International Advanced School for Muon Spin Spectroscopy
2019.08.20

Internal Magnetic Field in Solids Detected with μ^-SR

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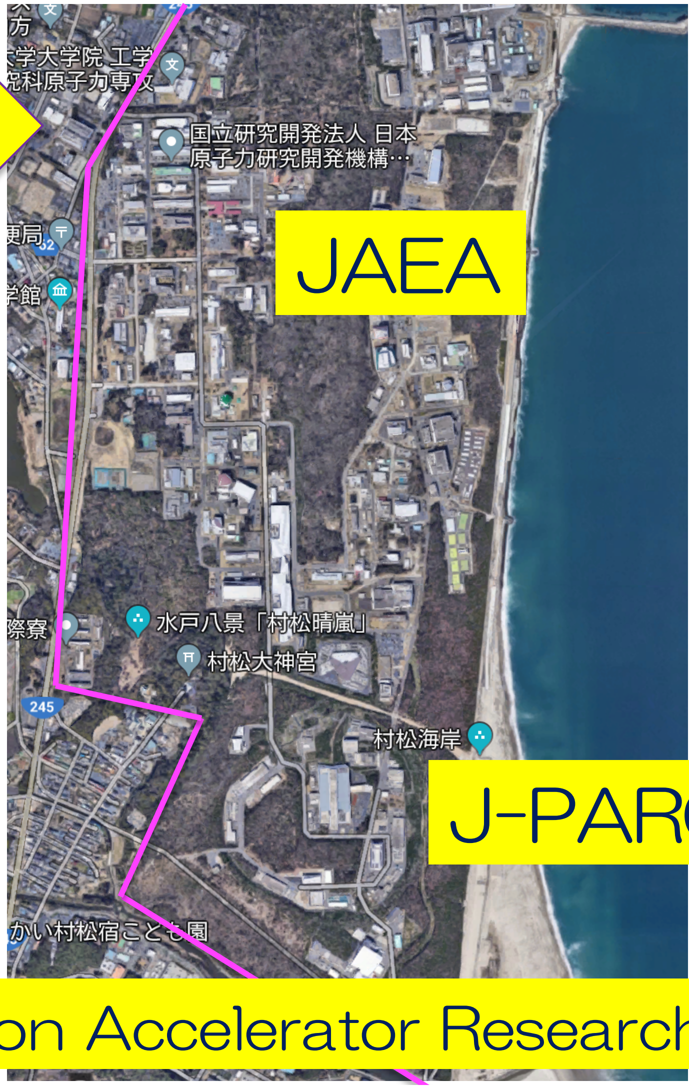
CROSS Neutron Science and Technology Center

CROSS
COMPREHENSIVE RESEARCH ORGANIZATION FOR SCIENCE AND SOCIETY

CROSS?

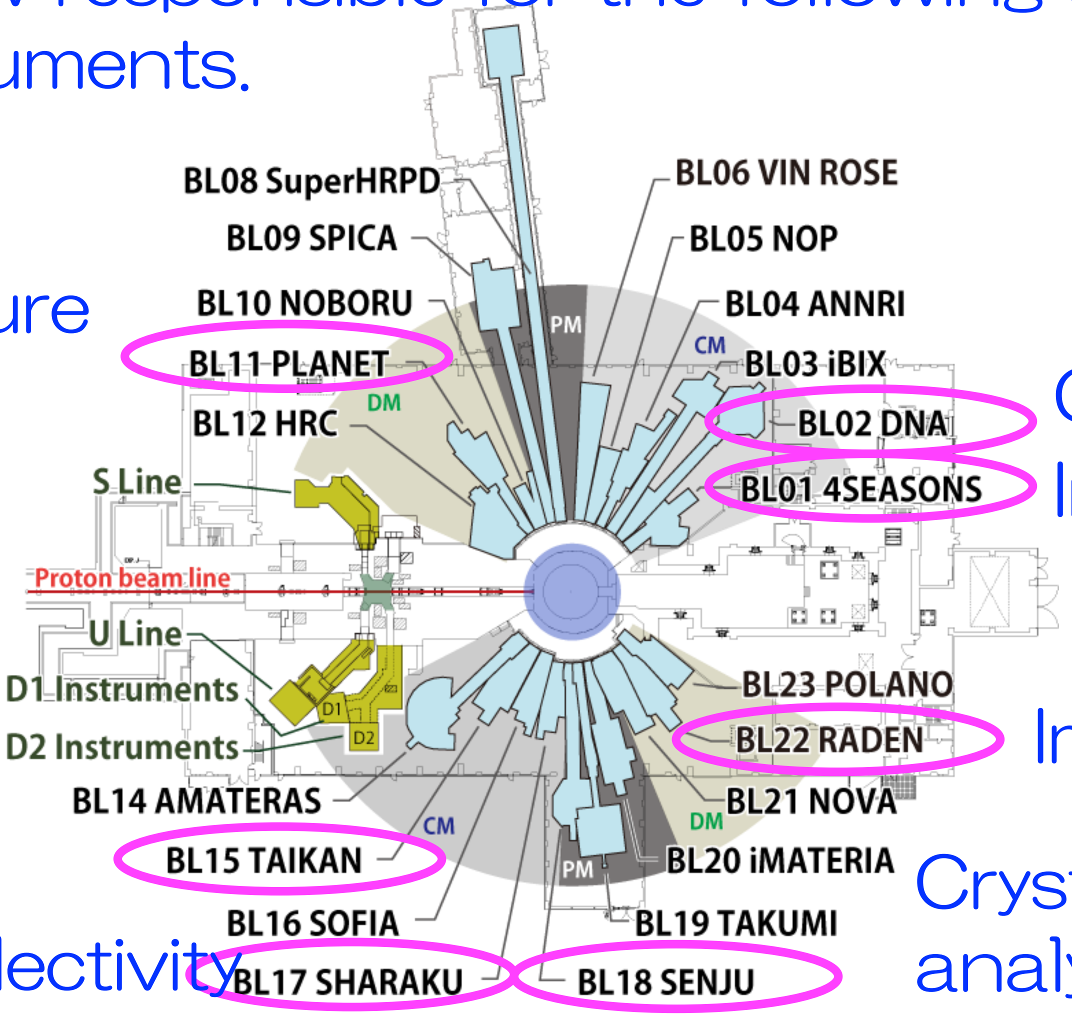
CROSS Neutron Science & Technology Center was established in 2011 to support neutron users in J-PARC.



Japan Proton Accelerator Research Complex

CROSS?

CROSS is now responsible for the following seven neutron instruments.



High-pressure diffraction

Quasielastic

Inelastic

Imaging

Small angle

Polarized Reflectivity

Crystal structural analysis

μ^+SR & μ^-SR

Advantages of μ^{+}SR

- Sensitive to local magnetic environments caused by both nuclear and electron in ZF

- Unique time window covers a gap between neutron and NMR

- Wide momentum range suitable from bulk to film samples

- Sample is not radioactivated

Disadvantages of μ^+SR

- Muon site is still ambiguous particularly at high temperatures, despite the recent progress of DFT+μ

- Implanted μ^+ may alter local environments

- Positive muon behaves as a light isotope of proton (m_μ=1/9m_p) in solids

- May not be suitable for observing hydrogen dynamics

We have μ^{-}SR!

Merits of μ^{-}SR

- Negative muon site is very clear, since it is captured by nucleus; i.e. at the lattice site
- Negative muon captured by nucleus is stable even above decomposition temperature of the target material
- Optimal tool for dynamics measurements

Difficulties in μ^-SR

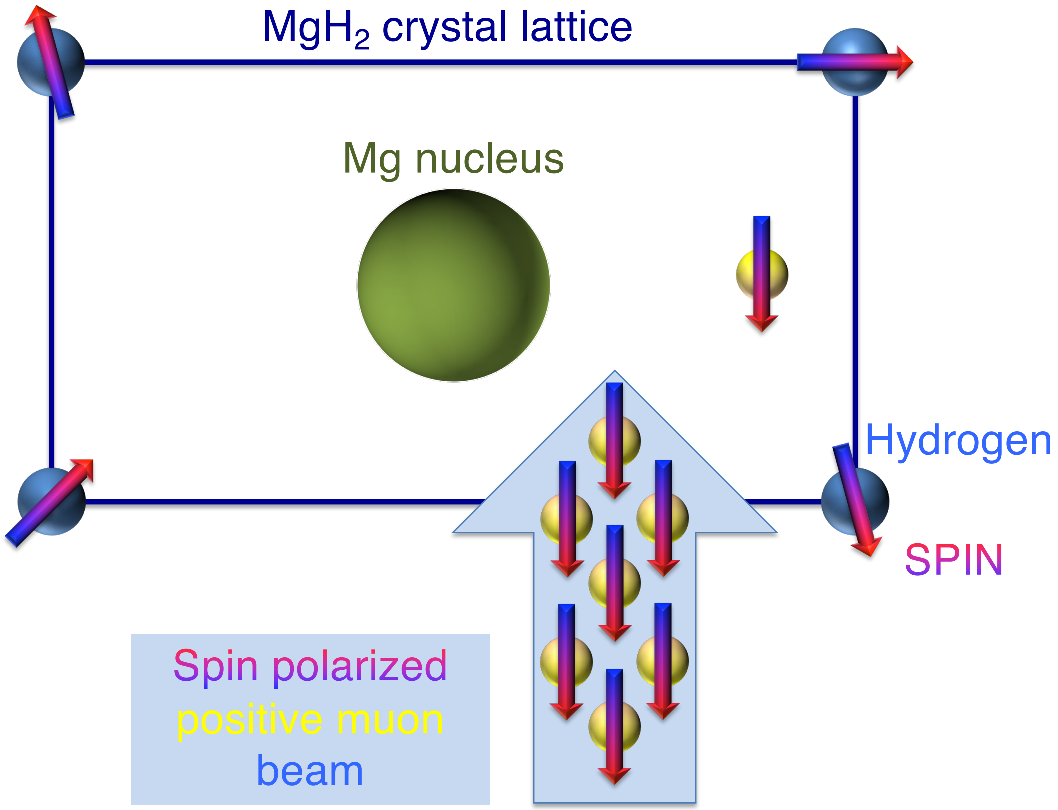
- μ^- behaves as a heavy electron (m_μ=200m_e) and is captured by a nucleus
- **decrease in spin polarization**

→need data with very high statistics

Decrease in Spin Polarization

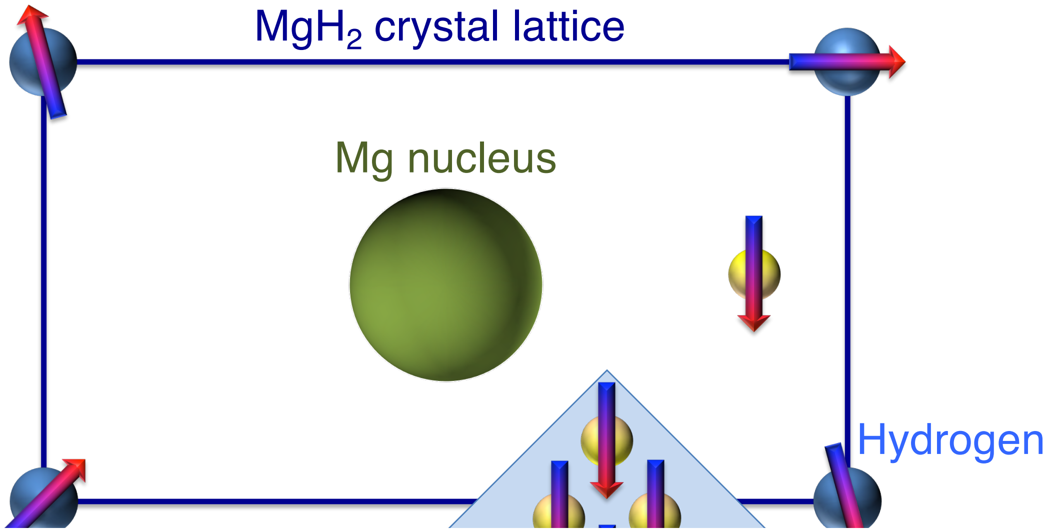
Decrease in Spin Polarization

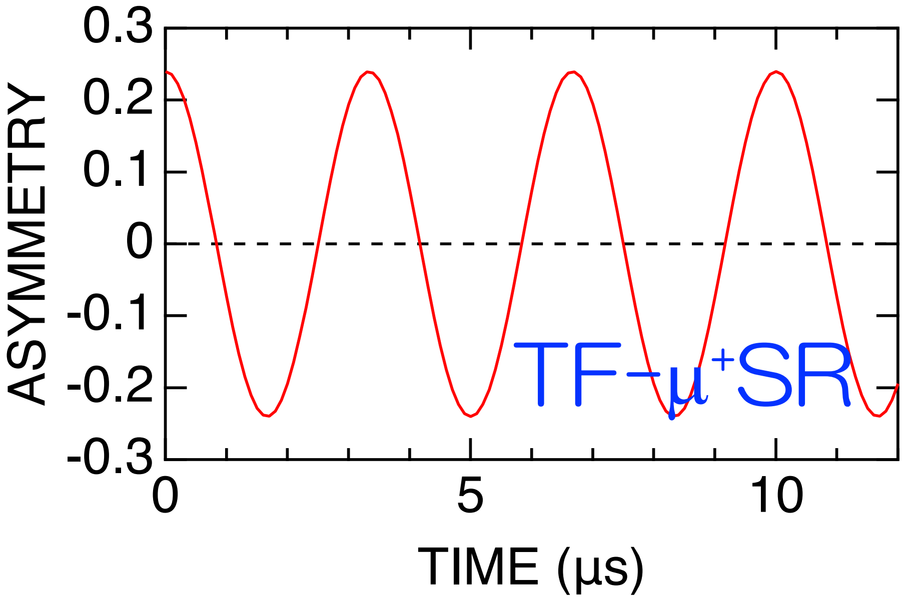
μ^+SR



Decrease in Spin Polarization

μ^+SR

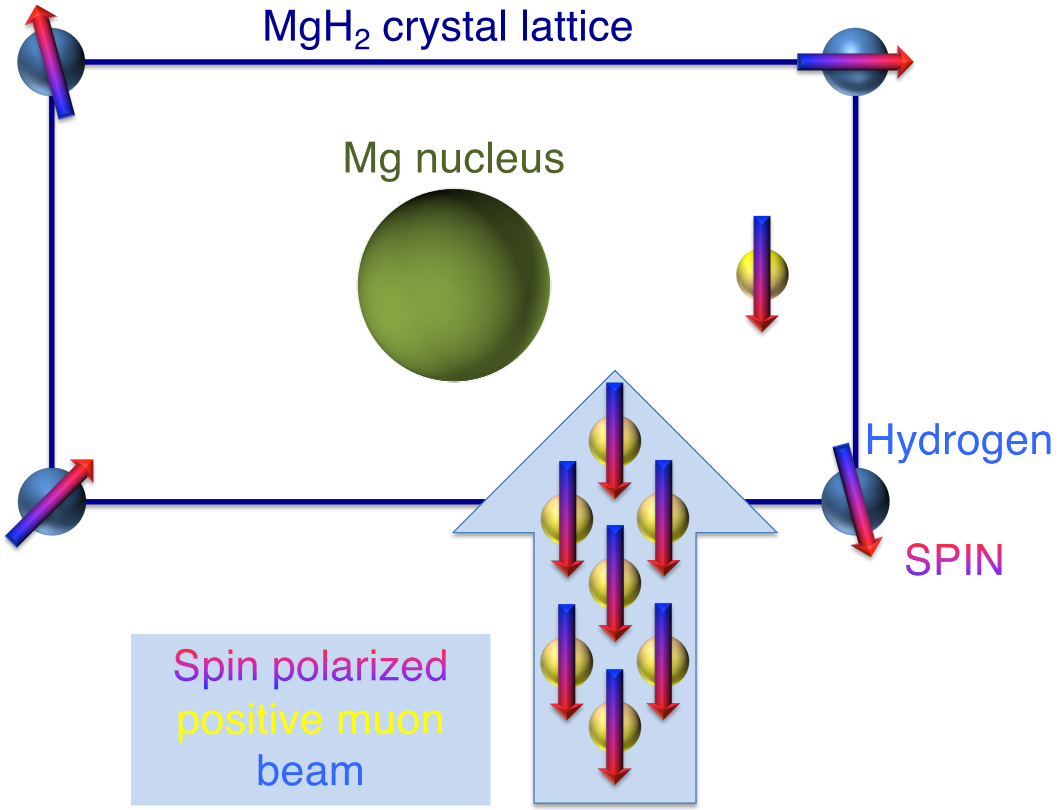




Decrease in Spin Polarization

μ^+SR

μ^-SR



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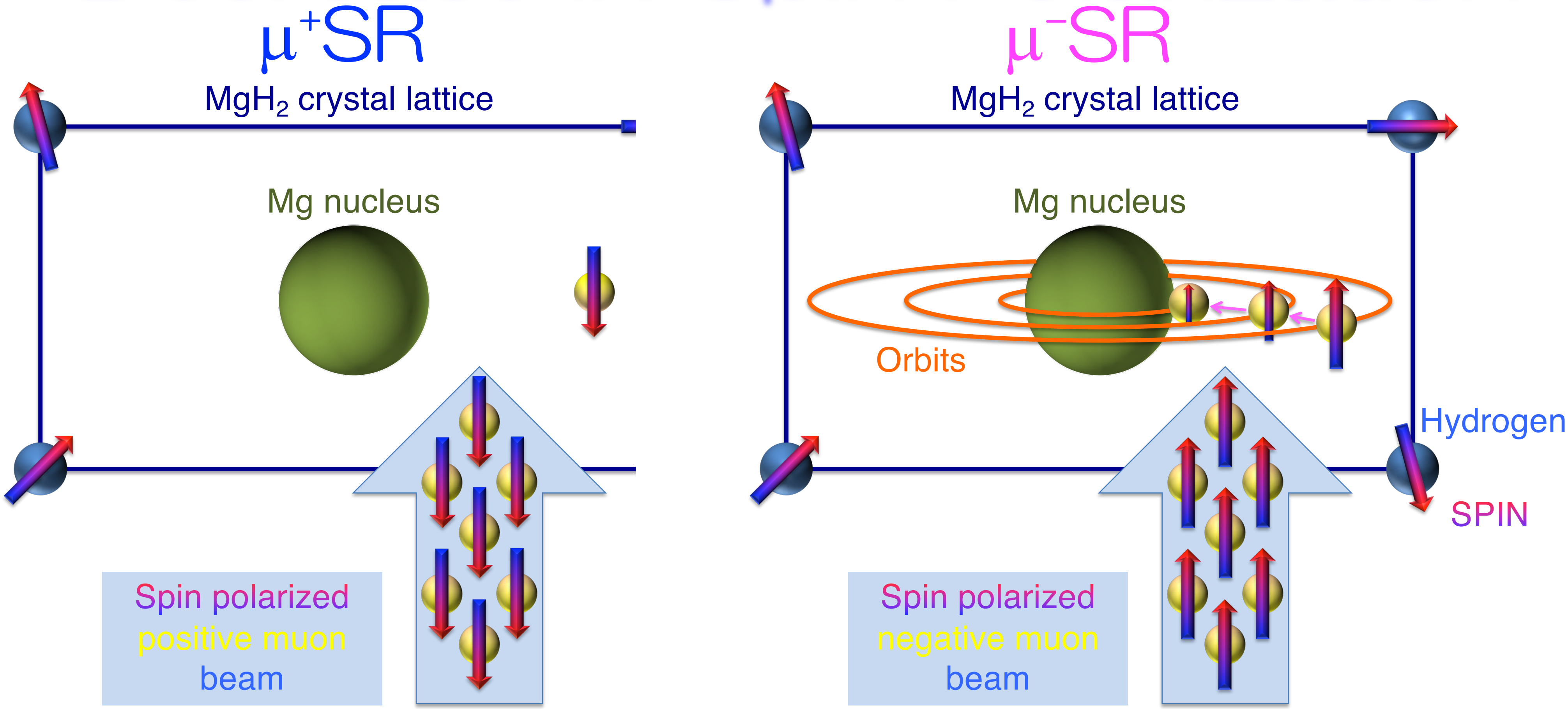

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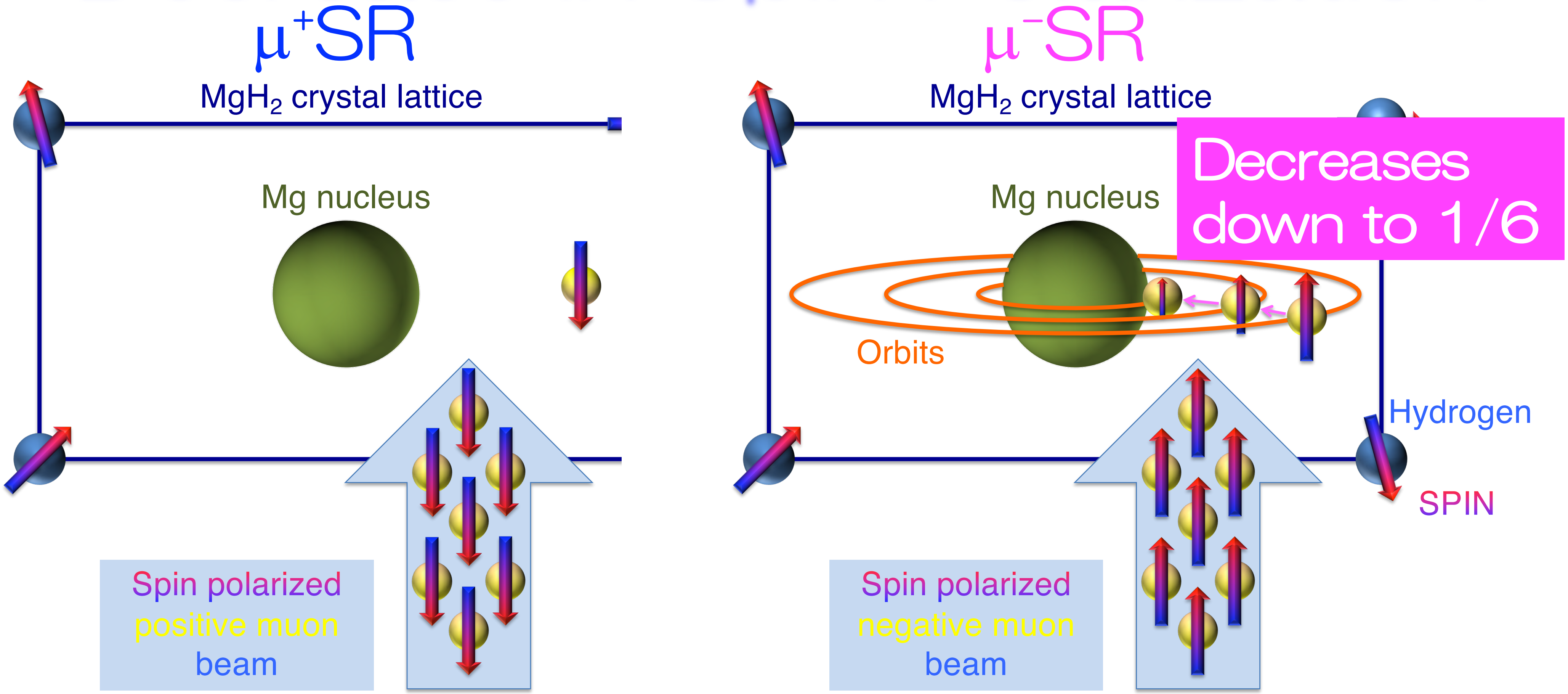
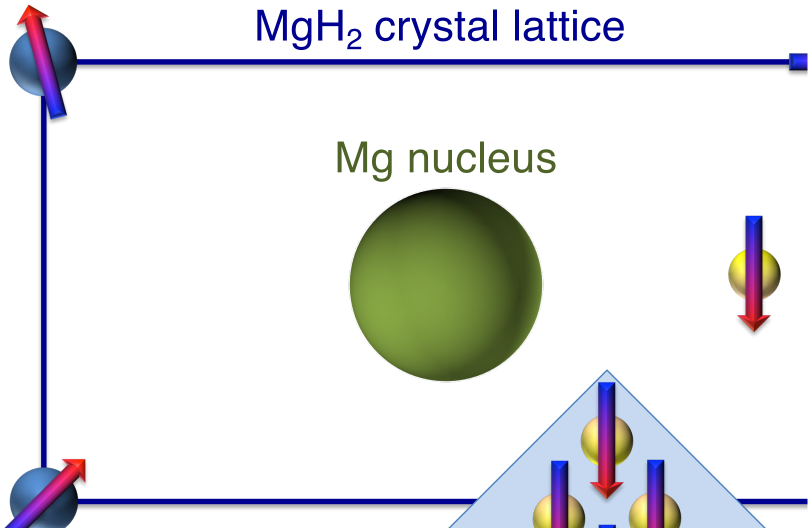
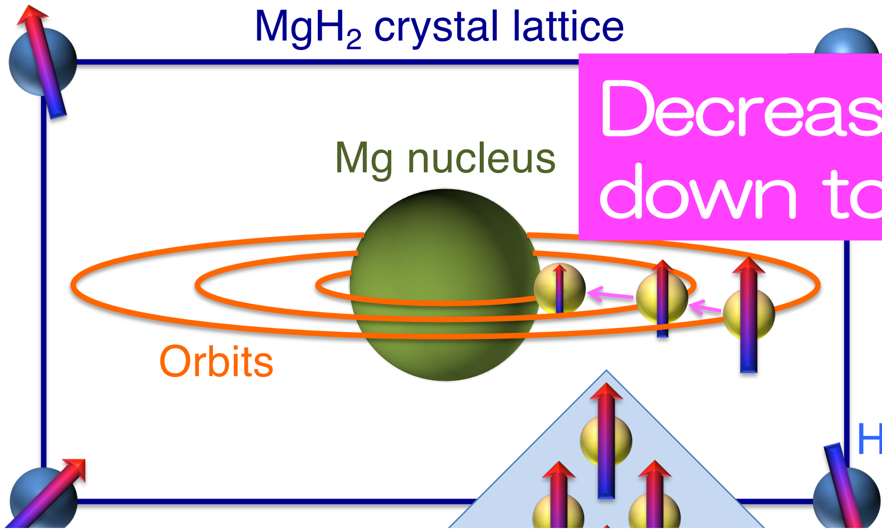


Decrease in Spin Polarization

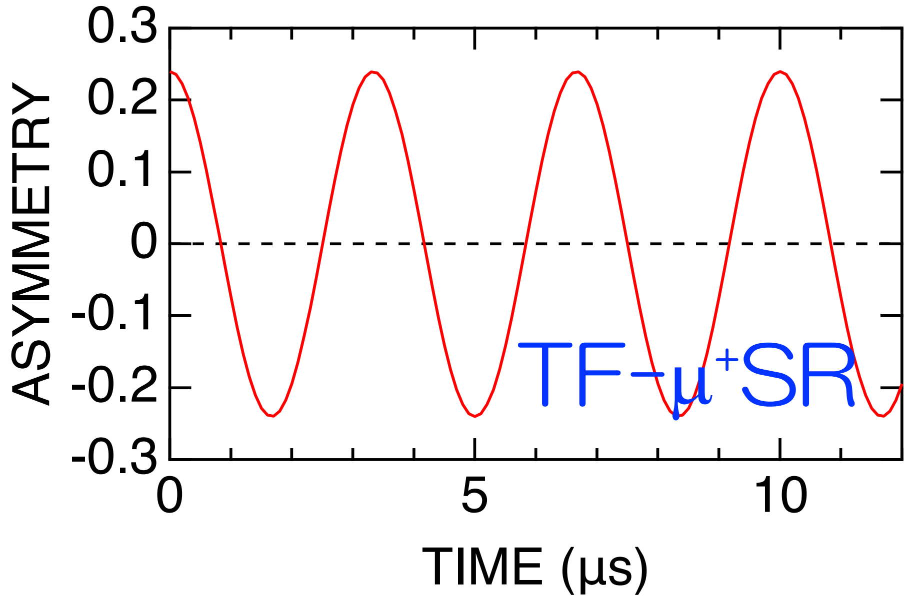
μ⁺SR

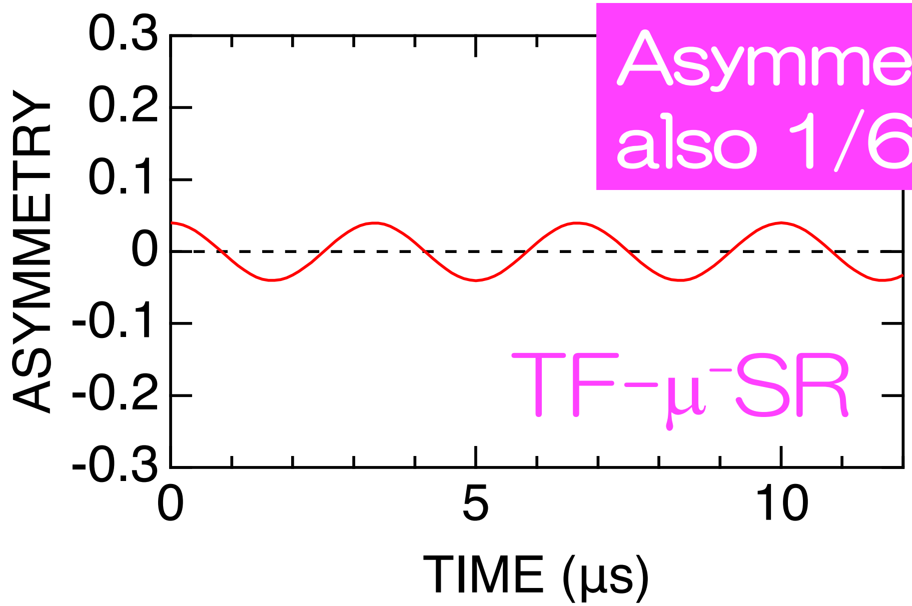


μ⁻SR



Decreases down to 1/6

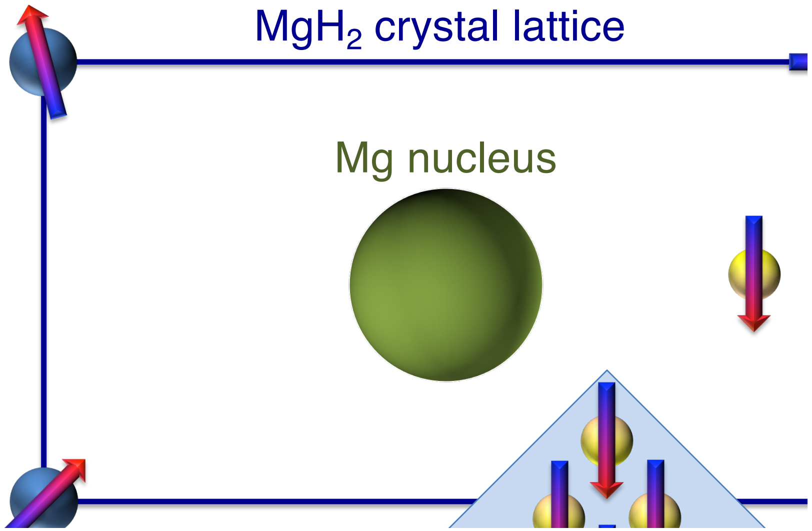




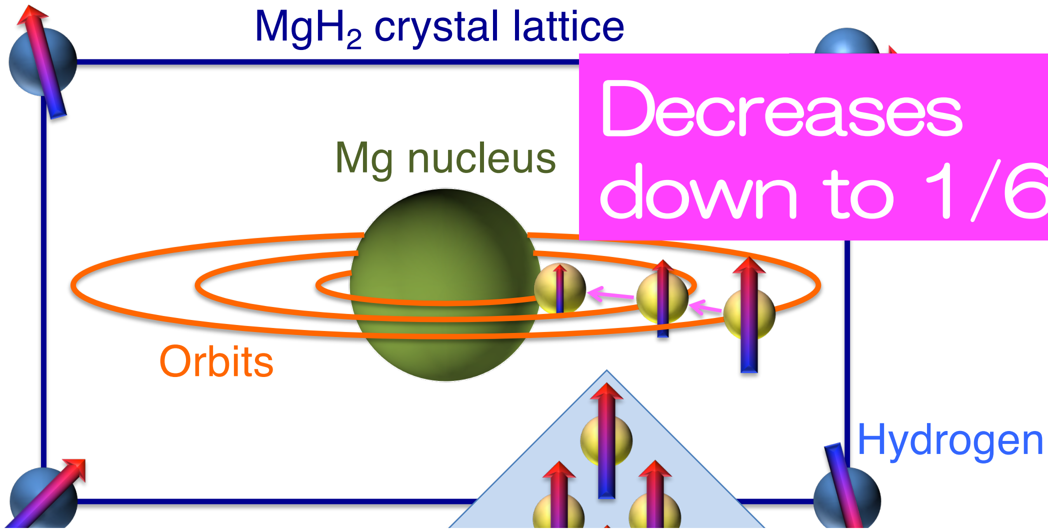
Asymmetry is also 1/6

Decrease in Spin Polarization

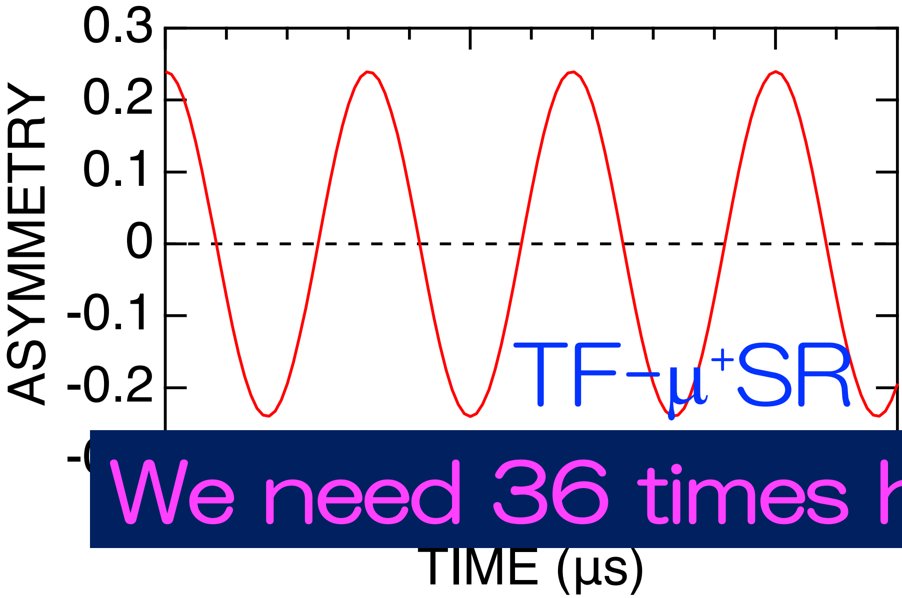
μ^+SR

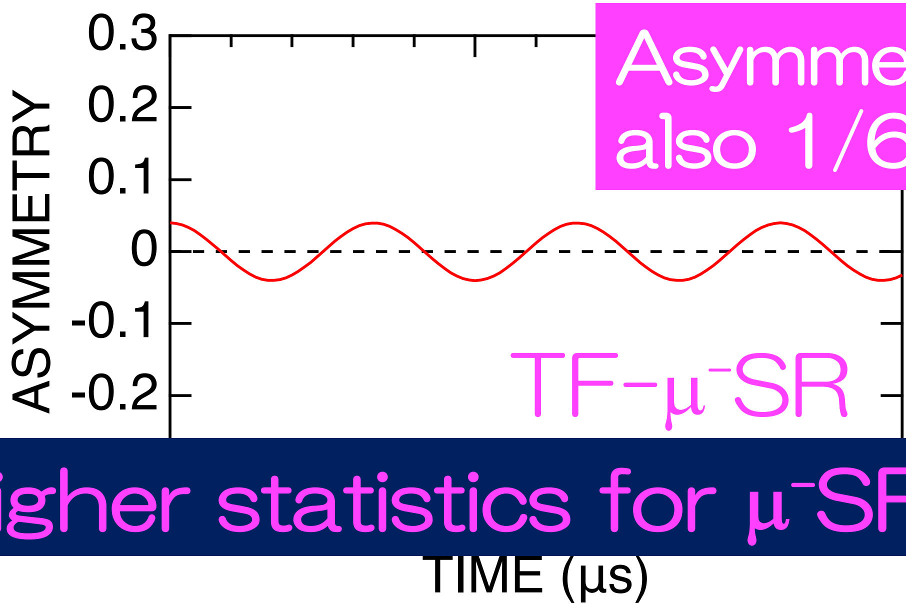


μ^-SR



Decreases down to 1/6





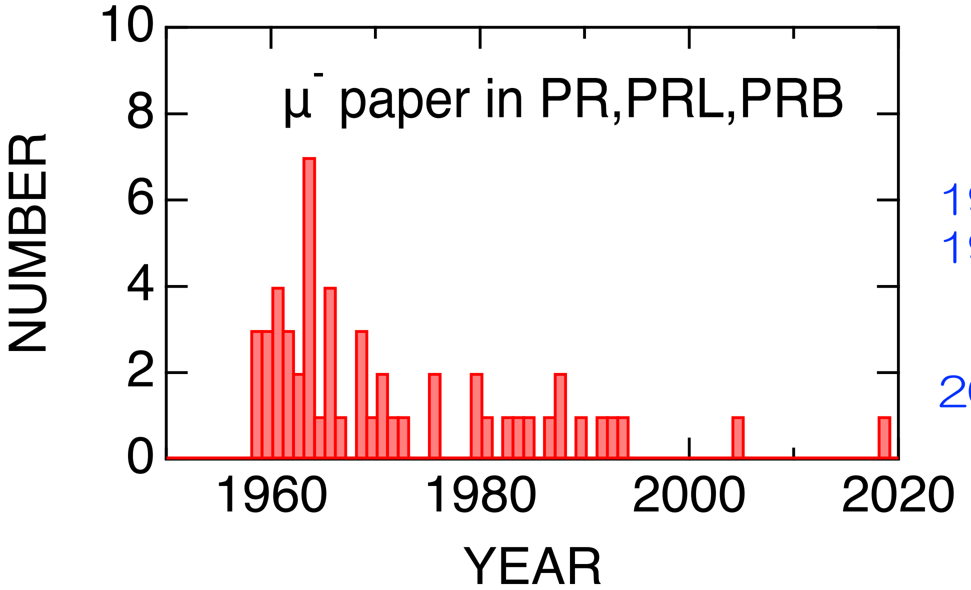
Asymmetry is also 1/6

We need 36 times higher statistics for μ^-SR.

Decrease in Spin Polarization

We need 36 times higher statistics for μ^-SR.

This is the main reason why the μ^-SR work eventually disappeared about 30 years ago.



1975 μ^-SR at O in MnO
1979 μ^-SR in Fe
2018 μ^-SR in MgH_2

μ^-SR and related papers

Decrease in Spin Polarization

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However, the combination between the intense pulsed muon beam in ISIS and J-PARC and the development of multi-detector counting system has drastically increased the counting rate of $\mu^\pm$SR.

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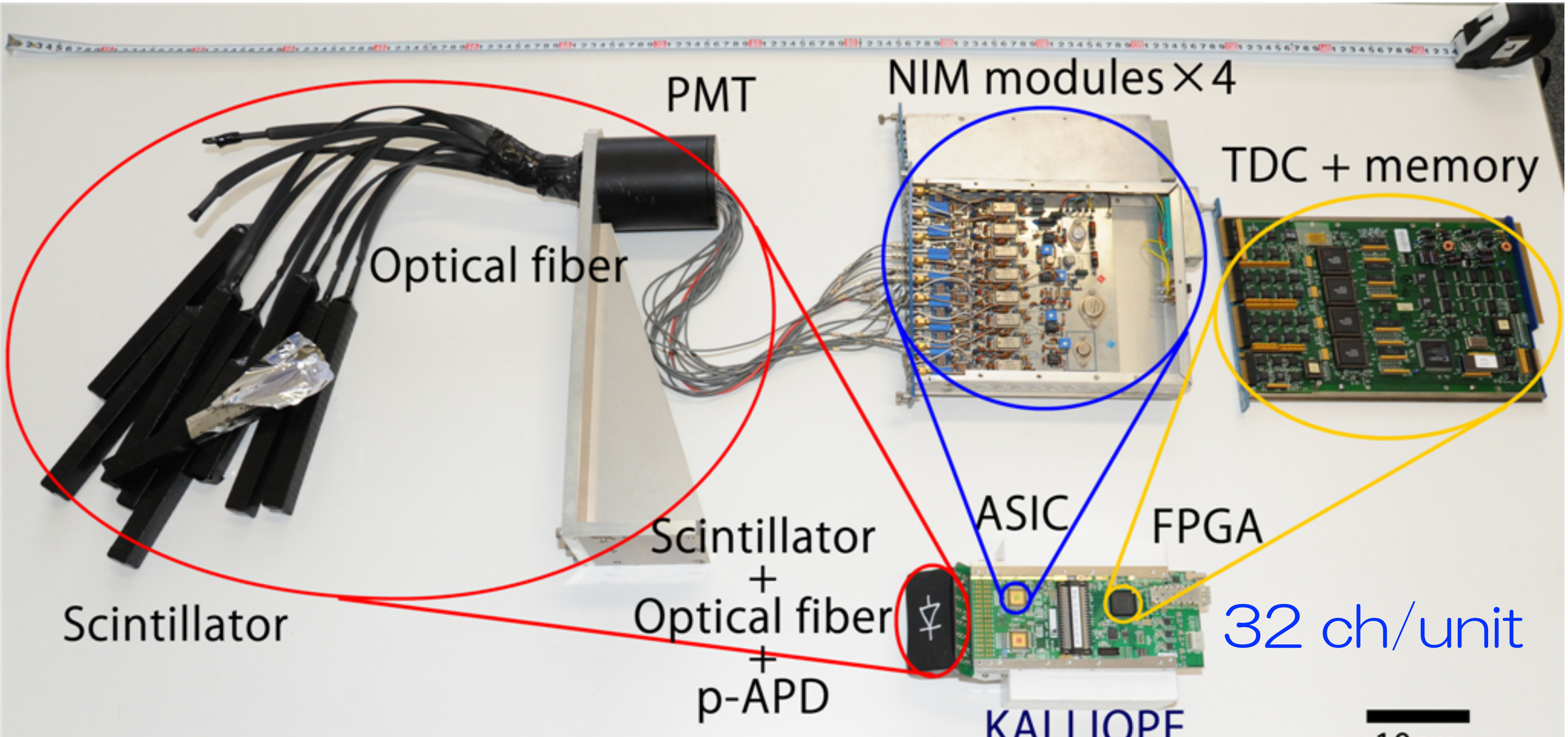

J-PARC multi-detector (KALLIOPE) system

ARGUS/ISIS 192ch, D1/J-PARC 640 ch.

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However, the combination between the intense pulsed muon beam in ISIS and J-PARC and the development of multi-detector counting system has drastically increased the counting rate of $\mu^{\pm}$SR.

This problem has been overcome!

Difficulties in μ^-SR

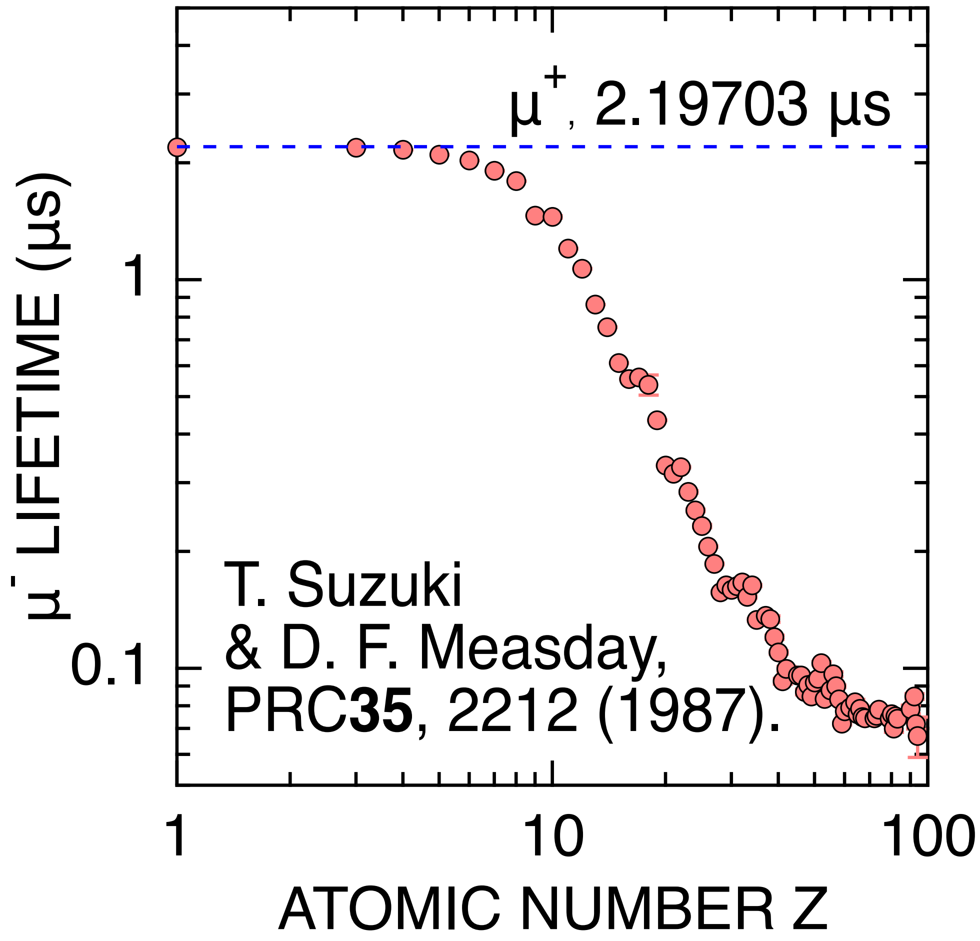
- μ^- behaves as a heavy electron (m_μ=200m_e) and is captured by a nucleus
- decrease in spin polarization

→need data with very high statistics

- μ^- lifetime depends on the nucleus, on which μ^- is captured

→data analysis is not easy

Lifetime of negative muon



Lifetime of μ^- decreases with increasing Z of nucleus on which μ^- is captured

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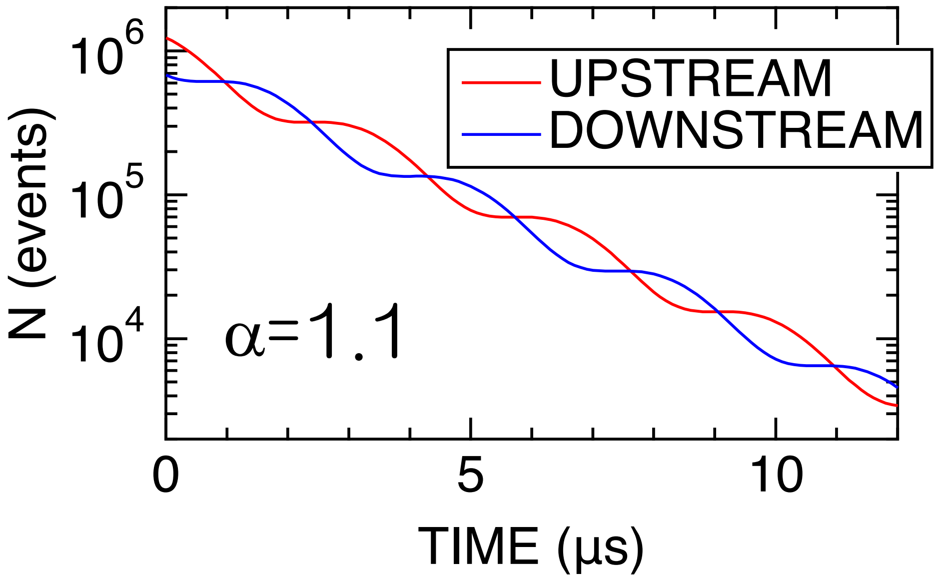
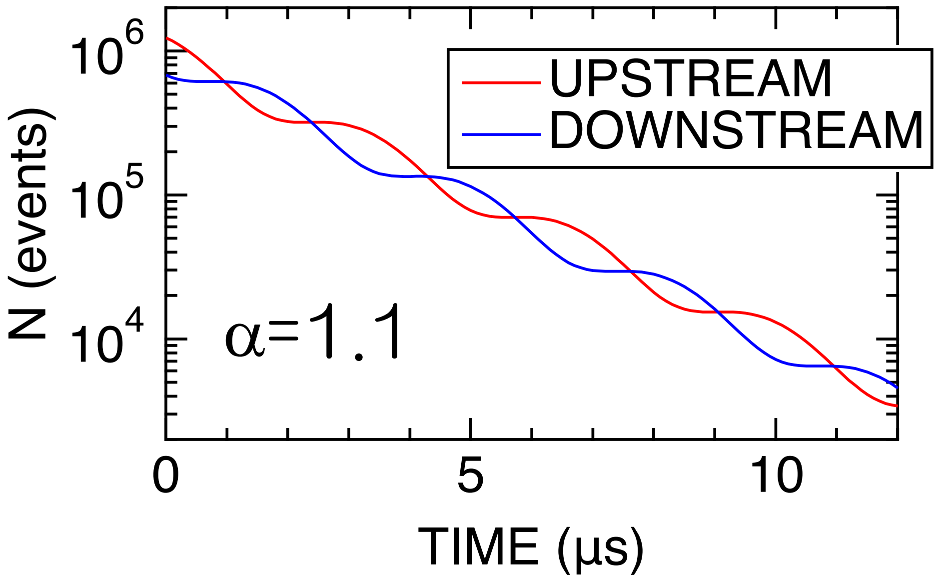
Multi-lifetime Components

μ^+SR



Multi-lifetime Components

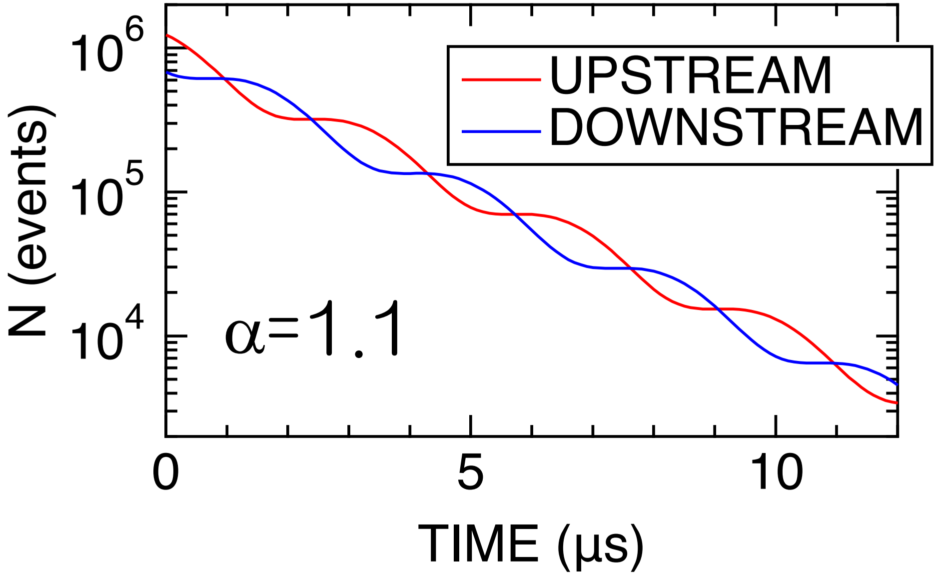
μ^{+}SR

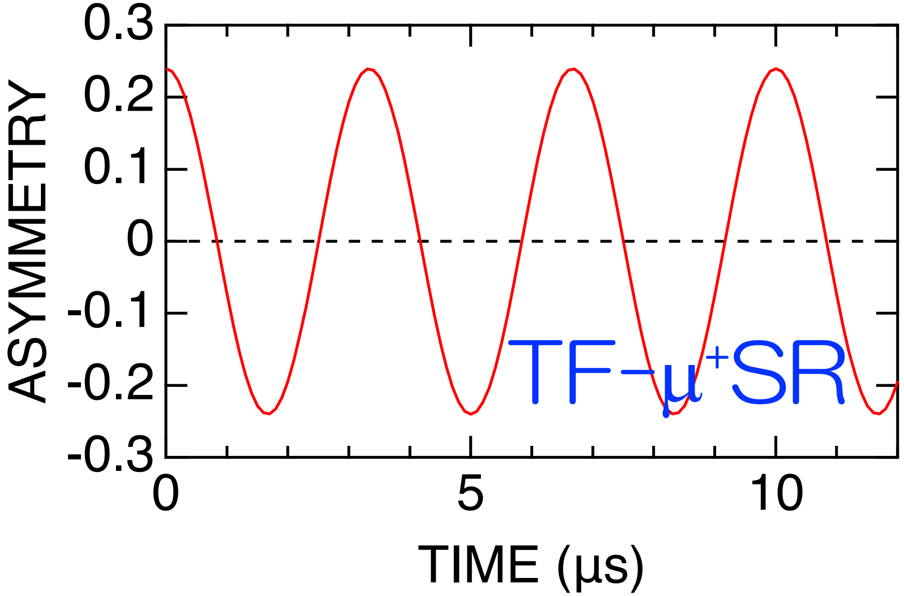


ASYMMETRY
$=(N^F-\alpha N^B)/(N^F+\alpha N^B)$

Multi-lifetime Components

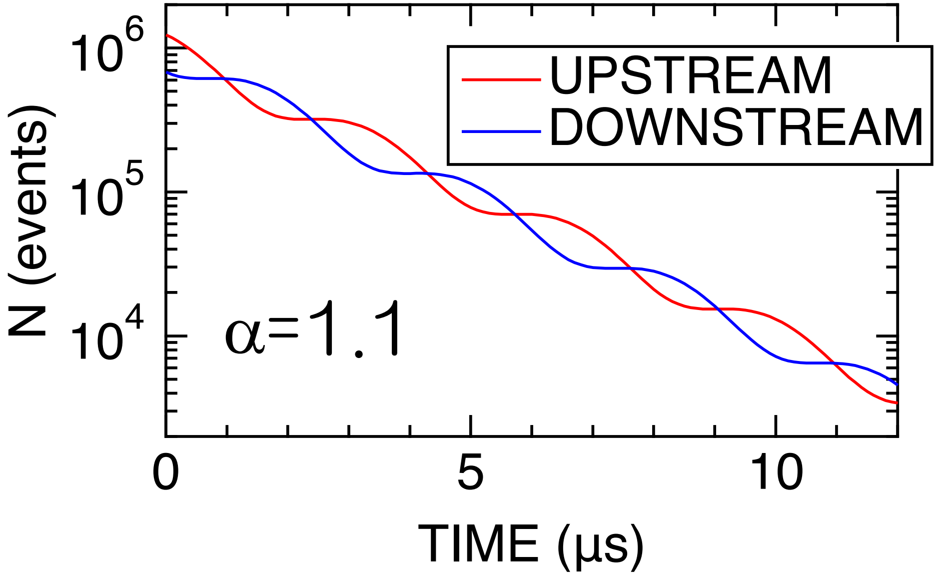
μ^+SR



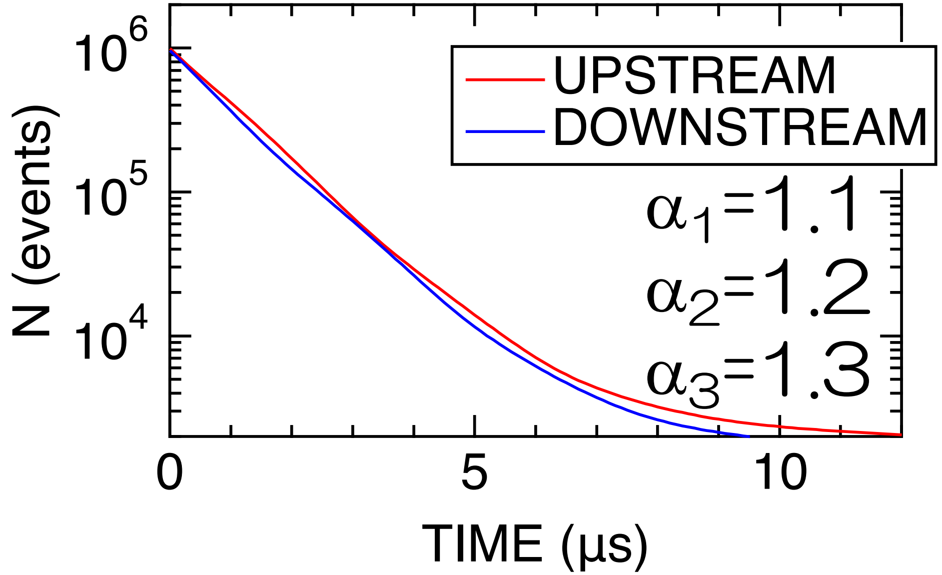


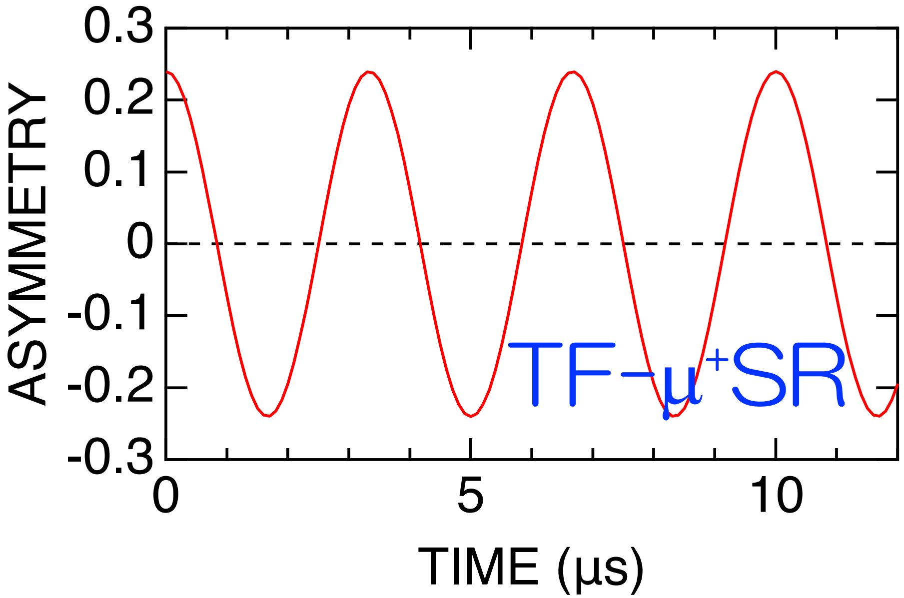
Multi-lifetime Components

μ^+SR



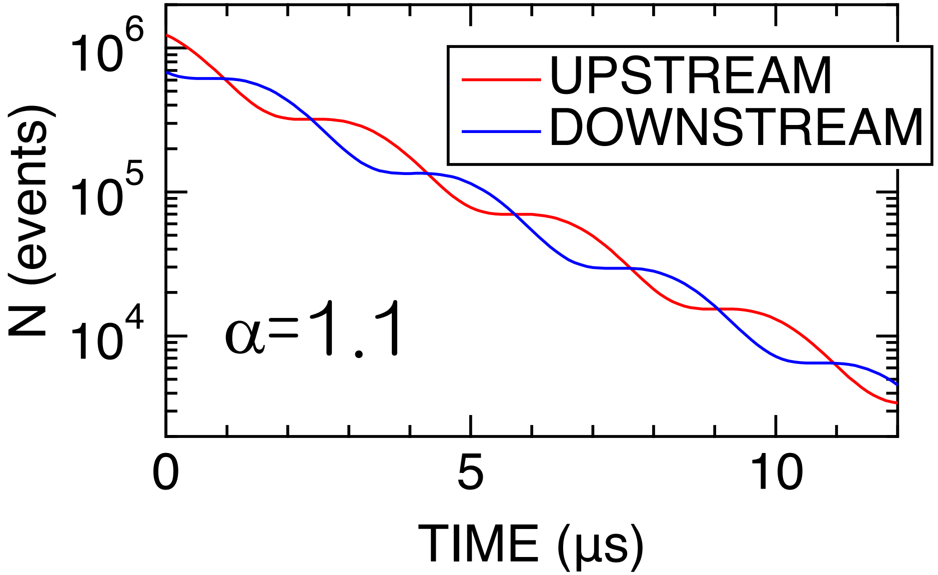
μ^-SR



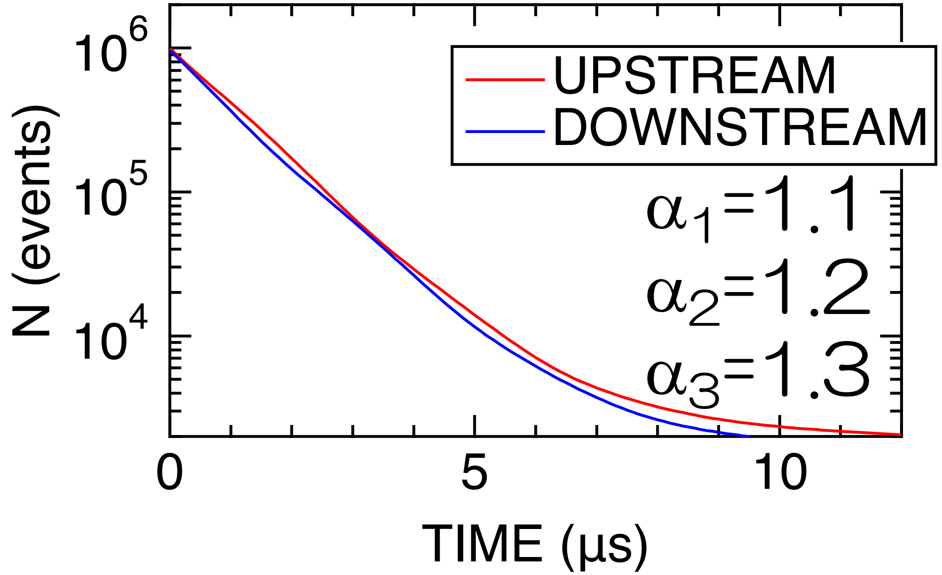


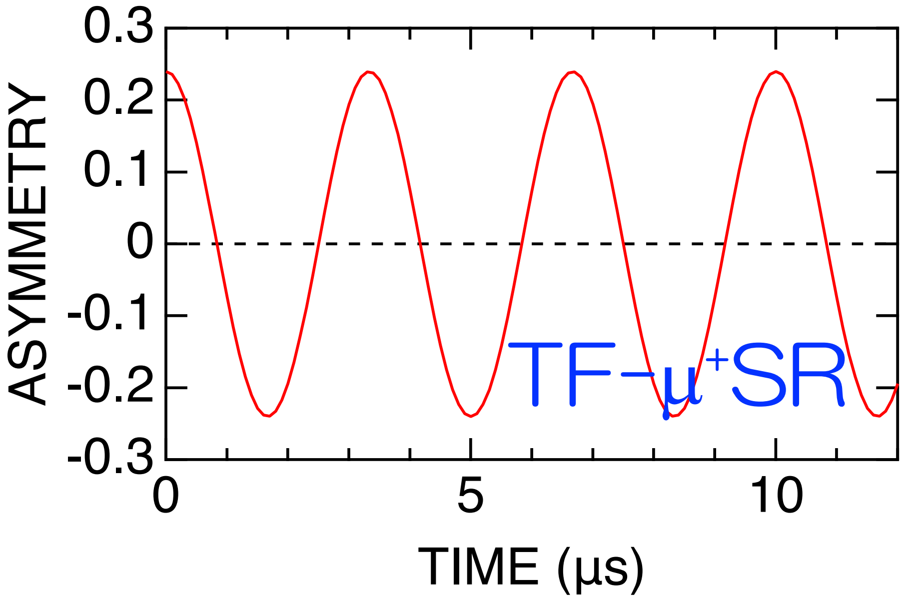
Multi-lifetime Components

μ⁺SR



μ⁻SR





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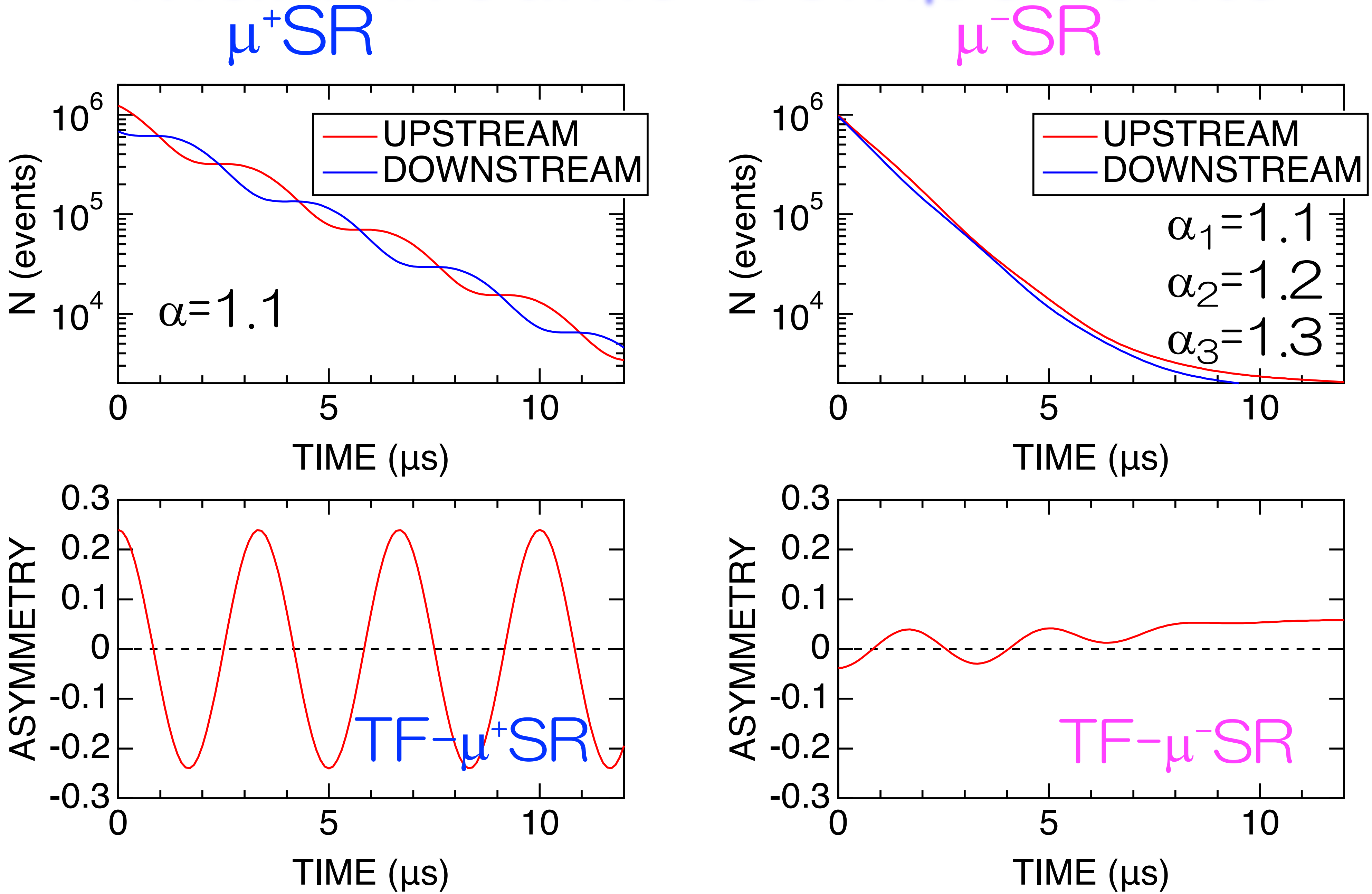
$=(N^F-\alpha_1 N^B)/(N^F+\alpha_1 N^B)$

Multi-lifetime Components



Difficulties in μ^{-}SR

- μ^{-} behaves as a heavy electron (m_{μ}=200m_e) and is captured by a nucleus
- decrease in spin polarization

→need data with very high statistics

- μ^{-} lifetime depends on the nucleus, on which μ^{-} is captured

→data analysis is not easy

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- **when a nucleus captures μ^-, such nucleus looks like the nucleus with Z-1**

→comparable to impurity NMR

- **high momentum μ^- beam is required**

→need a large amount of sample

Merits of μ^-SR

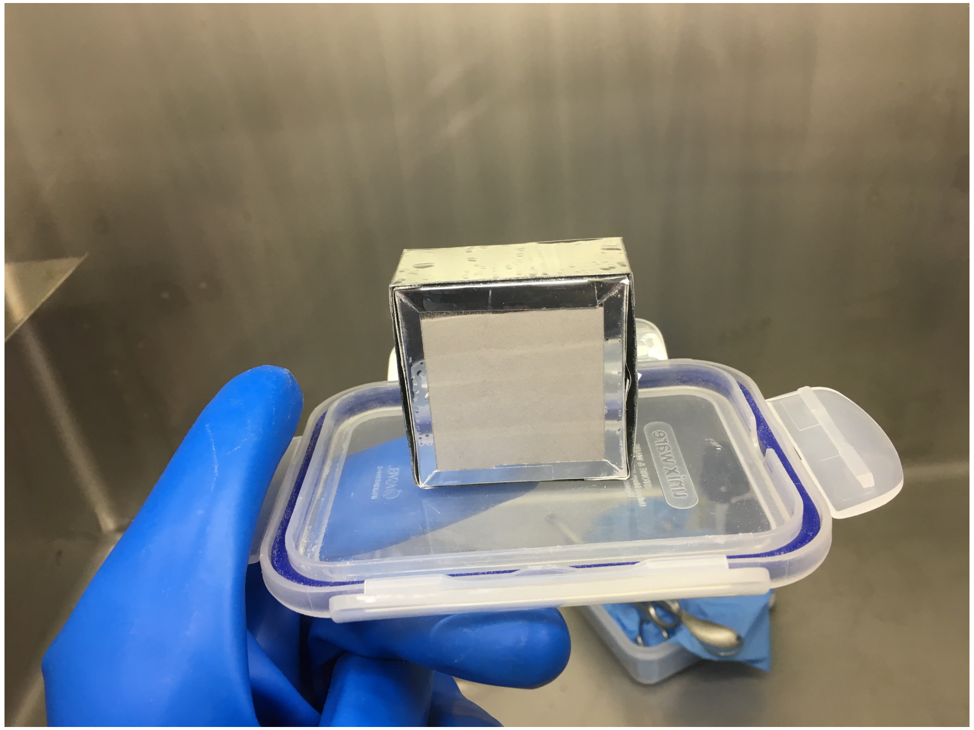
- Negative muon site is very clear, since it is captured by nucleus; i.e. at the lattice site

- Negative muon captured by nucleus is stable even above decomposition temperature

- Optimal tool for dynamics measurements

Thus, we have attempted to measure μ^-SR for a hydrogen storage material, MgH_2.

First μ^{-}SR Setup

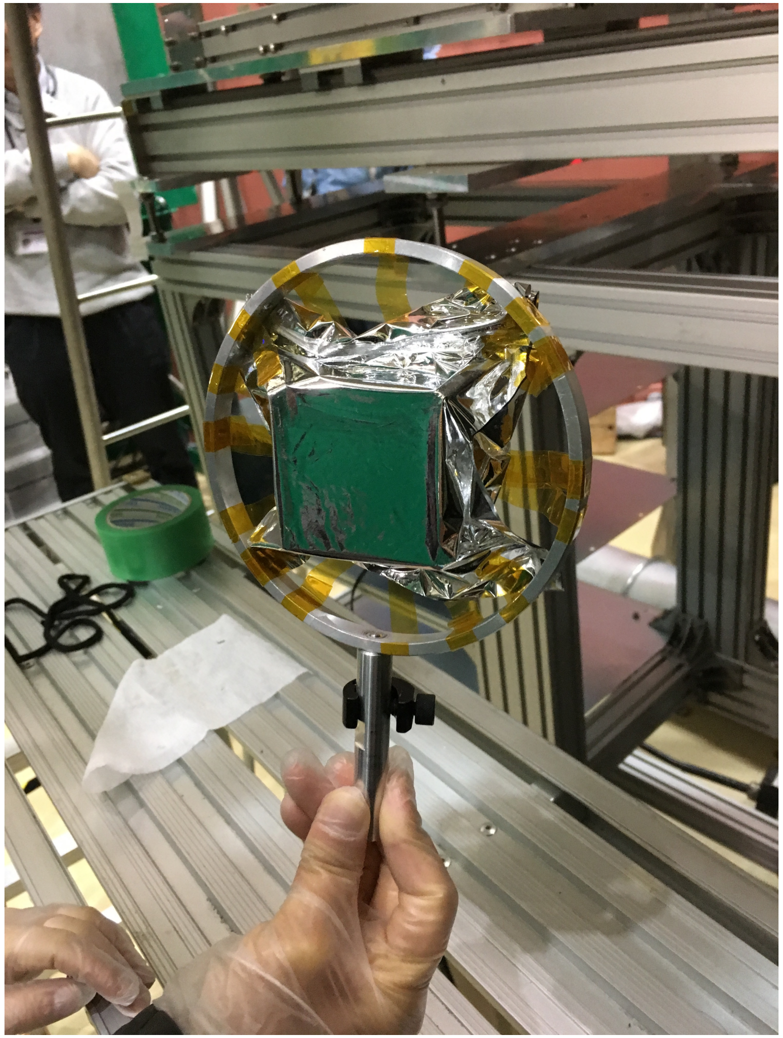


Momentum：50 MeV/c

Sample size

- $5*5*2cm^3$
- PET cell
- about 40g

Room temperature



Since MgH_2 is unstable in air, the PET cell was sealed into a plastic bag.

Recent Setup

Momentum：40 MeV/c

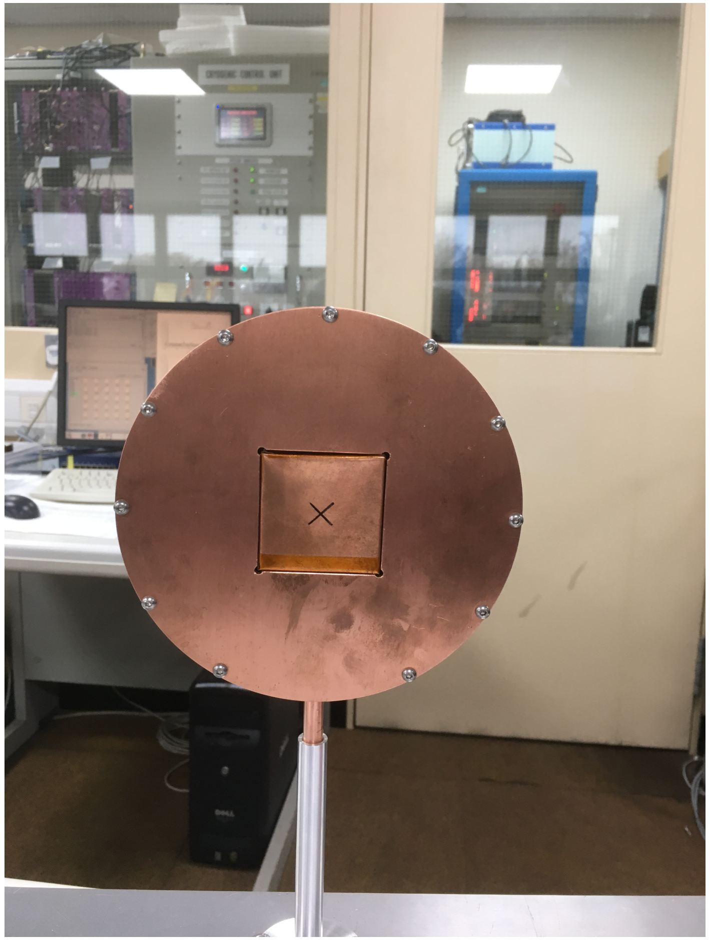
Sample size

- 35mmϕ*14mm
- Ti cell
- about16g

10-450 K

Since MgH_2 is unstable in air, the sample was sealed into a Ti cell with a gold O-ring.

More Sophisticated Setup



Momentum：62 MeV/c

Sample size

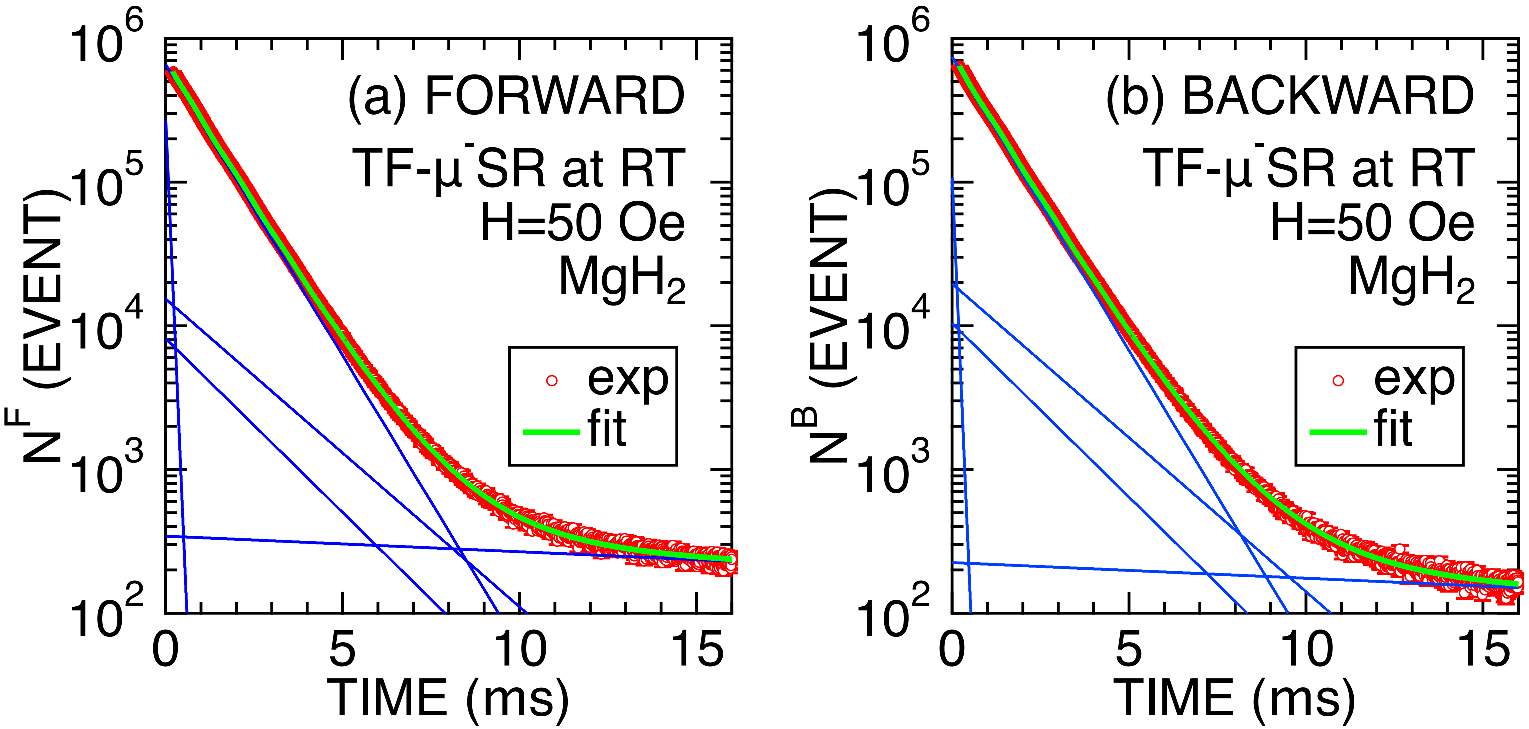
- 5*5*2 cm^3
- Cu cell
- about 51g

Room temperature

In order to avoid μ^-SR signal from the surrounding materials, the Cu cell is set into a Cu holder.

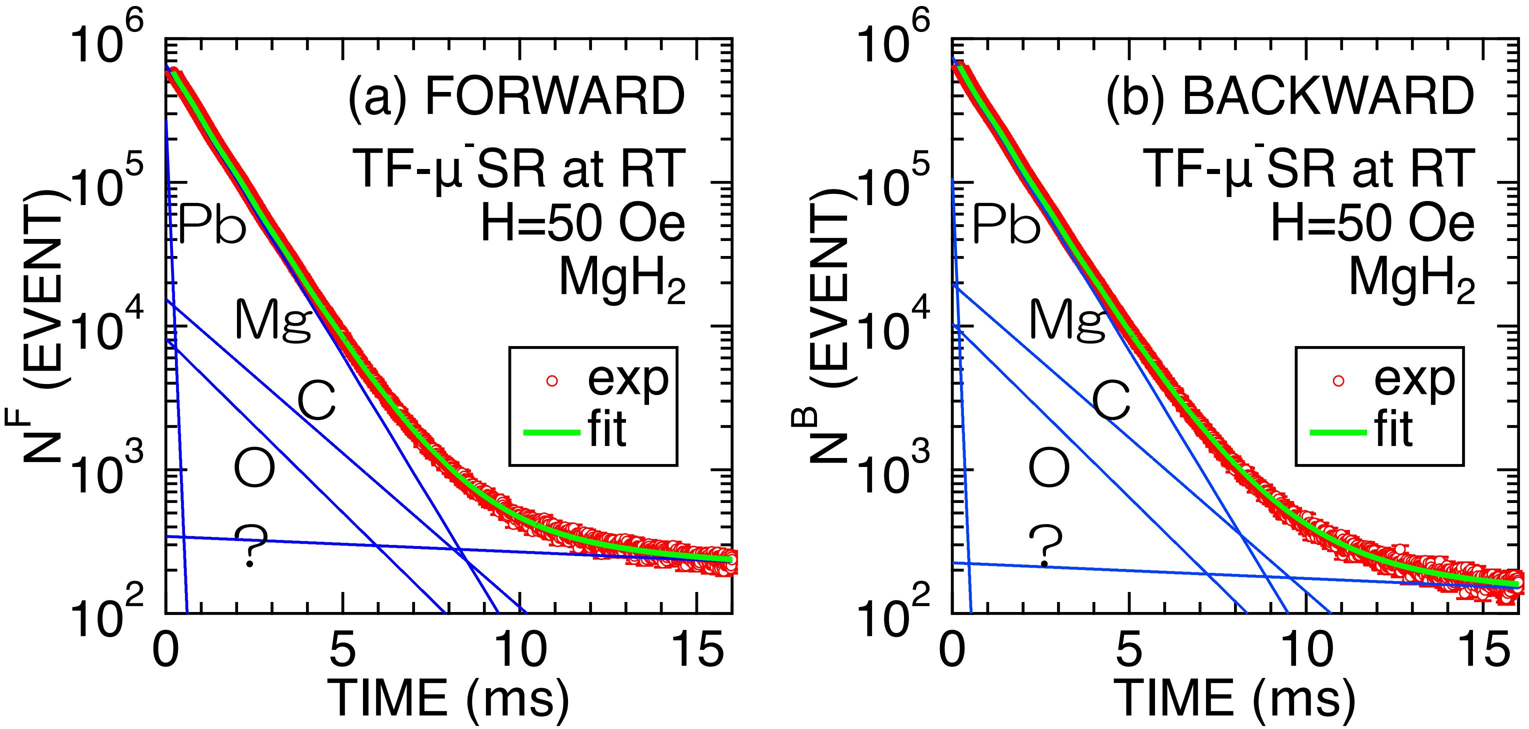
μ^-SR Spectra for MgH_2

Histogram of Forward (Upstream) & Backward (Downstream) Counters



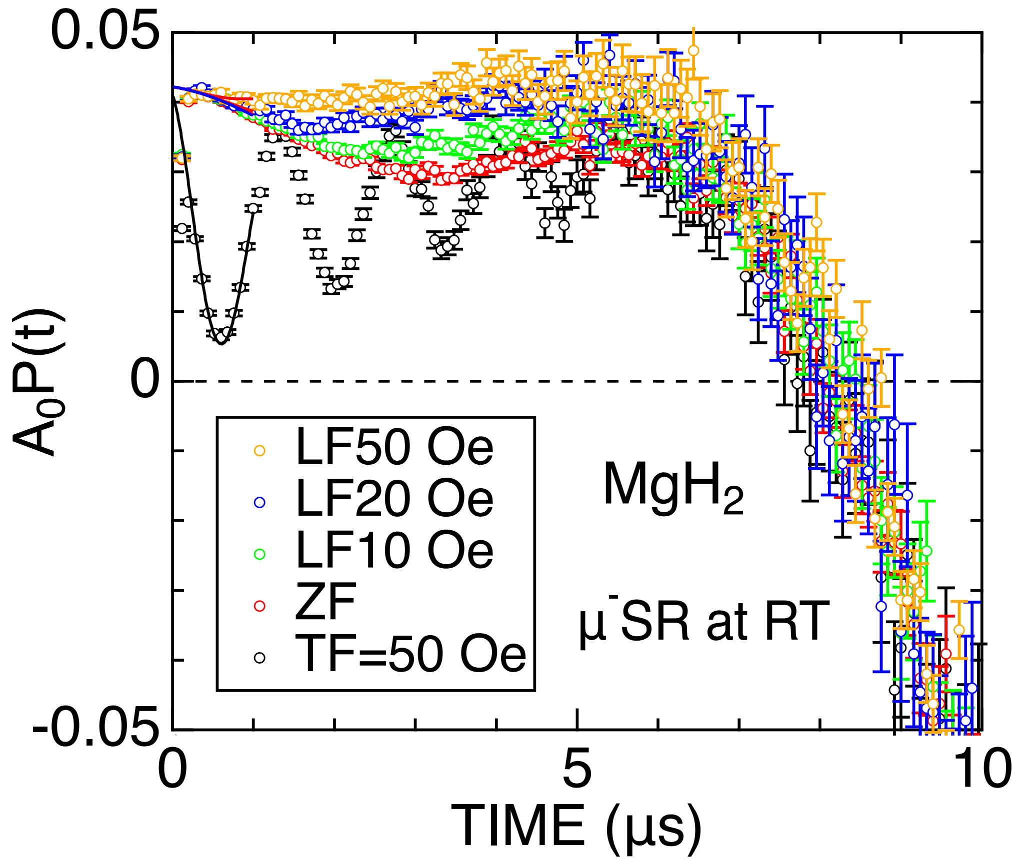
μ⁻SR Spectra for MgH_2

Histogram of Forward (Upstream) & Backward (Downstream) Counters



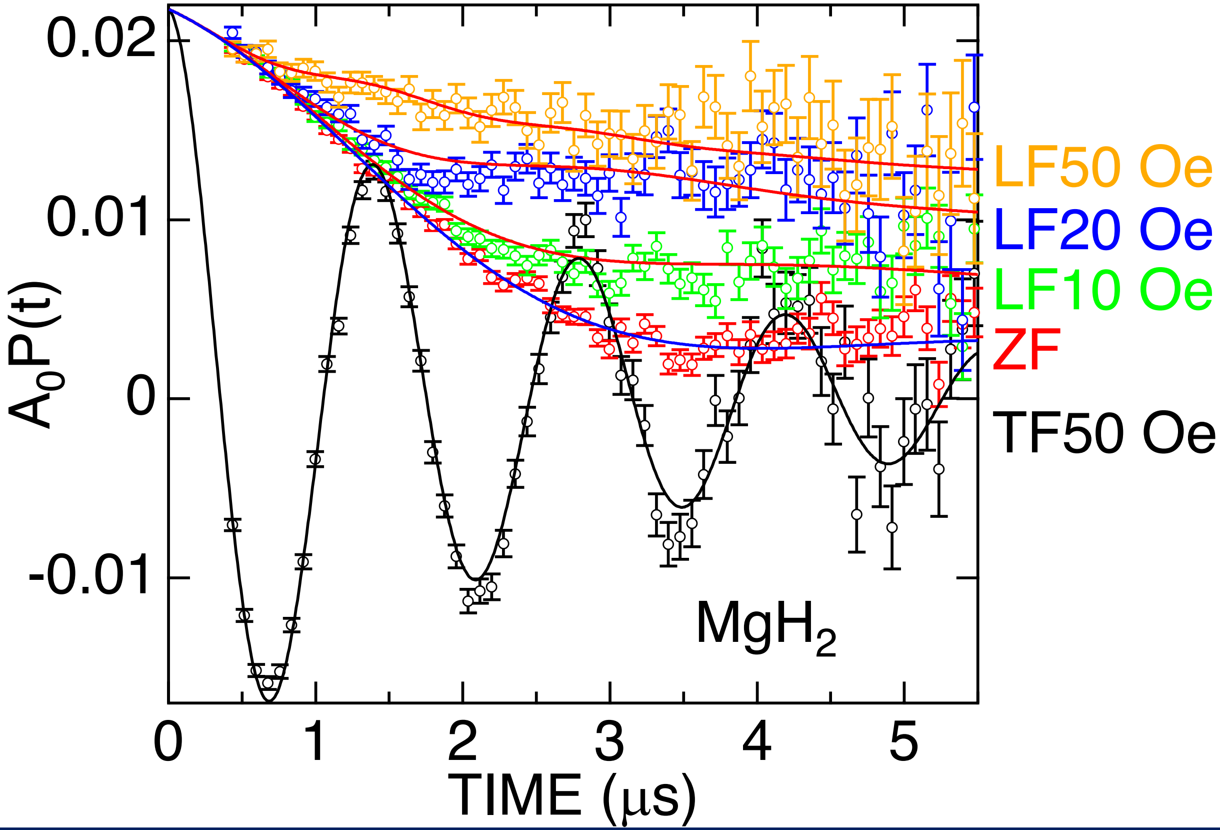
Consisting of five different lifetime components, such as, μ⁻ captured by Mg, C, O, Pb, and the other particle.

μ⁻SR Asymmetry Spectrum



- Non-linear background signal caused by uneven multi-lifetime components.
- LF decoupling behavior is clearly seen.

Fit the μ⁻SR Spectrum



- subtract a BG signal
- fit in the time domain between 0.2 and 5.5 μs
- Kubo-Toyabe and exponential decay signals
- such fit provides Δ=6.11(8) Oe (predicted as 6.82 Oe)

JS et al., *PRL* 121, 087202 (2018).

SUMMARY

- With an intense pulsed muon beam and the development of a counting system, the μ^-SR technique has been reborn in 2018.

- μ^-SR is useful to observe dynamics of H, ion, and light element in solids from a fixed viewpoint.

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- With an intense pulsed muon beam and the development of a counting system, the μ^-SR technique has been reborn in 2018.

- μ^-SR is useful to observe dynamics of H, ion, and light element in solids from a fixed viewpoint.

- To know H dynamics as a function of *T*, μ^-SR on MgH_2 is still in progress.
- To confirm the absence of breaking of time reversal symmetry, μ^-SR on MgB_2 is on going.
- To determine the diffusing species, μ^-SR on $LiFePO_4$ is also on going.

MESSAGE

Clarify μ^+SR ambiguity with μ^-SR!

What μSR can do by itself has to be done by μSR.

COLABORATORS

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Katsuhiko Ishida	Riken & ISIS
Adrian Hillier	ISIS
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FINIS