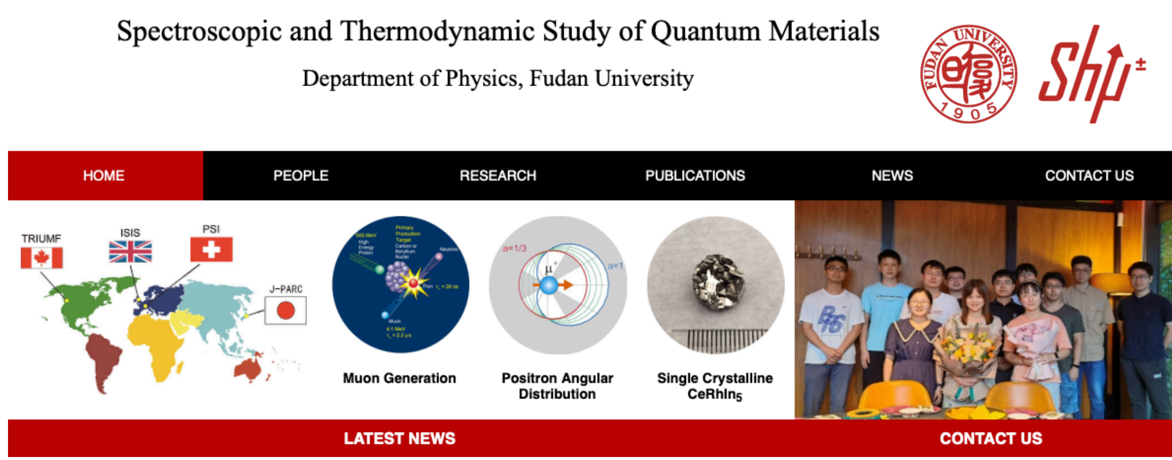
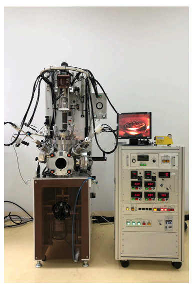
The Application of MuSR on the Study of Quantum Materials

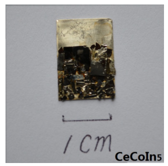


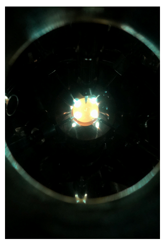
Lei Shu

Physics Department, Fudan University

Research



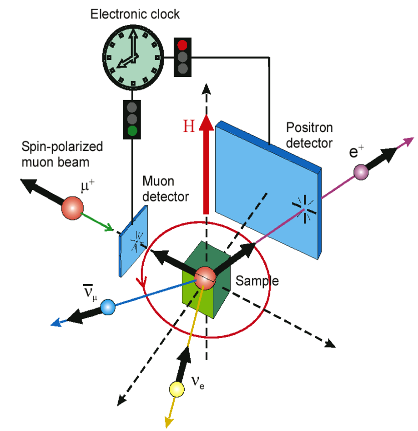




Muon Spin Relaxation

(MuSR)

Electrical resistivity, magnetic susceptibility, specific heat



Exotic behavior of Quantum materials

Superconductivity

Heavy fermion

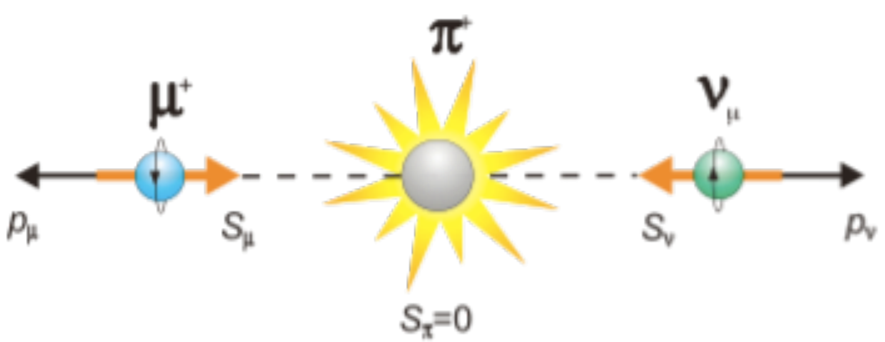
Quantum Spin Liquid

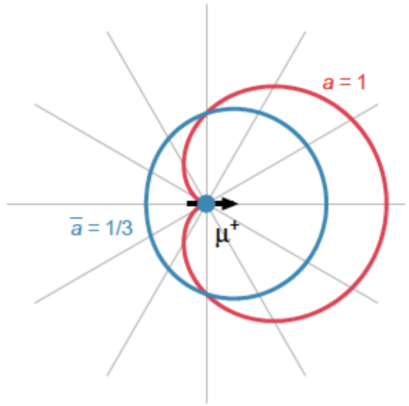
Outline

- Introduction of MuSR
- The application in studying quantum materials
  - ✓ Superconductivity
  - ✓ Quantum spin liquid
  - ✓ Heavy fermion

Two important principals of surface muon

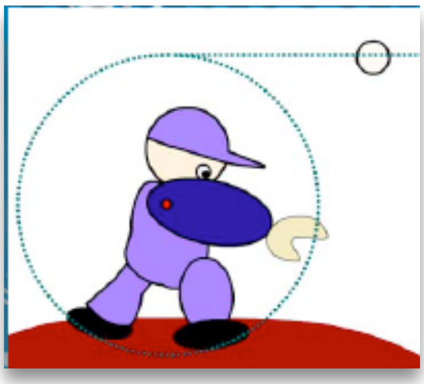
- Nearly 100% spin polarized muon
- Muon decay positron is preferentially emitted to muon spin direction

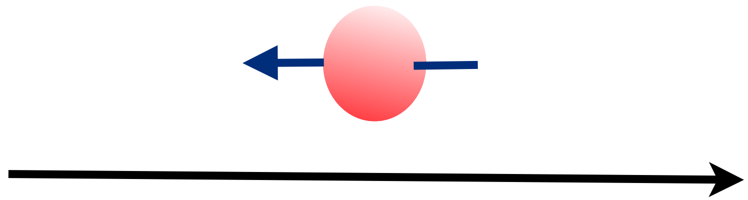




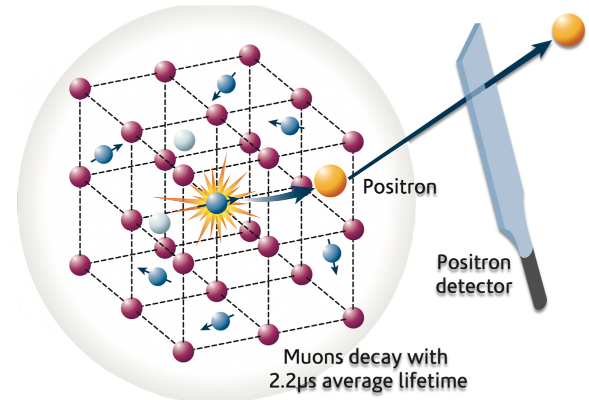
Principle of MuSR

Accelerator





Muon

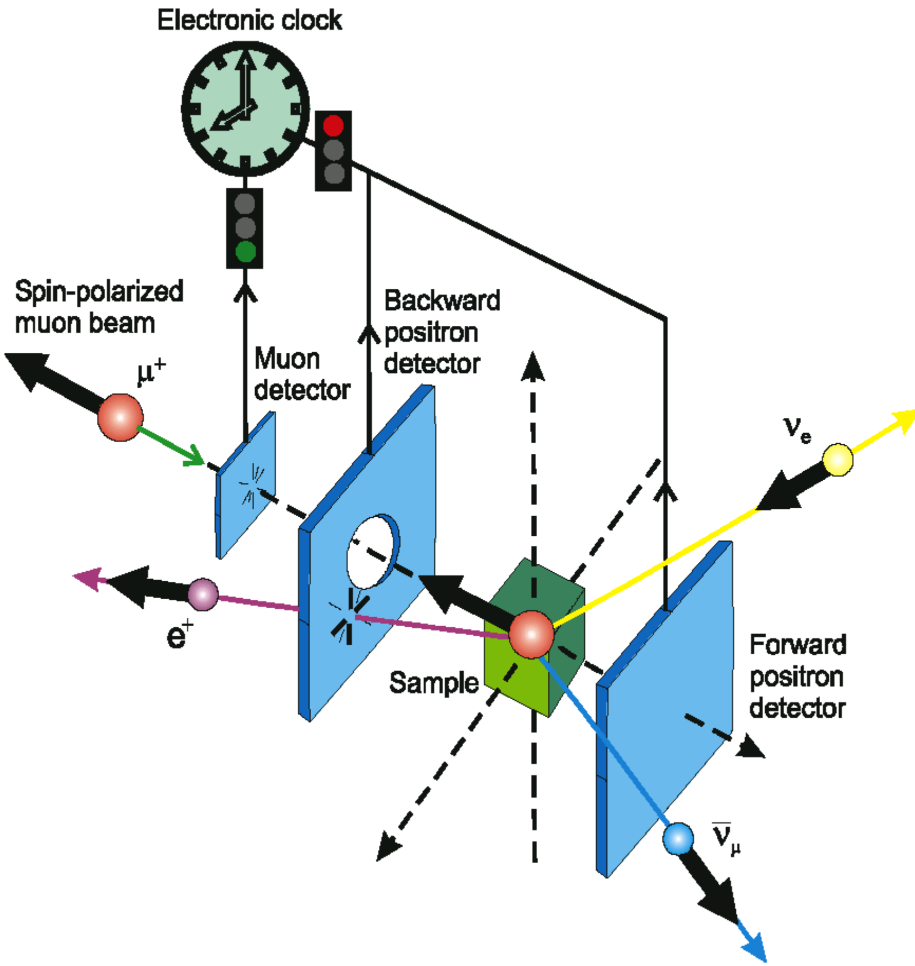


$$\mu^+ \longrightarrow e^+ + \nu_e + \nu_\mu$$

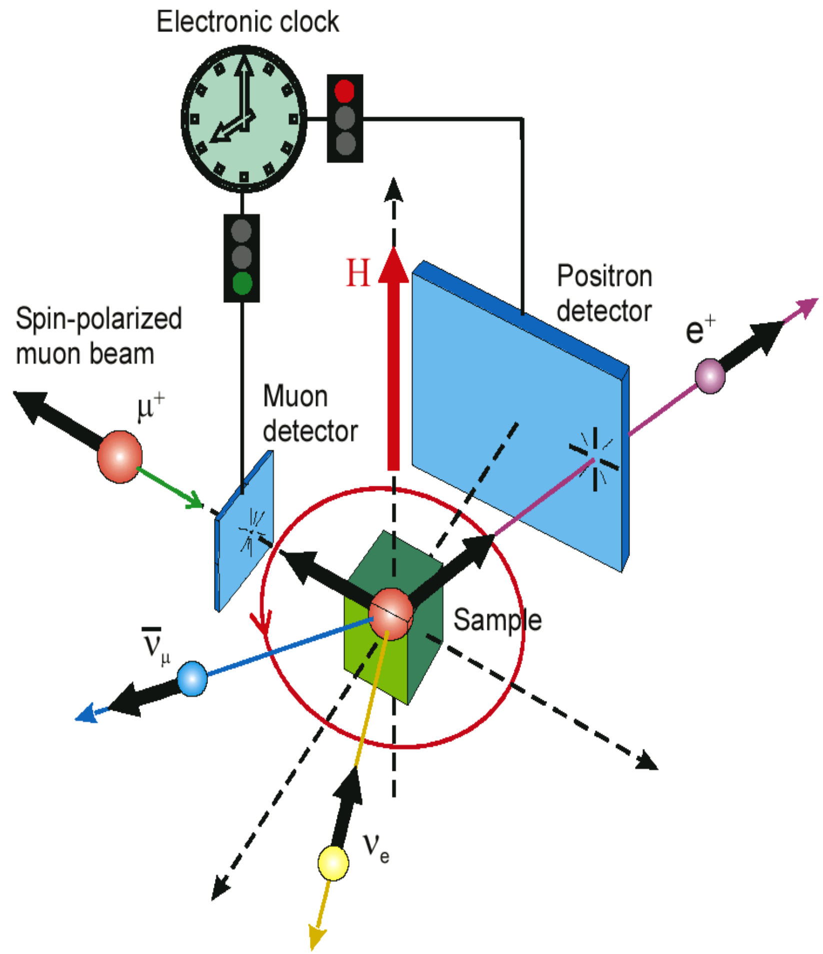
- Measuring the anisotropic distribution of the decay positrons from a bunch of muons deposited at the same condition

- Statistical average direction of the spin polarization (*P*) of the muon ensemble

- *P*(t) depends on the spatial distribution and dynamical fluctuations of the muon magnetic environment



Zero Field

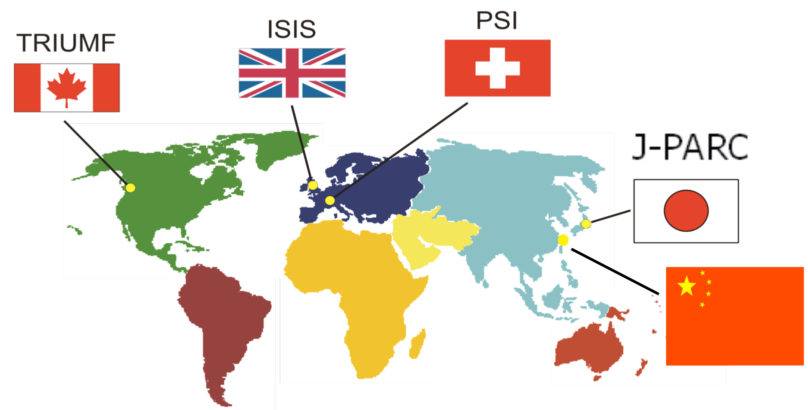


Transverse Field

Crucial Technique on studying Magnetism and Superconductivity

Advantage, Uniqueness, Irreplaceability

- Extreme sensitivity to small internal magnetic fields (0.1 G)
- Magnetic order, volume fraction
- Can measure magnetic fluctuation rates in the range 10^4 to 10^{12} Hz, complementary to NMR, neutron scattering…
- Muon can be implanted into any material (gas, liquid or solid), a large variety of environments (low temperature, high magnetic field, electric fields, high pressure, irradiated with light, applied RF pulses …)
- Single crystals, polycrystalline samples and thin films



Muon Source and beam lines are going to be built at CSNS!

AD. Hillier…L. Shu…et. al., "Muon spin spectroscopy", Nature Reviews Methods Primers 2022
殳蕾、倪晓杰、潘子文，"MuSR 技术在凝聚态物理中的应用"，物理 2021
Z. H. Zhu and L. Shu, "Muon Spin Relaxation Studies on Quantum Spin Liquid Candidates", Progress in Physics 2020

Superconductivity

MuSR on Superconductors

- Magnetic penetration depth （superfluid density）
- Knight shift
- Detect extremely small magnetic field (0.1 G)
- Magnetic order? Volume fraction

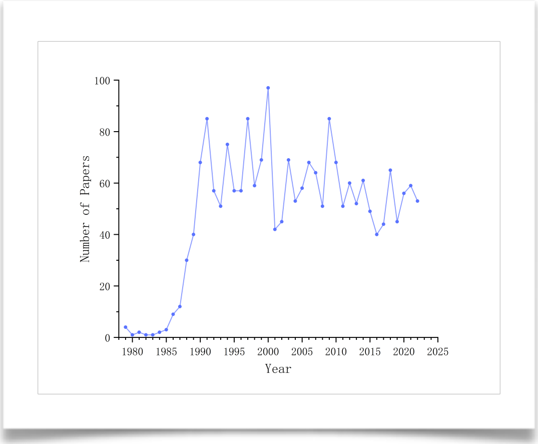
Superconducting gap symmetry

Time-reversal symmetry

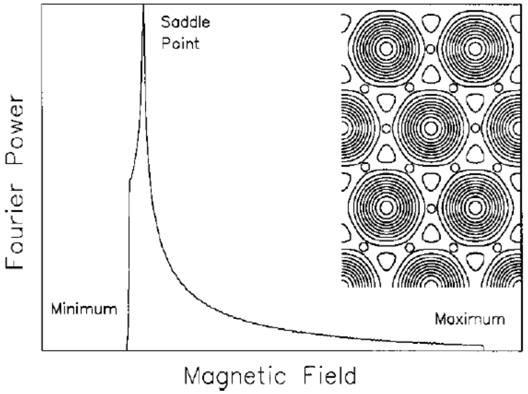
The relation between superconductivity & magnetism

Superconducting mechanism

Number of literatures on superconductivity studied by MuSR



Magnetic penetration depth（superfluid density）

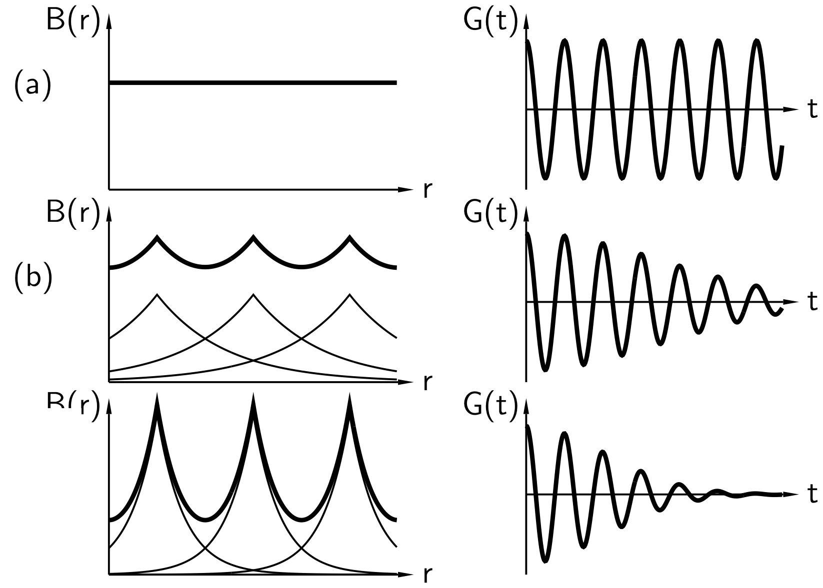


J. E. Sonier et al.,
Review of Modern Physics 72, 769 (2000)

Normal state

Superconducting state

Superconducting state with smaller penetration depth

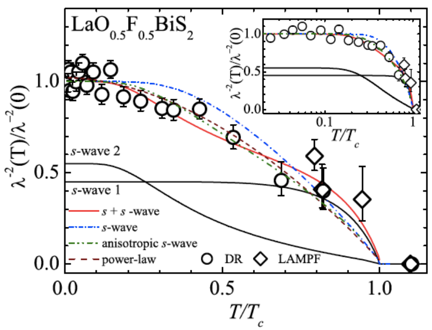


- **Absolute value of penetration depth** λ
- **Superfluid density** $\rho \sim 1/\lambda^2$
- **Superconducting pairing symmetry** $\rho(T)$

Only MuSR can directly measure the magnetic penetration depth

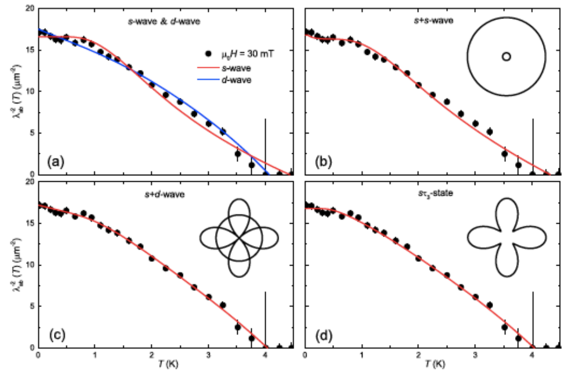
Symmetry of the Superconducting gap

$LaO_{0.5}F_{0.5}BiS$ *s+s*



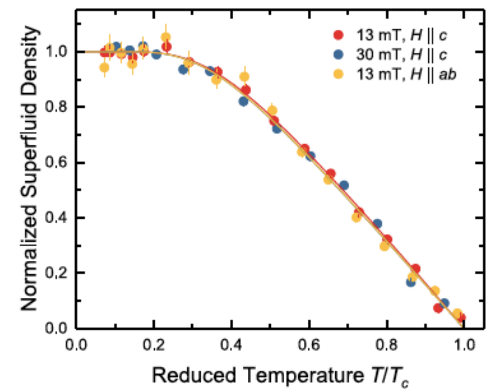
J. Zhang..L. Shu* PRB 2016

FeS *s+d*



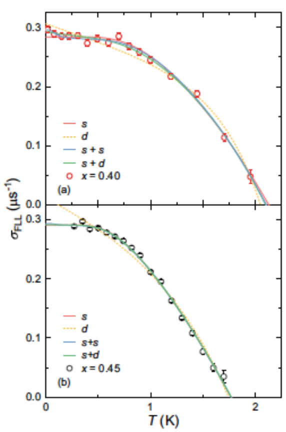
C. Tan..L. Shu* PRB 2018

$PbTaSe_2$ *S*



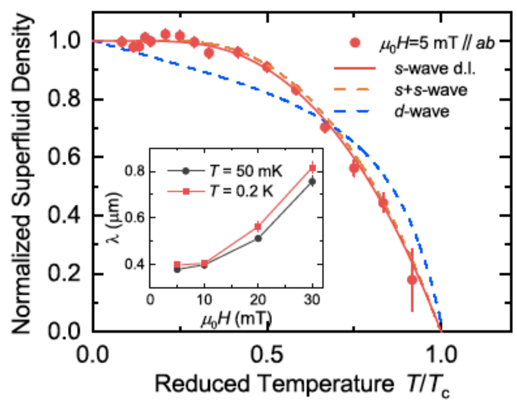
Z. H. Zhu…L. Shu* NJP 2022

$La_2(Cu_{1-x}Ni_x)_5As_3O_2$ *s+d*



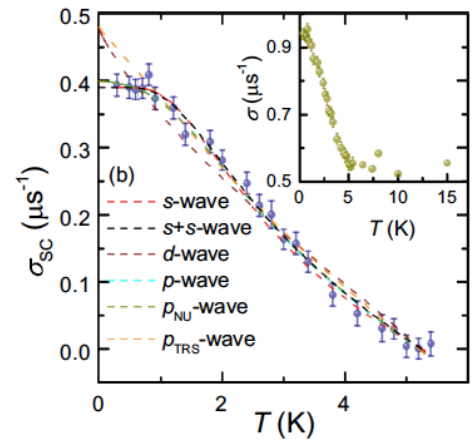
Q. Wu…L. Shu* PRB 2023

$BaNi_2As_2$ *s+s*



K. W. Chen…L. Shu* PRB 2024

$Pr_3Cr_{10-x}N_{11}$ *p?*



C. S. Chen…L. Shu* npj QM 2024

Time-reversal symmetry superconductivity

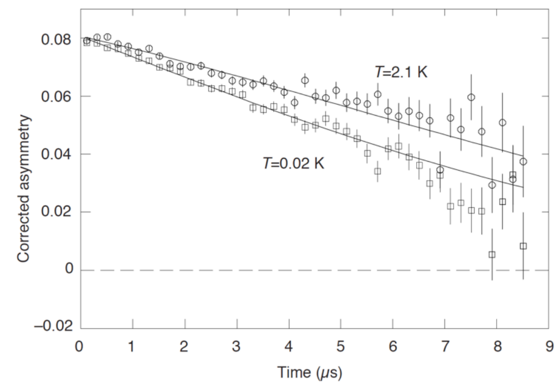
Time-reversal symmetry-breaking superconductivity in Sr_2RuO_4

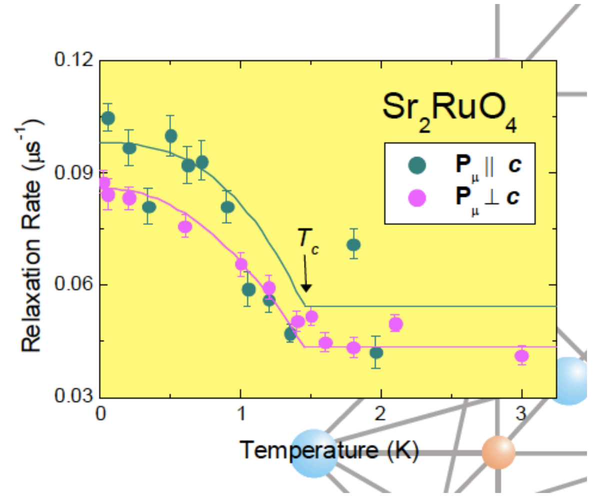
G. M. Luke*, Y. Fudamoto*, K. M. Kojima*, M. I. Larkin*, J. Merrin*, B. Nachumi*, Y. J. Uemura*, Y. Maeno†, Z. Q. Mao†, Y. Mori†, H. Nakamura‡ & M. Sigrist§

* *Department of Physics, Columbia University, New York, New York 10027, USA*
† *Department of Physics and § Yukawa Institute for Theoretical Physics, Kyoto University, Kyoto 606-8502, Japan*
‡ *Department of Material Science and Engineering, Kyoto University, Kyoto 606-8501, Japan*

Although the properties of most superconducting materials are well described by the theory[1] of Bardeen, Cooper and Schrieffer (BCS), considerable effort has been devoted to the search for exotic superconducting systems in which BCS theory does not apply. The transition to the superconducting state in conventional BCS superconductors involves the breaking of gauge symmetry

NATURE | VOL 394 | 6 AUGUST 1998

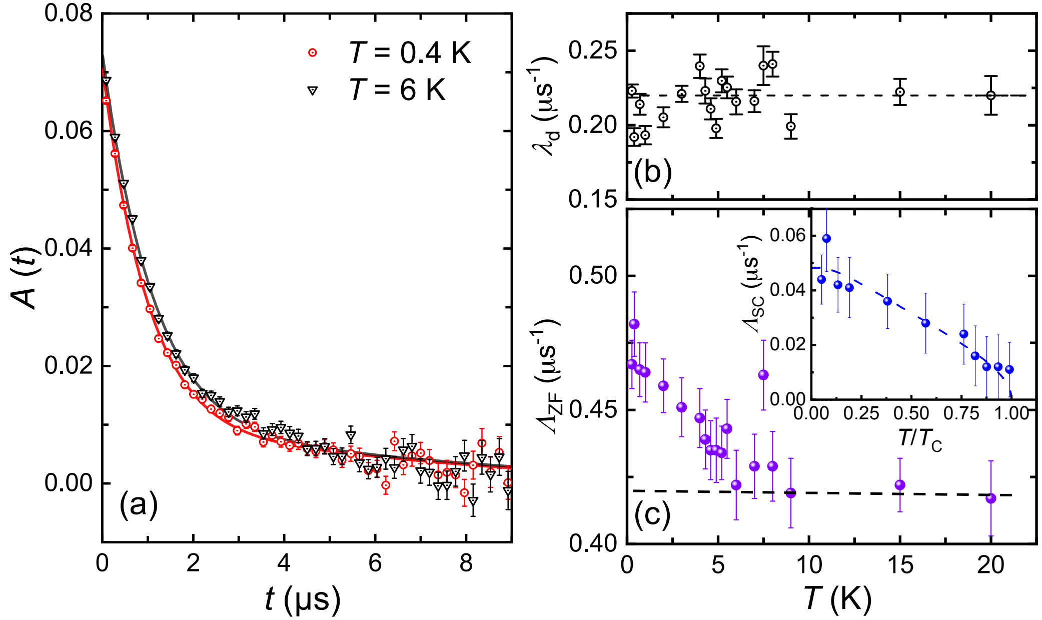




G. M. Luke et al., Nature 394, 558 (2000)

Time-reversal symmetry superconductivity

$Pr_3Cr_{10-x}N_{11}$

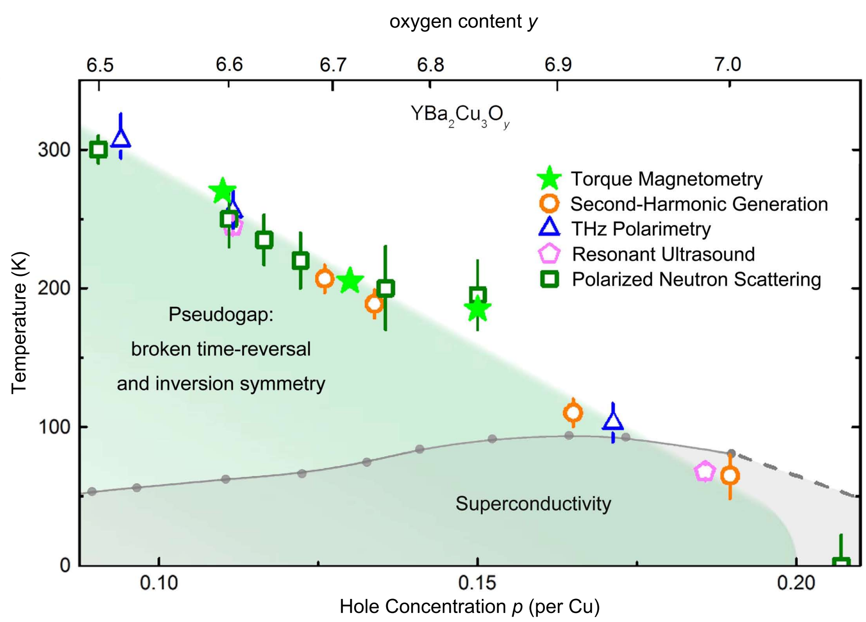


- The temperature-dependent superfluid density is consistent with a *p*-wave pairing symmetry.
- A time-reversal symmetry broken superconducting transition,
- A candidate of *p*-wave superconductor which breaks time-reversal symmetry.

C. S. Chen…L. Shu* npj QM 2024

Pseudogap in cuprate $YBa_2Cu_3O_y$

Previous experiments show (at T^*):
Broken time-reversal symmetry
Broken spatial-rotation and inversion symmetries



TRSB: left in skepticism

Local magnetic fields expected for such an order **not** observed in MuSR or NMR experiments

•MuSR, NMR: longer time scales (~10^{-5} s) >> other technique (~10^{-10} s)

•The local magnetic fields may be motionally narrowed by fluctuations (finite-size domains of ordered phase with different field orientations)

• New MuSR experiment: to test the possibility of dynamic relaxation, to obtain the fluctuation time scale and value of local magnetic fields.

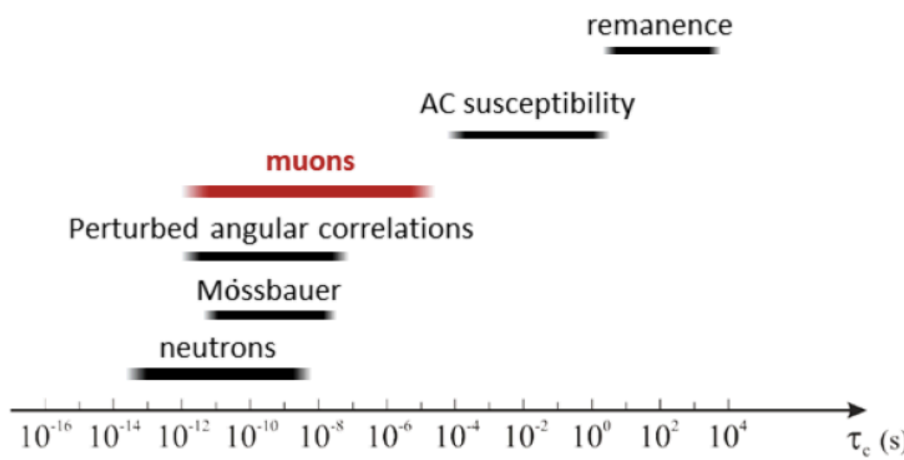


图 2.1-3 μSR 实验能有效填补多种实验对磁场频率覆盖的空白。图片由 A. Yaouanc 和 P. Dalmas De Réotier 所著专著[68]中第一章图 1.5 重新绘制。

张建，博士学位论文 2020

Pseudogap in cuprate $YBa_2Cu_3O_y$

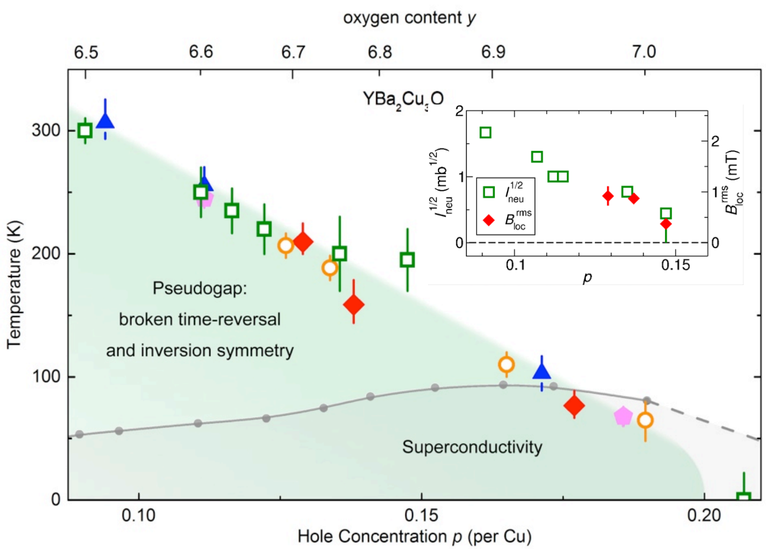


Table 1. Correlation times τ_c and rms muon local fields B_{loc}^{rms} from muon spin relaxation rates in $YBa_2Cu_3O_y$.

y	Temperature (K)	τ_c(ns)	B_{loc}^{rms} (mT)
6.72	80	5(2)	0.92(19)
6.77	85	10(3)	0.87(10)
6.83	93	25(10)	0.37(6)

- A magnetic field with rms width of larger than 1 mT fluctuating about 10^8 Hz has been discovered, setting in consistently at $T_{mag} = T^*$

- Critical slowing down of fluctuations at T_{mag} expected near time-reversal symmetry breaking transitions.

J. Zhang…L. Shu*, Science Advances 4 eaao5235 (2018)
Z. H. Zhu…L. Shu*, Phys. Rev. B 103 134426 (2021)

Quantum Spin Liquid

Quantum Spin Liquid

FM, AFM   Quantum Spin Liquid

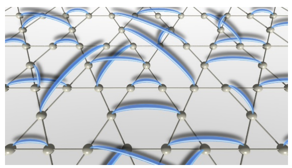
Broholm *et al.*, *Science* **367**, eaay0668 (2020)

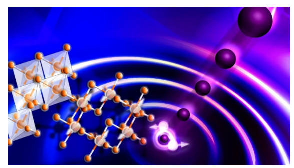
REVIEW

QUANTUM MATERIALS

Quantum spin liquids

C. Broholm[1], R. J. Cava[2], S. A. Kivelson[3], D. G. Nocera[4], M. R. Norman[5]*, T. Senthil[6]





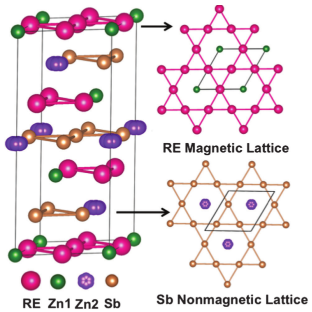
Spin liquids are quantum phases of matter with a variety of unusual features arising from their topological character, including "fractionalization"—elementary excitations that behave as fractions of an electron. Although there is not yet universally accepted experimental evidence that establishes that any single material has a spin liquid ground state, in the past few years a number of materials have been shown to exhibit distinctive properties that are expected of a quantum spin liquid. Here, we review theoretical and experimental progress in this area.

Absence of magnetic long range order down to zero temperature ; Highly entangled spin system

What can you measure with μSR

- Magnetic orders (long/short range, spin glass, weak magnetism)
- Spin dynamics T_1

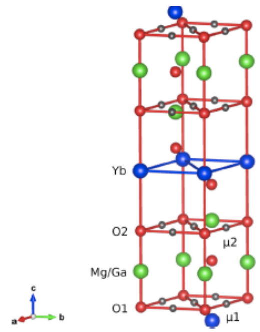
$Tm_3Sb_3Zn_2O_{14}$



Possible QSL ground state: a $\mathbb{Z}_2$ QSL

Z. F. Ding… L. Shu* PRB 2018

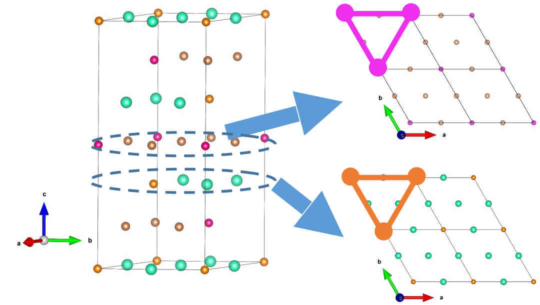
$YbMgGaO_4$



Persistent spin dynamics and absence of spin freezing

Z. F. Ding… L. Shu* PRB 2020

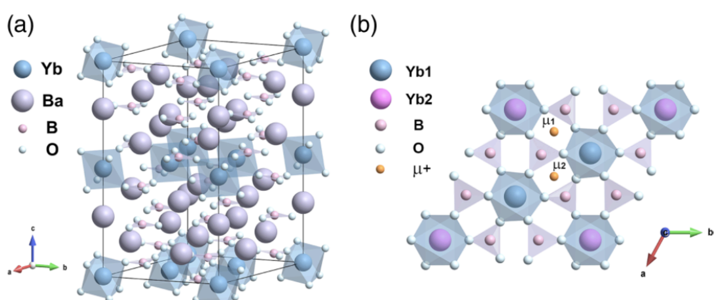
$Lu_3Sb_3Cu_2O_{14}$



Intrinsic properties of spin-liquids due to very high purity

Y. X. Yang…L. Shu*, arXiv:2102.09271

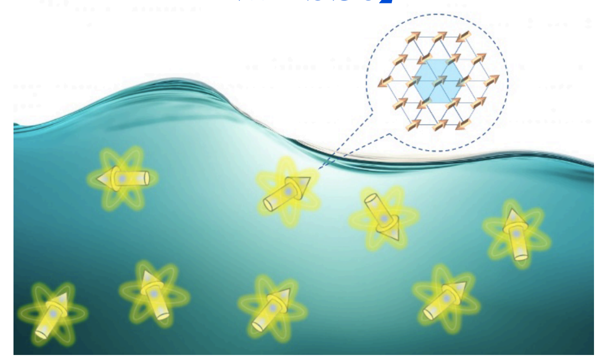
$Yb(BaBO_3)O_3$



Quantum magnet, dipole-dipole interaction dominant

C. Y. Jiang…L. Shu* PRB 2022

$NaYbSe_2$



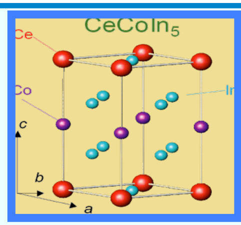
Fluctuating magnetic droplets immersed in a sea of quantum spin liquid

Z. H. Zhu…L. Shu*, the Innovation 2023

Heavy fermion

Renormalization of superfluid density in a heavy fermion

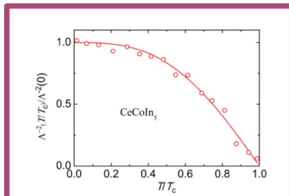
$CeCoIn_5$

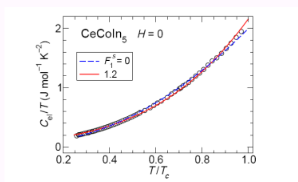


Very clean system:
$l_0 >> \xi$

SC： d wave

Normal： non-Fermi liquid ！





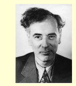
$$\frac{\Lambda^{-2}(T/T_c)}{\Lambda^{-2}(0)} = 1 - \frac{\left(1+\frac{1}{3}F_1^s\right)(T/T_c)^3}{1+\frac{1}{3}F_1^s(T/T_c)^3}$$

$$C_{el}(T) \propto \left[1+\frac{1}{3}F_1^s\frac{(1+\frac{1}{3}F_1^s)(T/T_c)^3}{1+\frac{1}{3}F_1^s(T/T_c)^3}\right]\left(\frac{T}{T_c}\right)^3$$

$$F_0^s = 1.2 \pm 0.3, \ F_1^s = 36 \pm 1$$
$$F_0^s \gg F_1^s$$

Lei Shu* et. al. Phys. Rev. Lett. 113 166401 (2014)

London **Magnetic penetration depth**
F. and H. London 1935



Landau **Fermi liquid theory**
Lev D. Landau 1956

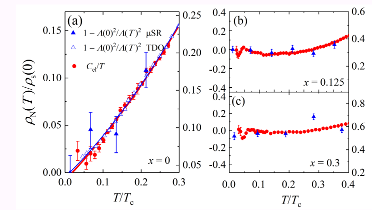
Leggett **Superfluid Fermi liquid**
Physical Review 140 A1869 1965

Varma **modified *Leggett* theory for heavy fermion**
Physical Review Letters 57 626 1986

Miyake and Varma **theory for unconventional superconductivity with non-Fermi liquid normal state**
Physical Review B 174501 2018

$Ce_{1-x}Yb_xCoIn_5$

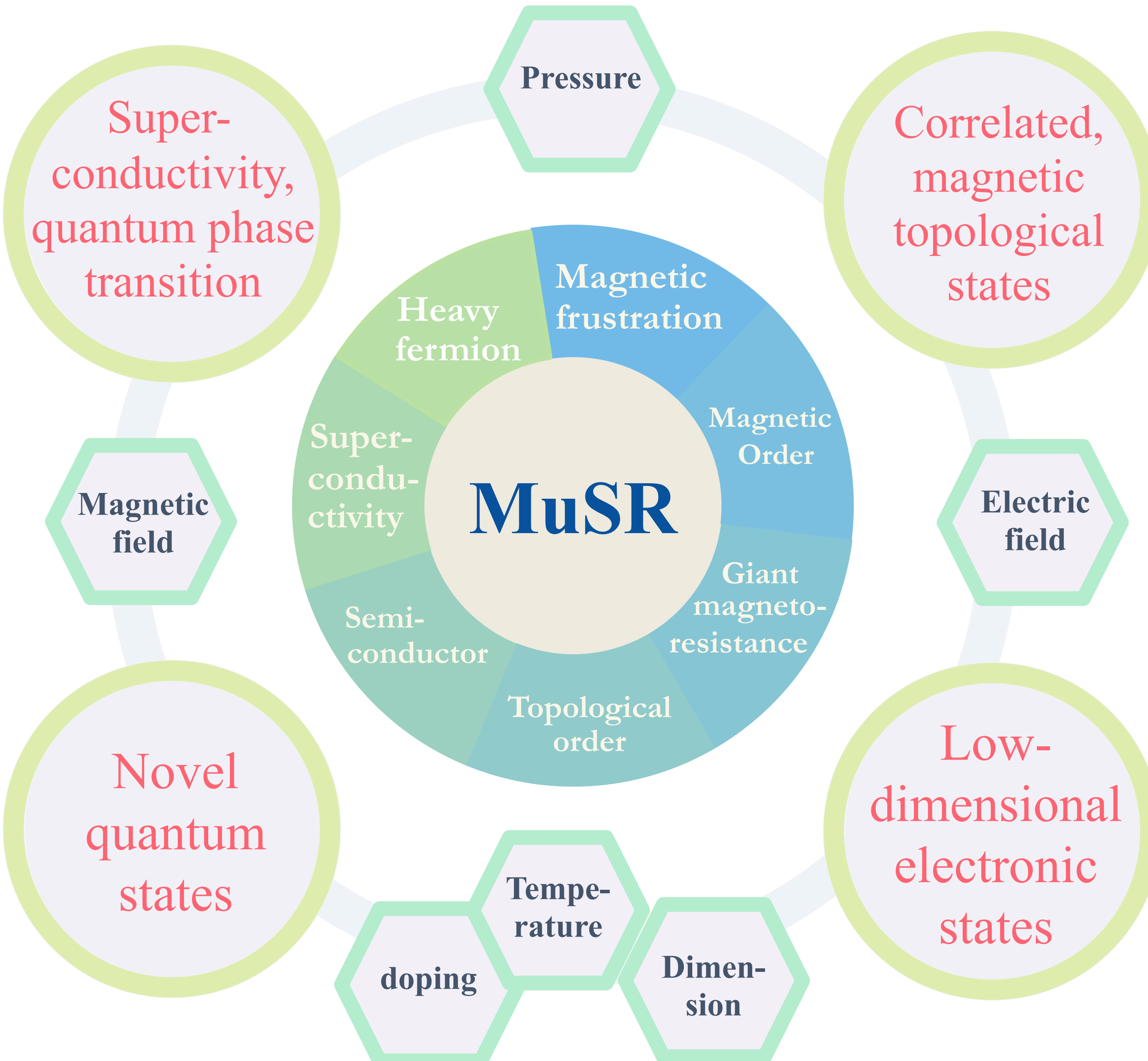
NFL—> FL



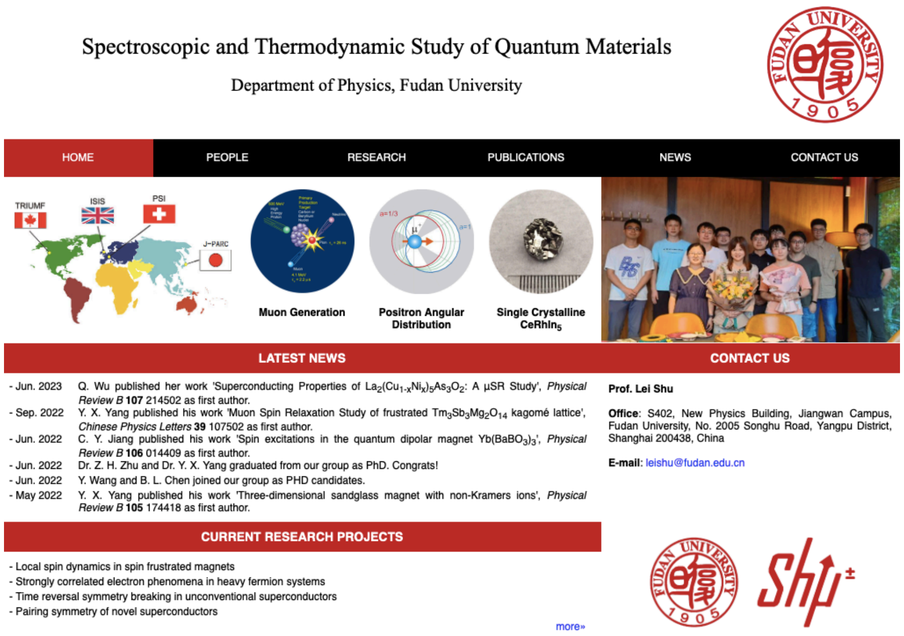
Same temperature dependence of Landau parameter

Z. F. Ding…Lei Shu*
Phys. Rev. B 99 035136 (2019)

- The first determination of Landau parameters in a heavy-fermion compound, tests the basic assumption of the theory of heavy fermions
- Non-Fermi liquid in the normal state, Landau Fermi liquid still applies to the thermal dynamical and transport behaviors in the superconducting state


Pressure
Super-conductivity, quantum phase transition
Correlated, magnetic topological states
Heavy fermion
Magnetic frustration
Magnetic Order
Super-conductivity
MuSR
Magnetic field
Electric field
Giant magneto-resistance
Semi-conductor
Topological order
Novel quantum states
Low-dimensional electronic states
Tempe-rature
doping
Dimen-sion

Thank you!



http://www.physics.fudan.edu.cn/tps/people/leishu/GroupHomepage.html