NED2026

缪子谱学交叉应用及前沿探测装置研发

潘子文[1]，梁昊[1]，叶邦角[1]
李强[2]，鲍煜[2]

[1] 中国科学技术大学物理学院

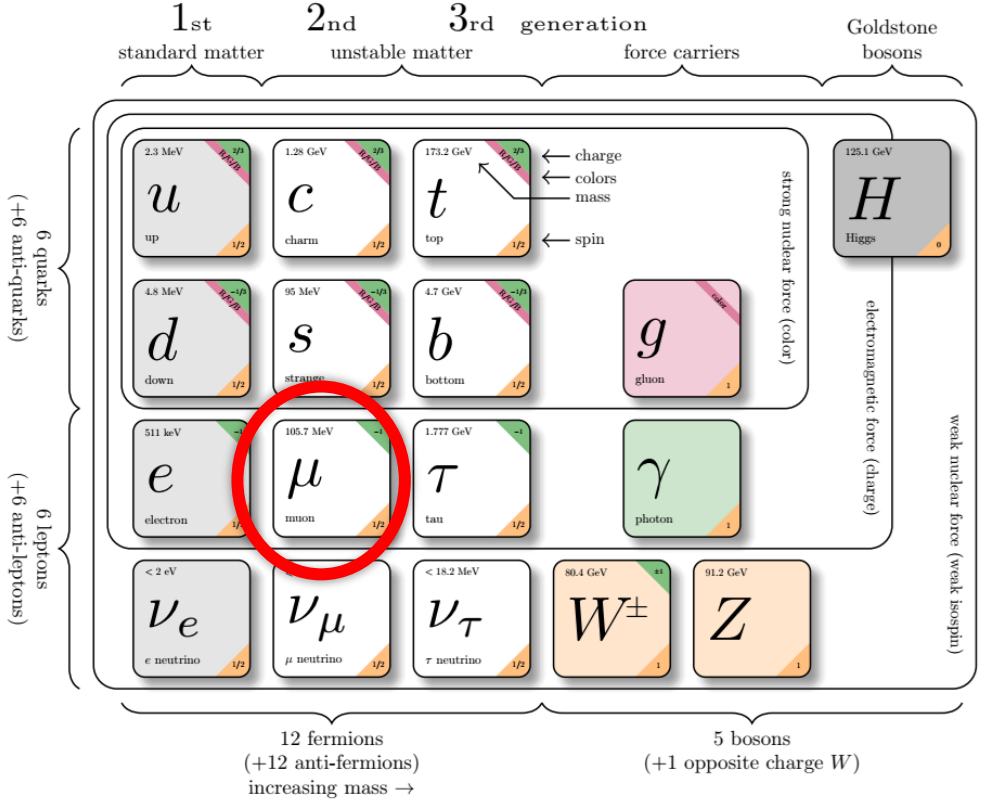
[2] 散裂中子源科学中心

2026/08/11, 河南登封

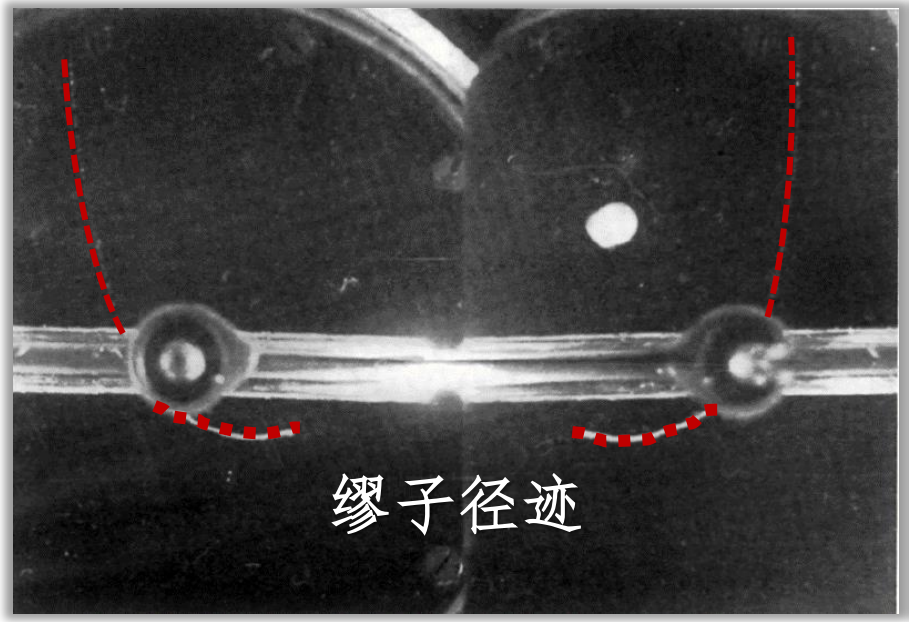
目录

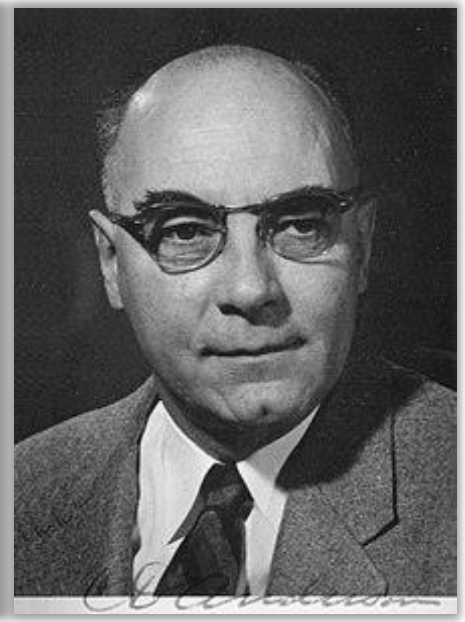
I. 缪子属性、来源及应用

物质分析探针



诺奖得主CD Anderson于1936年从宇宙线观测实验中发现缪子！

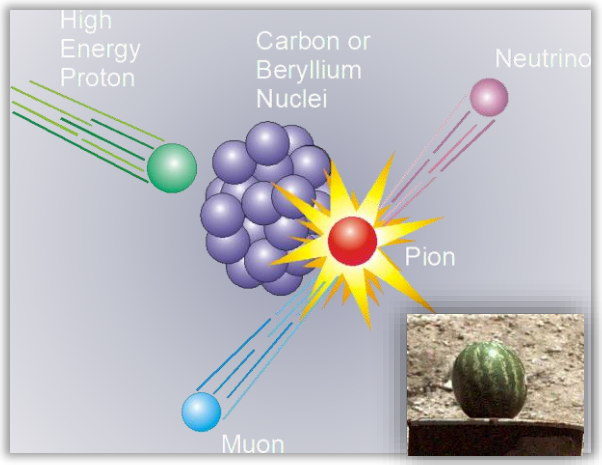




- 基本粒子, $m_e < m_\mu < m_p$
- 不稳定， 平均寿命~ 2.2 μs
- 自旋 ½, 点粒子, 100%极化, 量子磁探针

缪子来源

高能粒子碰撞

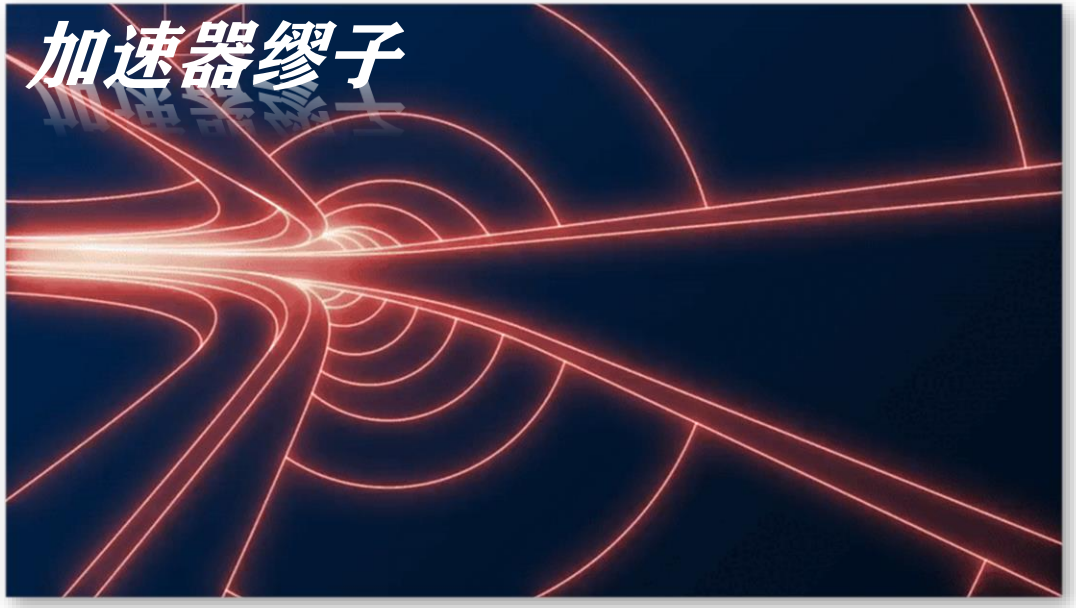


■ 质子碰撞

$$p + p/n \rightarrow \pi^{\pm} \rightarrow \mu^{\pm}$$

■ 电子碰撞

$$e^- + Z \rightarrow Z + \gamma \rightarrow \pi^{\pm} \rightarrow \mu^{\pm}$$
$$\rightarrow \mu^+ + \mu^-$$



国内缪子源建设与规划

■ ***缪子源应用研讨会Indico链接***

✓ *CSNS-MELODY*

✓ *SHINE*

✓ *HIAF*

✓ *CiADS*

μSR谱学磁性表征技术

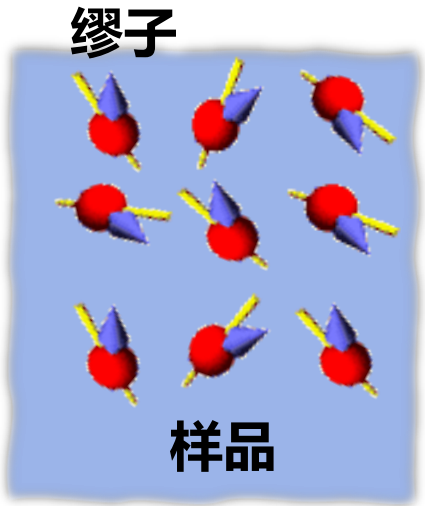
μSR: muon spin rotation/relaxation/resonance

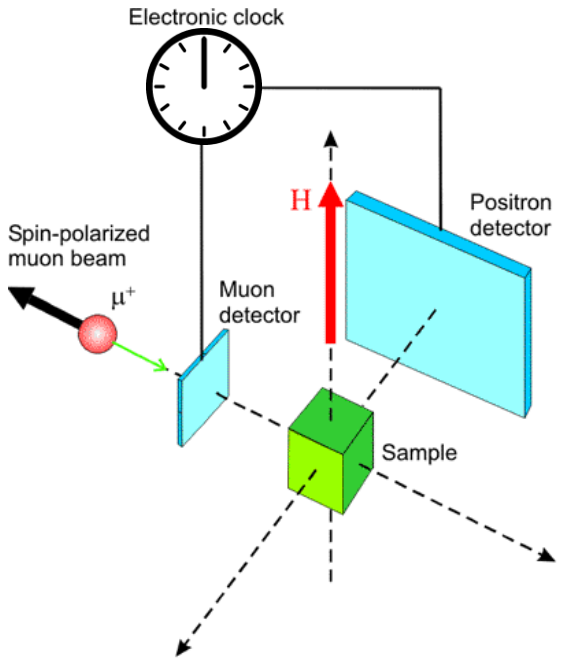
Larmor进动
(相互作用)

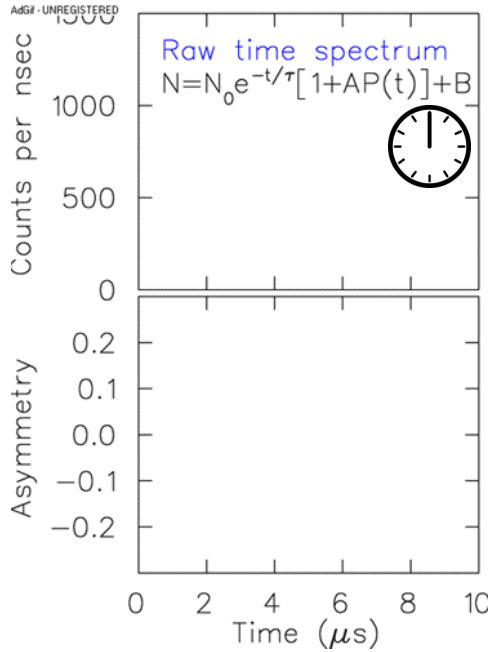
非对称衰变
(正电子探测)

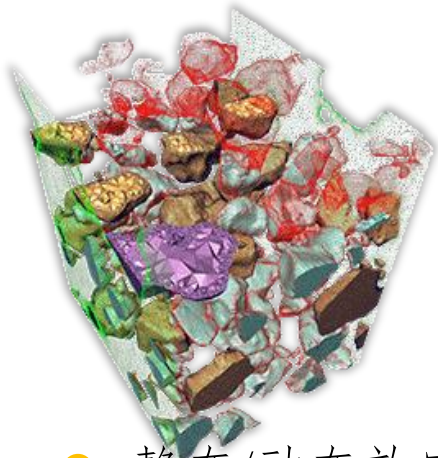
μSR实验谱
(分析)

物质表征
(性能)









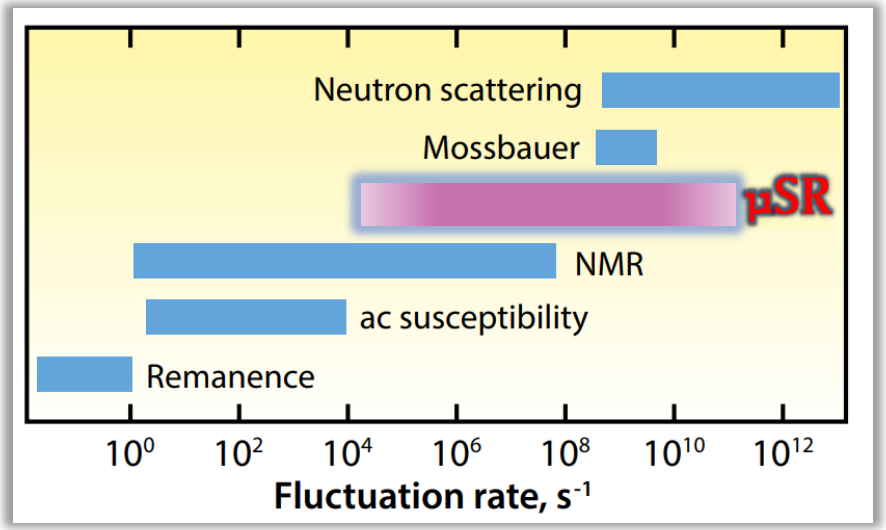
- 静态/动态效应
- 磁涨落
- 超导 / 磁 相
- 磁体积
- 电荷扩散
- 自由基
- …

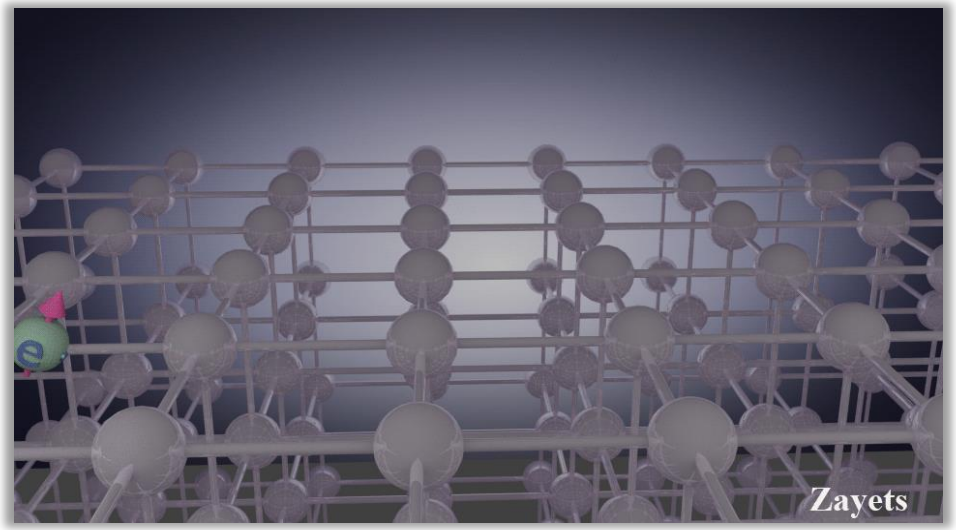
$$\frac{\mathrm{d}\boldsymbol{S}_\mu(t)}{\mathrm{d}t} = \gamma_\mu \boldsymbol{S}_\mu(t) \times \boldsymbol{B}_{\mathrm{loc}}(\mathrm{t})$$

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

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

技术优势





- **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)

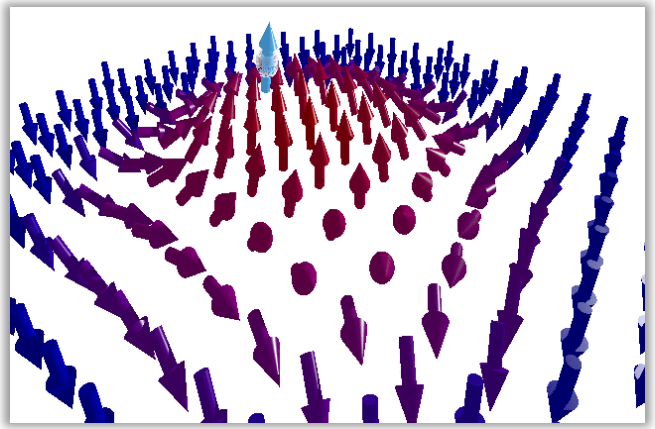
应用领域

● 被动探针

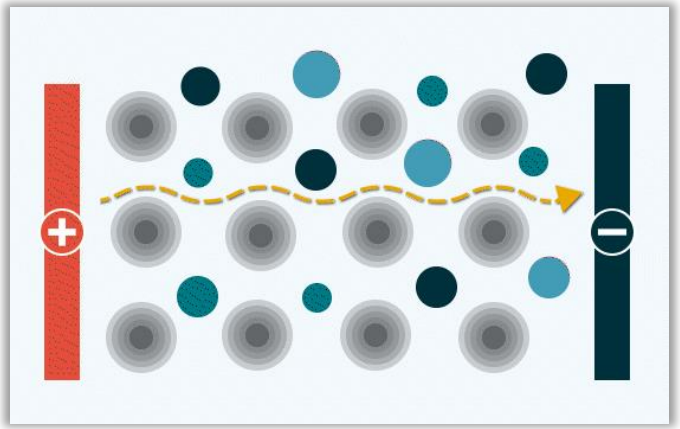
(heavy lepton)

超导

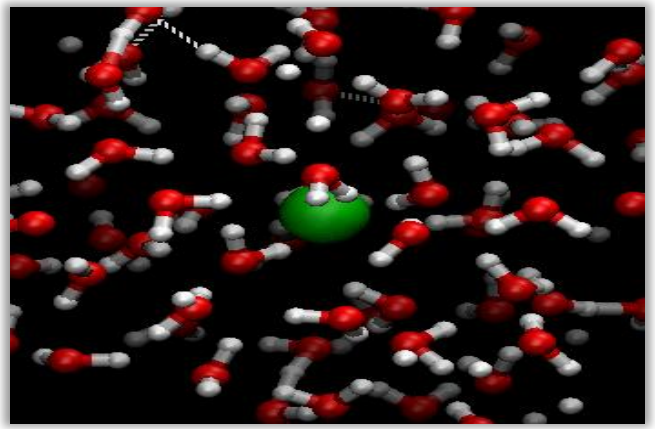
磁性



电荷输运/电池



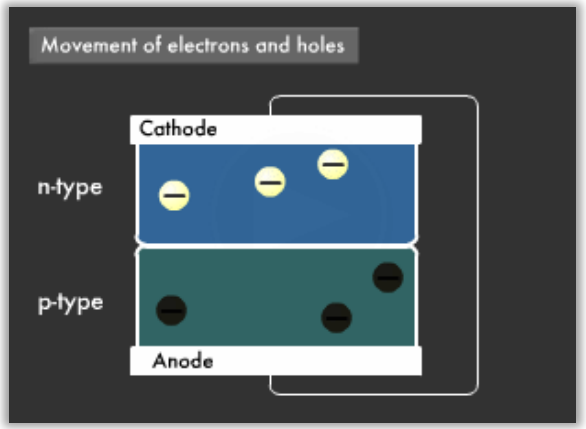
分子动力学



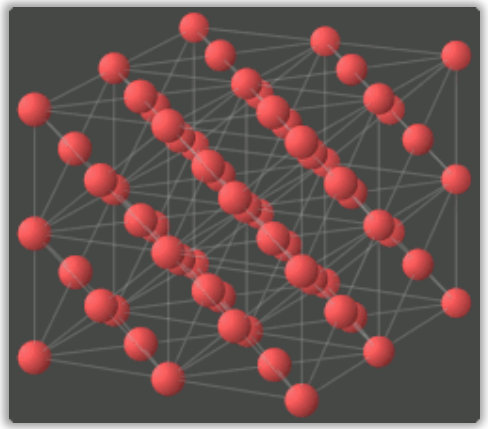
● 主动探针

(light proton)

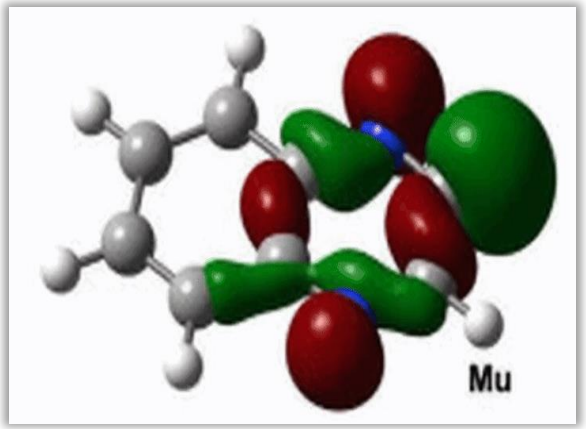
半导体



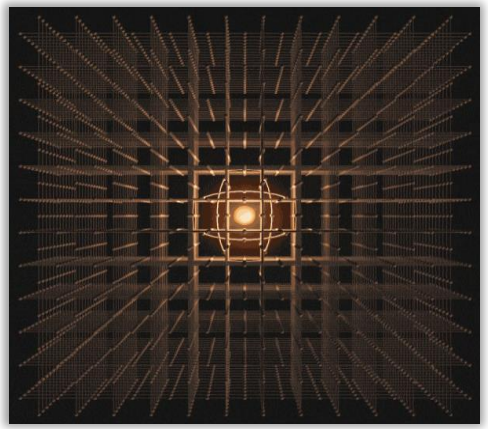
质子导体



自由基



极化子运动

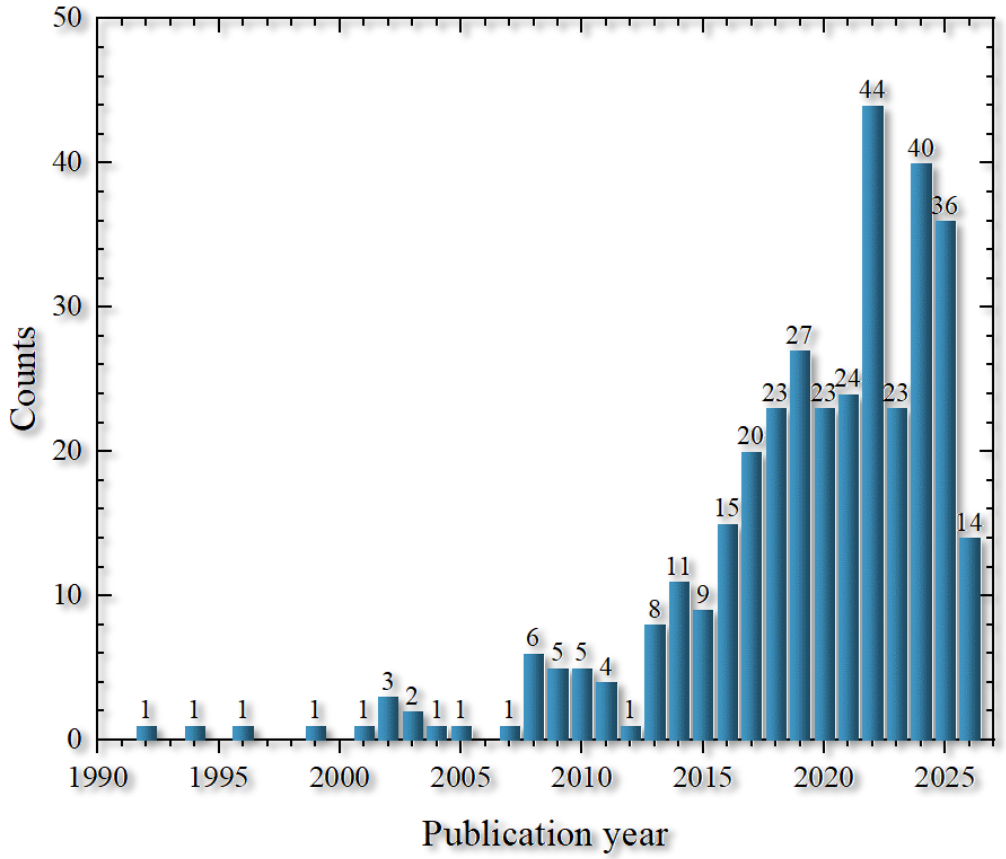


Nat. Rev. Meth. Primer : Muon Spin Spectroscopy

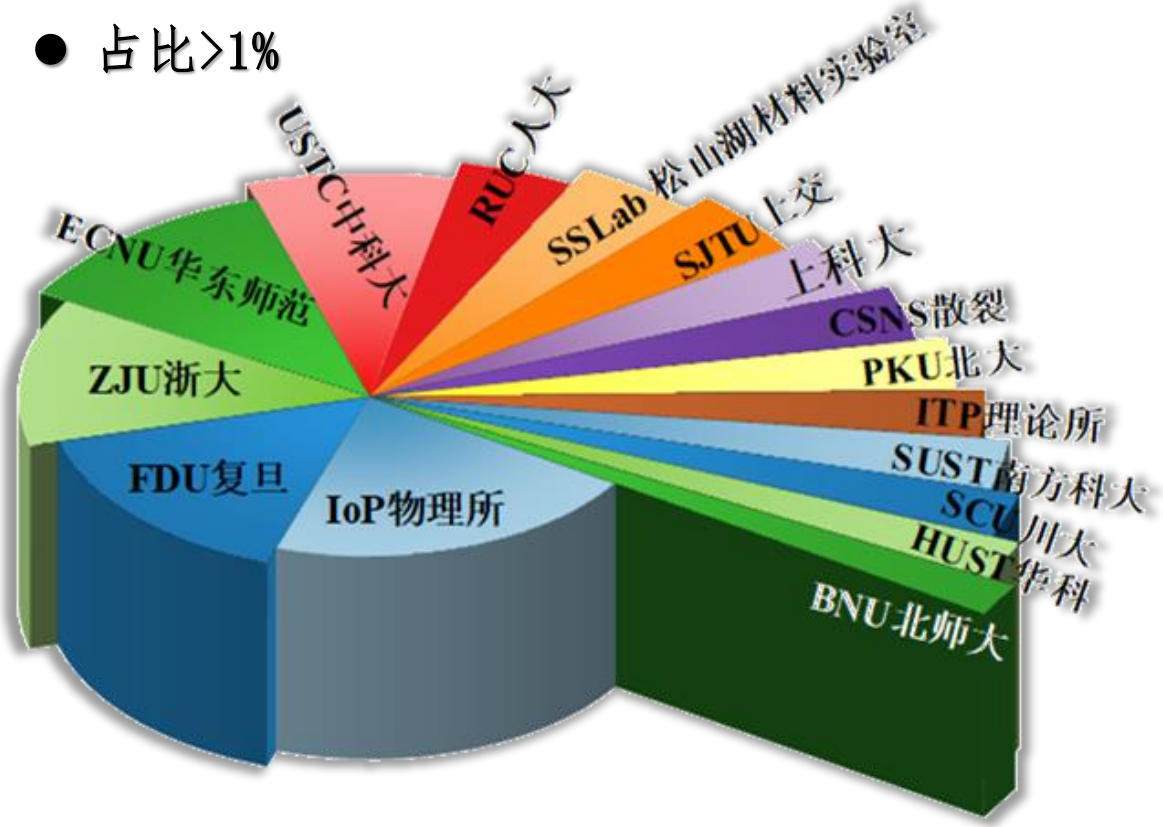
Courtesy Dr. Adrian Hiller @ ISIS Muons

μSR国内用户统计

~ 350 papers



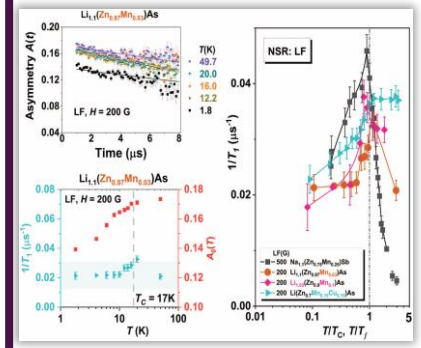
> 50 单位



Web of Science analysis (muon spin spectroscopy / muon spin relaxation / muon spin rotation) 2026/7

即将突破国内研究者仅能申请国外缪子束流开展前沿研究的现状！

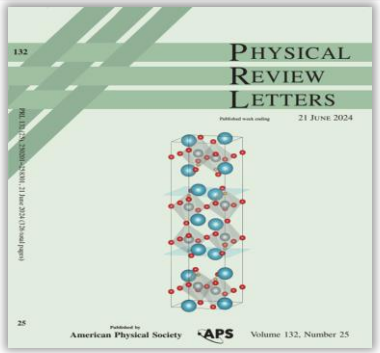
中国学者不同领域研究亮点



赵国强博士团队 @ 中科院物理所

- *Magnetic ground state, evolution, … new generation diluted ferromagnetic semiconductors Li(Zn,Mn)As: a μSR perspective.* **Materials Futures** *5, 045201 (2026)*

➢ ***稀磁半导体***



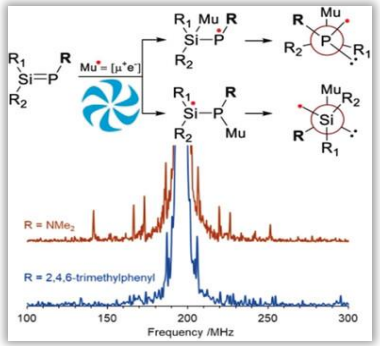
殳蕾教授团队 @ 复旦大学

Editor's suggestion and cover

- *Evidence of Spin Density Waves in $La_3Ni_2O_{7-\delta}$.* **Physical Review Letters** *132, 256503 (2024)*

PRL 2024 COLLECTION

➢ ***镍基超导体***



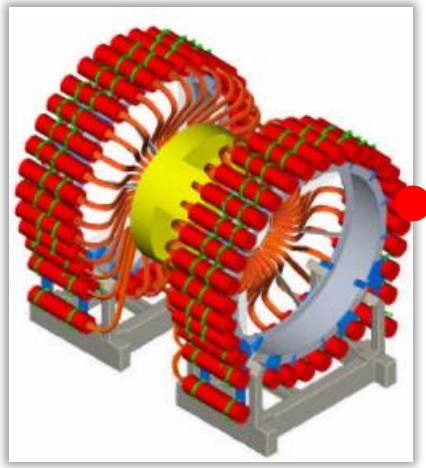
蔡元婧教授团队 @ 北京化工大学

- *Free Radical Chemistry of Phosphasilenes.* **Angewandte International Edition Chemie** *59, 16007 (2020)*

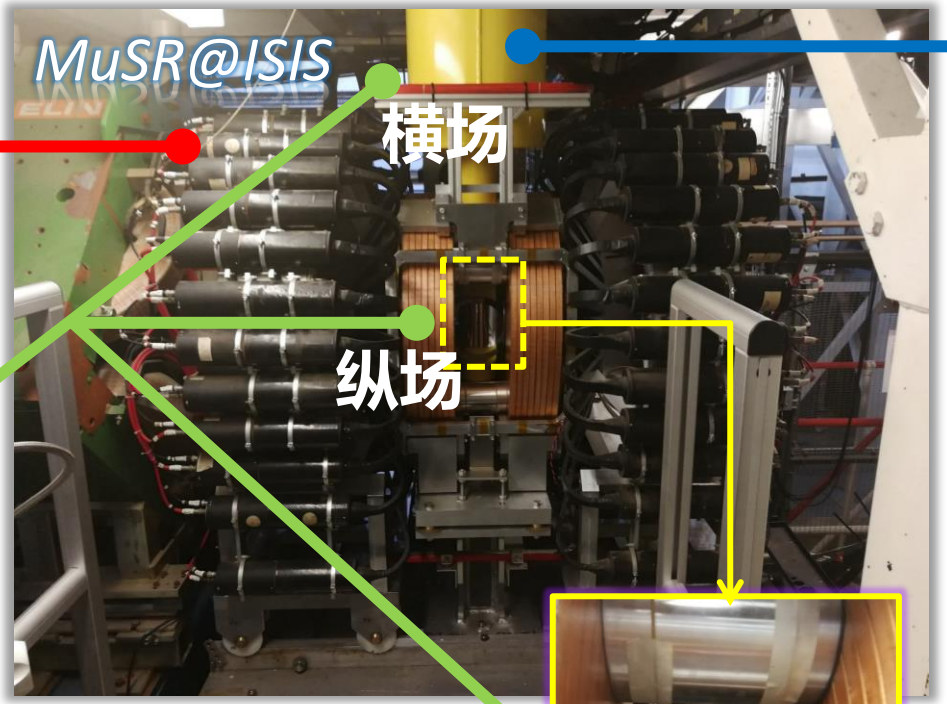
➢ ***自由基化学***

谱仪构成

探测器



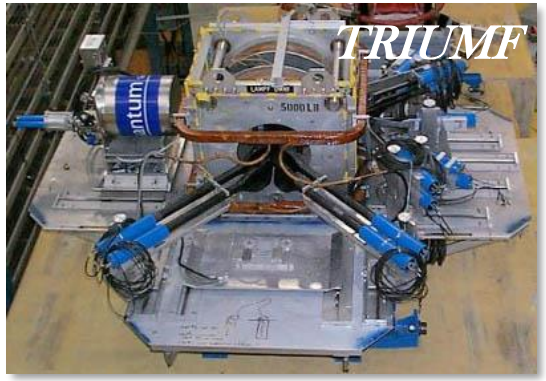
磁铁

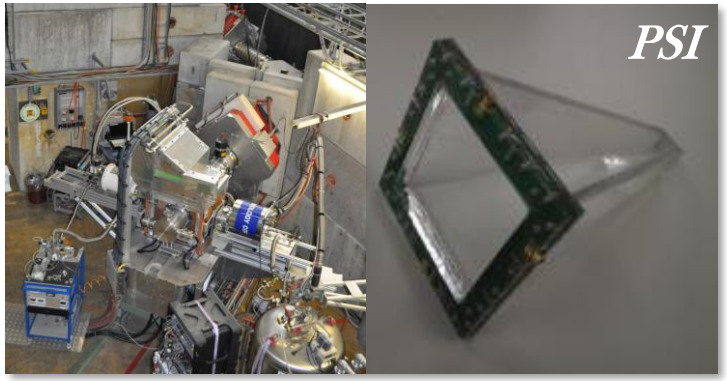


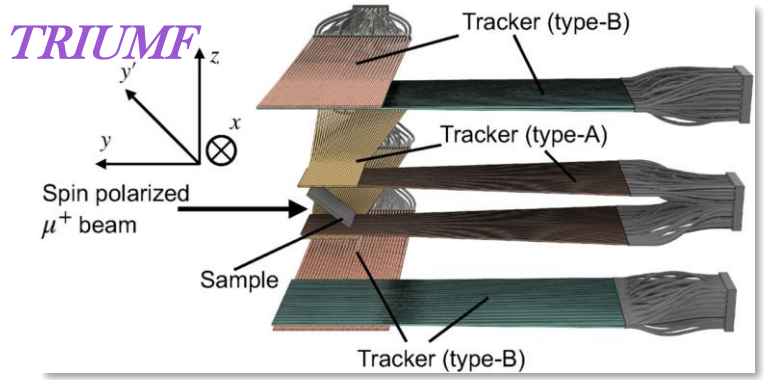
样品低温环境

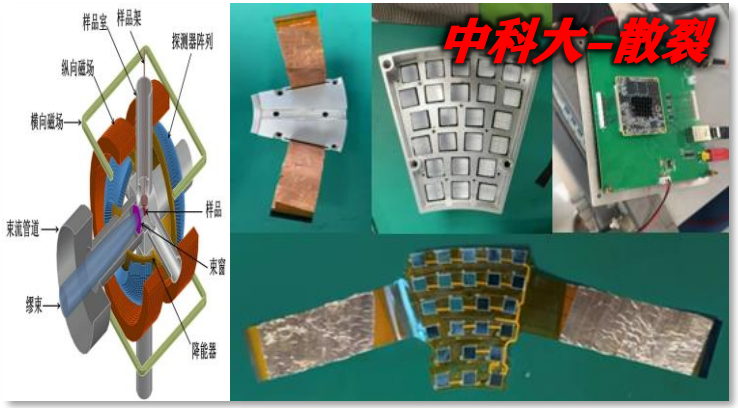
谱仪探测技术发展趋势

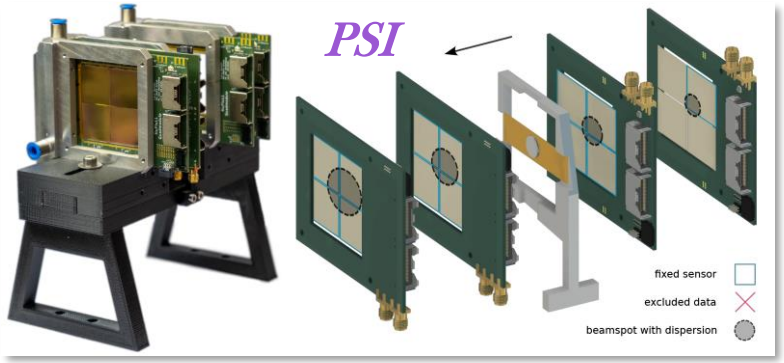
第一代	第二代	第三代
PMT / 计数	SiPM / 计数	像素 / 径迹







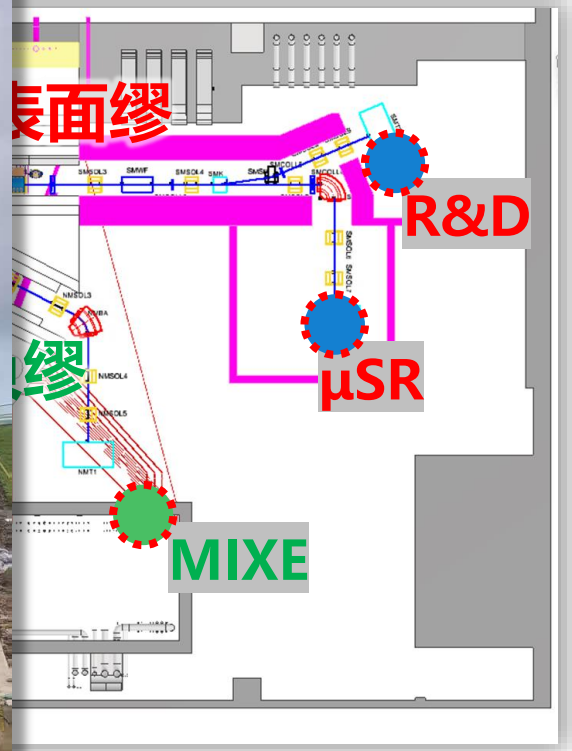




II. 两代μSR谱仪装置研发

MELODY脉冲束缪子源

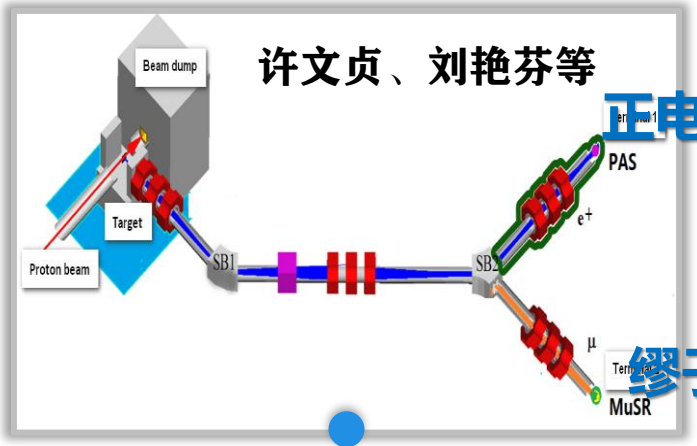
Muon stati … l inDustrY



- CSNS II: 靶站、
- 建设周期： 2024 – 2029（地面建筑已封顶）
- $10^5 – 10^7$ μ^+/s , 极化度> 95%, 脉宽130 ns

参考自鲍煜的报告

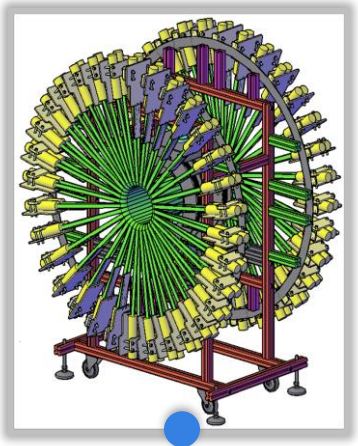
缪子谱仪研制时间线



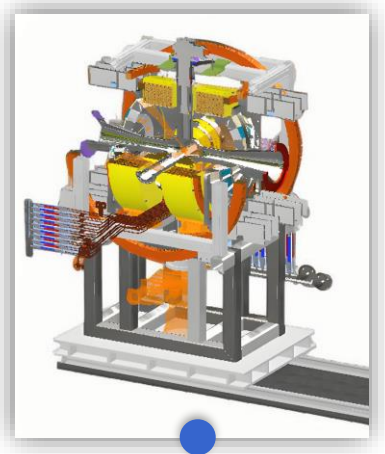
许文贞、刘艳芬等

正电子谱学

缪子谱学



潘子文（探测器）
梁昊（电子学）



束流预研

(2007 – 2014)

束流设计

PMT谱仪

(2015 – 2020)

第一代/128通道
从0到1突破

SiPM谱仪

(2024 – 2029)

第二代/3024通道
散裂II期建设

谱仪建设贡献者

USTC: 潘子文、杨天艺、袁琦、李雪健、梁昊、叶邦角(科大负责人)；董靖宇、倪晓杰、邓凡水等多人已毕业

CSNS: 李强、李样、韦隽昊、宁常军、冯美婵、黎晃、顾旻昊、于永积、程辉、胡海韬、鲍煜(MELODY负责人)等

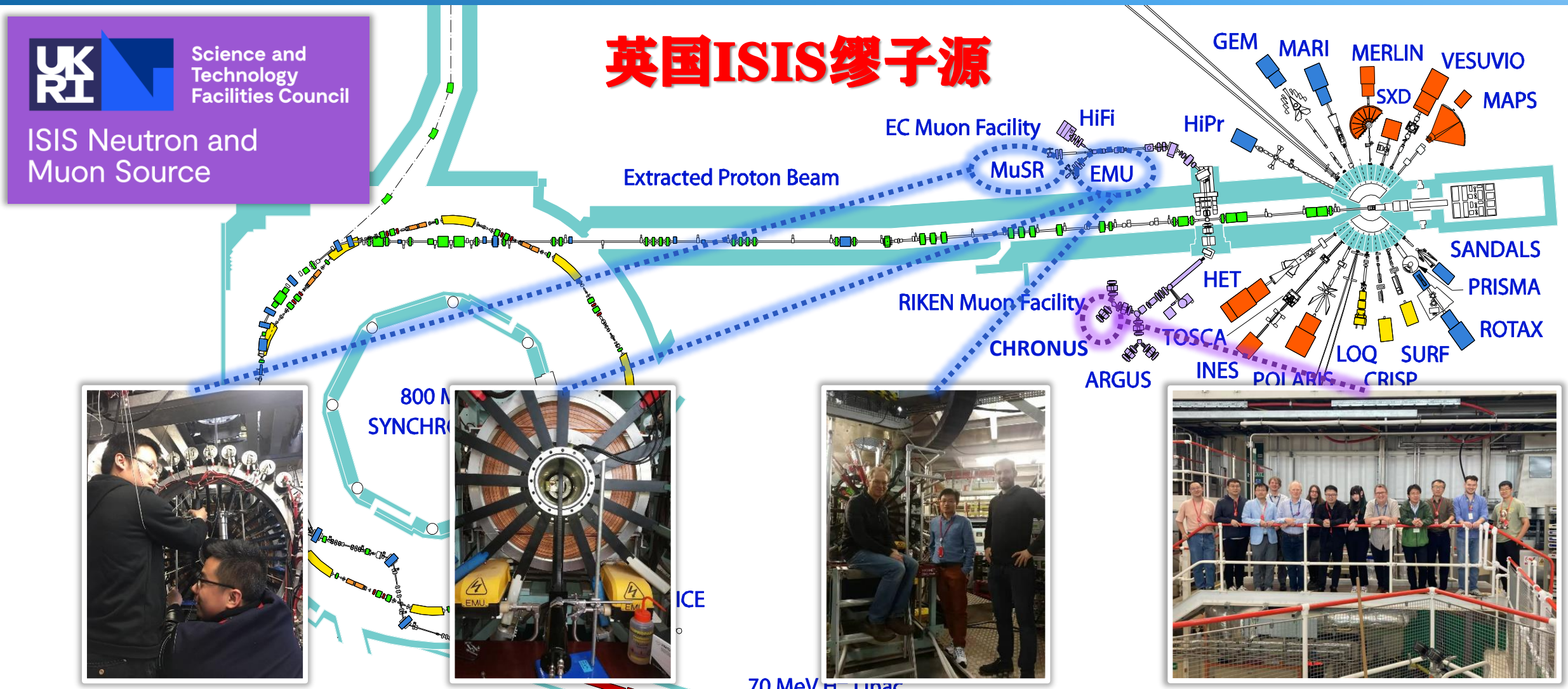
UCAS: 赵国强（数据采集与分析）

国际缪子束流测试

Science and Technology Facilities Council

ISIS Neutron and Muon Source

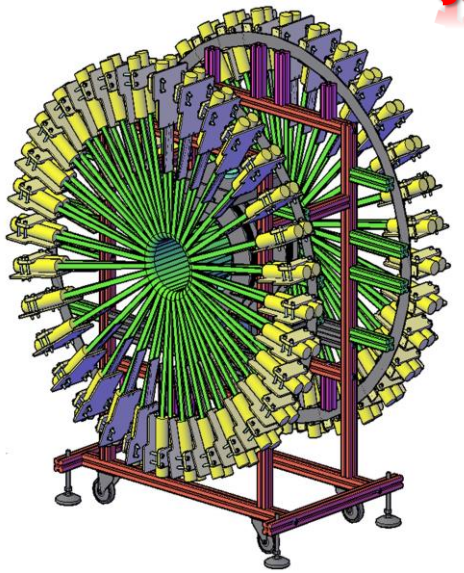
英国ISIS缪子源

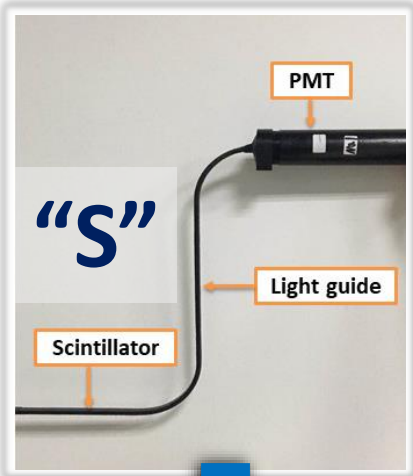


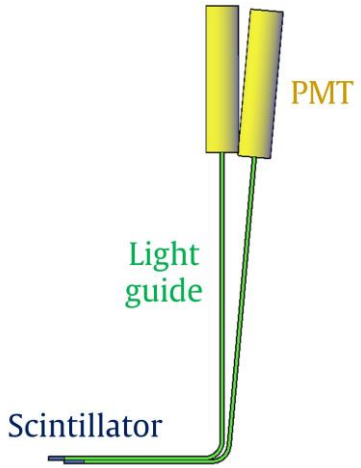
1-Gen detector 2018/03/14	1-Gen detector 2018/09/25	1-Gen detector 2019/11/13	2-Gen detector 2024/07/13

第一代PMT型谱仪研制

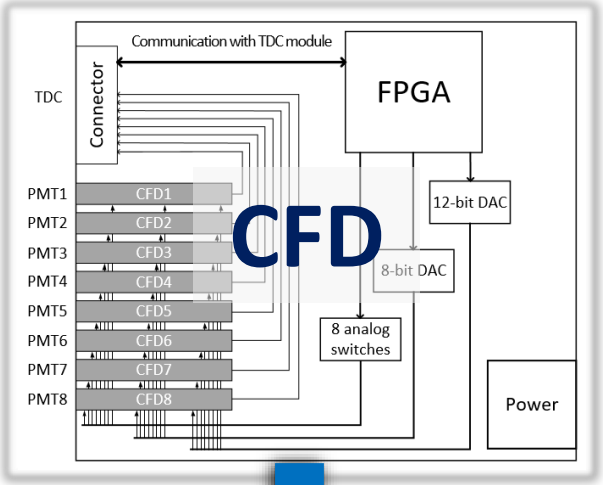
探测器

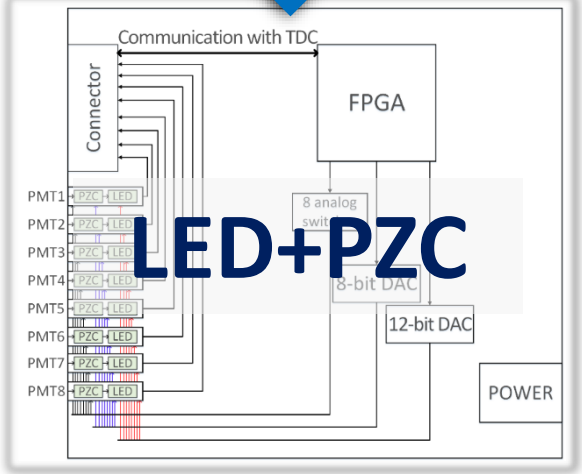




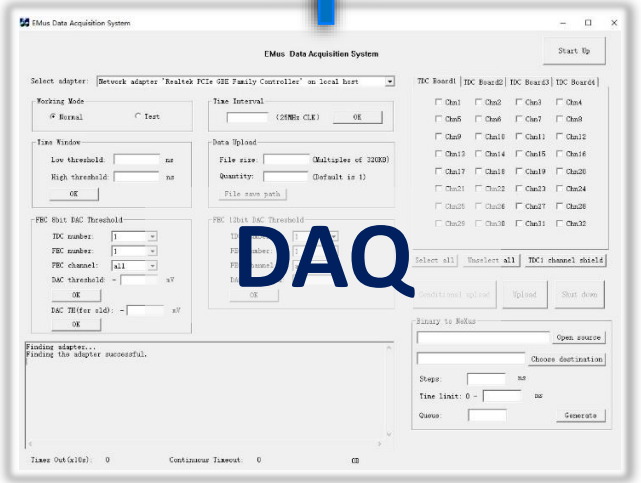


前端电子学





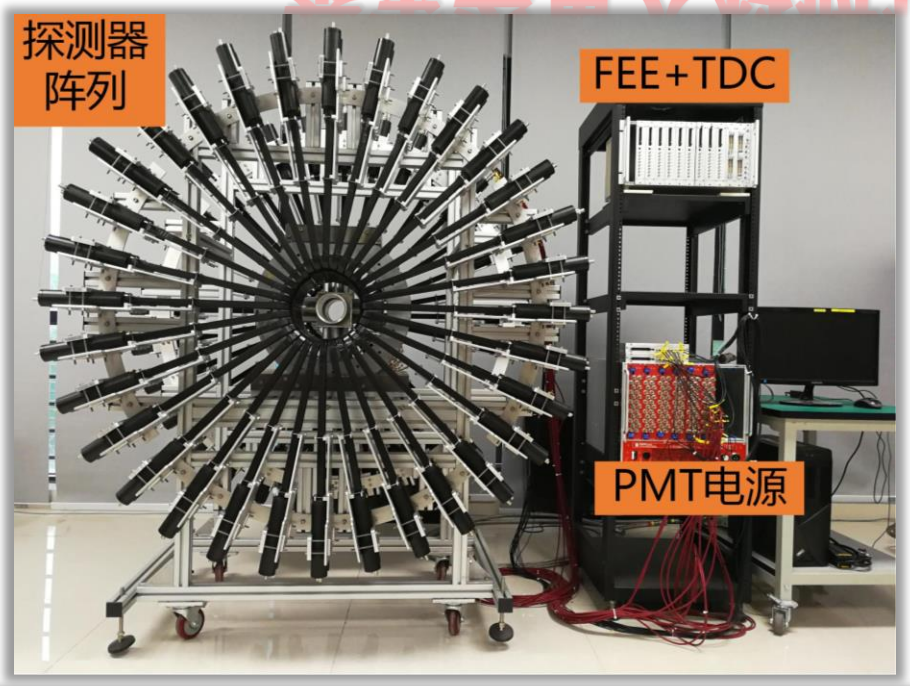
读出电子学



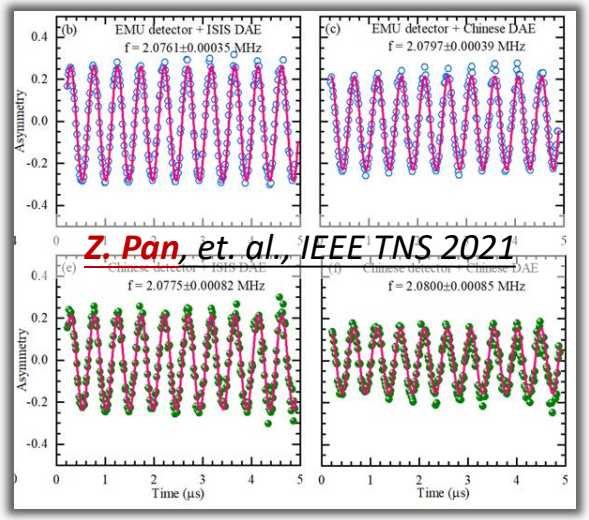
FEE: Front-End Electronics, LED: Leading-edge discrimination

第一代PMT型谱仪研制

基金委重大科研仪器项目专家组现场验收

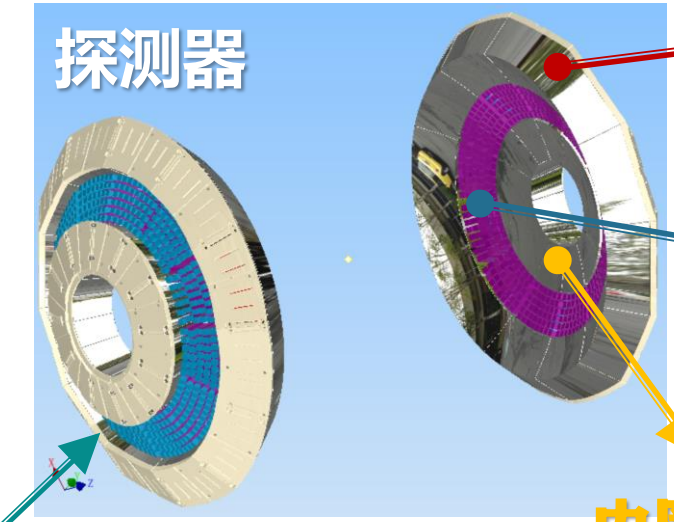


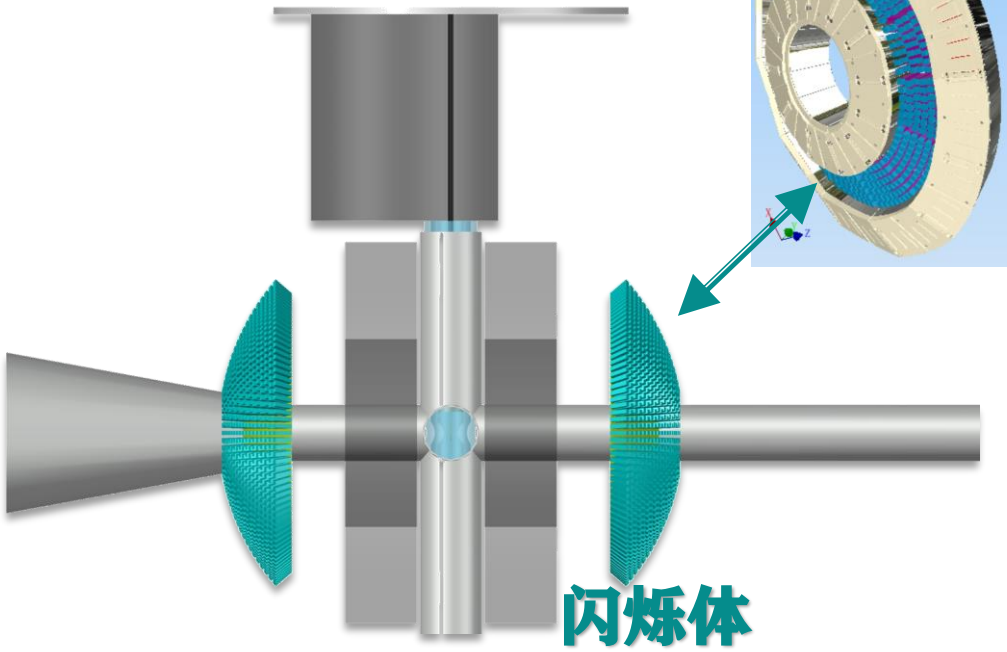
- ✓ 重大仪器研制项目《高流强缪子源关键技术研究》
- ✓ 总负责人：唐靖宇 ‖ 谱仪子课题：叶邦角
- ✓ 样机探测系统统计数性能及非对称因子均国际领先
- ✓ 精确测量样品局域磁场，满足用户实验需求
- ✓ 重大仪器结题唯一优秀，谱仪为亮点工作

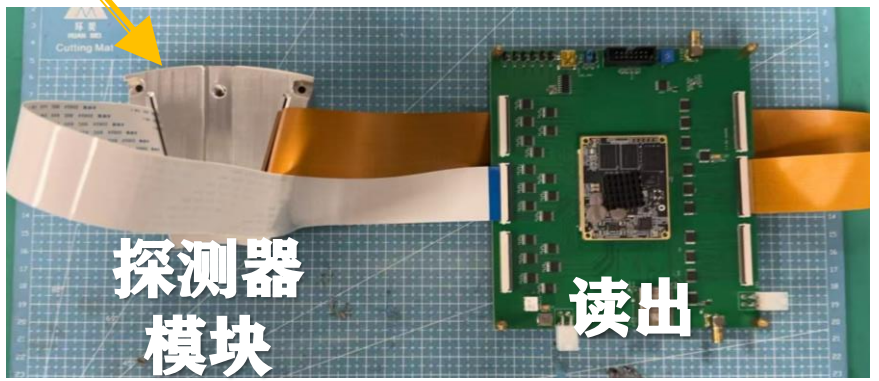


Z. Pan, et. al., IEEE TNS 2021

第二代SiPM型谱仪研制



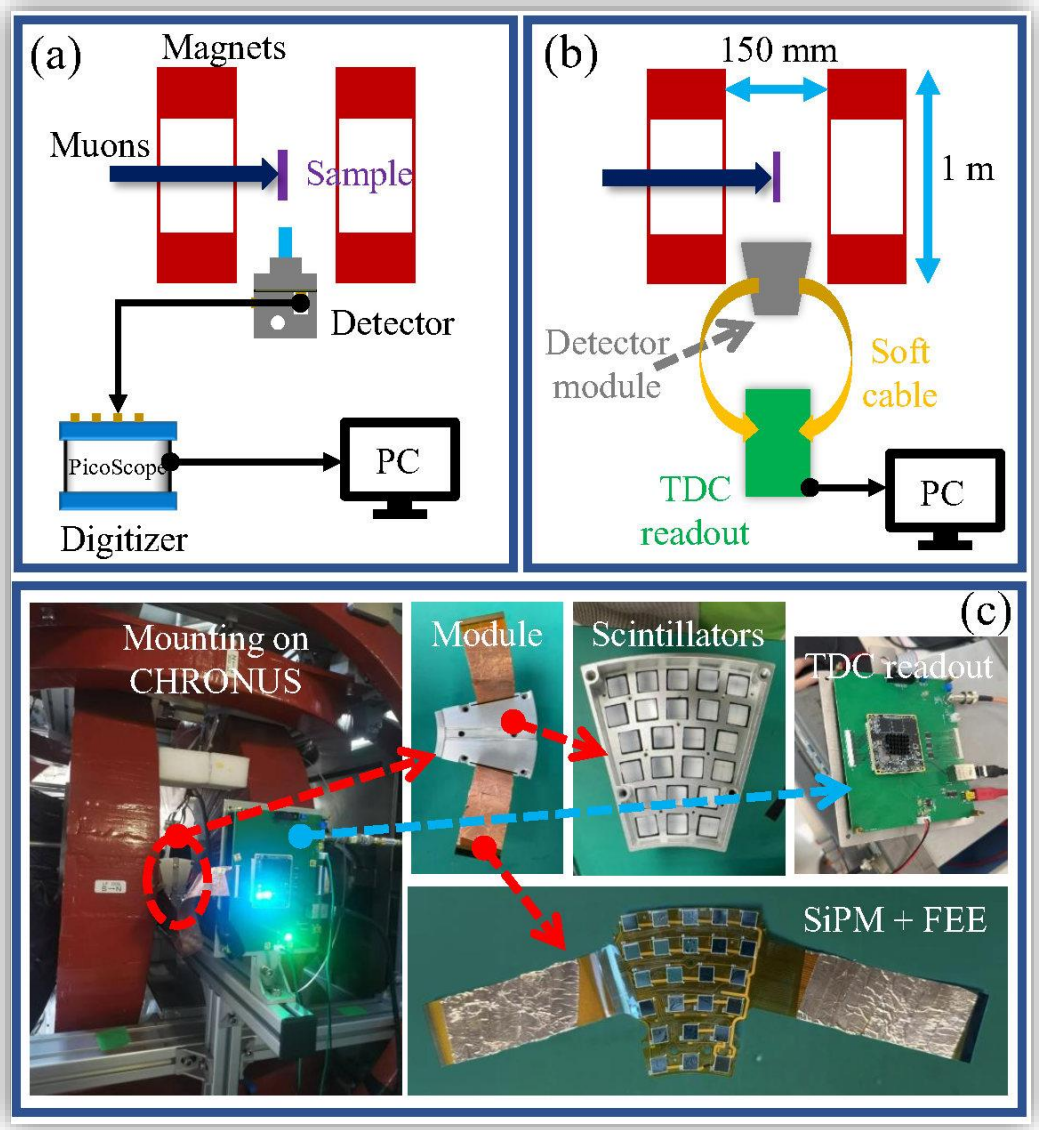


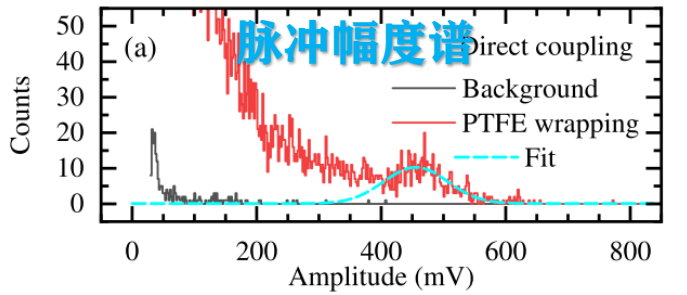


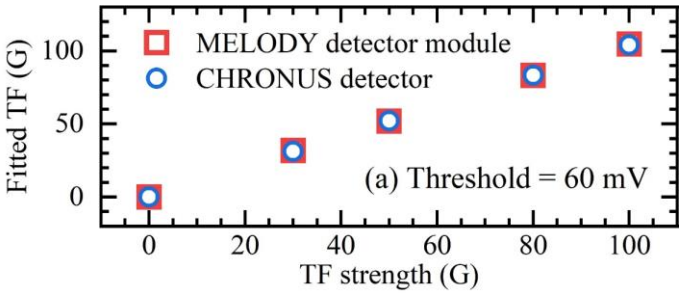
QL, ZWP, et al, μSR2020 proceeding (2023)

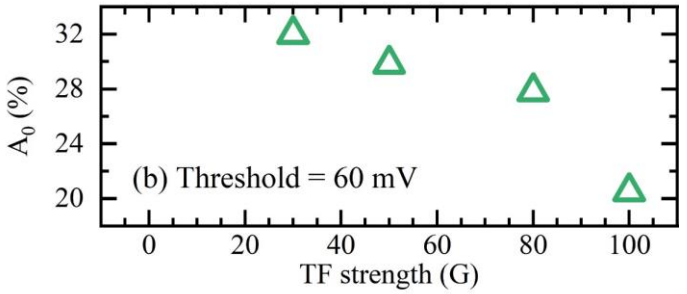
QL, ZWP, et al, μSR2025 proceeding (2025)

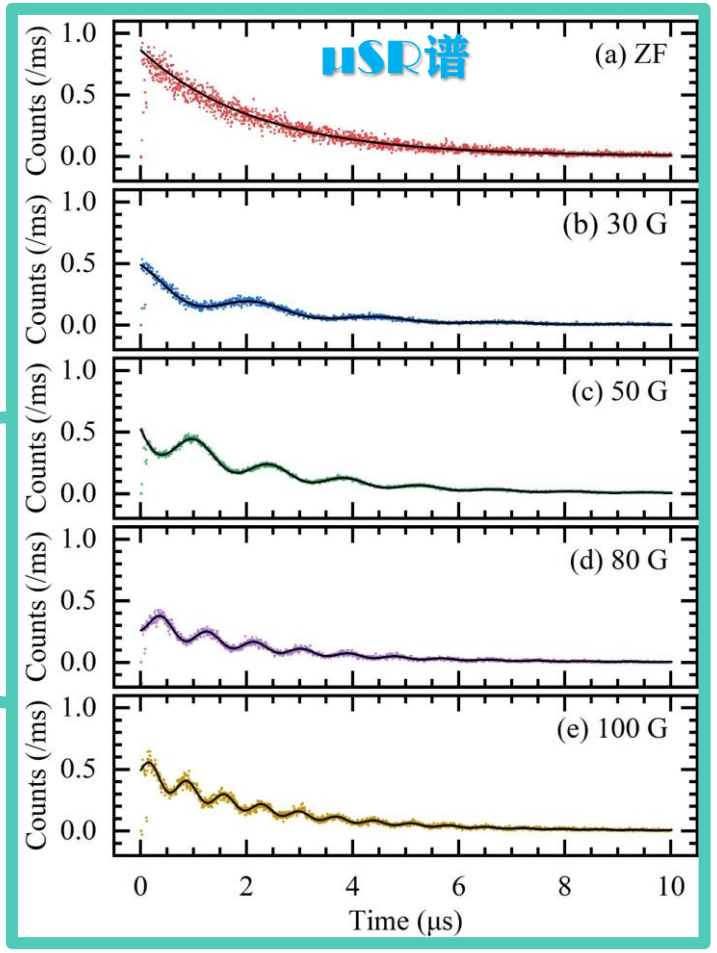
第二代SiPM型谱仪研制











- ISIS缪子束流测试成功验证第一版（软板）方案功能
- 第二版（硬板）方案即将进行缪子束流测试（正在申请ISIS束流）

NIMA 1082 (2026) 170918

III. 总结与技术展望

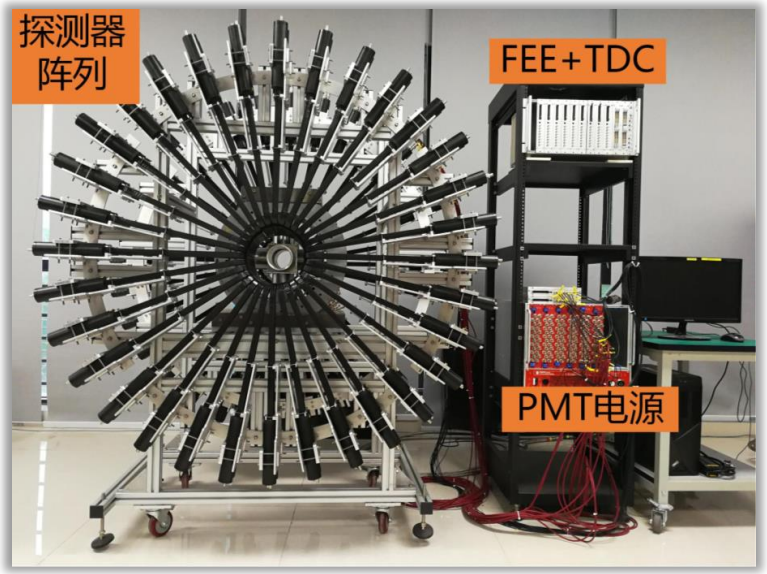
总结

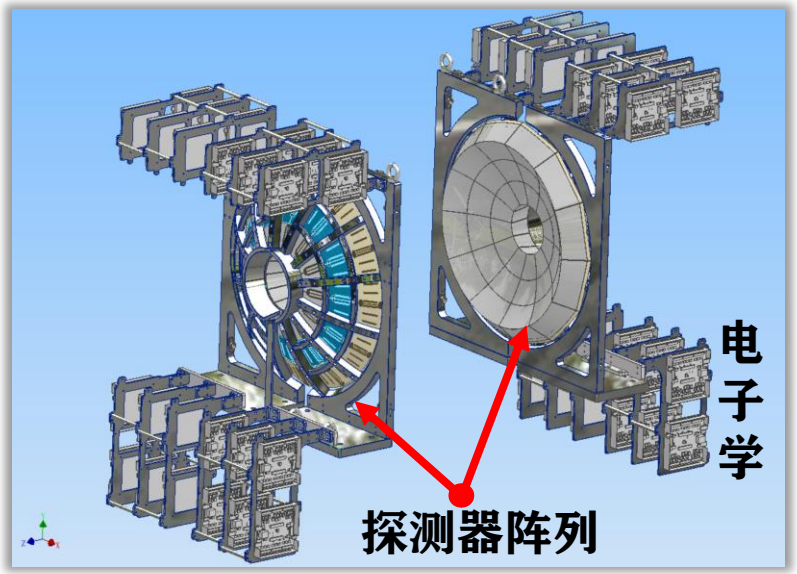
■ 缪子源

综述: *Z. Pan*, et al. (2026) IJMPA, 2630013*
潘子文, 等. (2026) 原子核物理评论[已接收]

- **宇宙线缪子**: 人人皆可利用
- **加速器缪子**:
  - 运行中: TRIUMF, PSI, MuSIC-RCNP, ISIS, J-PARC (mainly for applied sciences)
  - FermiLab, CERN (only for particle physics)
  - 建设中: MELODY-CSNS, CiADS/HIAF@IMP, RAON
  - 计划中: SHINE, SEEMS@SNS, JLab

■ USTC-CSNS团队两代μSR谱仪研发

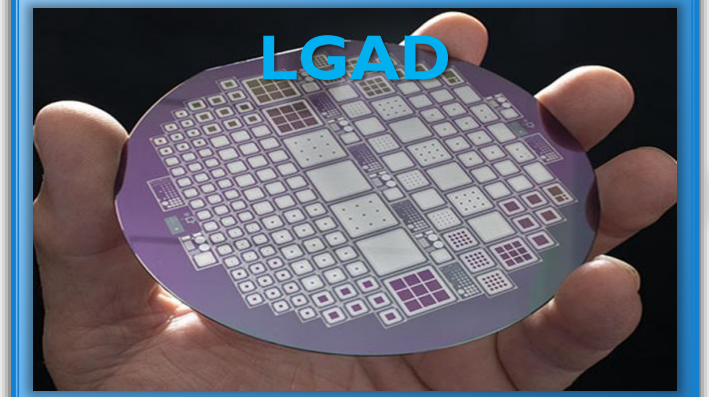


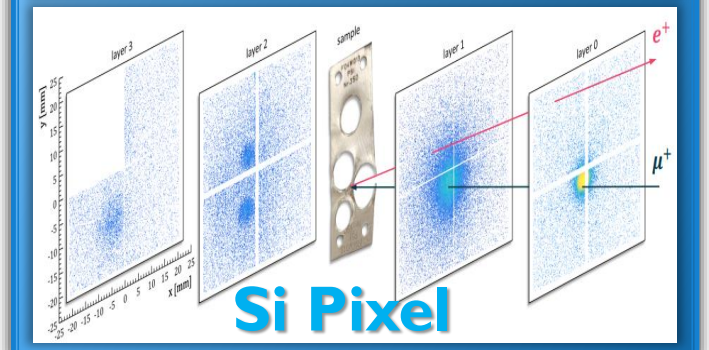


展望：μSR谱仪探测技术

● 探测器

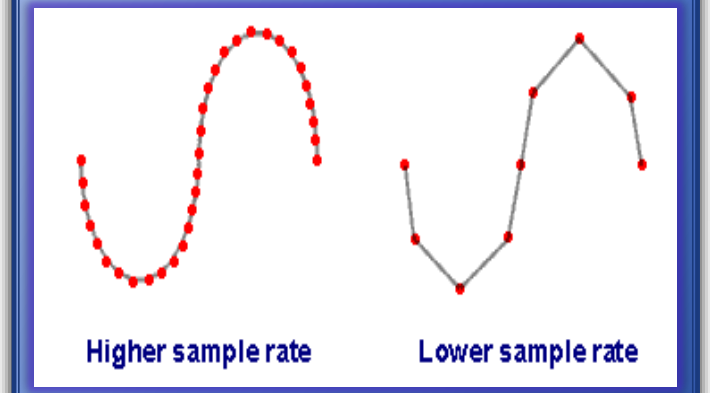
- ✓ 高粒度
- ✓ μ^+ / e^+径迹重构

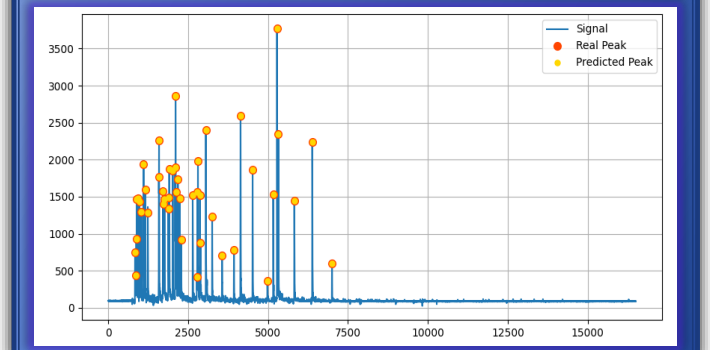




● 电子学

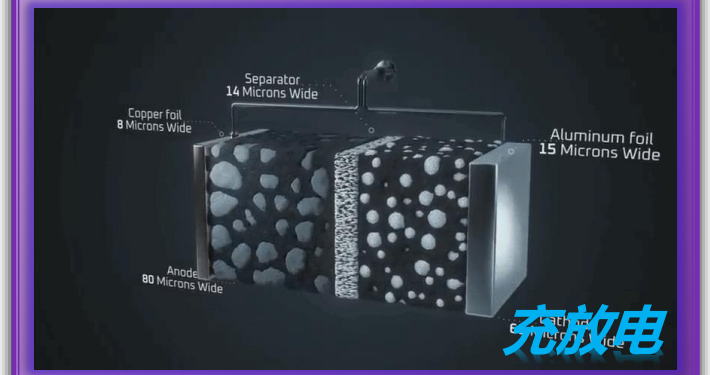
- ✓ 数字化读出
- ✓ 高分辨/快响应

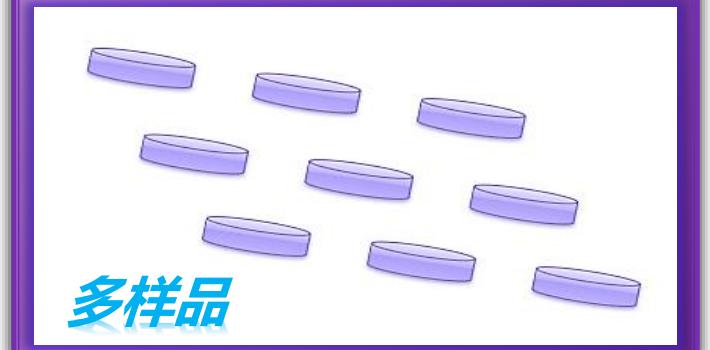




● 测量

- ✓ 动态原位测量
- ✓ 小样品/多样品





感谢各位专家，欢迎交流与合作！

- *感谢加速器/宇宙线/激光缪子领域所有老师、同事及合作者对本人工作的支持与帮助！*
- *感谢国自然基金委、自然资源部、广东省粤惠/粤莞联合基金、“小米青年学者”等多项基金对研究工作的经费支持！*