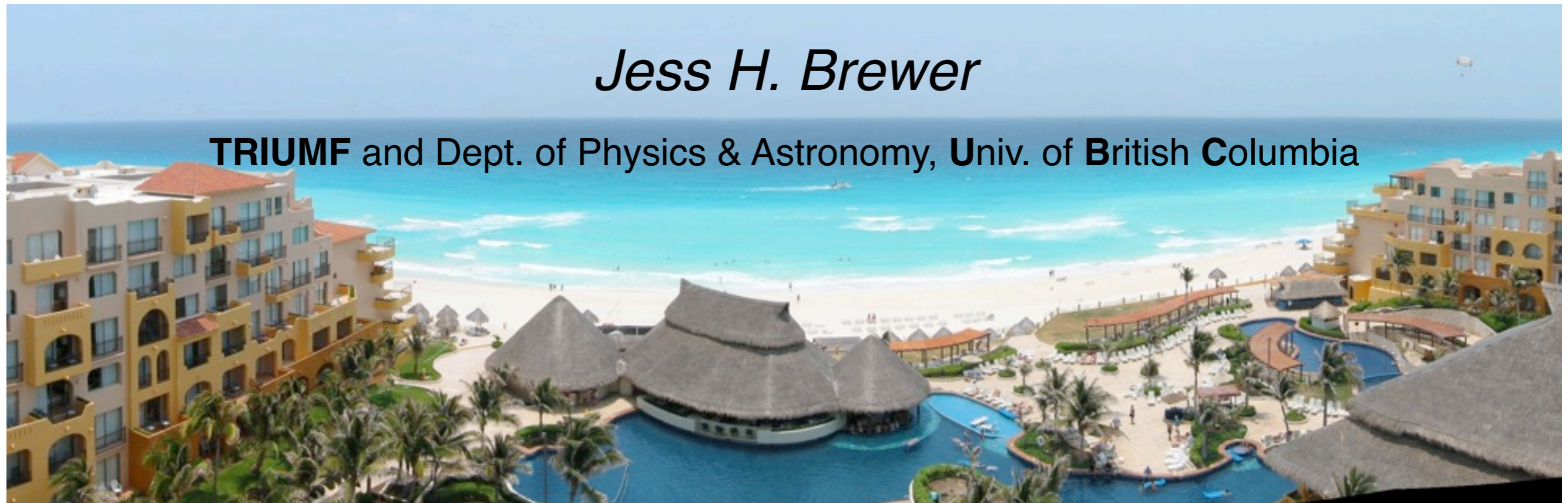


Yamaguchi Prize

2011

Jess H. Brewer

TRIUMF and Dept. of Physics & Astronomy, **Univ. of British Columbia**



What did I do to deserve this?

★ Born at the right time?

Before 1956: $\mu SR = Fantasy$

(violates “known laws of physics”)

● 1930s: **Mistaken Identity**

Yukawa’s “nuclear glue” **mesons** \neq **cosmic rays**

1937 Rabi: Nuclear Magnetic Resonance

● 1940s: **“Who Ordered That?”**

1940 Phys. Rev. Analytical Subject Index: “**mesotron**”

1944 Rasetti: 1st application of muons to condensed matter physics

1946 Bloch: Nuclear Induction (modern NMR with FID *etc.*)

1946 Various: “two-meson” π - μ hypothesis **Brewer: born**

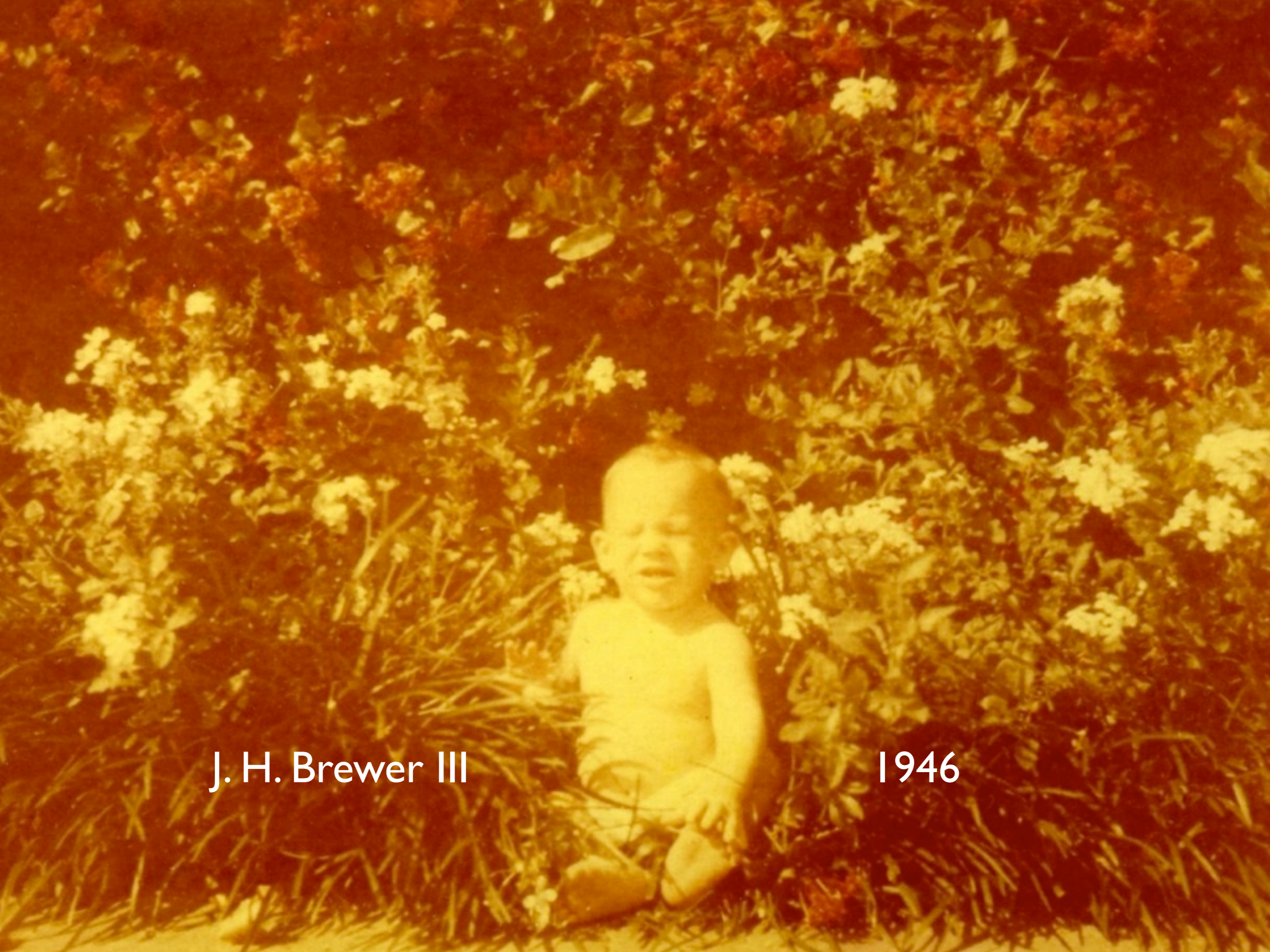
1947 Richardson: produced π & μ at Berkeley 184 in. Cyclotron

1949 Kuhn: “*The Structure of Scientific Revolutions*”

● 1950s: **“Particle Paradise”**

culminating in weird results with strange particles:

1956 Cronin, Fitch, . . . : “ τ - θ puzzle” (neutral **kaons**) \rightarrow **Revolution!**



J. H. Brewer III

1946

Seriously,

What did I do to deserve this?

Some possibilities:

- ★ Promote **μ SR** obsessively for 40 years.
- ★ Develop good tools.
- ★ “Borrow” other people’s ideas.
- ★ Ask unpopular questions, such as,

*‘Is everything we “know” **WRONG?**’*



Unpopular Questions

What are some things we “know”?

● The μ^+ is a “**gentle**” probe that does not disturb its host.

● If you see several **peaks** in the μ^+SR frequency spectrum, it means there are several corresponding muon **sites**.

● We **cannot** observe **muonium** ($\text{Mu} \equiv \mu^+e^-$) in **metals**.

That is, μ^+e^- HF interactions can only be observed directly if the electron is bound to the muon by their mutual Coulomb attraction (forming the muonium or Mu atom) *and* there are no big moments *or* free electrons around to spin-exchange with the Mu electron.



“Borrowed” Ideas

ORIGINATORS*

IDEAS

Firsov, Byakov; Ivanter, Smilga; Roduner, Percival . . .

Muonium Chemistry in Liquids

Bowen, Pifer, Kendall; Garner . . .

The Surface Muon Beam

Mobley; Johnston, Fleming . . .

Muonium Chemistry in Gases

Ferrell, Swanson; *Russians*; Kittel, Patterson, Kiefl . . .

Muonium in Semiconductors

Stoneham; Gurevich, Kagan . . . Prokof'ev, Storchak

Quantum Diffusion

Ivanter, Smilga; Fiory, Brandt . . . Sonier

Lineshape from Flux Lattice in SC

Percival; Eshchenko, Storchak . . .

Mu Formation via Radiolysis Electrons

de Gennes, Storchak

μ^+ -probed Spin Polarons

* (starting with earliest, running out of space, hence “...”)



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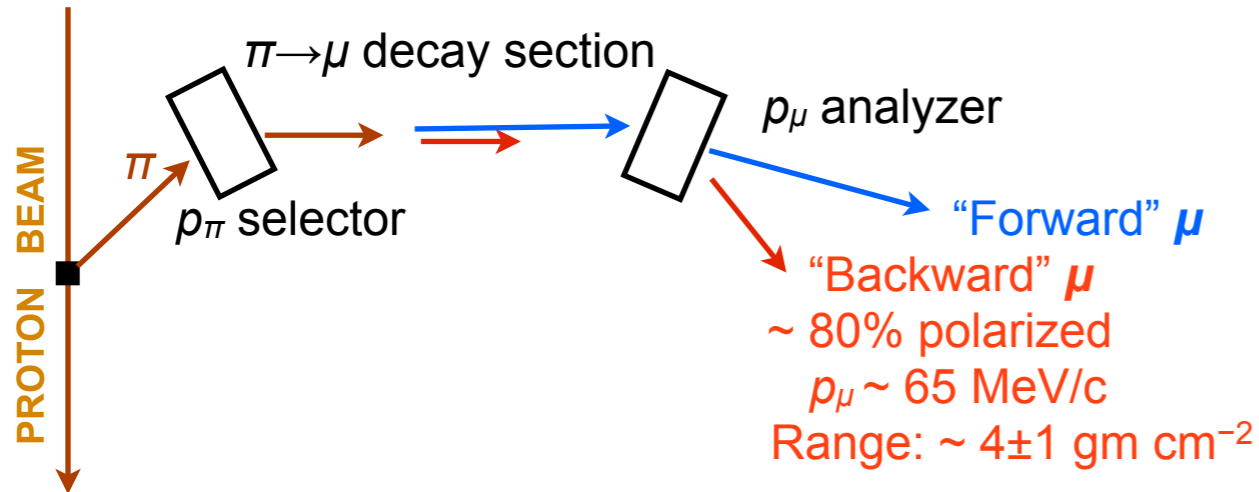
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Muon Beams

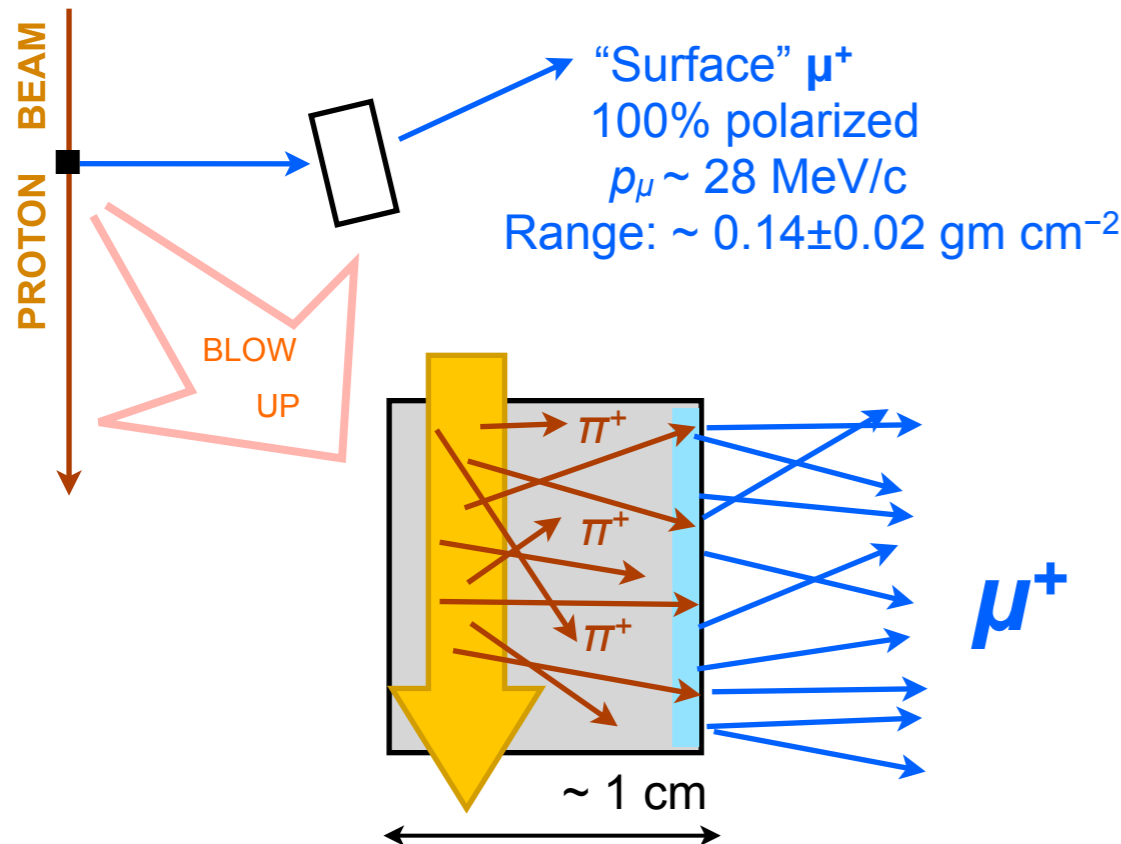


Quality Factors

DECAY MUON CHANNEL (μ^+ or μ^-)



"Arizona" or SURFACE μ^+ CHANNEL



PERFORMANCE of MUON BEAMS for μ SR

REQUIREMENTS:

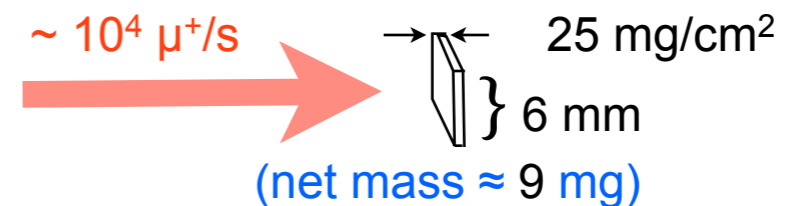
- HIGH POLARIZATION
 - HIGH FLUX ($> 2 \times 10^4 \text{ s}^{-1}$ on target)
 - SMALL SPOT SIZE ($< 1 \text{ cm}^2$)
 - SHORT STOPPING RANGE \Rightarrow low momentum
 - LOW CONTAMINATION of π , e etc.
- } LUMINOSITY

\therefore "QUALITY FACTOR"

$$Q = \frac{(\text{POLARIZATION})^2 \times \text{FLUX}}{(1 + \text{CONTAM.}) \times \text{RANGE} \times (\text{SPOT SIZE})} \text{ s}^{-1} \text{ gm}^{-1}$$

HISTORY of IMPROVEMENTS:

- Before Meson Factories: $Q \sim 10^3$ (1970)
- Decay channels at Meson Factories: $Q \sim 10^5$ (1975)
- Surface μ^+ beams at Meson Factories: $Q \sim 10^6$ (1980)
- "3rd generation" surface muon beams: $Q \sim 10^7$ (1990)

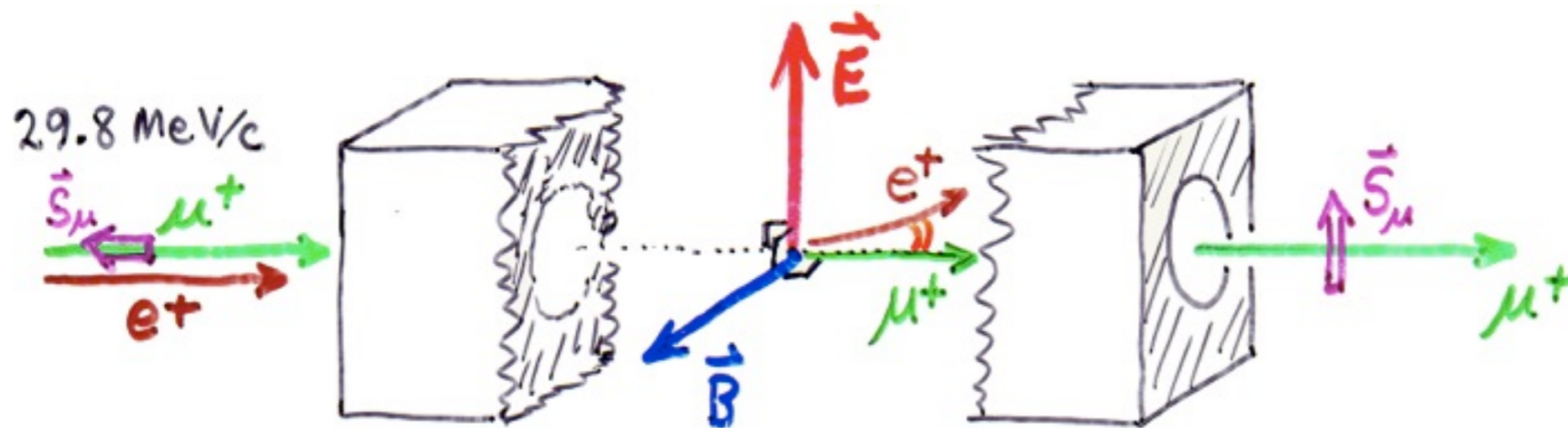


Low Energy (moderated) Muons at PSI: $Q \sim 10^9$ (2005)

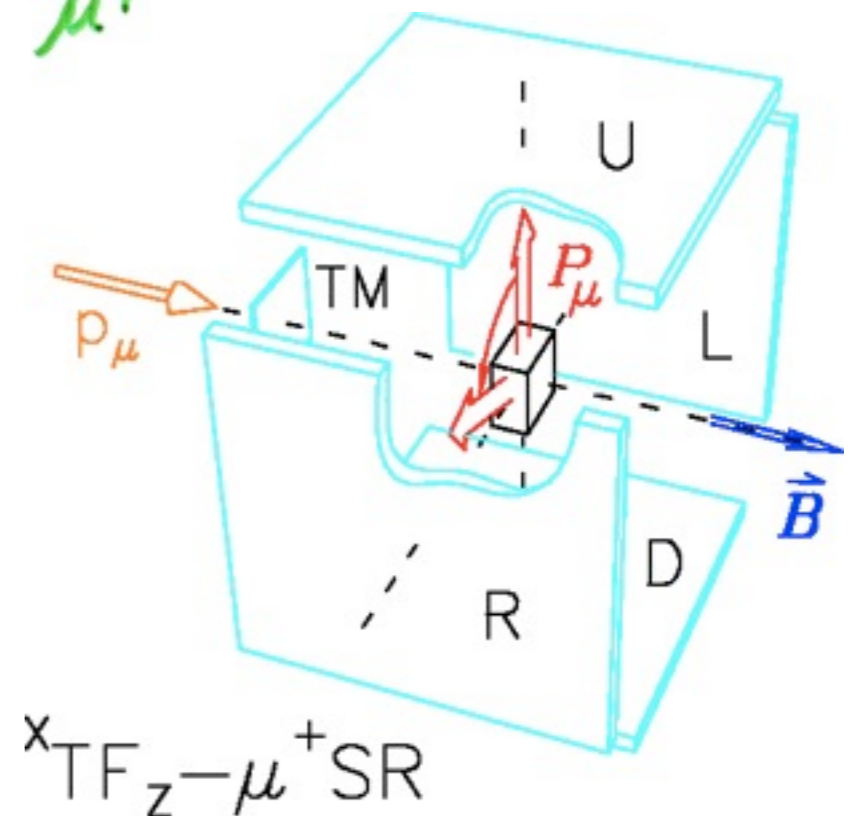
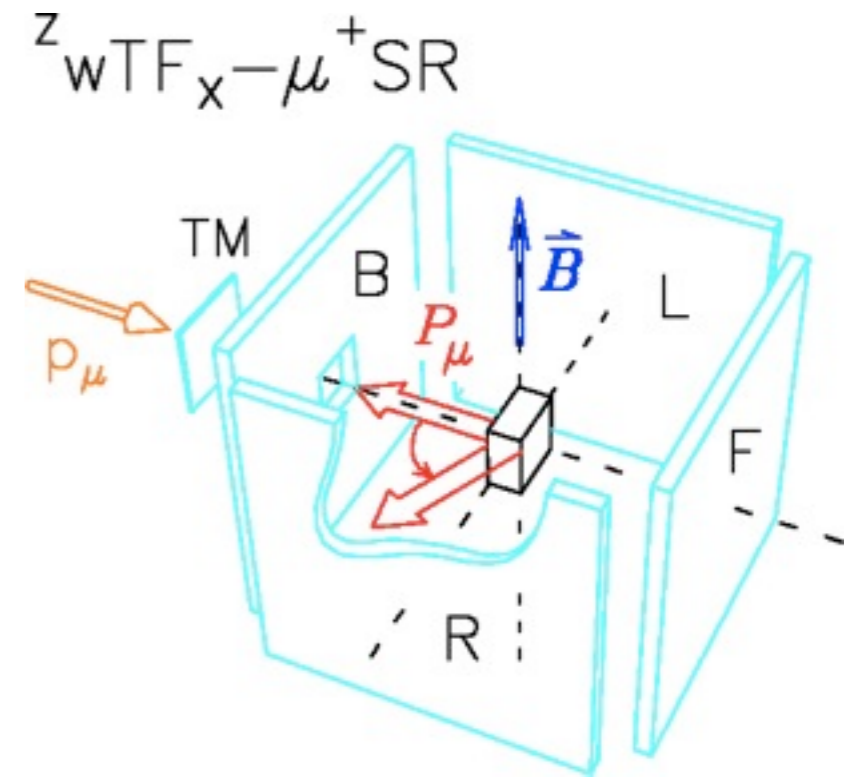
$E \times B$ velocity selector

("DC Separator" or Wien filter)

for **surface muons**:



- Removes beam **positrons**
- Allows TF- μ^+ SR in **high field** (otherwise B deflects beam)





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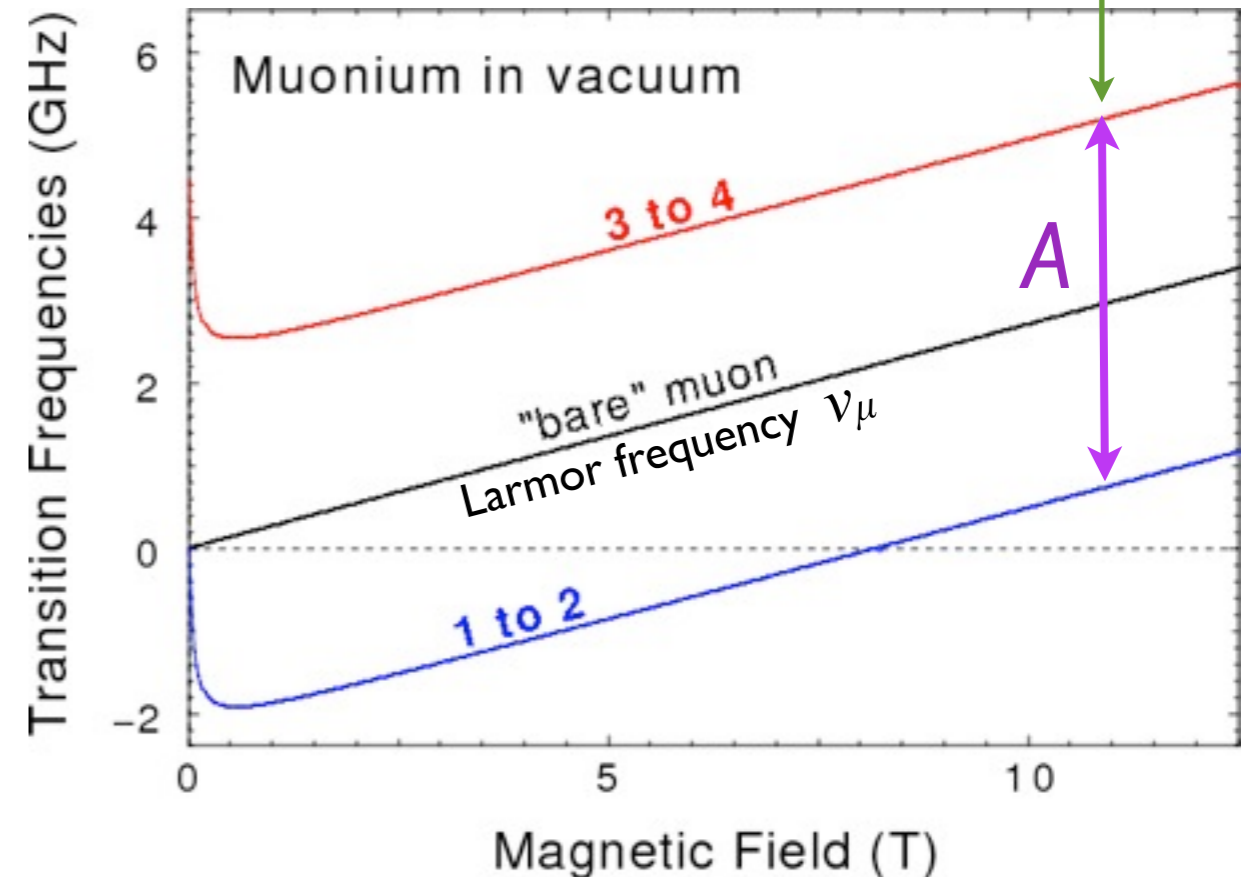
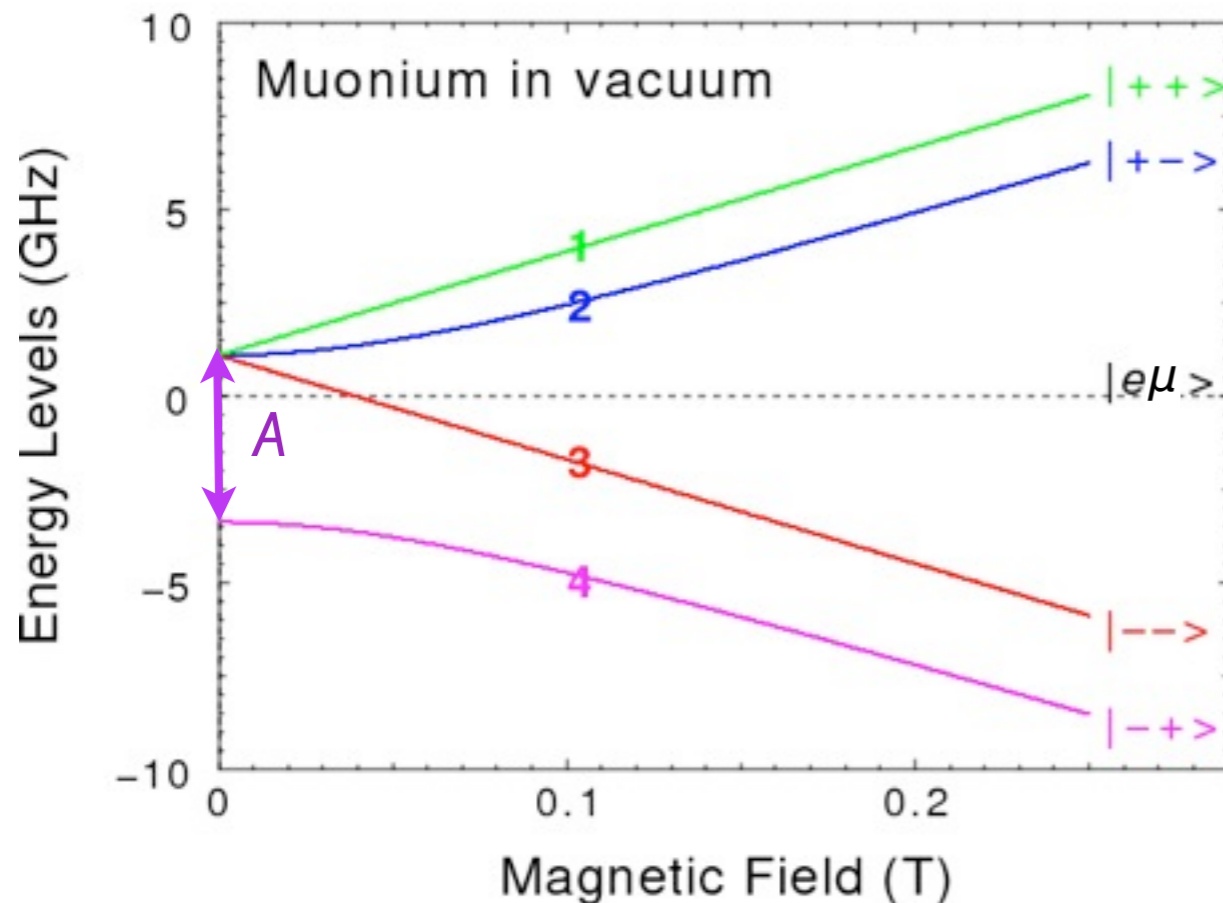
μ^+ -probed Spin Polarons

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Muonium ($\text{Mu} \equiv \mu^+ e^-$) Spectroscopy

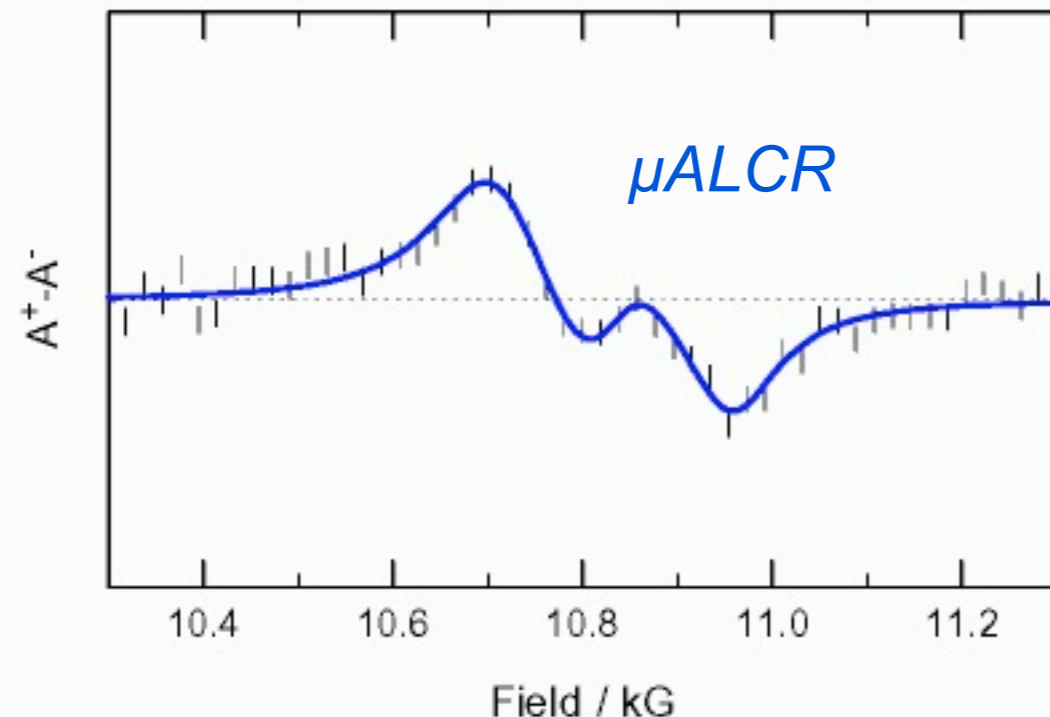
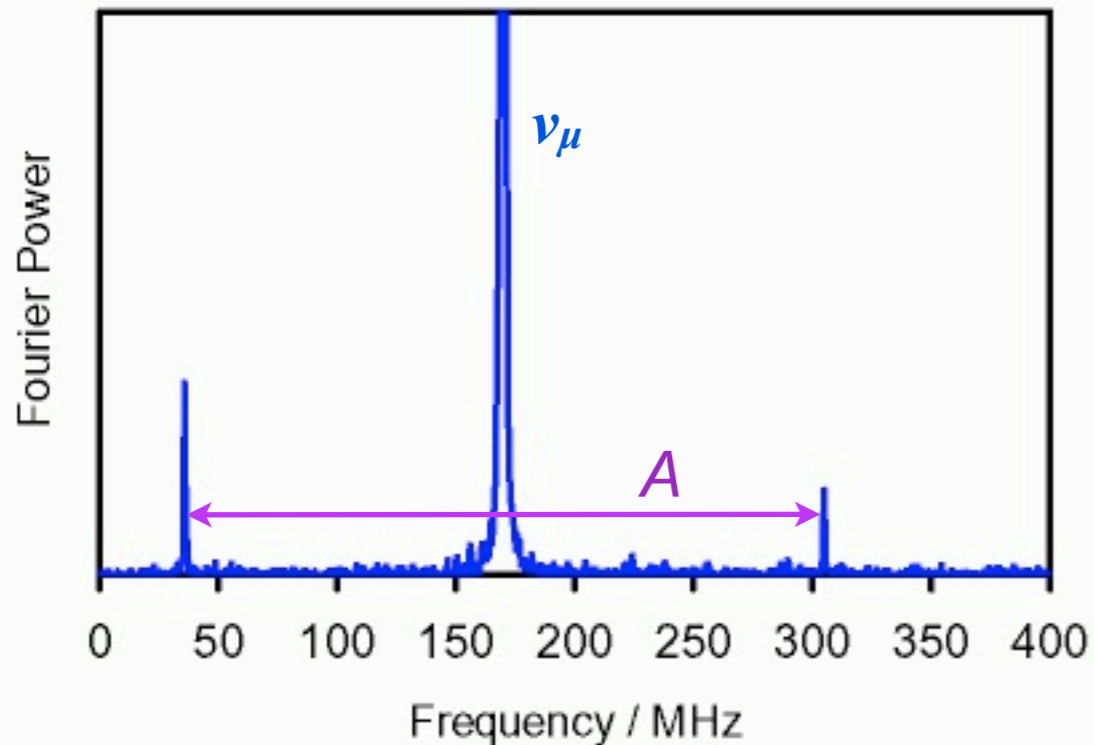
In a μSR experiment one measures a time spectrum at a given field and extracts **all** frequencies *via* FFT.

Breit-Rabi diagram



“Signature” of **Mu** (or other hyperfine-coupled $\mu^+ e^-$ spin states) in high transverse field: **two frequencies centred on ν_μ** and separated by the **hyperfine splitting $A \propto r^{-3}$** .

Muonated Radicals



Organic Free Radicals in Superheated Water

Paul W. Percival, Jean-Claude Brodovitch, Khashayar Ghandi, Brett M. McCollum, and Iain McKenzie

Apparatus has been developed to permit muon avoided level-crossing spectroscopy (μLCR) of organic free radicals in water at high temperatures and pressures. The combination of μLCR with transverse-field muon spin rotation (TF- μSR) provides the means to identify and characterize free radicals via their nuclear hyperfine constants. Muon spin spectroscopy is currently the only technique capable of studying transient free radicals under hydrothermal conditions in an unambiguous manner, free from interference from other reaction intermediates. We have utilized the technique to investigate hydrothermal chemistry in two areas: dehydration of alcohols, and the enolization of acetone. Spectra have been recorded and hyperfine constants determined for the following free radicals in superheated water (typically 350°C at 250 bar): 2-propyl, 2-methyl-2-propyl (tert-butyl), and 2-hydroxy-2-propyl. The latter radical is the product of muonium addition to the enol form of acetone and is the subject of an earlier Research Highlight. The figure shows spectra for the **2-propyl** radical detected in an aqueous solution of 2-propanol at 350°C and 250 bar.



Unpopular Questions

What are some things we “know”?

● The μ^+ is a “**gentle**” probe that does not disturb its host.

● If you see several **peaks** in the μ^+SR frequency spectrum, it means there are several corresponding muon **sites**.

● We **cannot** observe **muonium** ($\text{Mu} \equiv \mu^+e^-$) in **metals**.

That is, μ^+e^- HF interactions can only be observed directly if the electron is bound to the muon by their mutual Coulomb attraction (forming the muonium or Mu atom) *and* there are no big moments *or* free electrons around to spin-exchange with the Mu electron.

What's **WRONG** with that?

🌐 Is the μ^+ really a “**gentle**” probe that does not disturb its host?

Answer: *It depends on the host.*

In **good metals**, any disturbance of the *electron bands* “heals” almost instantly. ✓

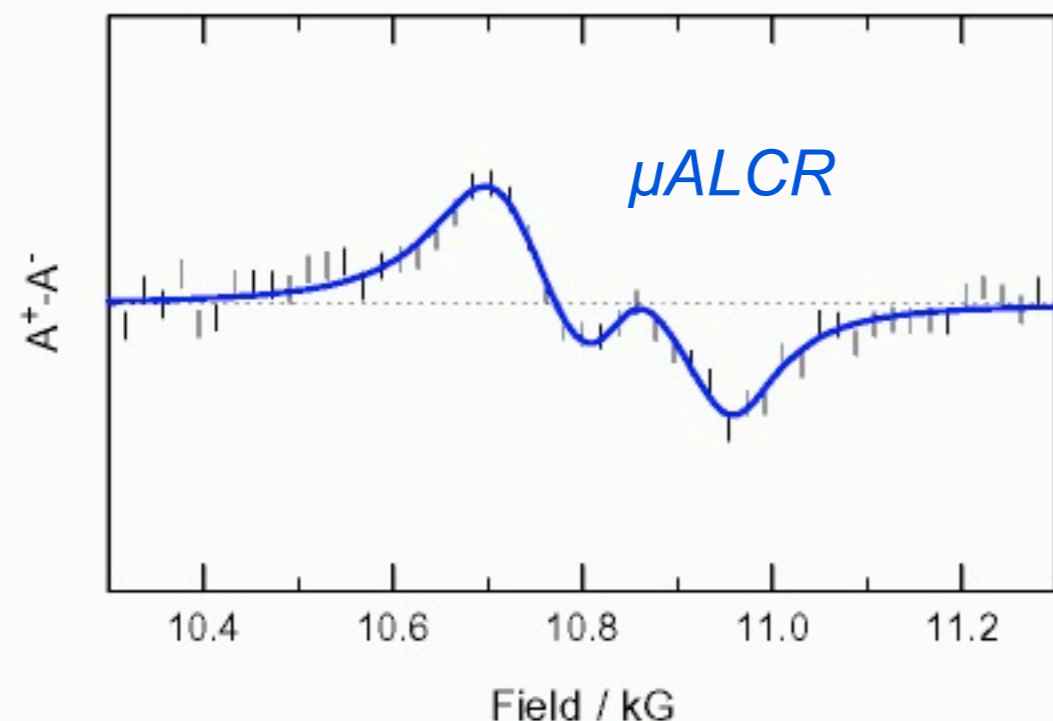
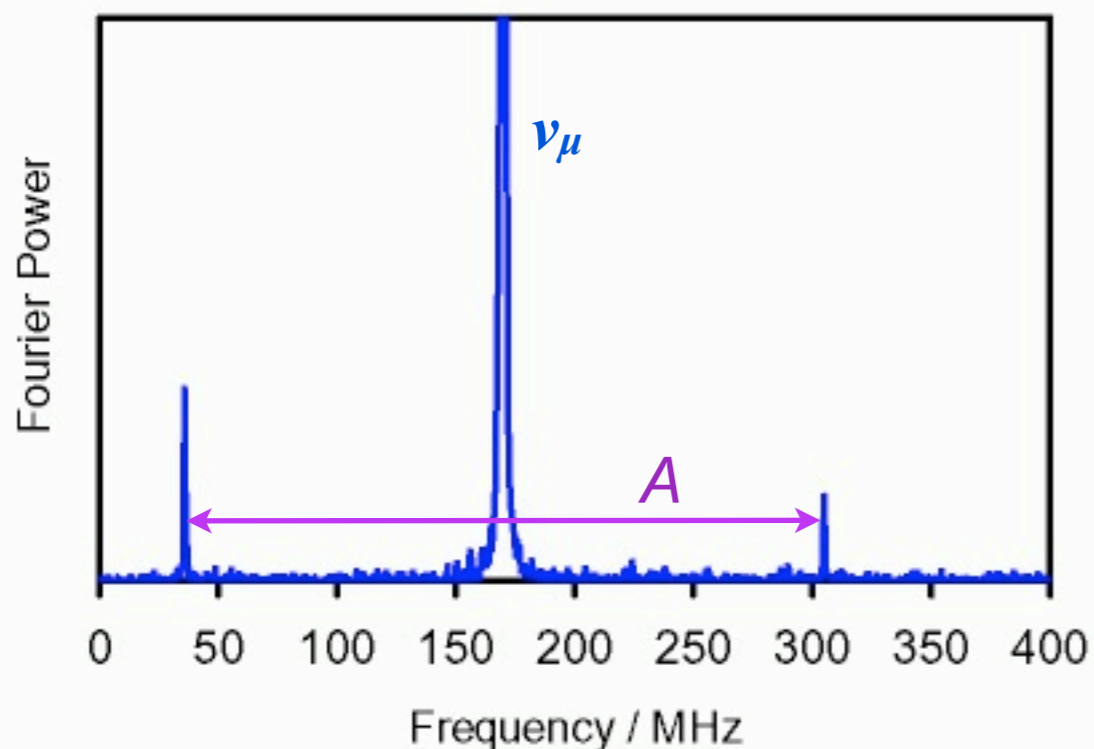
In **insulators** and **semiconductors**, a typical μ^+ deposits several MeV as it stops, releasing a large number of free electrons which are then attracted to the muons to form a hydrogen-like **muonium** ($\text{Mu} = \mu^+ e^-$) atom. In many cases the electron is initially captured into a *weakly-bound “shallow donor” state* which may or may not deexcite down to the ground state. ✗

In **magnetic materials** “balanced on the brink of order” the muon may perturb its immediate environment just enough to drive it into a state different from the bulk.

[See Dang, Gull & Millis, *Phys. Rev. B* **81**, 235124 (2010).] ?



Do multiple **peaks** *always* mean multiple **sites**?



Multiple Muon Sites in Superheated Water ?

Paul W. Percival, Jean-Claude Brodovitch, Khashayar Ghandi, Brett M. McCollum, and Iain McKenzie

Apparatus has been developed to permit muon avoided level-crossing spectroscopy (μLCR) of organic free radicals in water at high temperatures and pressures. The combination of μLCR with transverse-field muon spin rotation (TF- μSR) provides the means to identify and characterize free radicals via their nuclear hyperfine constants. Muon spin spectroscopy is currently the only technique capable of studying transient free radicals under hydrothermal conditions in an unambiguous manner, free from interference from other reaction intermediates. We have utilized the technique to investigate hydrothermal chemistry in two areas: dehydration of alcohols, and the enolization of acetone. Spectra have been recorded and hyperfine constants determined for the following free radicals in superheated water (typically 350°C at 250 bar): 2-propyl, 2-methyl-2-propyl (tert-butyl), and 2-hydroxy-2-propyl. The latter radical is the product of muonium addition to the enol form of acetone and is the subject of an earlier Research Highlight. The figure shows spectra for the **2-propyl** radical detected in an aqueous solution of 2-propanol at 350°C and 250 bar.



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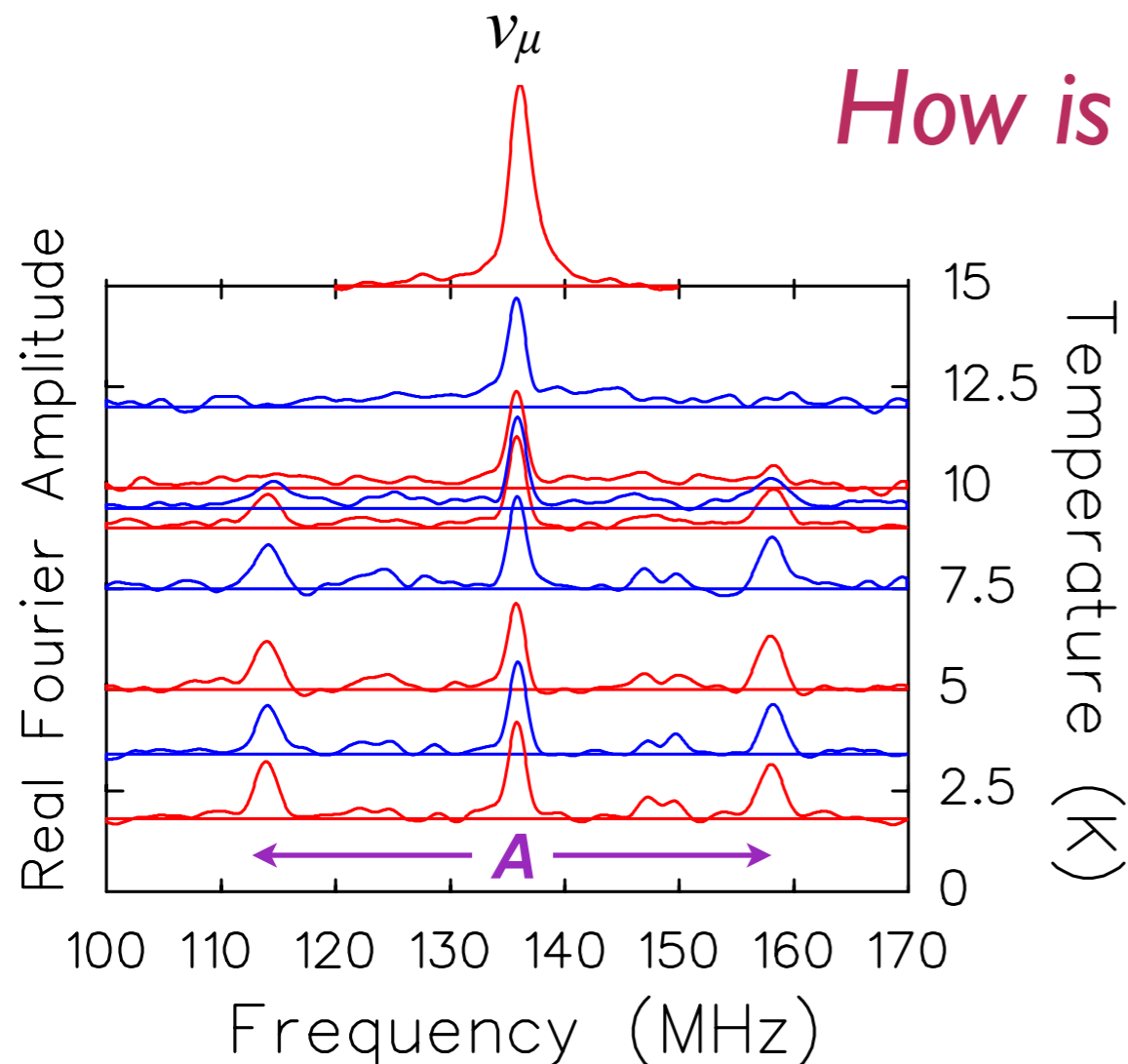
μ^+ -probed Spin Polarons

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NaV_2O_5 TF=1T

insulator

Mu formation? $A \approx 45$ MHz or $B_{\text{HF}} \approx 16$ G (effective HF field of the muon on the electron). But big V moments make much larger local fields; why don't they affect the spectrum?

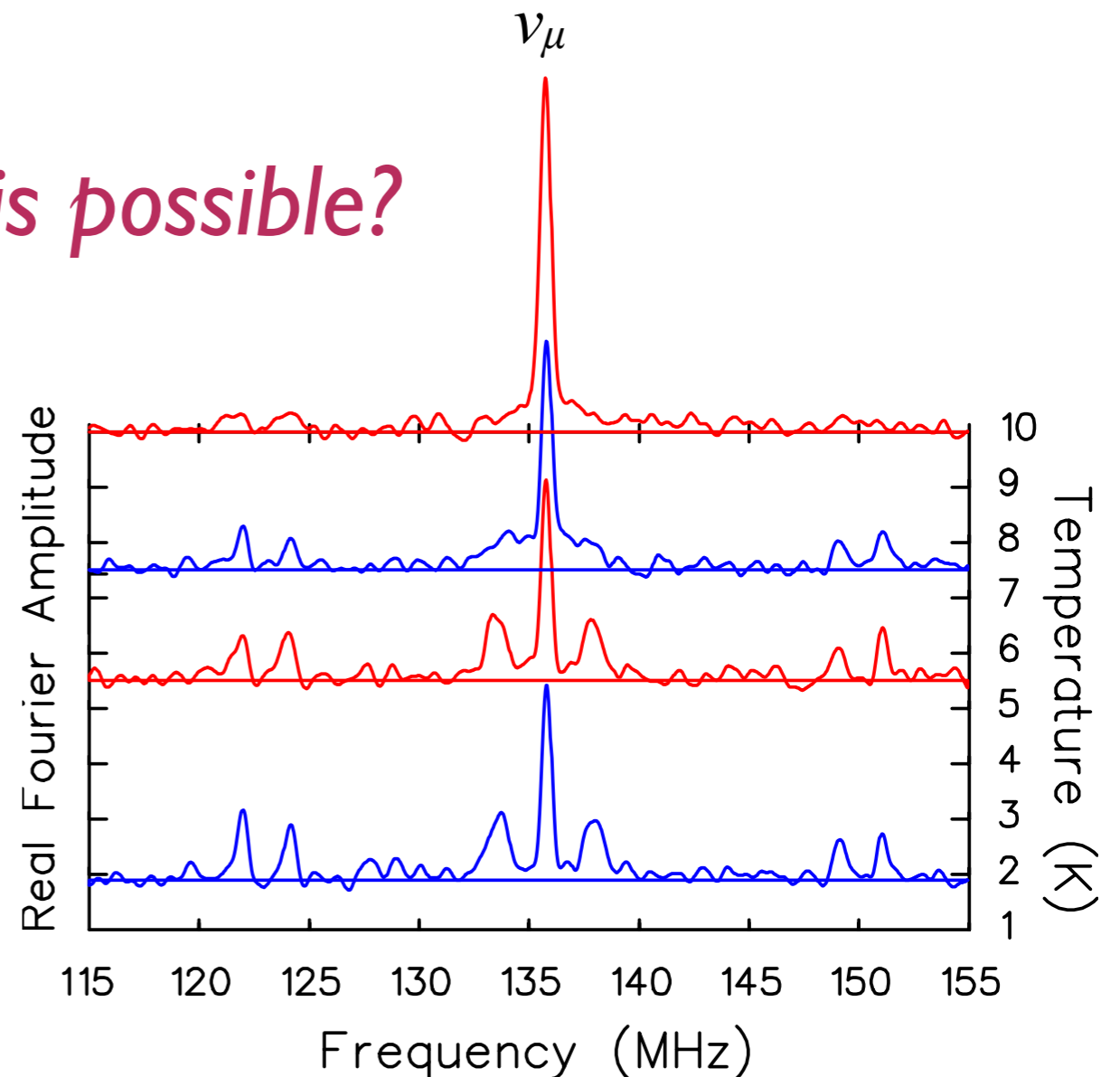


How is this possible?

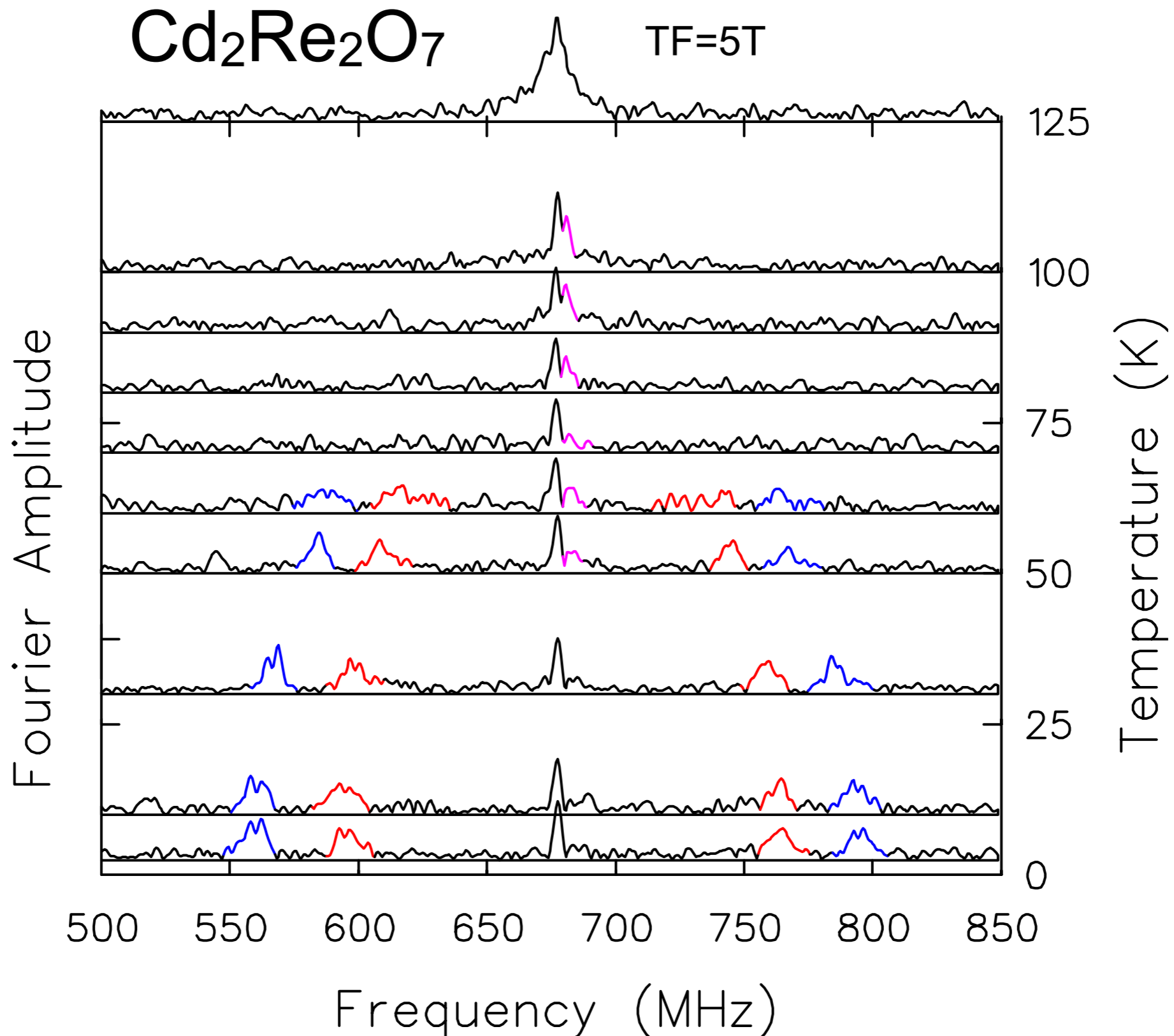
FeGa_3 TF=1T

semiconductor

Several different Mu species with different A 's? What about all the big Fe moments?

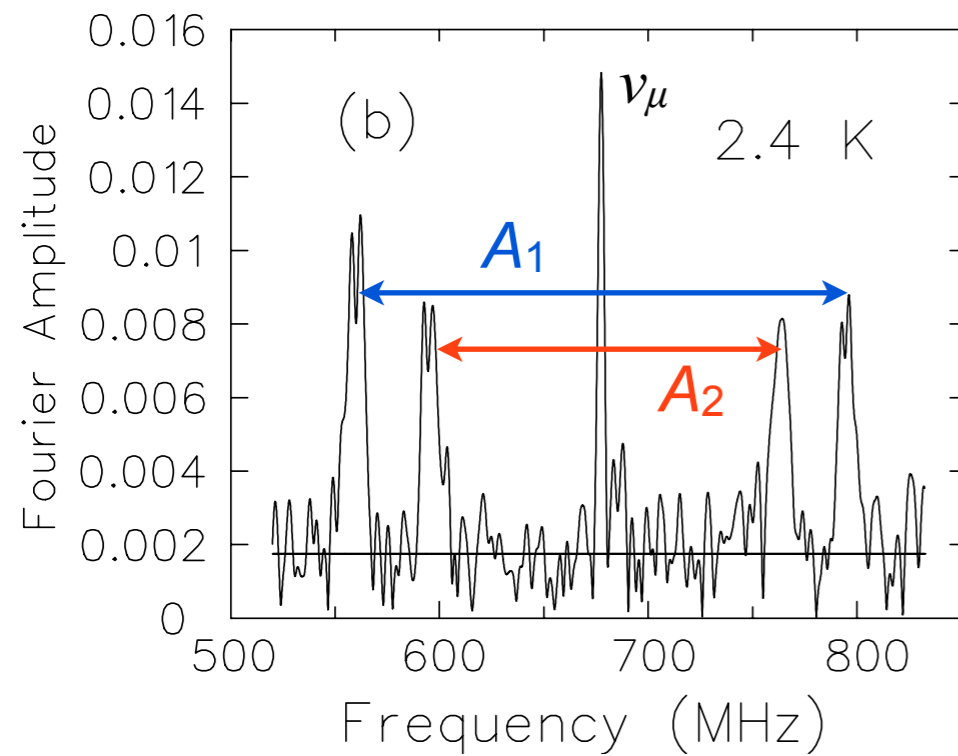
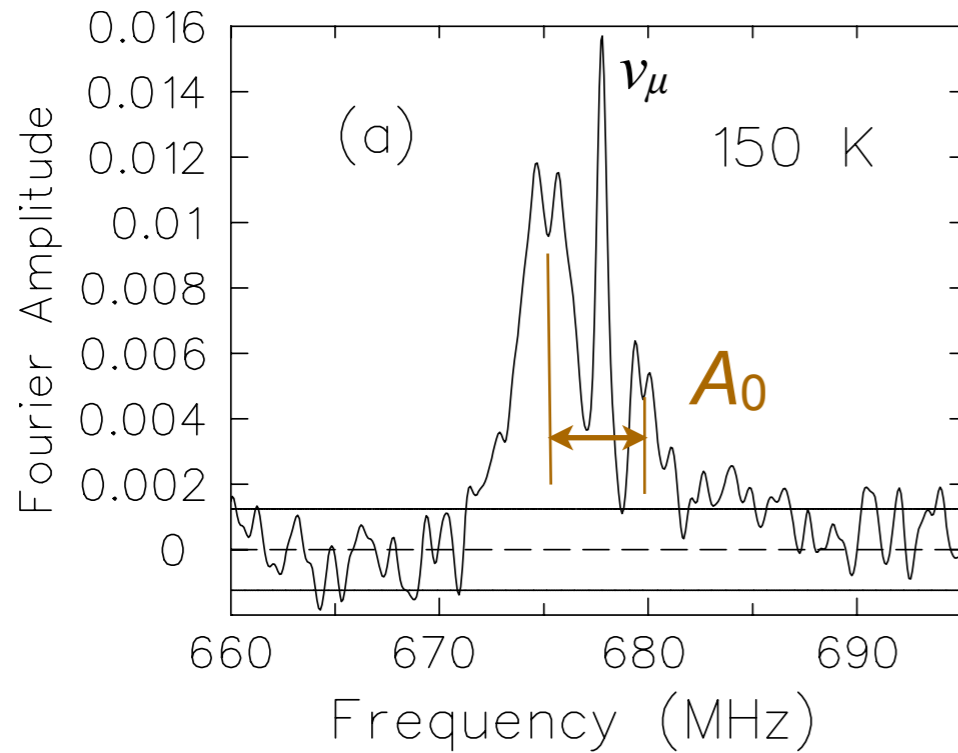


Geometrically frustrated magnetic pyrochlore



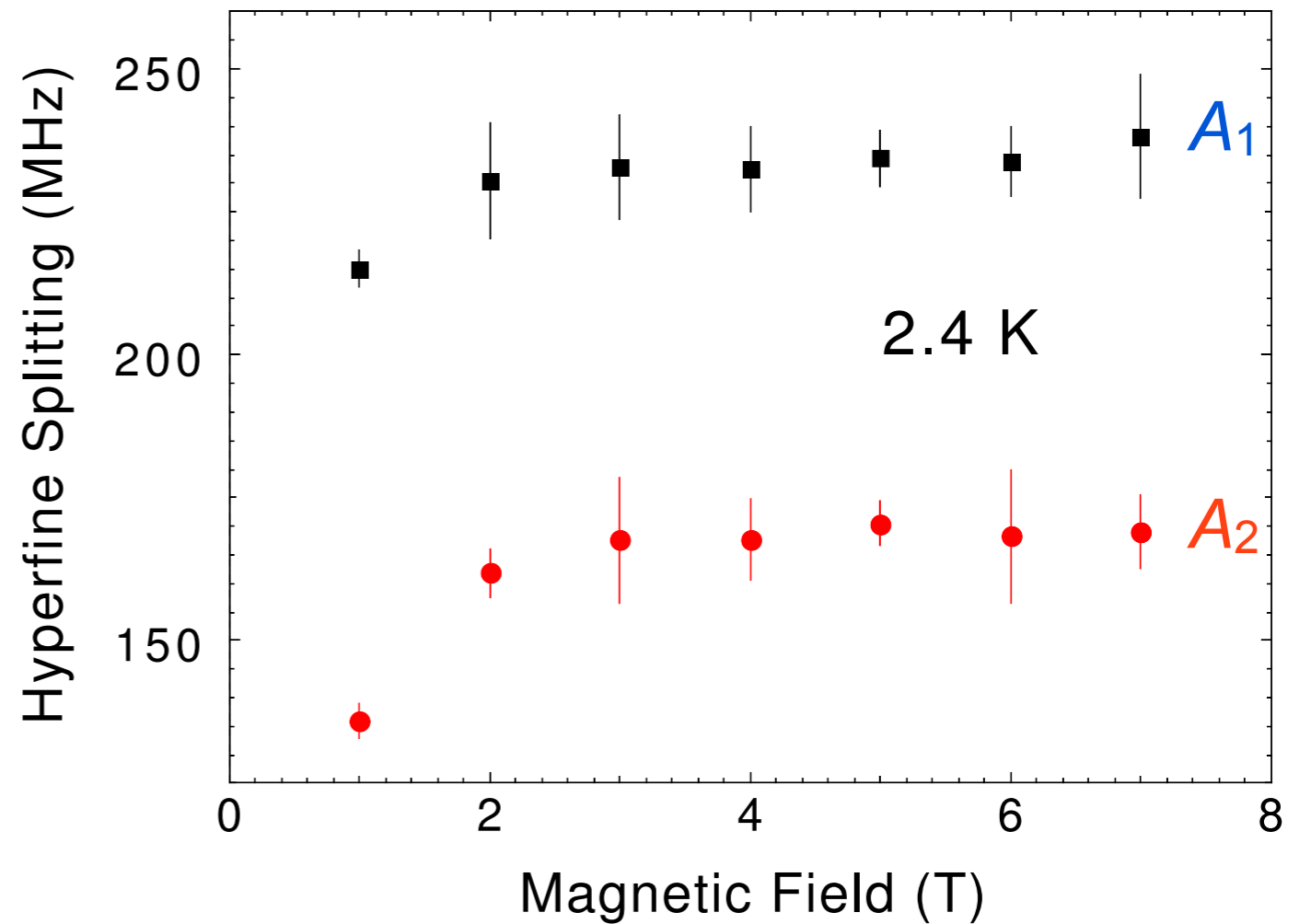
Cd₂Re₂O₇

TF=5T



Above 60K: small A_0 .

Below 60K: large A_1 & A_2 .



So it looks like we have Mu in NaV_2O_5 , FeGa_3 & $\text{Cd}_2\text{Re}_2\text{O}_7$.

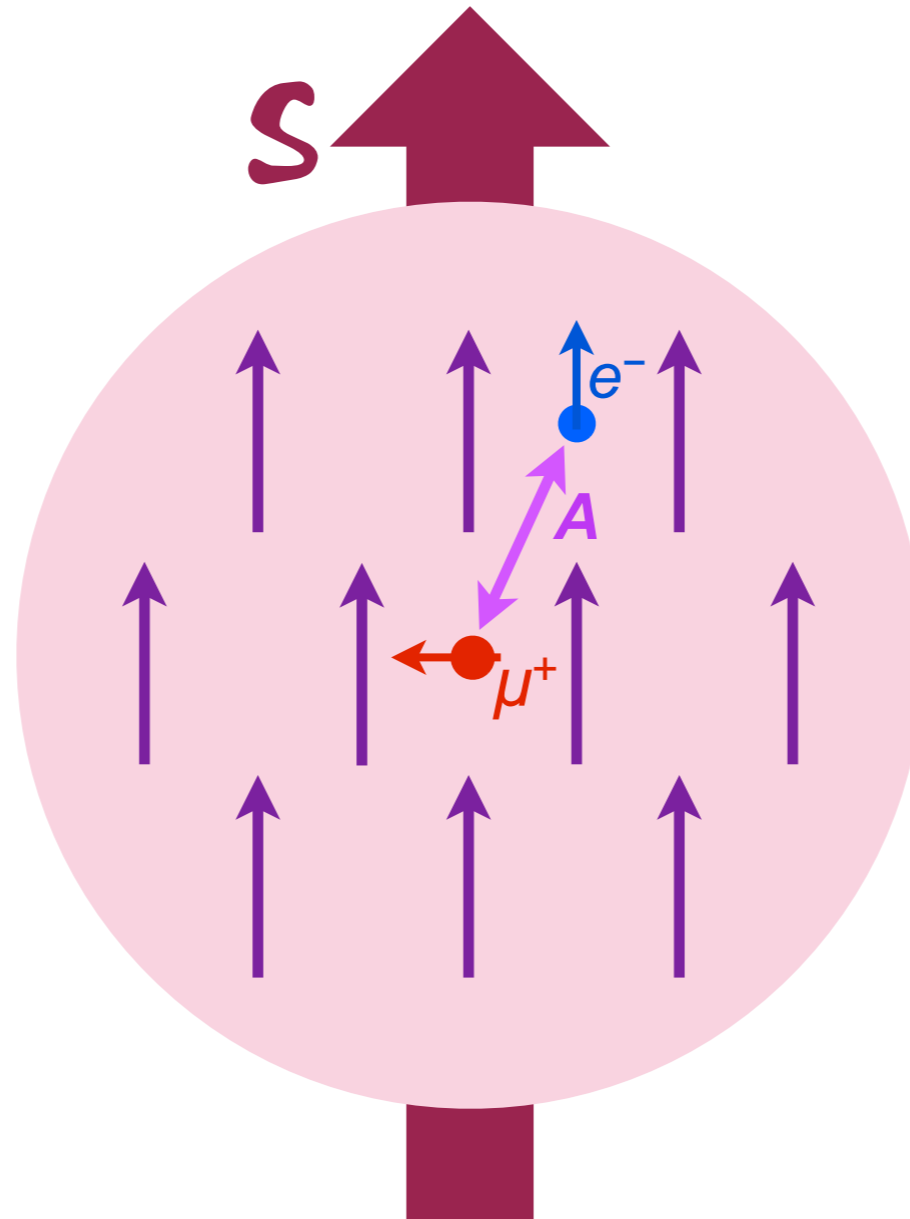
What's *WRONG* with that?

$\text{Cd}_2\text{Re}_2\text{O}_7$ is a *metal*!

- 👉 Can we observe muonium in [metals](#)? *It depends on what you mean by "muonium".* The Coulomb field of the μ^+ is *screened* by conduction electrons, so there is no *direct* binding of the e^- .
- ★ Can μ^+e^- HF interactions be observed directly if Coulomb binding is ineffective? *Something else must localize the electron near the muon!*
What could do that?
- ★ What if free electrons are around to spin-exchange with the localized electron? *Something must prevent electron spin-exchange!*
What could do that?

Answer:

a **BOUND** (to the μ^+) **SPIN POLARON**



The **SP** is a **nanoscale FM droplet** with a giant spin S and an electric charge of $-e$ in which the binding e^- has its spin “locked” to S but still has a **hyperfine interaction** A with the μ^+ spin.

Spin Polarons

PHYSICAL REVIEW

VOLUME 118, NUMBER 1

APRIL 1, 1960

Effects of Double Exchange in Magnetic Crystals*

P.-G. DE GENNES†

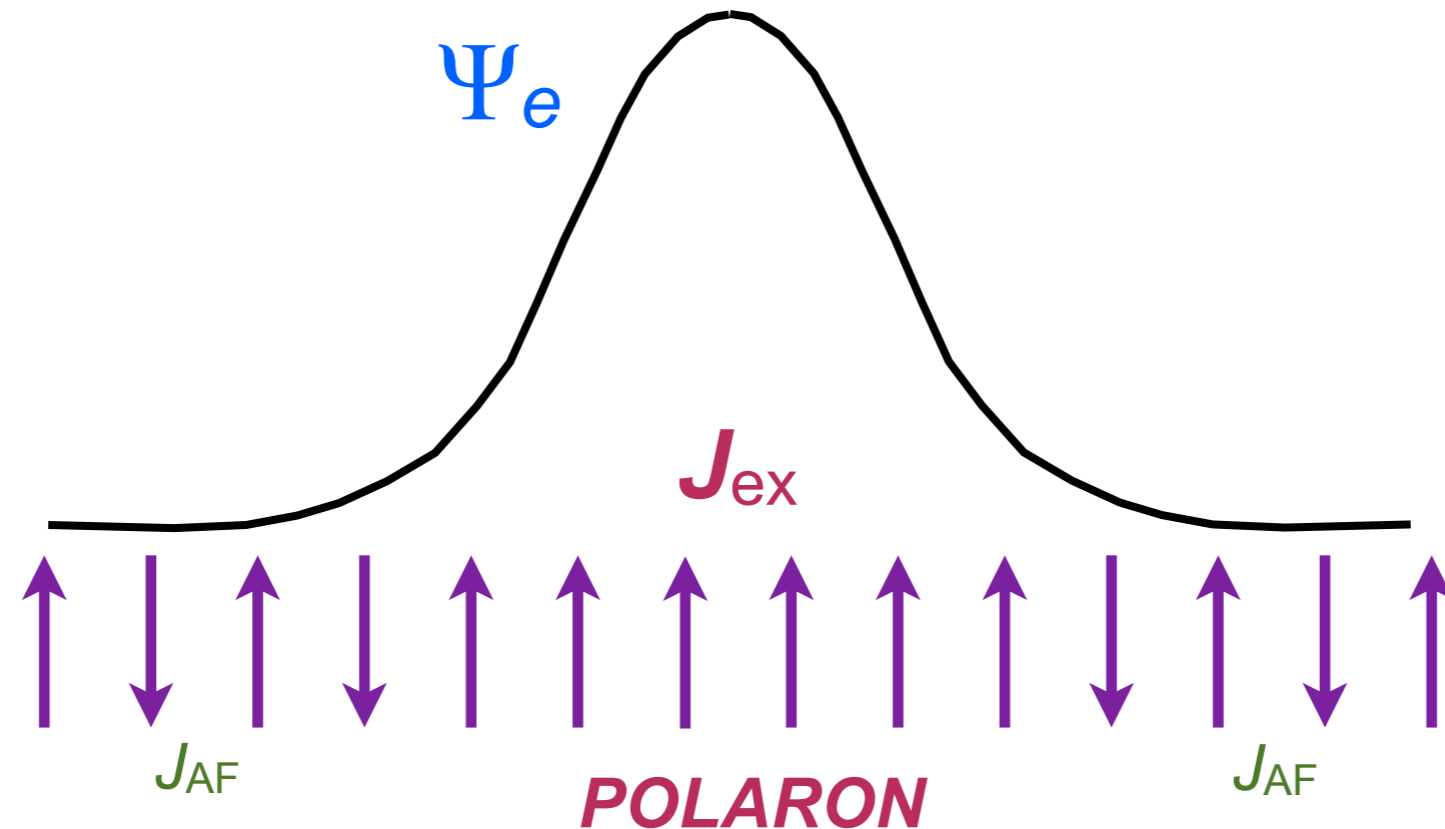
Department of Physics, University of California, Berkeley, California

(Received October 9, 1959)

This paper discusses some effects of mobile electrons in some antiferromagnetic lattices. It is shown that these electrons (or holes) always give rise to a distortion of the ground state spin arrangement, since electron transfer lowers the energy by a term of first order in the distortion angles. In the most typical cases this results in: (a) a nonzero spontaneous moment in low fields; (b) a lack of saturation in high fields; (c) simultaneous occurrence of "ferromagnetic" and "antiferromagnetic" lines in neutron diffraction patterns; (d) both ferromagnetic and antiferromagnetic branches in the spin wave spectra. Some of these properties have indeed been observed in compounds of mixed valency such as the manganites with low Mn^{4+} content. Similar considerations apply at finite temperatures, at least for the (most widespread) case where only the bottom of the carrier band is occupied at all temperatures of interest. The free energy is computed by a variational procedure, using simple carrier wave functions and an extension of the molecular field approximation. It is found that the canted arrangements are stable up to a well-defined temperature T_1 . Above T_1 the system is either antiferromagnetic or ferromagnetic, depending upon the relative amount of mobile electrons. This behavior is not qualitatively modified when the carriers which are responsible for double exchange fall into bound states around impurity ions of opposite charge. Such bound states, however, will give rise to local inhomogeneities in the spin distortion, and to diffuse magnetic peaks in the neutron diffraction pattern. The possibility of observing these peaks and of eliminating the spurious spin-wave scattering is discussed in an Appendix.

Mott picture of the self-trapped **magnetic polaron**

(stolen and caricatured from the original)



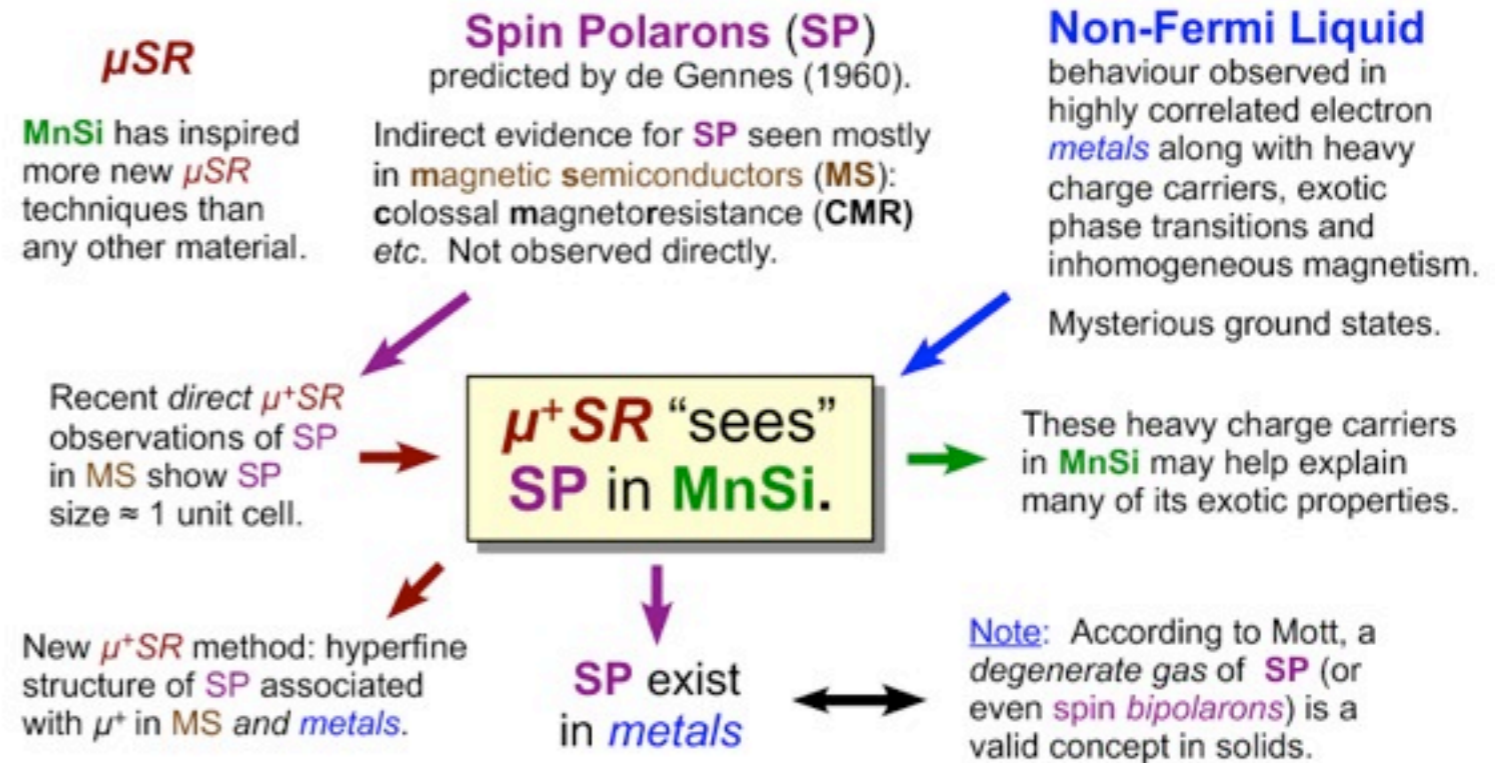
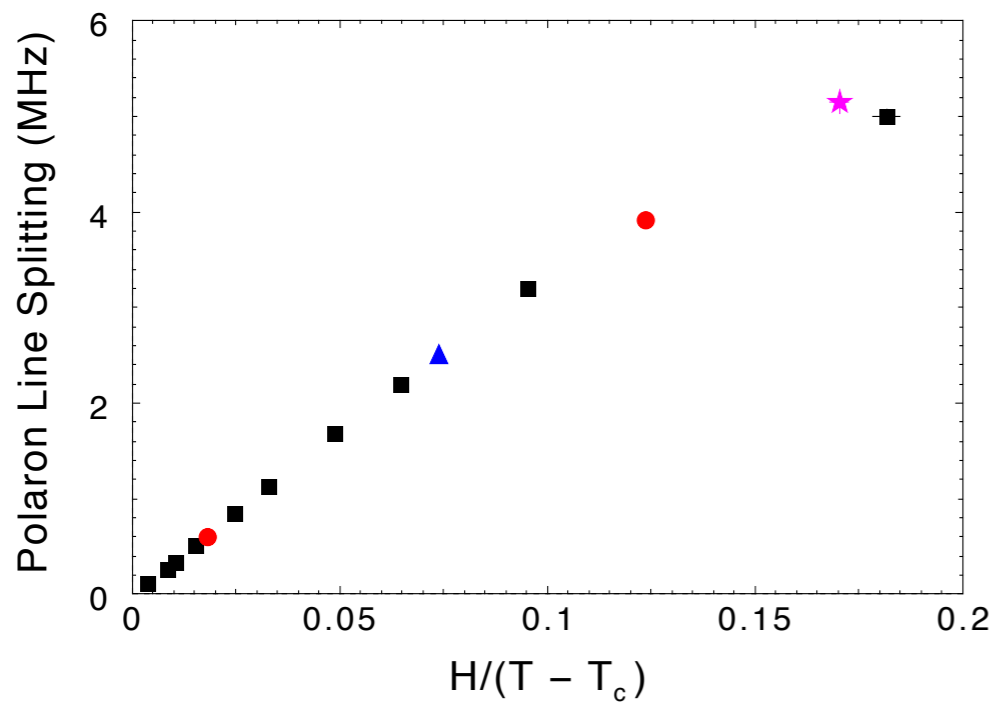
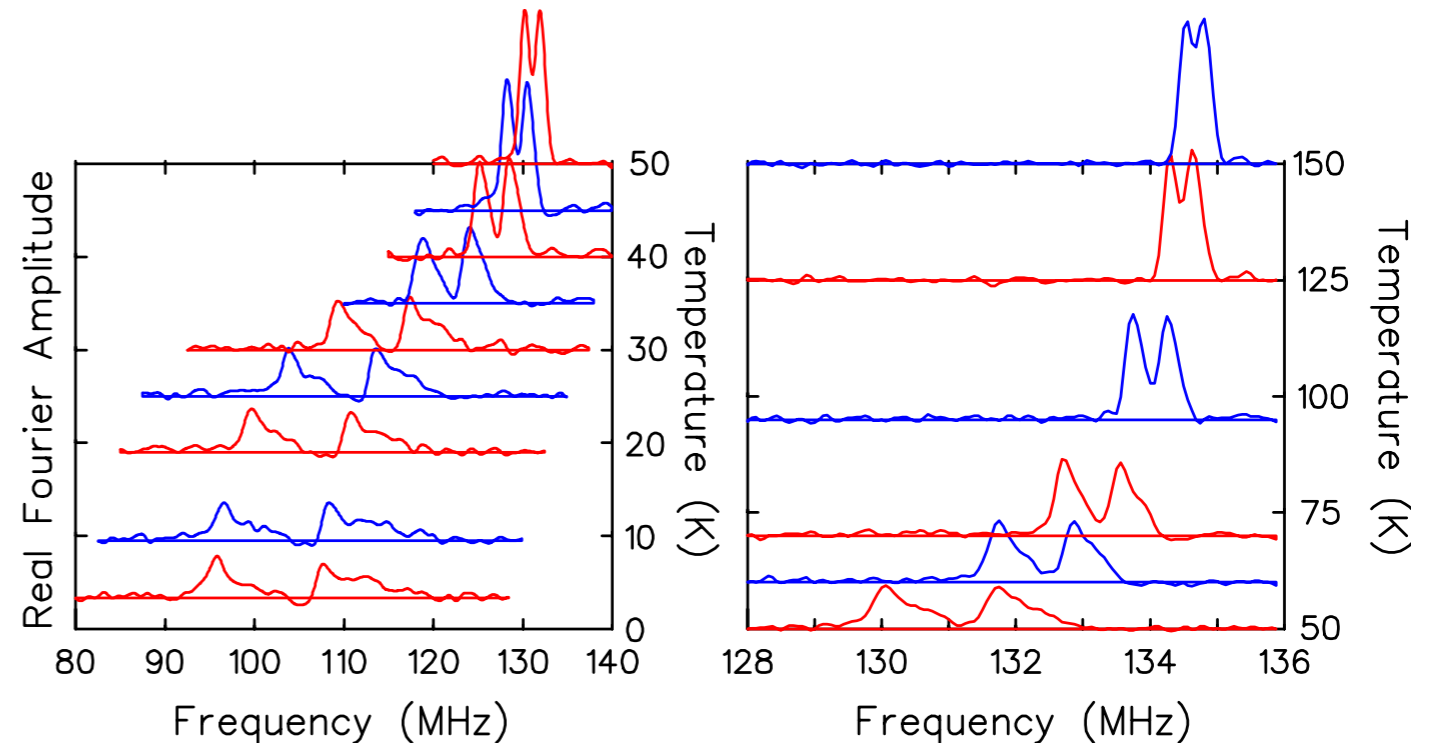
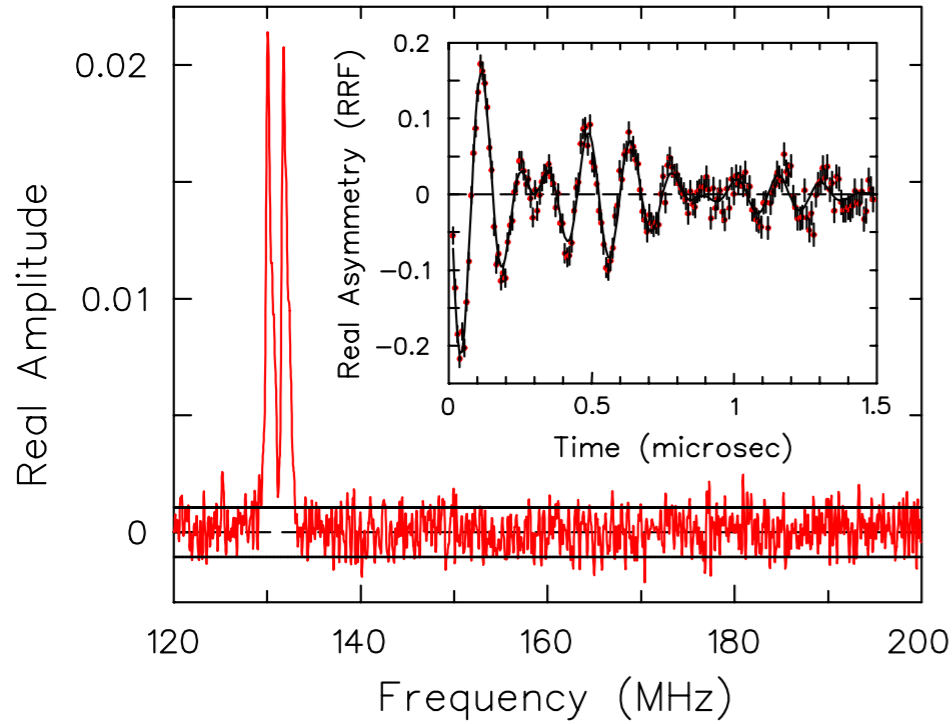
Localized spins with a *weak* direct AF coupling J_{AF} (or none; a paramagnet will also work fine) are **strongly FM** coupled through a *huge* (\sim eV) **exchange interaction** J_{ex} with **one** “extra” **conduction electron**, whose wavefunction Ψ_e is thereby **localized**. The kinetic energy of localization is compensated by $N_p J_{ex}$, where N_p is the number of localized spins in the **polaron**.

Are *other* examples of
spin polarons
revealed by **μ SR**?

itinerant ferromagnet

MnSi

TF=1T



Should you now accept

spin polarons

uncritically?

Sure, why not? :-)

But I will be satisfied if you just consider this possibility when you see multiple μ^+ SR frequencies in magnetic materials.

Finis



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