Chemistry, Physics, and μSR

A muon is a subatomic particle whose spin is highly sensitive to local magnetic and electronic fields. In 1957, it was discovered that "parity violation" in the weak decay of pions ($\pi^\pm$) to muons ($\mu^\pm$), and in the muons' subsequent decay to positrons or electrons ($e^\pm$), provided perfectly spin-polarized beams of muons, whose spin evolution could easily be monitored *via* the emitted $e^\pm$ by a variety of techniques. These techniques, collectively known as ***μSR (muon Spin Rotation-/Relaxation/Resonance)***, have a detection sensitivity higher than NMR by a factor of $\sim 10^{12}$. With the advent of "meson factories" like TRIUMF in the early 1970s, ***μSR*** found many applications in molecular and materials science.

Pion Decay: $\pi^+ \rightarrow \mu^+ + \nu_\mu$

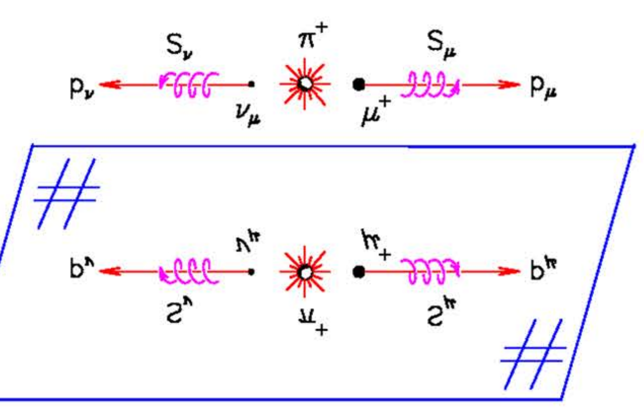
A pion stops in the "skin" of the primary production target. It then has zero linear momentum and zero angular momentum.

Conservation of Linear Momentum: The μ^+ is emitted with momentum equal and opposite to that of the ν_μ (neutrino).

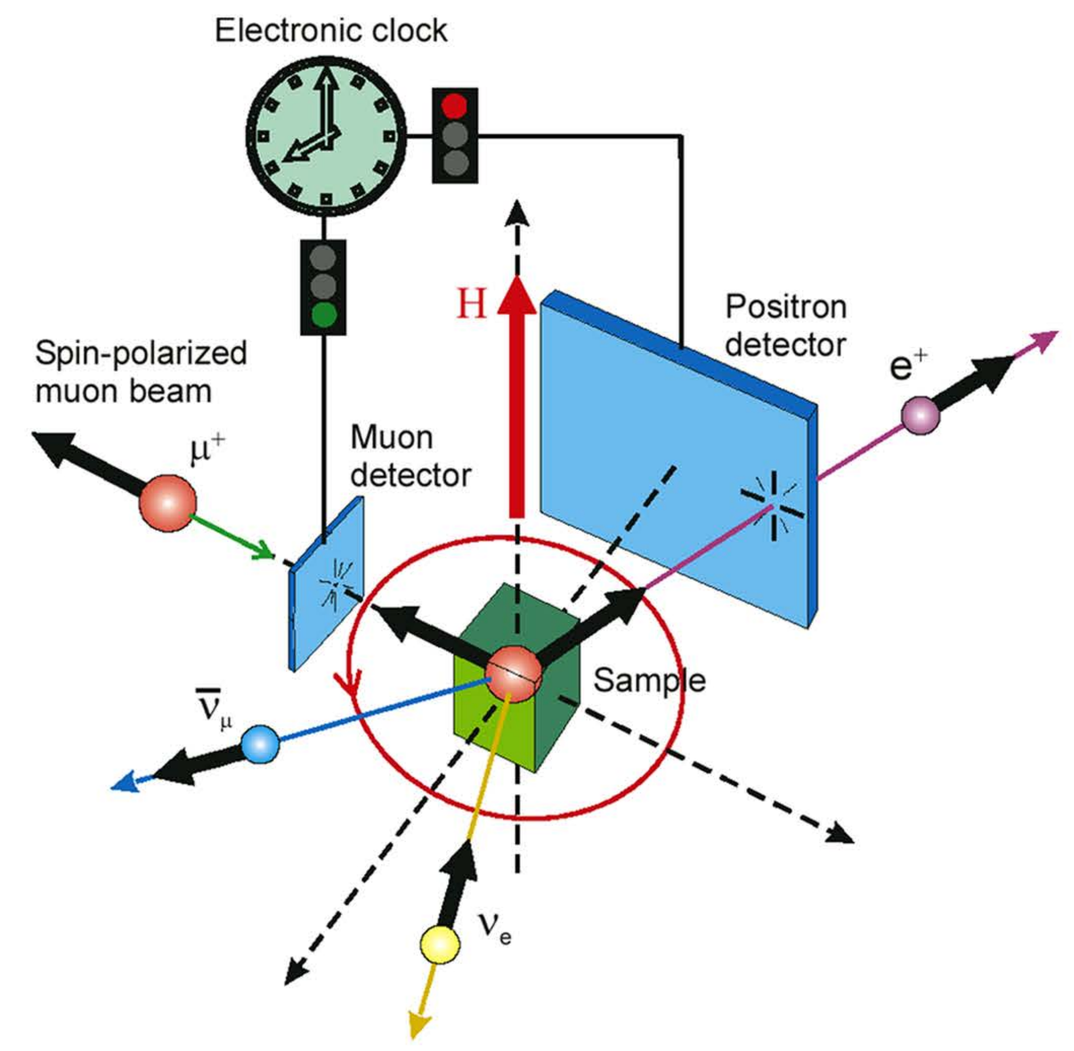
Conservation of Angular Momentum: μ^+ and ν_μ have equal & opposite spins.

Weak Interaction: Only "left-handed" ν_μ are created.

Thus the emerging μ^+ has its spin pointing antiparallel to its momentum direction.



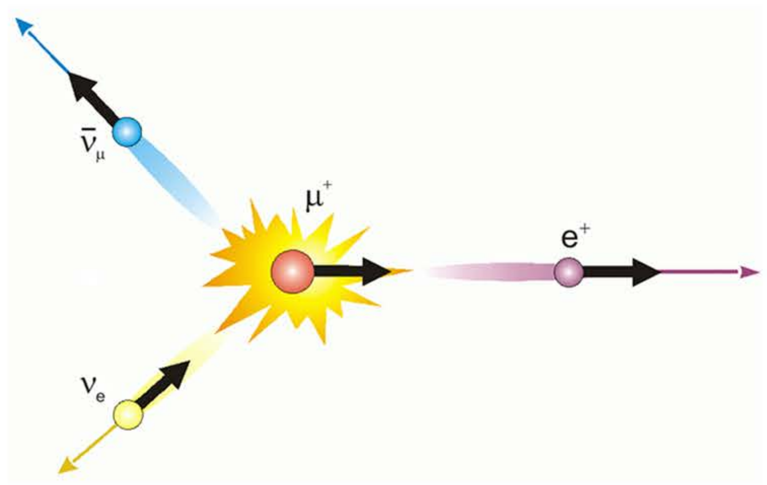
The reaction viewed in the mirror is *not* just as likely as the "normal" reaction; in fact it ***never happens at all!***



Transverse Field (TF) μSR setup

Muon Decay

Neutrinos have negative helicity, while antineutrinos have positive helicity. An ultrarelativistic positron behaves like an antineutrino. Thus the positron tends to be emitted along the μ^+ spin when ν_e and $\bar{\nu}_\mu$ go off together (highest energy e^+).



The First Beam at TRIUMF

In 1972, encouraged by John Warren (the first Director of TRIUMF) and Charles McDowell (then Head of UBC Chemistry), Don Fleming (a new Professor in UBC Chemistry at the time) hired Jess Brewer (a new PDF from Ken Crowe's group at UC Berkeley, now UBC Physics & Astronomy Professor Emeritus) to help build a muon channel (M20) at TRIUMF and thus develop a ***μSR*** program in Canada, including in muonium chemistry (Mu = μ^+e^-, a light isotope of hydrogen). Other key participants were Toshi Yamazaki and Ken Nagamine from the University of Tokyo and Ken Crowe from Berkeley, all of whom helped build M20 and expand the embryonic TRIUMF ***μSR*** program to embrace condensed matter physics.

"First beam" was achieved at TRIUMF in 1974. The first ***μSR*** spectrum ever seen in Canada was taken at M20 on July 11, 1975.

In the decades that followed, a wide variety of spectroscopic techniques were pioneered by the TRIUMF ***μSR*** groups and subsequently adopted by the ***μSR*** community worldwide.

"Muon Boardwalk"

Funding for the first M20 beam line did not come easily, as UBC Chemistry Professor Emeritus Don Fleming recalled:

> ...I think it was only $25K but that was a lot at that time, and put in perspective by Reg Richardson, who was Director of TRIUMF after John Warren, and who provided us with $1,000 to buy a Sears garden shed for a counting room. Dave Garner, a grad student at the time, suggested we buy a garage at Beaver Lumber (also about $1,000), which then fostered several other garages on the "muon boardwalk."
>
> The Fire Marshall later condemned all these and they were torn down, now only historical recollections.

The M20 beam line (circa 1986) in the Meson Hall provides muons for uSR studies in condensed matter physics and Mu chemistry. Recently upgraded (2013). Image source: TRIUMF.

This photo shows a top view of the installation of the three beam channels that were originally installed on the T2 target at TRIUMF in the period 1973-74: M9 originally for studies of muonic and pionic atoms (inset: Mike Pearce, U. Victoria), the original M20 channel for μSR studies (inset: Jess Brewer, UBC & TRIUMF), and the "BioMed" channel M8 used for negative pion radiation therapy for cancer treatment (inset: Ken Kendall, with BC Cancer at the time). Photo provided by Jess Brewer.

Research Using μSR

These techniques rendered ***μSR*** a unique and invaluable tool for studies in chemistry, semiconductor physics, magnetism, and superconductivity. The latter capability led to a strong Canadian program in high temperature superconductors (HT_C SC) and related materials, coinciding with the efforts of Dr. Walter Hardy's group in UBC Physics & Astronomy, starting in 1987.

μ^+ as a probe

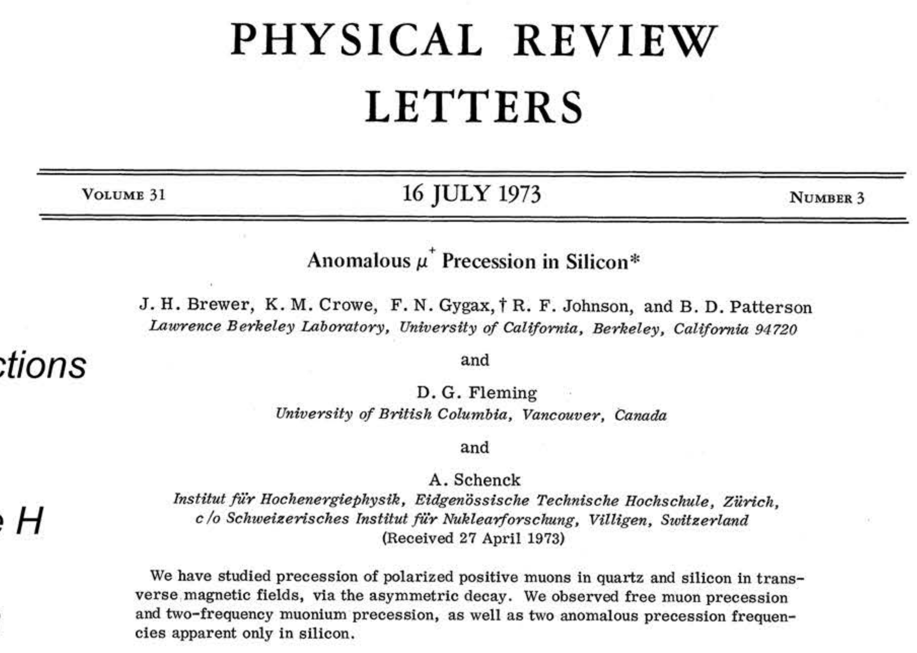
Probing Magnetism: unequalled sensitivity
- Detect local fields: electronic structure; ordering
- Reveals electron and/or nuclear spin dynamics

Probing superconductivity (especially HT_C SC)
- Evaluate the coexistence of superconductivity and magnetism
- Determine magnetic penetration depth λ and coference length ξ

Muonium as light hydrogen

(Mu = μ^+e^-) (H = p^+e^-)

In Chemistry:
- Can be studied in gases, liquids and solids
- The most sensitive test of reaction rate theories
- Can be used to study "unobservable" hydrogen atom reactions
- Facilittes discovery of new radical species
In Semiconductors:
- Until recently, μ^+SR provided the only data on metastable H states in semiconductors
- For Quantum Diffusion: μ^+ in metals (compare H^+); Mu in non-metals (compare H)



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Anomalous μ^+ Precession in Silicon*

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We have studied precession of polarized positive muons in quartz and silicon in transverse magnetic fields, via the asymmetric decay. We observed free muon precession and two-frequency muonium precession, as well as two anomalous precession frequencies apparent only in silicon.

Anomalous μ^+ Precession in Sililcon publishd in July, 1973.

This paper ushered in the whole field of muonium (Mu) in semiconductors, which is still important today (current research work by Rob Kiefl in Physics & Astronomy). It was actually carried out at the old 184" cyclotron at the "Rad Lab" at Berkeley in a collaboration between LBL, the Swiss ETH, and UBC Chemistry/ TRIUMF.

Poster prepared by Theresa Liao, Jess Brewer, and Don Fleming, 2014