Spectral Emission of fast non-Maxwellian Atoms at metallic Surfaces in low density Plasmas

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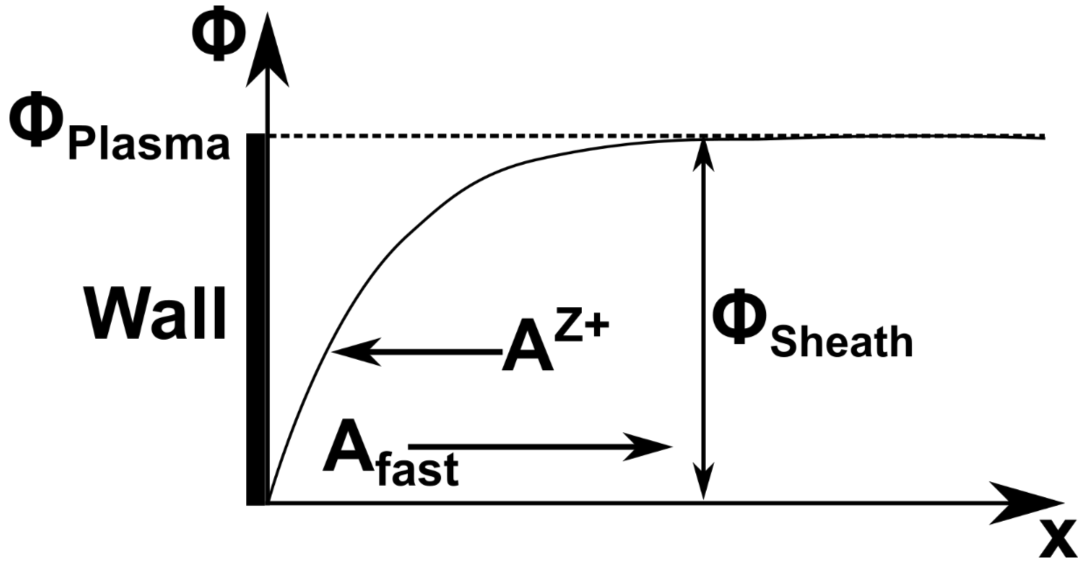
Origin of fast atoms



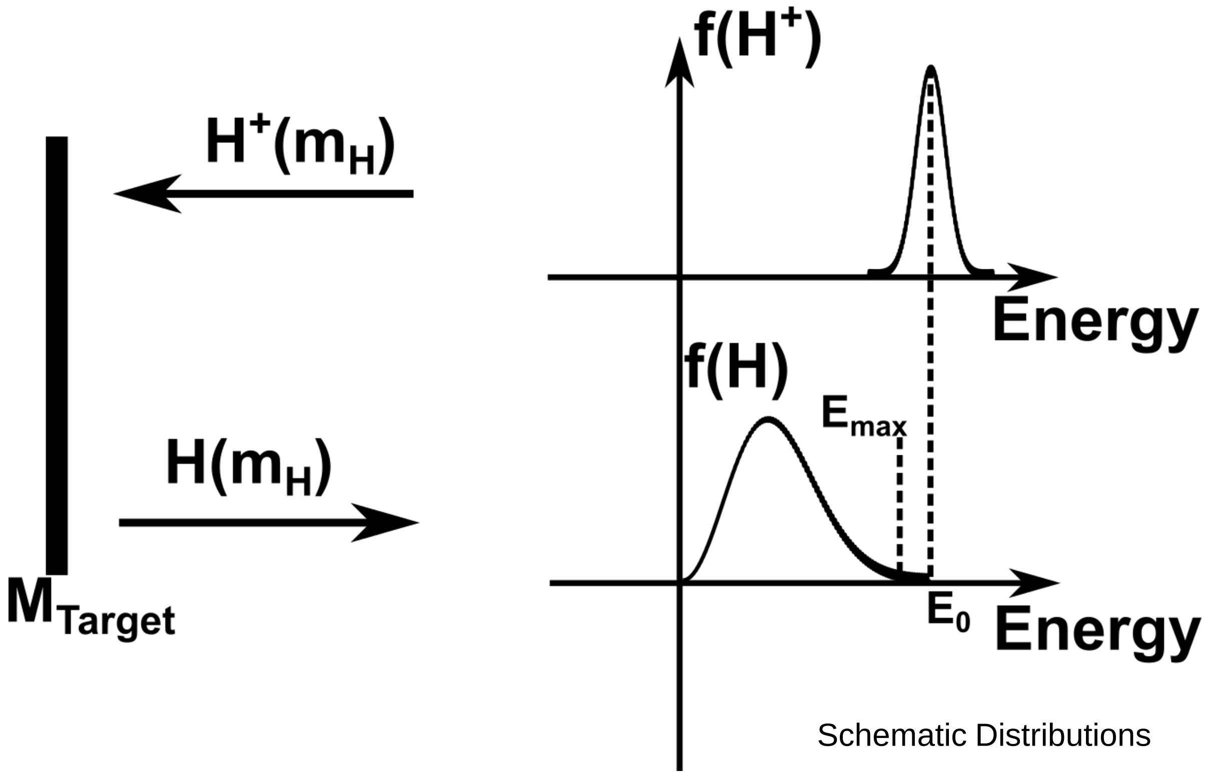
- Fast atoms: atoms with an energy higher than the thermal energy
- $\phi_{Sheath} = \phi_{Wall} - \phi_{Plasma}$
- $E_{kin} \sim Ze_0\phi_{sheath}$
- Fast atoms are present in many kind of plasmas (astrophysical plasmas [1], glow discharge [2], rf plasmas [3], microwave plasma [4], atmospheric plasmas [5]):
  - existence ≠ detection

[1] J.T. Clarke et al., **Geophys. Res. Lett. 16,** 587 (1989)
[2] N.M. Sisovic et al., **Eur. Phys. J. D. 41,** 347 (2007)
[3] T. Babkina et al., **Europhys. Lett. 72,** 235 (2005)
[4] U. Samm et al., **Plasma Phys. Contr. Fus. 29,** 1231 (1987)
[5] C. Oliveira et al., **Appl. Phys. Lett. 93,**, 041503 (2008)
and more

- Better understanding of plasma wall interaction
- Information about the surface
- Energy and angular distribution $f(E,\theta,v)$

Distribution of fast atoms

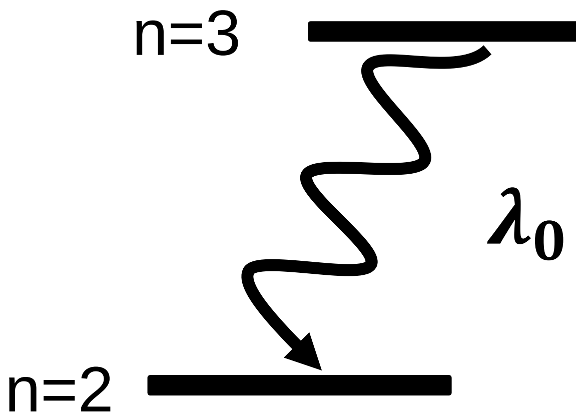
- Distribution of fast atoms
  $$f(H) = f\left(E_0, M_{Target}, m_H, \theta\right)$$
- Energy after reflection [1]
  $$\frac{E_{max}}{E_0} \approx \left(\frac{M_{Target} - m_H}{M_{Target} + m_H}\right)^2$$
- Energy of reflected atoms is always smaller than energy of the incoming ion
  → Binary collision [3]

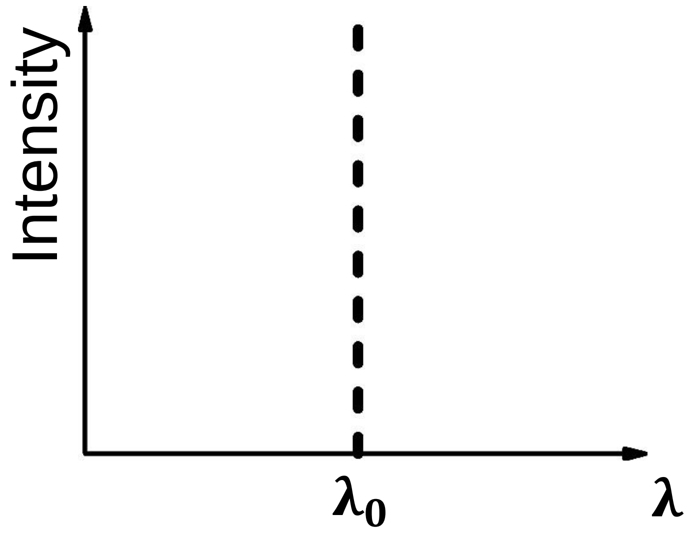


Schematic Distributions

[1] T. L. Alford et al., **Fundamentals of Nanoscale Analysis,** Springer Verlag (2007)
[2] W. Eckstein and H. Verbeek, **IPP 9/32,** (1979)
[3] W. Demtröder, **Experimentalphysik I,** Springer Verlag (2015)

Origin of Doppler-shifted signal





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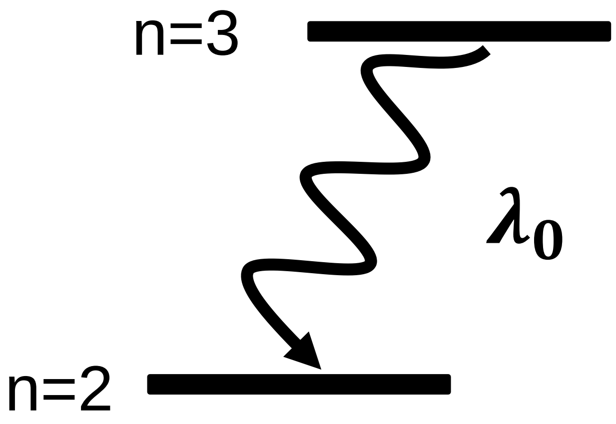
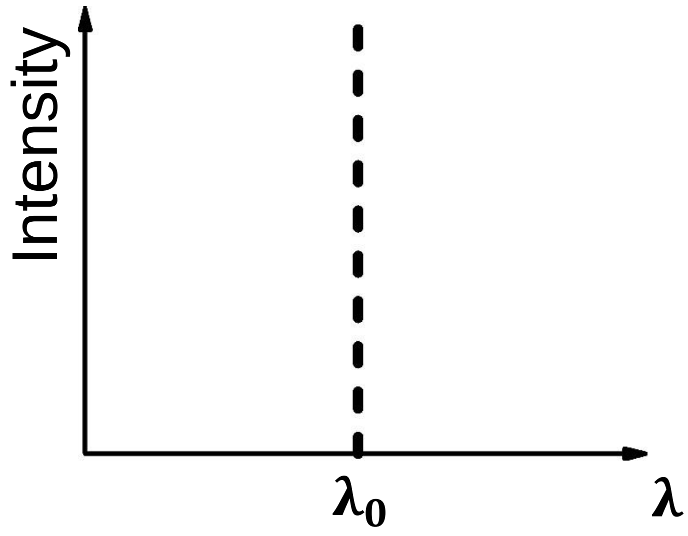
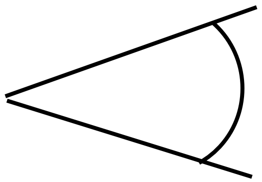
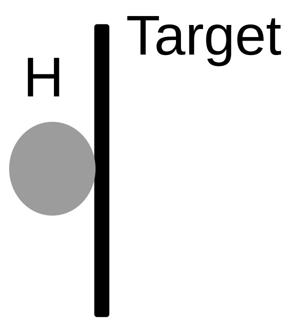




Spectrometer





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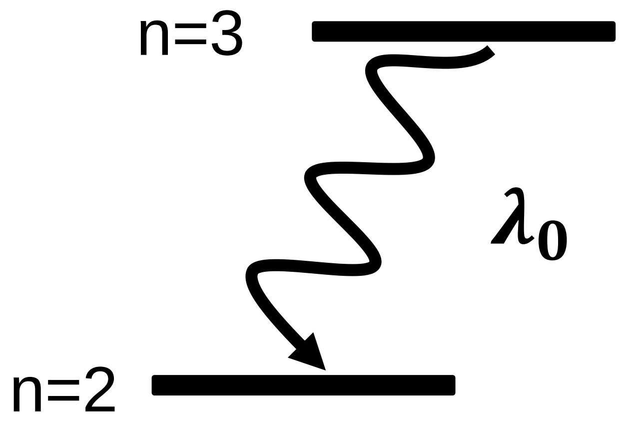

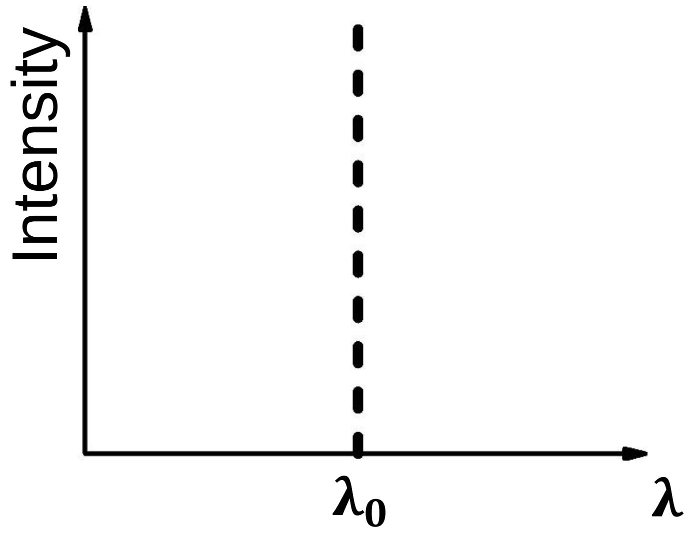

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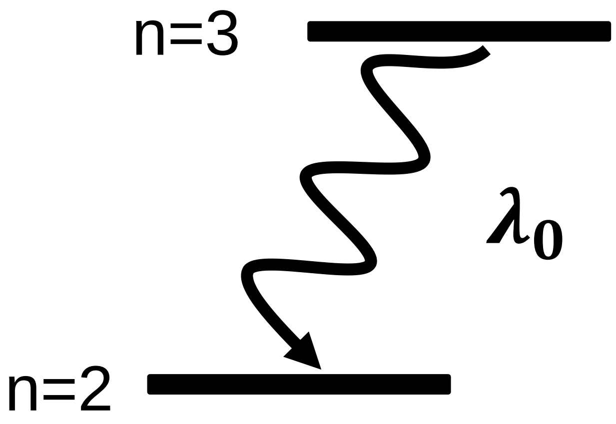
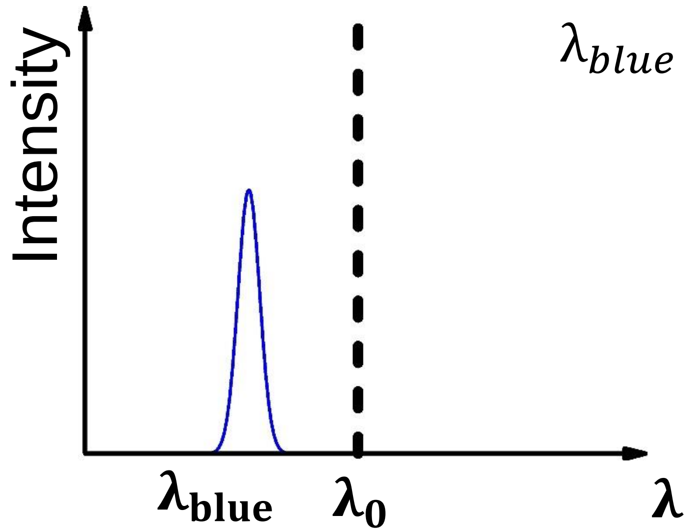
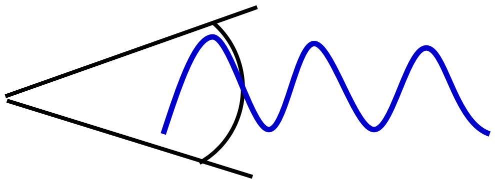
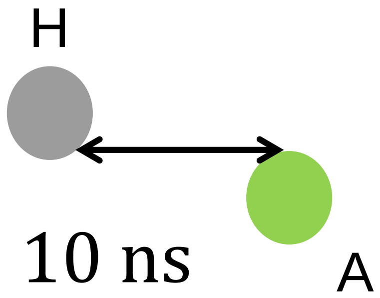


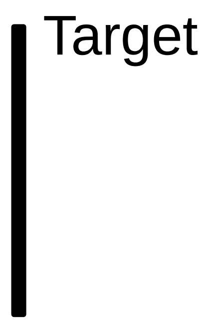


$$\lambda_{blue} = \lambda_0 \left(1 - \frac{|v_{atom}|}{c_{light}}\right)$$

Spectrometer







$$L = \tau \cdot v_H, \; \tau \approx 10 \text{ ns}$$

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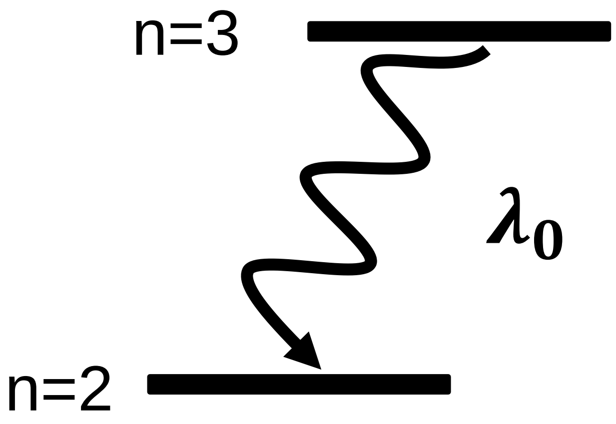
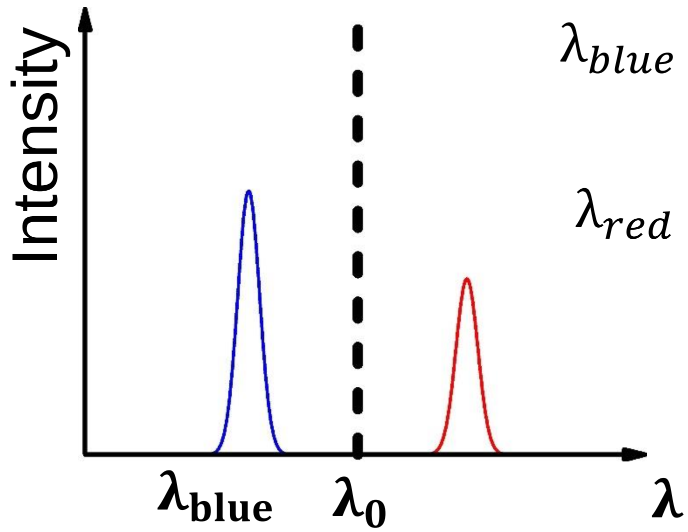
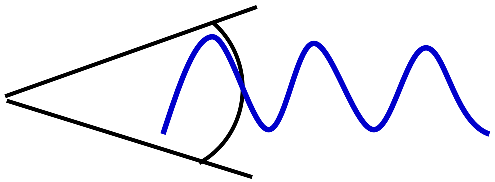


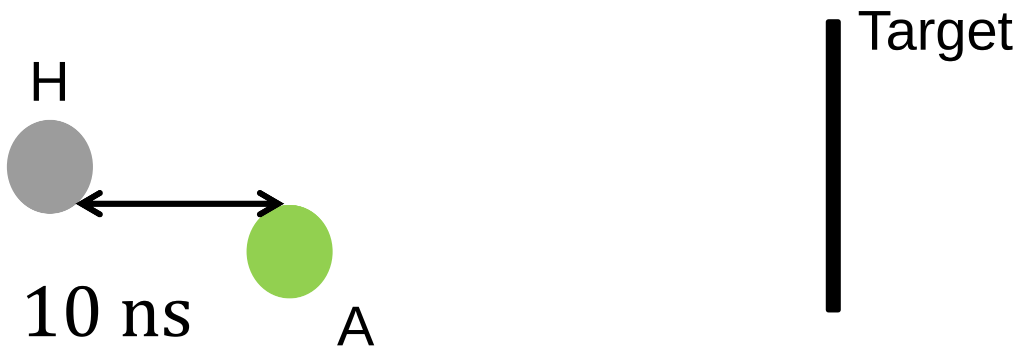


$$\lambda_{blue} = \lambda_0 \left(1 - \frac{|v_{atom}|}{c_{light}}\right)$$

$$\lambda_{red} = \lambda_0 \left(1 + \frac{|v_{atom}|}{c_{light}}\right)$$

Spectrometer

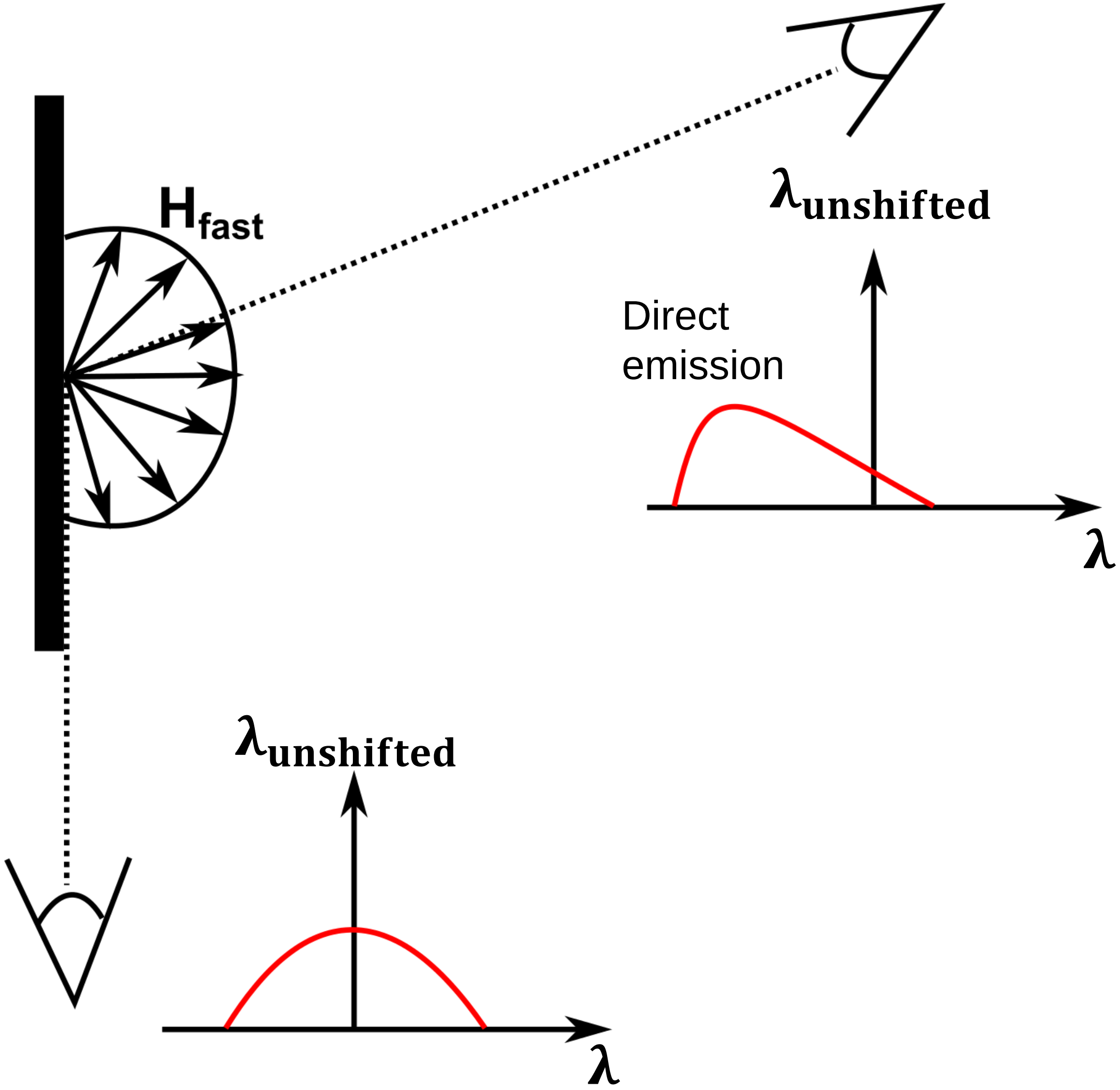




$$\mathrm{L} = \tau \cdot \mathrm{v_H}, \ \tau \approx 10 \ \mathrm{ns}$$

Observation of fast atoms at different angles

- Atoms are reflected in a hemisphere
- Different line of sights leads to different emission profiles



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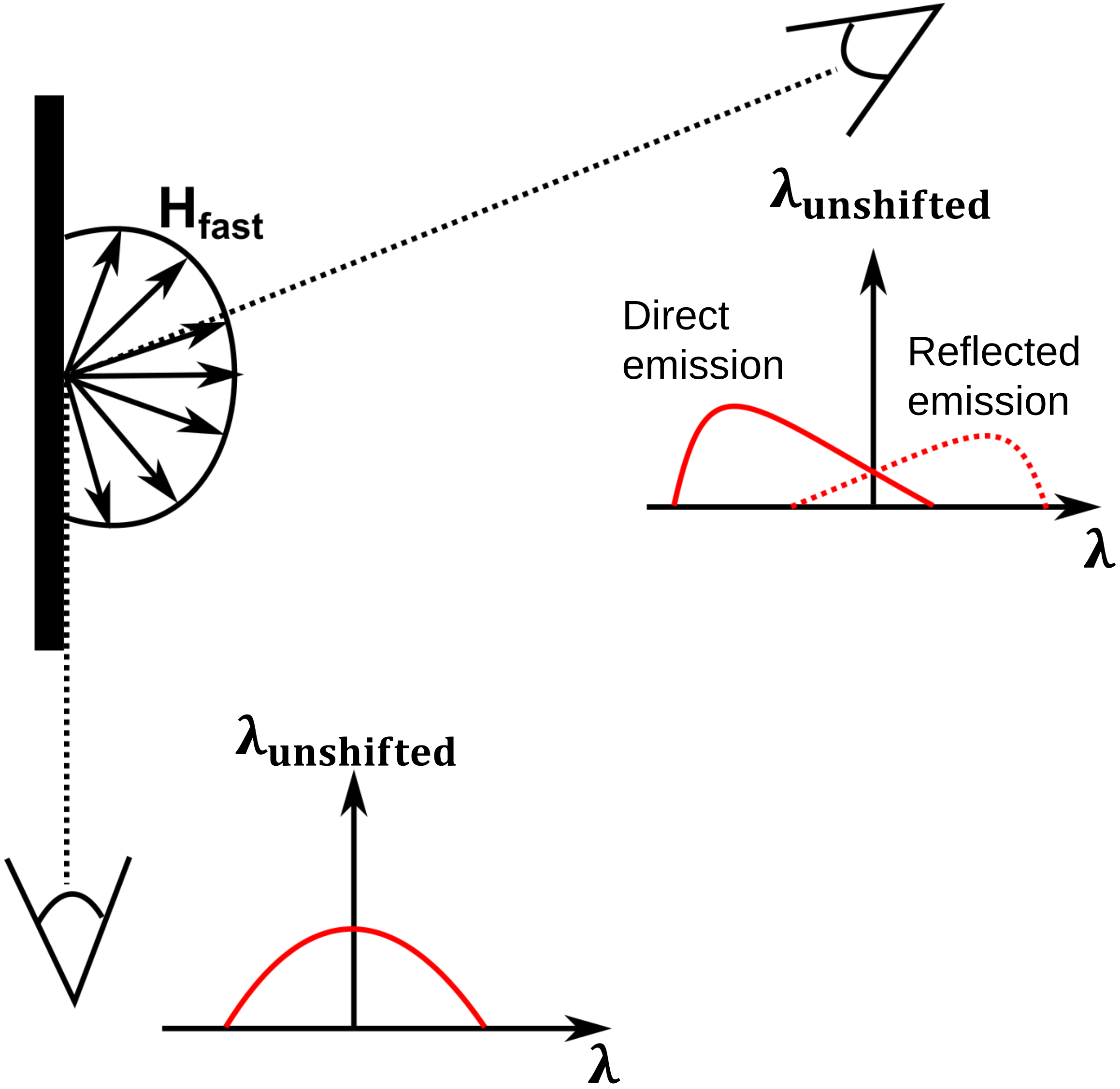
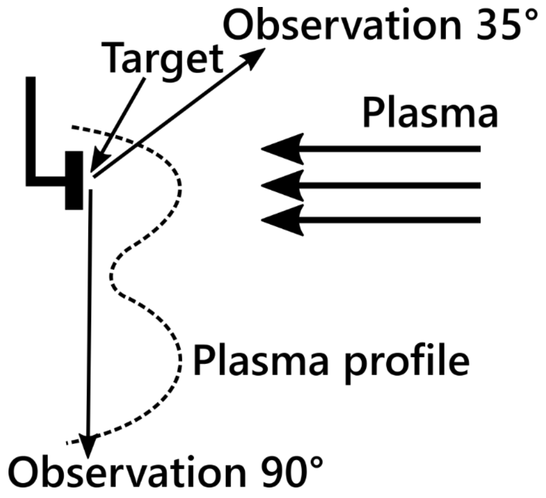
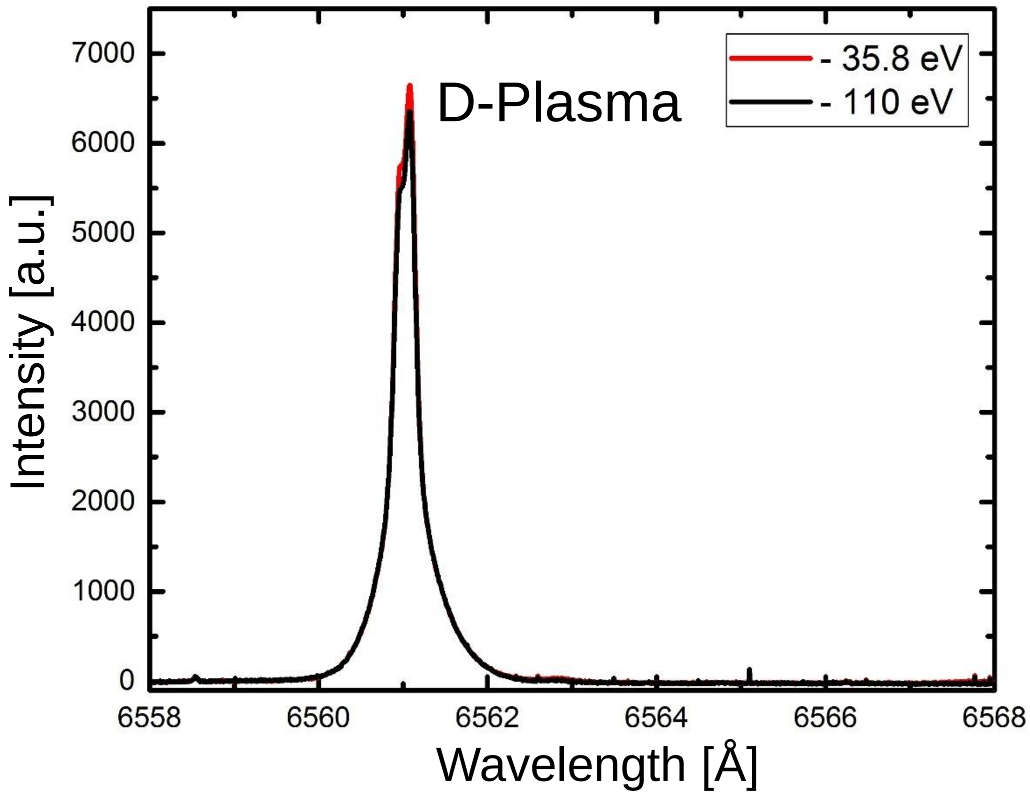


Experimental Setup



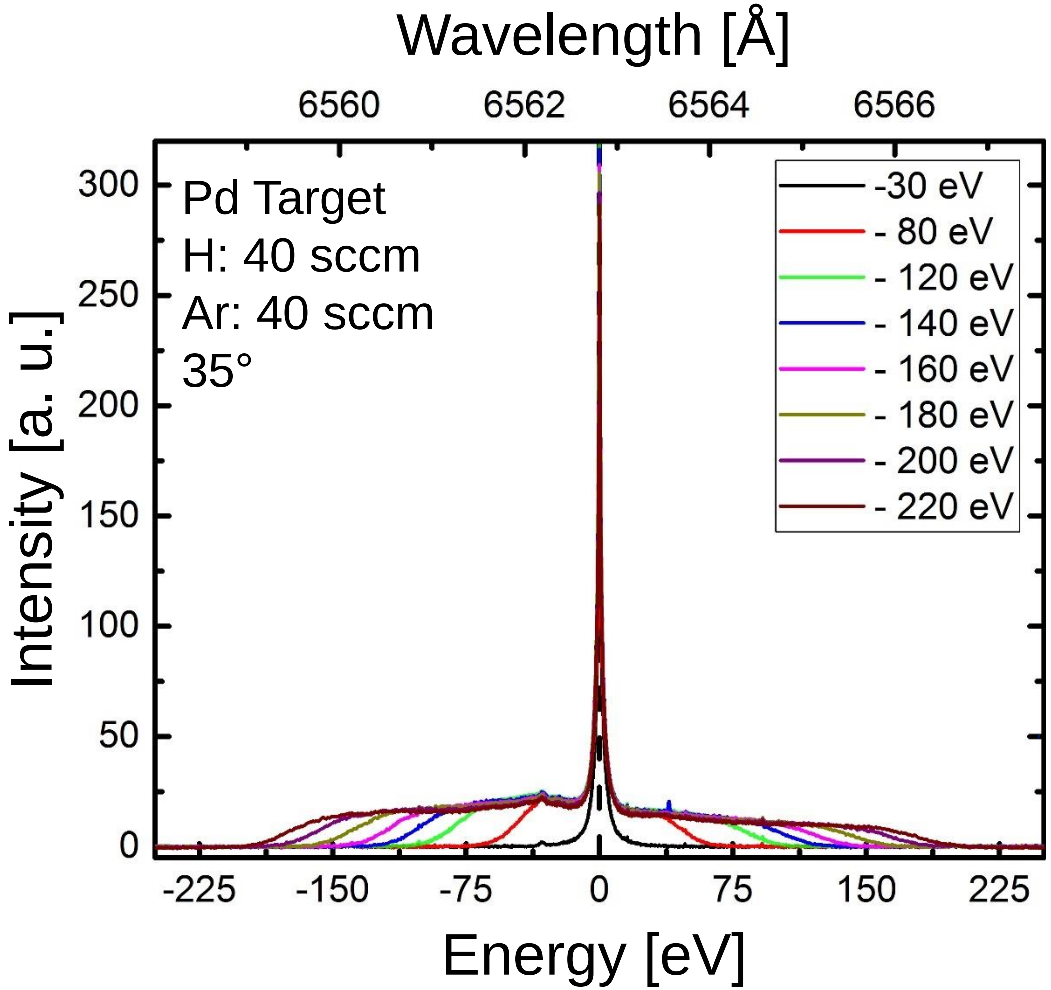
$n_e \approx 10^{11} - 10^{12}\ cm^{-3}$
$T_e \approx 8 - 20\ eV$
H-Ar mixed plasma
Target surface 1 cm²
Pressure $\approx 10^{-4}$ mbar

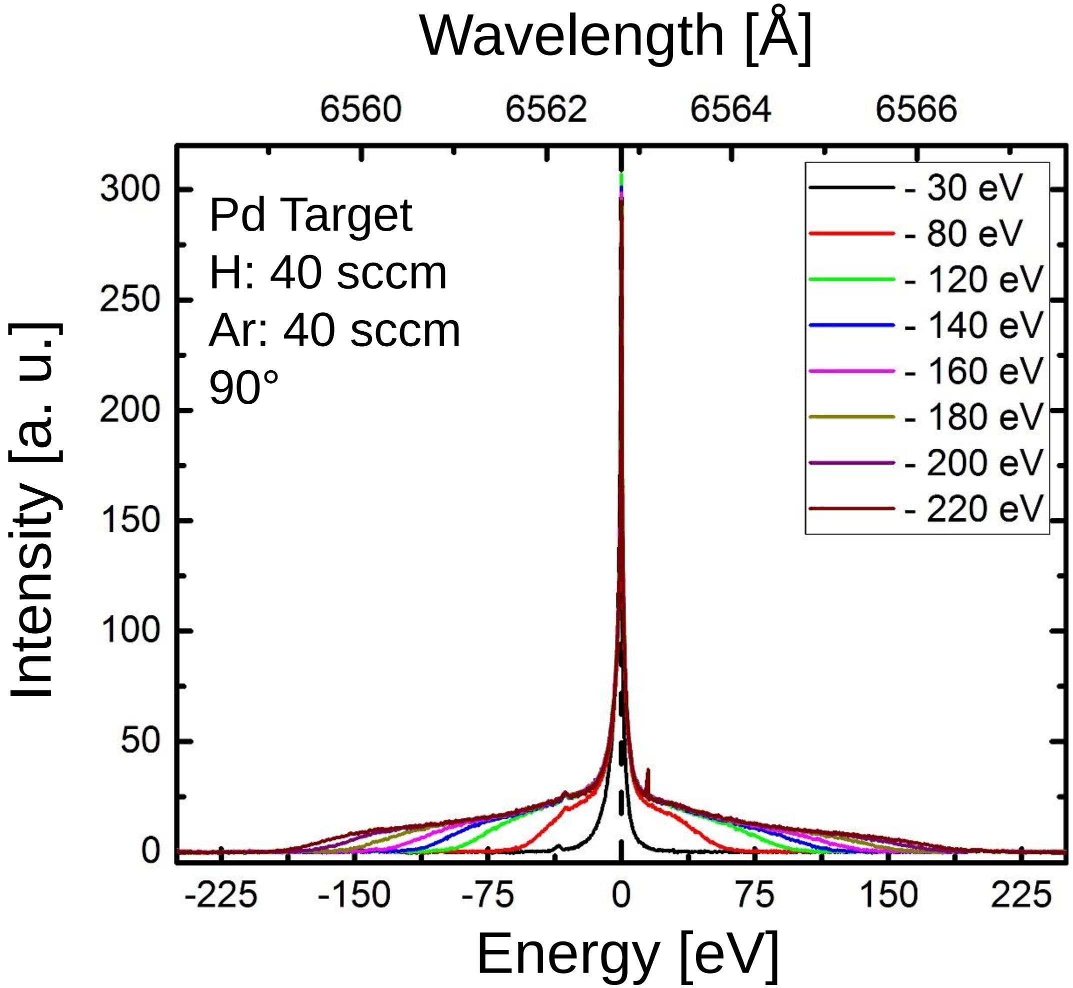
- Target position in the maximum of the plasma profile PSI-2 (linear plasma device)
- We investigate Balmer lines of hydrogen $(\mathrm{H}_\alpha, \mathrm{H}_\beta, \mathrm{H}_\gamma)$
- In a pure D- or H-Plasma no fast atoms can be detected
- In H-Ar mixed plasma we observe the highest signal intensity emitted by fast atoms



[1] A. Kreter et al., **Fusion Sci. Technol. 68**, 8 (2015)
[2] H. Kastelewicz and G. Fussmann, **Contrib. Plasma Phys. 44**, 352 (2004)

Observation of Fast Atoms





- Emission arises at potentials higher than – 30 eV
- Maximal energy of fast atoms differs with different target potential
- Maximal intensity stays constant
- red- and blue-shift are unsymmetrical at 35° and symmetrical at 90°

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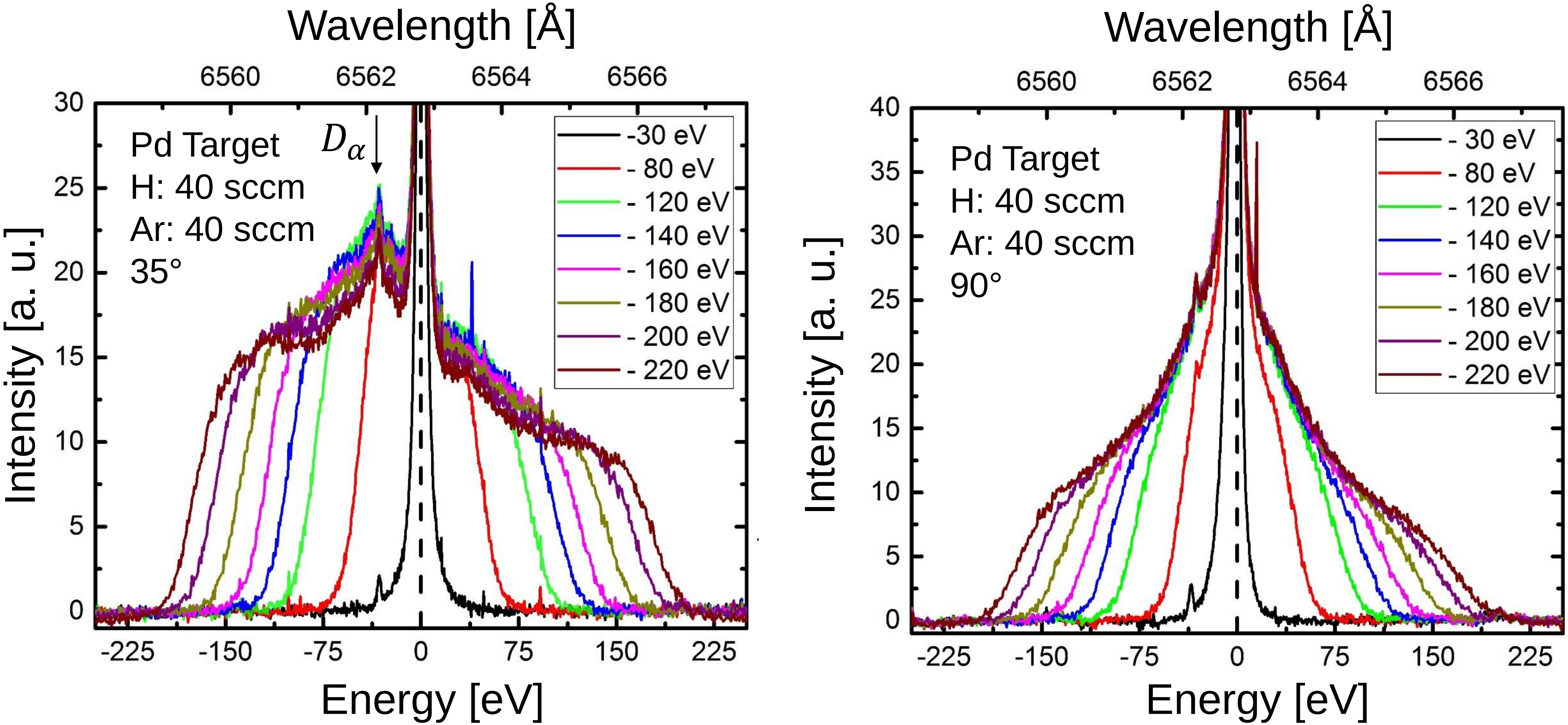

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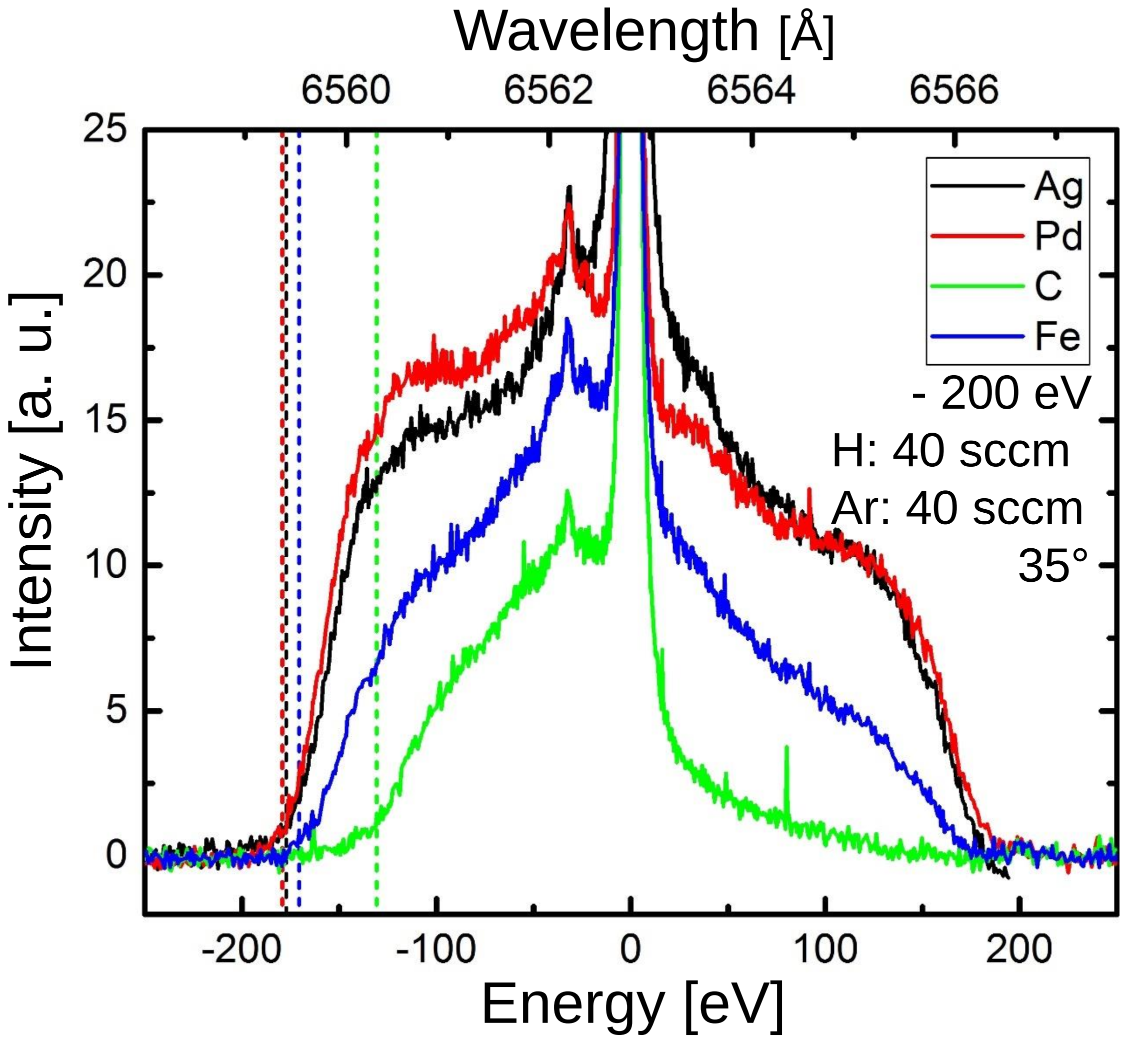
Emission for different target materials



- Clear indication, that fast atoms are produced at the target surface
  - Emission after backscattering process
- Maximal energy of fast atoms depends on the target material [1]

$$H^{+} + \mathrm{Target} \rightarrow H_{\mathrm{fast}} \rightarrow H_{\mathrm{fast}} + \mathrm{Ar} \rightarrow H^{*}$$

[1] T. L. Alford et al**., Fundamentals of Nanoscale Analysis,** Springer Verlag (2007)

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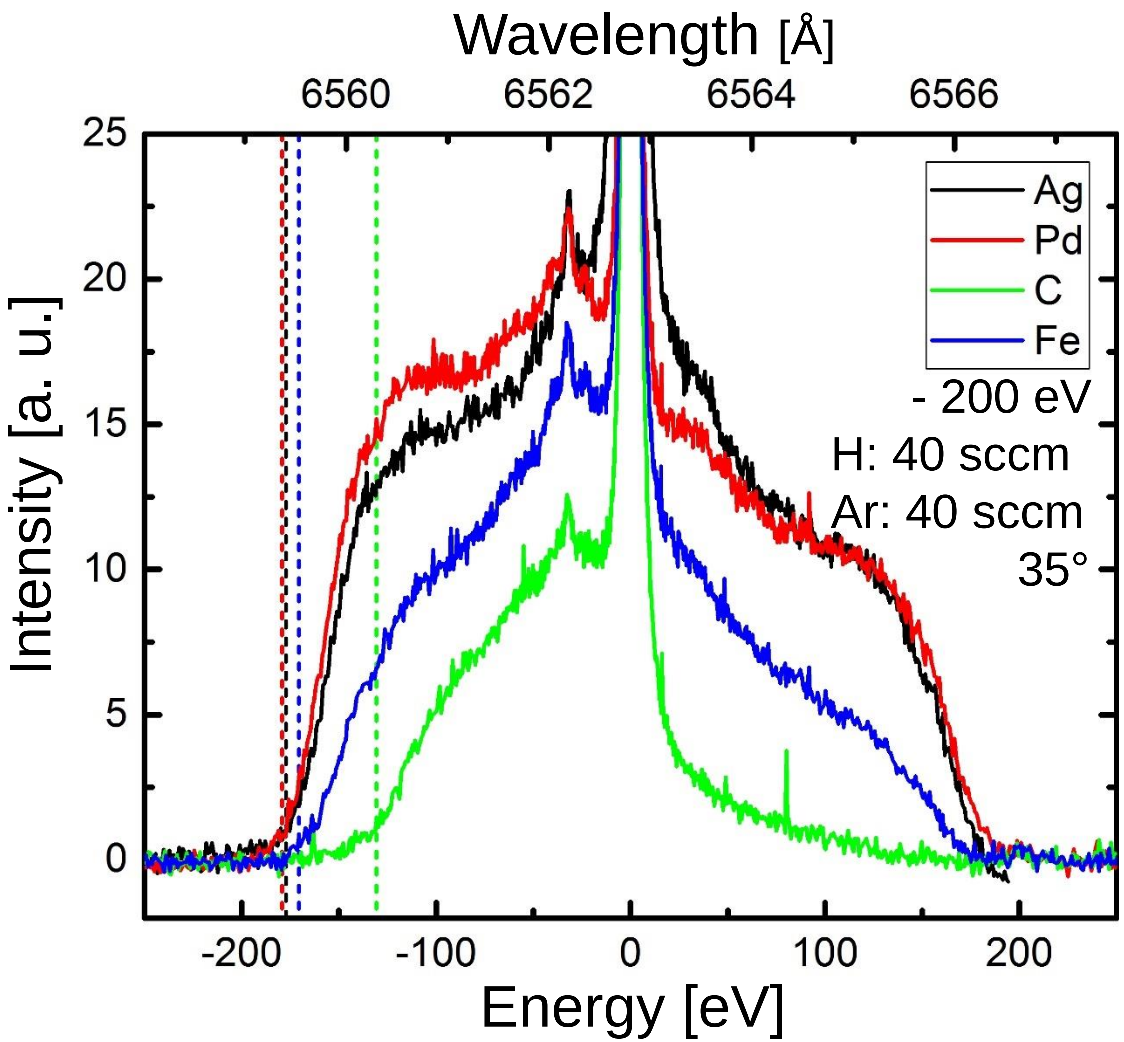

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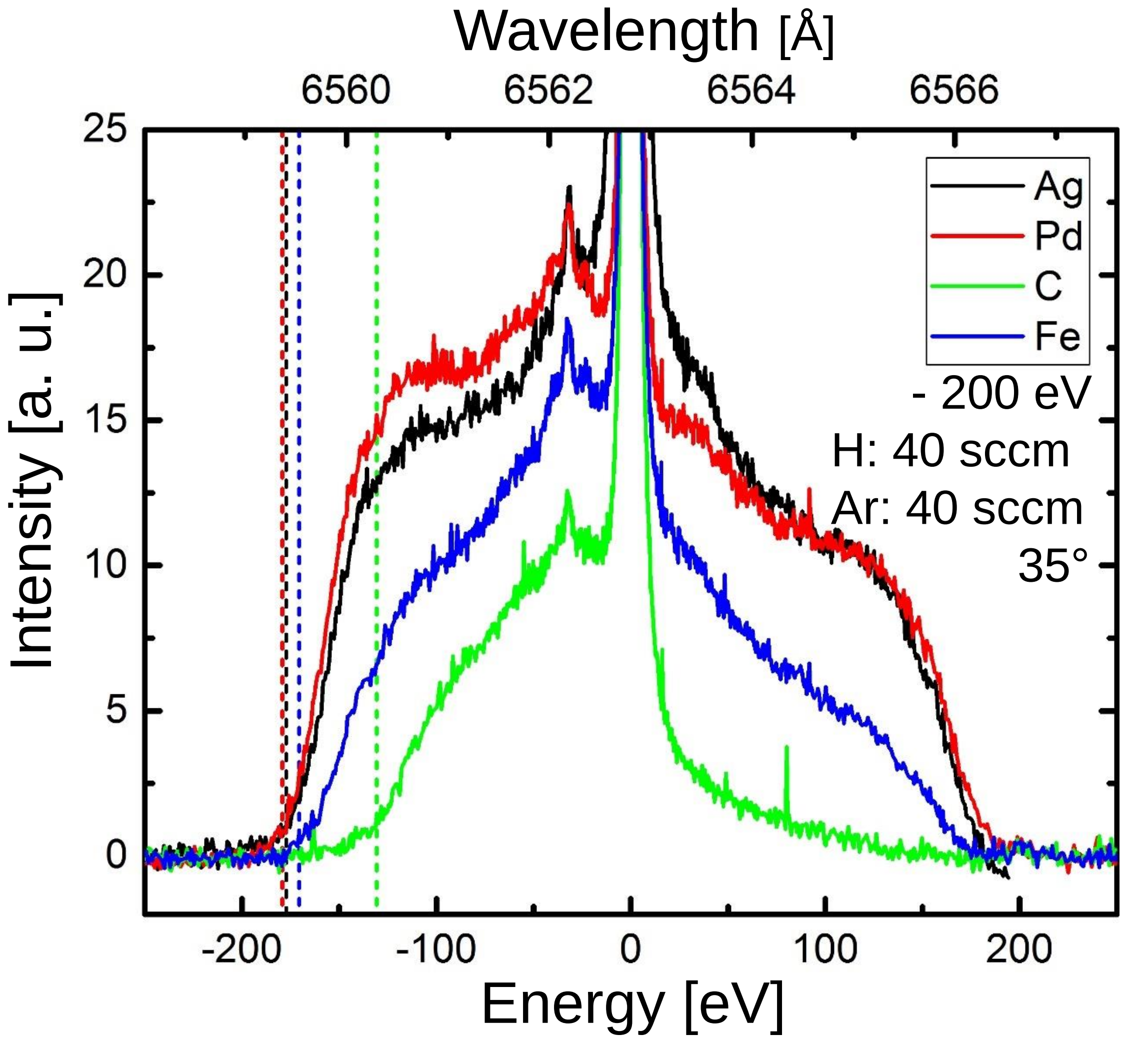

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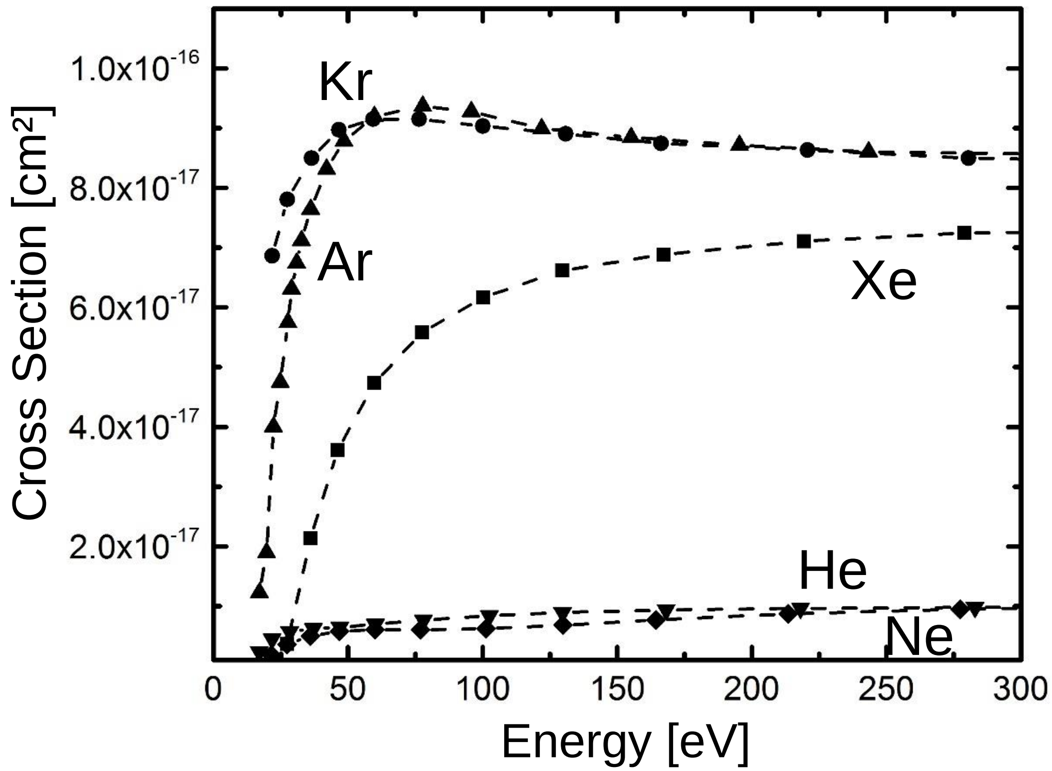
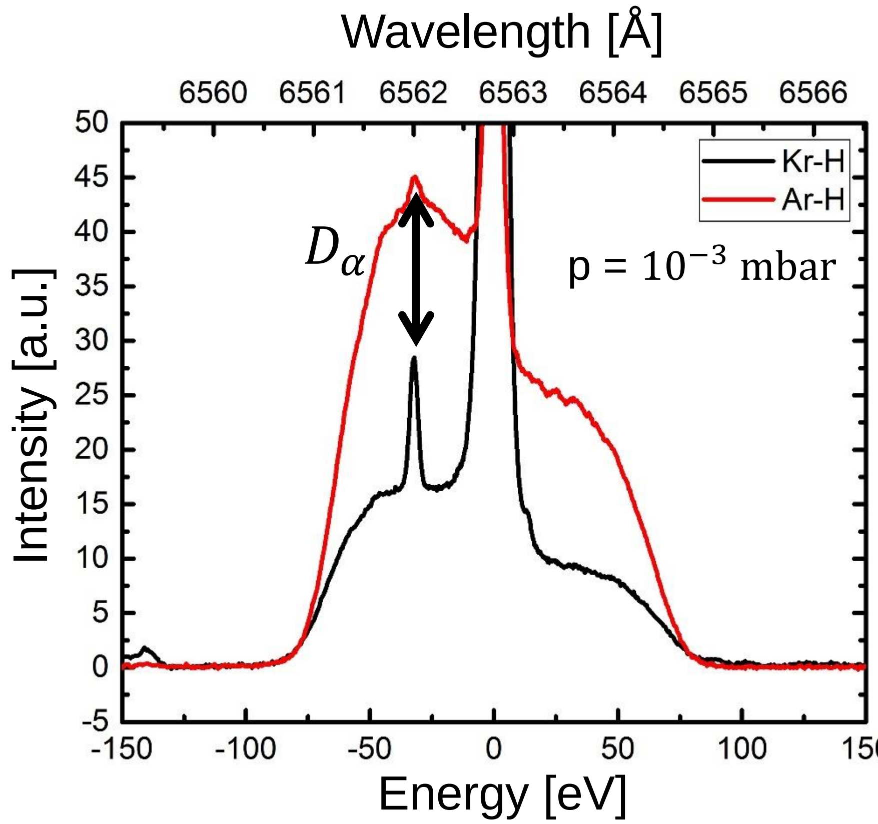
Excitation by argon ground state





- First assumption: excitation by ground state
- $H_{fast} + Ar \;\; \rightarrow (ArH)^* \;\rightarrow H^*_{fast} + Ar$ (excitation)
- Equal cross section for Ar and Kr
  - Kr-H: Intensity of fast atom emission significantly smaller [6,7]

[1] B. van Zyl et al., **Physical Review A 21**, 3 (1980)
[2] B. van Zyl et al., **Physical Review A 28**, 1 (1983)
[3] B. van Zyl et al., **Physical Review A 31**, 5 (1985)
[4] B. van Zyl et al., **Physical Review A 33**, 3 (1986)
[5] M. A. A. Clyne et al., **Chemical Physics 28**, (1978)
[6] C. Brandt et al., APIP 2015 Conference Proceedings (accepted)
[7] B. P. Lavrov and A. S. Melnikov, **Opt. Spectroc. 75,** 1152 (1993)

Ground state excitation cannot explain the experimental data.

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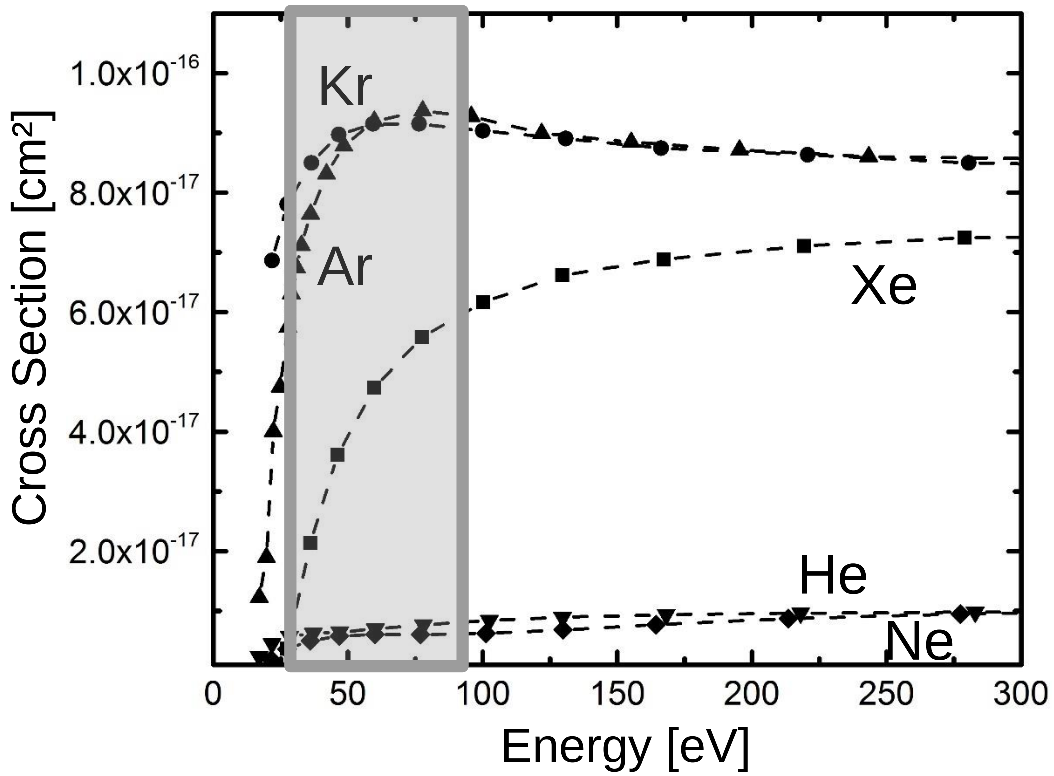

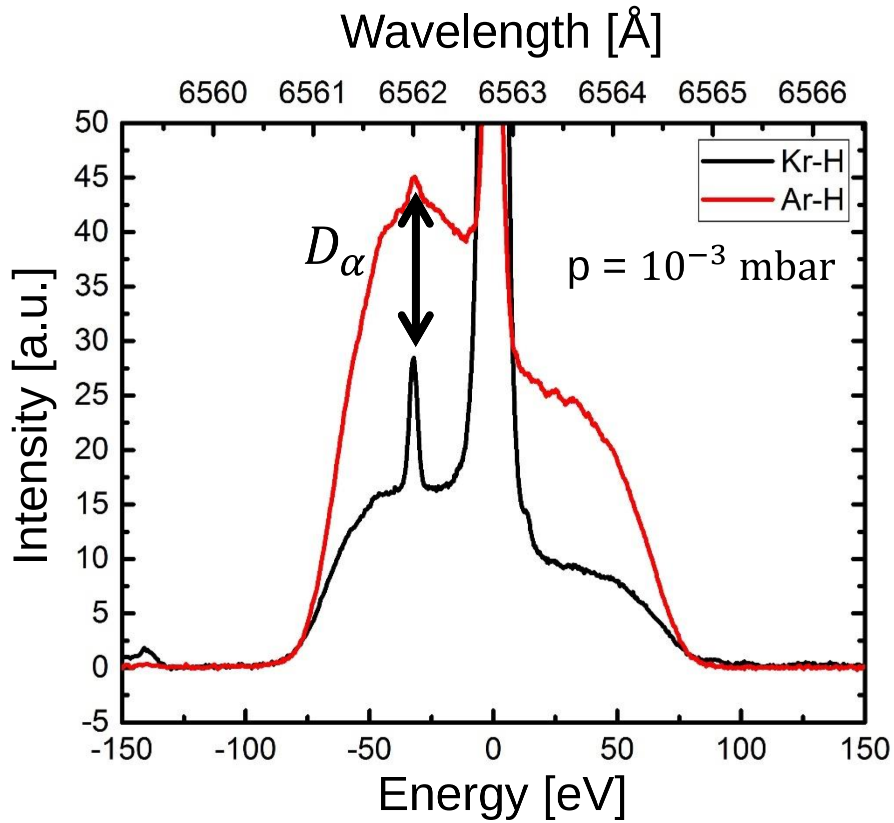

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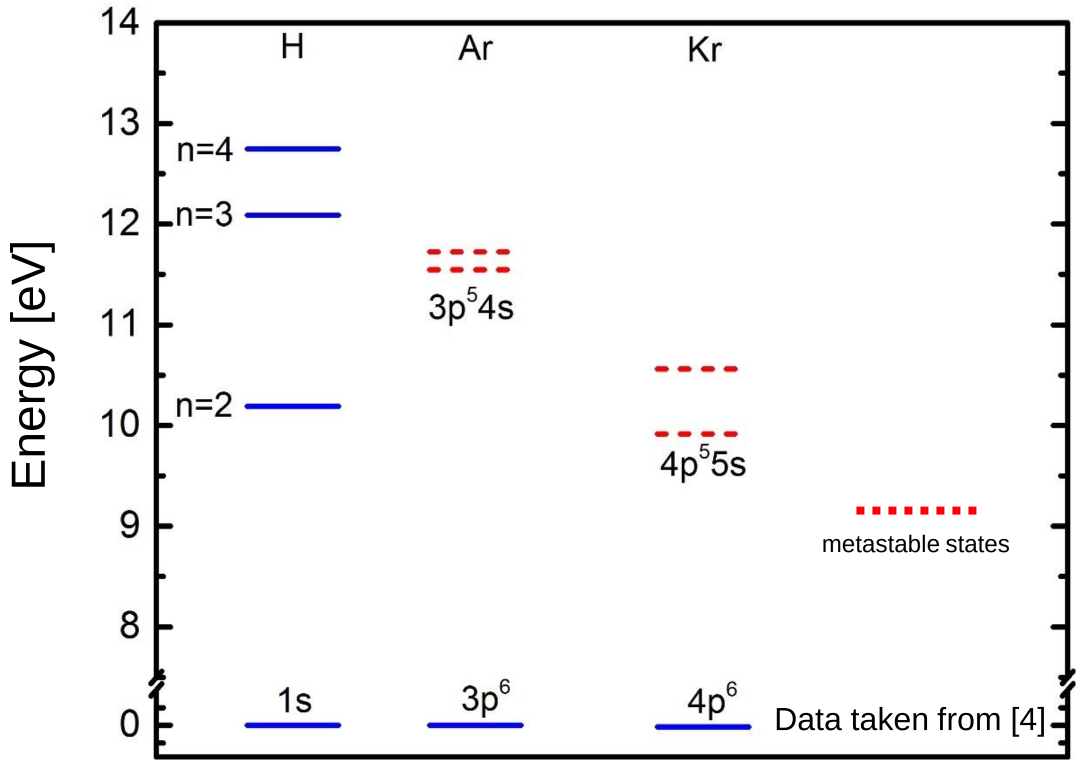
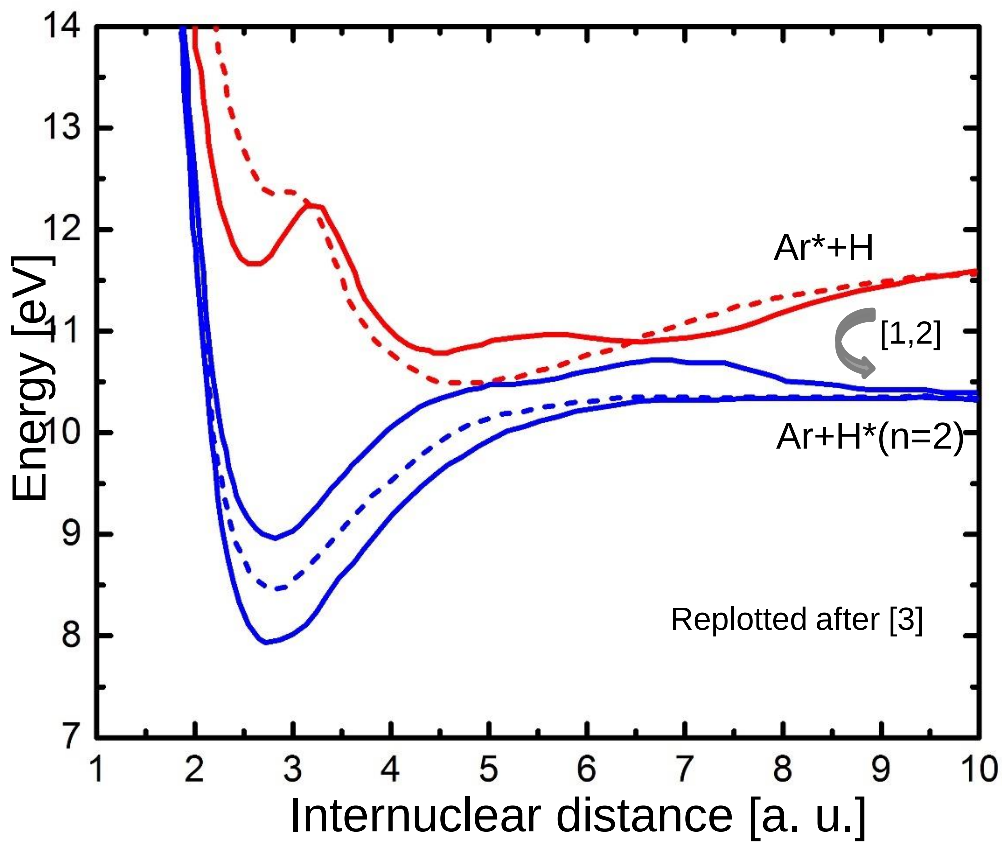
Excitation by argon metastable state





- Excitation with similar probabilities as the ground state excitation
- Excitation transfer observed by Clyne [1,2] → leads to broadening of Lyman-α line
  → non-adiabatic potential crossing
- $H_{fast} + Ar^* \rightarrow (ArH)^* \rightarrow H^*_{fast} + Ar$ (excitation transfer)
- Energy is released to excite H*(n=2)
- Energy is needed to excite H*(n=3)

[1] M. A. A. Clyne et al., **Chemical Physics 28**, (1978)
[2] M. A. A. Clyne et al., **Chemical Physics 47**, (1980)
[3] R.L. Vance and G. A. Gallup, **Chemical Physics 73,** 894 (1980)
[4] http://www.physics.nist.gov

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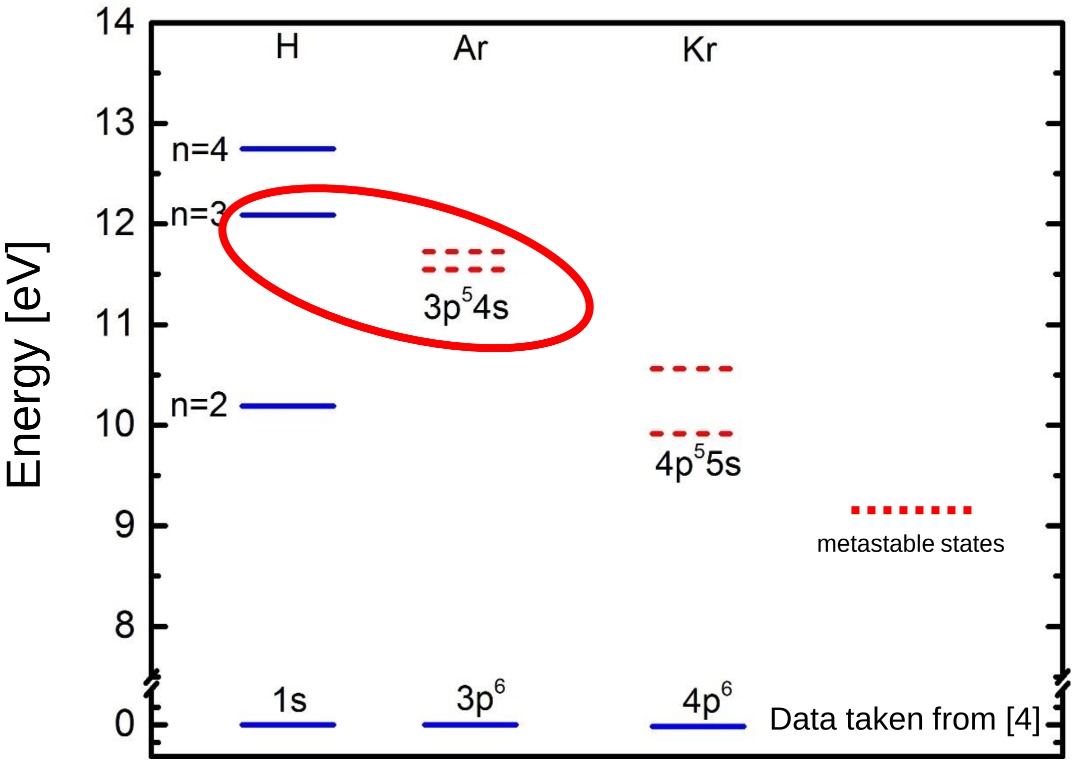

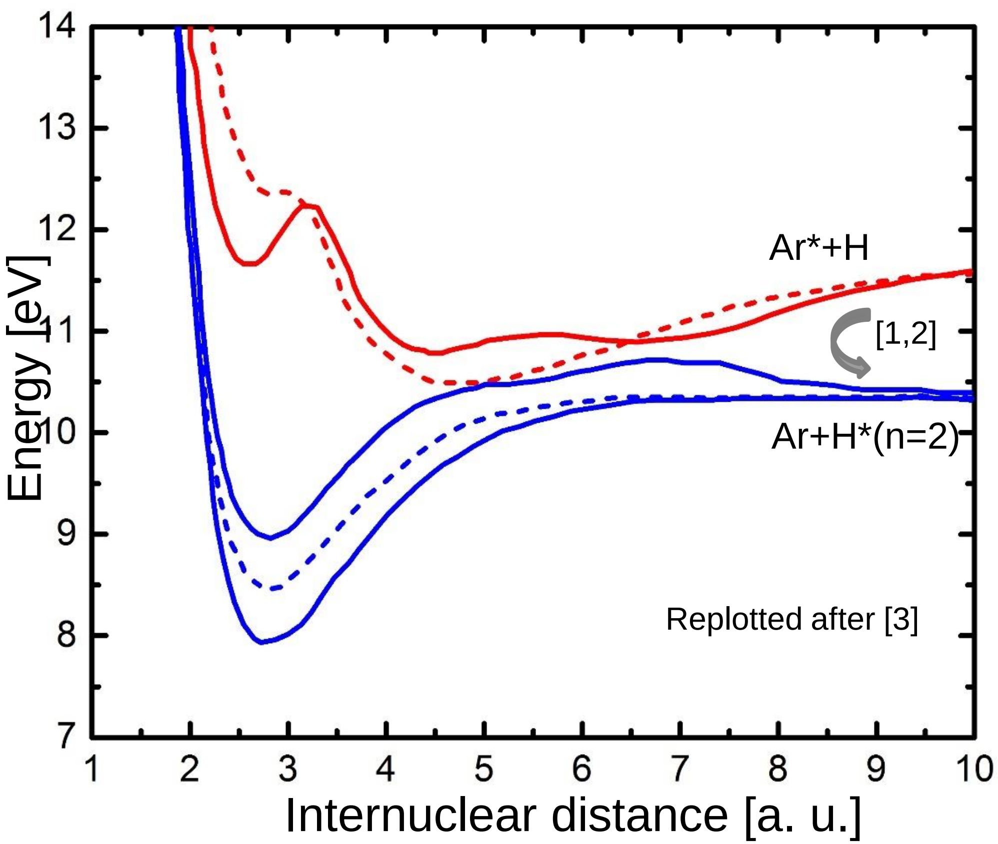

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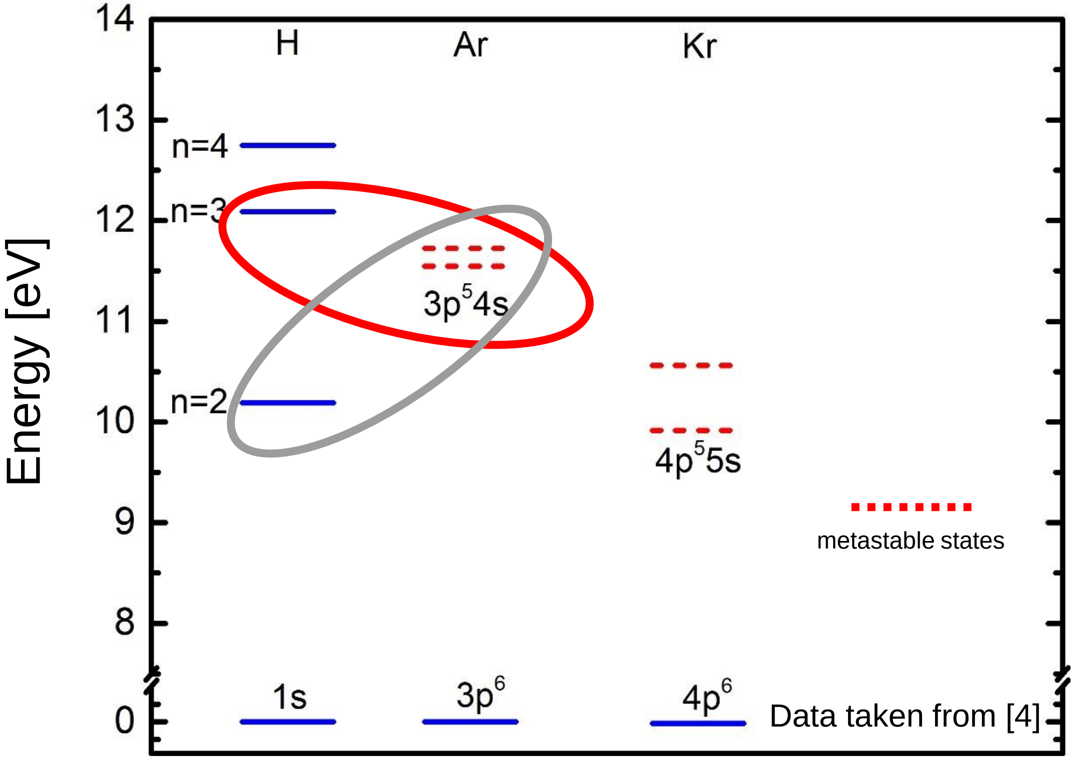

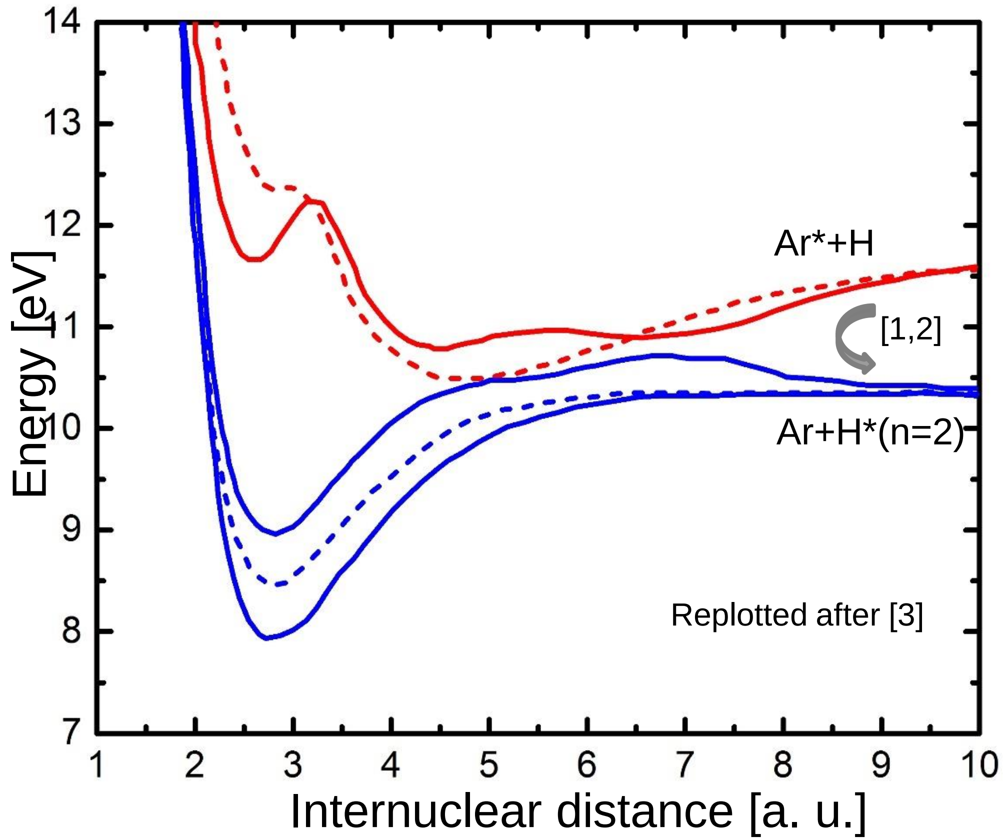

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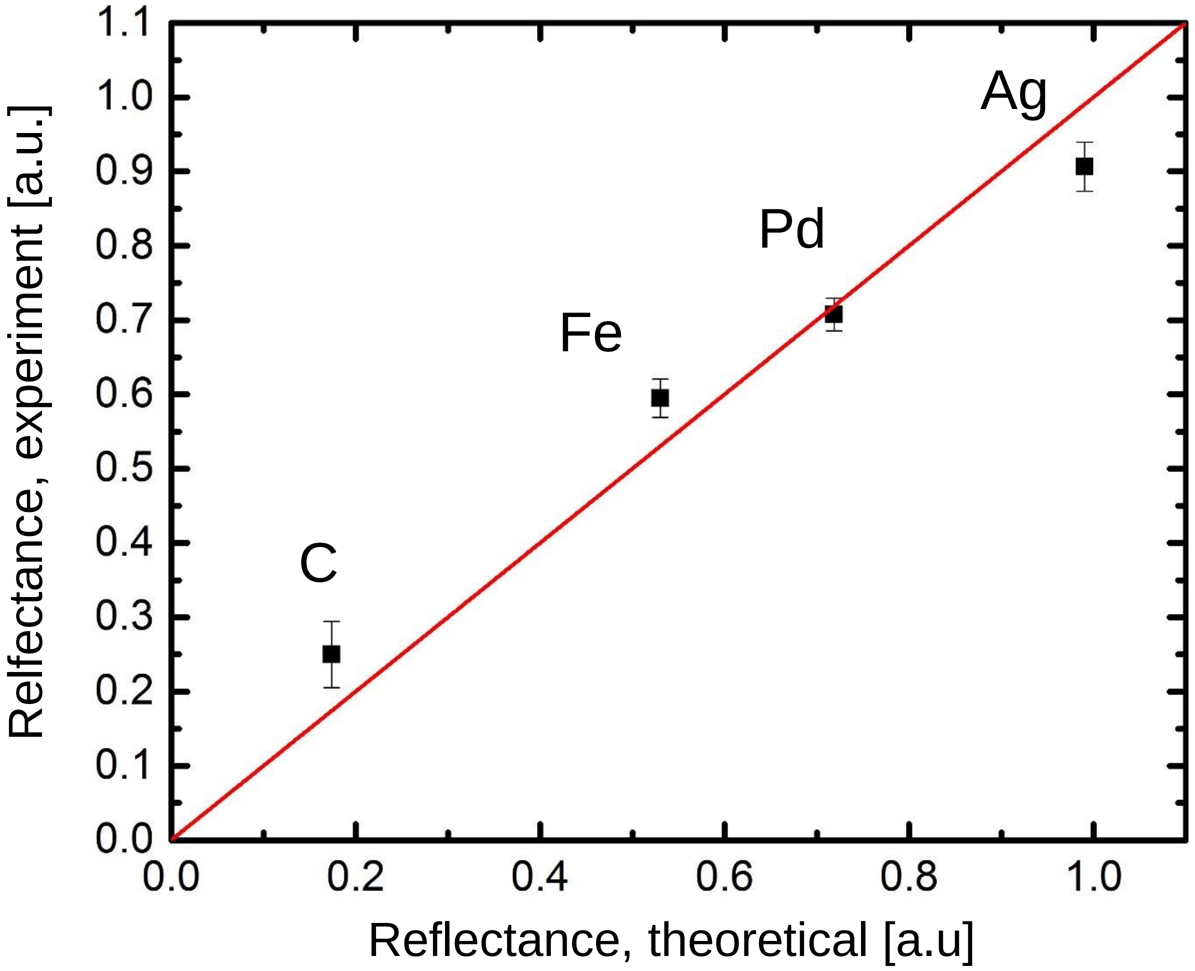
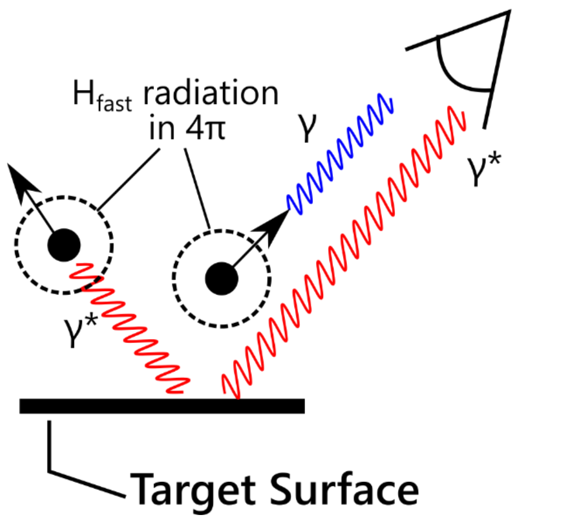
Reflectance measurements



- Calculation of reflectance as the ratio of blue- and red-shifted signal

$$R = \frac{\int I_{redshift}}{\int I_{blueshift}}$$

- Calculated reflectances are in agreement with values from literature [1]



[1] www.reflectiveindex.info
[2] T. Babkina et al., **Europhys. Lett. 72,** 235 (2005)
[3] M. R. G. Adamov et al., **IEEE Transactions on Plasma Science 31,** 444 (2003)

Conclusion

- Intensity of fast atoms is the highest for a H-Ar mixed plasma
- Origin of fast atoms is the target surface
  - No emission observed by ions moving towards the target
- Spectral reflectance of target surface can be obtained

Outlook

- Understand the source of emission
- Install new tunable laser system to measure metastable argon and krypton concentration (built by U. Czarnetzki et al., RUB)
- Modeling the distribution function of fast atoms