SCNT

第三届惠州大装置高精度物理研讨会

基于惠州大科学装置的μSR与β-NMR谱学应用

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[1]中国科学技术大学 || 近代物理系

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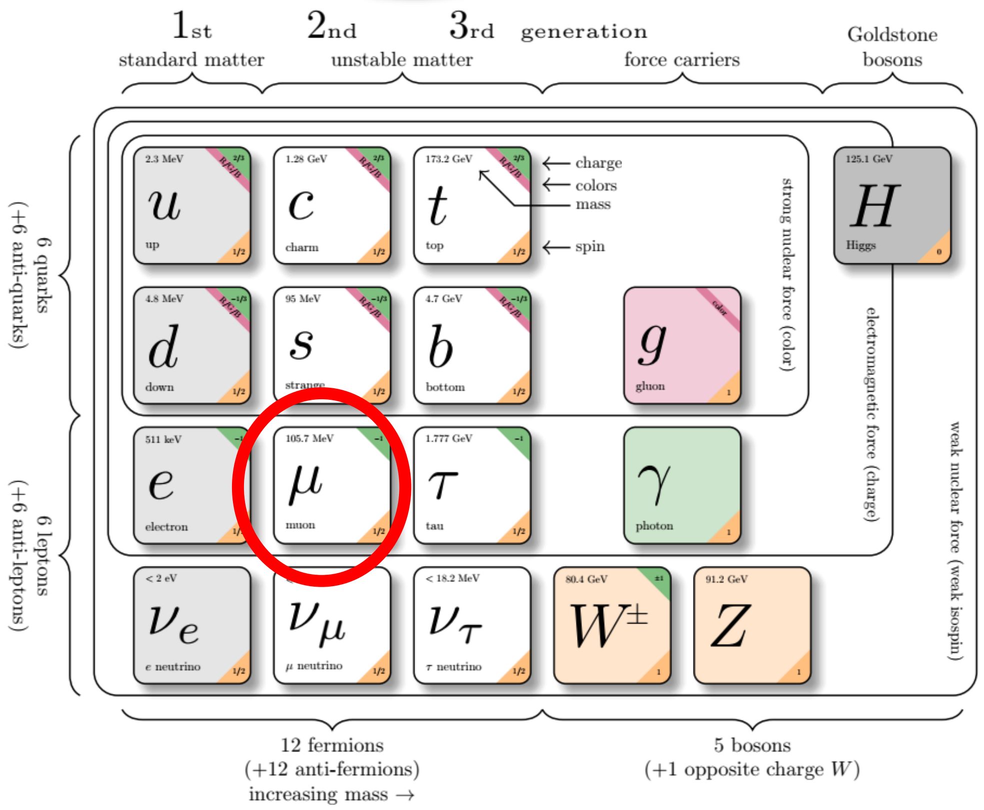
2025/04/21, 广东惠州

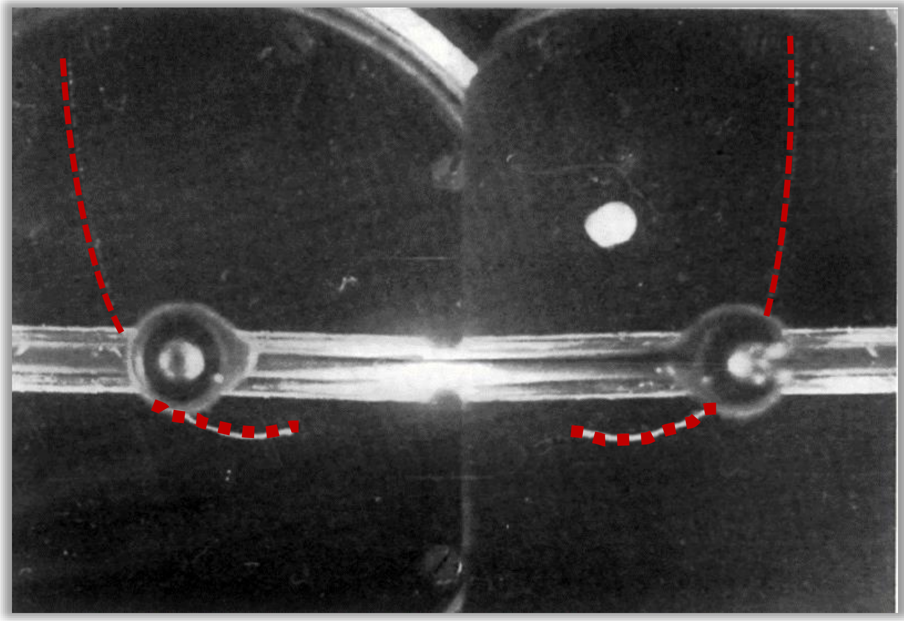
目录

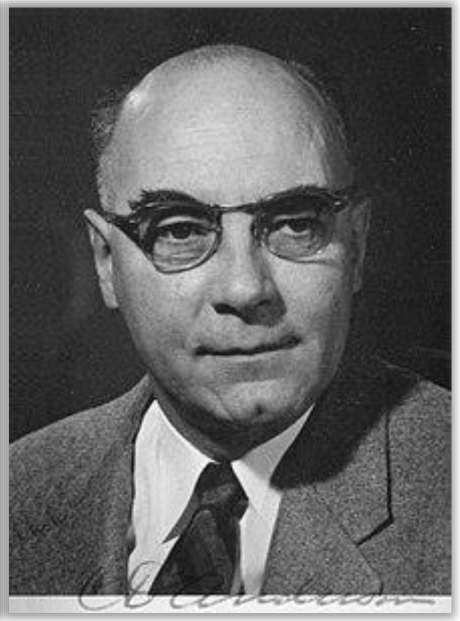
I. 缪子属性及来源

缪子的物理属性



诺奖得主CD Anderson于1936年从宇宙线观测实验中发现缪子



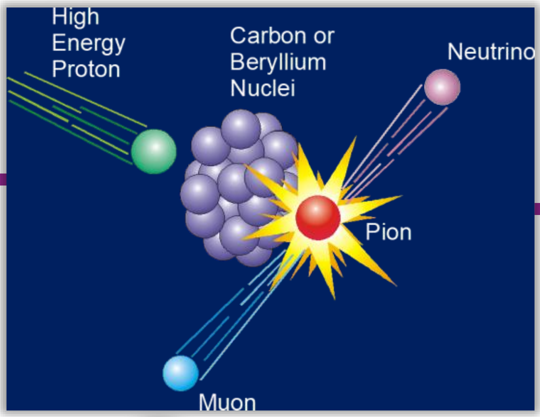


- 基本粒子, $m_e < m_\mu < m_p$
- 不稳定，平均寿命~ 2.2 μs
- 自旋 ½, 点粒子, 100%极化, 量子磁探针
- 宇宙线缪穿透性强, 天然成像探针
- Muonic X-ray能量高， 元素/同位素分析探针

缪子科学研究前沿

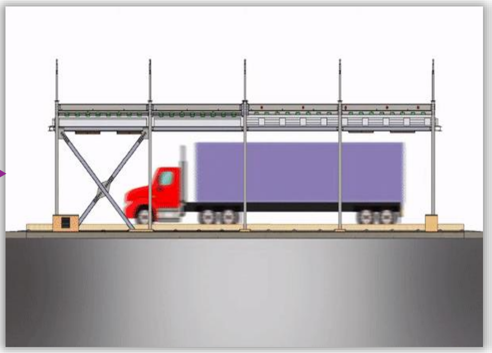
缪子：连接物质世界的极大与极小！

加速器

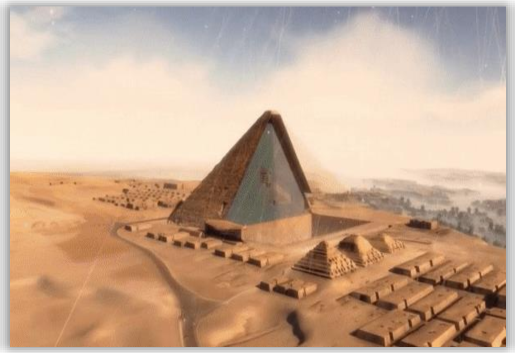


宇宙线

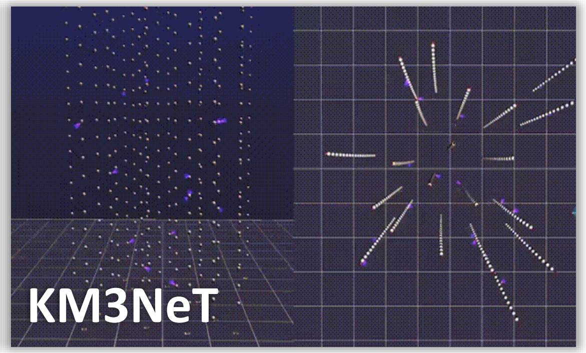
散射成像



透射成像

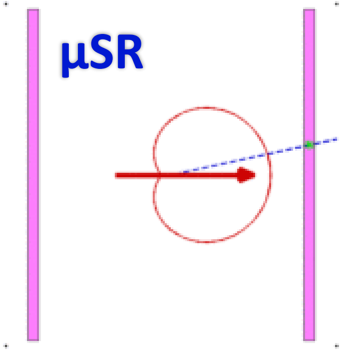


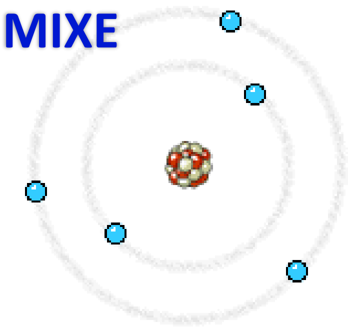
宇宙信使



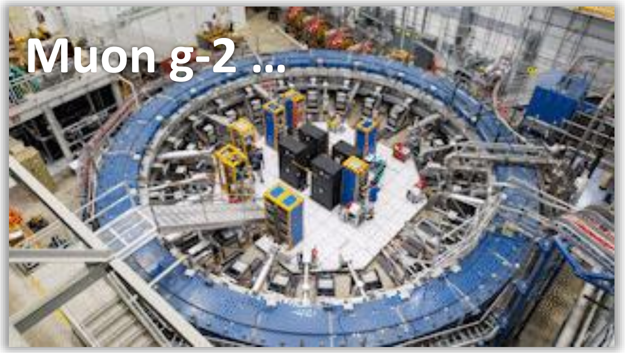
keV Low MeV Medium GeV High TeV

物质表征

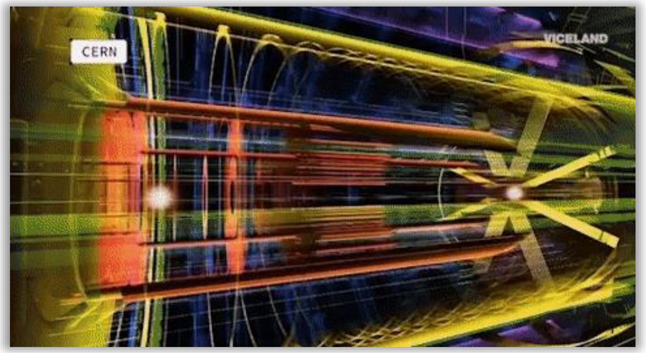




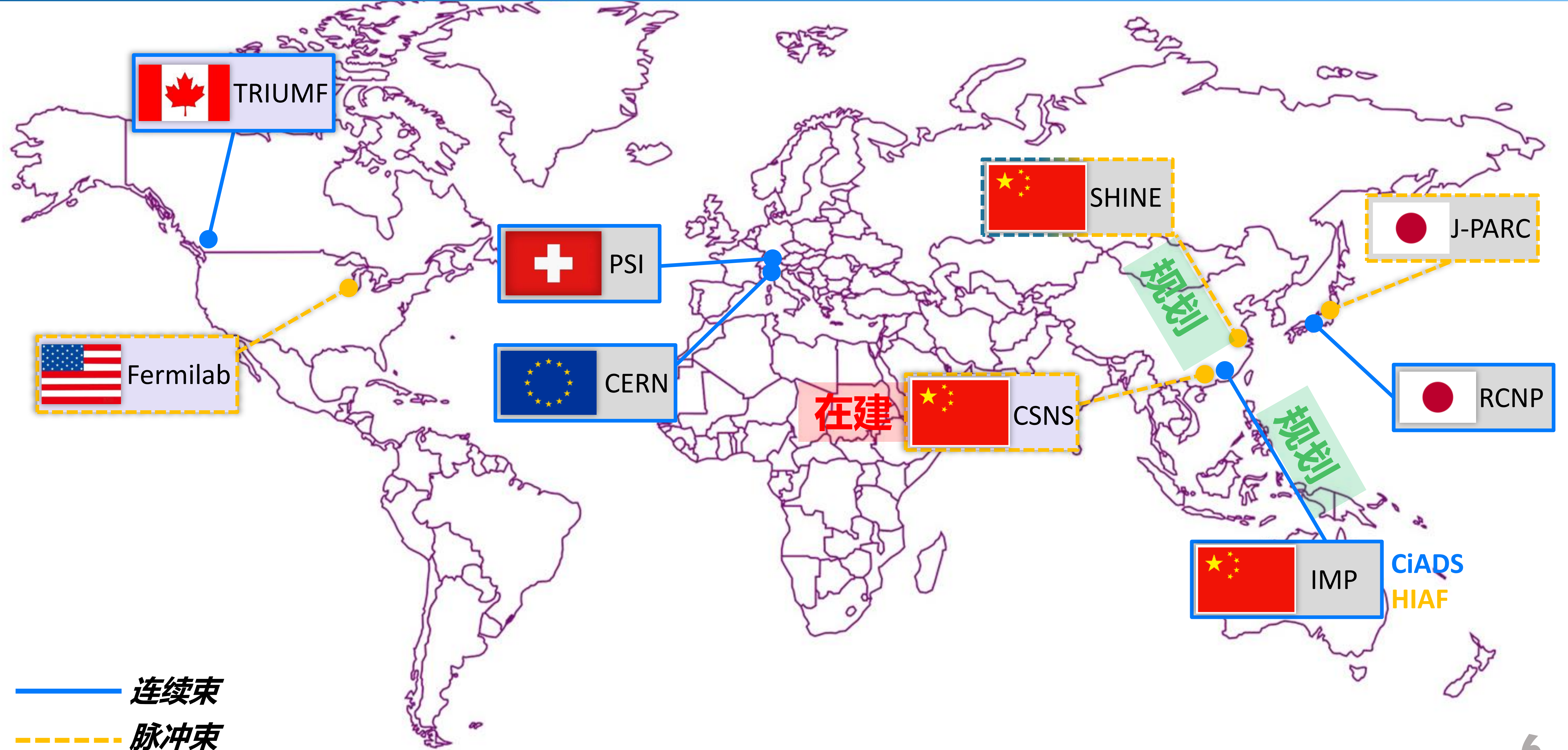
精密测量



缪子对撞机



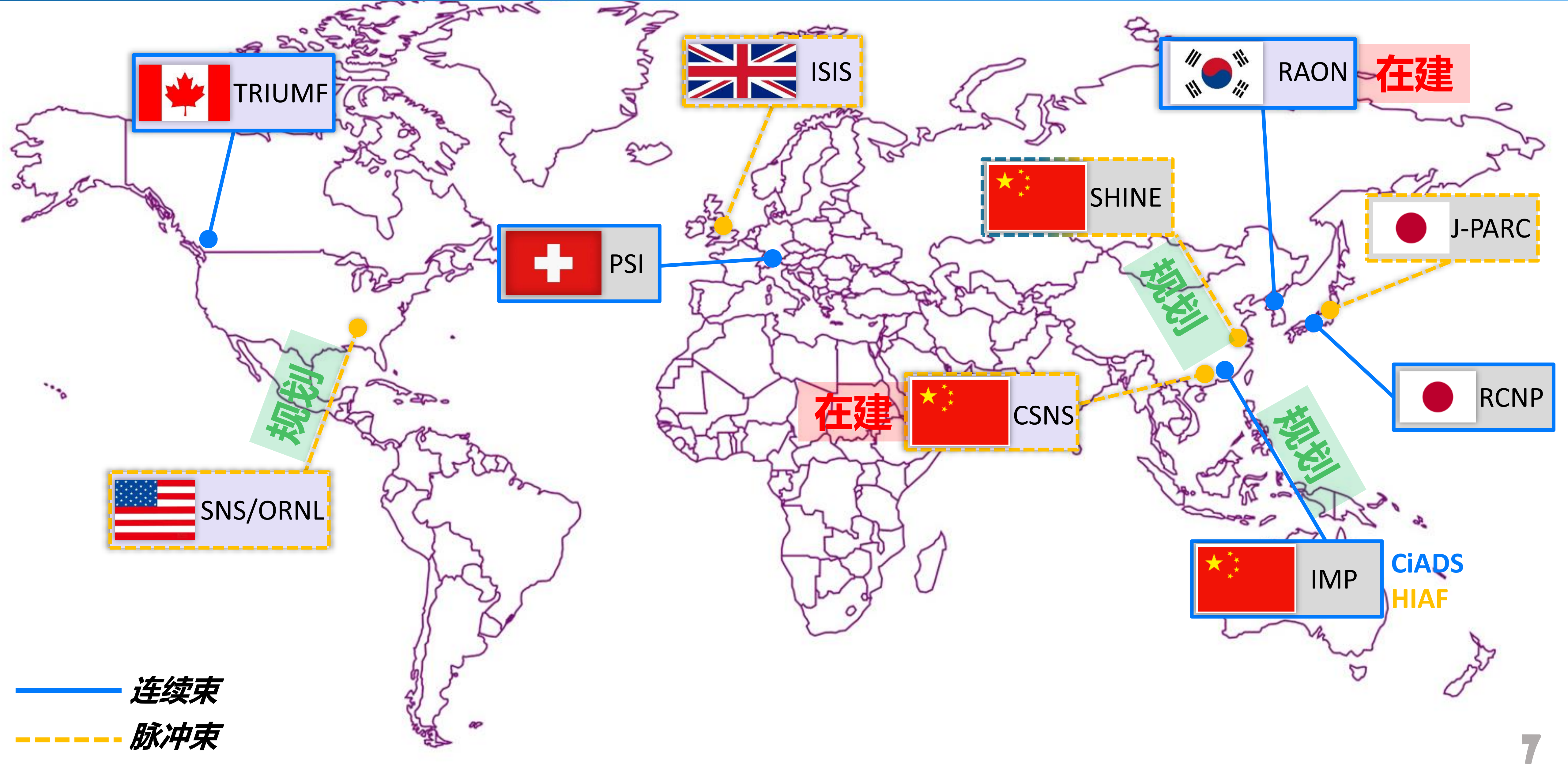
缪子源：基础研究



连续束

脉冲束

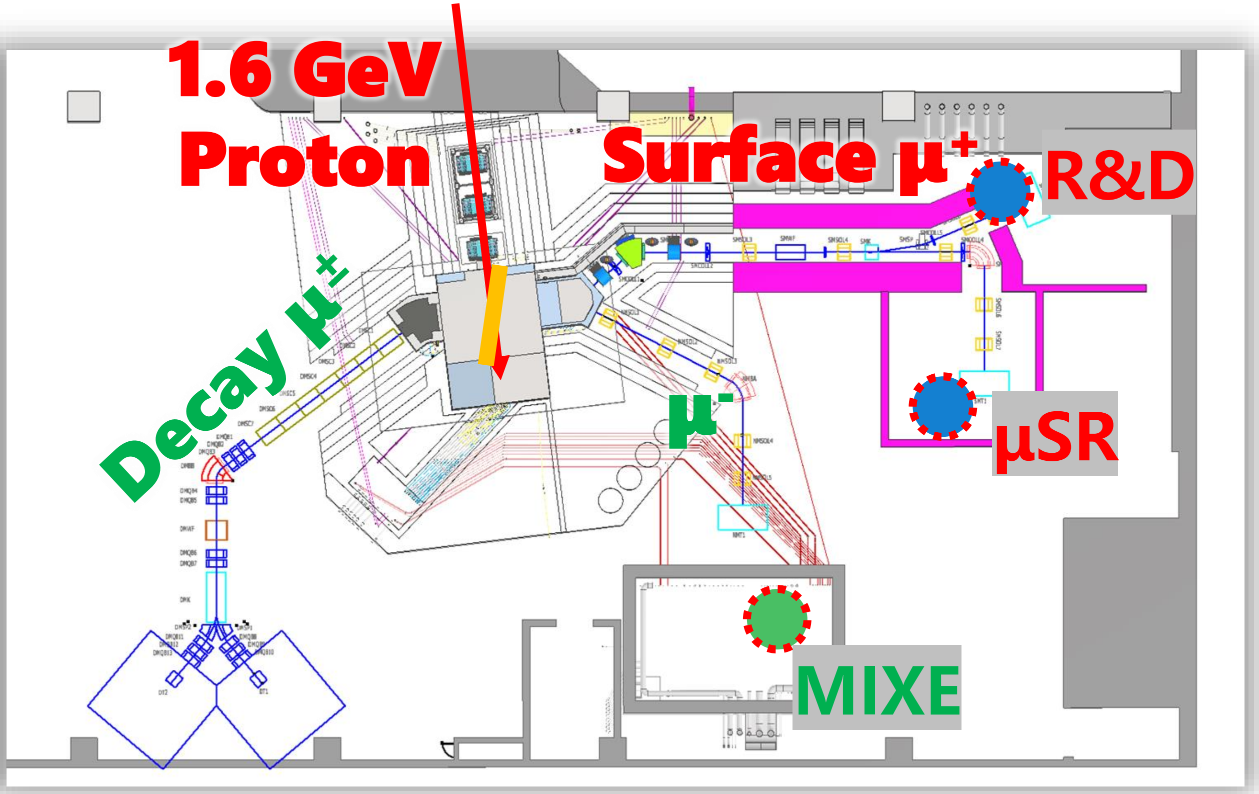
缪子源：应用研究



TRIUMF
ISIS
RAON
在建
SHINE
J-PARC
PSI
规划
规划
在建
CSNS
RCNP
规划
SNS/ORNL
IMP
CiADS
HIAF
连续束
脉冲束

国内缪子源：CSNS

广东·东莞 **M**uon station for sci**E**nce techno**LO**gy and in**D**ustr**Y**

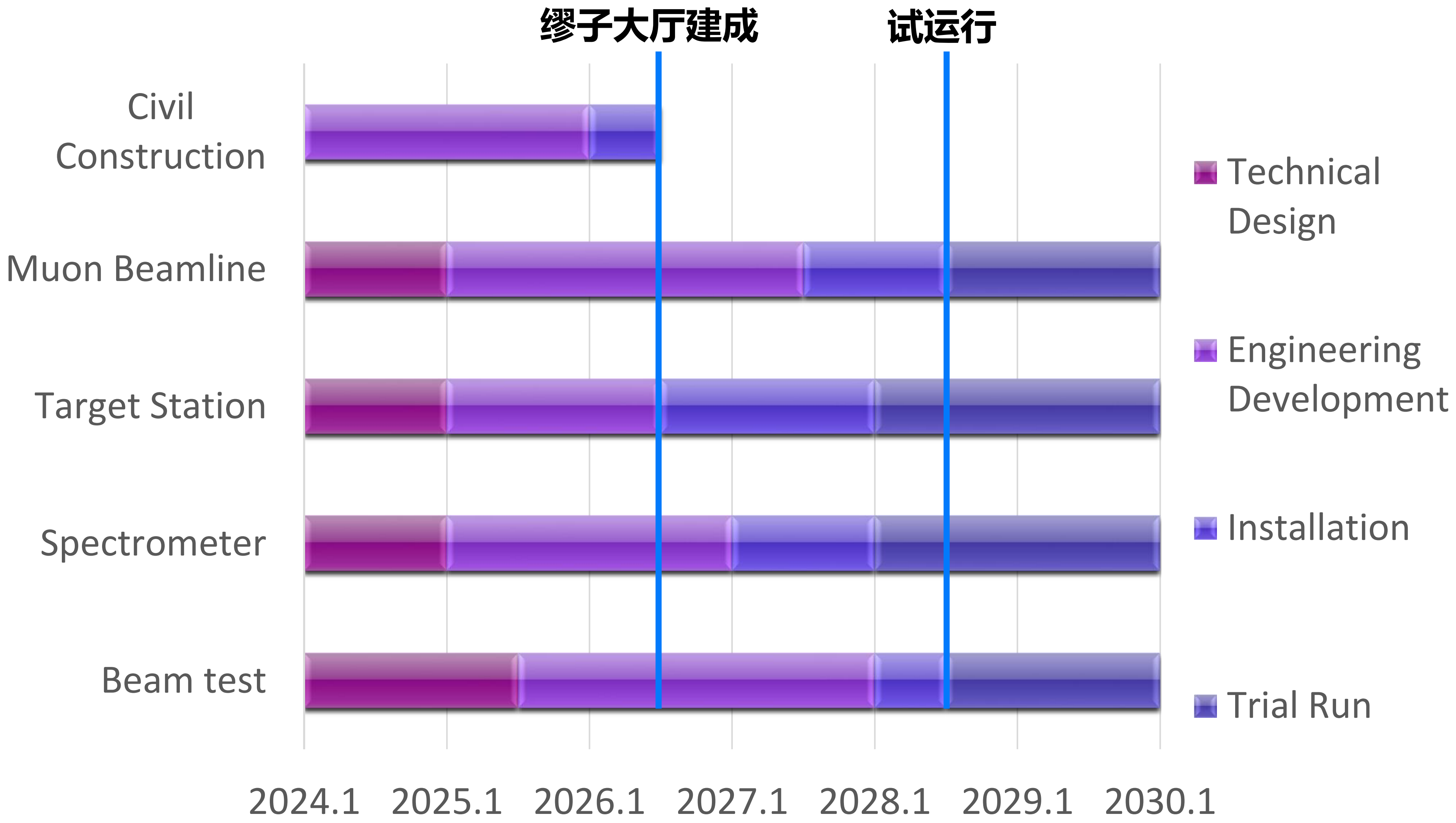


- CSNS II: 靶站, 1条表面缪束线, 1台μSR谱仪
- 建设周期：2024 - 2029
- $10^5 - 10^7$ μ^+/s , 极化度> 95%, 脉宽130 ns

参考自鲍煜的报告

国内缪子源：CSNS

广东·东莞 Muon station for sciEnce technoLOgy and inDustrY



MELODY-CSNS:

- 负责人： 鲍煜
- 靶 站：吴琛
- 束 线：吕游
- 谱 仪：李强

USTC collaborators:

- 负责人：叶邦角
- 探测器：潘子文
- 电子学：梁昊

国内缪子源：CSNS

MELODY

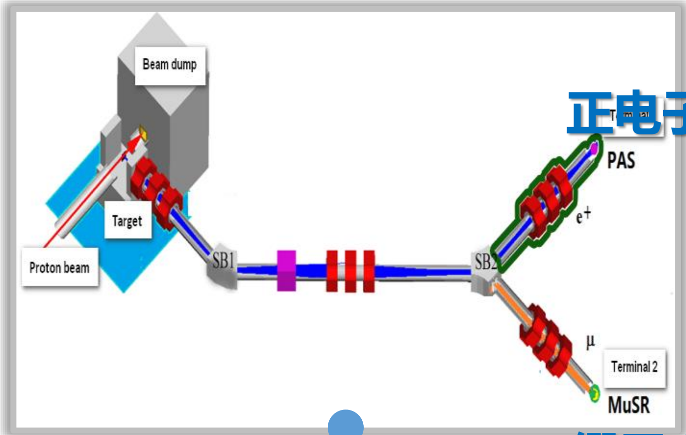
Review Report of the Physics Design of MELODY at the CSNS

Committee Membership:

Adrian Hillier, ISIS Neutron and Muon Facility, STFC/UKRI, UK (chair)
Stephen Cottrell, ISIS Neutron and Muon Facility, STFC/UKRI, UK
Naritoshi Kawamura, KEK, Japen
James Lord, ISIS Neutron and Muon Facility, STFC/UKRI, UK
Yasuhiro Miyake, KEK, Japan
Thomas Prokscha, Paul Scherrer Institut, Switzerland
Zaher Salman, Paul Scherrer Institut, Switzerland
Isao Watanabe, RIKEN, Japan

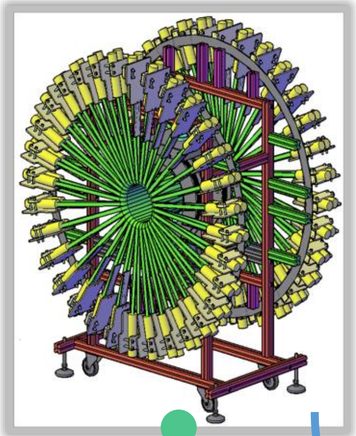
国内缪子源：CSNS

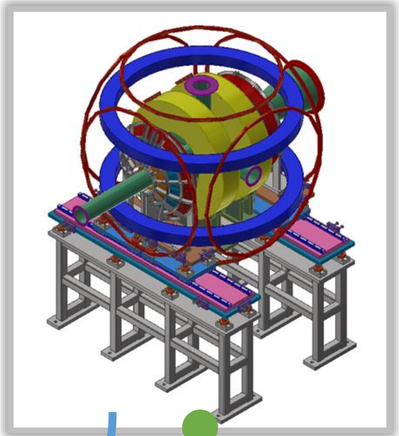
参与缪子谱仪研发 (中国科大叶邦角教授团队)



正电子湮没谱仪

缪子自旋谱仪





潘子文、梁昊等

Pre-study (2007-2014)：束线设计

Prototype R&D (2015-2020)：第一代PMT型谱仪 (关键技术研究)

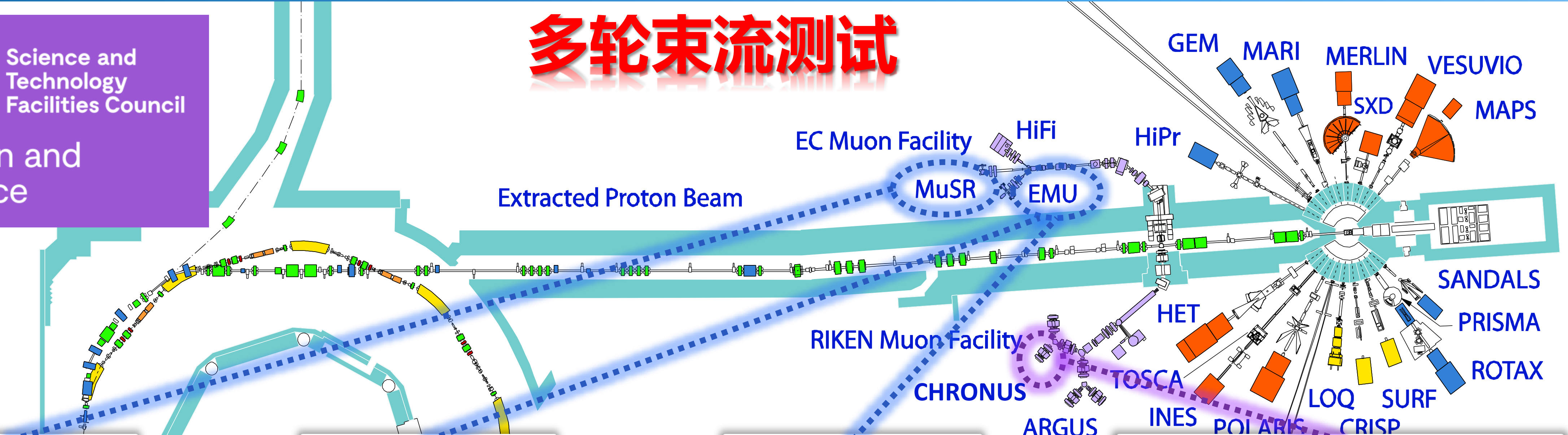
Construction (2024-2029)：第二代SiPM型谱仪 (工程谱仪)

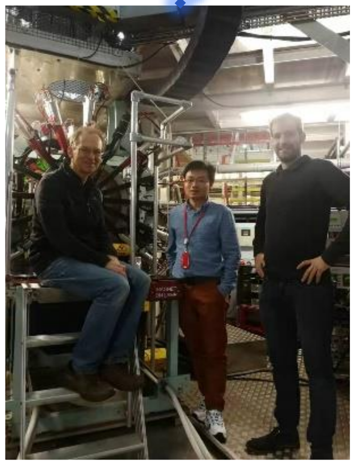
国内缪子源：CSNS

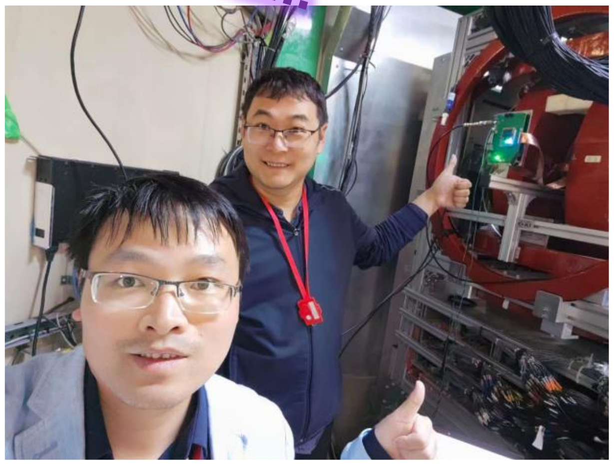
UKRI Science and Technology Facilities Council

ISIS Neutron and Muon Source

多轮束流测试



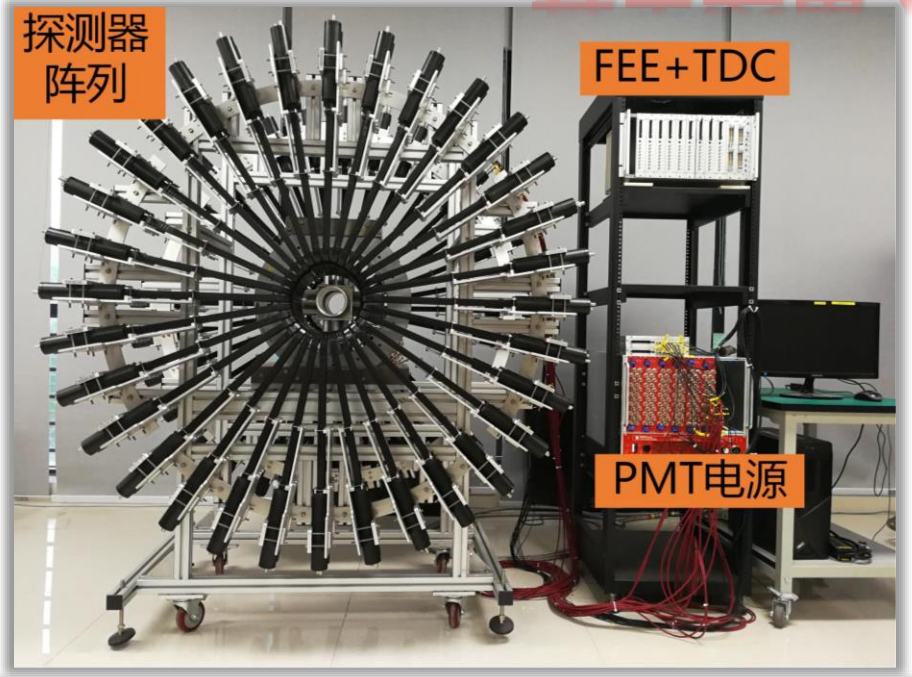




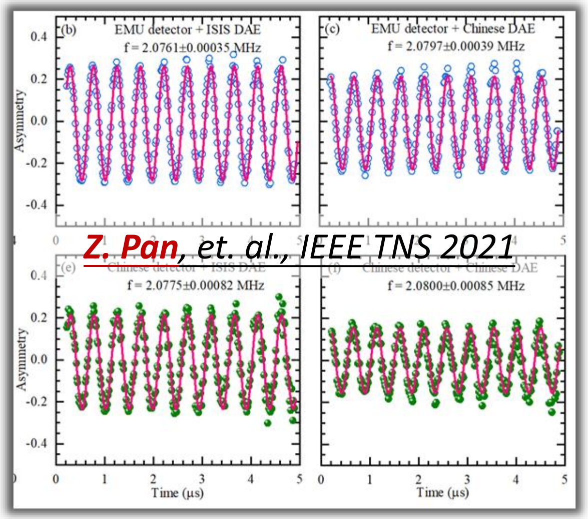
1st beam test 2018/03/14	2nd beam test 2018/09/25	3rd beam test 2019/11/13	1st beam test 2024/07/13

国内缪子源：CSNS

基金委重大仪器专家组现场验收



- ✓ 重大仪器研制项目《高流强缪子源关键技术研究》
- ✓ 总负责人：唐靖宇 || 谱仪子课题：叶邦角
- ✓ 样机探测系统统计数性能优于ISIS谱仪
- ✓ 精确测量样品局域磁场
- ✓ 重大仪器结题优秀，谱仪为亮点工作



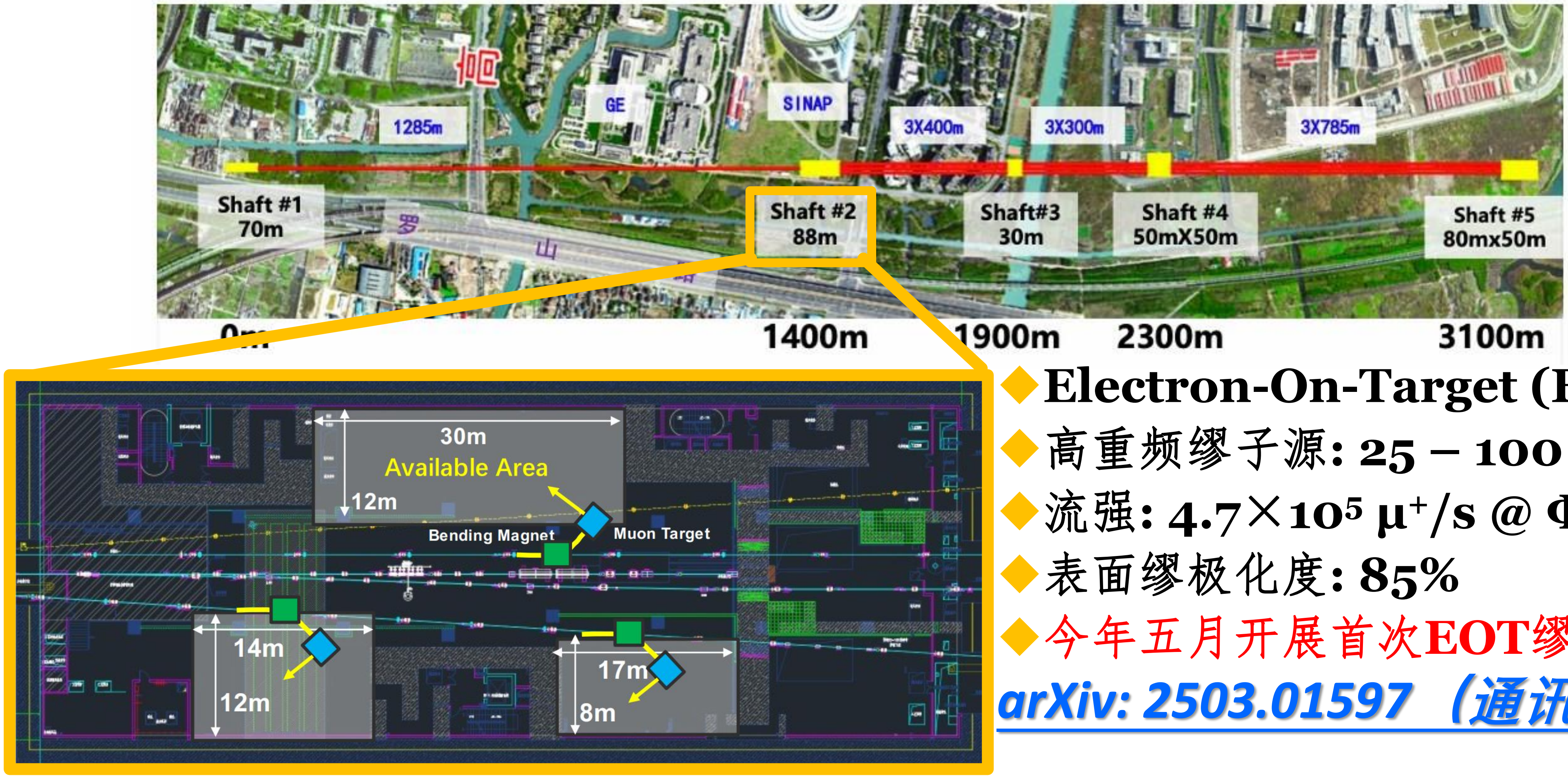
Z. Pan, et. al., IEEE TNS 2021

国内缪子源：SHINE

李政道研究所
TSUNG-DAO LEE INSTITUTE

SHINE
SHANGHAI HIGH REPETITION RATE XFEL AND EXTREME LIGHT FACILITY
硬X射线自由电子激光装置

上海•张江



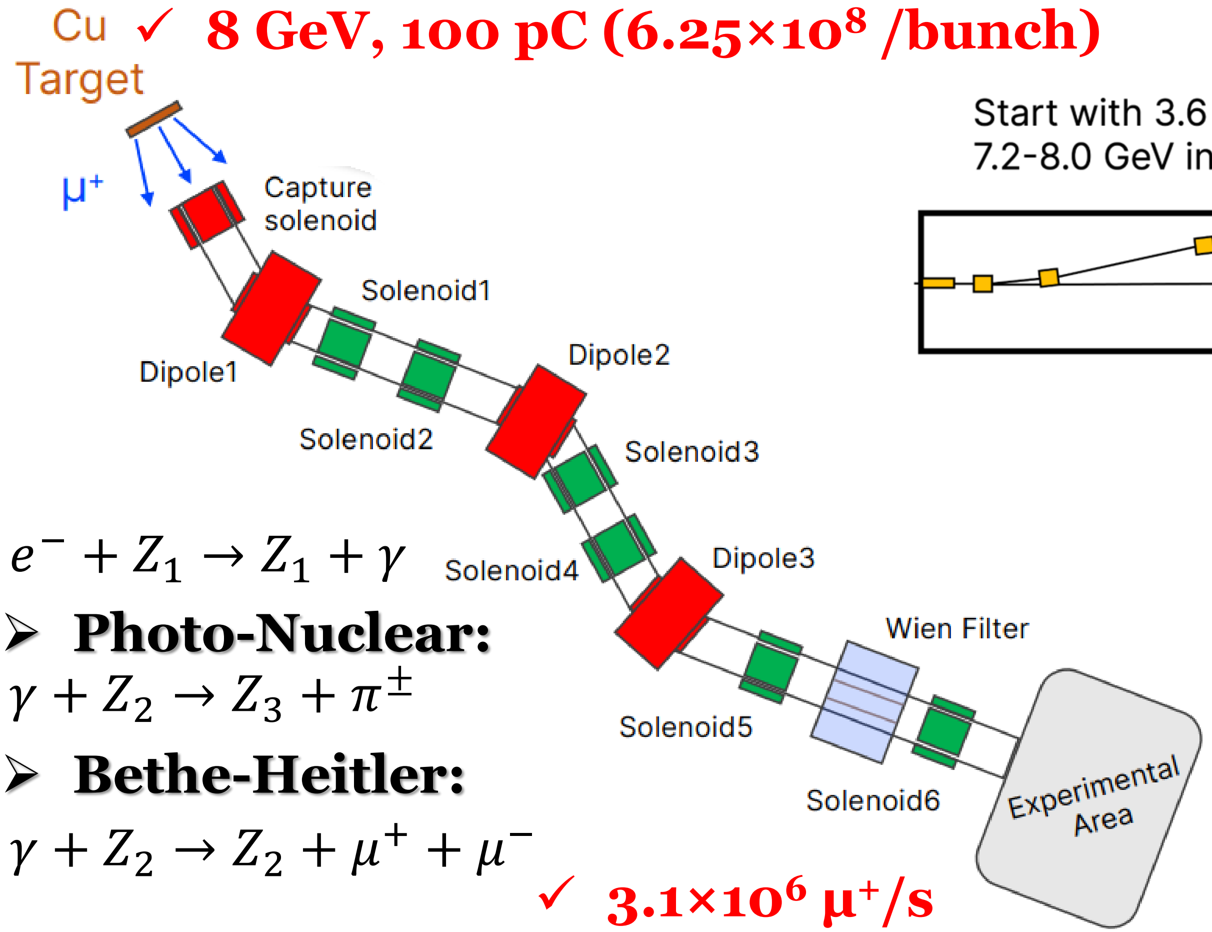
- Electron-On-Target (EOT)
- 高重频缪子源: 25 – 100 kHz
- 流强: 4.7×10⁵ μ⁺/s @ Φ30 mm
- 表面缪极化度: 85%
- 今年五月开展首次EOT缪子产生实验！

arXiv: 2503.01597（通讯：许金祥）

国内缪子源：SHINE

✓ 高能电子束

✓ 8 GeV, 100 pC (6.25×10^{8} /bunch)



$$e^- + Z_1 \rightarrow Z_1 + \gamma$$

➢ **Photo-Nuclear:**

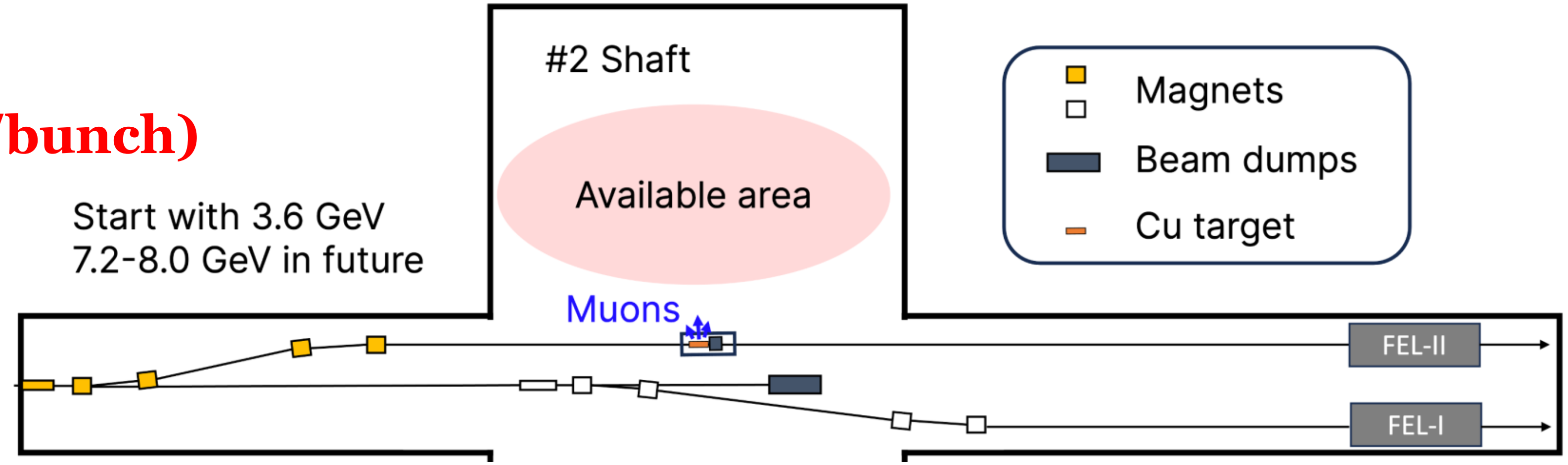
$$\gamma + Z_2 \rightarrow Z_3 + \pi^{\pm}$$

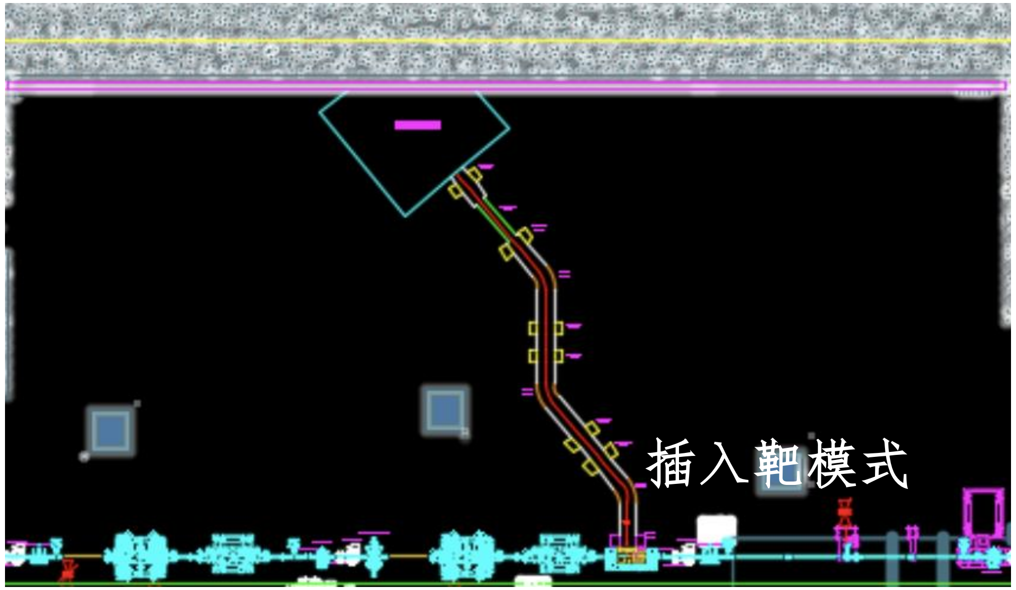
➢ **Bethe-Heitler:**

$$\gamma + Z_2 \rightarrow Z_2 + \mu^+ + \mu^-$$

✓ 3.1×10^{6} μ^+/s

✓ 50 kHz repetition rate





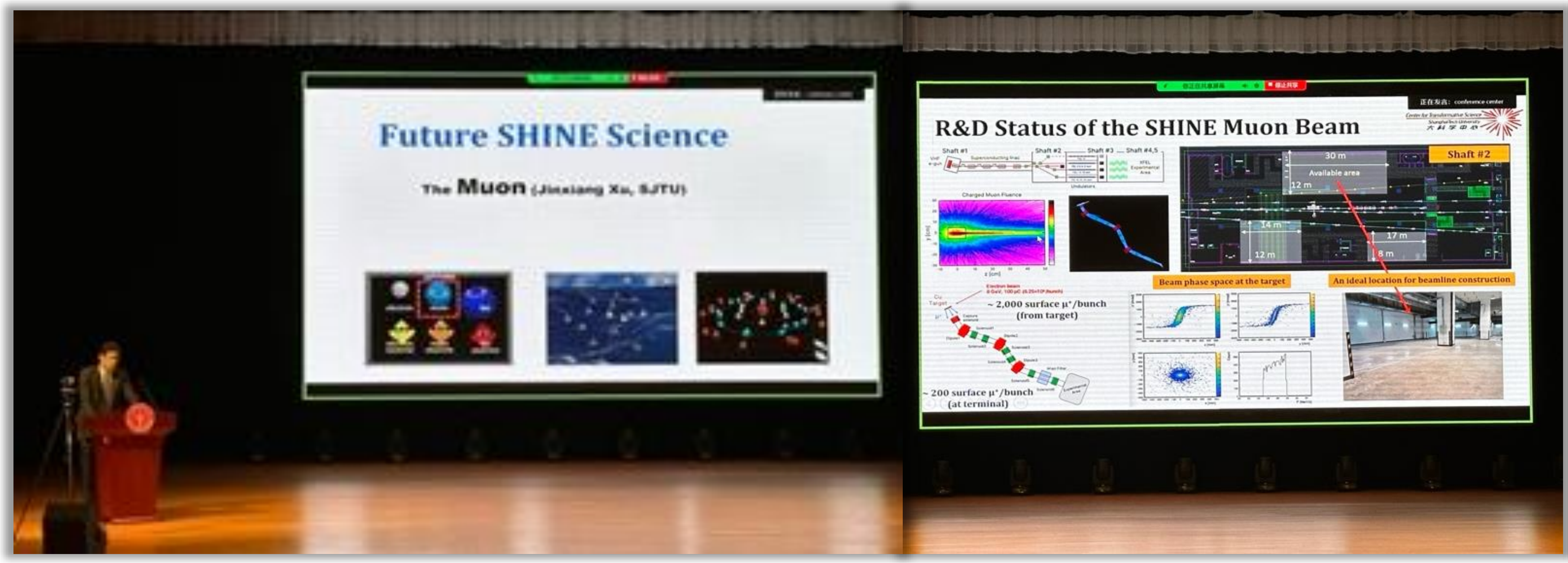
参考自许金祥的报告

国内缪子源：SHINE

- 缪子源已列入**SHINE Science Plus升级计划**
- SHINE Shaft#2束测在2025-2026年开展
- 预期~2030完成全缪束建设
- 科学实验面向应用（muSR等）需求
- 需要升级和进一步优化，以保持基础物理学领域的竞争力

参考自许金祥的报告

上科大刘志教授做“Future SHINE Science”报告



SHINE电子束应用研讨会参观

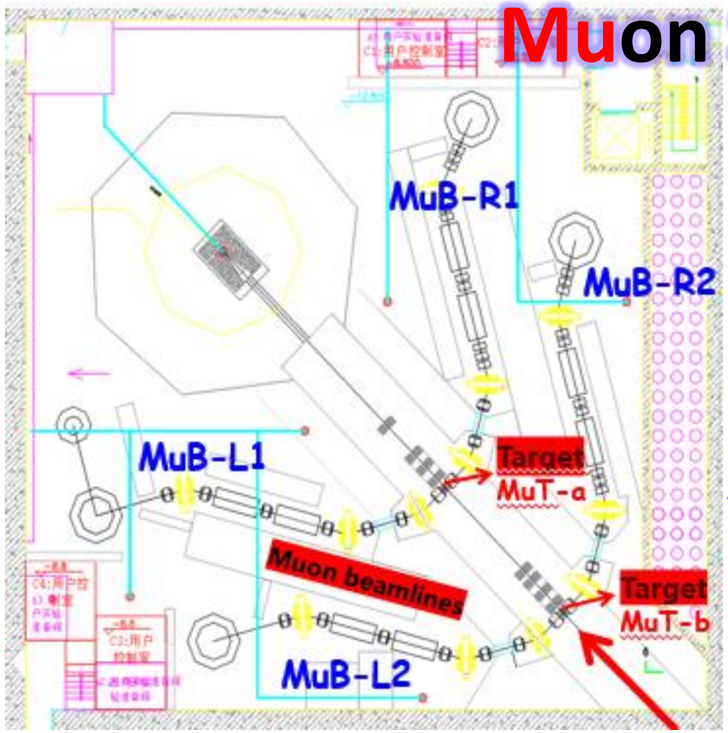
国内缪子源：CiADS / HIAF

广东•惠州

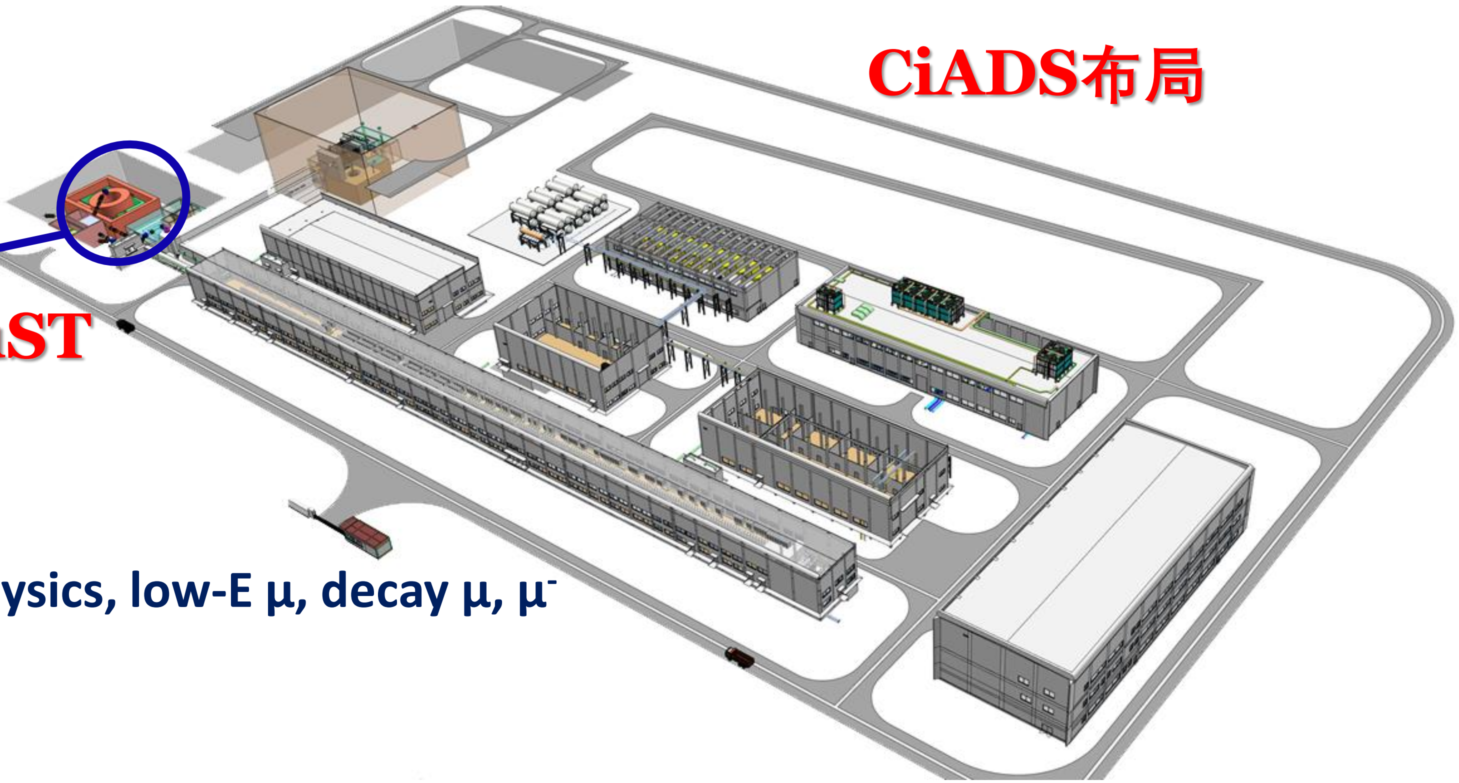
照片来自蔡汉杰的报告

国内缪子源：CiADS

Muon Science and Technology application terminal



MuST



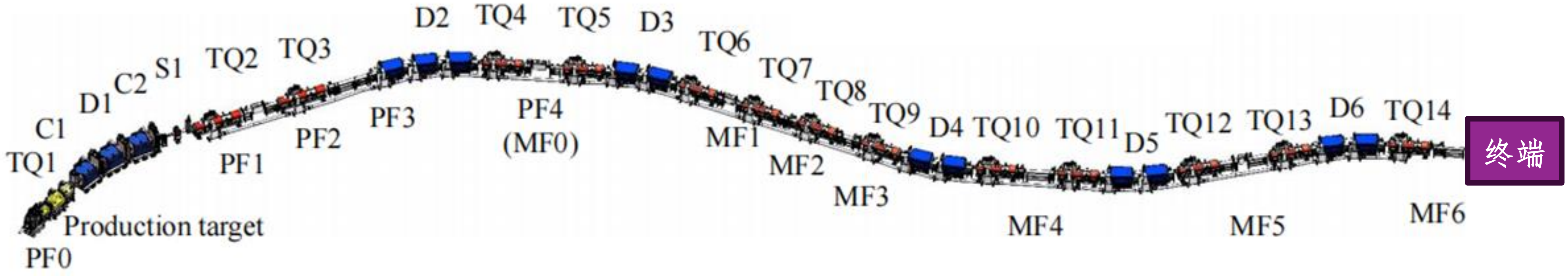
- ✓ L line: muon physics, low-E μ, decay μ, μ^-
- ✓ R line: μSR, μ^-

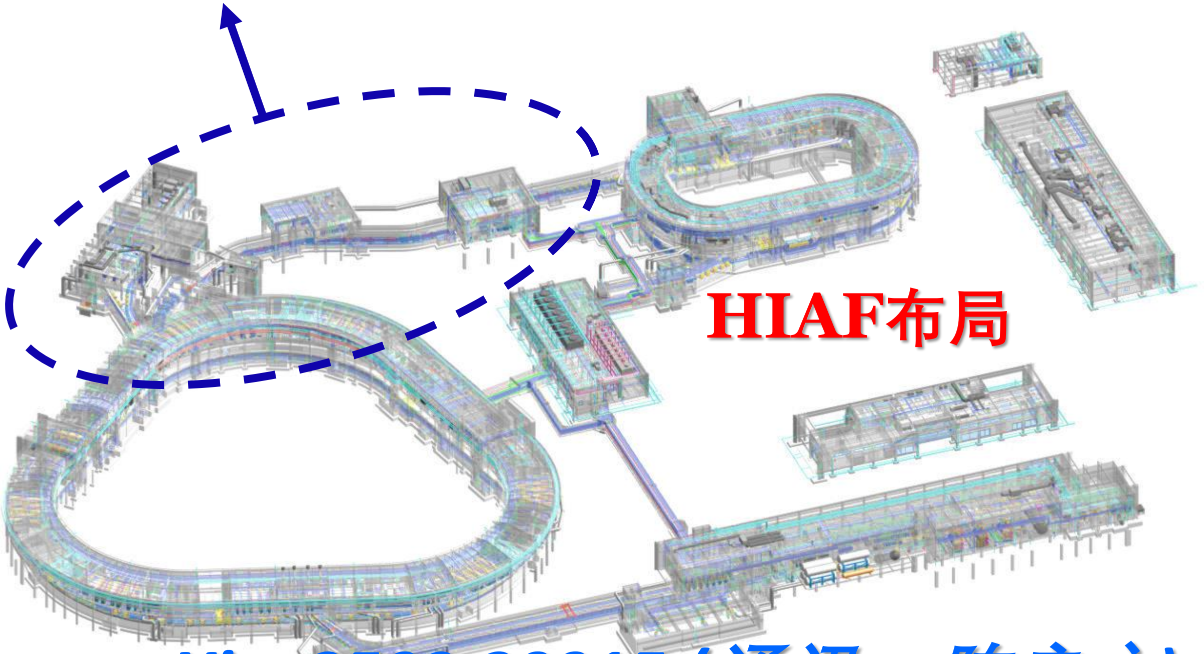
- 质子能量: 600 MeV
- 靶: 一期石墨 / 二期液态锂
- 运行模式: 连续束
- 流强: 5E7 ~ 1E10 μ^+/s（瞄准世界最高流强）, 4个终端
- 表面缪极化度： up to 99%
- 一期: MuT-a, L1&R1 || 二期: MuT-b, L2&R2

参考自蔡汉杰的报告

国内缪子源：HIAF

High energy FRagment Separator (HFRS)

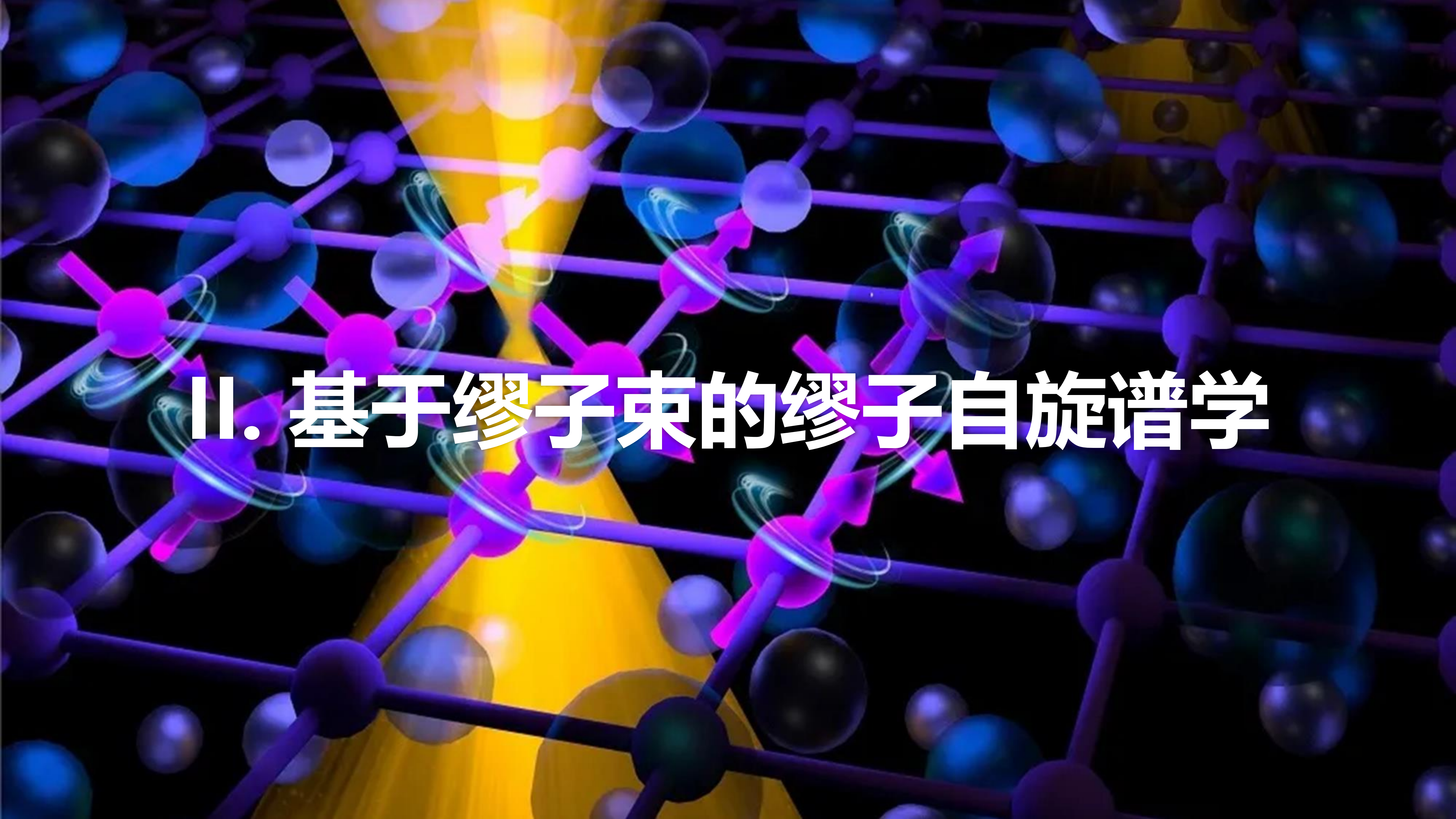




- 1 – 10 GeV， ~ 10^5 μ^+/s @ 1.5 GeV
- 单能： ~ 2%能散
- 应用：
- PKMu实验（李强、李奇特@ 北大）
- HIAF中微子振荡（葛韶锋@上交李所）
- 缪子-质子散射（尹航@华中师大、韩良@中科大）
- 缪束成像
- 新型缪子探测材料研发测试（米赵宏 @ 复旦马余刚院士团队）
- 缪子探测器标定（李清灵 @ 上海技物所孙胜利院士团队）。。。。。。

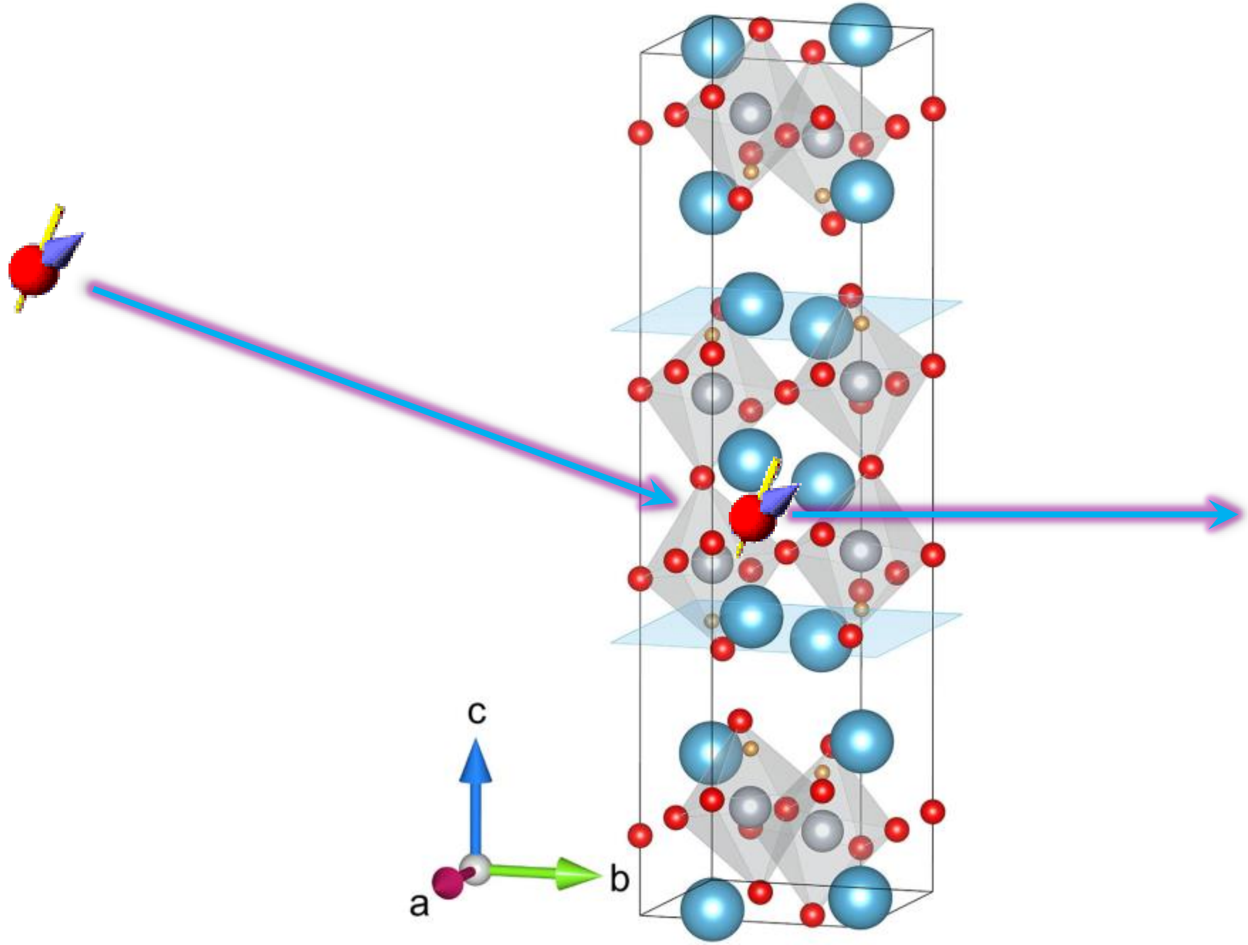
arXiv: 2502.20915 (通讯：陈良文)

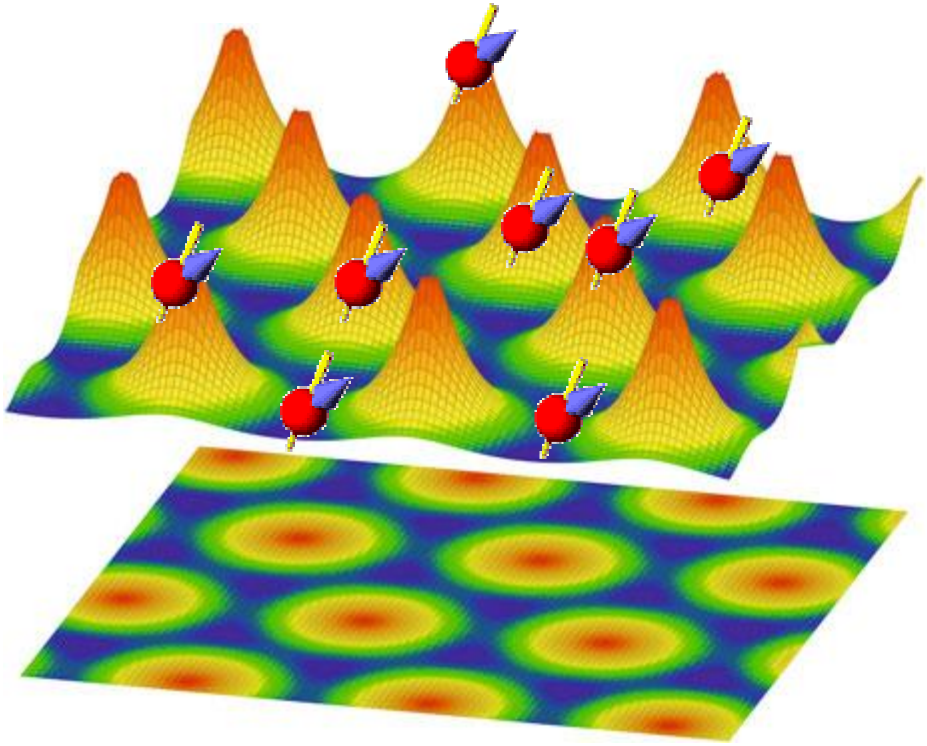
II. 基于缪子束的缪子自旋谱学



μSR谱学原理

μSR: muon spin rotation/relaxation/resonance

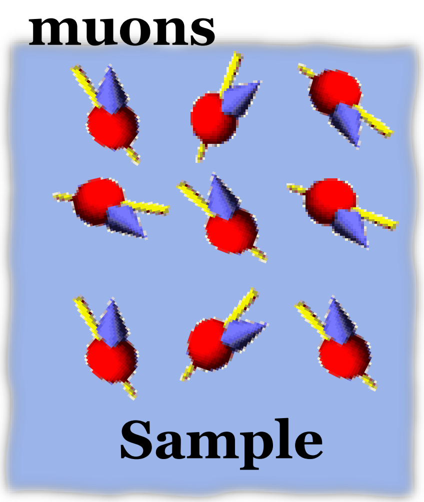




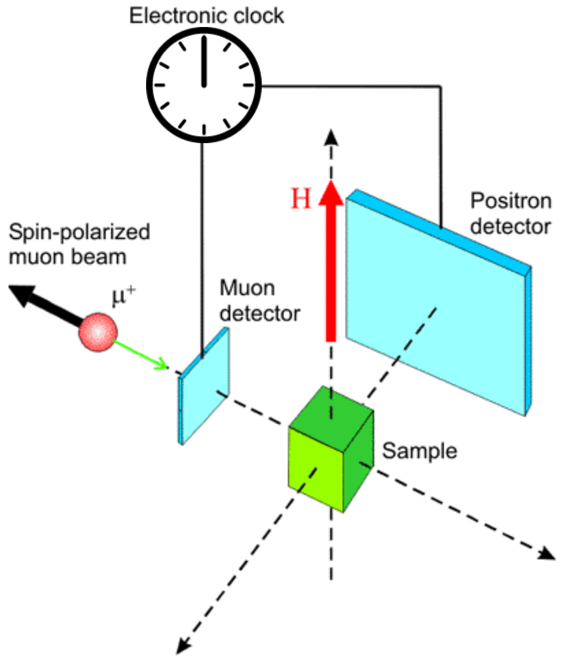
PRL Vol. 132 (2024) Front Cover: Lei Shu et al. A representation of the structure of polycrystalline La3Ni2O7−δ

μSR谱学原理

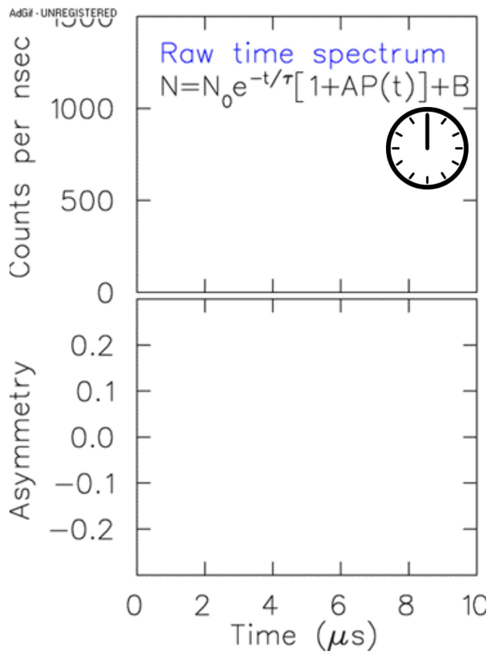
拉莫进动 (spin interaction) → **非对称衰变** (positron detection) → **μSR谱分析** (analysis) → **物质表征** (properties)



$$\frac{\mathrm{d}\boldsymbol{S}_\mu(t)}{\mathrm{d}t} = \gamma_\mu \boldsymbol{S}_\mu(t) \times \boldsymbol{B}_{\mathrm{loc}}(\mathrm{t})$$



$$\mu^+ \rightarrow e^+ + \nu_e + \bar{\nu}_\mu$$

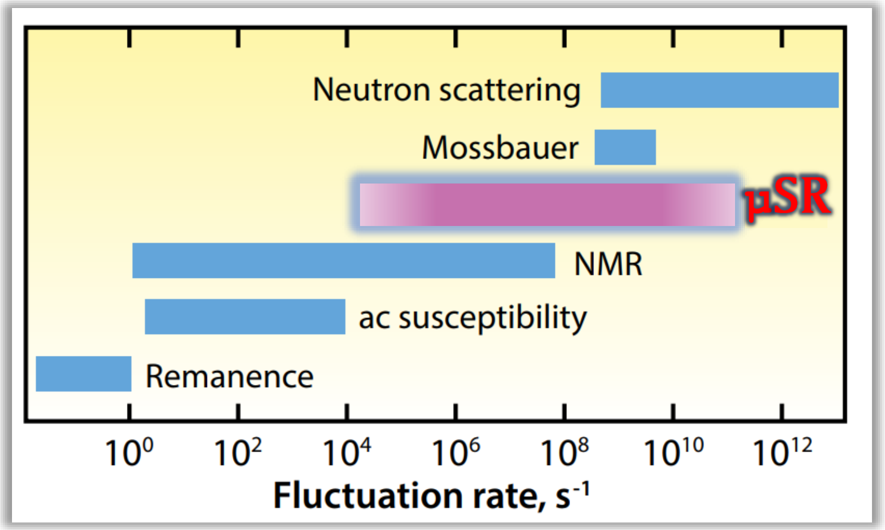


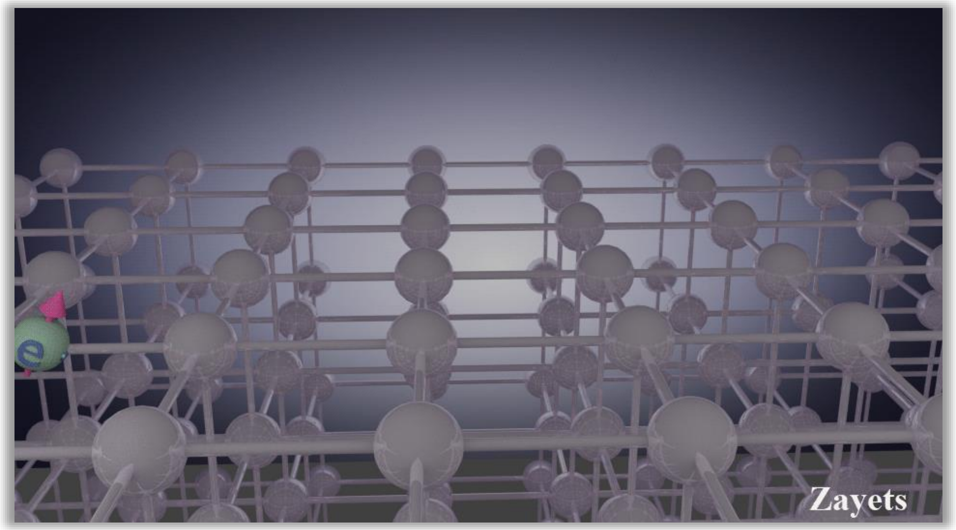
$$\frac{N_F(t) - N_B(t)}{N_F(t) + N_B(t)} = AP(t)$$

$$\omega = \gamma_\mu B_{\mathrm{loc}}$$

- 静态/动态磁场分布
- 磁性涨落
- 超导相VS磁性相
- 磁体积分数
- 载流子/电荷迁移扩散
- 自由基化学反应行为…

μSR谱学优势





- **局域量子磁探针** (no need to search reciprocal space)
- **独特的时间窗** (complementary to NMR/neutron scattering)
- **弱磁性灵敏** (small moment magnetism ~ 10^{-3} μ_B/Atom)
- **随机/不均匀磁性分布** (e.g. spin glasses)
- **短程有序** (where neutron scattering is not sensitive)
- **高度极化，可零场实验** (independent of temperature, unique measurements without disturbance of the system)
- **单粒子探测** (with extremely high sensitivity)
- **样品状态无限制** (in choice of materials to be studied)

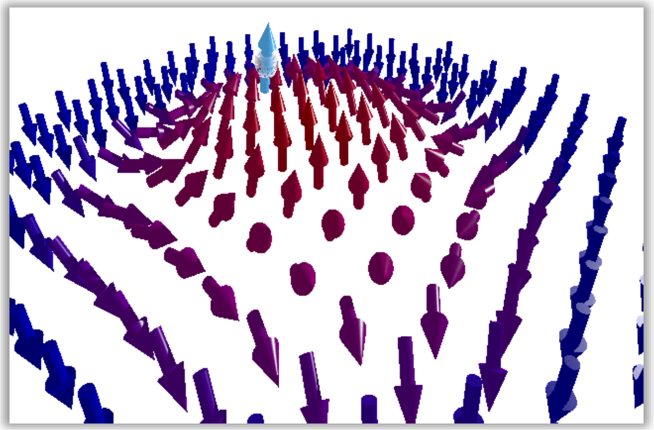
μSR谱学应用

● 被动探针
(heavy lepton)

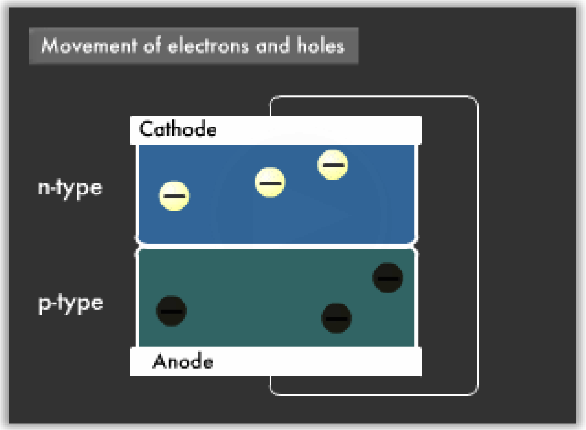
● 主动探针
(light proton)

超导

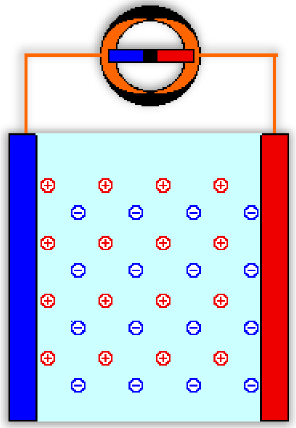
磁性



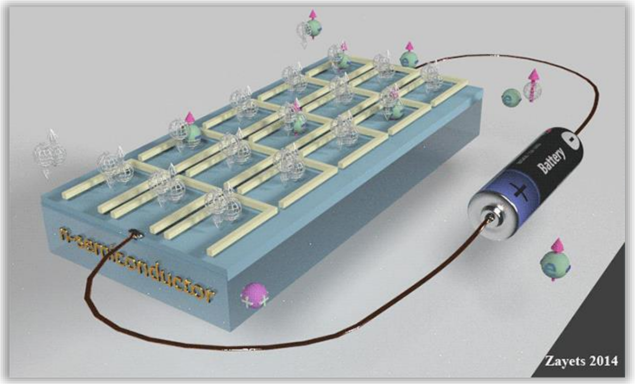
半导体



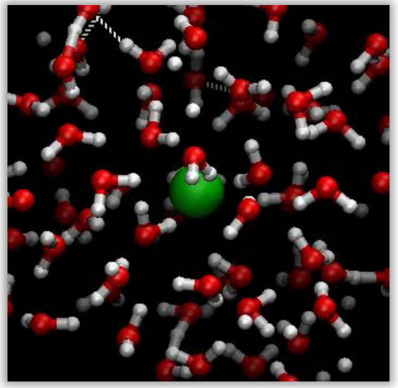
离子导体



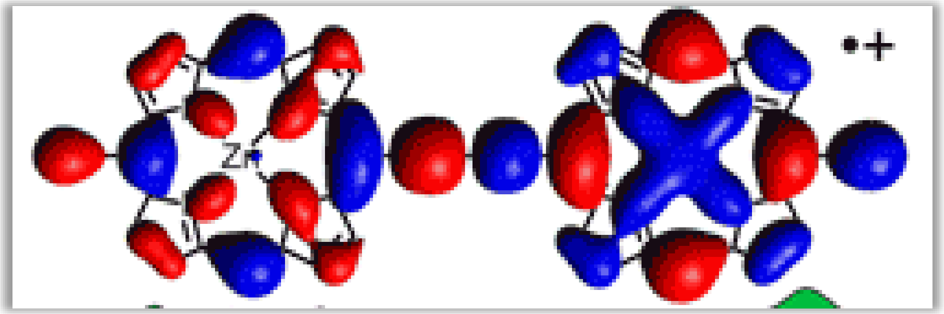
电荷输运/电池



分子动力学



极化子运动



…

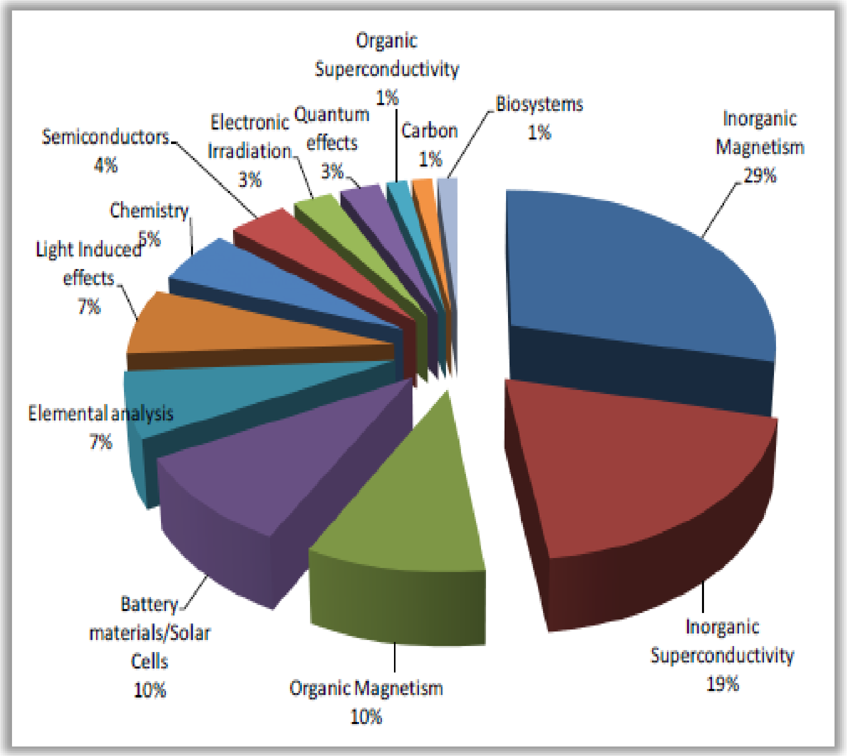
Nat. Rev. Meth. Primer： Muon Spin Spectroscopy

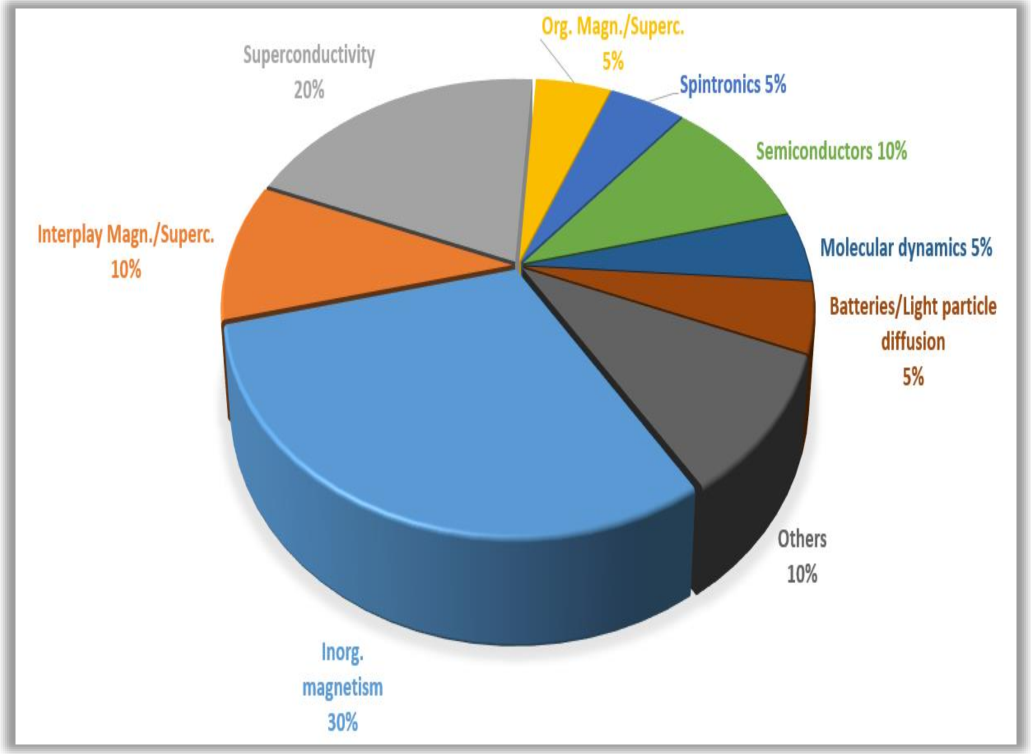
Courtesy Dr. Adrian Hiller @ ISIS Muons

μSR谱学应用

Science and Technology Facilities Council | ISIS Neutron and Muon Source

PAUL SCHERRER INSTITUT PSI



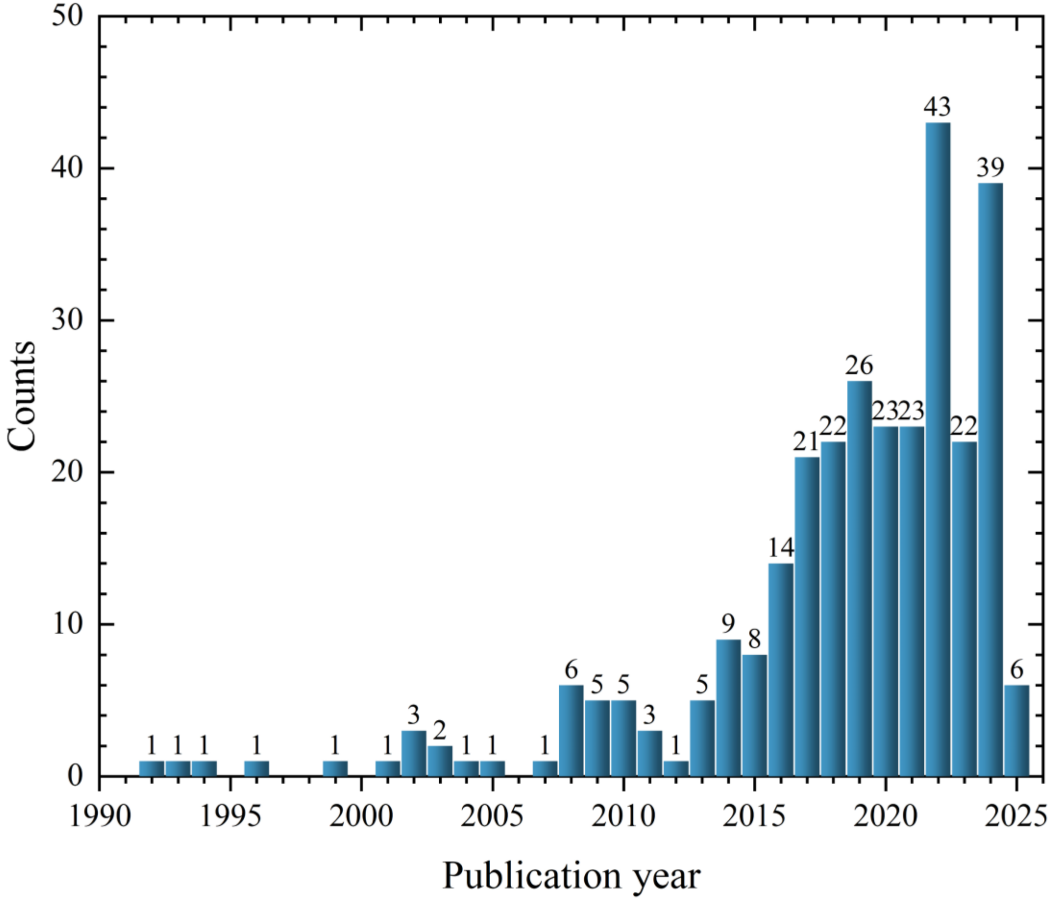


- Inorganic magnetism 29%
- Inorganic superconductivity 19%
- Organic magnetism 10%
- Battery/Solar cells 10%
- Semiconductors 4%

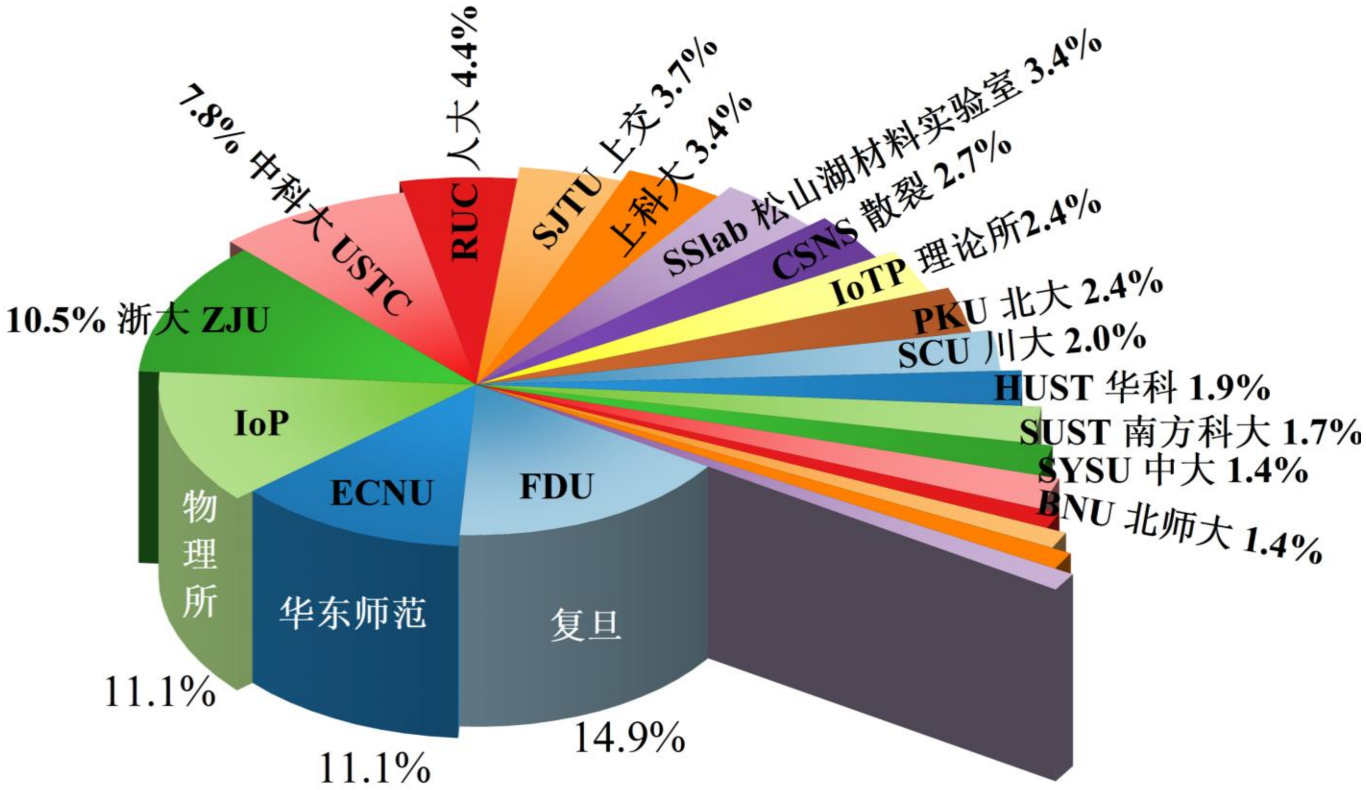
- Inorganic magnetism 30%
- Superconductivity 20%
- Interplay Magn./Superc. 10%
- Semiconductors 10%
- Battery/Light particle diffusion 5%

μSR国内用户统计

296篇论文



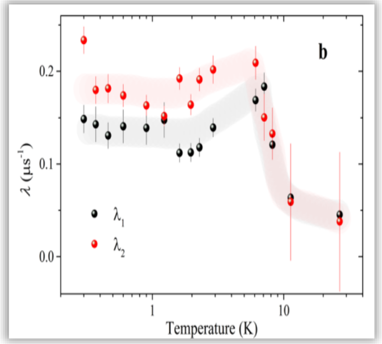
54家单位



Web of Science analysis (muon spin spectroscopy / muon spin relaxation / muon spin rotation) 2025/04

邓力，陈良文* : PLA 2024, PRB 2024 @ 东江实验室/近物所 （第一性原理计算及实验数据微观解析）

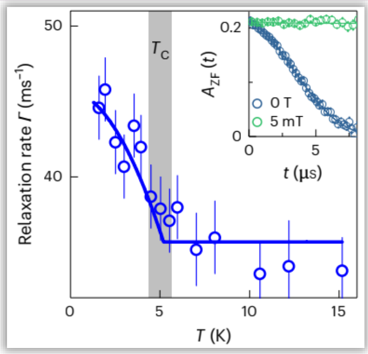
国内用户亮点文章



@J-PARC

赵金奎教授课题组 @ 松山湖实验室

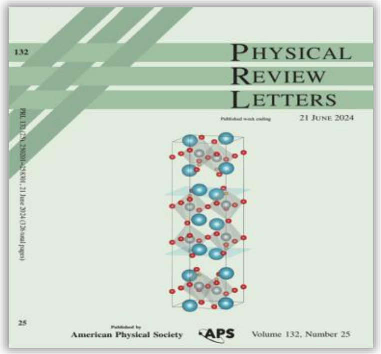
- ➢ *Signatures of the quantum spin liquid state in triangular-based zig-zag polyaromatic hydrocarbon radicals,* Chemical Science *16, 6345 (2025)*
- ➢ **μSR数据证明新合成的自由基有机物是一种新的量子自旋液体候选者**



@PSI

殷嘉鑫副教授课题组 @ 南方科大

- ➢ *Evidence for time-reversal symmetry-breaking kagome superconductivity,* Nature Materials *23, 1639-1644 (2024)*
- ➢ **证明了笼目超导体CsVSb存在时间反演对称破缺TRSB**



@TRIUMF

殳蕾教授课题组 @ 复旦大学

Editor's Suggestion

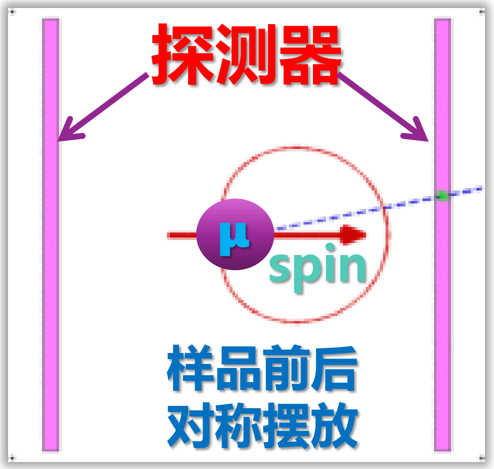
- ➢ *Evidence of Spin Density Waves in $La_3Ni_2O_{7-\delta}$,* Physical Review Letters *132, 256503 (2024)*
- ➢ **在新型镍基超导体中首次发现体磁性，为奇异超导电性研究提供关键磁性基态依据**

连续束 VS 脉冲束

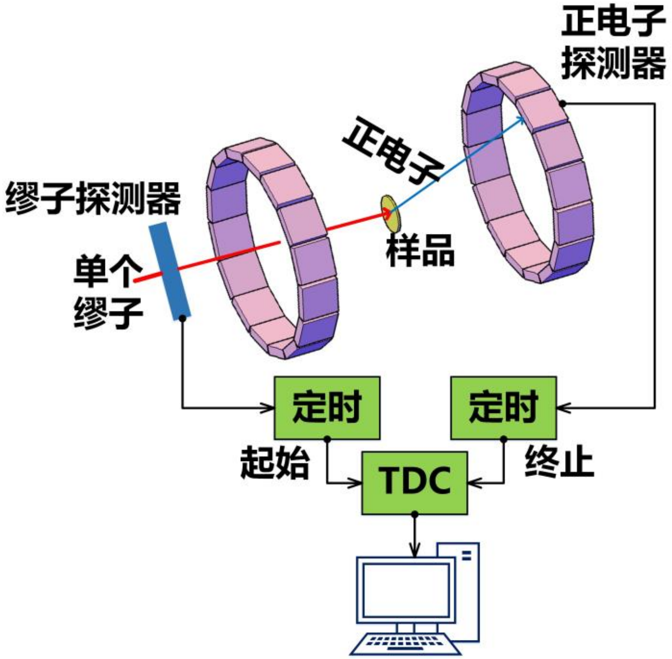
$$N(t) = N_0[1 + A_0\mathbf{P}(t)\cdot\hat{\mathbf{n}}]$$

$$N_{F/B}(t) = N_0[1 \pm A_0 \mathrm{P}(t)]$$

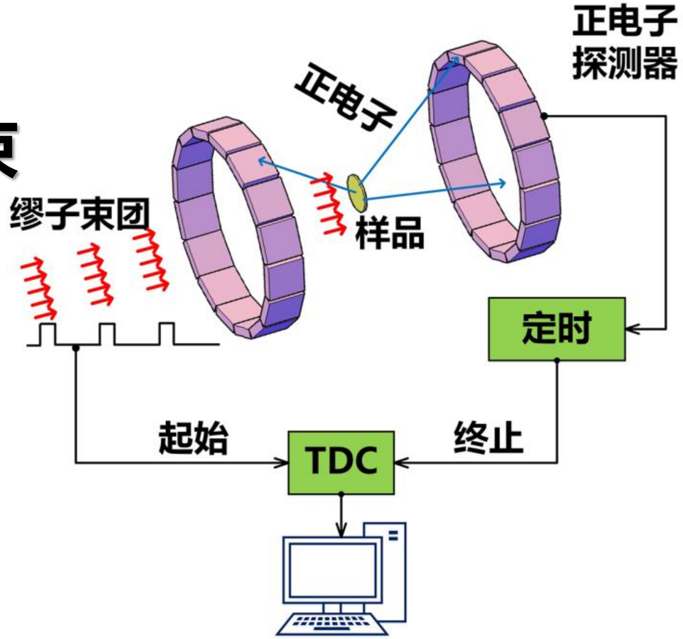
$$A_0\mathrm{P}(\boldsymbol{t}) = \frac{N_F - N_B}{N_F + N_B}$$



连续束

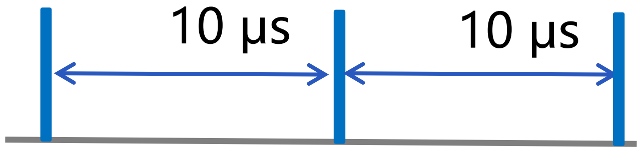


脉冲束



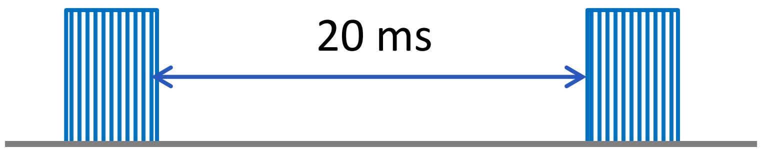
连续束 VS 脉冲束

连续束



- “脉冲宽度”为0
- 一对一探测
  - 计数率受限
  - 本底（μ-e错误符合）较高
  - mm级小束斑
- 高时间分辨，窄时间窗
  - 强磁场（> 1 T）测量
  - 快弛豫信号灵敏

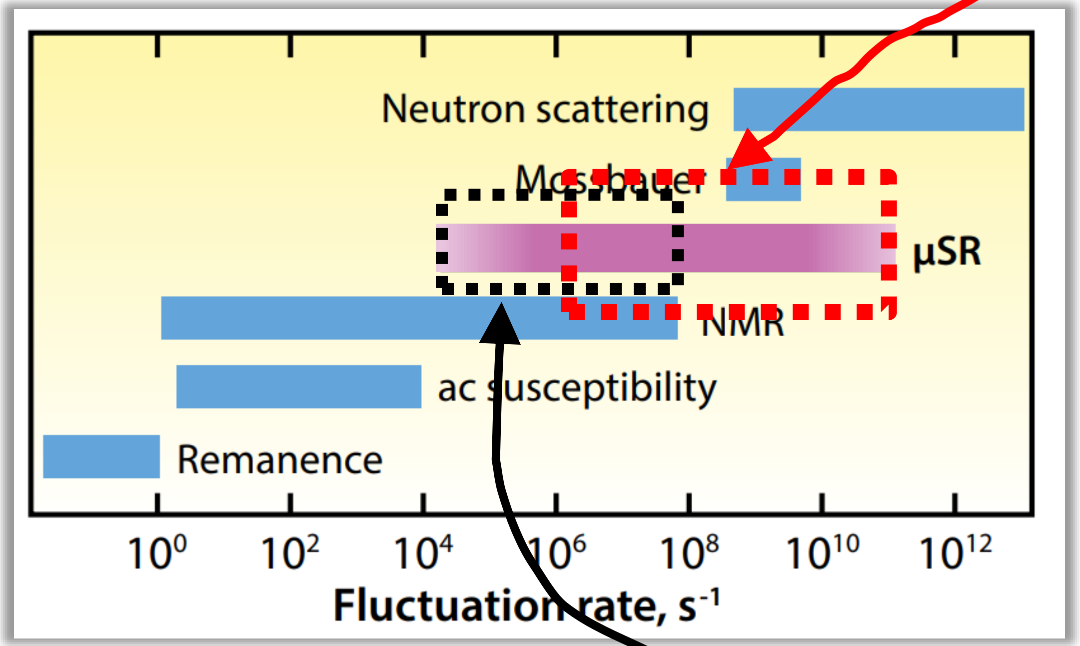
脉冲束

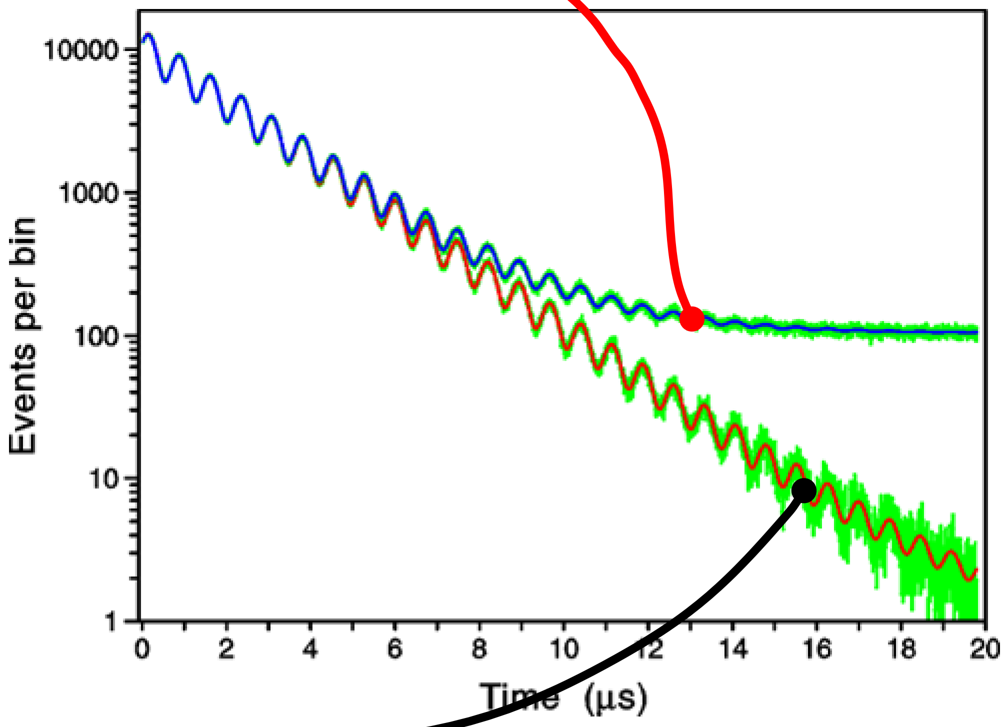


- 脉冲宽度10-100 ns
- 一对多探测
  - 计数率高
  - 几乎没有本底
  - 束斑大（~Φ30 mm）
- 时间分辨较差，宽时间窗
  - 测量较弱TF磁场（<0.1 T）
  - 慢弛豫信号灵敏

连续束 VS 脉冲束

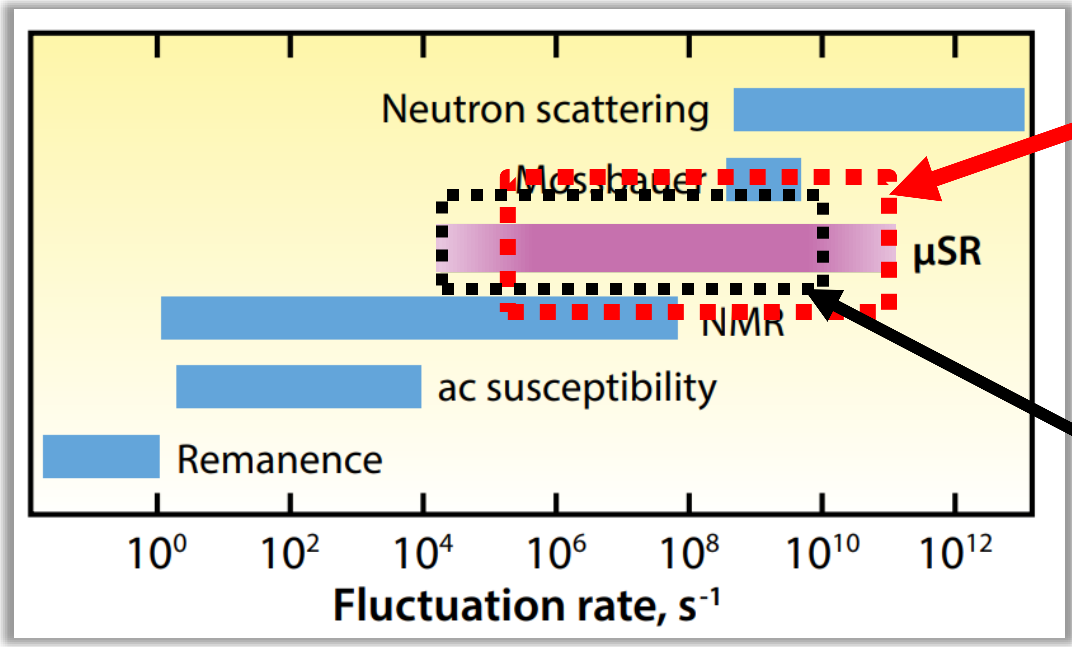
连续束



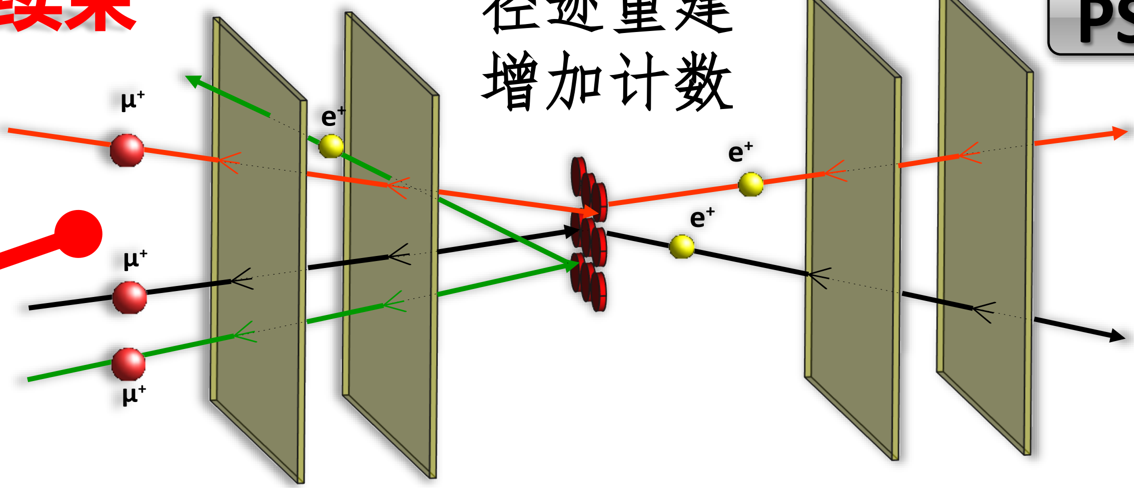


脉冲束

连续束 VS 脉冲束

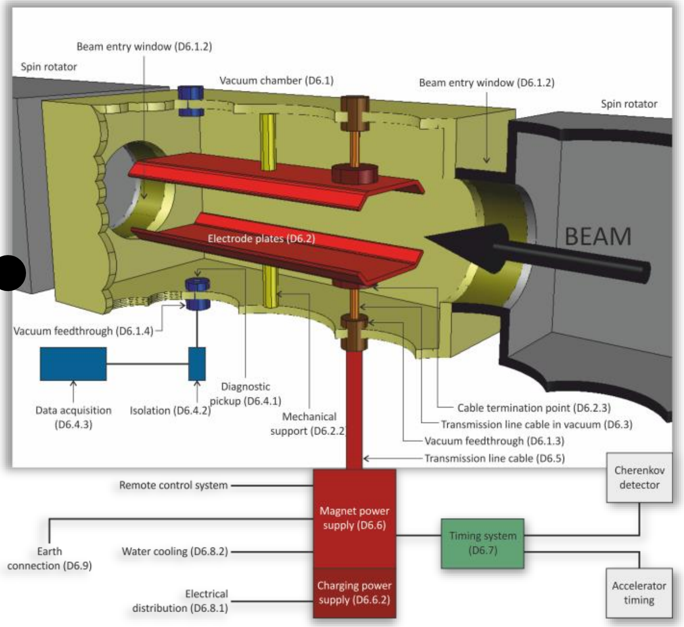


连续束



径迹重建
增加计数

PSI



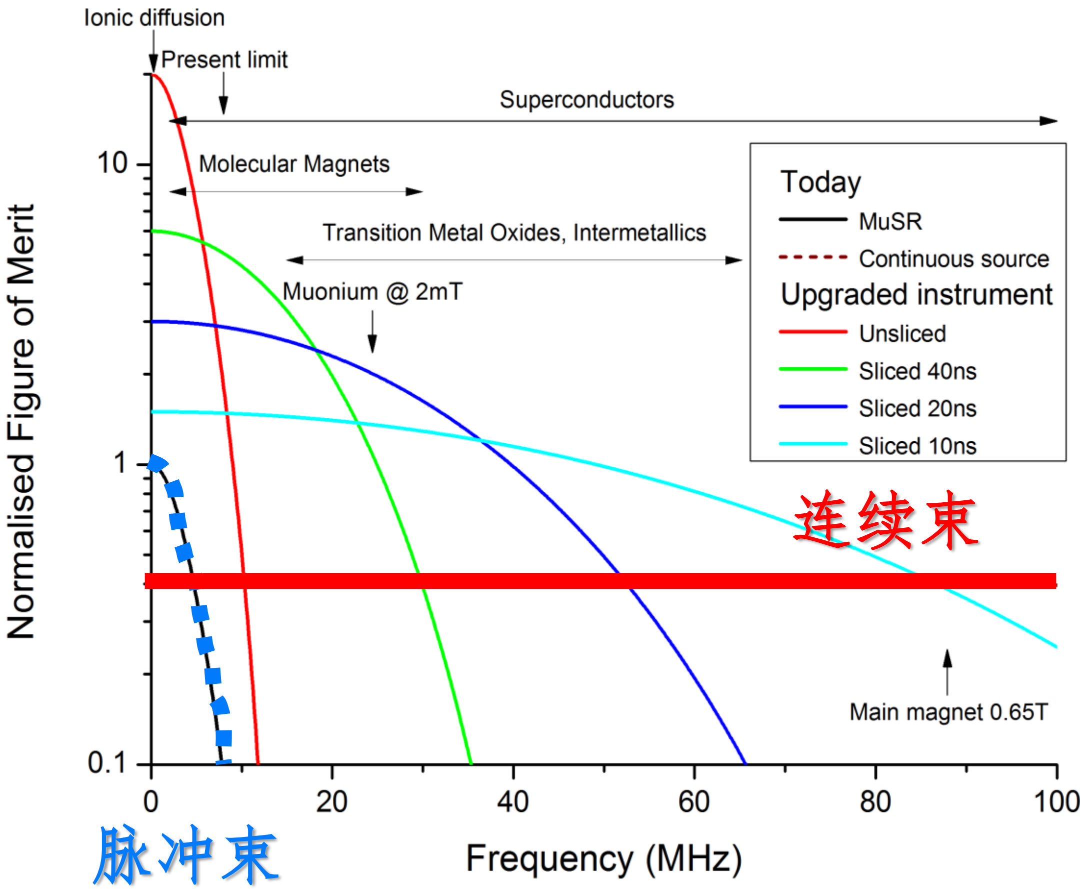
ISIS

束团
切割

脉冲束

连续束 VS 脉冲束

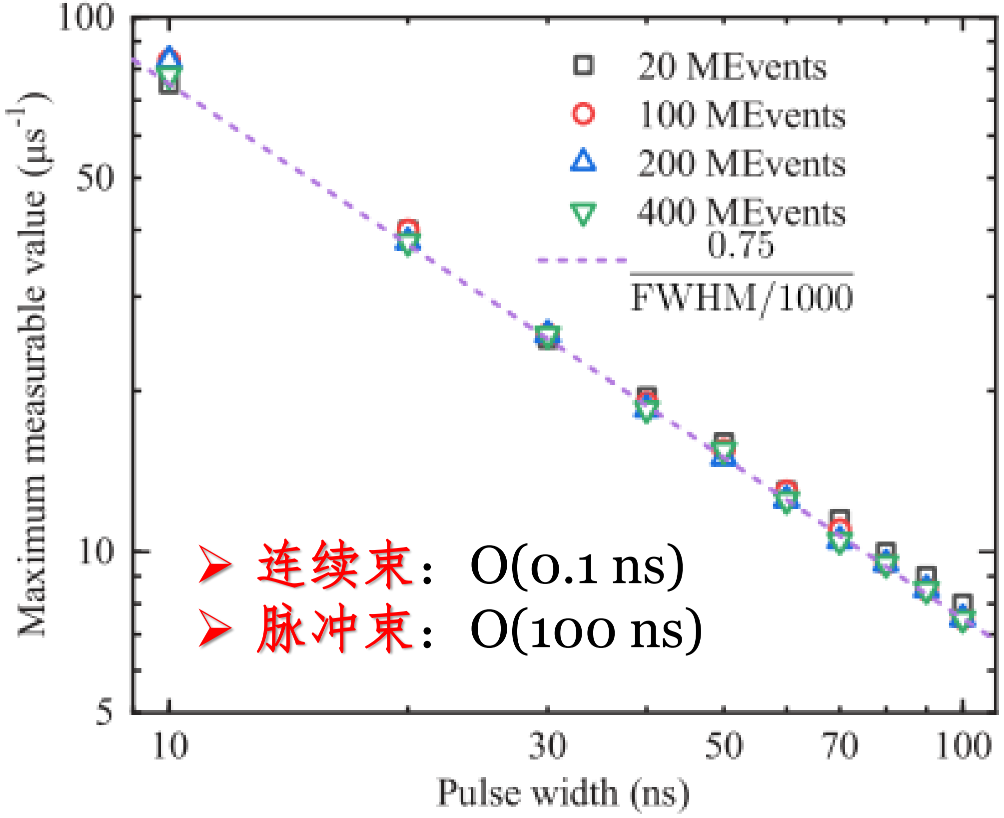
FoM = Rate • A²



ISIS Super MuSR design

驰豫频率表征范围 ∝ $1/\sigma_t$

σ_t即时间分辨，由束流脉宽和谱仪定时精度贡献

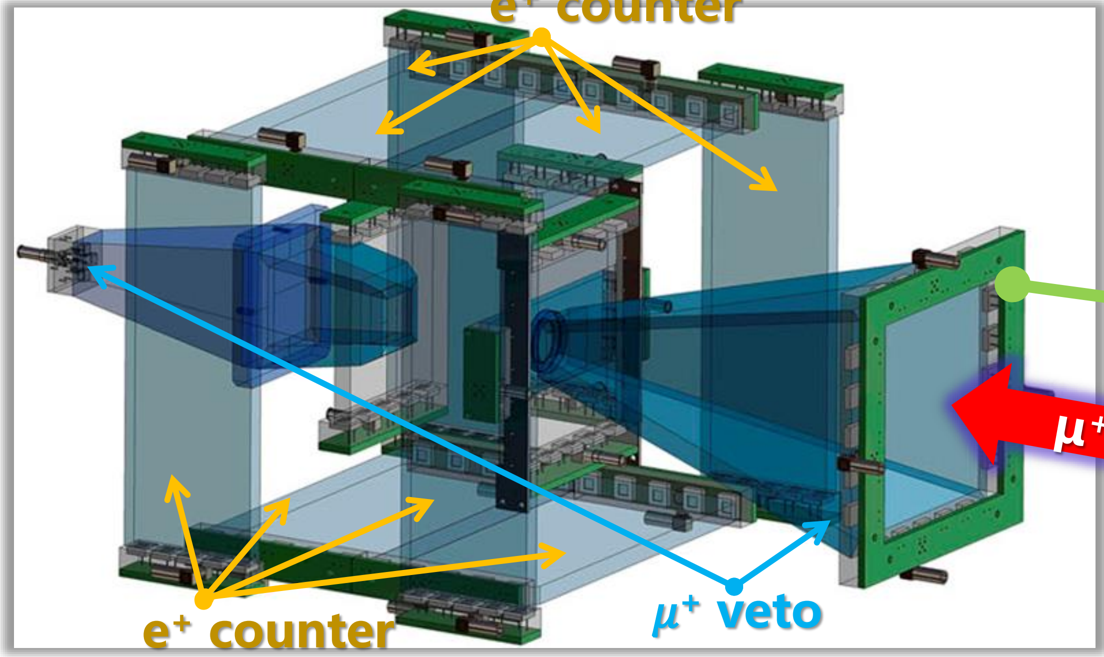


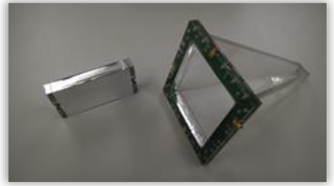
- 连续束： O(0.1 ns)
- 脉冲束： O(100 ns)

Z. Pan et al NIMA 2022

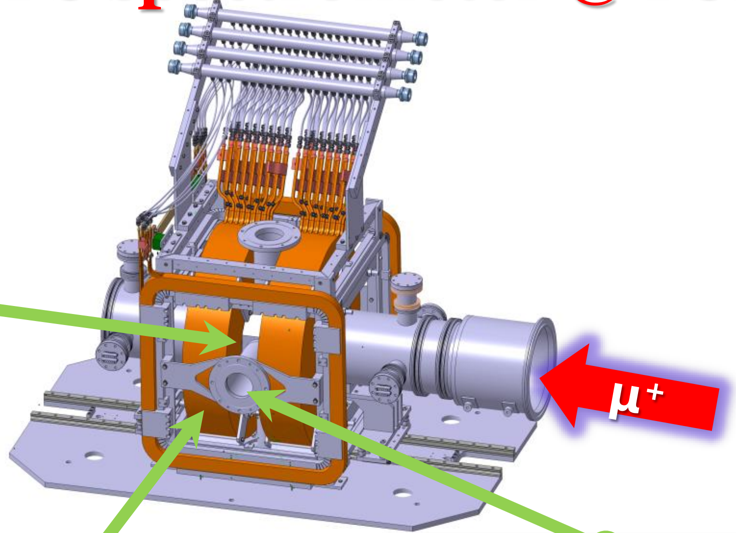
谱仪组成

GPS spectrometer @ PSI





探测器



磁铁

低温环境

III. 基于离子束的β-NMR谱学

β-NMR物理基础

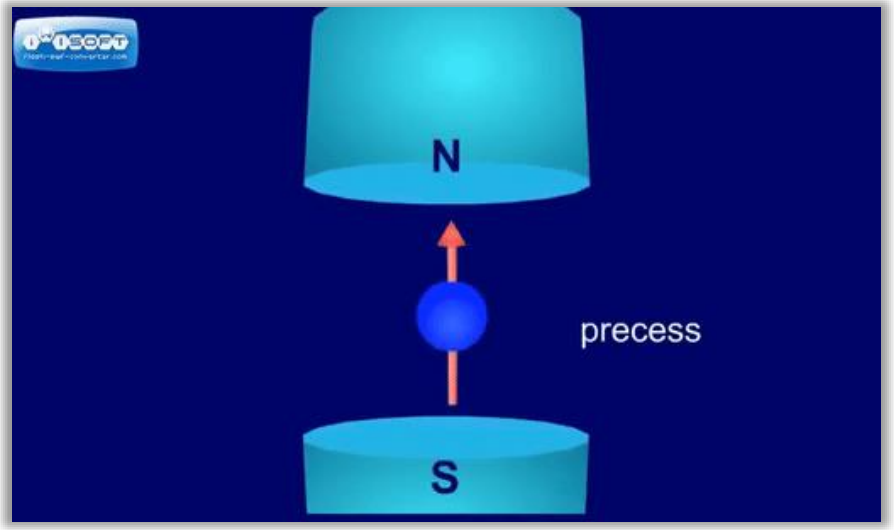
β detected Nuclear Magnetic Resonance (β-NMR)

- ✓ **非0自旋原子核存在磁偶极矩** → βNMR
- ✓ **I>1/2原子核存在非0电四极矩** → βNQR

$$\Delta E_{\mathrm{mag}} = |g_I| \cdot \mu_N \cdot B + \frac{1}{2} Q \cdot V_{ZZ}$$

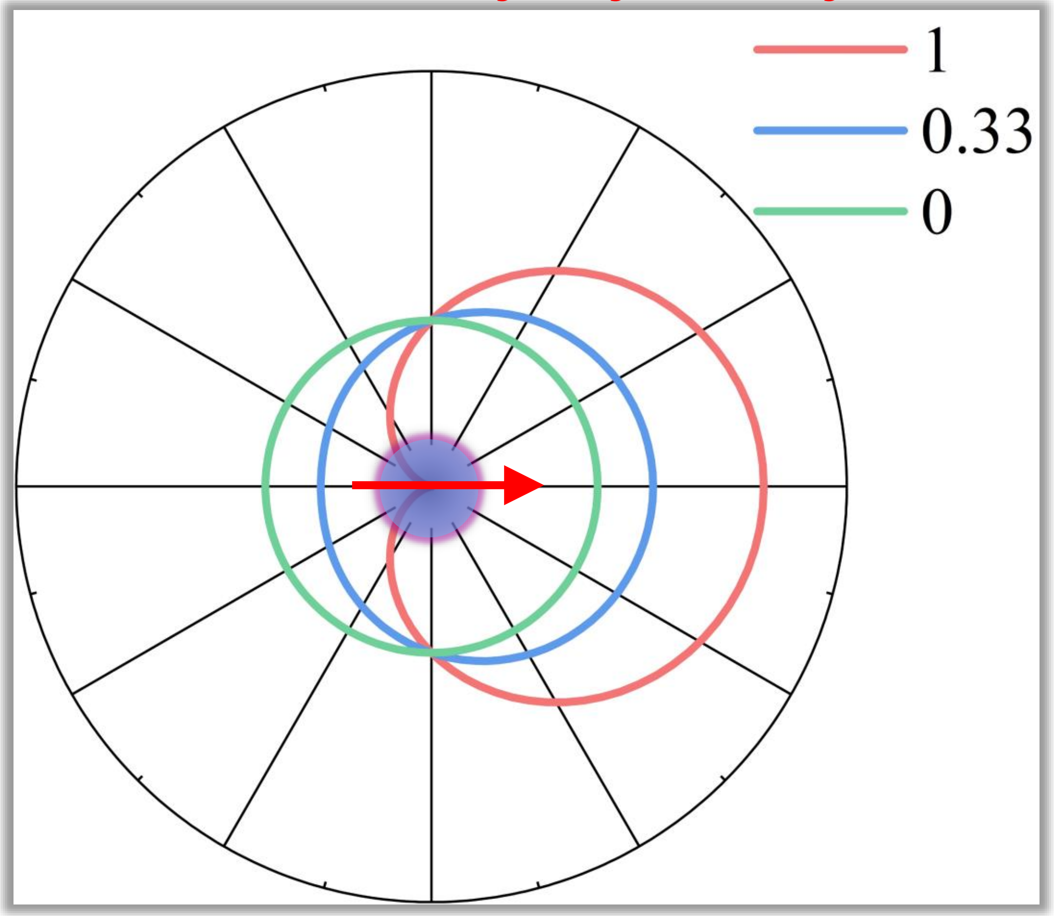
对确定的核素是已知的

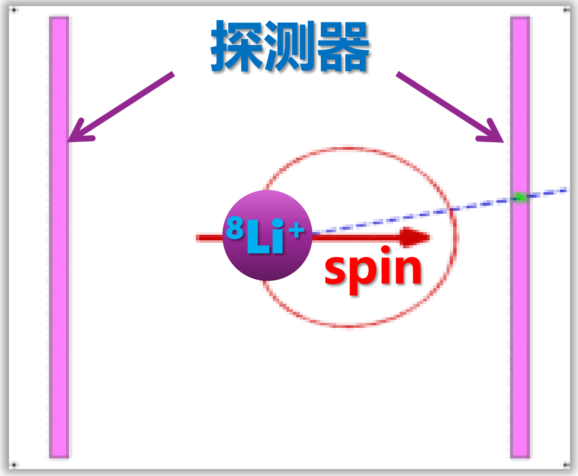
决定于局域原子（化学）环境



β detected Nuclear Magnetic Resonance (β-NMR)

Beta Decay Asymmetry





非对称因子（通过测量β电子的计数获得）

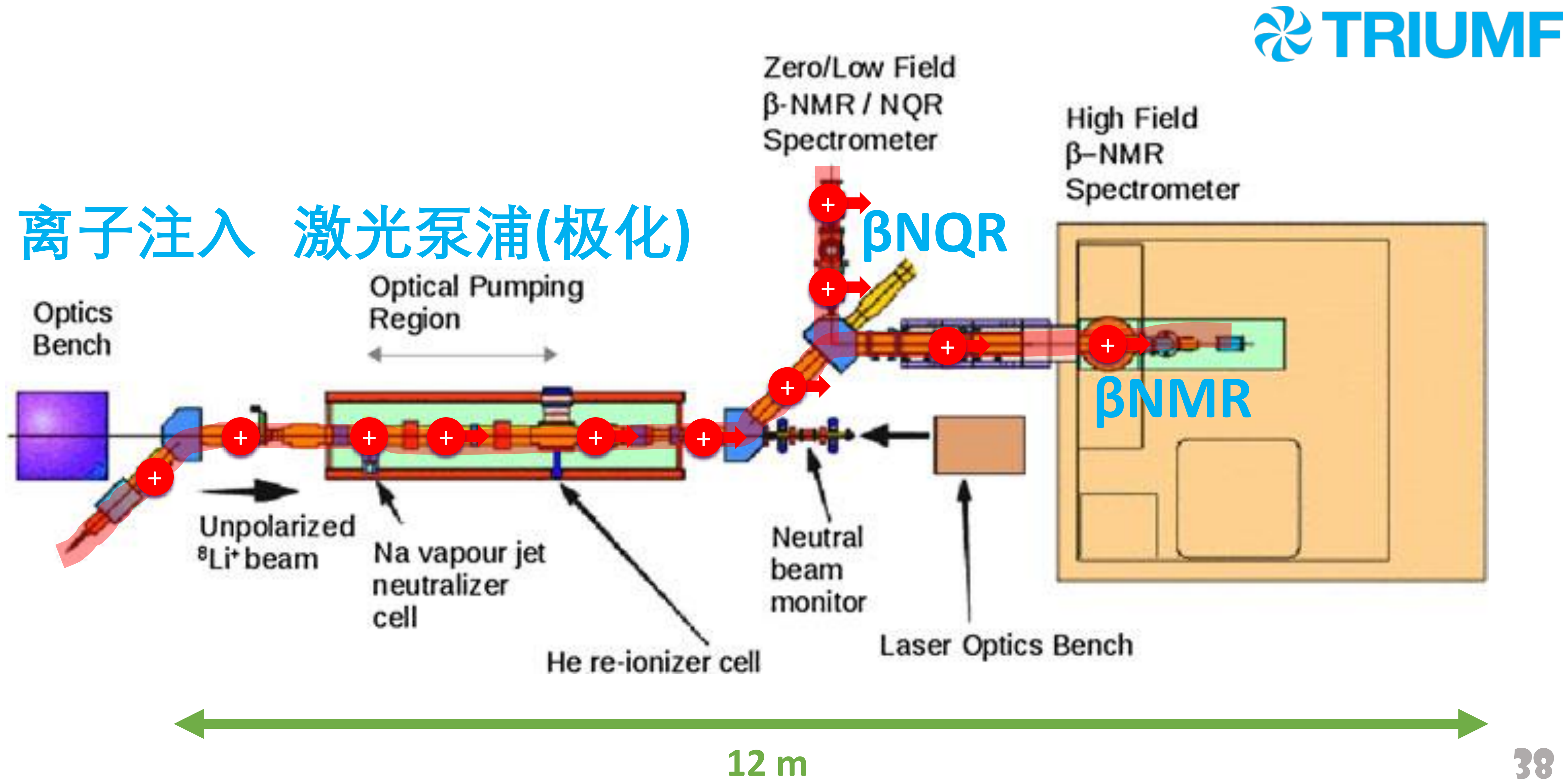
$$W(\theta) = 1 + A_\beta \frac{v}{c} P_I \cos\theta$$

缪子衰变Michel电子分布类似！

$$A = \frac{N^+ - N^-}{N^+ + N^-} = \frac{v}{c} A_\beta P_I$$

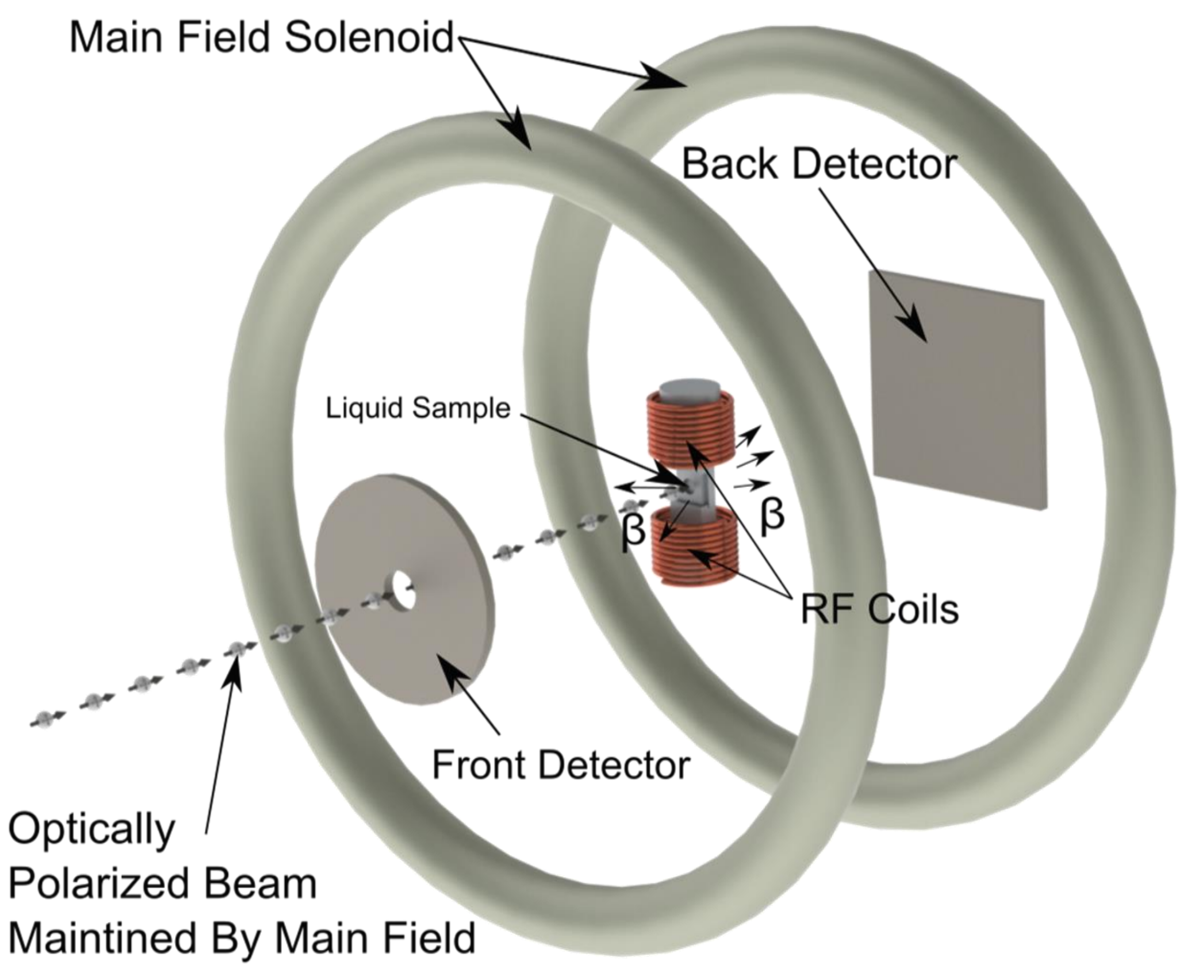
$$A_\beta = \begin{cases} \pm 1 & \text{for } I_f = I_i - 1, \\ \dfrac{\pm\rho^2/(I_i+1) - 2\rho\sqrt{I_i/(I_i+1)}}{1+\rho^2} & \text{for } I_f = I_i, \\ \mp \dfrac{I_i}{I_i+1} & \text{for } I_f = I_i + 1. \end{cases}$$

装置组成



TRIUMF
Zero/Low Field
β-NMR / NQR
Spectrometer
High Field
β–NMR
Spectrometer
离子注入 激光泵浦(极化)
βNQR
Optical Pumping
Region
Optics
Bench
βNMR
Unpolarized
⁸Li⁺ beam
Na vapour jet
neutralizer
cell
Neutral
beam
monitor
He re-ionizer cell
Laser Optics Bench
12 m

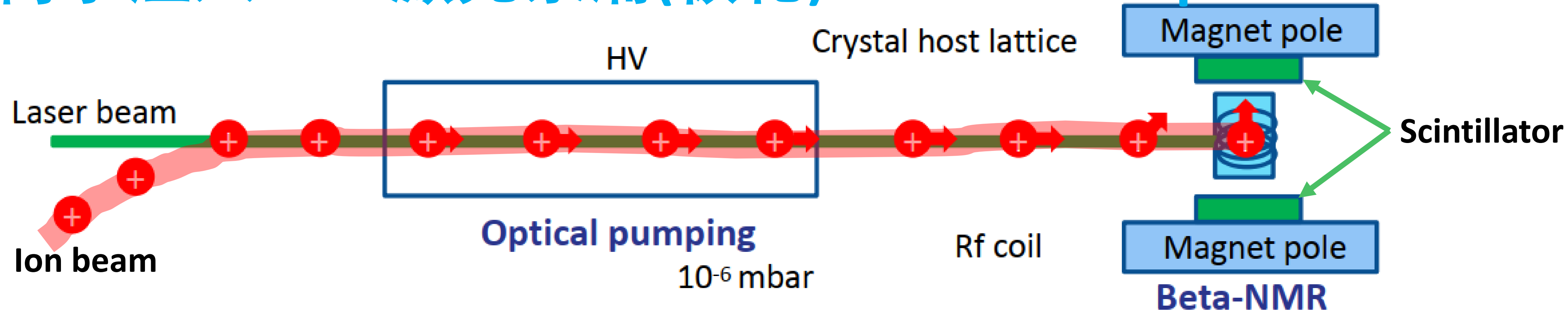
βNMR谱仪

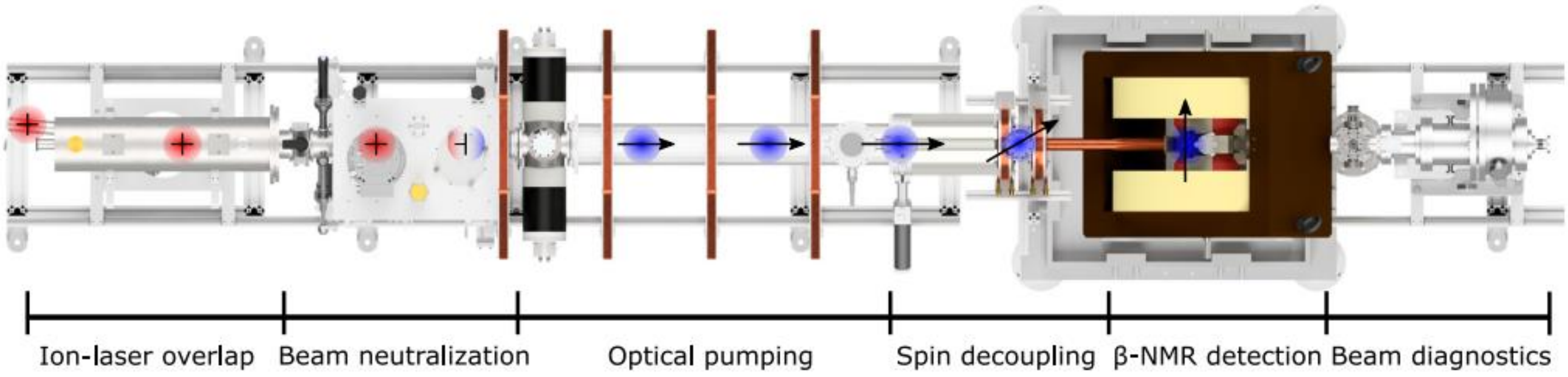

Main Field Solenoid
Back Detector
Liquid Sample
β
β
RF Coils
Front Detector
Optically
Polarized Beam
Maintined By Main Field

装置组成

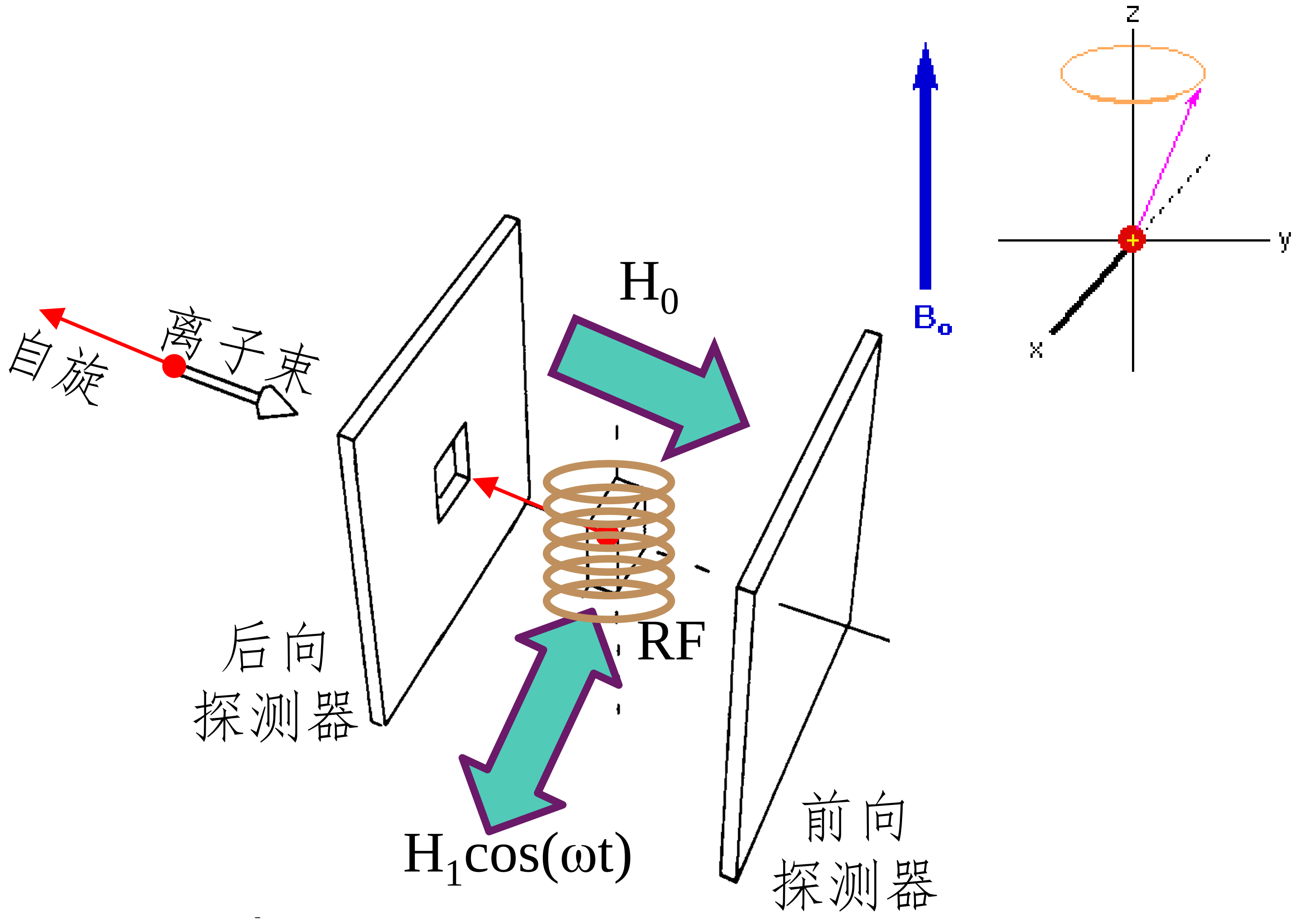
ISOLDE

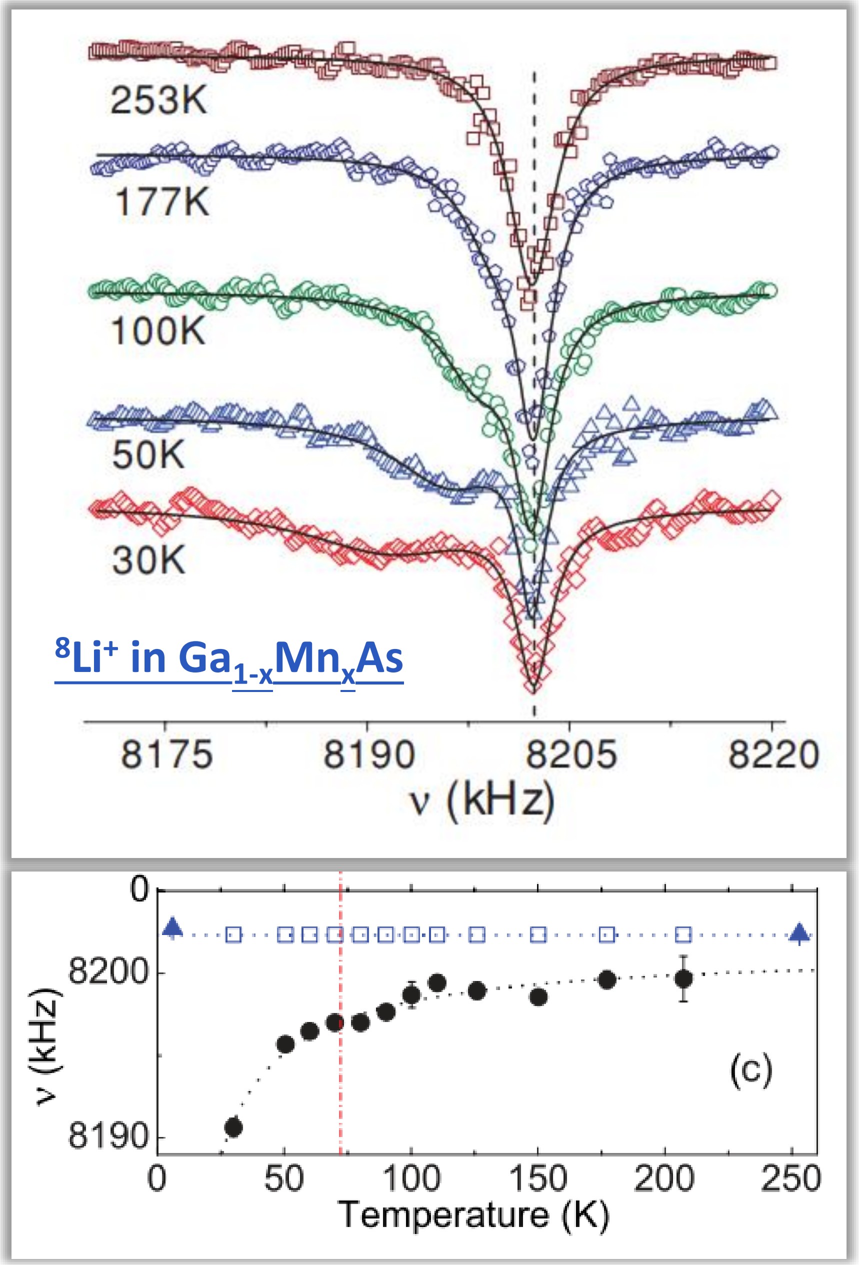
离子注入　　激光泵浦(极化)　　βNMR





主要测量方法：RF resonance





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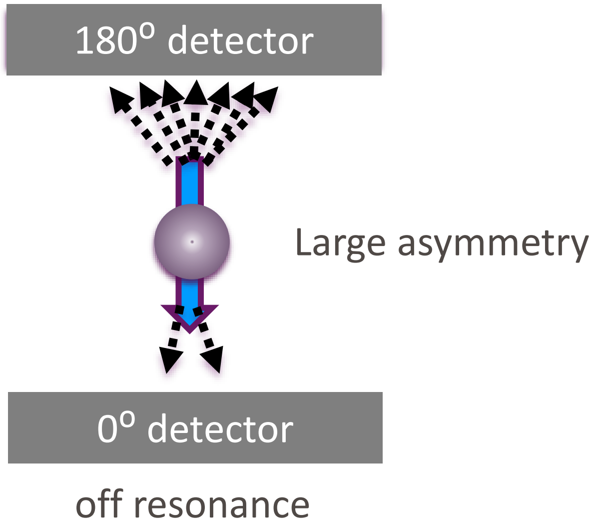
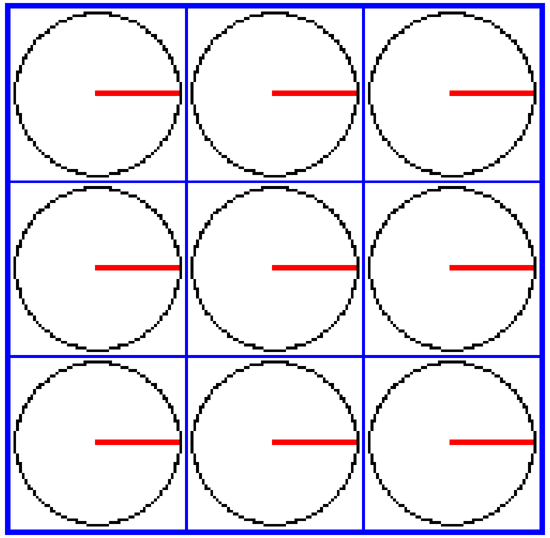
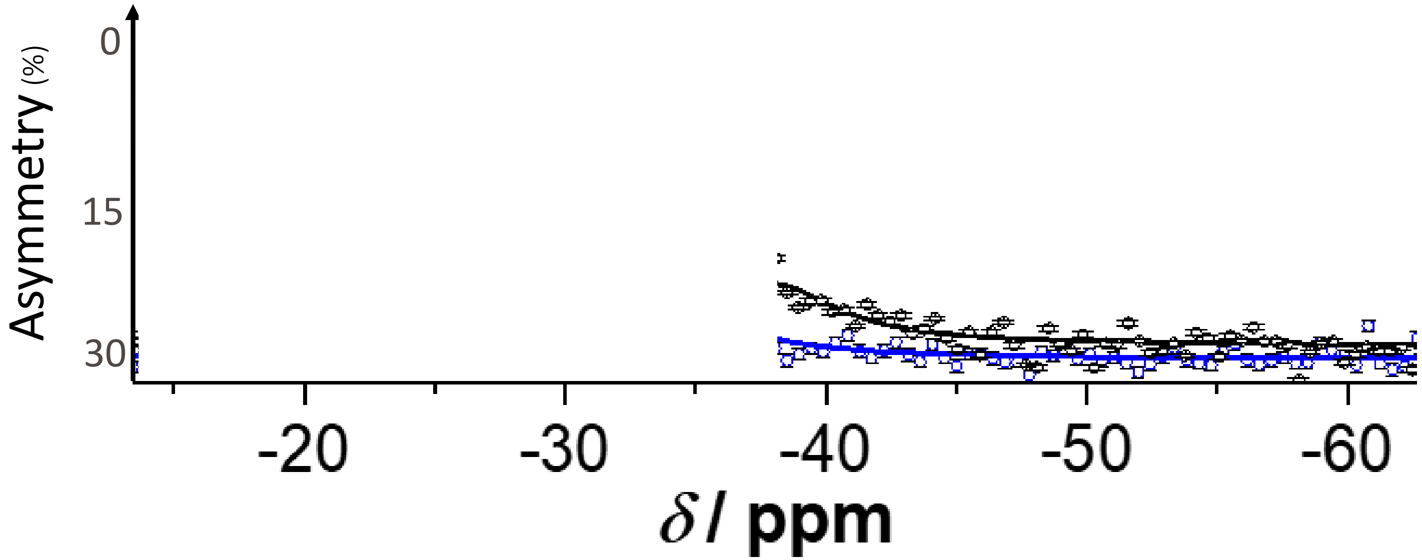
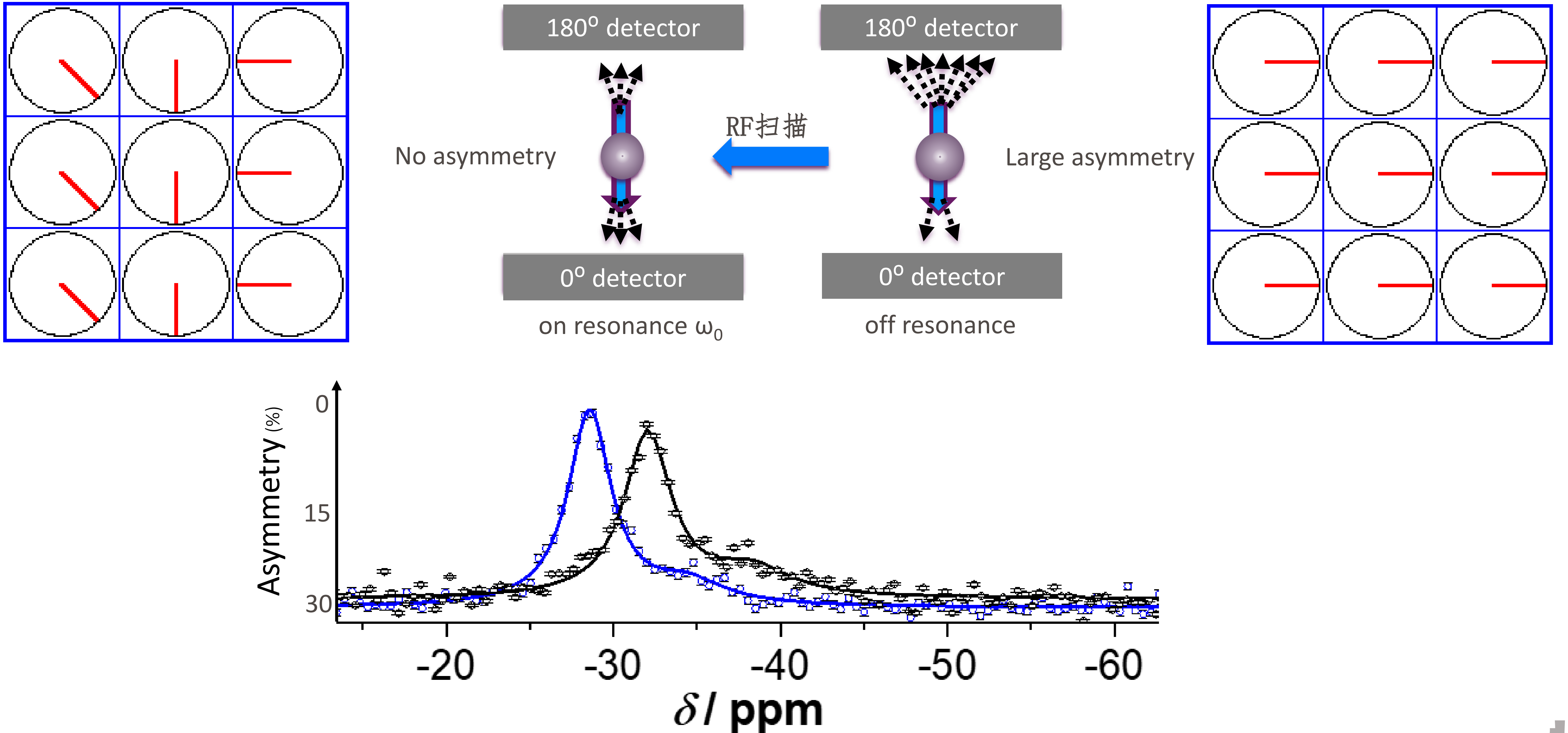


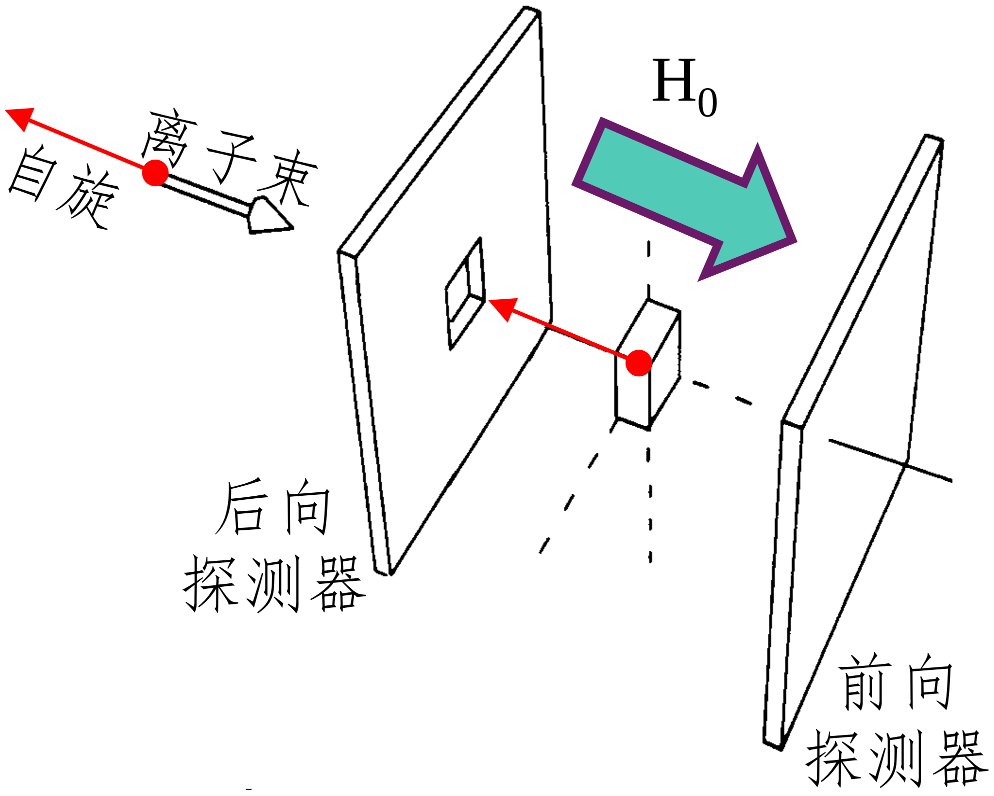


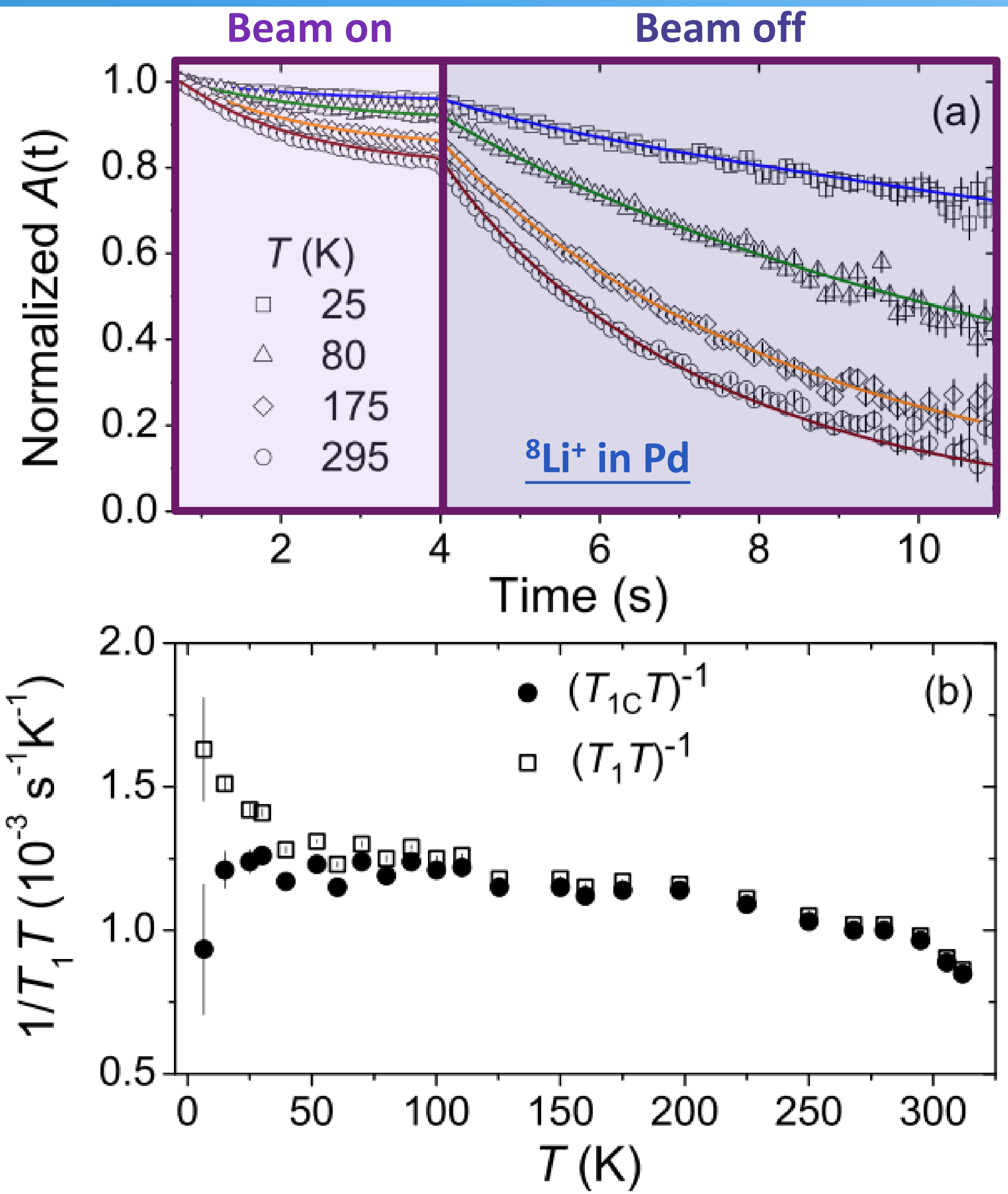


主要测量方法：RF resonance

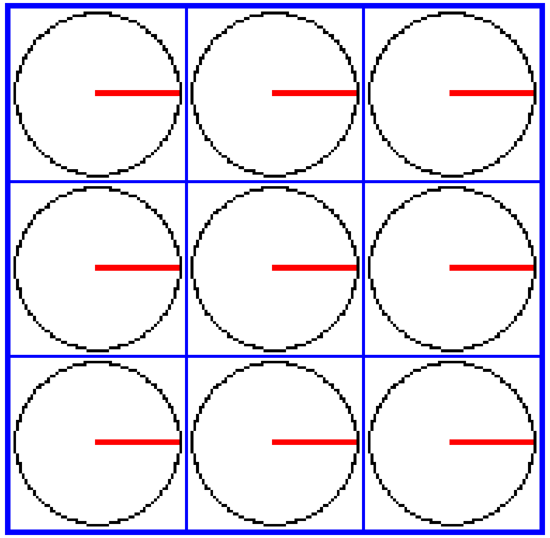


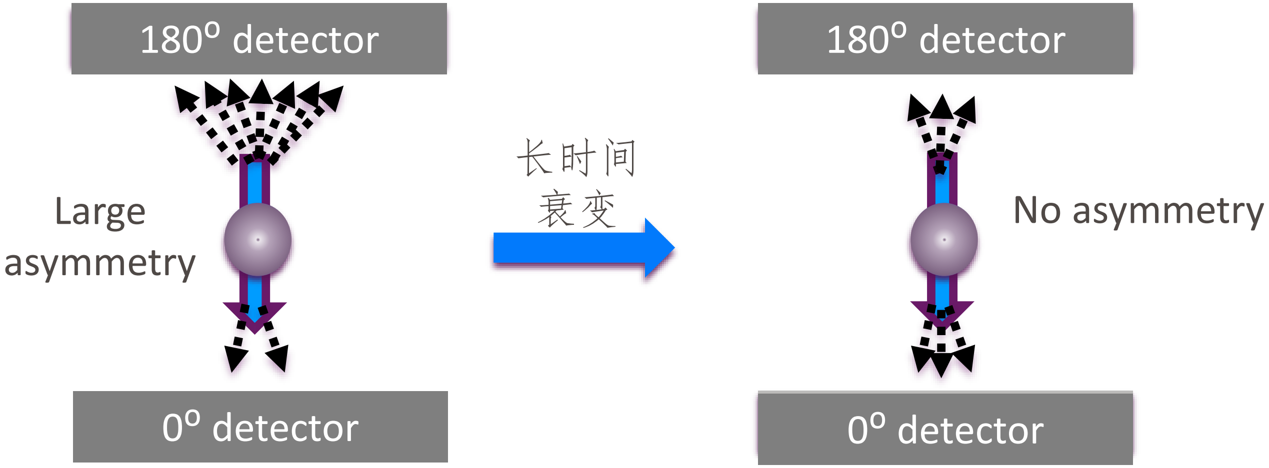
主要测量方法：spin-lattice relaxation

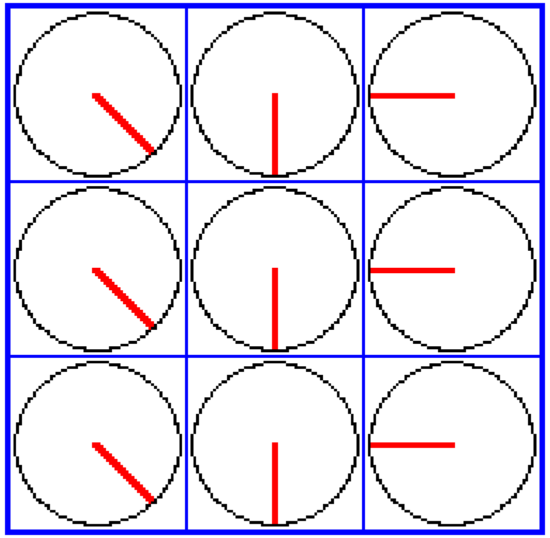


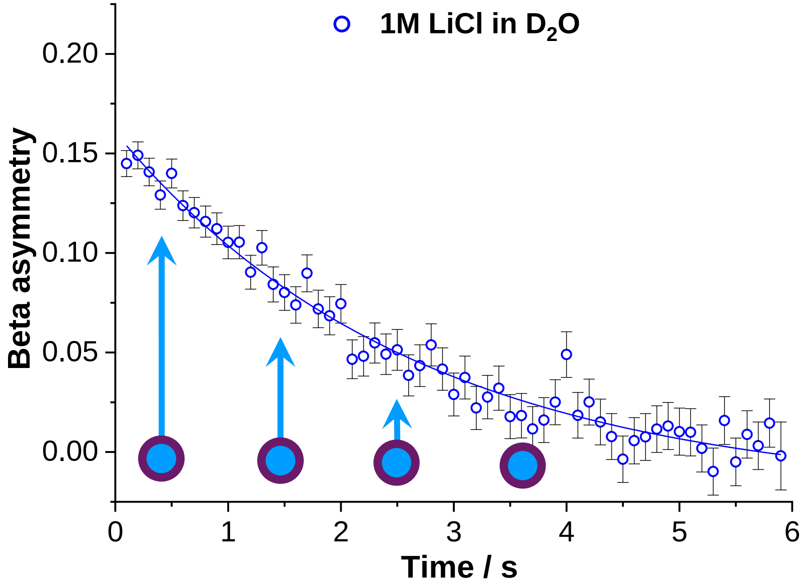


主要测量方法：spin-lattice relaxation









技术优势

◆**高信号幅度**：βNMR 通过测量极化离子的衰变β电子（10^7个原子核），常规NMR通过外磁场激励样品产生微弱precession信号并由RF线圈捕获信号（需要10^{17}个原子核，样品量大，只能获取bulk information），βNMR比之灵敏度高**10个数量级**

◆**高极化度**：使用极化激光调制离子束极化度，可以达到1%-100%（$^8Li^+$可以做到80%），传统NMR是由加在样品上的外磁场激励产生微软极化度<<1%（normally 0.001%），βNMR比之灵敏度高**5个数量级**

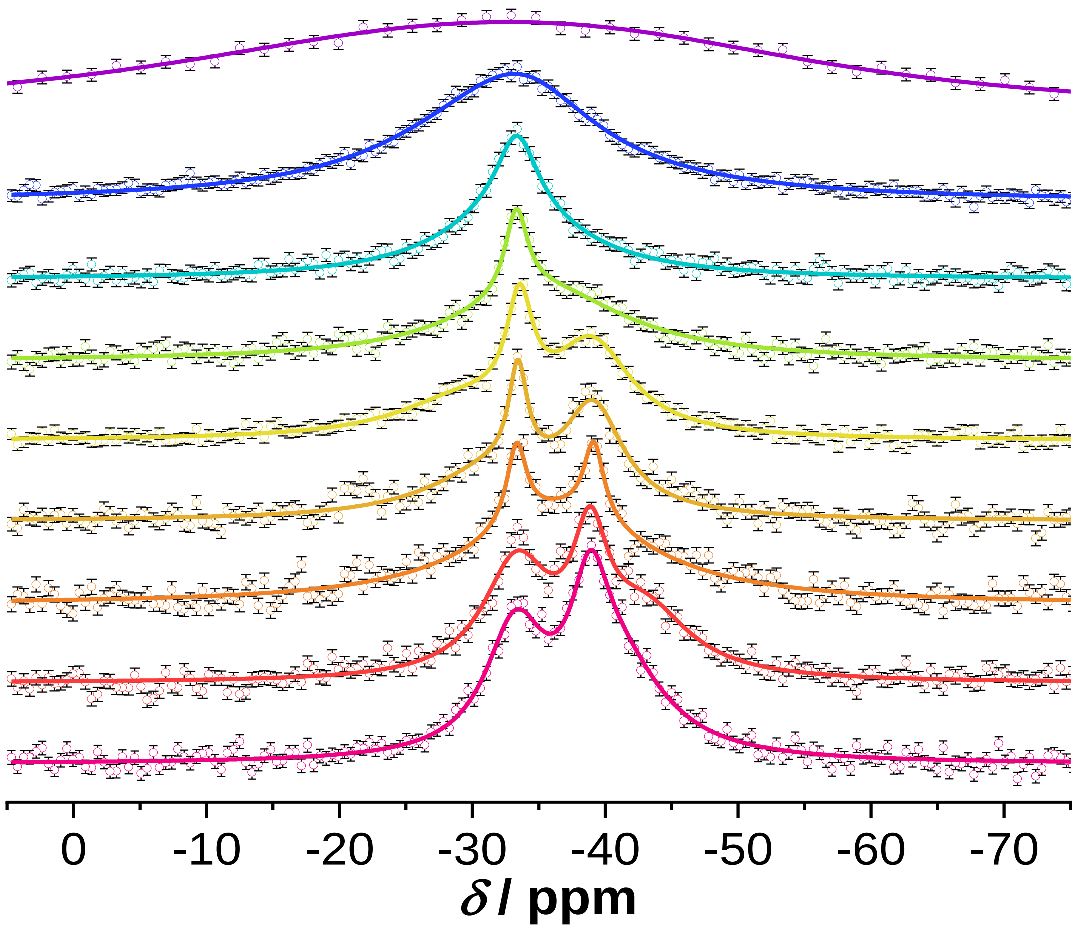
◆**高灵敏度**：结合以上两点因素，βNMR 比传统NMR灵敏度高**10个数量级**

◆**可测薄样品、可调节注入深度**：高灵敏度决定了βNMR 对样品量需求小，10^6个原子核量级；极化离子束能量低能，动量可调，可以获取样品不同深度信息（**2 – 200 nm**）

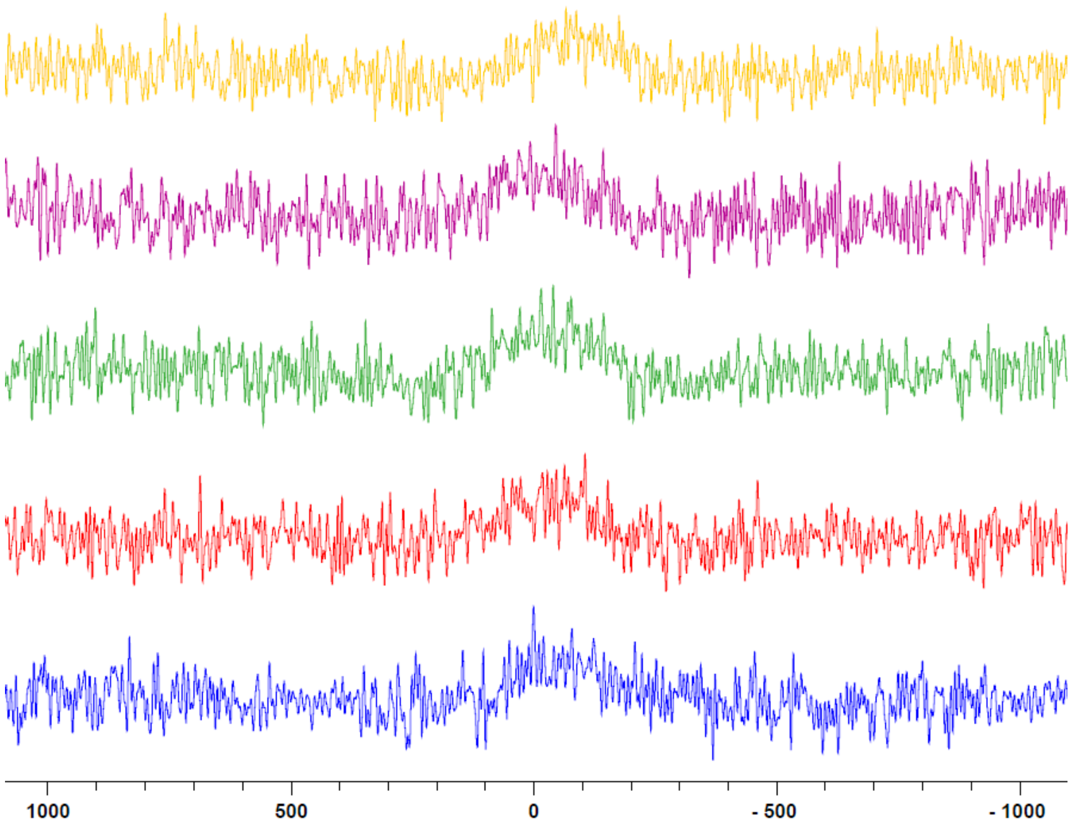
◆**放射性离子束RIB装置可提供多种短寿命核素**：元素周期表**大部分核素**均可生产

Spectra quality comparison of Mg-ATP binding in EMIM-Ac

βNMR (20 min)



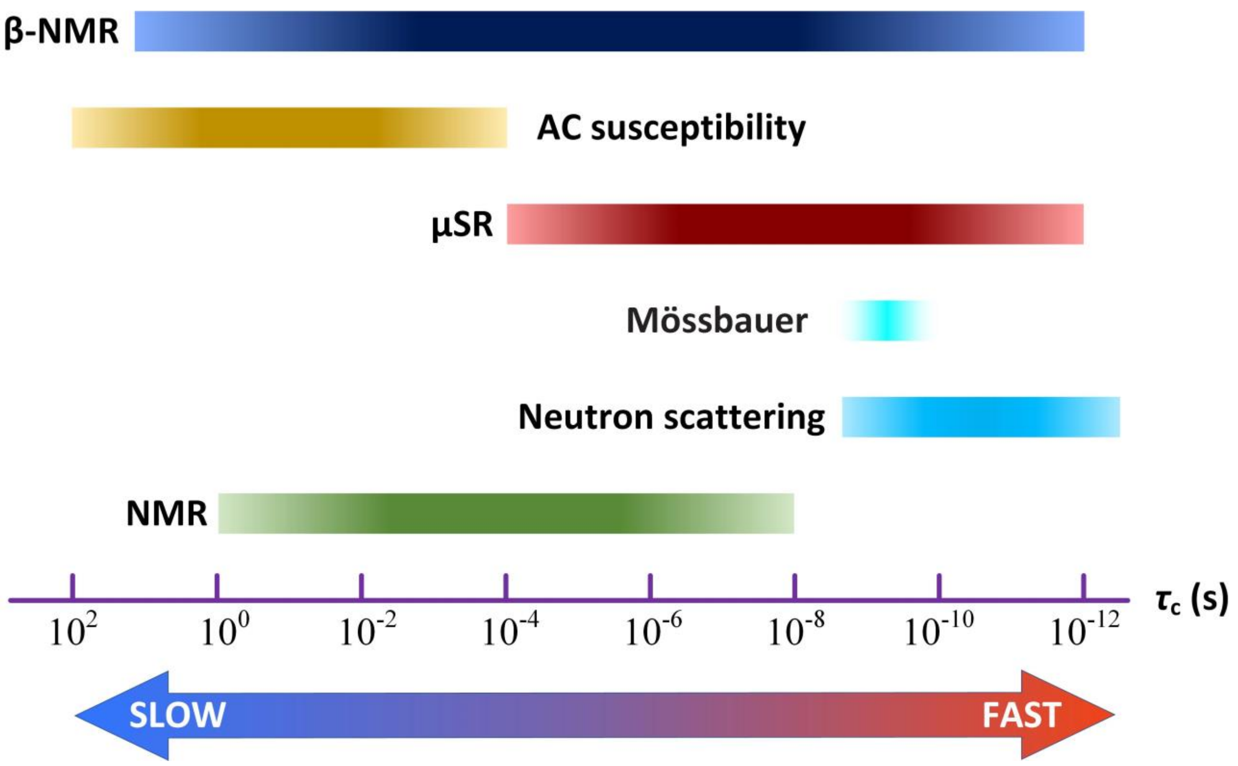
NMR (72 h)

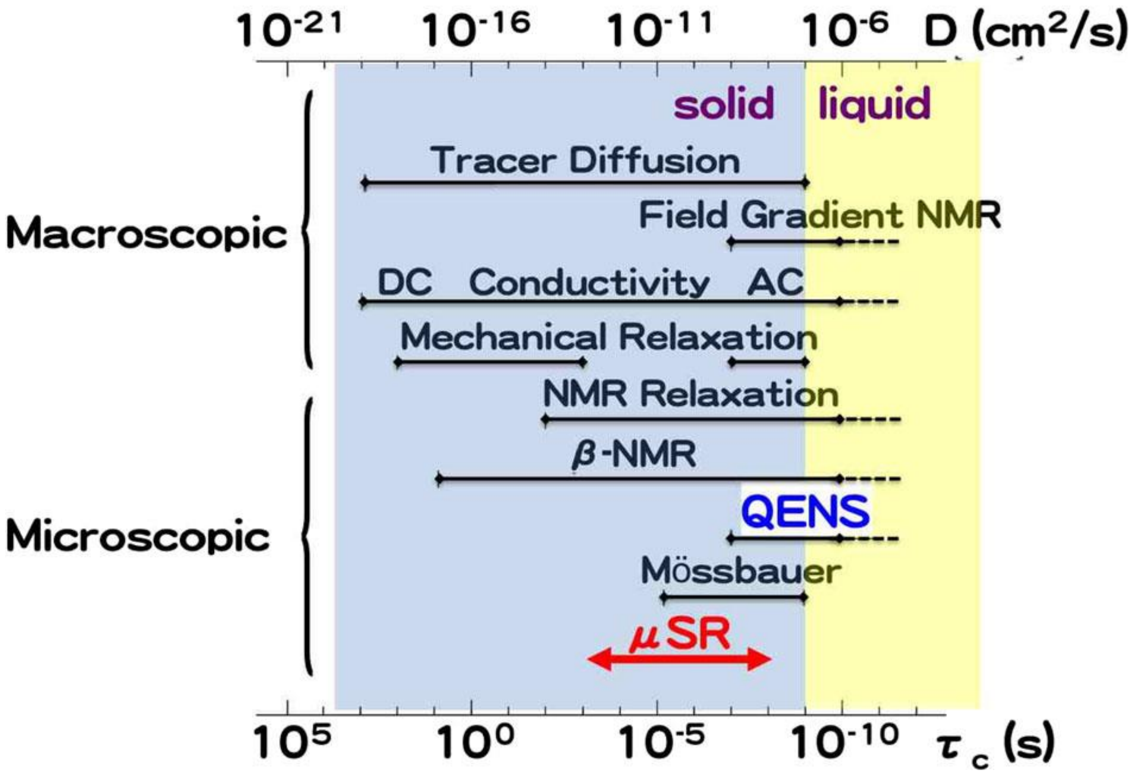


Manuscript in preparation by Monika Stachura

技术优势

测量范围广，与多种磁性表征技术互补!





Jun Sugiyama, Spin polarized beam for battery materials research: $\mu^{\pm}$SR and β-NMR, Hyperfine Interact (2019) 240: 17

应用领域

➢基础研究

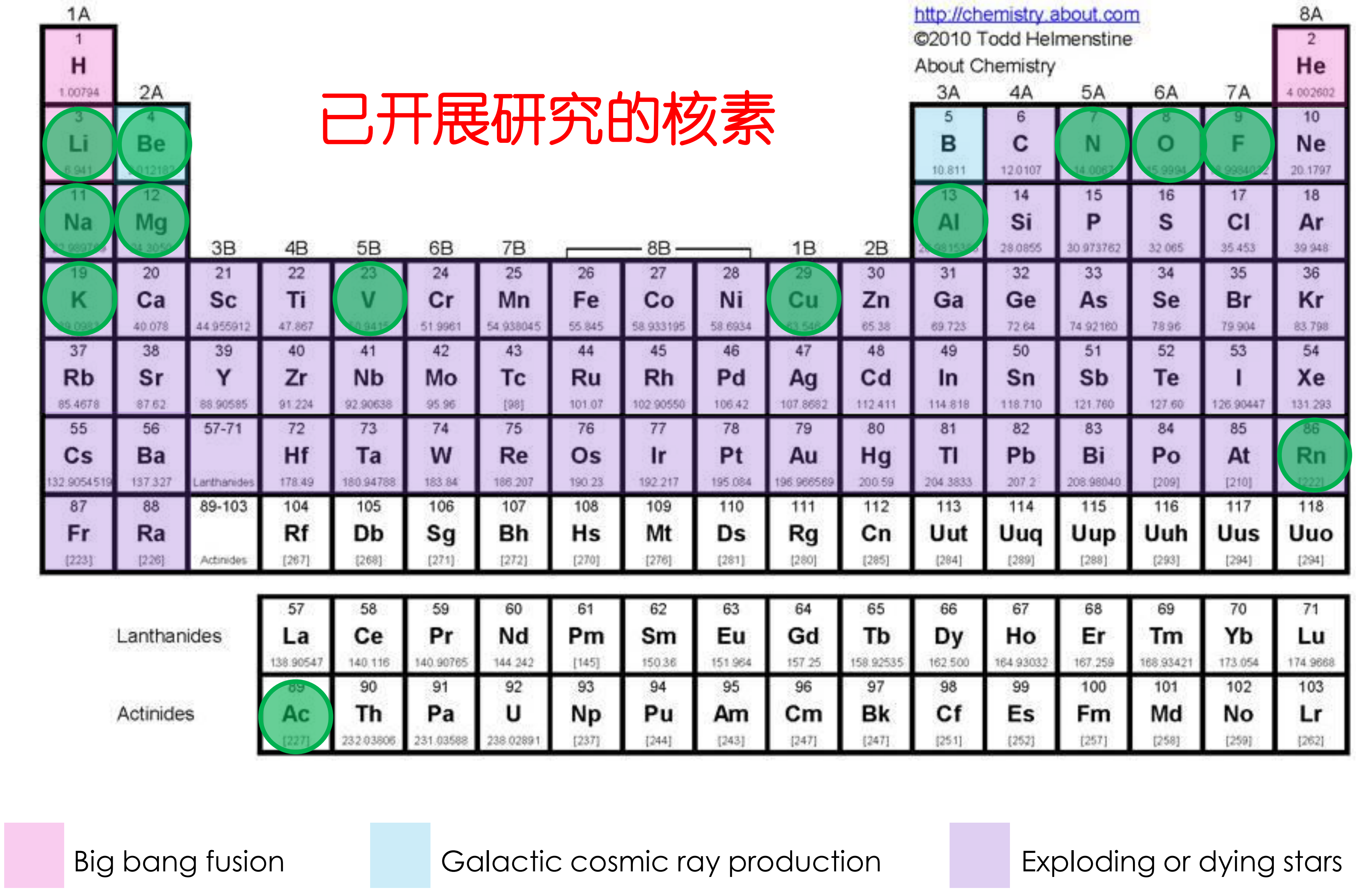
- 放射性核素核结构（磁矩、电极矩）、未知能级结构
- 原子核半径（charge radius, mass radius）
- Beta衰变、对称破缺、新物理

➢应用研究（analogue of NMR and μSR)

- 凝聚态研究（金属、绝缘体、超导、磁性物质、离子导体、半导体、半金属...）
- 化学（有机物...）
- 生命科学（组成生命物质的多种元素，如ATP-Mg、阿尔兹海默症-Cu、DNA-Na...）
- 能源科学（锂/钠/锌电池...）

应用领域

已开展研究的核素



应用领域

16th International Conference on Muon Spin Rotation, Relaxation and Resonance (2025/07/20 – 07/25)

ST. JOHN'S · NL 2025

The conference is being jointly organized by the Centre for Molecular and Materials Science at TRIUMF, Simon Fraser University, the University of British Columbia, and Memorial University of Newfoundland. It will cover all aspects of the use of muon spectroscopy and **β-NMR** in condensed matter, materials and molecular sciences,

15th International Conference on Muon Spin Rotation, Relaxation and Resonance (2023/08/28 – 09/02)

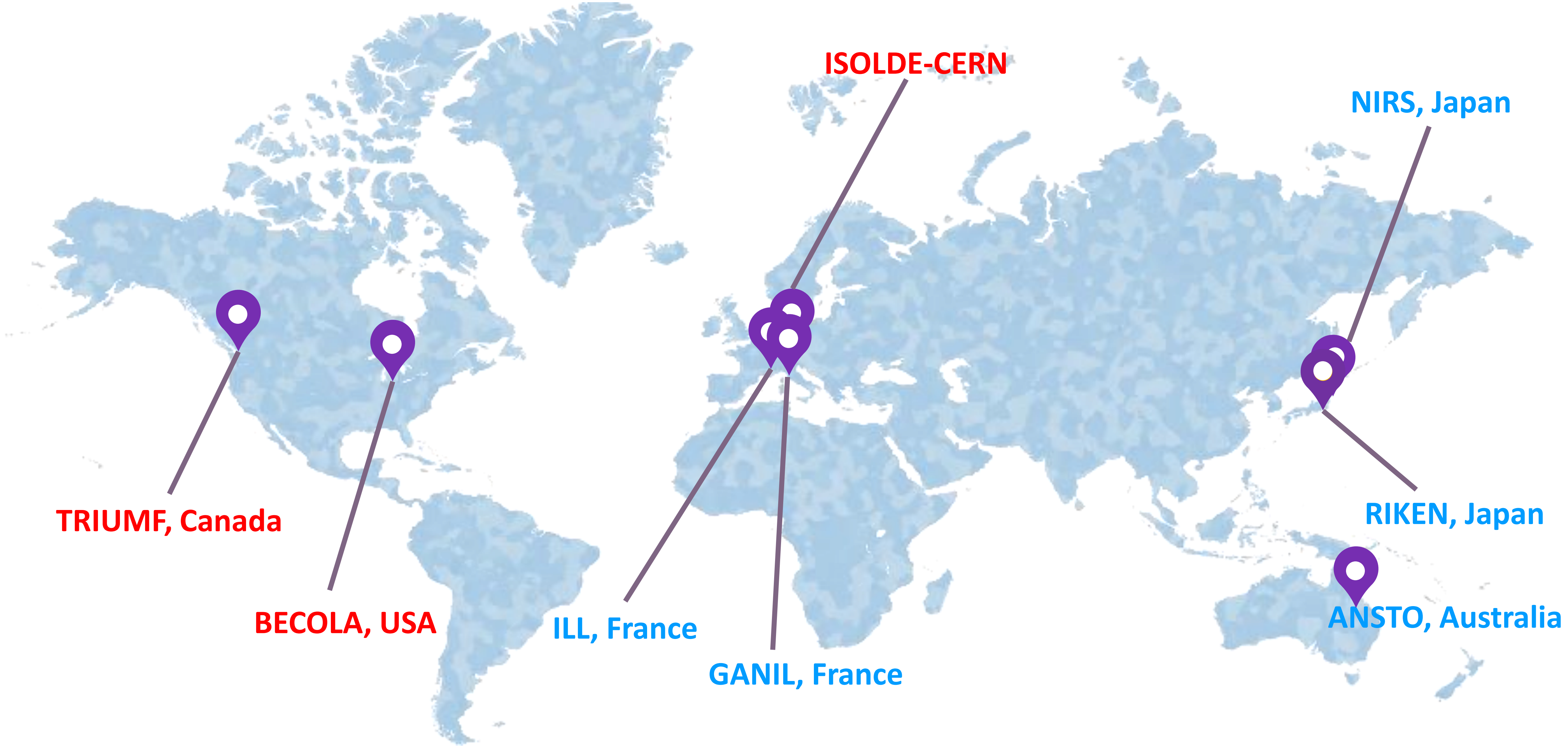
^{8}Li βNMR studies of Epitaxial Thin Films of the 3D topological Dirac semimetal Sr_3SnO

Inverse Laplace Transform Approaches to βNMR Relaxation

The Site and High Field βNMR Properties of $^{8}Li^{+}$ Implanted in α-Al_2O_3

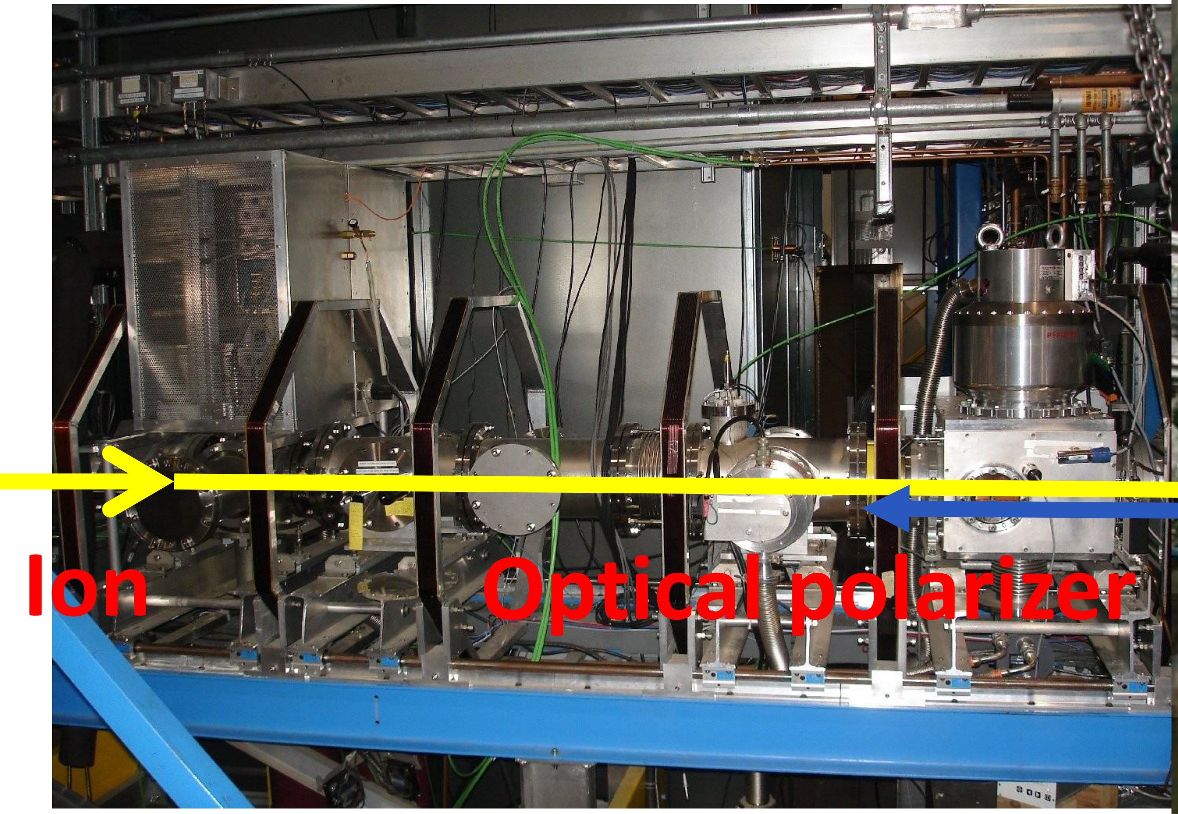
Effects of the rhombohedral distortion in $LaAlO_3$ on the quadrupolar splitting of the implanted $^{8}Li^{+}$ NMR

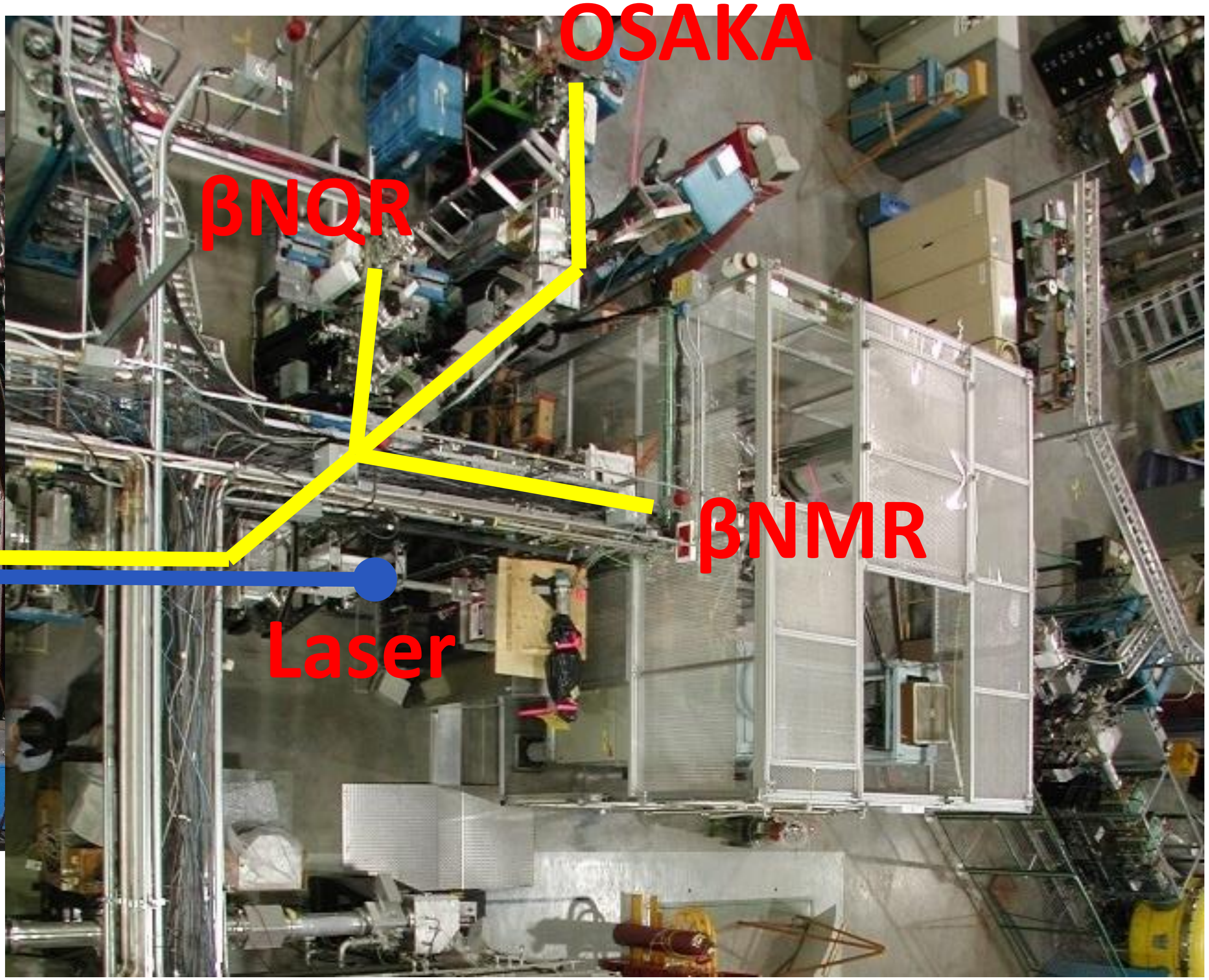
相关设施



ISOLDE-CERN
NIRS, Japan
TRIUMF, Canada
BECOLA, USA
ILL, France
GANIL, France
RIKEN, Japan
ANSTO, Australia

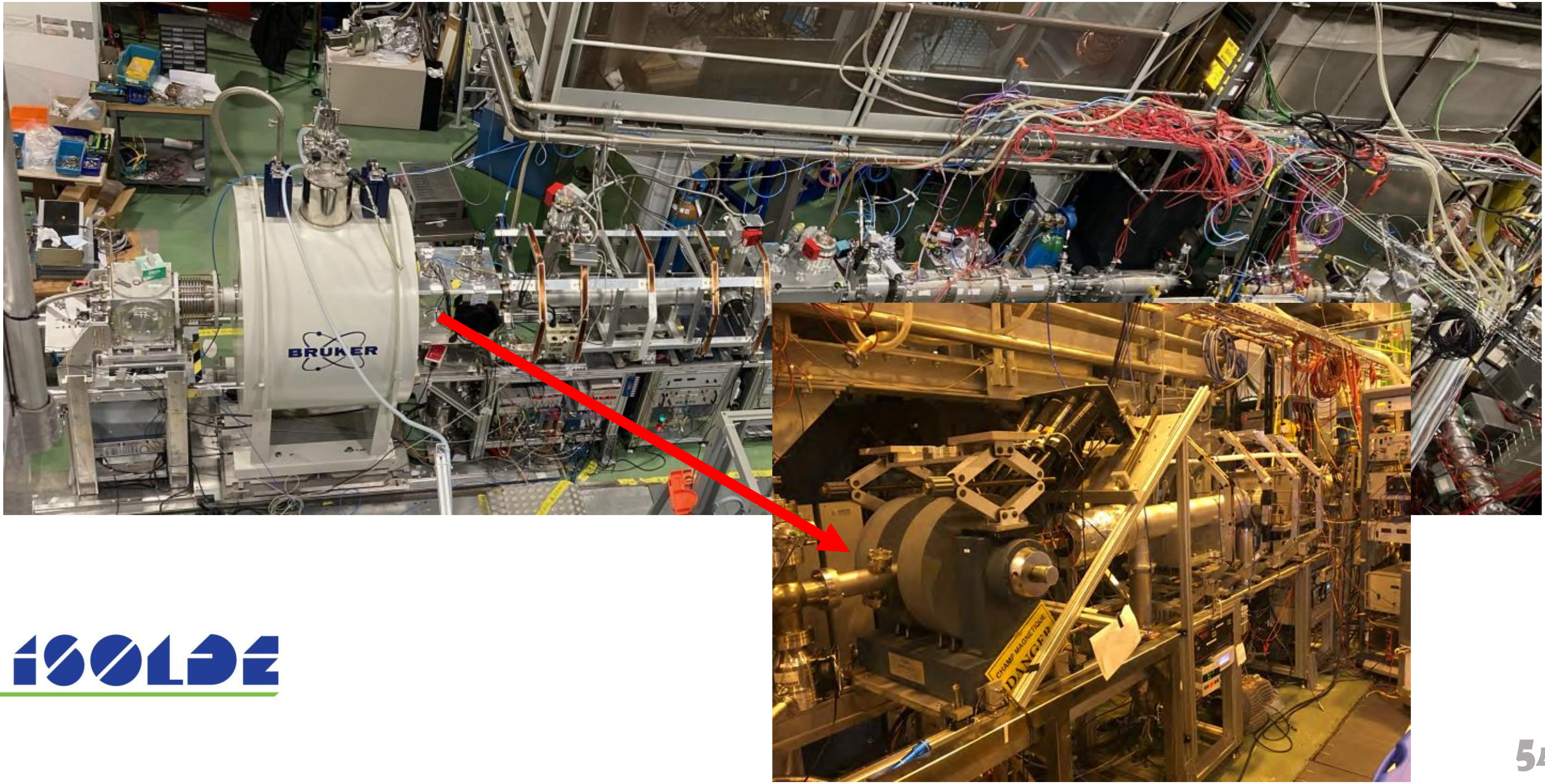
相关设施: ISAC @ TRIUMF





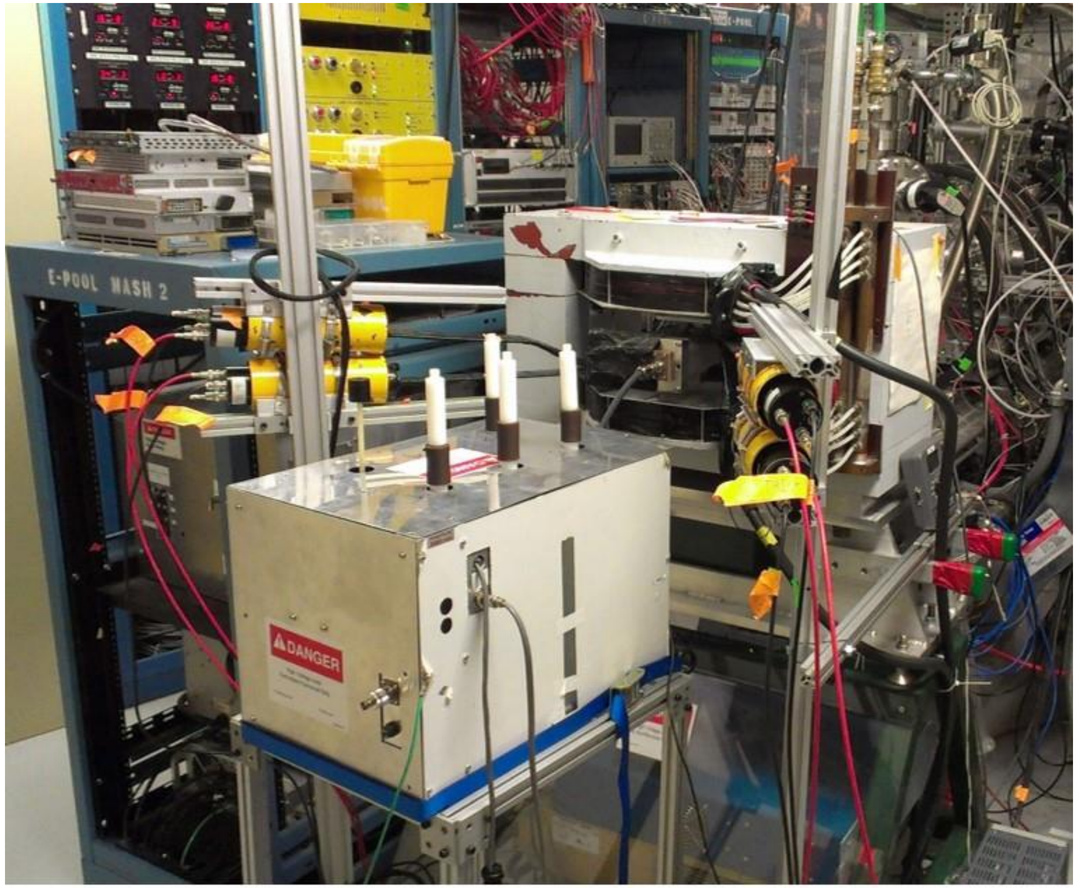
TRIUMF

相关设施: ISOLDE @ CERN



ISOLDE

相关设施: BECOLA @ Michigan State University



b-NMR equipment

BECOLA

IV. 总结

总结

缪子源/离子源

➢ **缪子**:

- 运行中: TRIUMF, PSI, MuSIC-RCNP, ISIS, J-PARC (mainly for applied sciences)
- FermiLab, CERN (only for particle physics)
- 在建: MELODY-CSNS, RAON
- 规划: SHINE@Shanghai Tech, CiADS/HIAF@IMP, SEEMS@SNS

➢ **离子**:

- TRIUMF, BECOLA, ISOLDE@CERN ...

主要应用

➢ **缪子**:

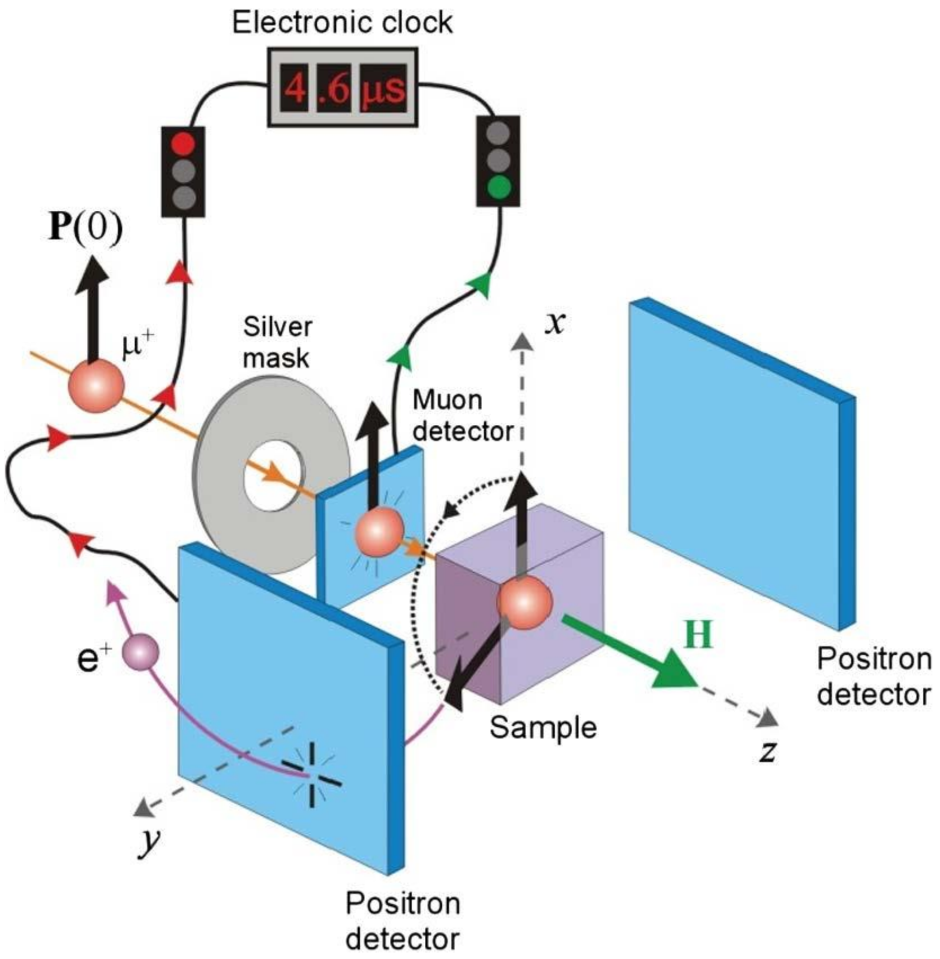
- Muon spin spectroscopy
- Muonic X-ray Elemental analysis

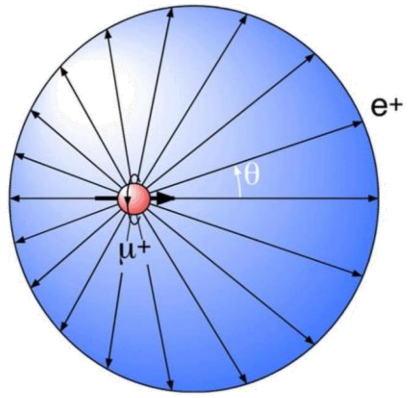
➢ **离子**:

- Beta-detected NMR

总结

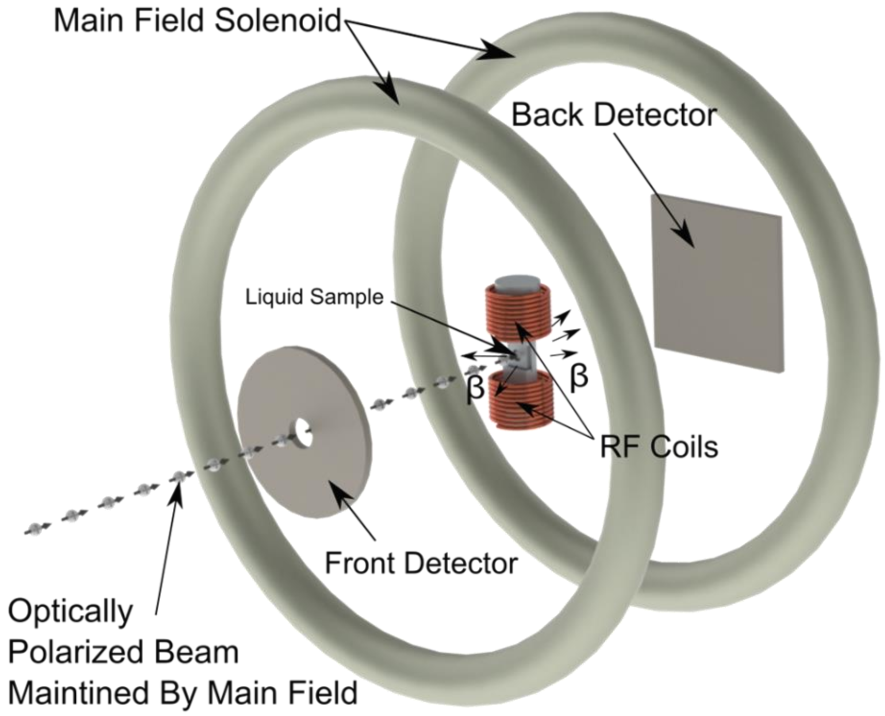
■ μSR





✓ 自旋进动
✓ 宇称不守恒

■ β-NMR



感谢各位专家，敬请批评指正！

- *感谢μSR、MIXE、缪子成像领域所有老师、同事及合作者对本人工作的支持！*
- *感谢国自然基金委、自然资源部、广东省粤惠联合基金、小米公益基金会对各项研究工作的经费支持！*