“缪子束加速和对撞机技术及其应用”论坛

缪子科学和多学科交叉应用

Muon science and its multidisciplinary applications

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中国科学技术大学

2022/04/16

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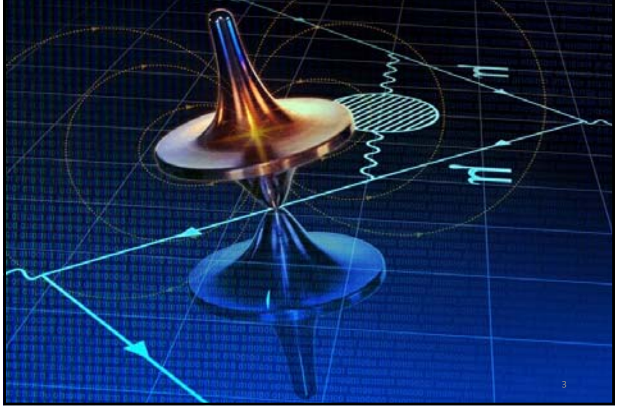
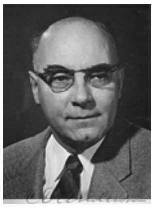
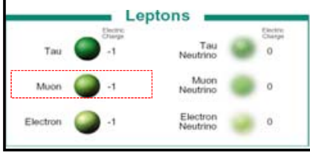
一、缪子和缪子源



Muons were discovered by C.D. Anderson in 1936



Carl David Anderson
(1905-991)



	charge	spin	mass	moment	$\gamma/2\pi$ (kHz G^{-1})	lifetime (μs)
e	±e	1/2	m_e = 0.51 MeV	657 μ_p	2800	∞
μ	±e	1/2	207 m_e = 105.7 MeV	3.18 μ_p	13.5	2.19
p	±e	1/2	1836 m_e = 938 MeV	μ_p	4.26	∞

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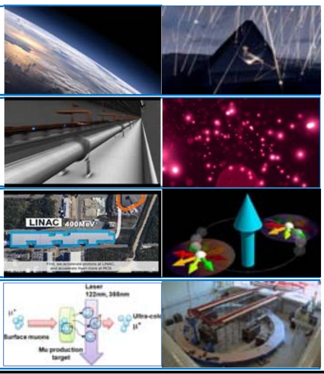
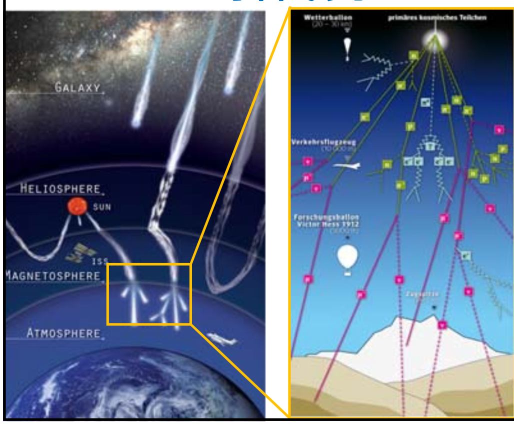
Muon sources

- GeV–TeV cosmic-ray muons
- GeV accelerator muons
- MeV muons
- eV–keV slow muons



宇宙线缪子

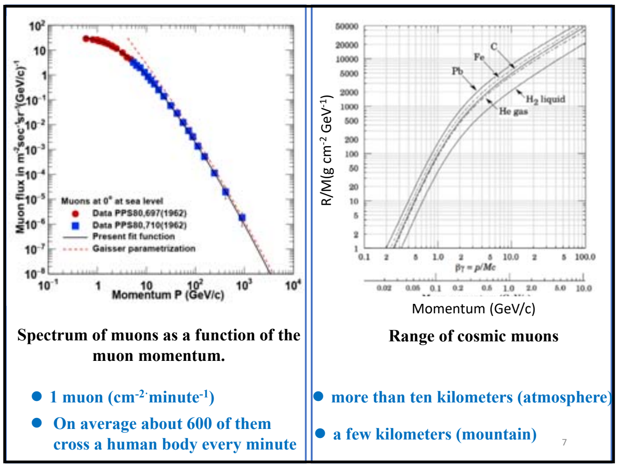


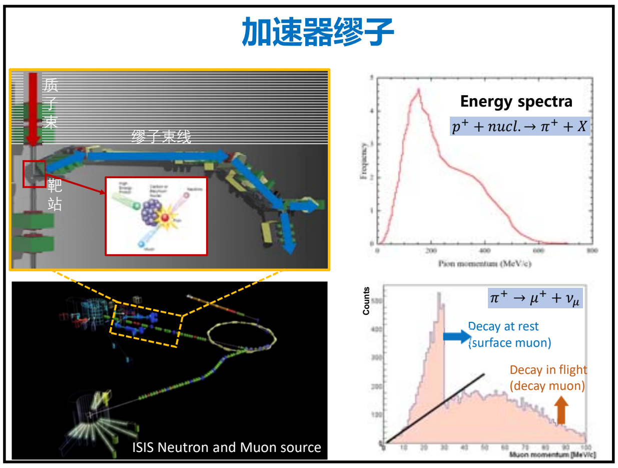
π产生

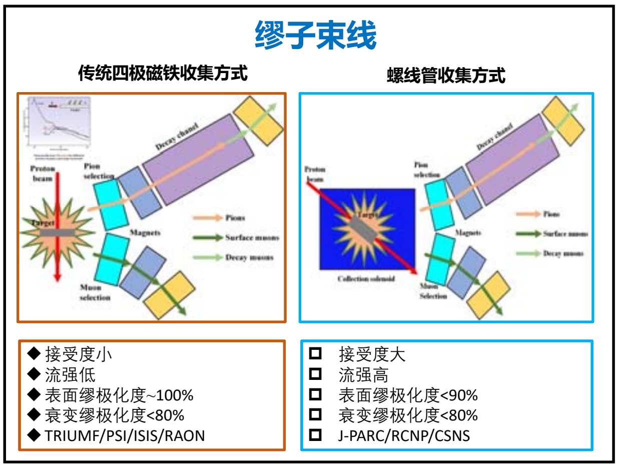
$$p^+ + p^+ \to p^+ + n + \pi^+$$
$$p^+ + n \to p^+ + p^+ + \pi^-$$
$$K^0 \to \pi^+ + \pi^-$$

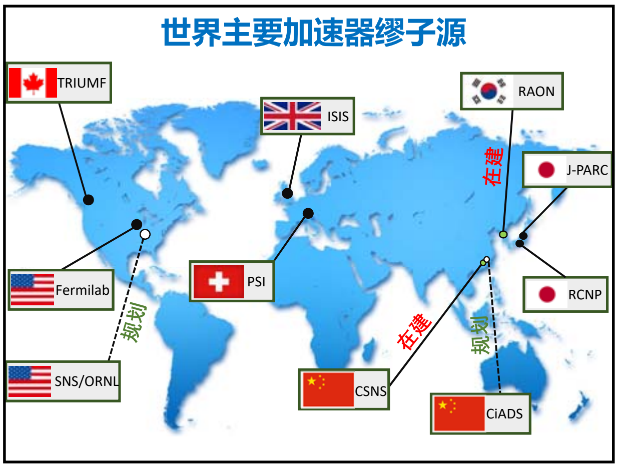
μ产生

$$\pi^+ \to \mu^+ + \nu_\mu$$
$$\pi^- \to \mu^- + \bar{\nu}_\mu$$









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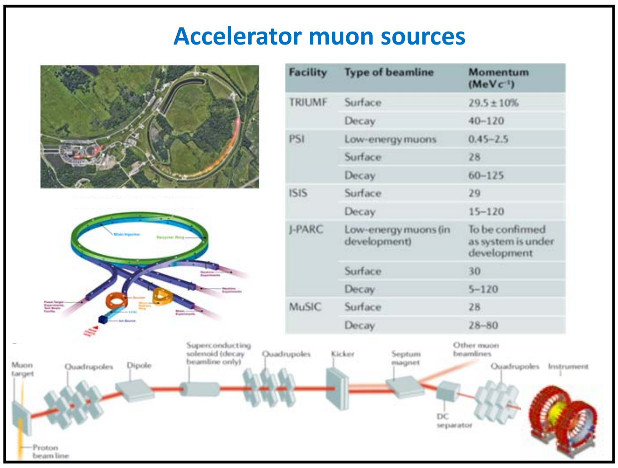
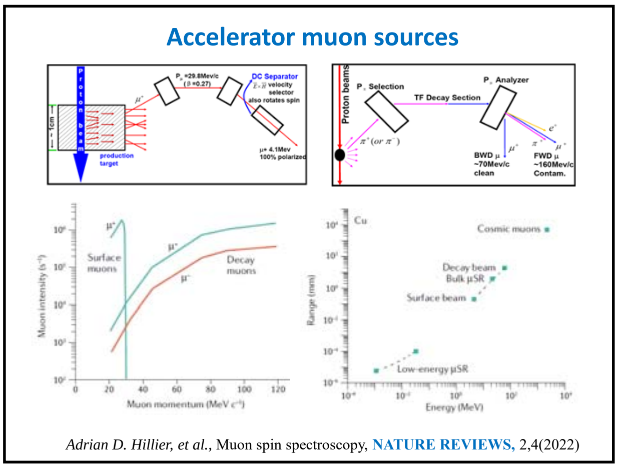
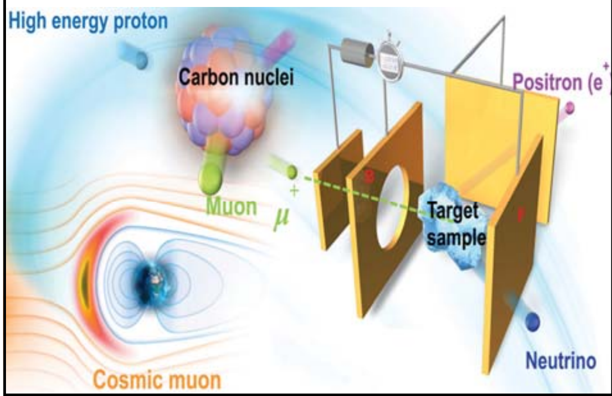
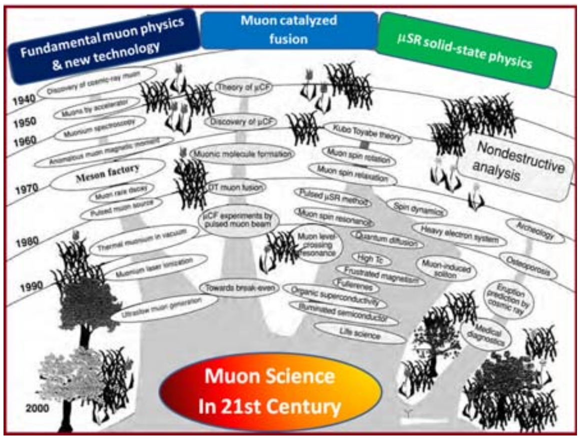


Facility	Type of beamline	Momentum (MeV c⁻¹)
TRIUMF	Surface	29.5 ± 10%
	Decay	40–120
PSI	Low-energy muons	0.45–2.5
	Surface	28
	Decay	60–125
ISIS	Surface	29
	Decay	15–120
J-PARC	Low-energy muons (in development)	To be confirmed as system is under development
	Surface	30
	Decay	5–120
MuSIC	Surface	28
	Decay	28–80



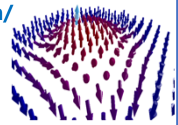
二、缪子与物质科学





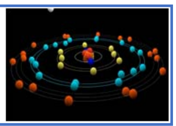
缪子自旋谱学(muon spin rotation/ relaxation/resonance, μSR)

精确表征与物质微观磁性相关的静态或动态过程



缪子原子X射线元素分析(muonic X-ray elemental analysis)

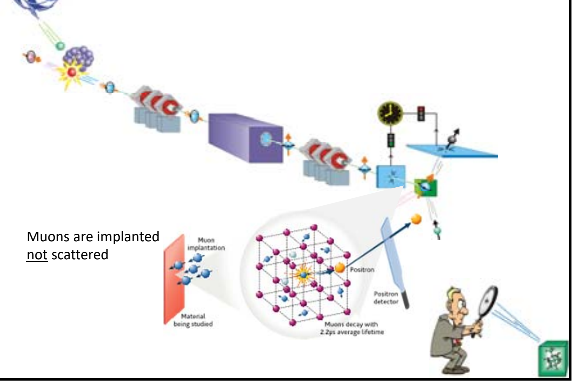
定量分析物质元素构成、浓度甚至化学状态



缪子催化聚变(muon-catalyzed fusion, μCF)

利用负缪与核结合更紧密的优势使氘氚或氘氚在常温甚至低温下发生聚变。

1. 缪子自旋谱学技术与应用



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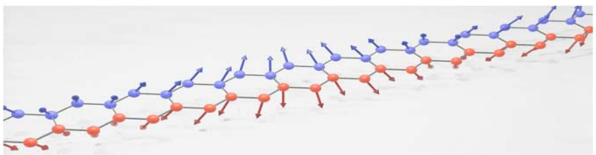
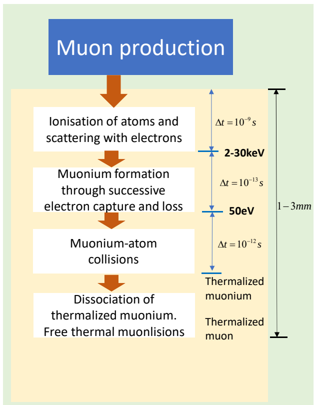
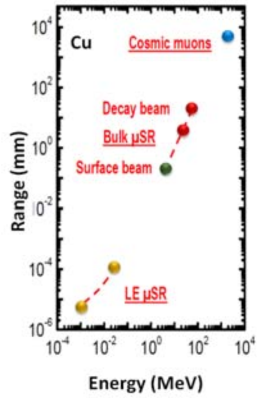
What is μSR

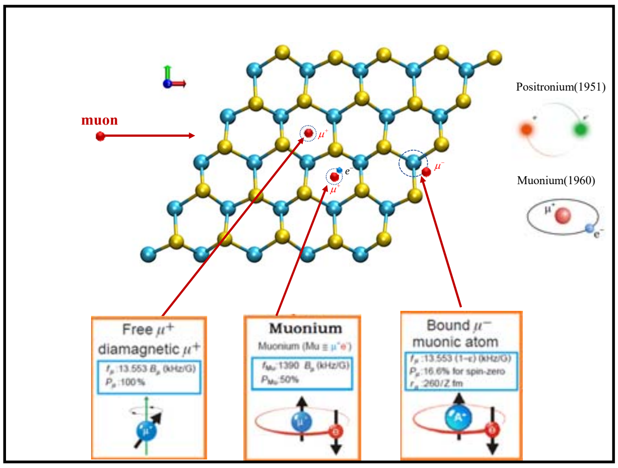
The acronym "μSR" was coined in 1974 in the μSR Newsletter:

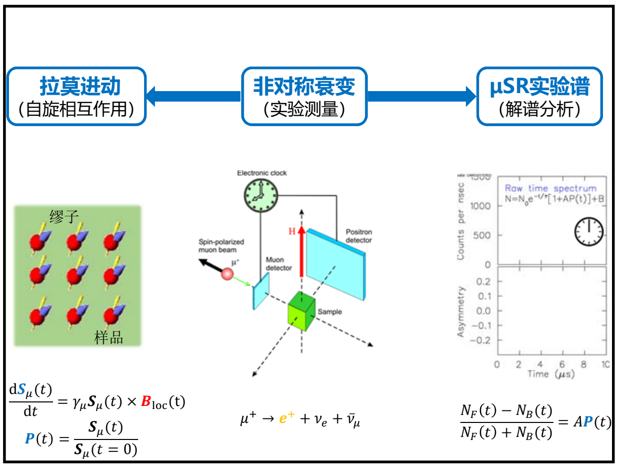
μSR stands for Muon Spin Relaxation, Rotation, Resonance, Research or what have you.

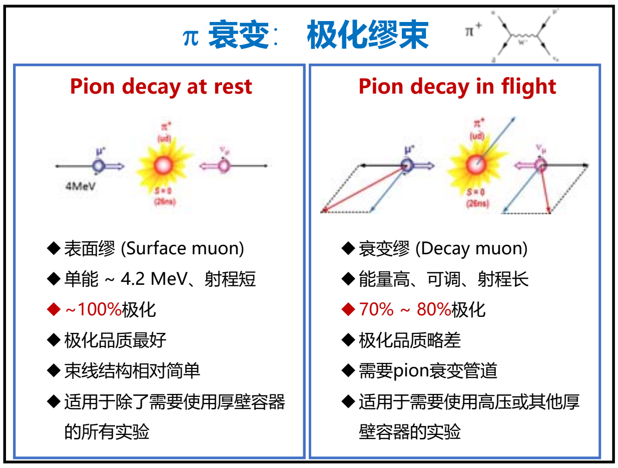


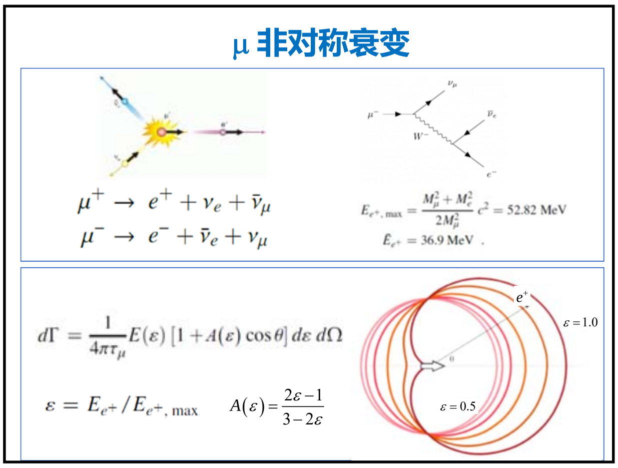












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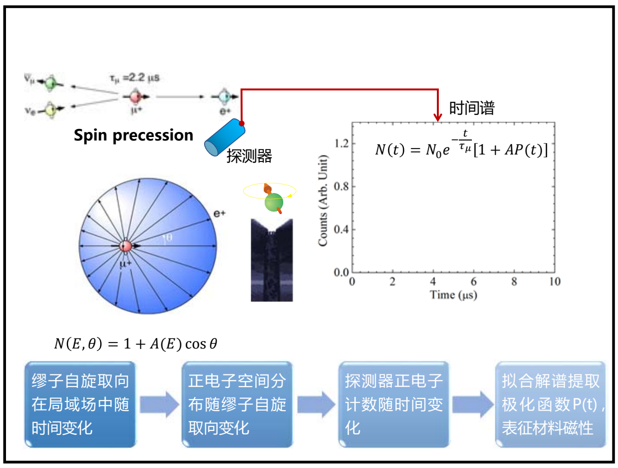
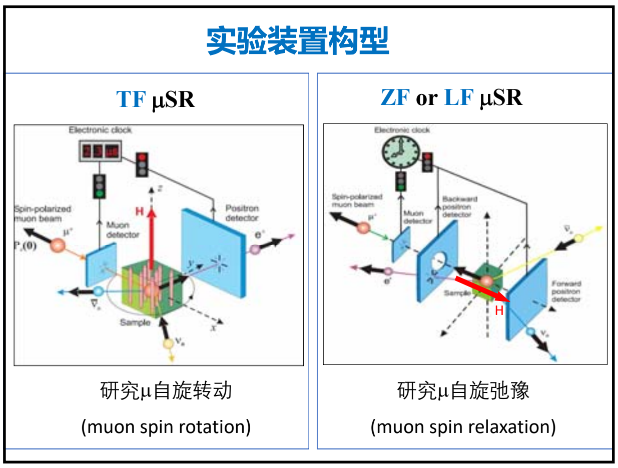
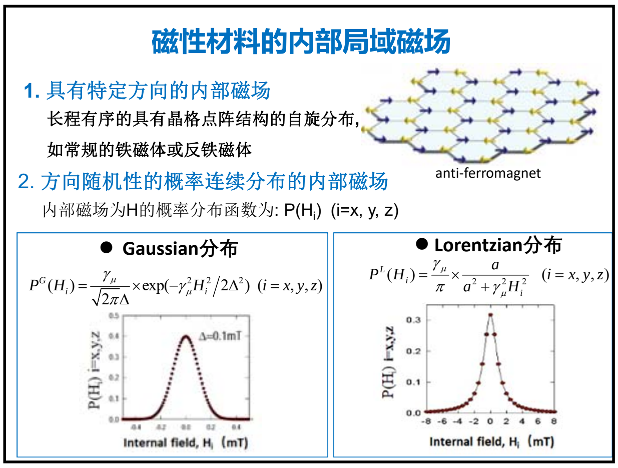
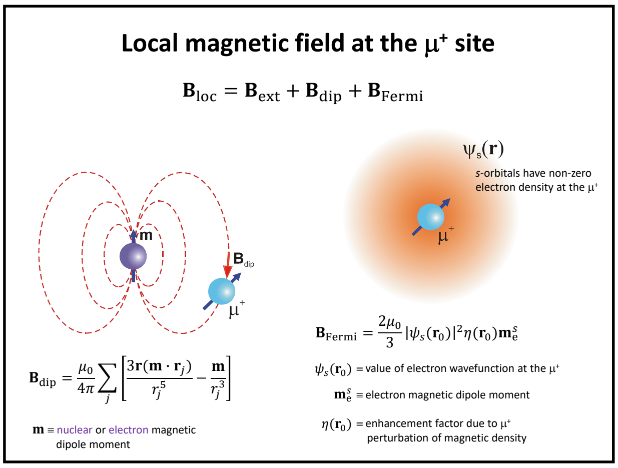
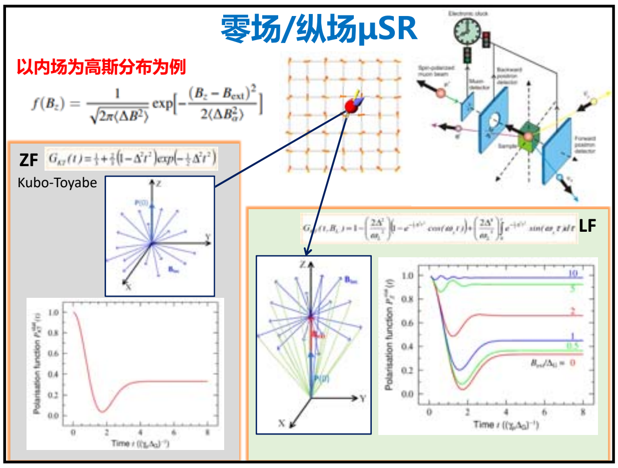
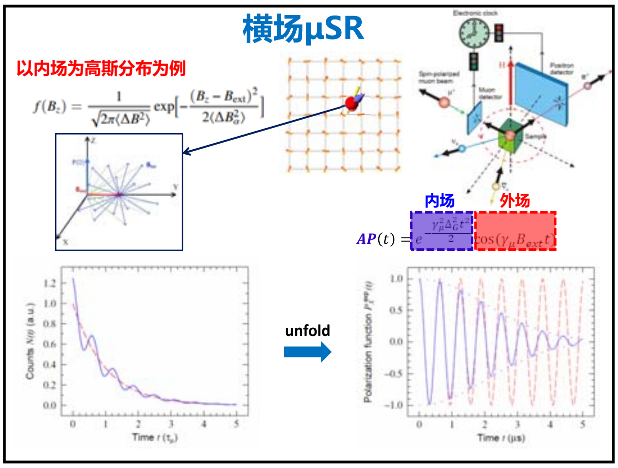


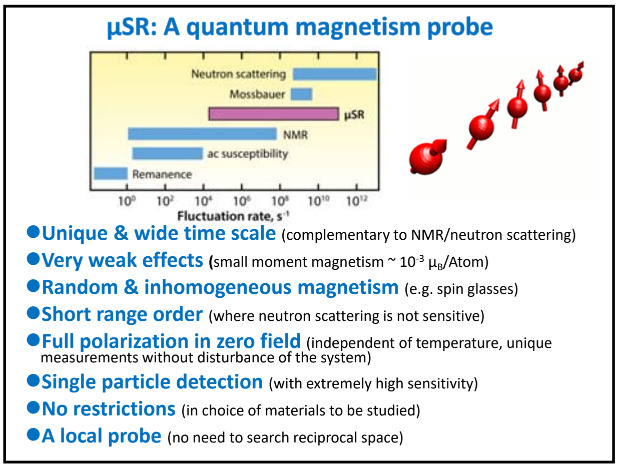


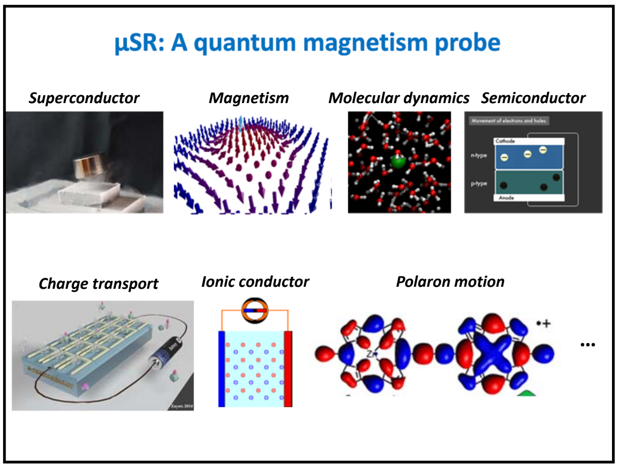

磁性材料的内部局域磁场
1. 具有特定方向的内部磁场
长程有序的具有晶格点阵结构的自旋分布，
如常规的铁磁体或反铁磁体
anti-ferromagnet
2. 方向随机性的概率连续分布的内部磁场
内部磁场为H的概率分布函数为: P(H$_i$) (i=x, y, z)
● Gaussian分布
$P^G(H_i)=\frac{\gamma_\mu}{\sqrt{2\pi}\Delta}\times\exp(-\gamma_\mu^2H_i^2/2\Delta^2)\ (i=x,y,z)$
Δ=0.1mT
P(H$_i$) i=x,y,z
Internal field, H$_i$ (mT)
● Lorentzian分布
$P^L(H_i)=\frac{\gamma_\mu}{\pi}\times\frac{a}{a^2+\gamma_\mu^2H_i^2}\ (i=x,y,z)$
P(H$_i$) i=x,y,z
Internal field, H$_i$ (mT)


Local magnetic field at the μ$^+$ site
$\mathbf{B}_{\text{loc}}=\mathbf{B}_{\text{ext}}+\mathbf{B}_{\text{dip}}+\mathbf{B}_{\text{Fermi}}$
$\psi_s(\mathbf{r})$
s-orbitals have non-zero electron density at the μ$^+$
m
B$_{dip}$
μ$^+$
$\mathbf{B}_{\text{dip}}=\frac{\mu_0}{4\pi}\sum_j\left[\frac{3\mathbf{r}(\mathbf{m}\cdot\mathbf{r}_j)}{r_j^5}-\frac{\mathbf{m}}{r_j^3}\right]$
m = nuclear or electron magnetic dipole moment
$\mathbf{B}_{\text{Fermi}}=\frac{2\mu_0}{3}|\psi_s(\mathbf{r}_0)|^2\eta(\mathbf{r}_0)\mathbf{m}_e^s$
$\psi_s(\mathbf{r}_0)$ = value of electron wavefunction at the μ$^+$
$\mathbf{m}_e^s$ = electron magnetic dipole moment
$\eta(\mathbf{r}_0)$ = enhancement factor due to μ$^+$ perturbation of magnetic density

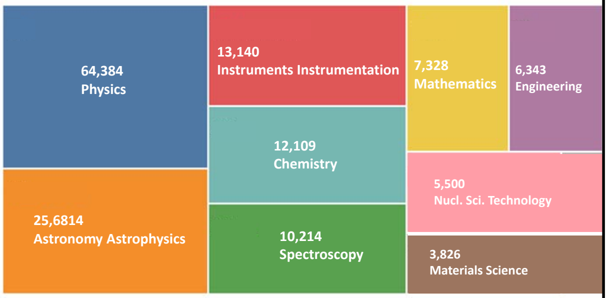

零场/纵场μSR
以内场为高斯分布为例
$f(B_z)=\frac{1}{\sqrt{2\pi\langle\Delta B^2\rangle}}\exp\left[-\frac{(B_z-B_{\text{ext}})^2}{2\langle\Delta B_\sigma^2\rangle}\right]$
ZF
Kubo-Toyabe
LF
Polarisation function
Time


横场μSR
以内场为高斯分布为例
$f(B_z)=\frac{1}{\sqrt{2\pi\langle\Delta B^2\rangle}}\exp\left[-\frac{(B_z-B_{\text{ext}})^2}{2\langle\Delta B_\sigma^2\rangle}\right]$
内场
外场
$AP(t)=e^{-\frac{\gamma_\mu^2\Delta_G^2t^2}{2}}\cos(\gamma_\mu B_{ext}t)$
unfold
Counts
Polarization function
Time t (μs)


μSR: A quantum magnetism probe
Neutron scattering
Mossbauer
μSR
NMR
ac susceptibility
Remanence
Fluctuation rate, s^{-1}
●Unique & wide time scale (complementary to NMR/neutron scattering)
●Very weak effects (small moment magnetism ~ 10^{-3} μ$_B$/Atom)
●Random & inhomogeneous magnetism (e.g. spin glasses)
●Short range order (where neutron scattering is not sensitive)
●Full polarization in zero field (independent of temperature, unique measurements without disturbance of the system)
●Single particle detection (with extremely high sensitivity)
●No restrictions (in choice of materials to be studied)
●A local probe (no need to search reciprocal space)

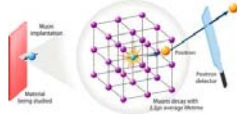

μSR: A quantum magnetism probe
Superconductor
Magnetism
Molecular dynamics
Semiconductor
Charge transport
Ionic conductor
Polaron motion
…

Web of Science, “muon”



Science with μSR

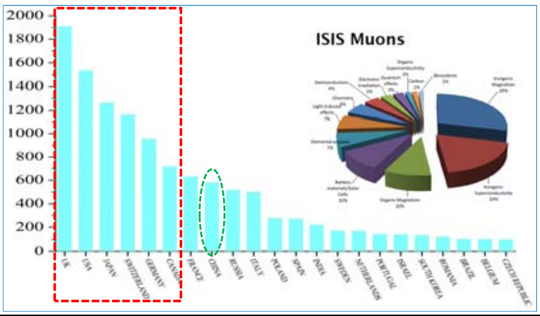
nature



- Mielke, C,et al., Time-reversal symmetry-breaking charge order in a kagome superconductor, Nature 602(2022)7896
- Al Ma'Mari,et al., Beating the Stoner criterion using molecular interfaces, Nature 524,(2015)7563
- Pratt, FL,et al; Magnetic and non-magnetic phases of a quantum spin liquid, Nature 471,(2011)7340
- Bramwell, ST, et al; Measurement of the charge and current of magnetic monopoles in spin ice, Nature 461,(2009)7266
- Li, Y.et al; Unusual magnetic order in the pseudogap region of the superconductor $HgBa_2CuO_{4+\delta}$, Nature 455, (2008)7211
- G.M. Luke et al., Time reversal symmetry-breaking superconductivity in Sr_2RuO_4 , Nature 394 (1998) 558.

Science with μSR

Showing 5,041 records for TOPIC: (muon spin)

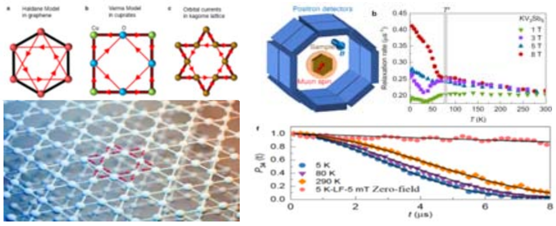


电荷秩序引起时间反演对称性破缺

Mielke, C,et al., Nature 602(2022)7896

PSI研究者在一个Kagome超导体中观察到了一种新型电子相的特征，这种电子相能够使电荷自发地循环流动。

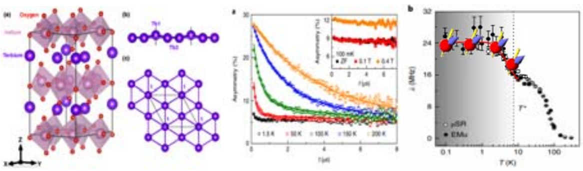
PSI研究团队利用超灵敏的μSR谱仪，在该材料内部测量到了弱的内部磁场，表明在一个相关的Kagome超导体中存在一种奇特的电荷排序。这些磁场打破了时间反演对称性（time-reversal symmetry），意味着一种异乎寻常的电荷秩序，其中电流在Kagome晶格的单位单元周围移动，被称为“轨道电流”。这些产生的磁性由原子晶格中电子的扩展轨道运动主导。这一发现，有助于理解高温超导性和开发新一代设备研究的量子现象。



反铁磁材料$TbInO_3$二维自旋液体行为研究

量子自旋液态理论是40多年前由诺贝尔奖得主菲利普·安德森(Philip Anderson)提出。在量子自旋液体中，磁矩表现得像液体，即使在绝对零度也不会冻结，这就产生了几种不同寻常的材料特性。它的一个突出特点就是其中蕴含着各种分数化的元激发。伊辛自旋—轨道耦合作用保护的超导相出现，可以构造马约拉纳费米子（Majorana fermions），为拓扑量子器件的实现提供了新的实验平台。

利物浦大学和麦克马斯特大学领导的一个国际研究小组在寻找物质的新状态方面取得了重大突破，利用ISIS的μSR谱仪，测量了低温下的磁性，发现钙钛矿相关的金属氧化物$TbInO_3$呈现出量子自旋液态。 $TbInO_3$中的奇异量子态来自于稀土元素铽材料中磁性离子周围复杂的局部环境。

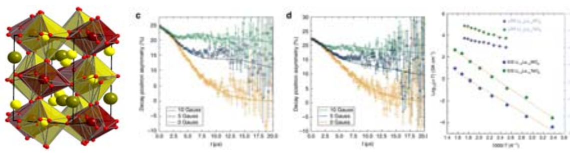


L. Clark, et al., ‘Two-dimensional spin liquid behaviour in the triangular-honeycomb antiferromagnet $TbInO_3$” *Nature Physics*, 15, 262 (2019)

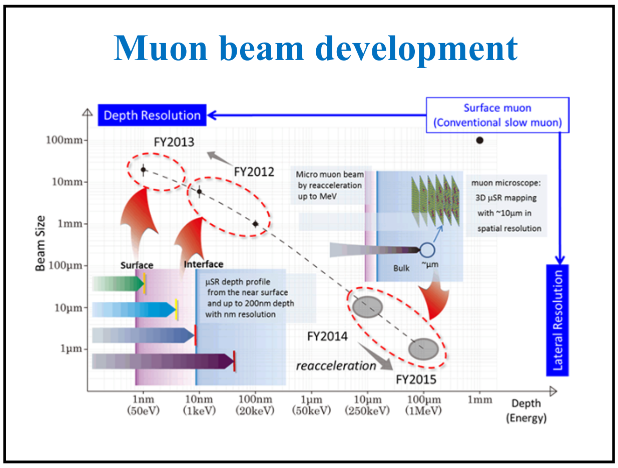
双钙钛矿型锂离子电池$Li_{1.5}La_{1.5}MO_6$ --下一代固态电池材料

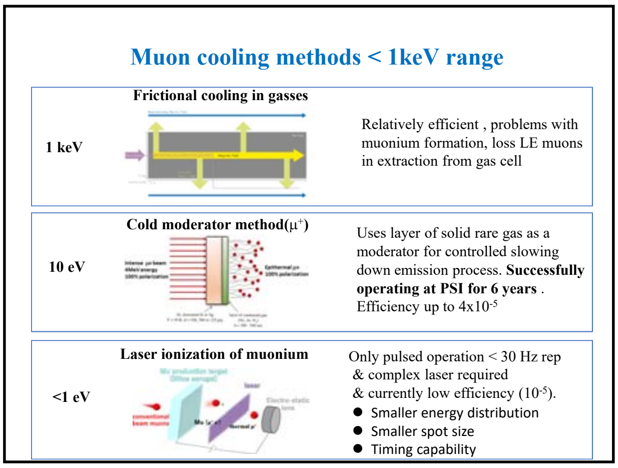
固态电池技术是一种安全提高电池能量密度的有效途径，然而固态电池仍面临电极和固体电解质之间界面问题的严重挑战。

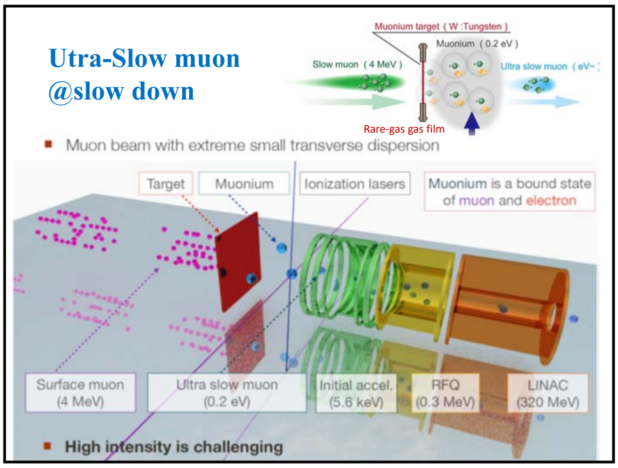
英国谢菲尔德大学研究者开发了一种新的双钙钛矿系列$Li_{1.5}La_{1.5}MO_6$,利用ISIS的EMU缪子谱仪等其他测量技术，发现了通过锂离子分布可以实现宏观离子扩散，同时通过定制组合物，可以使其具有负极或固体电解质功能。

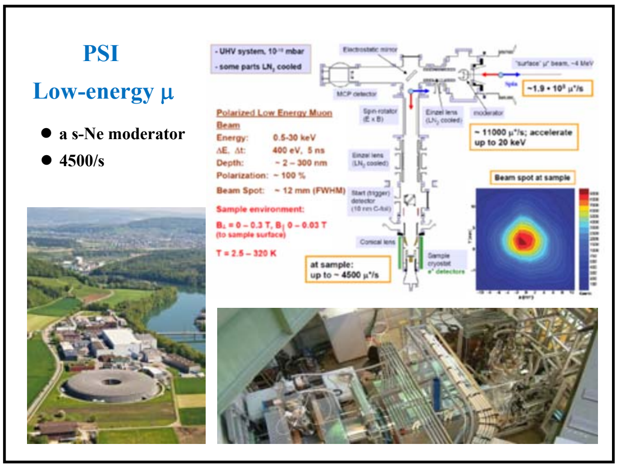


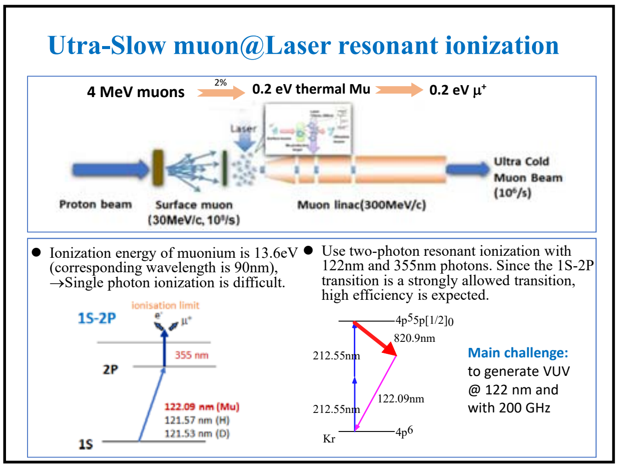
M. Amores, et al., ‘$Li_{1.5}La_{1.5}MO_6$ ($M = W^{6+}, Te^{6+}$) as a new series of lithium-rich double perovskites for all-solid-state lithium-ion batteries”, *Nat. Comm.* 11, 6392 (2020)

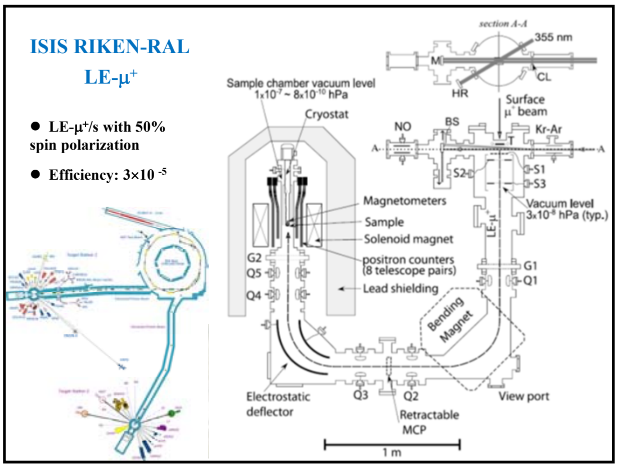

Muon beam development
Depth Resolution
Surface muon (Conventional slow muon)
Beam Size
100mm
10mm
1mm
100μm
10μm
1μm
FY2013
FY2012
FY2014
FY2015
Surface
Interface
Micro muon beam by reacceleration up to MeV
muon microscope: 3D μSR mapping with ~10μm in spatial resolution
μSR depth profile from the near surface and up to 200nm depth with nm resolution
Bulk
reacceleration
Lateral Resolution
1nm (50eV)
10nm (1keV)
100nm (20keV)
1μm (50keV)
10μm (250keV)
100μm (1MeV)
1mm
Depth (Energy)

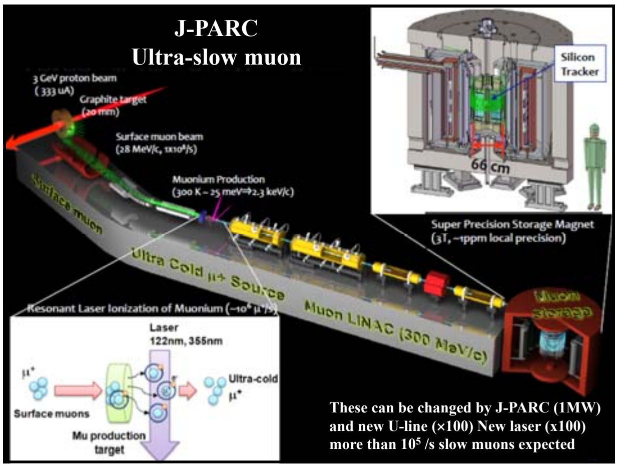

Muon cooling methods < 1keV range
Frictional cooling in gasses
1 keV
Relatively efficient , problems with muonium formation, loss LE muons in extraction from gas cell
Cold moderator method(μ+)
10 eV
Uses layer of solid rare gas as a moderator for controlled slowing down emission process. Successfully operating at PSI for 6 years .
Efficiency up to 4x10-5
Laser ionization of muonium
<1 eV
Only pulsed operation < 30 Hz rep & complex laser required & currently low efficiency (10-5).
Smaller energy distribution
Smaller spot size
Timing capability

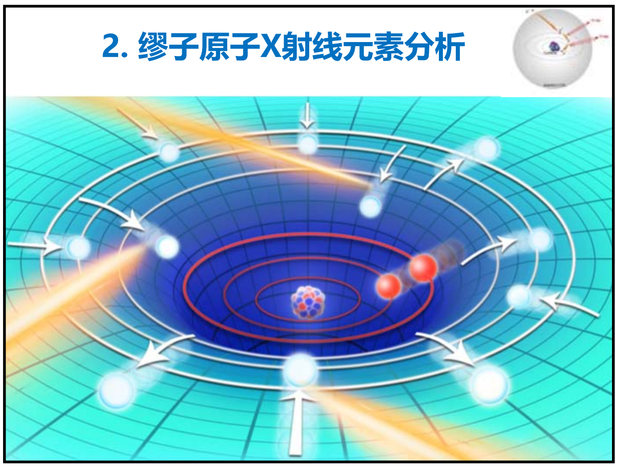

Utra-Slow muon @slow down
Muonium target (W :Tungsten)
Muonium (0.2 eV)
Slow muon (4 MeV)
Ultra slow muon (eV~)
Rare-gas gas film
Muon beam with extreme small transverse dispersion
Target
Muonium
Ionization lasers
Muonium is a bound state of muon and electron
Surface muon (4 MeV)
Ultra slow muon (0.2 eV)
Initial accel. (5.6 keV)
RFQ (0.3 MeV)
LINAC (320 MeV)
High intensity is challenging

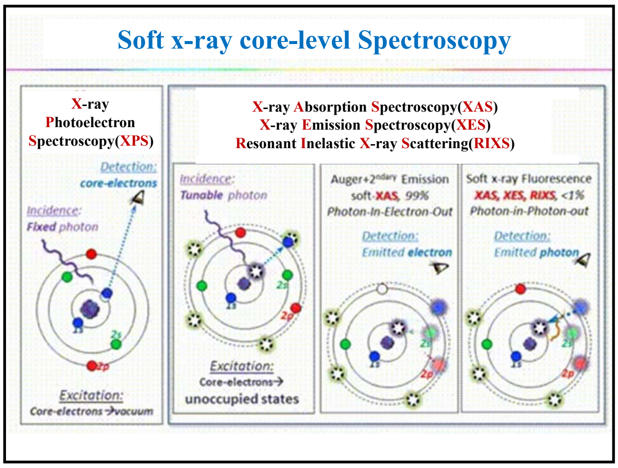

PSI
Low-energy μ
a s-Ne moderator
4500/s
Polarized Low Energy Muon Beam
Energy: 0.5-30 keV
Depth: ~ 2 – 300 nm
Polarization: ~ 100 %
Beam Spot: ~ 12 mm (FWHM)
Sample environment:
T = 2.5 – 320 K
~ 11000 μ+/s; accelerate up to 20 keV
at sample: up to ~ 4500 μ+/s
Beam spot at sample

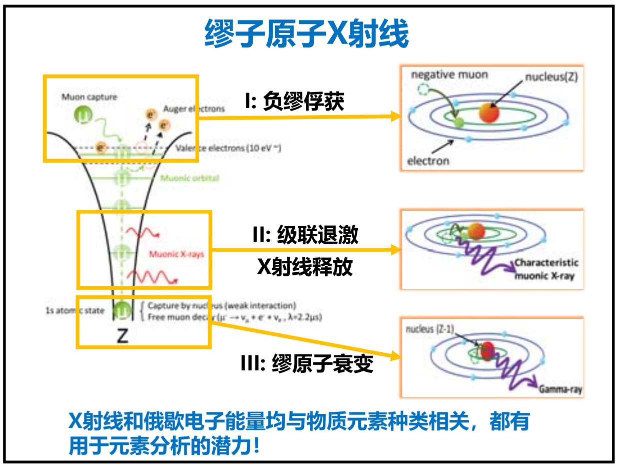

Utra-Slow muon@Laser resonant ionization
4 MeV muons
2%
0.2 eV thermal Mu
0.2 eV μ+
Laser
Proton beam
Surface muon (30MeV/c, 10^8/s)
Muon linac(300MeV/c)
Ultra Cold Muon Beam (10^6/s)
Ionization energy of muonium is 13.6eV (corresponding wavelength is 90nm), →Single photon ionization is difficult.
Use two-photon resonant ionization with 122nm and 355nm photons. Since the 1S-2P transition is a strongly allowed transition, high efficiency is expected.
Ionisation limit
1S-2P
355 nm
2P
122.09 nm (Mu)
121.57 nm (H)
121.53 nm (D)
1S
4p55p[1/2]0
820.9nm
212.55nm
122.09nm
212.55nm
Kr
4p6
Main challenge: to generate VUV @ 122 nm and with 200 GHz


ISIS RIKEN-RAL LE-μ+
LE-μ+/s with 50% spin polarization
Efficiency: 3×10 -5
section A-A
355 nm
Sample chamber vacuum level 1x10-7 ~ 8x10-10 hPa
Cryostat
Surface μ+ beam
Kr-Ar
Magnetometers
Sample
Solenoid magnet
positron counters (8 telescope pairs)
Lead shielding
Vacuum level 3x10-8 hPa (typ.)
Bending Magnet
Electrostatic deflector
Retractable MCP
View port
1 m









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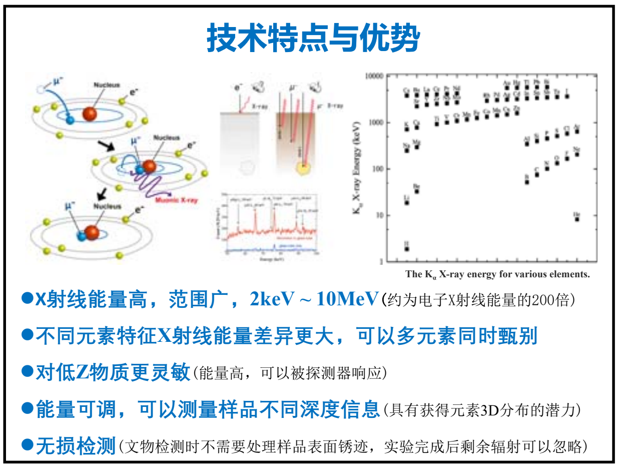
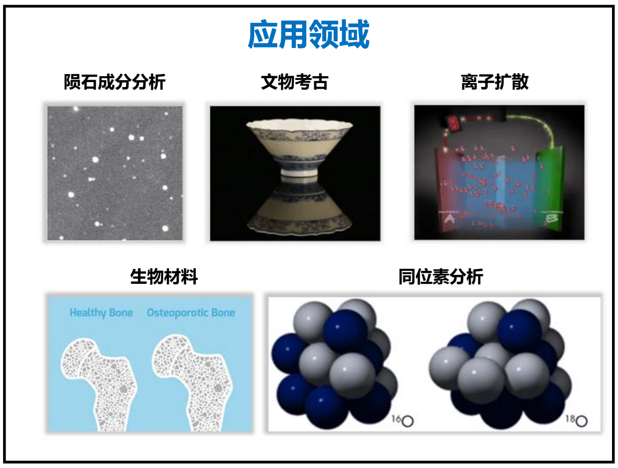
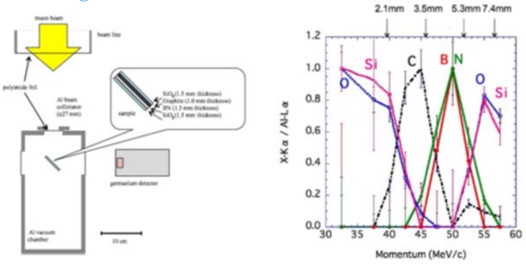




A new X-ray fluorescence spectroscopy for extraterrestrial materials using a muon beam

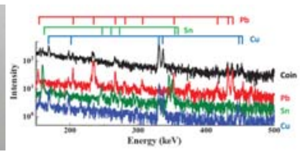
Controlling muon momentum from 32.5 to 57.5 MeV/c, we successfully demonstrate a depth-profile analysis of light elements (B, C, N, and O) from several mm-thick layered materials and non-destructive bulk analyses of meteorites containing organic materials. @J-PARC MUSE



Scientific Reports, 4，5072(2014)

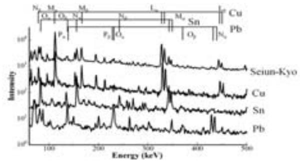
文物元素分析

中国秦朝古币

元素	含量 (%)
Cu	74±2
Sn	8±1
Pb	18±1

中国汉朝古镜

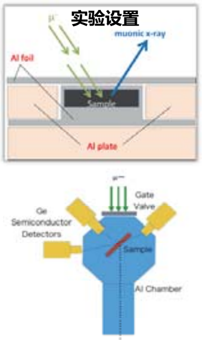



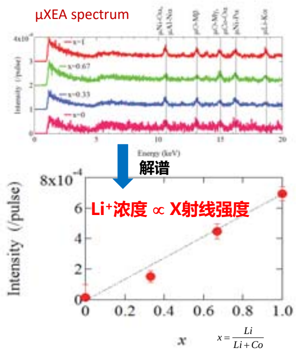
元素	含量 (%)
Cu	71.8±1.5
Sn	22.1±2.0
Pb	6.1±0.8

K. Ninomiya, et al., JPS Conf. Proc. 8, 033005 (2015)

锂离子电池

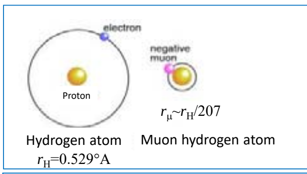
µXEA is a unique technique to detect all elements (except for H) in materials with a non-destructive way.





I. Umegaki, et al., JPS Conf. Proc. 21, 011041 (2018)

3. 缪子催化聚变



Muonic Hydrogen and the Proton Radius Puzzle

The proton radius measurement performed at PSI by means of the muonic hydrogen technique.

The size of the proton, Nature 466,213(2010)

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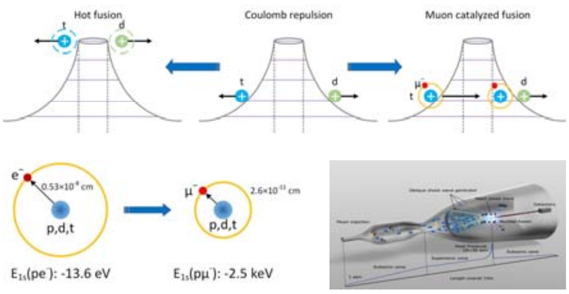
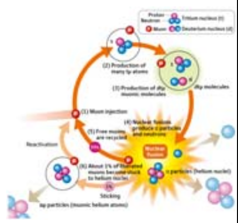


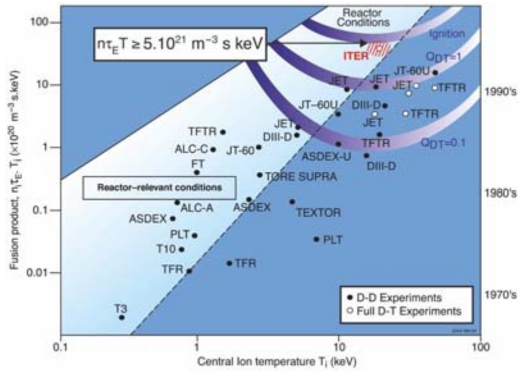
◆氘氚聚变需要克服库仑势垒;
◆热核聚变需要上亿度高温才能克服库仑势垒;
◆负缪质量是电子207倍，使氘氚间距缩短3个数量级，库仑势垒消失，聚变反应在常温或低温下就可发生。

- **1947 idea of MuCF (F.C. Frank, *Nature* 160, 525)**
- **1948 (A.D. Sakharov, Lebedev Rep.)**
- **1956 First observation of muon induced fusion (Alvarez in bubble chamber)**
- **1982- Observation of large dt fusion rate Studies in Dubna, LNPI(Leningrad Nuclear Physics Institute), LAMPF(Los Alamos Meson Physics Facility), PSI, TRIUMF**
- **1986- KEK**
- **1996- RIKEN-RAL**
- **Since that time µCF-research has spread over the world: 35 laboratories from 15 countries are involved in this activity now.**

$$DT\mu \to {}^4He + n + \mu + 17.58MeV$$
$$DD\mu \to {}^4He + n + \mu + 3.27MeV$$
$$DD\mu \to T + p + \mu + 4.03MeV$$
$$TT\mu \to He + 2n + \mu + 11.30MeV$$

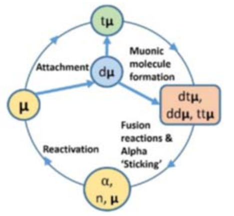


Lawson criterion for various hot fusion devices



Breakeven for μCF

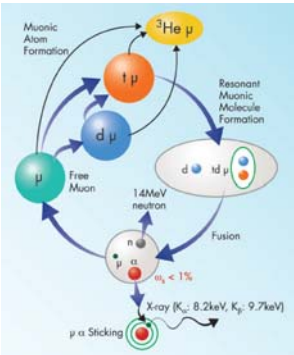
- The average energy cost to produce a muon as around 5GeV .
- The average energy produced per DT fusion is 17.6 MeV .
- Each muon must catalyze at least 5000/17.6 = 284 fusion reactions



- The 35% probability of reactivation and 1.5% sticking fraction of fusions per muon has been estimated to be between 150 and 200 fusions per muon.

Breakeven appears to be impossible without either reducing the energy cost of the muon or solving the sticking problem.

μCF循环



Cycle time:2×10^{-8} sec.
Muon lifetime:2.2×10^{-6} sec.

- 负缪在一次聚变后释放，可被再次俘获驱动下一次聚变反应；
- 聚变产生的α粒子也能俘获负缪（α sticking），导致μCF循环中断
- 300 次循环可以达到 scientific break-even， 1000 次循环达到 economic break-even，目前最好记录为150次（LAMPF, Dubna）

实验进展

μCF in laboratories

- Dubna: 观测到dtμ共振形成时的温度相关性
- LAMPF: 实现高密度下120个μCF cycle
- PSI: 研究不同的低密度dt混合物下的μCF cycle，α-μ探测
- TRIUMF: tμ原子束流
- KEK: 研究α sticking x-ray释放过程，μ转移到He过程
- RIKEN-RAL:研究α sticking x-ray释放过程，不同dt混合物下的μCF cycle

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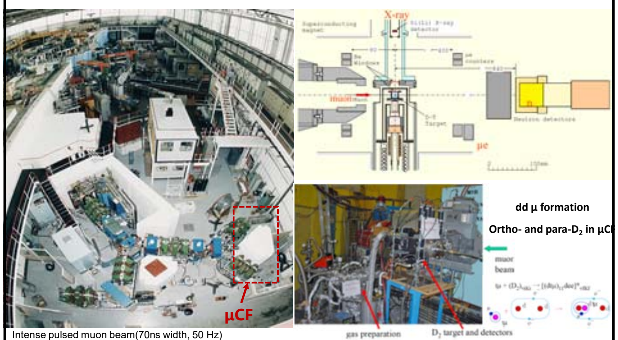
实验进展

Ishida@ RIKEN-RAL

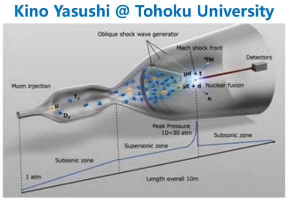


Intense pulsed muon beam(70ns width, 50 Hz)
800MeV x 200μA proton
20~150MeV/c μ+/μ- muon
5x104 μ-/s (55MeV/c)

Experimental configuration at RIKEN-RAL

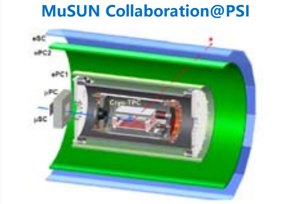
实验进展

Kino Yasushi @ Tohoku University



- 1993年前后开始μCF理论研究
- 提出和发展了“non-adiabatic coupled rearrangement channel method”
- 提出基于“Mach shock wave”的In flight μCF (IFμCF)实验，利用Mach激波机制将dtμ压缩至高密度状态

MuSUN Collaboration@PSI



- 2008年开始dμ原子研究
- 实验测量μ在纯氘气中被俘获形成dμ原子过程，实现d^3He聚变
- 已经在PSI进行10多次束流实验，已实现d^3He聚变率6.3×10^4 s^{-1}（最终需要达到1.48×10^8 s^{-1}）

The International Society for μSR Spectroscopy (ISMS)

International μSR Conferences

- The 15th μSR 2020 (Parma) postponed to 2022.
- The 14th μSR 2017 (Sapporo)
- The 13th μSR 2014 (Grindelwald)
- The 12th μSR 2011 (Cancun)

- **ISIS Muon Training School** (every two years, experiments)
- **ISIS Muon Advanced School** (theory, applications)
- **PSI Summer School on Condensed Matter Research**

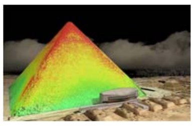
The Toshimitsu Yamazaki prize (Since 2005)

The Young Scientist Award (Since 2017)

三、缪子成像

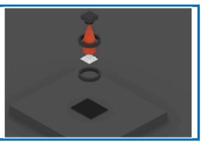
宇宙线缪子成像(cosmic-ray muon imaging, muography)

宇宙线缪子能量高、穿透能力强，是天然的非破坏性成像“探针”，可以对数个cm到数百米不同尺度物体成像。



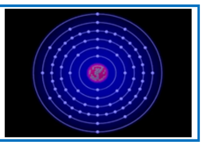
缪子束透射成像(muon beam transmission imaging)

缪子束流强度高、动量可调，通过测量其穿过物体不同质量厚度时强度衰减情况进行2D或3D精细成像。



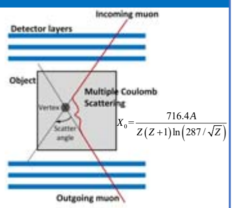
缪子原子X射线成像(muonic X-ray imaging)

原子核俘获负缪联跃迁释放特征X射线，利用二维像素探测器可以对样品内元素空间分布进行成像测量。



1. 宇宙线缪子成像

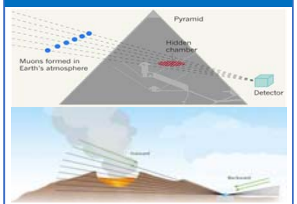
散射成像—缪子CT



- Multiple Coulomb Scattering
- Charged particles crossing material are deflected
- The deviation angle (projected on a plane)has a Gaussian distribution

$$\sigma(\theta_0)=\frac{13.6MeV}{\beta cp}\sqrt{\frac{x}{X_0}}\left(1+0.038\ln\frac{x}{X_0}\right)$$

透射成像—缪子望远镜



- Energy deposition of charged particles

$$-\frac{dE}{dx}\propto\rho\frac{Z}{A}\frac{1}{\beta^2}\left[\ln\frac{K\beta^2}{1-\beta^2}+\text{修正项}\right]$$

- Mass attenuation length following Beer-Lambert law

$$I=I_0e^{-\mu x}$$

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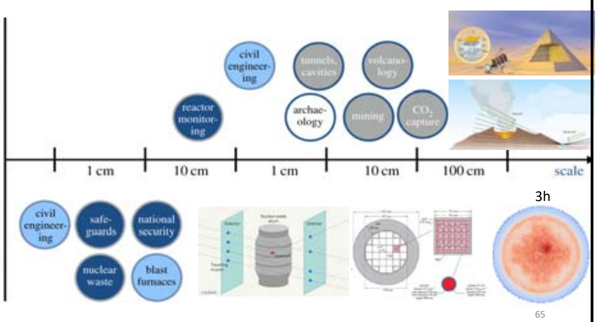
研究尺度

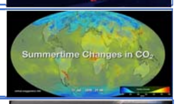
Muography **Muon tomography** (缪子CT) **Muon radiography** (缪子望远镜)



大型文化遗址无损考古： 重要古墓、重要历史遗址成像，提高历史文化遗产的研究水平。

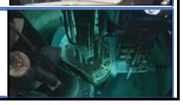
地质灾害监测： 活动火山监控、地震带活动监控、山体滑坡、大型水库坝体监测，提高自然灾害预警级别。

二氧化碳地质封存监测： 高分辨成像及地层平均密度的在线测量，为CO_2地质封存的监测提供了一种全新的解决思路。



国防装备监测： 核弹头监测、核走私监测，提高核与放射性材料的安保级别。

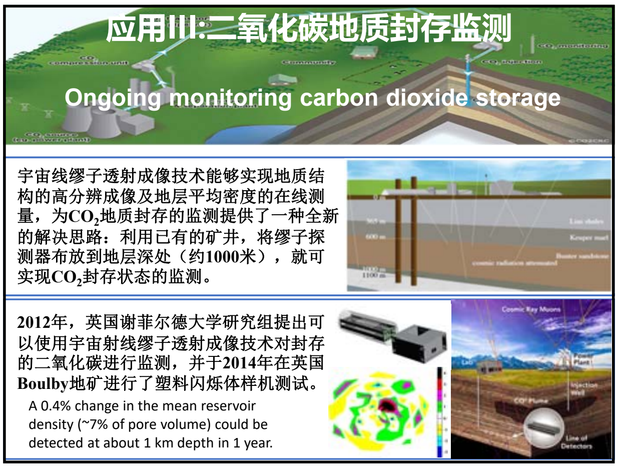
核电安全运行及核燃料监测： 反应堆堆芯、核燃料存储、核材料开采和运输。



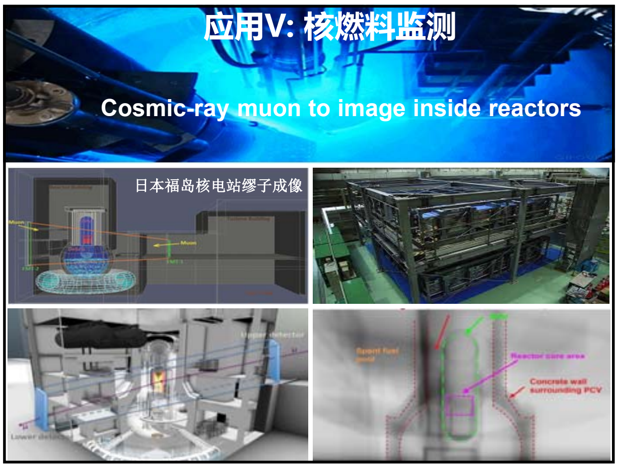

应用I: 大型文化遗址考古
Search for Hidden Chambers
1970: L.W. Alvarez (1968 Nobel Prize)
"Search for hidden chambers in the pyramids using cosmic rays".
Science 167: 832
2017年，日本和法国合作，用宇宙线缪子透射成像的方法，确定了胡夫金字塔内存在一个之前未被人们发现的隐藏墓室。
Discovery of a big void in Khufu's Pyramid by observation of cosmic-ray muons
Nature 552，2017


应用II: 地质灾害监测预警
Nature Caves Probing by Muography
1955年，澳大利亚E. P. George用透射成像探测Guthega-Munyang隧道内部结构。
2019年英国谢菲尔德大学用阵列探测器对Alfreton地下隧道进行扫描测量。
1995年东大K. Nagamine用宇宙射线缪子对筑波山进行了测量。
Run163
Spatial resolution:4 mm
Angular resolution:50 mrad

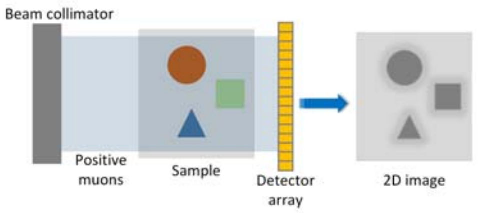

应用II: 地质灾害监测预警
Using Muography to Predict Volcanic Eruptions
浅间火山
日本萨摩硫黄岛火山
法国多姆火山
瓜德罗普岛拉苏弗里埃火山
研究人员正在摆放探测器阵列。


应用III:二氧化碳地质封存监测
Ongoing monitoring carbon dioxide storage
宇宙线缪子透射成像技术能够实现地质结构的高分辨成像及地层平均密度的在线测量，为CO_2地质封存的监测提供了一种全新的解决思路：利用已有的矿井，将缪子探测器布放到地层深处（约1000米），就可实现CO_2封存状态的监测。
2012年，英国谢菲尔德大学研究组提出可以使用宇宙射线缪子透射成像技术对封存的二氧化碳进行监测，并于2014年在英国Boulby地矿进行了塑料闪烁体样机测试。
A 0.4% change in the mean reservoir density (~7% of pore volume) could be detected at about 1 km depth in 1 year.


应用IV: 核材料监测
Inspection of Containers & Vehicles
2003年美国LANL国家实验室于研制出了世界上第一台宇宙线缪子散射成像的原理样机。
美国DSC公司，开发出了基于多种成像模式的被动探测系统。
放射性核燃料存贮监测
2017年意大利INFN建立了集装箱宇宙射线缪子成像的监测平台。
（几米的探测阵列，角分辨10mrad）


应用V: 核燃料监测
Cosmic-ray muon to image inside reactors
日本福岛核电站缪子成像

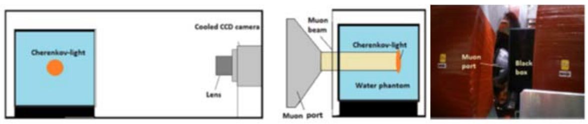
2. 缪子束透射成像



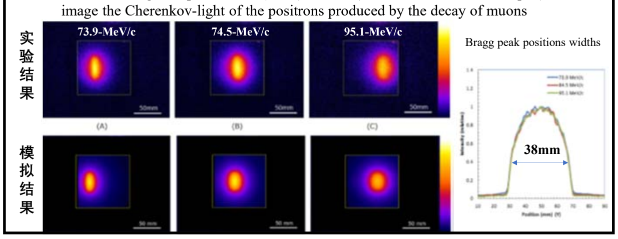
- 成像原理与宇宙线缪子CT类似，利用缪子束穿过物质时强度衰减的变化对物质进行成像
- 强度高，可以快速成像
- 动量可调，可以对不同深度进行成像

Optical imaging of muons @J-PARC

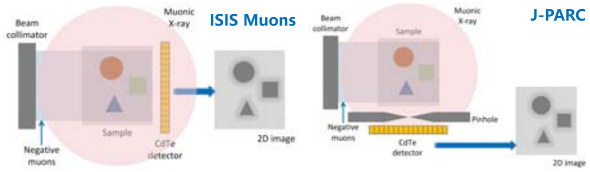
Scientific Reports, 10， 20790(2020)

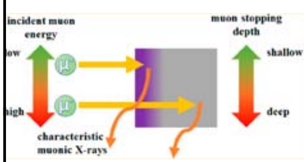


A cooled charge-coupled device (CCD) camera (BITRAN, BU-56DUV, Japan) to image the Cherenkov-light of the positrons produced by the decay of muons



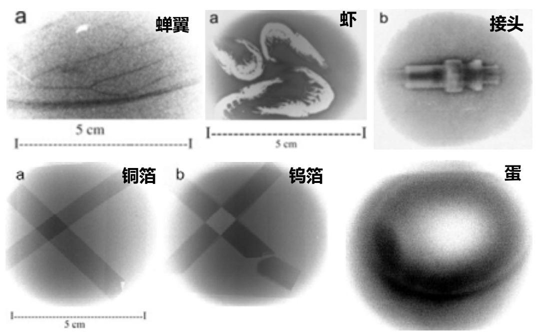
3. 缪子原子X射线成像





- 成像原理与SPECT类似，通过探测样品产生的缪子原子X射线成像;
- 成像方式有两种，即样品后直接放置探测器和侧边小孔成像;
- 强度高，可以快速成像;
- 动量可调，可以对不同深度进行成像.

muon images using imaging plates @J-PARC



M. Doyama, et al., **NIM A** 600, 60 (2009) resolution of 50 μm

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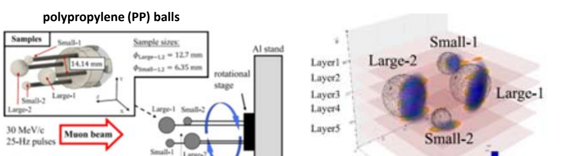
Non-destructive 3D imaging method using muonic X-rays

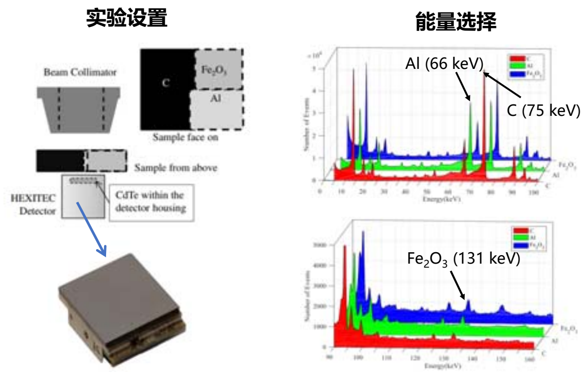
日本大阪大学等研究者利用**muonic X-rays**(J-PARC)用double-sided strip detector探测器对块材的**3D**成像。



Name	x direction (mm)		y direction (mm)		z direction (mm)	
	Mean	FWHM	Mean	FWHM	Mean	FWHM
Large-1	29.38	7.98	20.98	10.52	23.80	3.29
Large-2	12.01	8.54	19.20	12.29	16.07	3.13
Small-1	22.31	6.61	9.97	4.91	21.72	3.96
Small-2	20.85	8.71	30.97	5.31	19.18	4.12

Scientific Reports, 12，5261(2022)

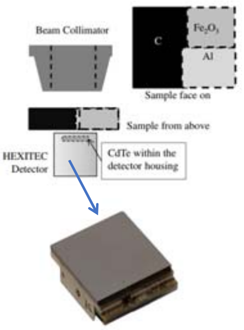
实验进展@ISIS Muons



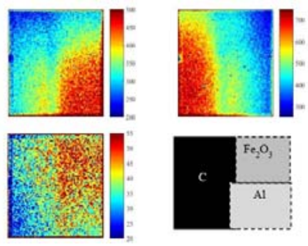
A. Hillier, et al., JPS Conf. Proc. , 011042 (2018)

实验进展@ISIS Muons

实验设置



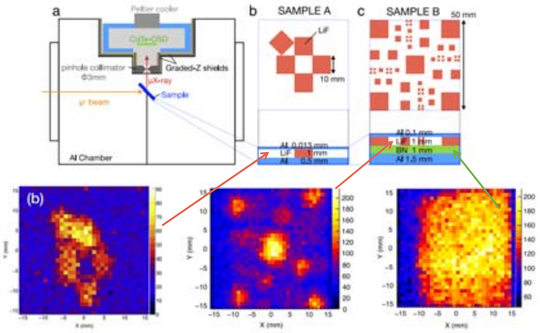
成像结果



A. Hillier, et al., JPS Conf. Proc. , 011042 (2018)

实验进展@J-PARC

动量层析成像@2018



M. Katsuragawa, et al., NIM A 912, 140 (2018)

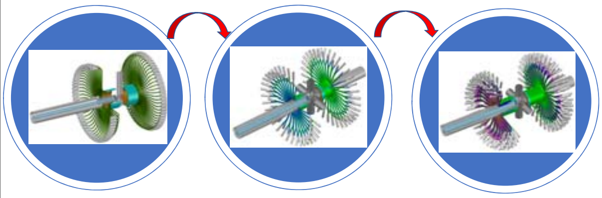
四、国内进展与展望

- **CSNS II期准备建设国内首个缪子源**
- **缪子源和谱仪研制进展**
  - ➢ 中国高能所团队完成了束流设计方案。
  - ➢ 中科大团队搭建了国内首台μSR谱仪，并提出下一代超高阵列谱仪方案。

- **凝聚态物质研究**
  - ☐ 束流需要向国际四大缪子源申请。
  - ☐ 国内一个研究组一年能申请到2次左右束流机时。
  - ☐ 北大、复旦、上交、浙大、中科大、华东师大、物理所等多家单位已经利用μSR表征材料磁性。
- **缪子束其他应用研究暂时空白**

MuSR design @ USTC

Updating muSR prototype to Baby-muSR spectrometer



128-channel
Two rings
Radius: 150 mm

128-channel
Four rings
Radius: 90 mm

256-channel
Eight rings
Radius: 90 mm

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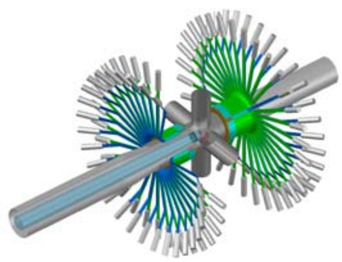
128-channel

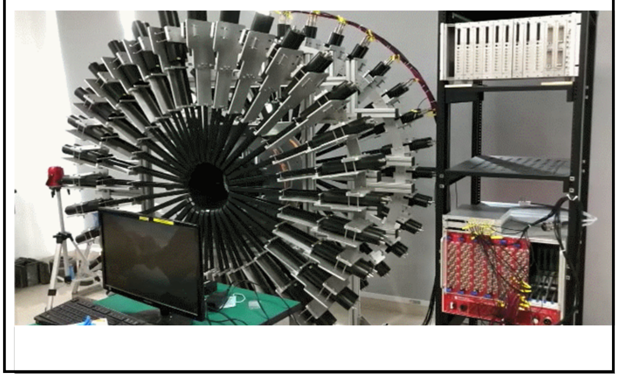


Radius: 95 mm (inner), 90 mm (outer)
Length: 40 mm (inner) 100 mm (outer)

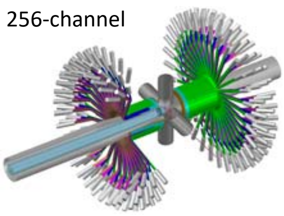
- ➢ When the degrader thickness is over 7 mm, the asymmetry reaches the highest by ~ 0.44 (ZF).
- ➢ The asymmetry of all rings is ~ 0.41.

	Rate	Mean count rate
All rings	0.0263	9.86
Inner ring	0.0150	11.25
Outer ring	0.010	8.25

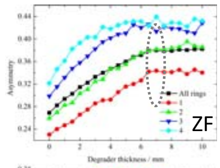
128-channel EMUS

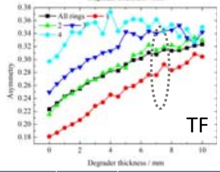


256-channel



Radius: 105 100 95 90 mm
Length: 25 40 70 100 mm

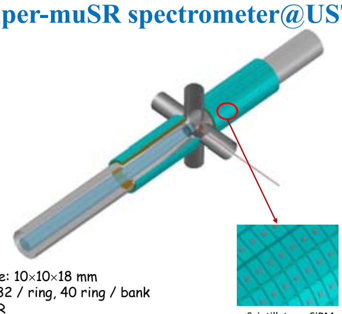




- When the degrader thickness is over 7 mm, the asymmetry reaches the highest by ~ 0.44 (ZF).
- The third ring and fourth ting can be grouped together.
- The asymmetry of all rings is ~ 0.38.

	Rate	Mean count rate
All rings	0.0462	6.77
First ring	0.0164	9.61
Second ring	0.0147	8.61
Third ring	0.0106	6.21
Fourth ring	0.0045	2.64

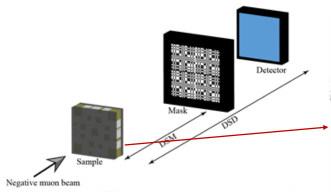
Super-muSR spectrometer@USTC

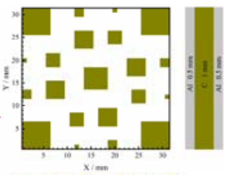


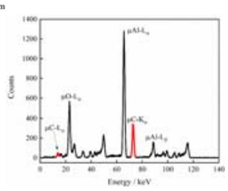
Scintillator size: 10×10×18 mm
Arrangement: 32 / ring, 40 ring / bank
Cryogenics: CCR
Sample supporter: fly-past
Degrader: Brass

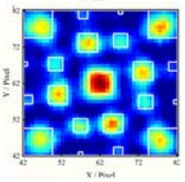
- When the number of detector rings is over 10, the asymmetry becomes larger than 0.4.
- We can group No. 10 – 40 together to get high asymmetry.
- For the 80% polarization, we still have 0.44×0.8=0.35 asymmetry

Muonic X-rays的多孔成像的图像方法@USTC









Reconstruction

●国内在宇宙线缪子成像应用方面处于起步阶段

●2021年7月中国科大召开首届国内缪子（μ）成像技术与应用研讨会

九院、近物所、原子能院、北大、兰大、安大、华北电力、南华大学和中国科大等10多家科研院所参会

●宇宙射线缪子成像谱仪研究进展

- ☐ 清华：MRPC阵列，散射成像
- ☐ 北大：RPC阵列，散射成像
- ☐ 中国科大：Micromegas和塑闪阵列，散射和透射成像
- ☐ 兰大：塑闪阵列，散射成像
- ☐ 北京卫星环境工程研究所：塑闪阵列，透射成像
- ☐ 原子能院:bulk micromegas阵列，散射成像

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高分辨缪子成像研究平台@USTC

Platform for μ Scattering tomography & Transmission imaging faCility (μSTC)

建设一个面向宇宙线缪子成像的多学科交叉应用研究平台。

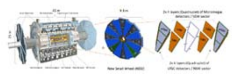
发展宇宙射线缪子成像核心技术，建成自主可控的成像装置研发平台，完成大尺度地质形貌**缪子望远镜**（位置分辨率<3mm）和高精度核素鉴别成像的**缪子CT**（位置分辨<150μm）工程样机的研制。

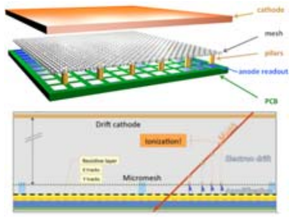
与国内的科技考古、地球科学、核科学技术、信息科学等专业深度合作，开展学科交叉研究，同时与国内的文物考古、地震测量、核能应用等相关专业单位合作开展工程应用。

缪子CT

Micromegas探测器

- 位置分辨约 ~150 μm
- 时间分辨好、计数率高
- 稳定性好、可以批量化生产

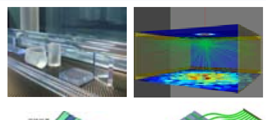


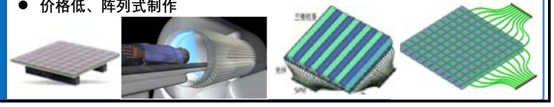


缪子望远镜

闪烁体+SiPM

- 位置分辨：~3 mm
- SiPM：高增益, 低电压供应
- 价格低、阵列式制作





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