

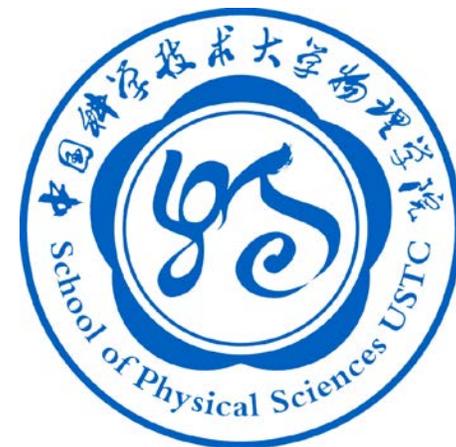


中国科学技术大学
University of Science and Technology of China

核技术在交叉科学中的应用 ---正电子湮没技术和Muon技术

叶邦角

物理学院
中国科学技术大学



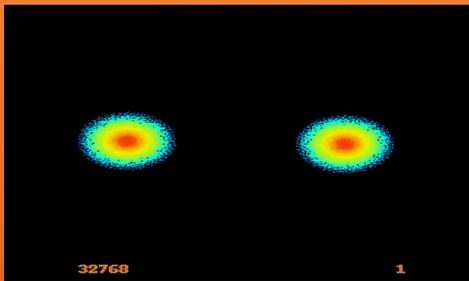
核探测与核电子学国家重点实验室

State Key Laboratory of Particle Detection and Electronics

中国科学技术大学部

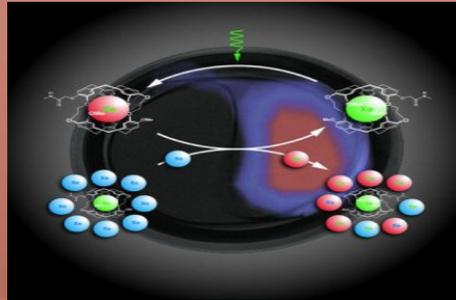
High energy physics

Particle physics

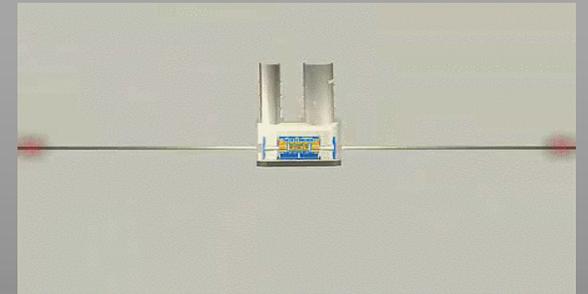


Nuclear physics

and application



Detecting techniques and electronics



Laboratory of Nuclear Solid State Physics



Staff and student

Professor (1)

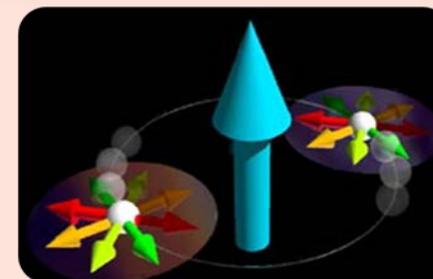
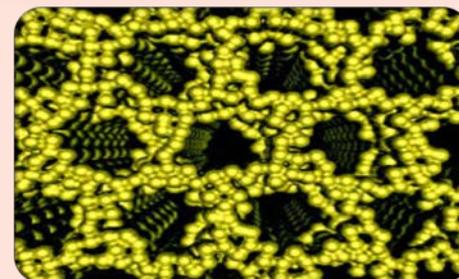
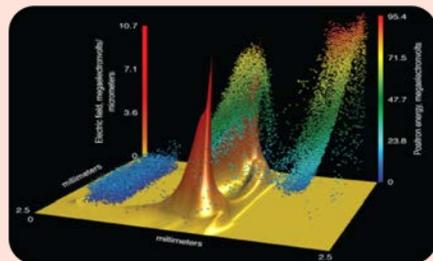
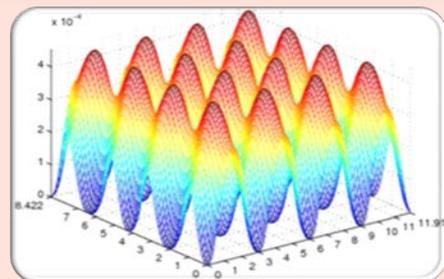
Associate professor (1) + Lecturer (1) , Post-doctoral (1) ,

PhD Students (12) + Master graduate students (5)



中国科学技术大学 核固体物理实验室

Laboratory of Nuclear Solid State Physics, USTC



理论研究

To develop positron annihilation theory and to calculate positron behavior in materials.

探测技术

To develop new methods and techniques for positron probe .

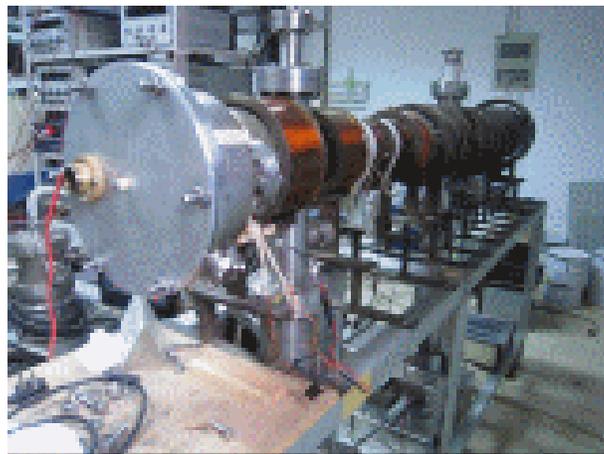
材料应用

To research microstructure of materials by using variety positron annihilation techn.

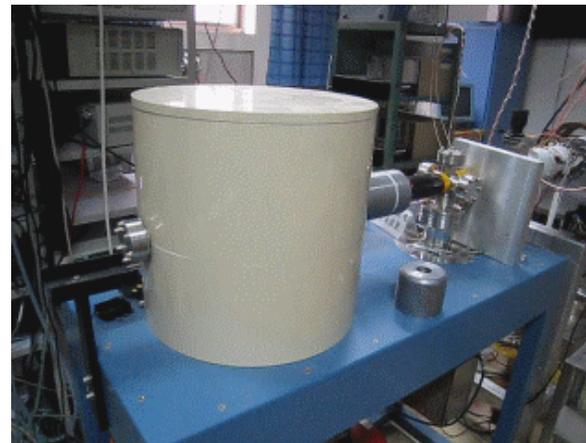
Muon科学

To develop the first muon beam in China and to develop detecting technique for muon probe .

LNSSP正电子装置和谱仪



Slow positron beam(20mCi)
(1992)



Pulsed positron beam(50mCi)
(2012)



Digital PAS
(2005)



Digital CDB
(2004)



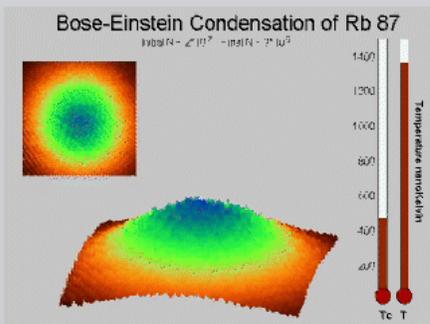
Semi-digital AMOC
(2009)



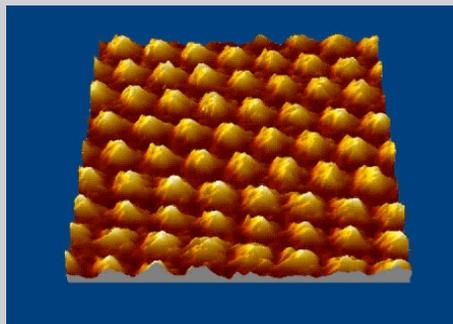
2D-PAS
(2012)

I. 正电子湮没探测技术及其应用

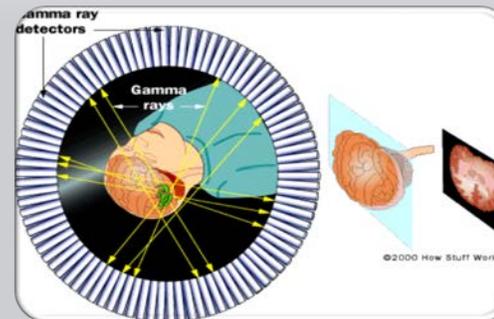
正电子科学



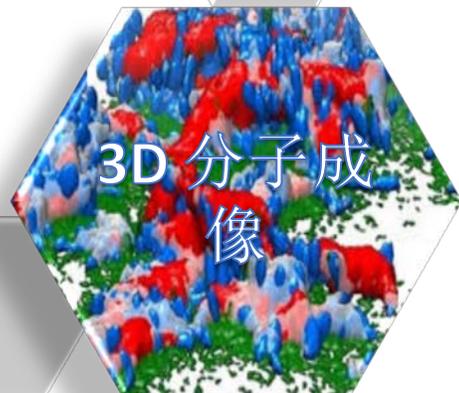
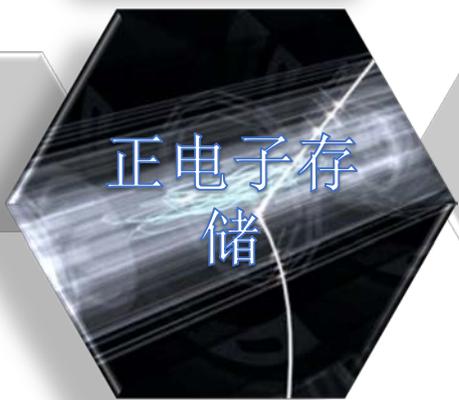
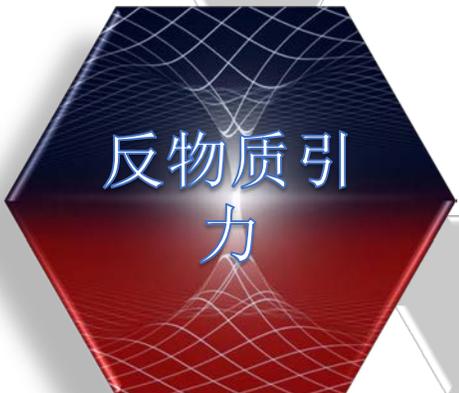
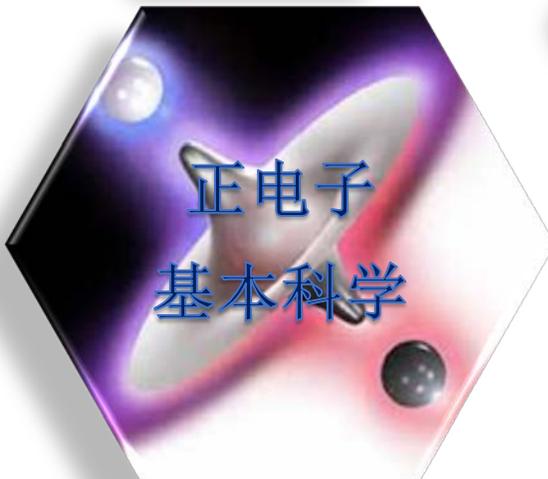
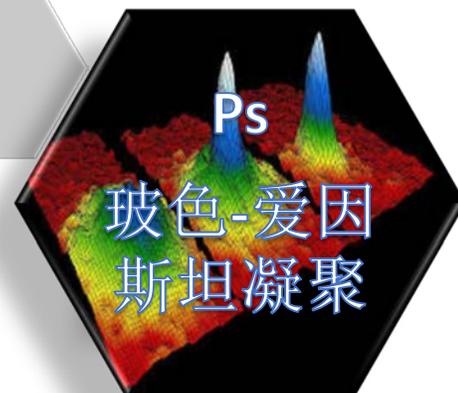
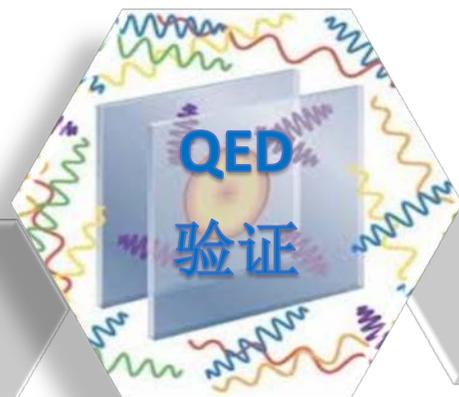
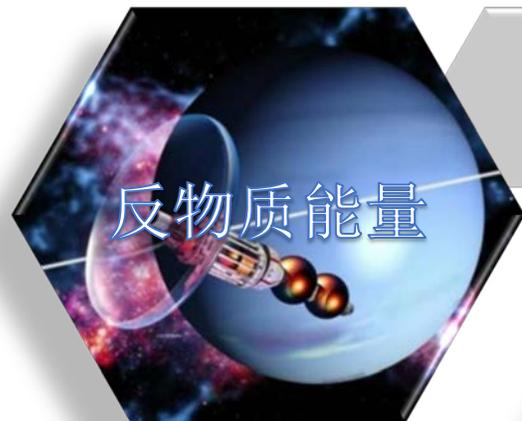
基本科学



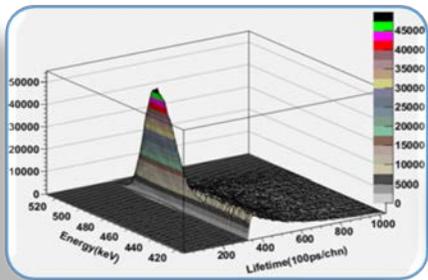
材料科学



探测技术

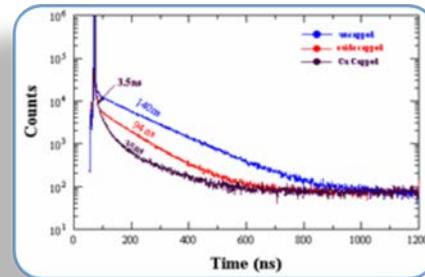


正电子探测艺术



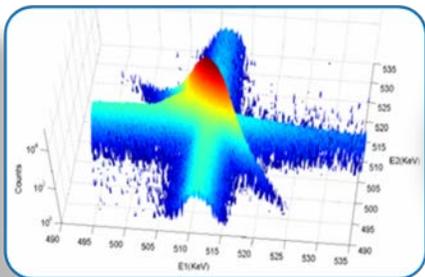
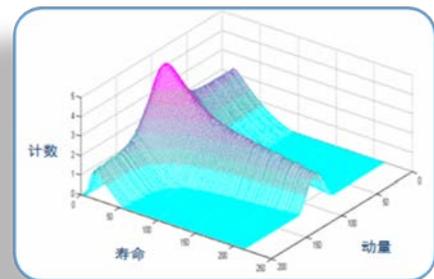
二维正电子谱仪

正电子湮没寿命谱仪



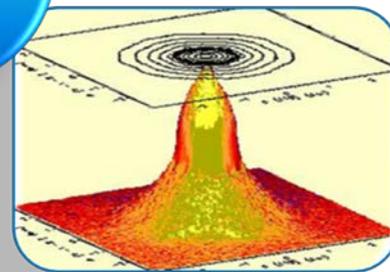
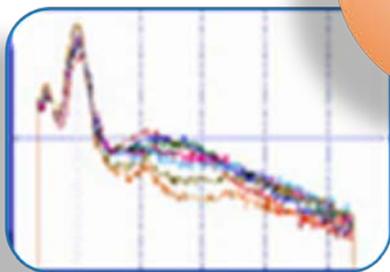
符合多普勒展宽谱仪

寿命-动量关联谱仪

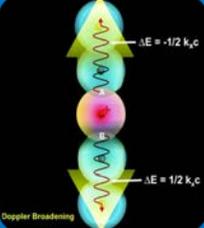


正电子偶素飞行时间谱仪

二维角关联谱仪



正电子湮没探测信息



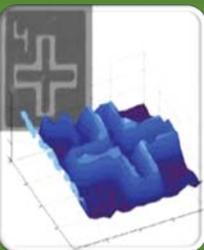
Energy (and momentum)

- Energy and energy broadening
- Momentum



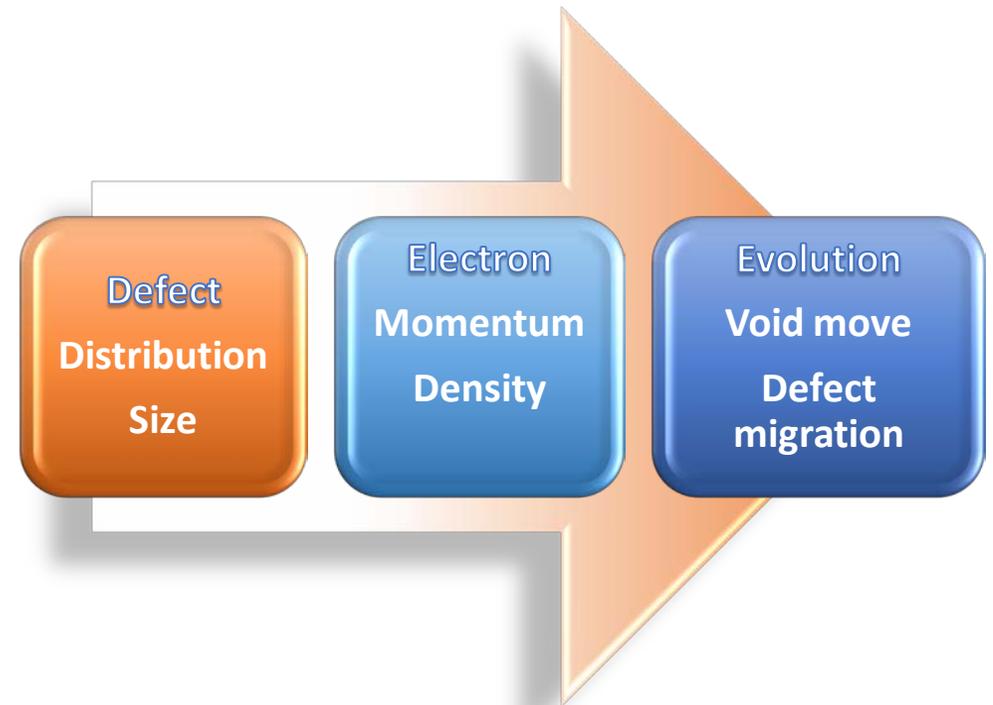
Time (lifetime)

- Annihilation lifetime
- Ps-TOF



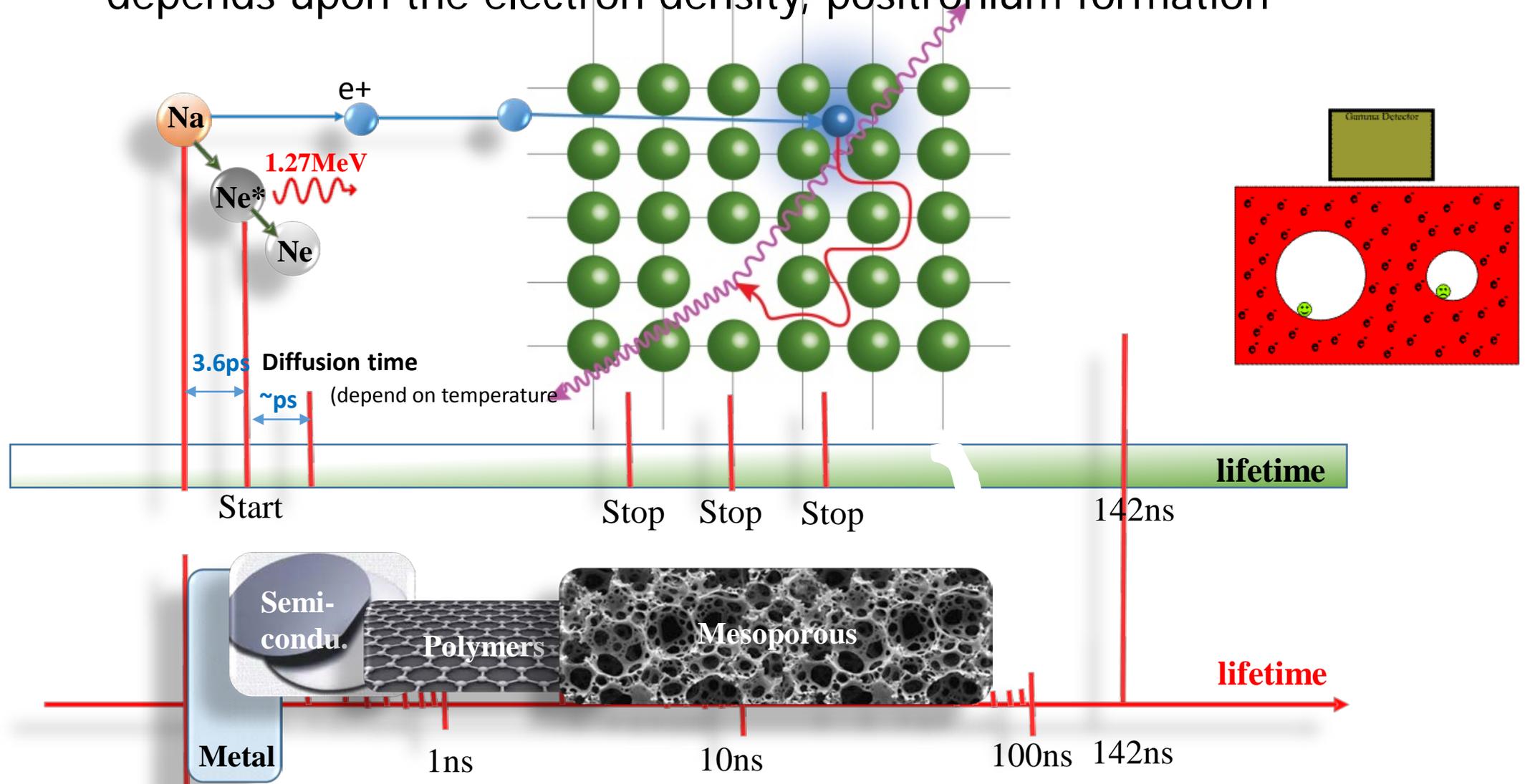
Space(depth and position)

- Injection depth
- Position resolution



正电子在固体材料

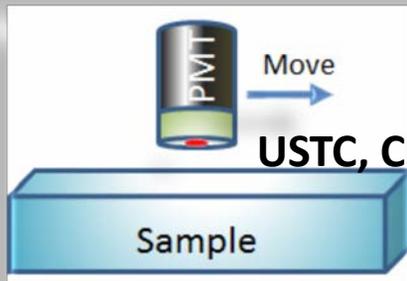
Positron lifetimes in various materials – depends upon the electron density, positronium formation



最近正电子湮没技术的发展

单样品寿命谱仪

- Based anticoincidence
- Detector moving



USTC, China

Sample

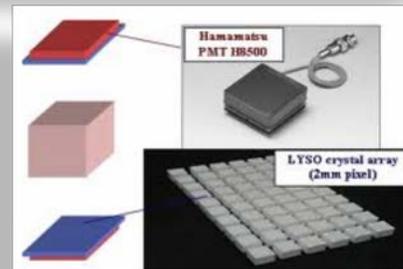
寿命谱仪

Δt : 180~220ps



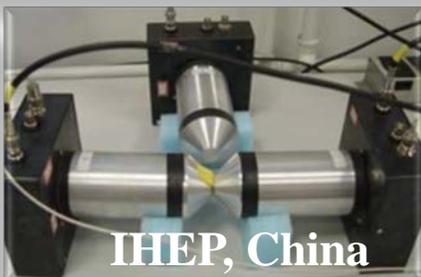
位置分辨寿命谱仪?

- Scintillators array
- Move ^{22}Na point source (scanning)



高分辨寿命谱仪

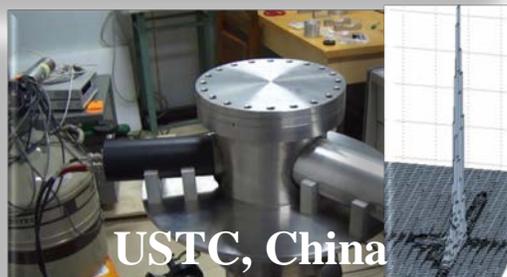
- 3γ coincidence
- Time resolutions $\sim 140\text{ps}$



IHEP, China

二维寿命谱仪

- 3γ measure, coincidence
- One scintillator with good energy resolution



USTC, China

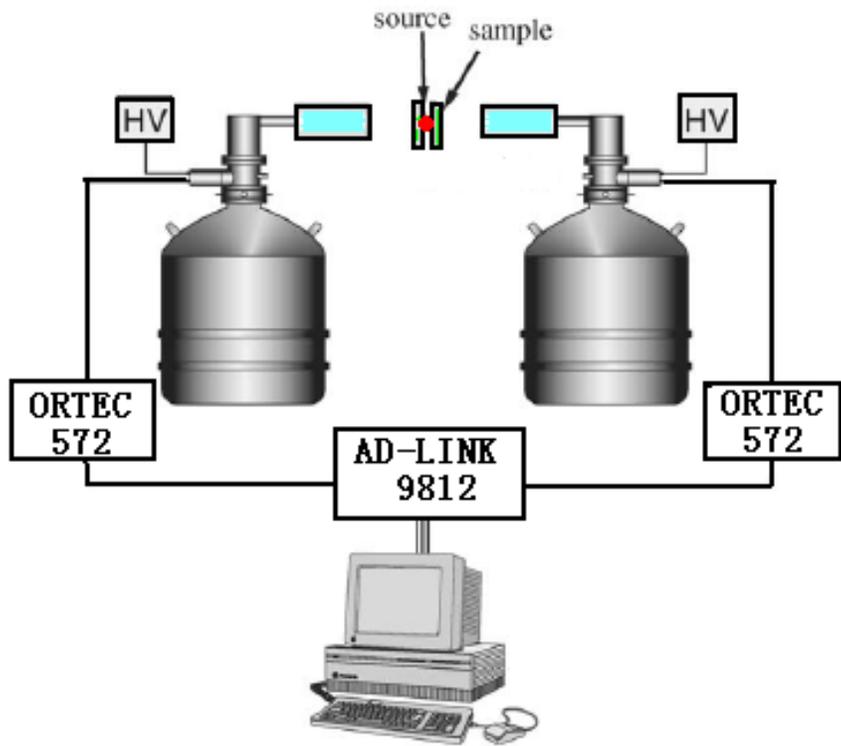
数字化寿命谱仪

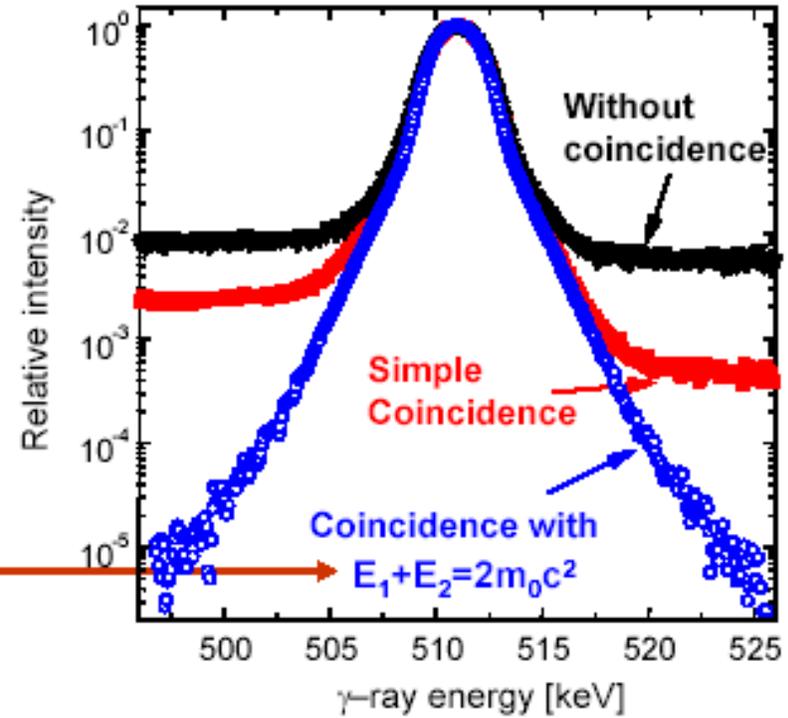
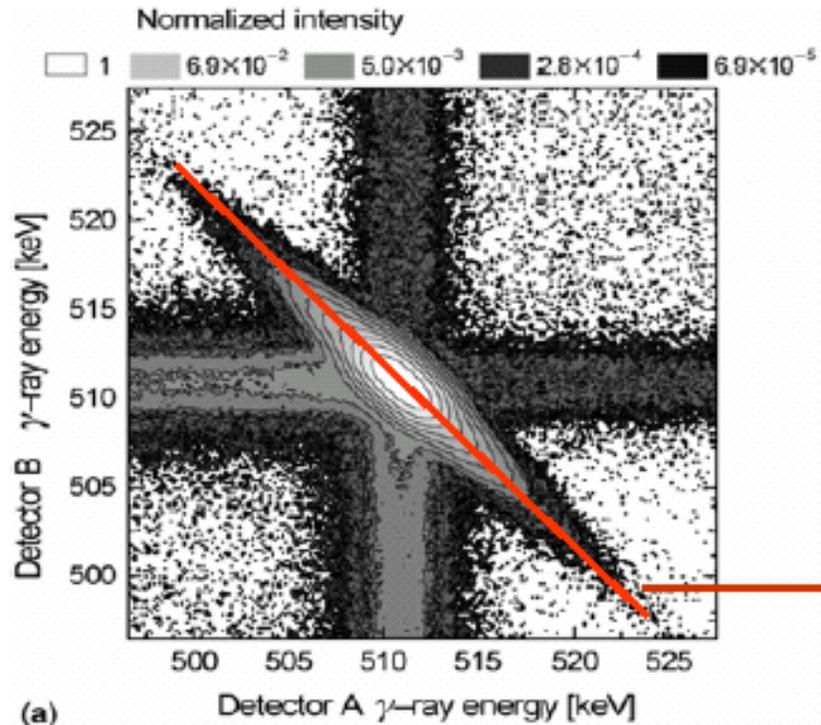
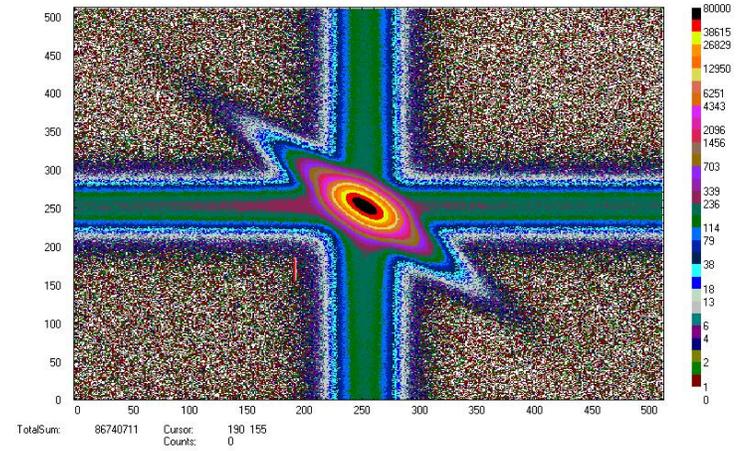
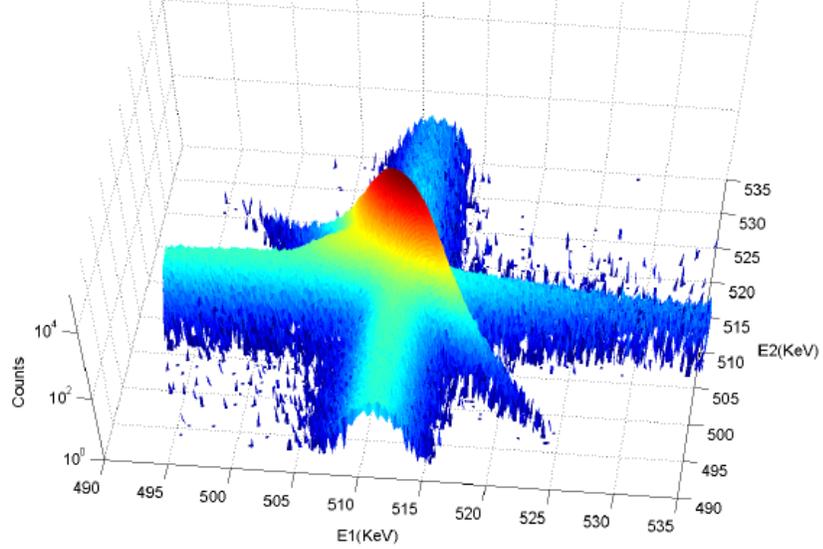
- Based oscilloscope
- Based acquisition card

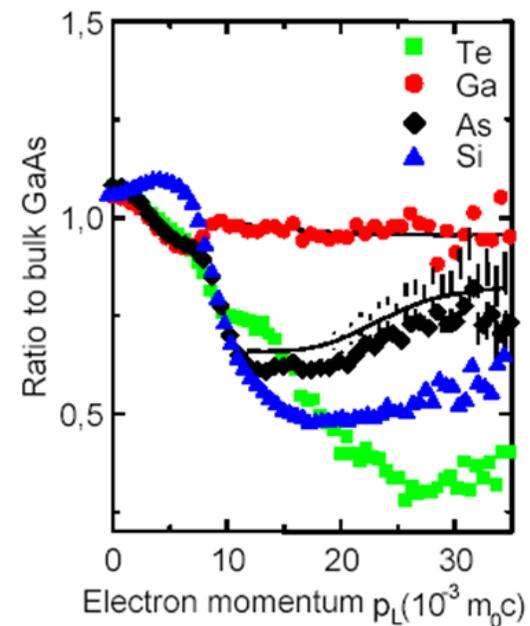
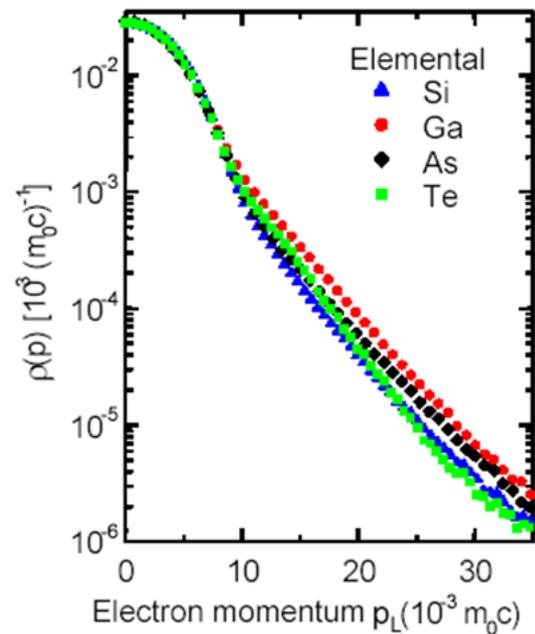
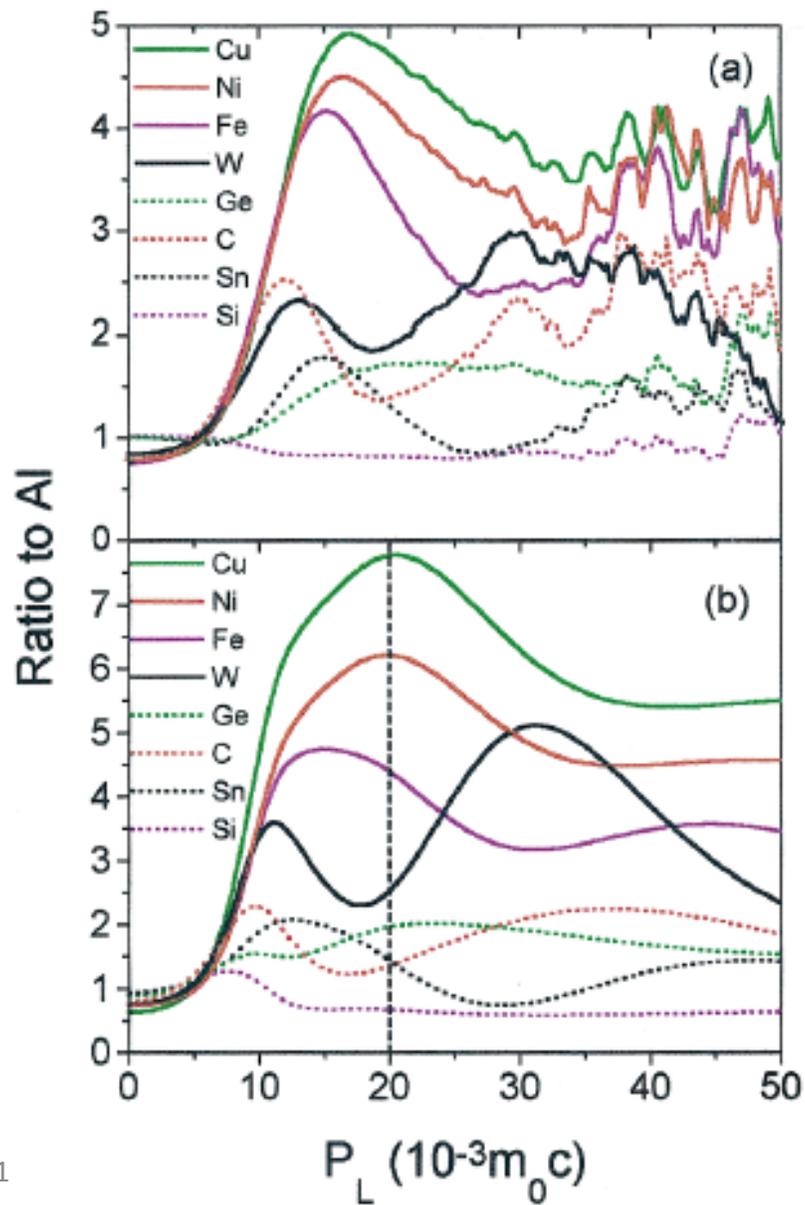


USTC, China

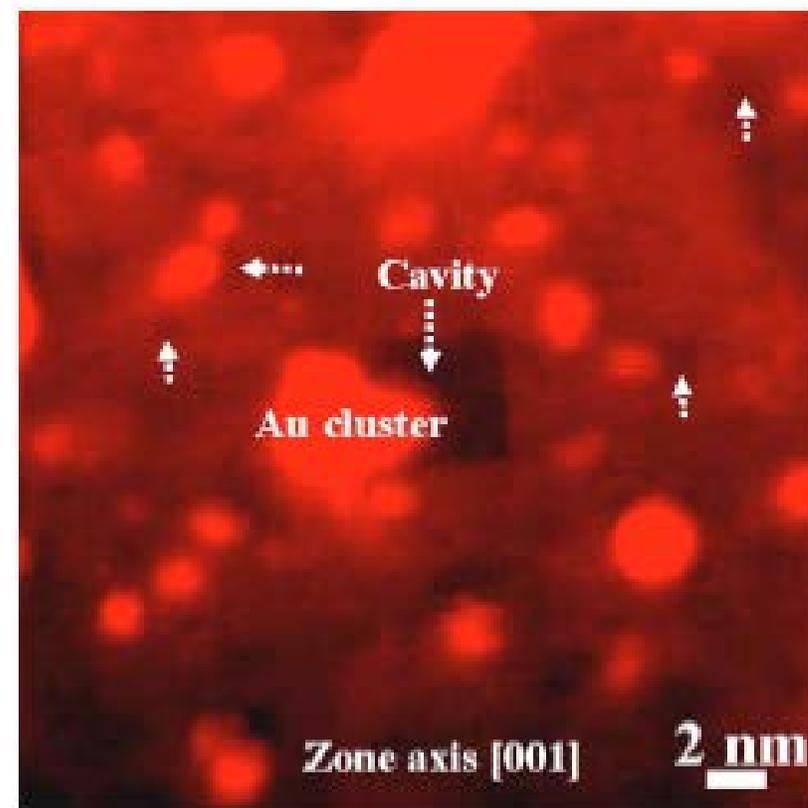
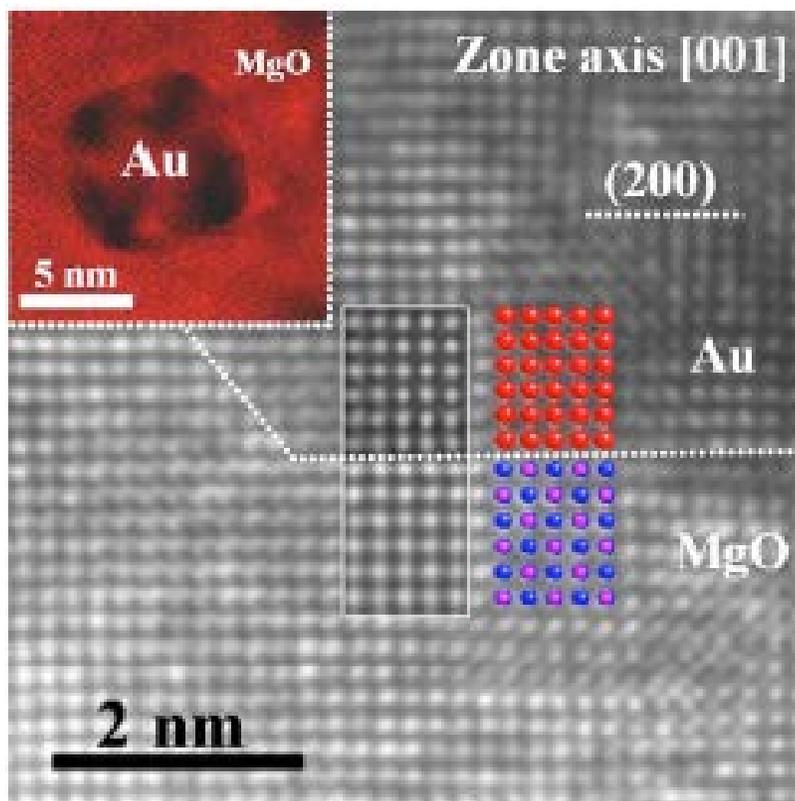
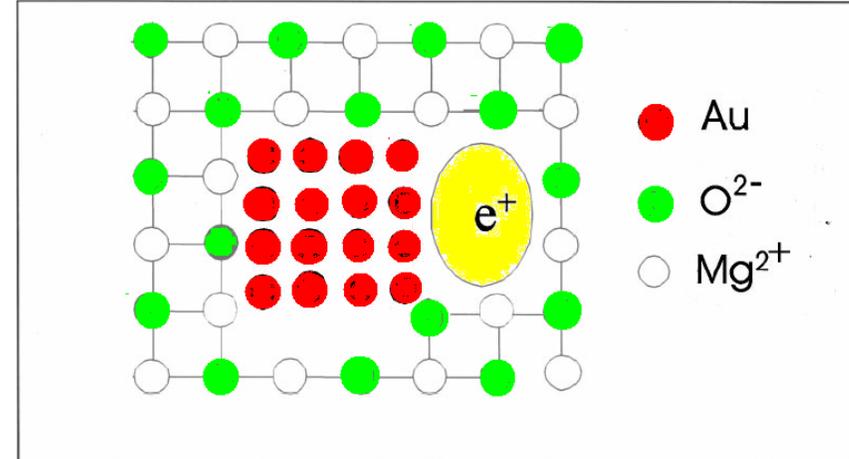
Doppler coincidence spectroscopy



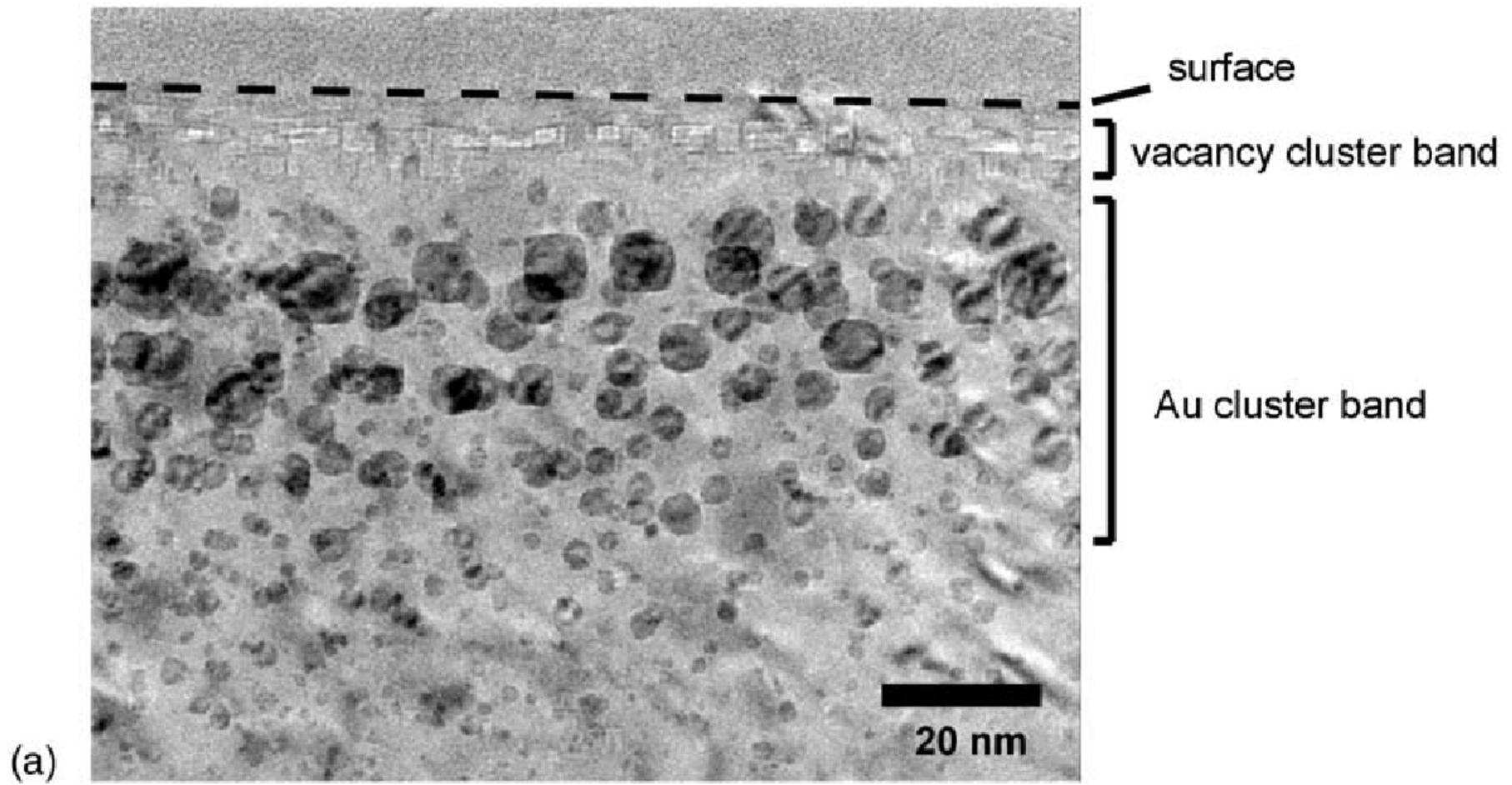




元素的“指纹鉴别”



Au with cavities - 30 keV, 10^{16} Au⁺ cm⁻² implanted at 1273K



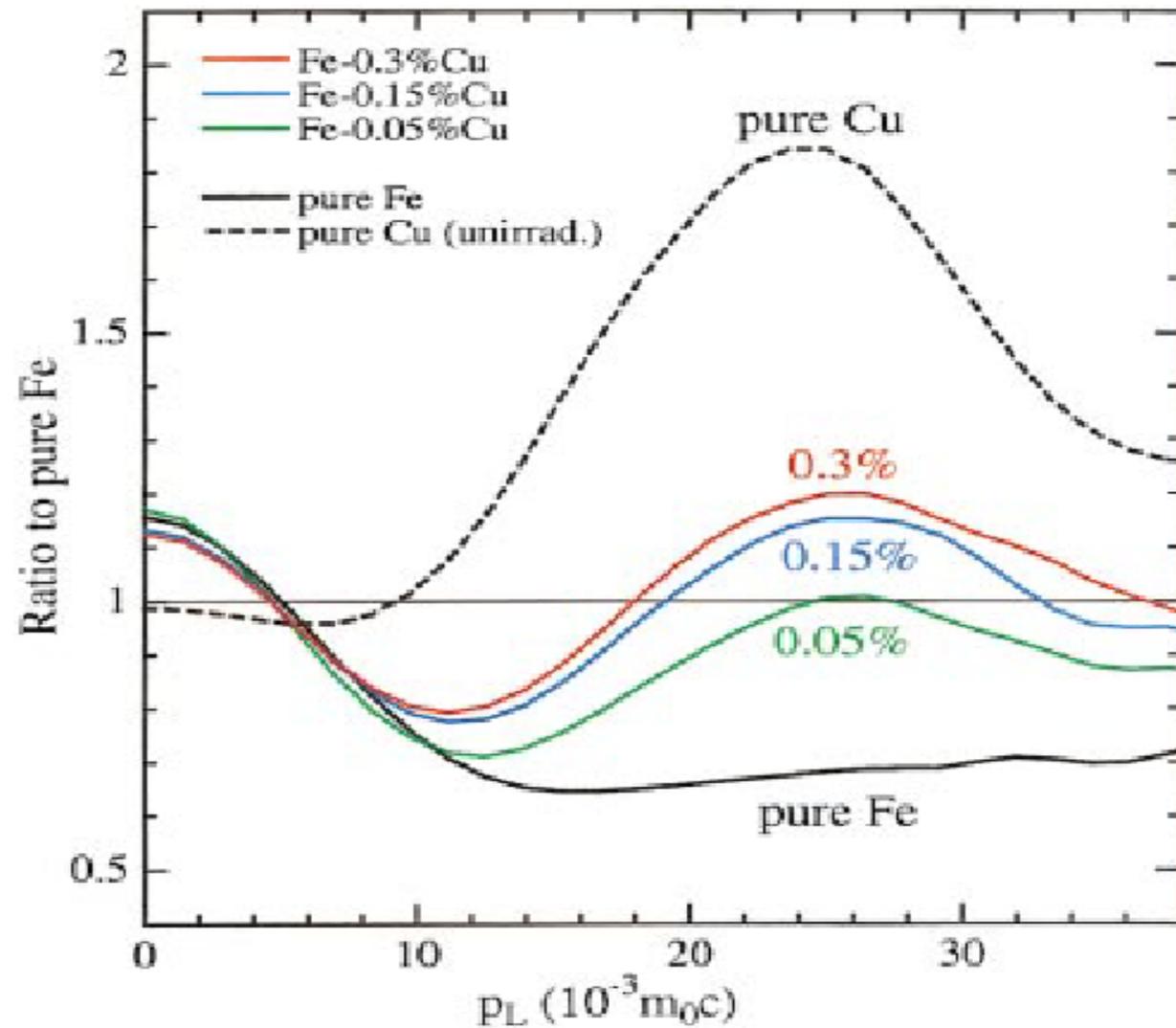


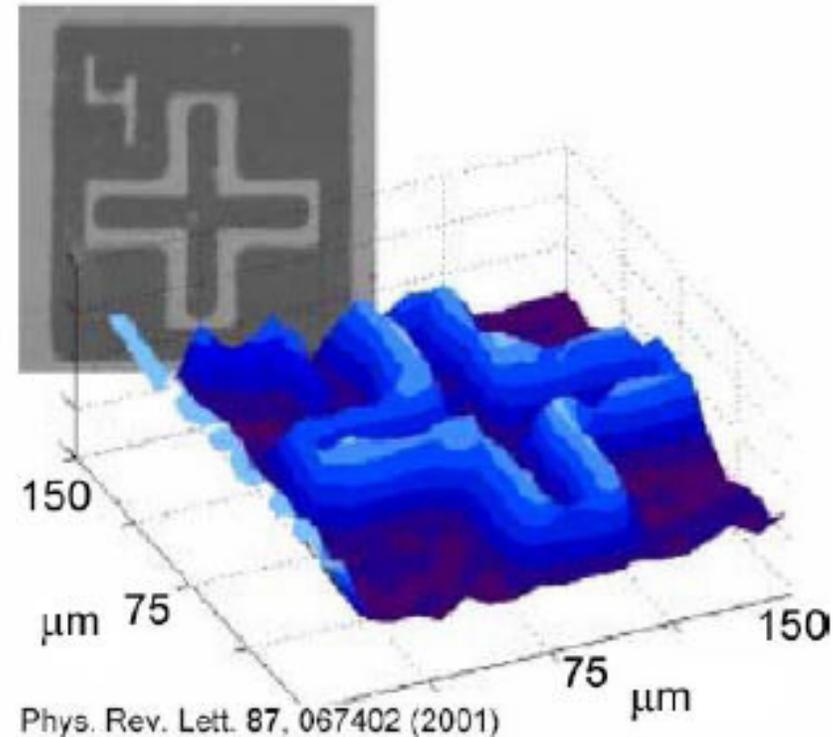
FIG. 2. (Color) CDB ratio spectra for Fe 0.3% Cu, Fe 0.15% Cu, Fe 0.05% Cu, and pure Fe irradiated with fast neutrons at about 300 °C, together with that for unirradiated pure Cu.

Scanning positron microscope

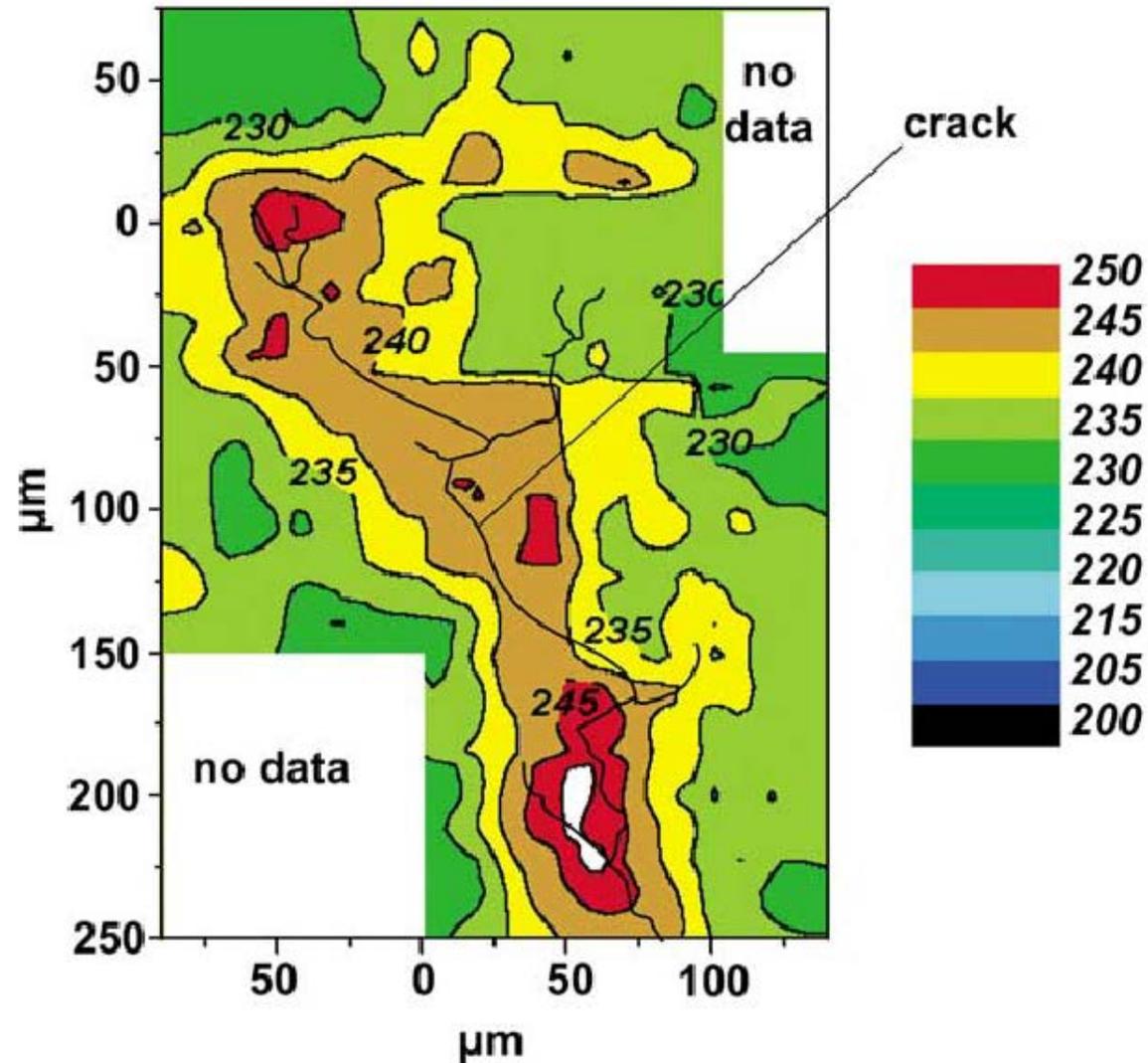
- Variable energy micro-beam of monoenergetic positrons
- Lateral resolution of $2\ \mu\text{m}$ is achieved
- Lifetime measurements at different beam energies are possible



- Principle disadvantage: broad positron implantation profile at high energies



Electron and positron beam image of the surface of a test chip. Light area is SiO_2 , dark area is platinum



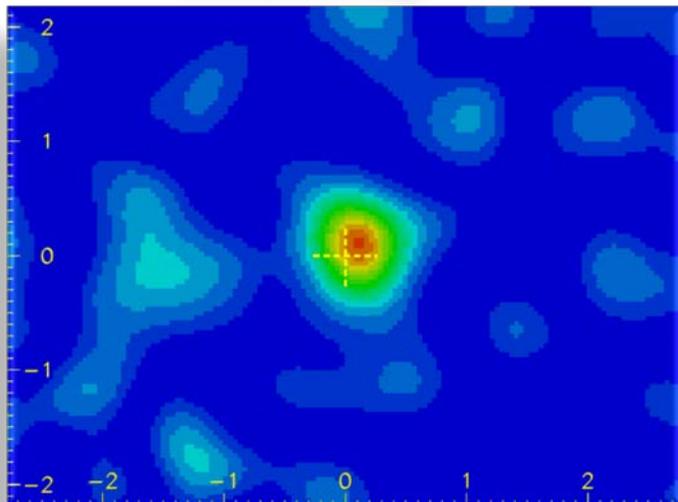
Fatigue crack in copper and map of mean positron lifetime [ps] at 5 keV positron implantation energy.

Positron annihilation spectroscopy as a basic tool for probing material

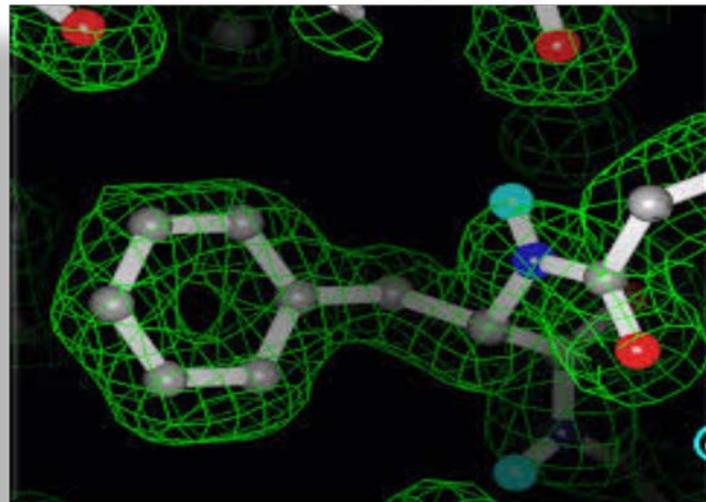
What we can provide
for material scientist?

- Less short measurement time;
- More information with higher accuracy.

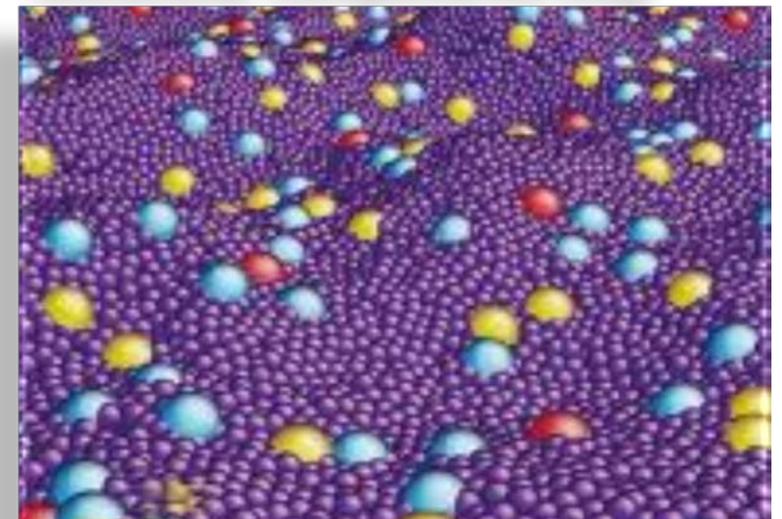
Defect map



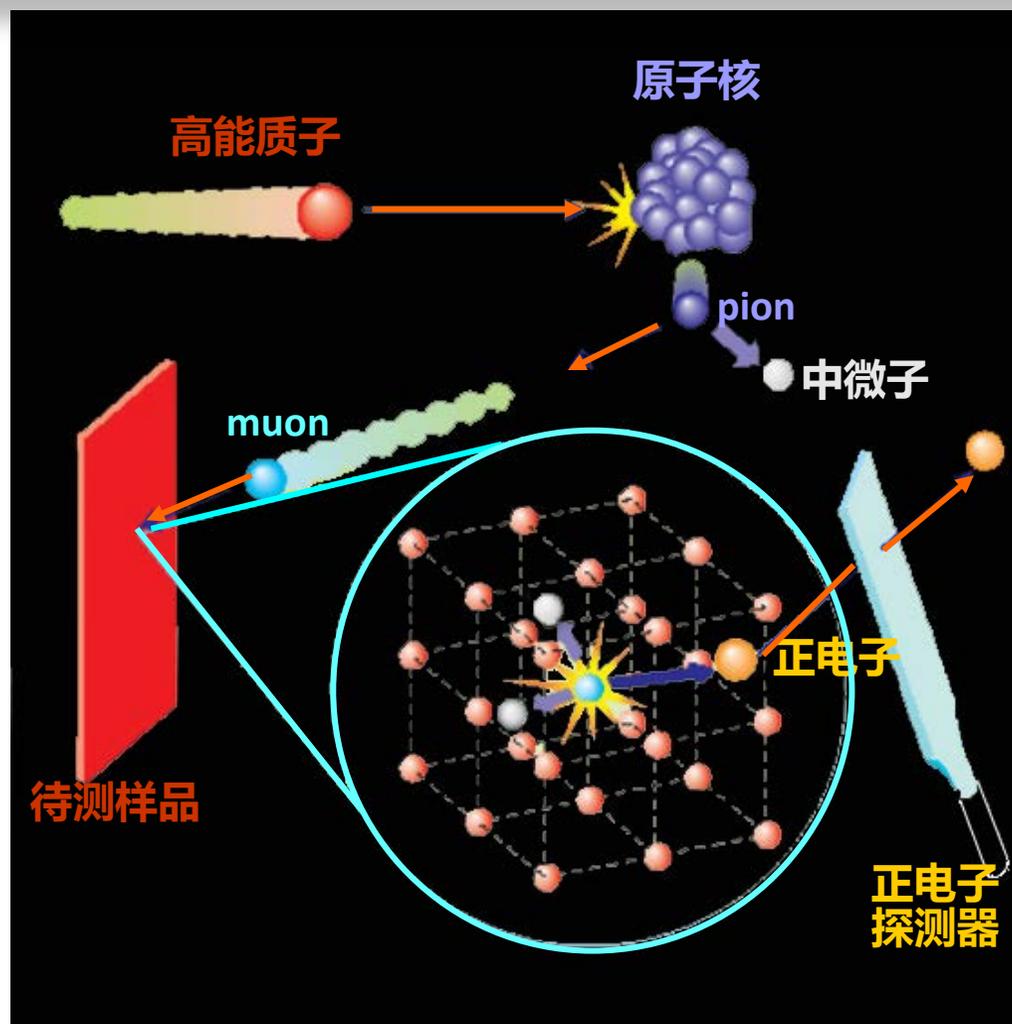
Electronic density map



Molecular components map

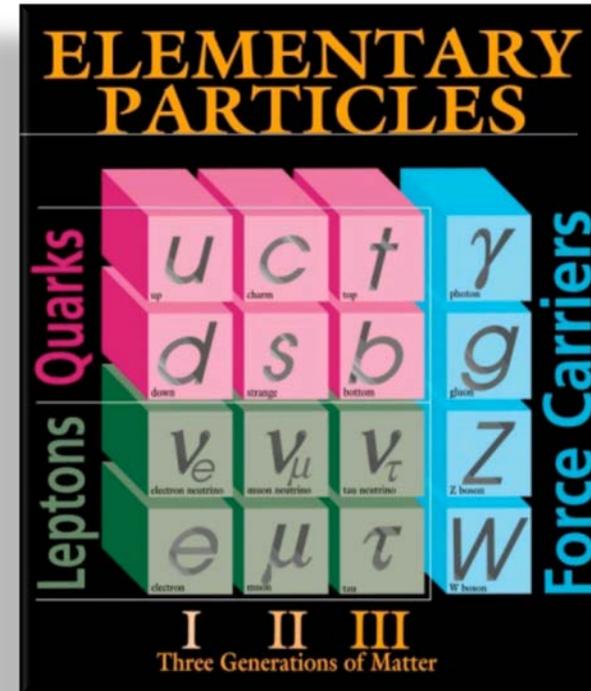


II. Muon科学及其应用



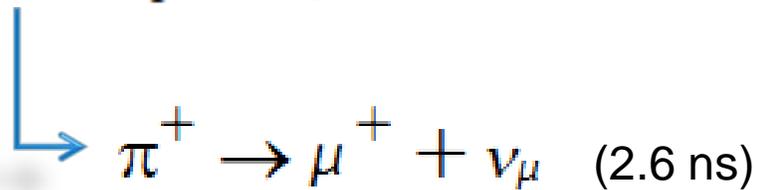
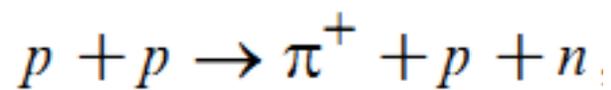
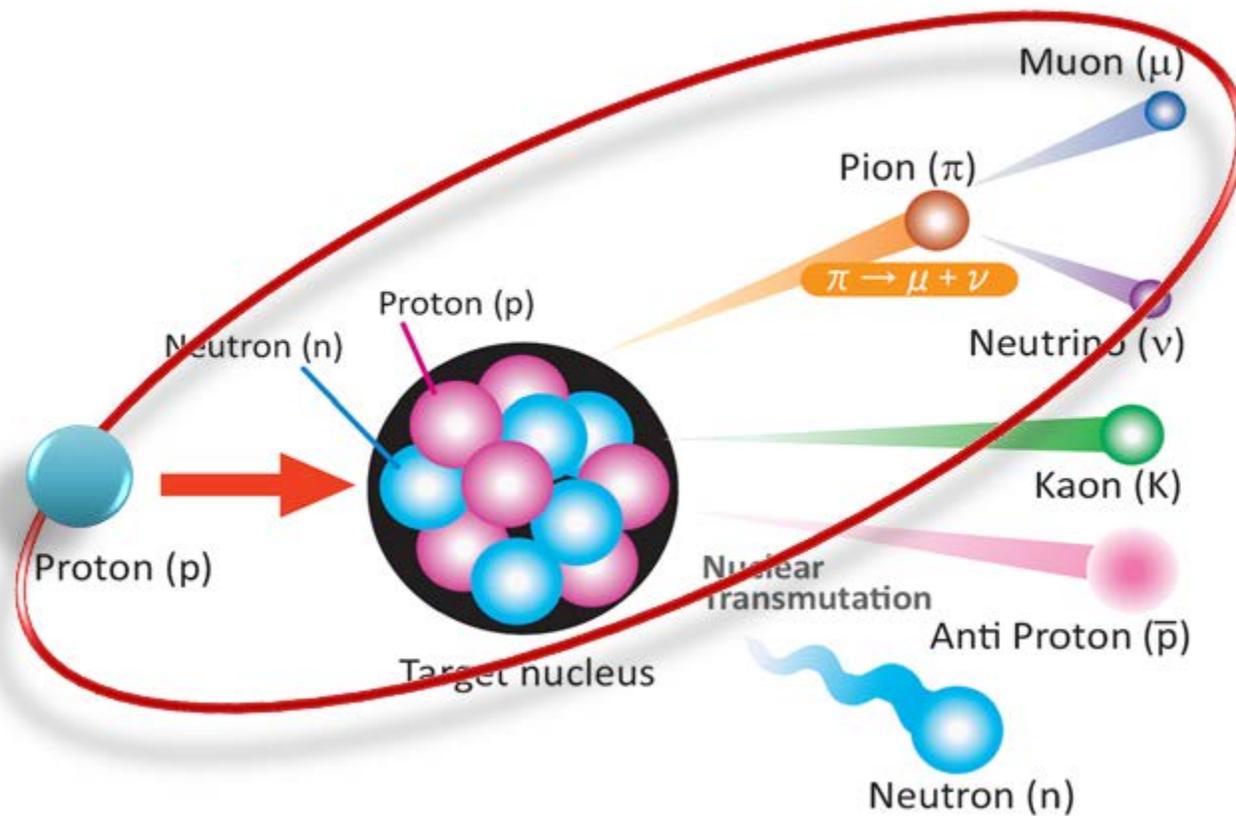
Mu的基本性质

- 类氢性：介于电子和质子之间广泛的应用：
- 地球物理（宇宙射线）、粒子物理（中微子）、材料科学（ μSR ）、能源研究（ μCF ）

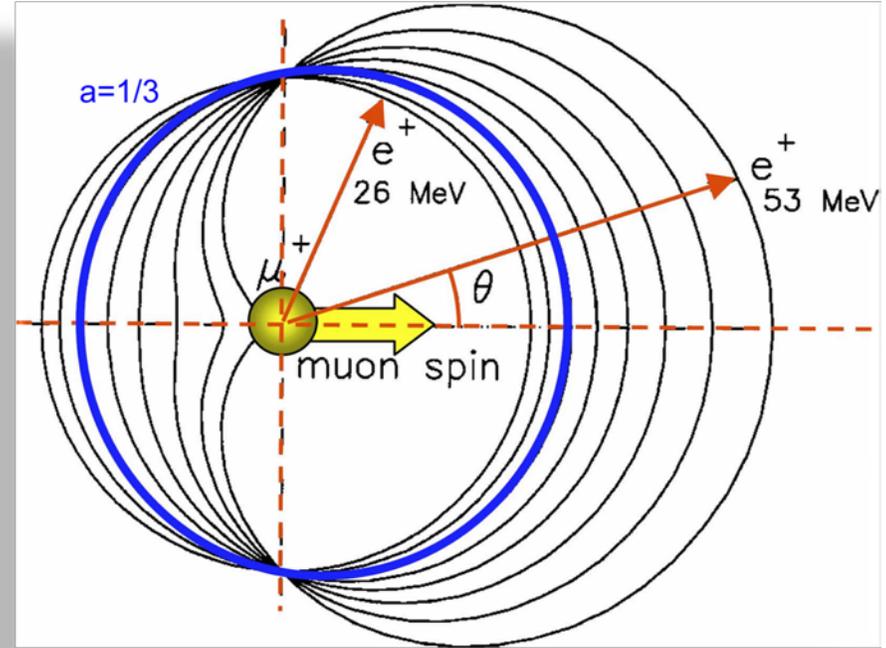
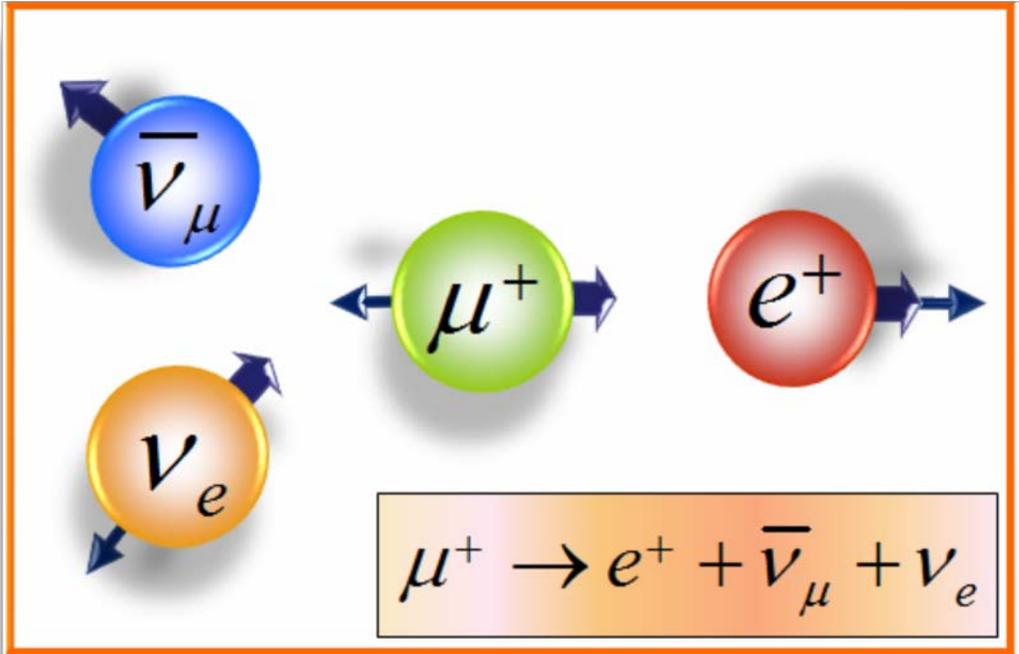


粒子	电荷	自旋	质量 MeV/c^2	磁矩 μ_p	旋磁比 $\gamma/2\pi \text{ kHz}\cdot\text{G}^{-1}$	寿命 μs
e	$\pm e$	1/2	0.51	657	2800	∞
μ	$\pm e$	1/2	105.7	3.18	13.5	2.197
p	$\pm e$	1/2	938	1	4.26	∞

Mu的产生机制

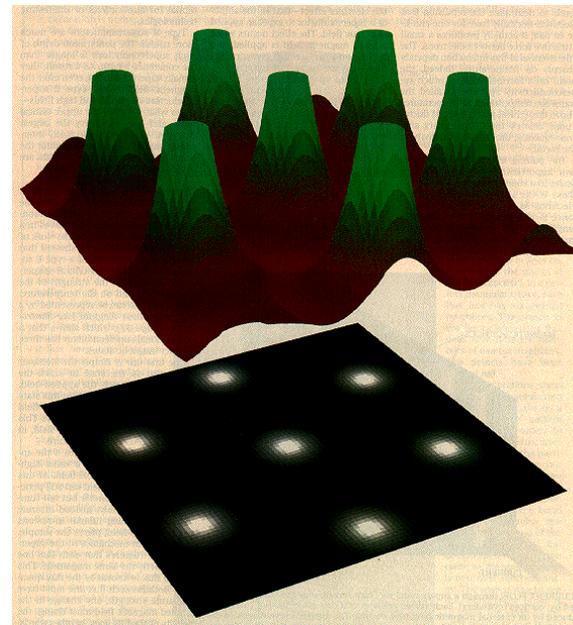
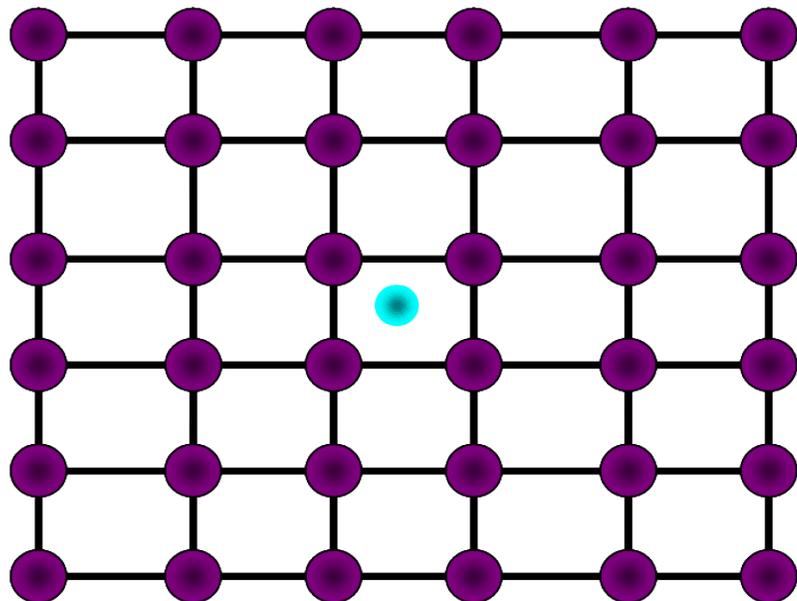


极化Mu的衰变



- 三体衰变: e^+ (0~52.83MeV)
- 正电子倾向于极化方向出射: $W(\theta) = 1 + a\cos(\theta)$
- 表面muon: $\sim 100\%$ 极化的 μ 束

极化Mu子束在材料中



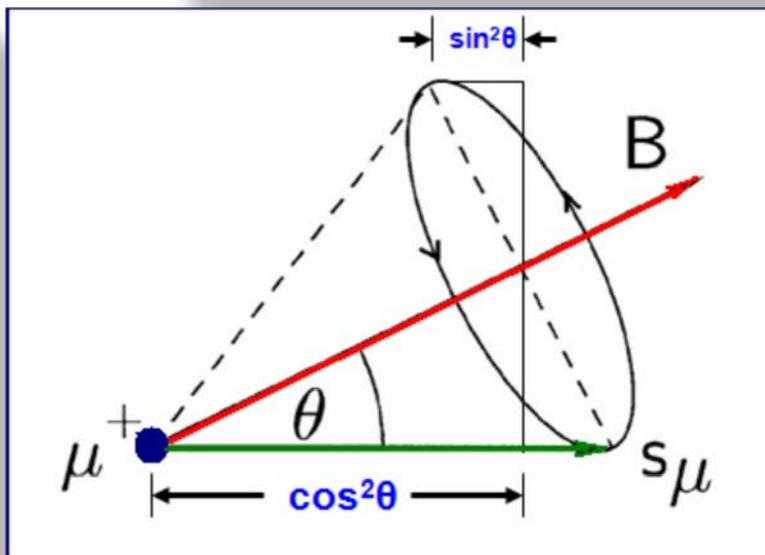
μ^+ 在凝聚态材料中：

- ✧ 不发生衍射或反射；
- ✧ 能在高电子密度区域内停留；
- ✧ 能使晶格产生扰动，微扰的程度与材料有关。

$\mu S R$

rotation
relaxation
resonance

Muon自旋进动



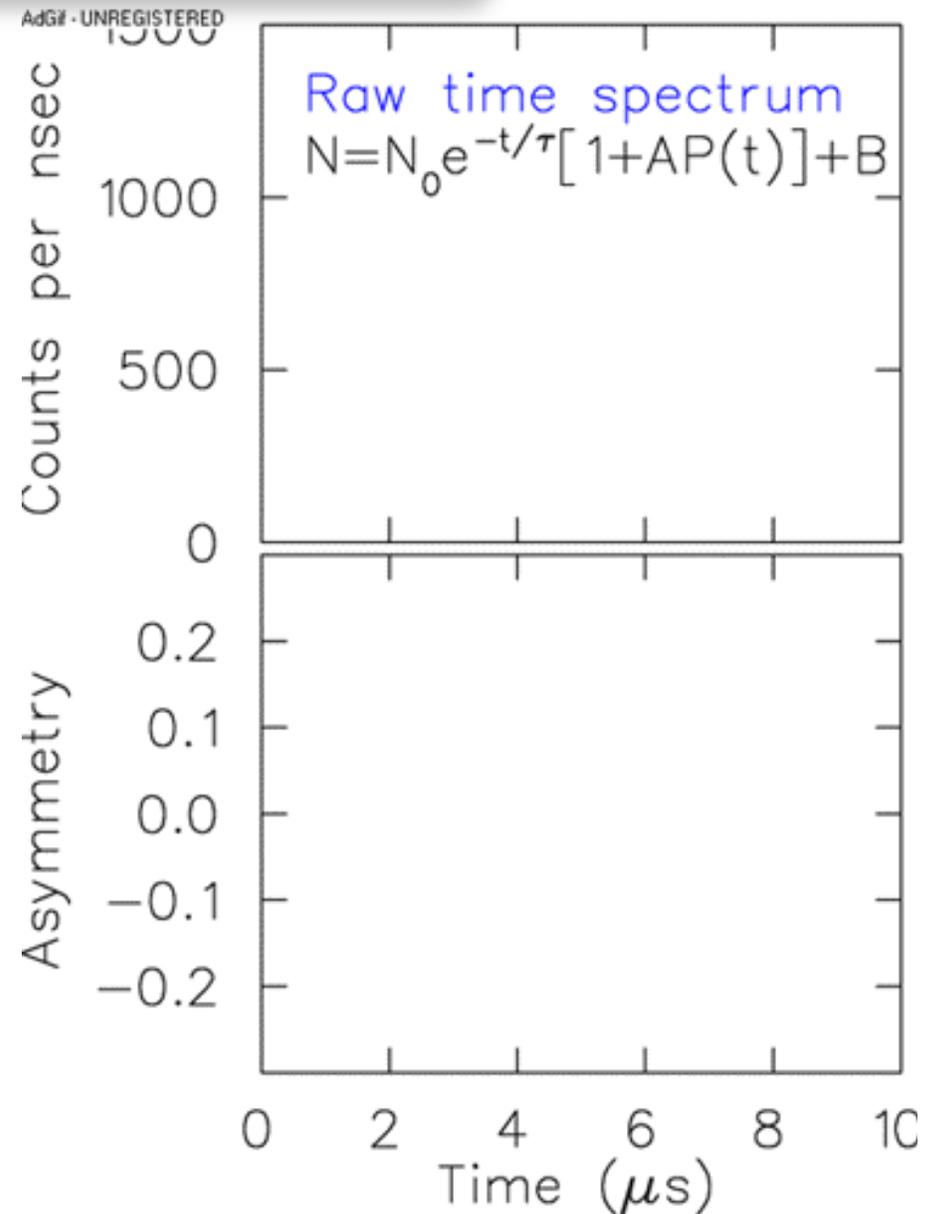
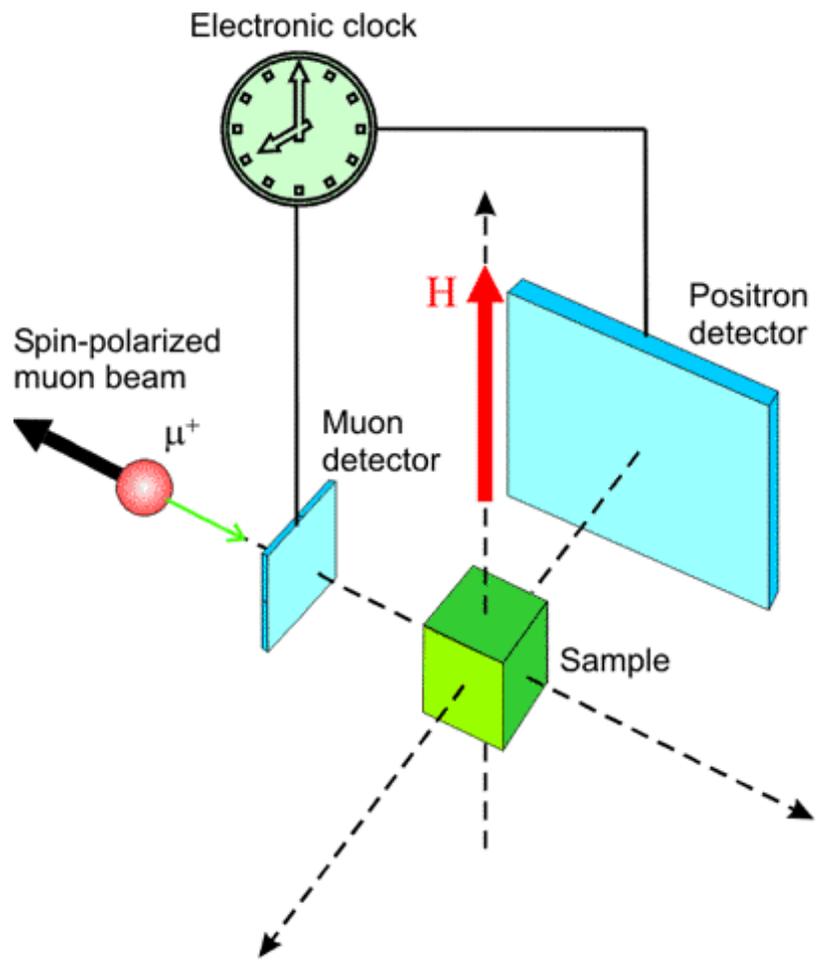
$$P(t) = \cos^2 \theta + \sin^2 \theta \cos(\gamma_\mu B t)$$

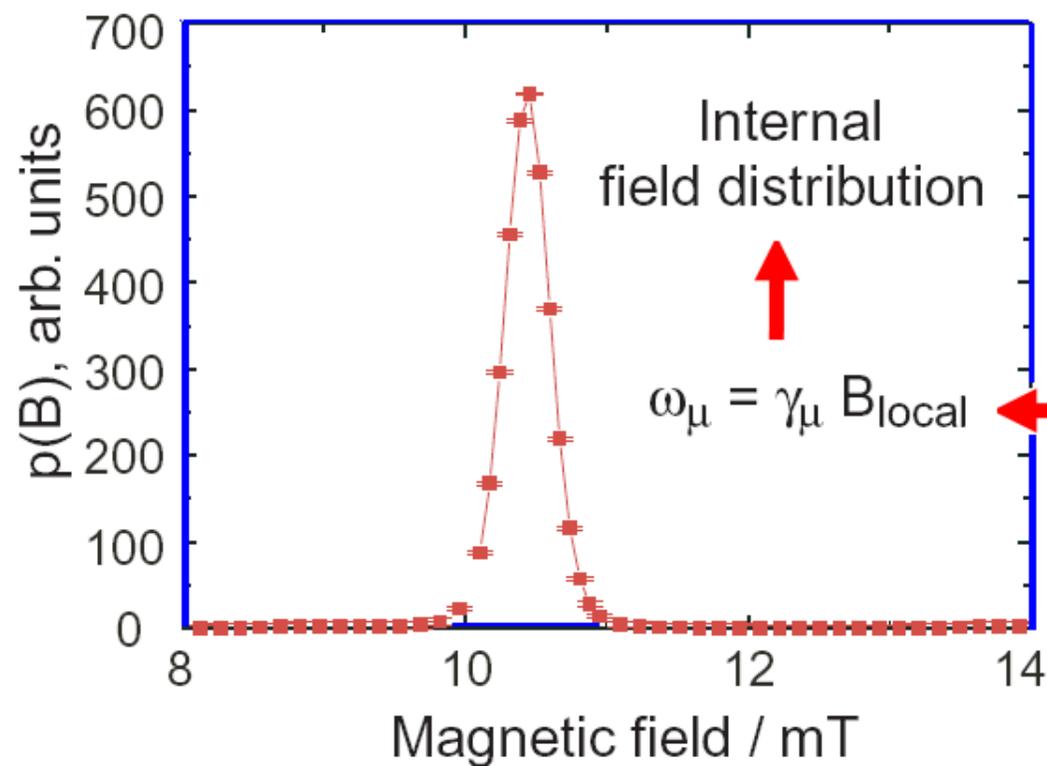
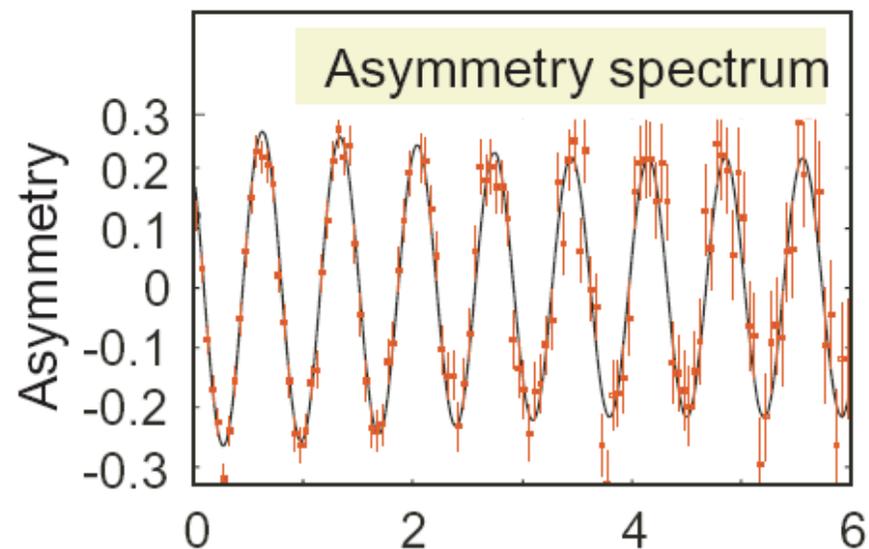
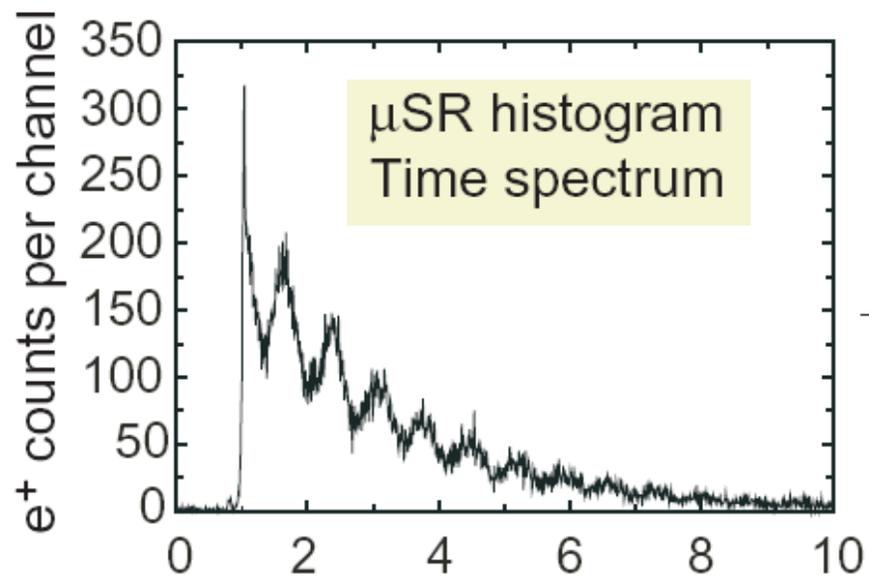
$P(t)$ 为极化函数， B 是局域磁场

➤ 极化 μ^+ 的探针性：

通过极化 μ^+ 在样品中衰变产生的 e^+ 这一时间信息，计算 μ^+ 在样品中的极化函数 $P(t)$ ，由拉莫方程算得样品中的磁结构。与电子和质子相比，muon可测量范围较大的磁场。

Muon Spin Rotation

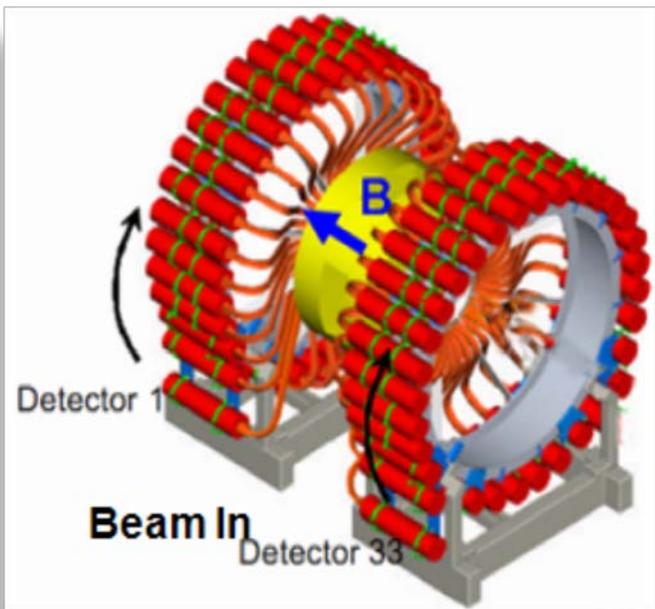




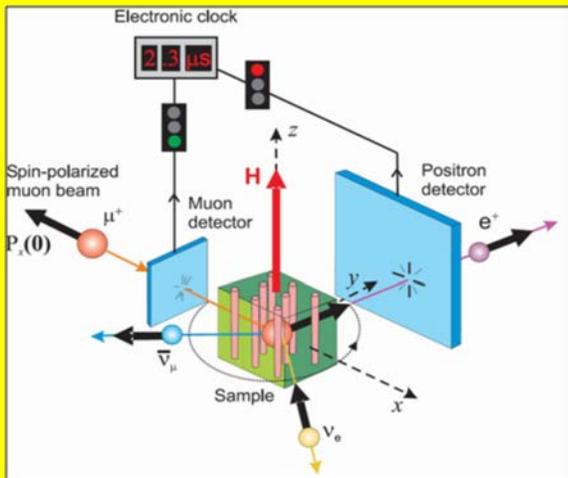
Fourier transformation
or
Maximum entropy analysis

Frequency spectrum
or
Field distribution

MuSR的优势

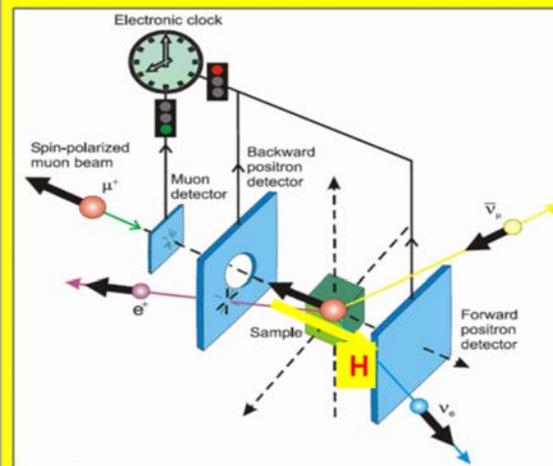


TF μ SR



研究 μ 自旋转动(muon spin rotation)

ZF or LF μ SR



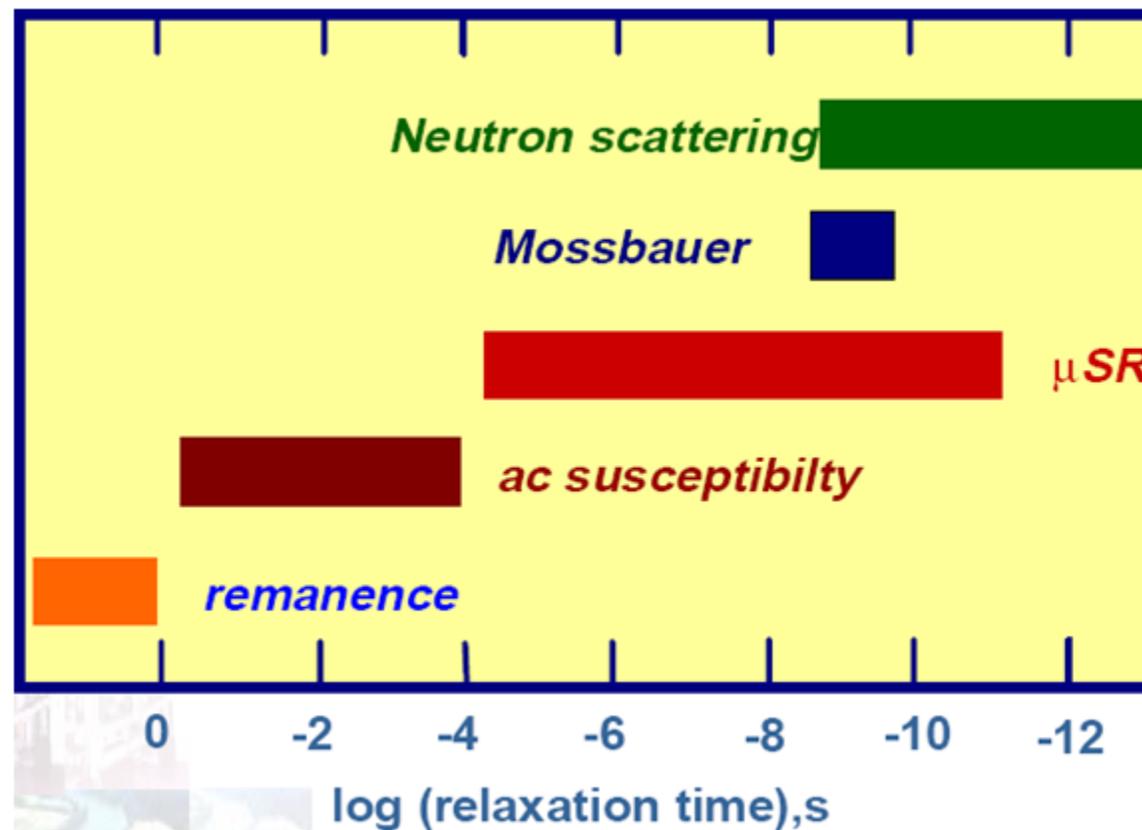
研究 μ 自旋弛豫(muon spin relaxation)

●结构简单，容易实现多种功能。

按照谱仪磁场与束流的方向关系，分为TF- μ SR、LF- μ SR、ZF- μ SR,可通过旋转探测器阵列轻松实现三种功能。



μ SR is a collection of methods that uses the muon spin to look at structural and dynamical processes in the bulk of a material on an atomic scale.



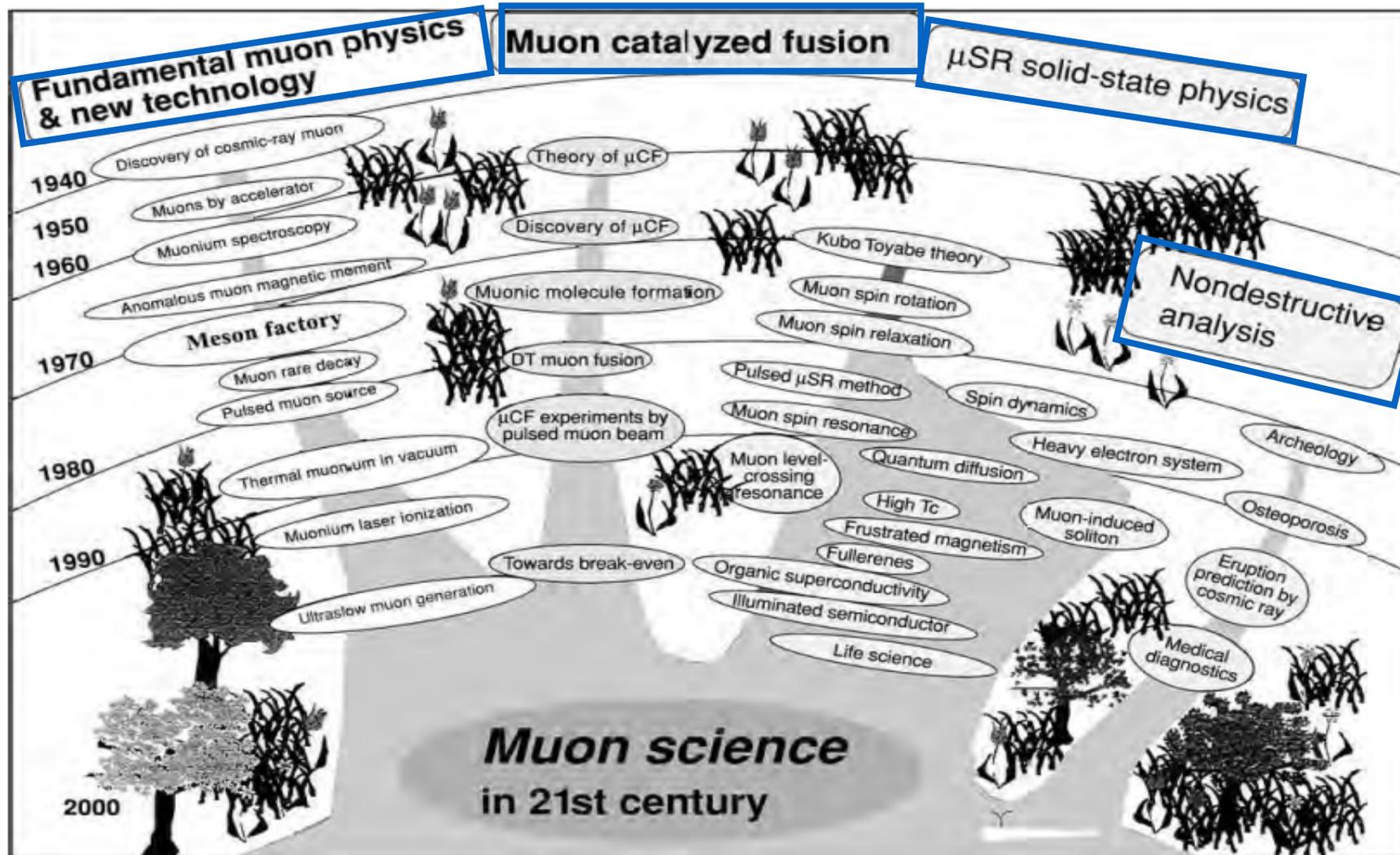
- 弛豫时间范围较广，该方面与其他技术互补；
- 对 neutron 吸收强烈的磁性材料，可用 μ SR 技术研究；
- 适用于磁场微观信息研究，可区分小区域内的大磁矩和大区域内的小磁矩

MuSR技术的优势

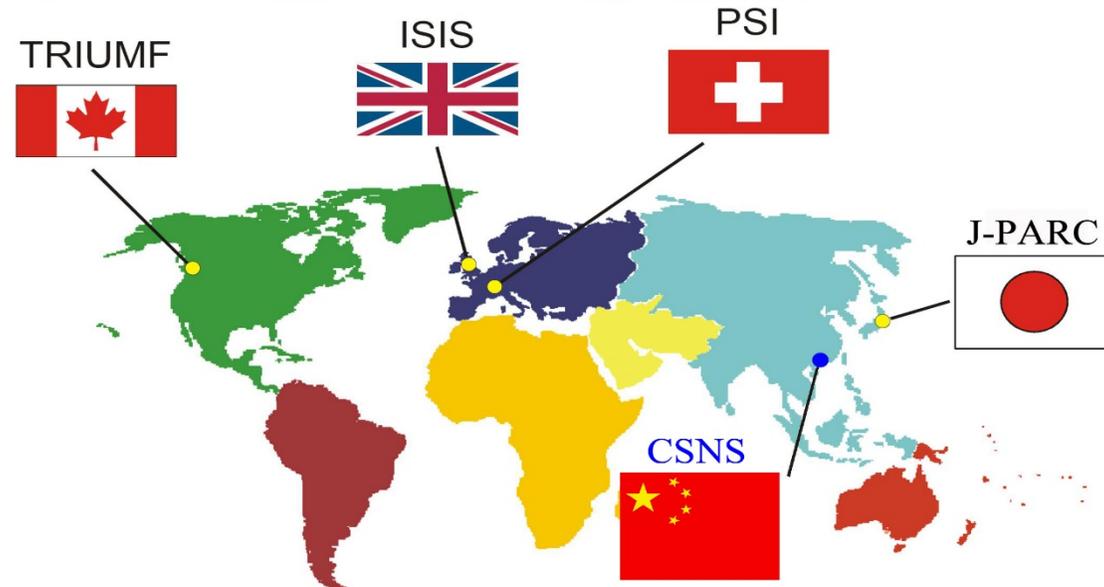


- 可测量较弱磁场 ($\sim 0.1\text{G}$)
- 可测量较短的弛豫时间 ($\sim 10^{-8}\text{ s}$)
- 探测样品的频率响应范围大 ($10^4 \sim 10^{12}\text{ Hz}$)
- 外加磁场是非必需的
- 对样品的状态要求较低 (固体液体均能测量)
- 对样品环境的要求较低 (高温高压强中子吸收等)

muon科学的发展和應用



国际上基于加速器的Muon源



实验室	质子能量 (MeV)	质子束流电流 (μA)	束流结构	衰变 μ (μ/s)	表面 μ (μ/s)	慢 μ (μ/s)
ISIS (英国)	800	180	脉冲	μ^+ : 4×10^5 μ^- : 7×10^4	4×10^4	--
J-PARC (日本)	3000	333	脉冲	$10^{6\sim7}$	3×10^7	$2\sim5 \times 10^5$
PSI (瑞士)	590	1800	连续	$\sim 10^8$	$10^7\text{-}10^8$	16000
TRIUMF (加拿大)	500	140	连续	$1\sim4 \times 10^6$	$\sim 2 \times 10^6$	--

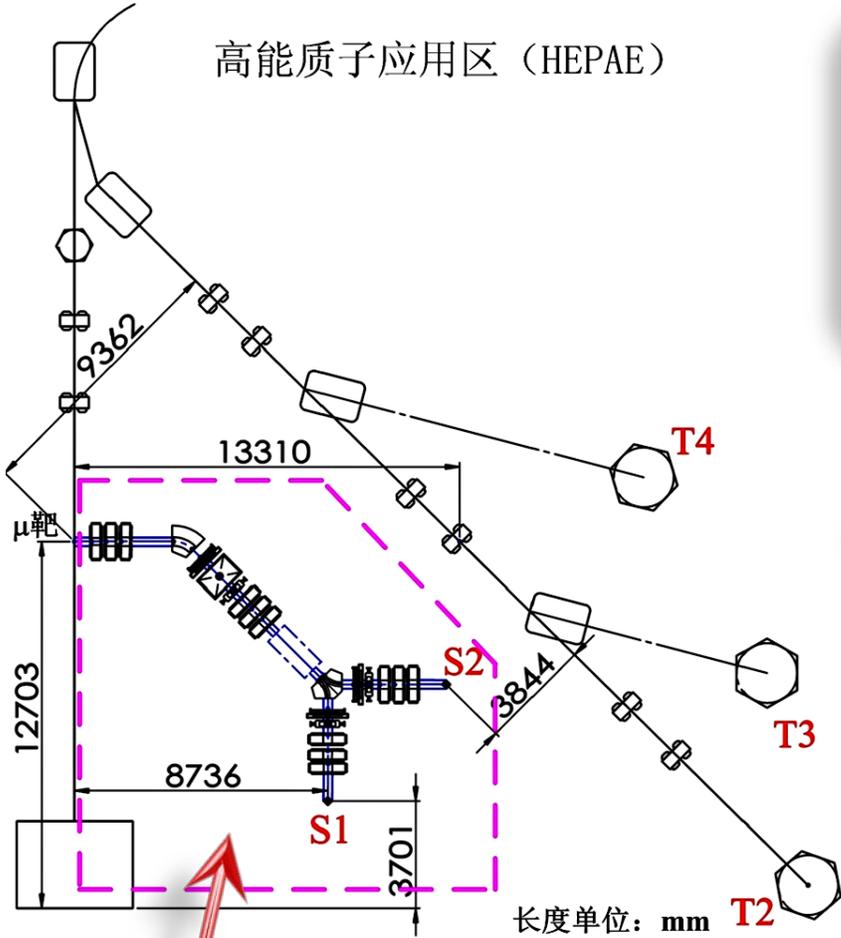
CSNS的建造为我国开展基于加速器的脉冲型MuSR研究提供了广阔的平台。

二、基于CSNS的Muon束线设计



1.常规表面Mu靶的设计

➤ 基于CSNS的试验型Mu源(EMuS)的设计条件:



试验型muon源装置: EMuS

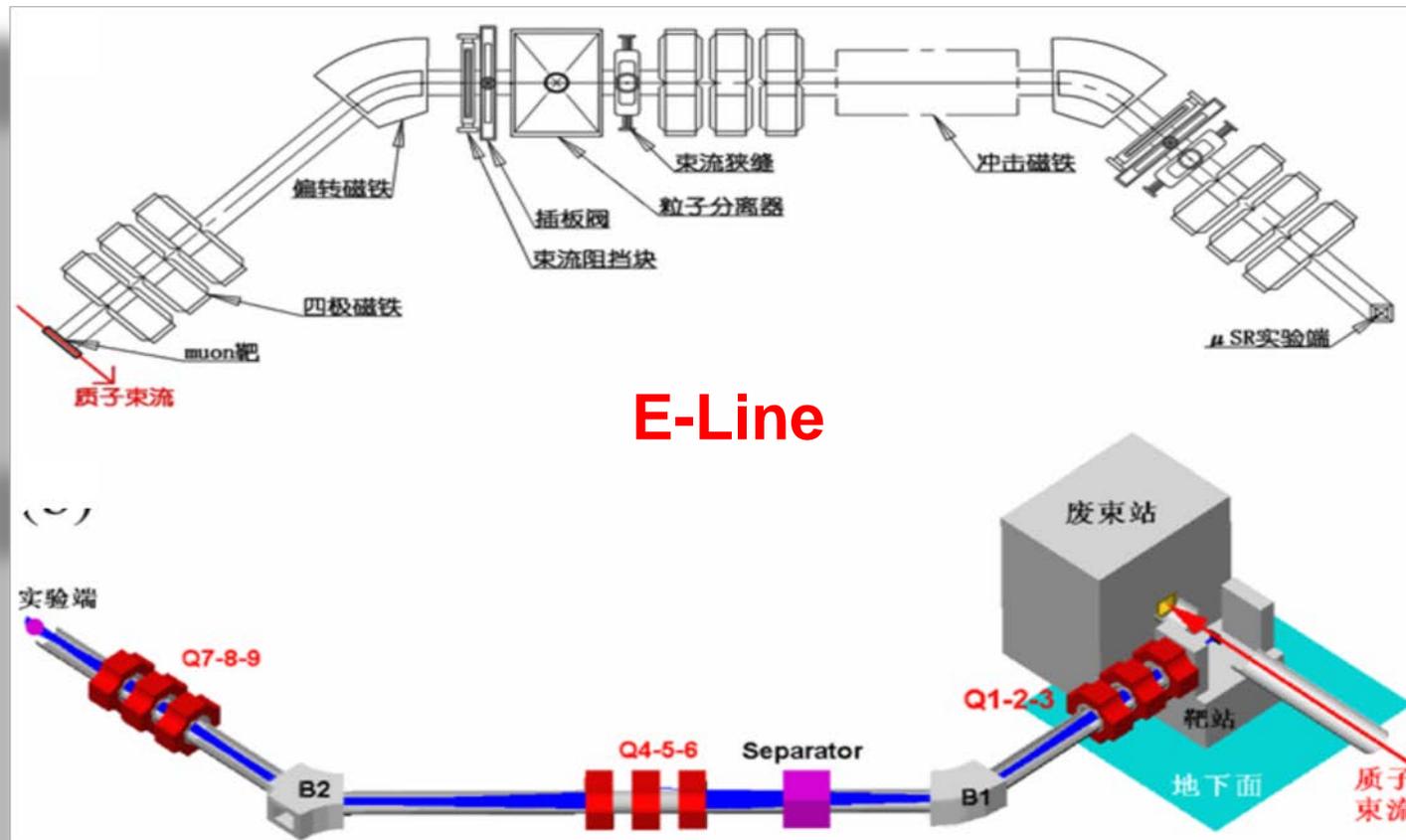
质子: 1.6GeV、1Hz、4kW
脉冲型、双束团 (70s)
1.88E+13/s
muon: 极化率较高的表面muon

沉积靶
不同于穿透型靶



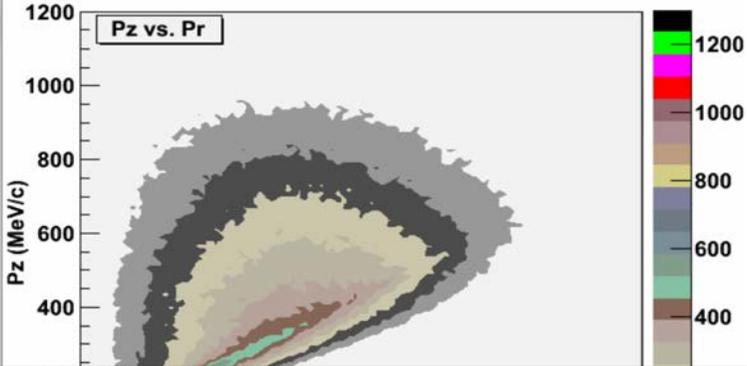
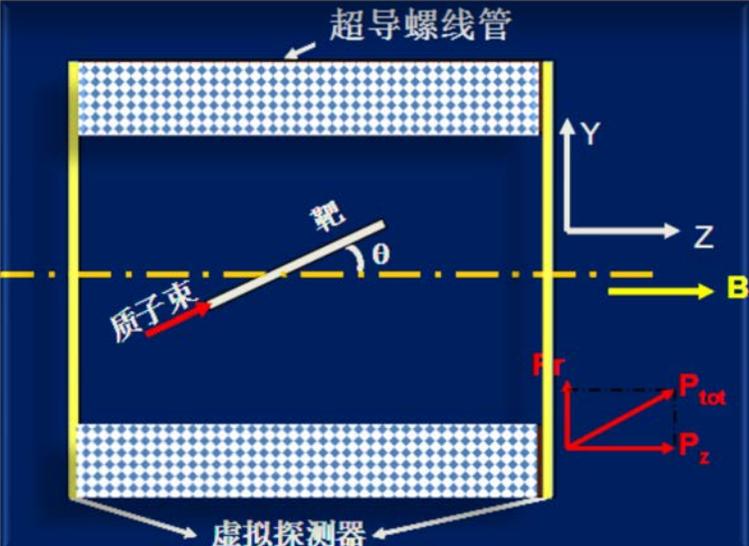
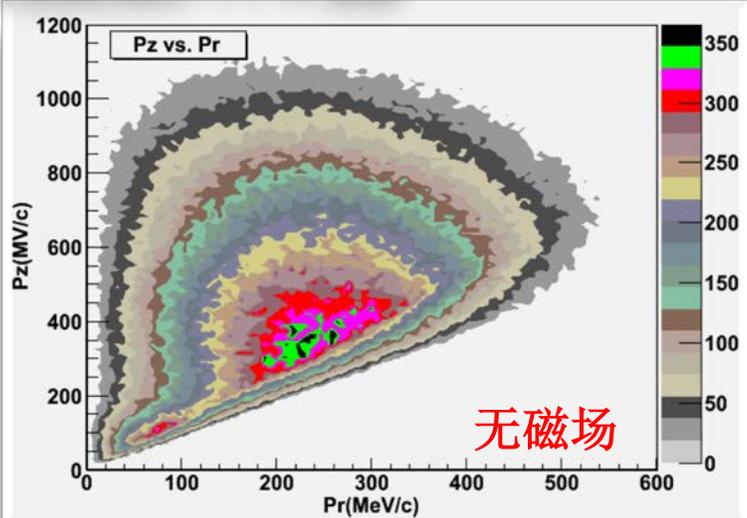
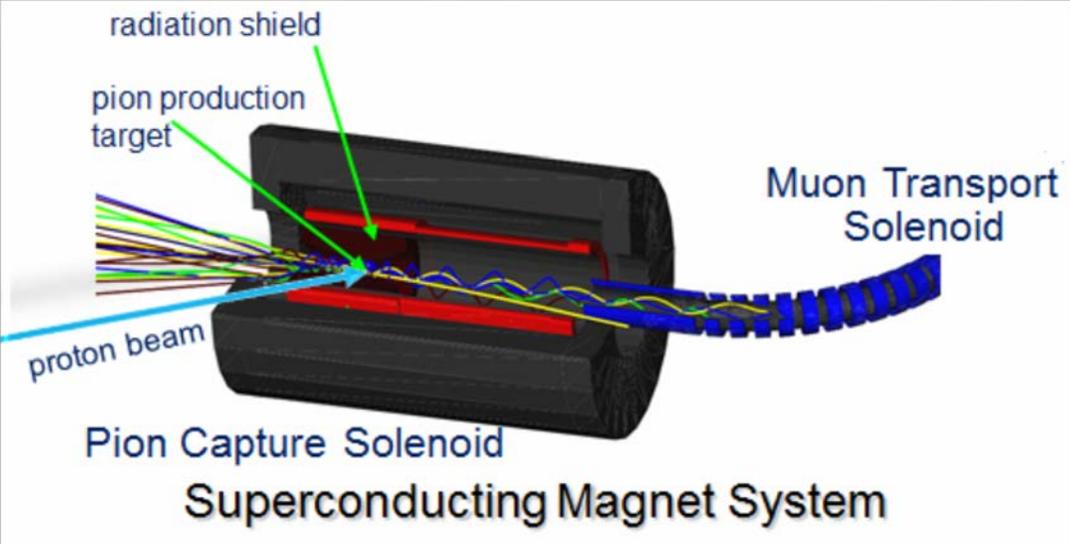
μ靶形状、材料、
捕获方位、热应力分析等方面

2. 常规表面Mu运输线的设计



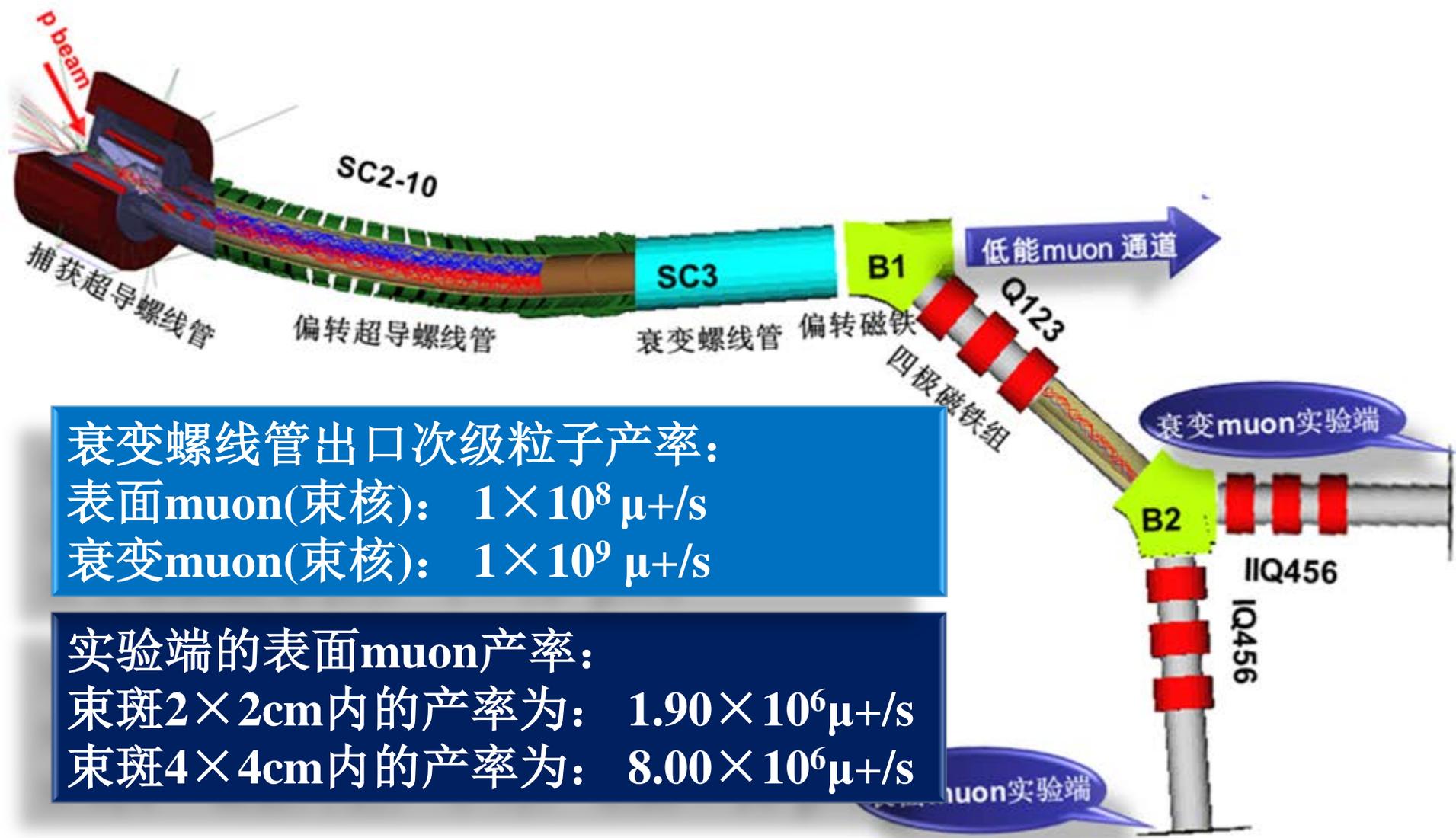
3.加强型Mu源设计初步

● 超导螺线管应用于加强型Mu源



- 采用超导螺线管设计收集带电粒子;
- 采用细长靶来增加可收集粒子的数目;
- 螺线管有助于低能粒子的收集 (如右图)

● 加强型Mu源设计布局



衰变螺线管出口次级粒子产率：
表面muon(束核): $1 \times 10^8 \mu^+/\text{s}$
衰变muon(束核): $1 \times 10^9 \mu^+/\text{s}$

实验端的表面muon产率：
束斑 $2 \times 2\text{cm}$ 内的产率为: $1.90 \times 10^6 \mu^+/\text{s}$
束斑 $4 \times 4\text{cm}$ 内的产率为: $8.00 \times 10^6 \mu^+/\text{s}$

●加强型Mu源的设计优势

- ☀ 可以同时俘获和输运表面muon,pion,和mu⁻(如有需要可再升级), 利用率更高, 可研究更多范围的材料;
- ☀ 提高了表面muon源的通量, 理想情况下可 $1 \times 10^{(8-9)} \mu^+/\text{s}$, 与世界上高通量的表面muon源(PSI,J-PARC)可比拟;
- ☀ 高能量的muon又为开展其它的实验准备了条件, 尤其是低能muon。采用低温慢化的方法(效率 1×10^{-3}), 得到的Low Energy muon 的量级可以用来实验, 扩大了 μSR 探针的在纳米, 多层等材料中的应用。

HAPPY NEW YEAR
and thank to everyone!