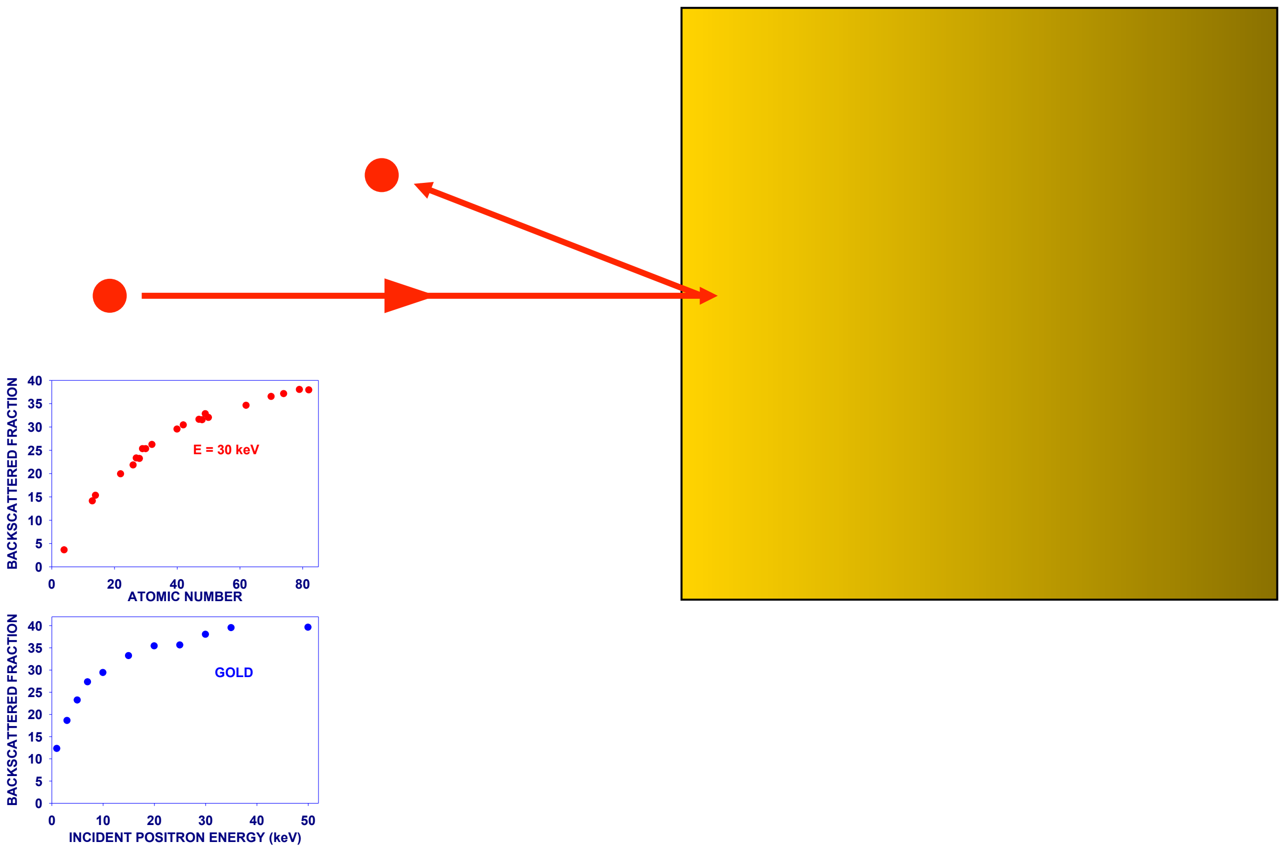
POSITRON AND POSITRONIUM INTERACTIONS WITH CONDENSED MATTER

Paul Coleman

University of Bath

THE FATE OF POSITRONS IN CONDENSED MATTER
POSITRON-SURFACE INTERACTIONS

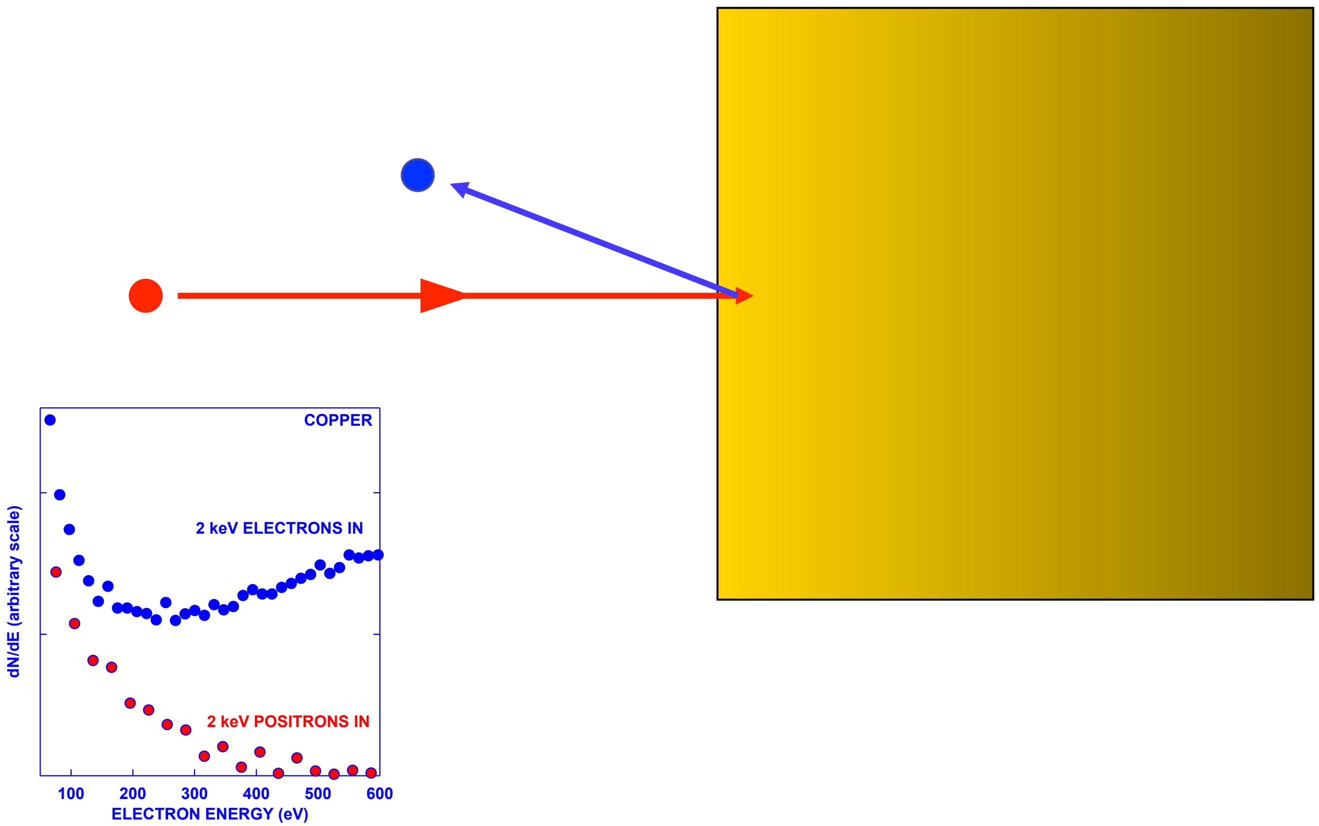
positron backscattering



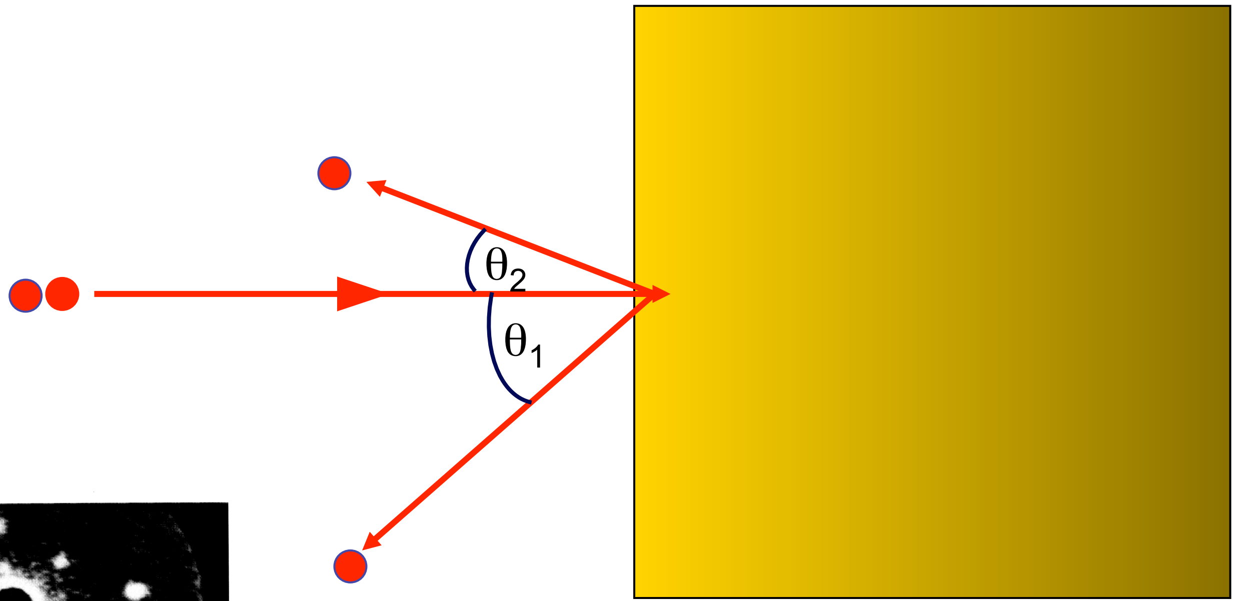
THE FATE OF POSITRONS IN CONDENSED MATTER

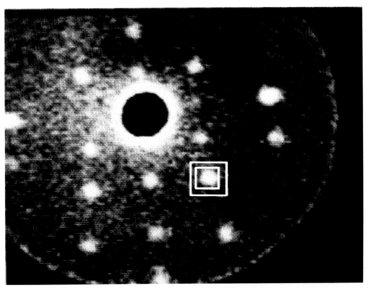
POSITRON-SURFACE INTERACTIONS

secondary electron emission

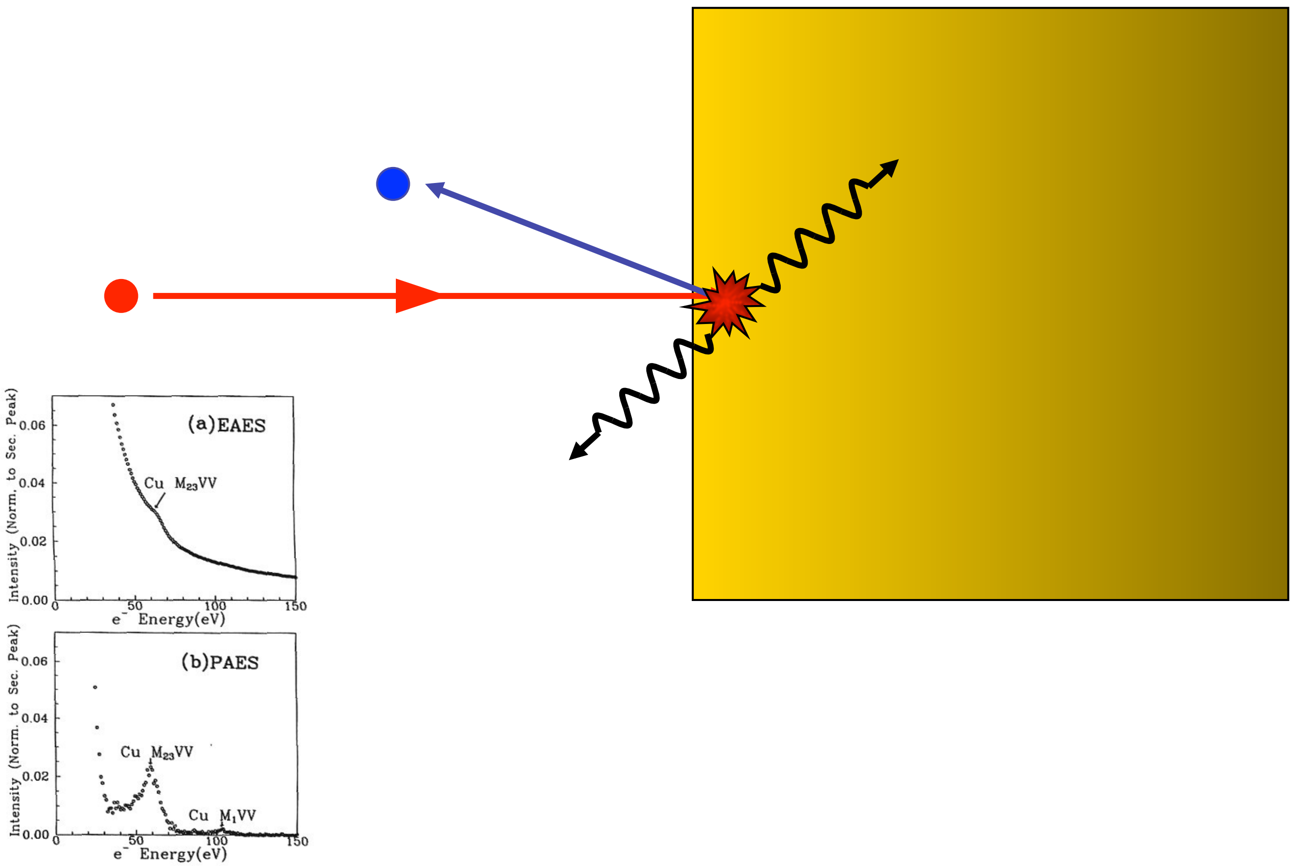


low-energy positron diffraction

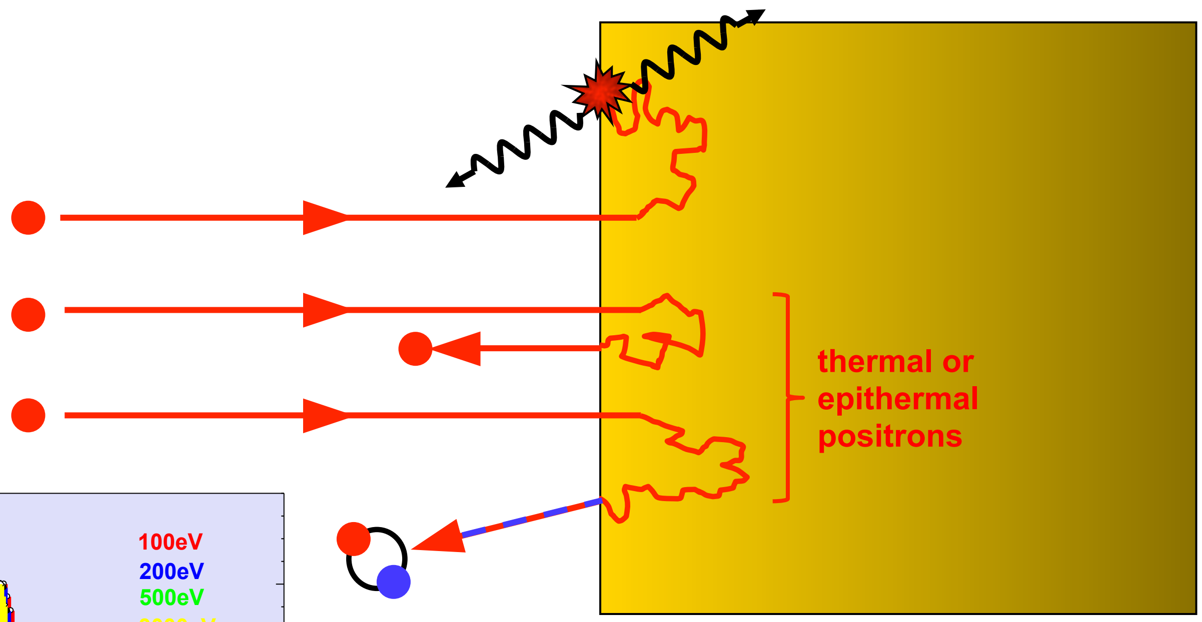


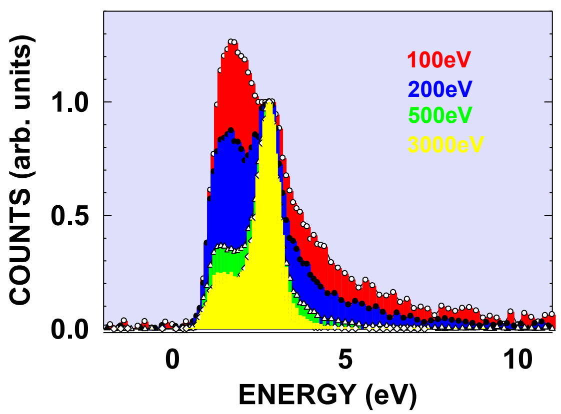


Auger electron emission



positron surface trapping, re-emission, positronium formation





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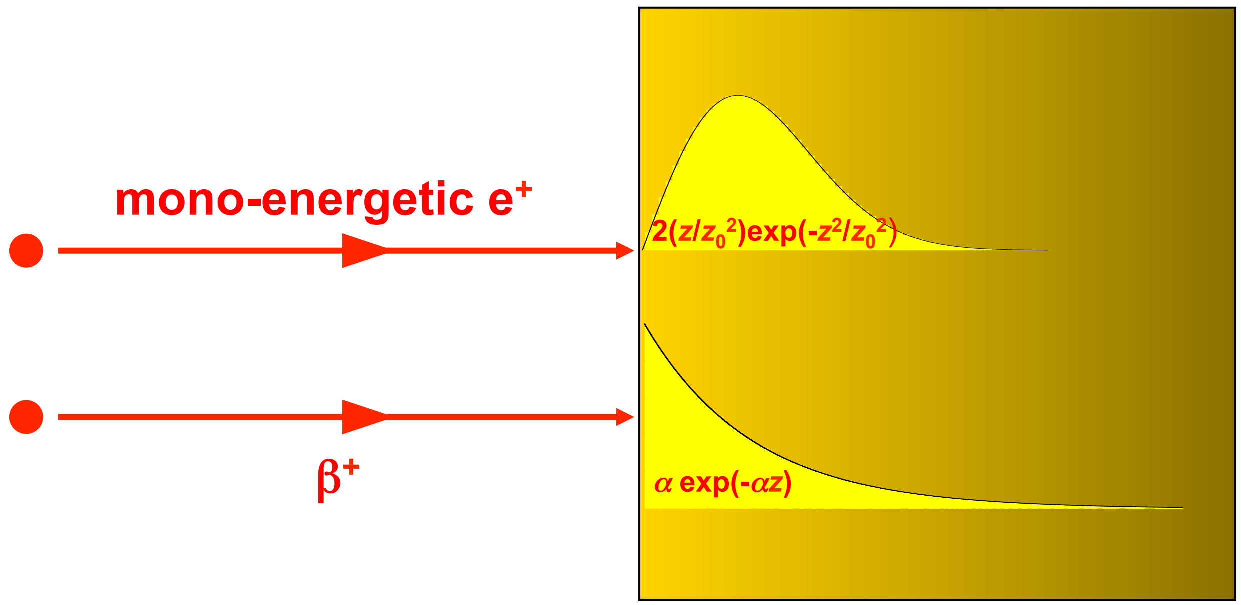
positron implantation

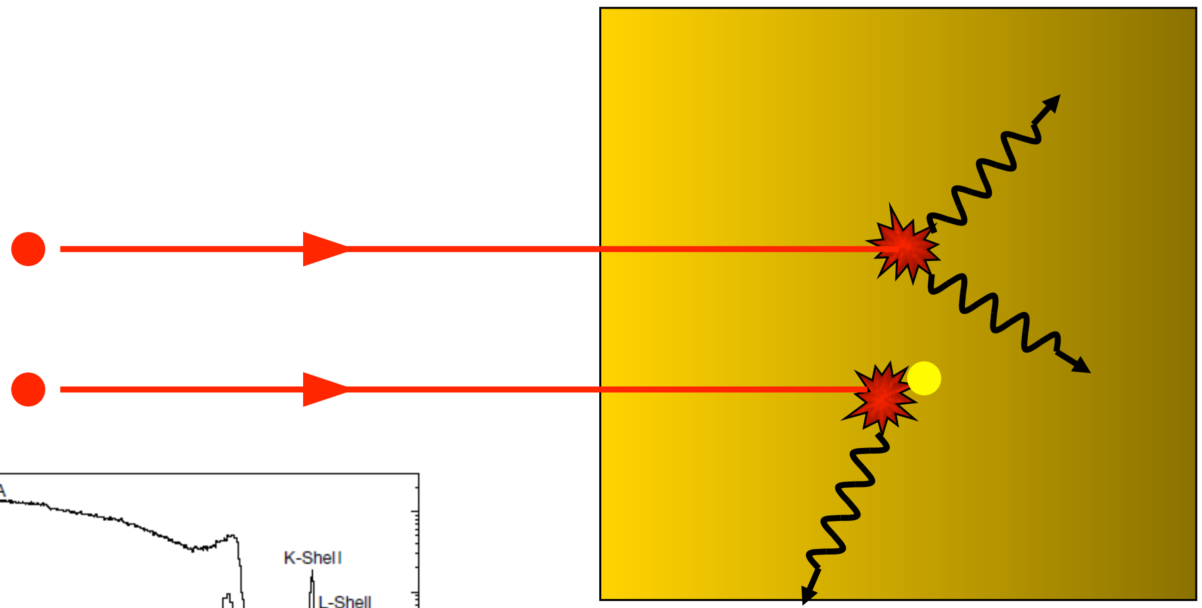
depth distributions at thermalisation (after ~ps):



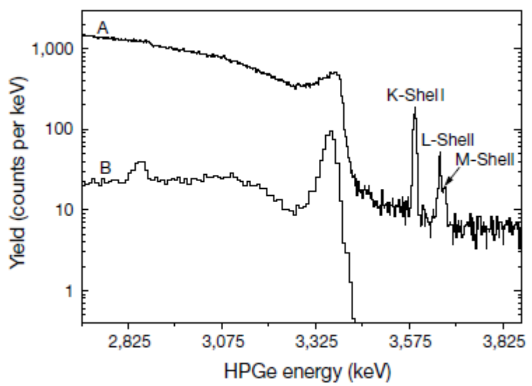
$P(z) = 2(z/z_0^2)\exp(-z^2/z_0^2)$ where $z_o = (40/\rho)E^{1.6}$ with density ρ in gcm^{-3} and E in keV

$P(z) = \alpha \exp(-\alpha z)$, with α (cm) ≈ $16\rho E_m^{-1.4}$ (ρ = density in gcm^{-3}, E_m = maximum beta positron energy in keV)

in-flight annihilation



2.65MeV
e^+s in Au



$$E_s = 2mc^2 + T_+ - |E_b|$$

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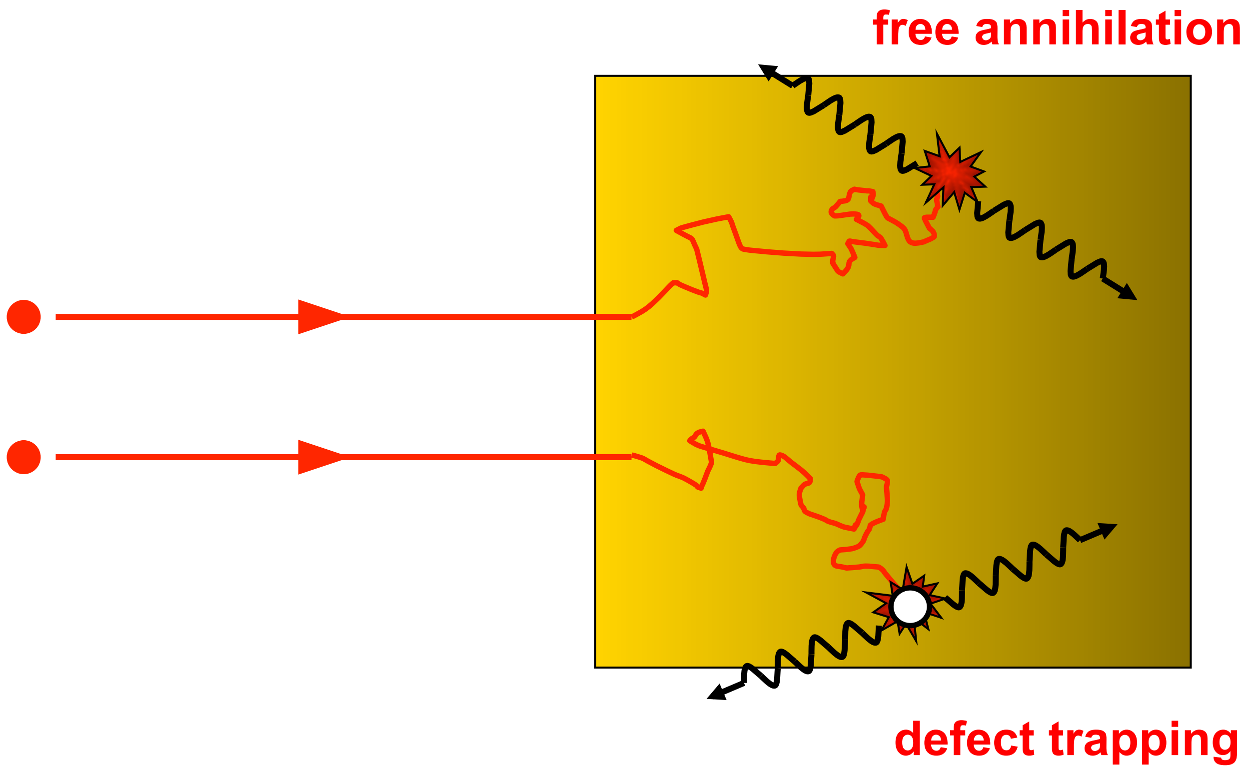
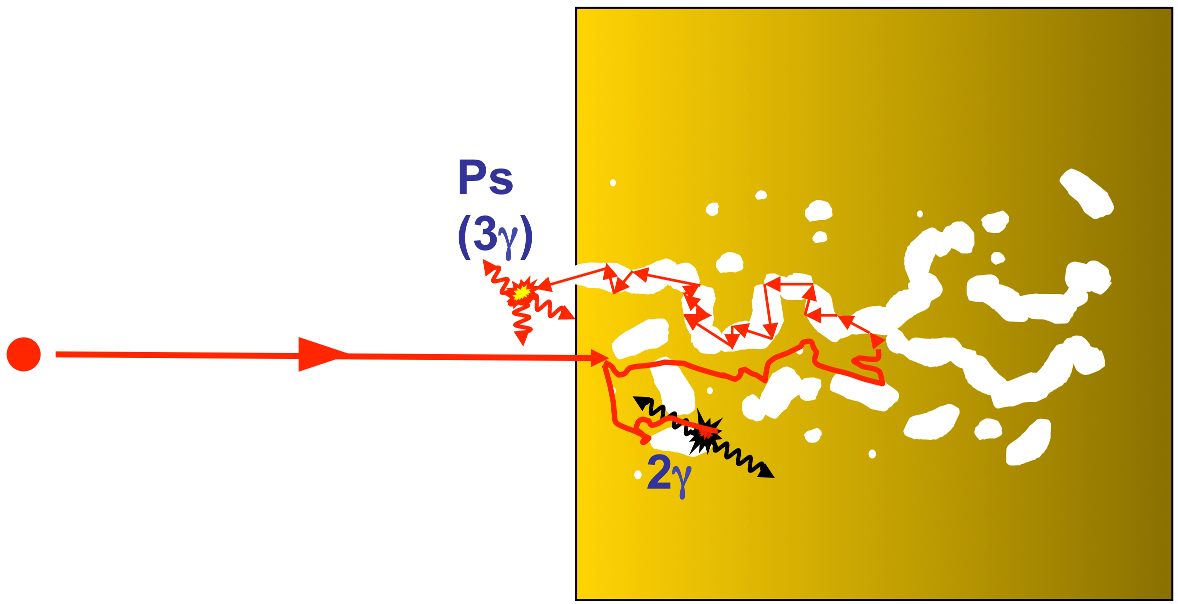
positron diffusion and annihilation



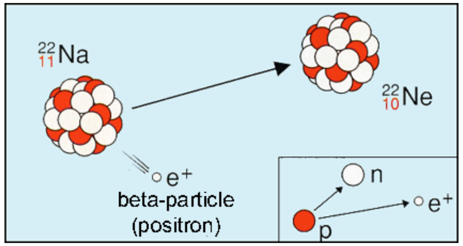
positronium formation – insulators, nanoporous materials

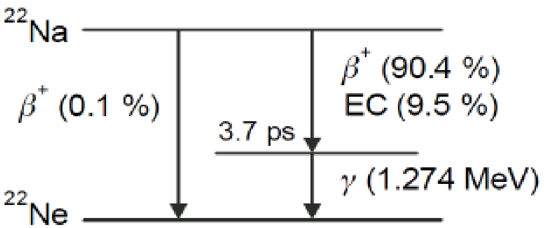


**** see later talks in this session ****

POSITRON SOURCES

RADIOACTIVE ISOTOPES – eg ^{22}Na



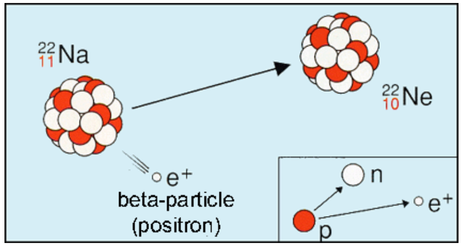


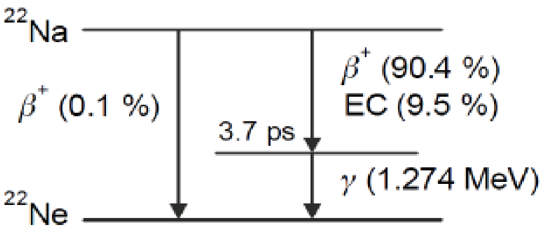
- Relatively long half-life (2.6 years)
- Relatively short biological half-life (3 days)
- 1.274 MeV γ can be used as a 'start' signal

The perennial problem – not enough positrons…

POSITRON SOURCES

RADIOACTIVE ISOTOPES – eg ^{22}Na





- Relatively long half-life (2.6 years)
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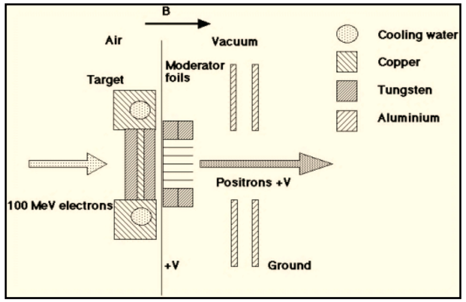
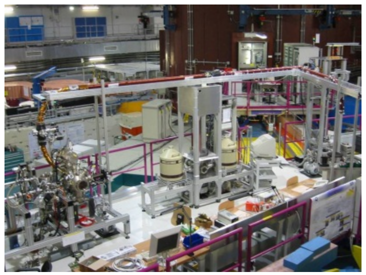
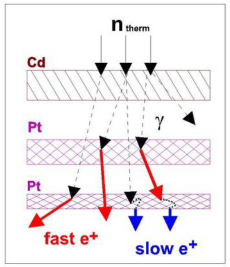
LINEAR ACCELERATORS – eg KEK, Japan



~ 10^2 MeV electrons
bremstrahhlung
pair production

RESEARCH REACTORS – eg NEPOMUC, Munich





n capture
gamma emission
pair production

POSITRON SPECTROSCOPIES

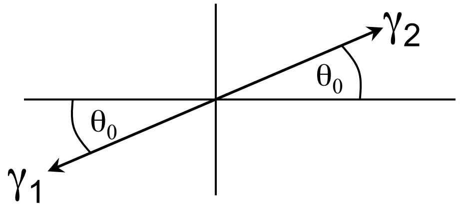
$\rho(\boldsymbol{p})$ = probability that a pair of annihilation gamma rays has total (ie ~ e^-) momentum $\boldsymbol{p}$

$\rho(p_x,p_y) = \int\rho(\boldsymbol{p})\, dp_z$ → **2-D ANGULAR CORRELATION**

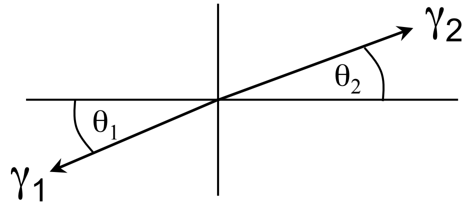
$\rho(p_z) = \iint\rho(\boldsymbol{p})\, dp_x\, dp_y$ → **DOPPLER BROADENING SPECTROSCOPY**

$\lambda = \iiint\rho(\boldsymbol{p})\, dpx\, dpy\, dpz$ → **LIFETIME SPECTROSCOPY**

ANGULAR CORRELATION OF ANNIHILATION RADIATION



C of M FRAME

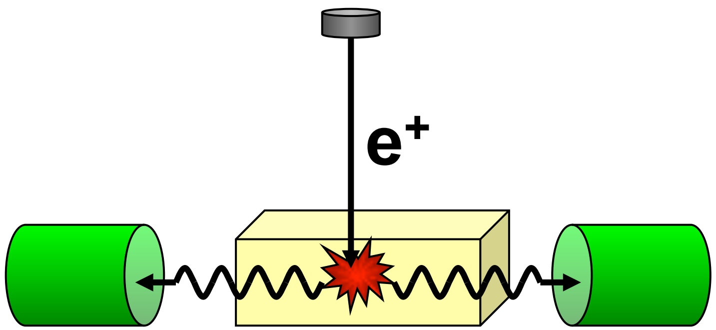


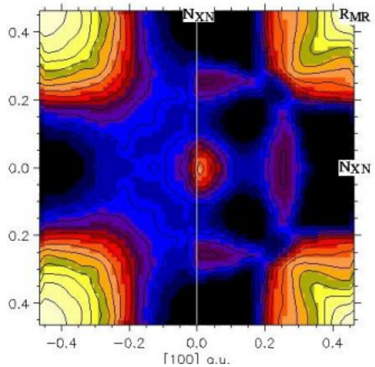
LAB FRAME

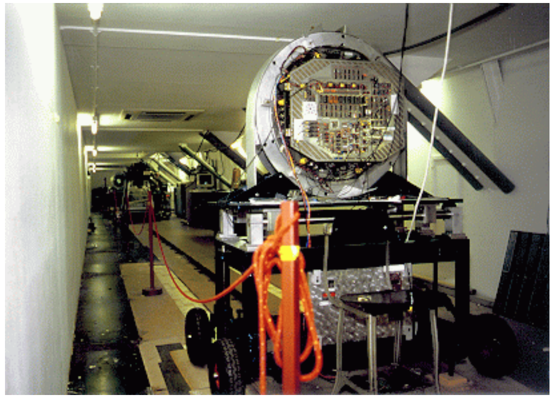
$$\delta\theta \approx p_t/mc \ (\sim 5\text{-}20 \text{ mrad})$$

where p_t is the component of momentum of the annihilating pair in a direction transverse to the gamma emission

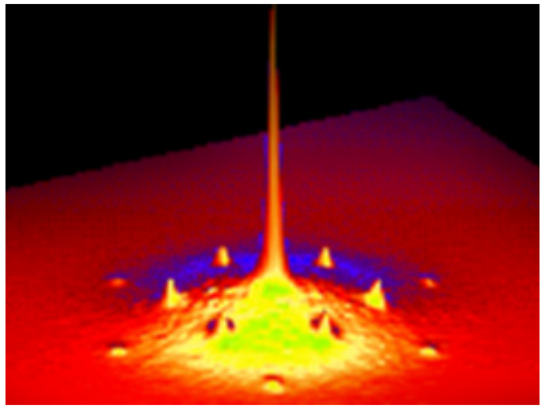
→ **electron momentum densities**







Bristol 2D-ACAR lab



2D-ACAR – quartz ↑

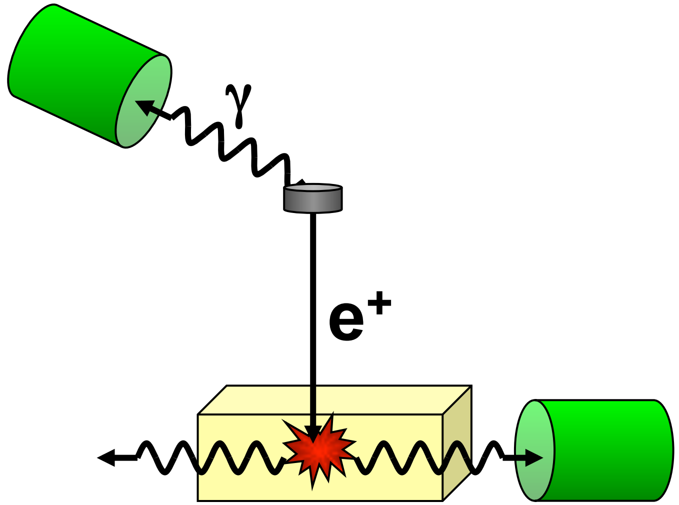
← 2D Fermi surface

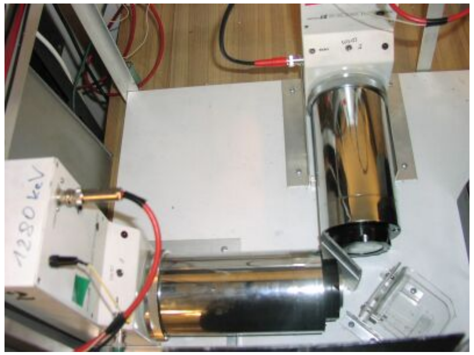
POSITRON LIFETIME SPECTROSCOPY

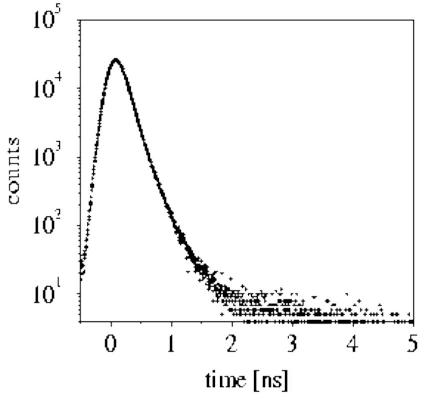
$$I(t) = \sum_i I_i \exp(-\lambda_i t)$$

↓

electron densities







positronium (Ps): e^+-e^- bound state

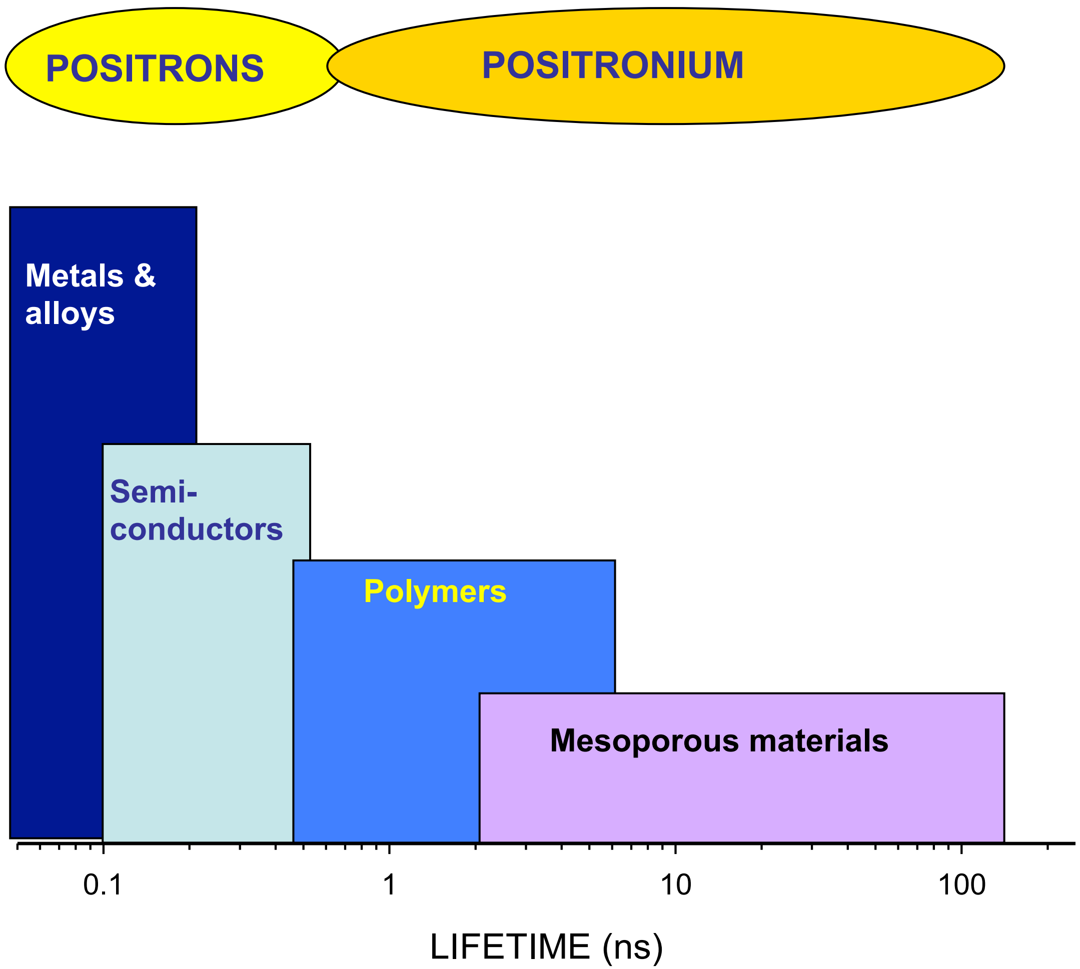
-formed in insulators

-para-Ps lives 125 ps in vacuum

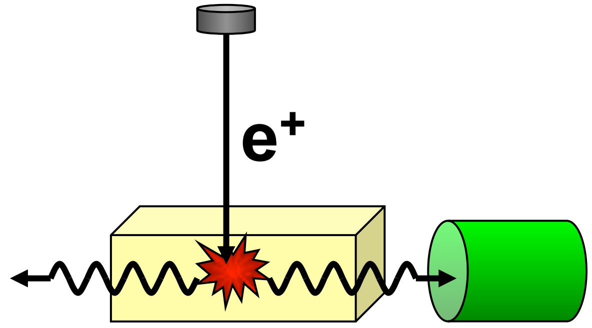
-ortho-Ps lives 142 ns in vacuum

-typical Ps lifetime in solids ~ ns

POSITRON LIFETIME MEASUREMENT



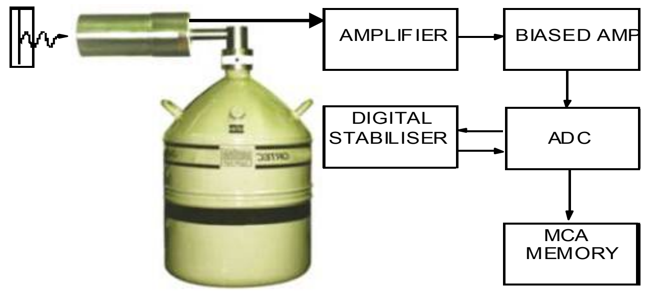
DOPPLER BROADENING SPECTROSCOPY



Doppler shift in the photon energy = ± $cp_z/2$

If p_z is from a 5eV electron $cp_z/2$ = 1130 eV
(~ the resolution of a high-purity Ge detector)

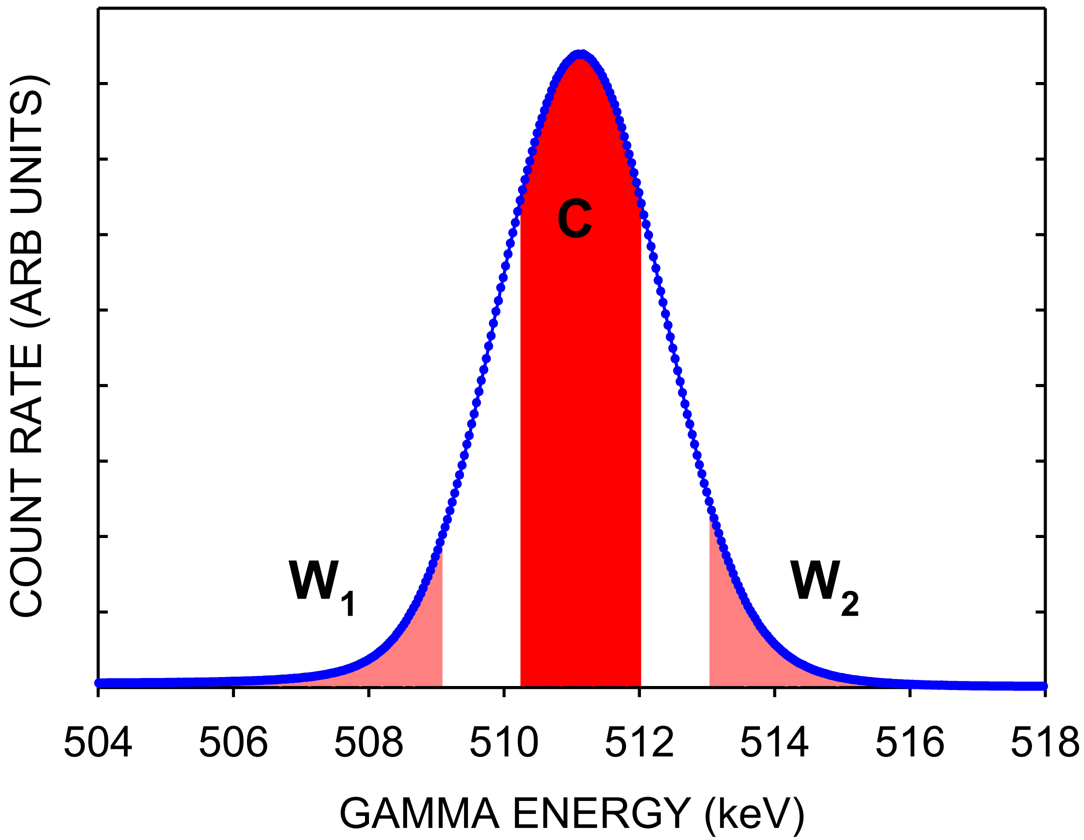
Doppler *broadening* around 511keV is measured



Good for rapid, low-resolution measurements of e^- momenta vs time, temperature etc.

DOPPLER BROADENING SPECTROSCOPY

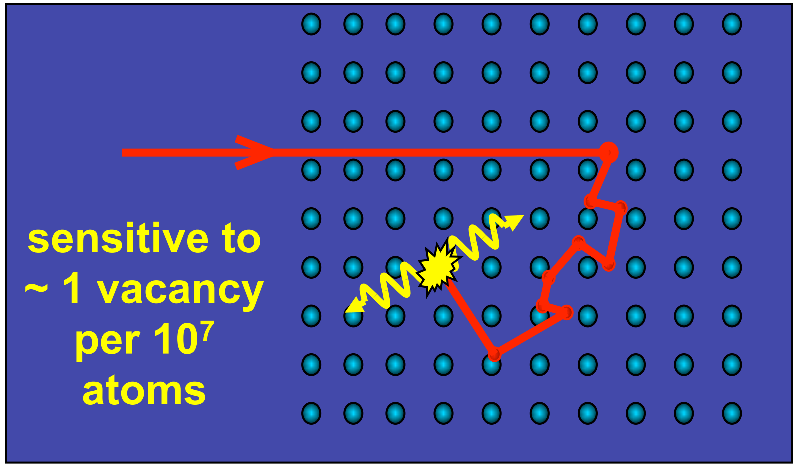
PARAMETERS:
Sharpness **parameter** $S = C/A$
Wing **parameter** $W = (W_1+W_2)/A$
where A **= total area under photopeak**

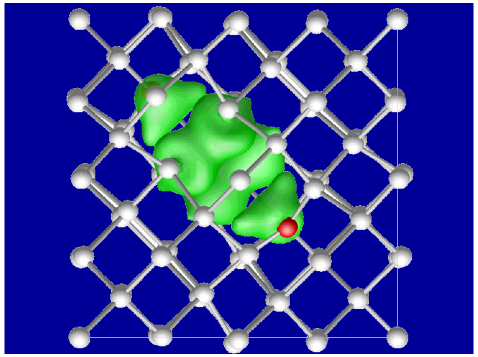


WHAT CAN BE STUDIED?

OPEN-VOLUME POINT DEFECTS

VACANCIES, VACANCY CLUSTERS, DISLOCATIONS, GRAIN BOUNDARIES, INNER/OUTER SURFACES





TRANSITION LIMITED TRAPPING:

High *C*, deep but narrow traps: $K = \nu C$

DIFFUSION LIMITED TRAPPING:

Low *C*, large traps: $K = 4\pi r DC$

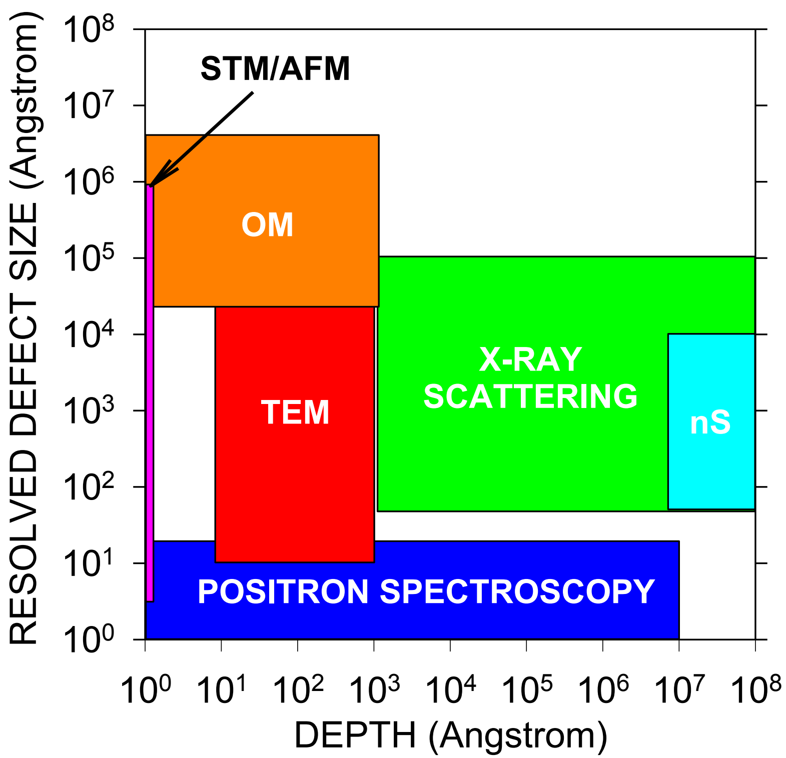
NEUTRAL VACANCY: no detrapping, $\tau > \tau_{bulk}$, less Doppler broadening: no temperature dependence

NEGATIVE VACANCY: no detrapping, $\tau > \tau_{bulk}$, less Doppler broadening: stronger trap at lower temperatures

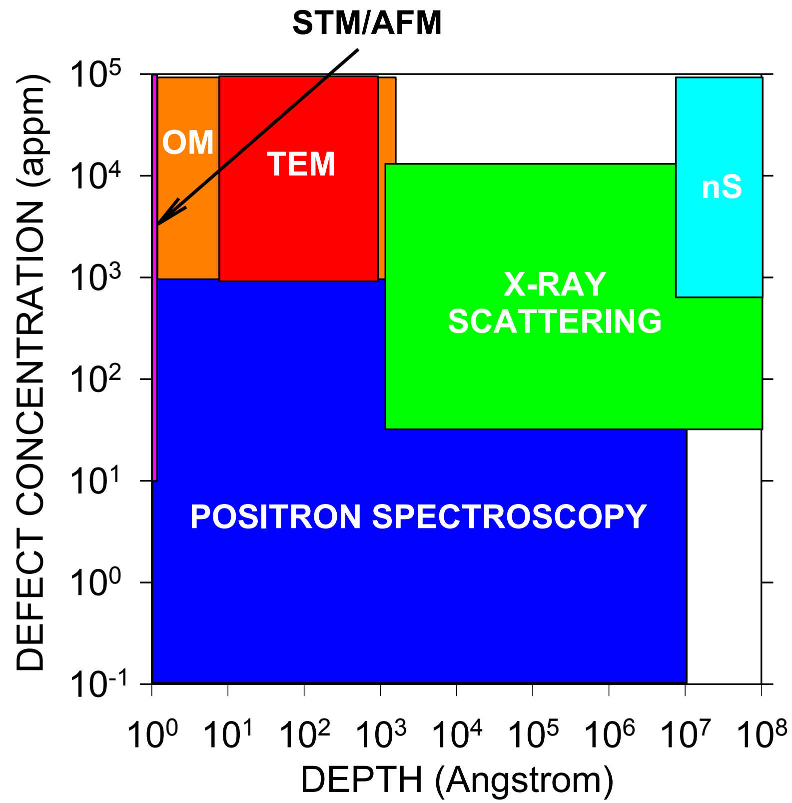
SHALLOW TRAP (eg NEGATIVE ION): detrapping below 300K, $\tau \sim \tau_{bulk}$, little Doppler broadening

SENSITIVITY TO OPEN-VOLUME POINT DEFECTS

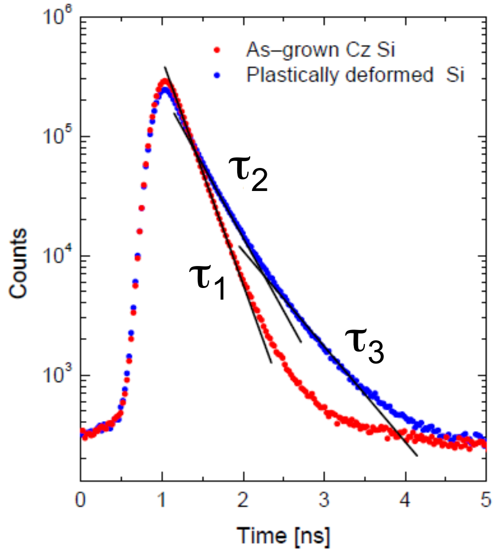
DEFECT SIZE

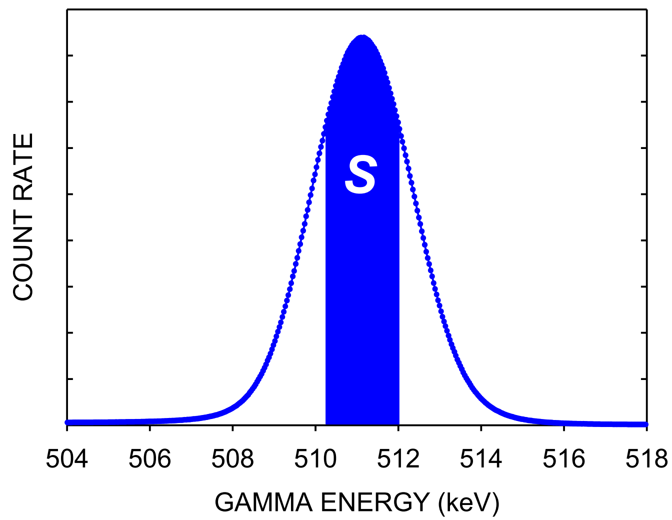


DEFECT CONCENTRATION



OPEN-VOLUME POINT DEFECTS: EXTRACTING CONCENTRATIONS





$$N(t) = \sum_i I_i \lambda_i \exp(-\lambda_i t)$$

$$S = \sum_i f_i S_i$$

for two states - bulk or defect:

$$\kappa_d = \nu C_d = \frac{I_d}{I_b}(\lambda_b - \lambda_d)$$

for two states - bulk or defect:

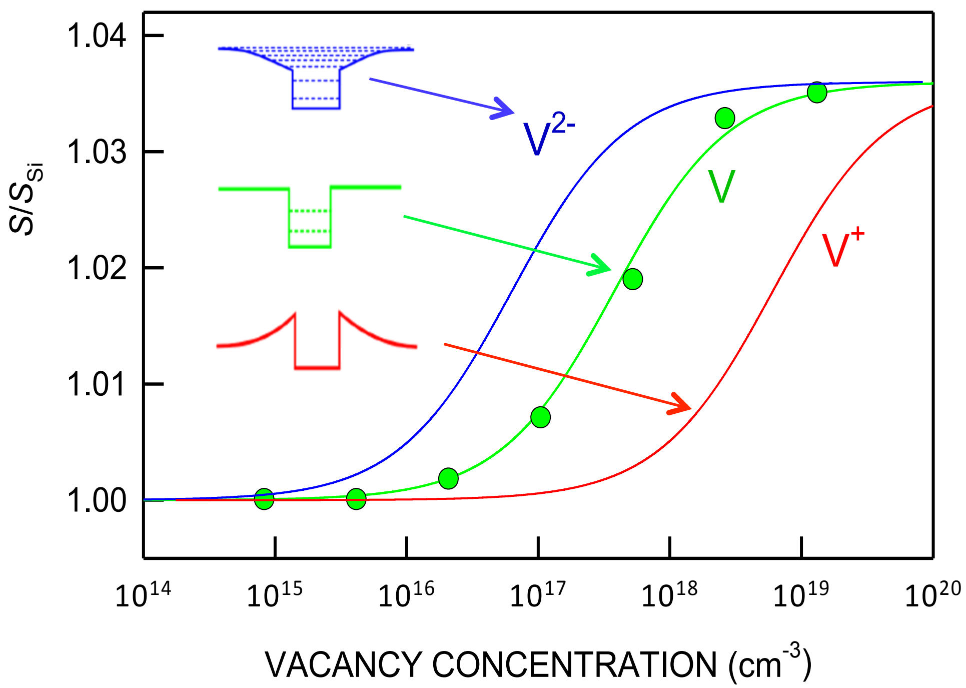
$$f_D = \frac{S - S_B}{S_D - S_B} = \frac{\nu C}{\nu C + \lambda_B}$$

ν is the specific trapping rate

OPEN-VOLUME POINT DEFECTS

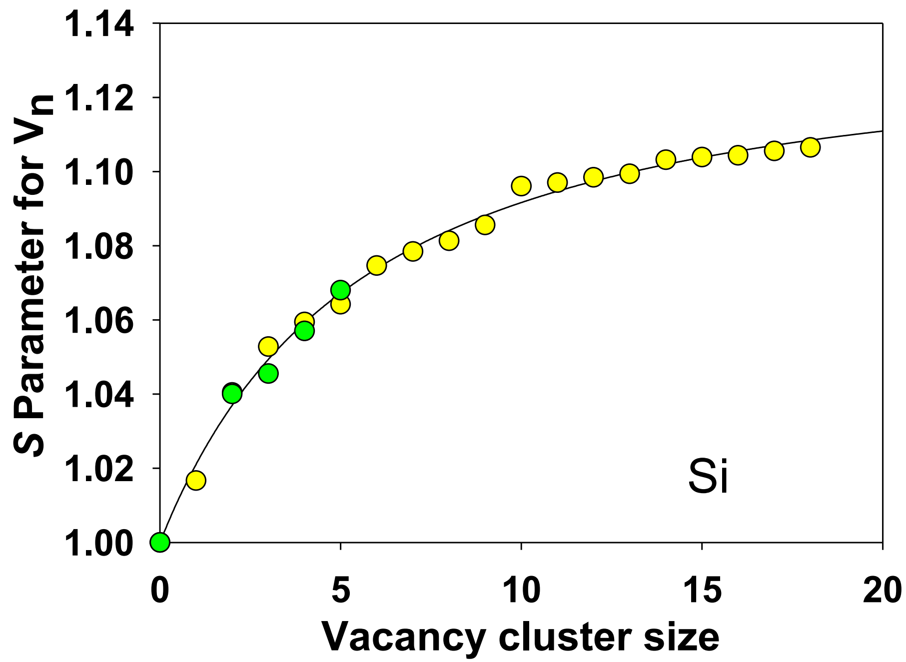
CONCENTRATION

ν is the specific trapping rate –
ν depends on charge state of the defect

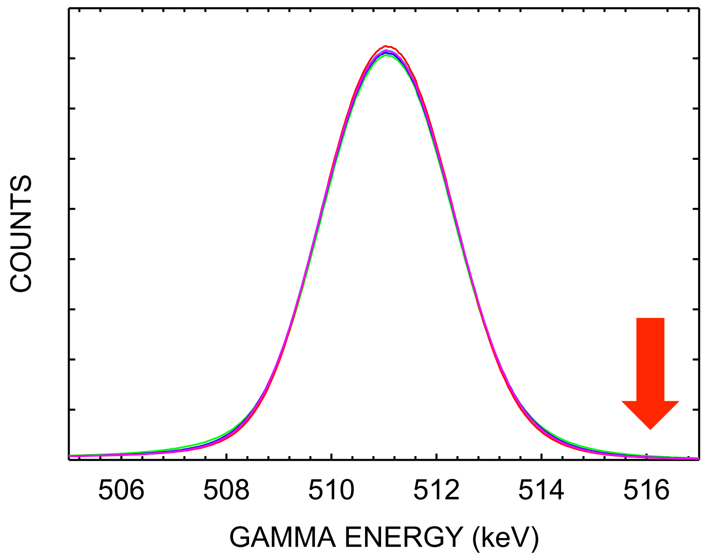


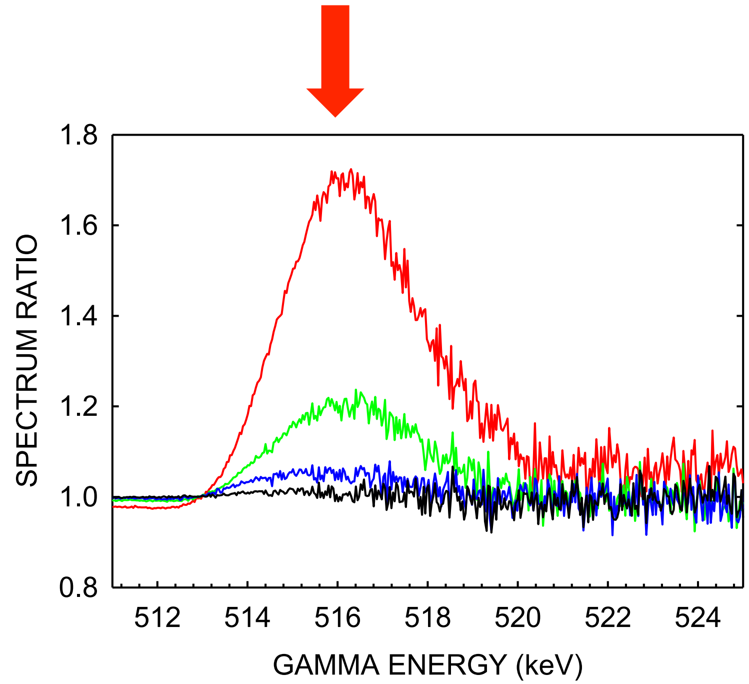
SIZE

τ and *S* are related to open volume of defect



CHEMICAL SPECIFICITY
- ANNIHILATION LINESHAPE ANALYSIS





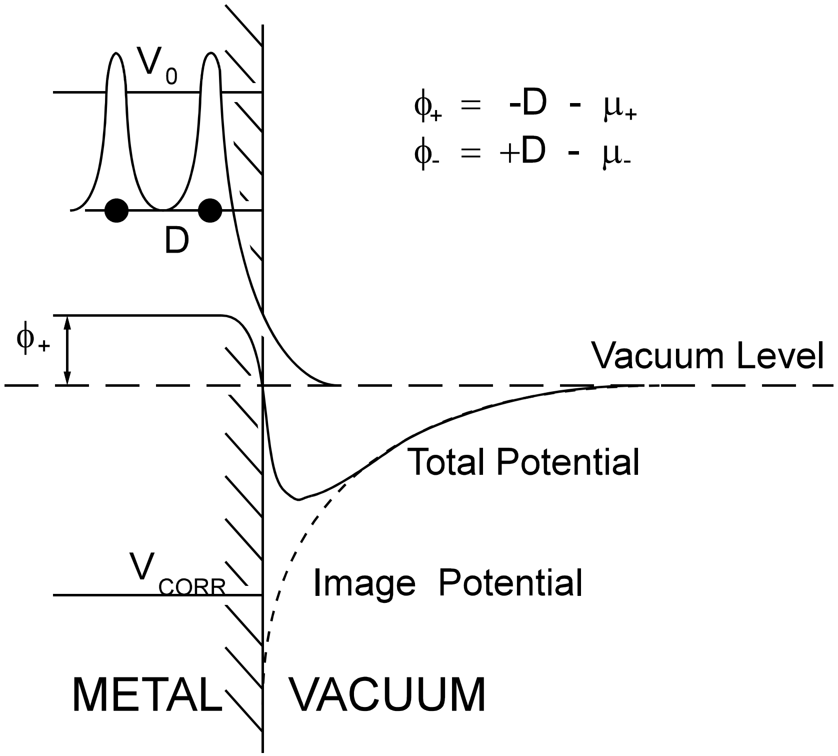
annihilation lines for
Si
Ge
$Si_{0.7}Ge_{0.3}$
$Si_{0.9}Ge_{0.1}$
$Si_{0.98}Ge_{0.02}$

spectrum ratios:
- **Ge/Si** (red)
- **$Si_{0.7}Ge_{0.3}$/Si = 30% of Ge/Si** (green)
- **$Si_{0.9}Ge_{0.1}$/Si = 10% of Ge/Si** (blue)
- **$Si_{0.98}Ge_{0.02}$/Si = 2% of Ge/Si** (black)

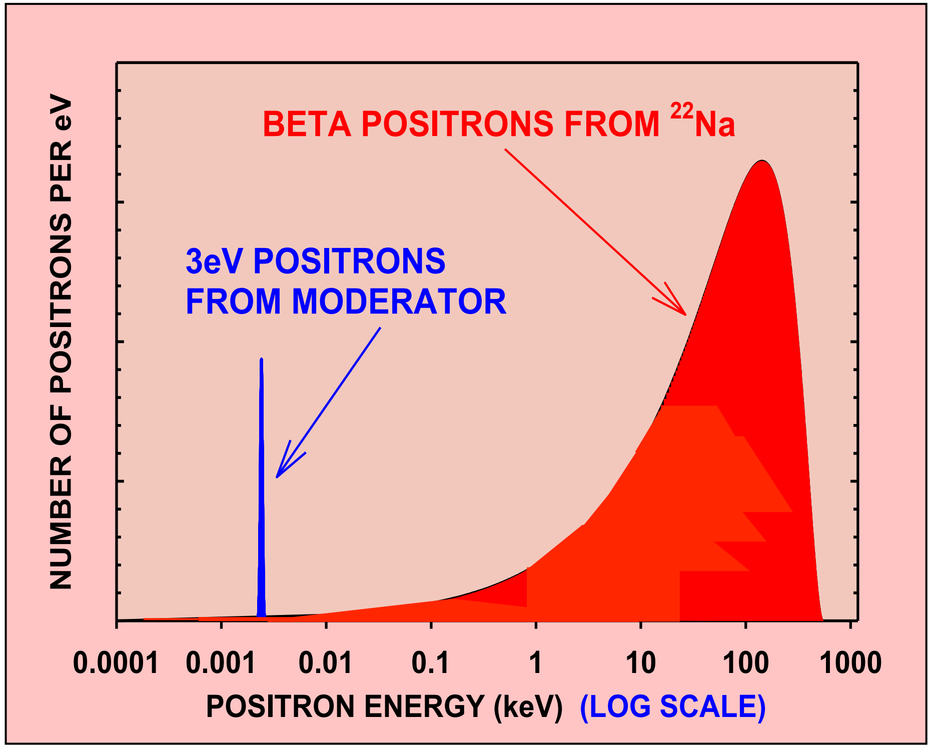
information on chemical environment and affinity

POSITRON MODERATION

NEGATIVE WORK FUNCTION



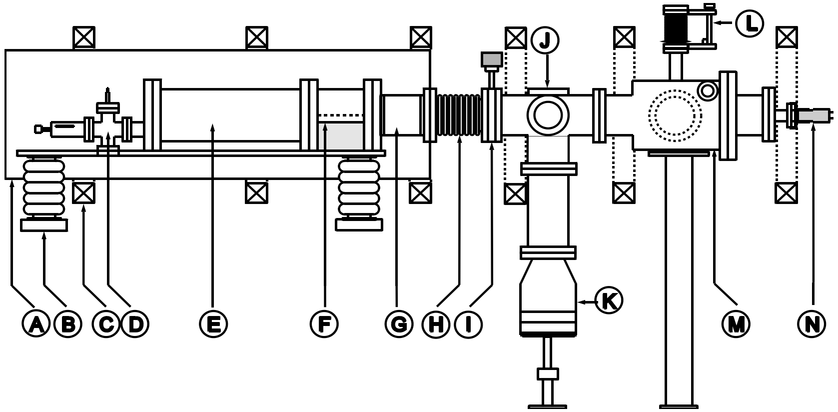
BETA SPECTRUM (0 – 540 keV, PEAK 180 keV)
RE-EMITTED POSITRONS (0 – 3eV, PEAK 1.5eV)



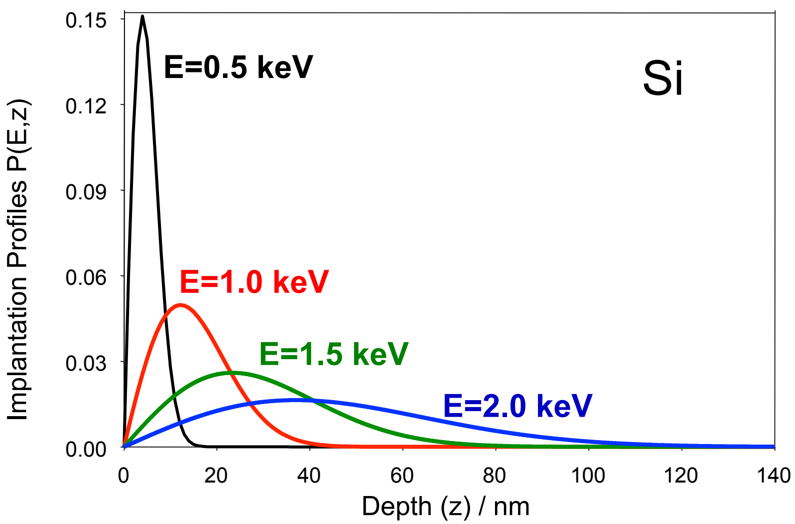
EMISSION FROM TUNGSTEN

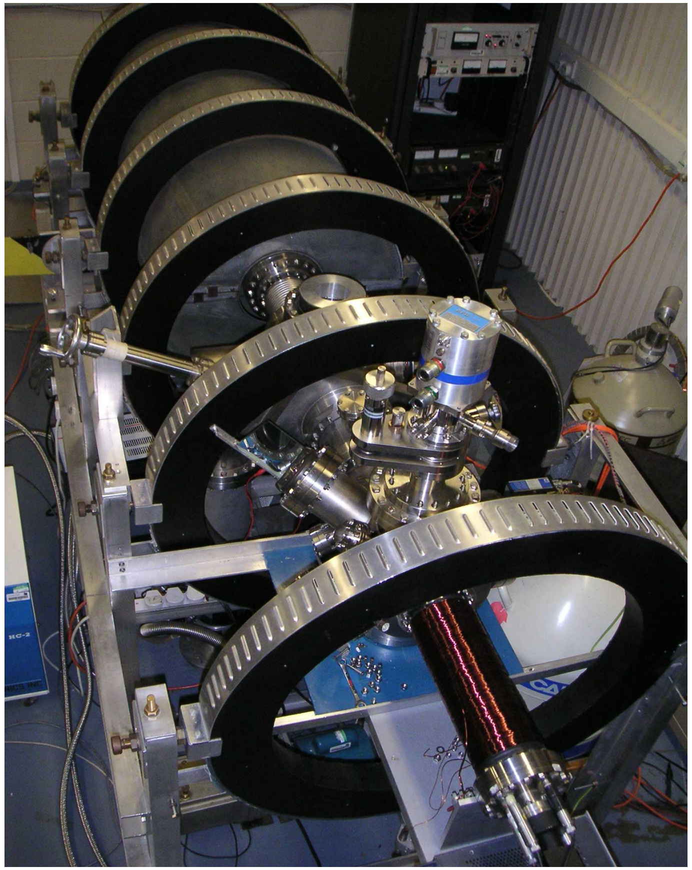
alternatives include moderation by solid rare gases

LAB-BASED POSITRON BEAMS

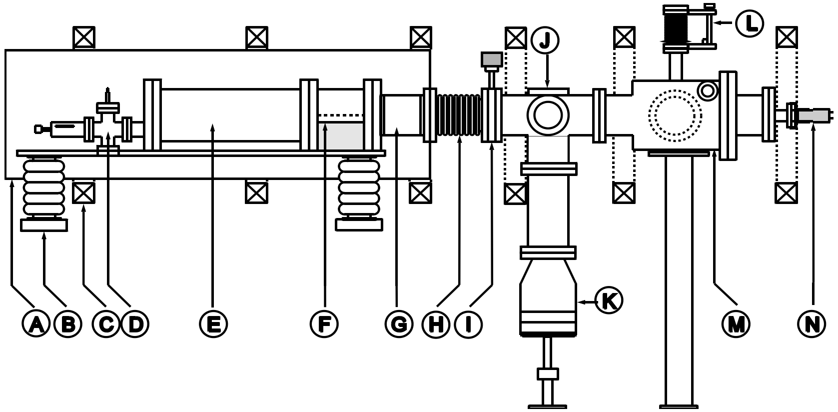


Magnetic-transport positron beam system



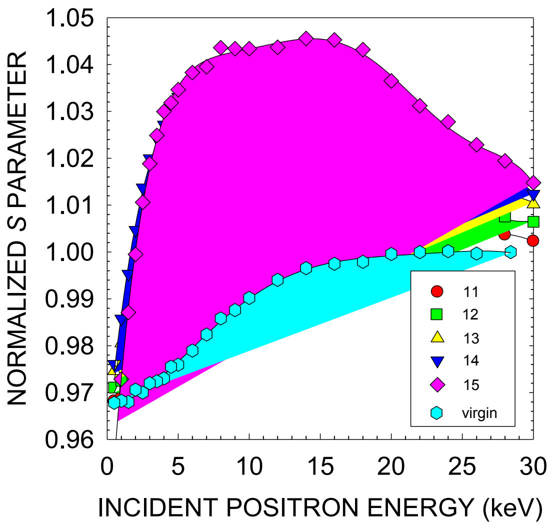


LAB-BASED POSITRON BEAMS

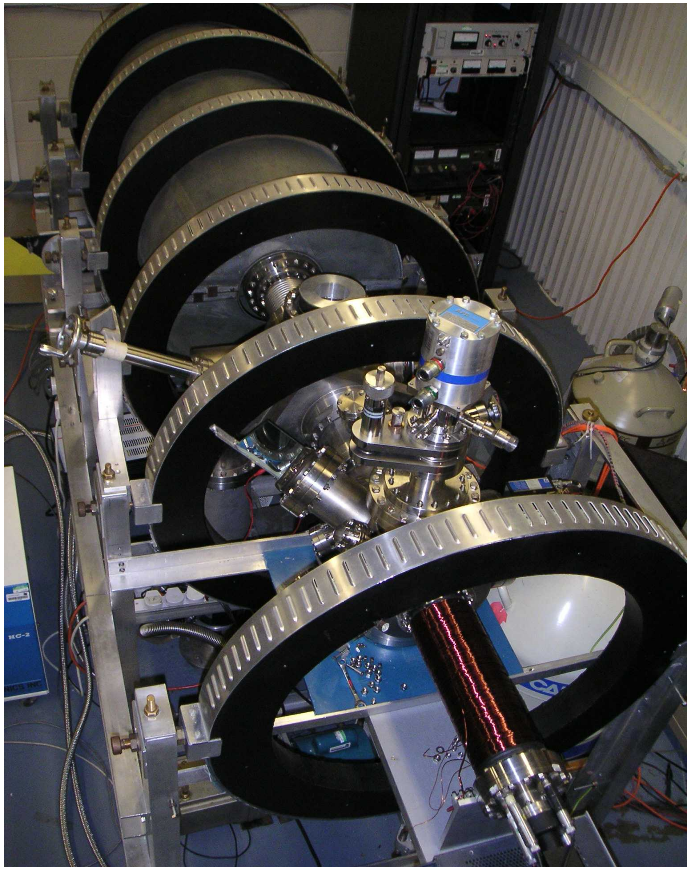


Magnetic-transport positron beam system

FZ Si implanted with 2MeV Si^+ ions at 10^n cm^{-2} (n = 0, 11, 12, 13, 14, 15)



depth sensitivity



also:
TRAP-BASED BEAMS
PULSED BEAMS

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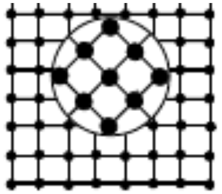
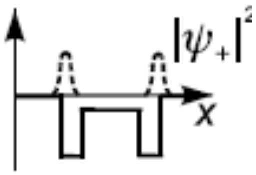
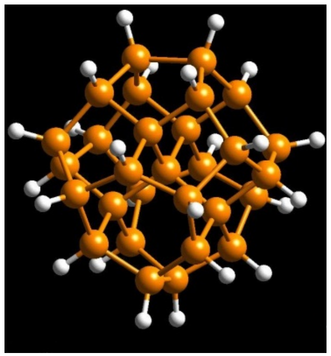
EXAMPLES OF POSITRON BEAM STUDIES OF SOLIDS

1. SILICON NANOCRYSTALS in SiO_2 MATRIX

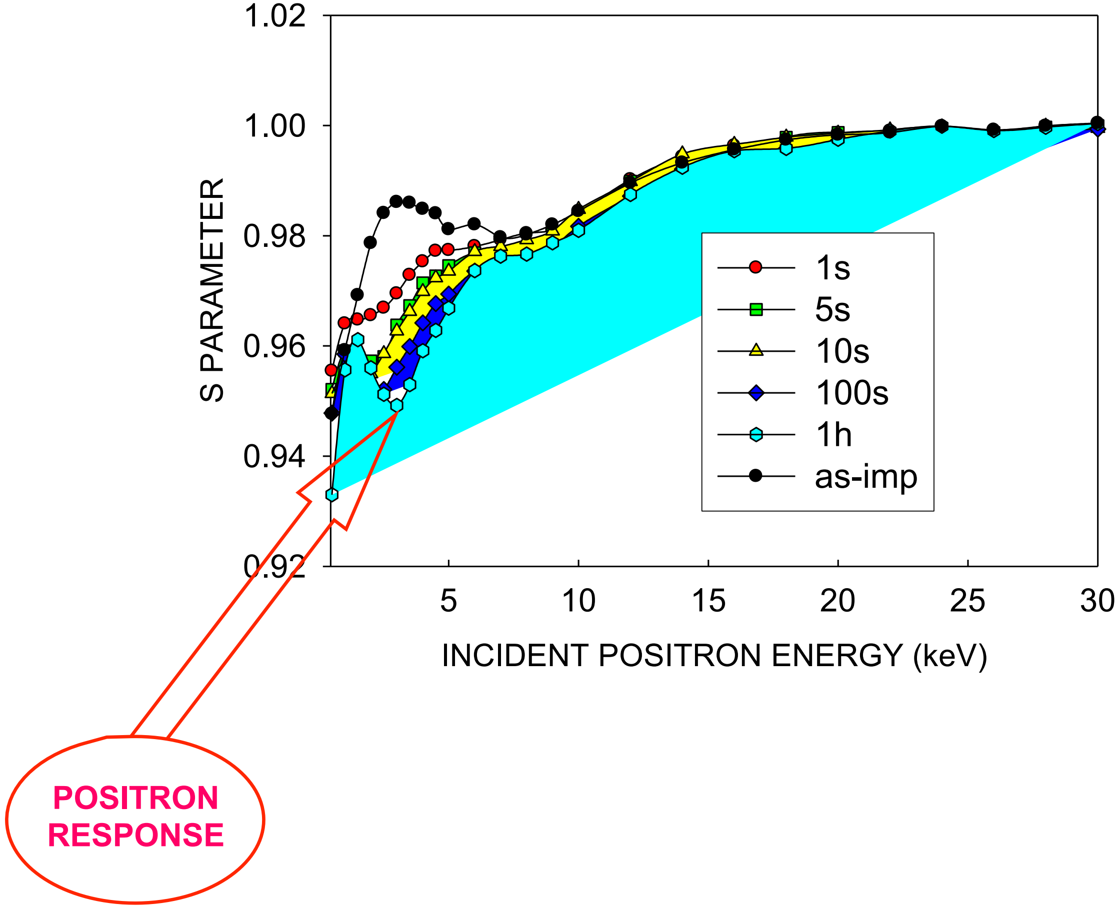




INTERFACE TRAPPING



Si-rich SiO_2 ANNEALED AT 1100ºC

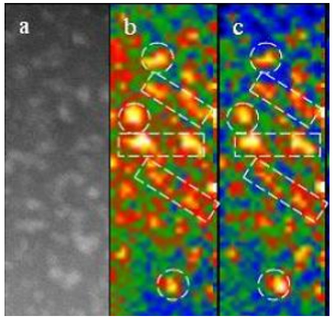


EXAMPLES OF POSITRON BEAM STUDIES OF SOLIDS

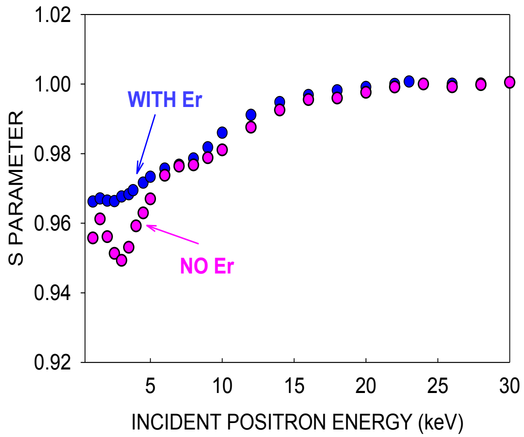
1. SILICON NANOCRYSTALS in SiO_2 MATRIX

ERBIUM and nSi

3-5nm clusters – Er and Si EELS responses coincident

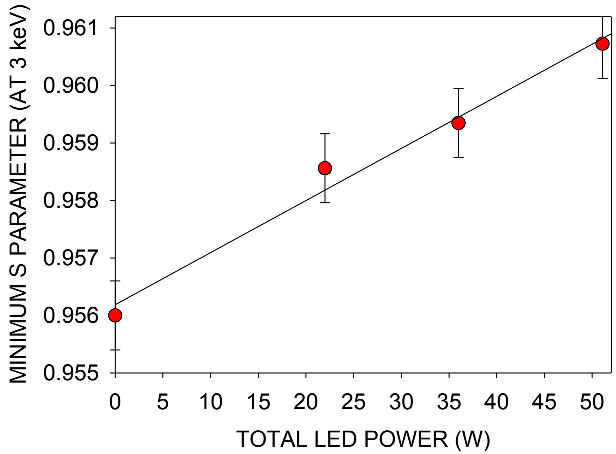


TEM Si Er



→ Er in interfaces

ILLUMINATION BY BLUE LEDs



EXAMPLES OF POSITRON BEAM STUDIES OF SOLIDS

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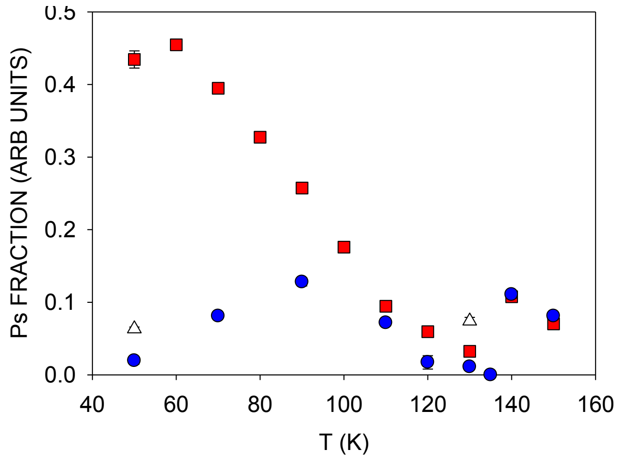
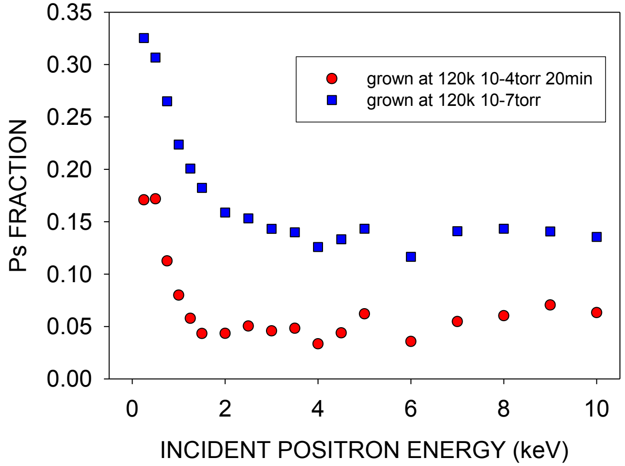
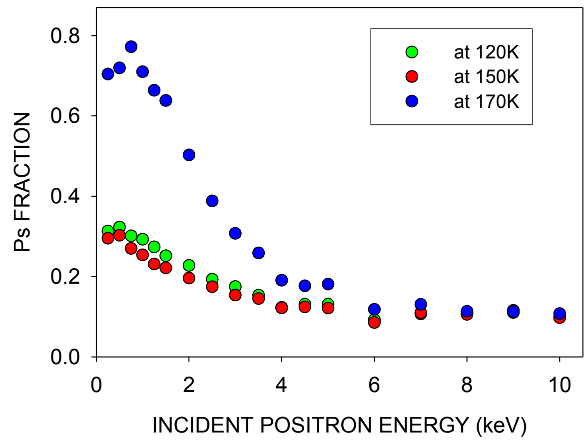
2. NANOPORES in ICE

CLOSED nm PORES: Ps DECAY TO 3γ and Ps LIFETIME DEPEND ON PORE SIZE

INTERCONNECTED PORES: ESCAPE POSSIBLE, 3γ FRACTION INCREASED, VACUUM LIFETIME







PORE COLLAPSE

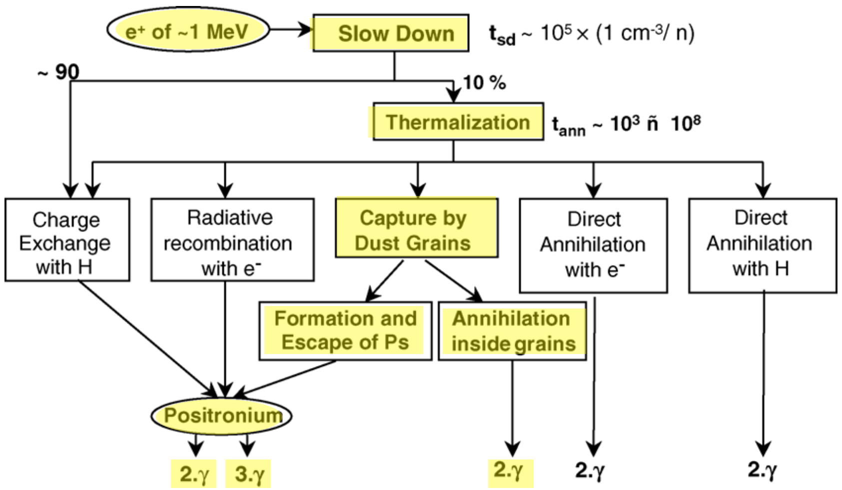
DEPENDENCE ON GROWTH RATE

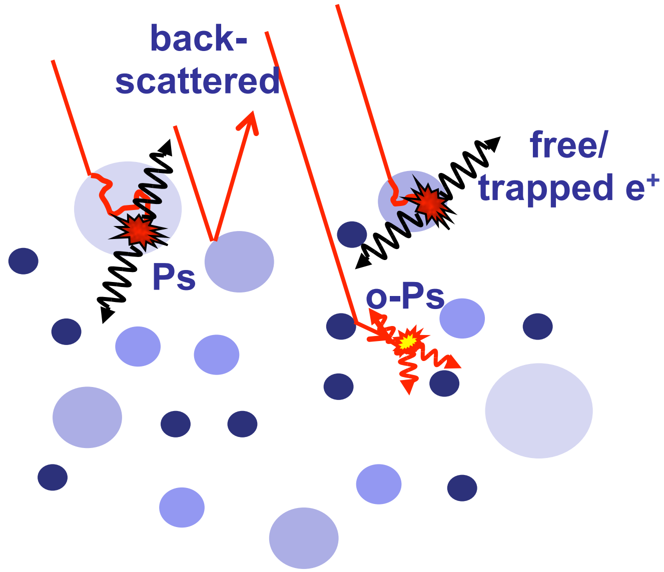
DURING SUBLIMATION

see poster for more information

POSITRON BEAMS:
APPLICATIONS IN ASTROPHYSICS

DUST in the ISM





N. Guessoum, P. Jean & W. Gillard
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DOPPLER BROADENING – CHEMICAL ANALYSIS

DOPPLER BROADENING – STRUCTURAL ANALYSIS

Ps FORMATION AND DECAY – PORES AND STRUCTURAL ANALYSIS

IN-FLIGHT ANNIHILATION ON MODEL SYSTEMS

POSITRON BEAMS:
APPLICATIONS IN ASTROPHYSICS

Thanks to past and present members of the Bath positron group

- and to you for your attention