Muon beams – a possible added benefit at an accelerator driven neutron source

IAEA School on Pulsed Neutron Sources:

Enhancing the Capacity for Materials Science

ICTP Trieste 2005

Kurt N Clausen
Condensed Matter Research with Neutrons and Muons
Paul Scherrer Institut
Switzerland

Acknowledgement

Thanks to:

H. Luetkens, A Amato, E Morenzoni, D Herlach

Labor für Myonenspinspektroskopie, Paul Scherrer Institut, PSI, Switzerland

This presentation is based on material provided by them

The Muon: A Very Sensitive, Local Magnetic Probe

Properties: $m_\mu \sim m_p/9$, $\gamma_\mu = 8.5161 \times 10^8$ rad s^{-1} T^{-1} (~ 3 μ_p,) $\tau_\mu = 2.197 \mu s$

Applications :

- Direct measurement of local magnetic fields: ~5 µT ... >5 T
- Static and dynamic magnetic properties of condensed matter
- Time scales: <ns ... ms
- Muonium as „light hydrogen" atom: H in materials, radicals, ...

Unique at PSI :

- Low energy muons (tunable energy 0.5 ... 30 keV)

    ☞ Near surface, depth dependent measurements on a nm scale

    ☞ Properties of thin films, multilayers, interfaces, ...

→ 100 % polarised
positive Myon

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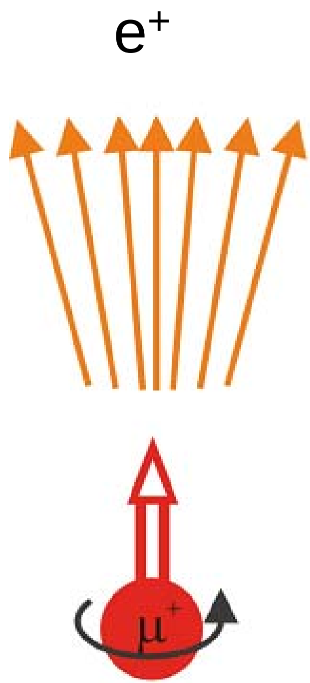
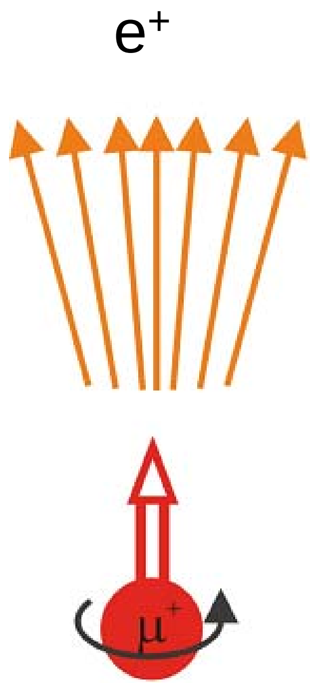
→ 100 % polarised positive Myon



Decays – after 2.2 μs with emission of positron along spin direction

→ 100 % polarised positive Myon



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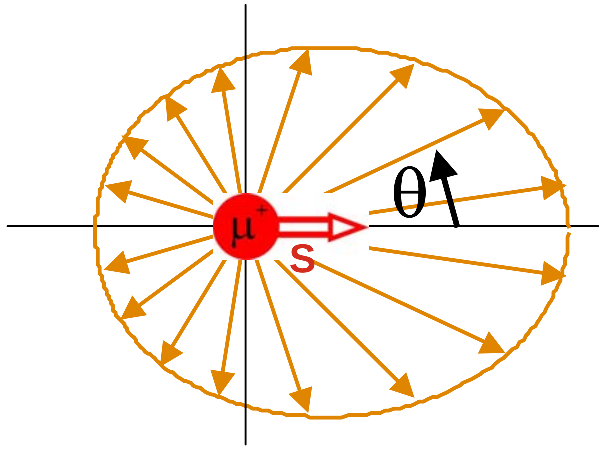

$$W(\theta) \propto \left(1 + \frac{1}{3} P \cdot \cos\theta\right)$$

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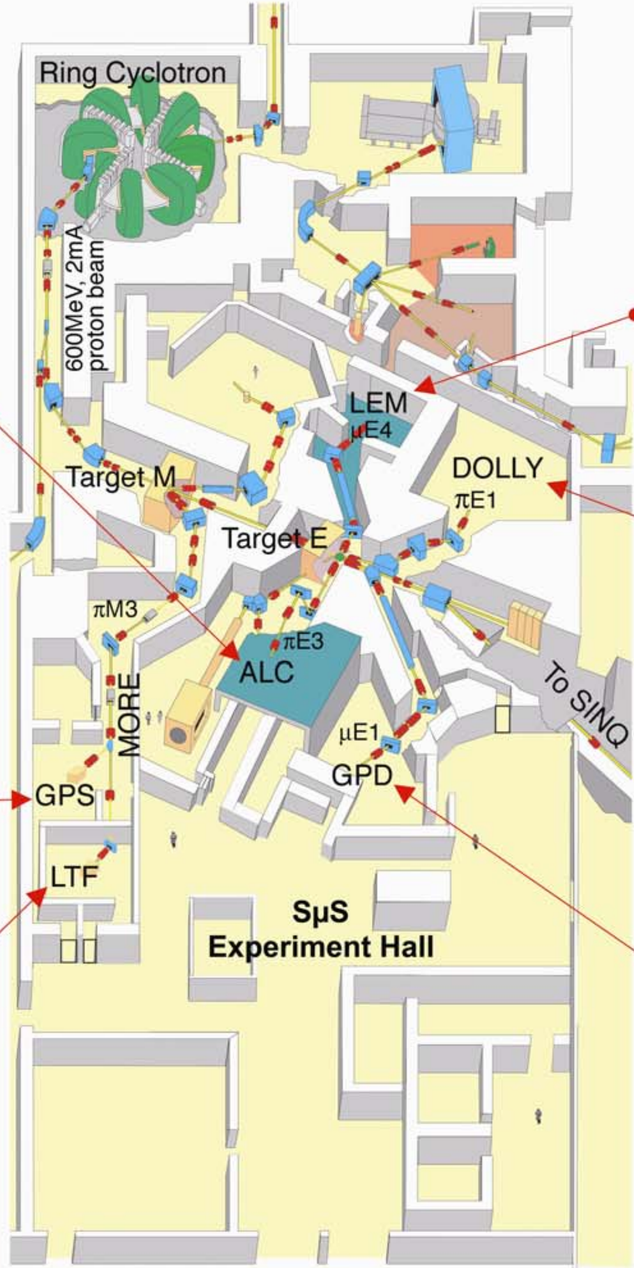
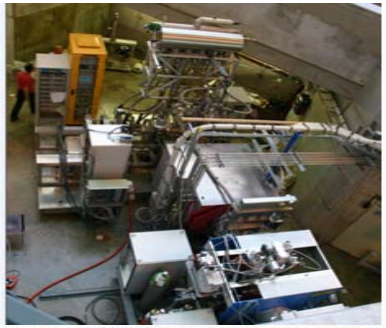
Swiss Muon Source SμS

ALC
Avoided Level Crossing Resonance Instrument
Muon energy: 4.2 MeV (μ^+)
Temperatures: 4.2 - 600 K
Magnetic Fields: 0 - 5 T

Contact: *A. Stoikov*
alexei.stoikov@psi.ch





LEM
Low Energy Muon Beam and Instrument
Tunable muon energy: 0.5 - 30 keV (μ^+)
Temperatures: 2.5 - 700 K
Magnetic fields: 0 - 0.1 T perpendicular,
0 - 0.03 T parallel to sample surface

Contact: *E. Morenzoni*
elvezio.morenzoni@psi.ch

GPS
General Purpose Surface Muon Instrument
Muon energy: 4.2 MeV (μ^+)
Temperatures: 1.8 - 900 K
Magnetic Fields: 0 - 0.6 T
Muons on Request (MORE)

Contact: *A. Amato*
alex.amato@psi.ch

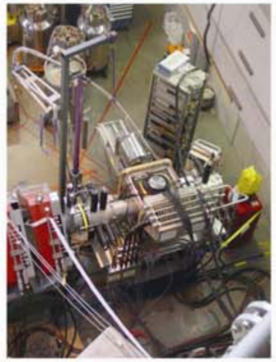
Shared Beam Surface Muon Facility

LTF
Low Temperature Facility
Muon energy: 4.2 MeV (μ^+)
Temperatures: 10 mK - 4.2 K
Magnetic fields: 0 - 3 T
Muons on Request (MORE)

Contact: *C. Baines*
chris.baines@psi.ch

DOLLY
General Purpose Surface Muon Instrument
Muon energy: 4.2 MeV (μ^+)
Temperatures: 1.8 - 900 K
Magnetic fields: 0 - 0.5 T

Contact: *R. Scheuermann*
robert.scheuermann@psi.ch

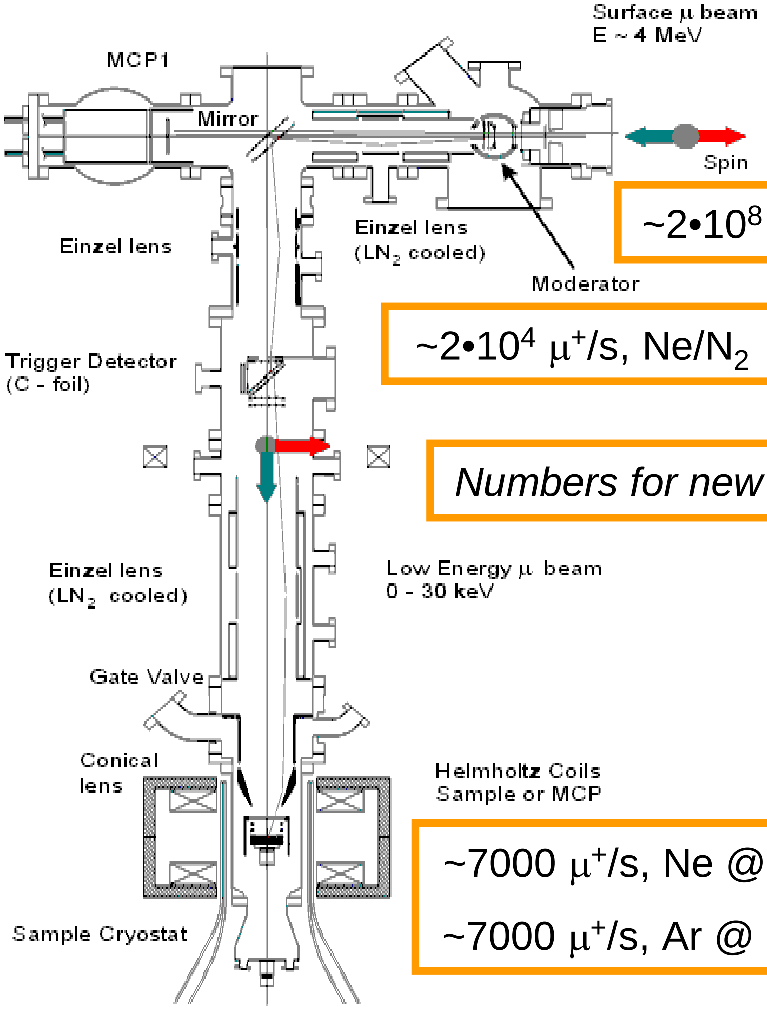


GPD
General Purpose Decay Channel Instrument
Muon energy: 5 - 60 MeV
(μ^+ or μ^-)
Temperatures: 2 - 500 K
Magnetic Fields: 0 - 0.5 T

Contact: *U.Zimmermann*
ulrich.zimmermann@psi.ch

Material provided by H. Luetkens, A Amato, E Morenzoni, D Herlach

Low Energy Muon Beam and Instrument – LEM



~2•10^8 μ$^+$/s

~2•10^4 μ$^+$/s, Ne/N$_2$

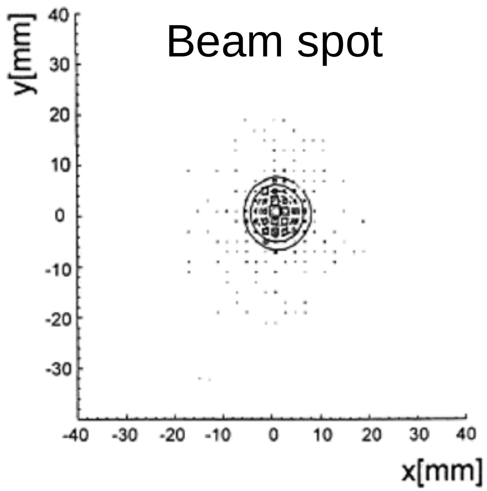
Numbers for new μE4

~7000 μ$^+$/s, Ne @ 12 kV

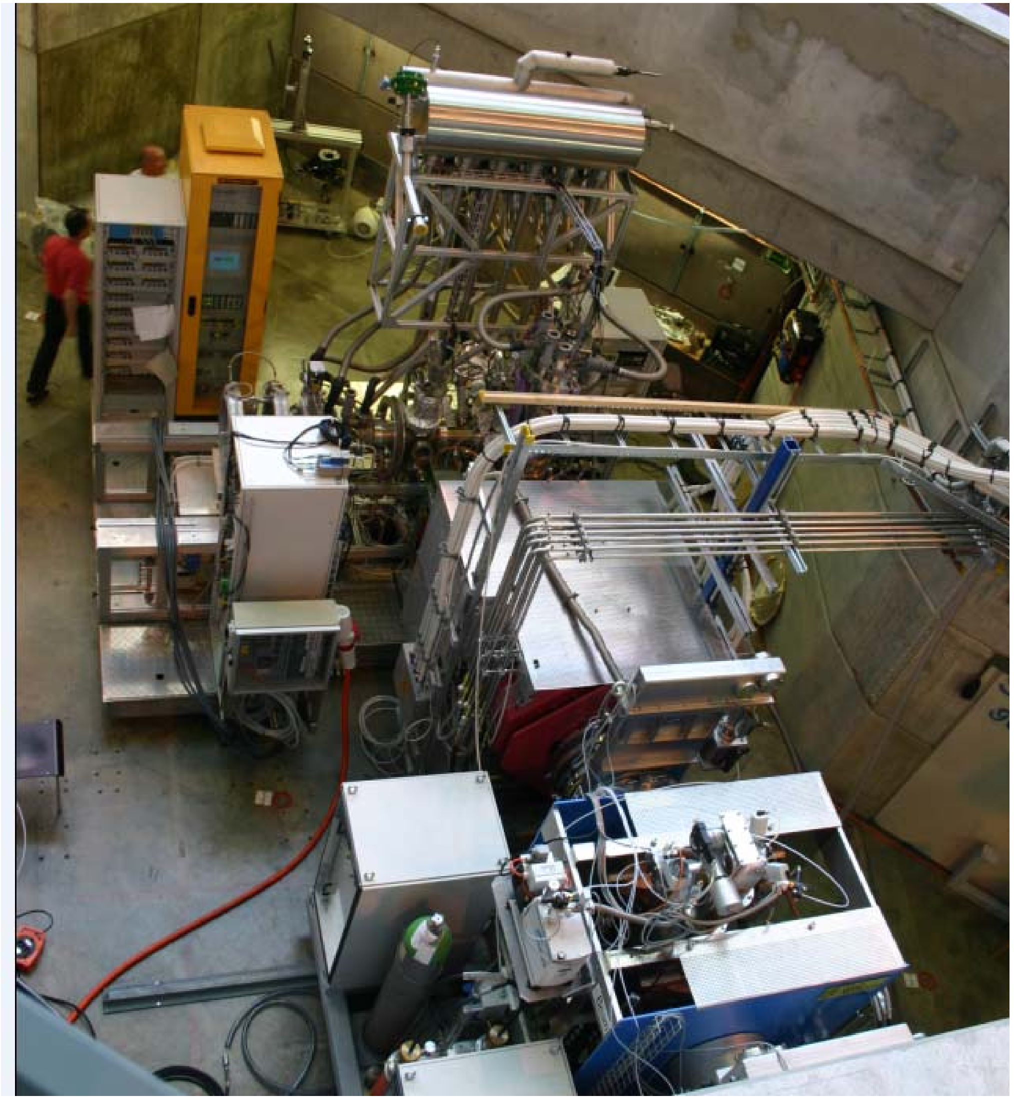
~7000 μ$^+$/s, Ar @ 20 kV

Worldwide unique:

- Polarized Low Energy μ$^+$ Beam
  ~ 0.5 - 30 keV (uncertainty 400 eV)
- Tunable implantation depth
  ~ 1 – 200 nm



Low Energy Muon Beam and Instrument – LEM



Layout of new µE4 beam
Commissioning 2005

New LEM Instrument

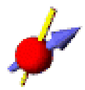
Material provided by H. Luetkens, A Amato, E Morenzoni, D Herlach

Prinzip eines μSR Experiments

Masse:	$m_\mu \approx 207\ m_e \approx 1/9\ m_p$
Magnetisches Moment:	$\mu_\mu \approx 3\ \mu_p$
Ladung:	$+e$
Lebensdauer:	$t_\mu \approx 2.2\ \mu s$
Polarisation:	100 %

Prinzip eines μSR Experiments

Myon



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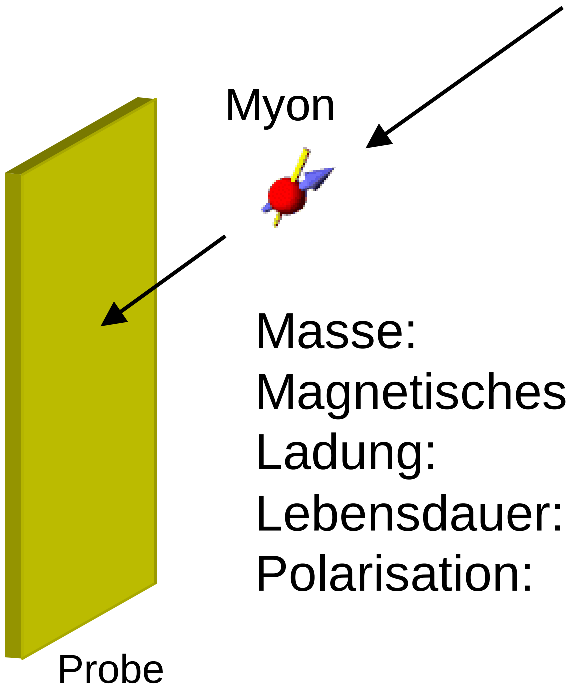
Polarisation:	100 %

Prinzip eines μSR Experiments

Implantation des Myons in die Probe



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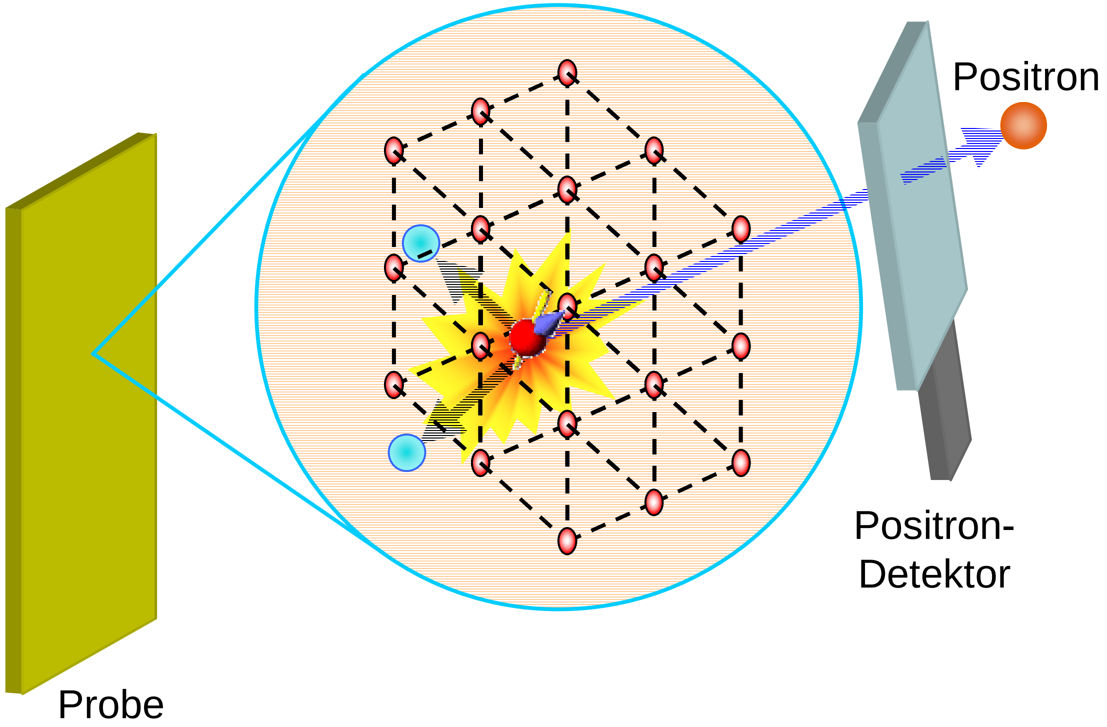
Ladung:	$+e$
Lebensdauer:	$t_\mu \approx 2.2\ \mu s$
Polarisation:	100 %

Prinzip eines μSR Experiments

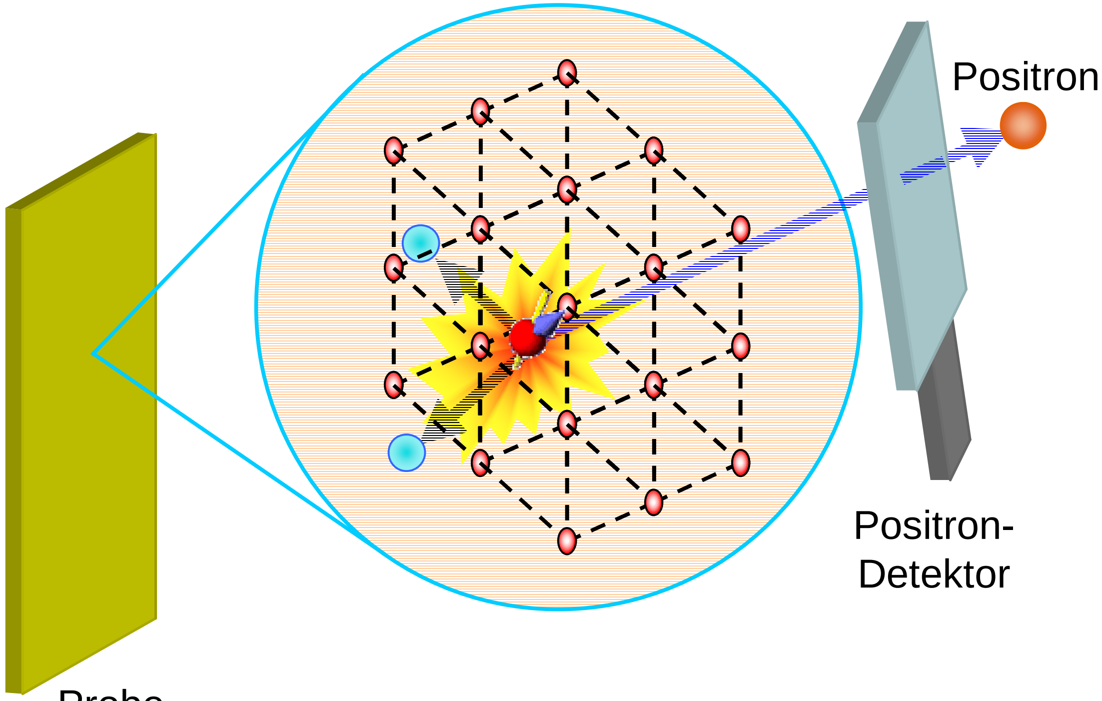
Wechselwirkung des Myonspins mit der Umgebung



2 μs

Prinzip eines μSR Experiments

Anisotroper Myonenzerfall in Richtung des Myonenspins



2 μs

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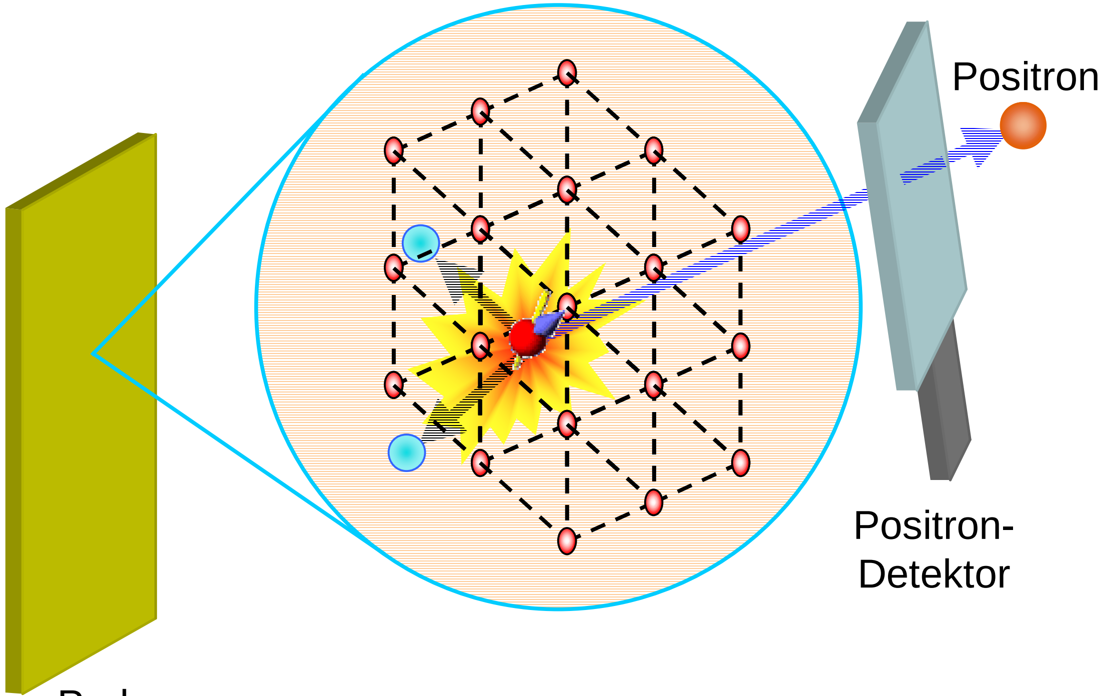
Prinzip eines μSR Experiments

Nachweis des Zerfallspositrons



2 μs

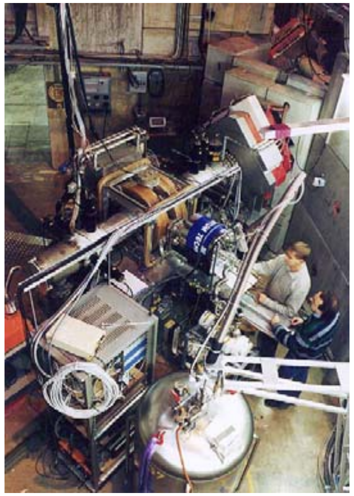
Anwendung 1: Magnetismus

Streumethoden:

(Neutronen, Röntgen)

Lokale Sonden:

(μSR, NMR, …)



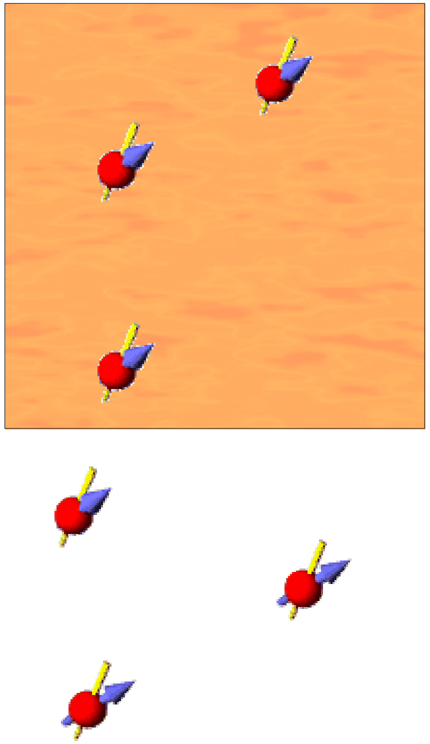
Eine Stärke der Myonen:

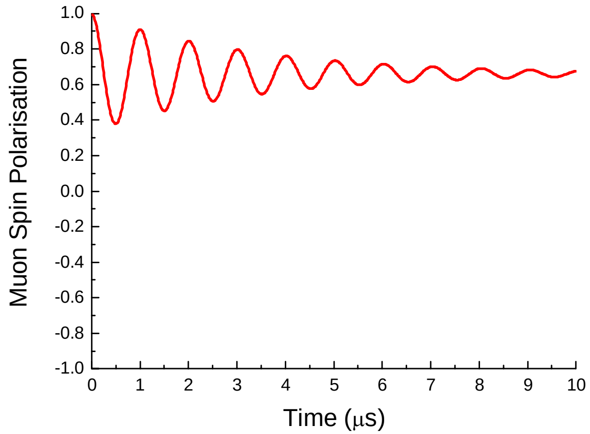
Untersuchung von magnetisch inhomogenen Materialien auf Grund von:

- Chemischer Inhomogenität (unsaubere Proben)
- Konkurrierenden Wechselwirkungen (interessant!)

Magnetisch Inhomogene Materialien

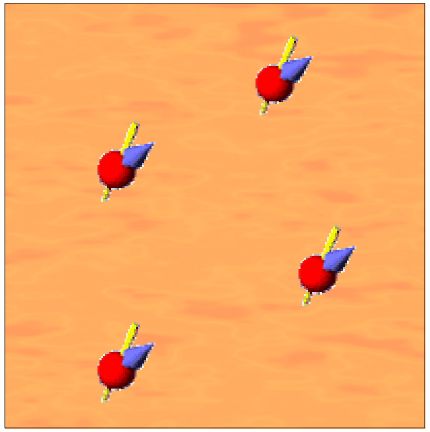
Homogen:

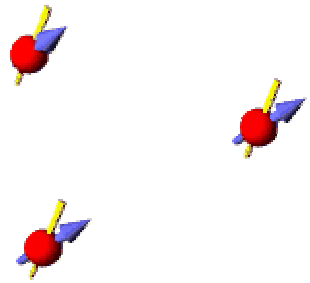


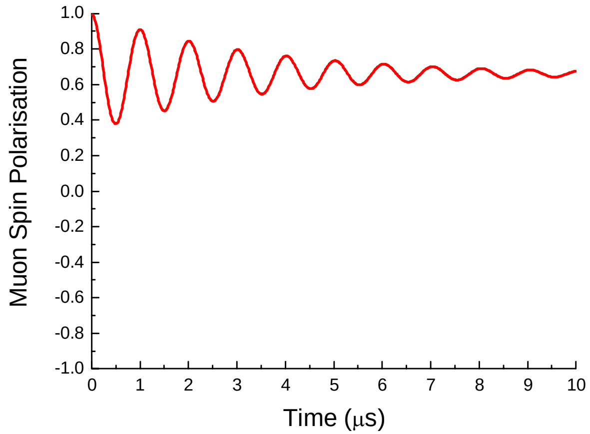


Magnetisch Inhomogene Materialien

Homogen:







Magnetisch Inhomogene Materialien

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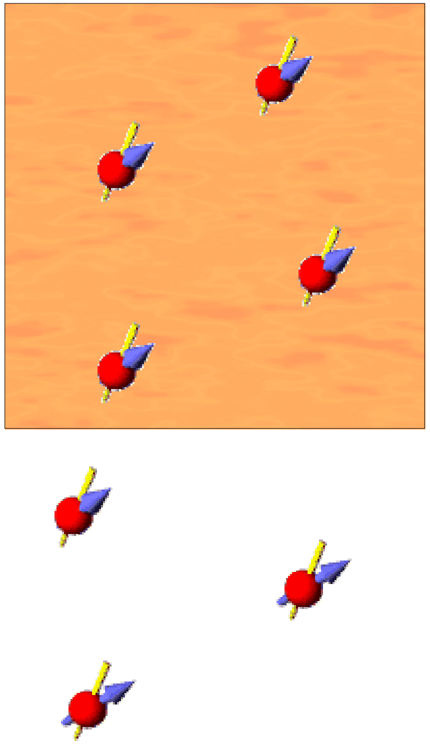

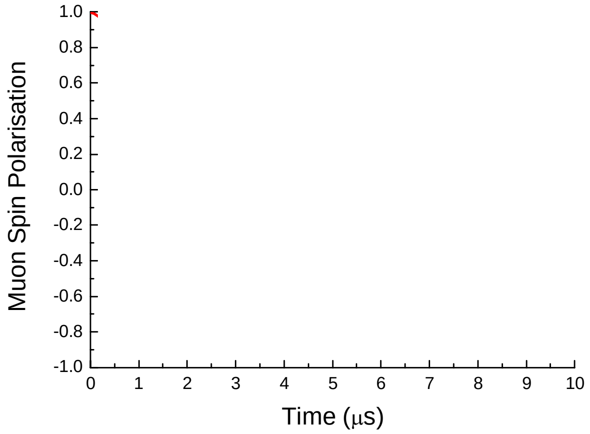

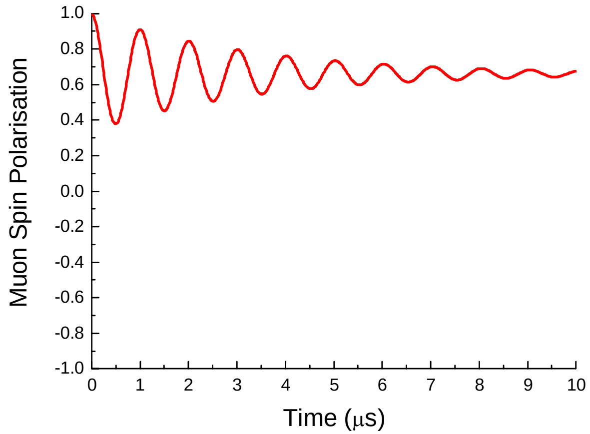

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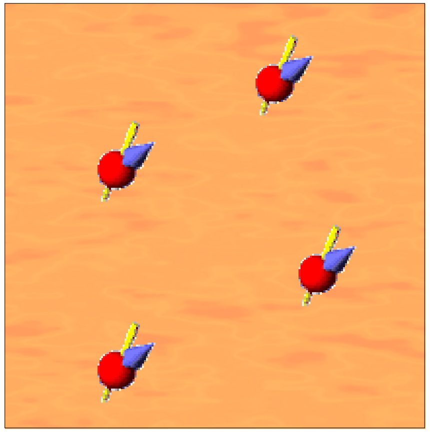
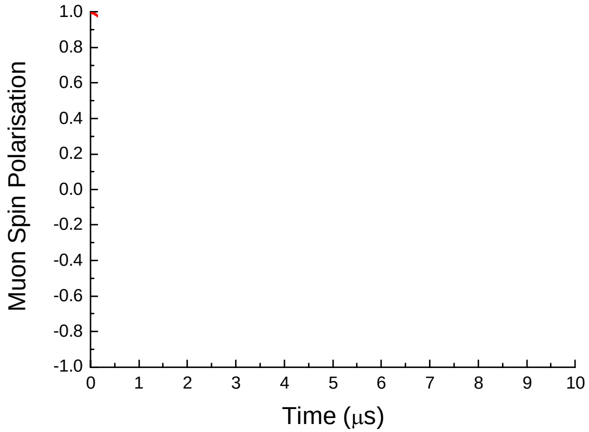
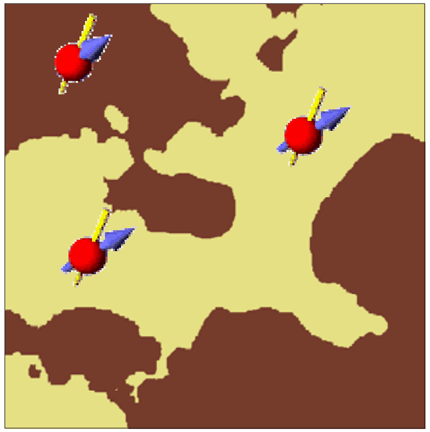
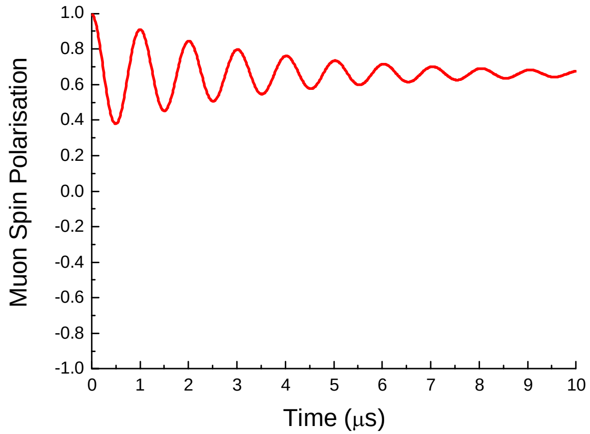




Inhomogen:





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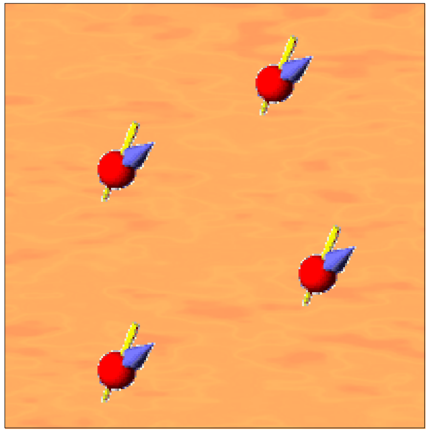

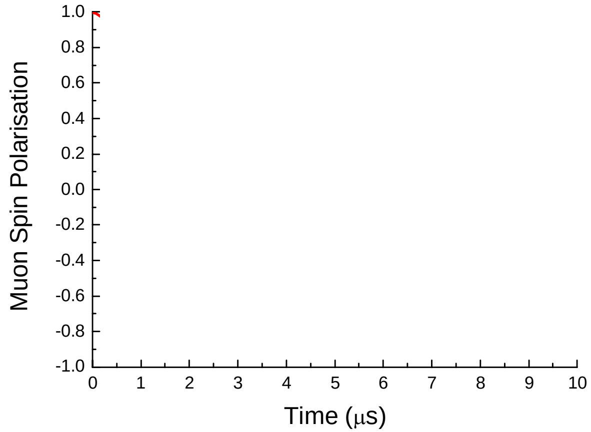

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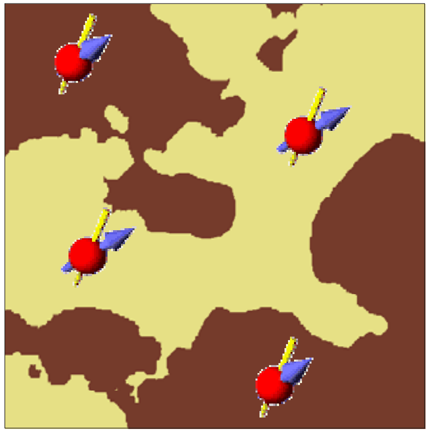

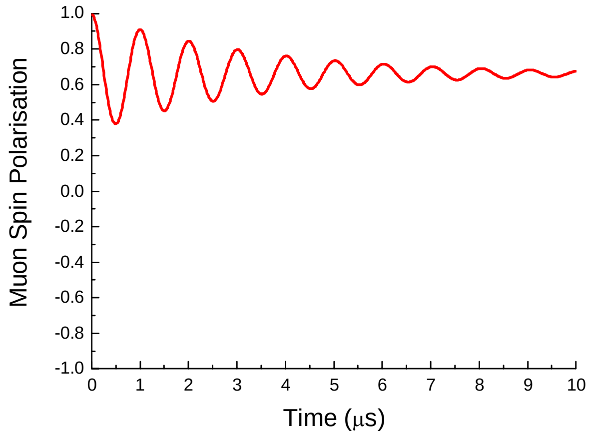

Magnetisch Inhomogene Materialien

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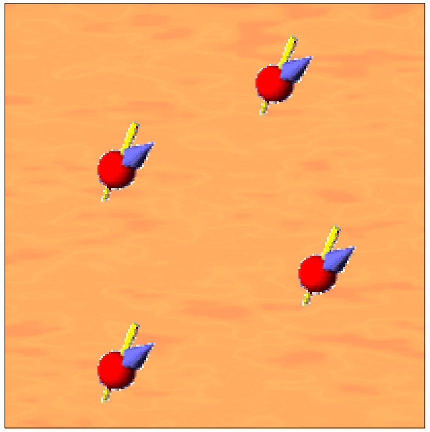

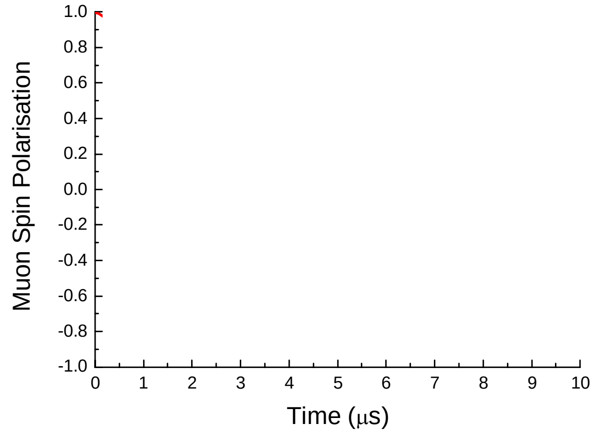

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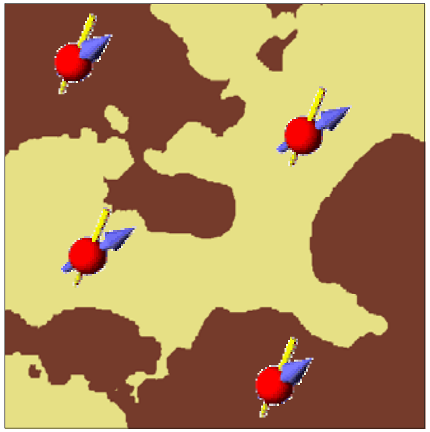

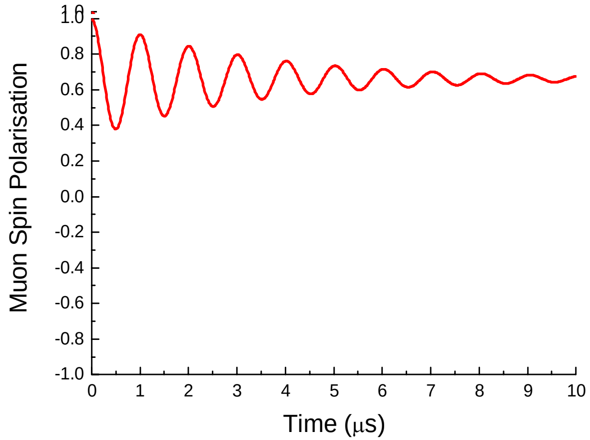

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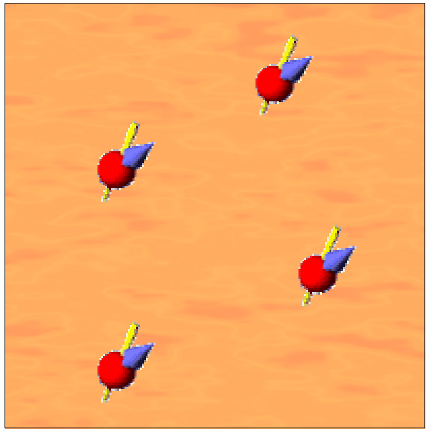
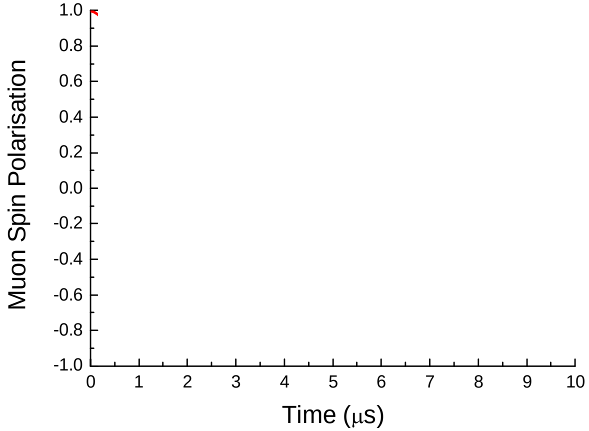
Magnetisch Inhomogene Materialien

Homogen:





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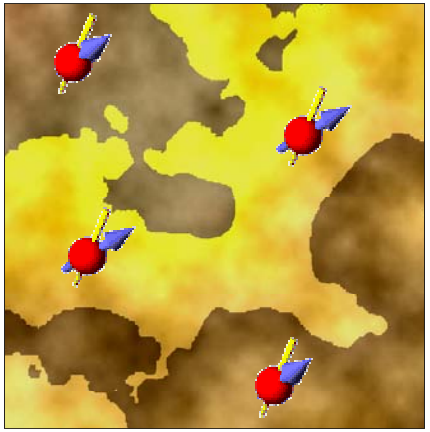

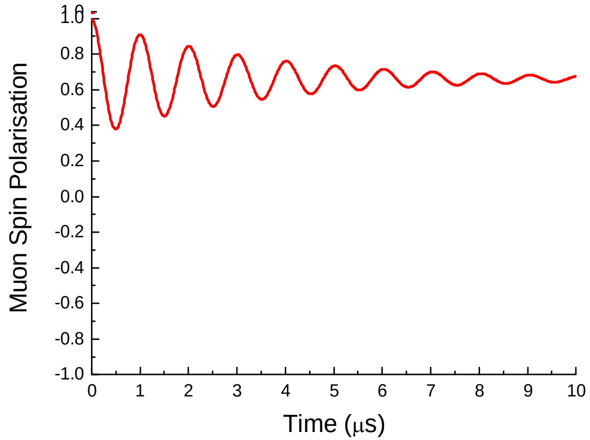

Magnetisch Inhomogene Materialien

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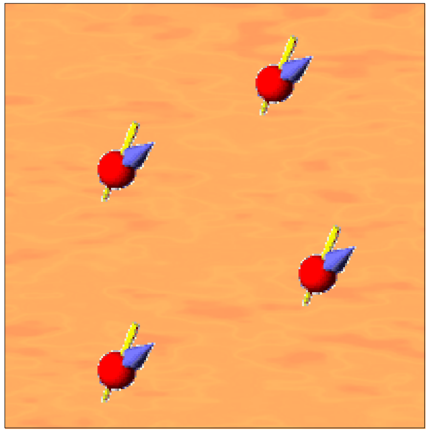
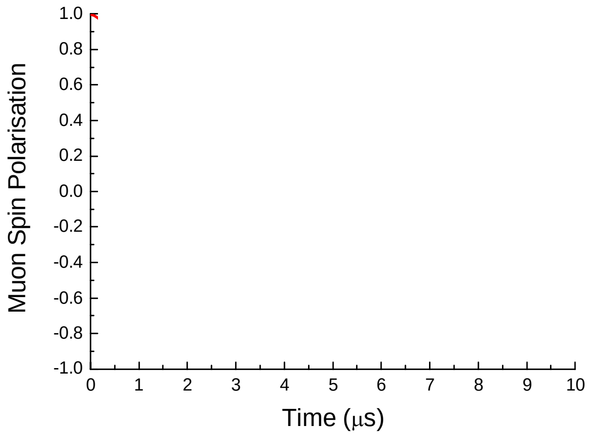
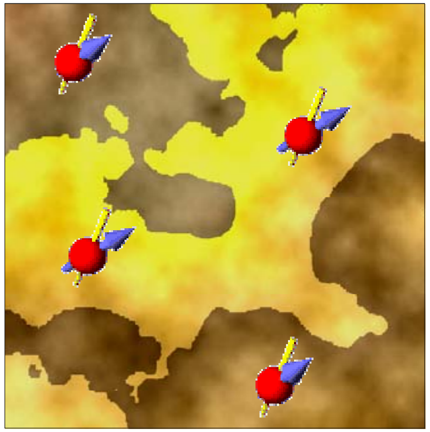
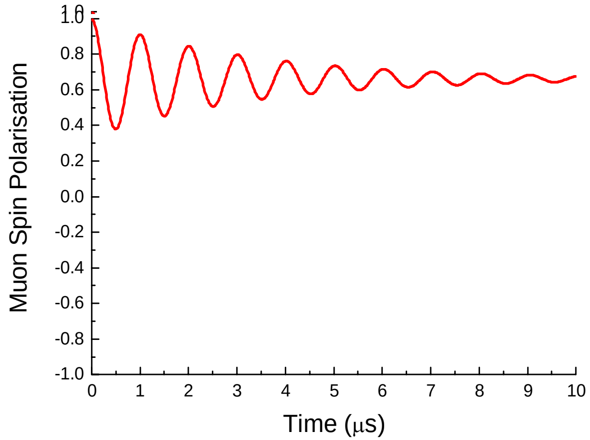




Inhomogen:

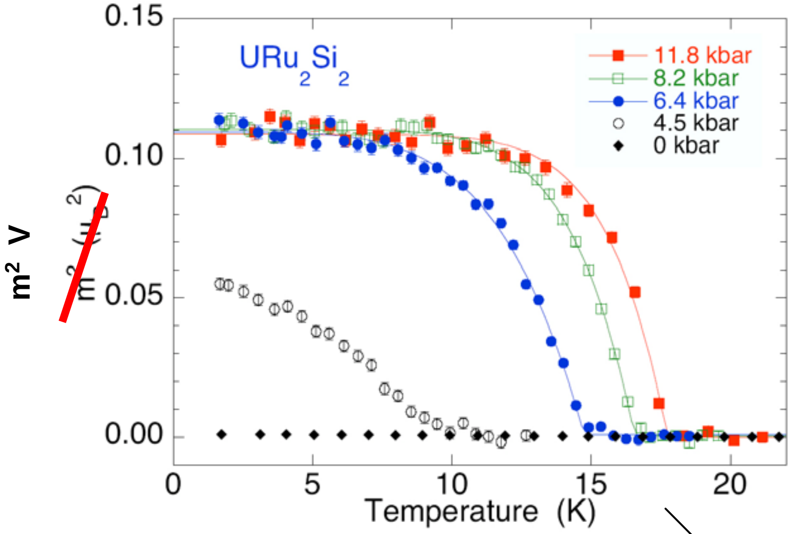




Amplitude	**= Magnetischer Volumenanteil**
Frequenz	**= Grösse der magnetischen Momente (Stärke)**
Dämpfung	**= Inhomogenität in den magnetischen Bereichen**

Beispiel 1: URu_2Si_2

Neutronenstreuung:
F. Bourdarot et al., condmat/0312206



Phasenseparation in magnetische und unmagnetische Bereiche.

Beispiel 1: URu_2Si_2

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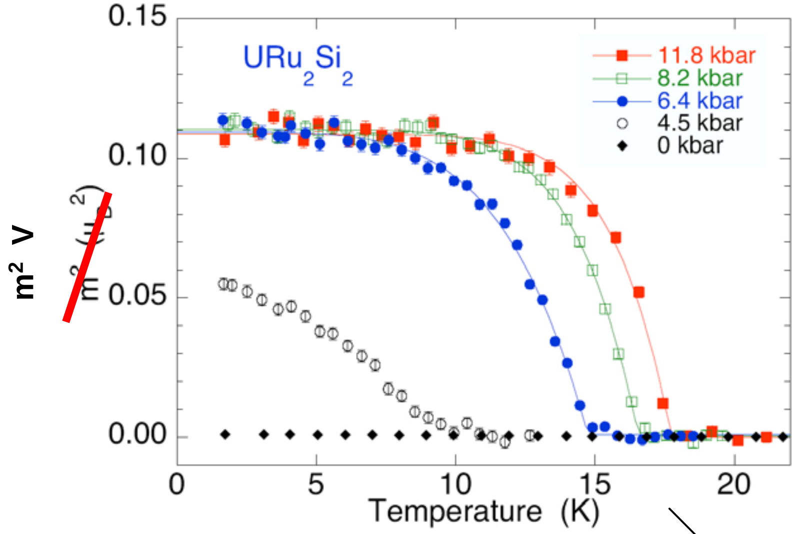
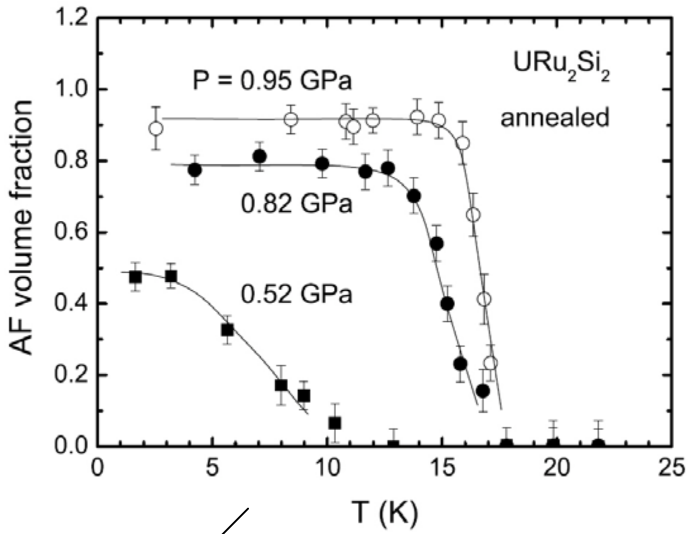


Myonen Spin Rotation:
A. Amato et al., J. Phys.: Condens. Matter **16** (2004) S4403



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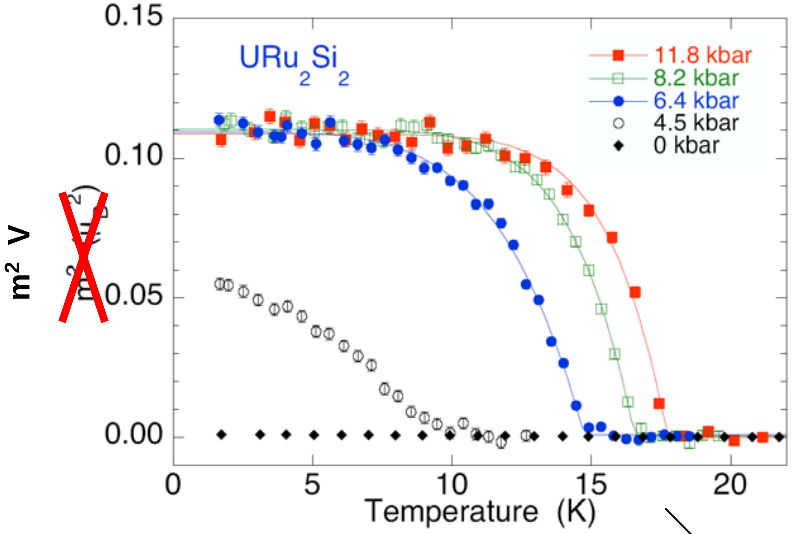

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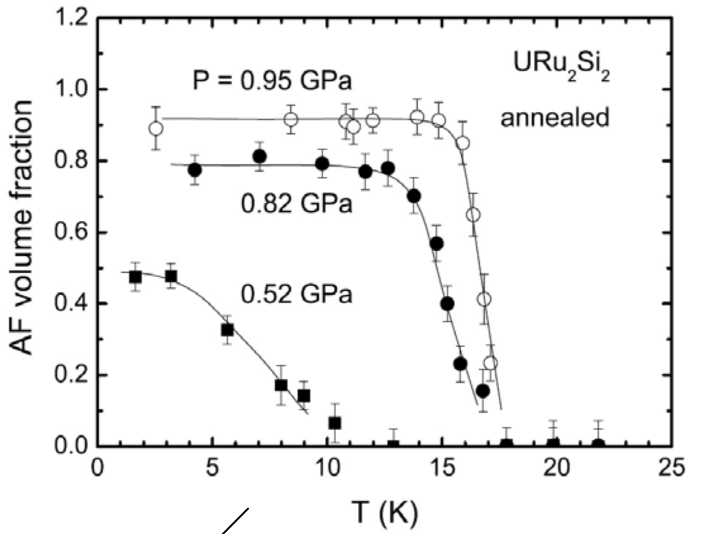

Phasenseparation in magnetische und unmagnetische Bereiche.

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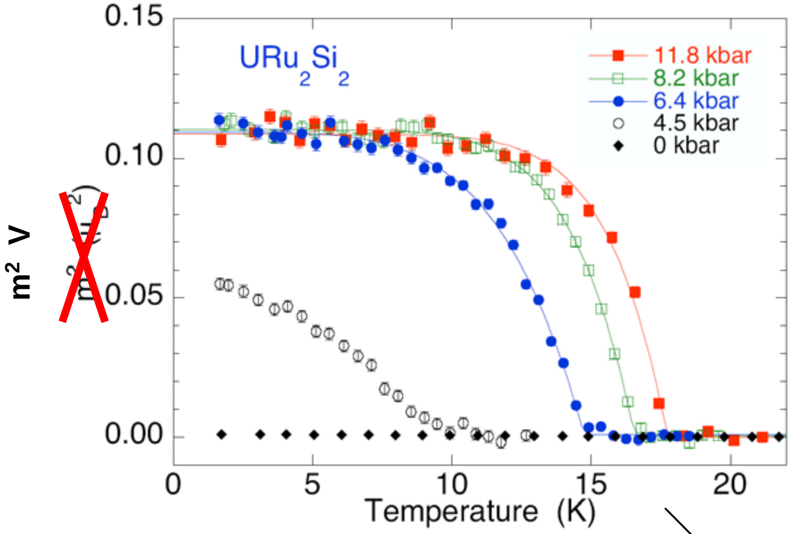

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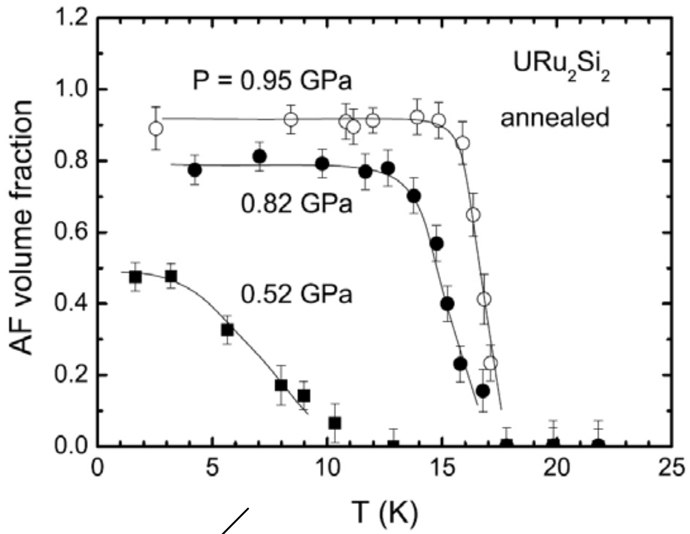

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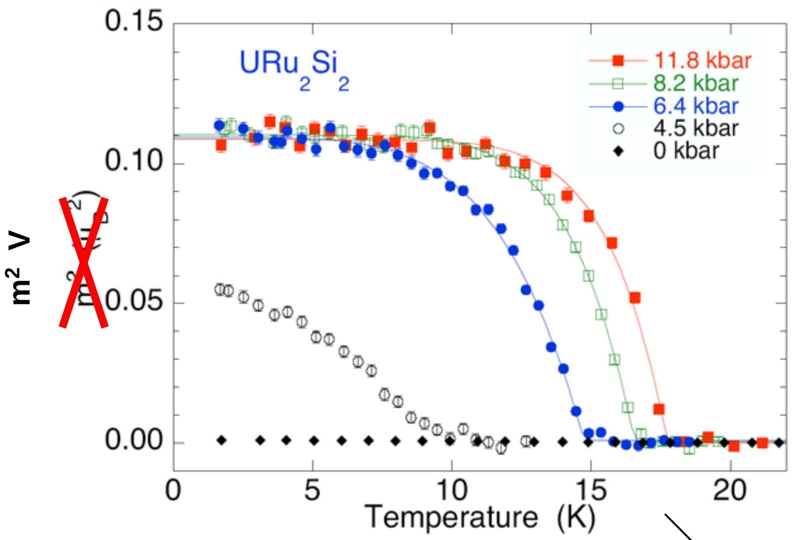

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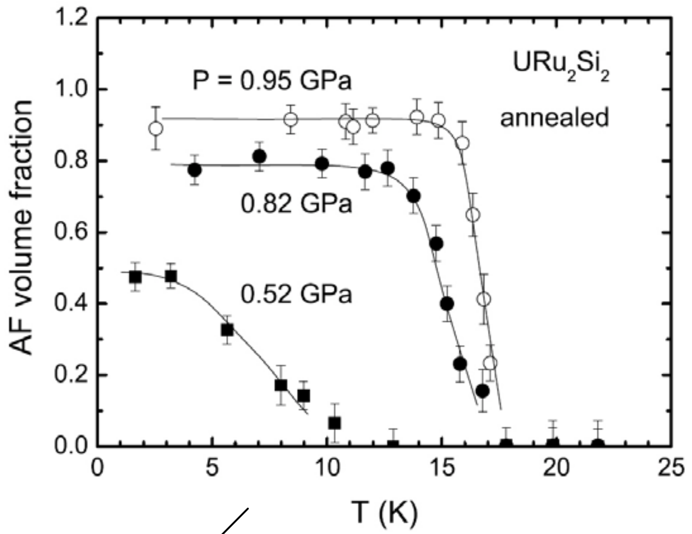
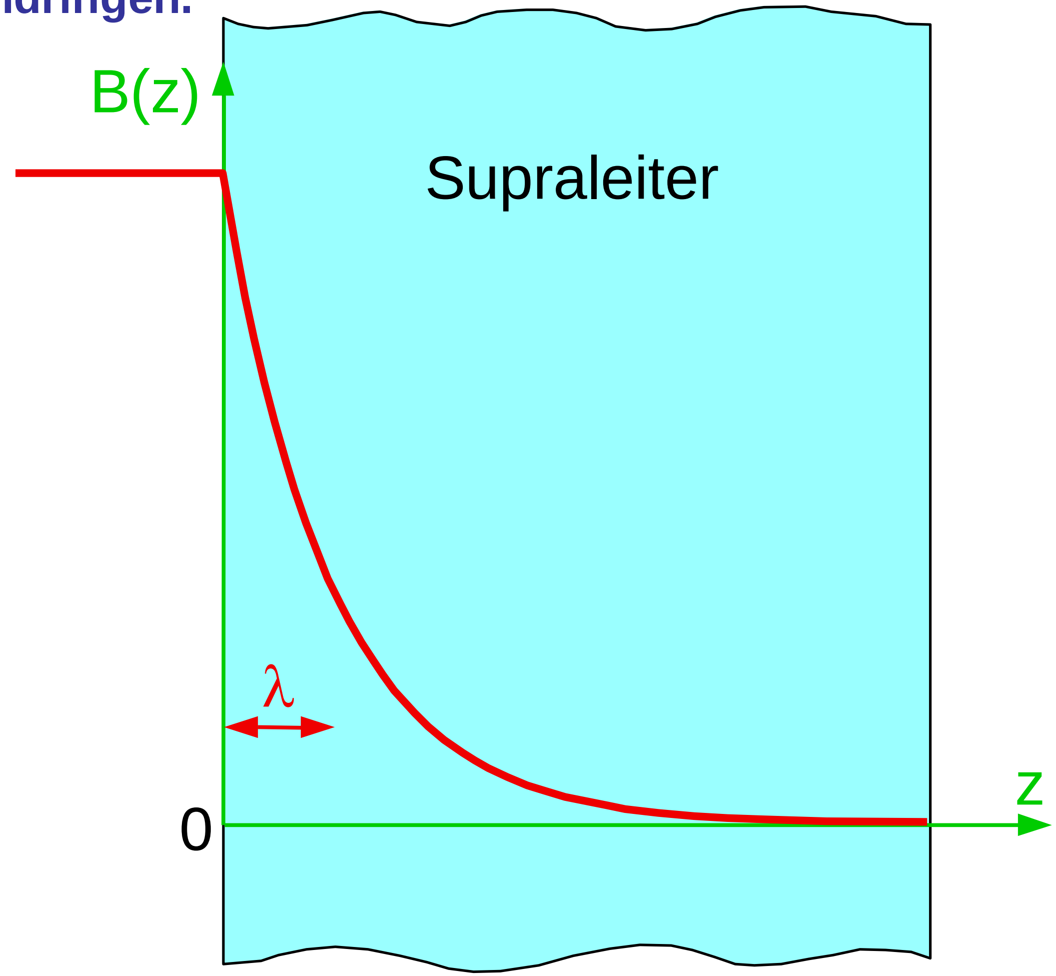


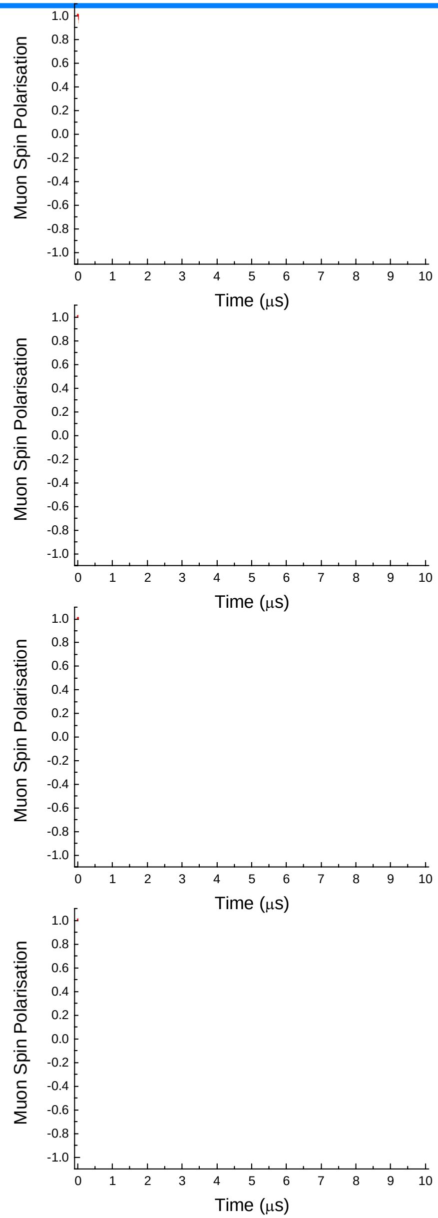
Phasenseparation in magnetische und unmagnetische Bereiche.

Erst die Kombination aus Neutronenstreuung und Myonen Spin Rotation ermöglicht die richtige Interpretation der experimentellen Daten.

Niederenergetische Myonen als mikroskopische Magnetfeldsonden

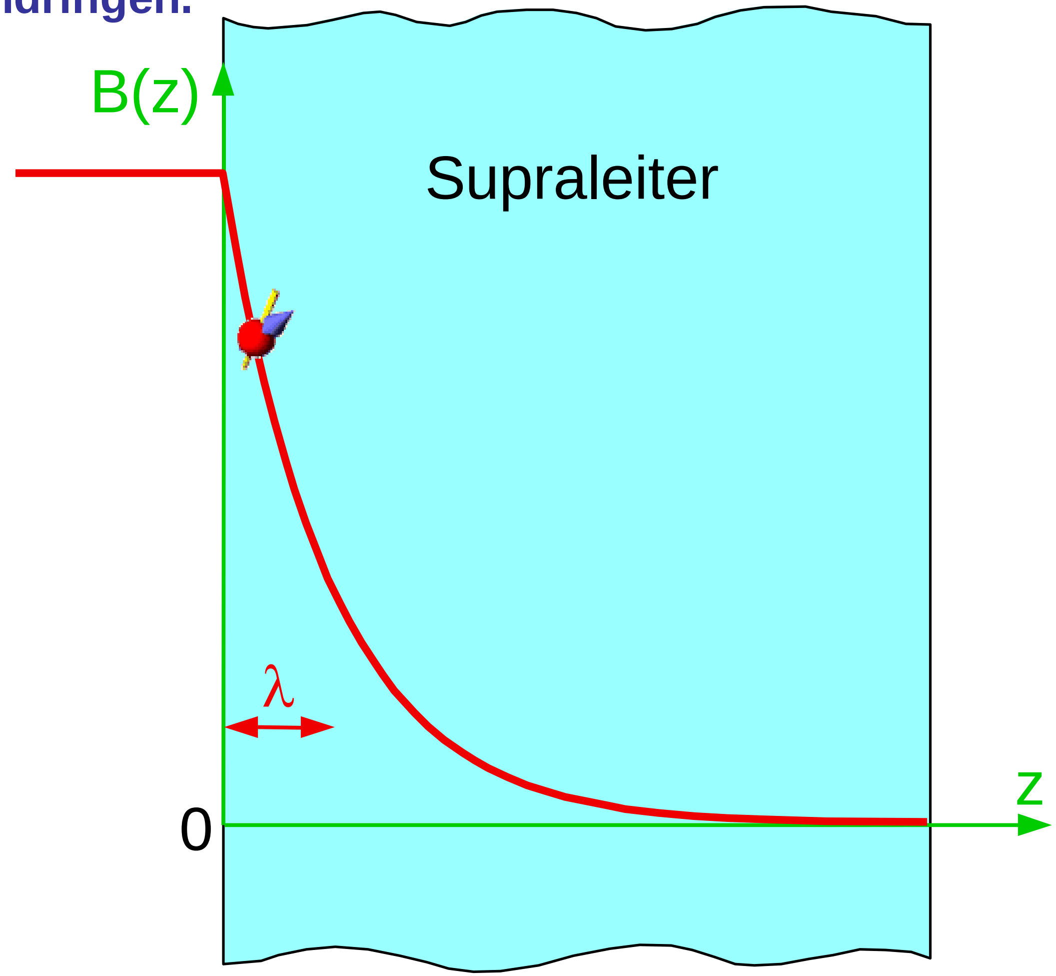
Ein externes Magnetfeld B(z) kann nur bis zu einer Tiefe z von der Grössenordnung λ eindringen.

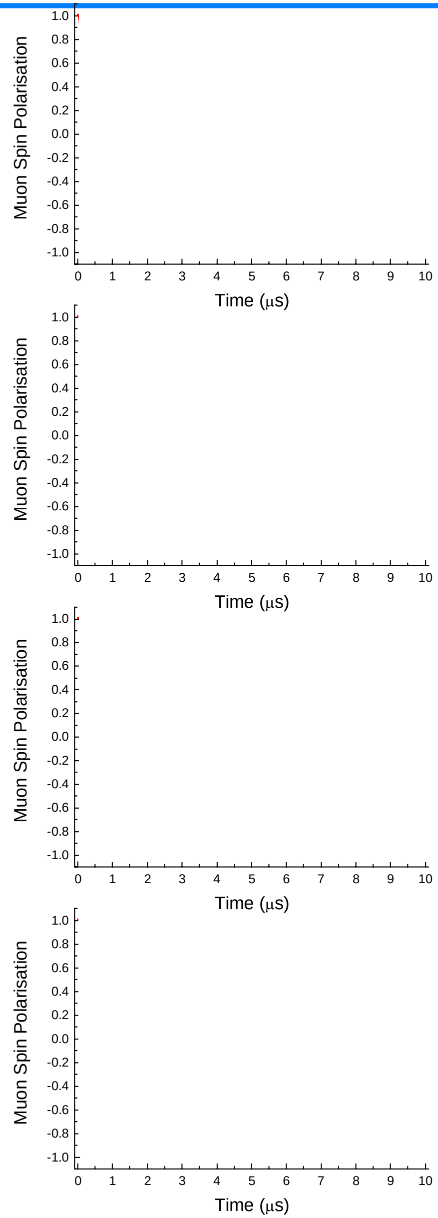




Niederenergetische Myonen als mikroskopische Magnetfeldsonden

Ein externes Magnetfeld B(z) kann nur bis zu einer Tiefe z von der Grössenordnung λ eindringen.





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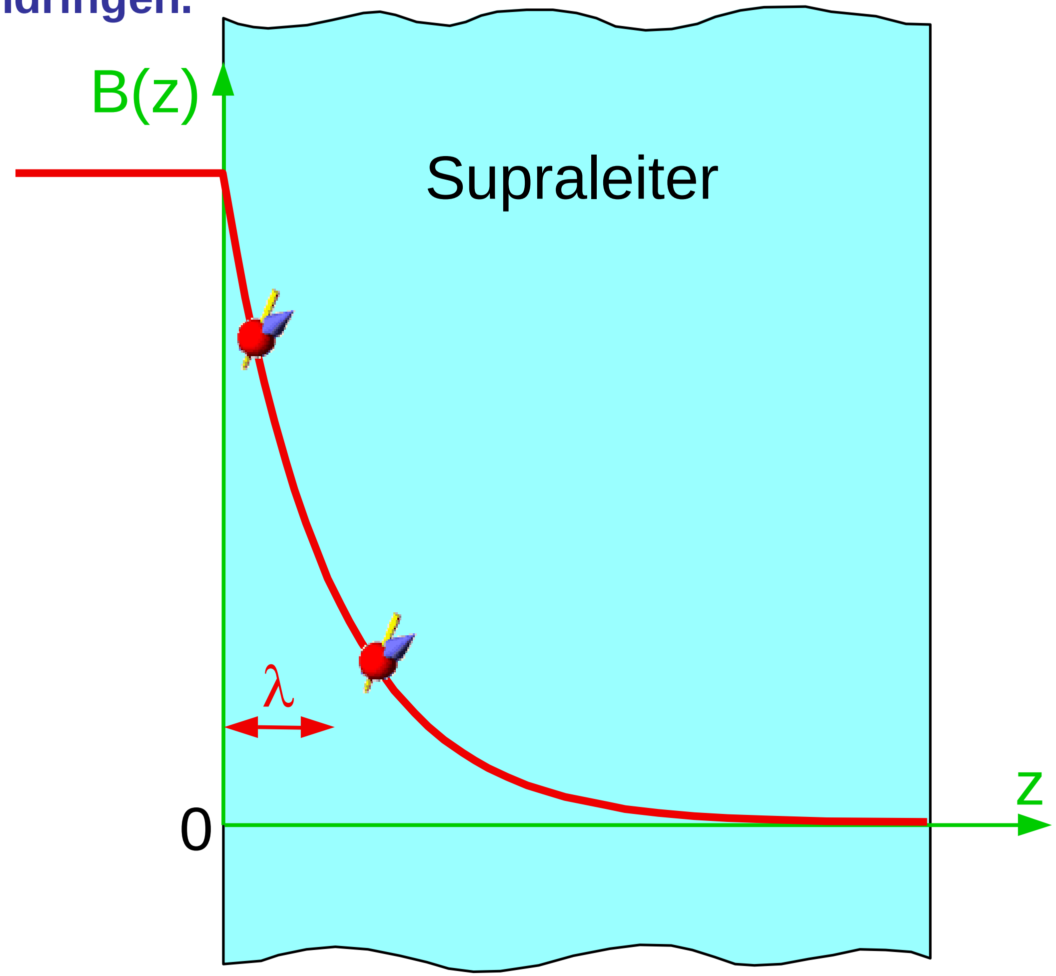

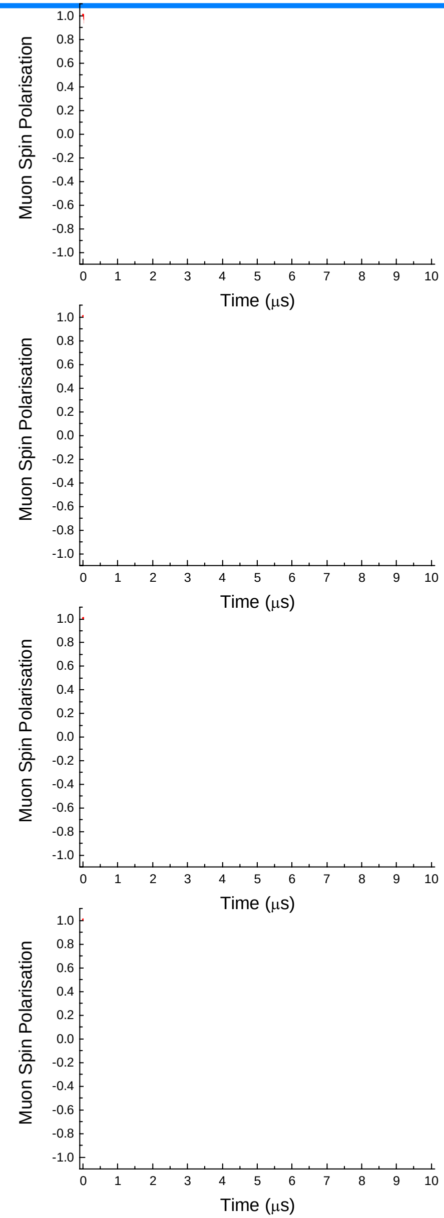

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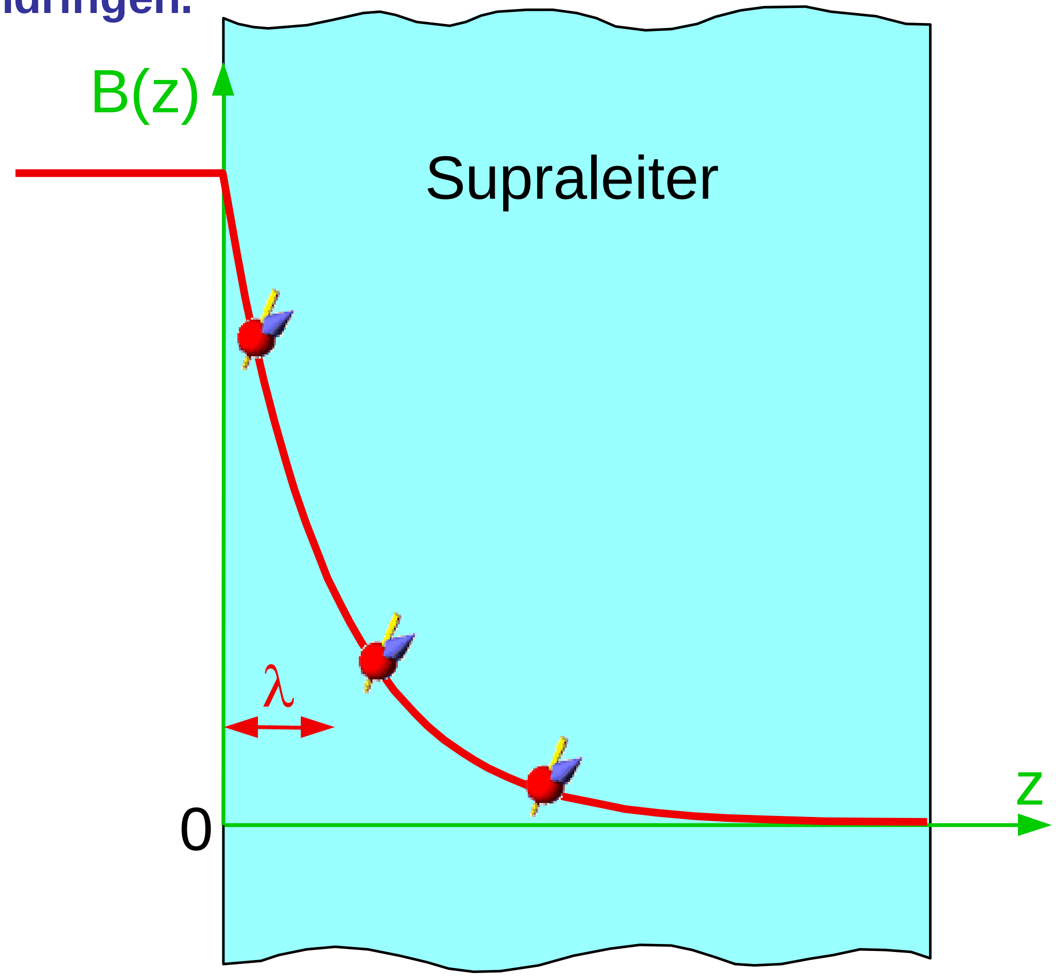

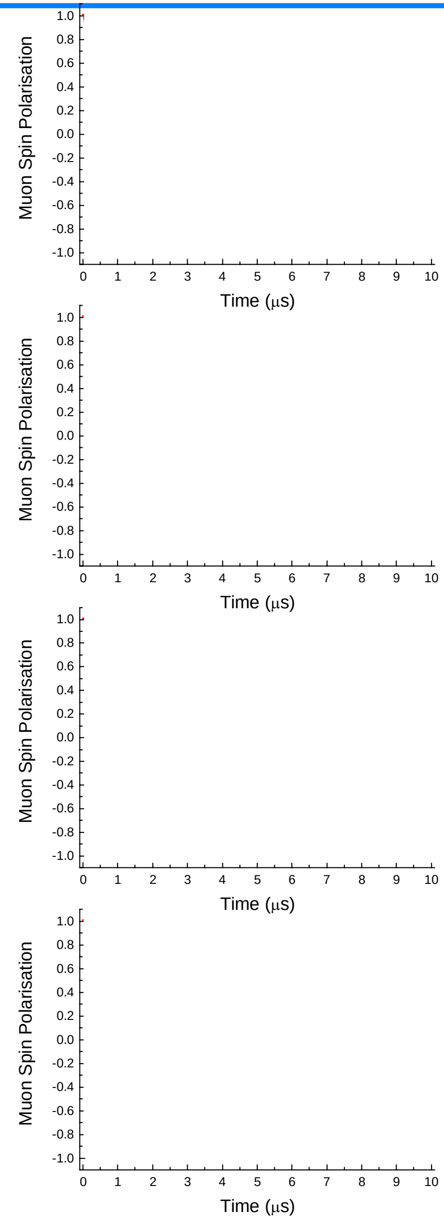

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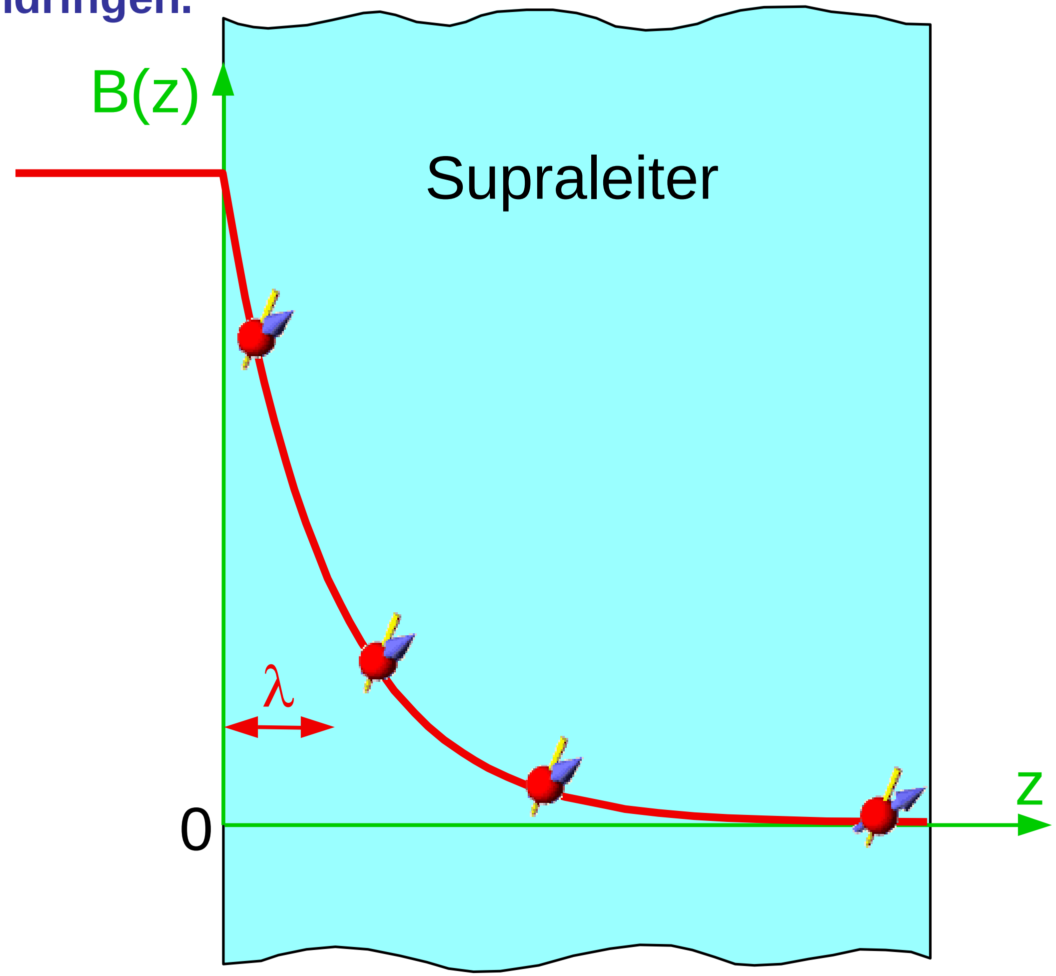
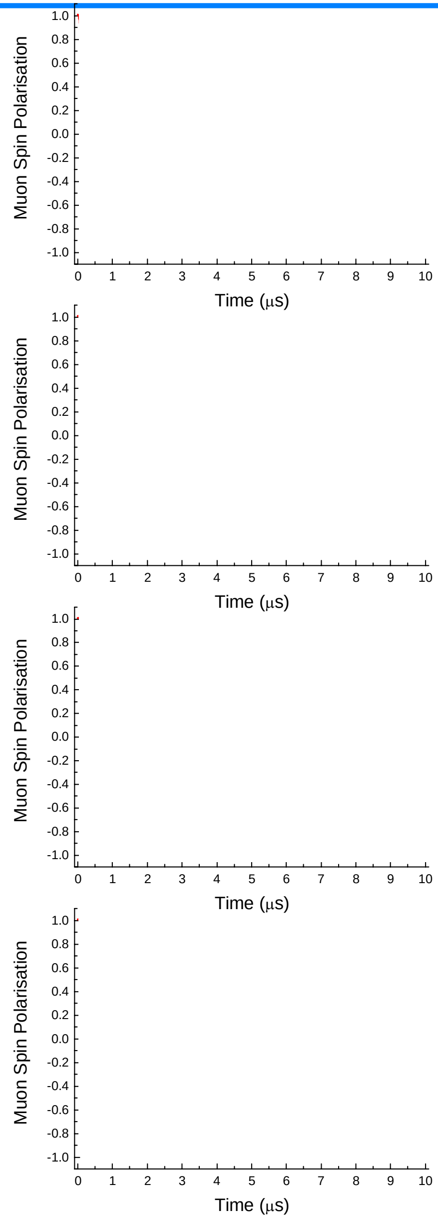
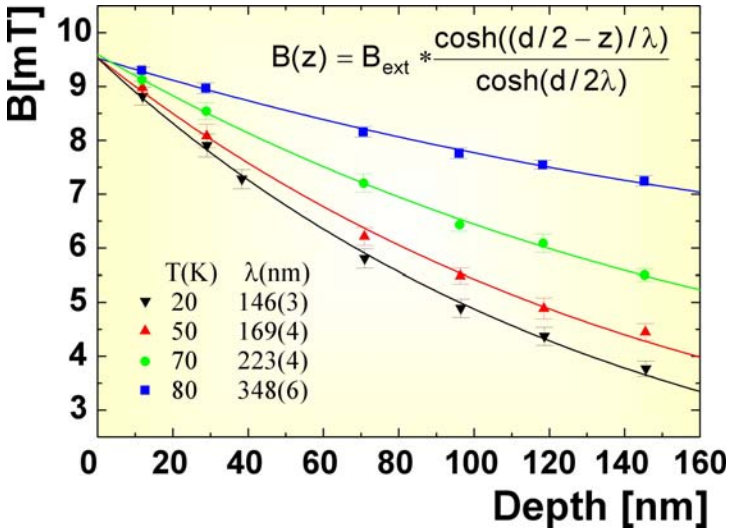




Magnetische Eindringtiefe

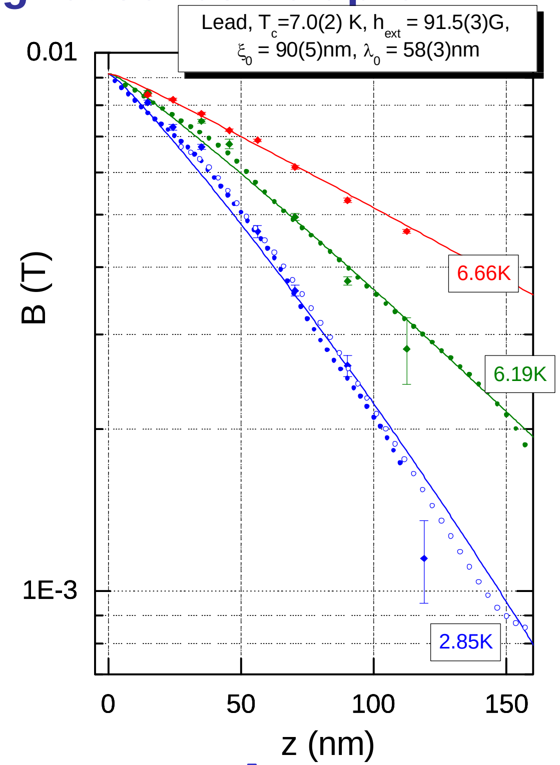
Magnetisches Feldprofil in YBCO:



$$B(z) = B_0 e^{-\frac{z}{\lambda_{ab}(T)}}$$

T.J. Jackson et al., Phys. Rev. Lett. **84** (2000) 4958.

Magnetisches Feldprofil in Pb:



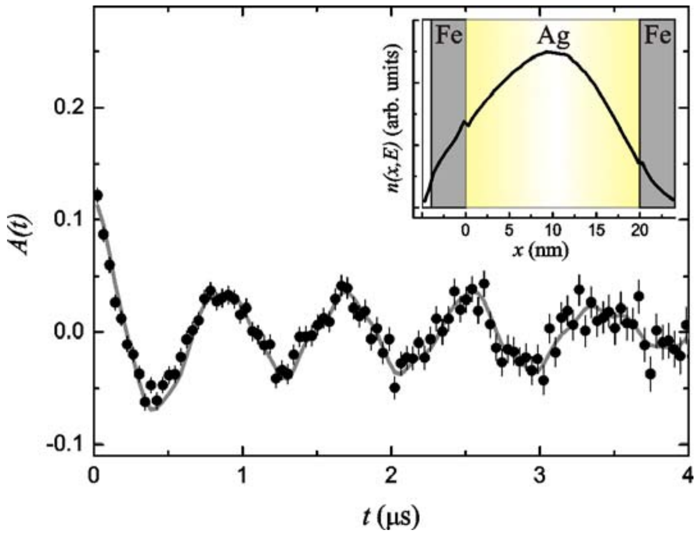
$$B(z) \neq B_0 e^{-\frac{z}{\lambda_{ab}(T)}}$$

A. Suter et al., Phys. Rev. Lett. **92** (2004) 087001.
A. Suter et al., Phys. Rev. B im Druck

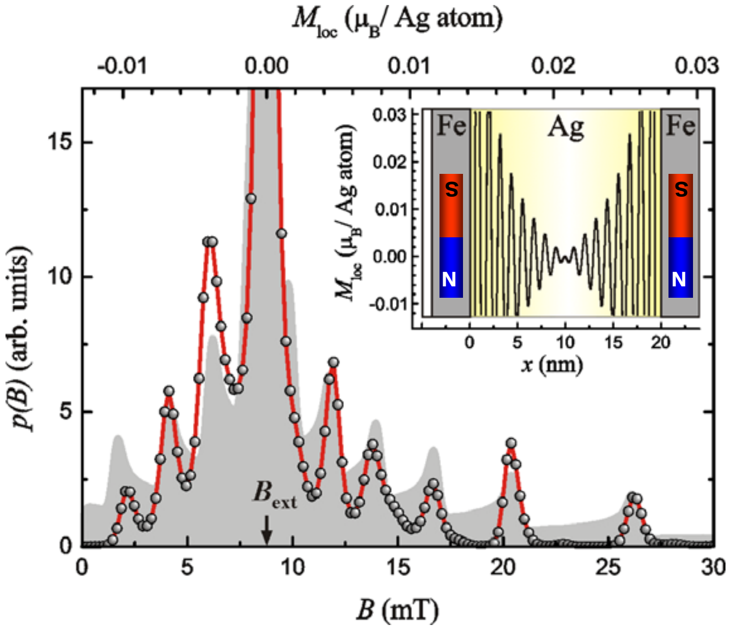
Material provided by H. Luetkens, A Amato, E Morenzoni, D Herlach

LE-μSR an Fe/20 nm Ag/Fe

LE-μSR Messung an Fe/Ag/Fe:



Magnetfeldverteilung in der Ag Schicht:



H. Luetkens et al., Phys. Rev. Lett. **91** (2003) 017204.

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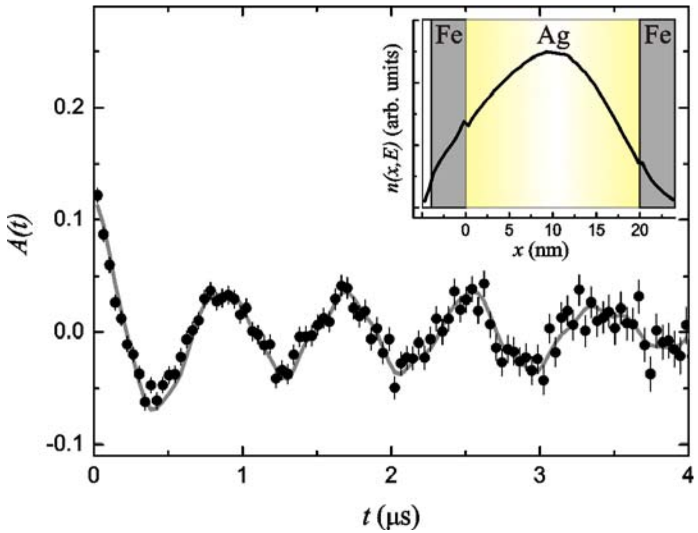

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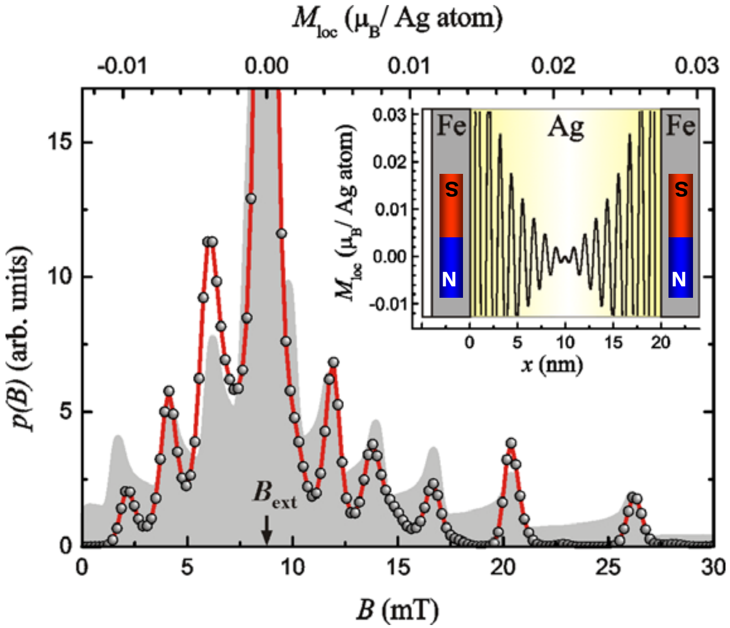

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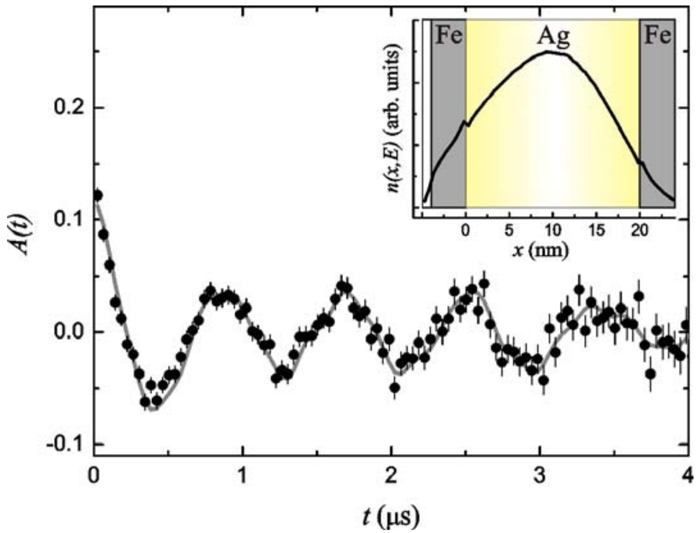

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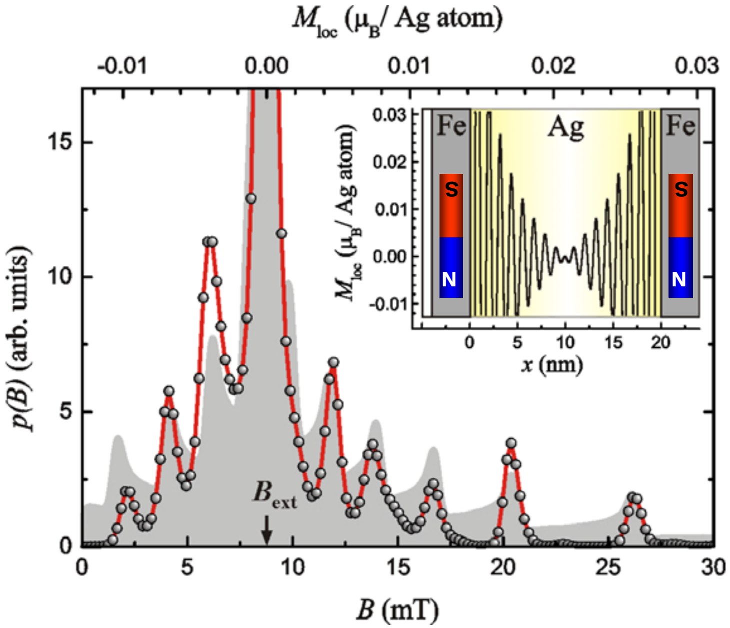

Die magnetischen Schichten induzieren eine oszillierende magnetische Polarisation in der Ag Schicht.

H. Luetkens et al., Phys. Rev. Lett. **91** (2003) 017204.

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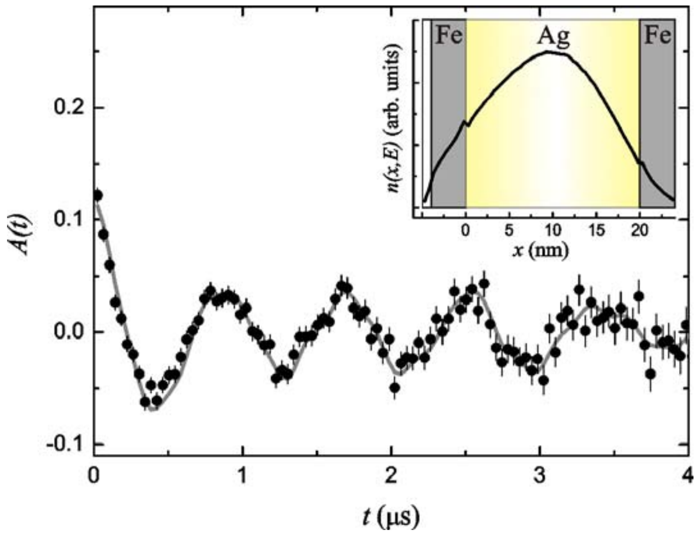

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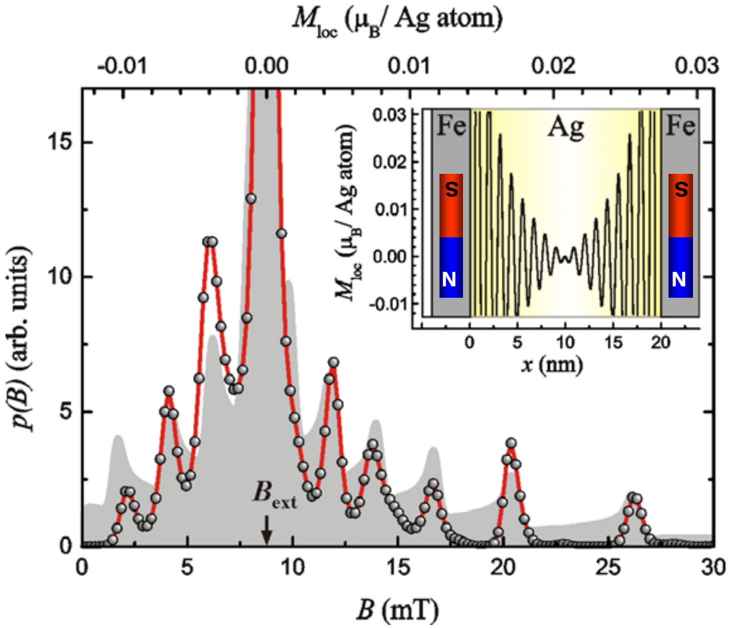

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Die Wechselwirkung der Schichten mit unterschiedlichen Eigenschaften führt zu neuartigen physikalischen Effekten!

H. Luetkens et al., Phys. Rev. Lett. **91** (2003) 017204.

Surface Magnetism in Superconducting $La_{2-x}Ce_xCuO_4$ Films

H. Luetkens [a], Y. Krockenberger [b], L. Alff [c], A. Tsukada [d], M. Naito [d], E. Morenzoni [a], T. Prokscha [a], A. Suter [a], R. Khasanov [a,e], T. Gutberlet [f], J. Stahn [f], M. Gupta [f], and H.-H. Klauss [g]

a) Labor für Myonenspinspektroskopie, Paul Scherrer Institut, CH-5232 Villigen PSI, Switzerland

b) Max-Planck-Institut für Festkörperforschung, D-70569 Stuttgart, Germany

c) Technische Universität Wien, A-1040 Wien, Austria

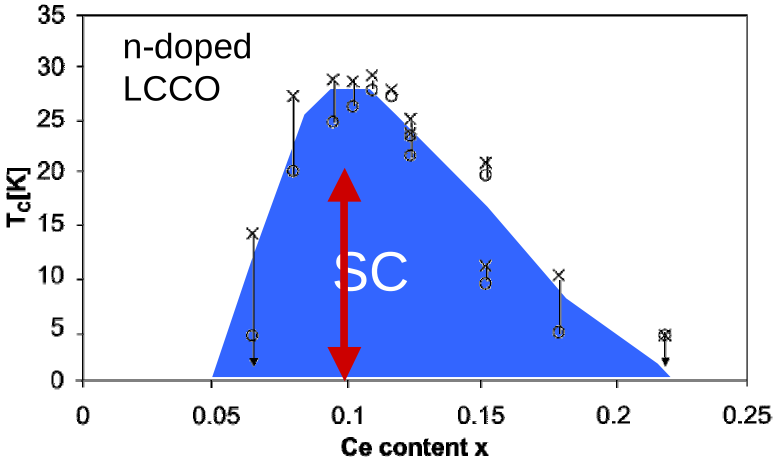
d) NTT Basic Research Laboratory, Atsugi 243-01, Japan

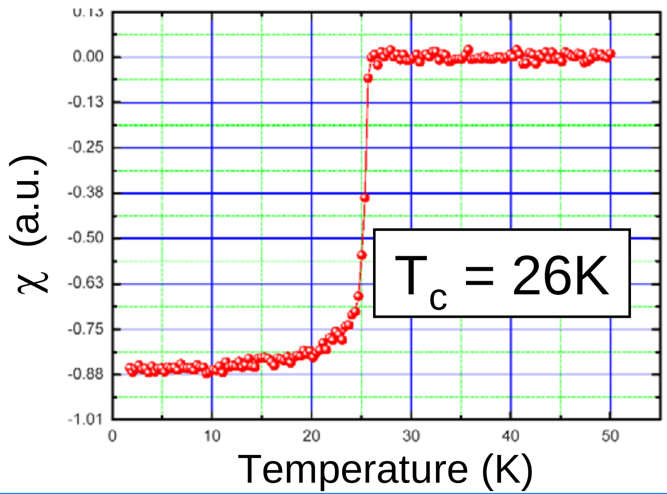
e) Physik Institut der Universität Zürich, CH-8057 Zürich, Switzerland

f) Labor für Neutronenstreuung, ETH Zürich & Paul Scherrer Institut, CH-5232 Villigen PSI, Switzerland

g) Institut für Physik der Kondensierten Materie, Technische Universität Braunschweig, D-38106 Braunschweig, Germany

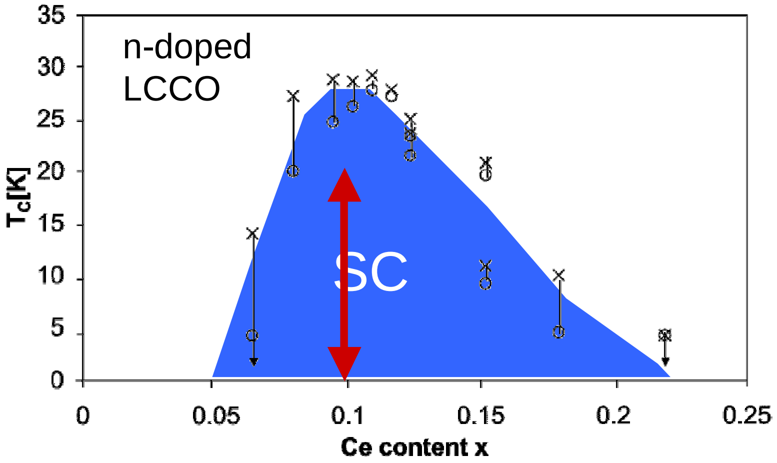
Why do we use $La_{2-x}Ce_xCuO_4$ films?

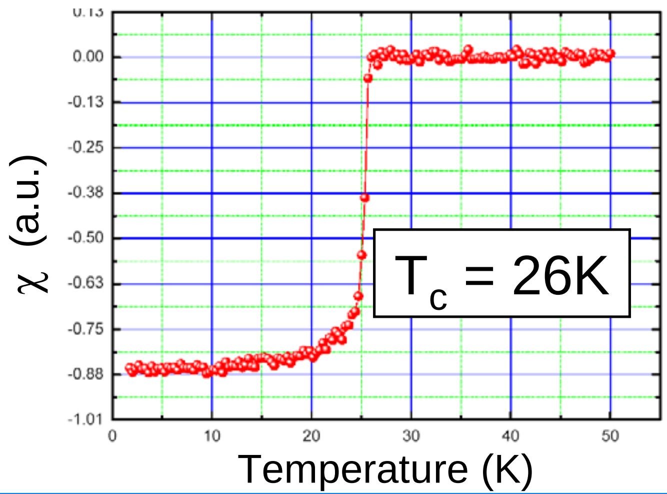




Why do we use $La_{2-x}Ce_xCuO_4$ films?

- La^{3+} is non-magnetic
- $La_{2-x}Ce_xCuO_4$ exists only as a thin film
- High quality films can be prepared
- High transition temperatures (Tc ~28K)





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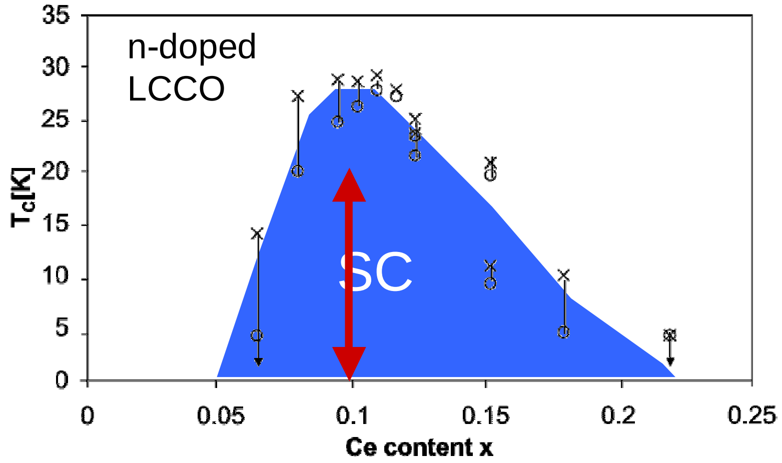
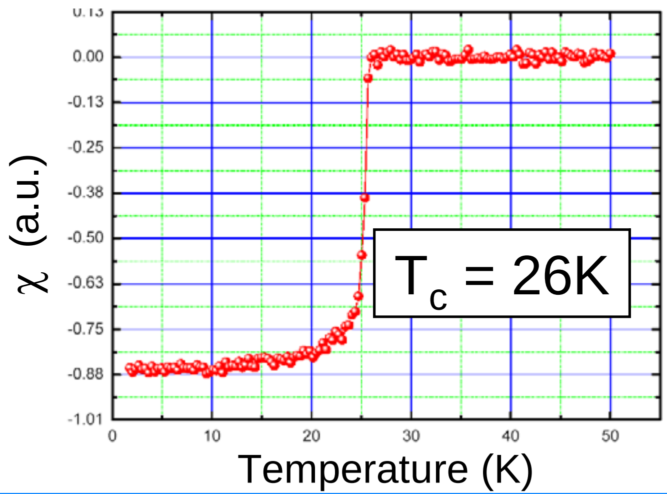


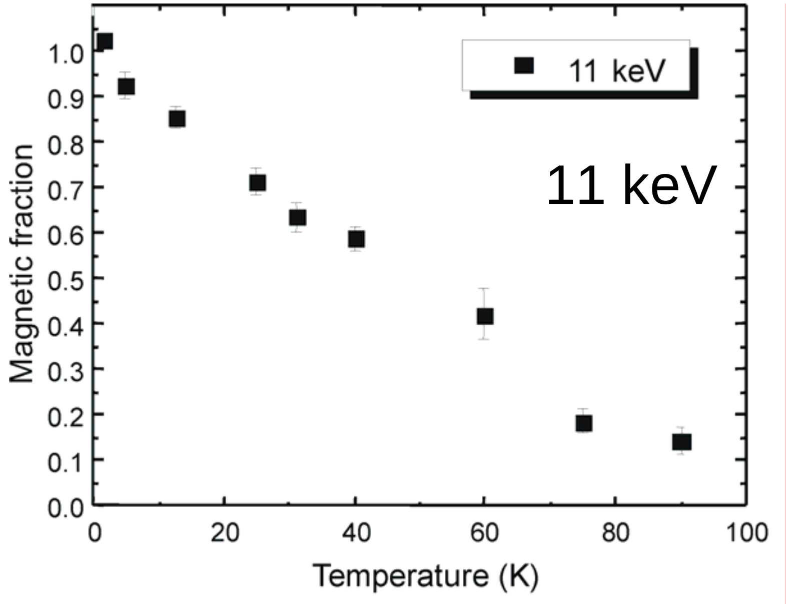
First sample:

20nm Ag/ 300nm $La_{1.9}Ce_{0.1}CuO_4$



ZF-LEμSR using 11keV muons

Magnetic volume fraction:



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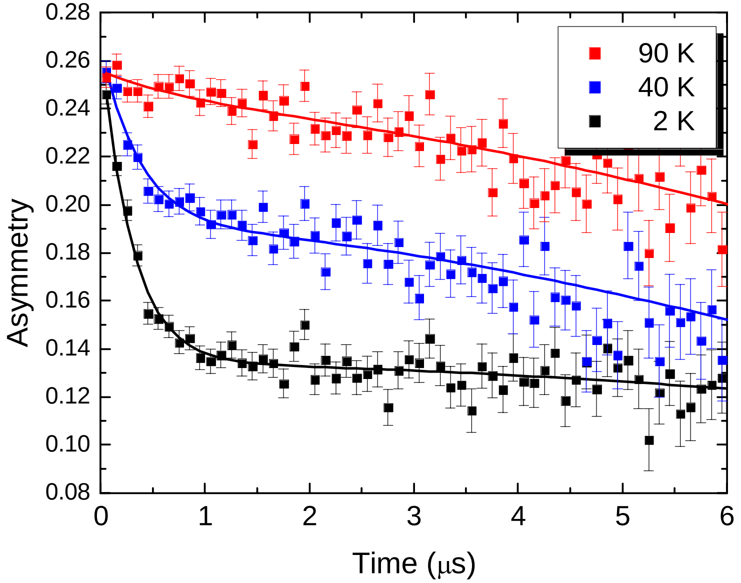

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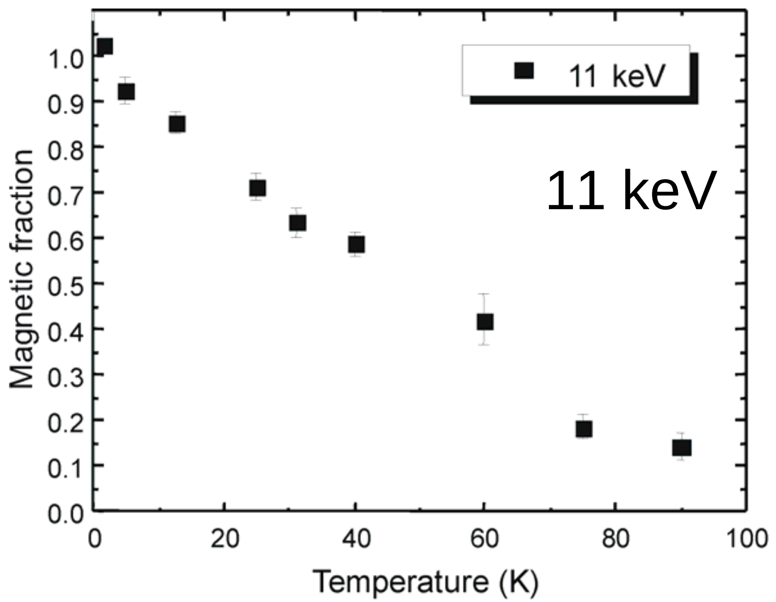

Material provided by H. Luetkens, A Amato, E Morenzoni, D Herlach

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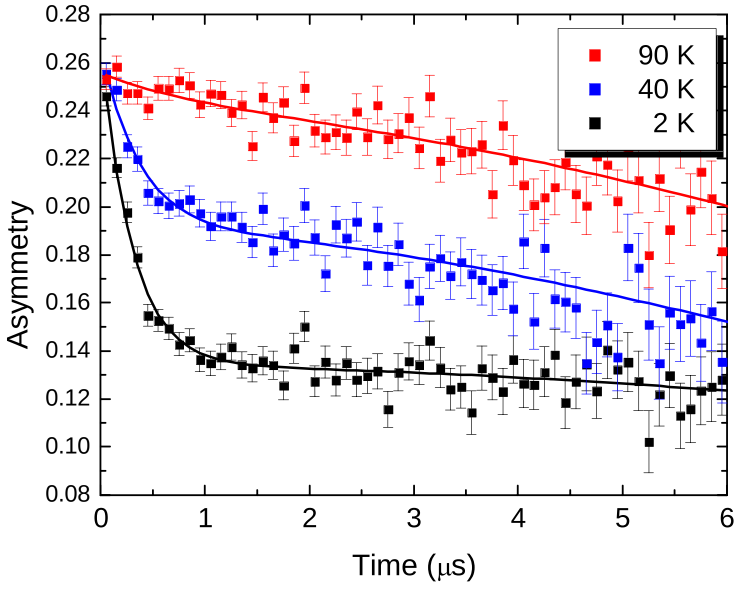

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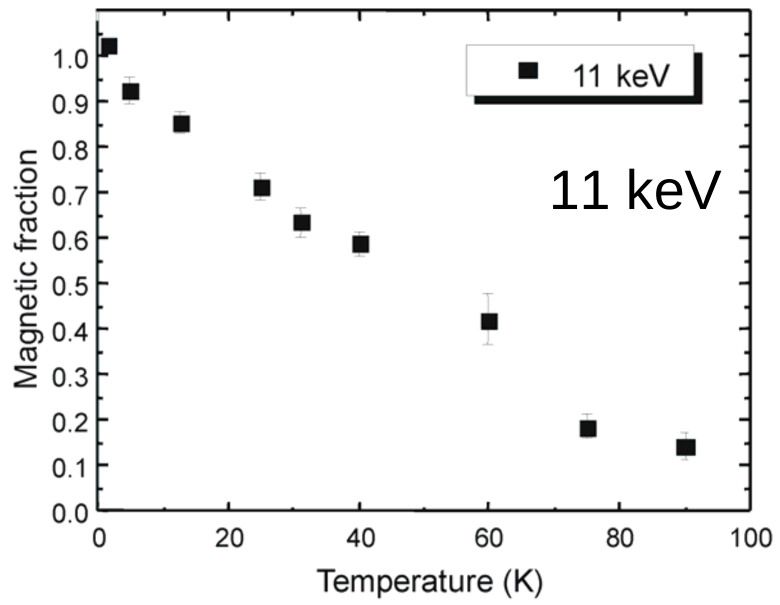
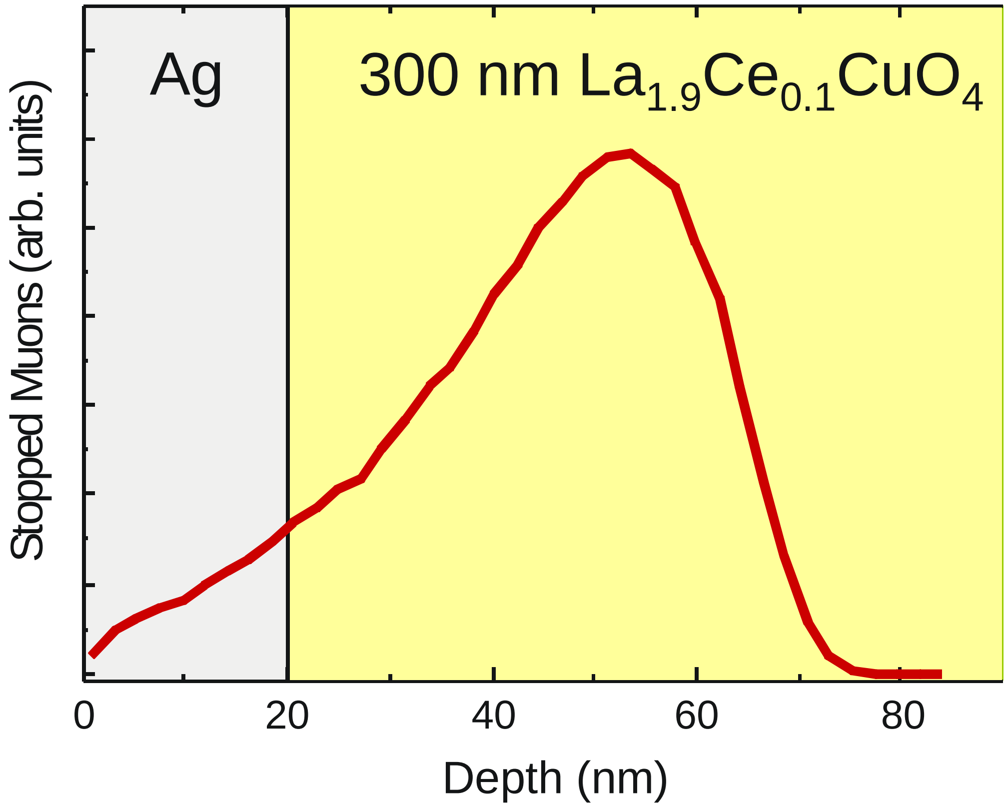
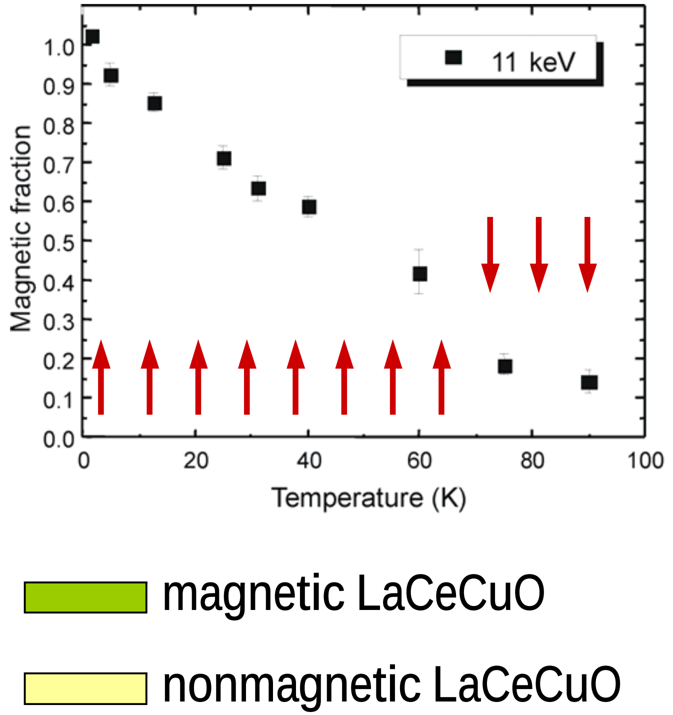


- Static magnetism (disordered)
- Relatively small relaxation rate ($\lambda \approx 3\ \mu s^{-1}$)

  $\Rightarrow$ small or diluted Cu moments (inhomogeneity on a nm scale)
- Magnetic volume fraction decreases with increasing temperature

ZF-LEμSR using 11keV muons





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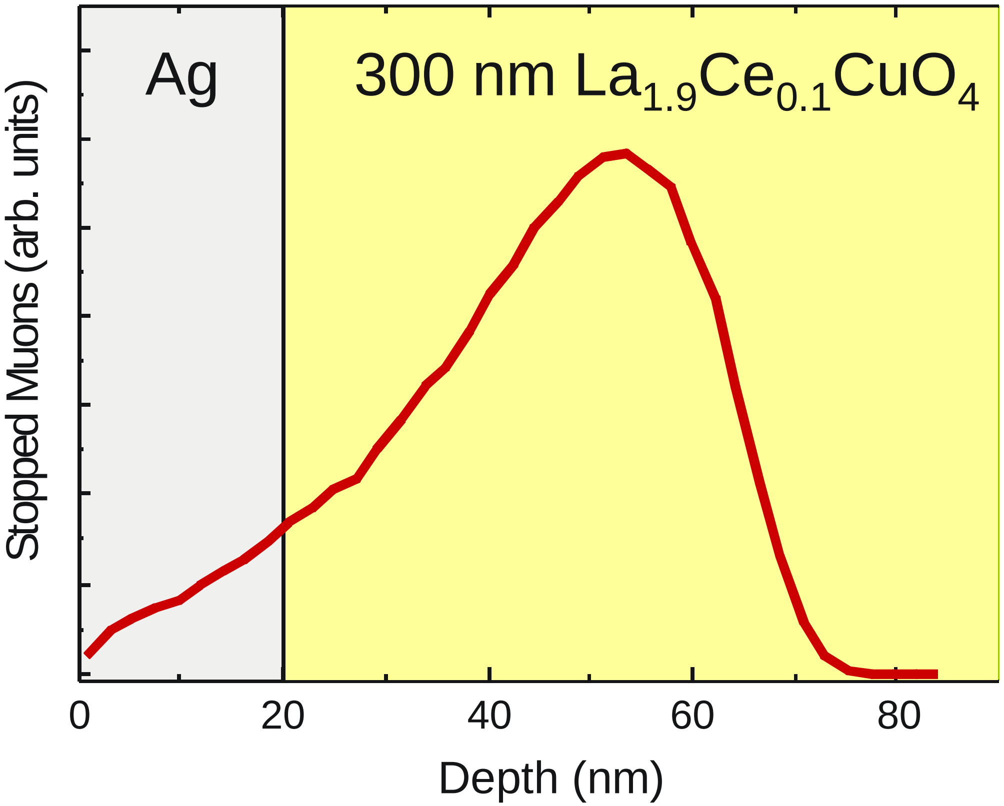
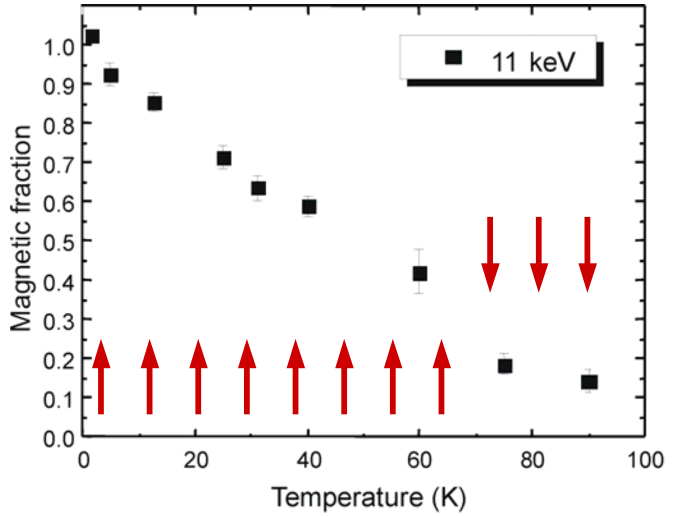




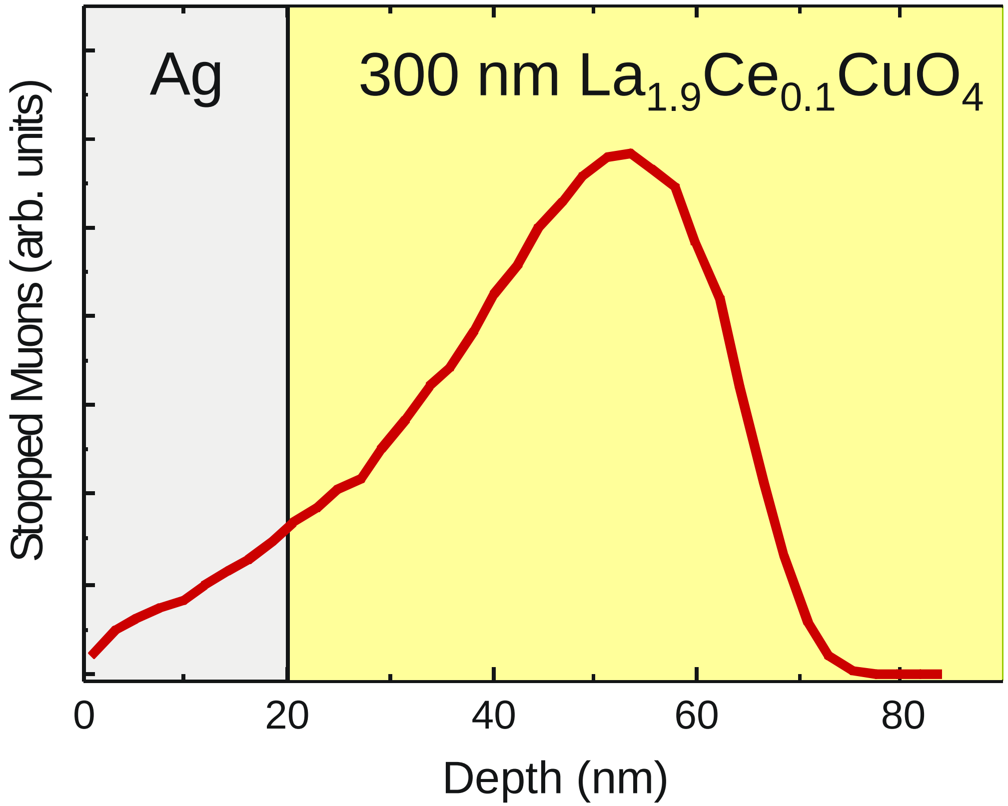
magnetic LaCeCuO

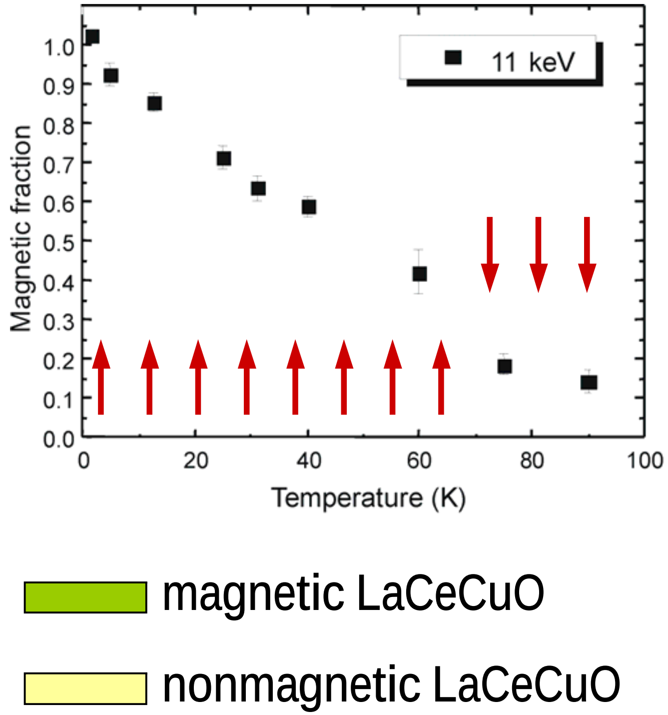
nonmagnetic LaCeCuO

Scenario 1:

Large clusters with different ordering temperatures

ZF-LEμSR using 11keV muons





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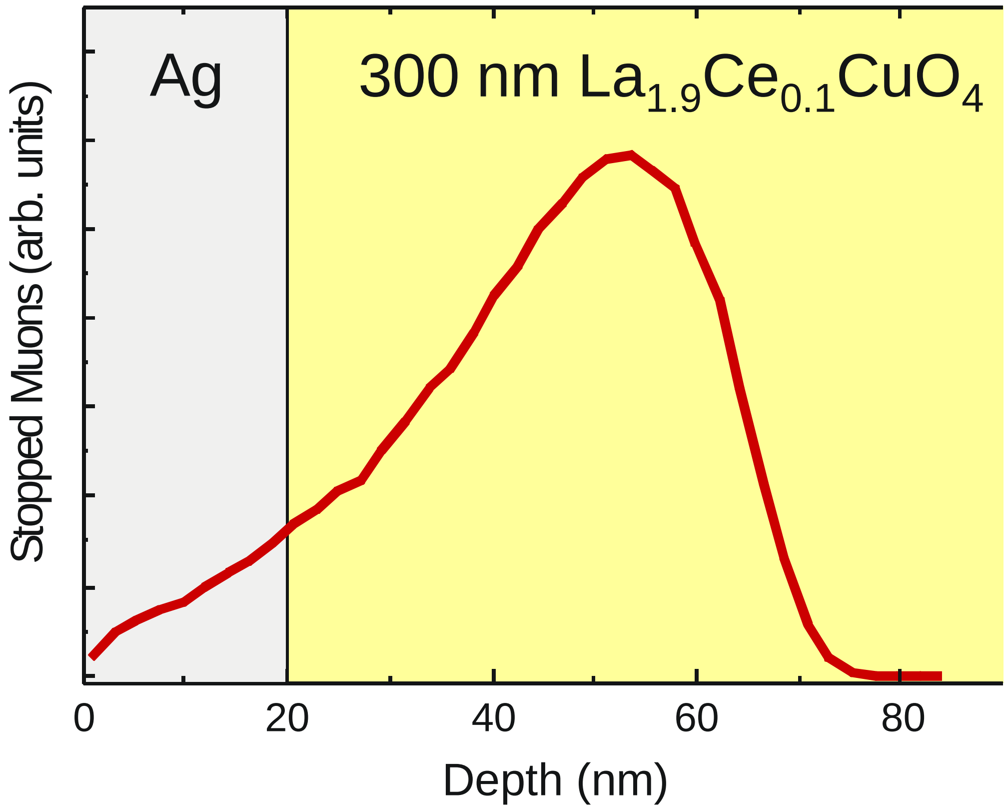
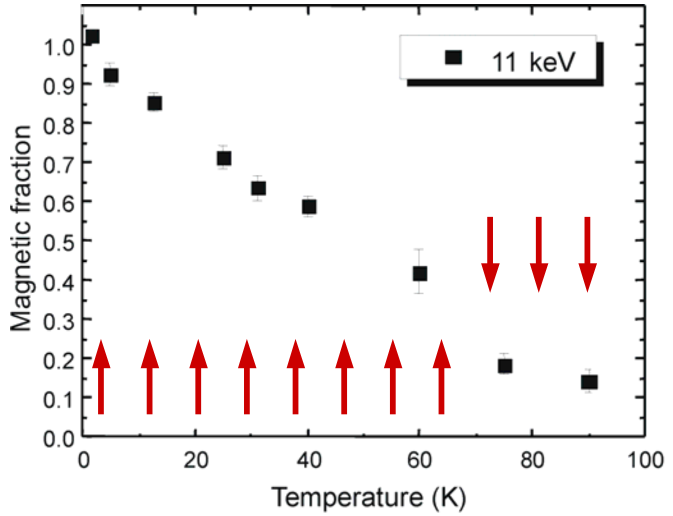
Material provided by H. Luetkens, A Amato, E Morenzoni, D Herlach

ZF-LEμSR using 11keV muons





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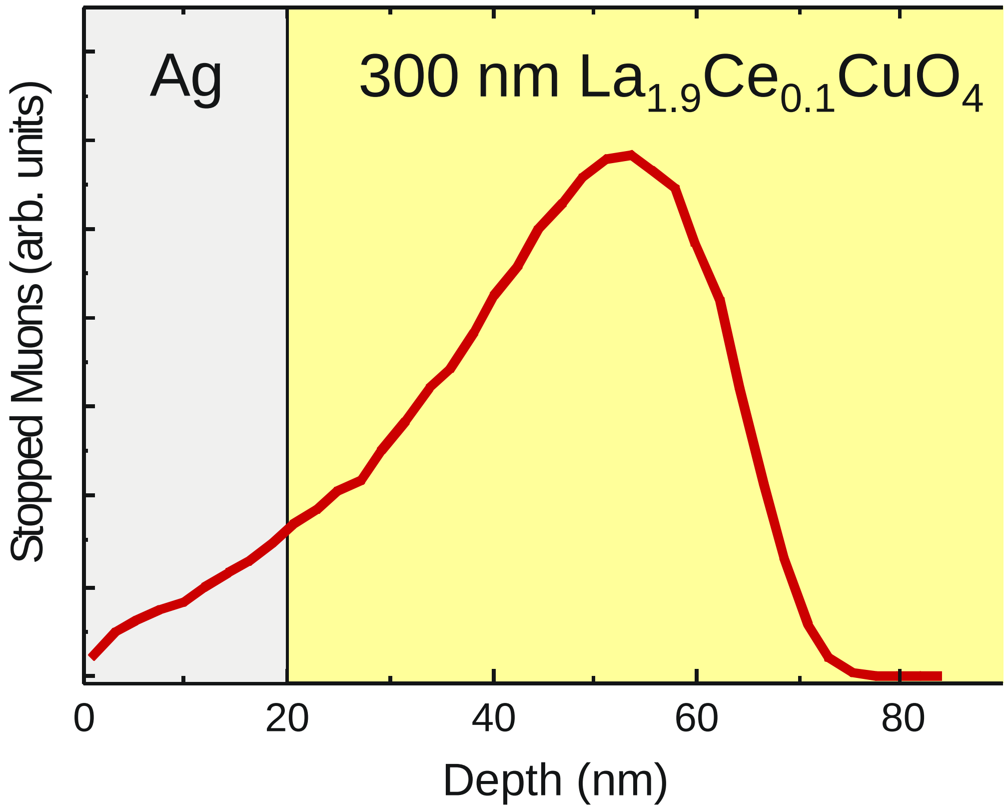
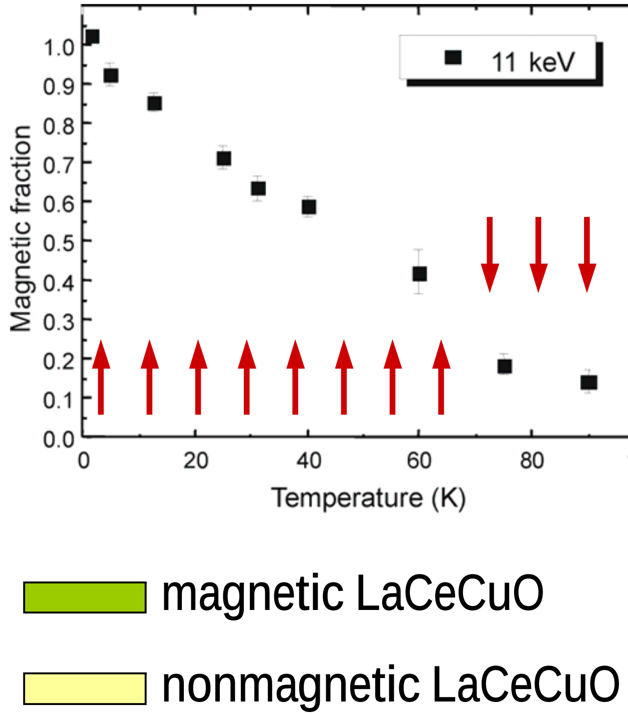
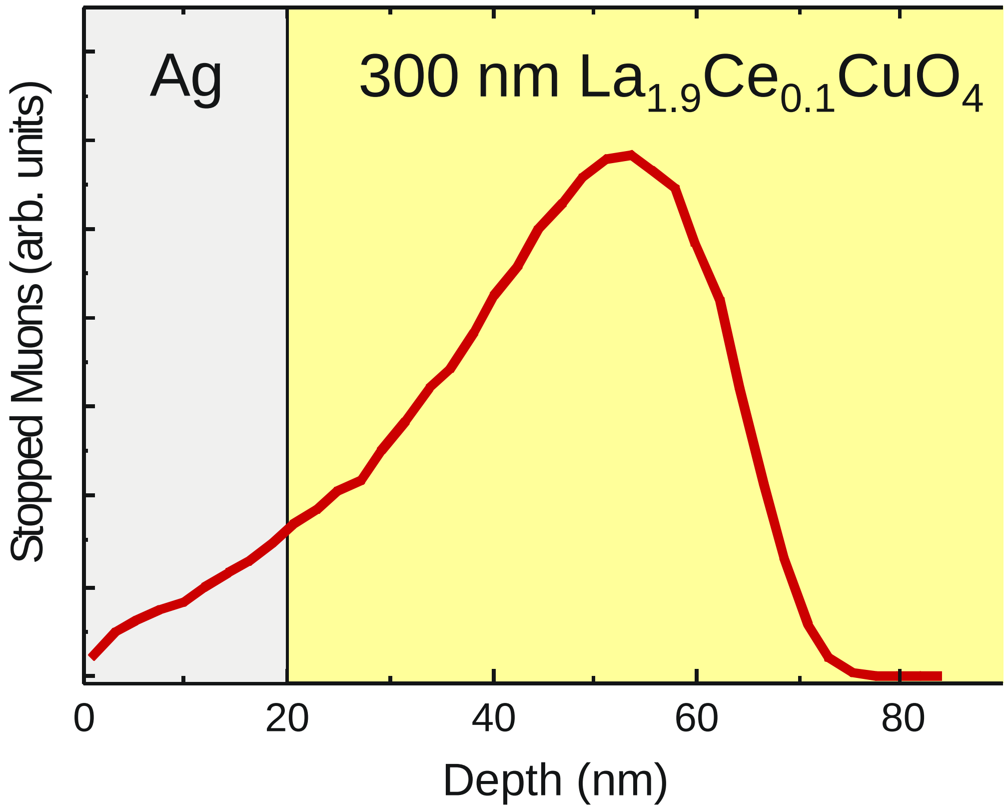


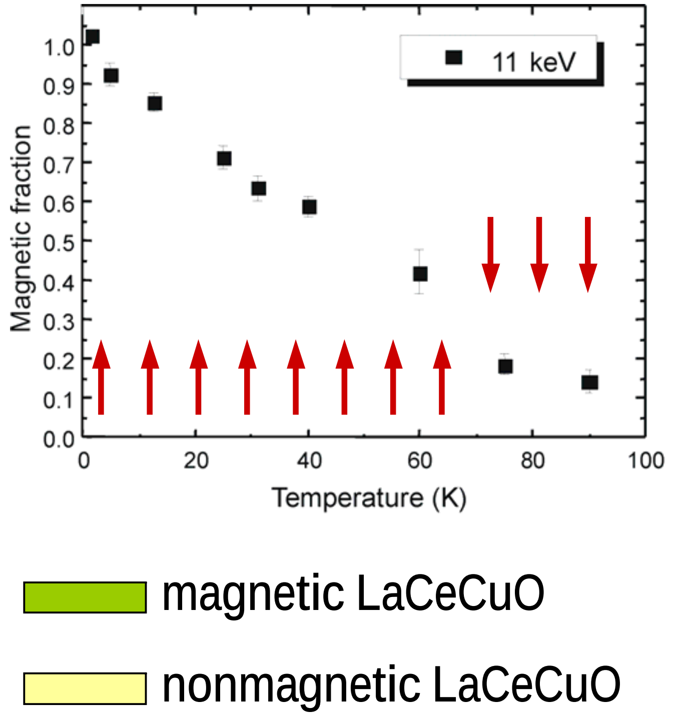


Scenario 2:

Temperature-dependent magnetic layer thickness

ZF-LEμSR using 11keV muons



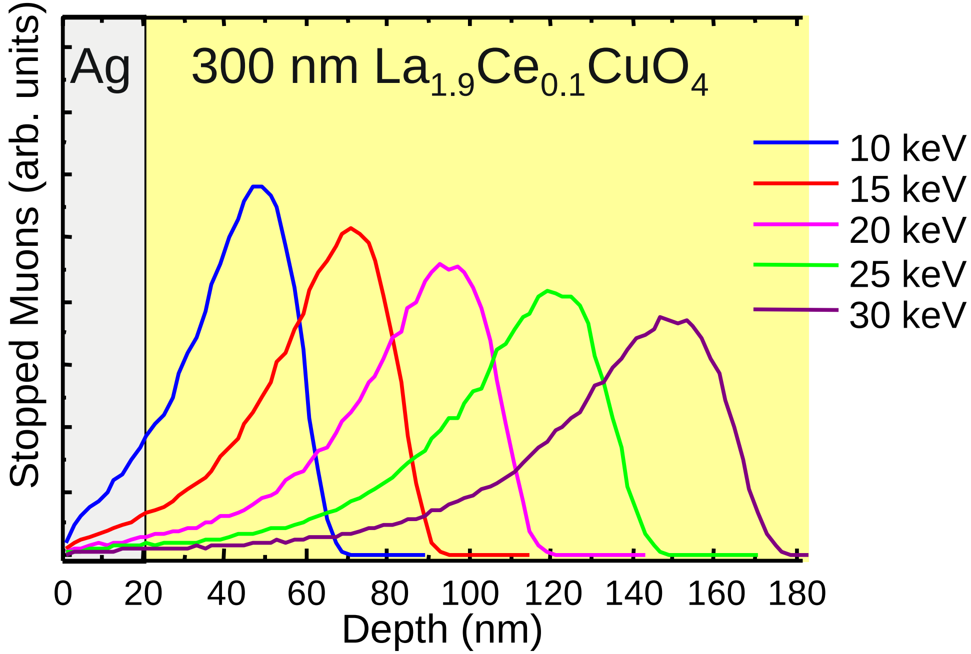


Scenario 2:

Temperature-dependent magnetic layer thickness

Depth-selective ZF-LEμSR

LE-μSR at controllable depth of the sample:



⇒ Magnetism is concentrated at the Ag/LaCeCuO interface

The thickness of the magnetic layer decreases with temperature

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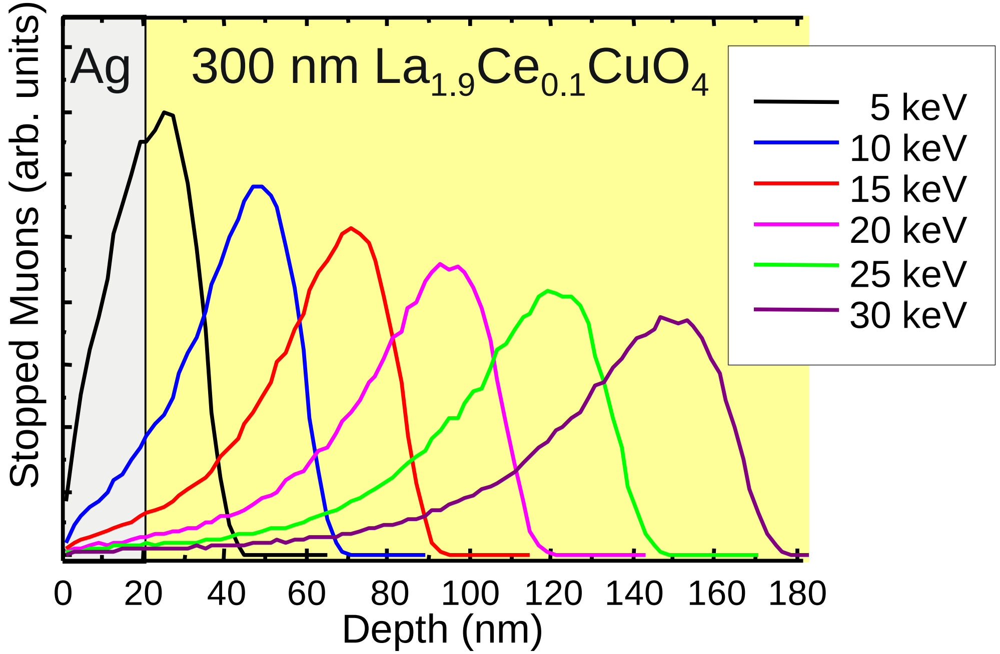

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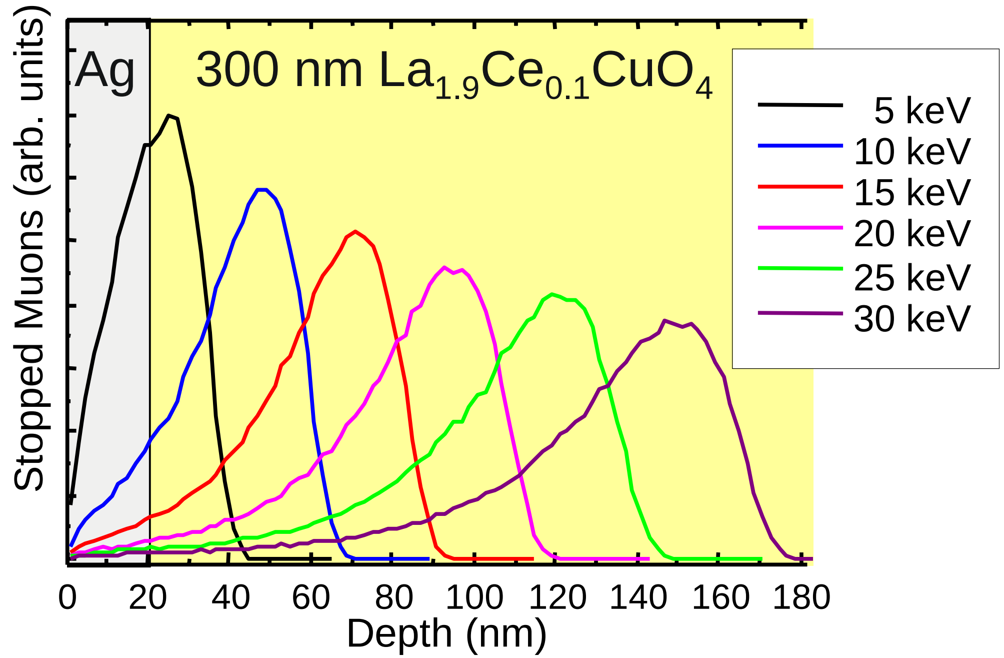

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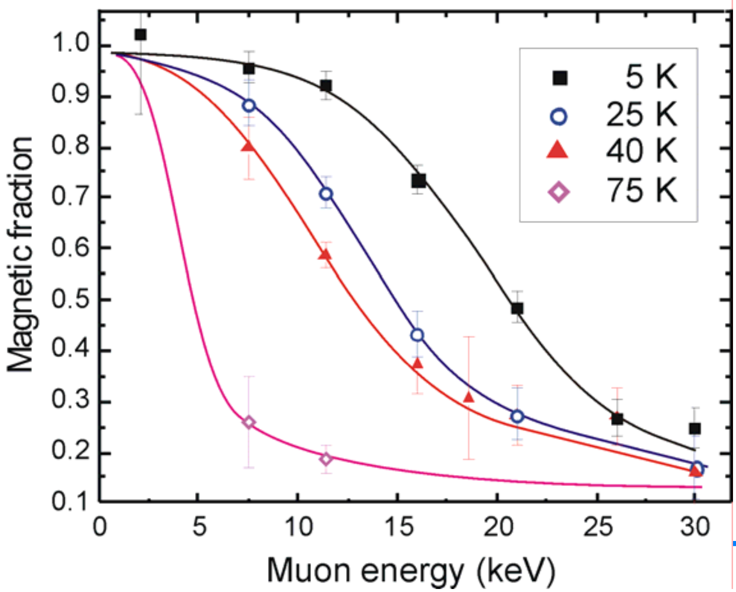

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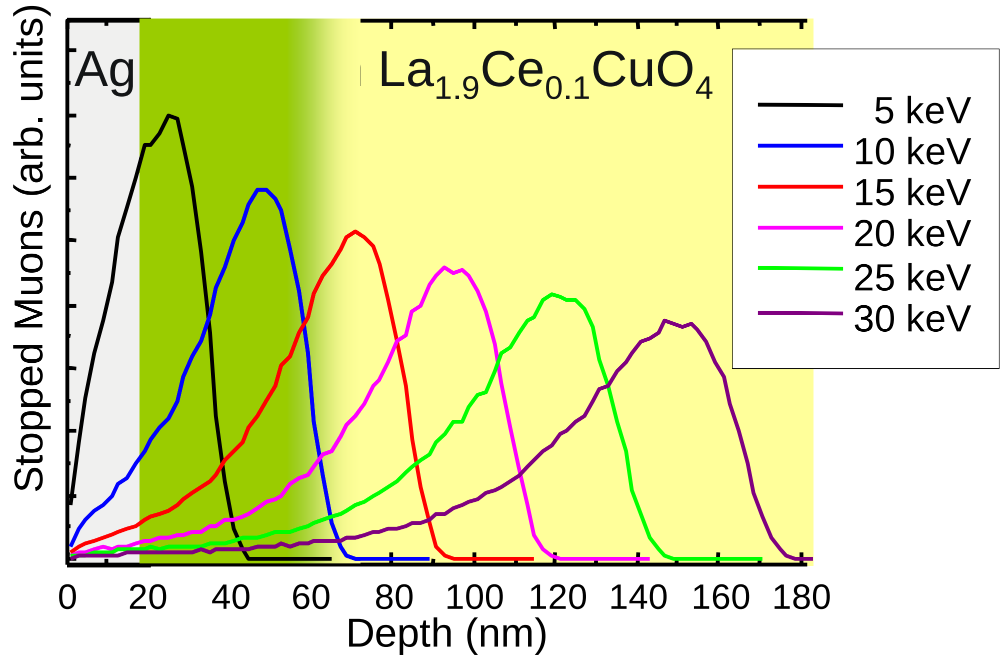

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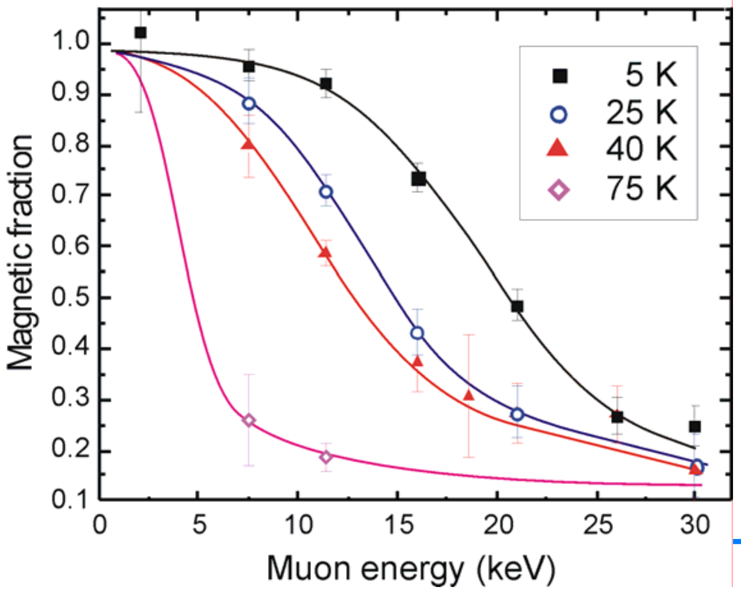

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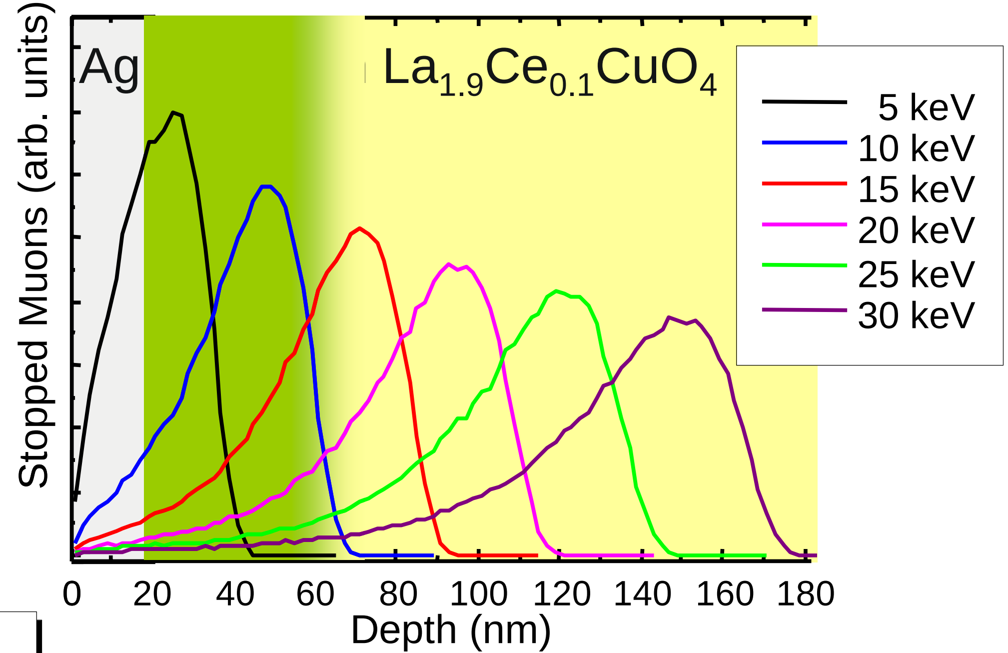

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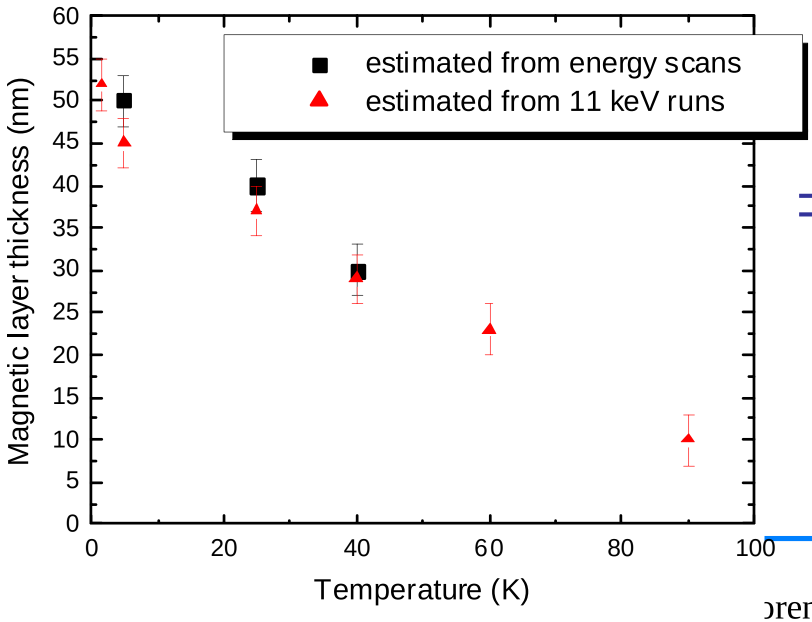

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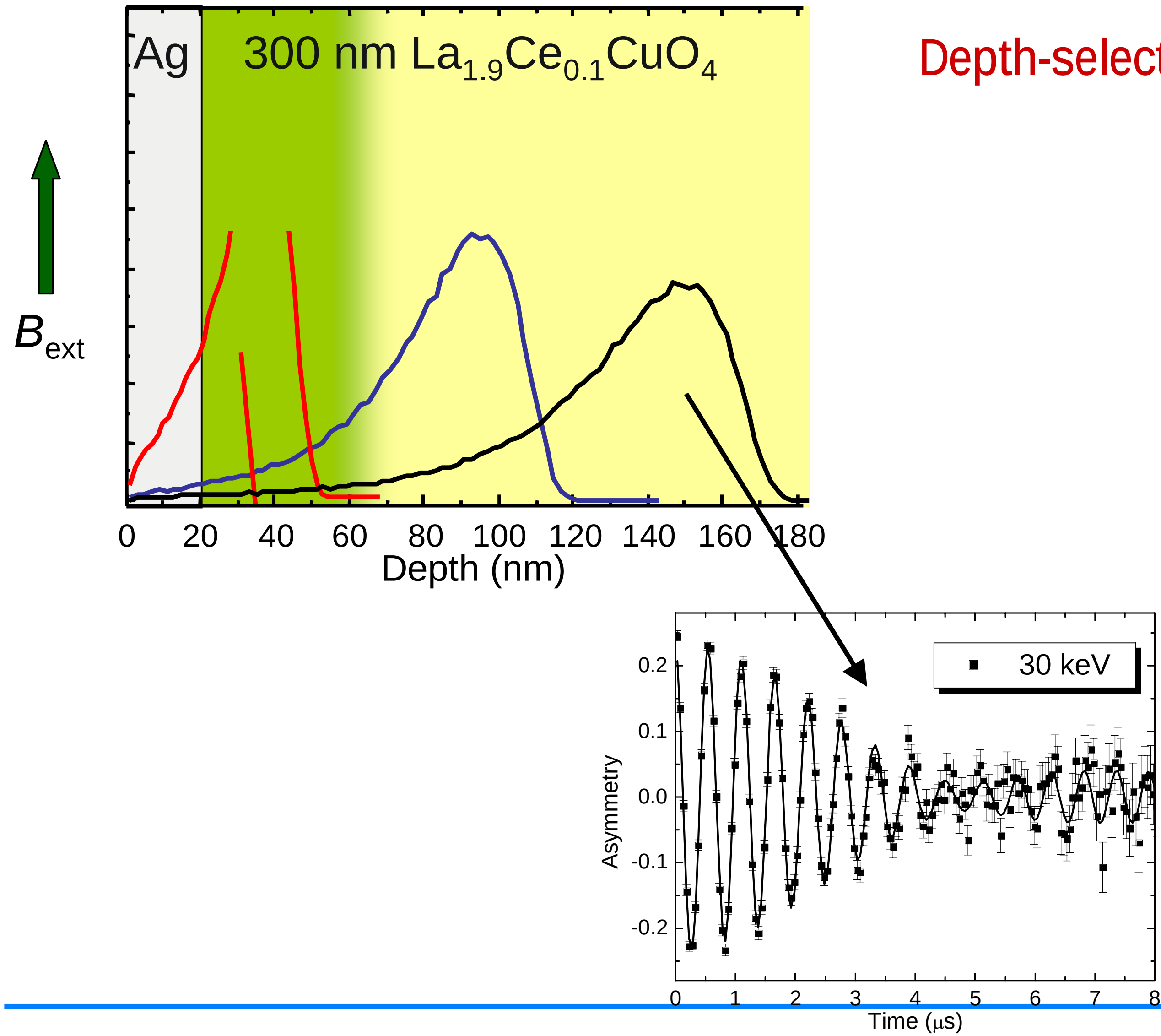
Superconducting Properties

Depth-selective TF-μSR



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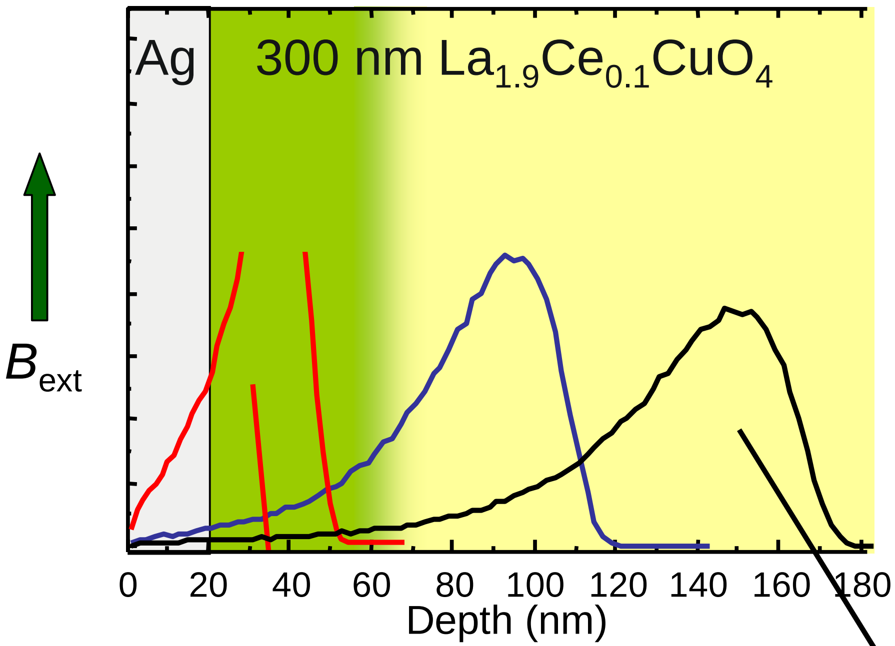
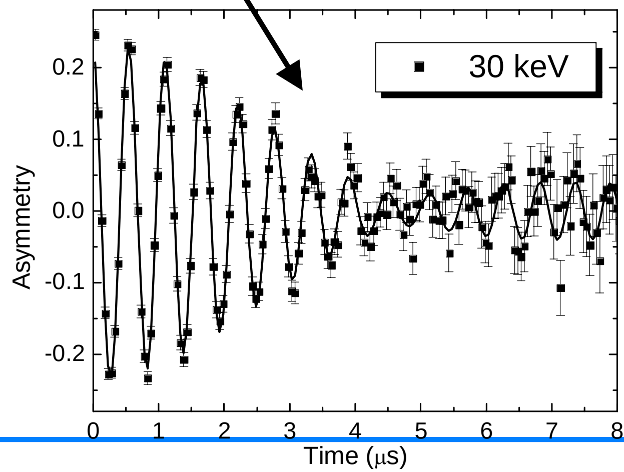


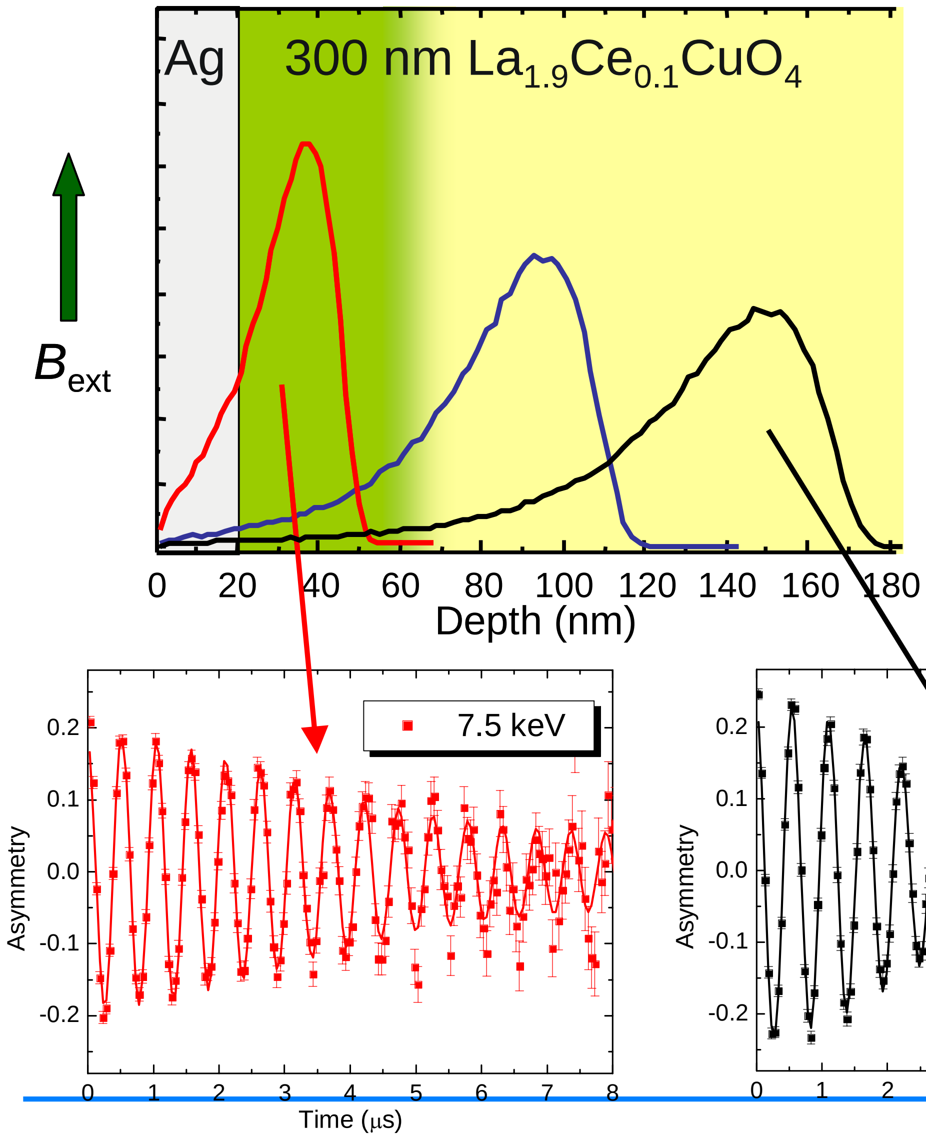


Depth-selective TF-μSR

1. ZFC to $T = 5$ K
2. Magnetic field $B_{ext} = 140$ G (parallel to the surface)

Material provided by H. Luetkens, A Amato, E Morenzoni, D Herlach

Superconducting Properties



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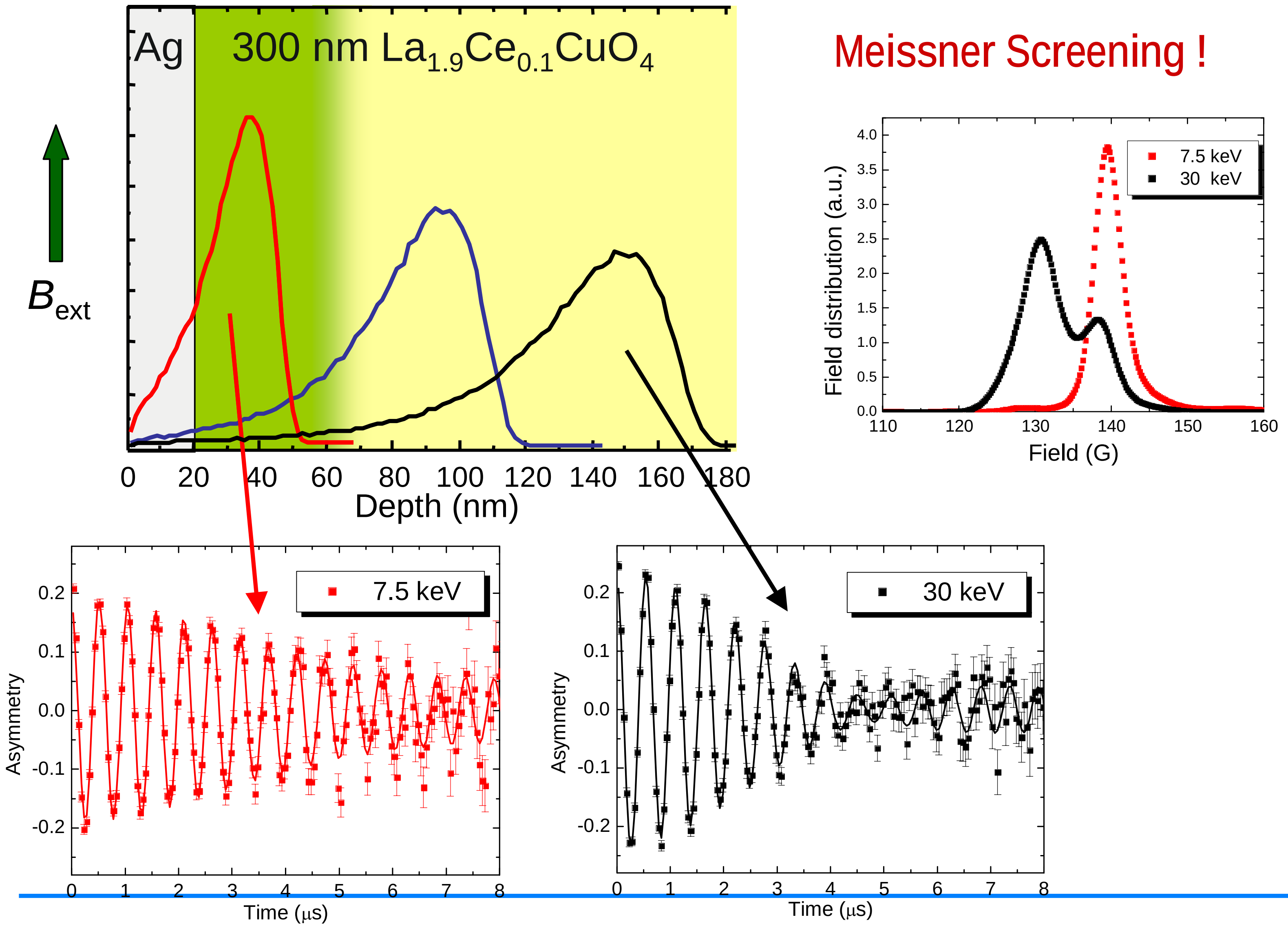

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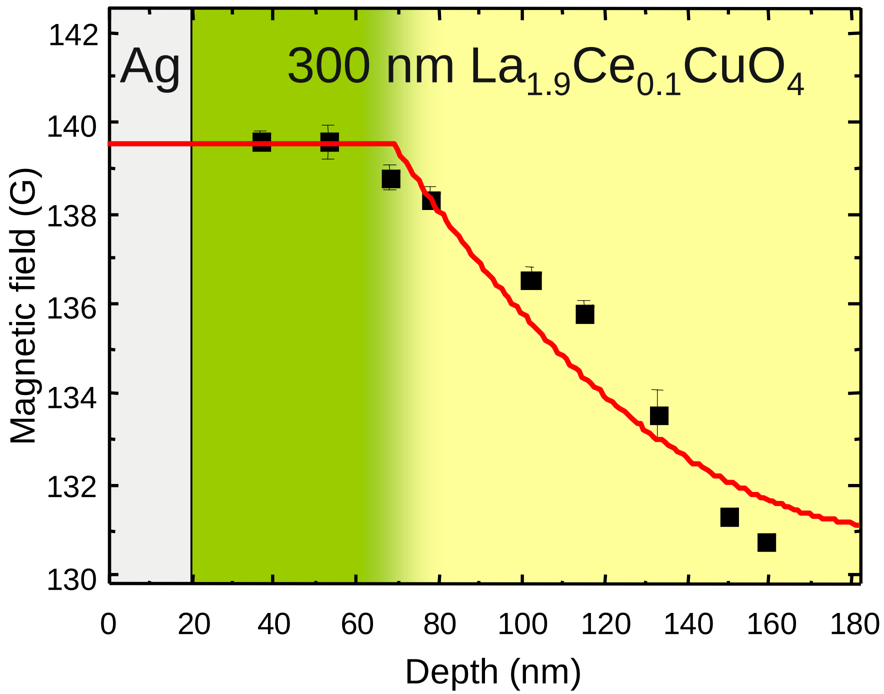
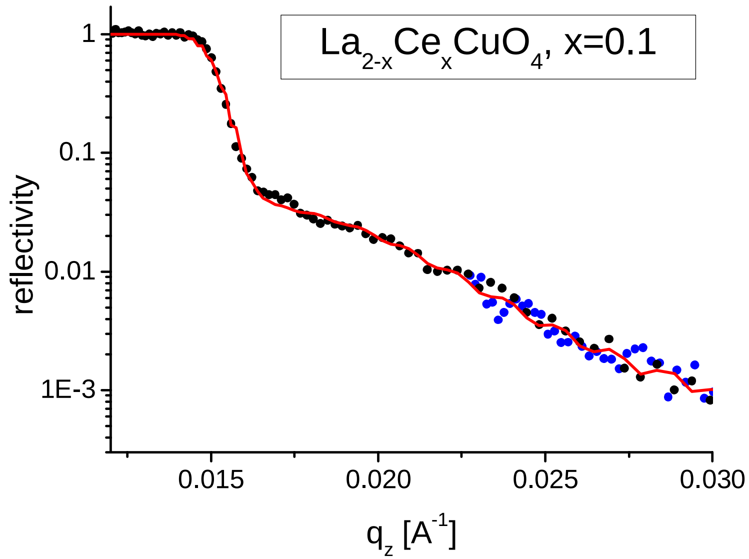
Magnetic Field Profile

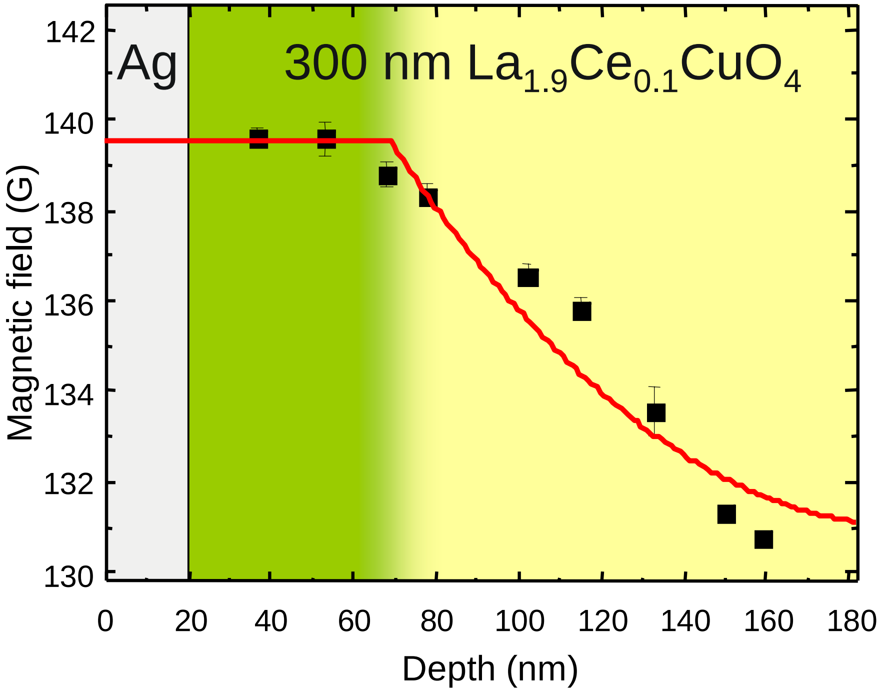


Neutron reflectivity:

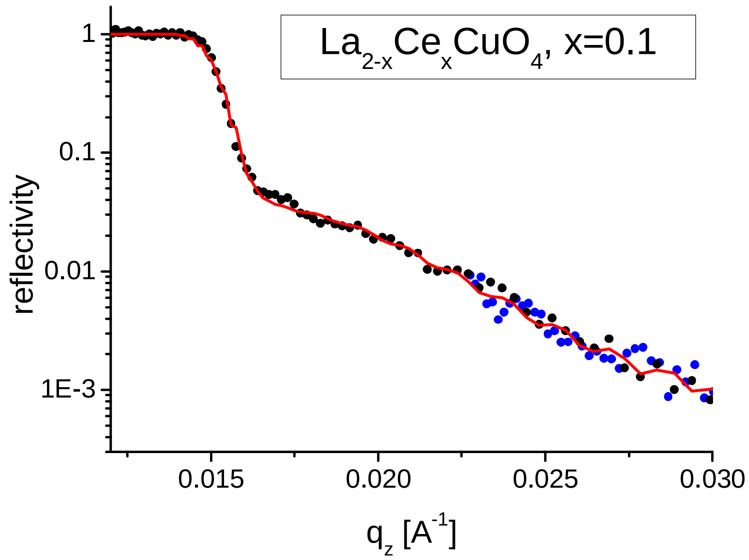


Material provided by H. Luetkens, A Amato, E Morenzoni, D Herlach

Magnetic Field Profile

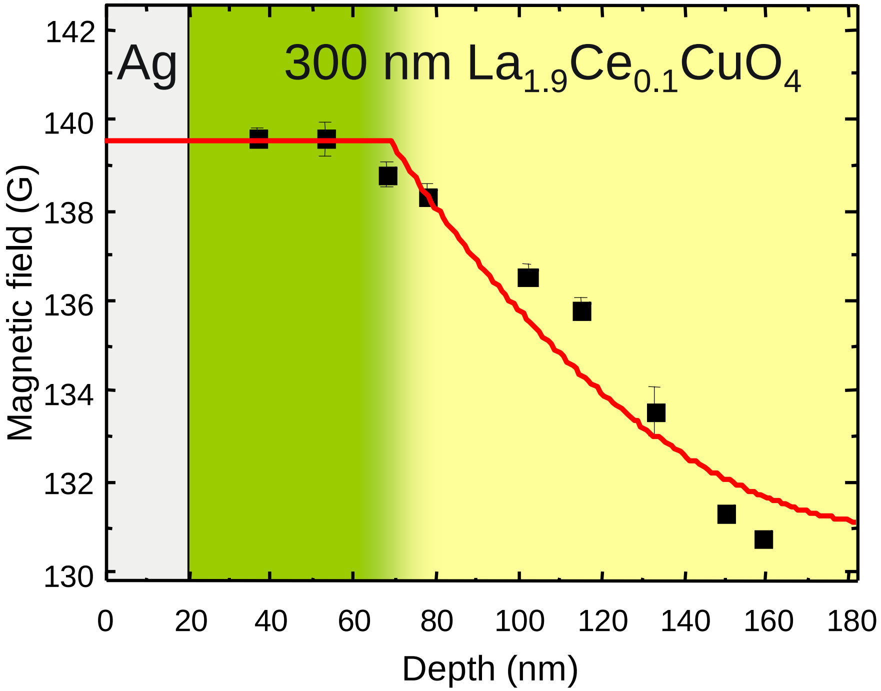


Neutron reflectivity:



- Effective Meissner screening $\Rightarrow$ bulk superconductivity
- Magnetic penetration depth $\lambda \approx 350$ nm
- Complementary PNR measurements in progress

Magnetic Field Profile



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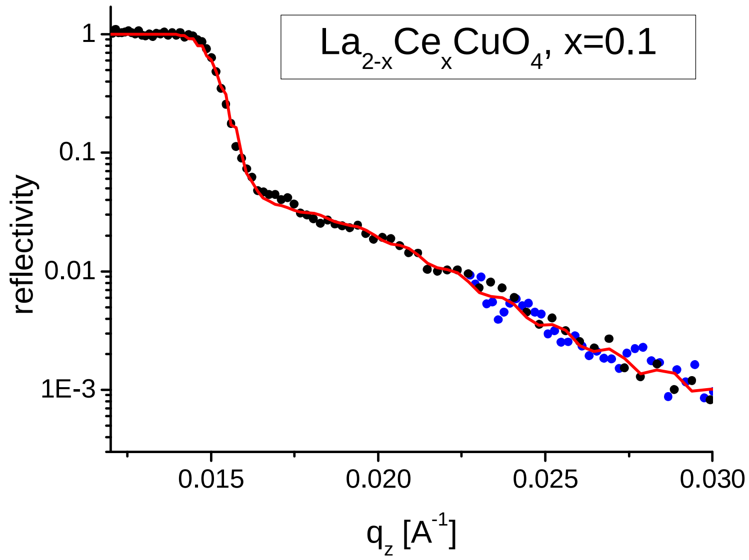

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Coexistence of magnetism and superconductivity in the same sample

Neutron and Muon portal – a key web-site

The key web-site for information on and links to neutron and muon sources World-wide is:

http://www.neutron-eu.net/

This site also contains information on how to get access to the European Facilities

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