Effects of Helium in Tungsten Studied by Positron Annihilation Spectroscopy

Vassily Vadimovitch Burwitz[1,2,3]*, Annemarie Kärcher[1,3], Maik Butterling[4], Eric Hirschmann[4], Emma Huntley[2], Adrian Langrehr[1], Maciej Oskar Liedke[4], Lucian Mathes[1,2], Thomas Schwarz-Selinger[3], Christoph Springl[1,2], Monia Vadrucci[5,6], Andreas Wagner[4], Christoph Hugenschmid[2]

[1]TU München, School of Natural Sciences, Physikdepartment, [2]TU München, Heinz Maier-Leibnitz Zentrum, [3]Max-Planck-Institut für Plasmaphysik, Garching bei München, [4]Helmholtz-Zentrum Dresden-Rossendorf, Institute of Radiation Physics, [5]ENEA, Development of Particle Accelerators and Medical Applications, Frascati (RM), Italy, [6]Italian Space Agency, Science and Innovation Directorate, Rome

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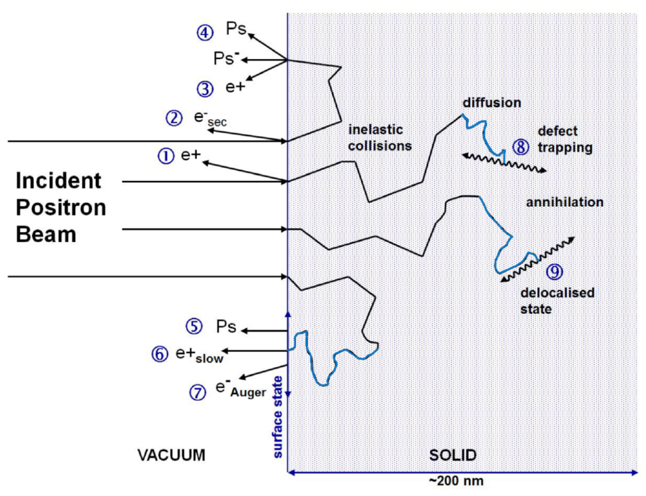
MOTIVATION

- Helium incident on divertor of fusion reactor:
  - Energy: 20 to $100\,\mathrm{eV}$
  - Flux: 1×10^{23} to $1\times10^{24}\,\mathrm{He/m^2/s}$

  [Yang and Fan 2022, Plasma Sci. Technol.]
- Known macroscopic effects:
  - Embrittlement
  - Blistering
  - Flaking

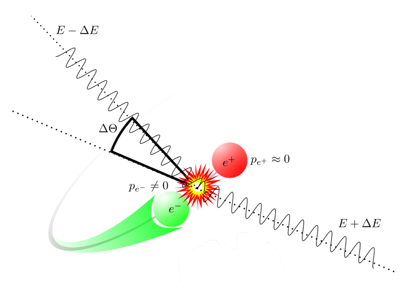
POSITRON IN SOLID



[Hugenschmidt 2016, Surf. Sci. Rep.], modified.

1. Thermalizes (by scattering).
2. Diffuses (if not trapped in open-volume defect).
3. Annihilates with electron.

ANNIHILATION



[Ceeh 2015, thesis]

Doppler-effect (relativistic):

$$\Delta E = \frac{p_L c}{2} \quad (1)$$

Lifetime:

$$\tau_{e^+} = \frac{1}{\rho_{e^-}} \quad (2)$$

SAMPLES

- Tungsten
- Monocrystalline (111)
- Cut by electrode discharge milling
- Polished (mechanically and electrochemically)
- Annealed (in vacuum at $>2300\,\mathrm{K}$ for $3\,\mathrm{min}$)

→ **"defect free"** as measured by PAS.

HELIUM IRRADIATION

Low-temperature plasma device
[Manhard 2017, Nucl. Fusion]

- Samples at room temperature
- Energy: $50\,\mathrm{eV}$ (Below kinetic damage threshold)
- Flux: $1.0\times10^{17}\,\mathrm{He/m^2/s}$ to $1.0\times10^{19}\,\mathrm{He/m^2/s}$
- Fluence: $1.8\times10^{20}\,\mathrm{He/m^2}$ to $8.9\times10^{21}\,\mathrm{He/m^2}$

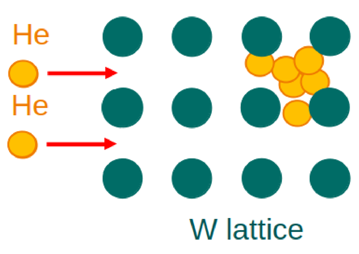
SUMMARY

- In "defect free" W: Parameter space limits for:
  - Clustering
  - Self trapping
- In predamaged W: No trap mutation observed.

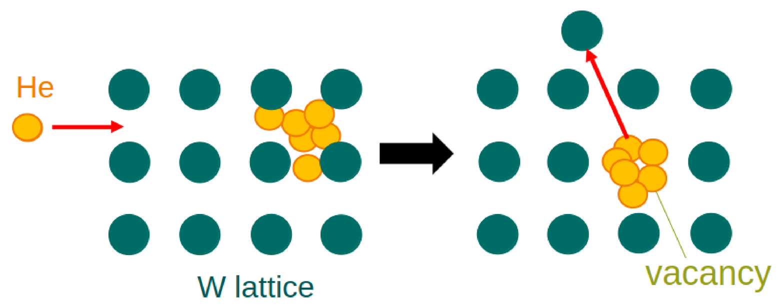
ATOMIC-LEVEL PROCESSES OF HELIUM IN W

As predicted by DFT [Boisse 2014, J. Mater. Res.] & MD [Pentecoste 2016, J. Nucl. Mater.].

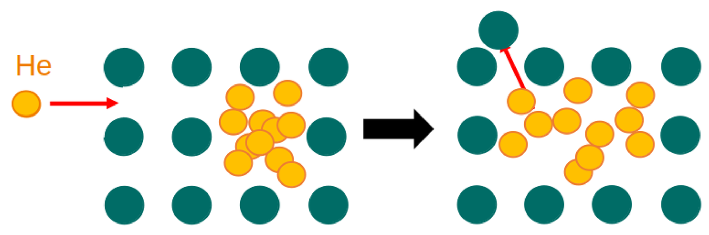
CLUSTERING



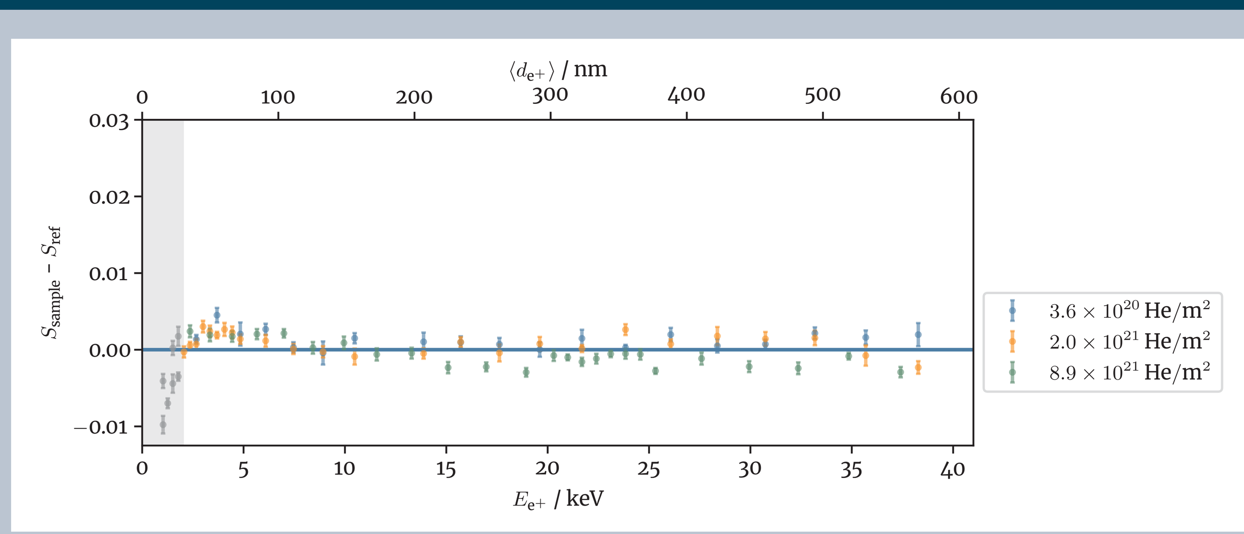
SELF TRAPPING



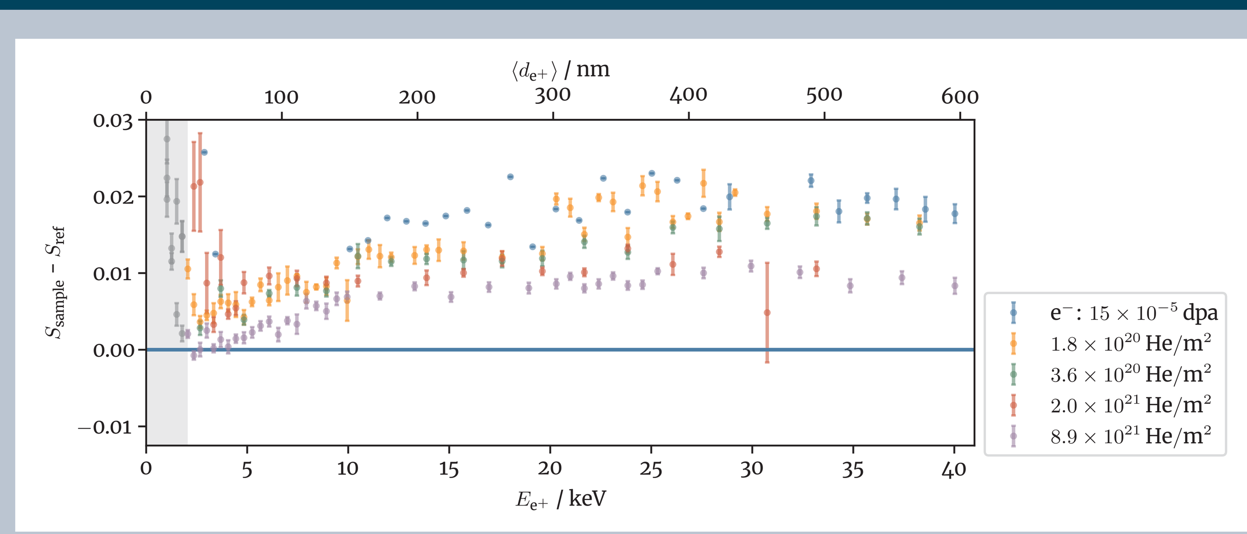
TRAP MUTATION



DBS MEASUREMENTS



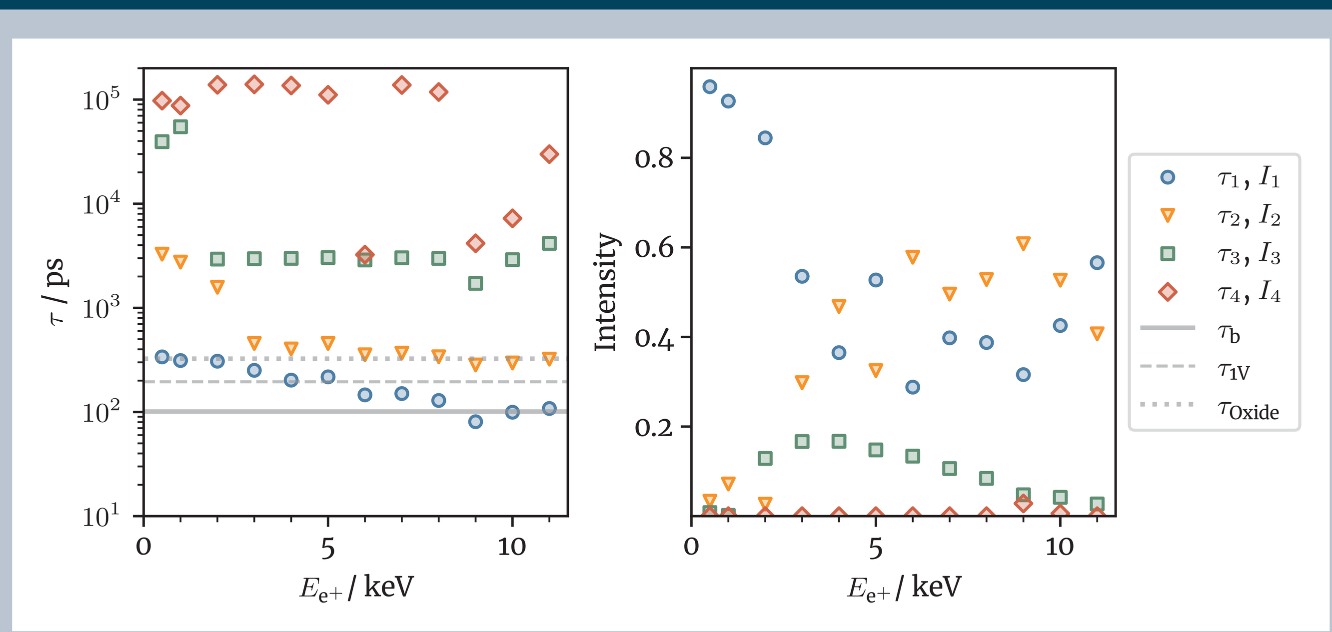
Helium in "defect free" W



Helium in W pre-irradiated with $4.5\,\mathrm{MeV}$ electrons.

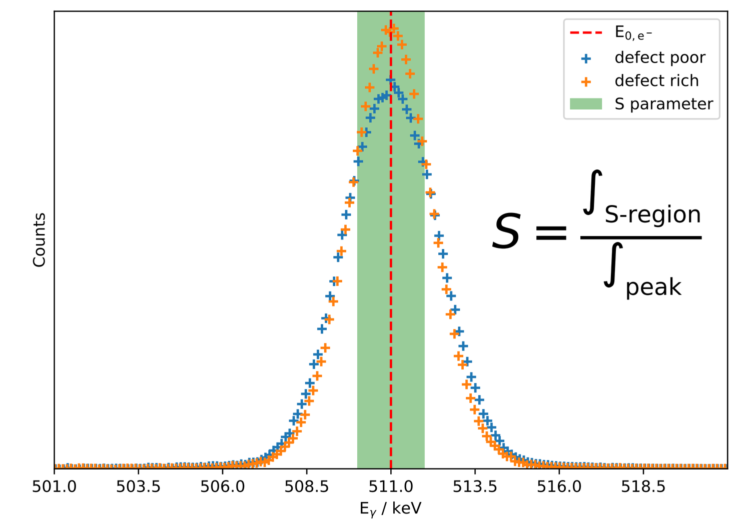
These measurements are two examples of a larger set. He flux is $1.0\times10^{17}\,\mathrm{He/m^2/s}$.

PALS MEASUREMENTS



This measurement (of W only) is an example representing a larger set of measurements.

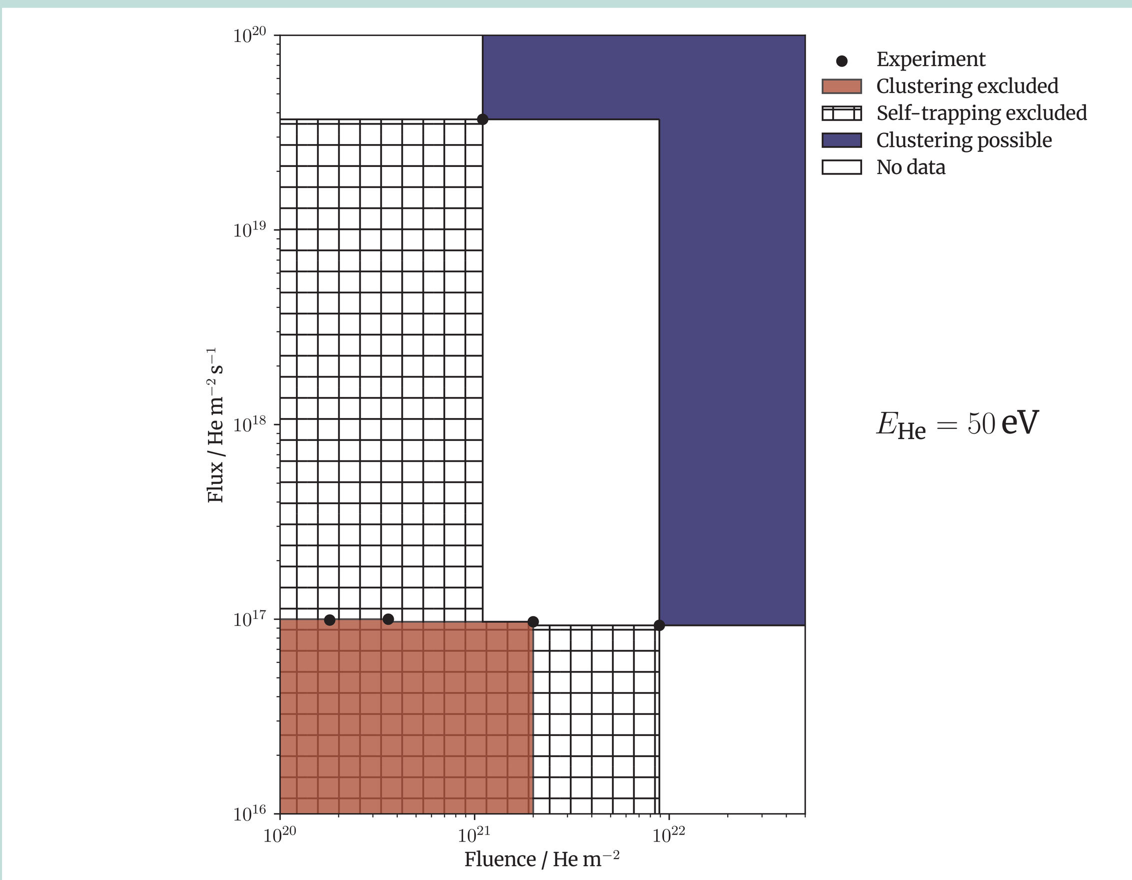
DBS



Doppler-broadening Spectroscopy (DBS):

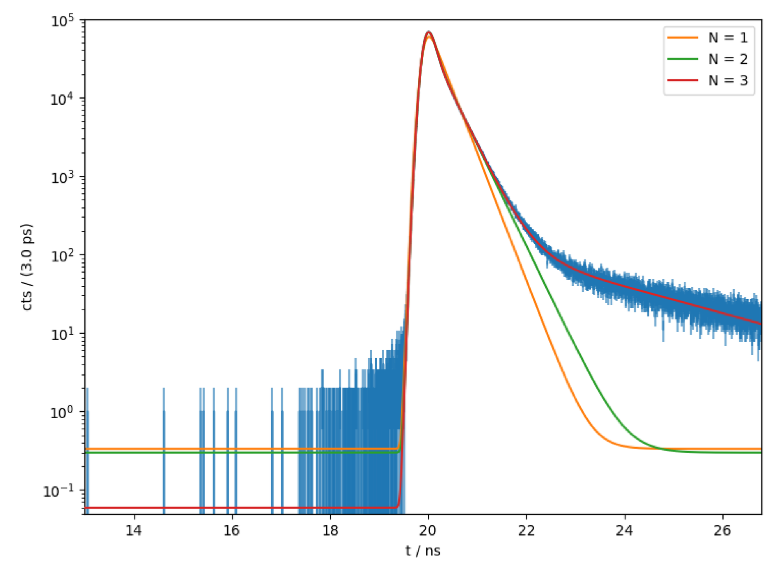
Sensitve to defect concentration.

HELIUM IN "DEFECT FREE" W



Input: conventional and depth-resolved DBS and PALS.

PALS



Positron Annihilation Lifetime Spectroscopy (PALS):

Sensitve to defect type and concentration.

$$N(t) = \sum_{i=0}^{k} \frac{I_i}{\tau_i} \exp\left(-\frac{t}{\tau_i}\right) \quad (3)$$

k number of annihilation sites
τ lifetime
I intensity

OUTLOOK

- Improve theory for PAS data analysis.
- Simulations of relevant Helium irradiation regimes (kinetic Monte Carlo, compare [Z. Yang 2017, FST]).

Corresponding author: *vassily.burwitz@ipp.mpg.de;

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