Laboratory Experiments of SWCX
- 太陽風を起源とする軟X線観測への原子物理の寄与 -

首都大学東京・理工学研究科・物理学専攻
原子物理実験研究室　　　田沼　肇

Hajime TANUMA

Department of Physics, Tokyo Metropolitan University

Activity of Atomic Physics Group in TMU

Collision Energy

Charge of Ions

E-ring
(electrostatic
ion storage ring)

10 - 30 keV

城丸 春夫, 松本 淳 (化学)
東 俊行 (理研)
間嶋 拓也 (京大工)

RCE @HIMAC / GSI
(resonant coherent
excitation)

GeV

東 俊行 (理研)

Drift Tube
(ion swarm in He gas
at 4.3 K, *etc.*)

0.5 - 100 meV

大槻 一雅 (電通大)
井上 洋子 (PD)

ECRIS
(electron cyclotron
resonance ion source)

1 - 100 keV

阪大レーザー研 / UCD (Dublin)
宇宙実験 (首都大)/ IAPCM (北京)

Contents of this talk

- Motivation – What's SWCX ?
- Features of CX of multiply charged ions
- Principle of the measurements
- Preliminary results
- Comparison with theoretical calculations
- Future plans

Solar Wind = extremely thin plasma

- *Negative* : **e^-** ~ 10 cm^{-3} around the Earth
- *Positive* : **H^+** ~ 90%, **He^{2+}** ~ 4%

  C^{q+}, **O^{q+}**, **Si^{q+}**, **Fe^{q+}**, **Ni^{q+}**, *etc.*
- *Velocity* : 250 - 400 km/s, 2×10^8 $cm^{-2}s^{-1}$

  (320 - 830 eV/u, 8 cm^{-3})

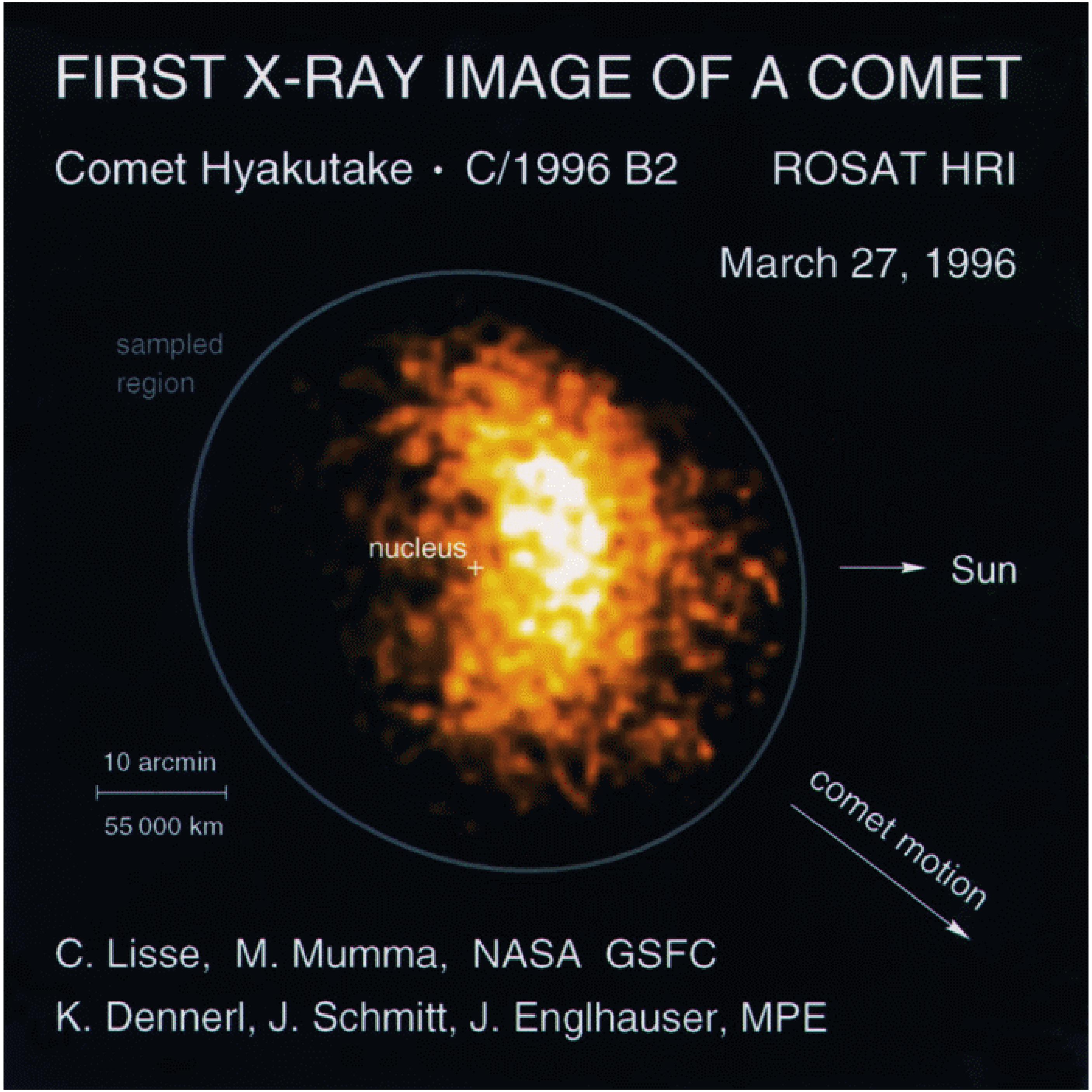
  400 - 800 km/s, 4×10^8 $cm^{-2}s^{-1}$

  (0.83 - 3.3 keV/u, 3 cm^{-3})

Solar-Wind Charge-eXchange emission :

$$O^{7+}(1s) + H \rightarrow O^{6+}(1snl) + H^+$$

$$\rightarrow O^{6+}(1s^2) + h\nu \ (\geq 561 \mathrm{eV})$$


FIRST X-RAY IMAGE OF A COMET
Comet Hyakutake • C/1996 B2
ROSAT HRI
March 27, 1996
sampled region
nucleus
Sun
10 arcmin
55 000 km
comet motion
C. Lisse, M. Mumma, NASA GSFC
K. Dennerl, J. Schmitt, J. Englhauser, MPE

X-ray Emission from Comets

T. E. Cravens, *et al.*

Science **296**, 1042 (2002);
DOI: 10.1126/science.1070001

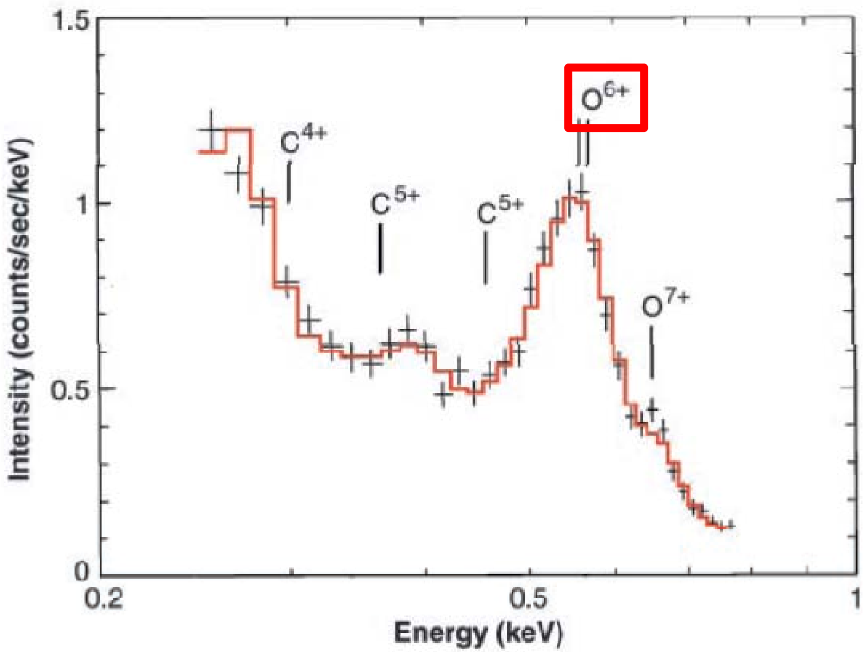


Fig. 2. Intensity versus photon energy. Soft x-ray spectrum of comet C/LINEAR 1999 S4 obtained on July 14, 2000, by the Chandra X-ray Observatory ACIS-S instrument. The solid red line is from a six-line best-fit "model" in which the line positions were fit parameters. The observational full-width half-maximum energy resolution was ΔE = .11 keV. The positions of several transition lines from multiply charged ions known to be present in the solar wind are indicated but were not part of the data fit. Adapted from (*22*).

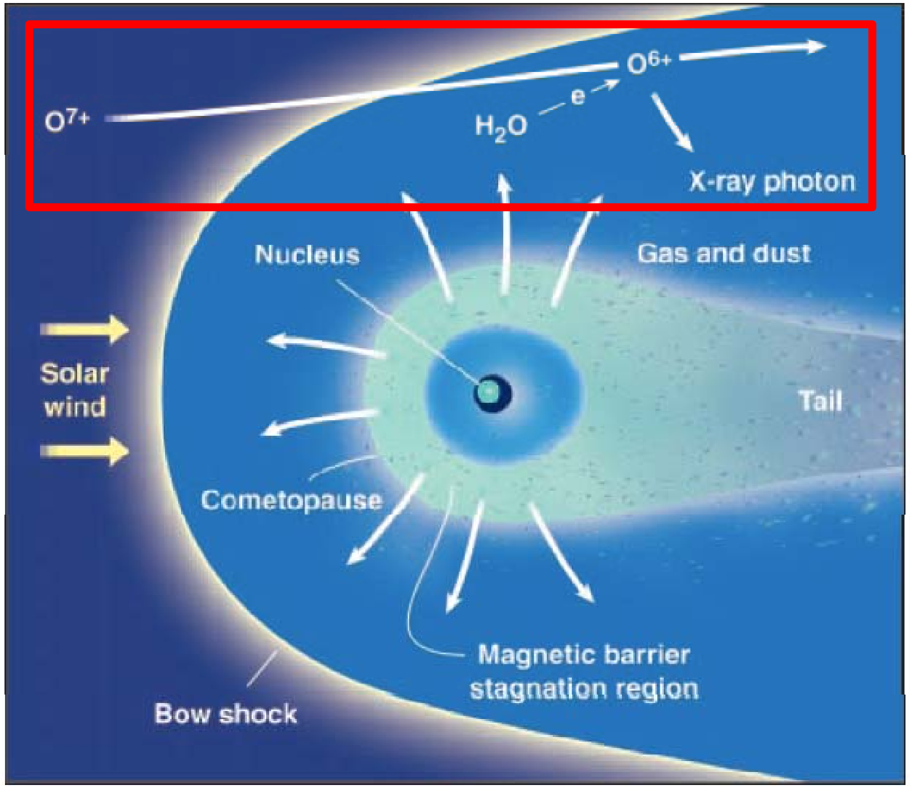
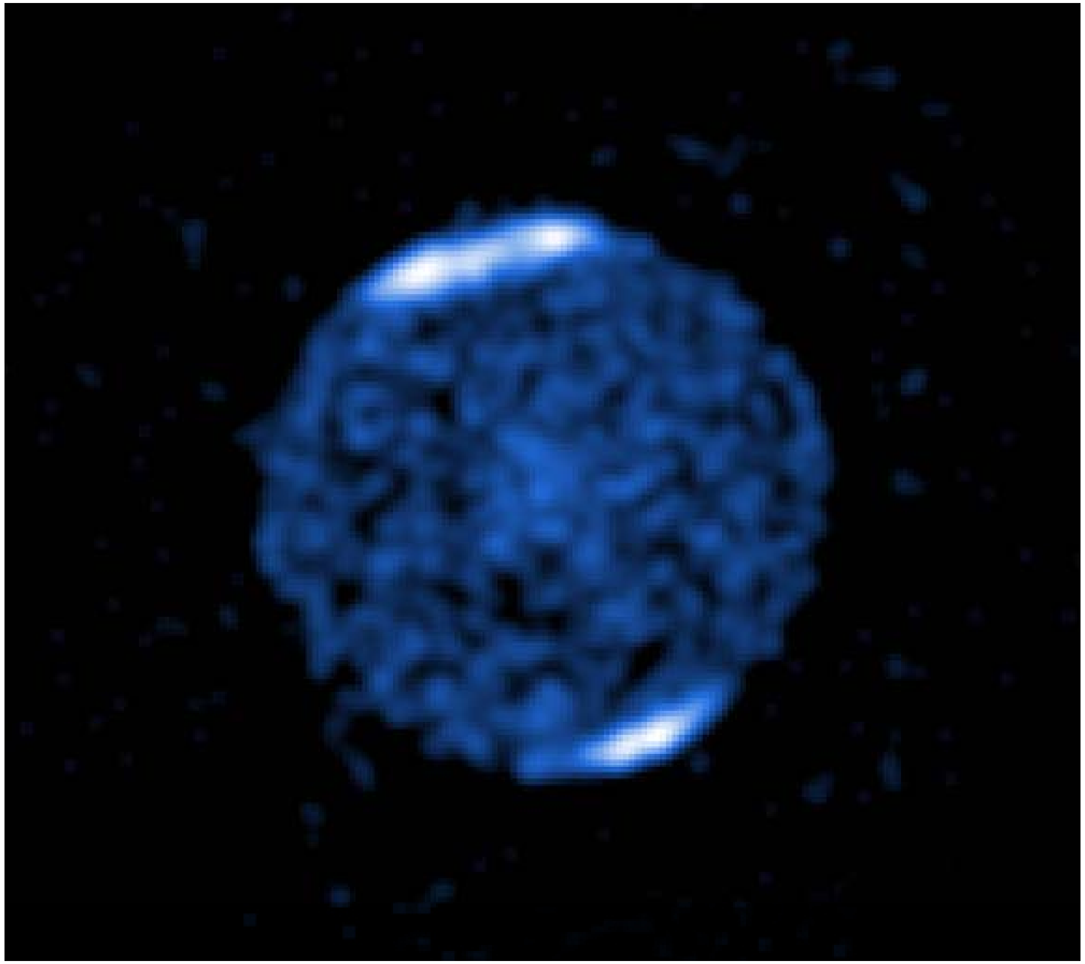
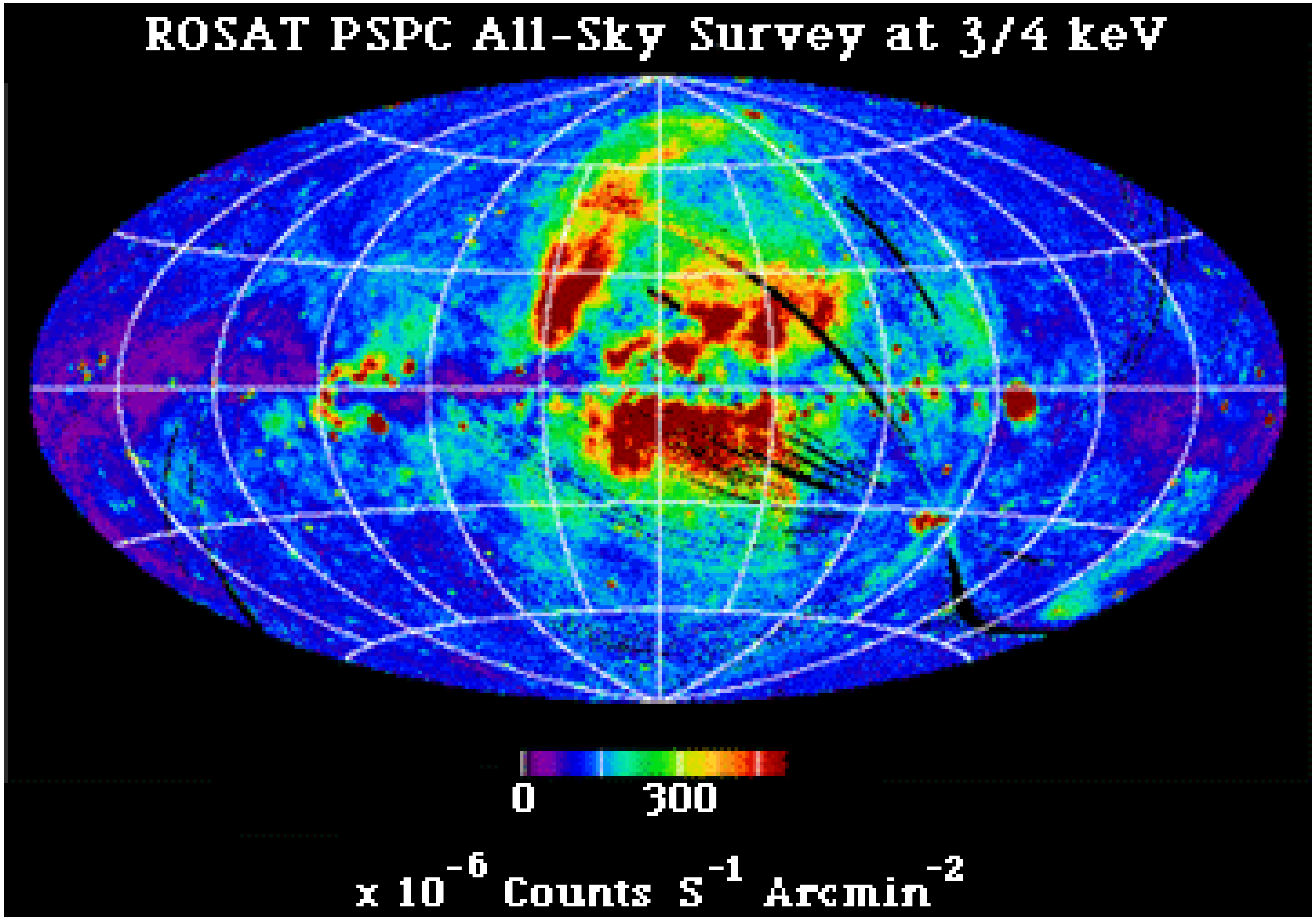


Fig. 3. Scheme of the solar wind/comet interaction. The location of the bow shock, magnetic barrier, and tail are shown. Also represented is a CT collision between a heavy solar wind ion and a cometary neutral water molecule, followed by the emission of an x-ray photon. The Sun is toward the left.



Chandra's image of Jupiter shows bright polar caps associated with auroral activity on Jupiter. X-ray spectra revealed that this activity is caused by highly charged ions of oxygen and other elements crashing into the atmosphere above Jupiter's poles. The charged particles were primarily ions of oxygen and other elements that were stripped of most of their electrons, which implies that the ions were accelerated to high energies in a multimillion-volt environment above the planet's poles.



3/4 keV diffuse background map from the ROSAT all-sky survey.
At 3/4 keV, the sky is dominated by the relatively smooth extragalatic background and a limited number of bright extended Galactic object.

Charge Exchange Madrid

29 September -1 October, 2010

European Space Astronomy Centre, Madrid, Spain

http://www.sciops.esa.int/index.php?project=CONF2010&page=CX2010

Suzaku (朱雀) the 5th Japanese X-ray astronomy satellite

(July 10, 2005 -)

SUZAKU papers on SWCX

PASJ: Publ. Astron. Soc. Japan **59**, S133–S140, 2007 January 25

Evidence for Solar-Wind Charge-Exchange X-Ray Emission from the Earth's Magnetosheath

Ryuichi FUJIMOTO,[1] Kazuhisa MITSUDA,[1] Dan MCCAMMON,[2] Yoh TAKEI,[1] Michael BAUER,[3] Yoshitaka ISHISAKI,[4] F. Scott PORTER,[5] Hiroya YAMAGUCHI,[6] Kiyoshi HAYASHIDA,[7] and Noriko Y. YAMASAKI[1]

A&A 475, 901–914 (2007)
DOI: 10.1051/0004-6361:20078271

Astronomy & Astrophysics

OVII and OVIII line emission in the diffuse soft X-ray background: heliospheric and galactic contributions*

D. Koutroumpa[1], F. Acero[2], R. Lallement[1], J. Ballet[2], and V. Kharchenko[3]

THE ASTROPHYSICAL JOURNAL, 676:335–350, 2008 March 20

COMPARING *SUZAKU* AND *XMM-NEWTON* OBSERVATIONS OF THE SOFT X-RAY BACKGROUND: EVIDENCE FOR SOLAR WIND CHARGE EXCHANGE EMISSION

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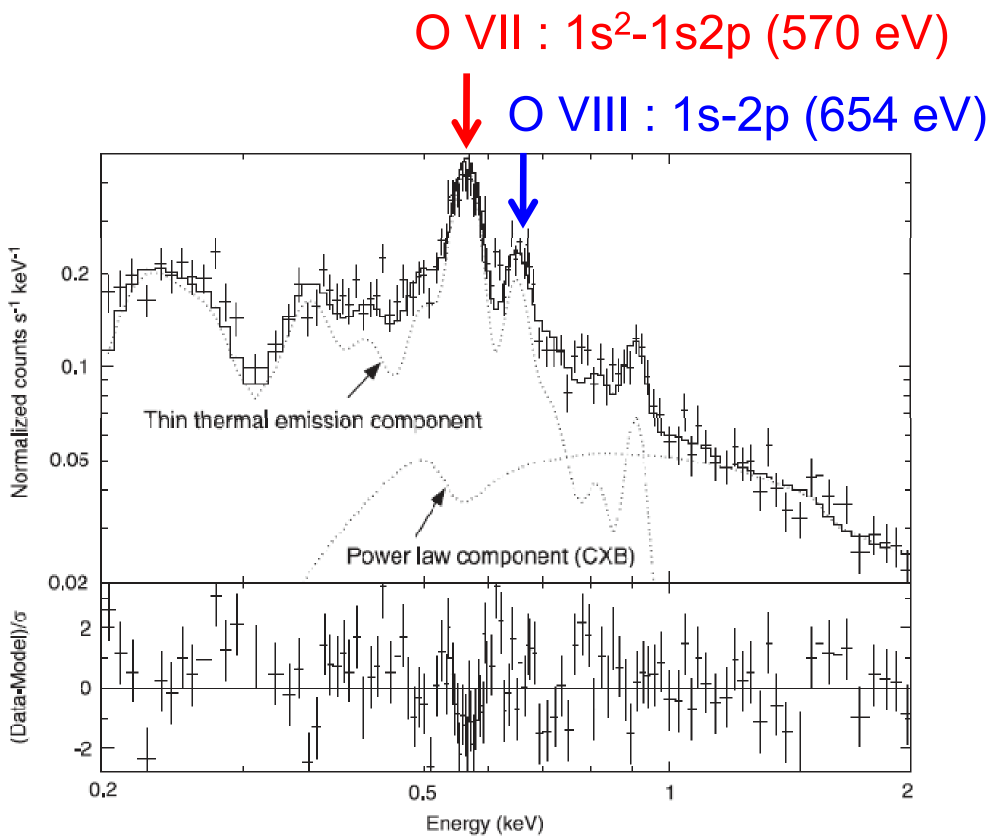
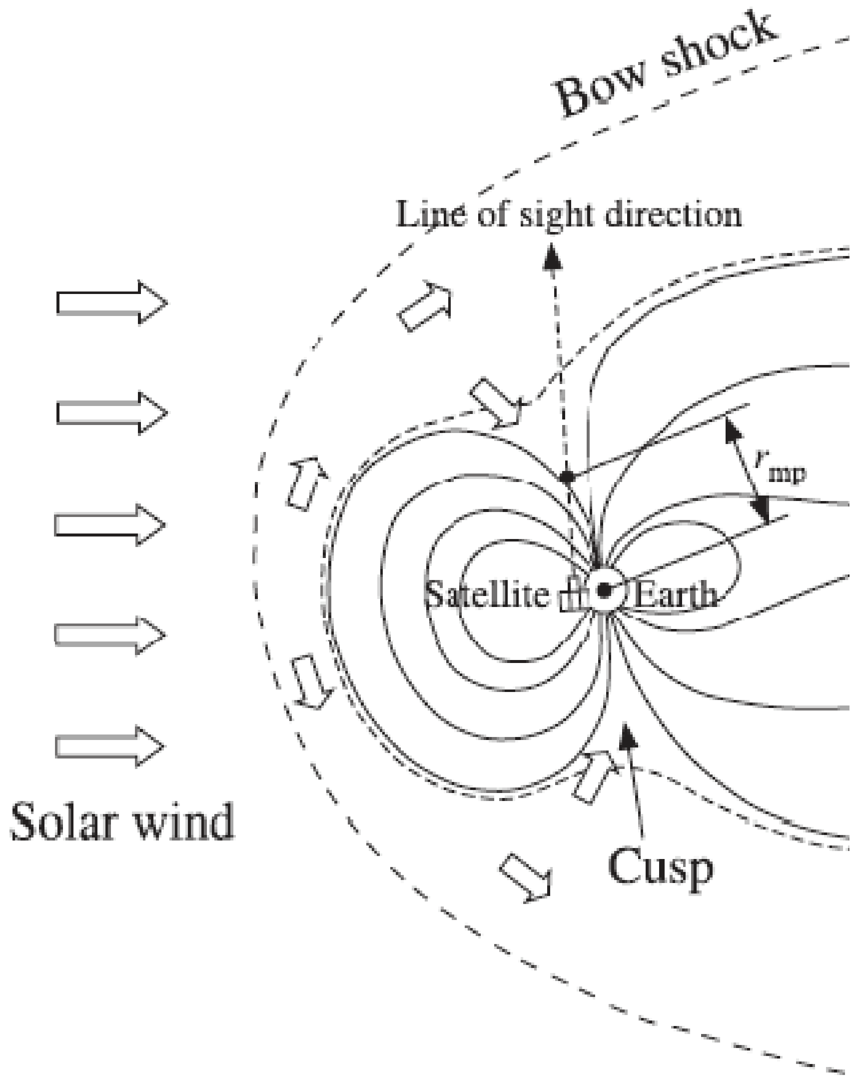
Received 2007 August 10; accepted 2007 December 19

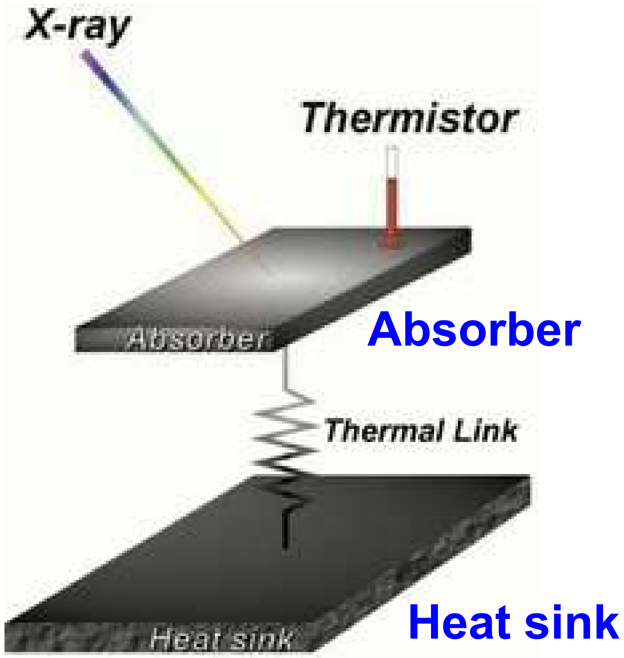
The Soft X-ray background observed by Suzaku

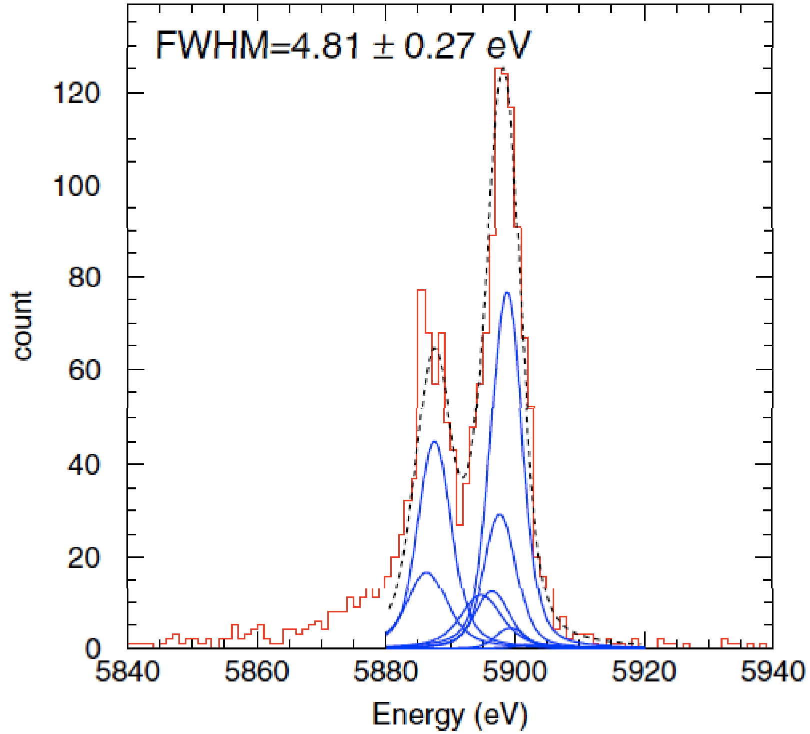


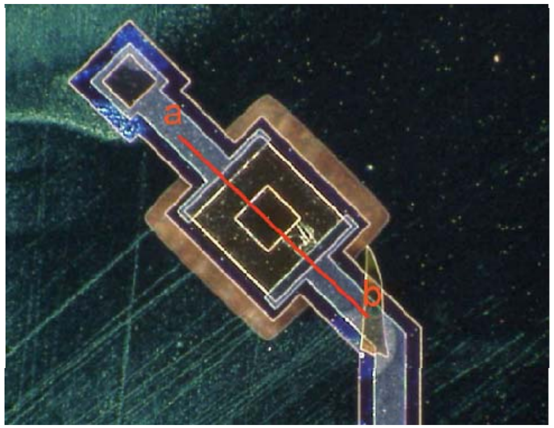


Low resolution ~ 100 eV

Transition Edge Sensor (TES) X-ray Micro-Calorimeter







Size of the absorber : $200 \times 200\ \mu m^2$

High resolution < 5 eV

Collaboration with

Astrophysics Groups (TMU and JAXA)

who are working for the development of TES micro-calorimeter

Goal : " High resolution spectroscopy of SWCX using the TES micro-calorimeter in Lab."

ex. $O^{7+}(1s) + H \rightarrow O^{6+}(1snl) + H^{+}$

$\rightarrow O^{6+}(1s^2) + h\nu \ (\geq 561\text{eV})$

Test measurements using Si(Li) detector

Charge Exchange : 電荷交換，荷電変換

Charge Transfer : 電荷移行，電荷移動

Electron Transfer : 電子移行，電子移動

Electron Capture : 電子捕獲

Single electron capture, SC :

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

"True" double electron capture, TDC :

$$A^{q+} + B \rightarrow A^{(q-2)+} + B^{2+}$$

Transfer ionization, TI :

$$A^{q+} + B \rightarrow A^{(q-1)+} + B^{2+} + e^{-}$$

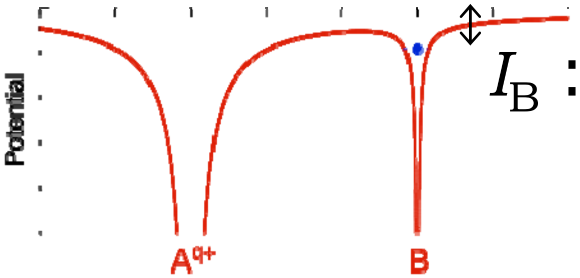
Some features of CX of MCI

- Very large cross sections (> 10^{-16} cm^2)
- Single capture is usually dominant.
- Almost constant CS at keV range
- Increase/ decrease at very low energies
- Strong capture state selectivity
- Simple scaling rules for cross sections
- Emission lines are generally polarized.

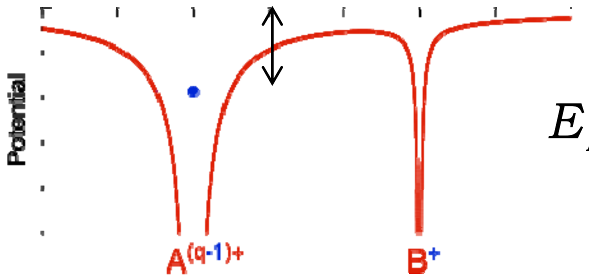
Historical Works on CX in Japan

- NICE project @ NIFS in Nagoya (1970s-80s)
  (Naked Ion Collision Experiments)
  Prof. Y. Kaneko and many guest researchers
- Classical over the barrier model
  H. Ryufuku, S. Sasaki, and T. Watanabe :
  Phys. Rev. A 21 (1980) 745.
- Strong state selectivity in electron capture of multiply charged ions

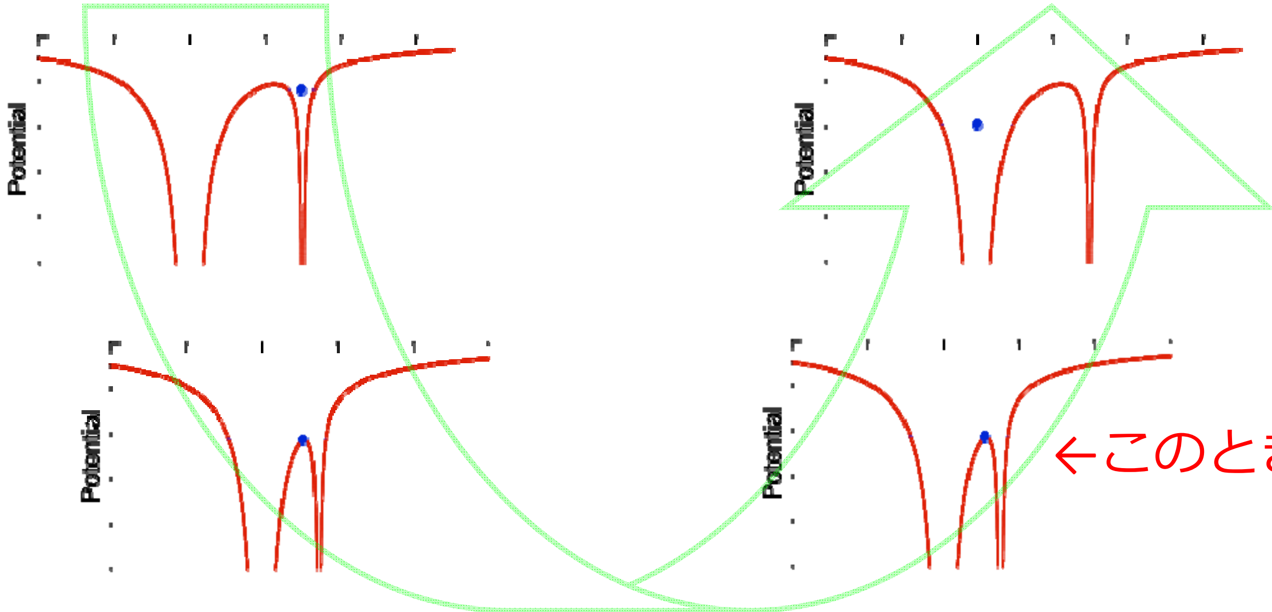
Classical over-the-barrier model



I_B : 標的のIP

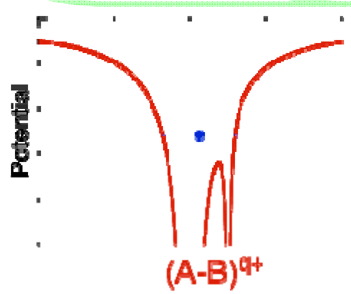


$$E_A = -\frac{(q-1)^2}{2n_A^2}$$



$$\sigma = \pi R_C^2$$

←このときの核間距離が重要



主量子数： $n_A = \left\{ \frac{1+2\sqrt{q}}{2I_B(q+2\sqrt{q})} \right\}^{\frac{1}{2}} q$

標的によって捕獲準位が異なる

(A. Niehaus, 1986)

Scaling rules for the constant cross section region

Empirical scaling rule :

Mueller-Salzborn : Phys. Lett. **62A** (1977) 391.

$$\sigma_{q,q-1} / \mathrm{cm}^2 = 1.43 \times 10^{-12} \frac{q^{1.17}}{(I / \mathrm{eV})^{2.76}}$$

Scaling rules based on COBM :

M. Kimura *et al.* : J. Phys. B **28** (1995) L643.

$$\sigma_q / \mathrm{cm}^2 = 2.6 \times 10^{-13} \frac{q}{(I / \mathrm{eV})^2}$$

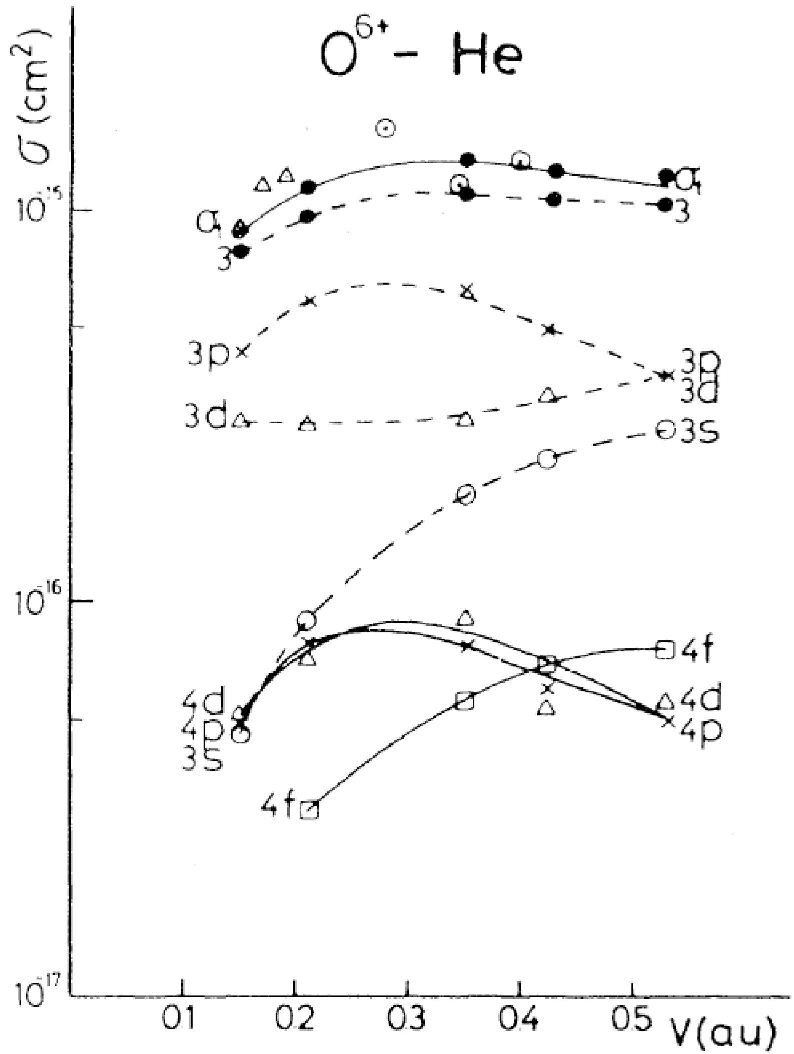
N. Selberg *et al.* : Phys. Rev. A **54** (1996) 4127.

$$\sigma_q^r / \mathrm{cm}^2 = 2.7 \times 10^{-13} qr \Big/ \left[I_1^2 I_r^2 \sum_{j=1}^{N} (j / I_j^2) \right]$$

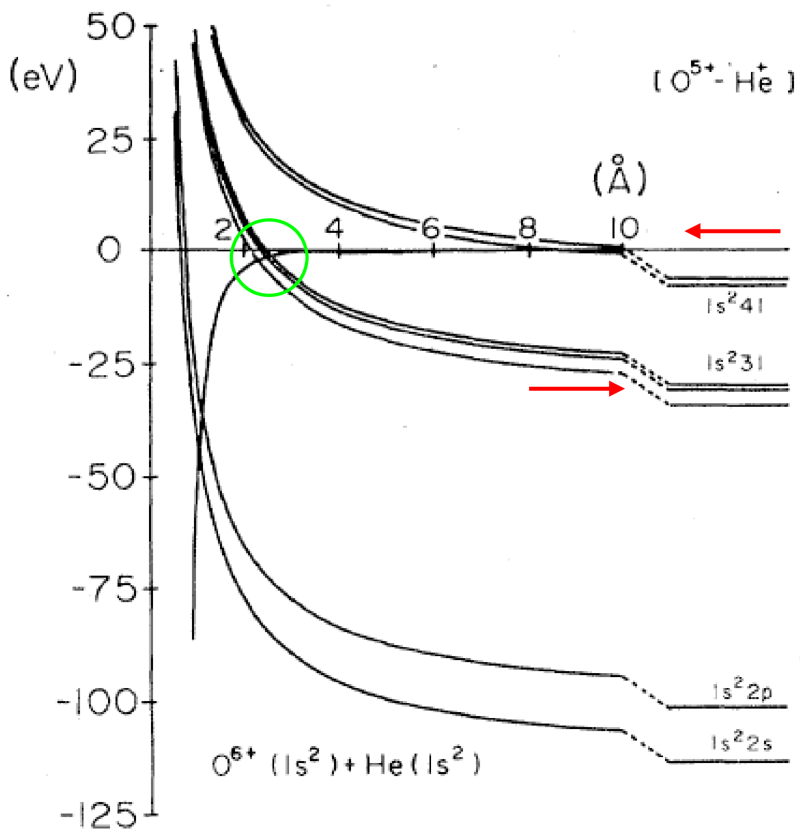
I_j : The *j*-th ionization energy in eV

N : # of outer shell e⁻ (2 for He, 8 for Ar and Xe)

電荷交換分光法による状態選別断面積



(Yu. S. Gordeev *et al.*, 1983)



粒子間ポテンシャルによる状態選択性の理解

(K. Okuno *et al.*, 1983)

電荷移行断面積のスケーリング則：

一価イオンでない限り，かなり普遍的

少なくとも，桁を見積もるのには使える

捕獲準位に関する予測：

・古典的オーバーバリアモデル

・ポテンシャル交差モデル

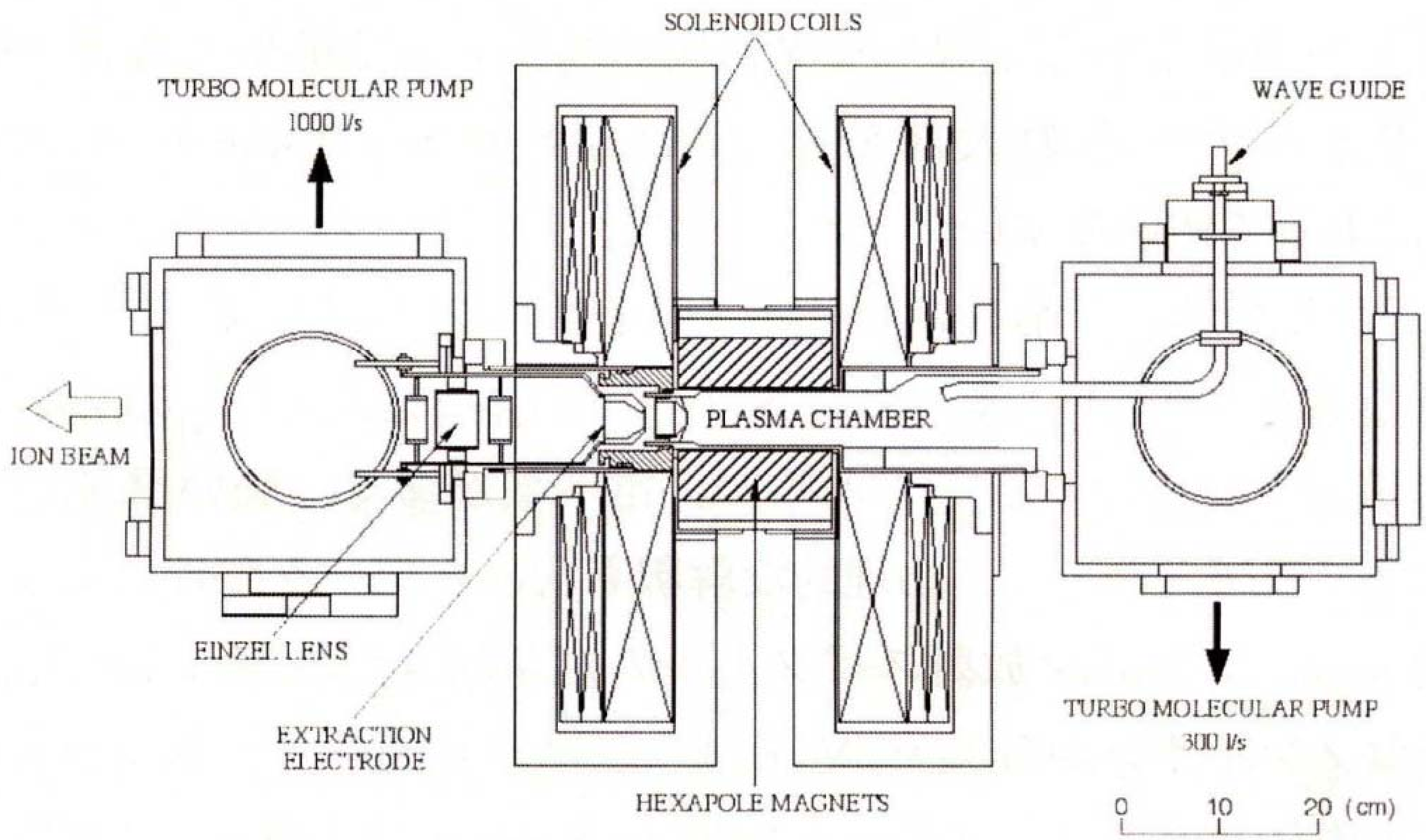
定性的には2つのモデルで説明できる場合が多い

その他の理論：

厳密な理論：緊密結合法 etc.

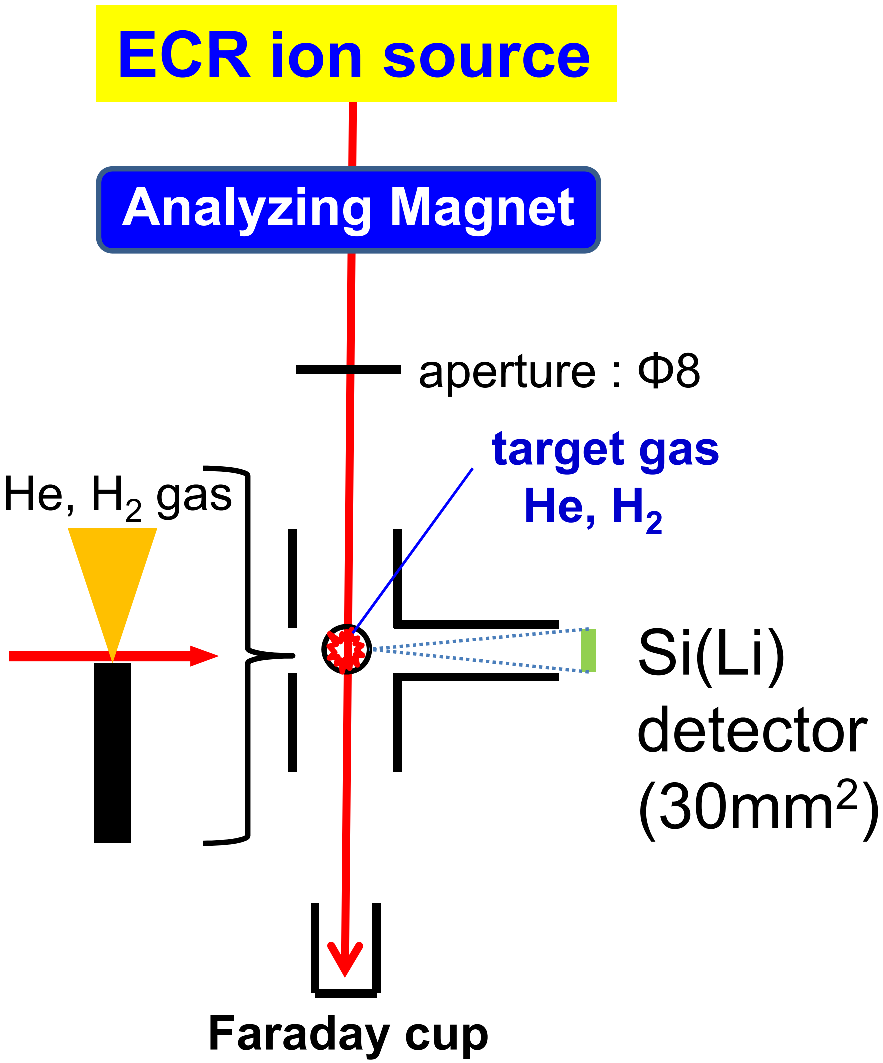
古典論：Classical Trajectory Monte Carlo

電子サイクロトロン共鳴型多価イオン源



MW : 14.25 GHz, 100 - 500 W   Coils & Magnets : B = 1 T

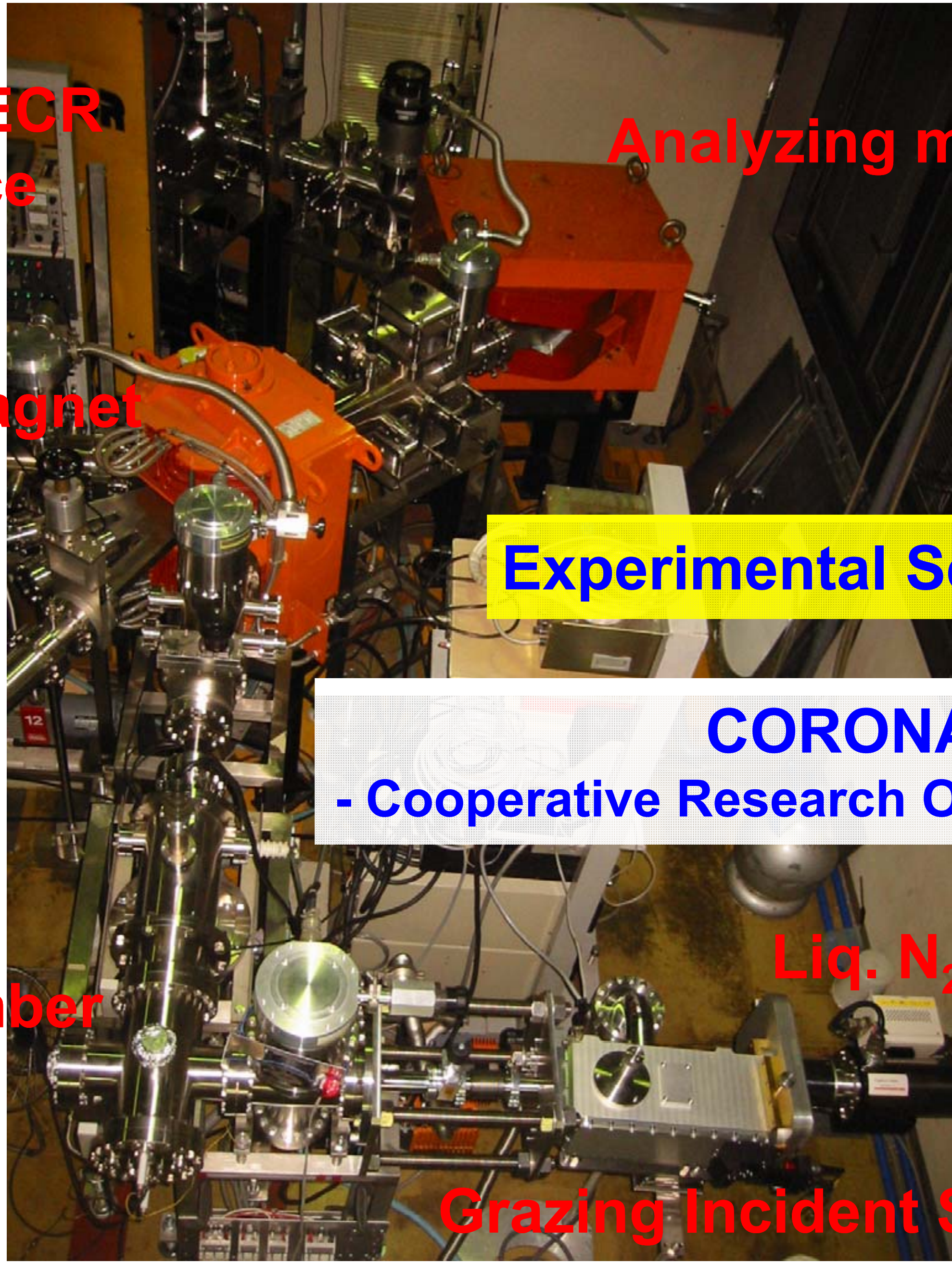
Experimental setup (1)



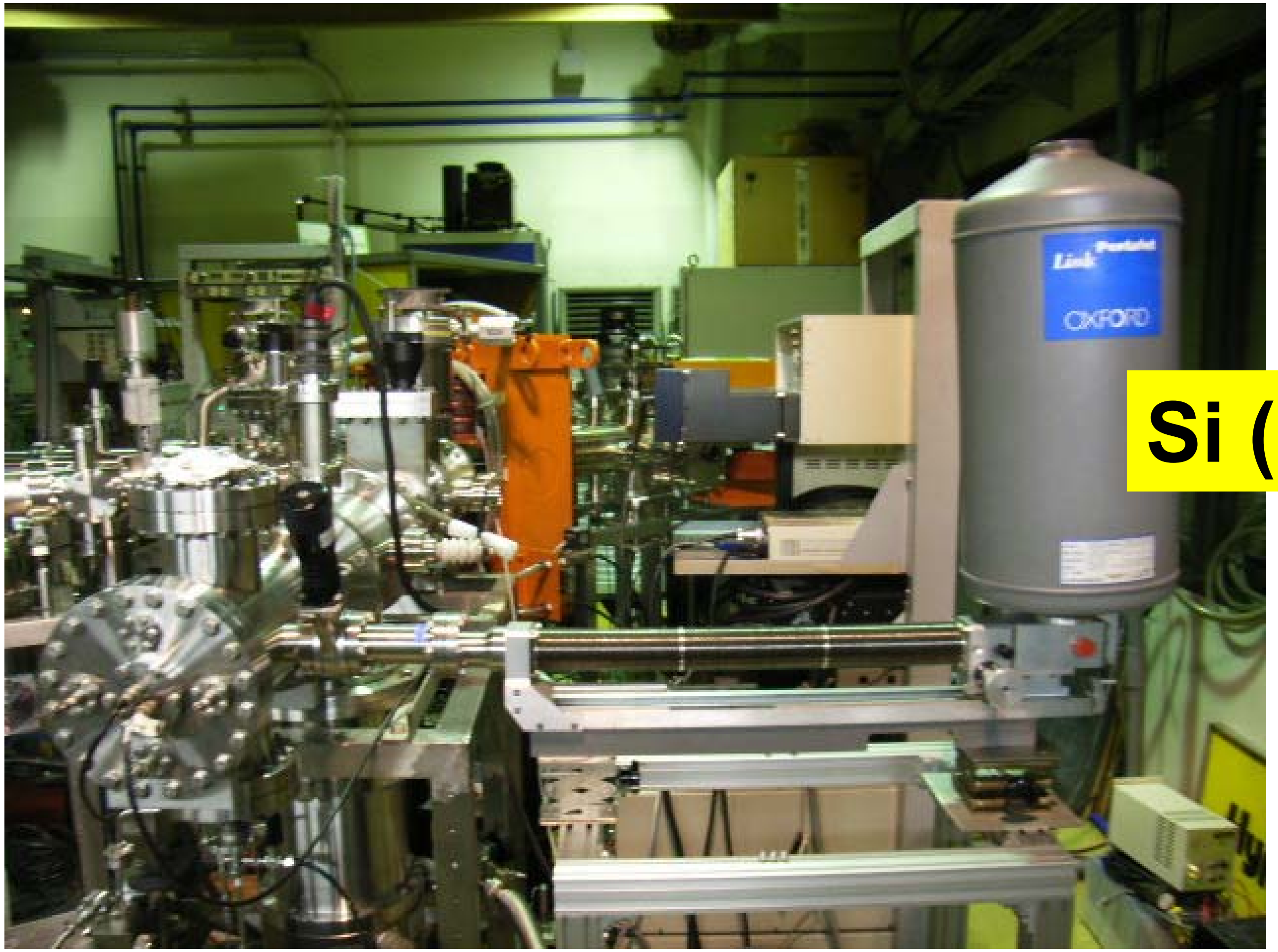
Experimental Setup

CORONA

- Cooperative Research On Novel Atoms -



Experimental setup (3)



Si (Li) detector

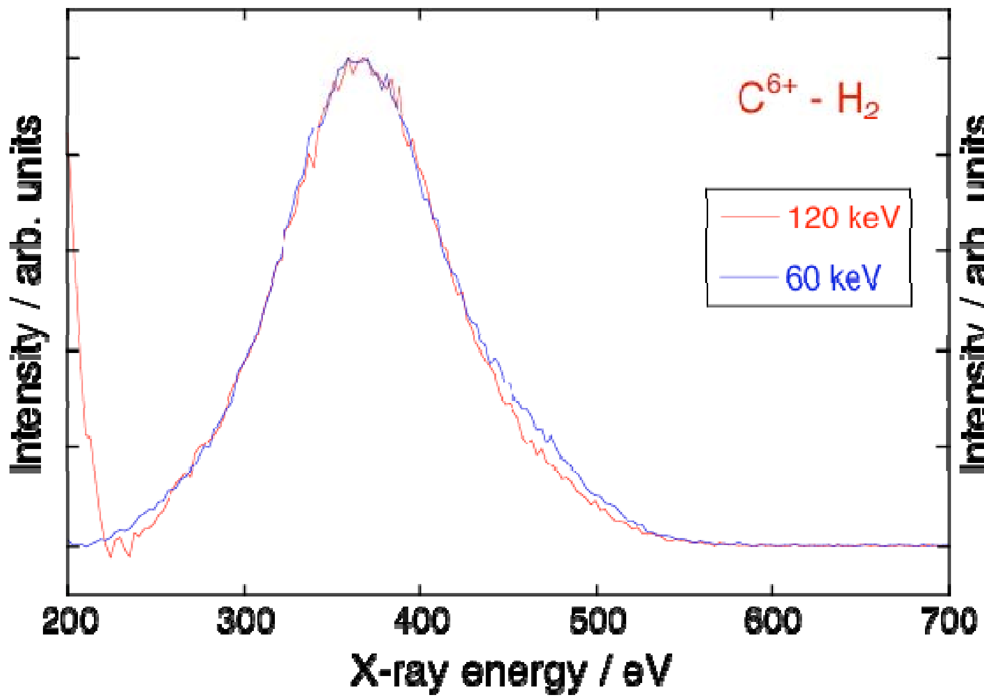
Window-less

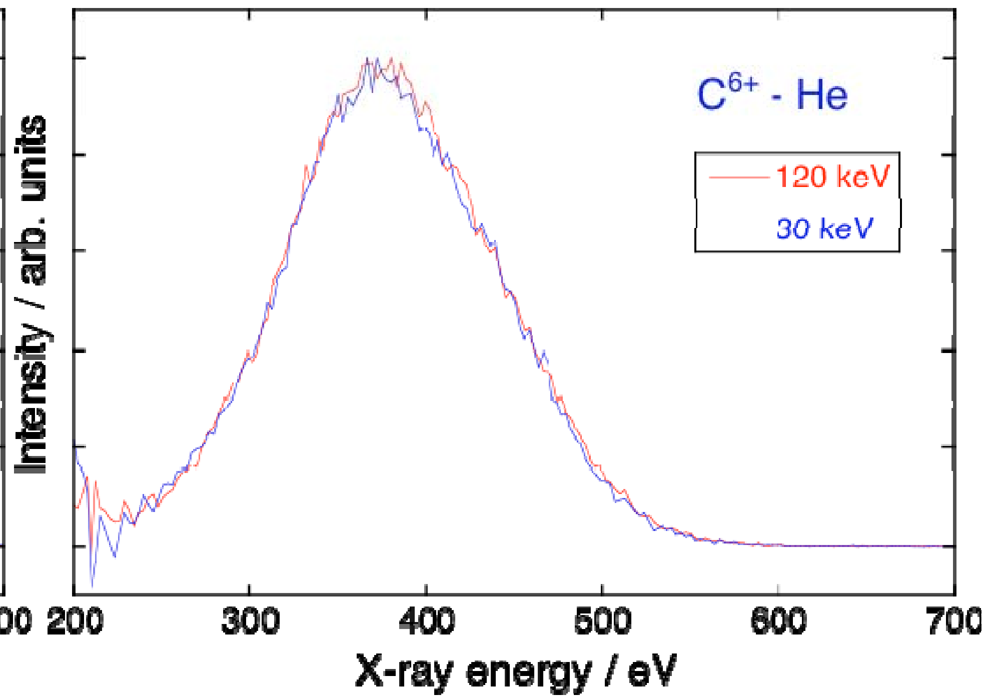
ΔE = 160 eV@5.9 keV

ΔE ~ 107 eV @ < 1 keV

Preliminary
experimental spectra
in collisions of bare ions
with H_2 and He

C^{6+} - H_2/He collisions (1)

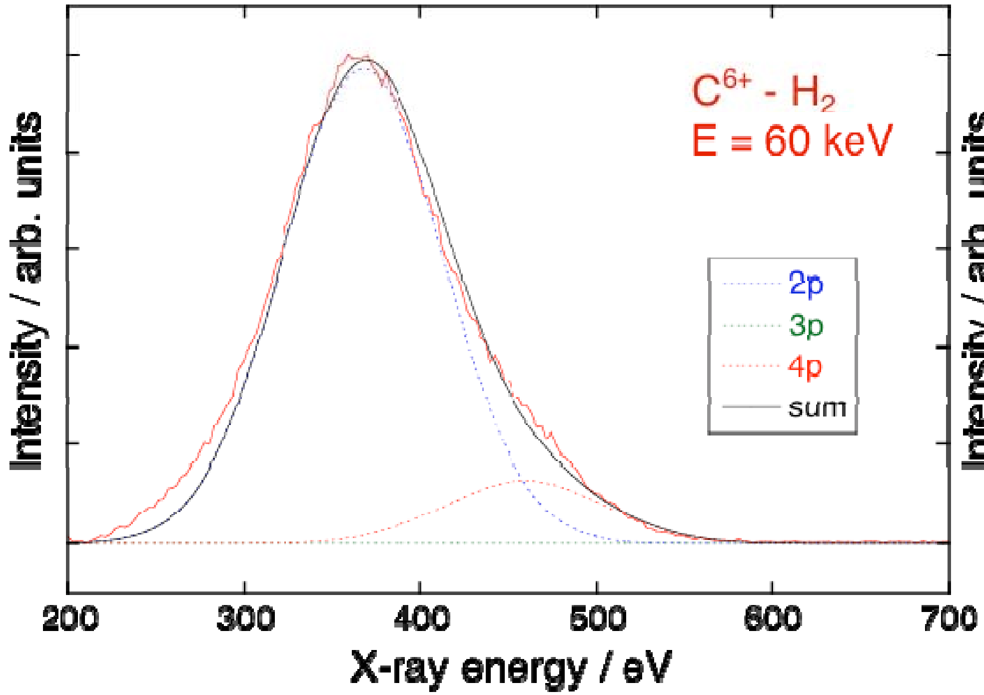


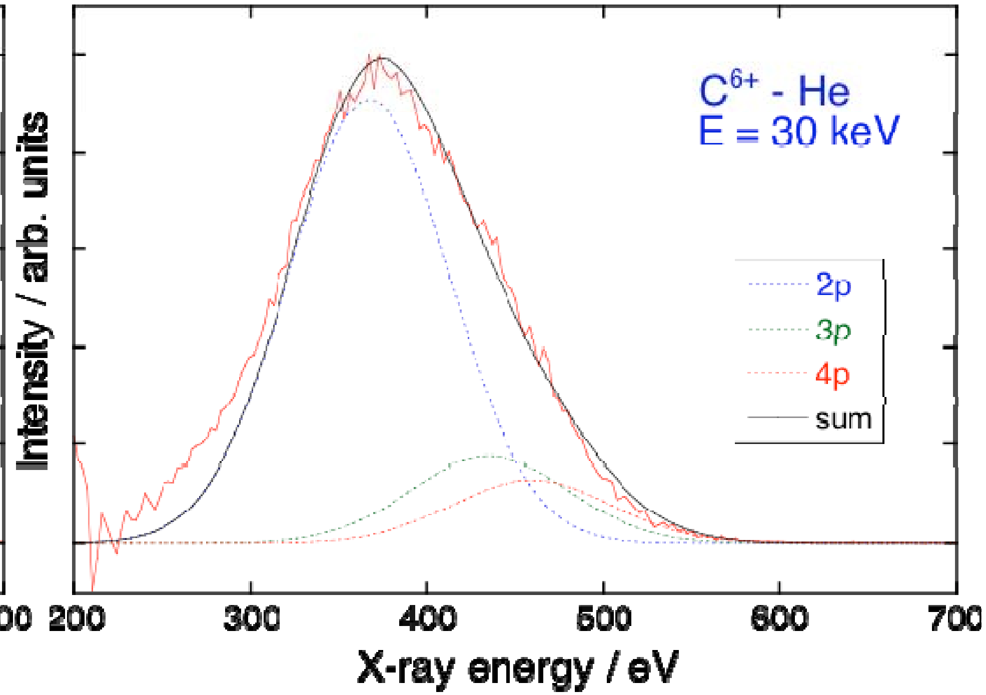


Relative intensity of soft X-ray emission :

Collision energy dependence is small in the shape of spectrum.

C^{6+} -H_2/He collisions (2)



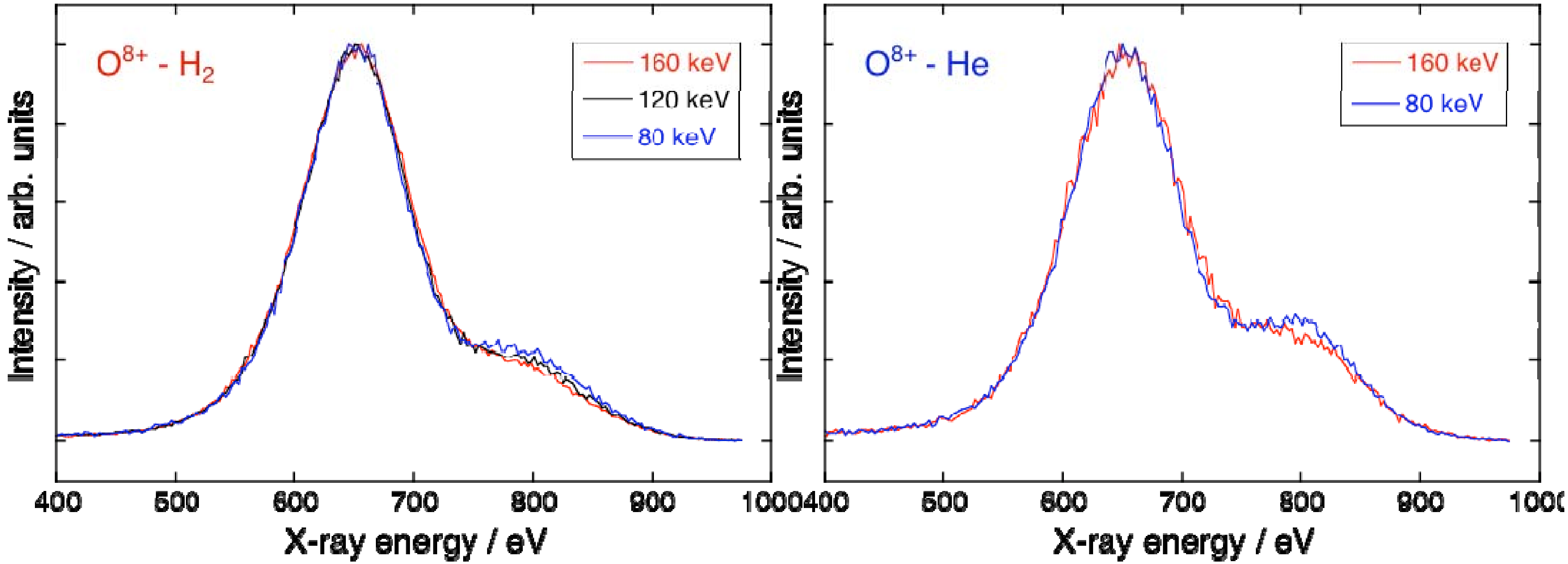


The 1s-2p transition is dominant.

2p > 4p >> 3p

2p > 3p > 4p

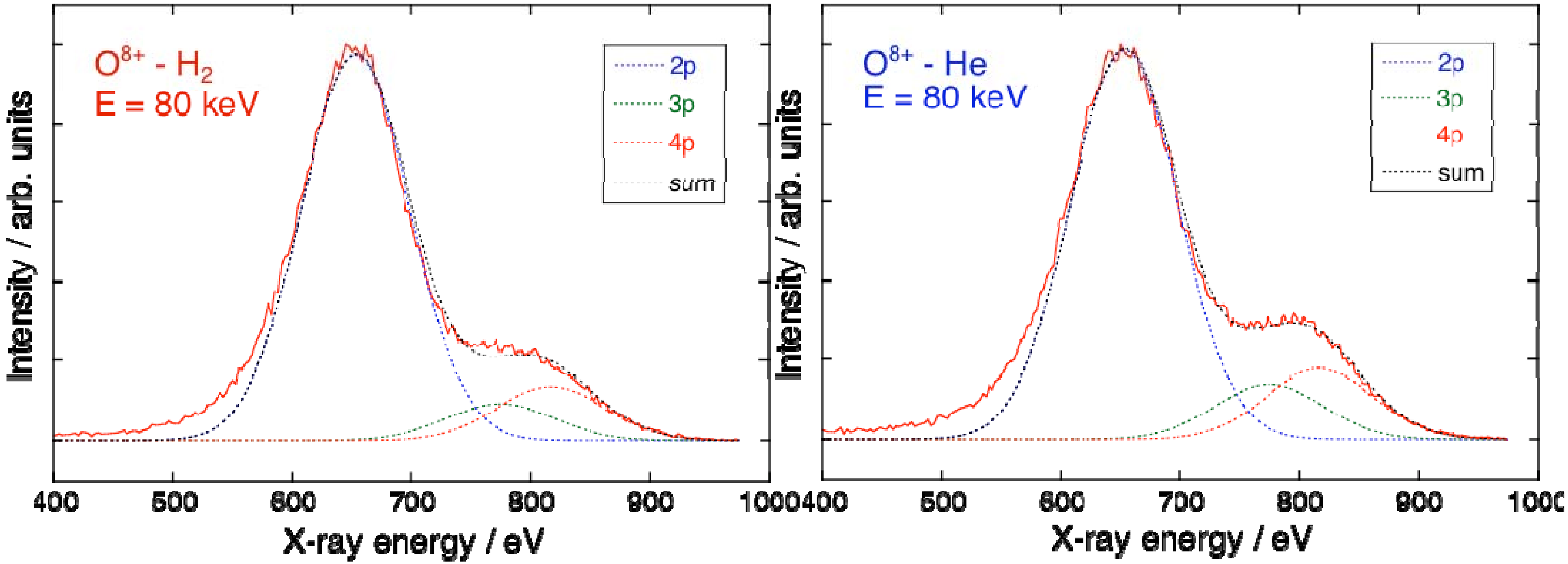
O^{8+} -H_2/He collisions (1)



Relative intensity of soft X-ray emission :

Collision energy dependence is small in the shape of spectrum.

O^{8+} -H_2/He collisions (2)



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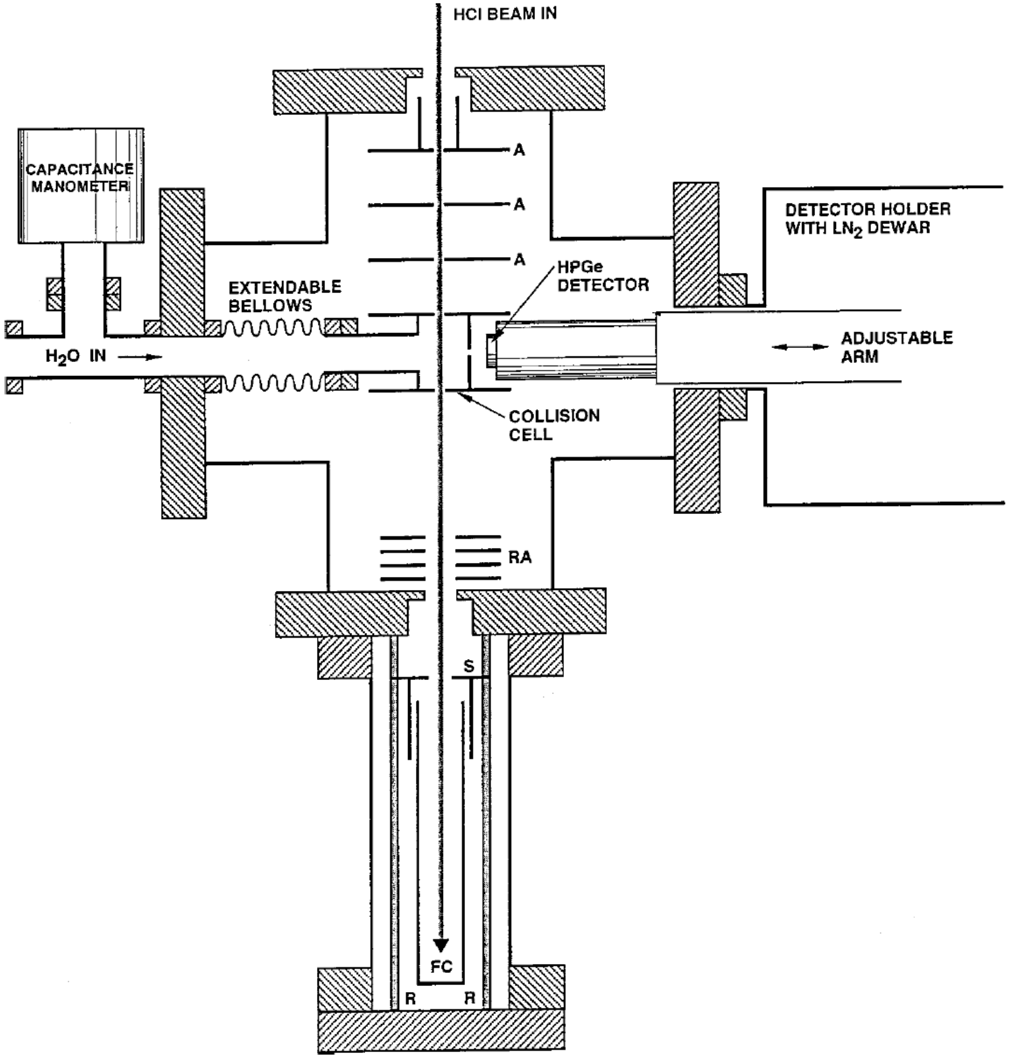
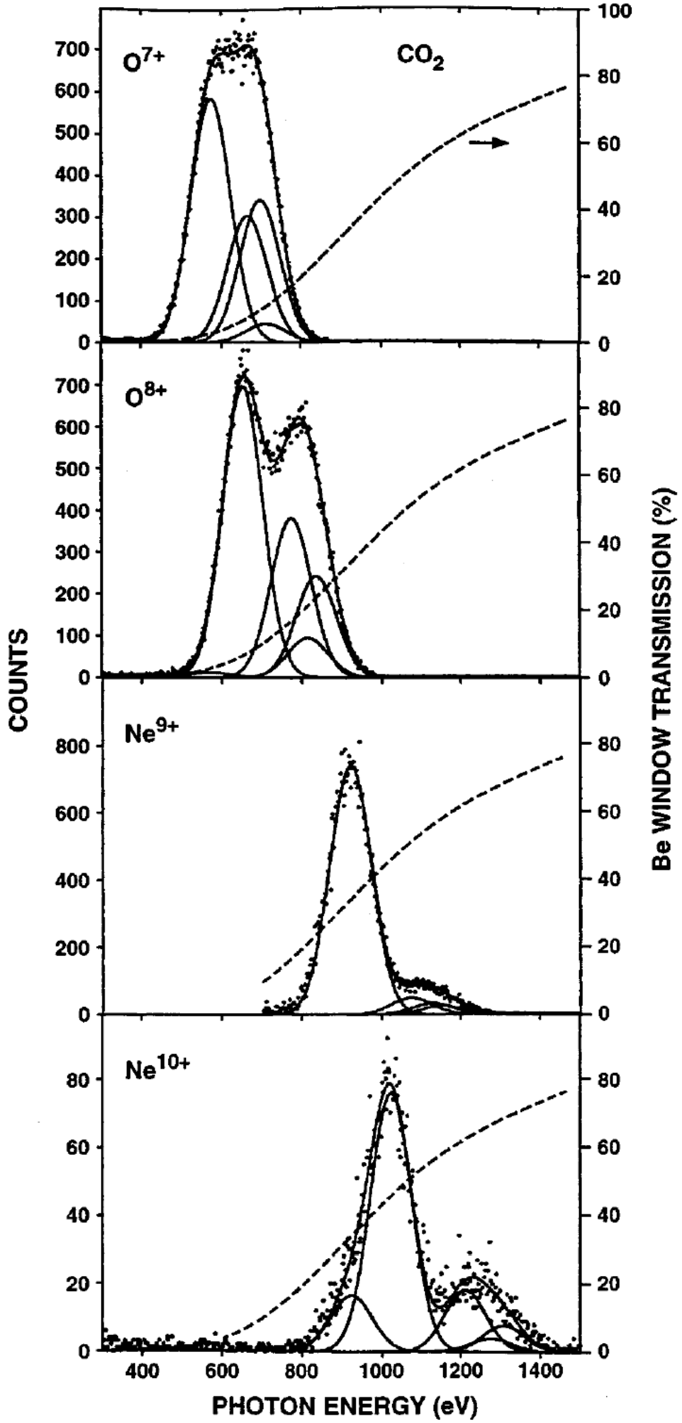
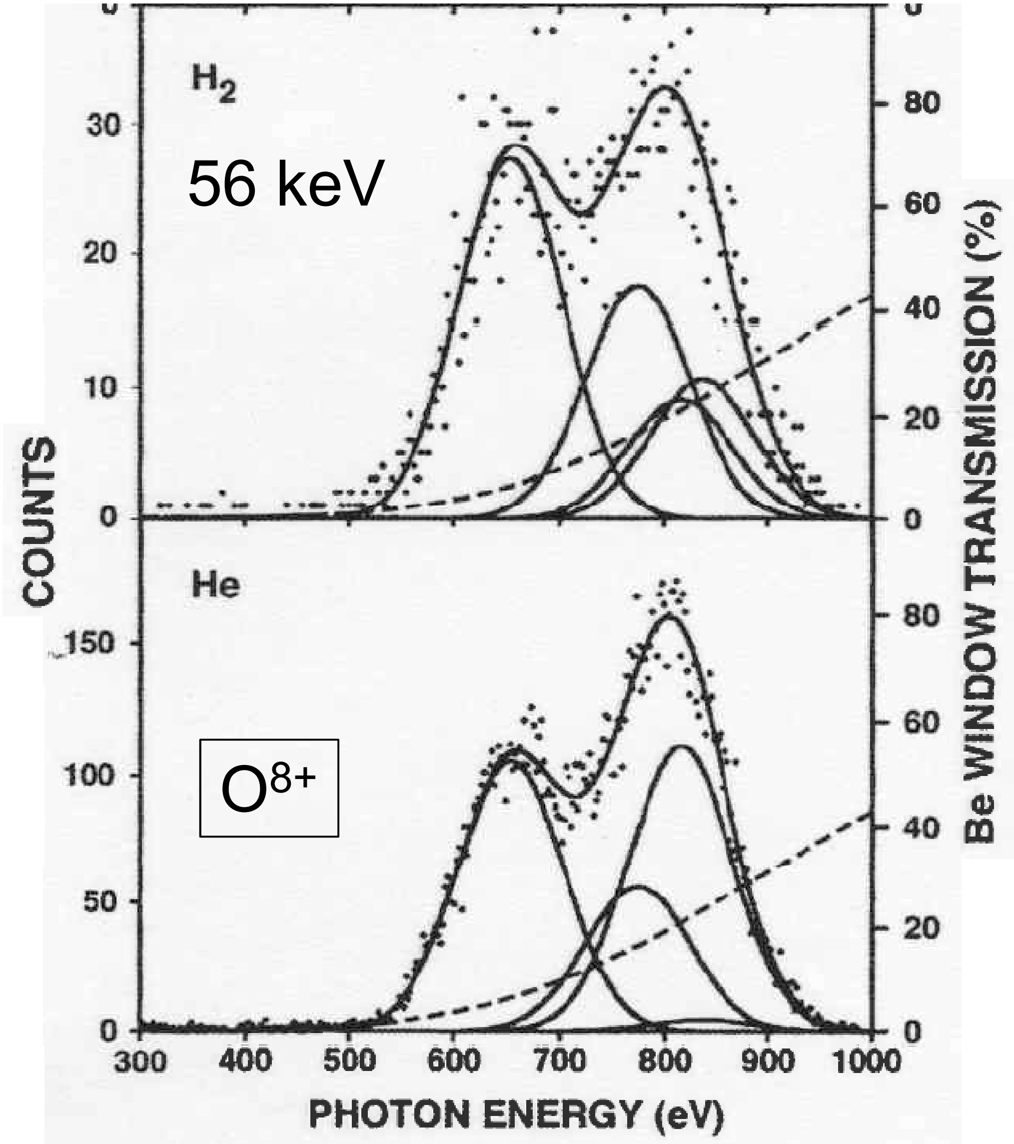




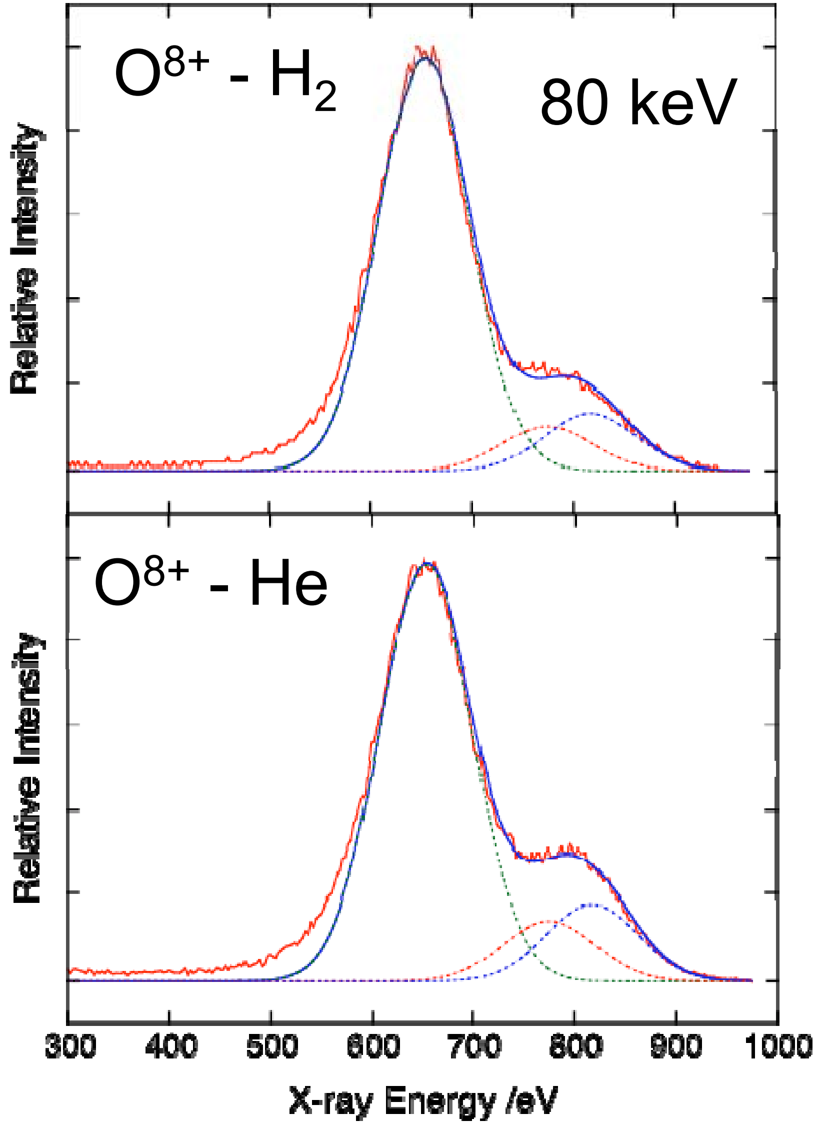
(J. Greenwood *et al*., 2001)

JPL

Be-window *vs* window-less



J. B. Greenwood *et al.* (2001)



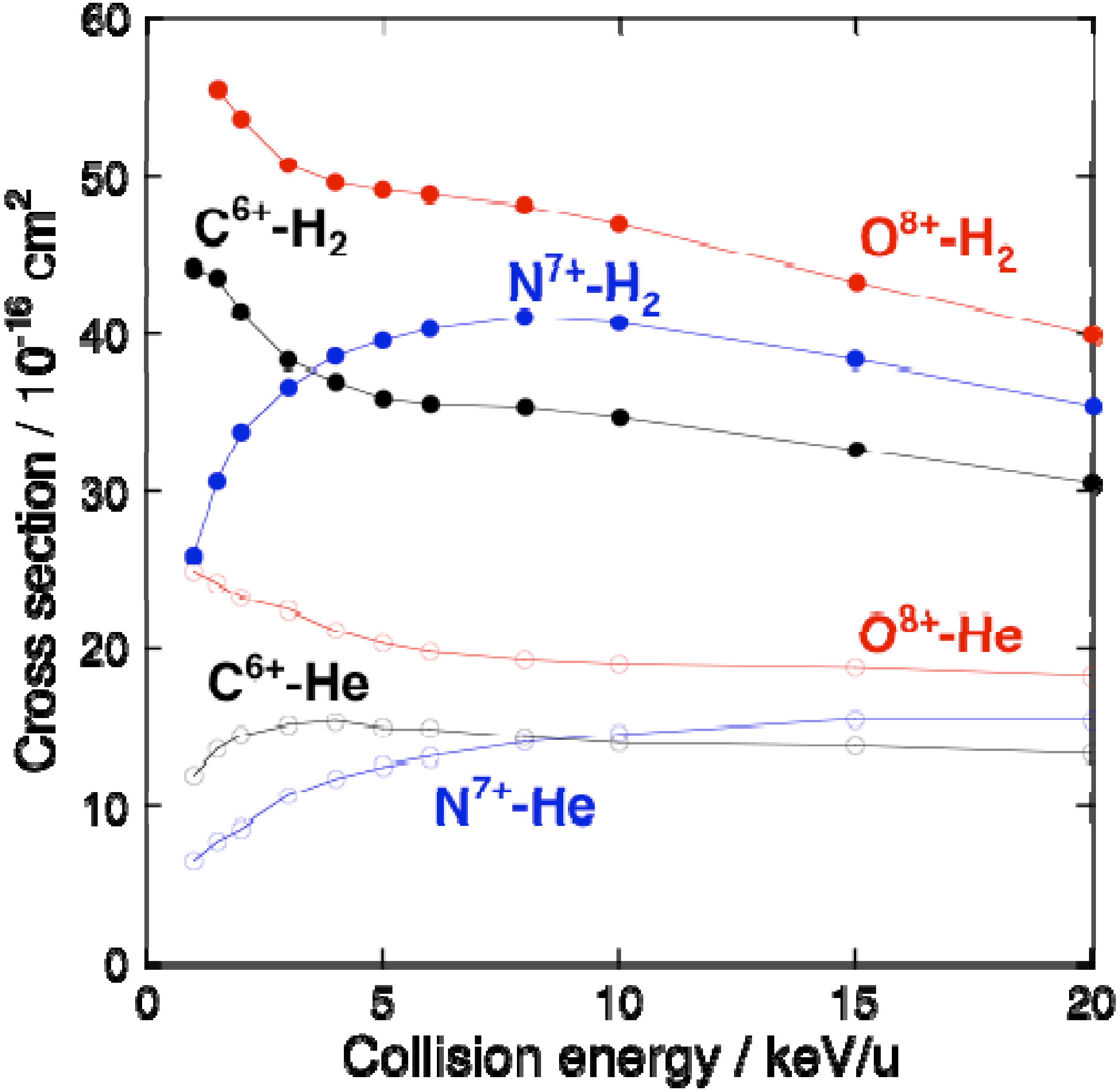
TMU (2010)

Be-window *vs* window-less

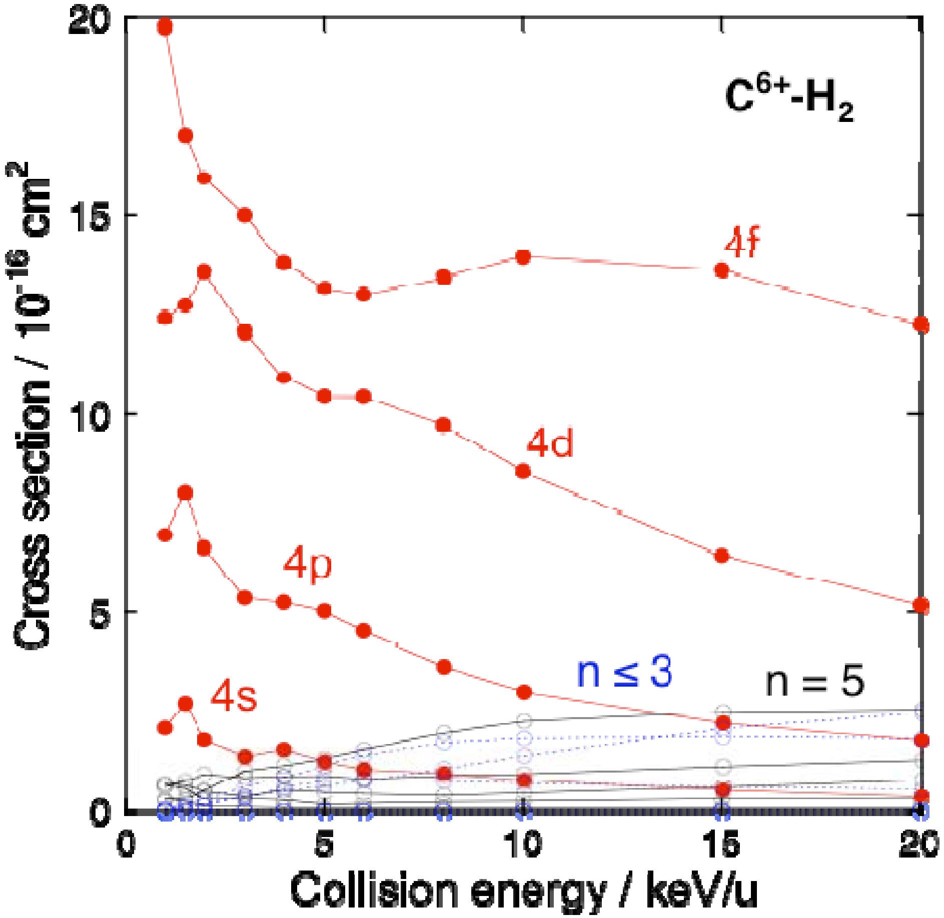
H_2	Greenwood *et al.*	TMU
1s-2p	69%	80%
1s-3p	17%	9%
1s-4p	7%	11%
1s-5p	7%	0%
He		
1s-2p	65%	76%
1s-3p	13%	10%
1s-4p	21%	14%
1s-5p	1%	0%

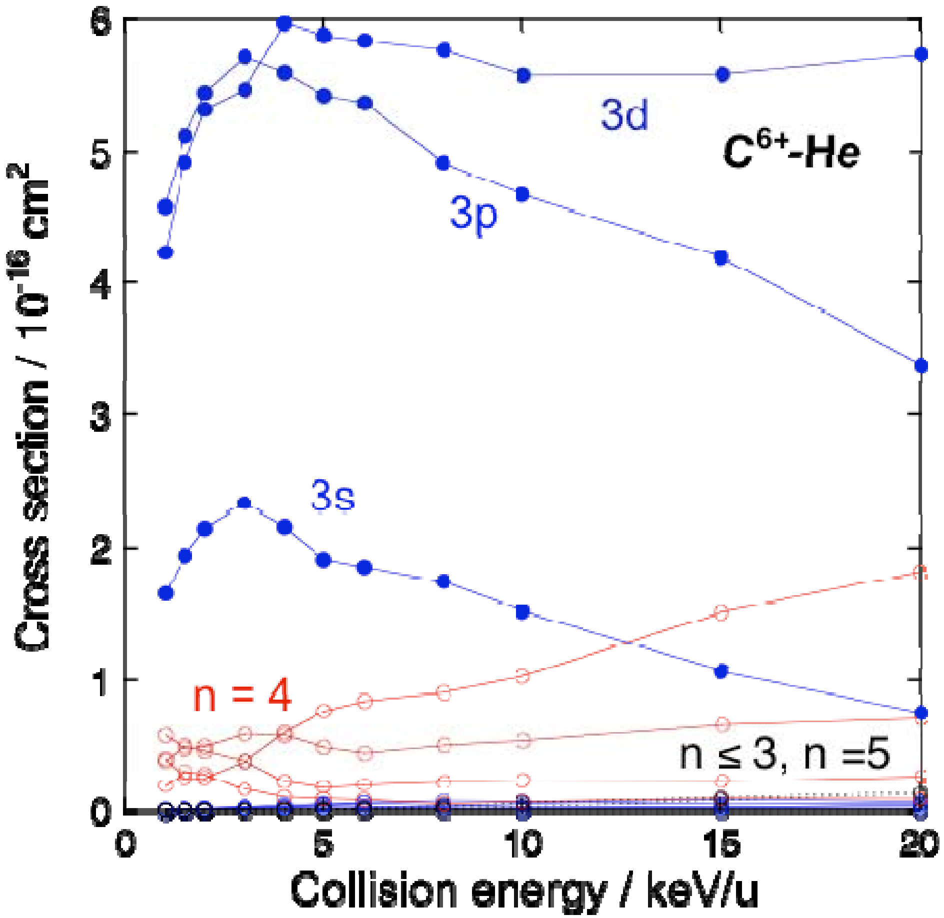
Comparison with theoretical calculations

TC-AOCC calculation

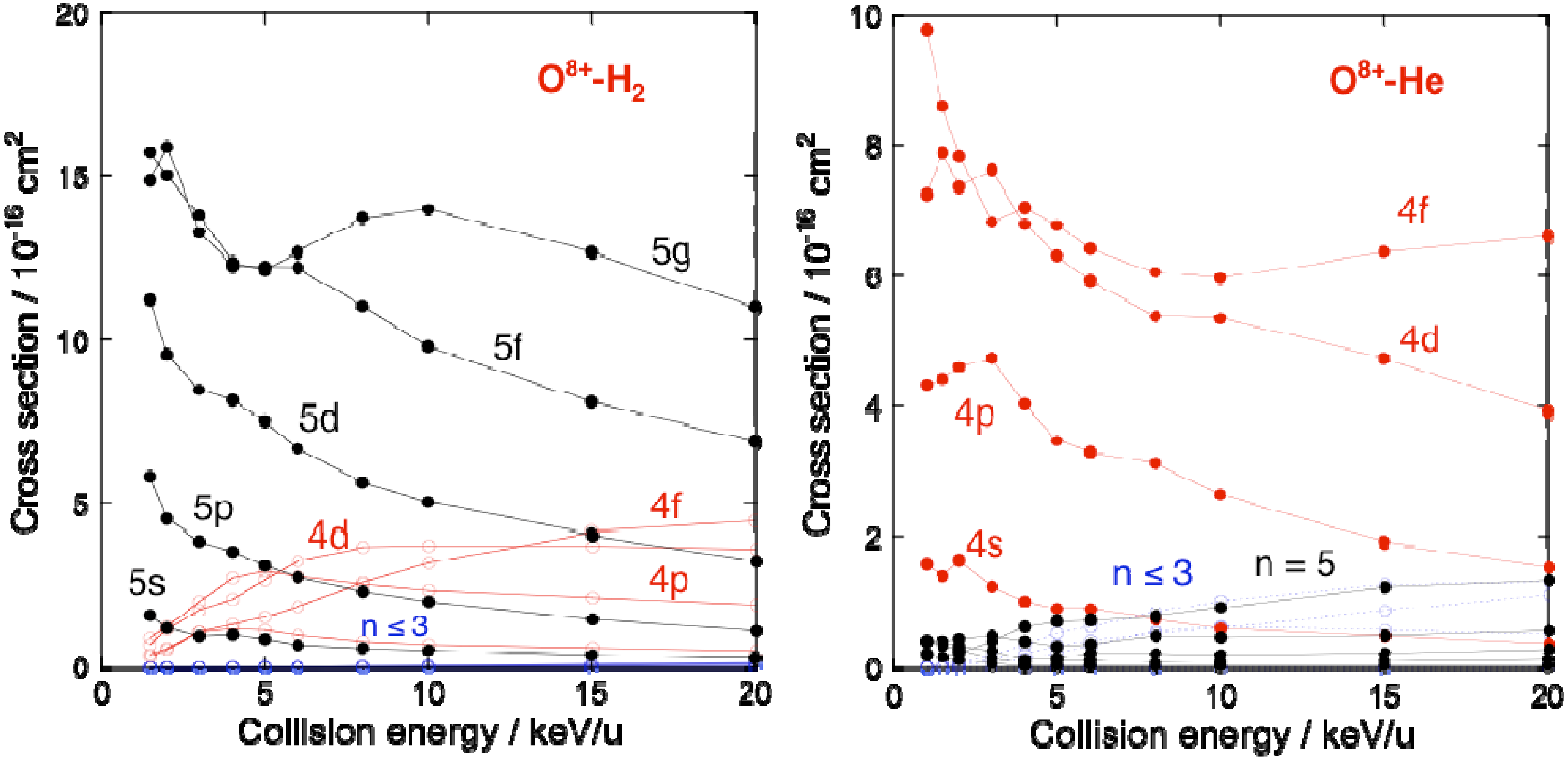


Partial cross sections (1)

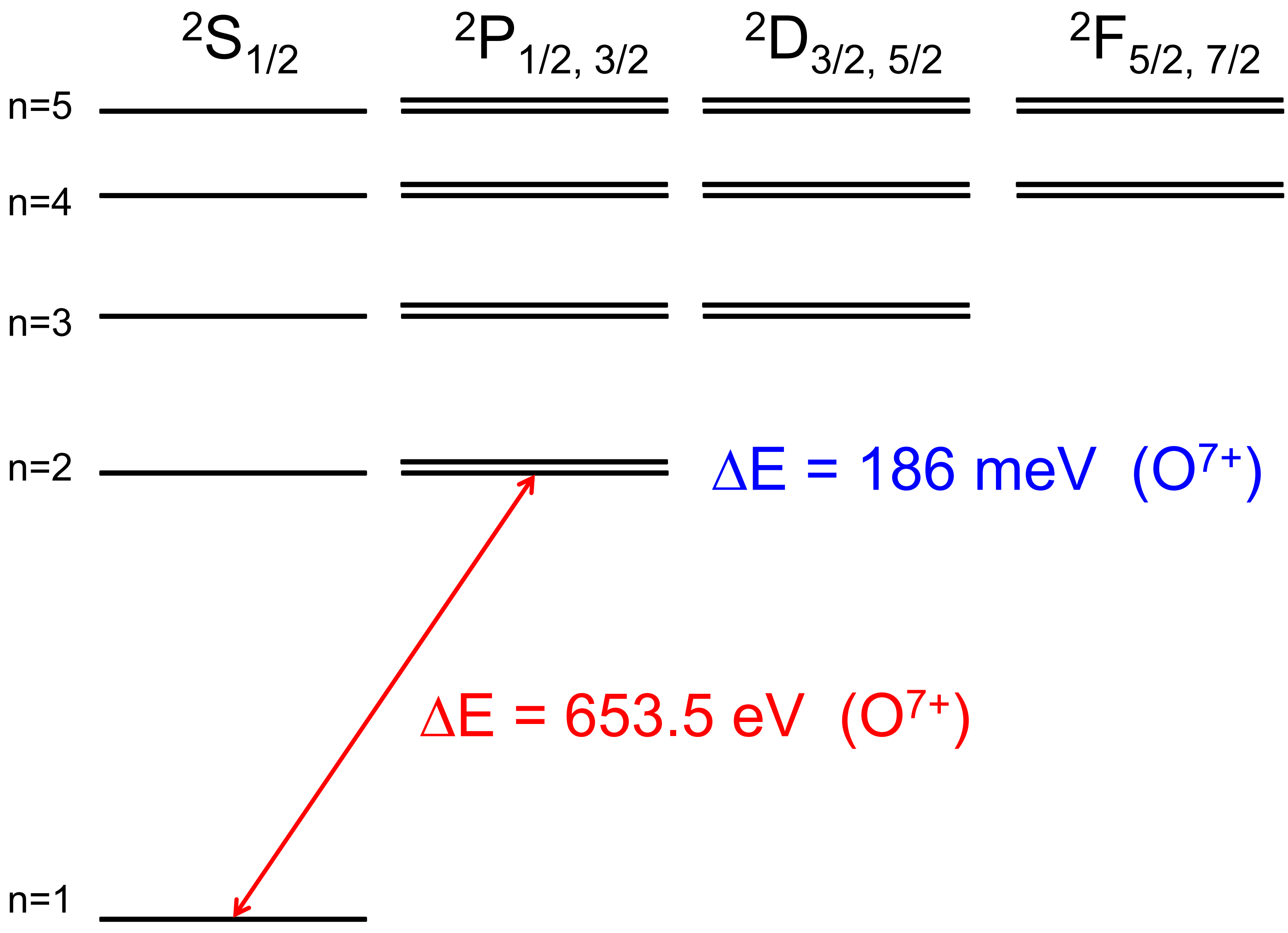




Partial cross sections (2)



Energy levels of H-like ions



Statistical weights in cross sections

$$\sigma(nl) = \sigma(nl)_{J=l-\frac{1}{2}} + \sigma(nl)_{J=l+\frac{1}{2}}$$

$$= \frac{\left\{2\left(l-\frac{1}{2}\right)+1\right\}\sigma(nl) + \left\{2\left(l+\frac{1}{2}\right)+1\right\}\sigma(nl)}{\left\{2\left(l-\frac{1}{2}\right)+1\right\} + \left\{2\left(l+\frac{1}{2}\right)+1\right\}}$$

$$= \frac{l}{l+2}\sigma(nl) + \frac{l+1}{l+2}\sigma(nl)$$

$np\ ^2P_{1/2} : np\ ^2P_{3/2}$ = 1 : 2

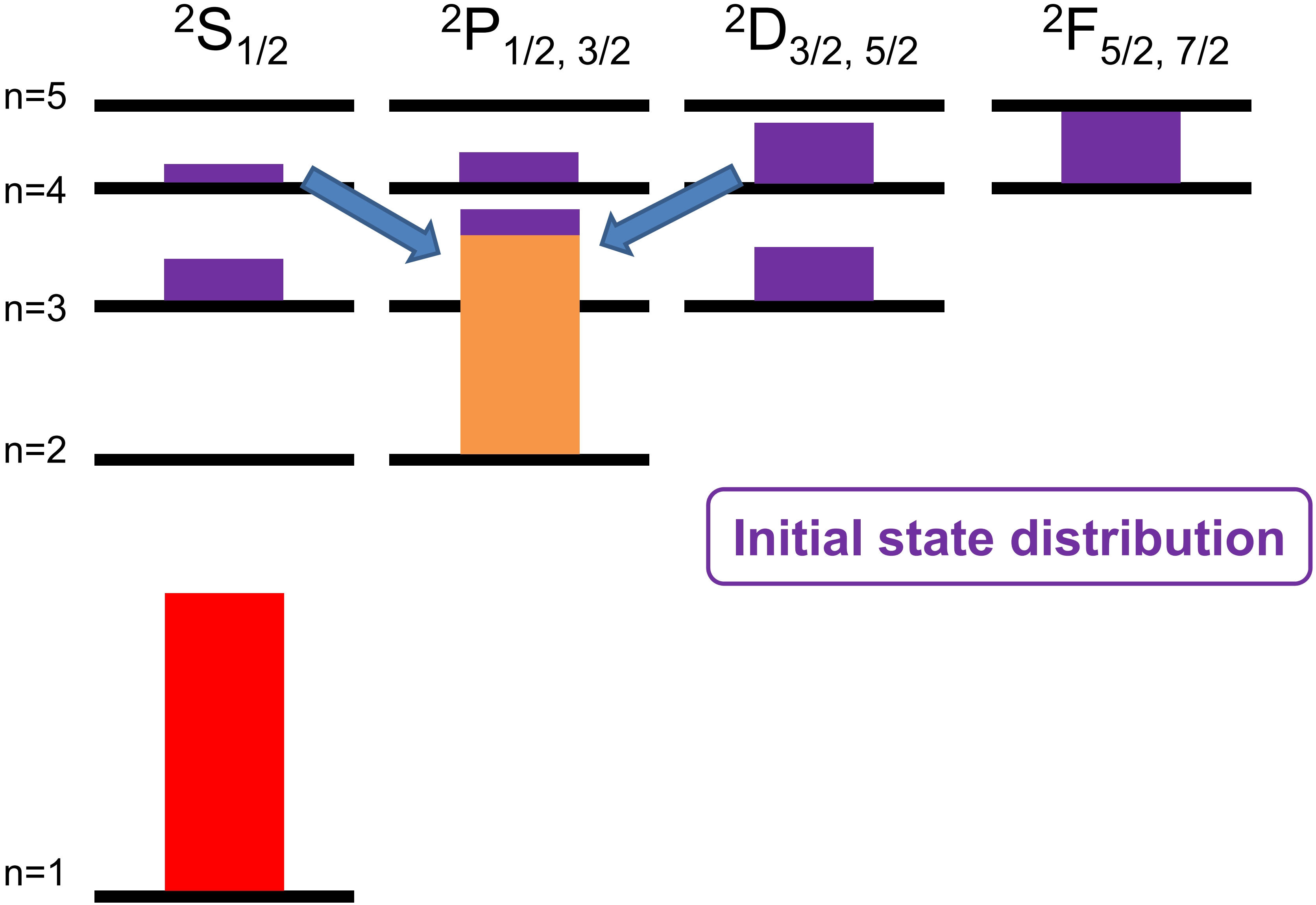
$nd\ ^2D_{3/2} : nd\ ^2D_{5/2}$ = 2 : 3

$nf\ ^2F_{5/2} : nf\ ^2F_{7/2}$ = 3 : 4

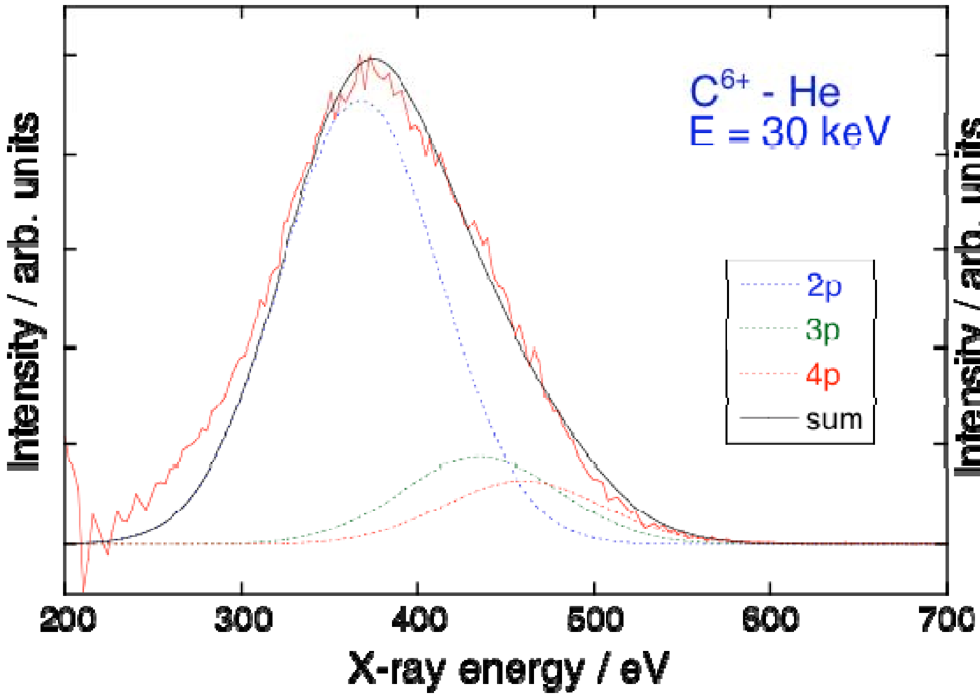
Now it is just assumption.

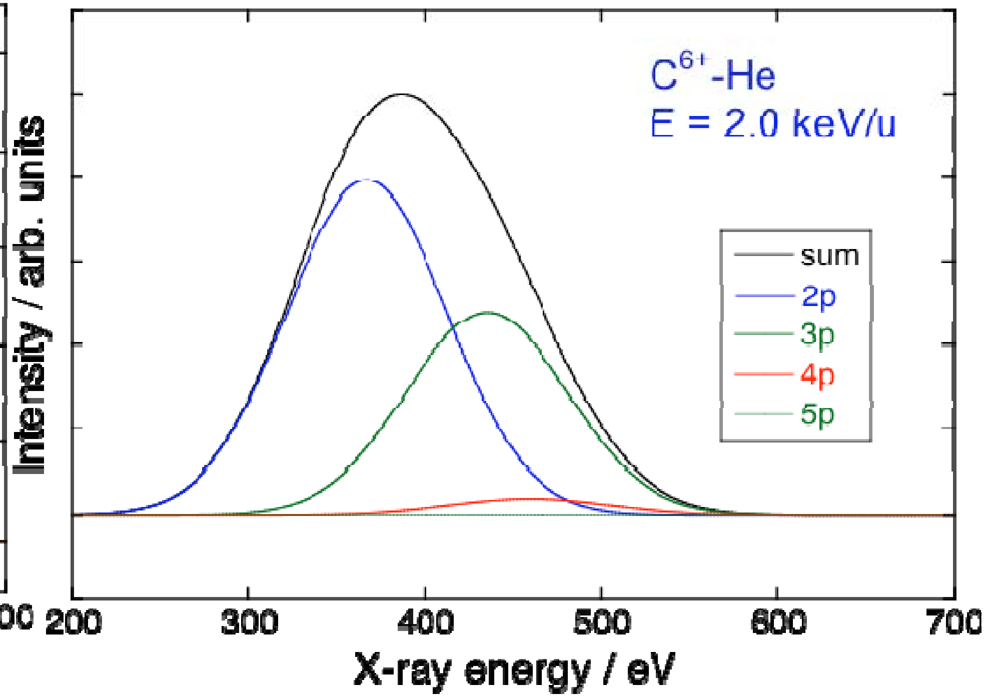
We must confirm it by experiments with help of theoretical calculations.

Cascade of transitions



C^{6+} - He collisions



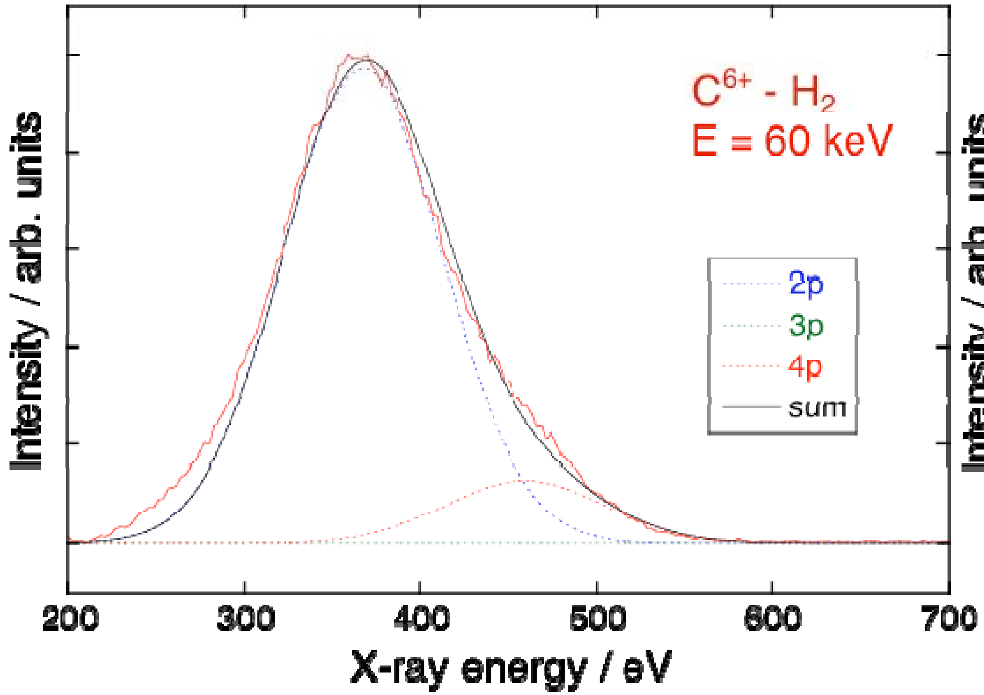


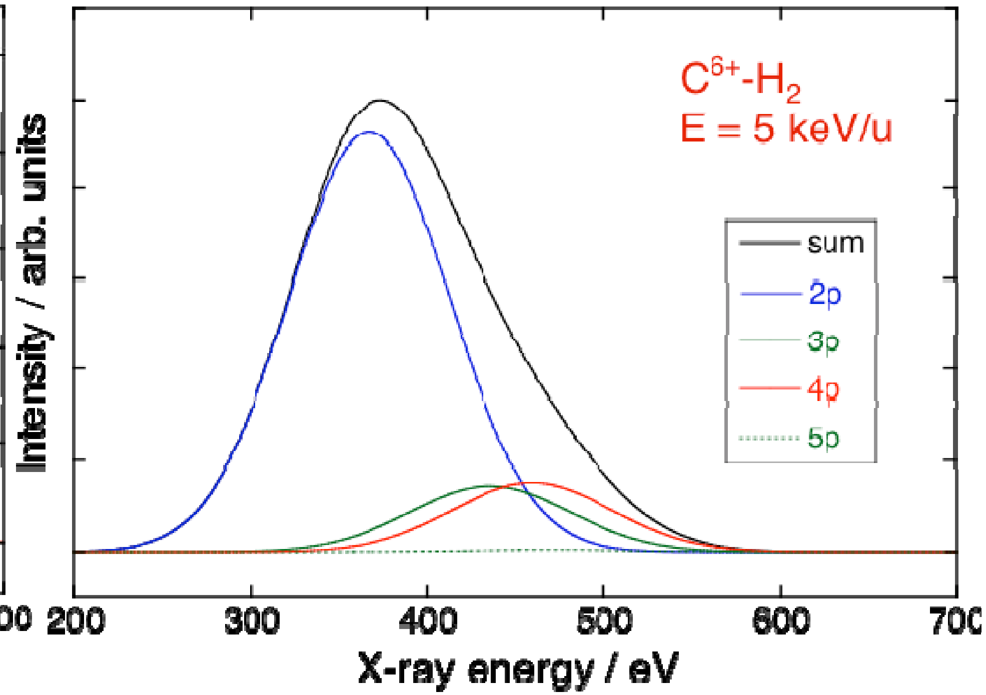
The 1s-2p transition is dominant.

2p > 3p > 4p

2p > 3p >> 4p

C^{6+} - H_2 collisions



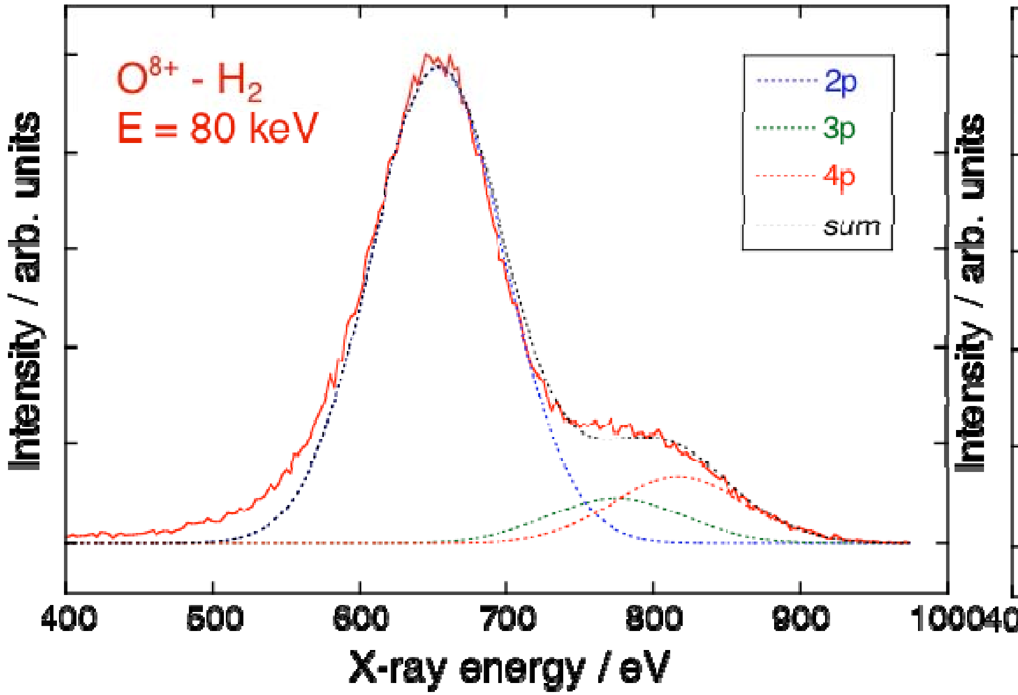


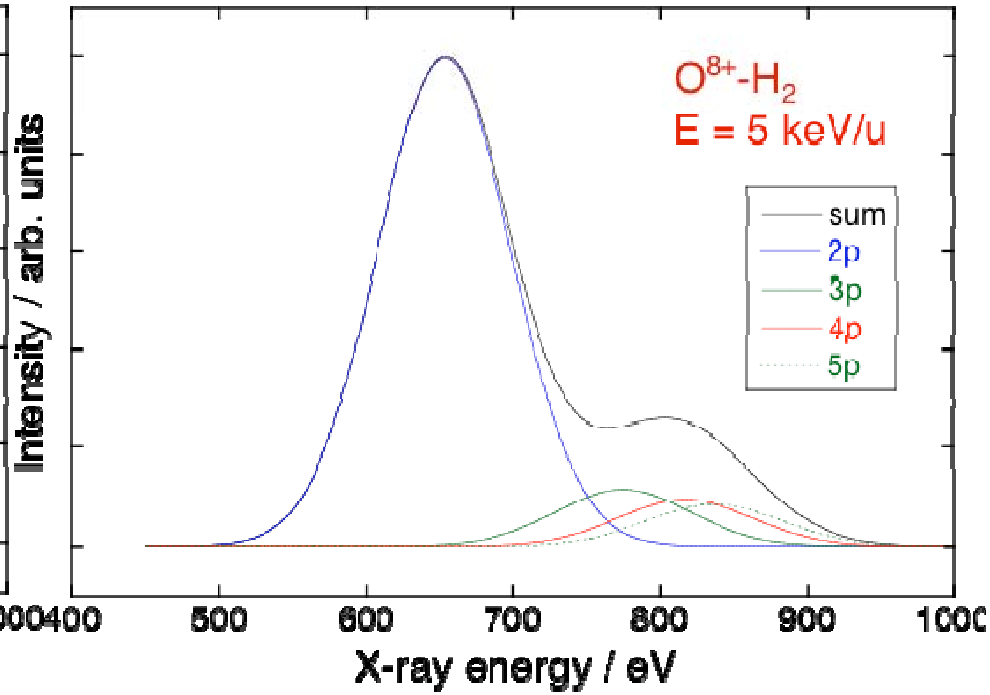
The 1s-2p transition is dominant.

2p > 4p >> 3p

2p > 3p ~ 4p

O^{8+} - H_2 collisions



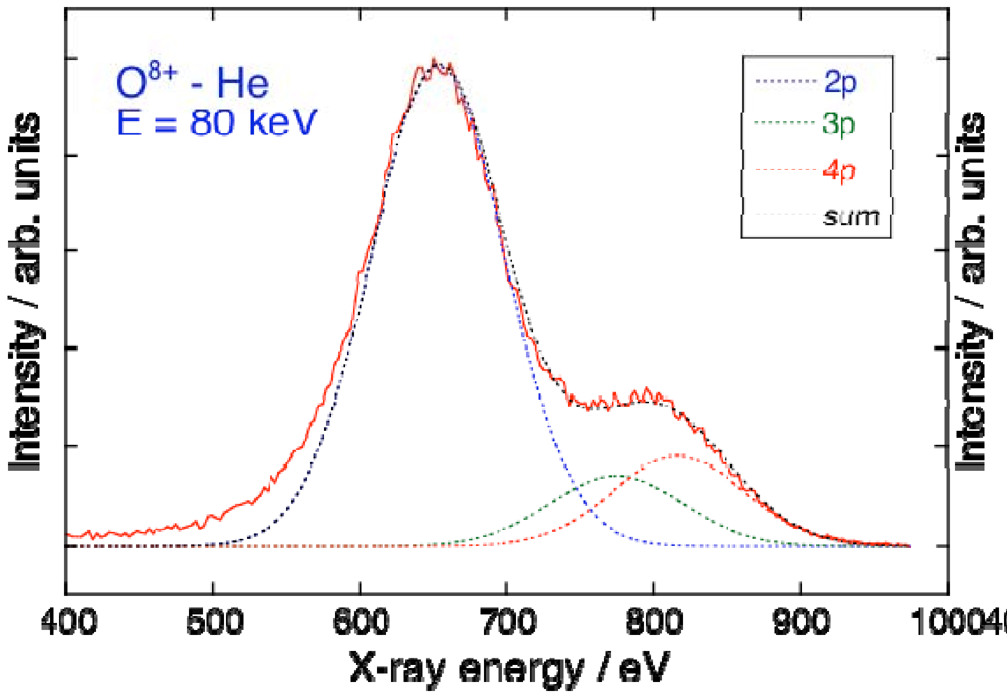


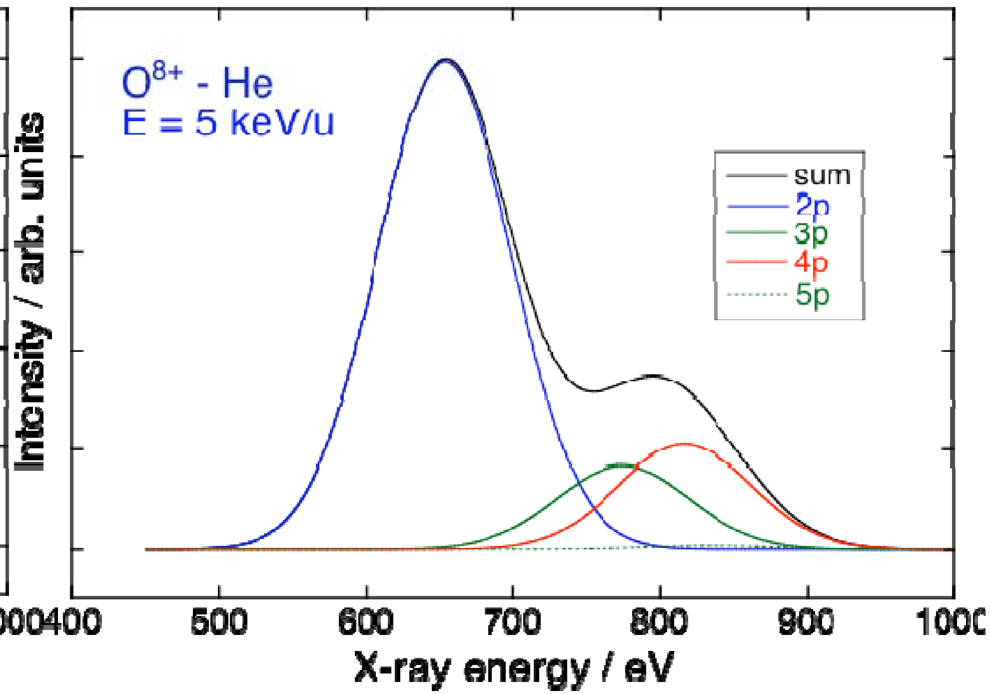
The 1s-2p transition is dominant.

2p > 4p > 3p

2p > 3p ~ 4p ~ 5p

O^{8+} - He collisions





The 1s-2p transition is dominant.

2p > 4p > 3p　　　　2p > 4p > 3p

Experiments *vs* AOCC

- C^{6+} cases – Agreements are very poor.

  - Energy calibration of the detector is difficult.

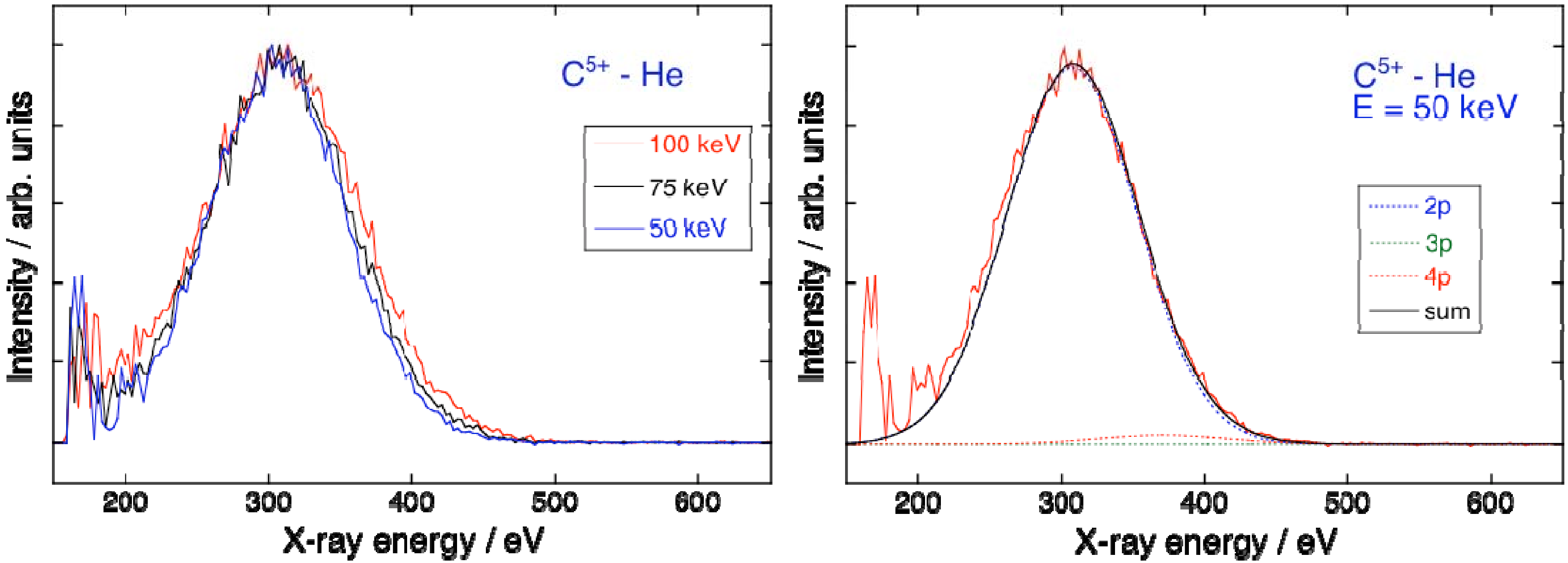
- Atomic target (He) > Molecular target (H_2)

  - Effect of molecular structure ?

  - MOCC should be applied.

Preliminary
experimental spectra in collisions of H-like ions with He

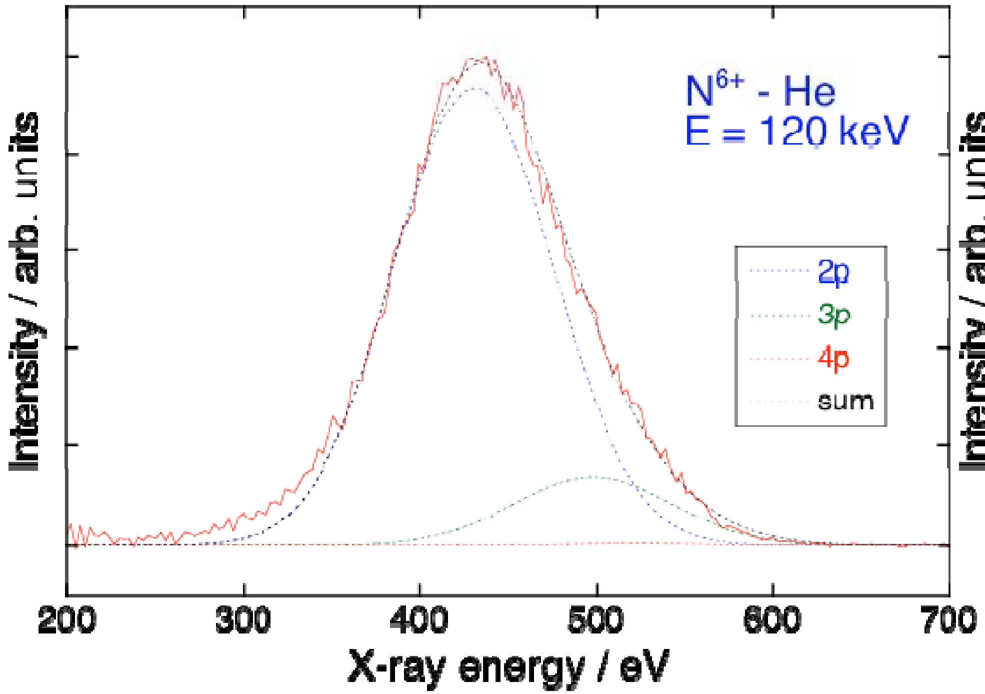
C^{5+} - He collisions

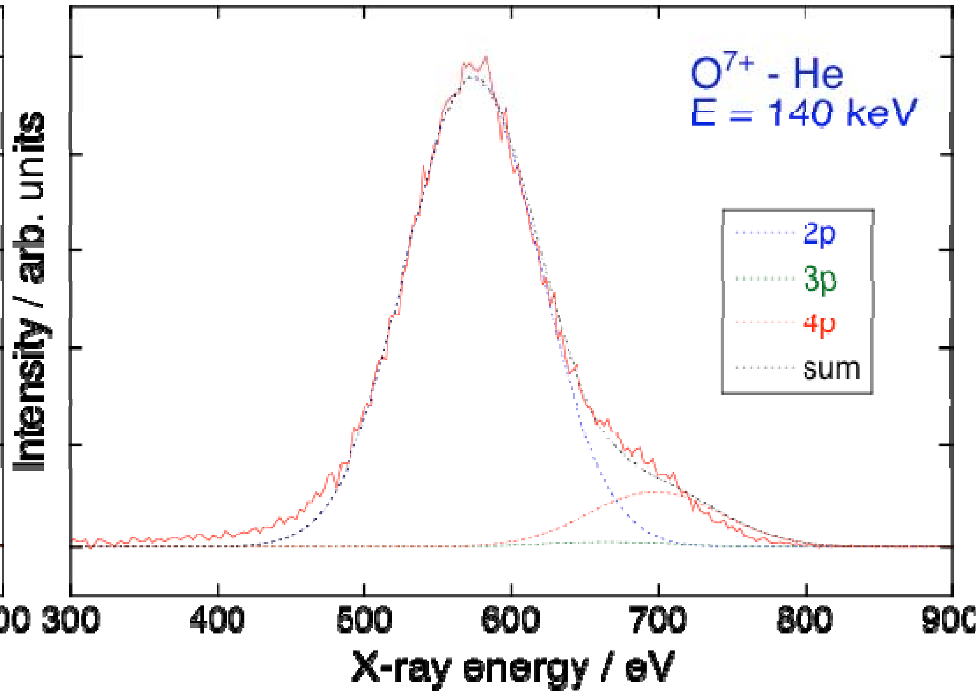


Relative intensity of soft X-ray emission :

Collision energy dependence is small in the shape of spectrum.

N^{6+} / O^{7+} - He collisions





The 1s-2p transition is dominant.

2p > 3p >> 4p

2p > 4p >> 3p

Bare ions *vs* H-like ions

Bare ion collisions :

$$A^{q+} + T \rightarrow A^{(q-1)+}(nl\ {}^2L_J) + T^+$$

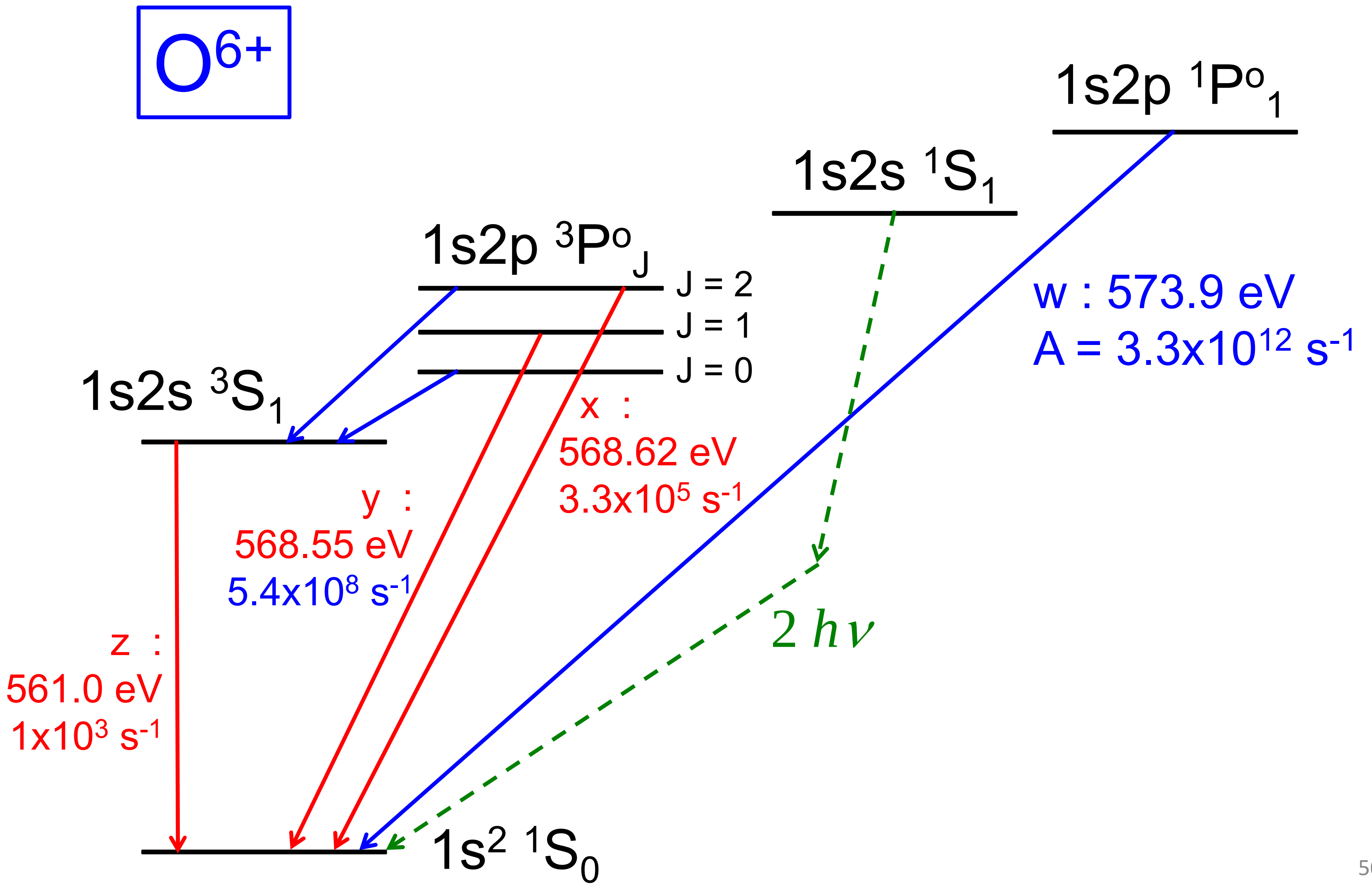
H-like ion collisions :

$$A^{q+}(1s) + T \rightarrow A^{(q-1)+}(1s\,nl\ {}^1L_J, {}^3L_J) + T^+$$

AOCC method can not treat this issue.

MOCC is necessary for H-like ion collisions.

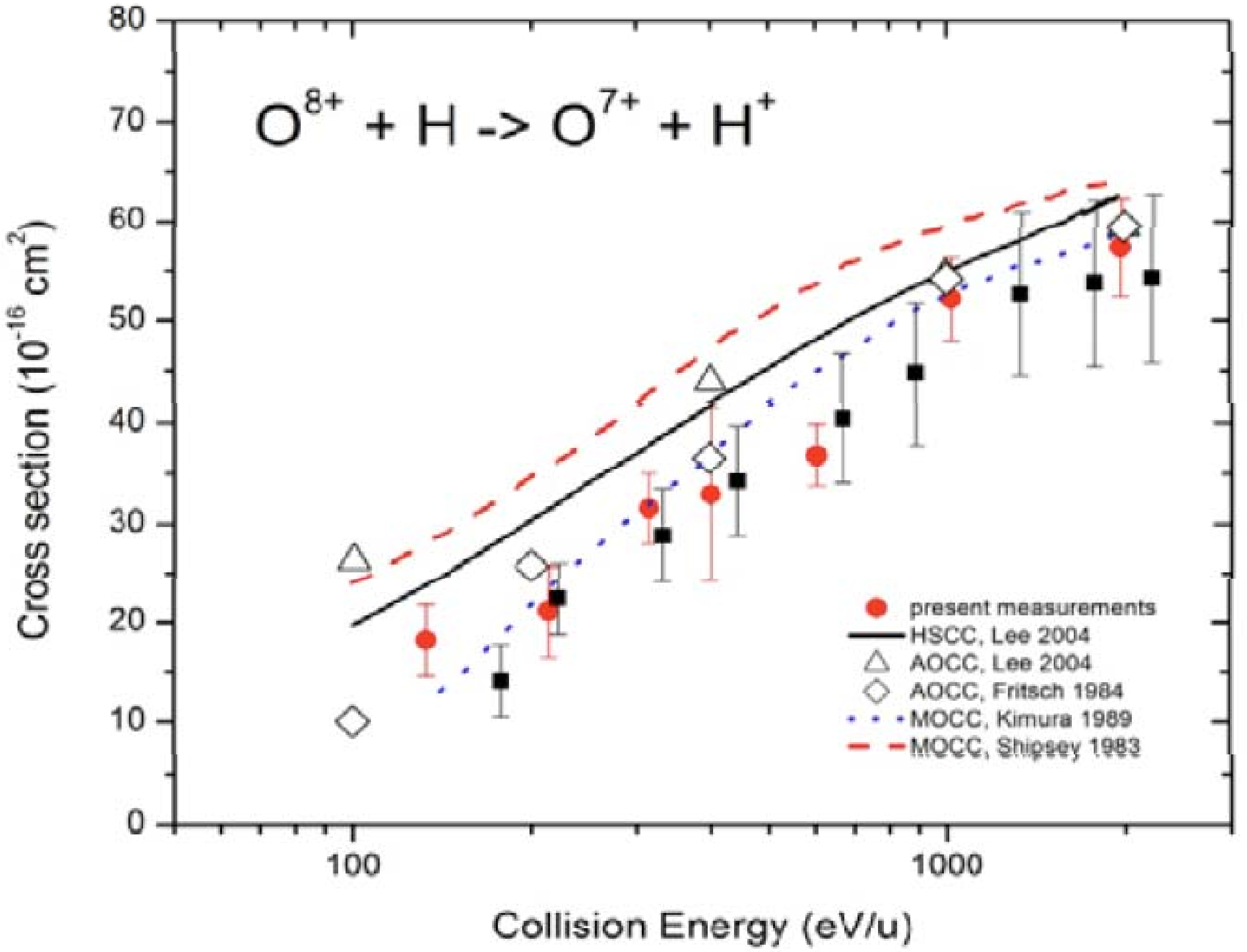
Energy levels of He-like ions



Future plans

- deceleration of ion speed up to 200 km/s
- absolute capture cross sections
- absolute emission cross sections
- measurements with a TES micro calorimeter
- introduction of an atomic hydrogen target source
- singlet-triplet ratios of produced He-like ions
- H/H_2 ratio from the target dependence data
- challenge to observation of forbidden lines
- contribution to the SWCX as atomic physicists

Good and Bad News



I. N. Draganić, D. McCammon, and C. C. Havener (2010)

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Thank you for your attention.

謝謝

御静聴ありがとうございました。