

缪原子谱学和缪子 寿命高精度实验

王 荣 (rwang@impcas.ac.cn)

中科院近代物理研究所

主要基于汶伟强、黄忠魁、马新文的ppt和计划书

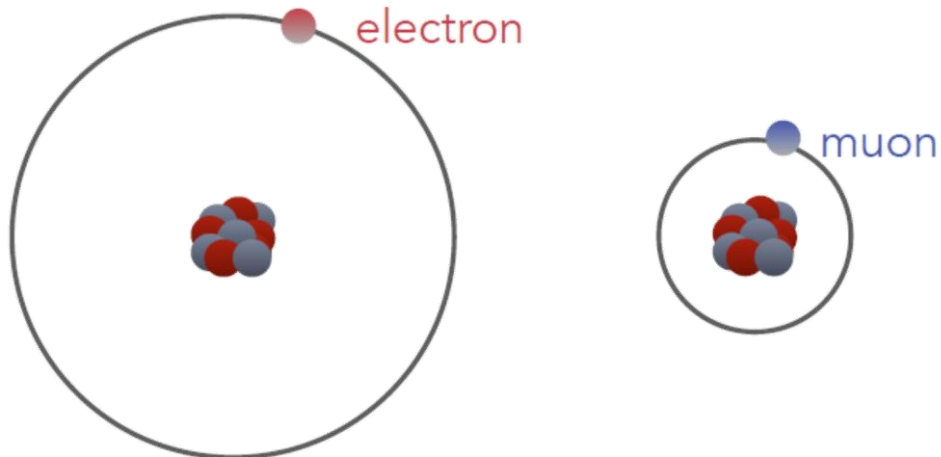
目录

- 缪原子和缪子素精密谱学的研究动机
- 缪原子谱学实验介绍
- 缪子素谱学实验介绍
- 缪子寿命高精度测量实验介绍

研究动机

缪原子(μ -A)

- 精确检验强场QED
- 研究核结构（半径、极化率）
- 探寻短程的新相互作用



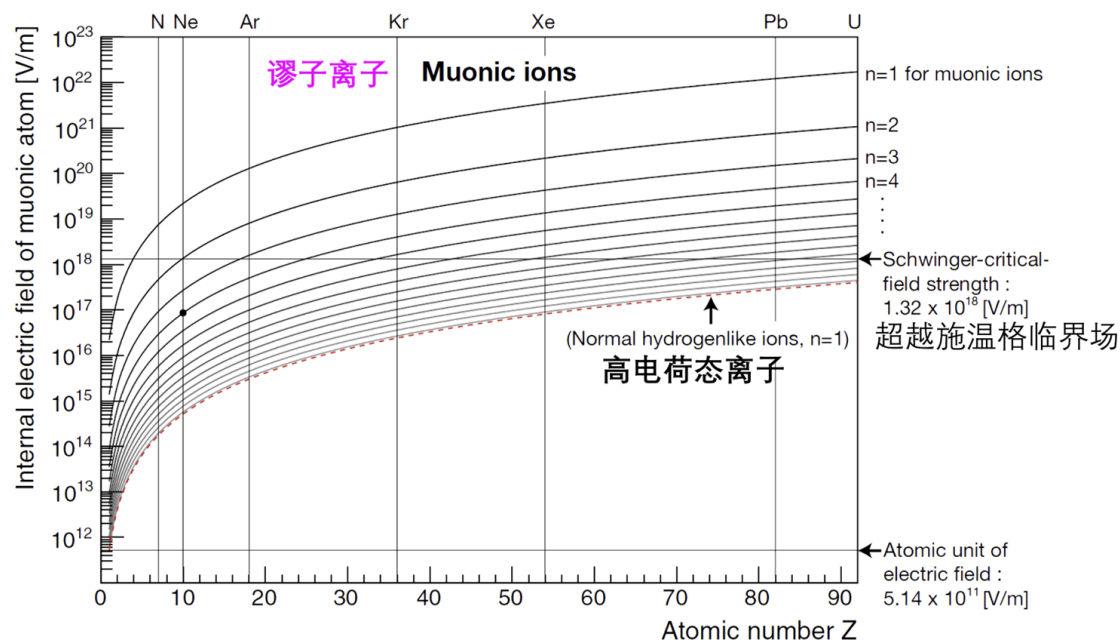
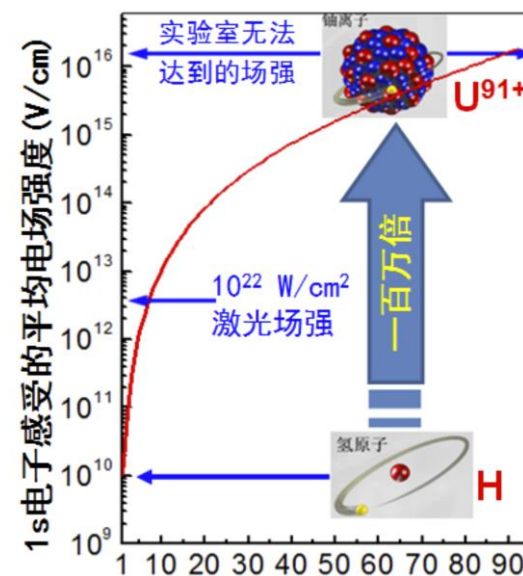
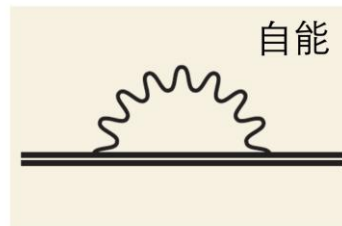
缪子素 (muonium μ^+e^- , M原子)

纯粹的QED系统

- 精确检验QED
- 探索未知相互作用力
- 精确测量 μ^+ 质量，并与 μ^- 质量比较，检验CPT守恒
- 测量 μ^+ 的磁矩
- 测量 μ 电荷与电子电荷的比值，检验两代轻子电荷相等性

缪原子谱学实验

- 检验强场QED的实验精度需要提高；强场QED的效应需要更多的实验检验！
- 类氢缪子离子中的缪子离原子核更近，场强更强，为极端强场QED理论提供了独一无二的实验条件。

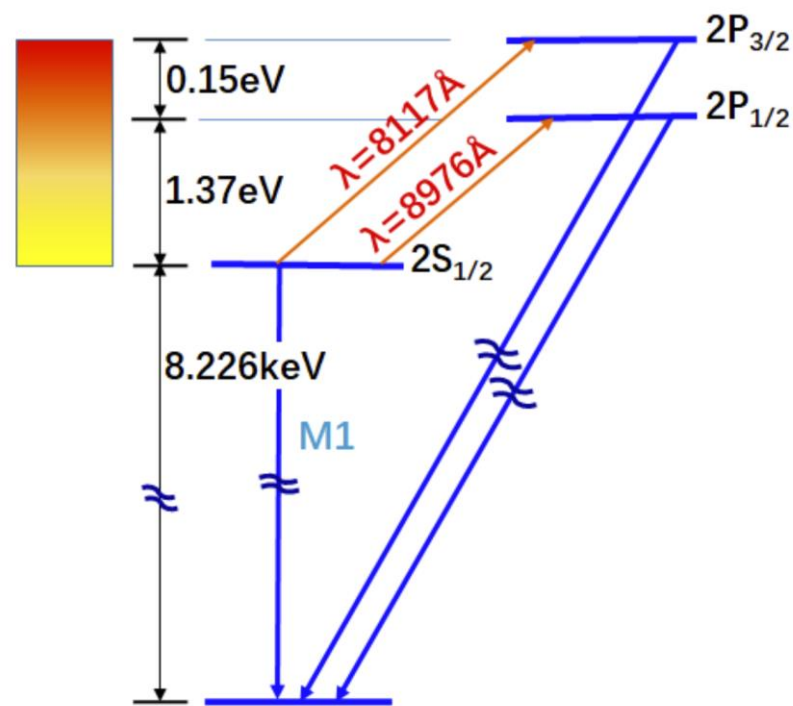


缪原子谱学实验介绍

针对缪原子开展的主要实验

- 缪原子跃迁X射线的精确测量
检验强场QED
寻找新的相互作用
- 缪原子兰姆位移的精确测量
原子核尺寸
原子核极化率

μ -氦离子($\mu^{-4}\text{He}^+$) ion的能级结构
n=1 and n=2



缪原子谱学实验介绍

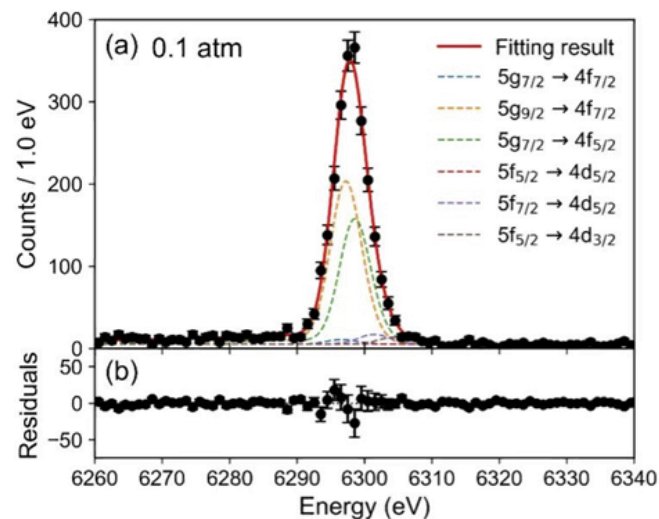
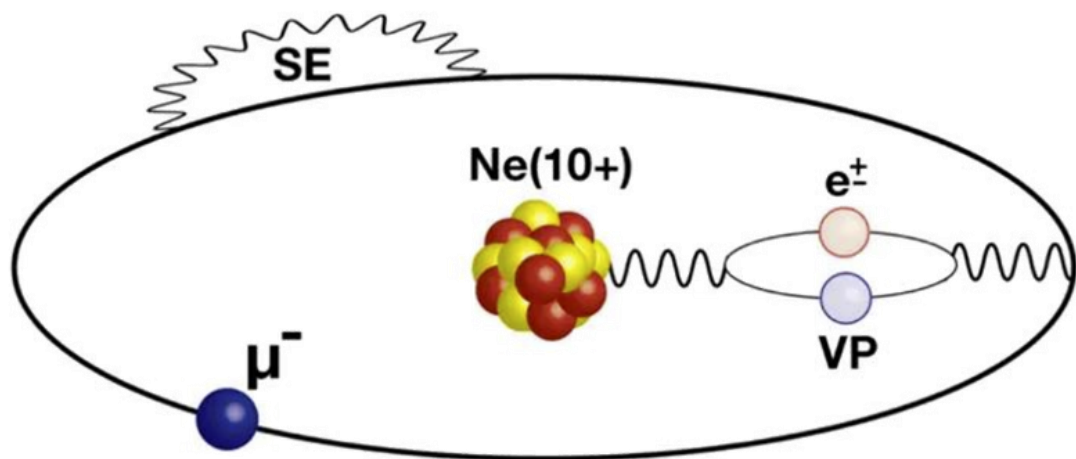
PHYSICAL REVIEW LETTERS **130**, 173001 (2023)

Proof-of-Principle Experiment for Testing Strong-Field Quantum Electrodynamics with Exotic Atoms: High Precision X-Ray Spectroscopy of Muonic Neon

T. Okumura^{1,*}, T. Azuma^{1,‡}, D. A. Bennett², I. Chiu³, W. B. Doriese², M. S. Durkin², J. W. Fowler², J. D. Gard², T. Hashimoto⁴, R. Hayakawa⁵, G. C. Hilton², Y. Ichinohe⁶, P. Indelicato⁷, T. Isobe⁸, S. Kanda⁹, M. Katsuragawa¹⁰, N. Kawamura⁹, Y. Kino¹¹, K. Mine¹⁰, Y. Miyake⁹, K. M. Morgan^{2,12}, K. Ninomiya³, H. Noda¹³, G. C. O'Neil², S. Okada^{14,||}, K. Okutsu¹¹, N. Paul⁷, C. D. Reintsema², D. R. Schmidt², K. Shimomura⁹, P. Strasser⁹, H. Suda⁵, D. S. Swetz², T. Takahashi¹⁰, S. Takeda¹⁰, S. Takeshita⁹, M. Tampo⁹, H. Tatsuno⁵, Y. Ueno¹, J. N. Ullom², S. Watanabe¹⁵ and S. Yamada⁶

¹Atomic, Molecular, and Optical Physics Laboratory, RIKEN, Wako 351-0198, Japan

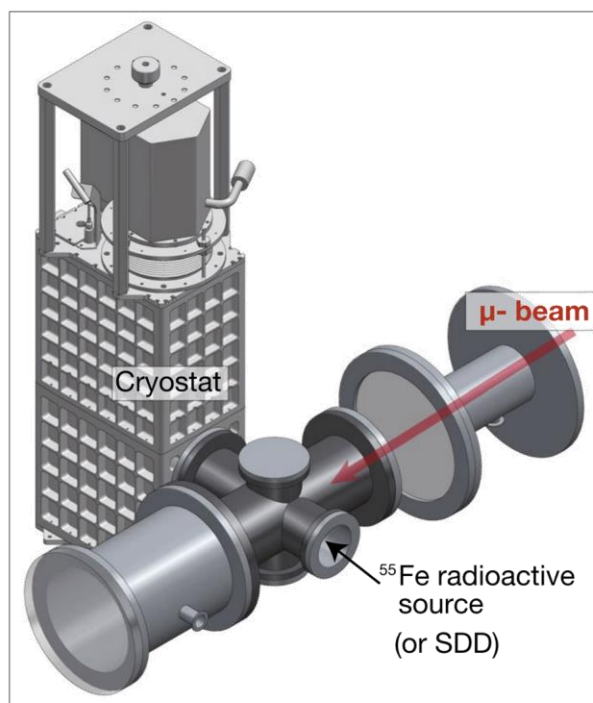
²National Institute of Standards and Technology, Boulder, Colorado 80305, USA



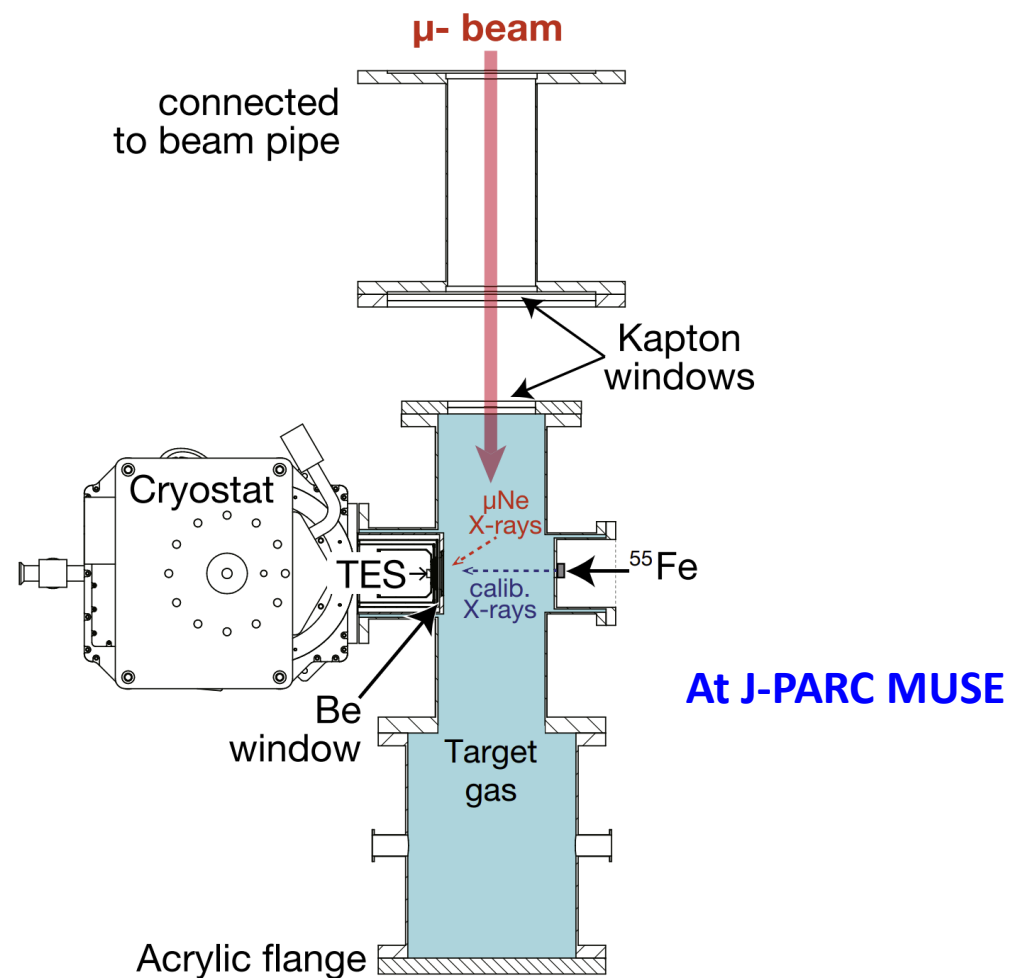
- μ -Ne离子的 $5g_{9/2} - 4f_{7/2}$ 跃迁能量 6297.08 ± 0.04 (stat) ± 0.13 (syst) eV
- 首次获得跃迁能量中极化QED效应的贡献为5.8%的精度
- 为新一代缪离子精密谱学实验奠定基础

缪原子谱学实验介绍

- 缪子源的重复频率25Hz, 每一个脉冲有 $\sim 10^4$ 个缪子
- 缪子的能量为20.5, 20.5, 21.5 MeV/c
- 氖气的气压为0.1, 0.4, 和 0.9个大气压
- 测量到的缪离子的X-ray的计数大约1-3个每秒

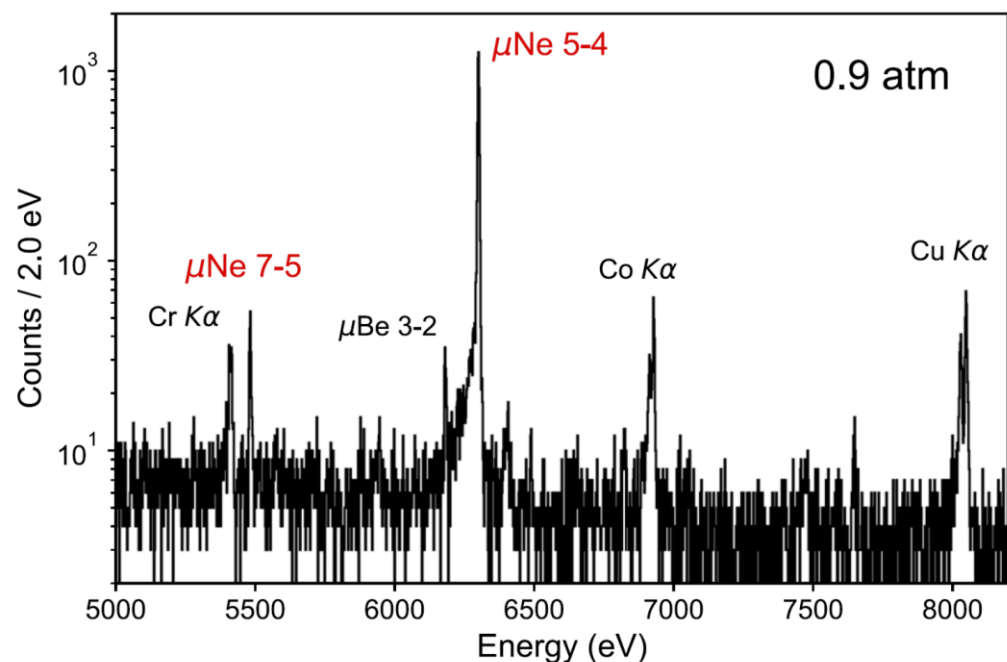


3D view

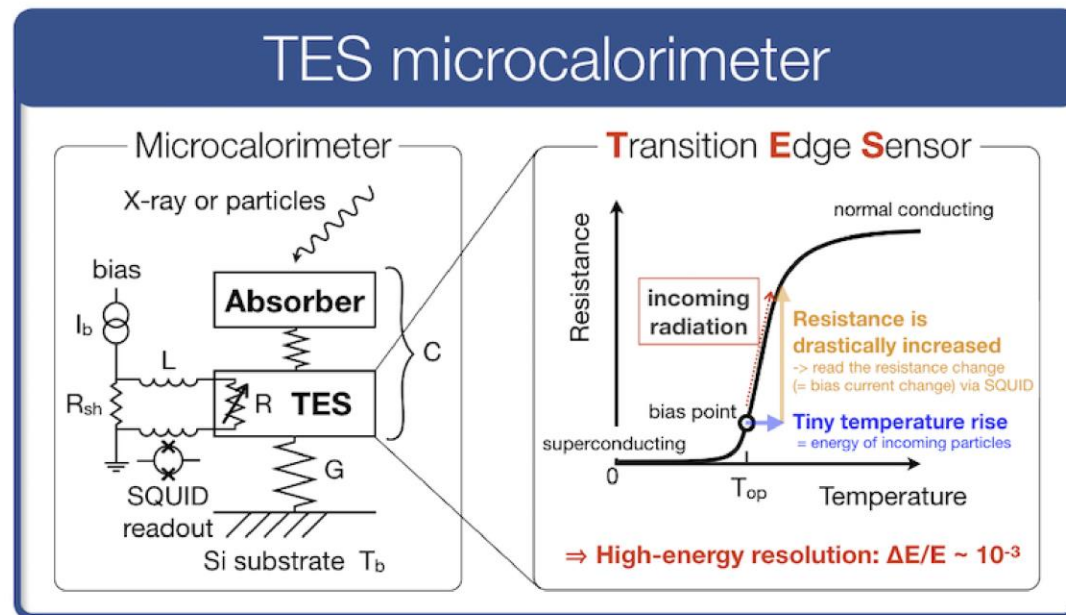


缪原子谱学实验介绍

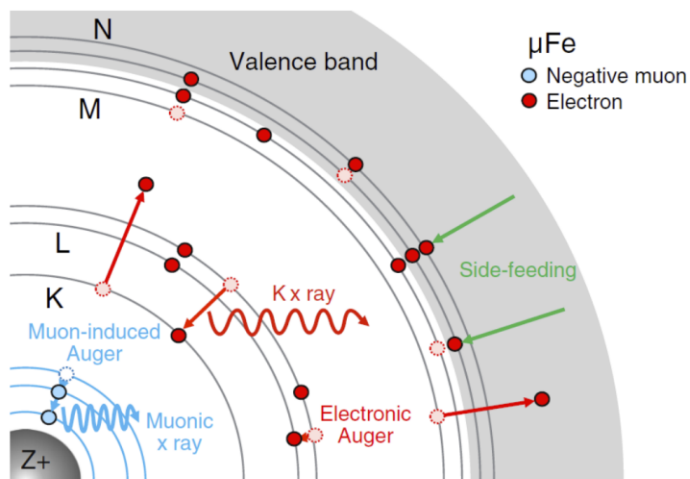
- 新一代低温X射线能谱仪(Microcalorimeters)
- 极高能量分辨: 3.3eV @6 keV, 10 eV @30 keV
- 具有大的能量测量范围和极高的探测效率



μ-Ne离子的X-ray能谱

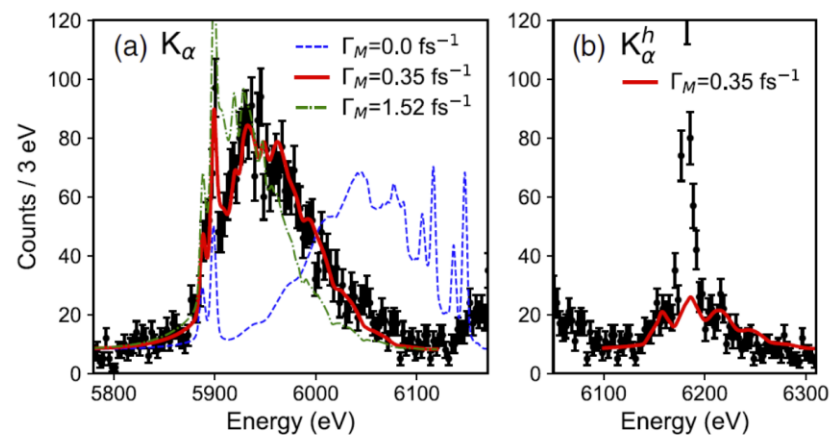
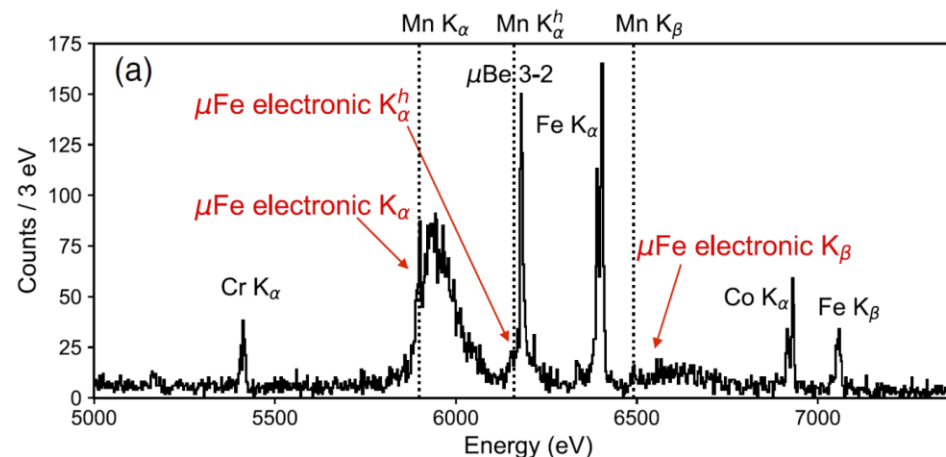


缪原子谱学实验介绍



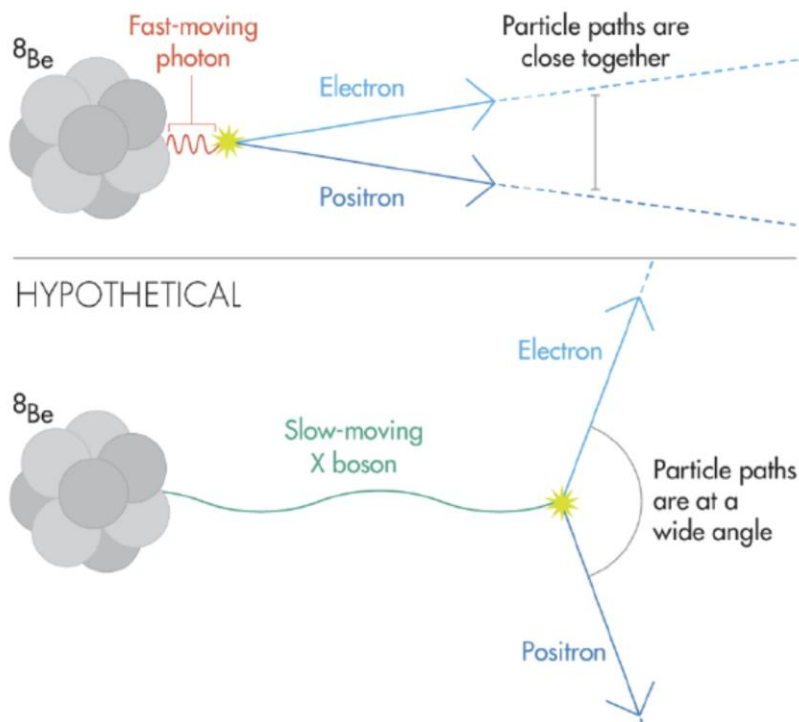
- 低能缪子束流20.5 MeV/c
- 100 μm 的铁箔靶
- TES微量能器

观测到了固态靶中的Side Electron Feeding!



缪原子谱学实验介绍

^8Be 实验的异常

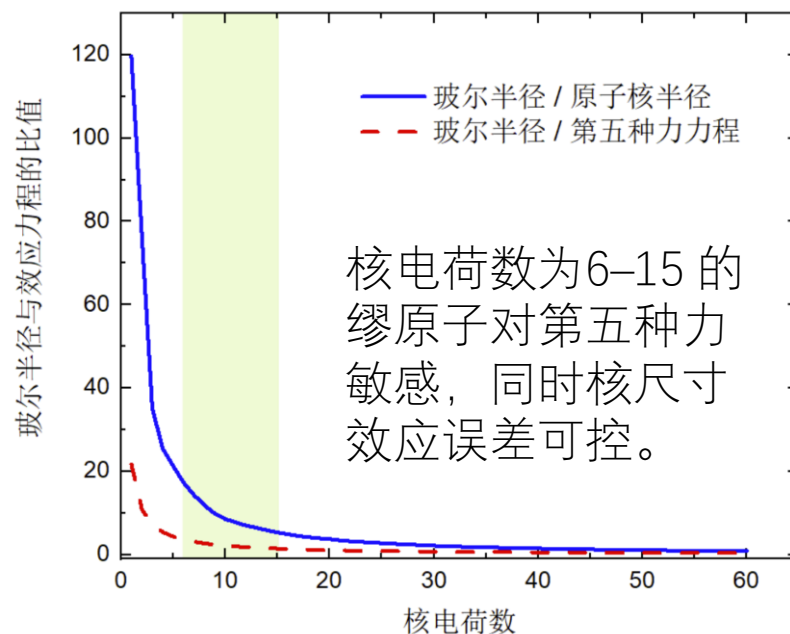


X17玻色子?
 疏质子第五种相互作用?

• 缪原子精密谱学方案

第五种力: $H_X^{(\mu, Y)} = \varepsilon_\mu \varepsilon_n (A - Z) \alpha \frac{e^{-m_X r}}{r}$

核尺寸效应: $H_{\text{FNS}} = \frac{2\pi}{3} Z \alpha r_n^2 \delta^{(3)}(\vec{r})$



核电荷数为6-15 的
 缪原子对第五种力
 敏感, 同时核尺寸
 效应误差可控。

arXiv:2312.13060

缪原子谱学实验介绍

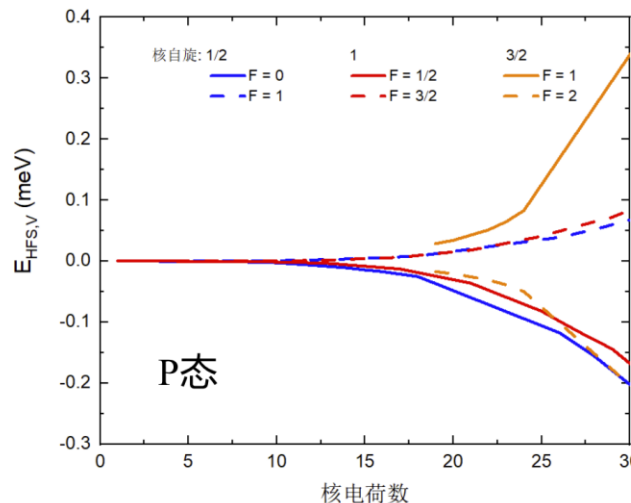
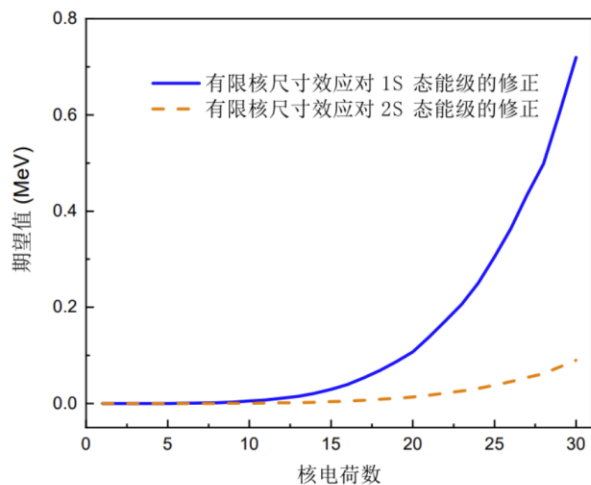
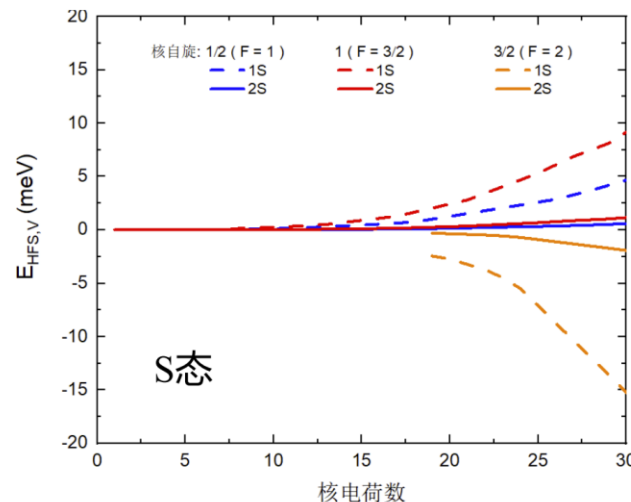
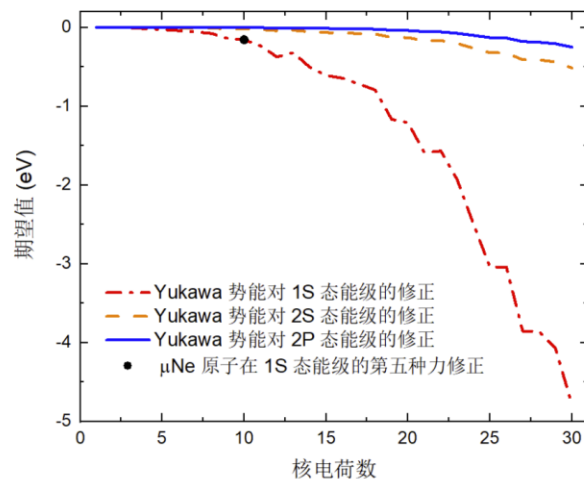
X17玻色子诱导的哈密顿量如下。

领头阶作用：

$$H_X^{(\mu, Y)} = \varepsilon_\mu \varepsilon_n (A - Z) \alpha \frac{e^{-m_X r}}{r}$$

超精细作用：

$$H_{\text{HFS}, V} = \frac{\hbar'_f \hbar'_N}{16 \pi m_f m_N} \left[-\frac{8\pi}{3} \delta^{(3)}(\vec{r}) \vec{\sigma}_f \cdot \vec{\sigma}_N - \frac{m_X^2 (\vec{\sigma}_f \cdot \vec{r} \vec{\sigma}_N \cdot \vec{r} - r^2 \vec{\sigma}_f \cdot \vec{\sigma}_N)}{r^3} e^{-m_X r} - (1 + m_X r) \frac{3 \vec{\sigma}_f \cdot \vec{r} \vec{\sigma}_N \cdot \vec{r} - r^2 \vec{\sigma}_f \cdot \vec{\sigma}_N}{r^5} e^{-m_X r} - \left(2 + \frac{m_f}{m_N} \right) (1 + m_X r) \frac{\vec{\sigma}_N \cdot \vec{L}}{r^3} e^{-m_X r} \right]$$



J. Chen, Q. Wu, X. Chen, Q. Wang, arxiv: 2312.13060

Ulrich D. Jentschura, Phys. Rev. A 101 (2020) 6, 062503

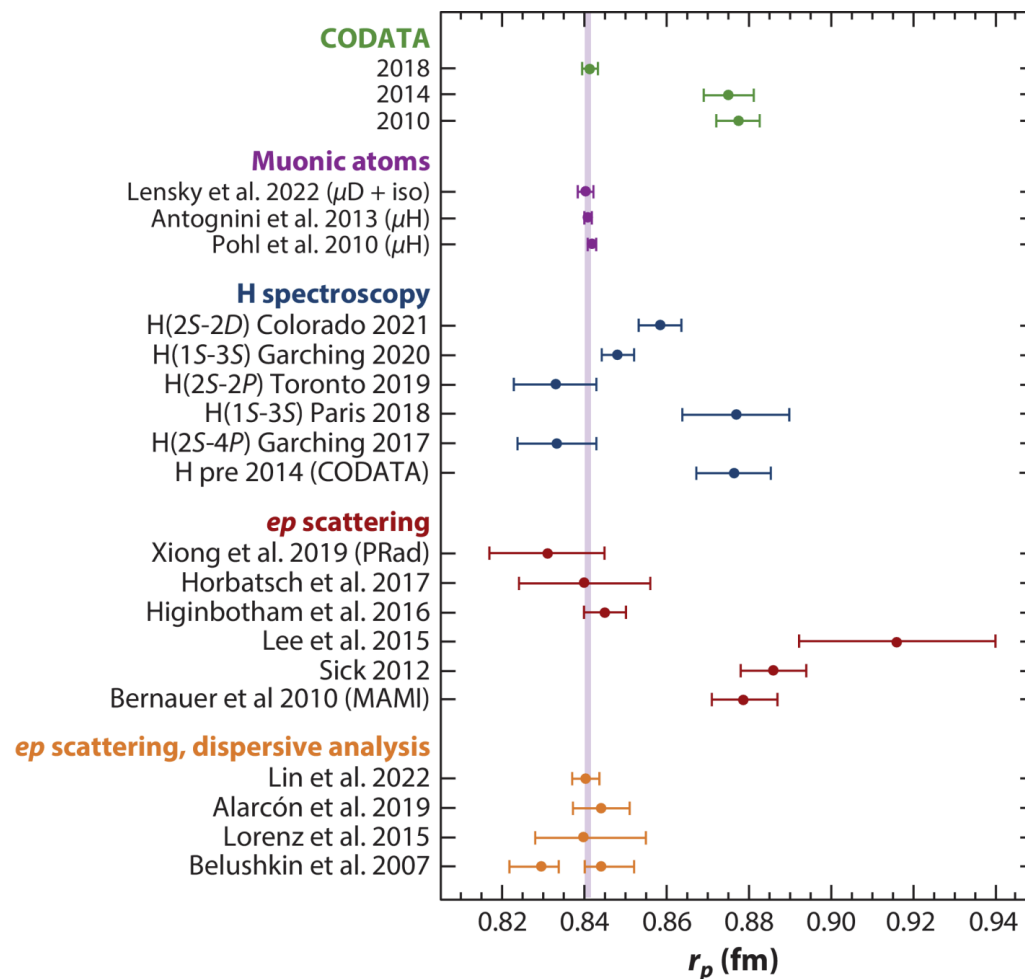
Ulrich D. Jentschura, Istvan Nandori, Phys. Rev. A 97 (2018) 4, 042502

缪原子谱学实验介绍

- 兰姆位移精确测量

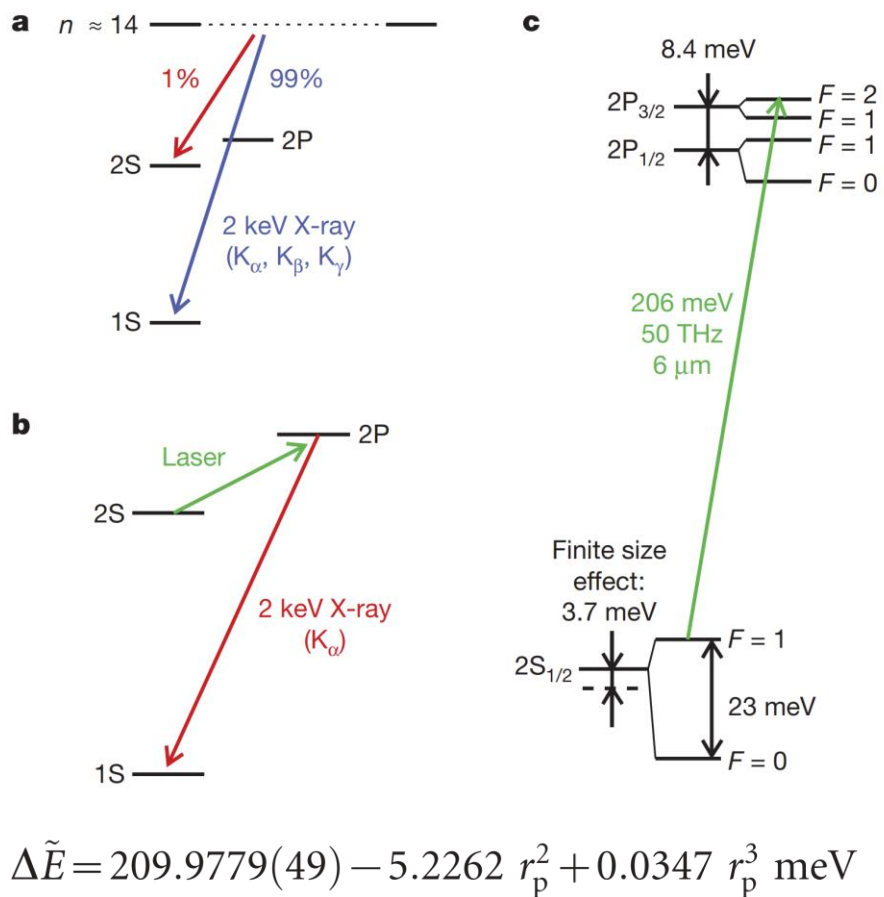
目标：精确提取核结构信息
(尺寸、极化率)

技术要求：激光谱学技术

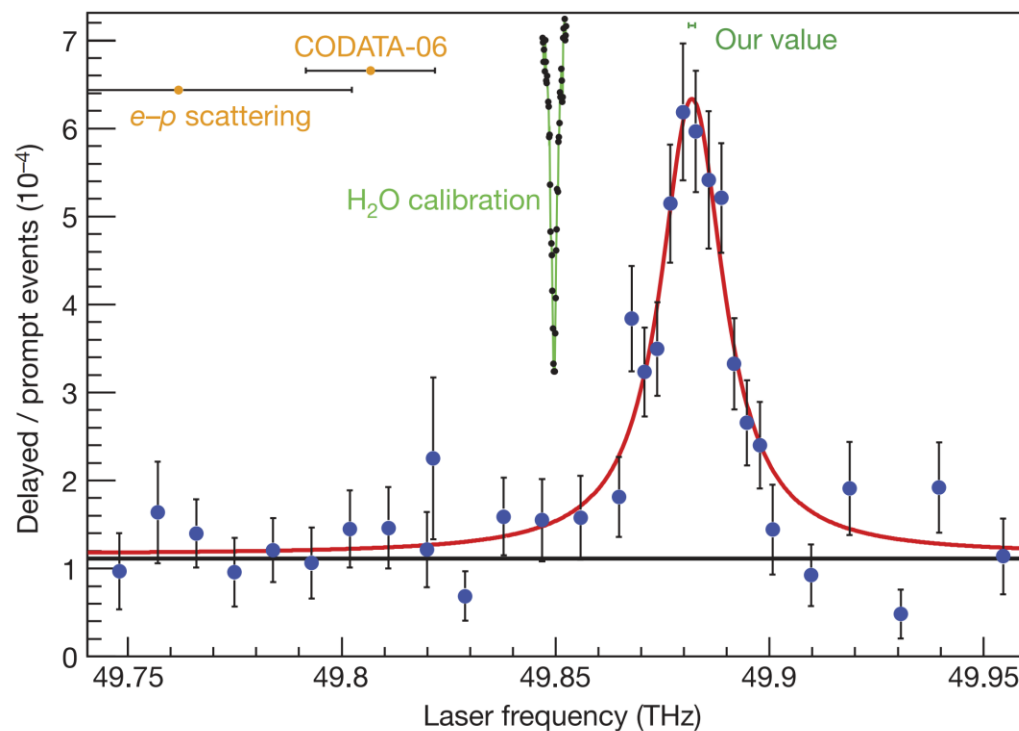


缪原子谱学实验介绍

[Nature 466 (2010) 213]

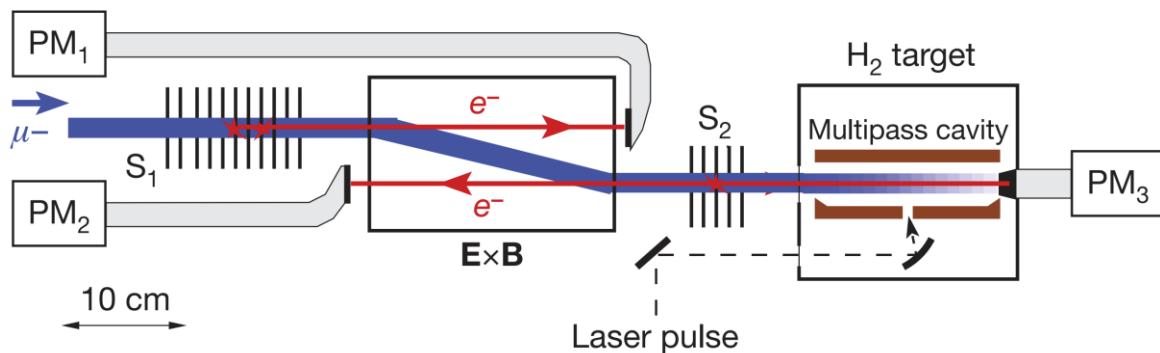


缪氢原子能级及实验原理



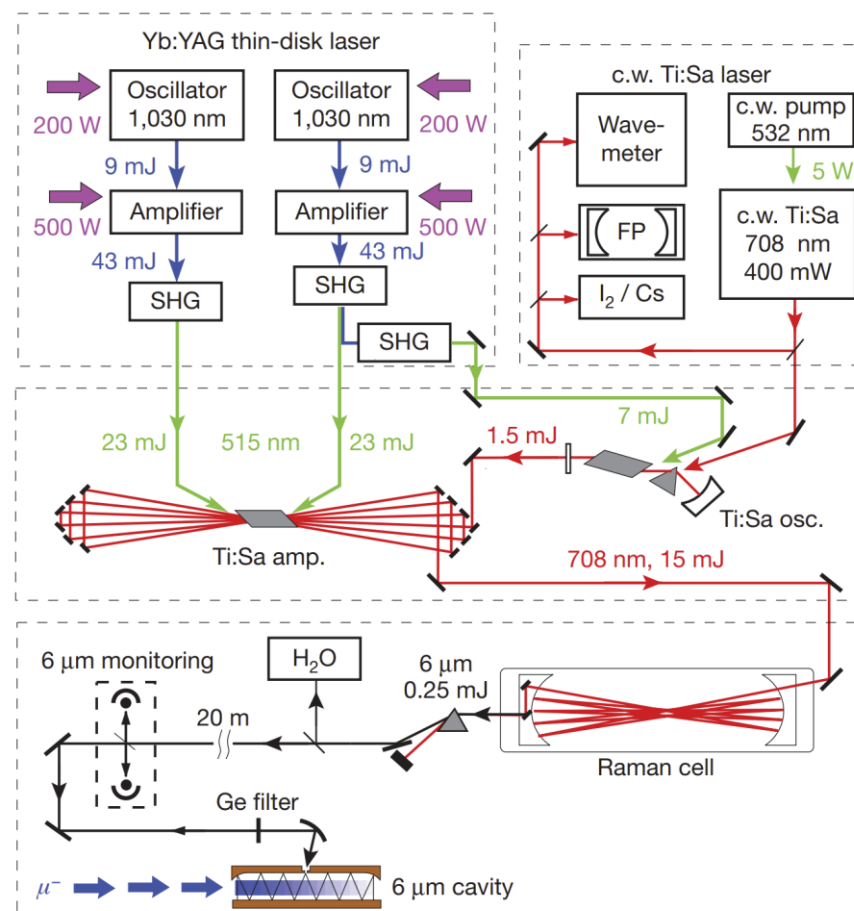
缪氢原子兰姆位移测量结果

缪原子谱学实验介绍



束流和靶设计

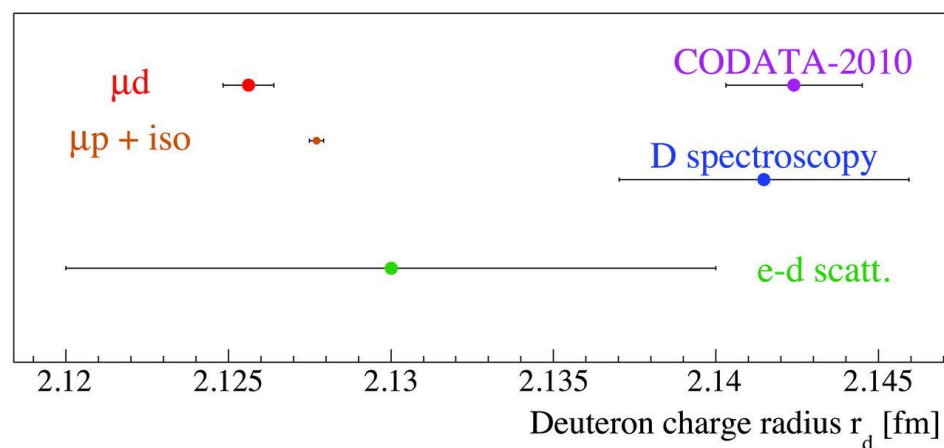
At $\pi E5$ beam of PSI
 5 keV μ^- beam
 1 hPa H^2 gas target



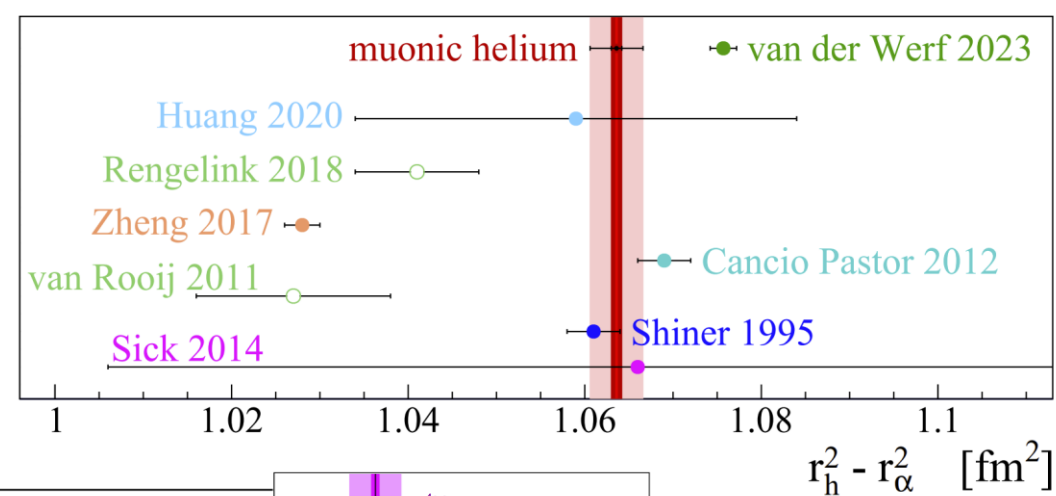
激光装置

缪原子谱学实验介绍

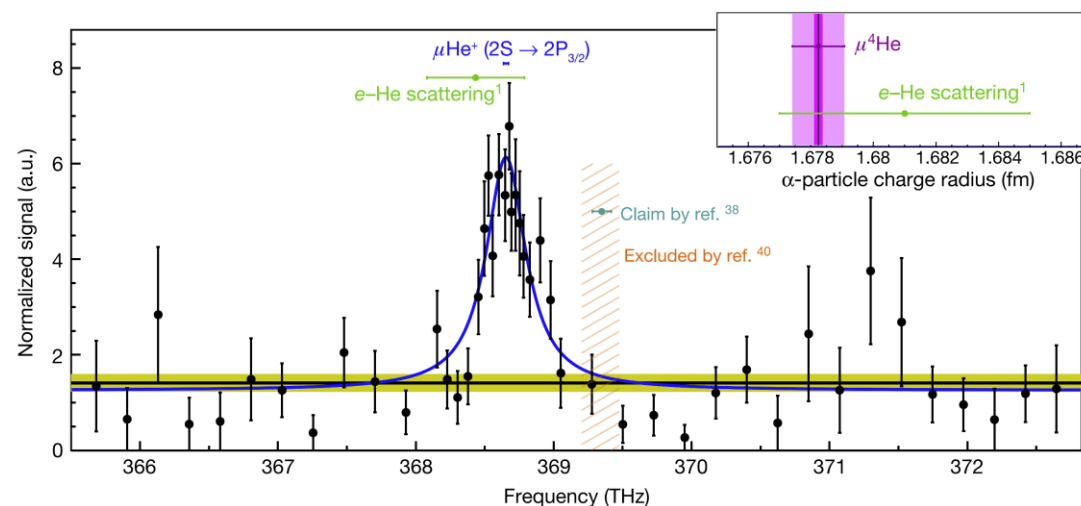
氘核半径缪原子谱学测量结果



氦3-氦4核半径平方差测量结果



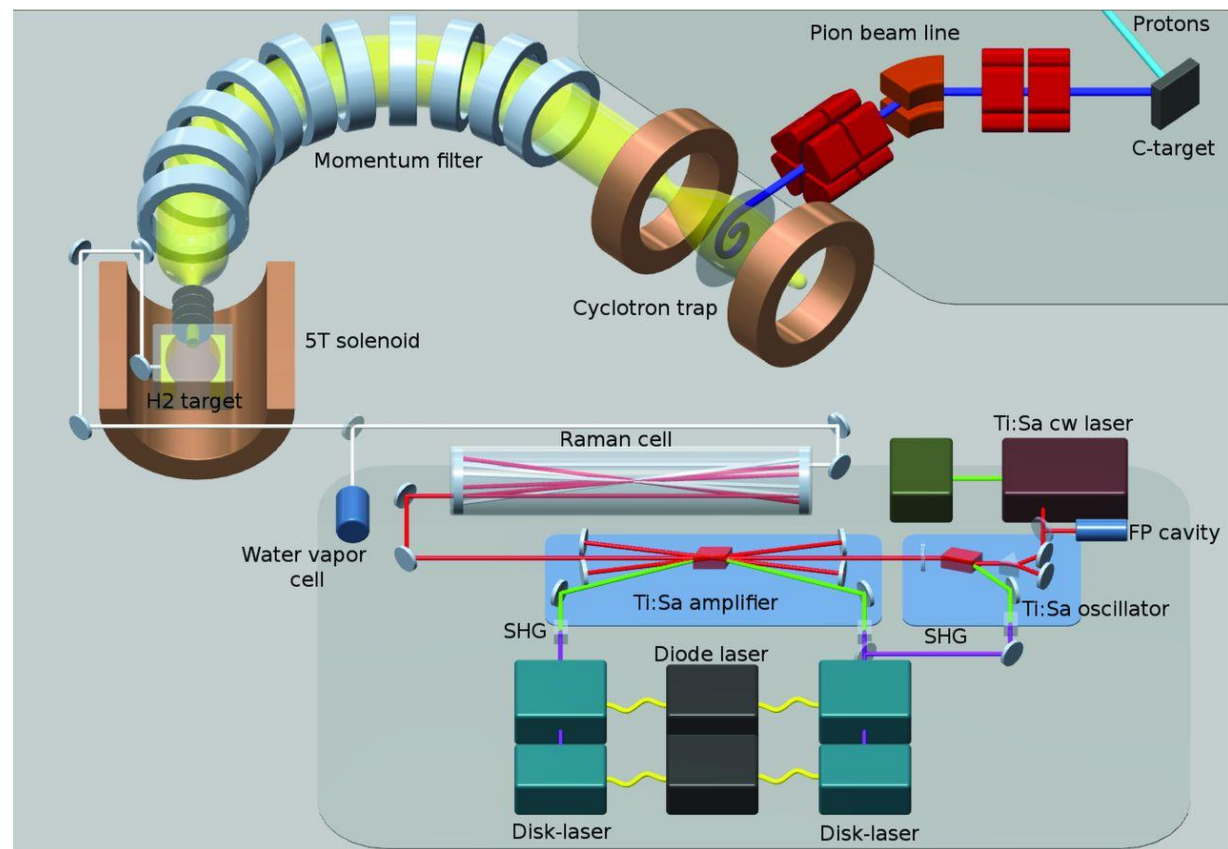
氦4核半径测量结果



缪原子谱学实验介绍

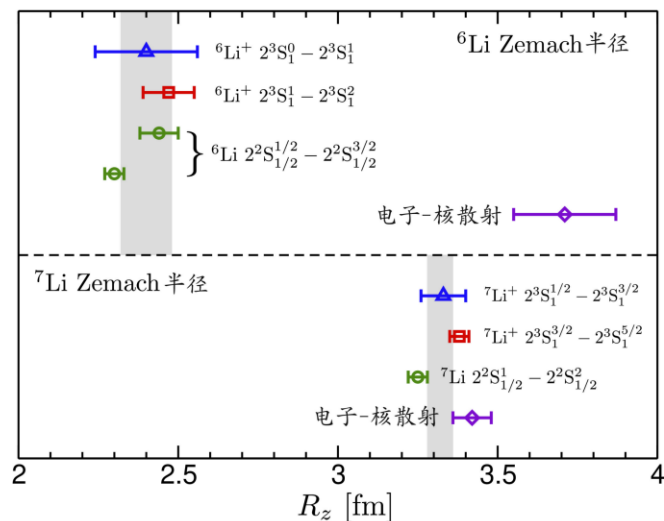
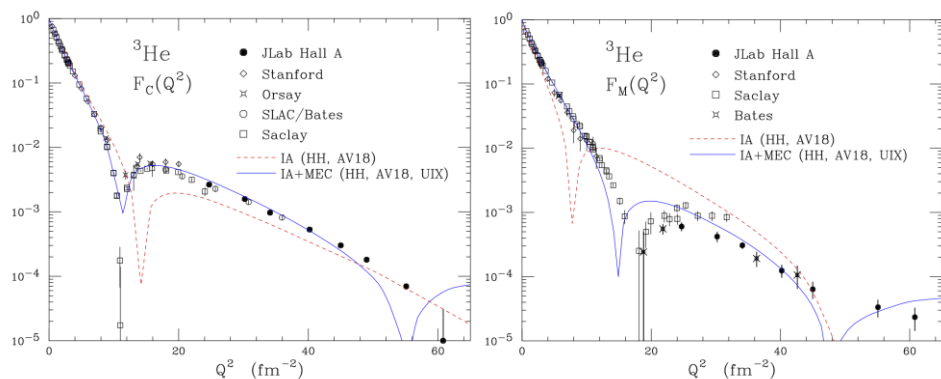
高精度激光光谱学装置示意图

目标：相对精度
提升至 10^{-6} 至 10^{-7}



缪原子谱学实验介绍

展望未来： CREMA 合作组最近提出了一项测量 μH 和 $\mu^3\text{He}^+$ 超精细结构的新研究计划。这项前沿实验旨在以高达 100ppm 的超高相对精度来确定缪子与原子核间双光子交换效应对超精细结构的影响。这一物理量的精确测定对于深入了解原子核的 Zemach 半径和核极化效应极为关键。通过对 $Z \geq 3$ 的缪原子超精细结构光谱的测量，不仅可以得到更加准确的原子核磁矩分布的信息，也能更好的理解核结构双光子交换效应对原子谱的修正。

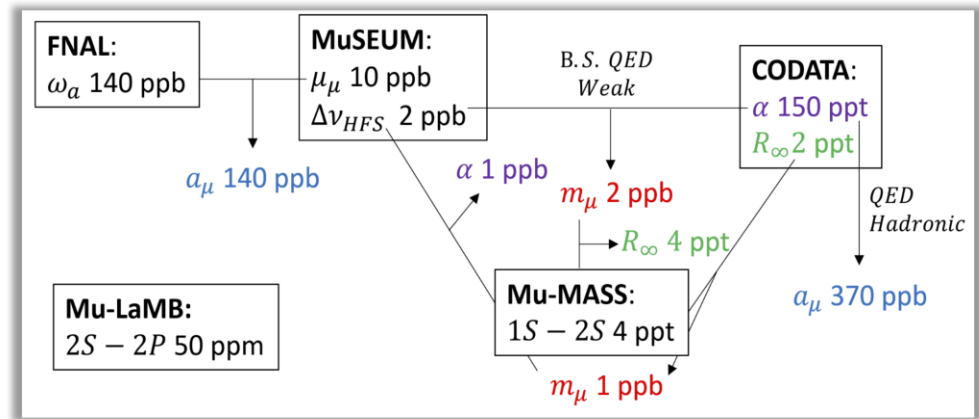
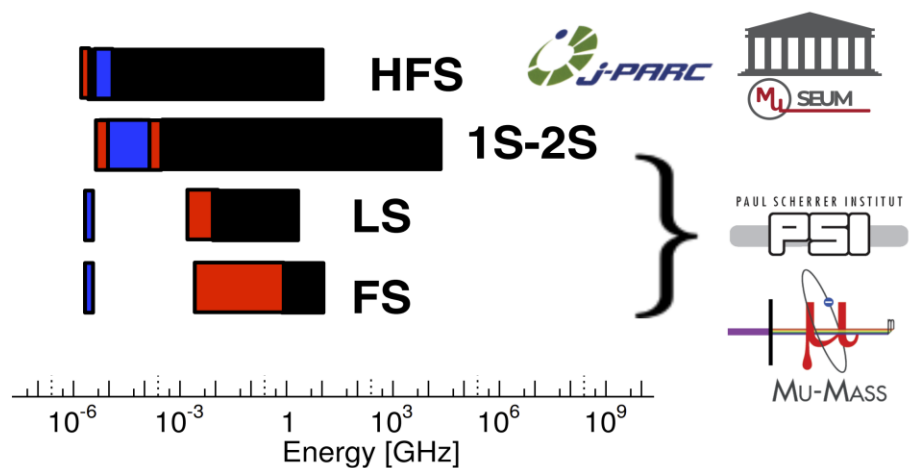


$$\delta_{\text{LS}} = \delta_{\text{QED}} + \mathcal{A}_{\text{OPE}} r_E^2 + \delta_{\text{TPE}}$$

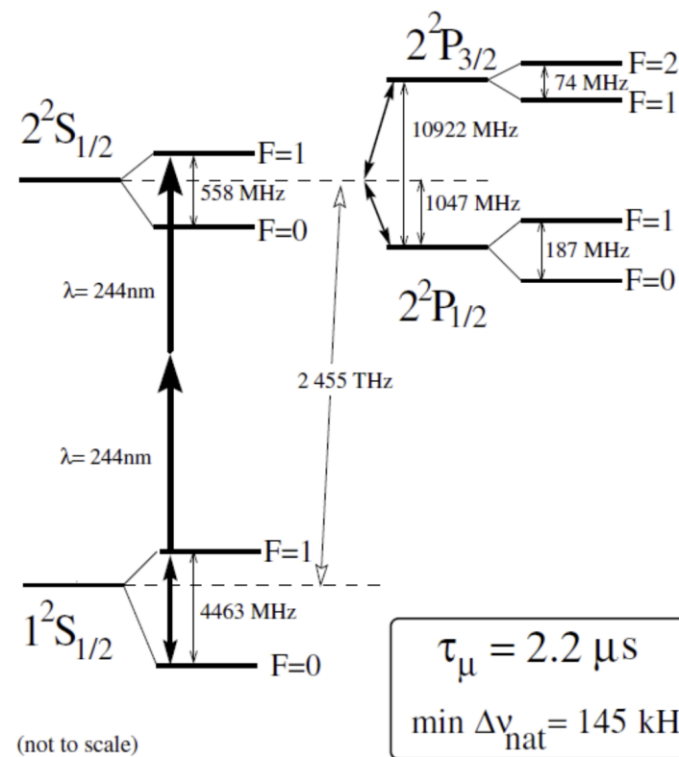
$$\delta_{\text{TPE}} = \delta_{\text{Zem}} + \delta_{\text{pol}}$$

缪子素谱学实验介绍

计划中三大缪子素谱学实验



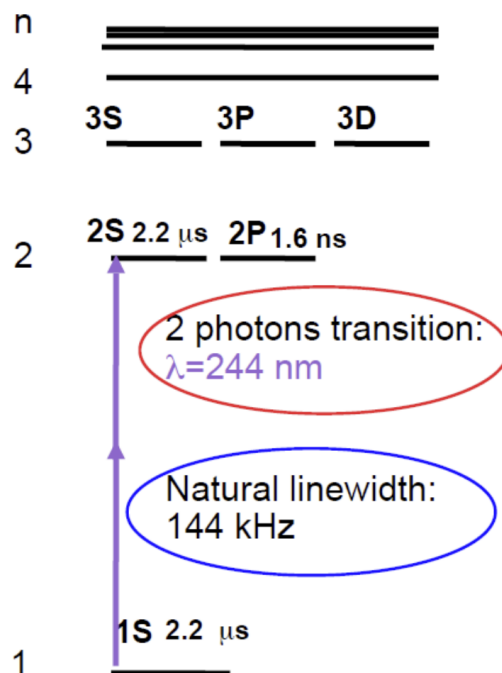
Muonium ($M=\mu^+e^-$) Energy Levels $n=1$ and $n=2$



Muonium的能级示意图

缪子素谱学实验介绍

Mu-MASS: 瞄准Mu原子1S-2S的能级跃迁, 逐渐提高其测量精度(10 kHz, 4 ppt)



得出物理量的对应精度:

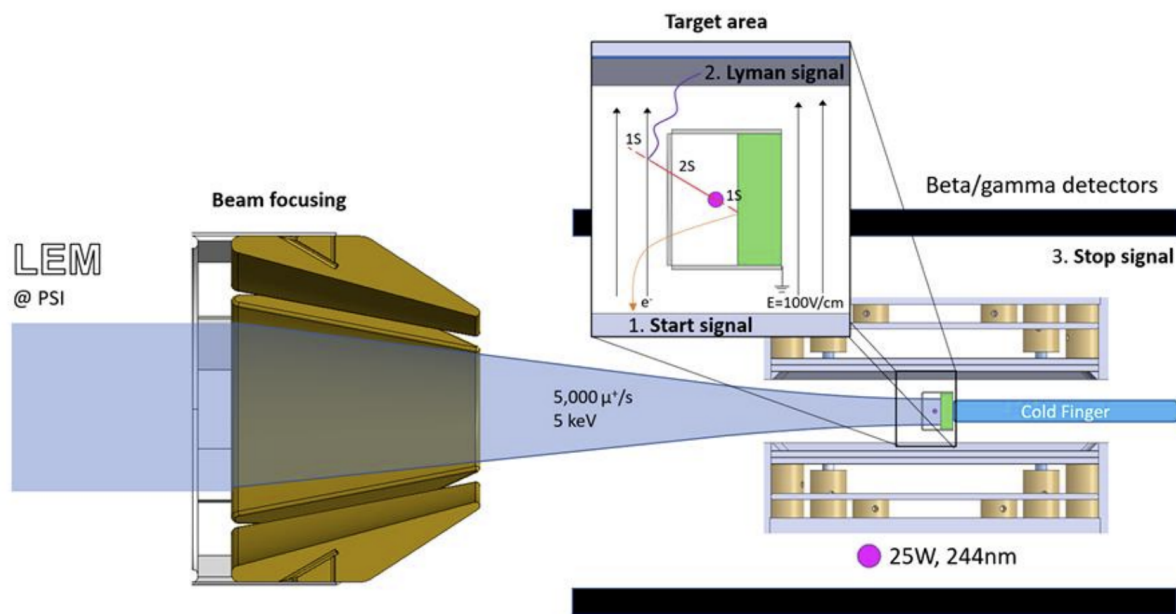
- Muon mass @ 1 ppb
- Ratio of q_e/q_μ @ 1 ppt
- Search for New Physics
- **Test of bound state QED (1×10^{-9})**
- **Rydberg constant @ ppt level**
- New determination of α @ 1 ppm
- Input to muon g-2

关键实验技术: 冷 Muonium (M) 源 + 紫外激光技术



缪子素谱学实验介绍

- 1980-2000 Muonium实验主要集中在TRIUMF, RAL and LAMPF;
- PSI的低能缪子束线 (LEM) 提高了缪子的流强和转换效率, 提高了统计记数。



典型参数:

- μ^+ 束能量: 5 keV
- 靶子面积: 6x20 mm
- 转换材料: 介孔二氧化硅薄膜
- 2S态激发效率: $\sim 10^6$
- Lyman-Alpha探测: CsI涂层的MCP探测器
- 探测窗口: ~ 10 ns
- 事件率: 几个/小时

Mu-MASS:实验装置示意图

缪子素谱学实验介绍

Measurement of the 1s-2s Energy Interval in Muonium

V. Meyer,¹ S. N. Bagayev,⁵ P. E. G. Baird,² P. Bakule,² M. G. Boshier,⁴ A. Breitrück,¹ S. L. Cornish,² S. Dychkov,⁵ G. H. Eaton,³ A. Grossmann,¹ D. Hübl,¹ V. W. Hughes,⁶ K. Jungmann,¹ I. C. Lane,² Yi-Wei Liu,² D. Lucas,² Y. Matyugin,⁵ J. Merkel,¹ G. zu Putlitz,¹ I. Reinhard,¹ P. G. H. Sandars,² R. Santra,¹ P. V. Schmidt,¹ C. A. Scott,³ W. T. Toner,² M. Towrie,³ K. Träger,¹ L. Willmann,¹ and V. Yakhontov¹

¹Physikalisches Institut der Universität Heidelberg, D-69120 Heidelberg, Germany

²Physics Department, University of Oxford, Clarendon Laboratory, Oxford OX1 3PU, United Kingdom

³Rutherford Appleton Laboratory, Chilton, Didcot, Oxon OX11 0QX, United Kingdom

⁴Physics Department, University of Sussex, Brighton BN1 9QH, United Kingdom

⁵Institute of Laser Physics, Novosibirsk 630090, Russia

⁶Physics Department, Yale University, New Haven, Connecticut 06520

(Received 12 July 1999)

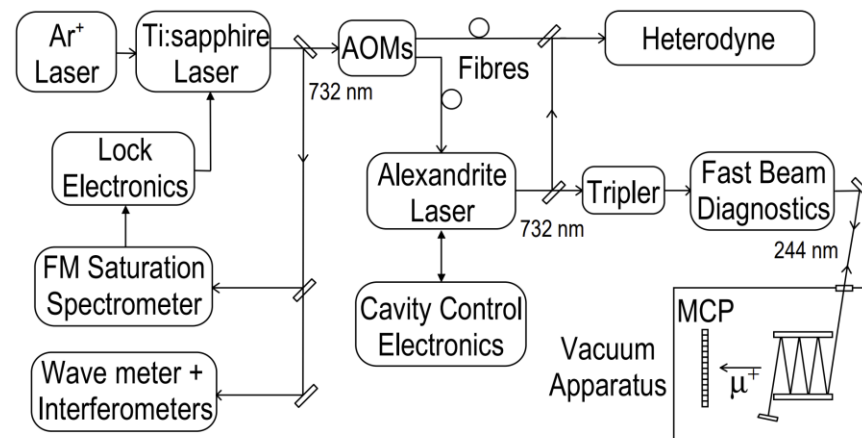
The 1s-2s interval has been measured in the muonium (μ^+e^-) atom by Doppler-free two-photon pulsed laser spectroscopy. The frequency separation of the states was determined to be 2 455 528 941.0(9.8) MHz, in good agreement with quantum electrodynamics. The result may be interpreted as a measurement of the muon-electron charge ratio as $-1-1.1(2.1) \times 10^{-9}$. We expect significantly higher accuracy at future high flux muon sources and from cw laser technology.

$$\Delta\nu_{1S-2S} = 2\,455\,528\,941.0(9.8) \text{ MHz } (\sim 4 \text{ ppb})$$

$$\Delta\nu_{LS} = 7\,049.4(9.9) \text{ MHz}$$

$$m_{\mu^+}/m_{e^-} = 206.768\,38(17),$$

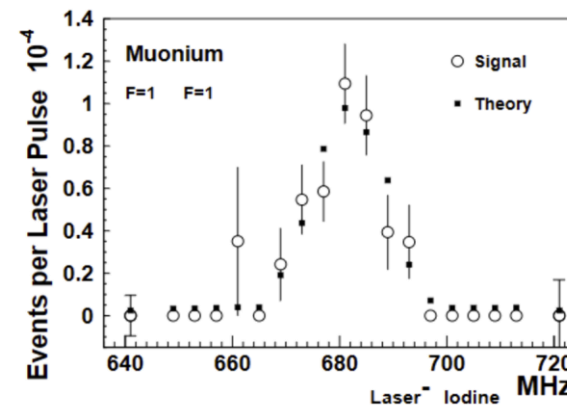
$$Z = q_{\mu^+}/q_{e^-} = -1-1.1(2.1) \times 10^{-9}$$



Facility: RALin Chilton, UK.

Repetition rate: 50 Hz

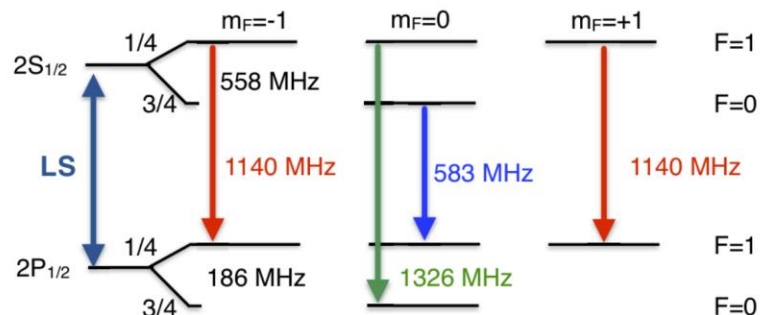
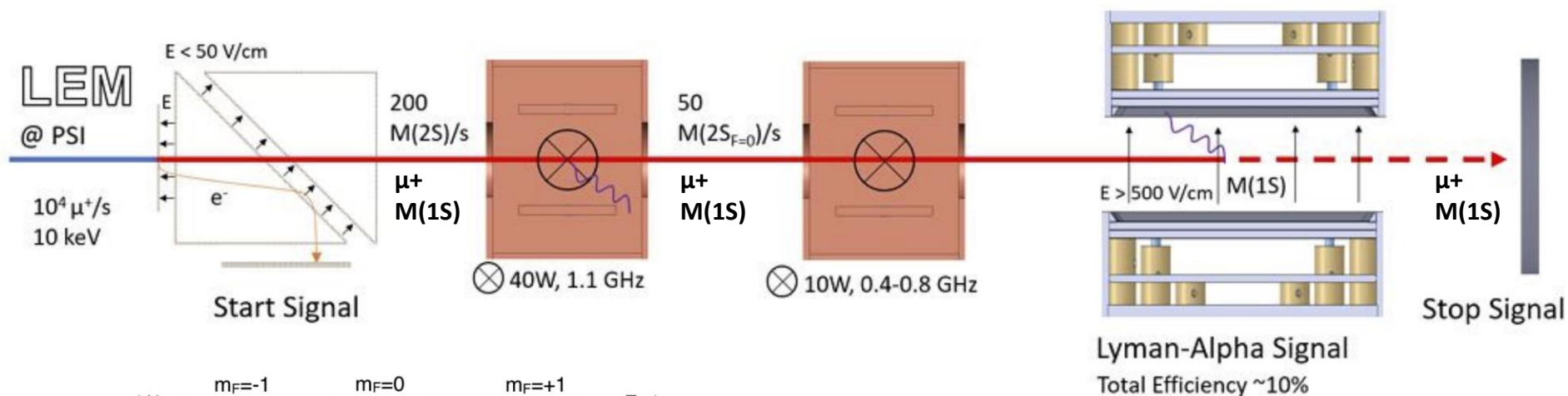
3500 μ^+ per pulse at $p=26.5$ MeV/c



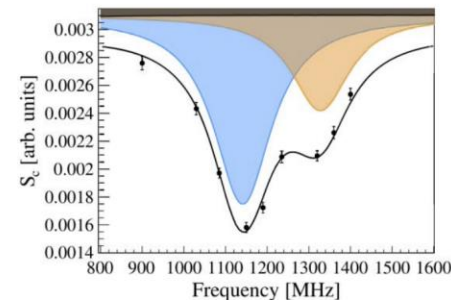
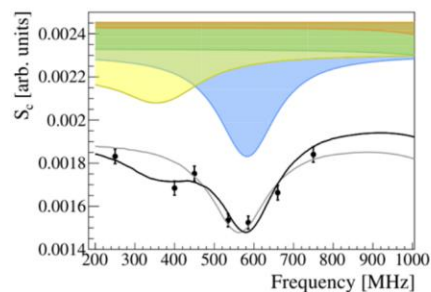
缪子素谱学实验介绍

- Muonium原子的 $2S_{1/2}-2P_{1/2}$ 跃迁位于微波段；
- 激光激发效率太低，采用束箔技术提升Mu(2S)的产生效率；

(a) Neutralization & Tagging (b) Hyperfine-selection (c) Scan resonance (d) Quenching & detection (e) Back detector



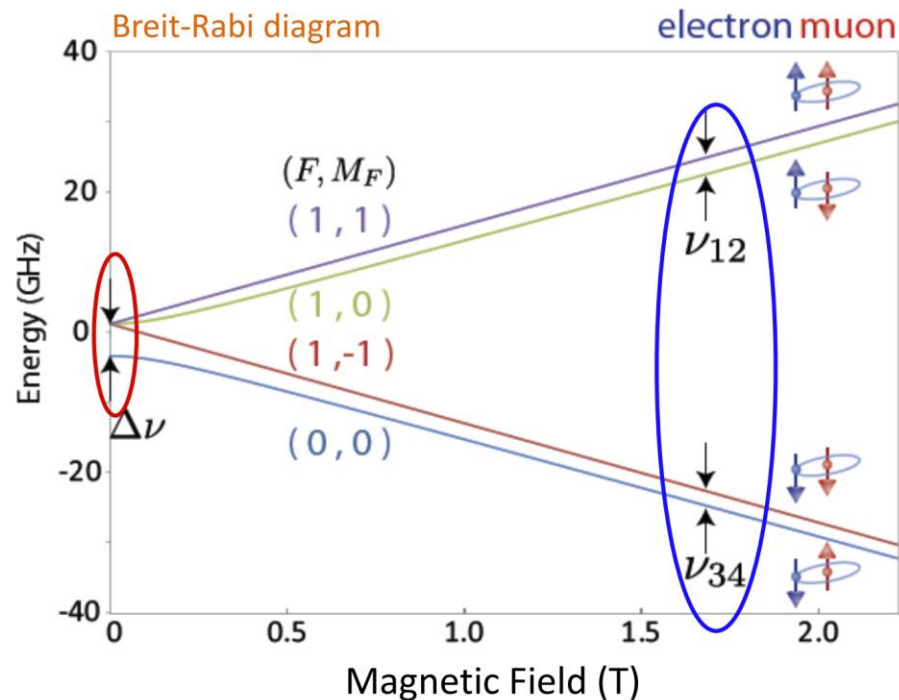
B. Ohayon et al., *Phys. Rev. Lett.* **128**, 011802 (2022)



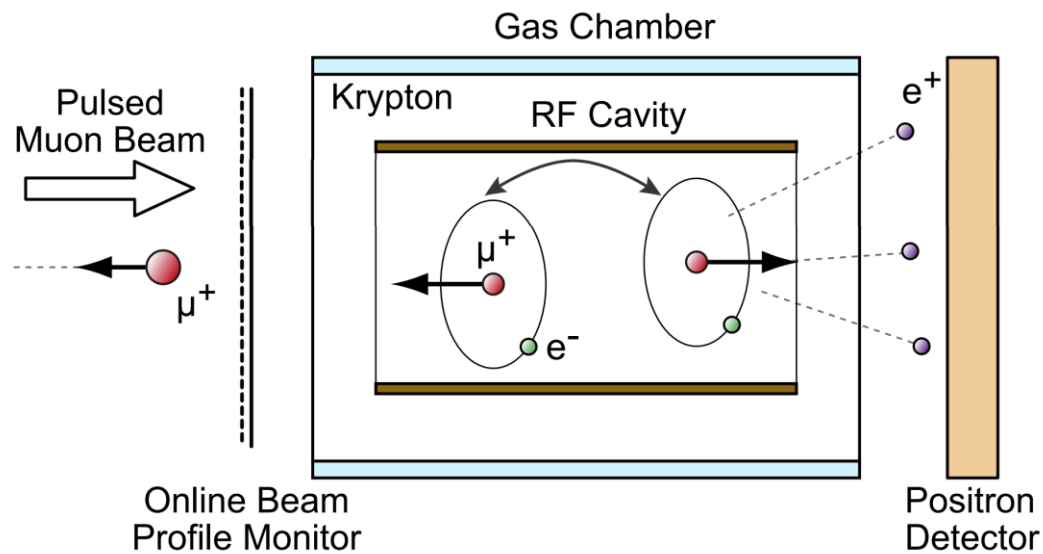
缪子素兰姆
位移测量

缪子素谱学实验介绍

Zeeman Splitting



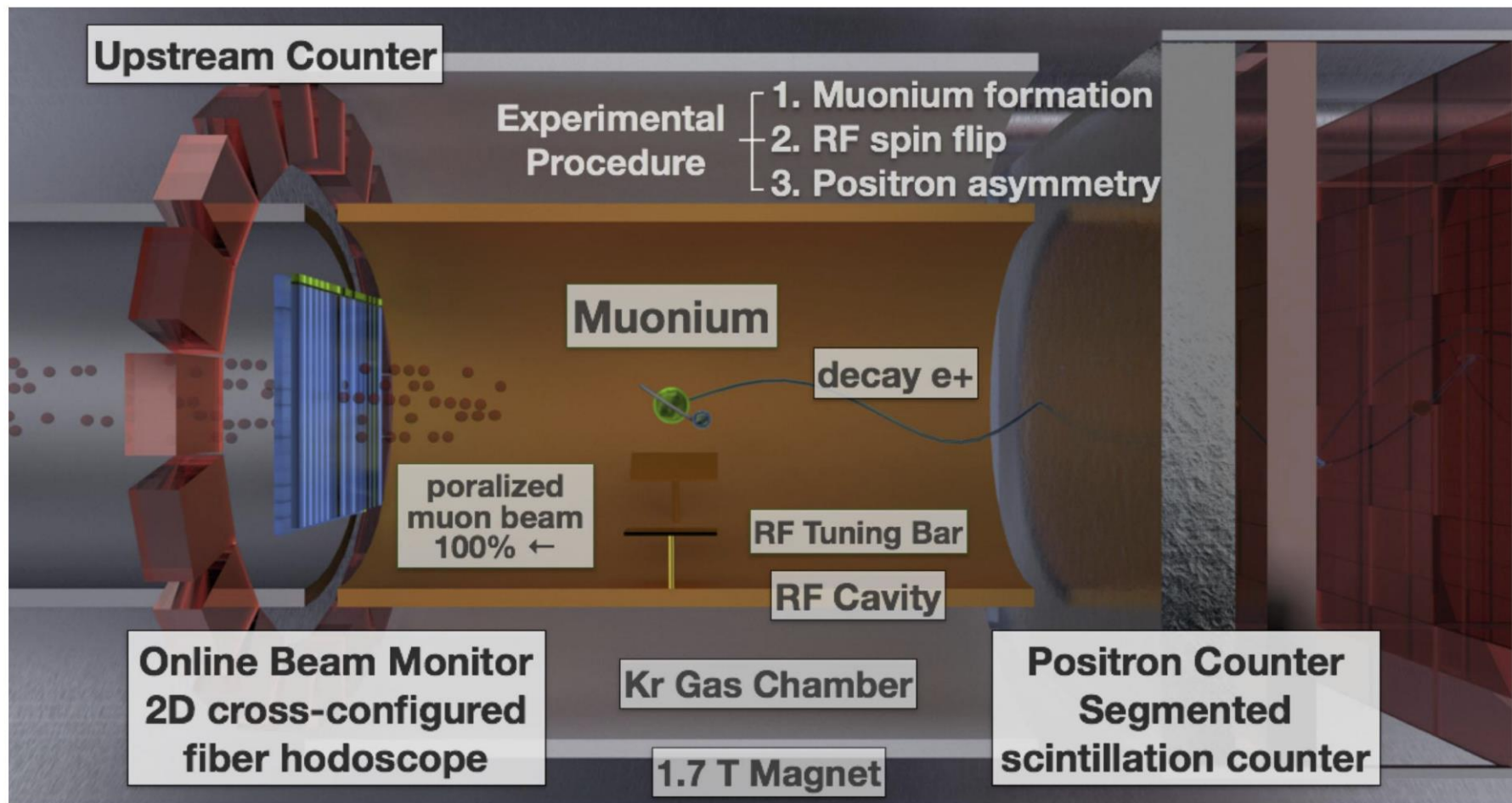
$$\nu_{12} + \nu_{34} = \Delta\nu_{\text{HFS}} \quad \nu_{12} - \nu_{34} \propto \mu_{\mu}/\mu_p \propto m_{\mu}/m_p$$



MuSEUM: 缪子素超精细结构实验

缪子素谱学实验介绍

核磁共振技术
翻转缪子自旋



缪子寿命高精度测量实验

研究动机

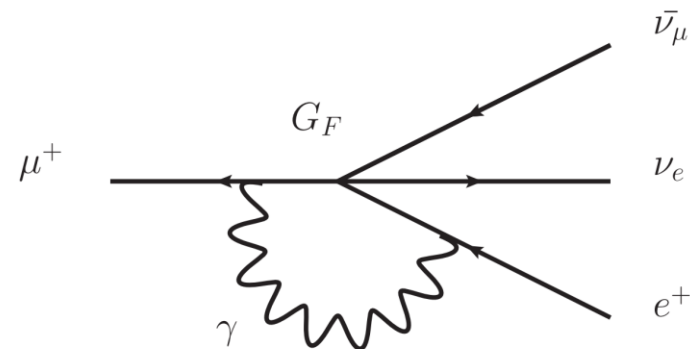
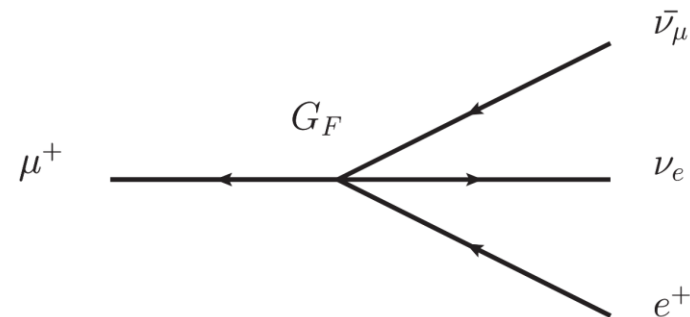
- 精确确定弱相互作用耦合常数
- 精确检验电弱理论并限制新物理

缪子寿命实验的优势

- QED修正理论误差小 (~ 0.15 ppm)

$$\frac{1}{\tau_\mu} = \frac{G_F^2 m_\mu^5}{192\pi^3} \left(1 + \sum_i \Delta q^{(i)} \right)$$

- 微秒量级的寿命，契合当前的电子技术



$$M_W^2 \left(1 - \frac{M_W^2}{M_Z^2} \right) = \frac{\pi\alpha}{\sqrt{2}G_F} \left(1 + \sum_i r_i \right)$$

缪子寿命高精度测量实验

PRL **106**, 041803 (2011)

PHYSICAL REVIEW LETTERS

week ending
28 JANUARY 2011

Measurement of the Positive Muon Lifetime and Determination of the Fermi Constant to Part-per-Million Precision

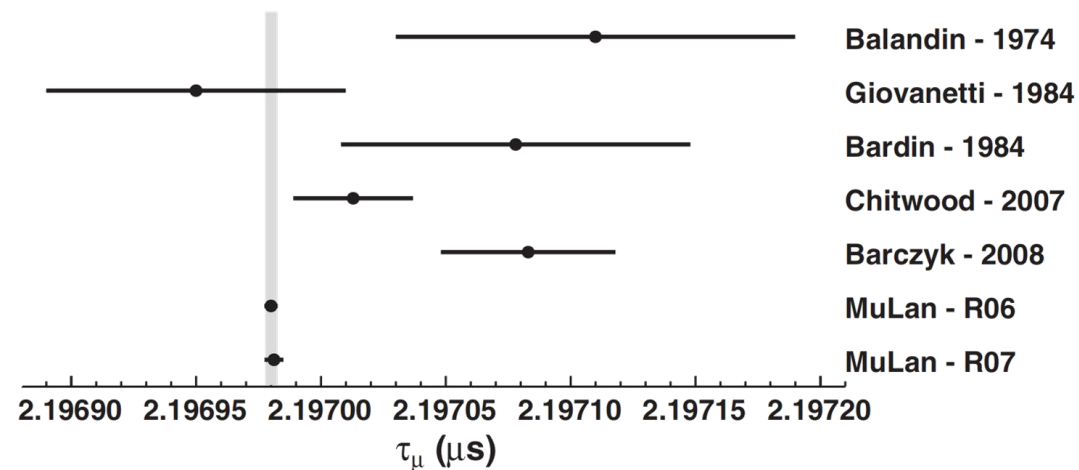
D. M. Webber,¹ V. Tishchenko,² Q. Peng,³ S. Battu,² R. M. Carey,³ D. B. Chitwood,¹ J. Crnkovic,¹ P. T. Debevec,¹ S. Dhamija,² W. Earle,³ A. Gafarov,³ K. Giovanetti,⁴ T. P. Gorringer,² F. E. Gray,⁵ Z. Hartwig,³ D. W. Hertzog,¹ B. Johnson,⁶ P. Kammel,¹ B. Kiburg,¹ S. Kizilgul,¹ J. Kunkle,¹ B. Lauss,⁷ I. Logashenko,³ K. R. Lynch,³ R. McNabb,¹ J. P. Miller,³ F. Mulhauser,^{1,7} C. J. G. Onderwater,^{1,8} J. Phillips,³ S. Rath,² B. L. Roberts,³ P. Winter,¹ and B. Wolfe¹

(MuLan Collaboration)

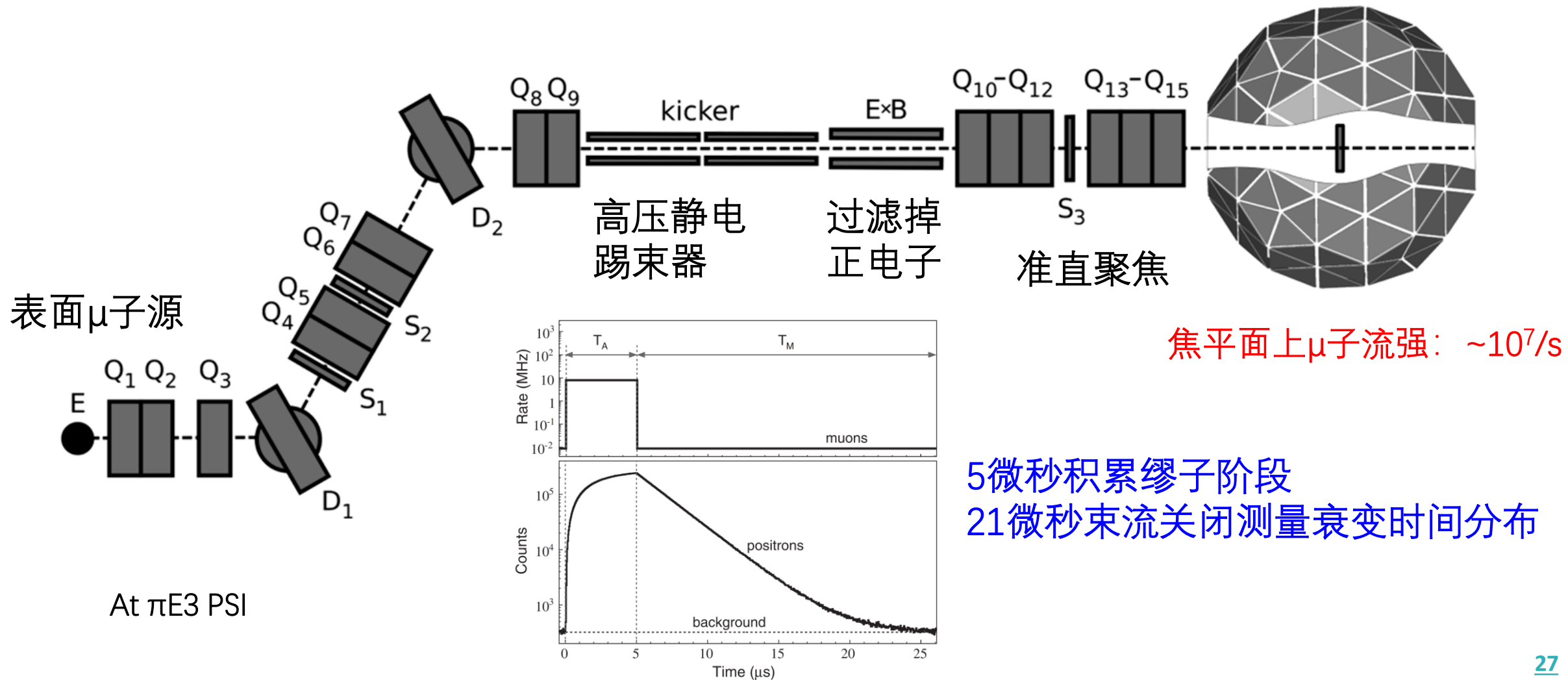
Data subset	Detector position [cm]			Magnet orientation	Detected positrons
	x	y	z		
R06-A	0	0	0	L	6.1×10^{11}
R06-B	0	0	0	R	5.0×10^{11}
R07-A	0	0	0	L	2.1×10^{11}
R07-B	0	0	0	R	2.4×10^{11}
R07-C	1.0	-1	0	L	3.2×10^{10}
R07-D	0.5	-1	0	L	1.4×10^{10}
R07-E	0.5	0	0	L	3.0×10^{10}
R07-F	0.5	-0.5	0	R	1.8×10^{10}

$$\tau_{\mu}(\text{MuLan}) = 2196980.3(2.2) \text{ ps (1.0 ppm)}$$

$$G_F(\text{MuLan}) = 1.1663787(6) \times 10^{-5} \text{ GeV}^{-2} \text{ (0.5 ppm)}$$



缪子寿命高精度测量实验



缪子寿命高精度测量实验

- 缪子停止靶

Arnokromelll铁磁合金 (0.5mm, $B=0.4T$)

石英 (2mm, $B=150G$)

(控制自旋转动、退极化的系统误差)

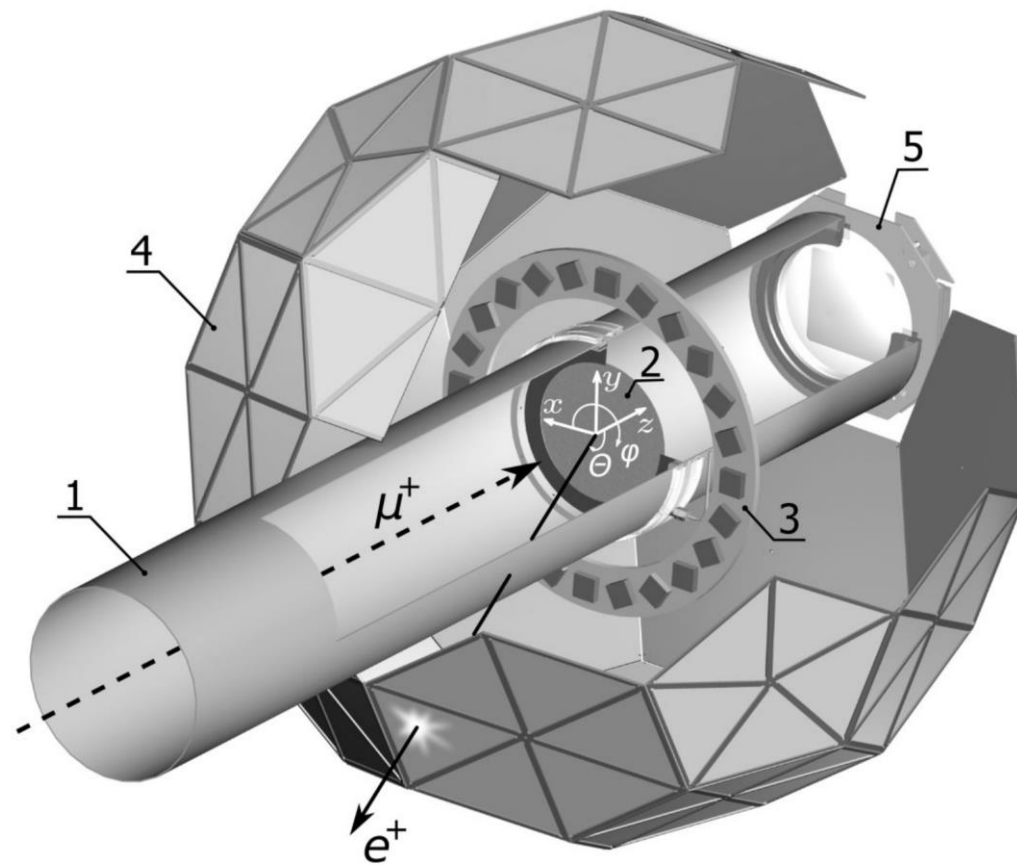
- 正电子探测器

170块三角形塑闪探测模块

(每模块有两片3mm厚探测器符合测量)

类似足球几何

- 波形采样ADC (450MHz, 8bit)

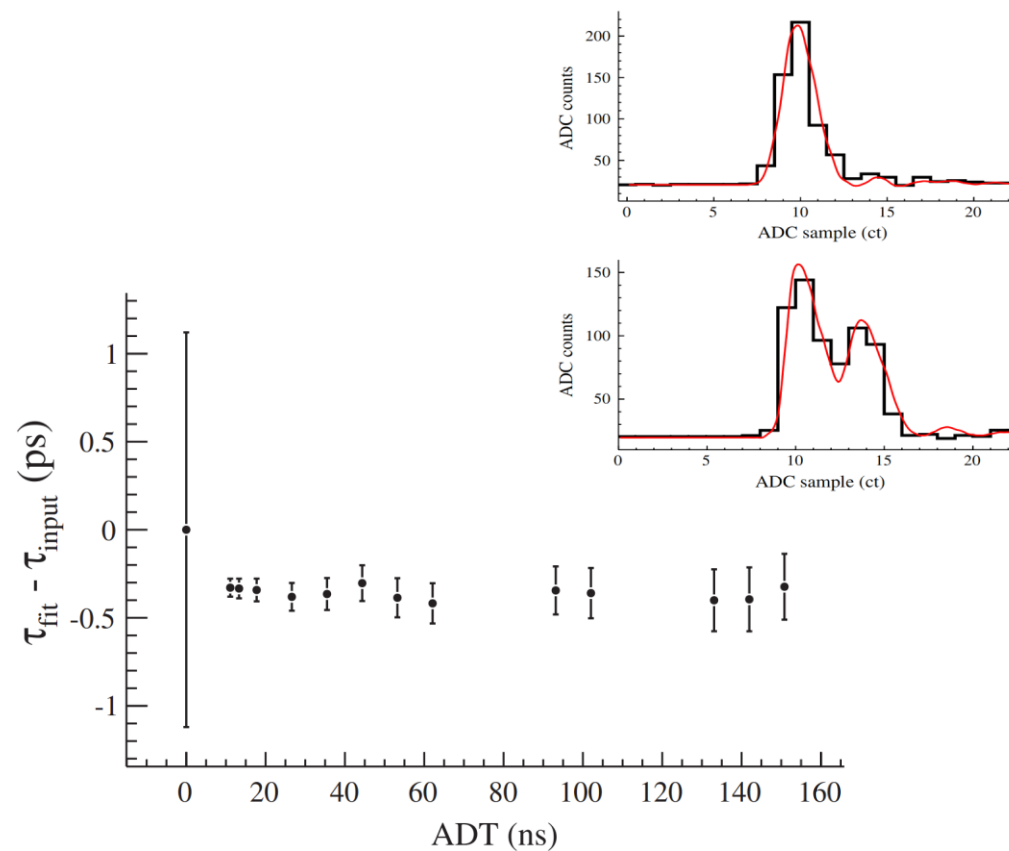


缪子寿命高精度测量实验

误差分析

Uncertainty	R06 (ppm)	R07 (ppm)
Kicker stability	0.20	0.07
μ SR distortions	0.10	0.20
Pulse pileup		0.20
Gain variations		0.25
Upstream stops		0.10
Timing pick-off stability		0.12
Master clock calibration		0.03
Combined systematic uncertainty	0.42	0.42
Statistical uncertainty	1.14	1.68

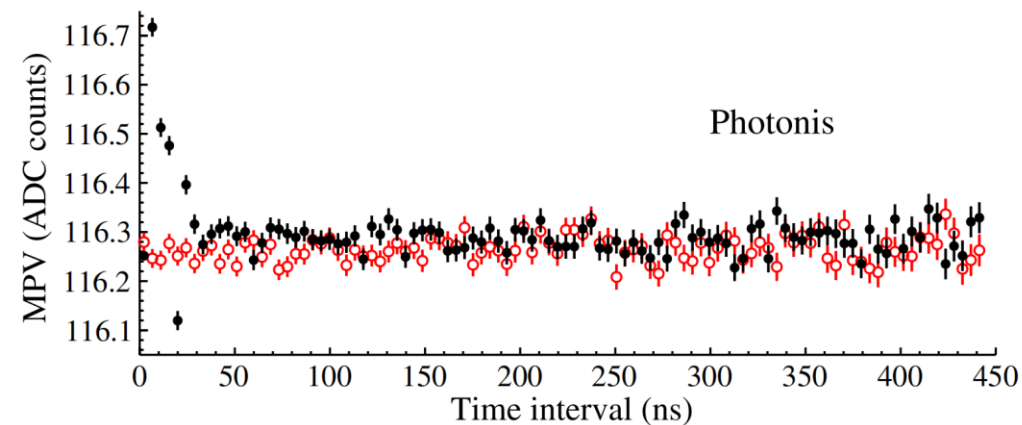
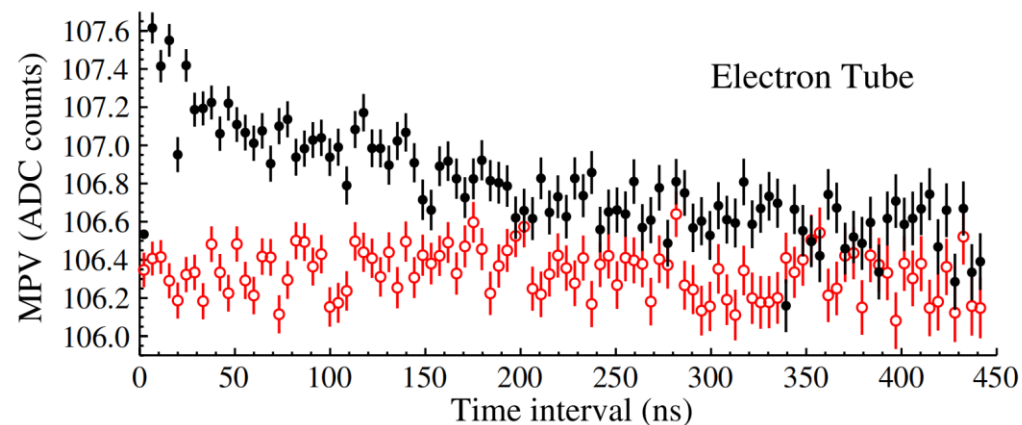
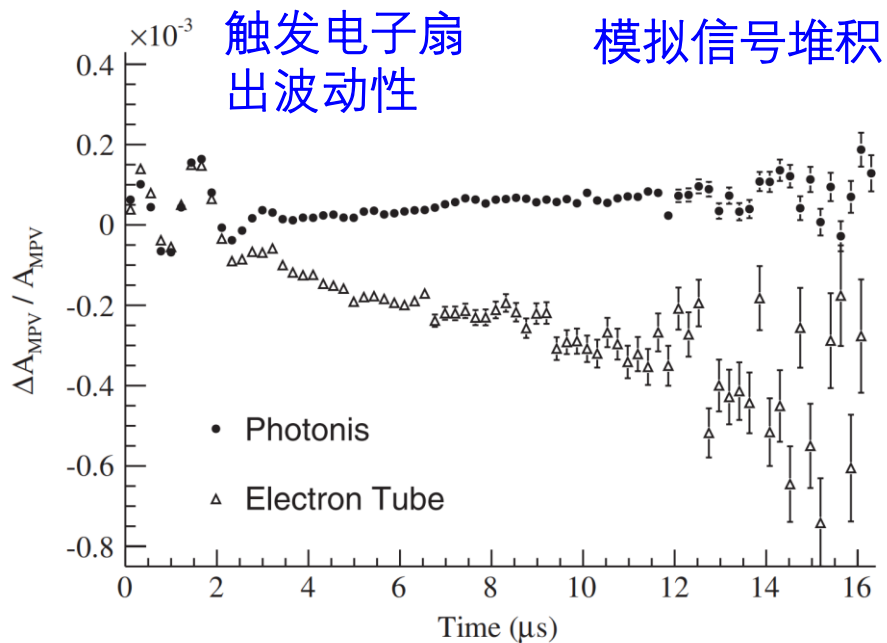
事例堆积和死时间修正



缪子寿命高精度测量实验

- 增益变化修正

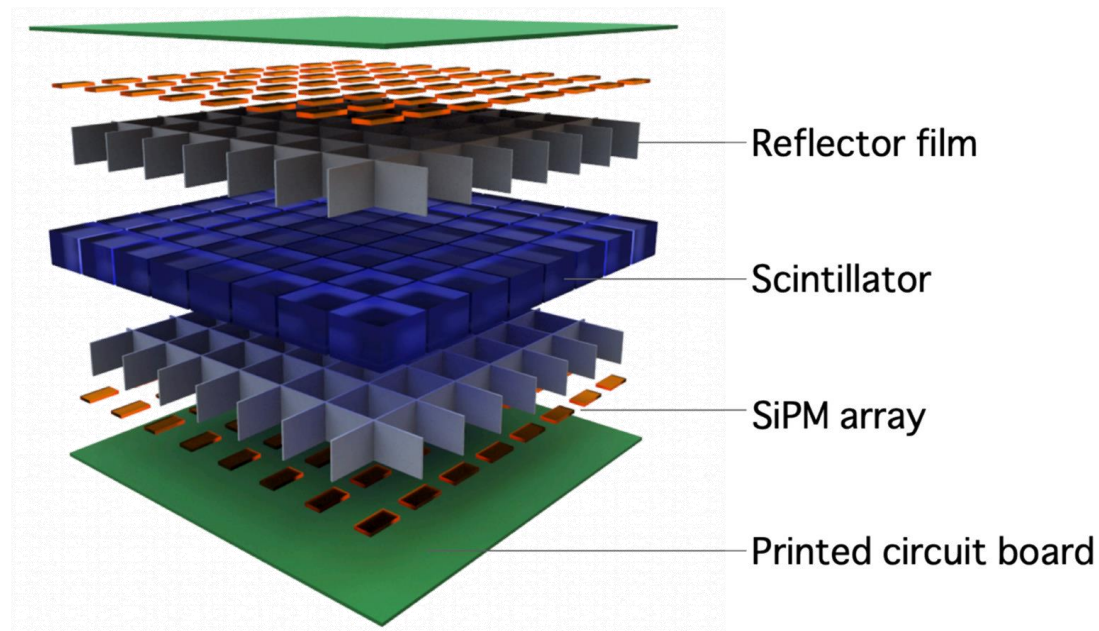
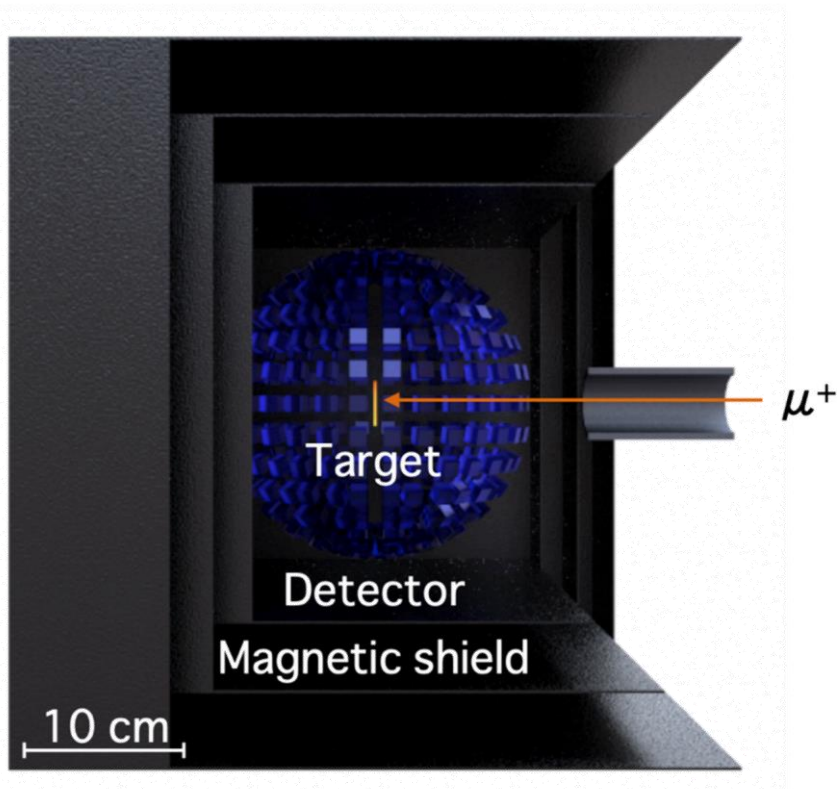
使用两种不同厂家的PMT。



缪子寿命高精度测量实验

未来J-PARC缪子寿命实验提议

- ✓ MUSE H-Line表面缪子流强: $10^8/s$
- ✓ 磁场屏蔽来消除缪子自旋进动和退极化的影响
- ✓ 高分割化的正电子探测器 (14000, $3 \times 3 \text{ mm}^2$)
- ✓ 目标统计量 10^{14}



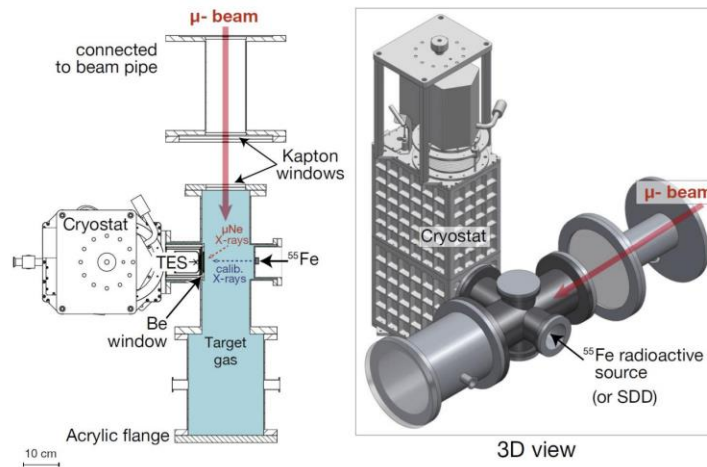
小结

- 缪原子高精度谱学实验和缪子寿命高精度测量实验的目标既是**高精度测量电弱基本常数、验证基本对称性**，同时也是为了**新物理新发现**。
- 高精度既取决于缪子流强（我们有优势），也取决于探测器、激光、电子学等的灵敏度和分辨率。探测器方面我们需逐渐积累优势。

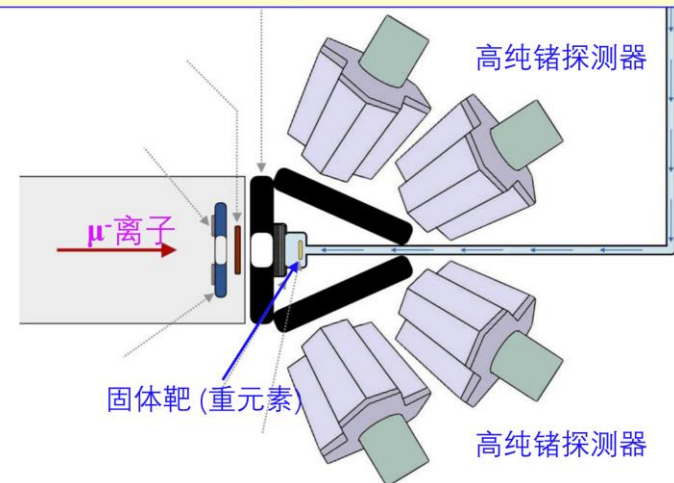
➤ 缪原子谱学实验设想

（汶伟强、黄忠魁、马新文）

- 缪离子 + 气体靶 + 低温X射线能谱仪
- 极高能量分辨: 3.3eV@6keV, 50eV@60keV
- 具有大的能量测量范围和极高的探测效率



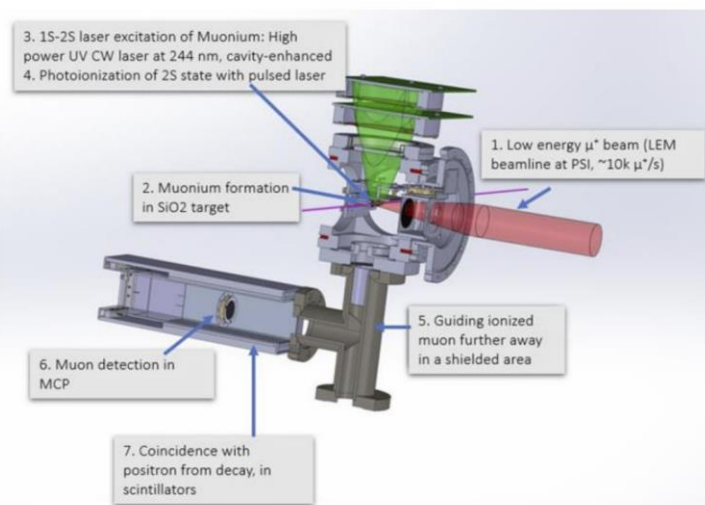
- 缪离子 + 固体靶(重元素) + 高纯锗X射线能谱仪
- X-ray能量5~300 keV, 分辨: 550eV@122keV
- 能够探测高能X-ray, 开拓重元素缪离子实验



小结

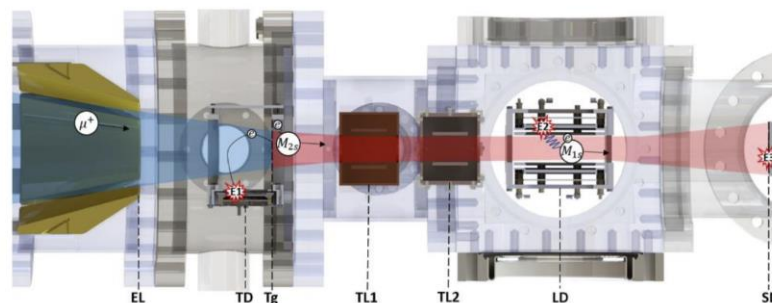
- M原子1S-2S跃迁的精密测量
- M原子n=2以及n>2 兰姆位移精密测量

● 低温Muonium源 + UV激光 + 光子探测器



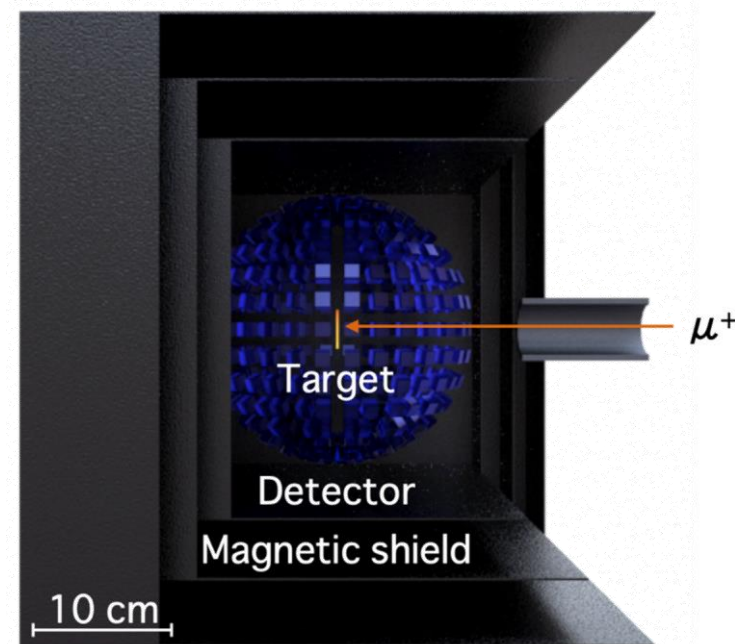
— 汶伟强、黄忠魁、马新文

● 低温Muonium源 + 微波系统 + 光子探测器



- 配备对应n=1→n=2的跃迁波长的激光系统
- 配备对应超精细跃迁的微波系统

- 缪子寿命高精度测量 (<ppm)



谢谢！欢迎各位专家学者的问题和建

Backup

- 真缪子素($\mu^+\mu^-$)的谱学研究 (最小尺寸的纯QED束缚系统)

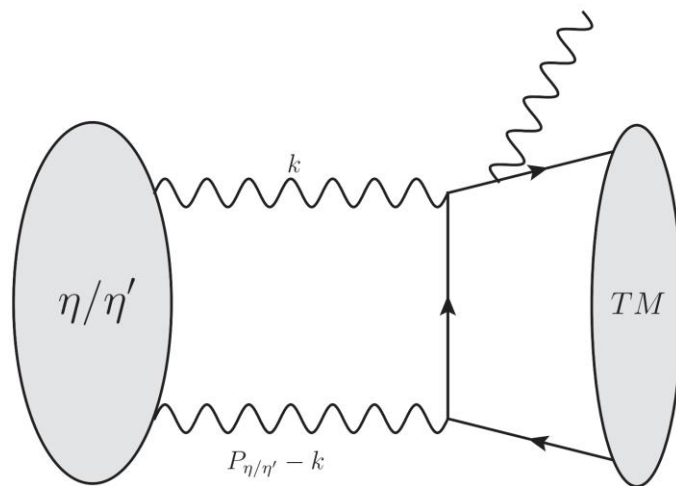
精确探测短程新相互作用

产生方式: 小角度正负电子融合、两体衰变 $\eta \rightarrow \mathbf{TM} + \gamma$ 、 $\mu^+\mu^-$ 结合……

- 反缪子素实验 (μ^-e^+)

正反物质对称性

μ^- 束流, 正电子源



$$BR(\eta \rightarrow (\mu^+\mu^-)\gamma) \approx 10^{-9}$$

Backup

- 缪子参与的自旋相关的新相互作用

类轴粒子传递的自旋相关的新相互作用

$$V_{SP}(r) = \frac{\hbar^2 g_S g_P}{8\pi m} \left(\frac{1}{\lambda r} + \frac{1}{r^2} \right) \frac{\exp(-r/\lambda)}{r} \vec{\sigma} \cdot \hat{r}$$

$$V_{VA}(r) = \frac{\hbar g_V g_A}{2\pi} \frac{\exp(-r/\lambda)}{r} \vec{\sigma} \cdot \vec{v}$$

