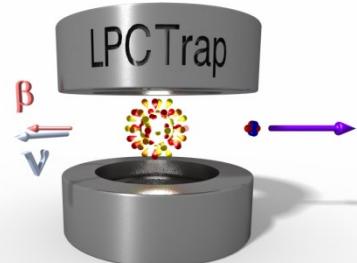
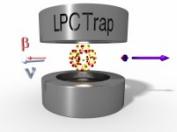


Electron shake-off Status: Same as last year...

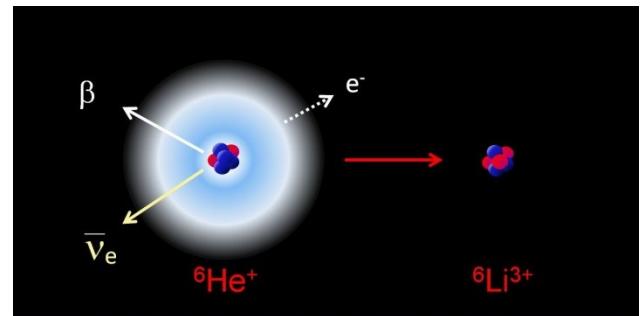
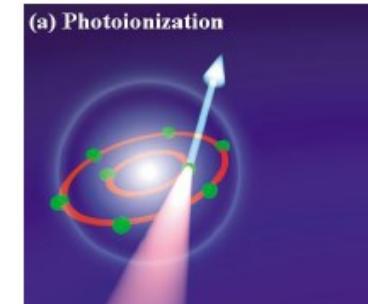


The electron shake-off (SO)



- SO is a fundamental atomic process: ionization resulting from the sudden change of the central potential...

- Creation of a vacancy in atomic inner shell
 - Fast collisions
 - Photo-ionization
- Change of the nuclear charge
 - α decay
 - Nuclear electron capture (EC)
 - β decay

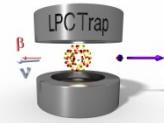


β decay \rightarrow Potential changes in $\sim 10^{-18}$ s \ll atomic relaxation time!

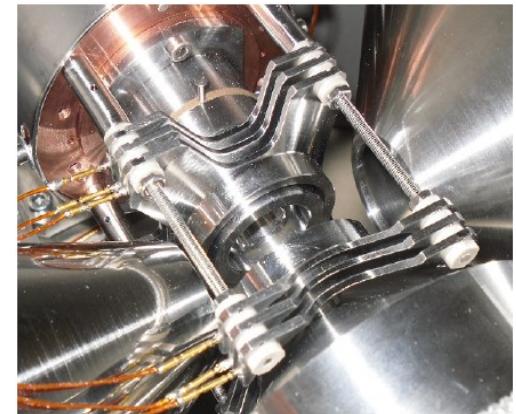
Ideal study case for atomic physics (very fast process)

- SO probabilities calculated in the sudden approximation limit

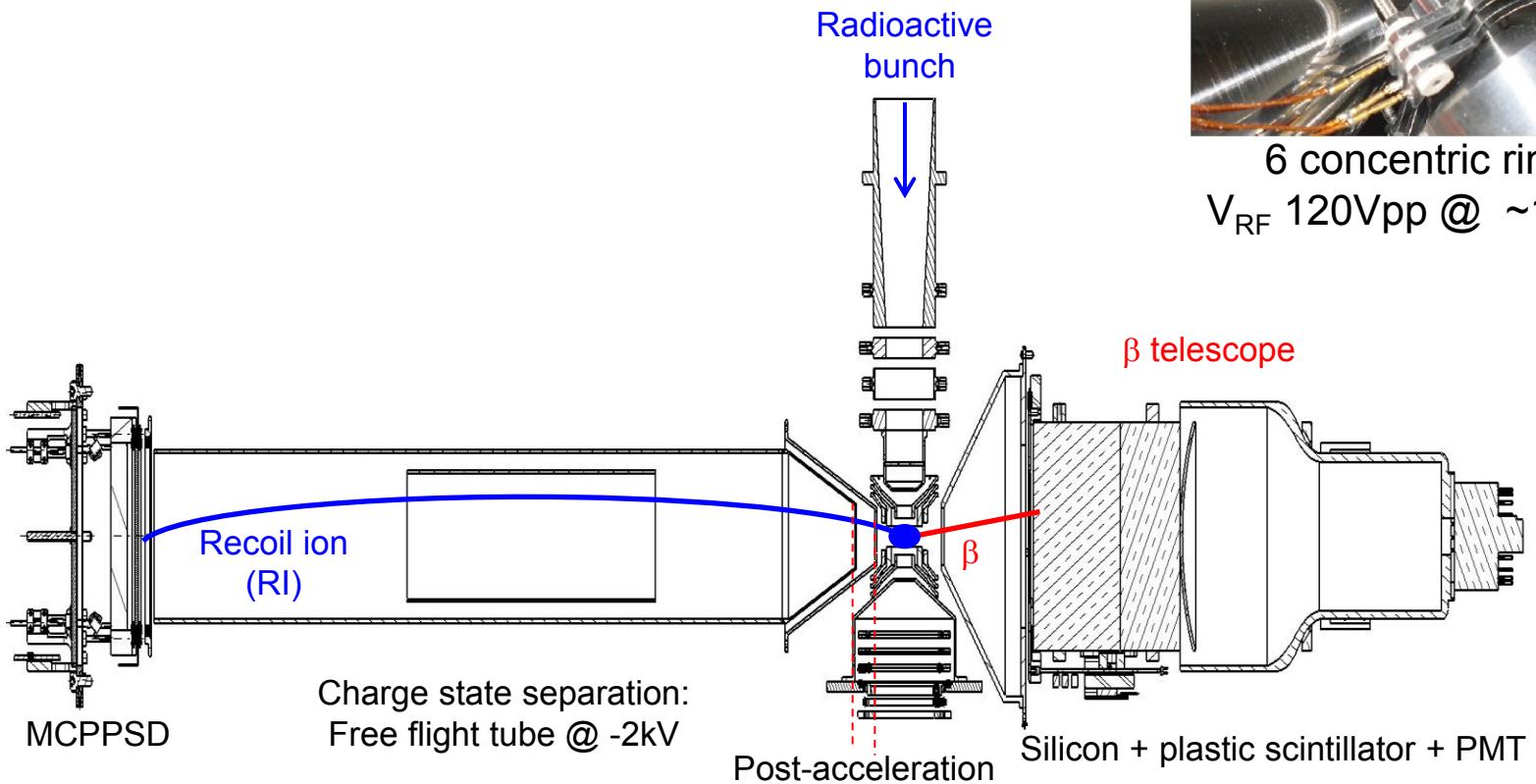
LPCTrap principle



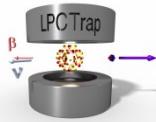
- Injection & confinement of decay source in a Paul trap
 - “universal” trap (works for any singly charged ion)
 - ions almost at rest, in vacuum
 - large solid angle for detection
- Detection in coincidence (RI & β particle)



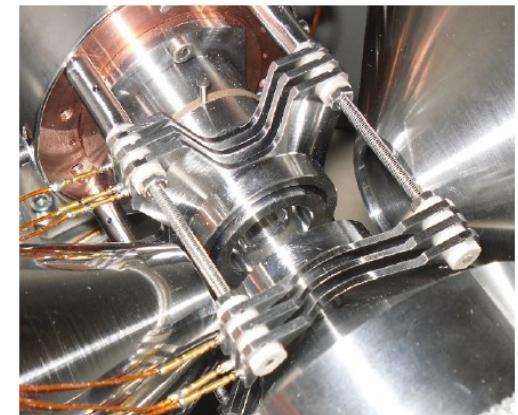
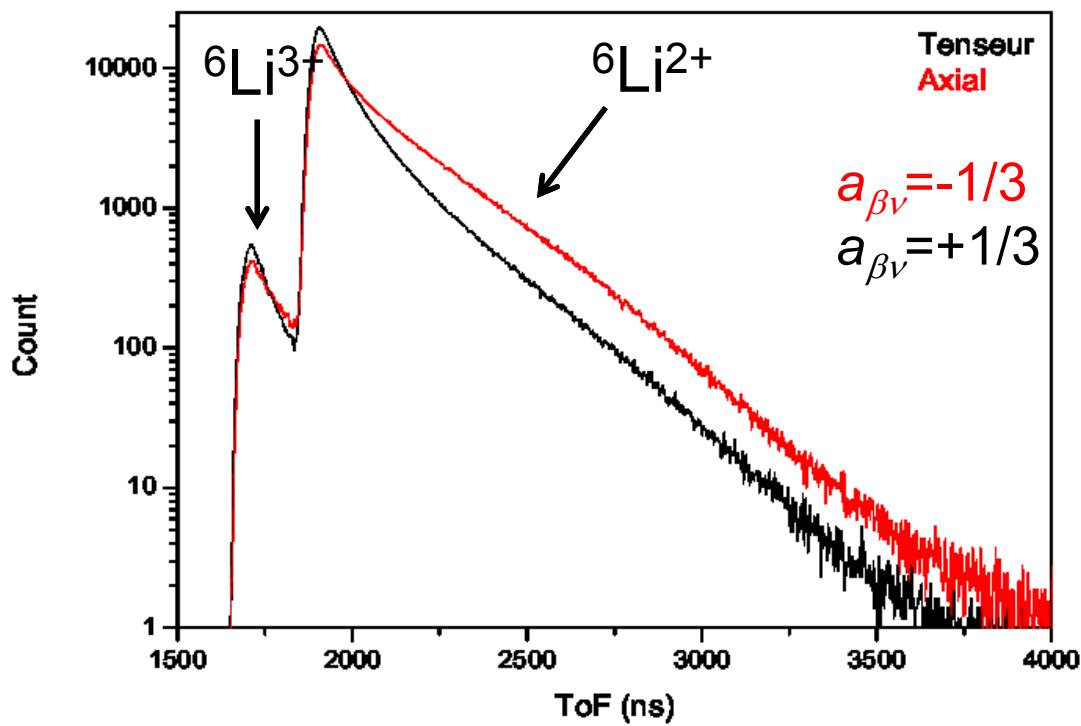
6 concentric rings
 V_{RF} 120Vpp @ ~1 MHz



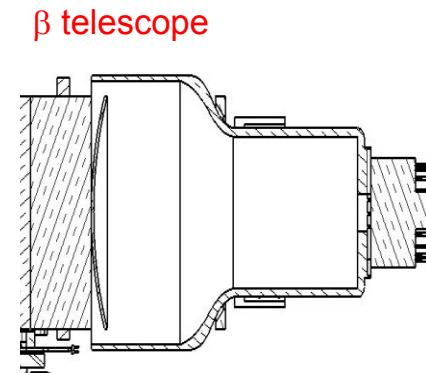
LPCTrap principle



- Injection & confinement of decay source in a Paul trap
 - “universal” trap (works for any singly charged ion)
 - ions almost at rest, in vacuum
 - large solid angle for detection
- Detection in coincidence (RI & β particle)
 - RI TOF measurement (simulation for ${}^6\text{He}^+$ decay)

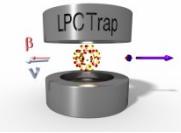


6 concentric rings
 V_{RF} 120Vpp @ ~1 MHz



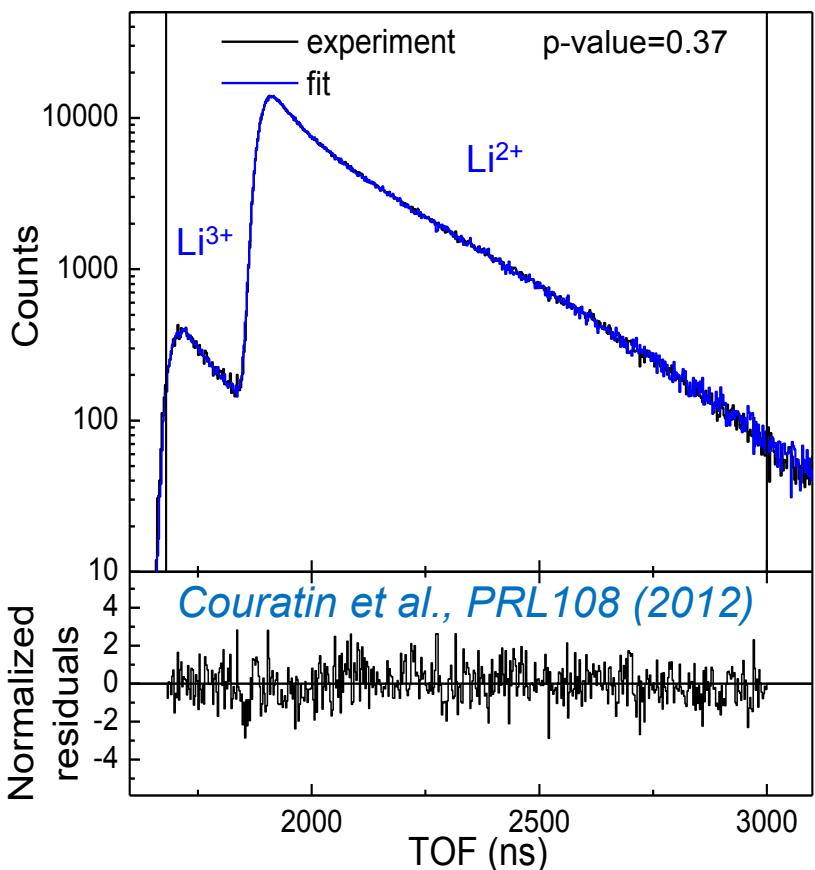
γ + plastic scintillator + PMT

Results with ${}^6\text{He}^+$ decay



■ Experimental conditions (2010):

- ${}^6\text{He}^+$ Intensity $\sim 10^8$ pps
- ~ 1.5 nA of ${}^{12}\text{C}^{2+}$ contamination (lost in RFQ)
- $\sim 1.2 \cdot 10^6$ « good » coincidences in ~ 4 days



■ Shake-off analysis:

- Complete Monte-Carlo simulation including all relevant systematic effects
- Fit of $P_{\text{shake-off}}$ assuming $a_{\beta\nu} = -1/3$

Systematic error budget

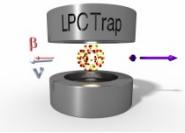
Source	Corr. (10^{-5})	Error (10^{-5})	Method
$a_{\beta\nu}$		4.0	[20]
β scattering	39	4.0	GEANT4
Background		3.5	present data
E_β calibration		1.7	present data
MCP efficiency	-9	1.2	present data
Total	30 ^a	7.0	

[20] F. Glück, Nucl. Phys. A628, 493 (1998).

$$P_{\text{shake-off}} = 0.02339(35)_{\text{stat}}(07)_{\text{syst}}$$

Quite high precision!!!

$$\Delta P_{\text{shake-off}} = 3.6 \cdot 10^{-4}$$

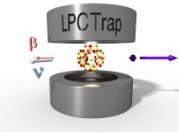


- Why high precision can be interesting here?
 - What can contribute to the ionization:
 - Nuclear charge change
 - Recoil effect (the nucleus gets away from the bound electron)
 - Direct collision β – electron (very small)
 - Multi-electron processes (e-e correlation & Auger electrons)
 - ${}^6\text{He}^+$ is particularly interesting:
 - Only one electron system
 - No e-e correlation, no secondary process (Auger emission)
→ Pure electron Shake-off
 - Analytic full quantum calculation in sudden approximation is possible using hydrogen like wavefunctions

$$P_{\text{so}} = 1 - \sum_{n,l,m} |\langle 1, 0, 0, Z | \exp(-i\vec{K}\cdot\vec{r}) | n, l, m, Z' \rangle|^2$$

→ Perfect textbook case for theory!

shake-off theory for ${}^6\text{He}^+$ decay



- SA: $P_{\text{so}} = 1 - \sum_{n,l,m} |\langle 1, 0, 0, Z | \exp(-i\vec{K}\vec{r}) | n, l, m, Z' \rangle|^2$
 where n , l and m are the radial, orbital momentum and orbital momentum projection numbers respectively, $Z = 2$ ($Z' = 3$) is the number of protons in the initial (final) system and \vec{K} is the wave vector of the final system. For the SO following the β decay of ${}^6\text{He}^+$ ions, this leads to

$$P_{\text{so}} = (2.338 \cdot 10 + 0.004 \cdot 12 E_{\text{rec}}) \times 10^{-2}, \quad (2)$$

Monopole contribution recoil contribution

- Correction for direct collision (with β^-): $\delta P_{\text{so}} = -\frac{1}{(\hbar c)^2} \int_0^{R_0} dR_1 \int_0^{R_0} dR_2$
 $R = ct \quad \delta V(r, R) \rightarrow e^2/R \quad \text{or} \quad e^2/r$
 $R_0 = 2\langle 1s, Z | r | 1s, Z \rangle \quad (93\% \text{ of charge})$

$$\longrightarrow \delta P_{\text{so}} = \frac{-20 \times 10^{-5}}{\text{collision contribution}}$$

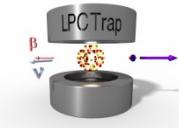
$$\langle P_{\text{so}} \rangle = 0.023 \cdot 22 \quad P_{\text{so}}^{\text{exp}} = 0.02339(36)$$

No surprise....

But first precise test of theory for a shake-off process!!!

PRL « highlight », Couratin et al., PRL108 (2012)

Results with $^{35}\text{Ar}^+$ decay

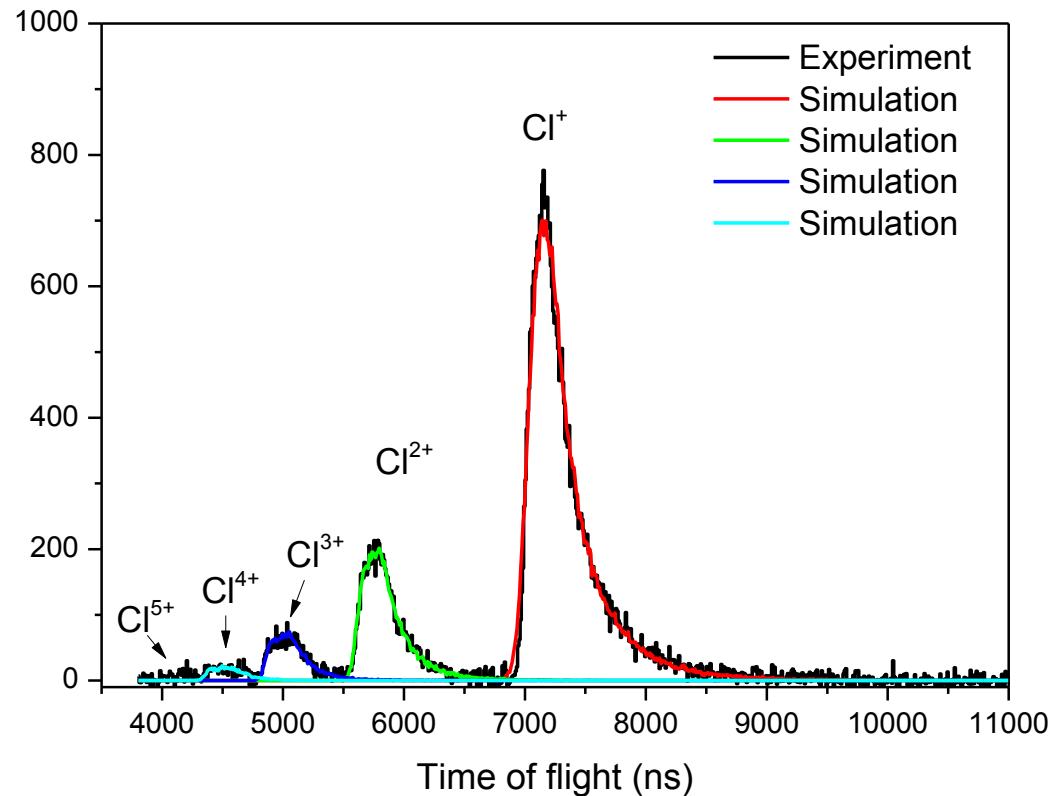


■ Experimental conditions (2011):

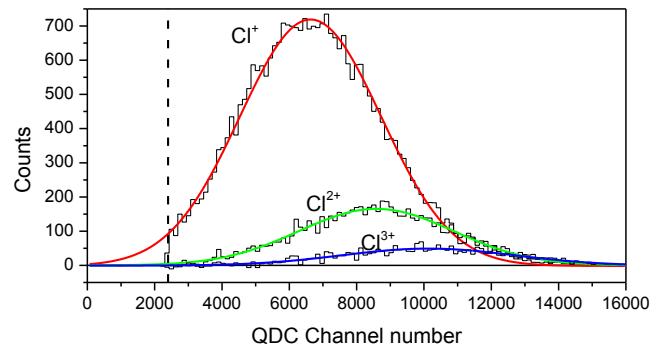
- $^{35}\text{Ar}^+$ Intensity $\sim 10^7$ pps
- Efficiency limited by stable contaminants
- $\sim 4 \times 10^4$ coincidences in ~ 32 hours

■ Shake-off analysis:

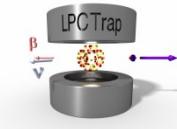
- $P_{\text{shake-off}}$ extraction by peak integration
- Corrections:
 - Peak tails recovering with M-C simulations (assuming $a_{\beta\nu} = 0.9004$)
 - RI detection efficiency (dependency on charge state)



Couratin et al., PRA88 (R) (2013)



Theory for $^{35}\text{Ar}^+$ decay



- For $^{35}\text{Ar}^+$ decay ($T_{1/2}=1,8\text{s}$ $E_{\beta\text{max}}=4,9\text{MeV}$)

(Theory by Bernard Pons, CELIA, Bordeaux)

- Sudden Approximation
- Independent electron model (IPM)
- Restricted Open-shell Hartree-Fock (wave functions calculations)
- Direct collision and shake-up neglected
- Auger transitions (Kaastra and Mewe)

$$p_i = 1 - \sum_{n' \leq 3} \left\{ \left| \langle \varphi_{n'l_i}^{(\text{Cl})} | \varphi_{n_il_i}^{(\text{Ar}^+)} \rangle \right|^2 + K^2 \left| \langle \varphi_{n'l_i \pm 1}^{(\text{Cl})} | \mathbf{r} | \varphi_{n_il_i}^{(\text{Ar}^+)} \rangle \right|^2 \right. \\ \left. - K^2 \text{Re} \langle \varphi_{n'l_i}^{(\text{Cl})} | \varphi_{n_il_i}^{(\text{Ar}^+)} \rangle^* \langle \varphi_{n'l_i}^{(\text{Cl})} | r^2 | \varphi_{n_il_i}^{(\text{Ar}^+)} \rangle \right\}.$$

$$P_{qs}^{\text{ion}} = \sum_{i_1=1}^N p_{i_1} \sum_{i_2 > i_1}^N p_{i_2} \dots \sum_{i_{qs} > i_{qs-1}}^N p_{i_{qs}} \prod_{j \neq i_1, \dots, i_{qs}}^N (1 - p_j)$$

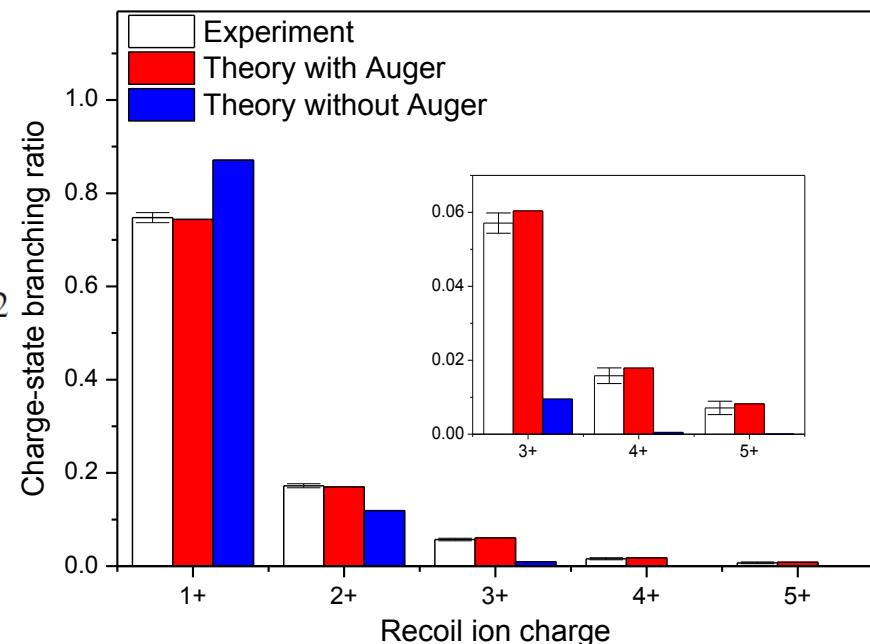
+ Auger emission probability for each ionization string

**Excellent agreement! (1% precision for charged RI)
Strong contribution of Auger effects!**

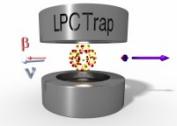
Couratin et al., PRA88 (R) (2013)

Neutral Cl production:

Experiment: 72(10) %
Theory: 73,9 %

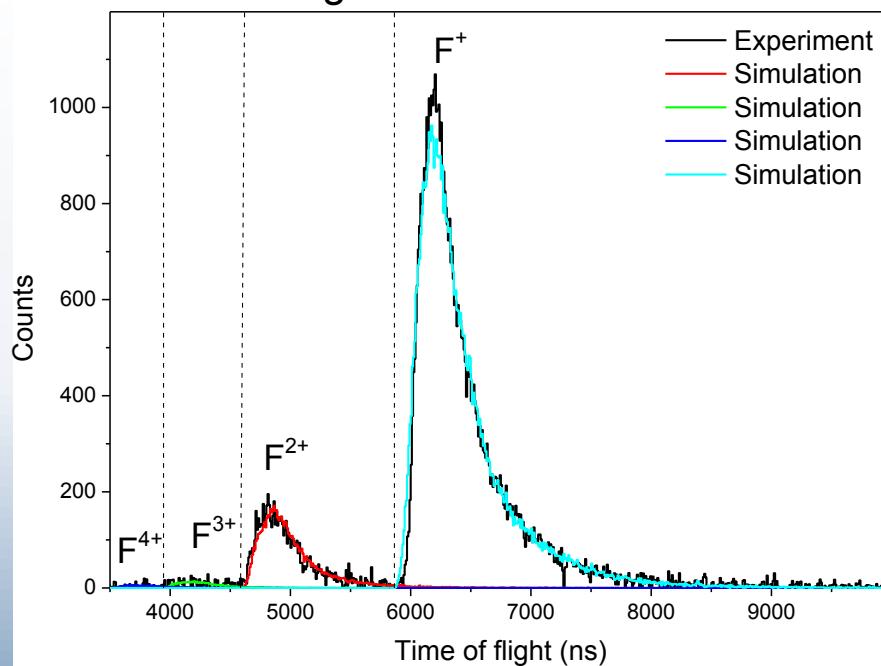


Results with $^{19}\text{Ne}^+$ decay



■ Experimental conditions (2013):

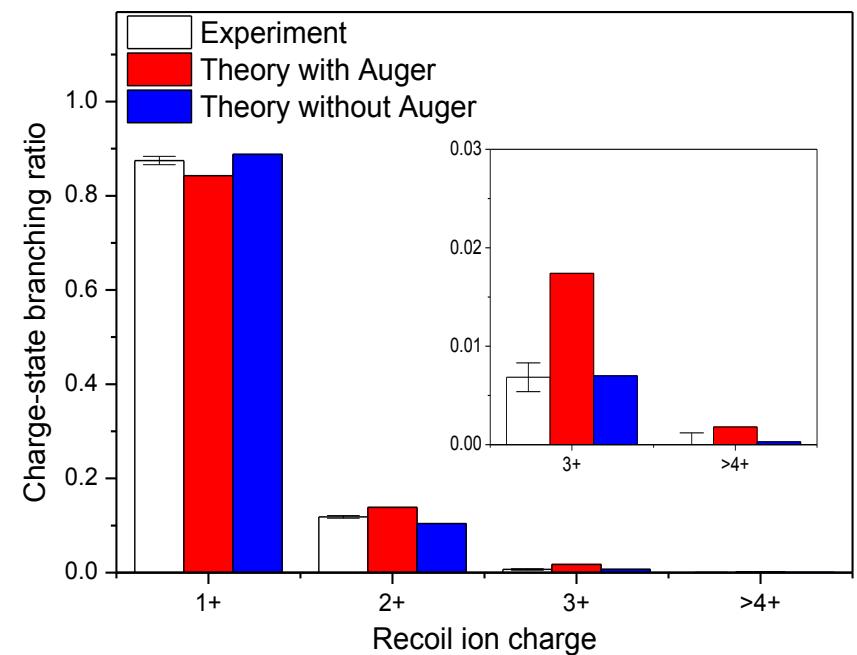
- ^{19}Ne Intensity $\sim 10^8$ pps
- $\sim 10 \text{ nA}$ of $^{18}\text{OH}^+$ \rightarrow Use of $^{19}\text{Ne}^{2+}$
- $\sim 200 \text{ pA}$ of $^{19}\text{F}^{2+}$ contaminants (limiting factor)
- Long half life ($\sim 17 \text{ s}$)
- $\sim 1.1 \cdot 10^5$ « good » coincidences in $\sim 1 \text{ week}$



Neutral F production:

Experiment: $69,5(4,2) \%$

Theory: $76,49 \%$



Overestimation of neutrals (1.7σ discrepancy) & overestimation of ($2+, 3+, 4+$) charge states (up to 5σ discrepancy)

→ Possible test with Theory: include shake-up probabilities...

Thank you



- G. Ban
- D. Durand
- X. Fabian
- X. Fléchard
- E. Liénard
- F. Mauger
- G. Quemener



- P. Delahaye
- J-C. Thomas



- A. Méry

KU LEUVEN

- M. Breitenfeldt
- C. Couratin
- P. Finlay
- T. Porobic
- N. Severijns
- S. Van Gorp
- Ph. Velten



- O. Naviliat-Cuncic



- B. Fabre
- B. Pons