A New Setup for Observation of **Forbidden Lines** from Metastable Ions produced in **Charge Exchange Collisions**

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Atomic Emissions in Plasmas

Excitation by Electron Impact : Major

$$\mathrm{A}^{q+} + \mathrm{e}^- \rightarrow \mathrm{A}^{q+*} + \mathrm{e}^- \rightarrow \mathrm{A}^{q+} + h\nu + \mathrm{e}^-$$

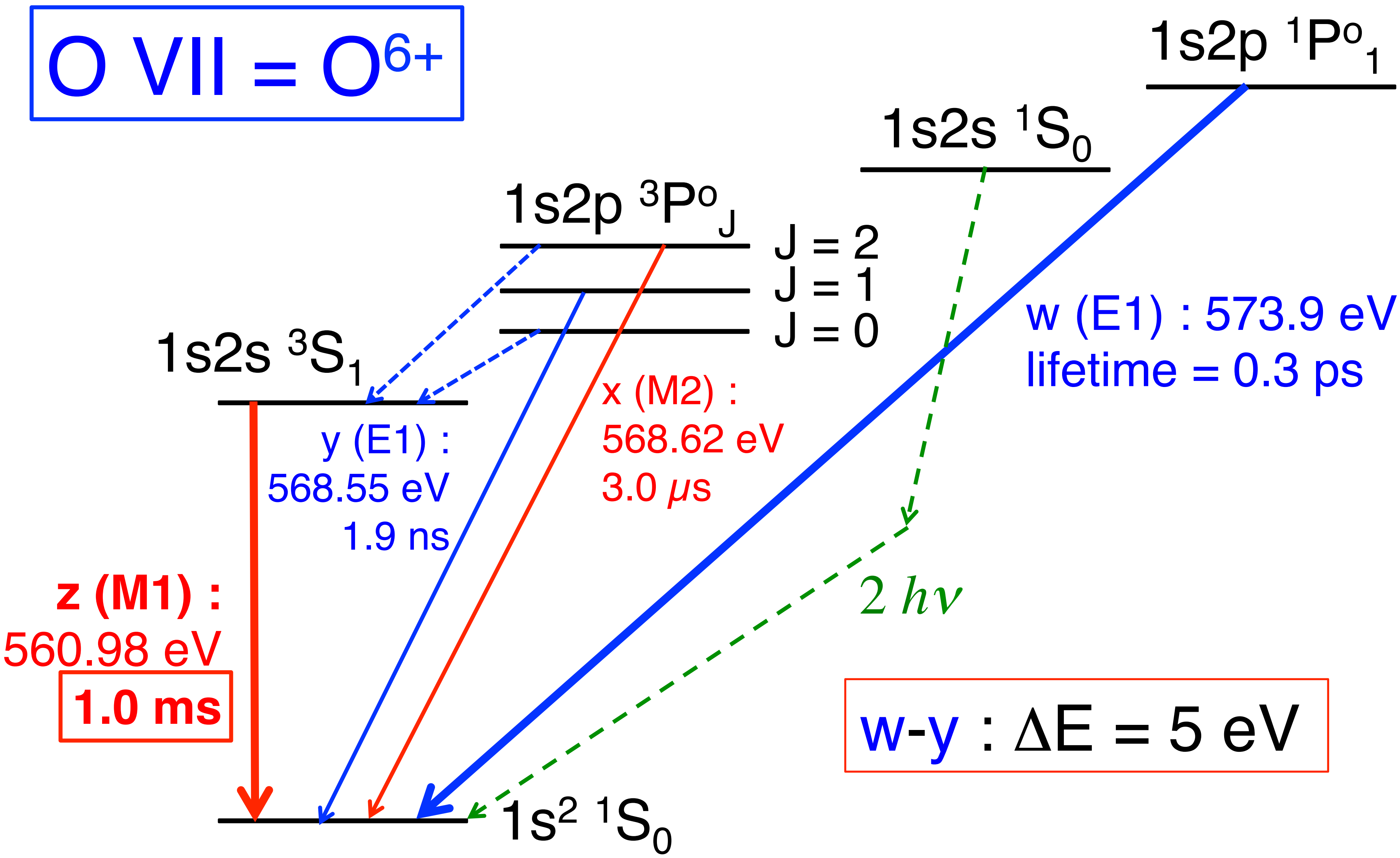
Recombination (Ion - Electron) : Minor

$$\mathrm{A}^{q+} + \mathrm{e}^- \rightarrow \mathrm{A}^{(q-1)+*} \rightarrow \mathrm{A}^{(q-1)+} + h\nu$$

Charge Exchange (Ion - Neutral) : Very Minor

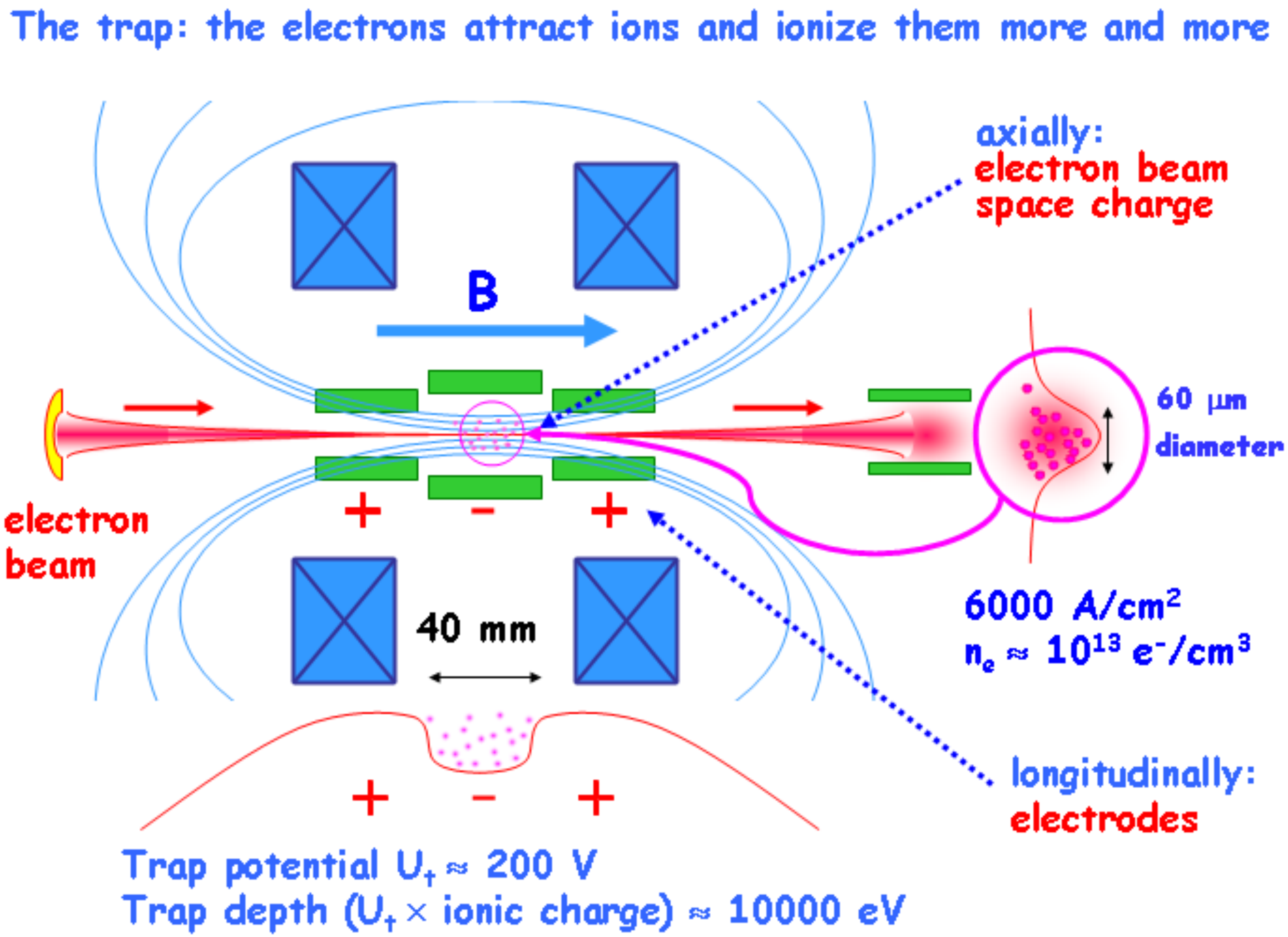
$$\mathrm{A}^{q+} + \mathrm{B} \rightarrow \mathrm{A}^{(q-1)+*} + \mathrm{B}^- \rightarrow \mathrm{A}^{(q-1)+} + h\nu + \mathrm{B}^-$$

Energy levels of He-like O ions



I. M. Savukov *et al.* (2003)

EBIT (Electron Beam Ion Trap)



The Principle of an EBIT @ Heidelberg

Spectra of He-like Ions by EBIT

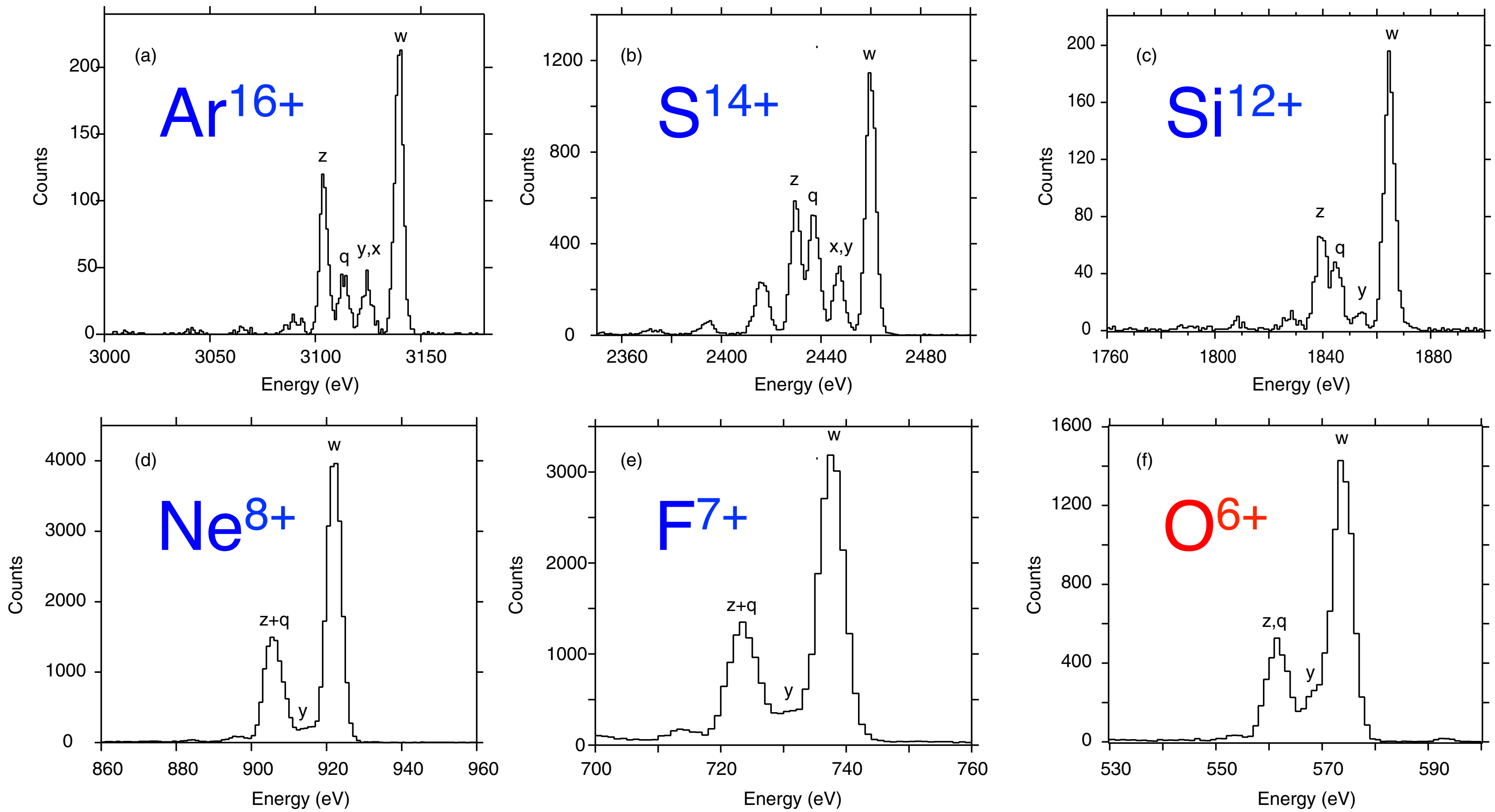


Figure 3. X-ray emission of heliumlike (a) argon, (b) sulfur, (c) silicon, (d) neon, (e) fluorine, and (f) oxygen measured with the ECS instrument on SuperEBIT.

In light elements, w > z (r > f) by electron impact.

P. Beiersdorfer *et al*. JPCS <u>163</u>, 012022 (2009).

Atomic Emission in Plasmas

Excitation by Electron Impact : E1 transitions

$$A^{q+} + e^- \rightarrow A^{q+^*} + e^- \rightarrow A^{q+} + h\nu + e^-$$

Recombination (Ion - Electron) : E1 & non E1

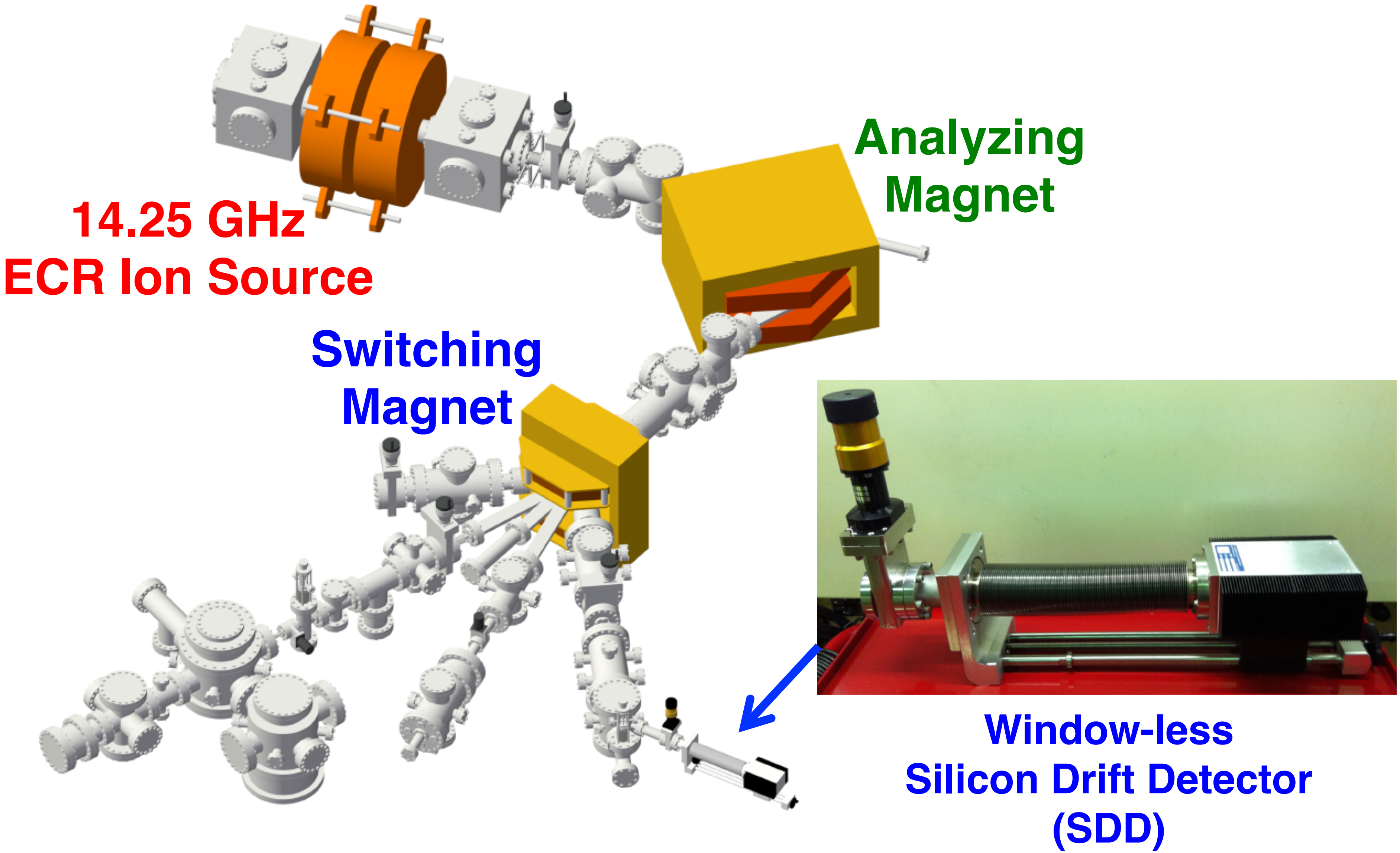
$$A^{q+} + e^- \rightarrow A^{(q-1)+^*} \rightarrow A^{(q-1)+} + h\nu$$

Charge Exchange (Ion - Neutral) : E1 & non E1

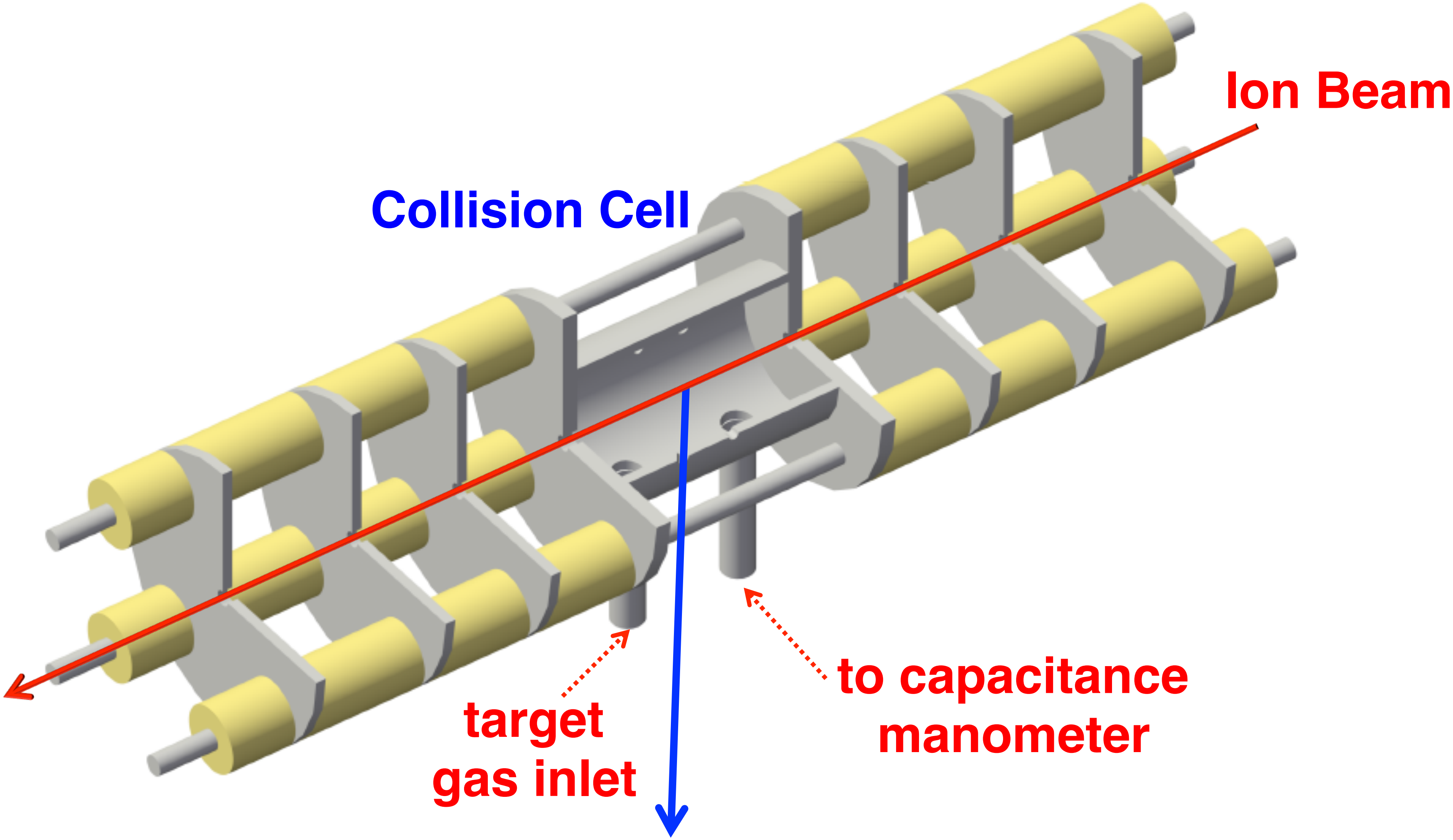
$$A^{q+} + B \rightarrow A^{(q-1)+^*} + B^- \rightarrow A^{(q-1)+} + h\nu + B^-$$

→ Ion Beam Collision Experiments

Multiply Charged Ion Beam Lines

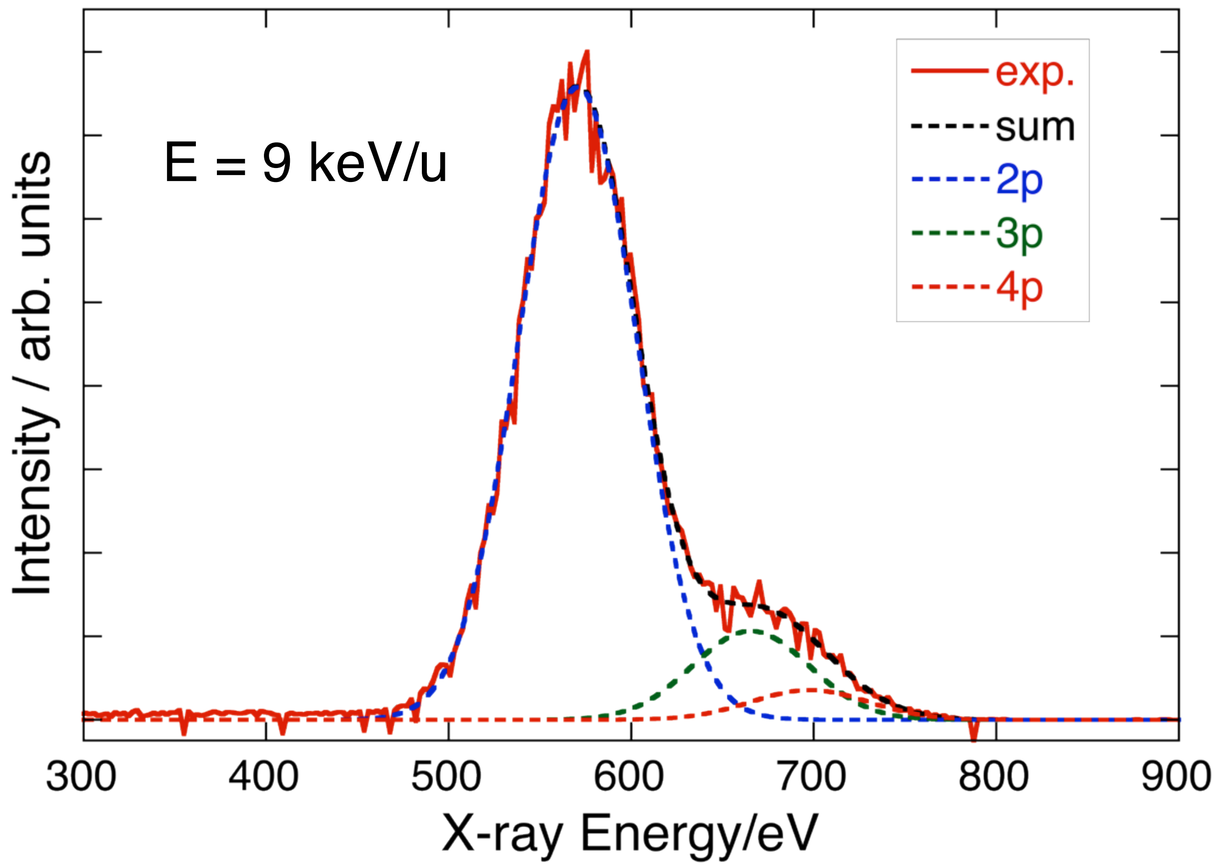


Setup for X-ray measurements



Magic Angle = 54.736°

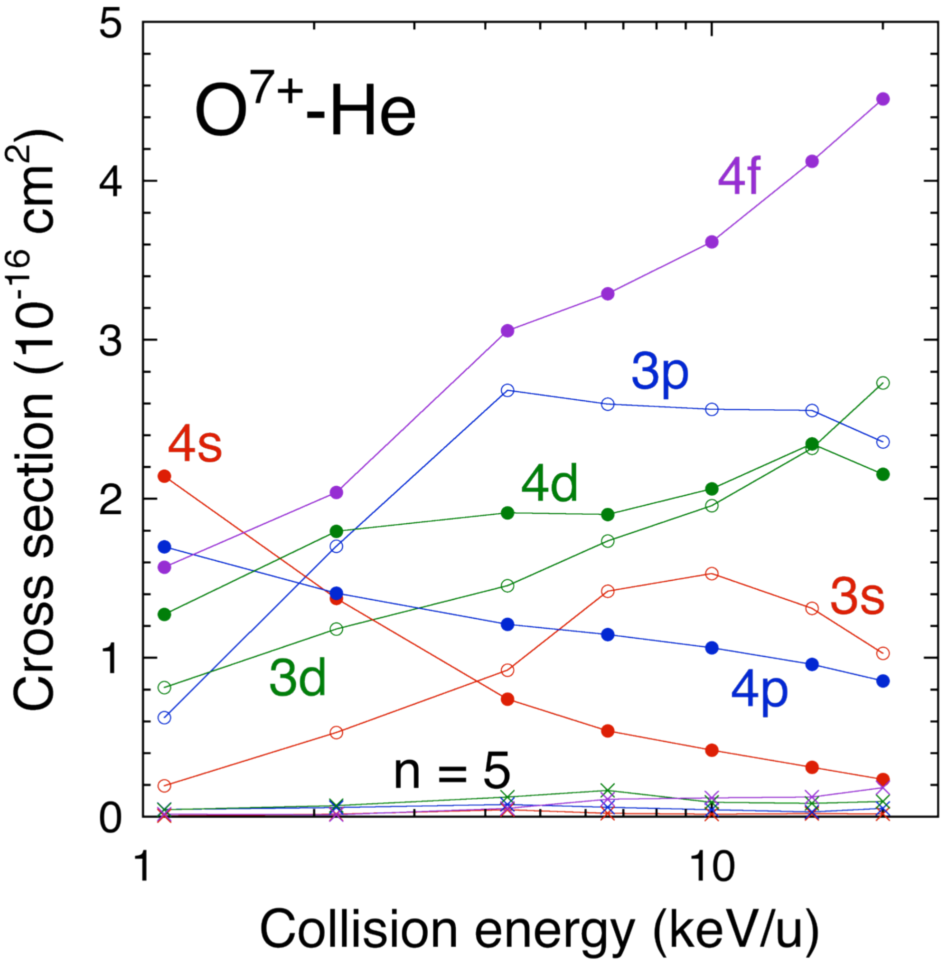
X-ray spectra in O^{7+} - He collisions



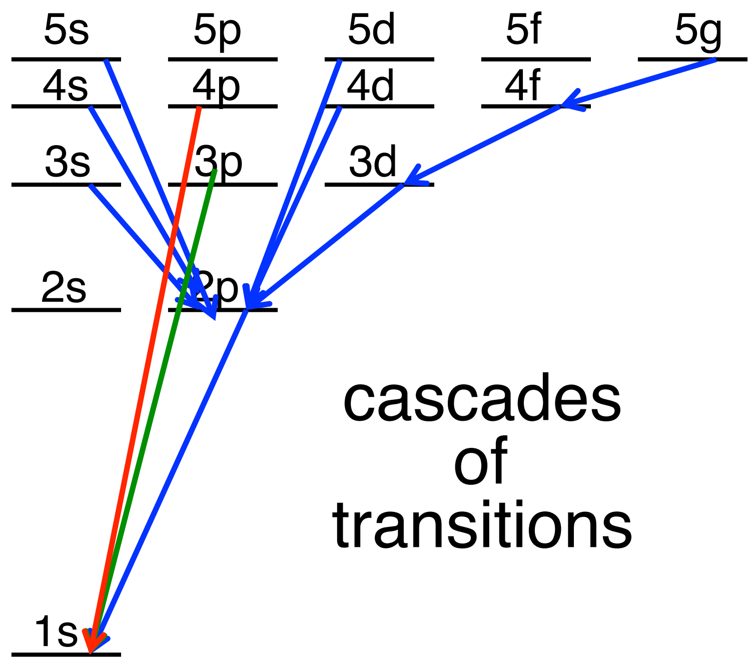
Intensity : 1s - 2p > 1s - 3p > 1s - 4p

Emission cross sections can be estimated from the spectra.

Capture Cross Sections in O^{7+} - He



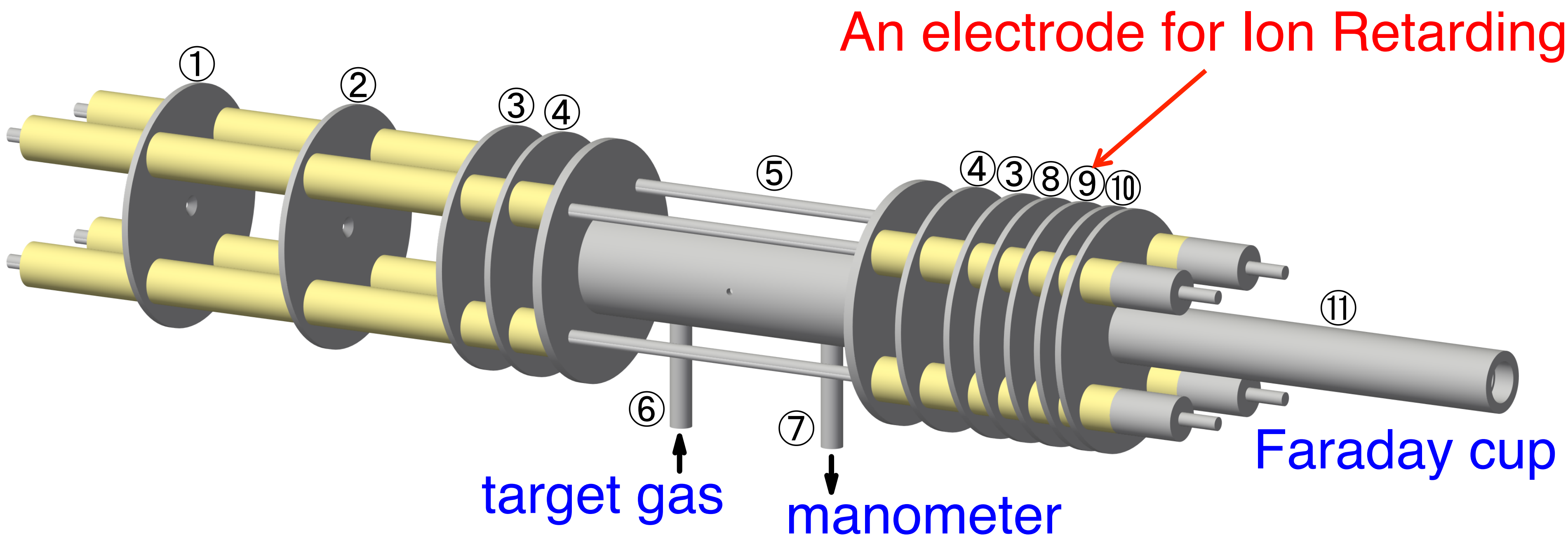
(Ling Liu, private communication)

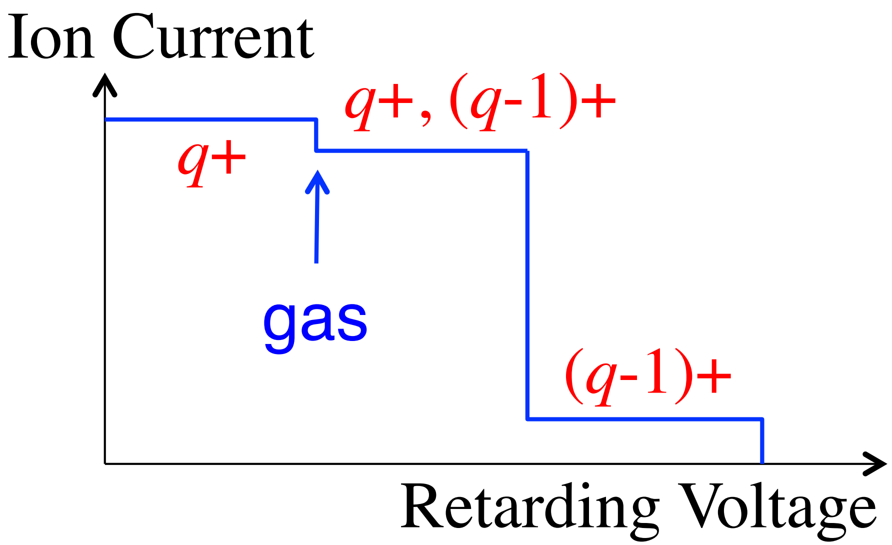


Dominant Capture Levels
n = 4 (4s, 4p, 4d, 4f)

The $1s^2$-1s2p transition is dominant due to the cascade from higher excited states (3s, 3d, 4s, 4d, 4f, 5s, 5d, 5g).

Setup for cross section measurements





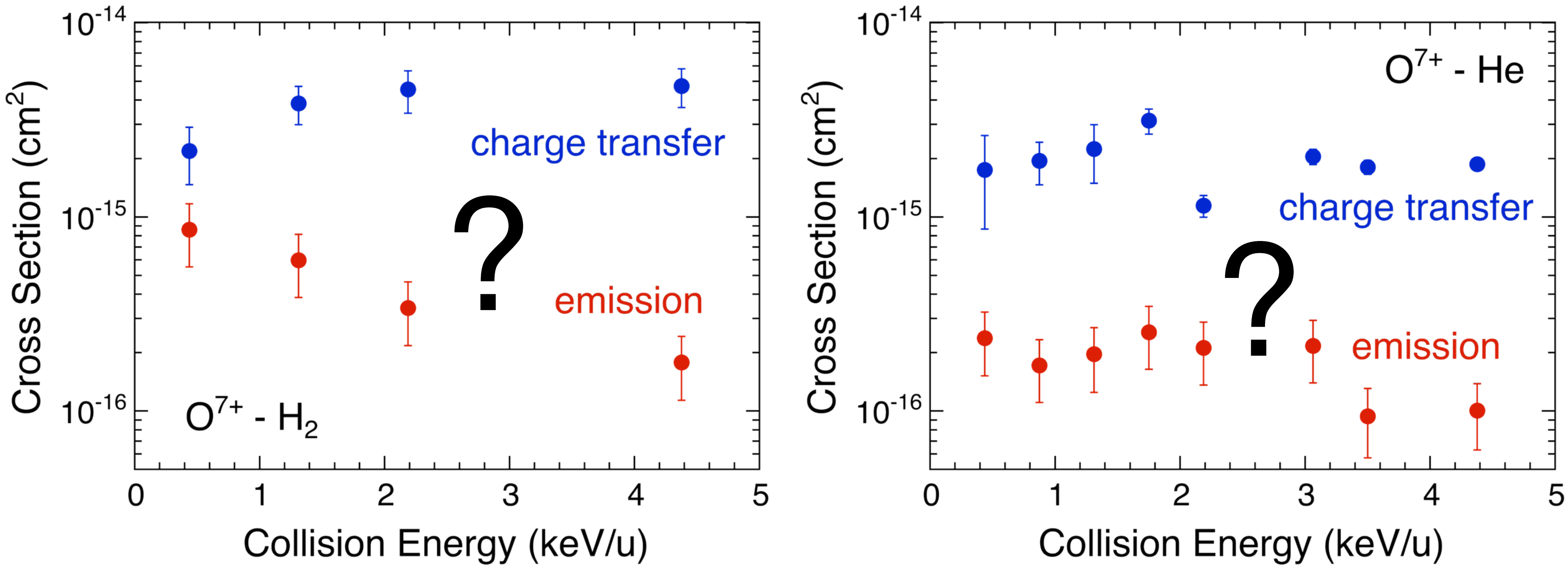
Single CX cross section :

$$\sigma \approx \frac{qI_{q-1}}{nL\left[(q-1)I_{q,q-1} + I_{q-1}\right]}$$

n : number density

L : gas cell length

Preliminary Results of Cross Sections



statistical weights of triplet and singlet = 3 : 1

$$\frac{\sigma_{\mathrm{CX}}}{\sigma_{\mathrm{X\text{-}ray}}} \approx \frac{\sigma_{\mathrm{Singlet}} + \sigma_{\mathrm{Triplet}}}{\sigma_{\mathrm{Singlet}}} \approx \frac{1+3}{1} = 4$$

Triplet / Singlet Ratio in CX = 3 ?

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Final-state-resolved charge exchange in C^{5+} collisions with H

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statistical weights

$$\frac{\sigma_{\mathrm{Triplet}}}{\sigma_{\mathrm{Singlet}}} = 3$$

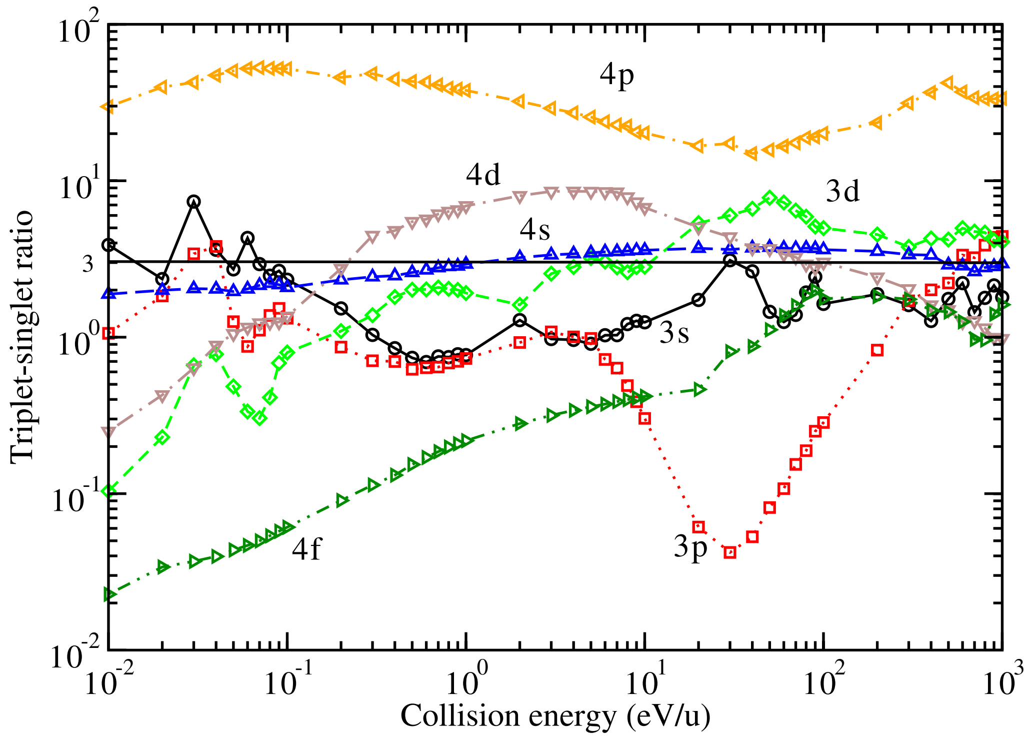


Figure 12. Triplet–singlet ratios obtained from QMOCC results for n, l-resolved cross sections for C^{5+}+H.

We want to observe the forbidden emission lines
from the triplet states with **long lifetimes**
which are produced in the charge exchange collisions.

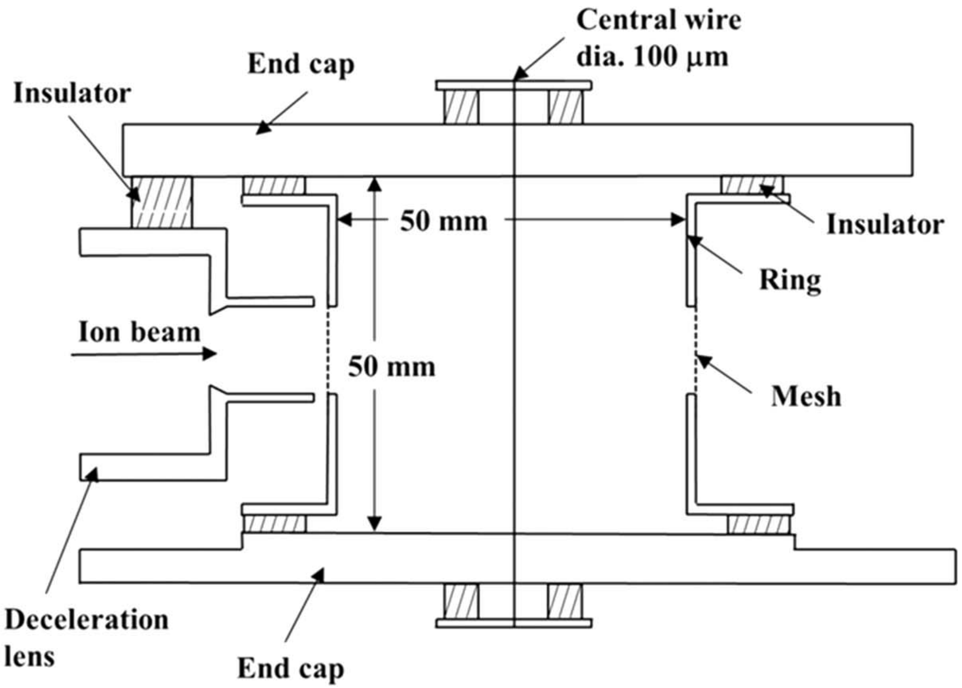
lifetime ~ 1 ms

ion velocity ~ 1000 km/s

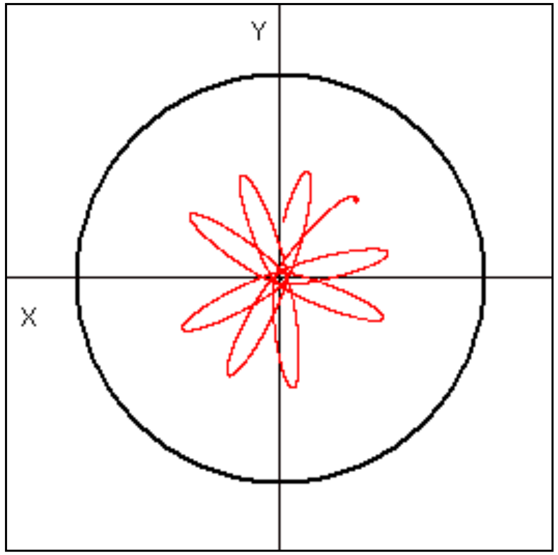
flight length ~ 1 km >> laboratory size

We need to storage ions in an ion trap.

Direct Observation of Emission from Triplet by an Ion Trap



Side view of a Kingdon trap



Top view of a trajectory of an ion in the trap

K. H. Kingdon, Phys. Rev. **21**, 408 (1923).

D. A. Church *et al*., Nucl. Instrum. Meth. B **56/57**, 1185-1187 (1991).

N. Numadate *et al*., Rev. Sci. Instrum. **85**, 103119 (2014).

A Timing Chart of the Kingdon Ion Trap

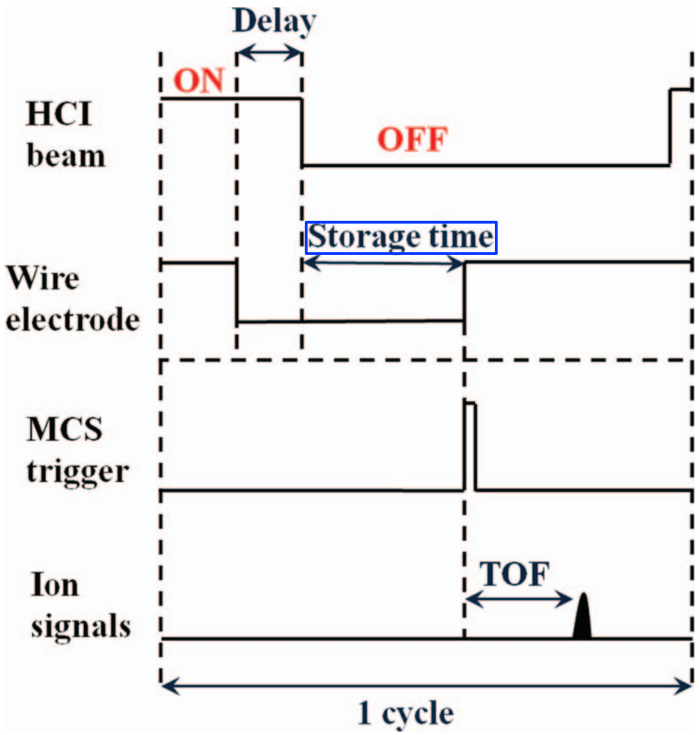


FIG. 3. A timing chart of the ion trapping experiment. A master oscillator generates trigger pulses for controlling the timing. The HCI beam is chopped by the upstream deflector. The delay-time is set to be shorter than 10 ms for the present experiment.

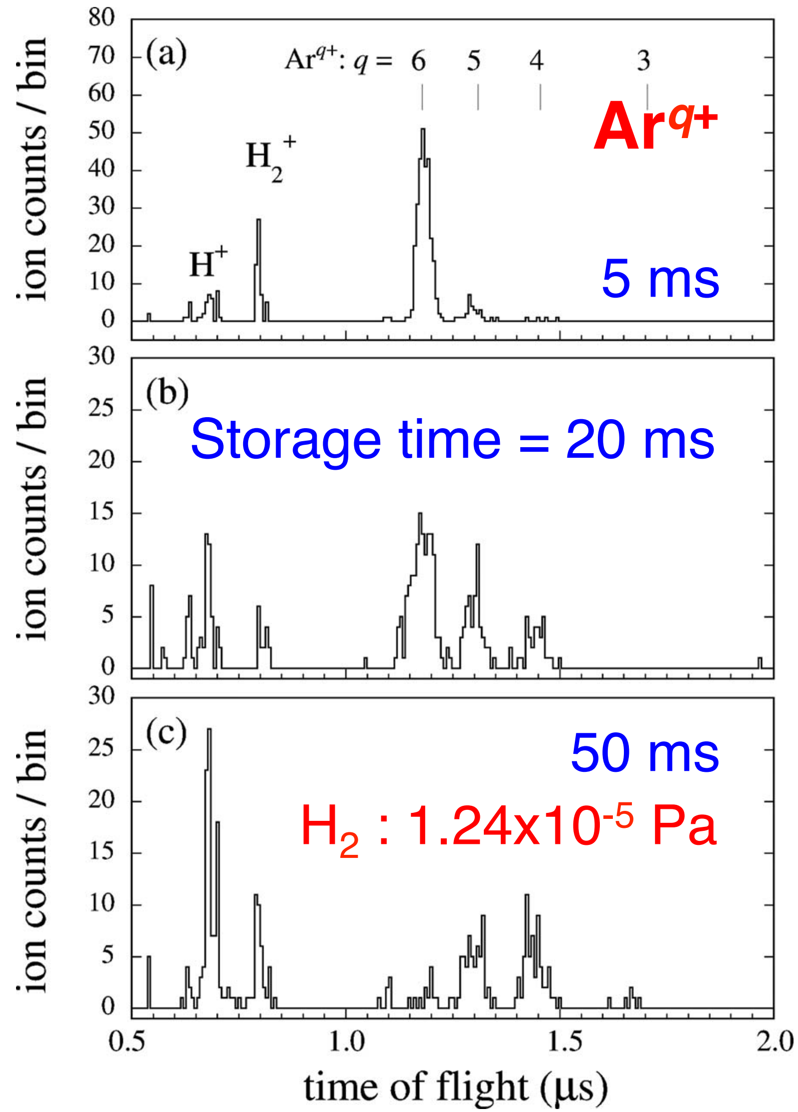
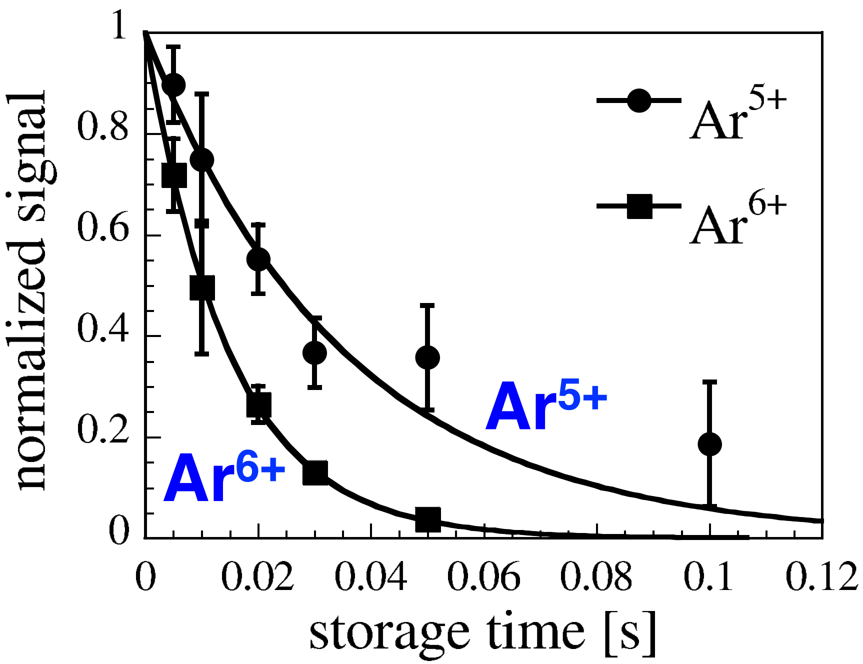


FIG. 7. TOF spectra of ejected ions after (a) 5 ms, (b) 20 ms, and (c) 50 ms storage time when Ar^{6+} ions were injected into the Kingdon trap. The number of switching cycles for obtaining the spectrum is 10 000. The pressure of H_2 gas is 1.24×10^{-5} Pa.

N. Numadate *et al.*, Rev. Sci. Instrum. **85**, 103119 (2014).

Storage Ions in the Kingdon Trap



$$I(t) = I_0 e^{-kt}$$

$$k = \sigma n v$$

σ : cross section
n : number density
v : ion velocity

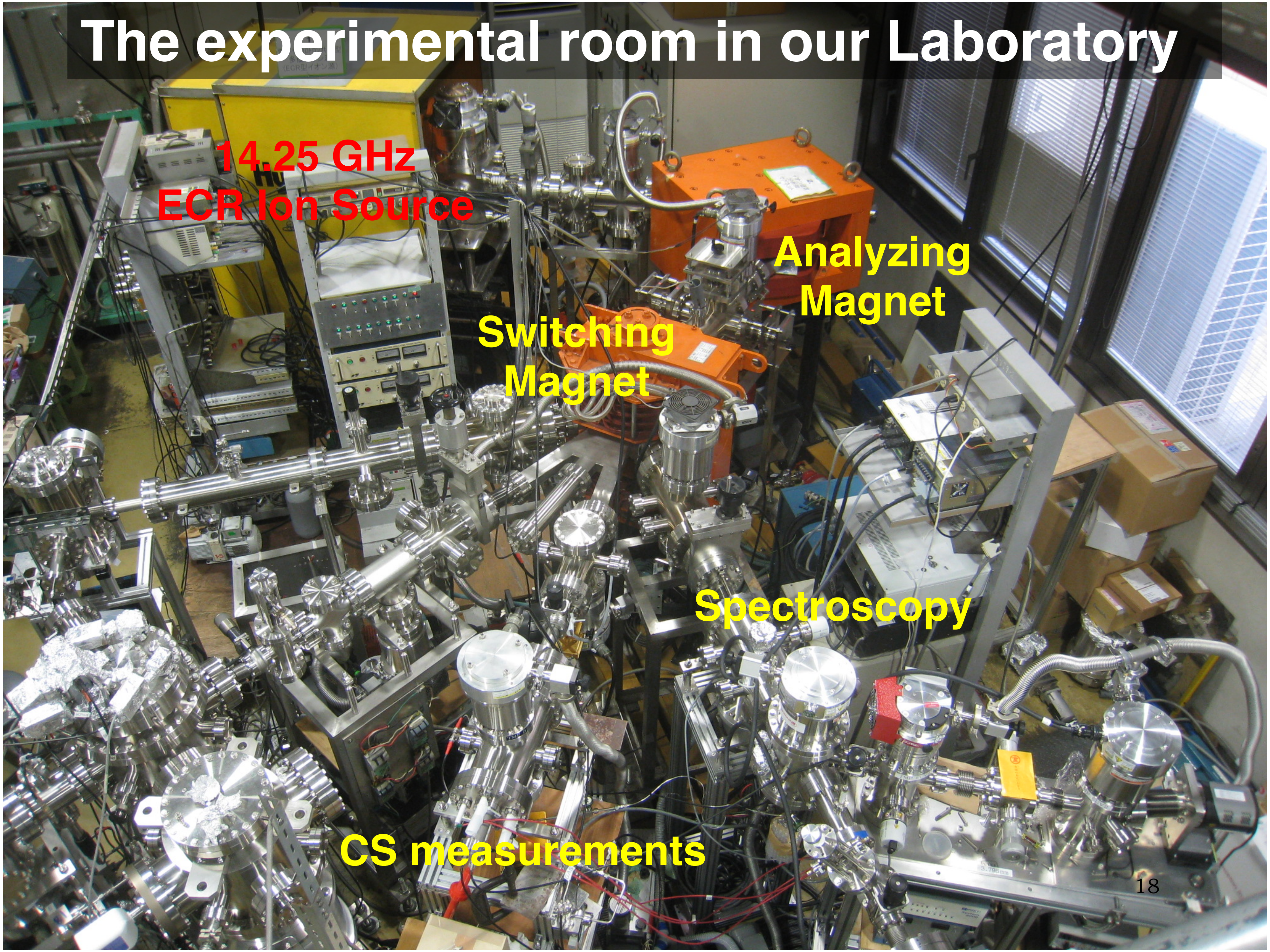
Fig. 8. A plot of the extracted Ar^{5+} and Ar^{6+} as a function of storage time at H_2 pressure of 1.24×10^{-5} Pa. The data are well fitted by single exponential functions. The decay rate of the Ar^{5+} and Ar^{6+} are determined to be 28 ± 6 s^{-1} and 67 ± 6 s^{-1}, respectively.

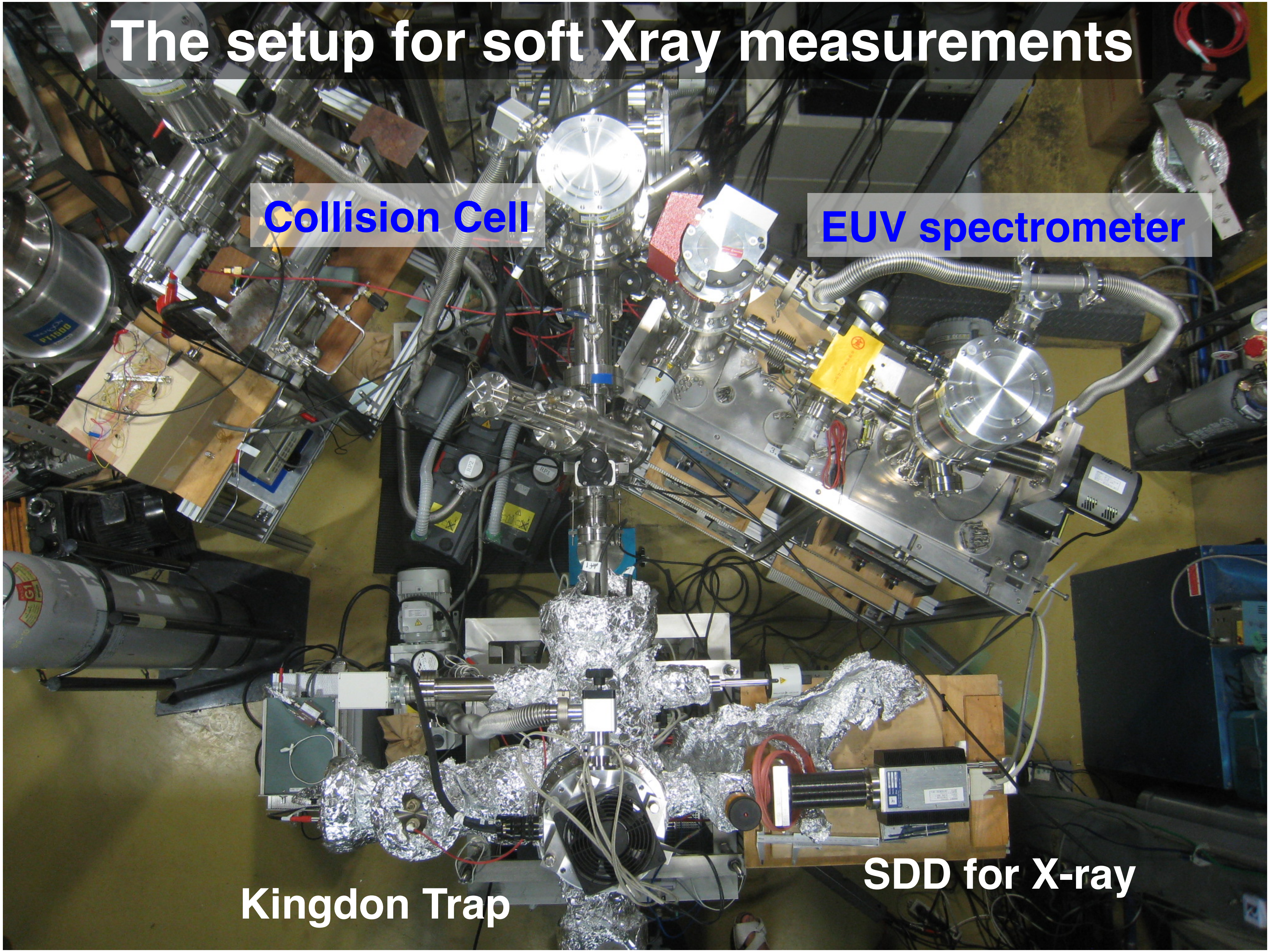
Without gas introduction, the ion can be stored more long time.

This trap will be used for observation of soft X-ray emission from the metastable ions produced in CX collisions.

K. Numadate *et al.*, Rev. Sci. Instrum. **85**, 103119 (2014).

The experimental room in our Laboratory




The setup for soft Xray measurements
Collision Cell
EUV spectrometer
Kingdon Trap
SDD for X-ray

Summary

Present Projects :

- Capture CS > Emission CS
- Difference - Metastable states with long lifetimes
- Development of Kingdon ion trap for observation of forbidden lines
- We will observe them soon.

Feature Plans :

- Hydrogen atom target
- Inter-combination lines
- Various kinds of ions

Dream :

- Population distribution of ions in CX has negative temperature. → X-ray Laser ?

Collaborators:

Astrophysics Group, Tokyo Metropolitan University:

T. Ohashi, Y. Ishizaki, Y. Ezoe, S. Yamada

JAXA / ISAS:

K. Mitsuda, K. Shinozaki

IAPCM (Beijing):

L. Liu, J-G. Wang

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