NIFS, 22 December, 2017

準安定励起イオンの衝突過程

$$1s2s + e^- \rightarrow 1s2snl \rightarrow 1s^22s + h\nu$$

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Charge eXchange Spectroscopy (CXS)

$$P^{q+} + T \rightarrow P^{(q-t)+*} + T^{t+}$$

$\downarrow$ **photon : energy, intensity**

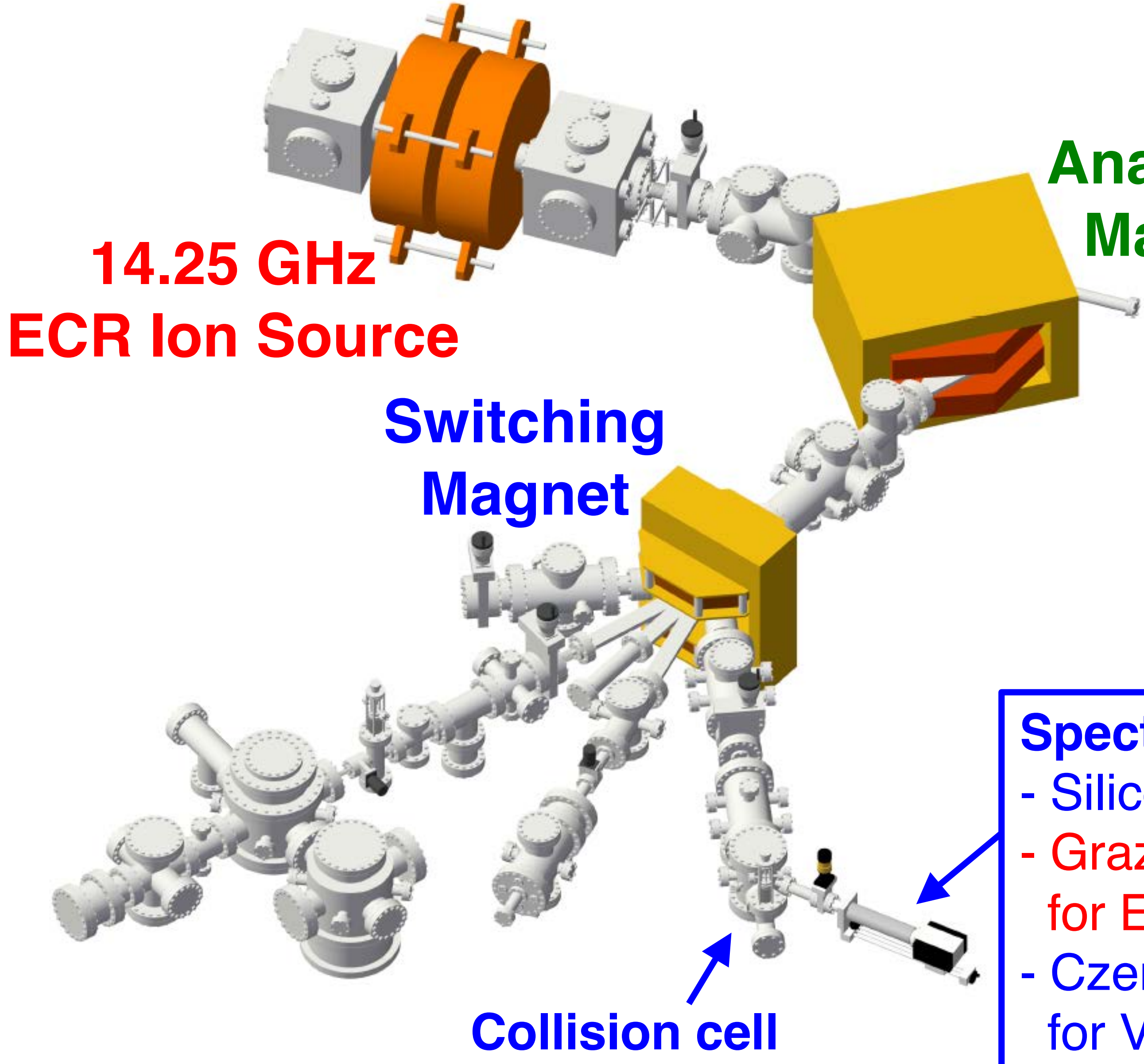
$$P^{(q-t)+}$$

P : projectile, T : target

Experimental method for measurements of

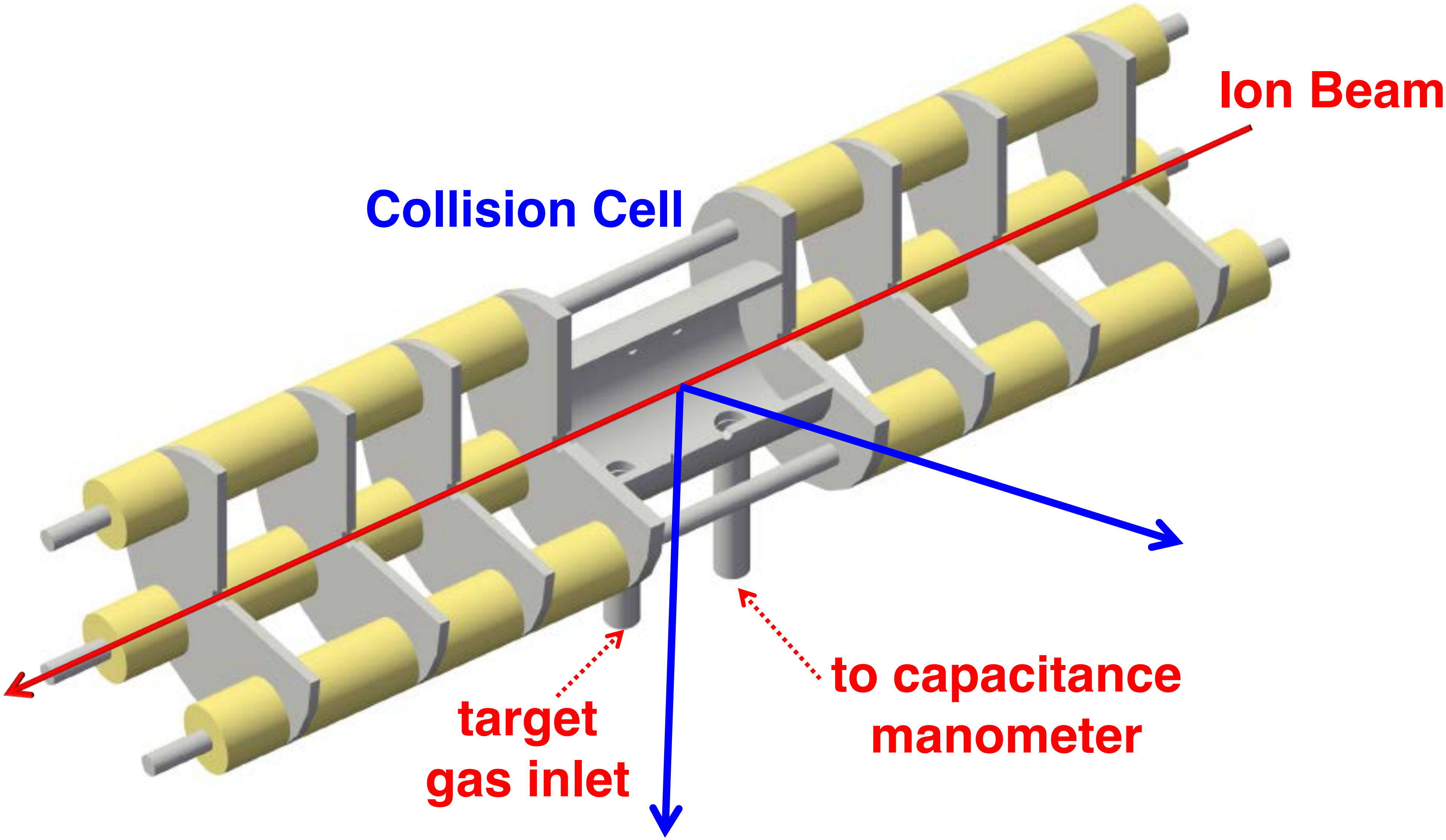
1. **Charge transfer cross sections**
2. **Transition wavelengths**

Multiply Charged Ion Beam Lines in TMU



Spectrometers
- Silicon Drift Detector for X-ray
- Grazing Incident Spectrometer for Extreme Ultra-Violet
- Czerny-Turner Spectrometer for Visible and UV

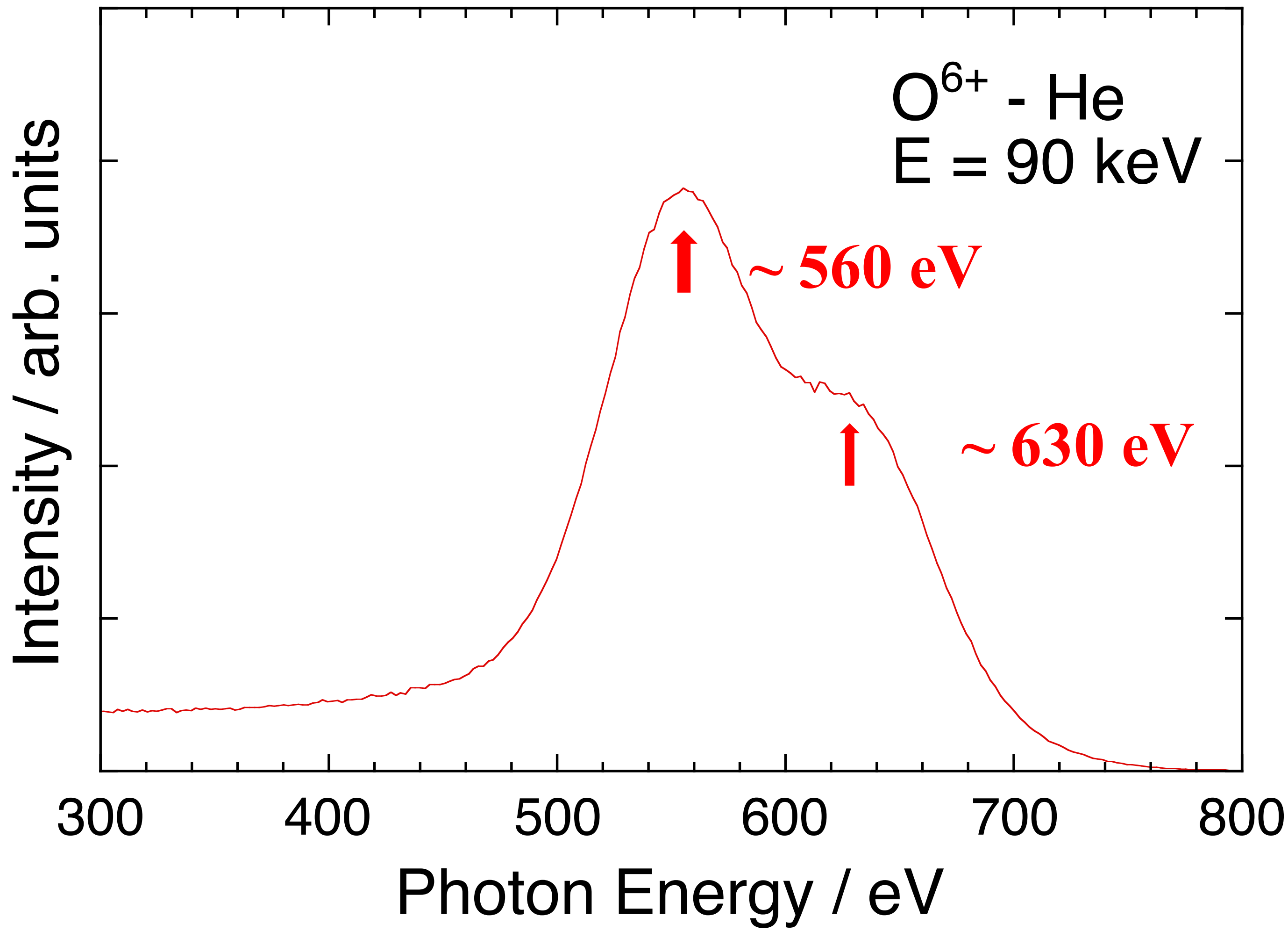
Setup for X-ray / EUV measurements



Magic Angle = 54.736˚

Spectra with a Silicon Drift Detector (SDD)

Un-expected Soft X-ray emissions in collisions of O^{6+} ions with He



O^{5+} ($1s^2\,nl$) :
< 138 eV
= max. energy from O^{5+}

Silicon Drift Detector (SDD) : $\Delta E \sim 70$ eV

Energy Level Data in NIST ASD

O^{5+}	$1s^2 2s\ ^2S_{1/2}$	: IP = 138.12 eV
	$1s2s(^3S)2p\ ^4P_J$	: 554.24 eV
	$1s2s(^3S)2p\ ^2P_J$	: 562.59 eV
	$1s2s3s\ ^4S_{3/2}$	: 636.03 eV

$h\nu \sim$ 560 eV : O^{5+} $1s^2 2s - 1s2s2p$

$h\nu \sim$ 630 eV : O^{5+} $1s^2 2s - 1s2s3p$ (?)

Why 1s2s*nl* states are produced?

Meta-stable states in a primary ion beam

He-like ions : few % of 1s2s $^3S_1$ from ECRIS

$$O^{6+}(1s2s\ ^3S_1) + He \rightarrow O^{5+}(1s2s\mathit{nl}) + He^+$$
$$\rightarrow O^{6+}(1s^2) + e^- \quad \text{: Auger (auto-ionization)}$$

$$O^{6+}(1s2s\ ^3S_1) + He \rightarrow O^{5+}(1s2s\mathit{nl}) + He^+$$
$$\rightarrow O^{5+}(1s^2 2s) + h\nu$$

Auger process is dominant for light atoms.

Theoretical Auger and X-ray emission rates

TABLE II. Theoretical Auger and x-ray emission rates (in a.u.[a]) for states of the $1s2s2p$ configuration of Li-like ions of atomic number Z.

State \ Z	6 C		7 N		8 O		9		10	
	Auger	x ray	Auger	x ray	Auger	x ray	Auger	x ray	Auger	x ray
$^2P_{1/2}^{(+)}$	1.48(−3)	2.21(−6)	1.65(−3)	4.57(−6)	1.78(−3)	8.46(−6)	1.89(−3)	1.45(−5)	1.98(−3)	2.36(−5)
$^2P_{1/2}^{(-)}$	2.01(−4)	1.72(−5)	2.05(−4)	3.58(−5)	2.06(−4)	6.64(−5)	2.09(−4)	1.13(−4)	2.15(−4)	1.80(−4)
$^2P_{3/2}^{(+)}$	1.48(−3)	2.16(−6)	1.66(−3)	4.38(−6)	1.79(−3)	7.87(−6)	1.89(−3)	1.30(−5)	1.99(−3)	1.99(−5)
$^2P_{3/2}^{(-)}$	1.92(−4)	1.73(−5)	1.90(−4)	3.60(−5)	1.82(−4)	6.70(−5)	1.74(−4)	1.15(−4)	1.66(−4)	1.84(−4)
$^4P_{1/2}$	6.50(−9)	4.19(−11)	1.26(−8)	2.25(−10)	2.13(−8)	9.34(−10)	3.29(−8)	3.24(−9)	4.78(−8)	9.84(−9)
$^4P_{3/2}$	1.73(−9)	1.04(−10)	2.60(−9)	5.57(−10)	3.17(−9)	2.33(−9)	3.07(−9)	8.17(−9)	2.15(−9)	2.48(−8)
$^4P_{5/2}$	2.06(−10)	3.97(−13)	4.45(−10)	1.69(−12)	8.49(−10)	5.73(−12)	1.48(−9)	1.66(−11)	2.43(−9)	4.21(−11)

[a]1 a.u. $= 27.21$ eV/$\hbar = 4.134 \times 10^{16}$ sec^{-1}. Numbers in parentheses stand for powers of 10, e.g., $1.48(-3) = 1.48 \times 10^{-3}$.

Auger > X-ray

M. H. Chen *et al*., Phys. Rev. A **27** (1993) 544.

Previous experiments in Grenoble, France

Observation of X-ray transitions

$N^{5+}(1s2s\ ^3S)$ + He / H_2 at 48 keV (3.4 keV/u)

M. G. Suraud *et al.*, J. Phys. B **21** (1988) 1219.

$C^{4+}(1s2s\ ^3S)$ + H_2 at 40 keV (3.3 keV/u)

L. Guillemot *et al.*, J. Phys. B **23** (1990) 3353.

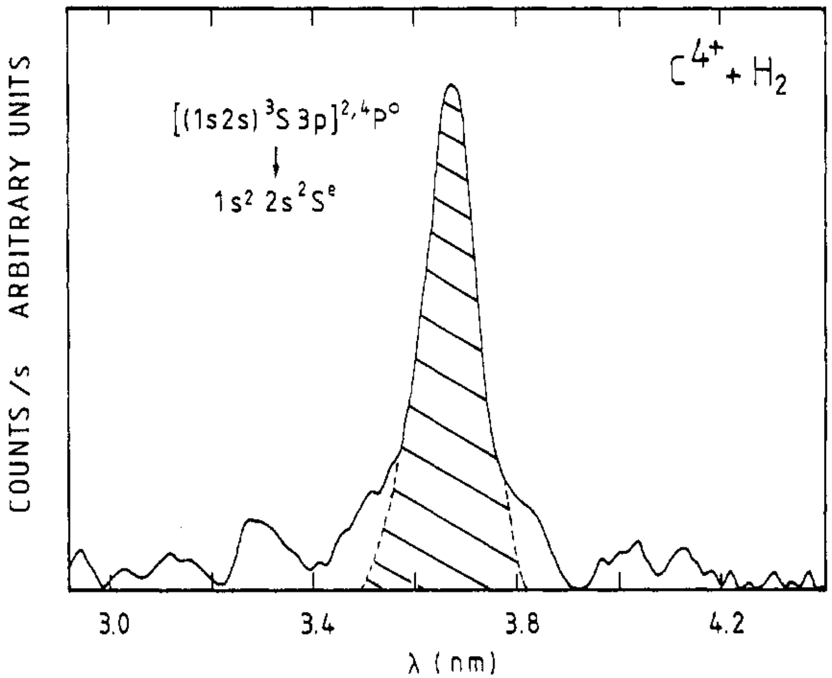
$O^{6+}(1s2s\ ^3S)$ + He at 60 keV (3.8 keV/u)

S. Bliman *et al.*, J. Phys. B **25** (1992) 2065.

Previous experiments in Grenoble, France

$C^{4+}(1s2s\ ^3S) + H_2$ at 40 keV (3.3 keV/u)

only one transition : $1s^22s\ ^2S - 1s2s(^3S_1)3p\ ^{2,4}P^o$

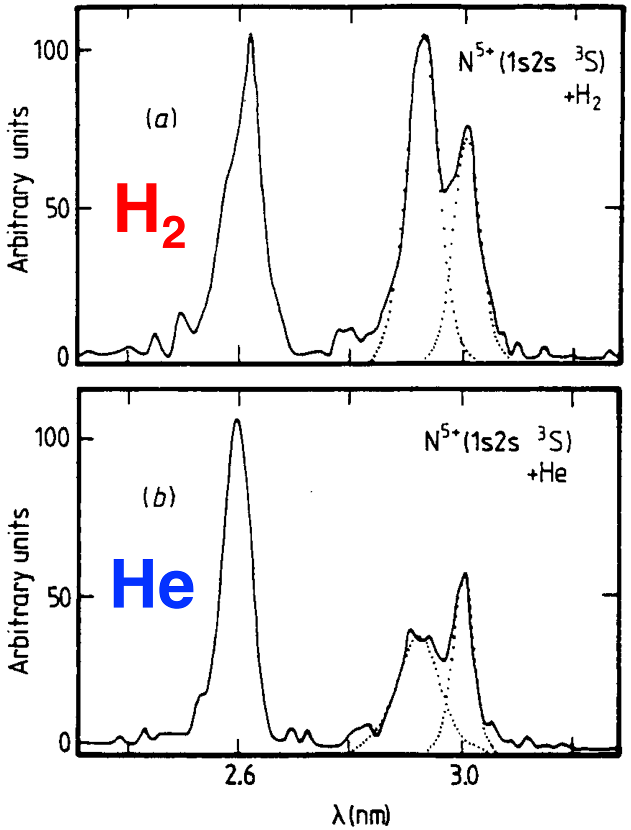


No X-ray emission in $C^{4+}(1s2s\ ^3S)$ - He collisions

L. Guillemot *et al.*, J. Phys. B **23** (1990) 3353.

Previous experiments in Grenoble, France

$N^{5+}(1s2s\ ^3S) + H_2$ / He at 40 keV (3.3 keV/u)



$1s^22s\ ^2S$ - $1s2s3p\ ^{2,4}P^o$

$1s^22s\ ^2S$ - $1s2s2p\ ^2P^o$

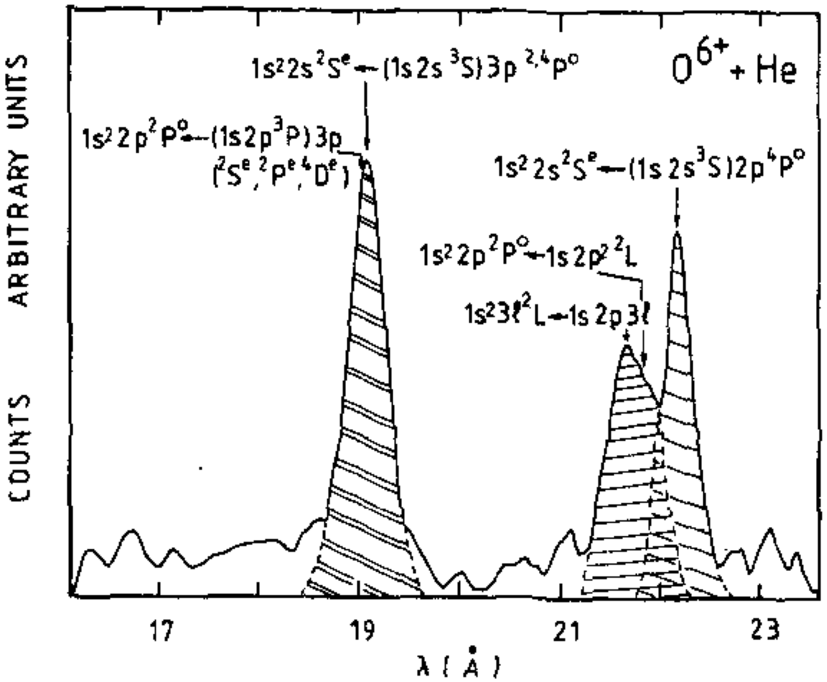
$1s^22s\ ^2S$ - $1s2s2p\ ^4P^o$

Target dependence

M. G. Suraud *et al*., J. Phys. B **21** (1988) 1219.

Previous experiments in Grenoble, France

$O^{6+}(1s2s\ ^3S)$ + He at 60 keV (3.8 keV/u)



$1s^22s\ ^2S - 1s2s3p\ ^{2,4}P^o$
(or $1s^22p\ ^2P - 1s2p3p\ ^2L^o$)

$1s^22p\ ^2P^o - 1s2p^2\ ^{2,4}L$
$1s^23l\ ^2L - 1s2p3l\ ^{2,4}L$

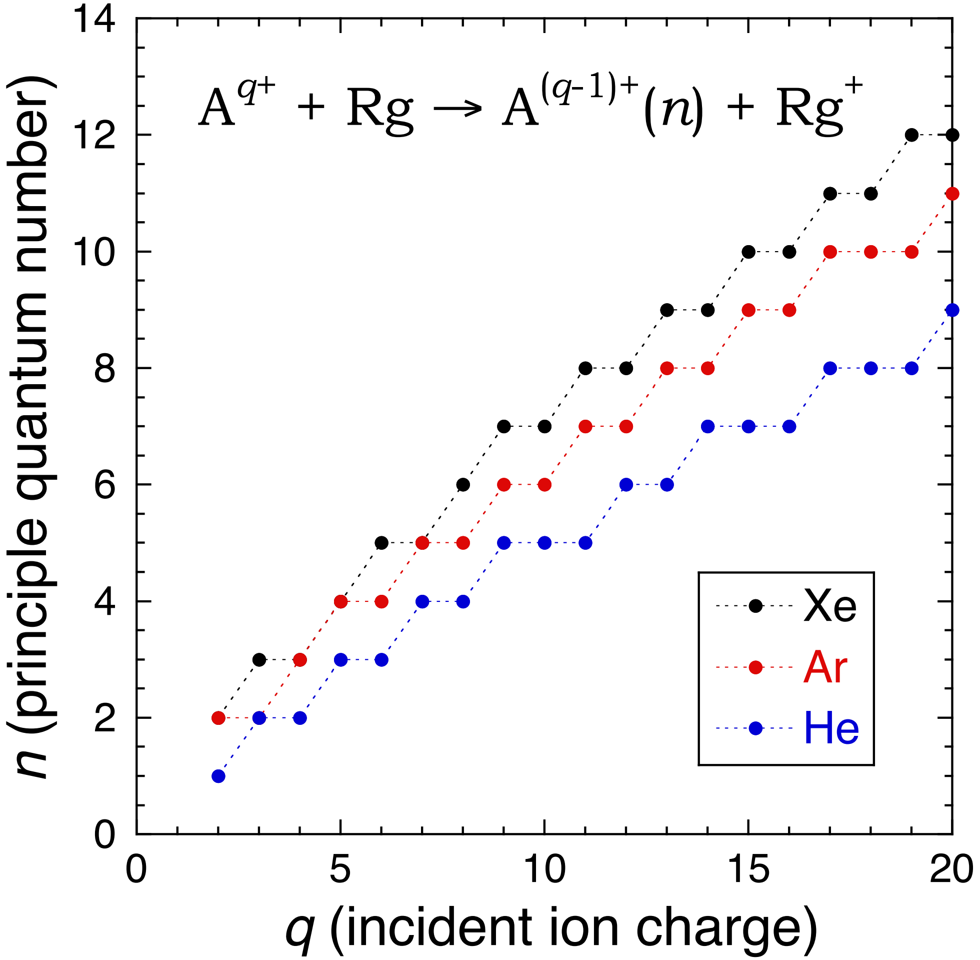
$1s^22s\ ^2S - 1s2s2p\ ^4P^o$

S. Bliman *et al.*, J. Phys. B **25** (1992) 2065.

Spectra with
a Grazing Incident Spectrometer
(GIS)
equipped with a grating for 5-20 nm

Classical Over the Barrier Model

Prediction of dominant capture level



$$n \approx \sqrt{\frac{1+2\sqrt{q}}{2I_t\left(q+2\sqrt{q}\right)}} \cdot q$$

I_t : IP of target in atomic unit
1 au = 27.2 eV

Xe : 12.130 eV

Ar : 15.760 eV

He : 24.588 eV

Classical Over the Barrier Model

Ionization Potentials

He : 24.588 eV

H_2 : 15.98 eV

Ar : 15.760 eV

N_2 : 15.60 eV

Xe : 12.130 eV

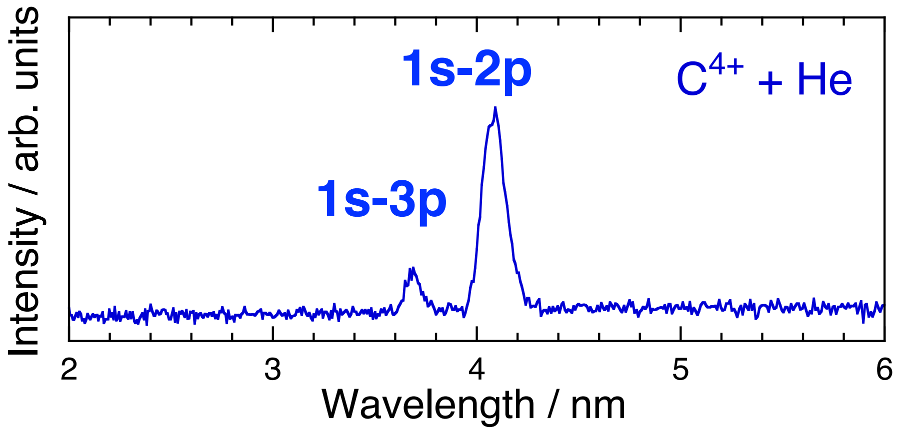
O_2 : 12.30 eV

In the emission spectra,

H_2, Ar, and N_2 might be similar.

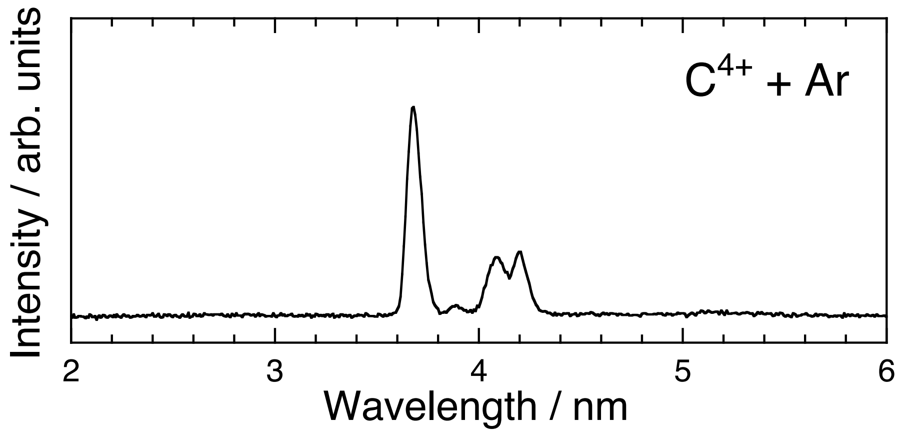
Xe and O_2 might be similar.

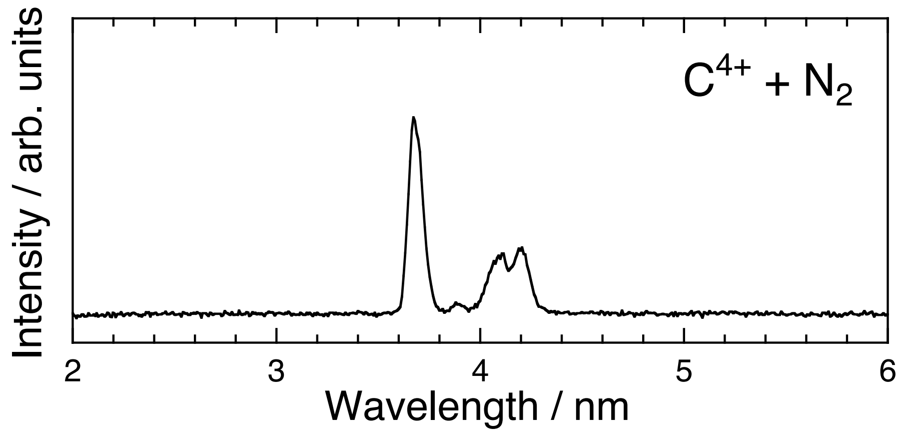
X-ray spectra with a GIS (1)

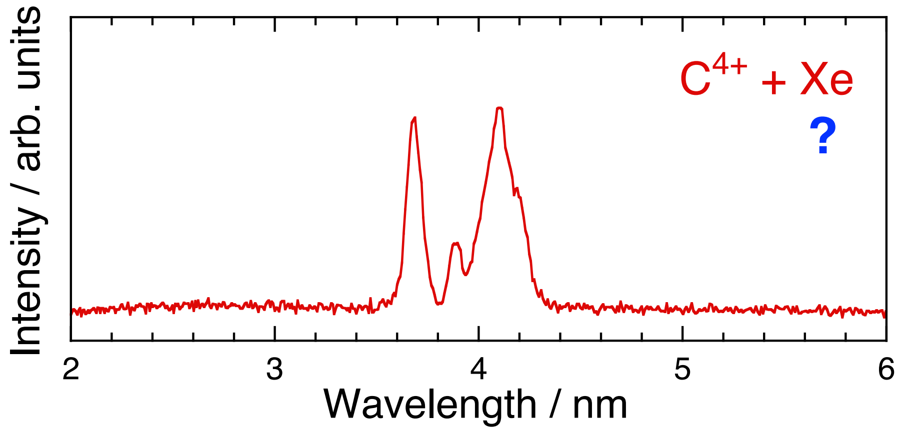


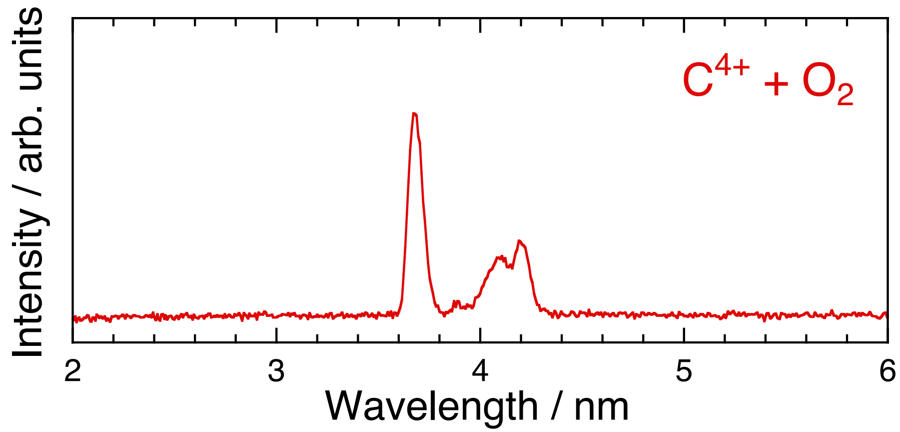
3.9 nm: $1s^2 2s2p$-$1s2s2p3p$ (?)

Double Collision

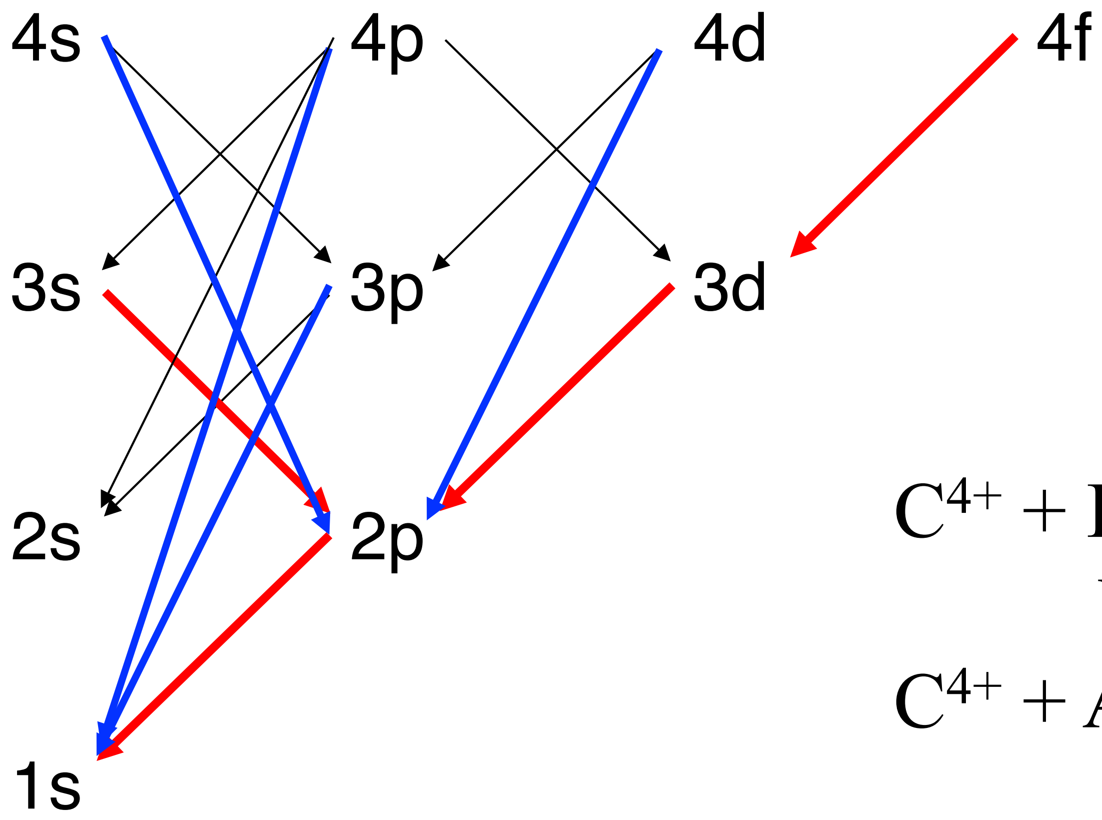








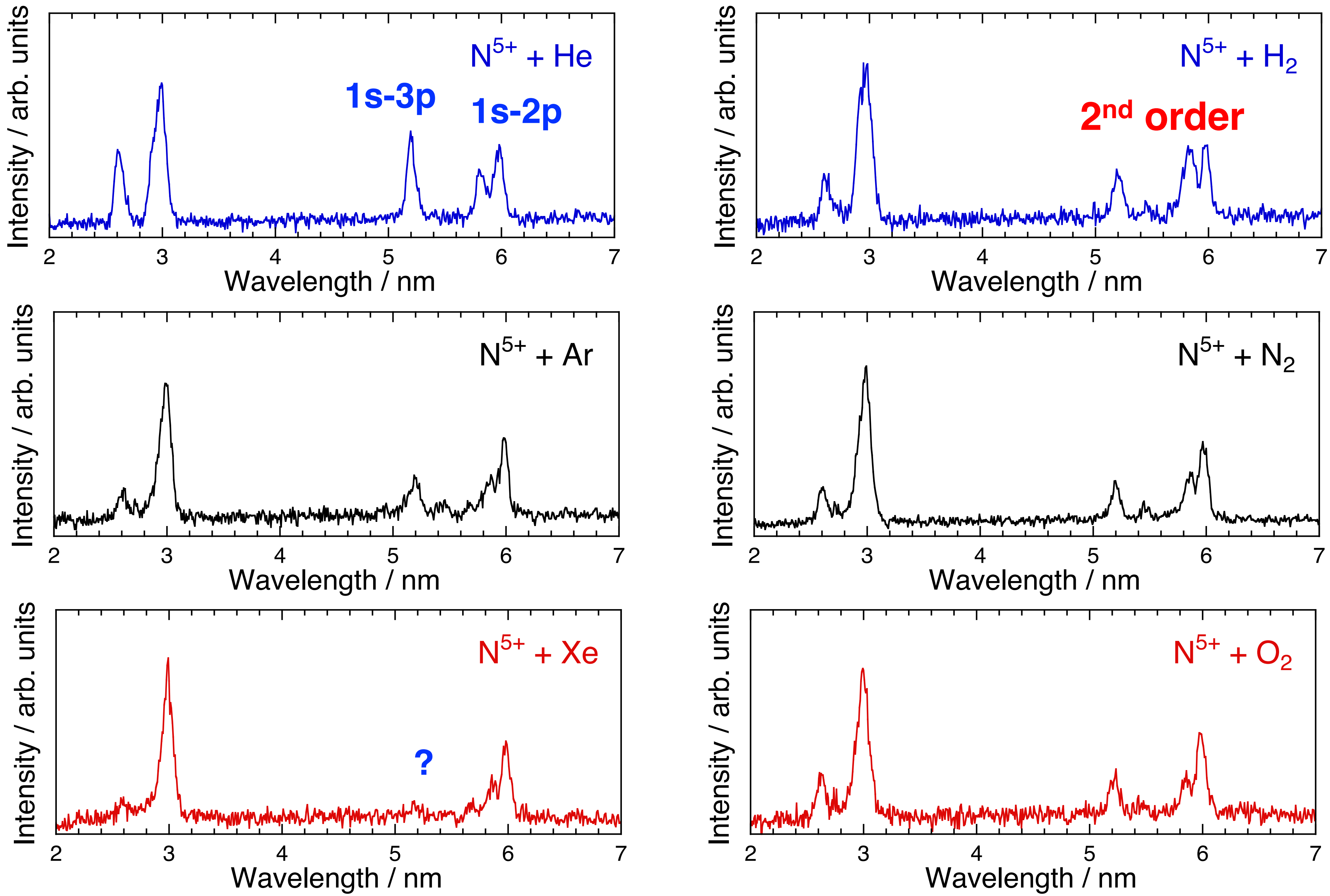
Discussion (1)



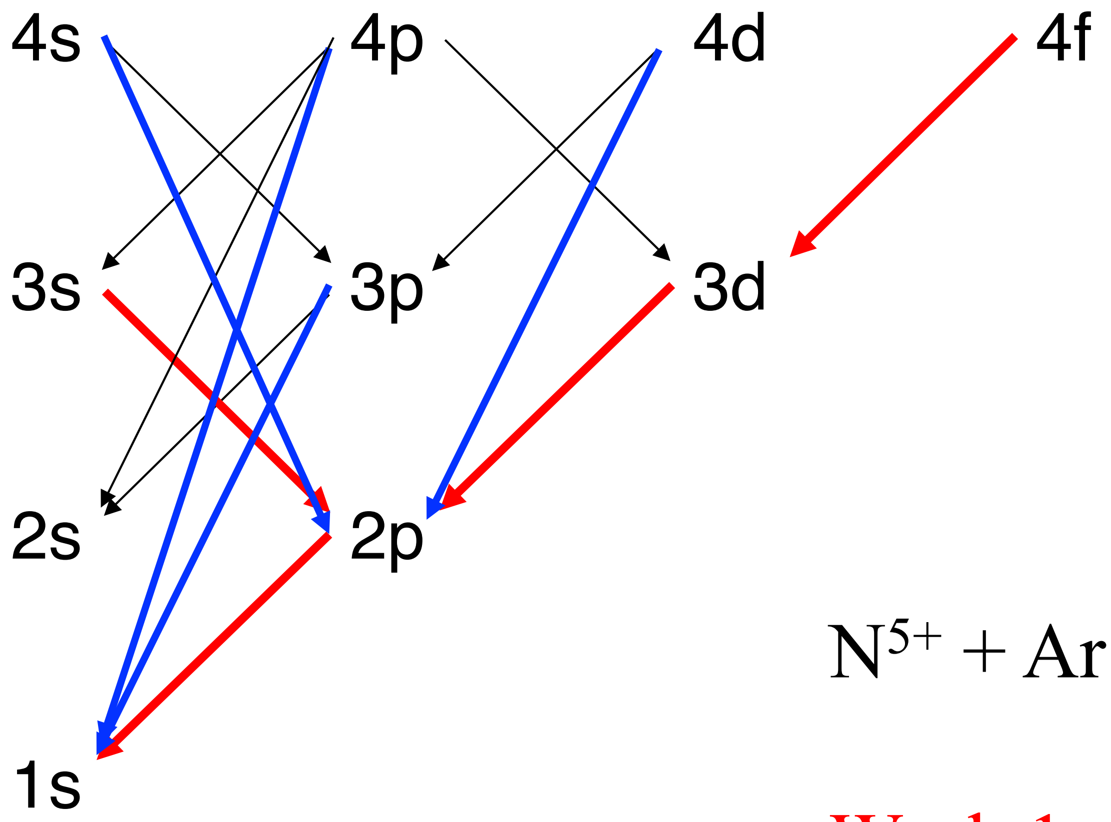
E1 transitions :
red : 100%
blue : dominant

C^{4+} + He : $n = 2$ is dominant.
Weak 1s-3p transition
C^{4+} + Ar : $n = 3$ is dominant.
Strong 1s-3p transition
C^{4+} + Xe : $n = 3$ is dominant.
Weak 1s-3p transition ?
3s, 3d >> 3p

X-ray spectra with a GIS (2)



Discussion (2)



E1 transitions :

red : 100%

blue : dominant

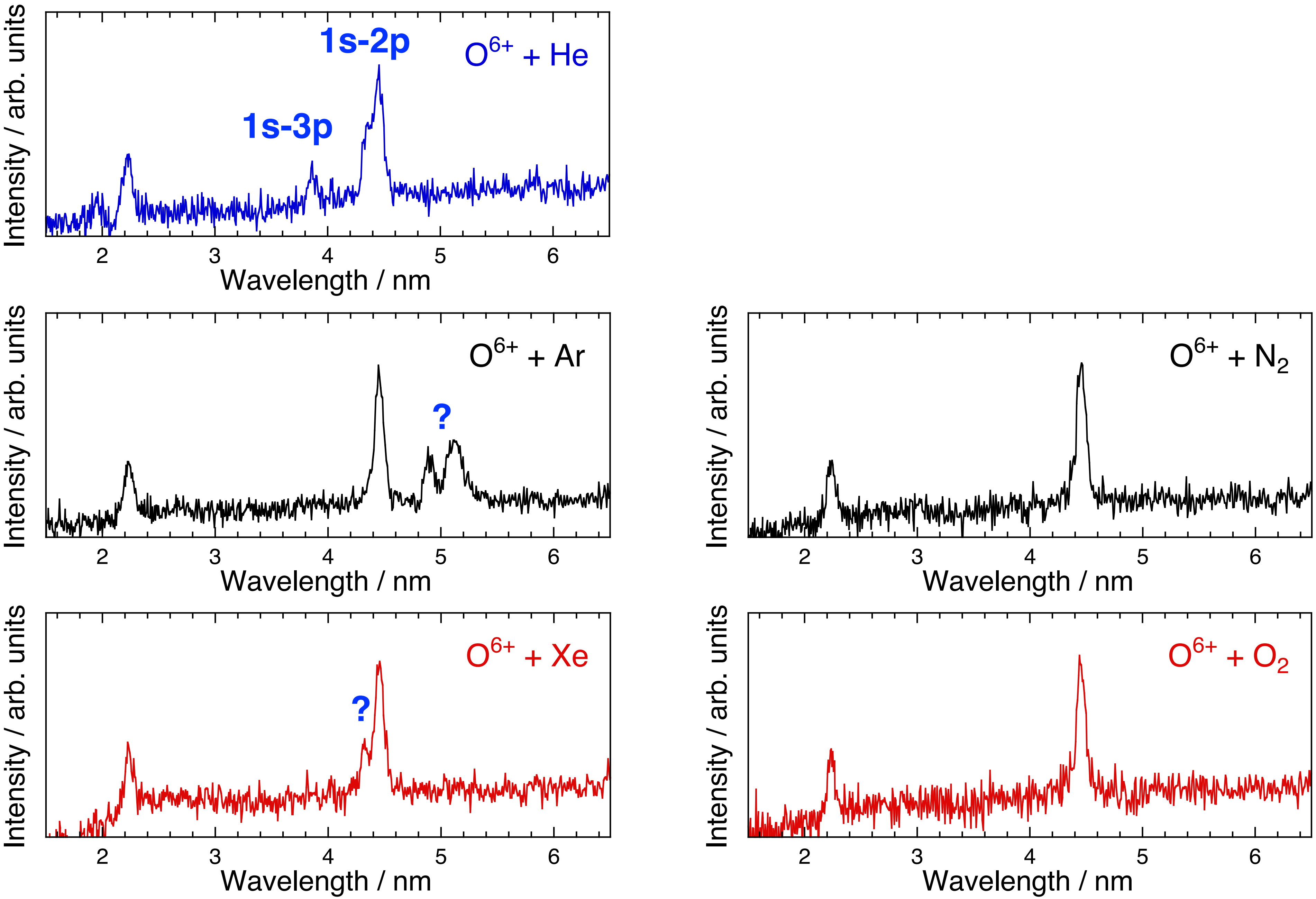
N^{5+} + Ar *etc.* : $n = 4$ is dominant.

Weak 1s-3p transition in Xe ?

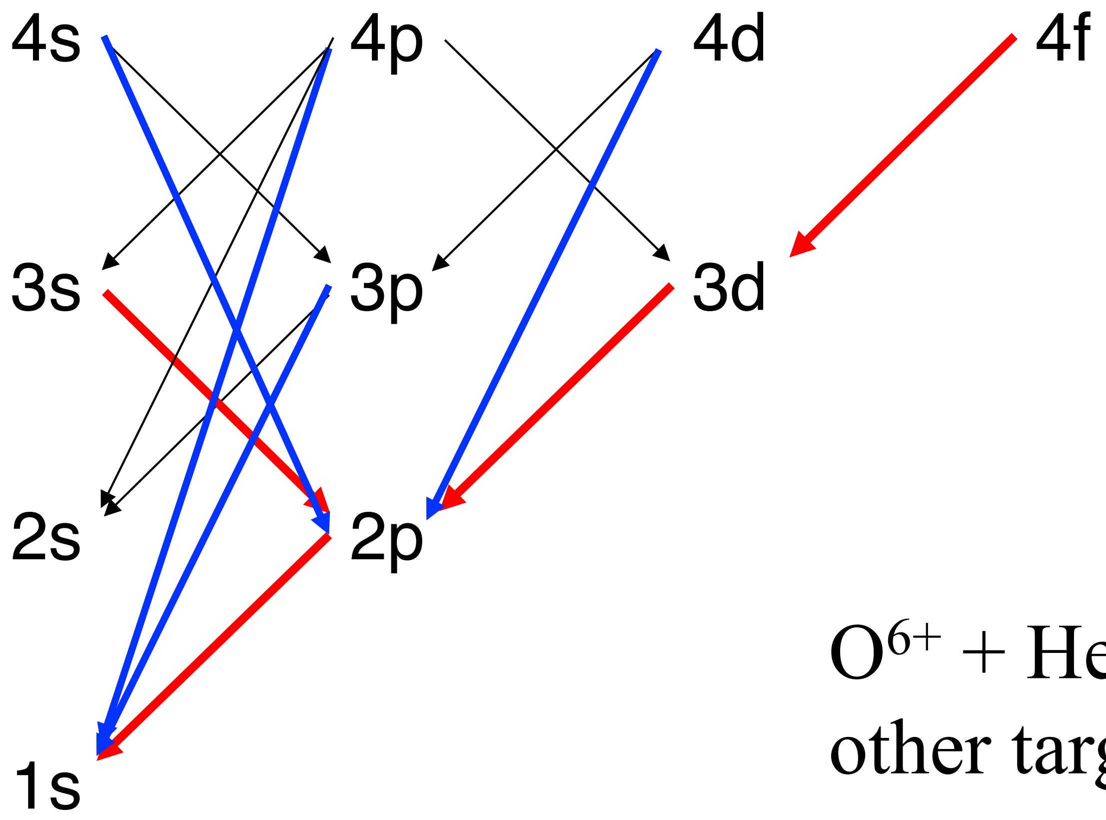
(No 1s-4p transition)

→ 4f might be dominant (?).

X-ray spectra with a GIS (3)



Discussion (3)



E1 transitions :

red : 100%

blue : dominant

O^{6+} + He : $n = 3$ is dominant.

other targets : $n \geq 4$

1s-3p transition in only He ?

4f might be dominant.

Summary and Outlook

1. Soft X-ray emissions from inner-shell excited Li-like ions were observed for the second time even though auto-ionization is main process.
2. Target dependences have been observed, and some of them could be explained with some assumption. But, we still have several questions.
3. Contribution of quartet states with long lifetimes must be revealed.
4. Another grating for 1-5 nm
5. Theoretical calculations for state-selective capture cross sections and transition rates between excited states are necessary to understanding the capture and cascades processes.