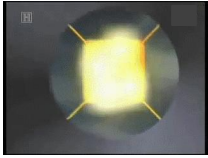



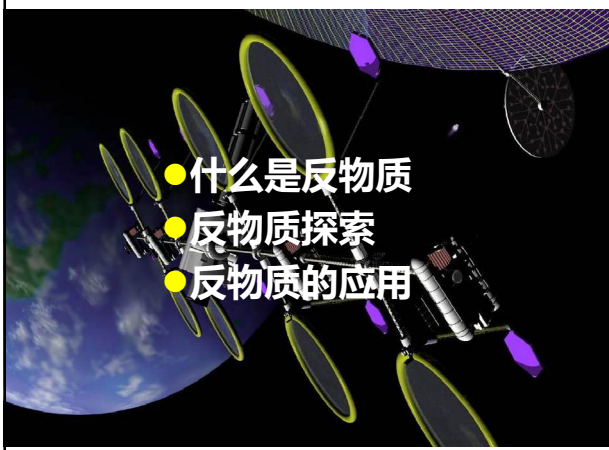
**反物质探索及其应用**



Bangjiao YE

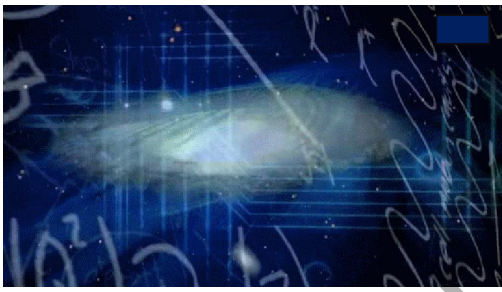
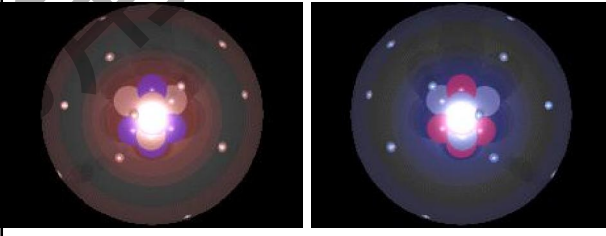


**中国科学技术大学物理学院**  
The School of Physical Sciences, USTC




- 什么是反物质
- 反物质探索
- 反物质的应用

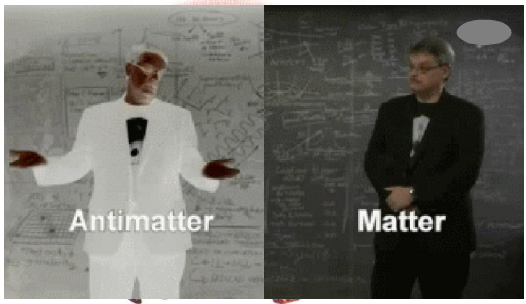
**一、什么是反物质**

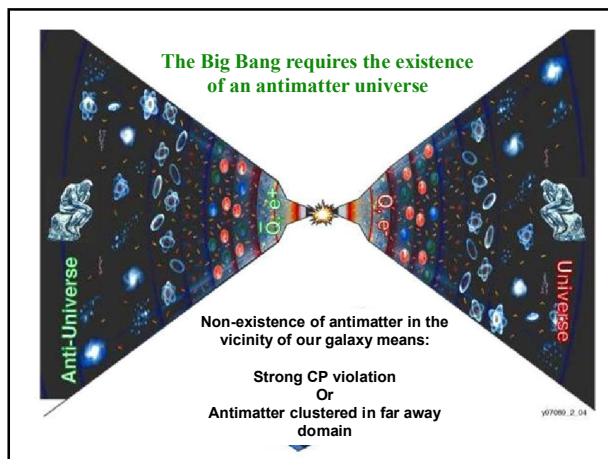
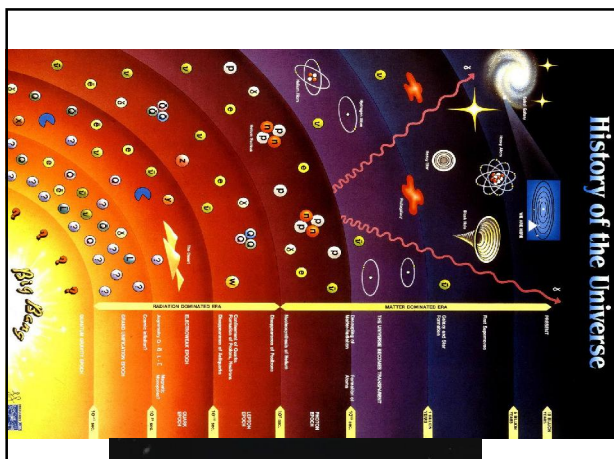
电子+质子+中子      正电子+反质子+反中子



电子                      反电子



也许宇宙中还有一个反你,你遇到反你时,小心不要握手!



大爆炸形成了我们的宇宙，应该是既有物质，又有反物质，2种物质世界应该是完全对称的。

那么，我们的另一半在哪里？

科学家们相信宇宙中某一个地方应该存在着一个反物质世界！

科学家在 $20\text{Mpc} \sim 10^8$ 光年范围没观测到宇宙中有反物质存在的证据，主要是由物质组成的。

由宇宙中的星体，气体可得

重子数/光子数= $10^{-9} \sim 10^{-10}$

可有  $(N_B - N_{\bar{B}})/(N_B + N_{\bar{B}}) = 10^{-9} \sim 10^{-10}$

### 大爆炸产生的反物质哪里去了？

- 大爆炸初期，温度很高，宇宙介质是由正反物质构成的。几乎所有的粒子都具有相同的数密度。
- 随着宇宙的冷却，介质中某中粒子的静质量与温度在一个数量级时，通过热碰撞产生几率显著下降，而它的湮灭却依然容易发生。
- 温度 $T$ 由宇宙膨胀动力学决定，衰变速率由微观动力学决定，两者不可能如此好地协调。当温度降至与某种粒子的静质量相等以后，该粒子将逐渐消失。

- 如果湮灭过程中 $C$ 或 $CP$ 略有破坏，则介质中正反粒子的数量开始不相等。
- 温度降至大统一尺度能量以下时，重子数不对称过程被冻结。
- 温度降至 $1\text{GeV}$ 时，正反重子开始通过湮灭而消失。若正粒子数略大于反粒子数，湮灭后只剩下正粒子多余的部分。
- 重子数应远小于光子数，这正是目前的状况。

**Before time = 1 microsecond (after Big Bang)**  
 Energy  $\longleftrightarrow$  protons + antiprotons

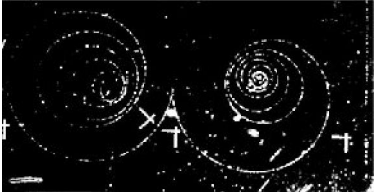

**After time = 1 microsecond**  
 Energy  $\longleftarrow$  protons + antiprotons

Small excess (1/1000 000 000) of protons ?  
 (CP violation)

time = 1  $\mu$ s : The big antimatter massacre:

1 000 000 001 protons  
 + 1 000 000 000 antiprotons  
 = 1 proton + energy

## 二、反物质探索

**1928年, Dirac把量子论和相对论结合在一起,得到了一个描述电子运动的方程式.**

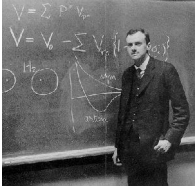
$$i\gamma\partial\Psi = m\Psi$$

## 电子运动的Dirac方程

$$\left(\sum_{\mu=1}^4 i\gamma_{\mu} \frac{\partial}{\partial x_{\mu}} - \frac{m_0c}{\hbar}\right)\Psi = 0$$

得到电子的能量为:

$$E^+ = \sqrt{p^2c^2 + m_0^2c^4}$$

$$E^- = -\sqrt{p^2c^2 + m_0^2c^4}$$


Paul Dirac 大胆地预言一切粒子都存在其反粒子, 电子的反粒子就是正电子.

这是第一次提出反物质的存在.

**In 1932, Carl Anderson discovers the positron**

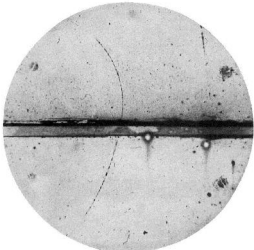
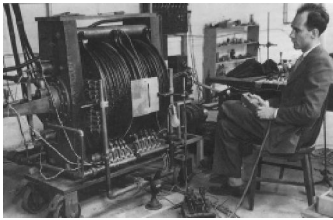



FIG. 1. A cloud chamber photograph showing the production of a positron. The track of the positron is the upper track, and the track of the electron is the lower track. The tracks are produced by the ionization of the gas in the chamber.

CARL D. ANDERSON

The production and properties of positrons  
 Nobel Lecture, December 12, 1936

## 赵忠尧与诺贝尔奖擦肩而过



中国科学技术大学的缔造者之一, 近代物理系首任系主任

赵忠尧在1927年到加州理工学院攻读学位，做硬 $\gamma$ 射线吸收系数的测量工作。赵忠尧用放射性元素钍衰变的中间产物Thc（即铊208）作辐射源，它能辐射出能量为2.6MeV的 $\gamma$ 射线。测量这种硬 $\gamma$ 射线在几种物质中的吸收系数之后，赵忠尧意外地发现，射线只在通过轻元素时吸收的情况才与公式相符，当通过重元素时，出现了反常现象，实际吸收量远大于公式给出的量。

1929年底，赵忠尧将结果整理成论文。但由于实验结果与密立根教授预期的不相符，密立根不甚相信。文章交他之后两三个月仍无回音，幸而替密立根代管研究生工作的鲍恩(Bowen)教授十分了解该实验从仪器设计到结果分析的全过程，他向密立根教授保证了实验结果的可靠性，文章才得以于1930年5月在《美国国家科学院院报》上发表。



R. A. Millikan  
(1868.3.22-1953.12.19)



Carl D. Anderson  
(1905.9.3-1991.1.11)



Zhao Zhongyao,  
(1902.6.27.-1998.5.28)

1930年春天，他重新实验，他发现， $\gamma$ 射线被铅散射时，除康普顿散射外，伴随着前述的反常吸收还有一种特殊的光辐射出现。当时测定的这种特殊辐射的强度是大致各向同性的，并且每个光子的能量与一个电子质量的相当能量很接近。

这一结果表明， $\gamma$ 射线在重元素中的特殊吸收不是由康普顿效应引起的，它揭示了一种新的反应机制。赵忠尧将这个实验结果写成第二篇论文，题目为《硬 $\gamma$ 射线的散射》，并于1930年10月在美国《物理评论》杂志上发表。



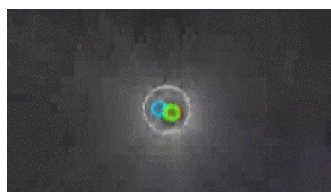
1996 北京医院



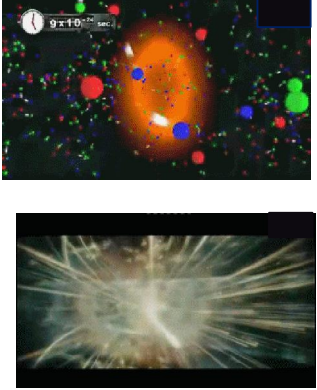
科学家们希望能在实验室制造出反物质！



欧洲世界最大的加速器



重现宇宙产生初期的景象，包括反物质产生！




通过粒子碰撞还把能量转换成反物质，即粒子与反粒子。

### 反质子的发现

1955年10月，全世界的媒体的头条新闻都是：“*New Atom Particle Found; Termed a Negative Proton*”.

Segre' 和他的小组朝着自然界物质与反物质的对称性迈进了重要的一步。

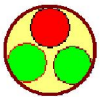


Segre' and Chamberlain were awarded the Nobel Prize in 1959.

### 反中子发现


- 1956, B. Cork等科学家宣布发现反中子.

$2d+u$



Neutron

$2\bar{d}+\bar{u}$



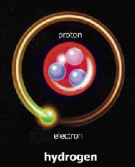
Anti-Neutron

### 反原子核的发现

1965, 2组科学家(CERN, A. Zichichi; USA-BNL, L. Lederman)同时宣布发现antideuteron, 即由反质子和反中子组成的核。

### 反原子的发现

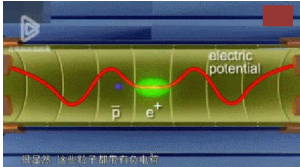
1995年底，以奥尔特勒为首的CERN PS210小组发现反原子。尽管他们在23000个计数中仅仅得到9个事例。1996年CERN正式宣布发现反原子。



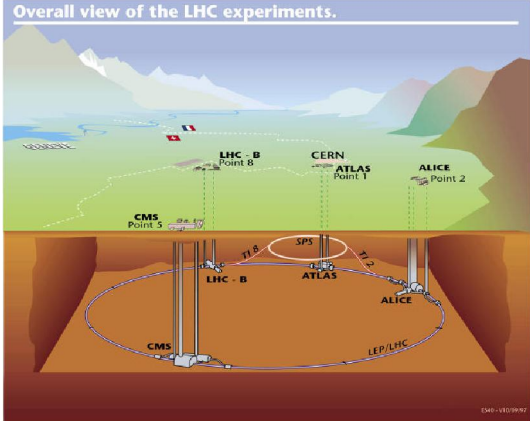
hydrogen



anti-hydrogen



带电粒子在电势阱中



Overall view of the LHC experiments.

- 1995年11月13日，在伦敦威斯敏斯特教堂，在紧挨着牛顿纪念碑的地方，举行了狄拉克纪念碑的揭幕仪式（1984年10月20日去世），纪念碑上写着：

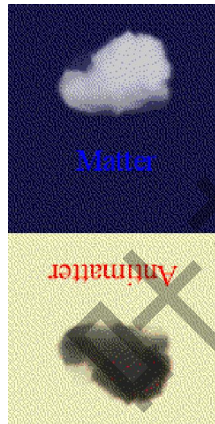
$$i\hbar\partial\Psi = m\Psi$$

## 寻找太空中的反物质



## 太空中的反物质

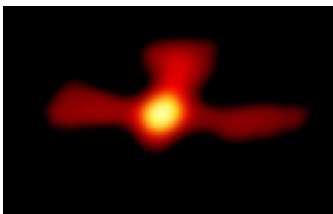
随着正电子，反质子，反中子和反原子的陆续发现，科学家们开始设想在我们的宇宙中是否存在反行星，反恒星，反星系团。甚至存在反宇宙。



- 过去的20多年来，科学家们试图把探测仪器用气球和卫星送到尽可能高的地方，寻找来自太空的反物质信息。这种尝试是非常困难的。



1997年4月，美国海军研究实验室、西北大学和加州大学伯克利分校等五个著名研究机构的天文学家宣布，他们利用先进的伽马射线探测卫星发现在银河系上方约3500光年处有一个不断喷射反物质的反物质源。它喷射出的反物质在宇宙中形成了一个高达2940光年的“喷泉”。这是宇宙反物质研究领域的一个重大突破。



## Searching for distant anti-galaxy: Finding antinuclei in the cosmic rays

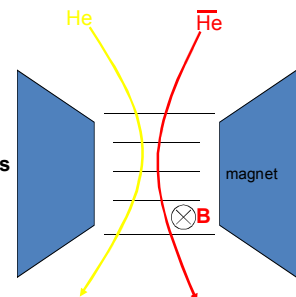
To identify He, we need to know:

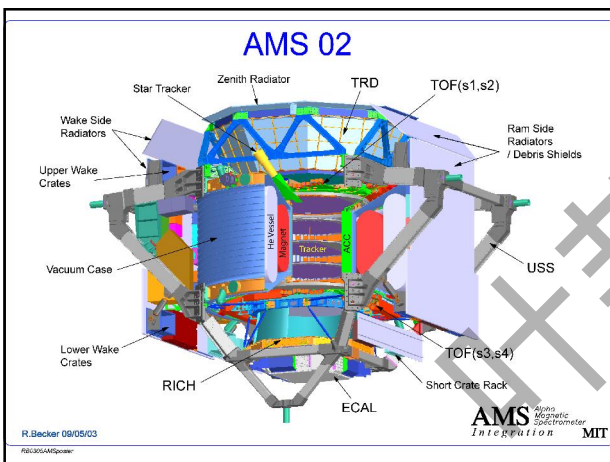
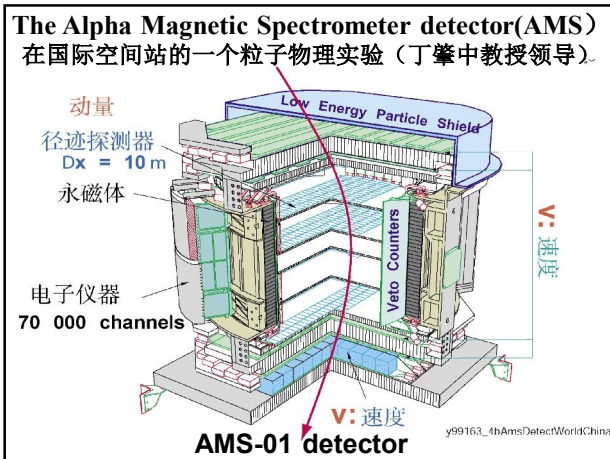
- Momentum,  $p$
- Charge,  $|Q|$
- Sign of charge,  $\text{sign}(Q)$

Basically Magnet + Tracker is what we need.

- Track curvature –  $Q/P$
- $dE/dx \sim |Q|$

The detector has to operate outside of earth atmosphere.



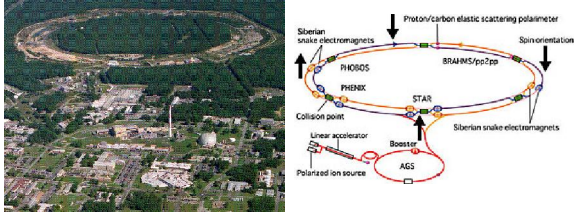


## 反<sup>4</sup>He核素发现

美国布鲁克海文国家实验室的相对论重离子对撞机 (RHIC) 获得重大发现：中国科学家参加的 **RHIC-STAR** 国际合作组探测到氦核的反物质粒子——反氦4核。将于**29日**出版的英国《自然》(Nature) 杂志于北京时间**4月25日**凌晨在线发表了该成果。由中国科学家队伍研制的飞行时间探测器在该实验中起了关键的作用。

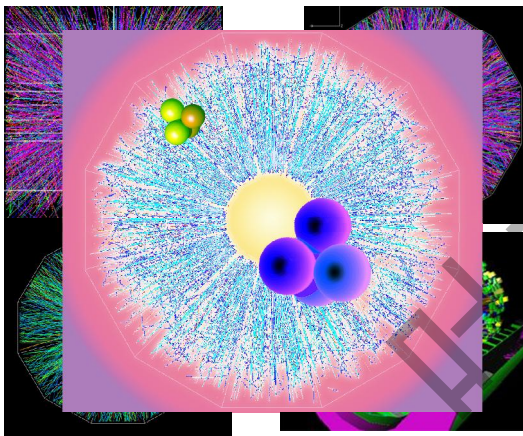
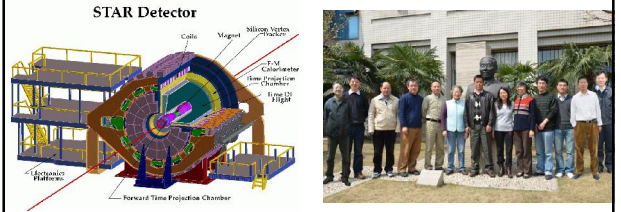
反氦-4又名反 $\alpha$ 粒子，是迄今为止所能探测到的最重的反物质原子核，也很可能是未来很长一段时间内所能探测到的最重反物质原子核，因为下一个更重的稳定反物质原子核产生的可能性是反氦-4的百万分之一，而以现在的加速器技术几乎不可能实现。

The Relativistic Heavy Ion Collider (RHIC) at the Brookhaven National Laboratory (BNL) took first collision data in June-September, 2000. The collider has two intersecting rings with counter propagating beams. Below you see some initial images from head-on collisions of gold nuclei with a total energy of 26 TeV (65 GeV/nucleon in each beam).

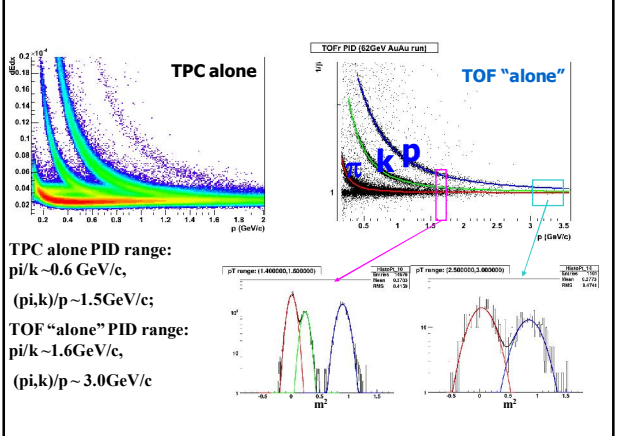
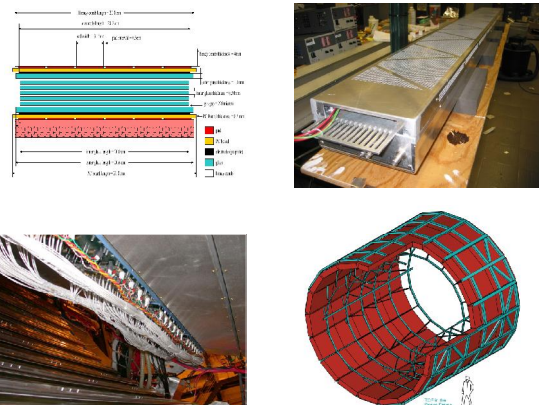
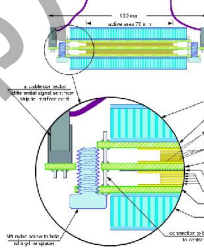


### STAR中国合作组

STAR合作组由来自12个国家的54科研单位组成。其中STAR中国合作组成员包括中国科学技术大学、中国科学院近代物理研究所、中国科学院上海应用物理研究所、清华大学、华中师范大学、山东大学等。



中国科学院和美国能源部共同出资研制并于2009年安装在STAR探测器上的“大型飞行时间探测装置”(TOF)，在反物质4的鉴别过程中发挥了关键的作用





### 三、反物质的应用

● Fundamental science

Anti-matter knowledge

● Material science

Microstructure explanation

● Industrial application

Industrial CT  
A successful application is Medical PET

### 1. Fundamental Science

Fundamental Science

Test Quantum Electrodynamics

Ps Bose-Einstein Condensation

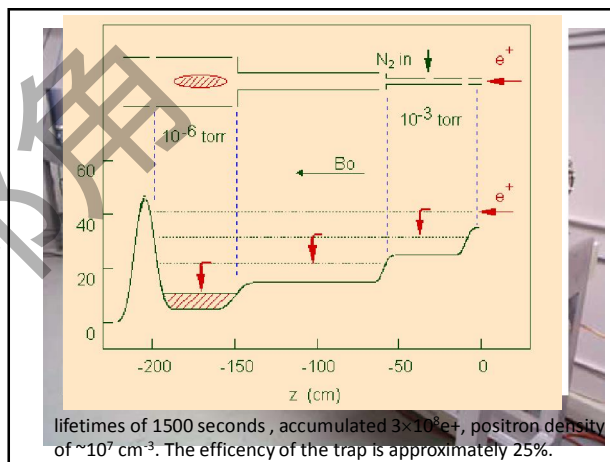
Gravitation of Ps

Anti-matter Energy

Extra-dimension

### Anti-matter Energy

	<b>TNT</b>	<b><math>4.7 \times 10^6 \text{ J/Kg}</math></b>
	<b>裂变</b>	<b><math>7.1 \times 10^{13} \text{ J/Kg}</math></b>
	<b>聚变</b>	<b><math>7.5 \times 10^{14} \text{ J/Kg}</math></b>
	<b>正-反物质湮灭</b>	<b><math>1.8 \times 10^{17} \text{ J/Kg}</math></b>



### Multicell Positron Trap Electrods

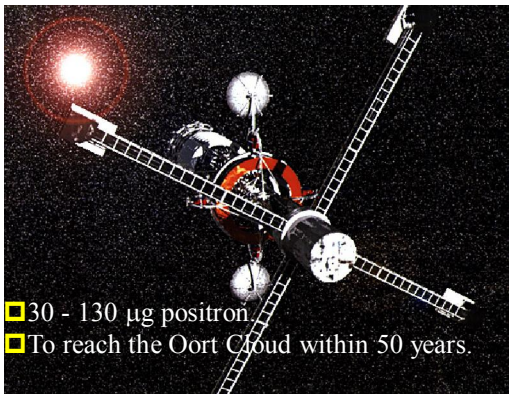
$N \sim 10^{12}$

Clifford Surko, a professor of physics at UC San Diego who is constructing what he hopes will be the world's largest antimatter container,



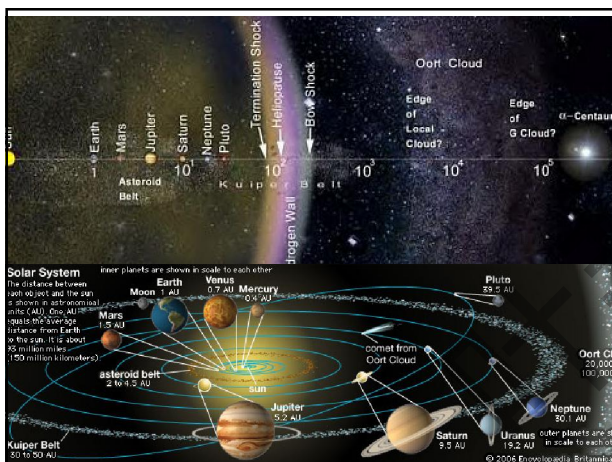
### 宇宙飞船新能量

化学燃料不能满足航天的要求，必须大大增加燃料的能量密度。美国宇航局2001年召开的“先进空间推进器研讨会”上，K.J.Meyer提出用正电子能量转换作航天器的能源的设想。他们认为10年内可实现这一目标。

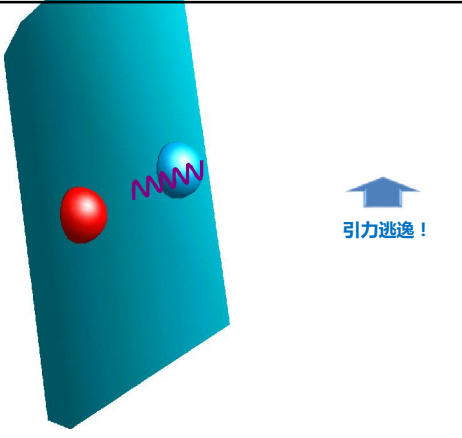
30 - 130  $\mu\text{g}$  positron.  
To reach the Oort Cloud within 50 years.

**ICAN-II**



### 宇宙存在一个额外维吗？

质量消失了，引力逃逸了！

引力逃逸！

Volume 125B, number 2.3      PHYSICS LETTERS      26 May 1983

### Do we live inside a domain wall?

V.A. RUBAKOV and M.E. SHAPOSHNIKOV  
*Institute for Nuclear Research of the Academy of Sciences of the USSR, 60th October Anniversary Prospect 7e, Moscow 117312, USSR*

Received 7 February 1983

We discuss the possibility that space-time has  $(3+N)+1$  dimensions, but ordinary (light) particles are confined in a potential well which is narrow along  $N$  spatial directions and flat along three others. A five-dimensional model is considered in which this picture arises naturally. In a universe of this type, processes looking like  $e^+e^- \rightarrow \text{nothing}$  are possible at high energies.

**电子偶素-目前世界上质量最小的原子**

$E = 6.8eV \quad D = 1.06\text{\AA}$        $E = 13.6eV \quad R = 0.53\text{\AA}$

**Ortho-positronium and extradimension**

- Presently there is a big interest in models with additional dimensions which might provide solution to the gauge hierarchy problem. In Randall-Sundrum model typeII particles can be trapped on the brane, where they are expected to be metastable, they decay into continuum Kaluza-Klein modes. From the point of view of an observer in 3d-"brane" the particle disappear into the bulk of the additional dimension.

In a recent paper it was pointed out that this mechanism could result in a disappearing of ortho-positronium into the bulk of additional dimensions. The probability was calculated to be:

$Br(o-Ps \rightarrow \text{extra dimensions}) \approx 3 \times 10^4 \left(\frac{m_e}{k}\right)^2$       Tunneling of a particle through extra-dimension (V. A. Rubakov)

$10^9 < Br(o-Ps \text{ extradim}) < 10^8$

**追踪逃逸的引力，也许可以找到额外维！**  
如果额外维存在，物质就可能从额外维逃逸！

Invisible: 无光子衰变

**理论学家预言**  
 $10^9 < BR(o-Ps \text{ 逃逸到额外维}) < 10^8$

**第一个实验结果, Moscow, USSR (1989)**  
 $BR(o-Ps \text{ 逃逸到额外维}) \leq 5.8 \cdot 10^{-4}$   
Aycock et al. (Phys. Lett. B 220, 317 (1989))

**最新的结果, ETH (2007)**  
 $BR(o-Ps \text{ 逃逸到额外维}) < 4.2 \times 10^{-7}$  (90% C.L.)

**实验一定是“高大上”吗？**

**实验并不复杂！唯一的难度是，耐心！**

**期待存在一个额外维！**

**2. Positron Science**

Material Science

- Solid State Physics
- Materials Design
- Surface Science and Catalysis
- Industrial Materials
- Nano Science

### 正电子技术应用

<ul style="list-style-type: none"> <li>□ 半导体</li> <li>□ 超导体</li> <li>□ 薄膜</li> <li>□ 界面</li> <li>□ 多孔材料</li> </ul>	<ul style="list-style-type: none"> <li>□ 纳米材料</li> <li>□ 巨磁阻</li> <li>□ 金属</li> <li>□ 多聚物</li> <li>□ 量子点</li> </ul>
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2014/12/4

### Positron Science

Positron experimental arts

- Positron Annihilation Spectroscopy
- Coincidence Doppler Broadening
- 2D-Angular Correlation of Annihilation Radiation
- Age-Momentum Correlation
- Positron annihilation induced Auger Electron Spectroscopy
- Low Energy Positron Diffraction
- Slow positron beam
- Micro positron beam
- High energy positron beam

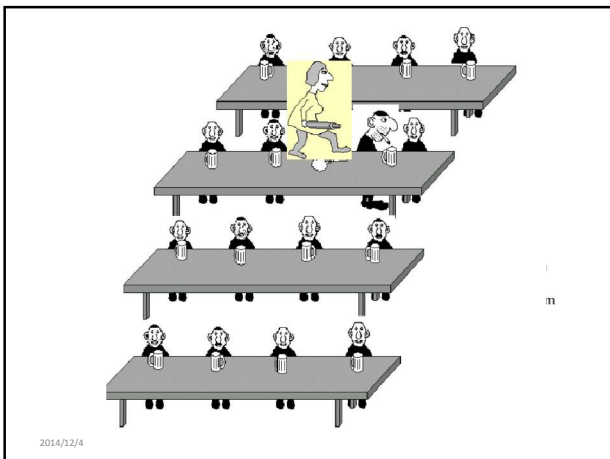
### 二、正电子湮灭探测技术

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### 正电子技术的优越性

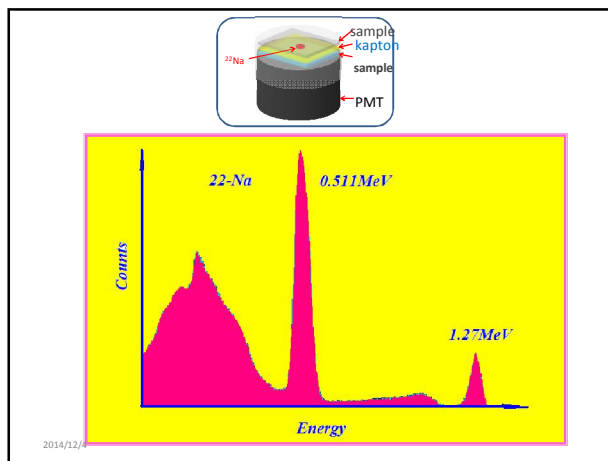
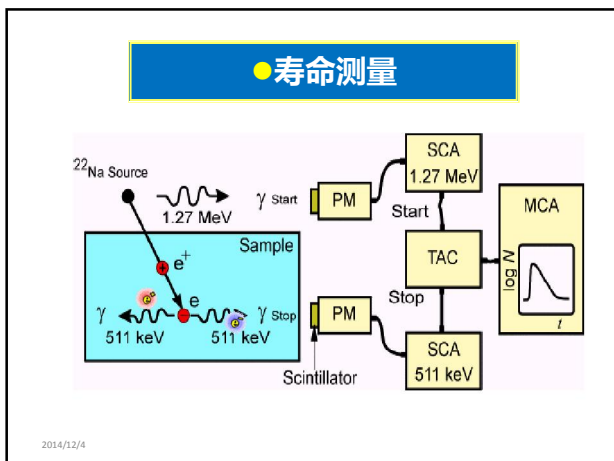
- 对缺陷及原子尺度的微结构变化极为灵敏；
- 无损探测，主动式寻找缺陷；
- 可探测真实表面（几个原子层）的物理化学信息；
- 探测物体内部局域电子密度及动量分布；
- 正电子是电子的反粒子，容易与电子分辨，又可形成电子偶素；
- 慢正电子技术具有能量可调性，因而可获得缺陷或结构不均匀性沿样品深度的分布。

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### 正电子湮灭基本测量技术

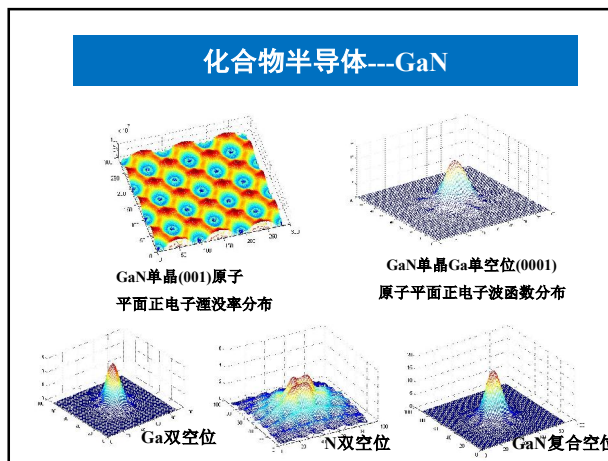
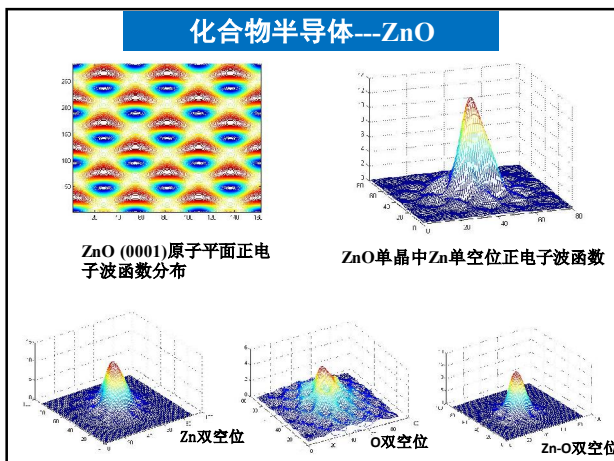
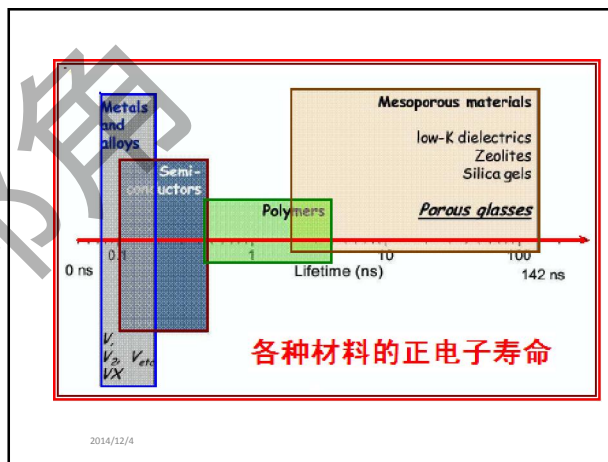
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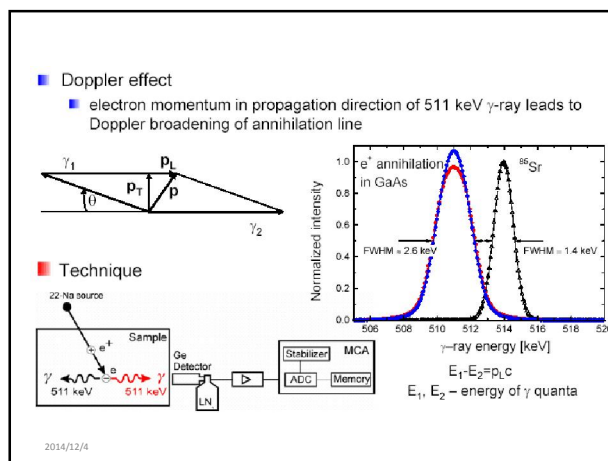
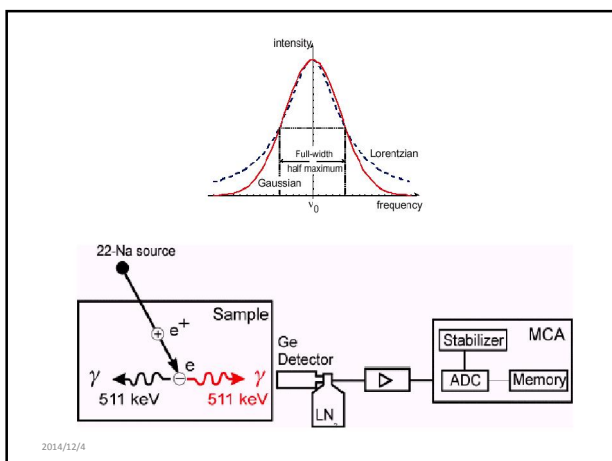
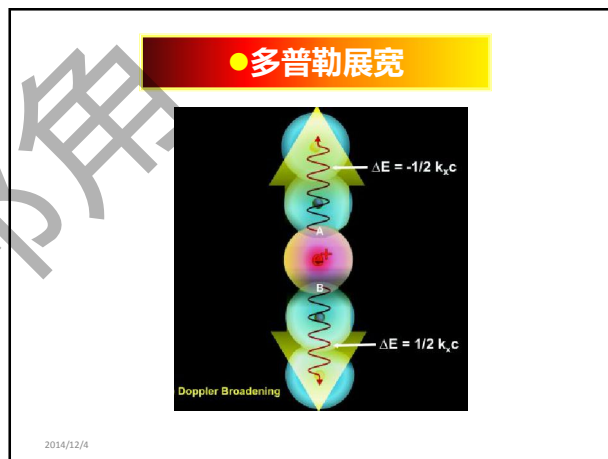
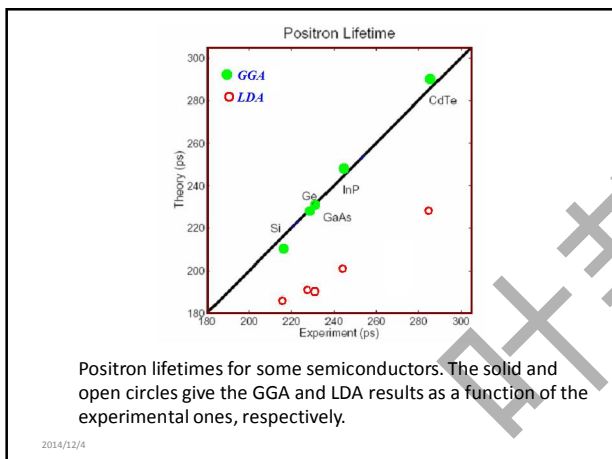
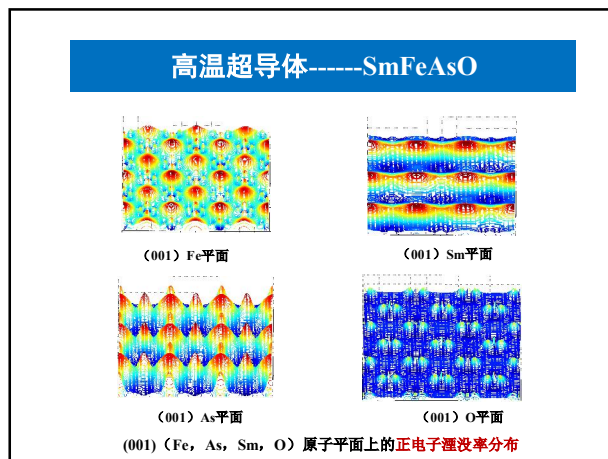
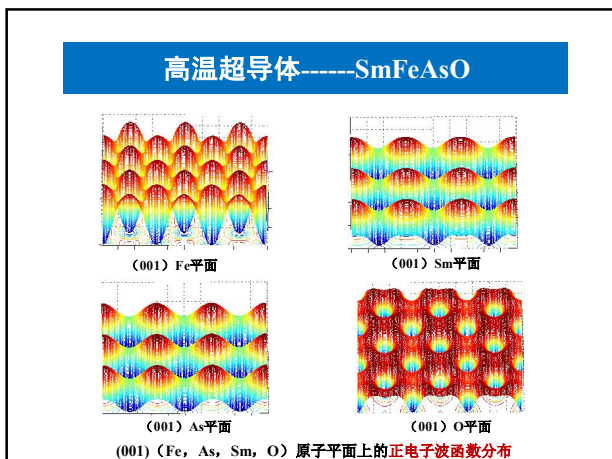


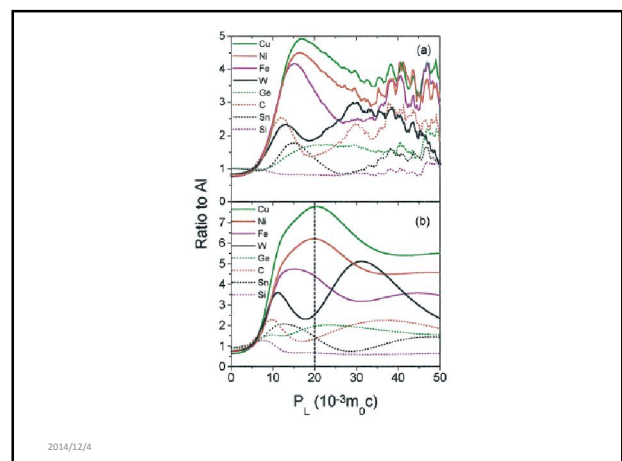
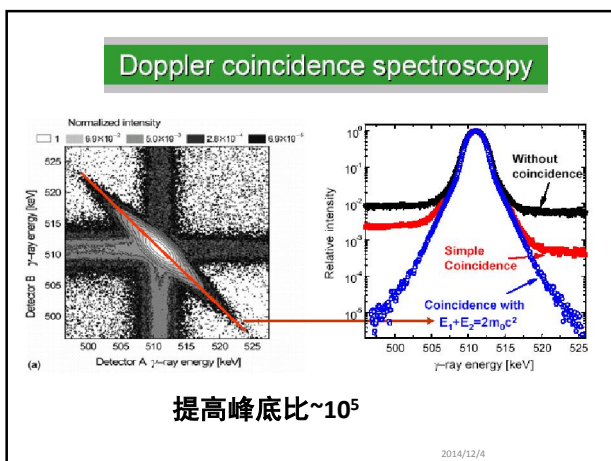
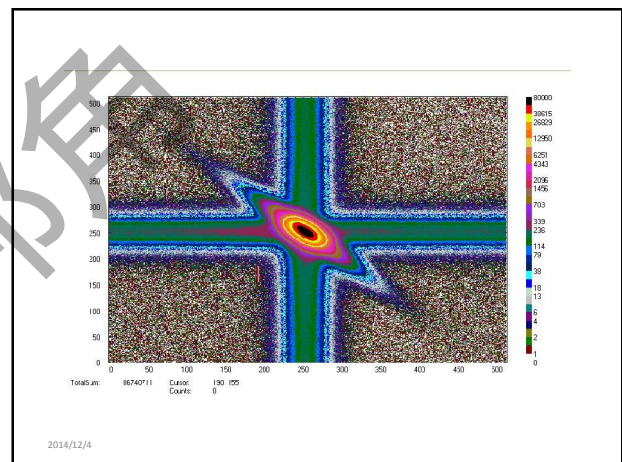
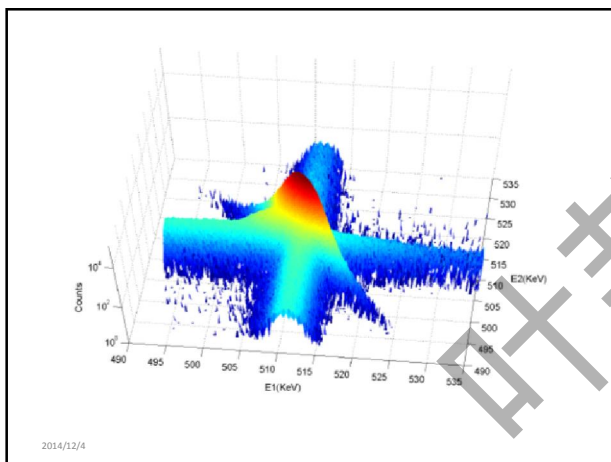
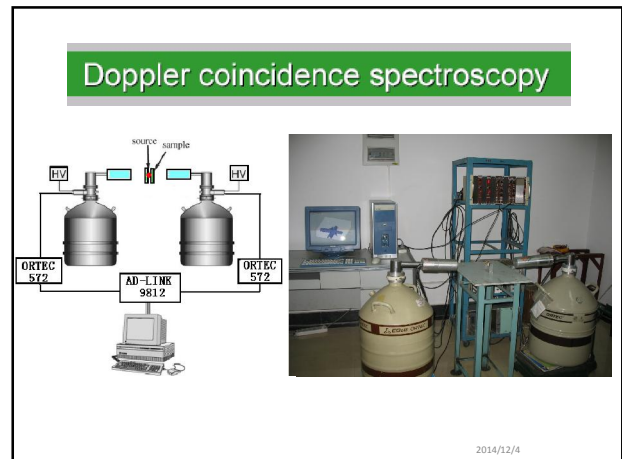
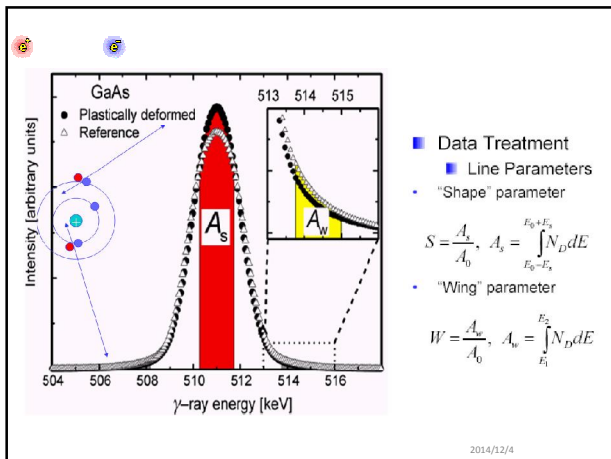
### Defects in Materials

Defect Type	Size	Materials
Atomic Vacancies	.1 nm	Metals
Dislocations	1 nm-10 $\mu$ m	Metals
Voids	.1 nm-1 $\mu$ m	Composites
Holes	.1 nm-10 $\mu$ m	Polymers

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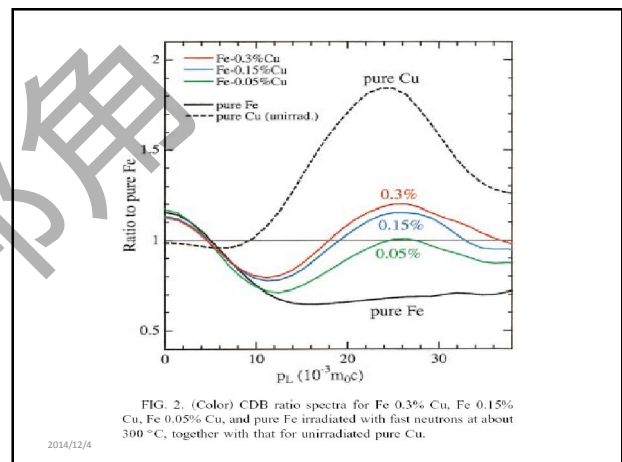
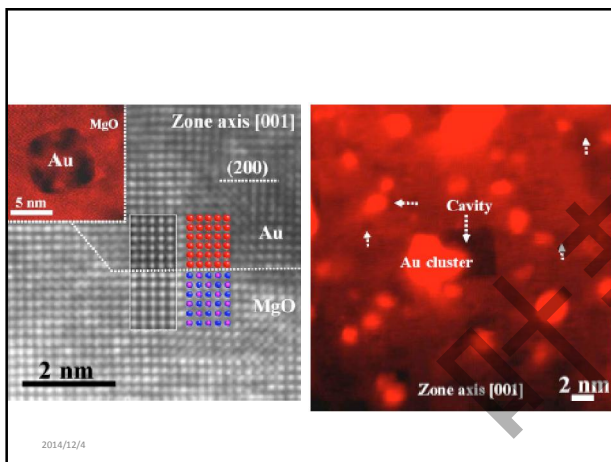
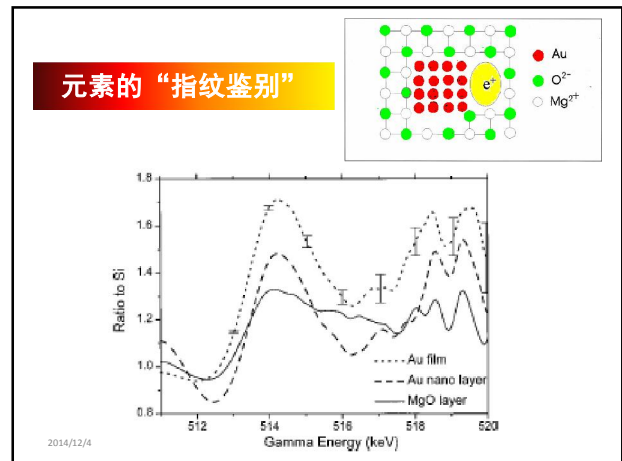
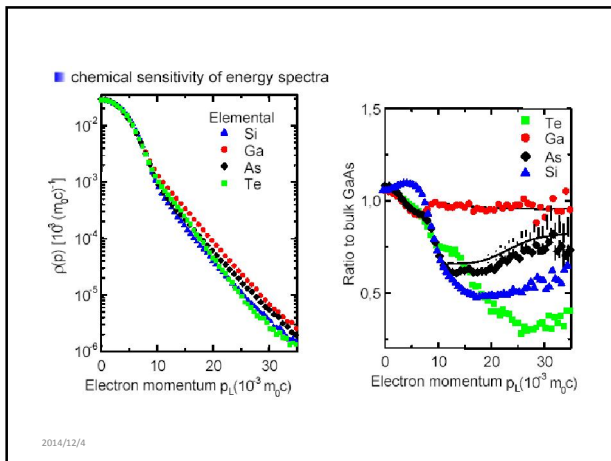
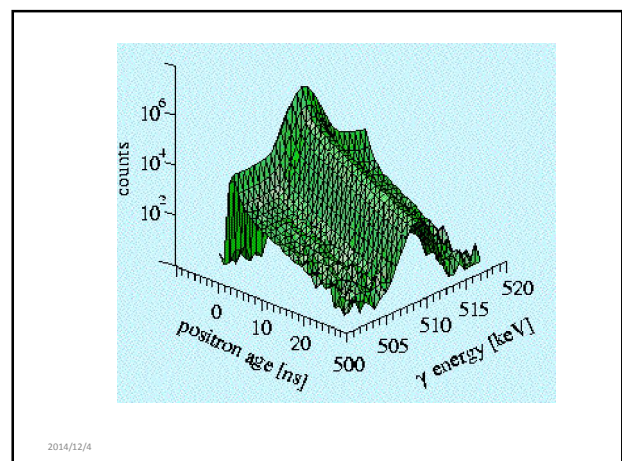
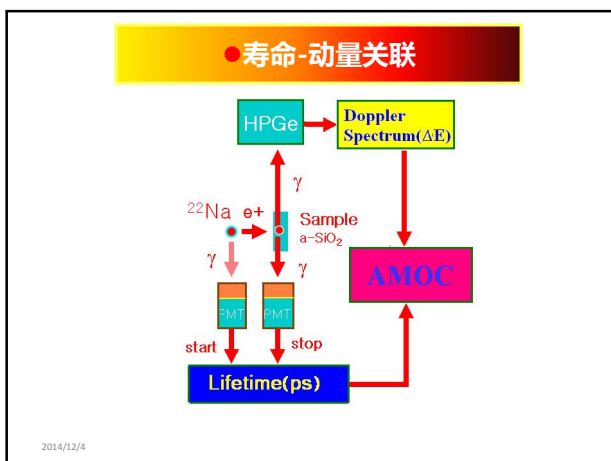
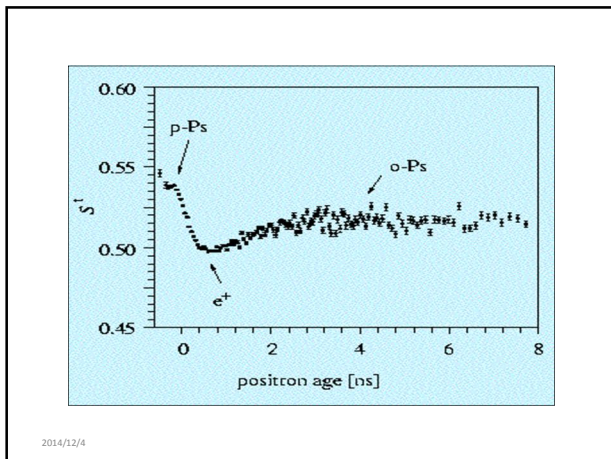


FIG. 2. (Color) CDB ratio spectra for Fe 0.3% Cu, Fe 0.15% Cu, Fe 0.05% Cu, and pure Fe irradiated with fast neutrons at about 300 °C, together with that for unirradiated pure Cu.

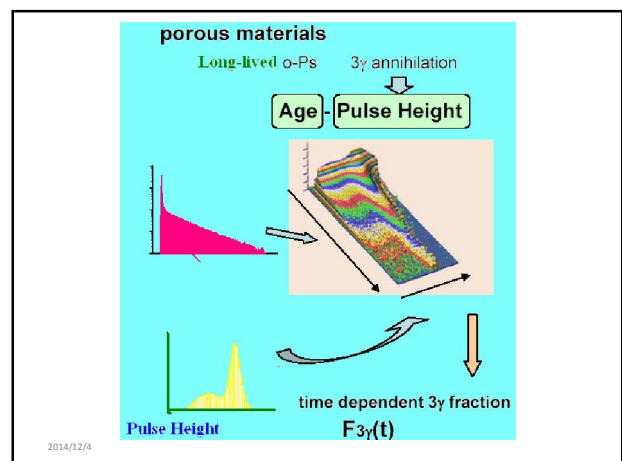
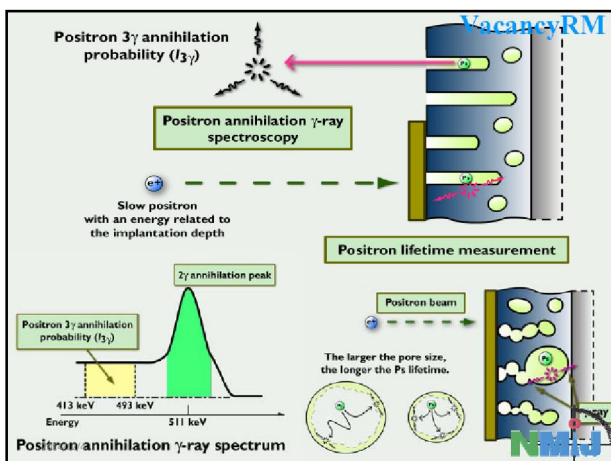
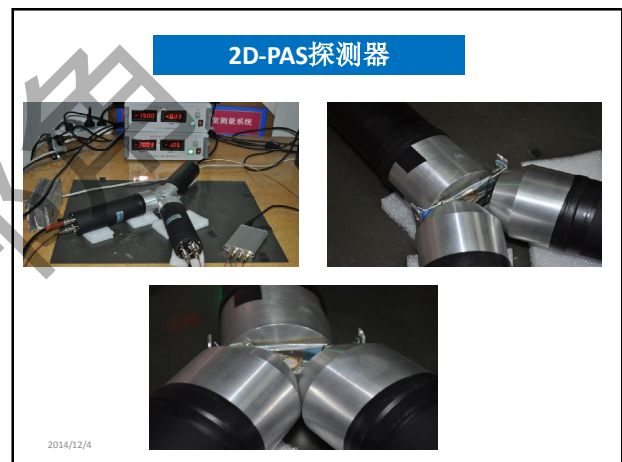
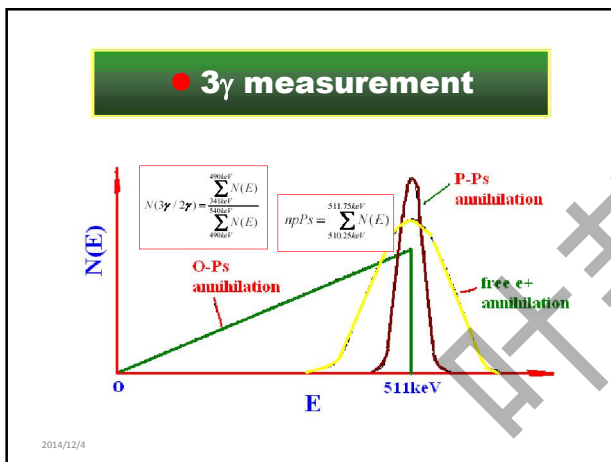






### p-Ps和o-Ps热化湮灭的各种特性

	热化p-Ps	非热化p-Ps	O-Ps pick-off	自由e+
年龄				
多普勒展宽				
S-参数				



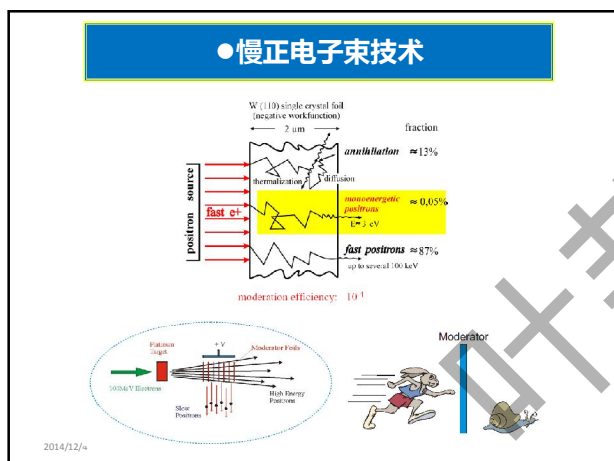
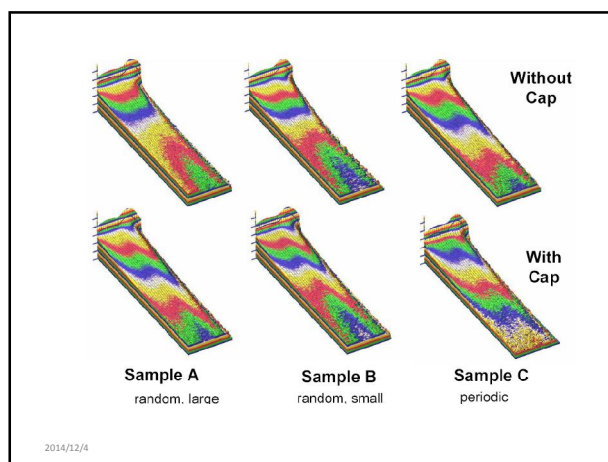
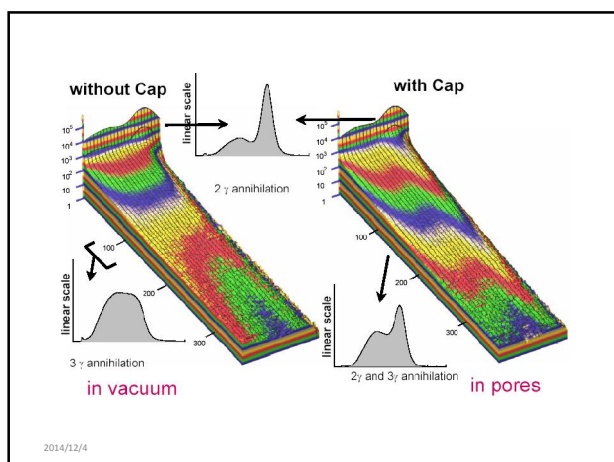
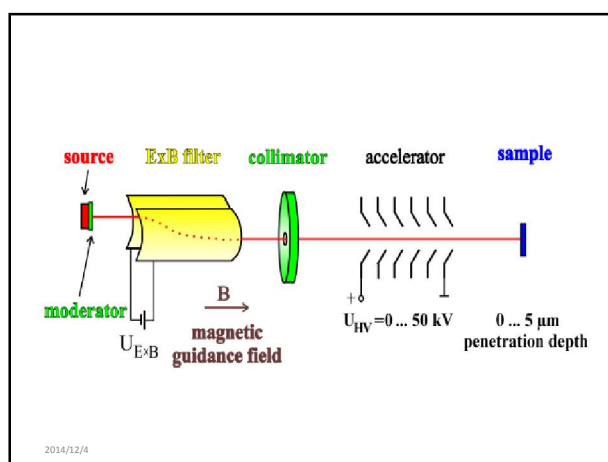
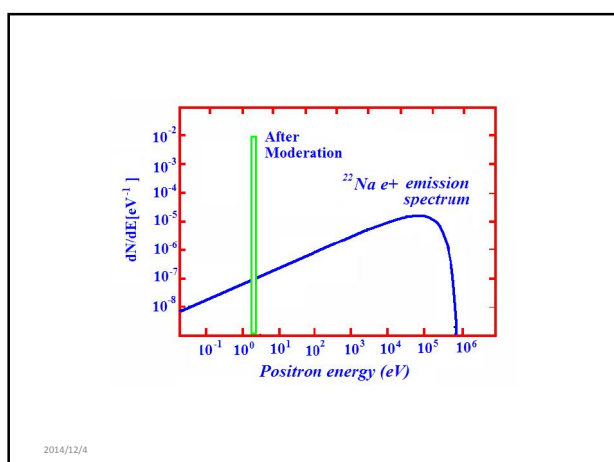


Table shows typical values for the efficiency, emission energy and energy spread of selected materials and different geometries.

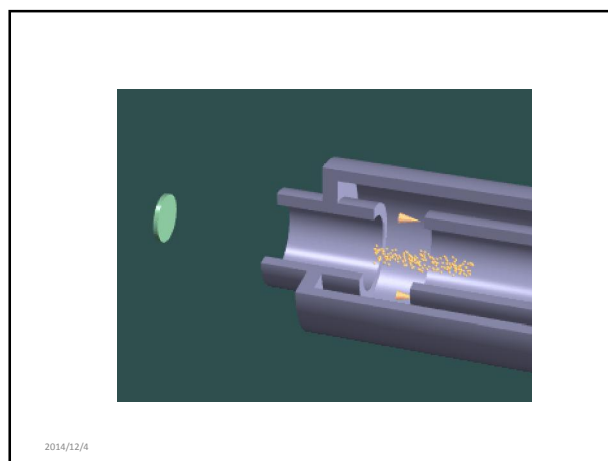
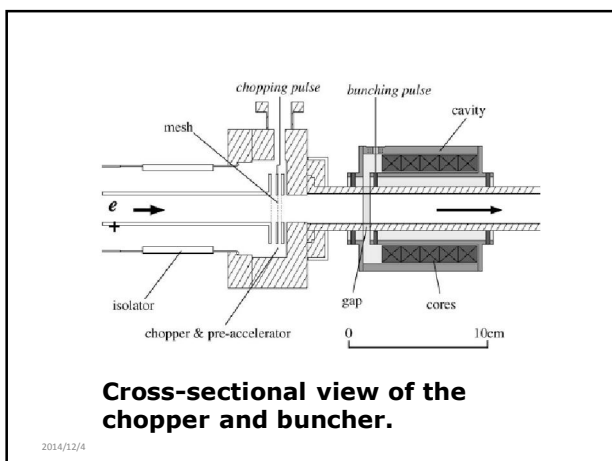
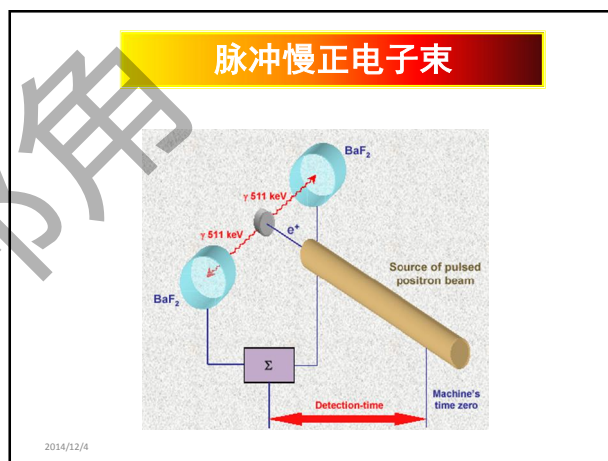
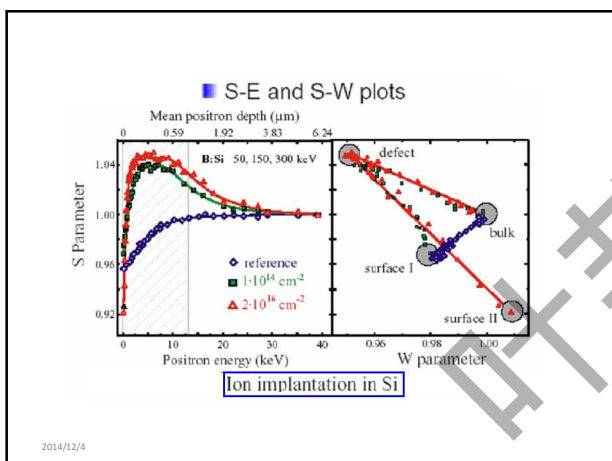
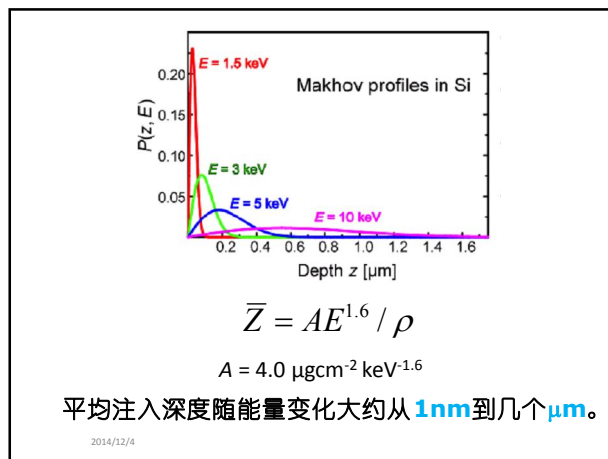
Moderation parameters for selected moderator materials

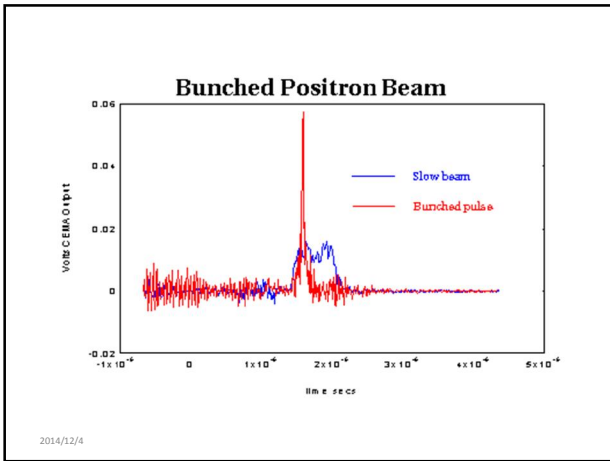
Type	$\epsilon_{typ}$	$E_{emiss}$ (eV)	$\Delta E$ (eV)	$T_{ann}(^{\circ}C)$
Reflection W	$10^{-3}$	$\sim 3$	$\leq 1$	$>2200$
Transmission W	$2 \times 10^{-4}$	$\sim 3$	$\leq 1$	$>2200$
Transmission Cu	$5 \times 10^{-5}$	$< 1$	$< 0.5$	650
Transmission Ni	$5 \times 10^{-5}$	$< 1$	$\sim 0.2$	650
Transmission solid Ne	$5 \times 10^{-3}$	$\sim 10$	10	NA





我国第一个慢正电子束装置





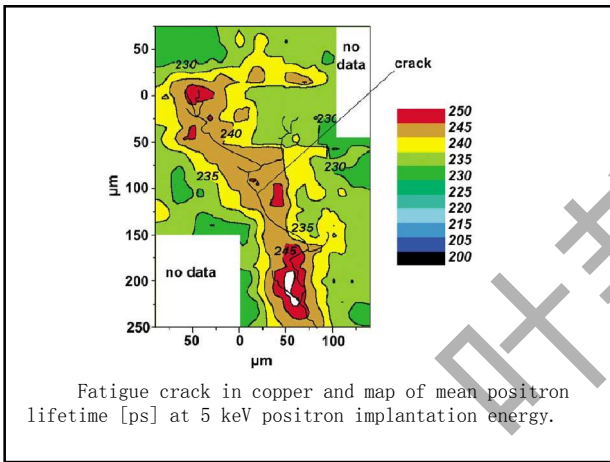
### Scanning positron microscope

- Variable energy micro-beam of monoenergetic positrons
- Lateral resolution of 2 μm is achieved
- Lifetime measurements at different beam energies are possible

Principle disadvantage: broad positron implantation profile at high energies

Phys. Rev. Lett. 87, 097402 (2001)

Electron and positron beam image of the surface of a test chip. Light area is SiO<sub>2</sub>, dark area is platinum



Intense e<sup>+</sup> microbeam, Microchannel plates, e<sup>+</sup> e<sup>-</sup>, Translation system, Vacuum chamber, Sample, Objective lens, BaF<sub>2</sub> scintillation detector

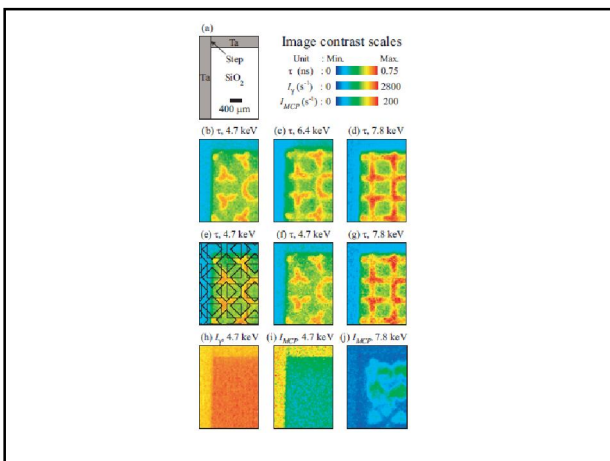
H<sup>+</sup> ion beam (50 keV, 10<sup>16</sup>cm<sup>-2</sup>)  
Ar<sup>+</sup> ion beam (150 keV, 10<sup>16</sup>cm<sup>-2</sup>)  
30 mesh  
Rotate 45°  
Depth 600nm  
a-SiO<sub>2</sub>  
Depth 200nm

Focused e<sup>+</sup> beam  
Sample  
100μm × 50 μm × 50 μm  
Total: 3500pixels

Minimal Depth (Energy)  
200 nm (4.7 keV)  
350 nm (6.4 keV)  
500 nm (7.8 keV)

lifetime: short to long (400 μm)

Defects created by Ar<sup>+</sup> and H<sup>+</sup>  
Defects created by I<sup>+</sup>



### 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

High energy physics  
Particle physics

Nuclear physics  
and application

Detecting techniques  
and electronics

Laboratory of Nuclear Solid State Physics

**Staff and student**

- 1 Professor + 2 retired professors
- 1 Lecturer
- 2 Post-doctoral
- 12 PhD Students
- 5 Master graduate students

中国科学技术大学  
核固体物理实验室  
Laboratory of Nuclear Solid State Physics, USTC

Theory research

3 PhD students  
1 Master student

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

Detecting techniques

1 Postdoc  
3 PhD students  
1 Master student

To develop new methods and techniques for positron probe.

Material application

1 Postdoc  
3 PhD students  
2 Master students

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

Muon beam and  $\mu$ SR

3 PhD students

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

### Conventional PAS

Resolution: about 240 ps  
Count rate: about 100 cps

### Digital CDB

It is first digital CDB spectroscopy in China (2003)  
Count rate: about 200 cps

### Digital PAS

Time resolution: ~185ps

### AMOC

Count rate: ~30cps

### 2D-PAS

Count rate: ~30-40cps

Slow positron beam,  $20\text{mCi } ^{22}\text{Na}$

$^{51}\text{Cr}$   $^{22}\text{Na}$

The RGM-1 solid neon moderated system has been bought from the FIRST POINT SCIENTIFIC COMPANY. Now it is being installed to match with the original beam.

Moderator material:	Solid neon
Moderator temperature:	7-8.4K
Beam transport:	Magnetic
Source shielding:	In vacuo; Elkotte external; lead shot
Separation filter:	Magnetic deflection
Moderator diameter:	8 mm
Beam diameter:	<3mm (depending on B) - * demonstrate 8 mm in a B field of 125 Gauss
Positron flux:	8 million/sec (50 mCi $^{22}\text{Na}$ ) - * +10% demonstrated using NaI scintillator
Energy spread:	1.3-2.5 eV (1.7eV typical)
Moderator decay rate:	<5% per day - * to be demonstrated
Moderator regrowth time:	<20 min total - * <30 min to be demonstrated
Base pressure:	<10 <sup>-8</sup> Torr

### MeV Positron beam based on CSNS

Proton beam from CSNS → Target: Graphite → Transmission Line → Chopper (400ns) → Collimator → Sample → Move/retainer → 128 detectors

Electronics: Chopper → Start → CFD → Delay → Fast coincidence → TAC → MCA → PC

Stop → CFD → Delay → TAC → MCA → PC

Pulse Generator (2.5MHz) → Start



叶邦角