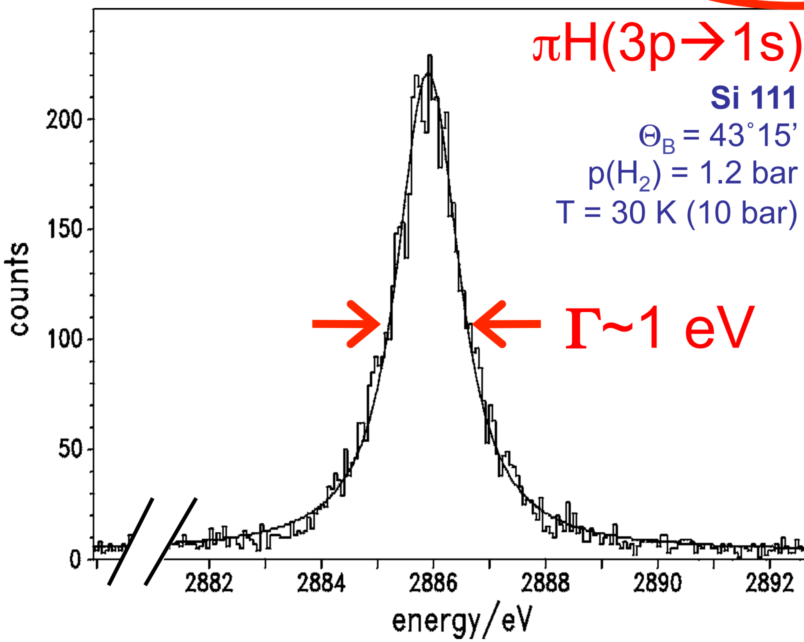
- new measurements highly charged ion X-ray transitions
- simulation of the instrument

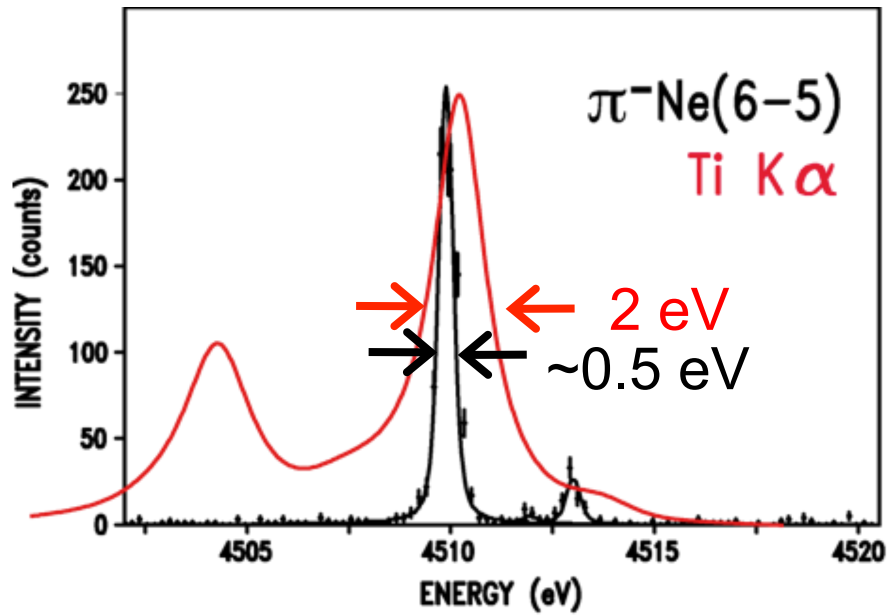
Accurate investigation to the atomic cascade

- new theoretical approaches
- new experiment with muonic hydrogen

Crystal spectrometer characterization

$$\Gamma_{exp} = \Gamma_{crystal} \otimes \Gamma_{Doppler} \otimes \Gamma_{1s}$$





How to characterize the response function of the spectrometer?

Where to find a X-ray line with a Γ<0.5 eV?

- Fluorescence X-ray: too broad!!
- Pionic atoms (no Coulomb explosion): too low count rate!!
- … highly charged ion radiation!!

Spectrometer characterization from He-like S, Cl, Ar M1 transitions

Ideal for spectrometer response function studies

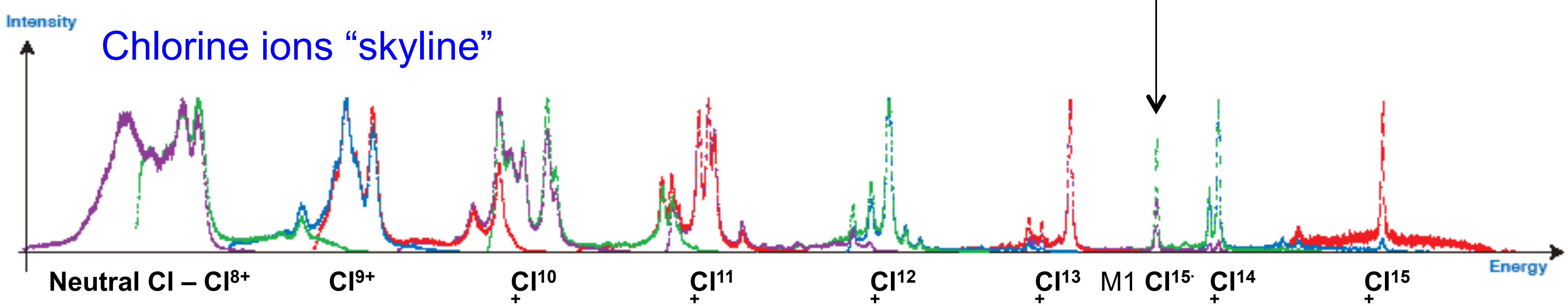
X-ray emission from a confined hot plasma (ECR ion source)

Measurement with:

- Different crystal
- Different crystal aperture
- Different focal position
- Different X-ray energies (Ar, Cl, S)

- **Transition width << 1meV**
- **Doppler broadening < 40 meV**

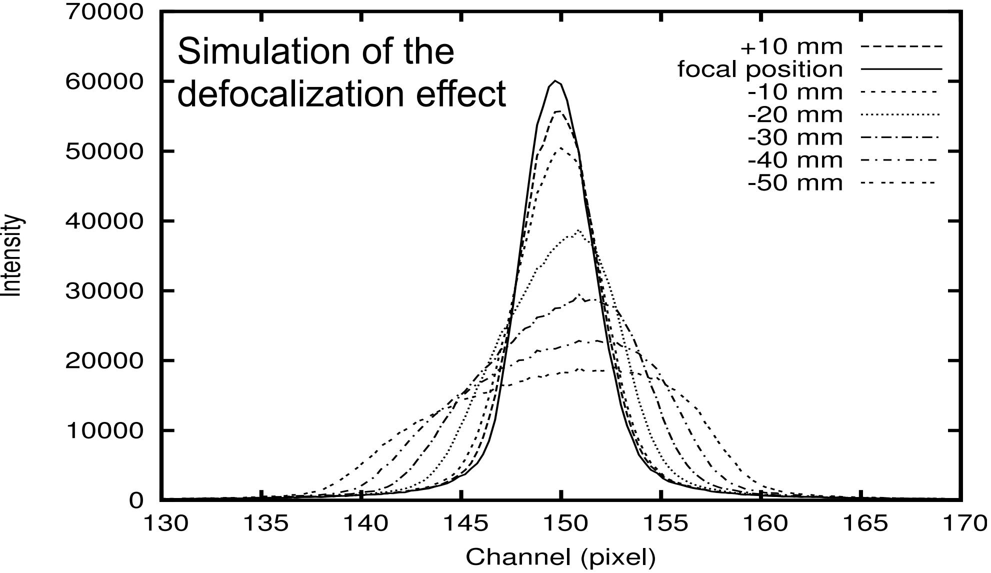
1s2s $^3S_1 \rightarrow 1s_2$ $^1S_0$ (M1)



Anagnostopoulos et al., Nucl. Instrum. Metl
Anagnostopoulos et al., Nucl. Instrum. Metl
M.T. et al., J. Phys. CS **58**, 129 (2007)

Covita et al., Rev. Sci. Instum. **79**, 033102 (2008)
Schlesser *et al.*, Phys. Rev. A **88**, 022503 (2013)
Gotta and Simons, Spectrochim. Acta, Part B **120**, 9-18 (2016)

Spectrometer characterization from He-like S, Cl, Ar M1 transitions



Ideal for spectrometer response function studies

Measurement with:

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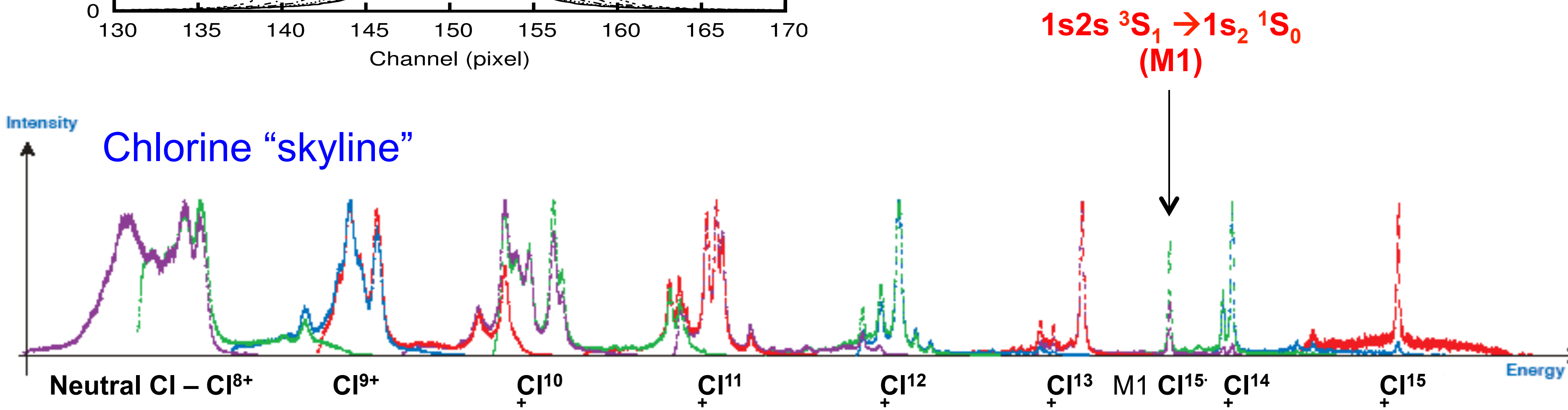
- Different crystal aperture
- Different focal position
- Different X-ray energies (Ar, Cl, S)



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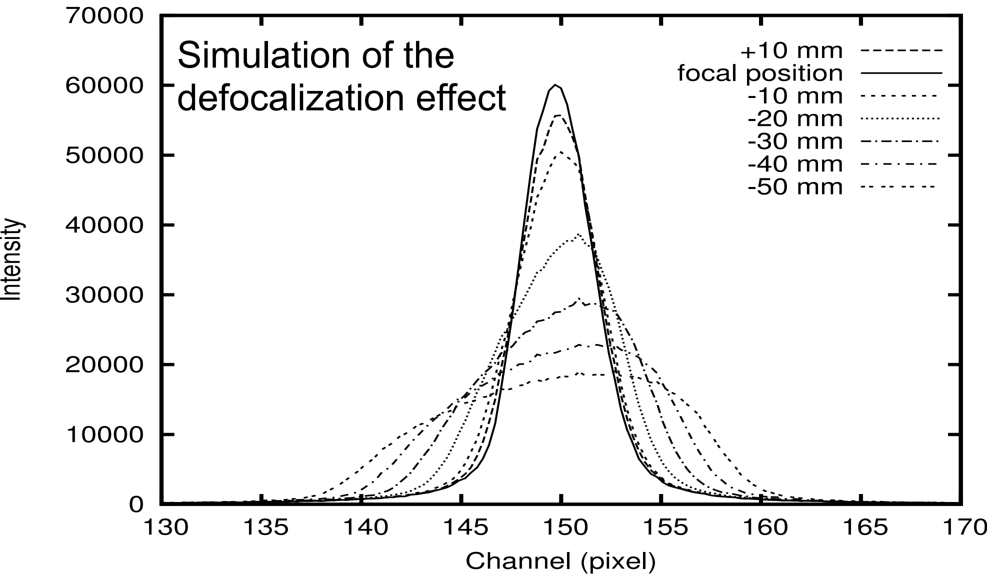

Ideal for spectrometer response function studies

Measurement with:

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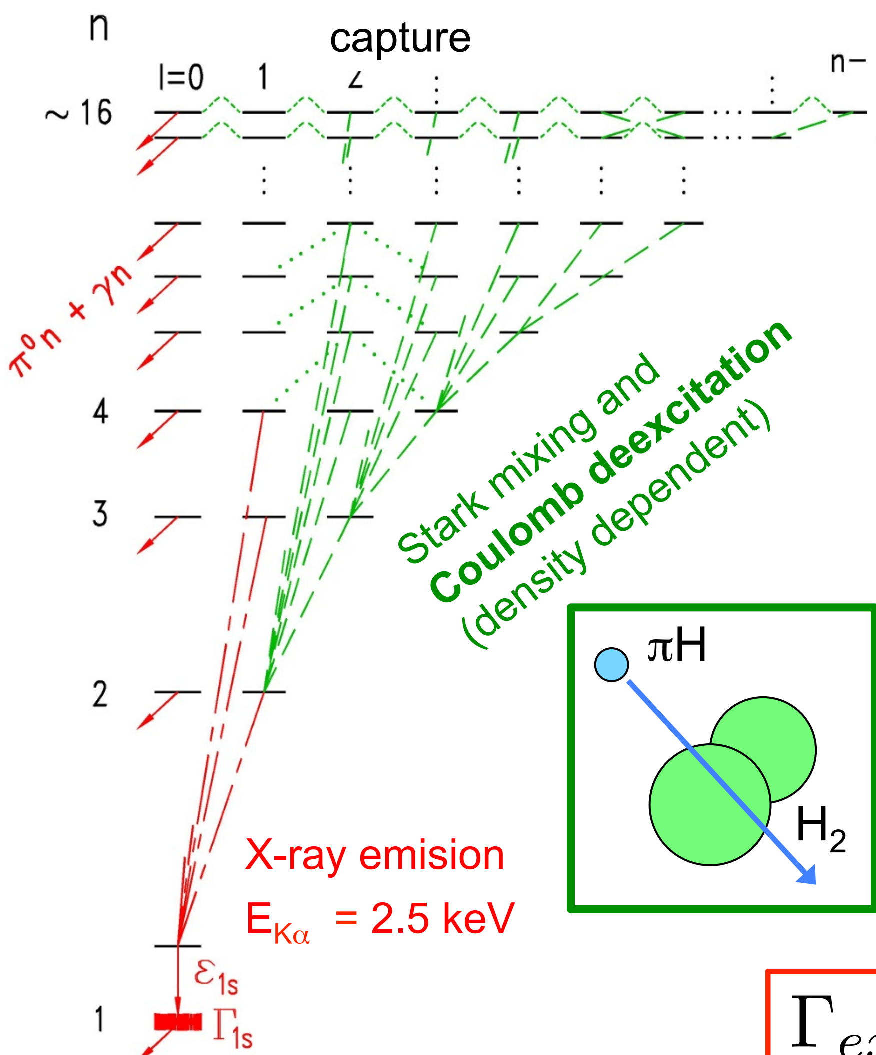
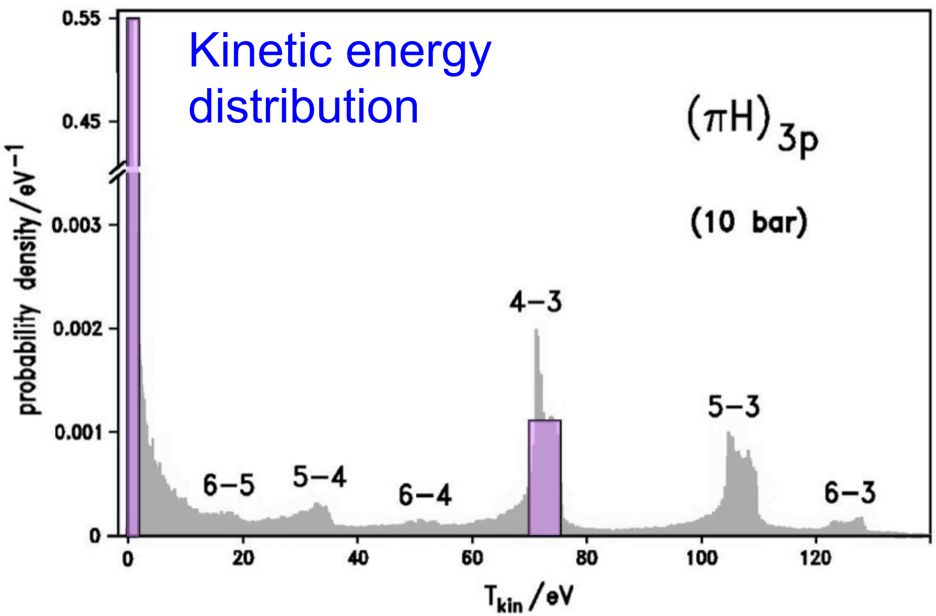
$$\Gamma_{exp} = \Gamma_{crystal} \otimes \Gamma_{Doppler} \otimes \Gamma_{1s}$$

Anagnostopoulos et al., Nucl. Instrum. Metl
Anagnostopoulos et al., Nucl. Instrum. Metl
M.T. et al., J. Phys. CS **58**, 129 (2007)

Covita et al., Rev. Sci. Instum. **79**, 033102 (2008)
Schlesser *et al.*, Phys. Rev. A **88**, 022503 (2013)
Gotta and Simons, Spectrochim. Acta, Part B **120**, 9-18 (2016)

Transitions induced by collisions in πH





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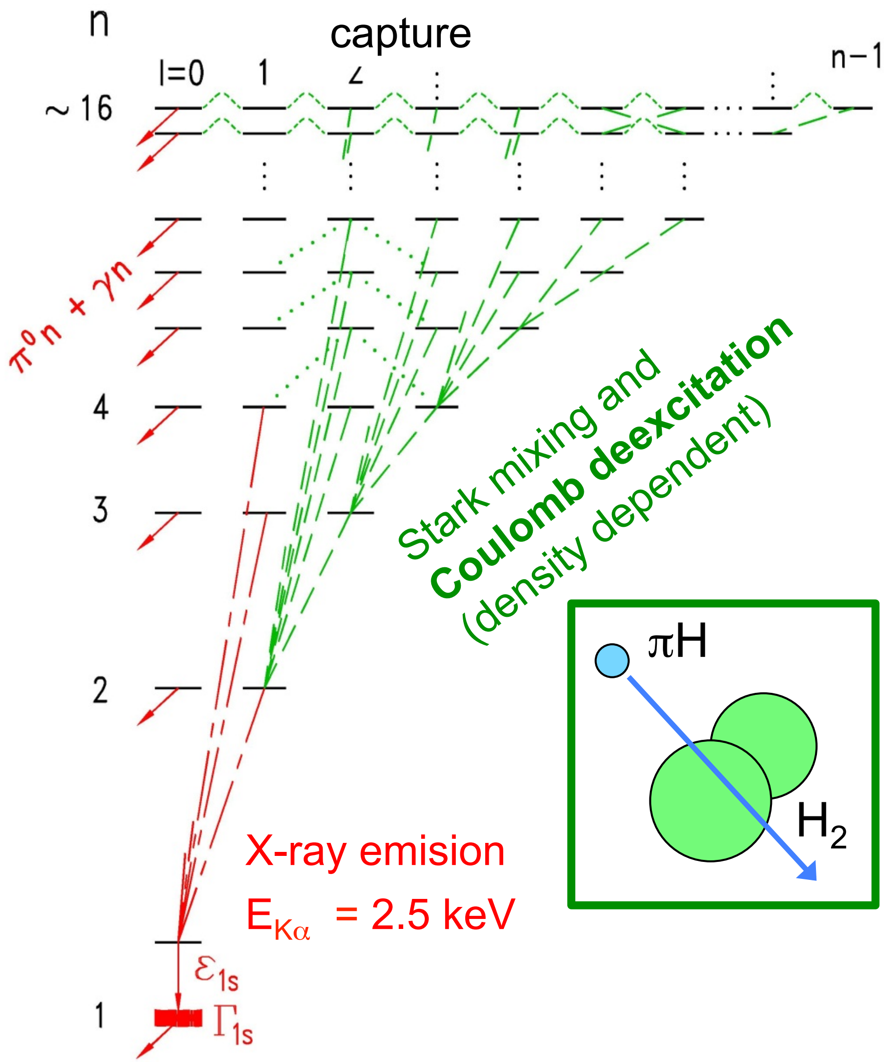
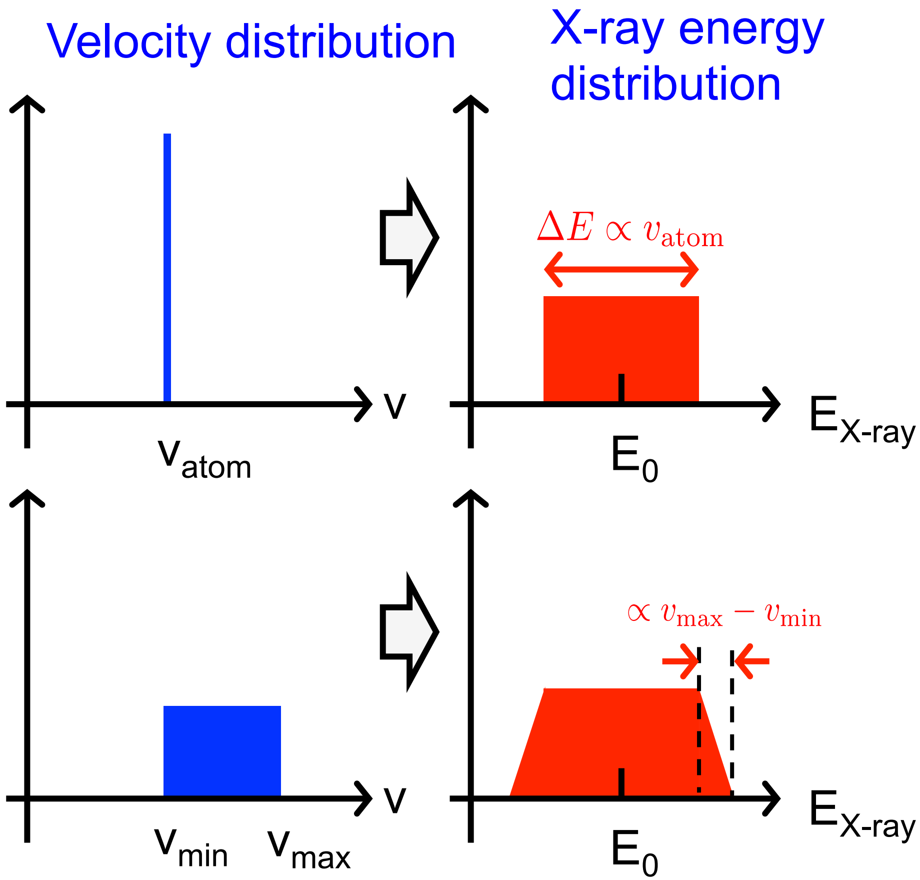
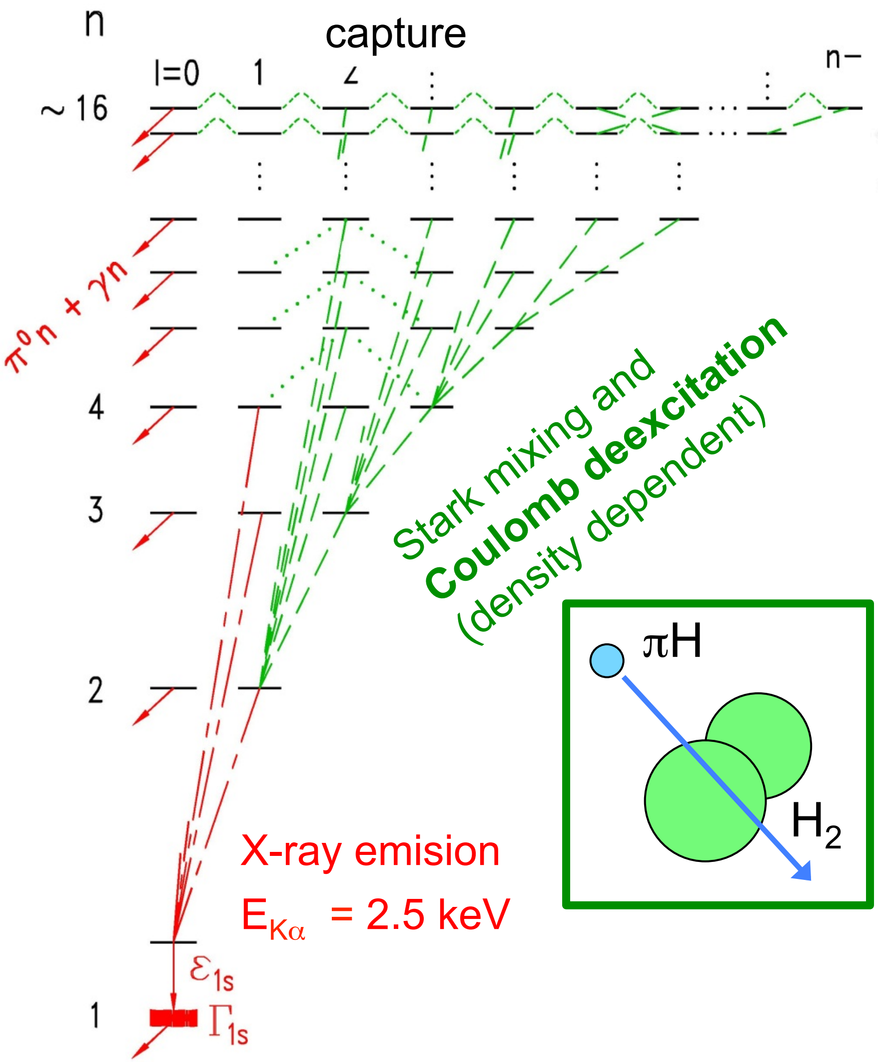
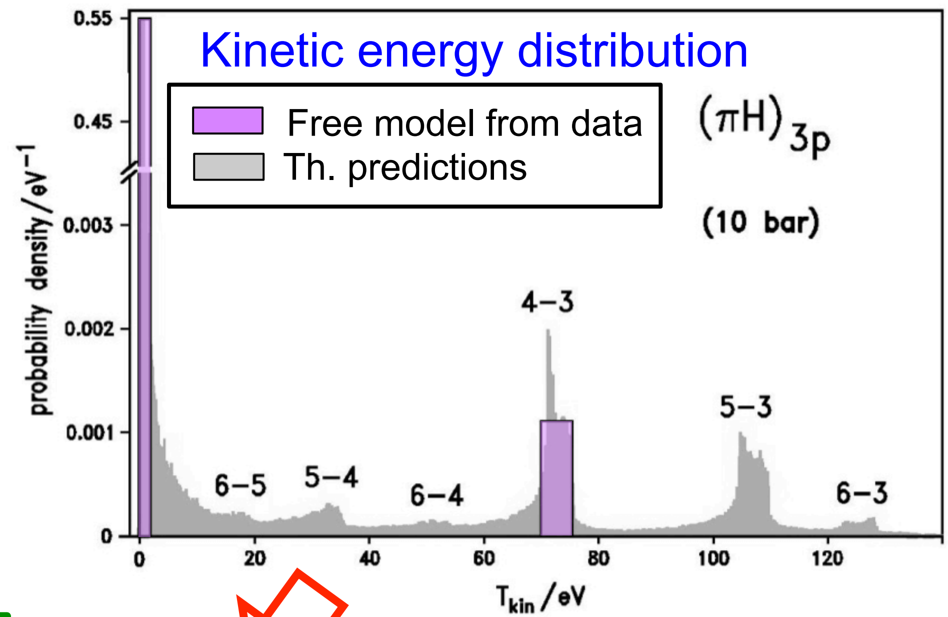
Transitions induced by collisions in πH



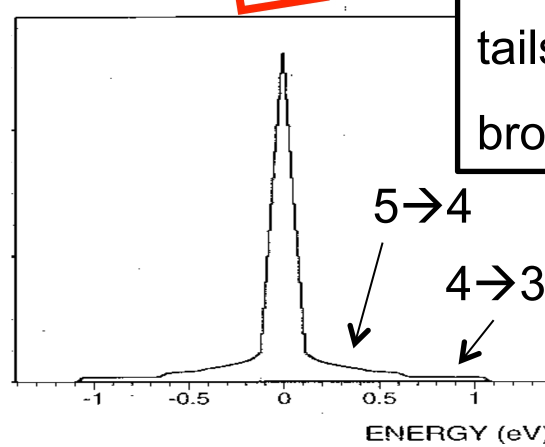


Transitions induced by collisions in πH





tails from Doppler broadening



μH(3p-1s)

MC simulation

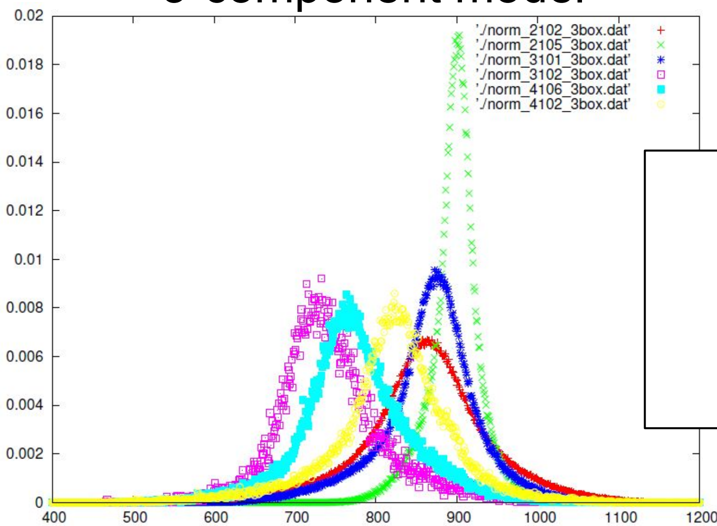
Pionic hydrogen hadronic width summary

Work in progress

$$\Gamma_{exp} = \Gamma_{crystal} \otimes \Gamma_{Doppler} \otimes \Gamma_{1s}$$

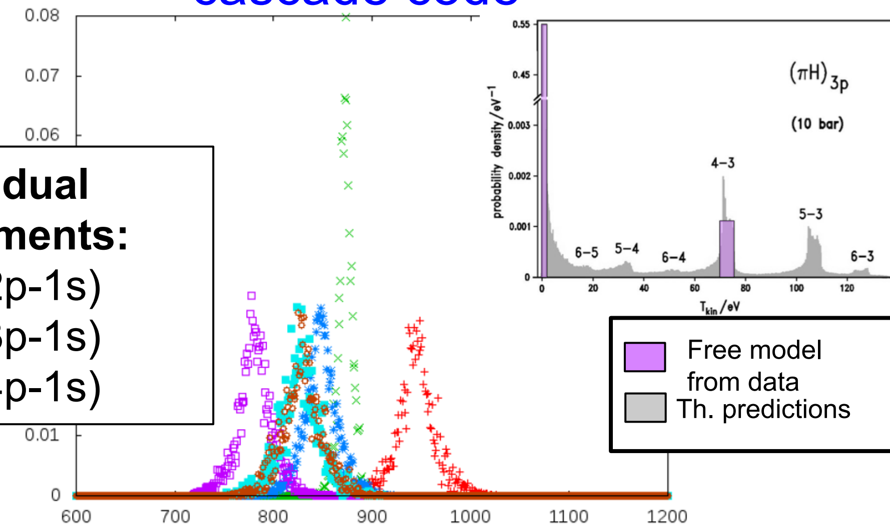
Phenomenological approach

3-component model



6 individual measurements:
2 x πH(2p-1s)
2 x πH(3p-1s)
2 x πH(4p-1s)

Kinetic energy distribution from cascade code



$\Gamma_{1s} = 0.85^{+0.04}_{-0.05}$ eV(± 4-5%) preliminary

Already 3-4 times better accuracy than Sigg et al. Phys. Rev. Lett.**75** 3245 (1995)

$\Delta\Gamma \rightarrow \Delta\Gamma/2$ with a good cascade understanding

Shift and width related to the pion-nucleus scattering length and cross sections

πH

$$\epsilon_{1s}^{\pi H} \propto a_{\pi^- p \to \pi^- p} + corr.$$ ✔

$$\Gamma_{1s}^{\pi H} \propto (a_{\pi^- p \to \pi^0 n})^2 + corr.$$ Ok…

πD

$$\epsilon_{1s}^{\pi D} \propto a_{\pi^- p \to \pi^- p} + a_{\pi^- n \to \pi^- n} + corr.$$

$$\Gamma_{1s}^{\pi D} \propto \Im m(a_{\pi d \to \pi d})$$

→ Basic pion-nucleon interaction properties

Strong interaction in simple bound systems

Shift and width related to the pion-nucleus scattering length and cross sections

πH

$$\epsilon_{1s}^{\pi H} \propto a_{\pi^- p \to \pi^- p} + corr.$$ ✔

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→ Basic pion-nucleon interaction properties

Strong interaction in simple bound systems

Shift and width related to the pion-nucleus scattering length and cross sections

πH
$$\epsilon_{1s}^{\pi H} \propto a_{\pi^- p \to \pi^- p} + corr. \qquad \propto a^+ + a^- + f_{LEC}(c_1, f_1, f_2)$$
$$\Gamma_{1s}^{\pi H} \propto (a_{\pi^- p \to \pi^0 n})^2 + corr. \qquad \propto (a^-)^2 + g(c_1, f_2)$$

Low energy constants of the effective Chiral Perturbation Lagrangian

πD
$$\epsilon_{1s}^{\pi D} \propto a_{\pi^- p \to \pi^- p} + a_{\pi^- n \to \pi^- n} + corr. \ \propto a^+ + h.o.(a^+, a^-) + h_{LEC}(c_1, f_1, f_2)$$
$$\Gamma_{1s}^{\pi D} \propto \Im m(a_{\pi d \to \pi d})$$

Isospin cattering lengths $a^{\pm}$

πN isospin symmetry
(2 quark flavour only)

$$1 \otimes 1/2 \Rightarrow 1/2 \oplus 3/2$$

⇨ **a^+ isoscalar**
a^- isovector

πN scattering lengths results

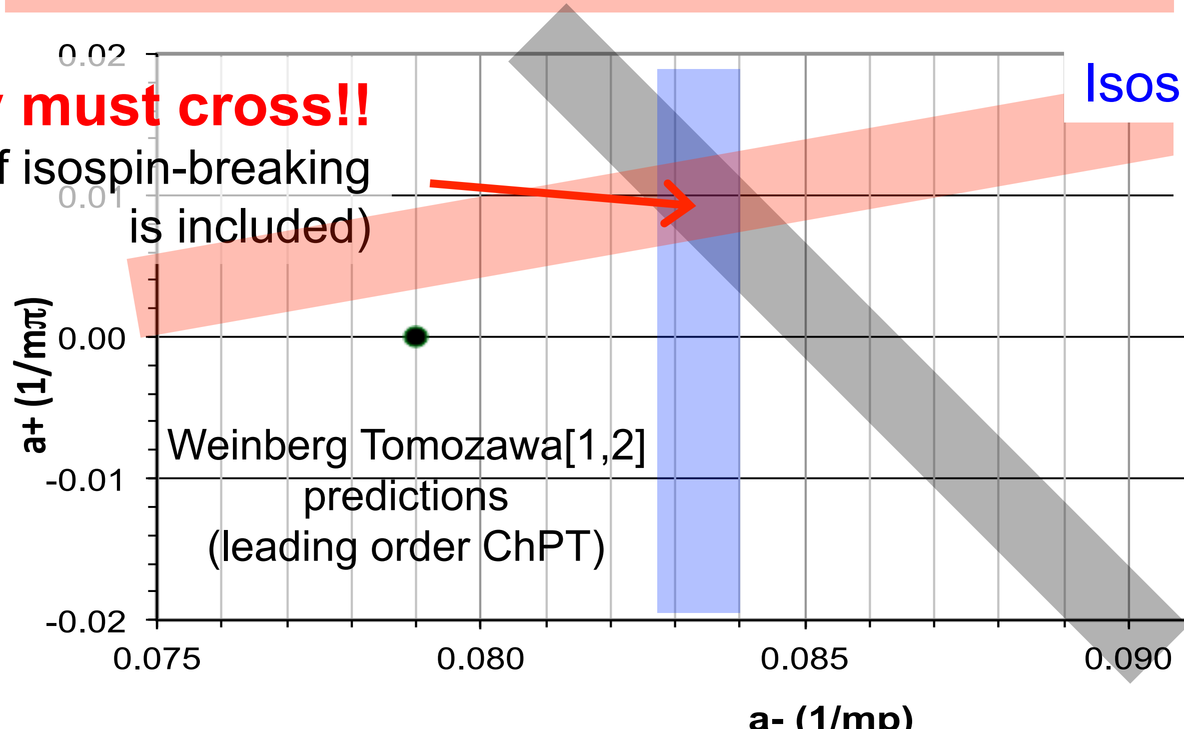
πH
$$\epsilon_{1s}^{\pi H} \propto a^+ + a^- + f_{LEC}(c_1, f_1, f_2)$$
$$\Gamma_{1s}^{\pi H} \propto (a^-)^2 + g(c_1, f_2)$$

πD
$$\epsilon_{1s}^{\pi D} \propto a^+ + h.o.(a^+, a^-) + h_{LEC}(c_1, f_1, f_2)$$

Qualitatively comparison with the Chiral Pert. Theory predictions

They must cross!!

(if isospin-breaking is included)



Isospin cattering lengths $a^{\pm}$

πN isospin symmetry (2 quark flavour only)

a^+ isoscalar

a^- isovector

[1] Weinberg, Phys. Rev. Lett. **17**, 616 (1966)

[2] Y. Tomozawa, Nuovo Cim. A **46** 707 (1966)

πN scattering lengths results

πH:

$$\epsilon_{1s}^{\pi H} \propto a^+ + a^- + f_{LEC}(c_1, f_1, f_2)$$

$$\Gamma_{1s}^{\pi H} \propto (a^-)^2 + g(c_1, f_2)$$

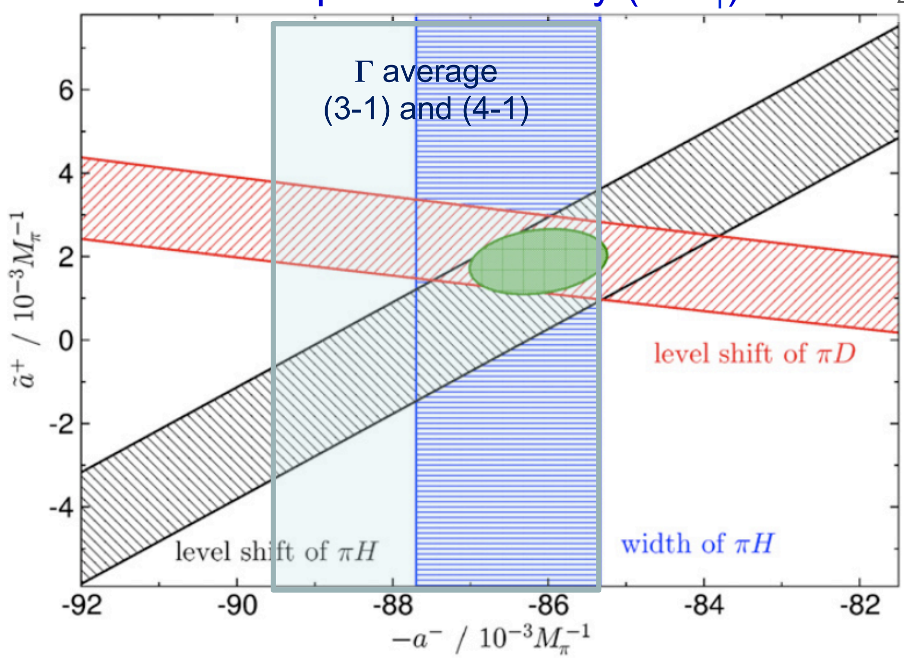
πD:

$$\epsilon_{1s}^{\pi D} \propto a^+ + h.o.(a^+, a^-) + h_{LEC}(c_1, f_1, f_2)$$

Quantitatively comparison with the Chiral Pert. Theory predictions

Δ exp ≈ 2 × Δ theory (no f_1)

Δ exp << Δ theory (with correction with f_1 involved)



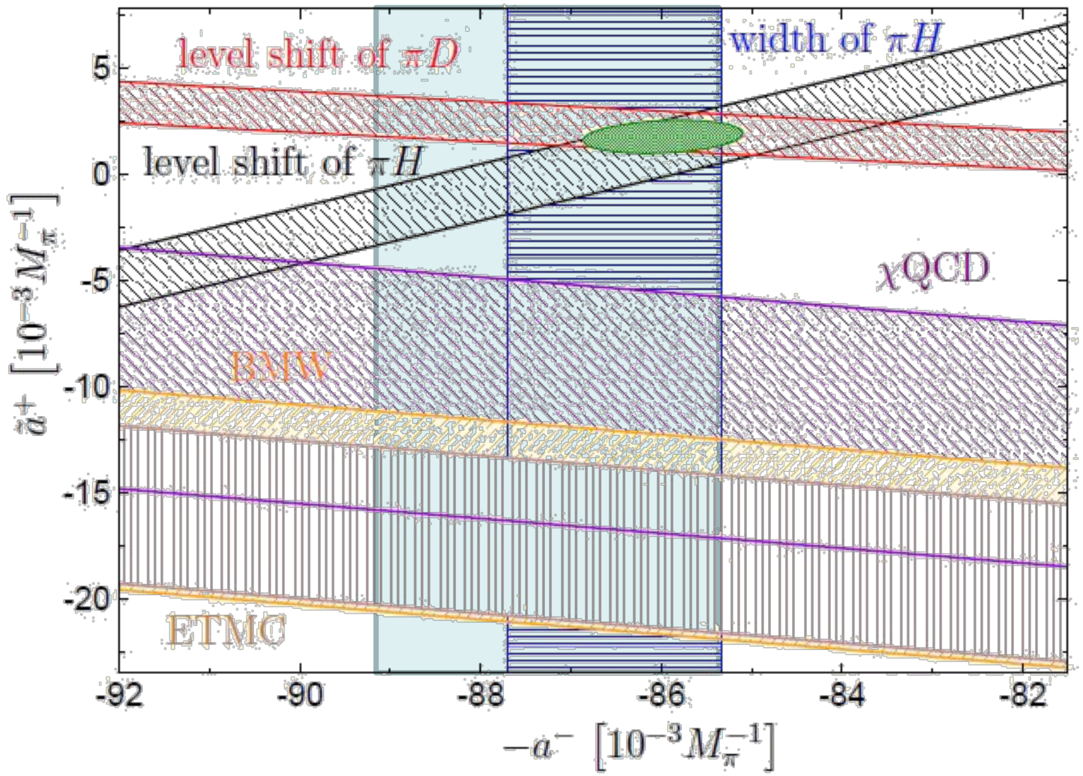
Δ exp << Δ theory (with correction with f_1 involved)

- consistency ✓
- $a^+ > 0$!!
- Constraints on f_1
- **πD decisive**

Fig. 2. Combined constraints in the $\tilde{a}^+$–a^- plane from data on the width and energy shift of πH, as well as the πD energy shift.

Baru et al., Phys. Lett. B **694**, 473-477 (2011).
Baru et al., Nucl. Phys. A **872**, 69-116 (2011).

Beyond chiral perturbation theory, lattice calculations and dark matter detection



← pionic atoms analysis

?

← Lattice predictions of the **sigma term**

M. Hoferichter, J. Ruiz de Elvira, B. Kubis, and U.-G. Meißner, Phys. Lett. B **760**, 74-78 (2016)

a^+ → **sigma term** $\sigma_{\pi N} = \frac{m_u + m_d}{4M} \langle p | \bar{u}u + \bar{d}d | p \rangle \leftrightarrow \langle p | \bar{s}s | p \rangle$ **contents** ➔ 59.1 ± 3.5 MeV

Crucial for the interpretation of dark-matter direct-detection experiments!!

J. Ellis, K.A. Olive, and C. Savage, Phys. Rev. D **77**, 065026 (2008)

a^- → pion–nucleus coupling constant via GMO sum rule

Summary

- Introduction
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  - Study of strong interaction force at low energy
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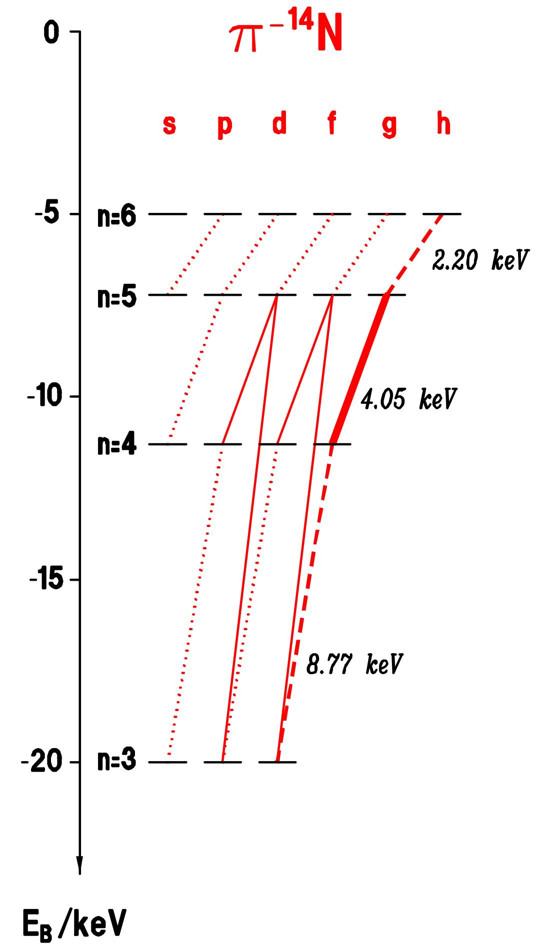
  - Production
  - Lamb shift measurement
  - Vacuum decay experiment
- Pionic atoms
  - Production
  - Pionic hydrogen and deuterium spectroscopy
  - **Pion mass measurement**
- Conclusions and outlooks

Pion mass measurement from πN and μO X-ray spectroscopy

Pion mass (unknown) or muon mass (reference)

$$E_{\text{X-ray}} = mc^2 \frac{(Z\alpha)^2}{2} \left(\frac{1}{n_f^2} - \frac{1}{n_i^2} \right) + \mathcal{O}(Z^4\alpha^4)$$

QED calculation only

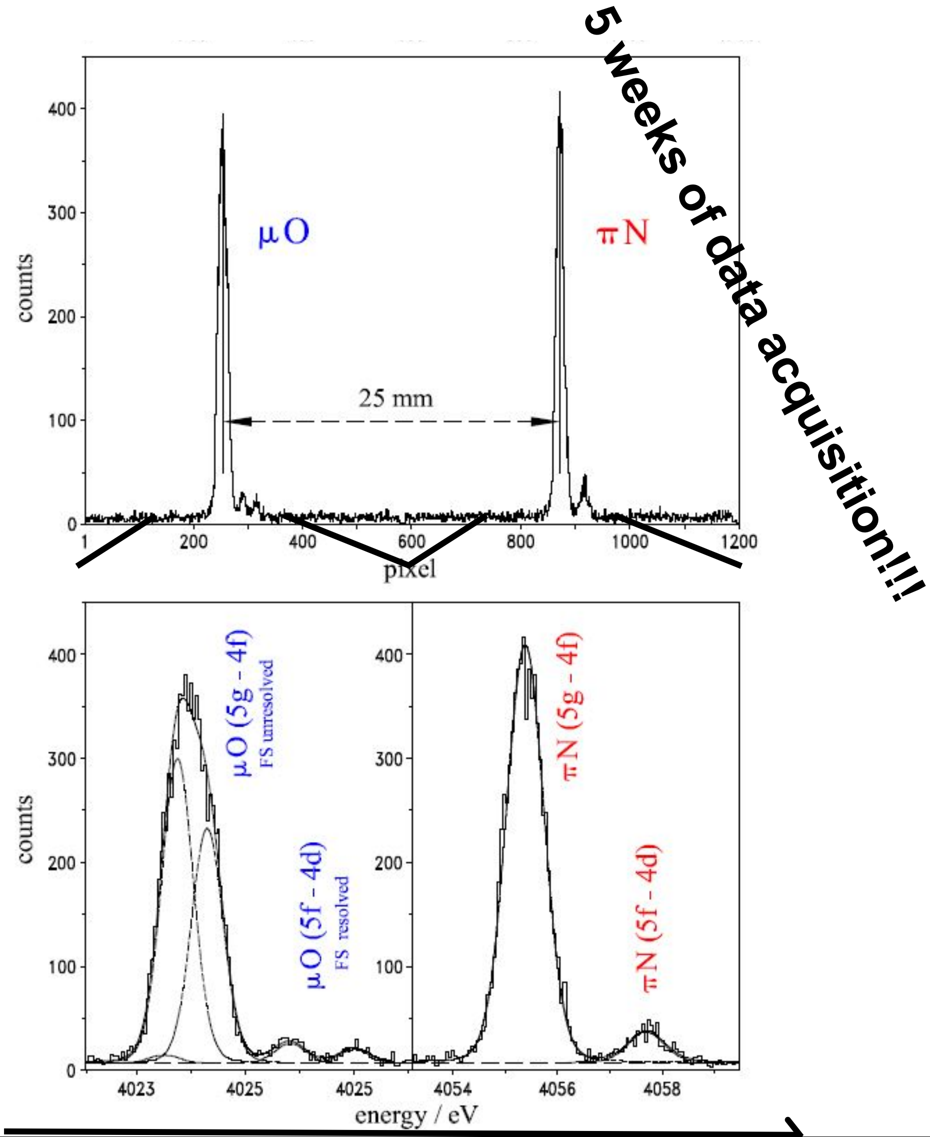


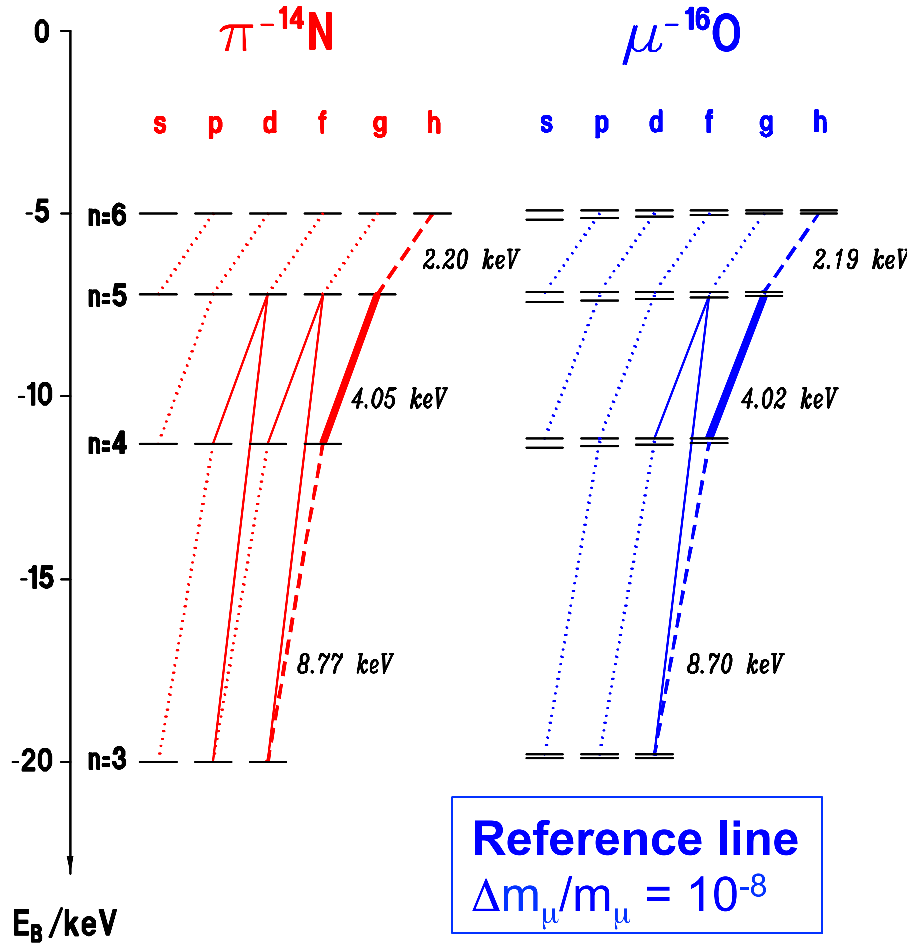
Circular transition enhanced

$$|n, \ell = n\rangle \rightarrow |n-1, \ell = n-1\rangle$$

Strong interaction effects minimized

5g-4f transitions in πN and μO





Reference line
$\Delta m_\mu / m_\mu = 10^{-8}$

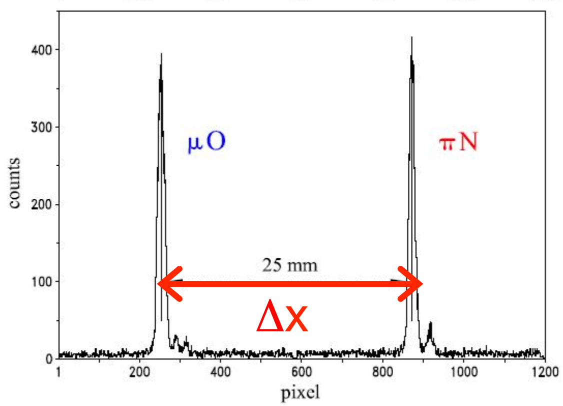
Muon = ½-spin particle

→ fine structure in μO

From the line position to the pion mass

From the spatial diff. to the angular position diff.

$$\Delta\Theta = -2\arctan\left(\frac{\Delta x}{2D}\right)$$



From the angular position diff. to the transition energy

$$E_{\pi N} = E_{\mu O}\frac{1}{\cos\Delta\Theta - \frac{\sqrt{1-[hc/(2dE_{\mu O})]^2}}{hc/(2dE_{\mu O})}\sin\Delta\Theta}$$

$$\frac{hc}{E} = 2d\sin\Theta_B$$

Bragg law

where

$$E_{\mu O} = \underset{\text{Dirac}}{f_{\text{QED}}}(m_\mu) = \tilde{m}_\mu c^2\frac{(Z\alpha)^2}{2}\left(\frac{1}{n_f^2} - \frac{1}{n_i^2}\right) + \underset{\text{Dirac}}{\mathcal{O}_{\text{QED}}}(Z^4\alpha^4)$$

From the transition energy to the **pion mass**

$$m_\pi = \underset{\text{Klein-Gordon}}{f^{-1}_{\text{QED}}}(E_{\pi N})$$

QED calculation (for πN) [1], ...

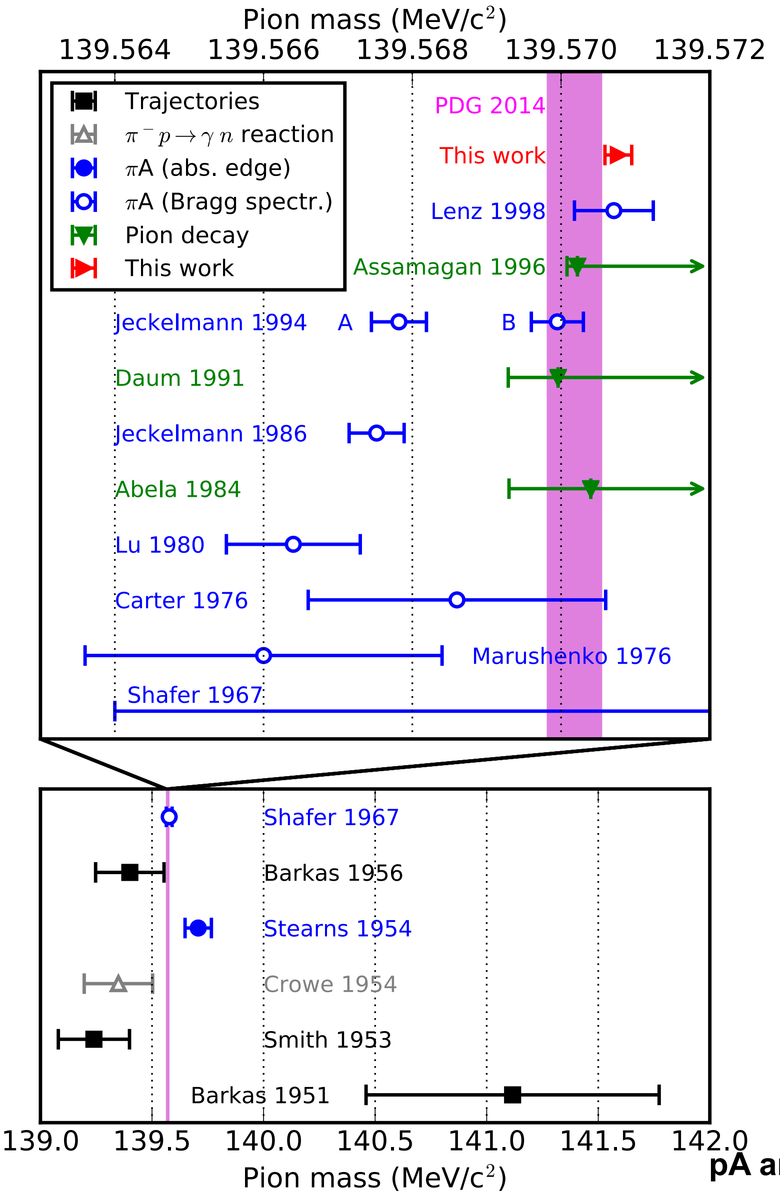
[1] M.T. and P. Indelicato, Phys. Rev. A **76**, 012510(2007)

List of systematic effects

type of uncertainty	μO / arcsec	πN / arcsec	total / arcsec	uncertainty / ppb
index of refraction shift	13.22	12.94	- 0.28	± 20
silicon lattice constant				± 2
bending correction	14.01	13.71	0.30	± 20
penetration depth correction	-0.07	-0.07	0	± 4
focal length				± 670
CCD alignment				± 340
pixel distance				± 120
alignment of detector normal				$^{+0}_{-30}$
detector height offset				$^{+0}_{-35}$
shape of target window				± 100
shape of reflection				± 225
individual curvature correction				± 150
temperature correction				± 30
response function and Doppler broadening				$^{+290}_{-350}$
line pattern modelling				$^{+190}_{-290}$
fit interval				± 15
QED energy				± 350
conversion constant *hc*				± 2
$4f$ strong interaction 45 μeV		0.003	-0.003	± 10
$5g$ strong interaction 0.2 μeV		0.000	0.000	± 0
K electron screening				± 0
total systematic error				$^{+950}_{-1000}$
statistical error				± 820

Total uncertainty: 1.3×10^{-6}
Statistical: 0.8×10^{-6}
Systematics: $\sim1\times10^{-6}$

The new measurement of the pion mass



Particle data group [1]:
139.57018 ± 0.00035 MeV/c^2
→ **2.5x10^{-6}** accuracy

Our work [2]:
139.57077 ± 0.00018 MeV/c^2
→ **1.3x10^{-6}** accuracy

- No effect of eventual remaining K-shell electrons (<10^{-9})
- High accuracy calibration line (0.25x10^{-6} from theory calc.)

Improved accuracy for X-ray standards from pionic atoms [3]

[1] Particle Data Group. Chinese Phys. C **38**, 090001 (2014)
[2] M.T. *et al.*, Phys. Lett. B **759**, 583-588 (2016)
[3] D.F. Anagnostopoulos *et al*, Phys. Rev. Lett. **91**, 240801 (2003)

Summary

- Introduction
  - Test of QED in strong field
  - Study of strong interaction force at low energy
- Heavy highly charged ions
  - Production
  - Lamb shift measurement
  - Vacuum decay experiment
- Pionic atoms
  - Production
  - Pionic hydrogen and deuterium spectroscopy
  - Pion mass measurement
- **Conclusions and outlooks**

Conclusions and perspectives for pionic atoms

- End of a long measurement campaign
- New input for investigation on strong interaction at low energy
- Deeper understanding (but not yet complete) of the atomic cascade and cross sections in exotic atomic systems
- New measurement of the pion mass

Next…

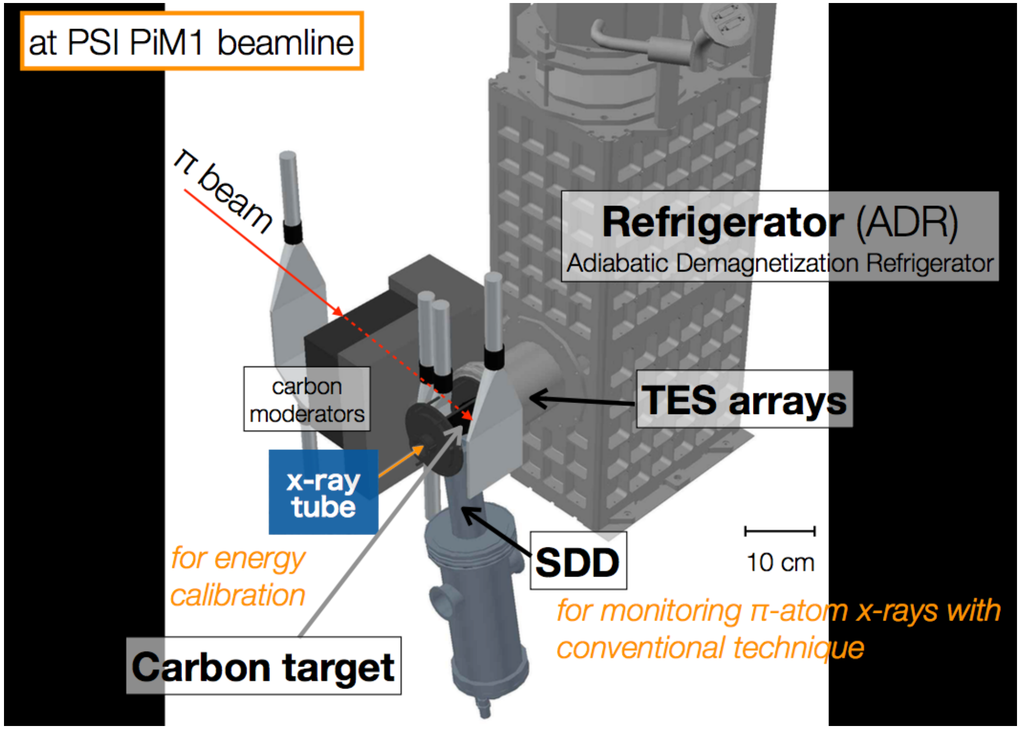
- Atomic cascade and cross sections calculations has to be improved
- New high-resolution experiments with πT and πHe? → Additional constraints on a^+ a^-
- …
- Resolution improvement?
  - Crystal spectrometer: 0.5 → 0.2 eV?
  - Microcalorimeter [1]? Lower resolution but higher efficiency
- New measurement of the pion mass: laser spectroscopy of πHe^+

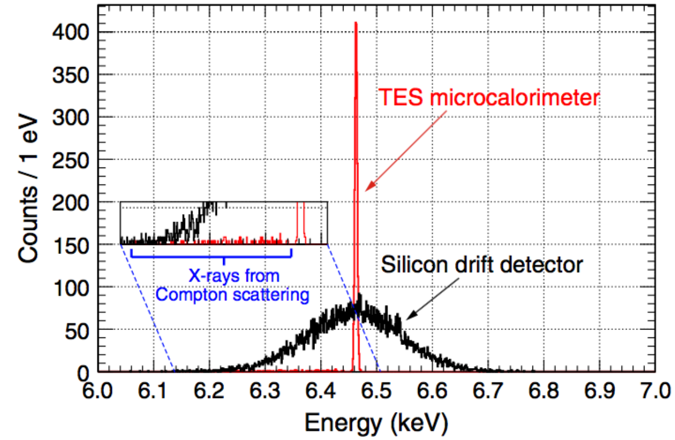
  Proposed experiment at PSI from Hori and co. [2]

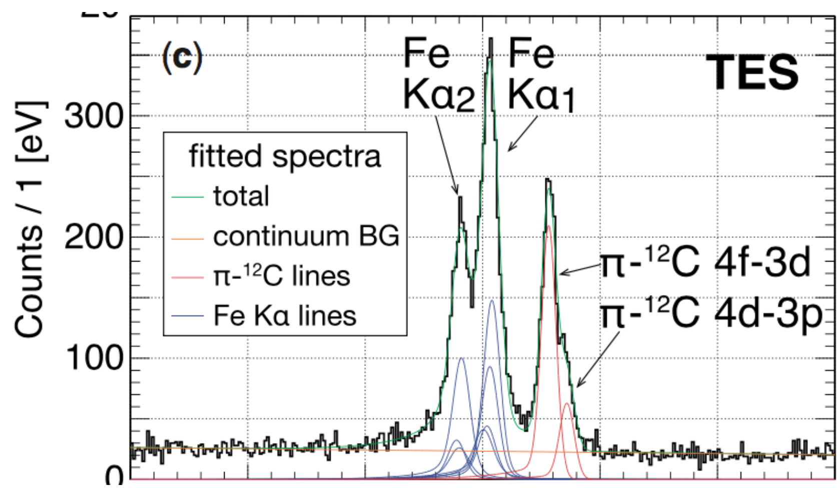
[1] S. Okada *et al.*, Prog. Th.Exp. Phys. **2016**, (2016)

[2] M. Hori *et al.*, Phys. Rev. A **89**, 042515 (2014)

Microcalorimeter measurement of πA and KA







S. Okada, D.A. Bennett, C. Curceanu *et al.*, Progress of Theoretical and Experimental Physics **2016**, (2016)
S. Okada, D.A. Bennett, W.B. Doriese *et al.*, J. Low Temp. Phys. **176**, 1015-1021 (2014)

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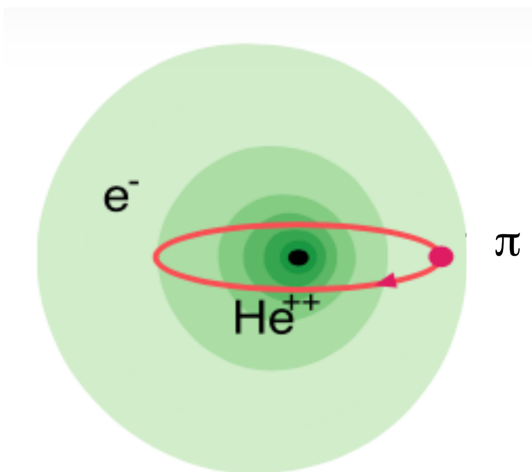
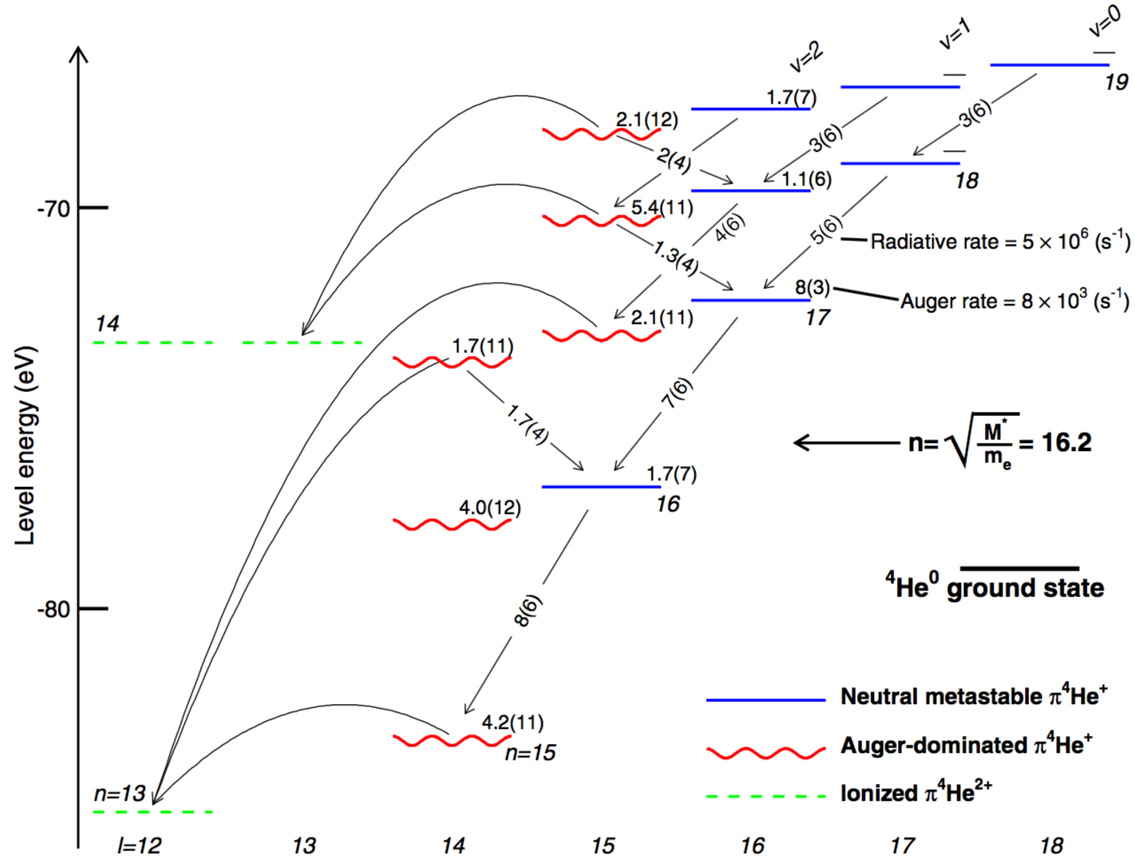
Pion mass measurement by laser spectroscopy of πHe^+





Goal accuracy: better than 1ppm

M. Hori *et al.*, Hyperfine Interact. **233**, 83-87 (2015).
M. Hori *et al.*, Phys. Rev. A **89**, 042515 (2014).

Conclusions and perspectives for heavy highly charged ion

- New QED tests in the strong Coulomb field (non perturbative regime)
- New phenomenon expected (spontaneous emission of positrons from the vacuum decay)
- Two-loop QED not yet tested in hydrogenlike systems

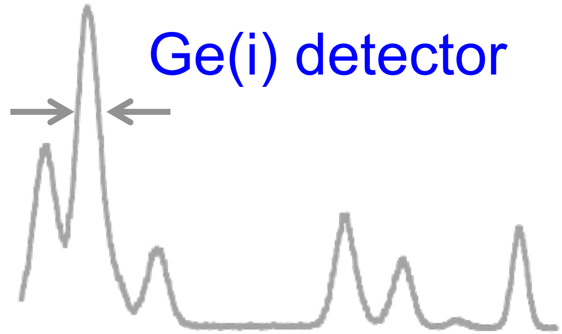
Next…

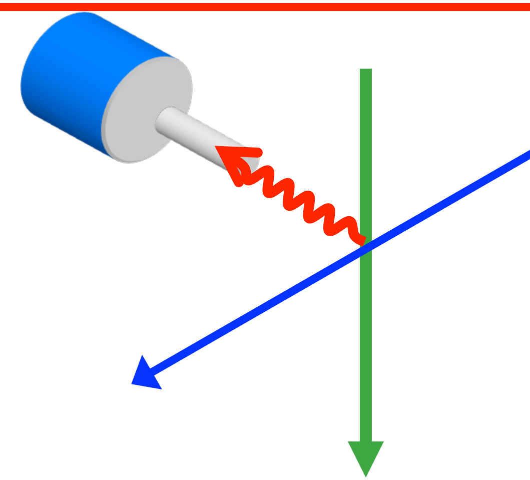
- Many new experiments already in preparation for the future
- New experimental methods in development
- New FAIR facility in construction and commissioning

Towards an accuracy of 1 eV of the 1s level Lamb shift

Resolution:
400 eV at 60 keV

$\varepsilon = 10^{-4}$

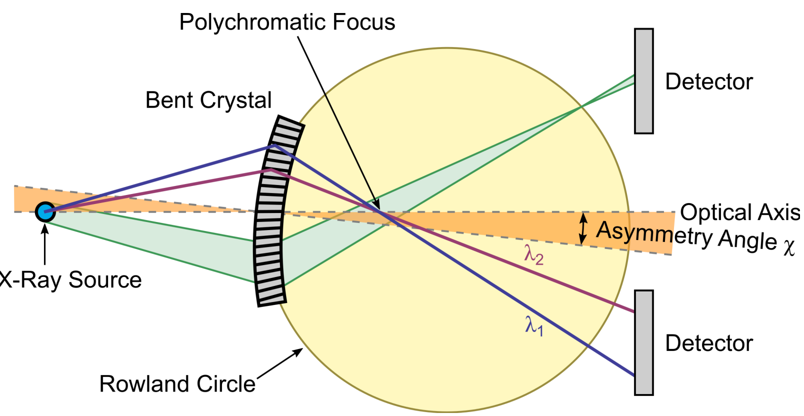




U^{91+} Lamb shift δE =4.6 eV

Crystal spectroscopy

Res: ~**50 eV** at 60 keV **$\varepsilon = 10^{-8}$**



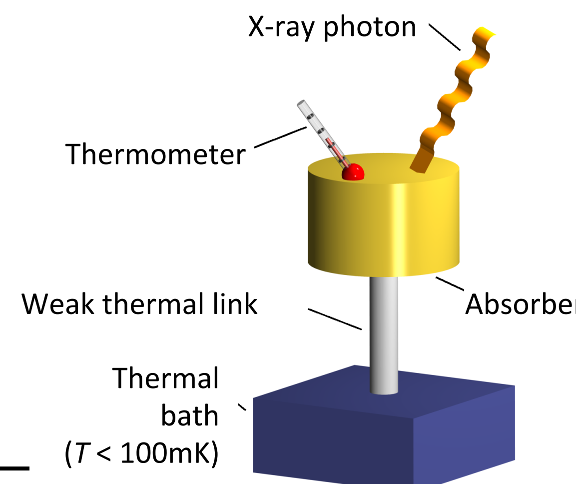
FOCAL spectrometer
T. Gassner, M.T. et al submitted to PRL

Microcalorimeters

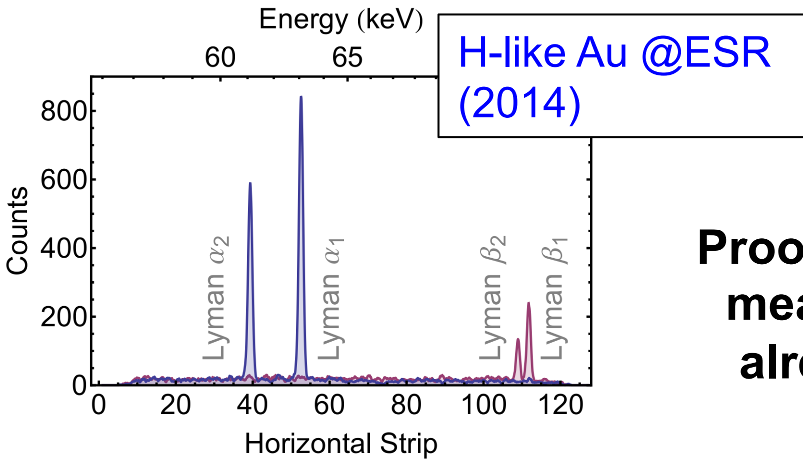
Res: ~**50 eV** at 60 keV **$\varepsilon = 10^{-4-6}$**

Resistive and magnetic microcalorimeters

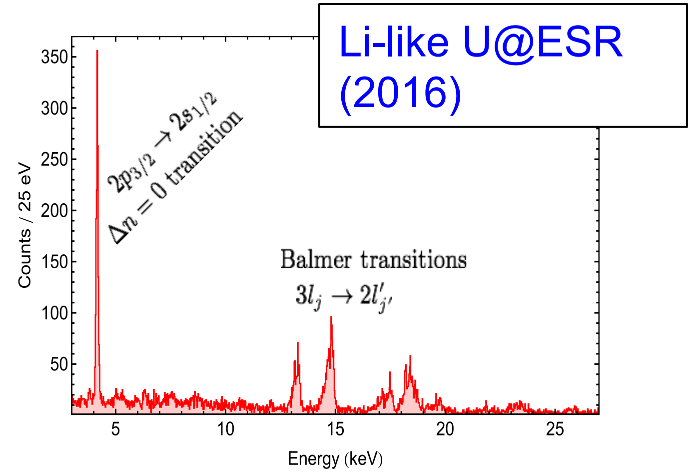
S. Kraft-Bermuth *et al.*, J. Phys. B **50**, 055603 (2017)
C. Pies *et al.*, J. Low Temp. Phys. **167**, 269-279 (2012)



Towards an accuracy of 1 eV of the 1s level Lamb shift



Proof of principle measurements already done!



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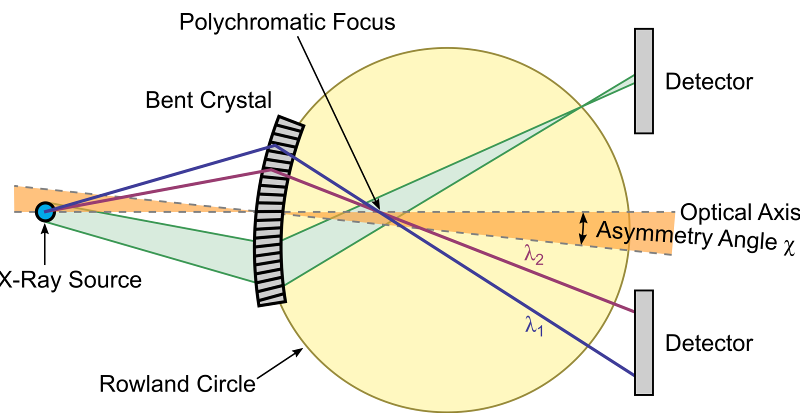
Res: ~50 eV at 60 keV **$\varepsilon = 10^{-8}$**

Microcalorimeters

Res: ~50 eV at 60 keV **$\varepsilon = 10^{-4-6}$**



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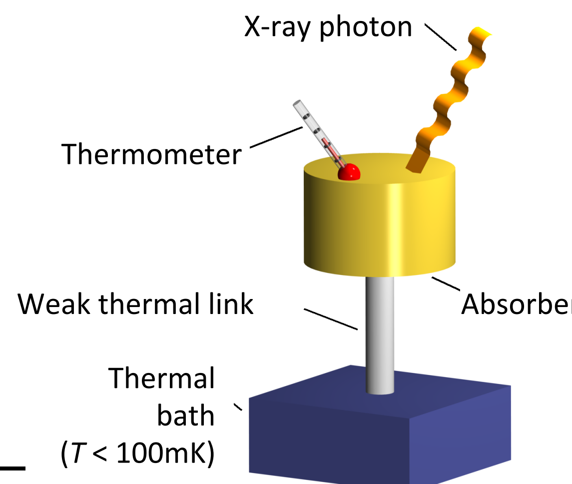
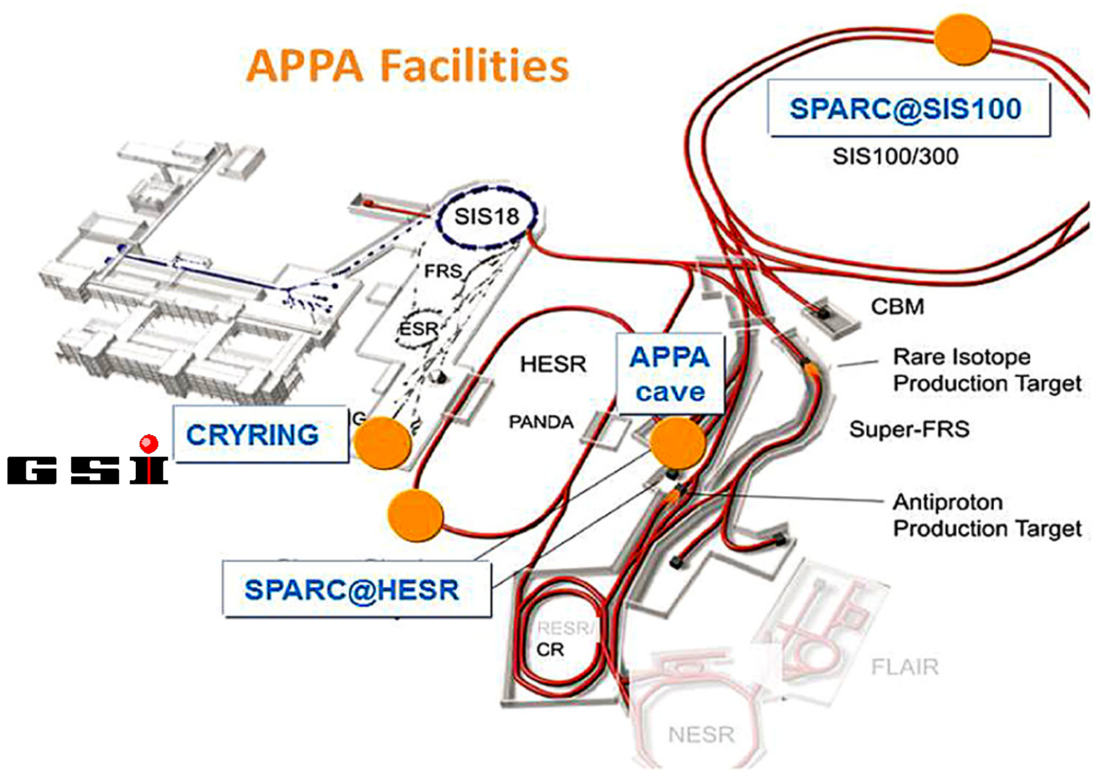
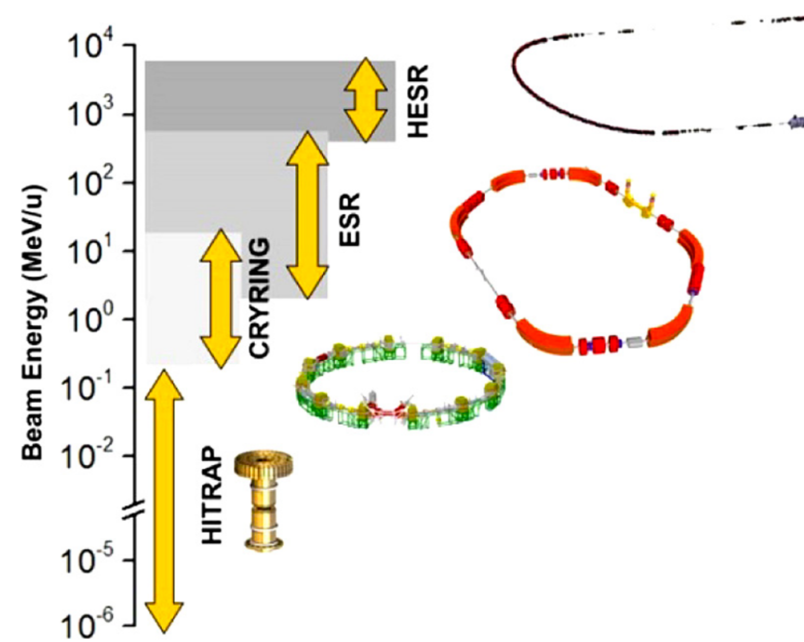
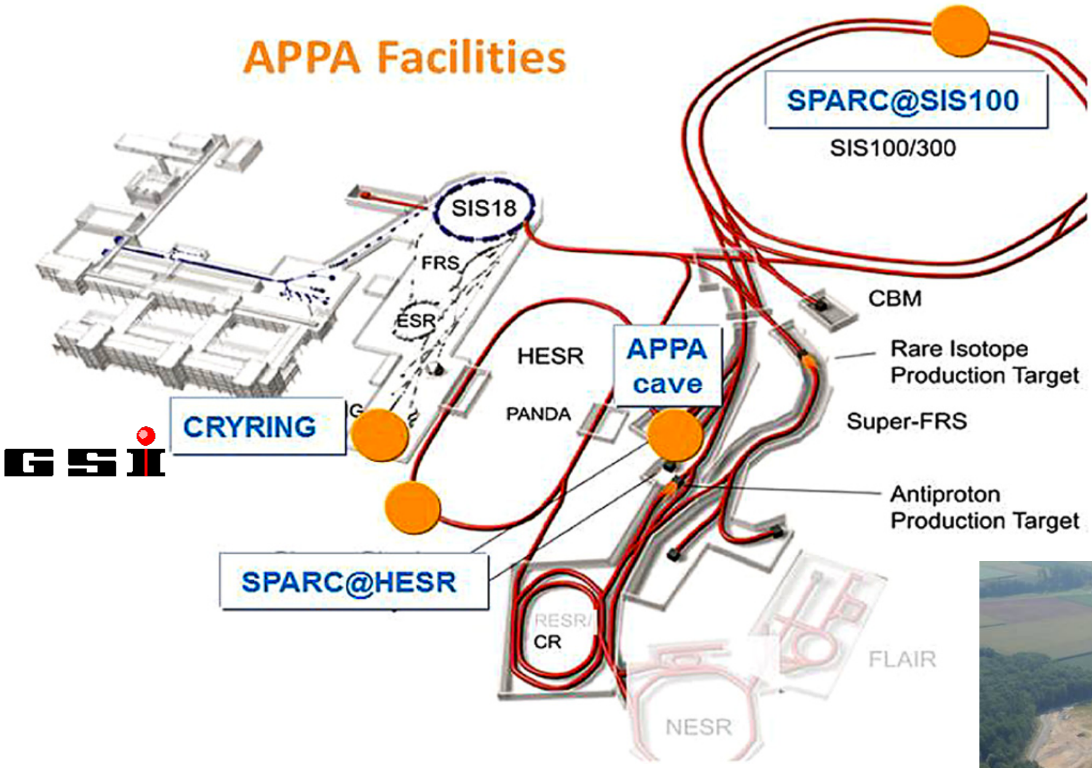






Availability of highly charged ions up to bare U with energies between 10 GeV/u to rest

FAIR facility



Phase-0: 2018-2019
Phase-1: 2024

Availability of highly charged ions up to bare U with energies between 10 GeV/u to rest

Thank you!

D. Banas, H.F. Beyer, K.H. Blumenhagen, F. Bosch, C. Brandau, A. Bräuning-Demian, H. Bräuning, W. Chen, Chr. Dimopoulou, E. Förster, T. Gaßner, S. Geyer, A. Gumberidze, S. Hagmann, S. Heß, R. Heß, P.-M. Hillenbrand, P. Indelicato, P. Jagodzinski, T. Kampfer, Chr. Kozhuharov, M. Lestinsky, D. Liesen, Yu.A. Litvinov, R. Loetzsch, B. Manil, R. Märtin, F. Nolden, N. Petridis, M.S. Sanjari, K.S. Schulze, M. Schwemlein, A. Simionovici, U. Spillmann, M. Steck, Th. Stöhlker, C.I. Szabo, S. Trotsenko, I. Uschmann, G. Weber, O. Wehrhan, N. Winckler, D. Winters, N. Winters, E. Ziegler

F. D. Amaro, D. F. Anagnostopoulos, A. Blechmann, S. Biri, P. Bühler, D. S. Covita, J. M. F. dos Santos, H. Fuhrmann, H. Gorke, D.Gotta, A. Gruber, M. Hennebach, A. Hirtl, T. Ishiwatari, Th. Jensen, E.-O. Le Bigot, V. E. Markushin, J. Marton, M. Nekipelov, V. Pomerantsev, V. Popov, S. Schlesser, A. Schmelzbach, Ph. Schmid, L. M. Simons, Th. Strauch, M. Theisen, J. F. C. A. Veloso, J. Zmeskal

S. Cervera, V. Gafton, T. Kirchner, E.V. Gafton, D. Hannani, S. Hidki, E. Lacaze, E. Lamour, A. Lévy, S. Macé, M. Maranglolo, J. Mérot, F. Mezdari, J.-Y. Pacquet, C. Prigent, J.-M. Ramillon, J.-P. Rozet, A. Salehzadeh, S. Steydli, D. Vernhet