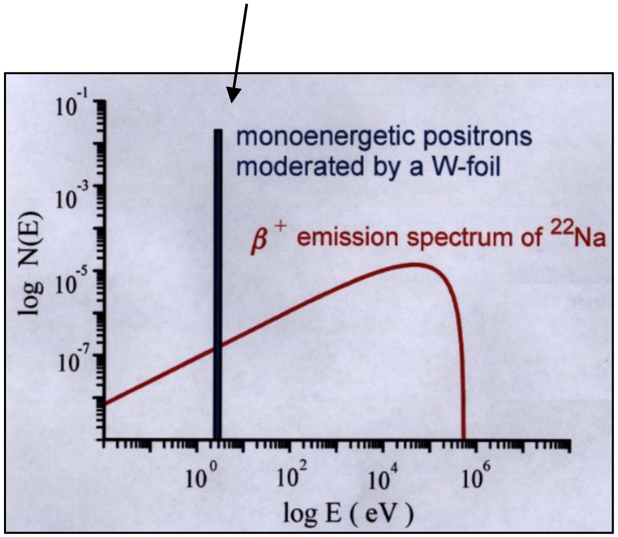
Slow positron beam

- positrons emitted by ^{22}Na β^+ radioisotope

moderated positrons



- mean positron penetration depth $\int_0^\infty z\,P(z)\,dz = \frac{1}{\alpha}$

example:

Mg: $\alpha^{-1} = 154\ \mu\text{m}$

Al: $\alpha^{-1} = 99\ \mu\text{m}$

Cu: $\alpha^{-1} = 30\ \mu\text{m}$

- probability that a positron penetrates into a depth *z* $\quad P(z) = \alpha\, e^{-\alpha z}$

$$\alpha\left[\text{cm}^{-1}\right] = 16\,\frac{\rho\left[\text{g cm}^{-3}\right]}{E_{\max}^{1.4}\left[\text{MeV}\right]}$$

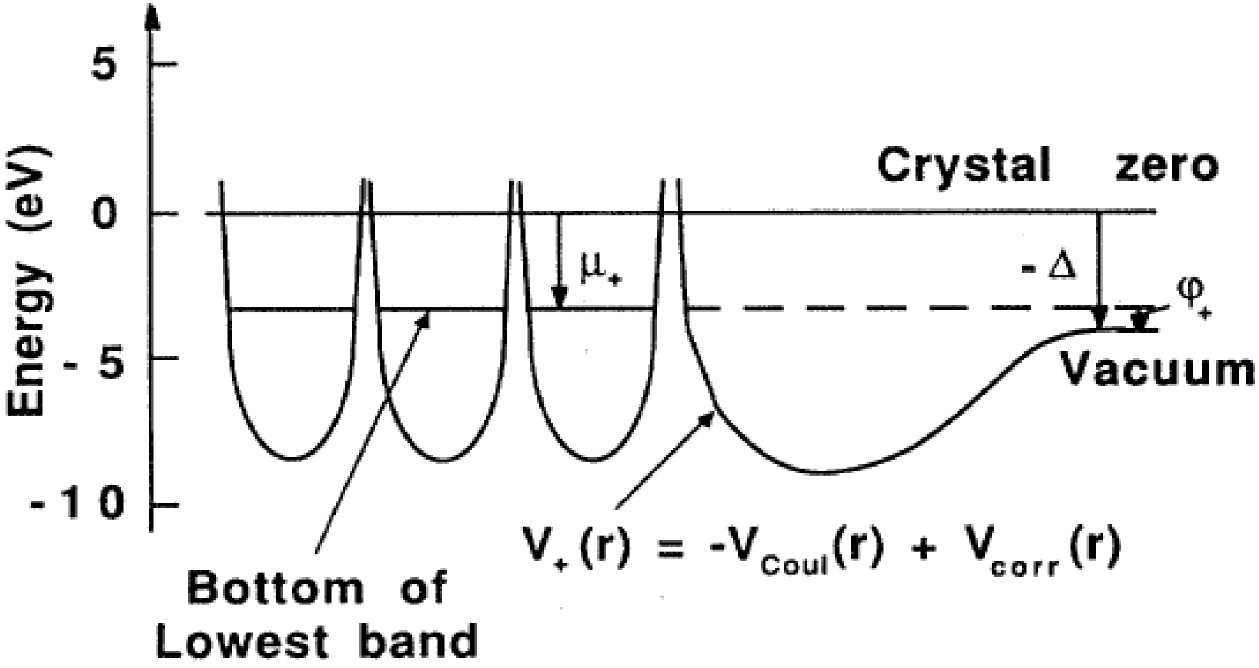
ρ – material density

$E_{\max} = 0.545\ \text{MeV}$ (pro ^{22}Na)

Positron moderation

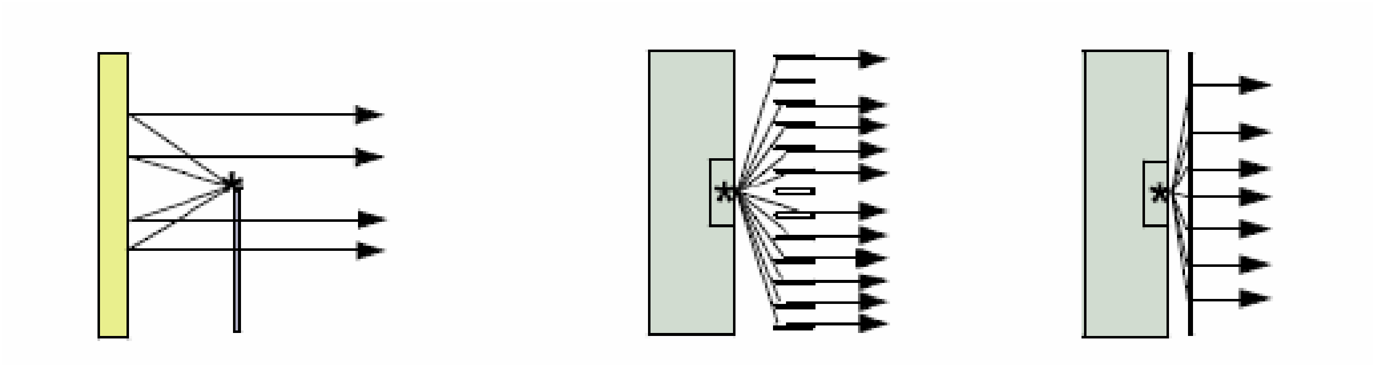
Positron work function

material	ϕ_+
Al (100)	-0.16(3)
Al (111)	0.065(3)
Cr (100)	-1.76(5)
W (100)	-3.0(1)
W (110)	-3.0(2)
Ne	0.61(1)
Ar	1.55(5)



Positron moderation

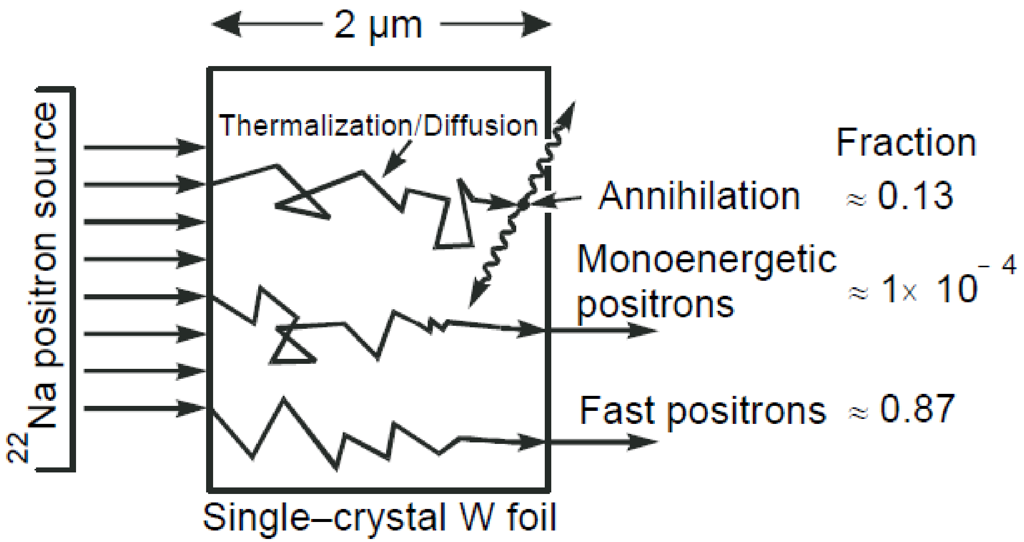
Examples of positron moderator geometries



back-scattering venetian blind transmission geometry

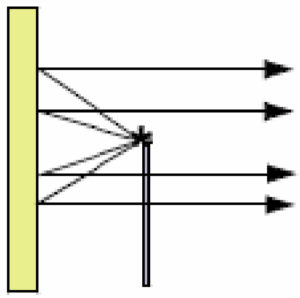
moderator efficiency:

$$\varepsilon = \frac{N_{thermalized}}{N_{incident}}$$

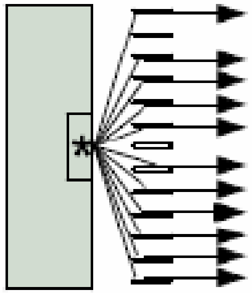


Positron moderation

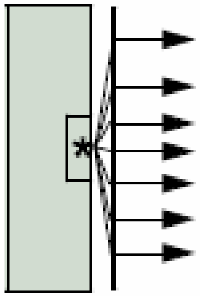
Examples of positron moderator geometries



back-scattering



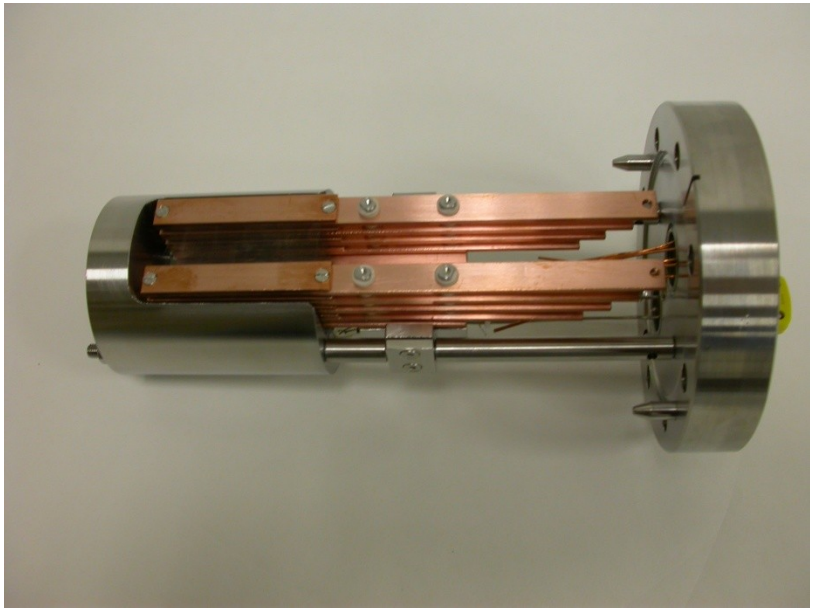
venetian blind



transmission geometry

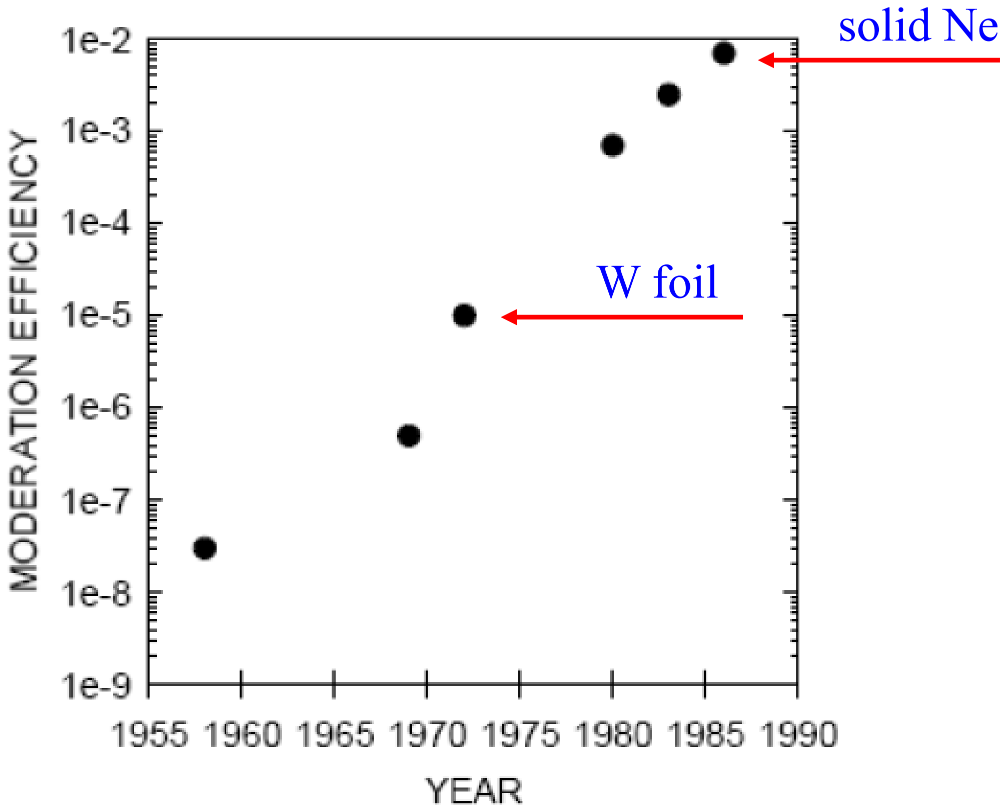
moderator efficiency:

$$\varepsilon = \frac{N_{thermalized}}{N_{incident}}$$



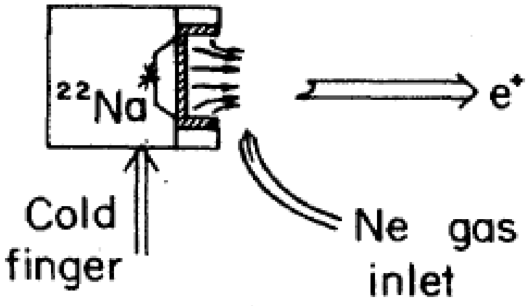
Positron moderation

moderator efficiency: $\varepsilon = \frac{N_{thermalized}}{N_{incident}}$



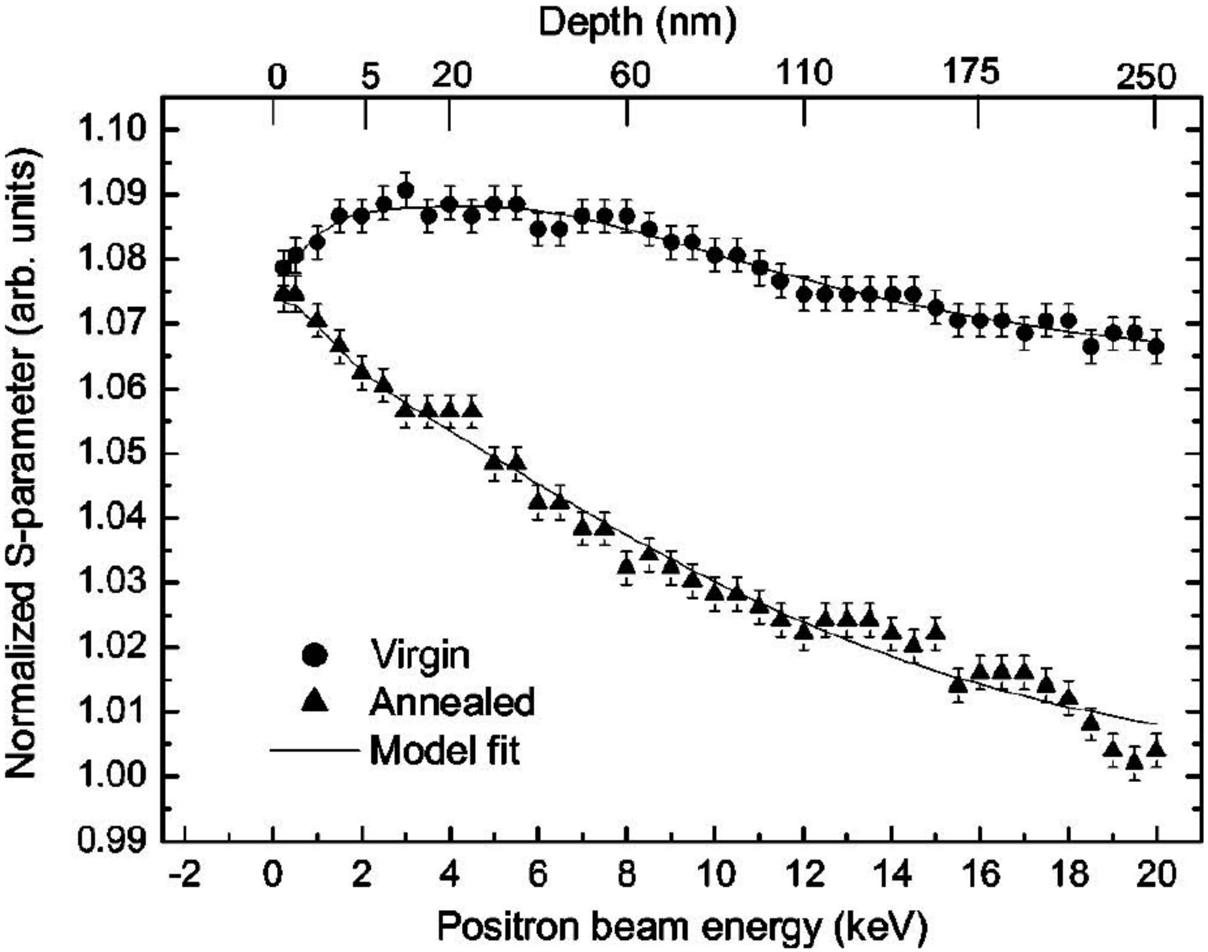
solid Ne

W foil



Positron moderation

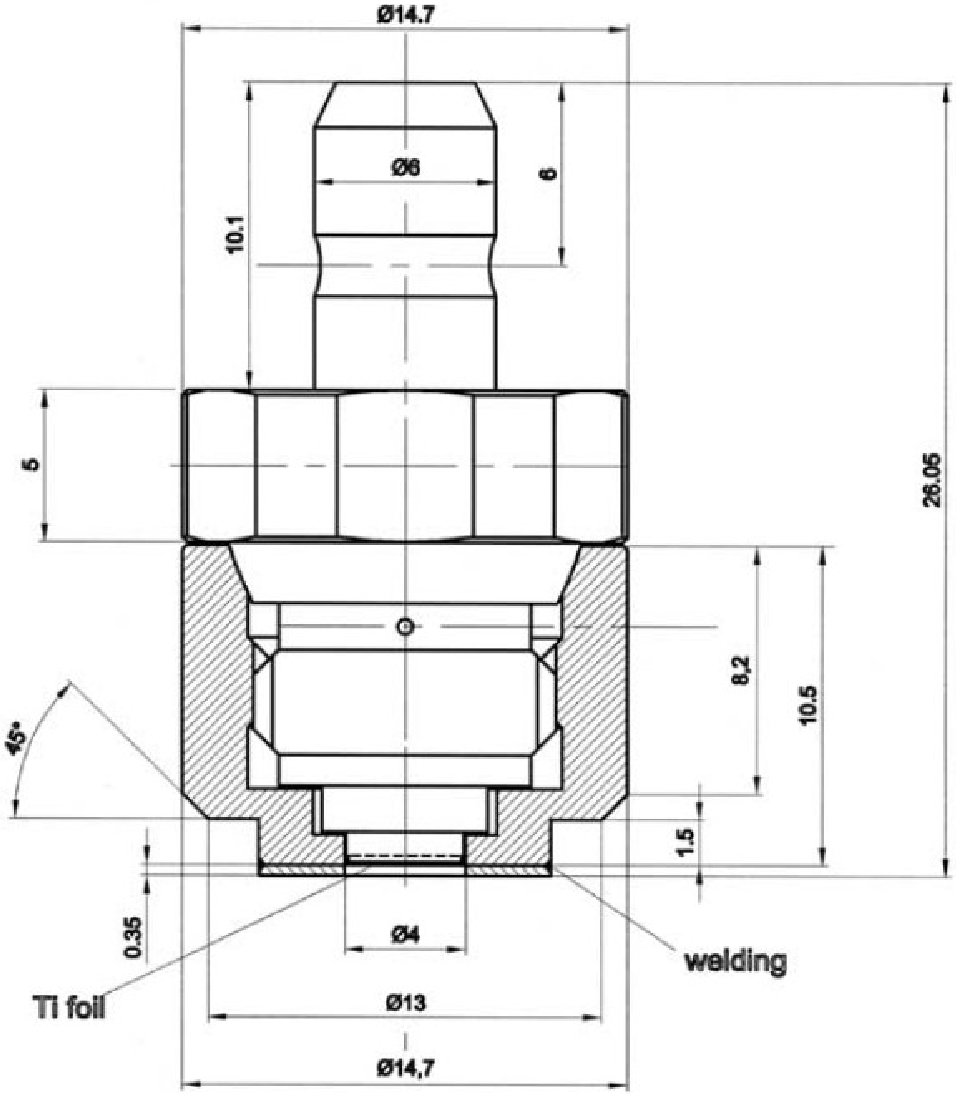
polycrystalline W foil



Slow positron beam

^{22}Na source for slow positron beam

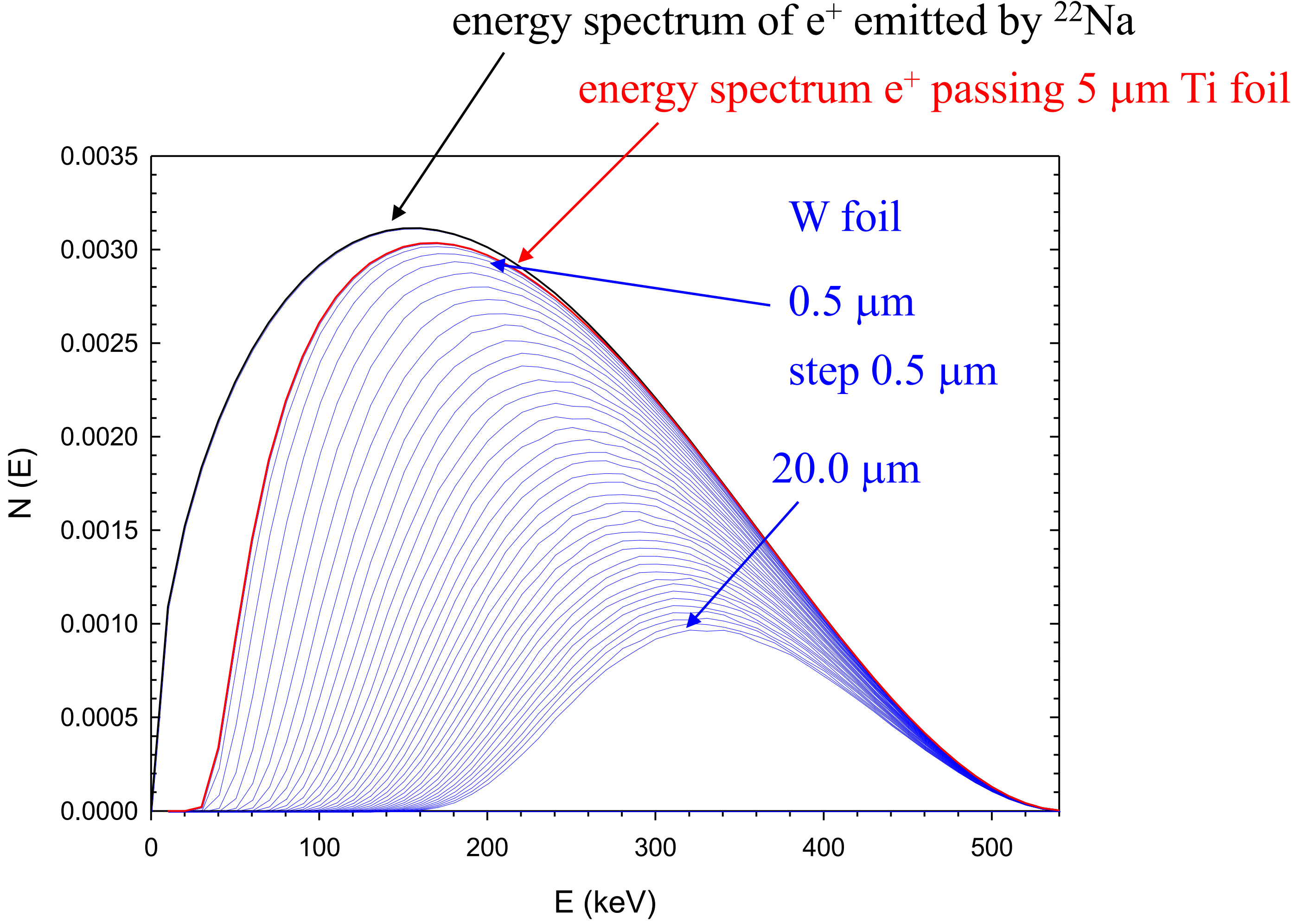
- iThemba Labs (Jižní Afrika)
- 50 mCi = 1.85 GBq
- conventional positron source $A \approx 1$ MBq
- source for slow positron beam $A \approx 1$ GBq



Slow positron beam

^{22}Na source for slow positron beam

- output window - 5 μm Ti foil



energy spectrum of e^+ emitted by ^{22}Na

energy spectrum e^+ passing 5 μm Ti foil

W foil

0.5 μm

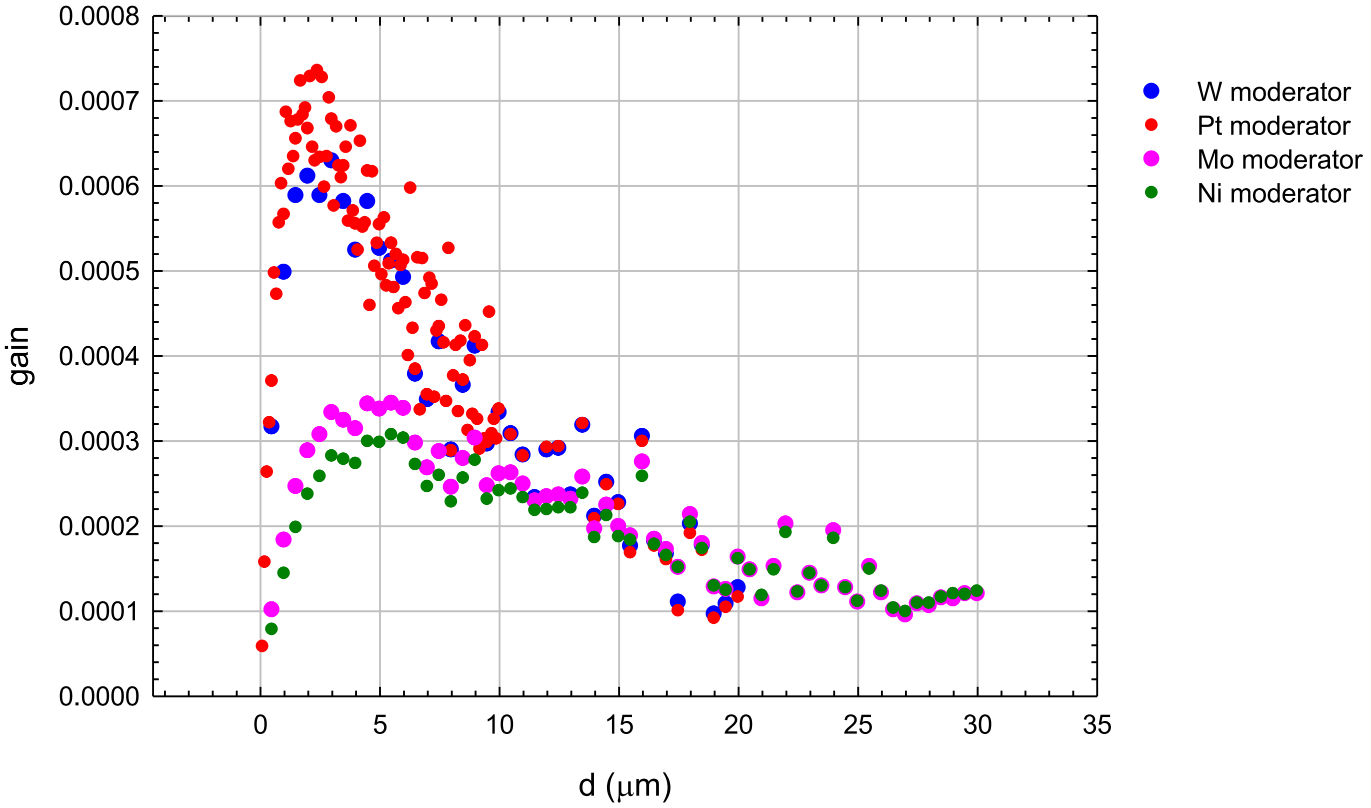
step 0.5 μm

20.0 μm

Slow positron beam

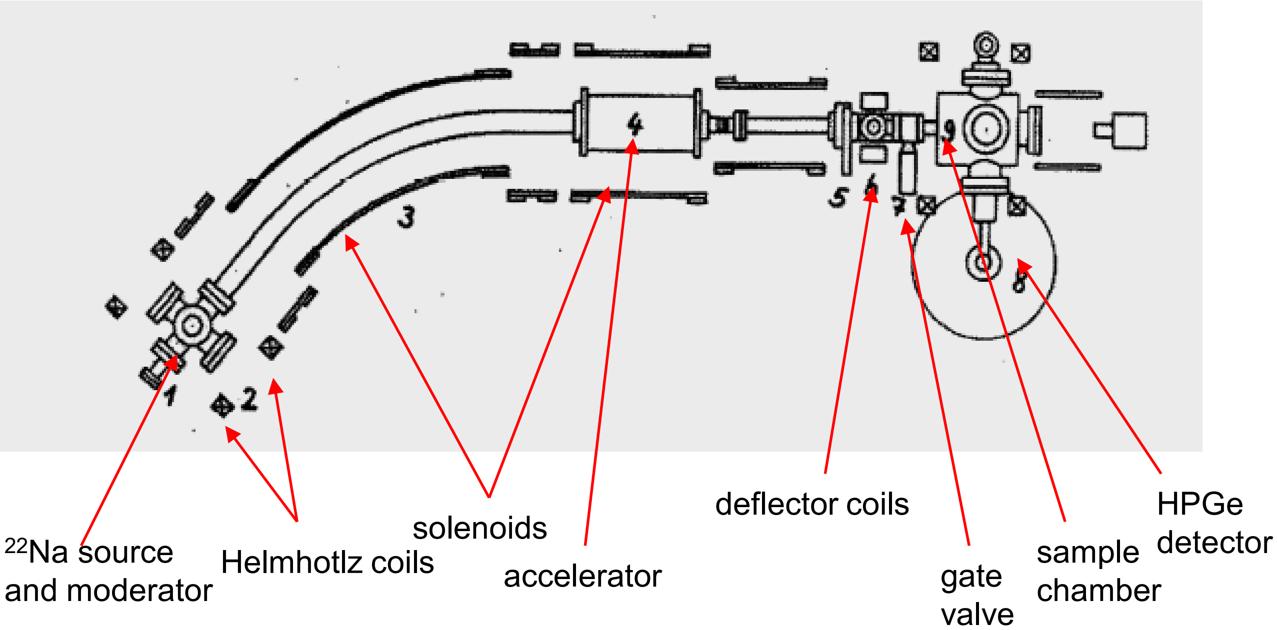
^{22}Na source for slow positron beam

- output window - 5 μm Ti foil
- transmission geometry of moderator
- slow positron yield



Slow positron beam

- continuous slow positron beam (Helmholtz-Zentrum Dresden Rossendorf)
- selection of slow positrons – bending of the beam
- magnetic guiding of the beam using solenoids



^{22}Na source and moderator

Helmhotlz coils

solenoids

accelerator

deflector coils

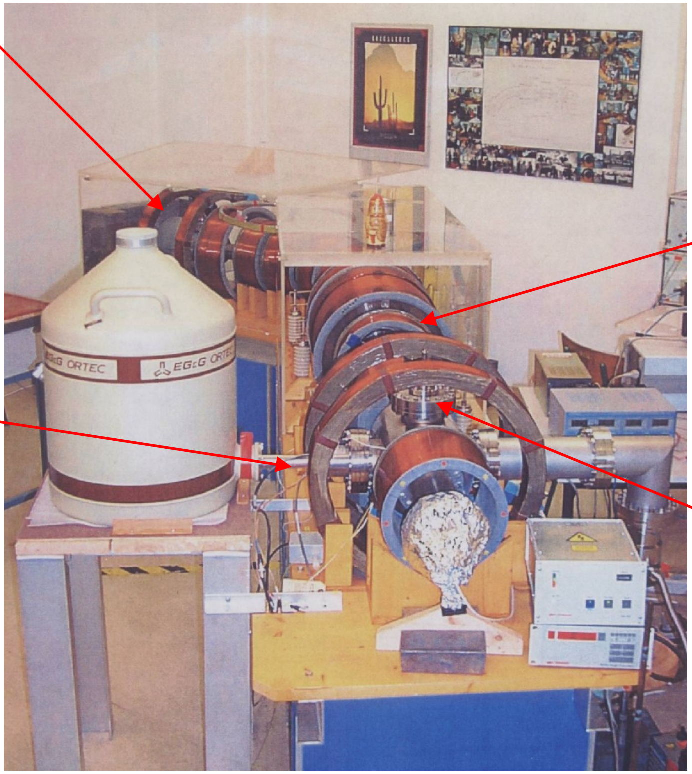
gate valve

sample chamber

HPGe detector

Slow positron beam

- continuous slow positron beam (Helmholtz-Zentrum Dresden Rossendorf)
- selection of slow positrons – bending of the beam
- magnetic guiding of the beam using solenoids



^{22}Na positron source + W moderator

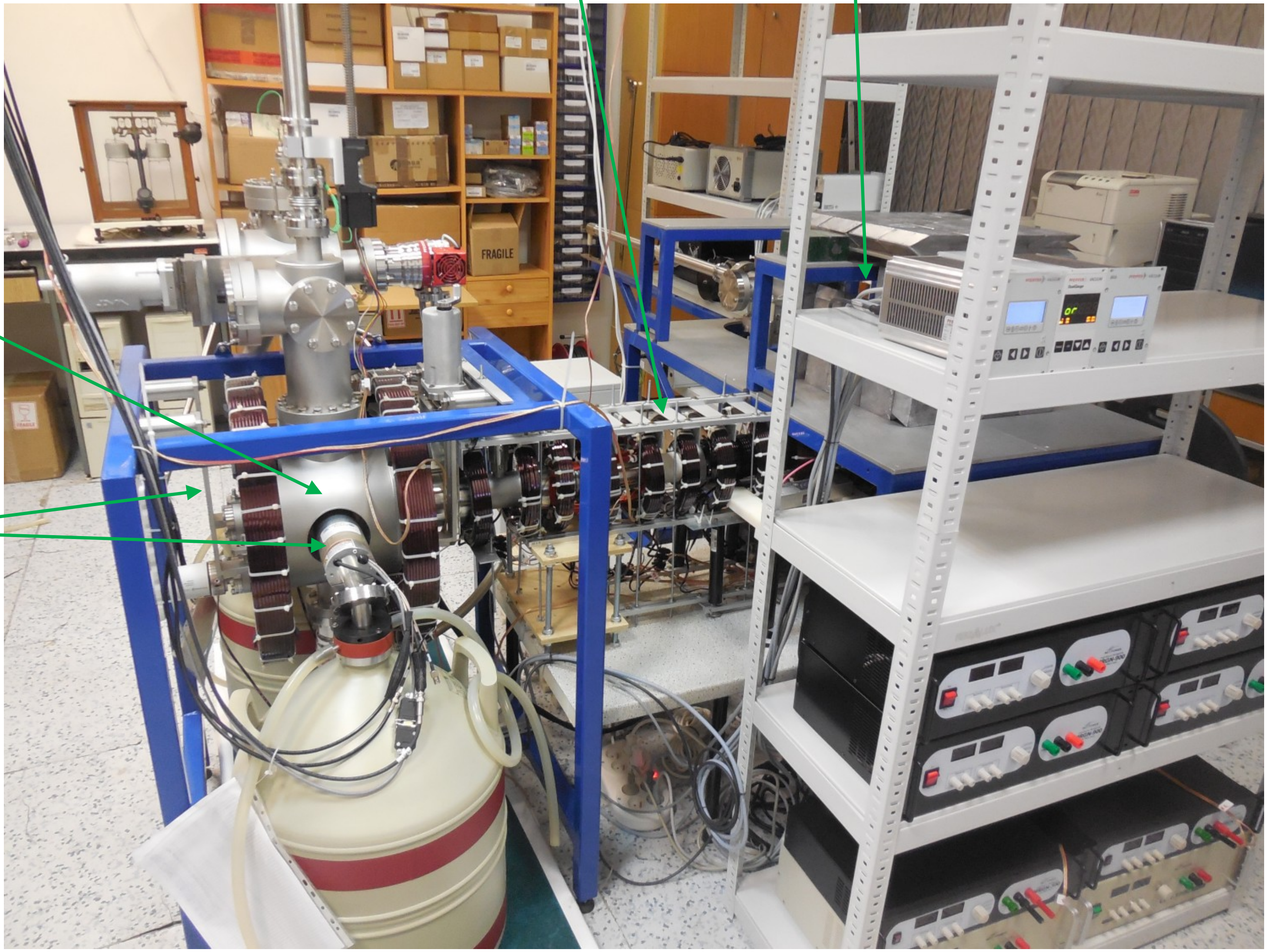
accelerator

HPGe detector

sample chamber

Slow positron beam

- slow positron beam (MFF UK)
- selection of slow positrons – bending of the beam
- magnetic guiding of the beam using solenoids



^{22}Na positron source
+ W moderator

accelerator

sample chamber

HPGe detector

Implantation profile of monoenergetic positrons

- monoenergetic positrons with energy E

$$P(z,E)=\frac{mz^{m-1}}{z_0^m}\exp\left[-\left(\frac{z}{z_0}\right)^m\right]$$

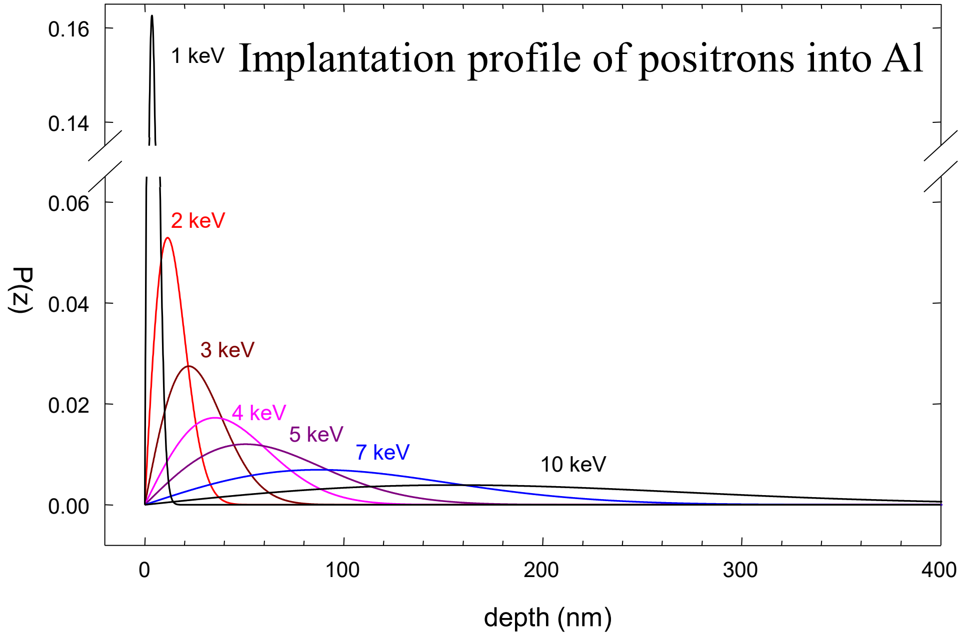
$$z_0=\frac{AE^r}{\rho\Gamma\left(1+\frac{1}{m}\right)}$$

$$A=4\times10^{-3}\ \mathrm{gcm^{-2}keV^{-r}}$$

$$m=2$$

$$r=1.6$$

- mean penetration depth: $\bar{z}=\frac{AE^r}{\rho}$


Implantation profile of positrons into Al

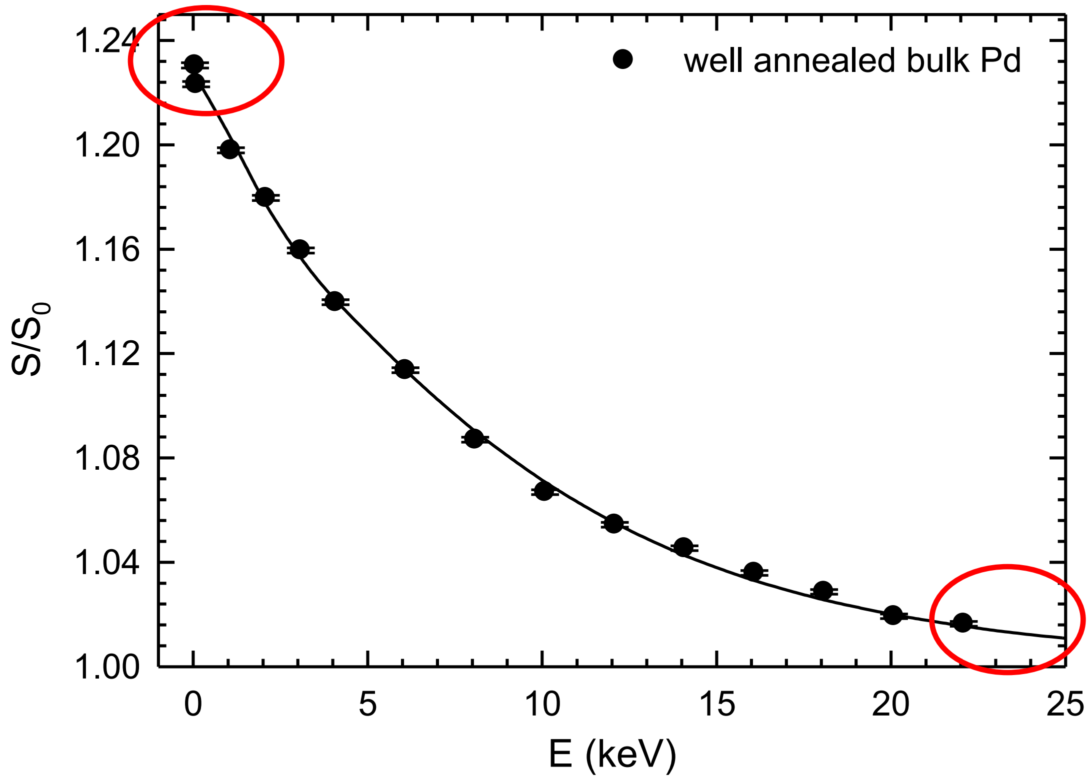
Slow positron beam with tunable energy

- study of defect depth profile
- investigation of thin films
- measurement of positron back-diffusion

Characterization of defects in Pd

- characterization of defects using a slow positron beam with variable energy
- mean positron diffusion length: $L_+ = (151 \pm 4)$ nm

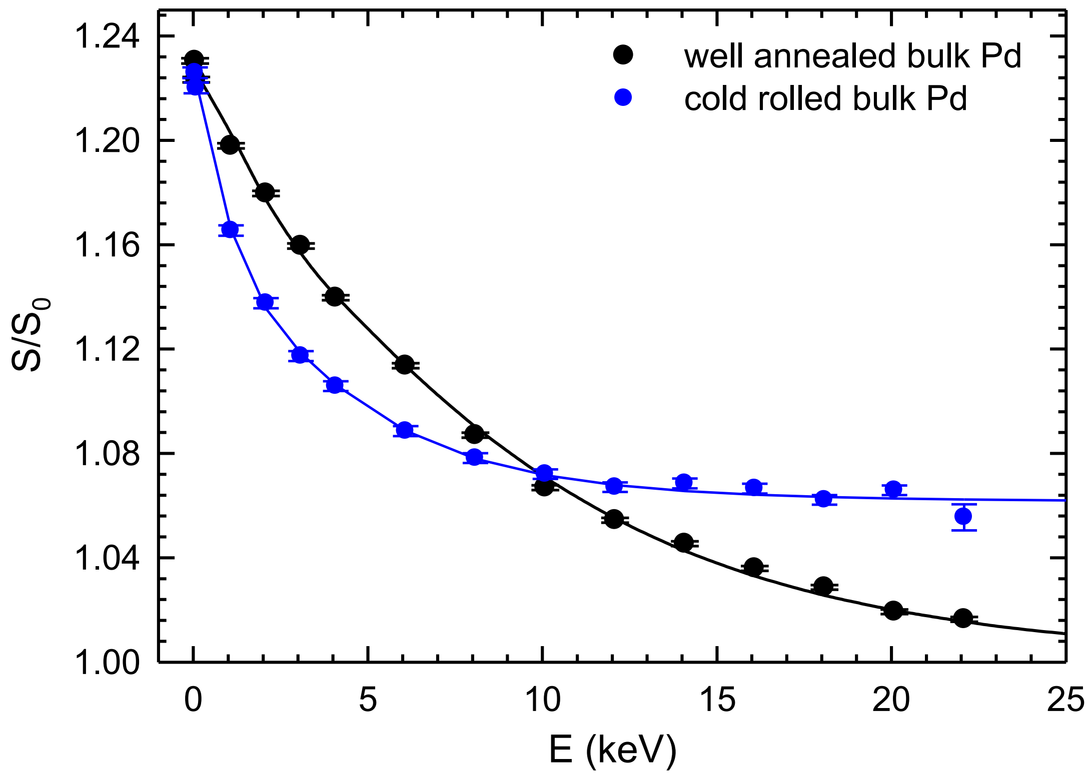
surface state



annihilation in Pd layer

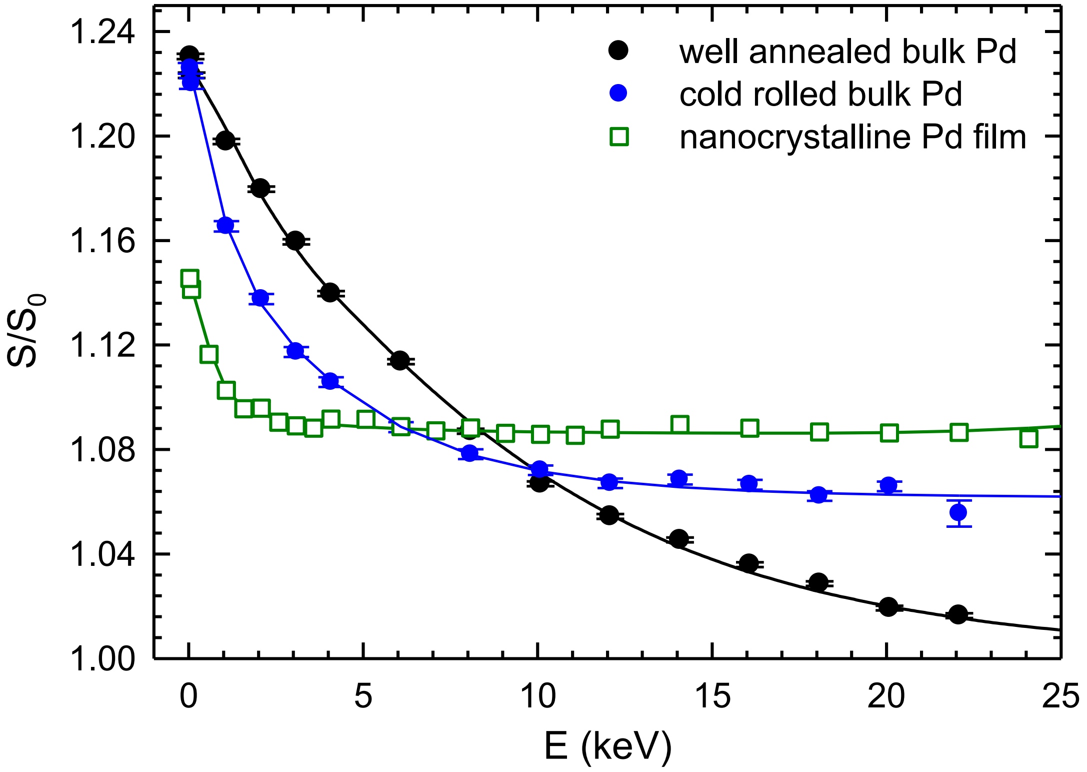
Characterization of defects in Pd

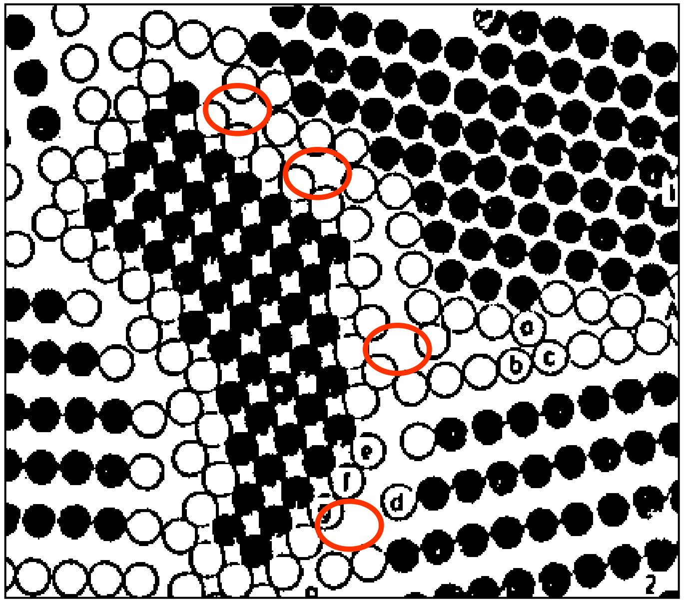
- characterization of defects using a slow positron beam with variable energy
- plastic deformation → increase of S, shortening of L_+



Characterization of defects in Pd

- characterization of defects using a slow positron beam with variable energy
- nanokrystalline Pd film – positron trapping in misfit defects at grain boundaries



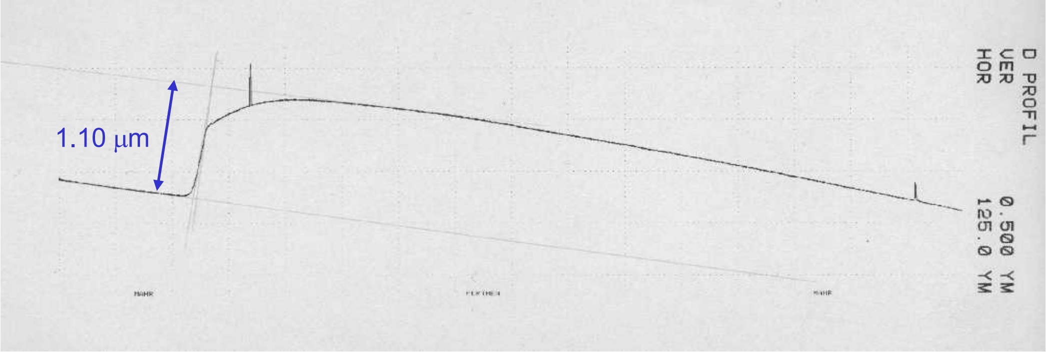


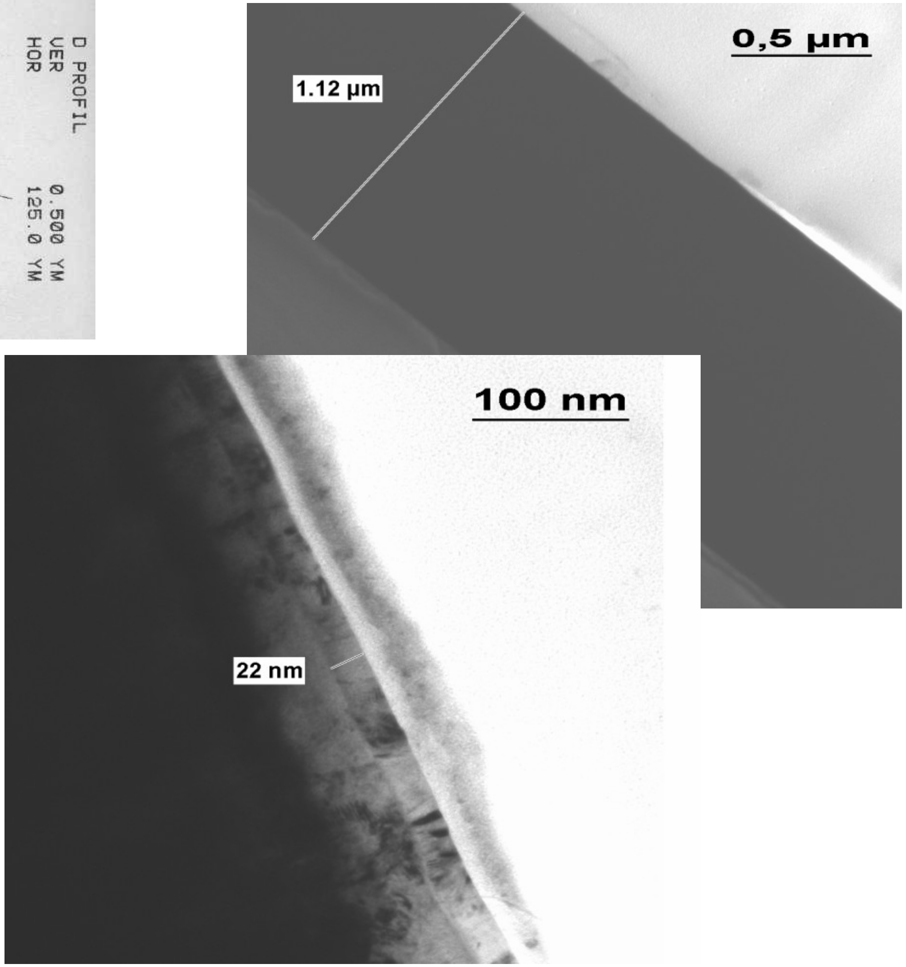
Thin Nb films doped by hydrogen

Nb film with thickness of 1.1 μm covered by a Pd cap with thickness of 20 nm

- thickness (1100 ± 50) nm (profilometry)

(1120 ± 20) nm (TEM)

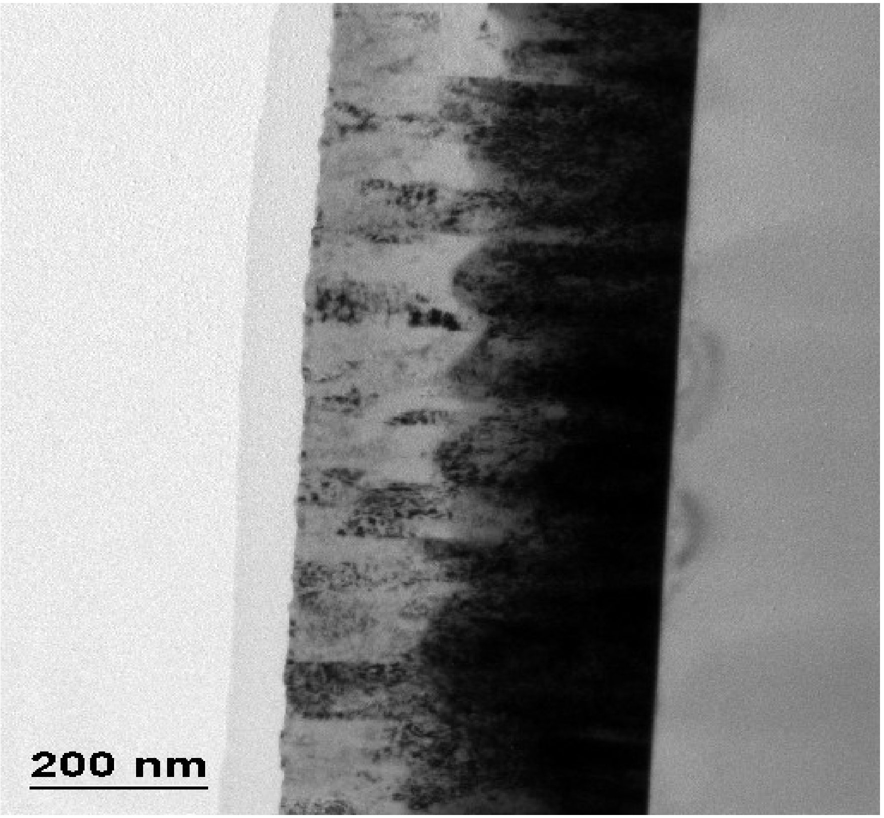


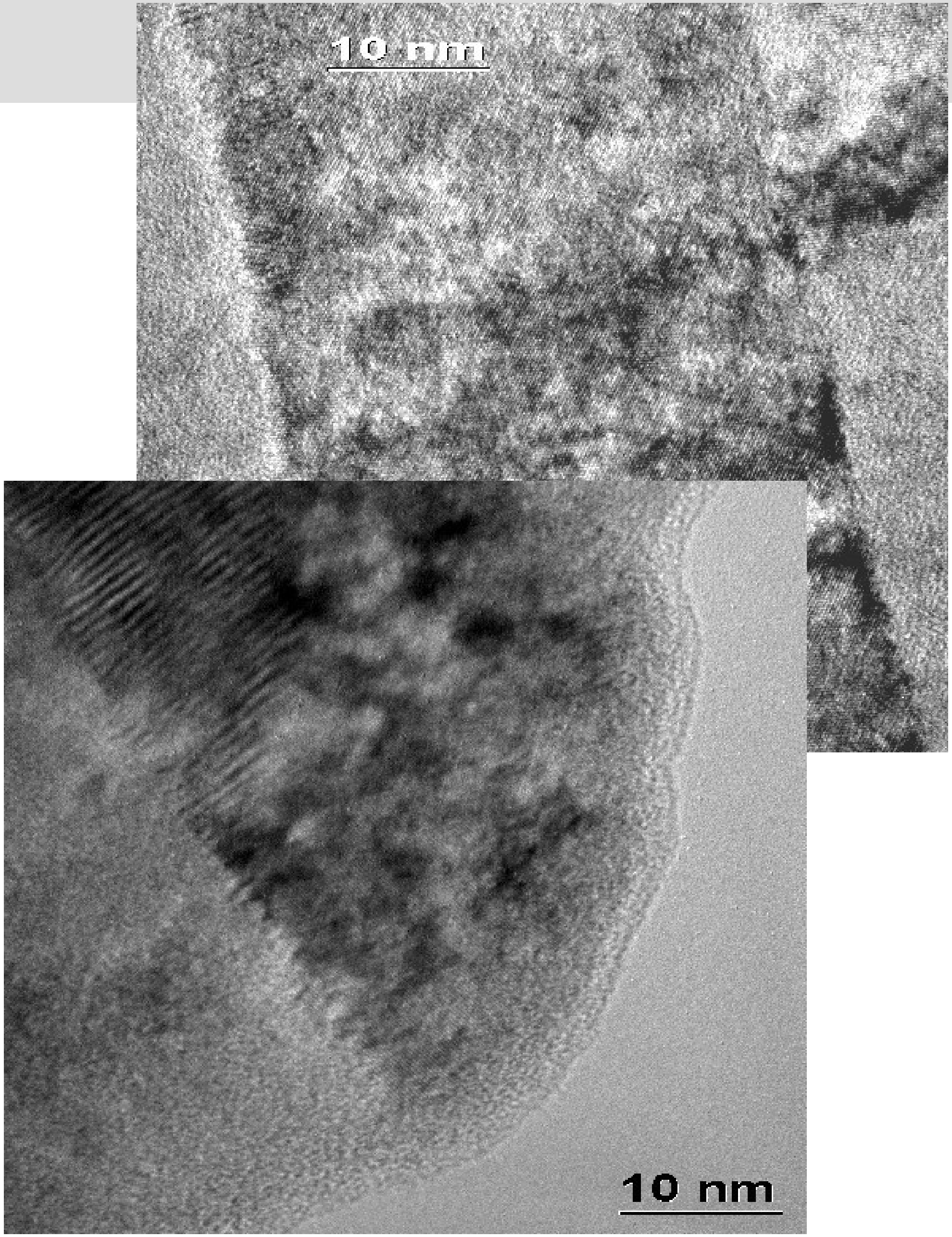


- a Pd cap (20 nm) deposited on surface

Thin Nb films doped by hydrogen

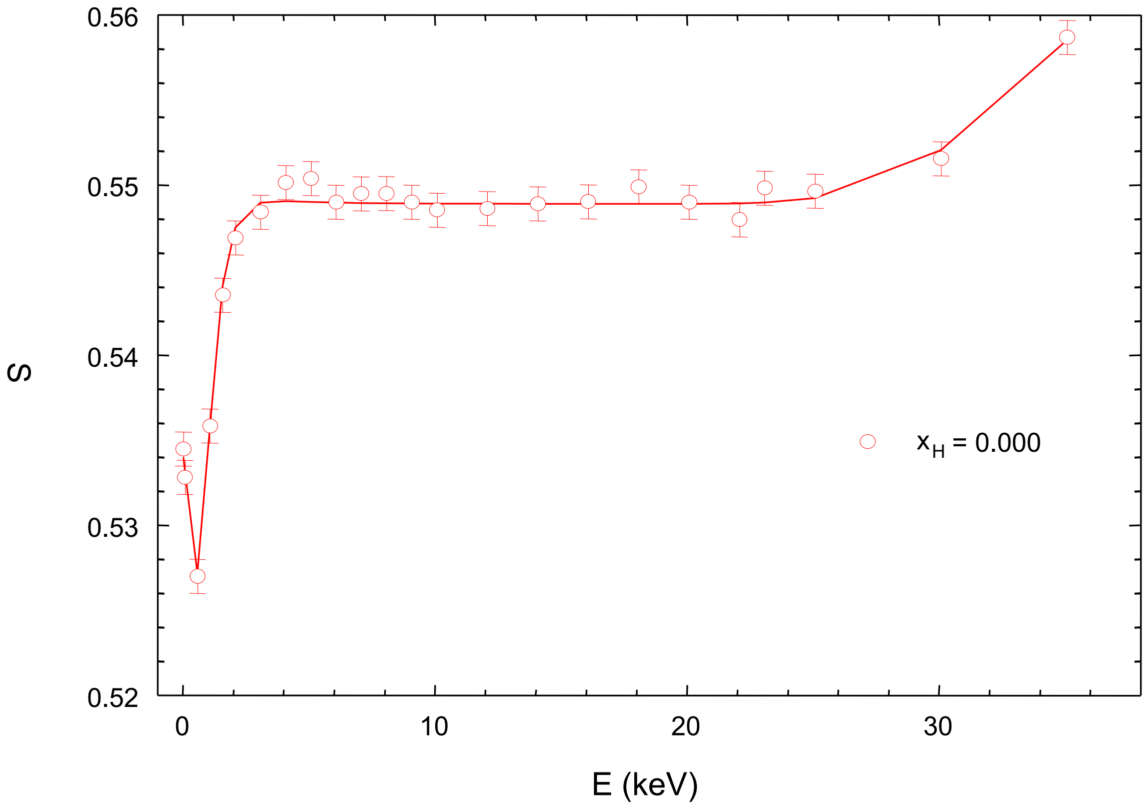
- column like crystallites
- crystallite width ≈ 50 nm





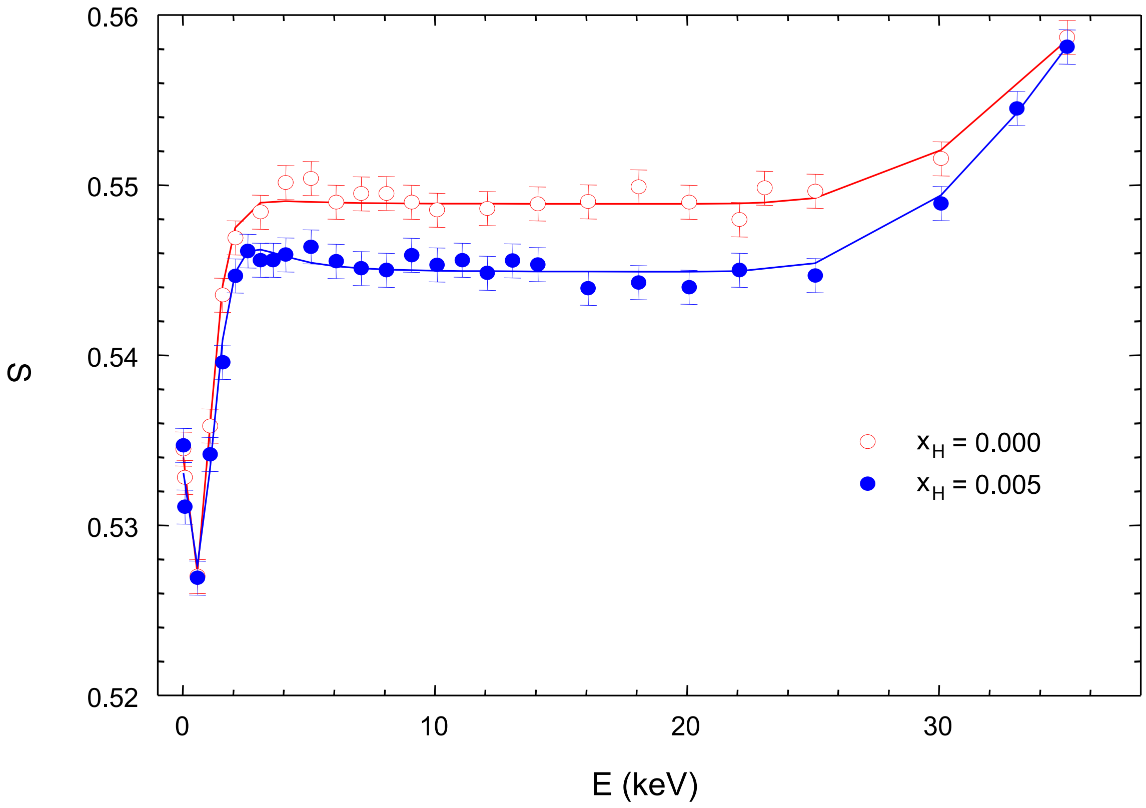
Thin Nb films doped by hydrogen

Nb film with thickness of 1.1 μm covered by a Pd layer with thickness of 20 nm



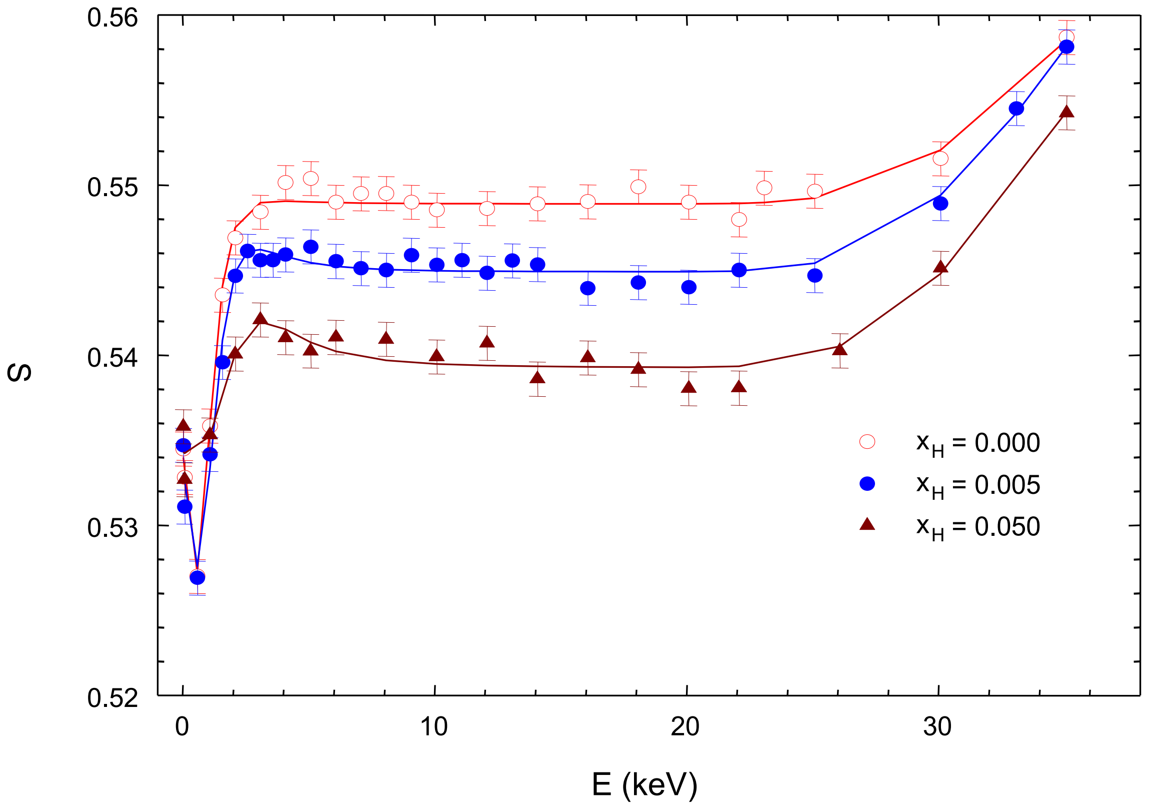
Thin Nb films doped by hydrogen

Nb film with thickness of 1.1 μm covered by a Pd layer with thickness of 20 nm



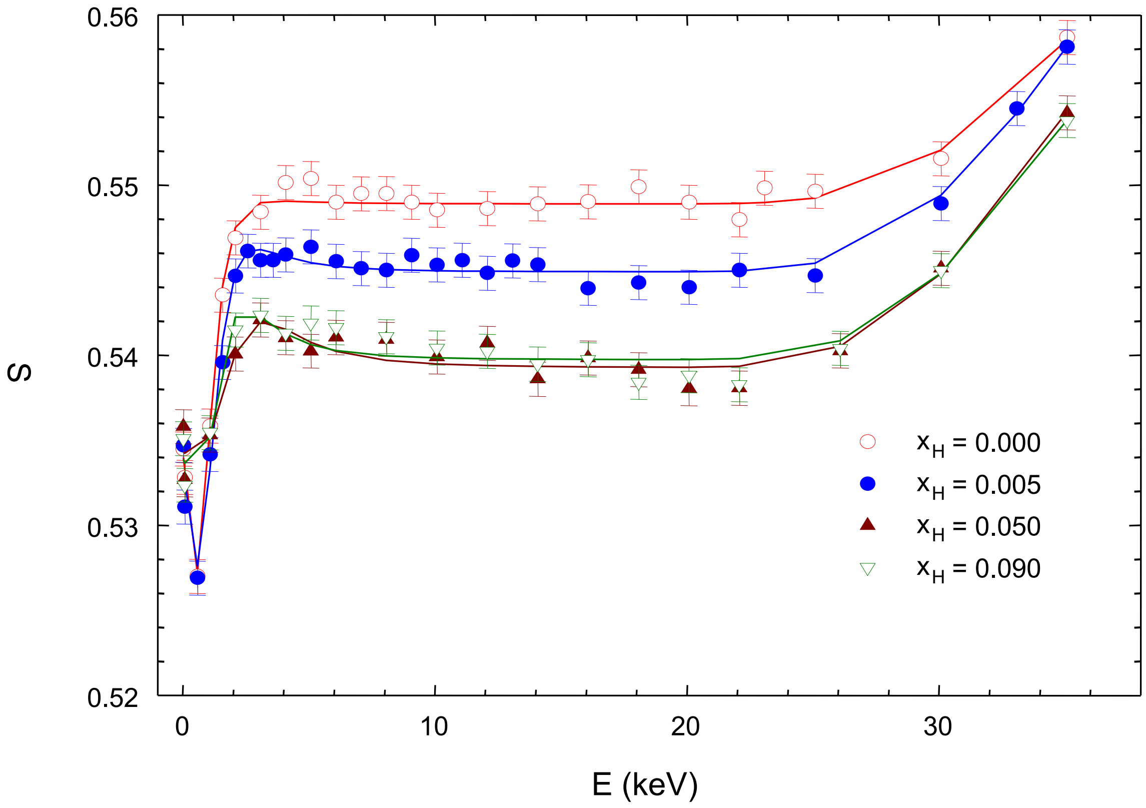
Thin Nb films doped by hydrogen

Nb film with thickness of 1.1 μm covered by a Pd layer with thickness of 20 nm



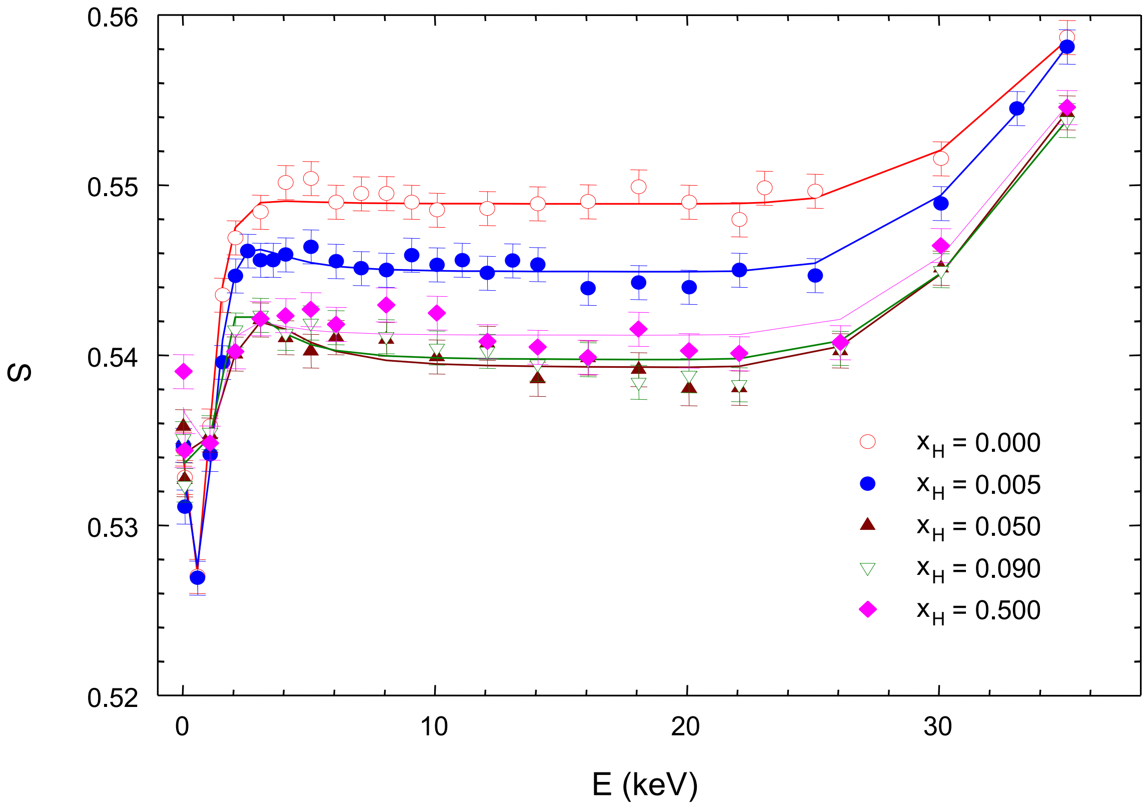
Thin Nb films doped by hydrogen

Nb film with thickness of 1.1 μm covered by a Pd layer with thickness of 20 nm



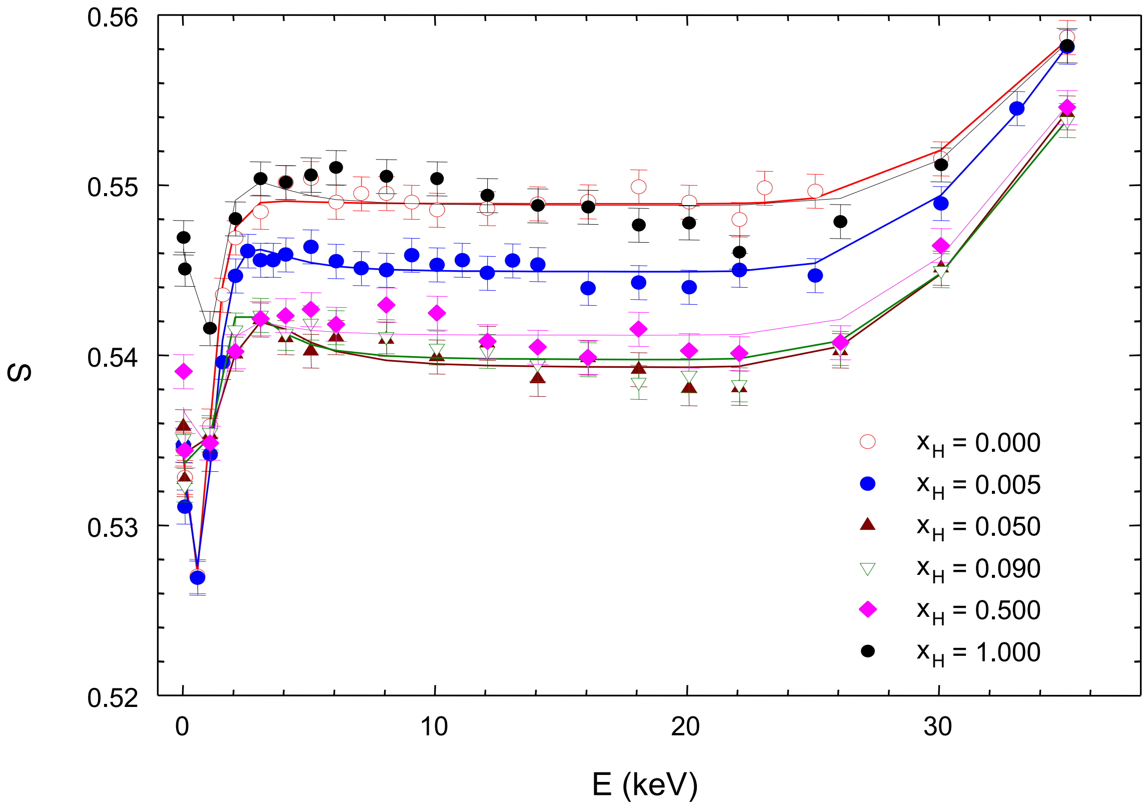
Thin Nb films doped by hydrogen

Nb film with thickness of 1.1 μm covered by a Pd layer with thickness of 20 nm



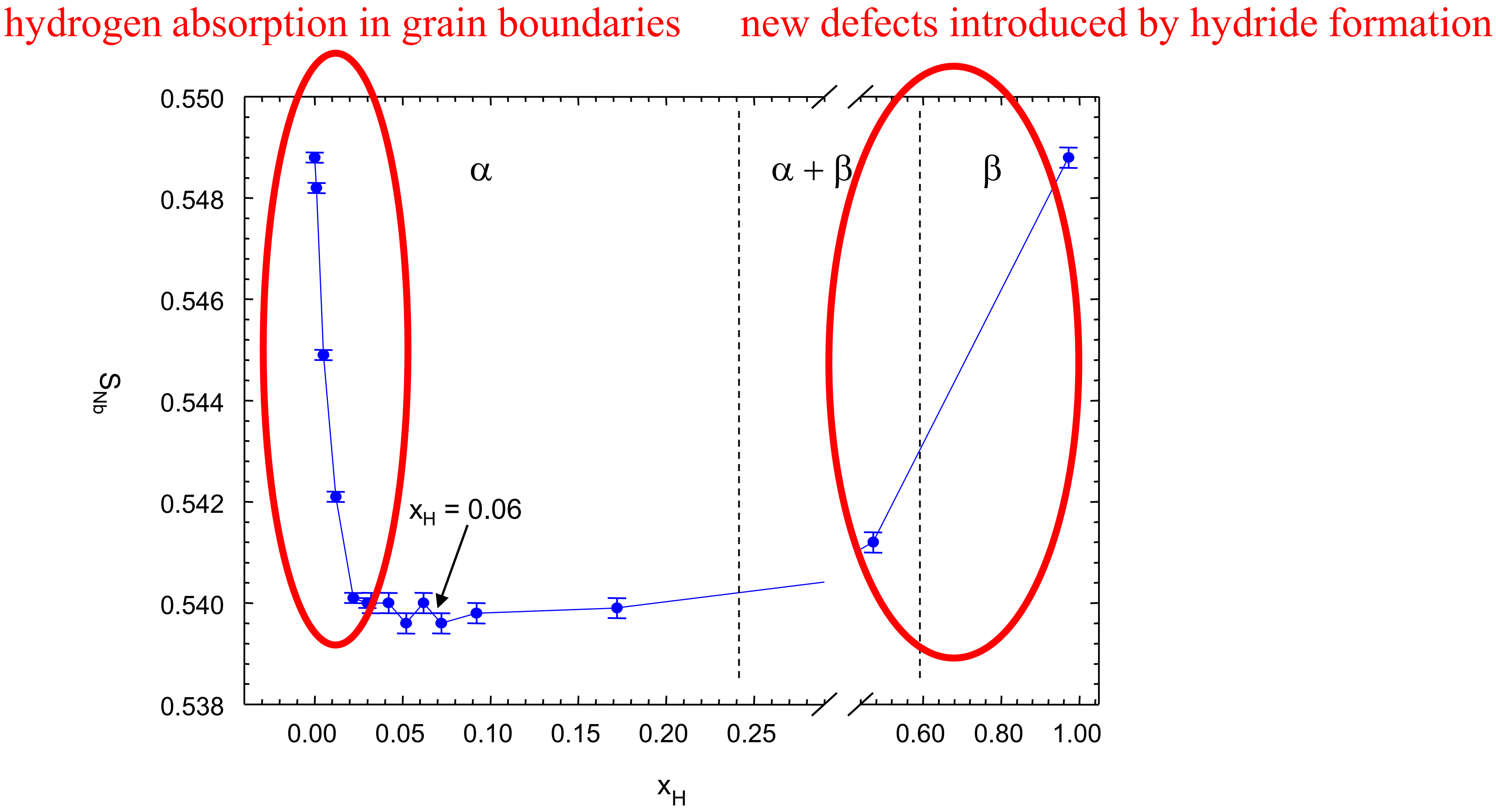
Thin Nb films doped by hydrogen

Nb film with thickness of 1.1 μm covered by a Pd layer with thickness of 20 nm



Thin Nb films doped by hydrogen

Nb film with thickness of 1.1 µm covered by a Pd layer with thickness of 20 nm



Measurement of positron back-diffusion

- measurement of positron diffusion length L_+
- presence of defects → shortening of L_+
- defect concentration: $$c_V = \frac{1}{\nu\tau_B}\left(\frac{L_{+,B}^2}{L_+^2} - 1\right)$$

$L_{+,B}$ – positron diffusion length in defect-free sample $L_{B,+} = \sqrt{D_+\tau_B}$

ν – specific positron trapping rate

Measurement of positron back-diffusion

- **example: vacancies in FeAl alloys**

$$c_V = \frac{1}{\nu_V}\frac{I_2}{I_1}\left(\frac{1}{\tau_B}-\frac{1}{\tau_V}\right)$$

- measurement of positron lifetime
- free positron component cannot be resolved in positron lifetime spectra when its intensity $I_1 < 5\%$ (saturated positron trapping)
- it corresponds to vacancy concentration $c_V > 2 \times 10^{-4}$

$$c_V = \frac{1}{\nu_V \tau_B}\left(\frac{L_{+,B}^2}{L_+^2}-1\right)$$

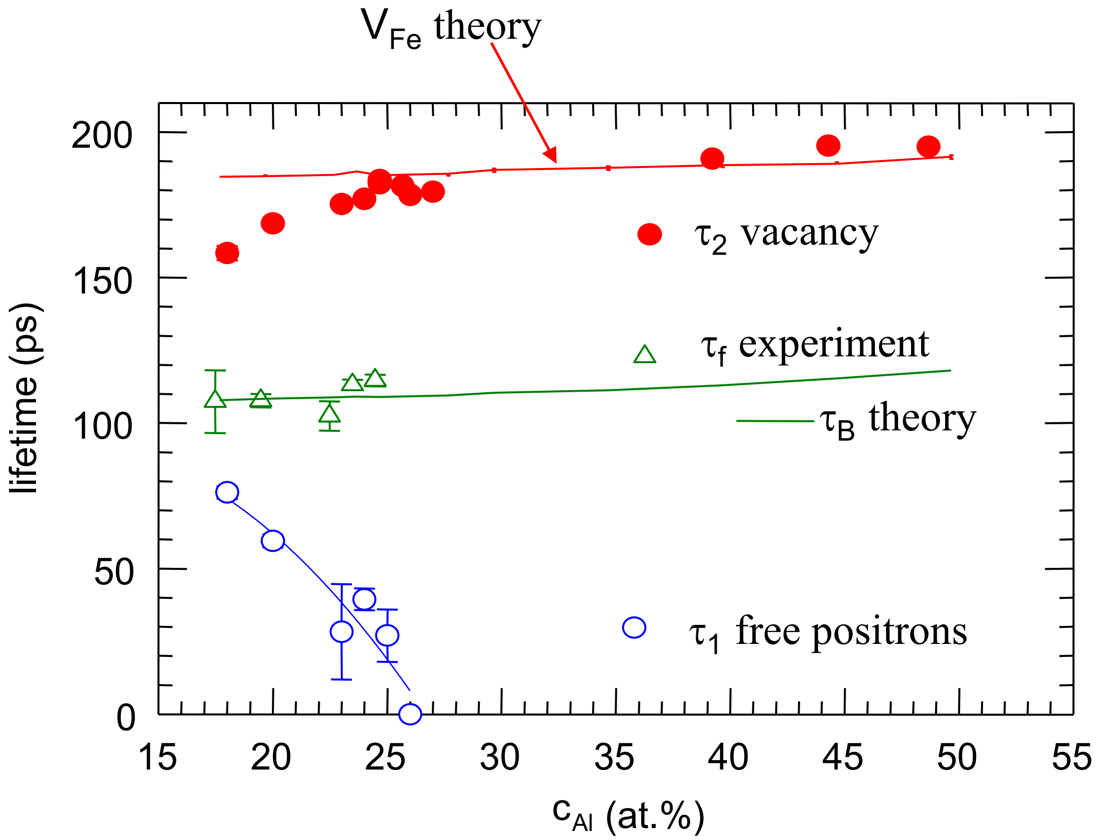
- measurement of positron back-diffusion
- positron diffusion length can be determined when $L_+ < 1$ nm
- it corresponds to vacancy concentration $c_V > 7 \times 10^{-2}$

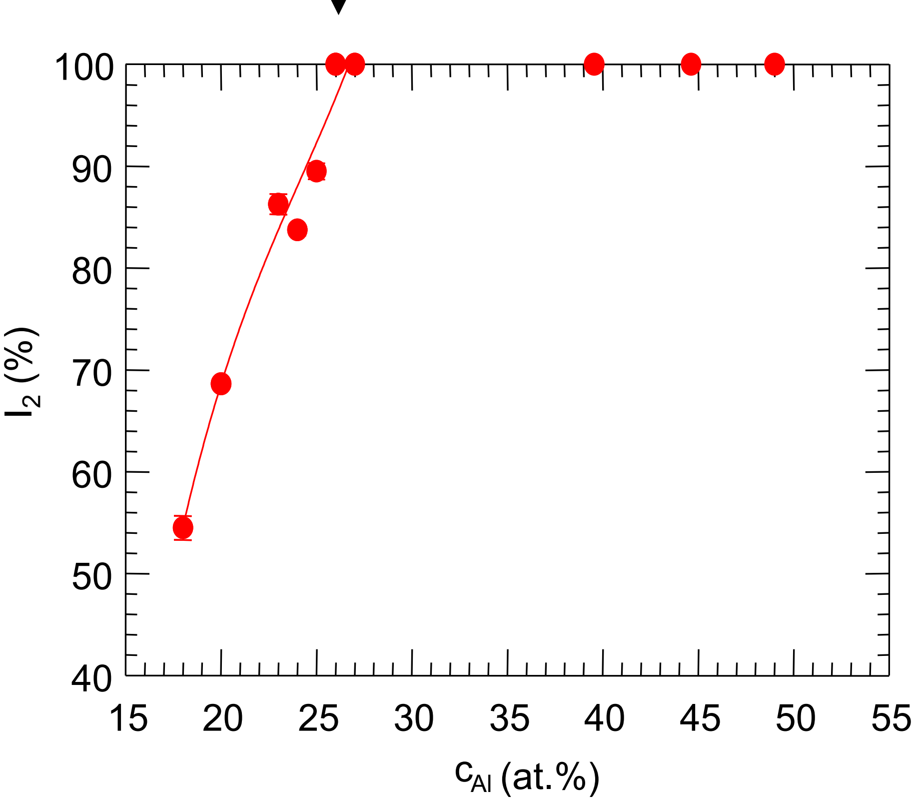
Quenched-in vacancies in Fe-Al alloys – positron lifetime spectroscopy

- two-component spectrum:
  τ_1 – free positrons
  τ_2 – positrons trapped in vacancies

$$\tau_f = \left(\frac{I_1}{\tau_1} + \frac{I_2}{\tau_2} \right)^{-1}$$

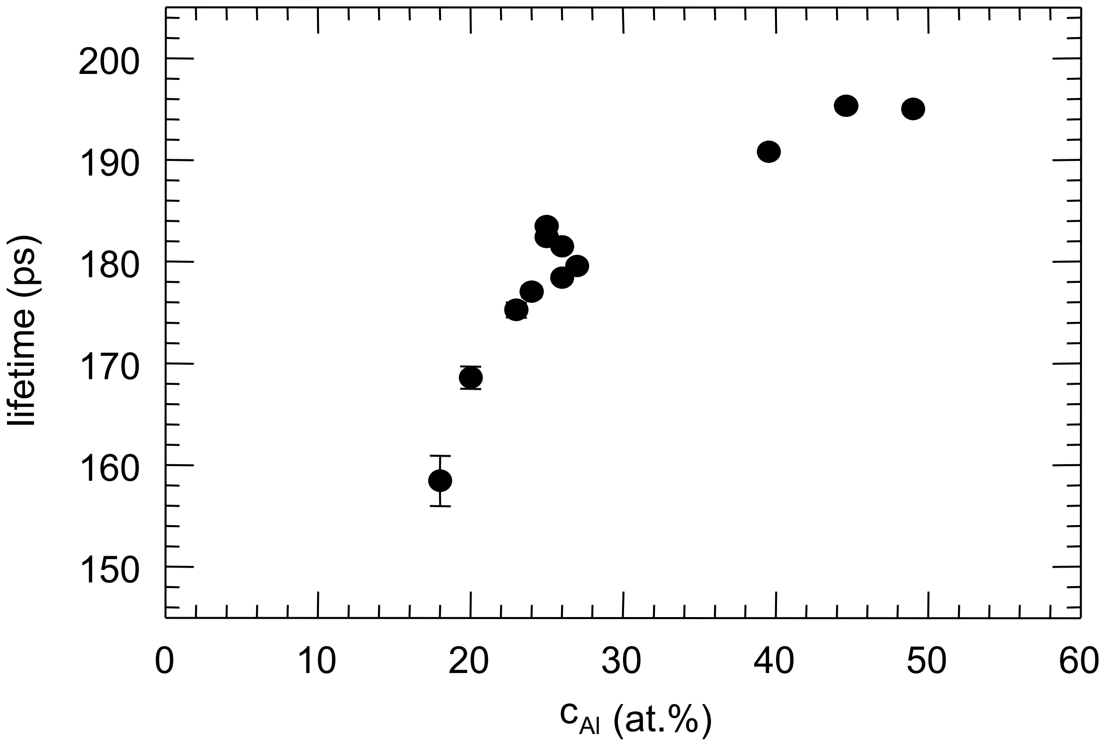
$c_{Al} \geq 26$ at.% → saturated trapping



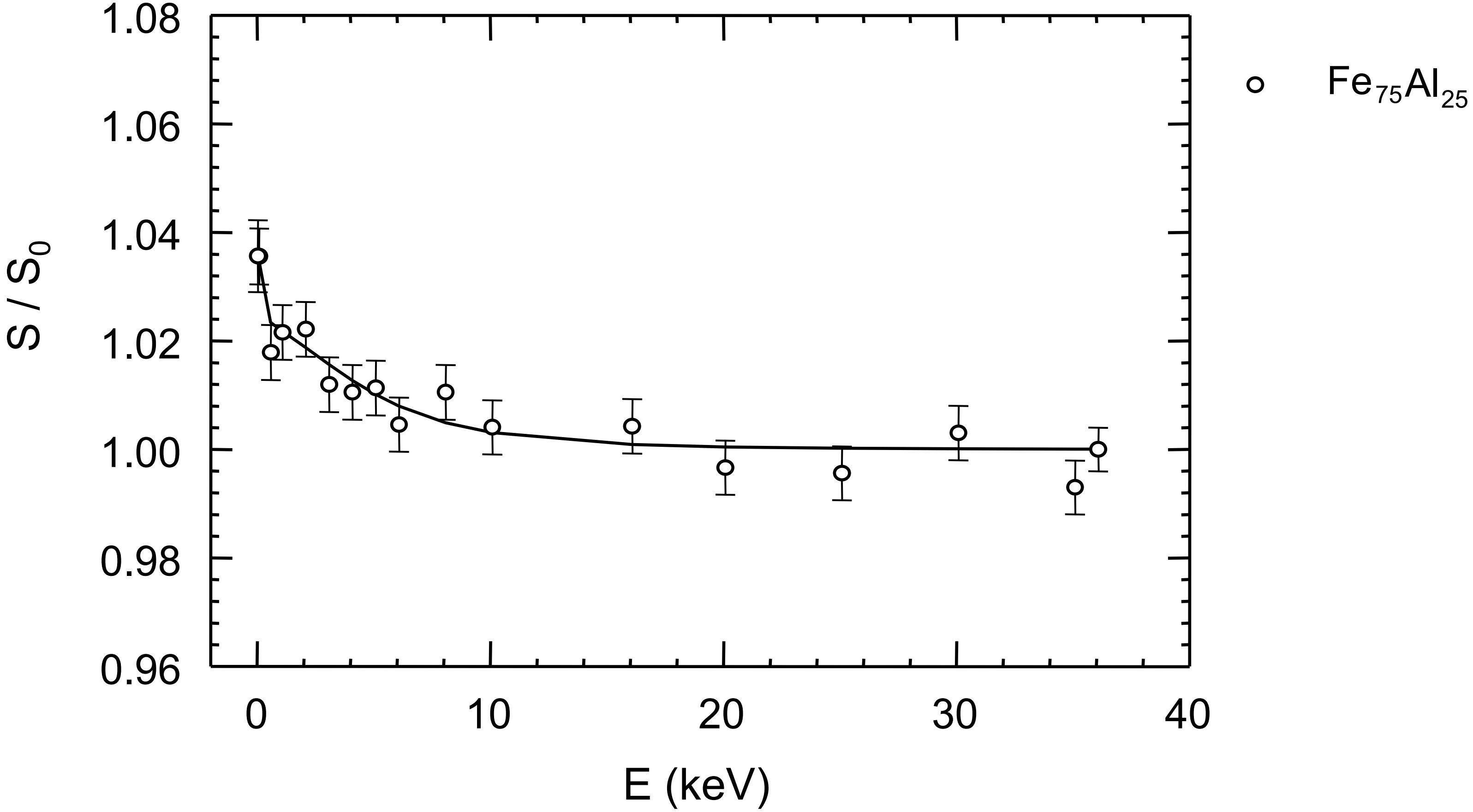


Quenched-in vacancies in Fe-Al alloys – positron lifetime spectroscopy

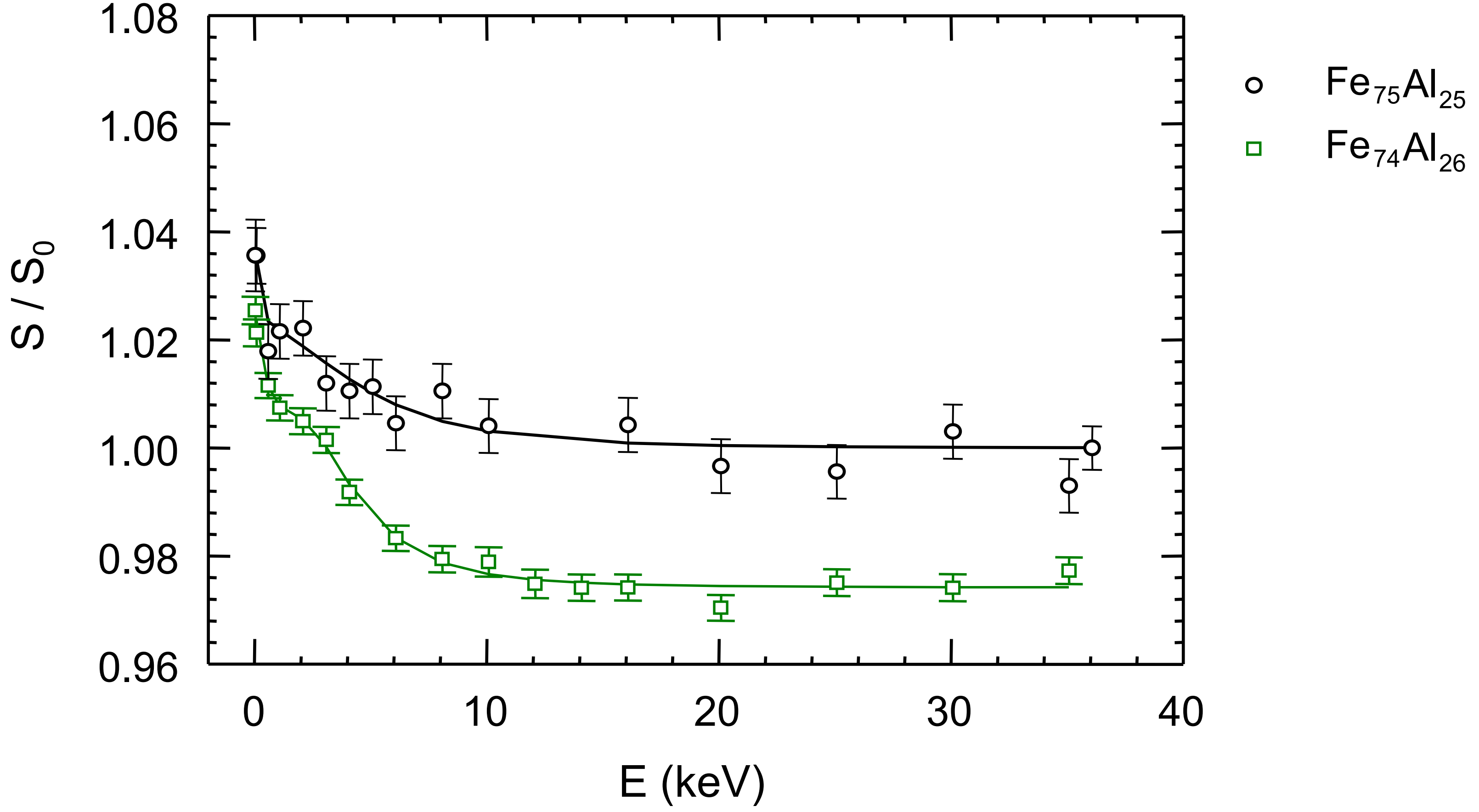
- lifetime τ_2 of positrons trapped in vacancies
- increasing concentration of Al ions around vacancies



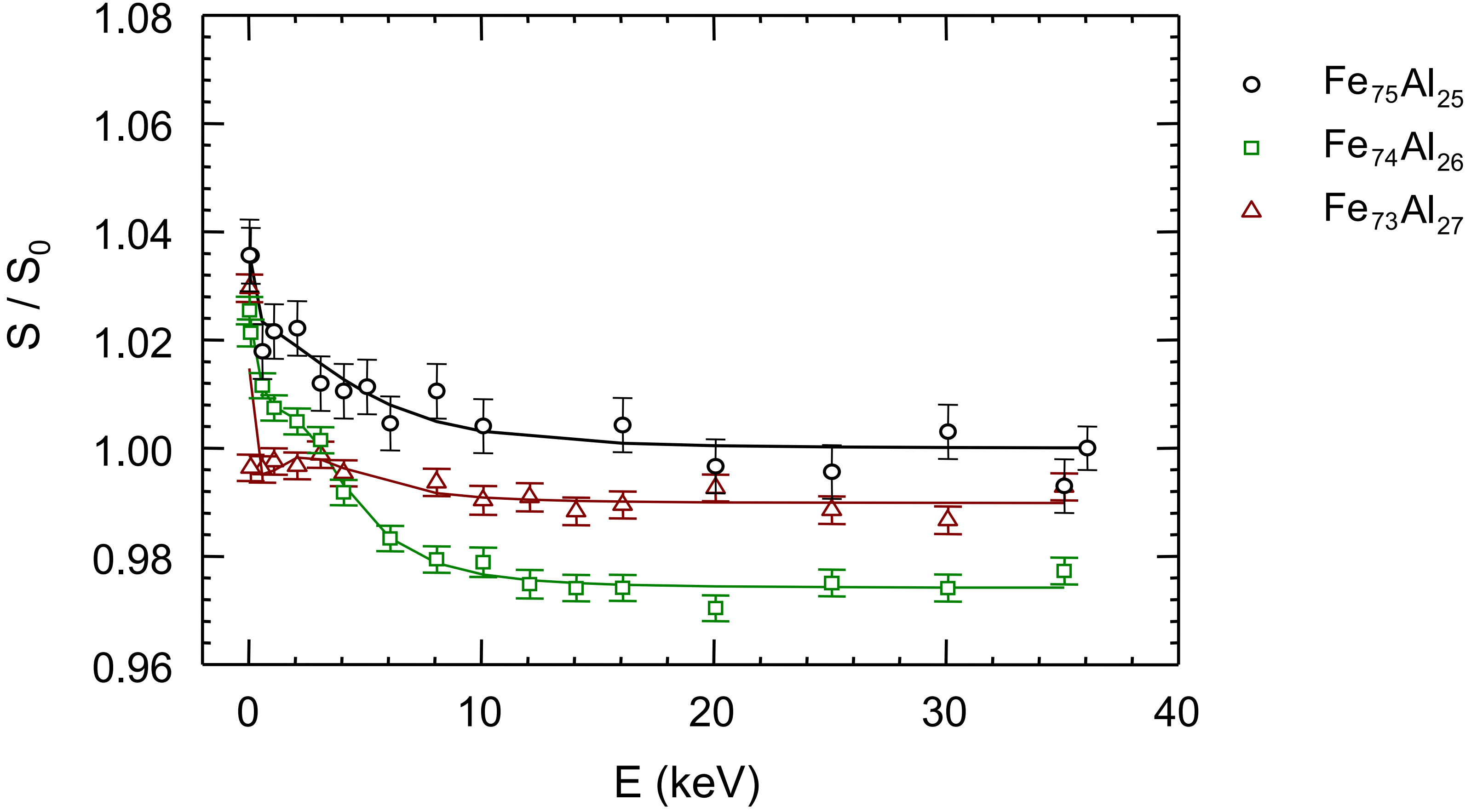
Quenched-in vacancies in Fe-Al alloys – positron back-diffusion



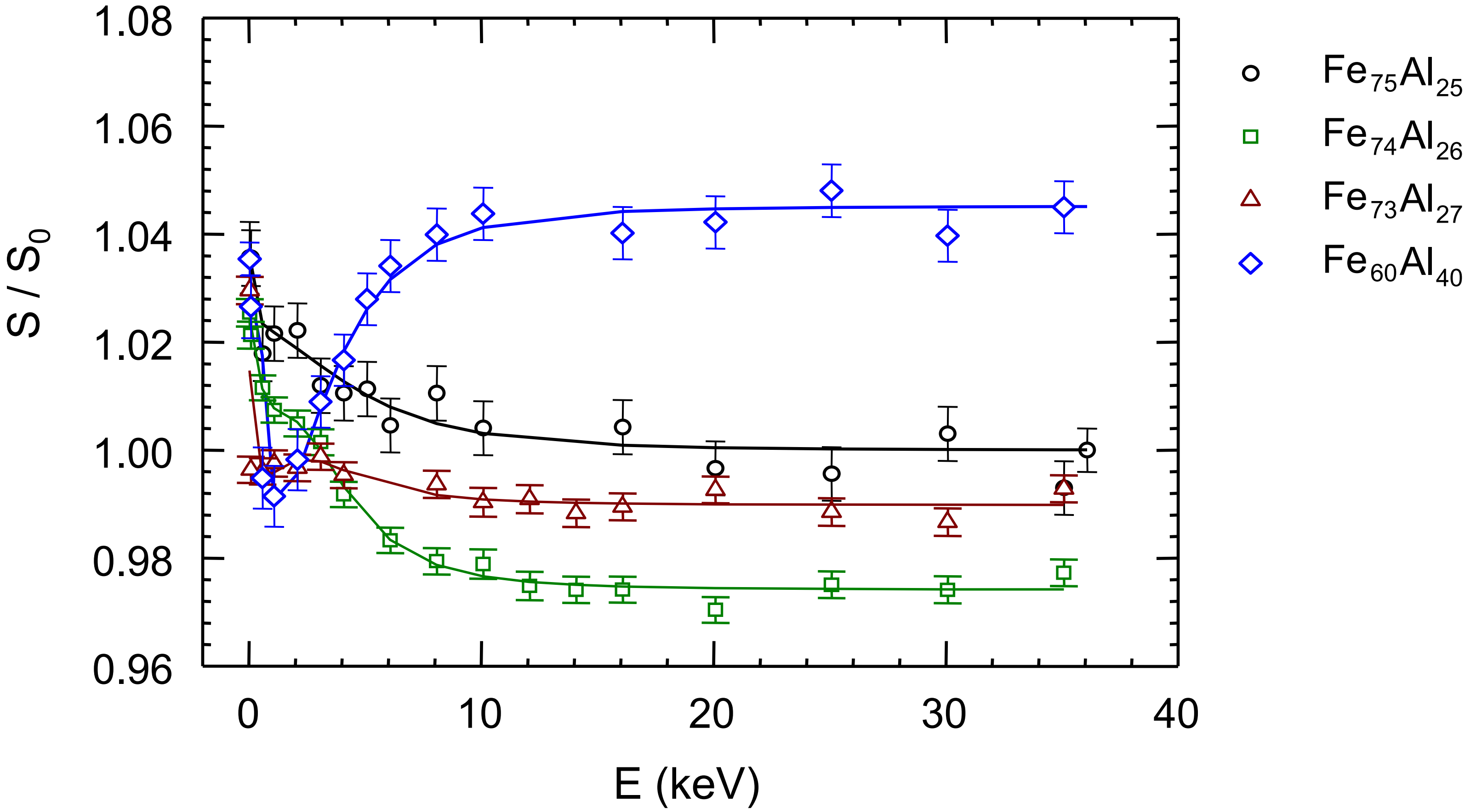
Quenched-in vacancies in Fe-Al alloys – positron back-diffusion



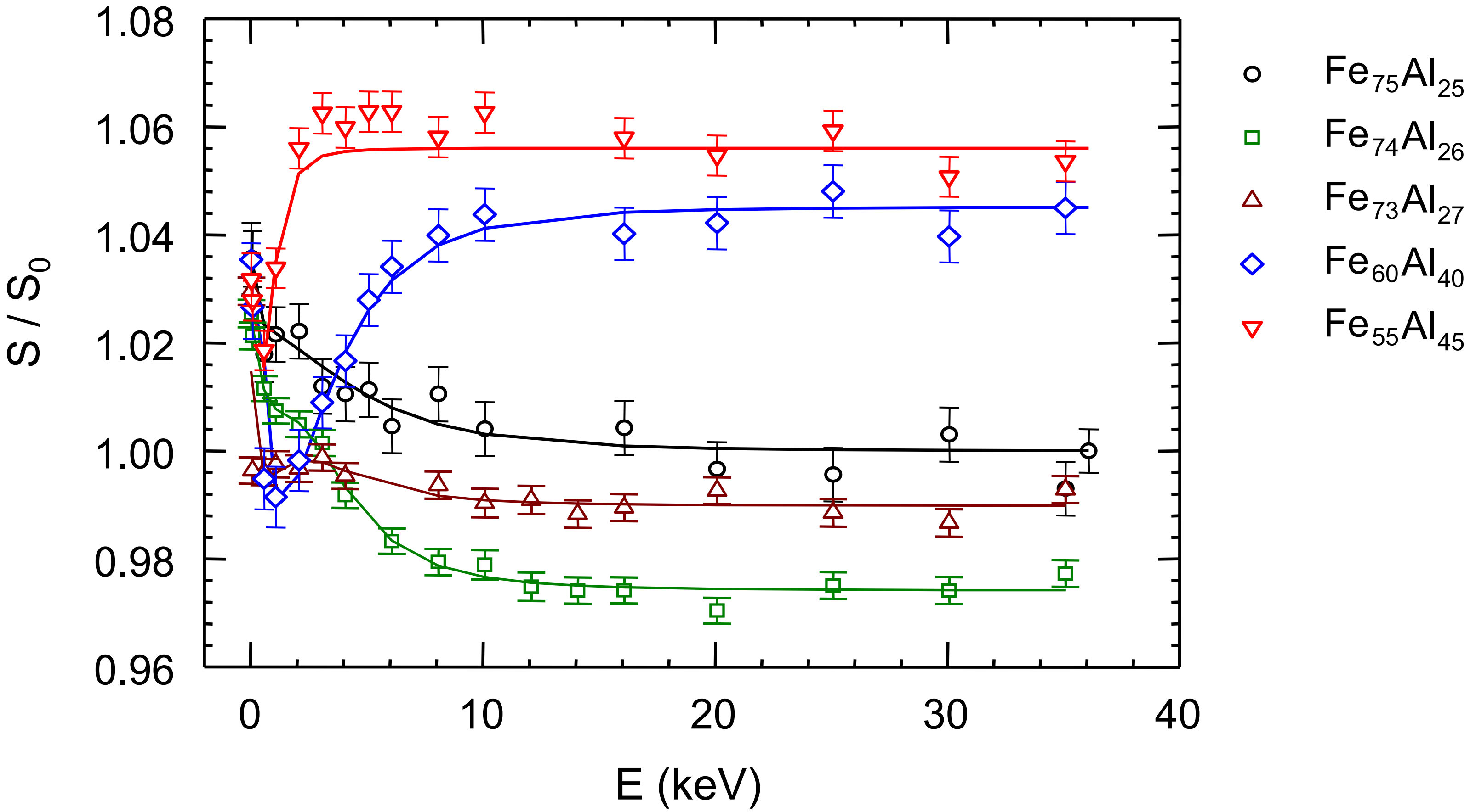
Quenched-in vacancies in Fe-Al alloys – positron back-diffusion



Quenched-in vacancies in Fe-Al alloys – positron back-diffusion

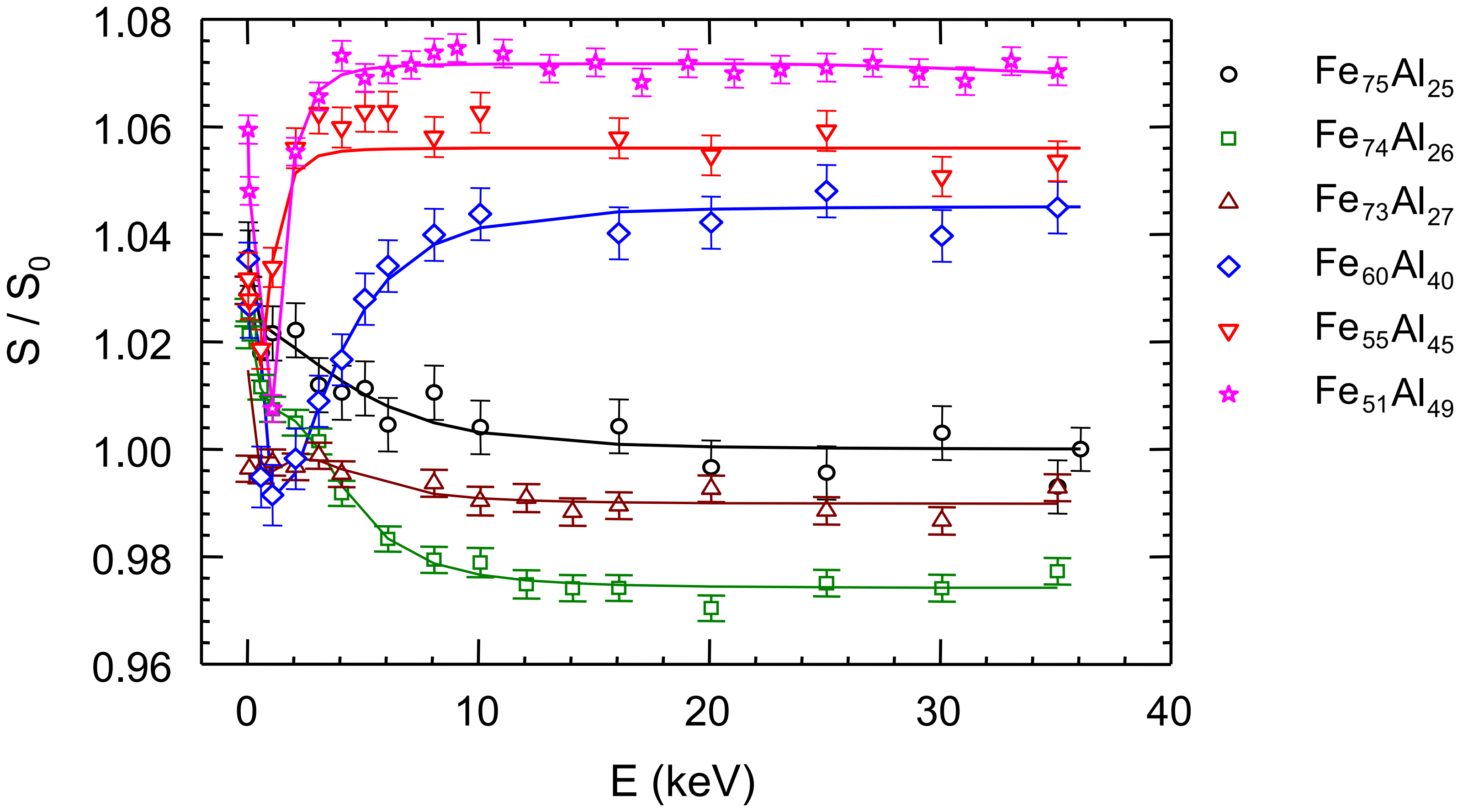


Quenched-in vacancies in Fe-Al alloys – positron back-diffusion



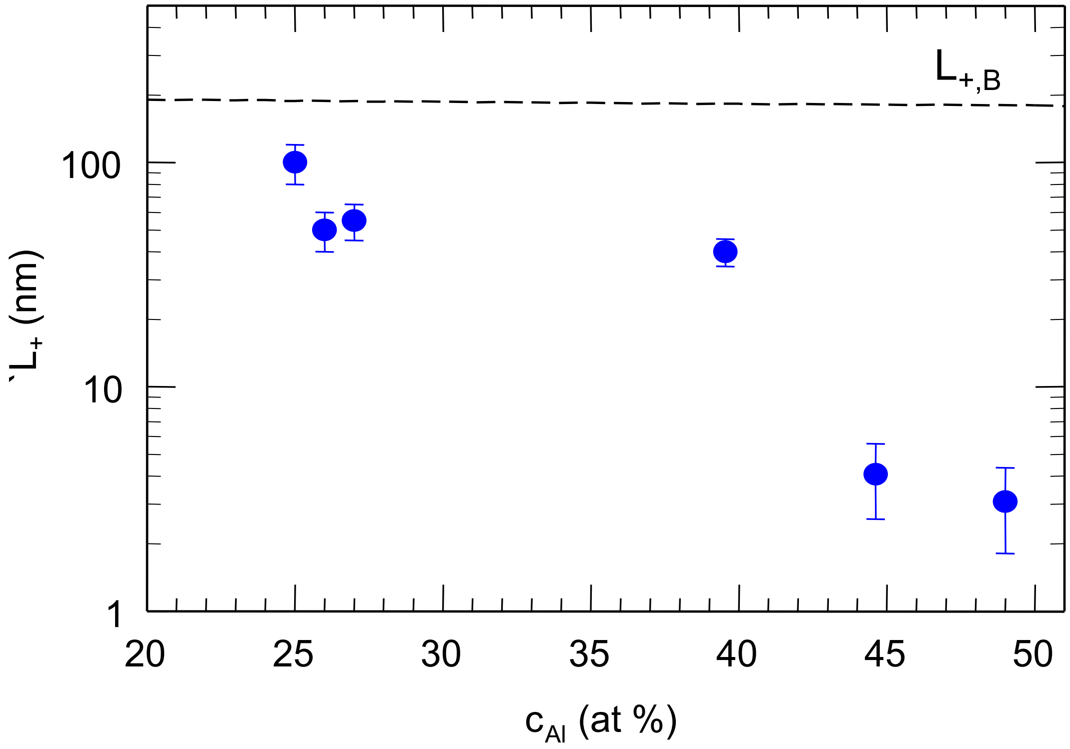
Quenched-in vacancies in Fe-Al alloys – positron back-diffusion

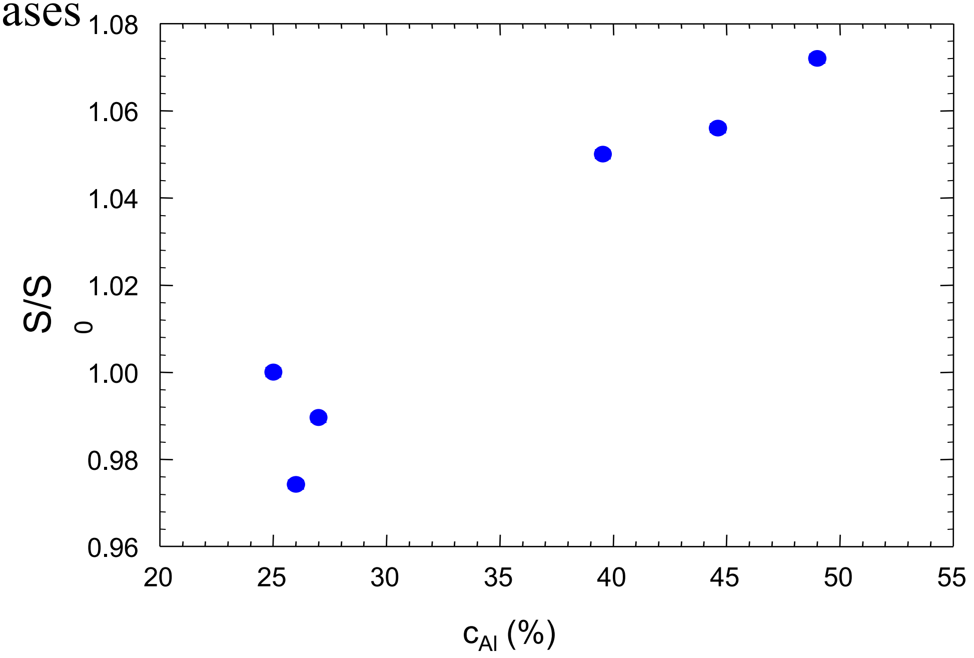
- two layers:
- (i) oxide on the surface 15-20 nm (ii) Fe-Al alloy



Quenched-in vacancies in Fe-Al alloys – positron back-diffusion

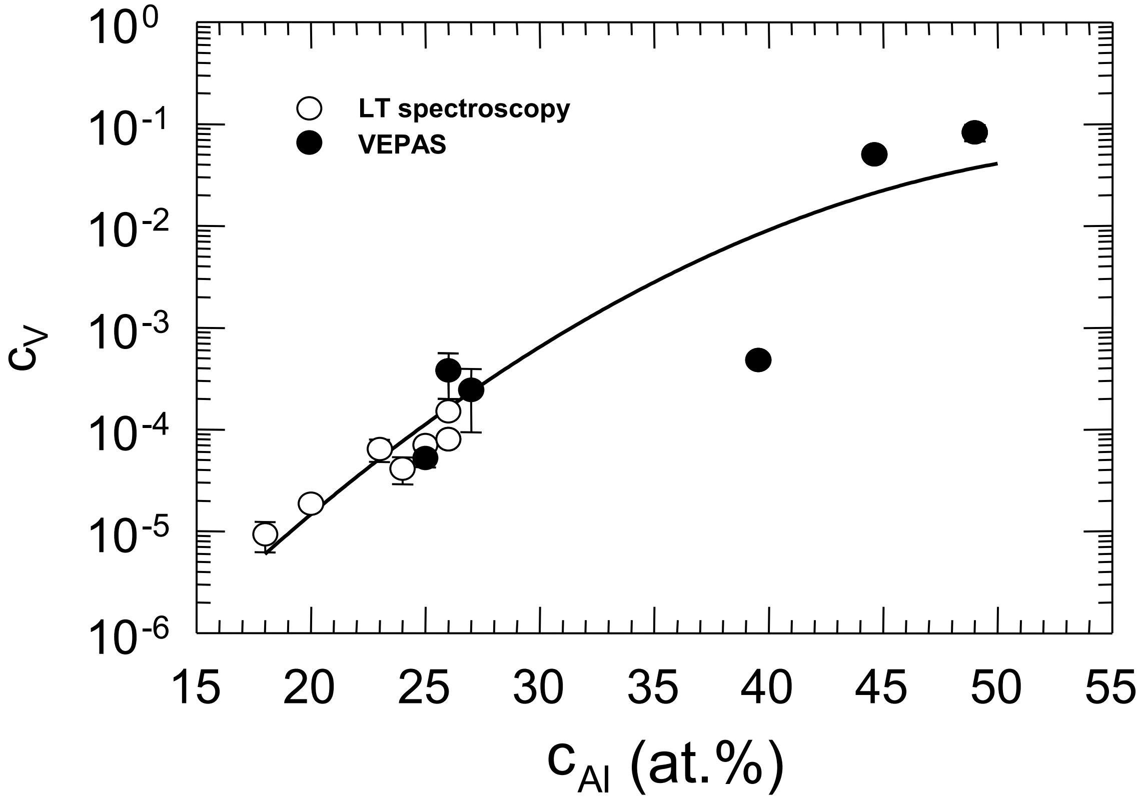
- with increasing Al content L_+ decreases and S increases
- vacancy concentration increases with Al content


positron diffusion length


S parameter

Quenched-in vacancies in Fe-Al alloys

- $Fe_{75}Al_{25}$: positron lifetime spectroscopy: $c_V = (7.0 \pm 0.5) \times 10^{-5}$
  positron back-diffusion : $c_V = (5 \pm 1) \times 10^{-5}$



Quenched-in vacancies in Fe-Al alloys