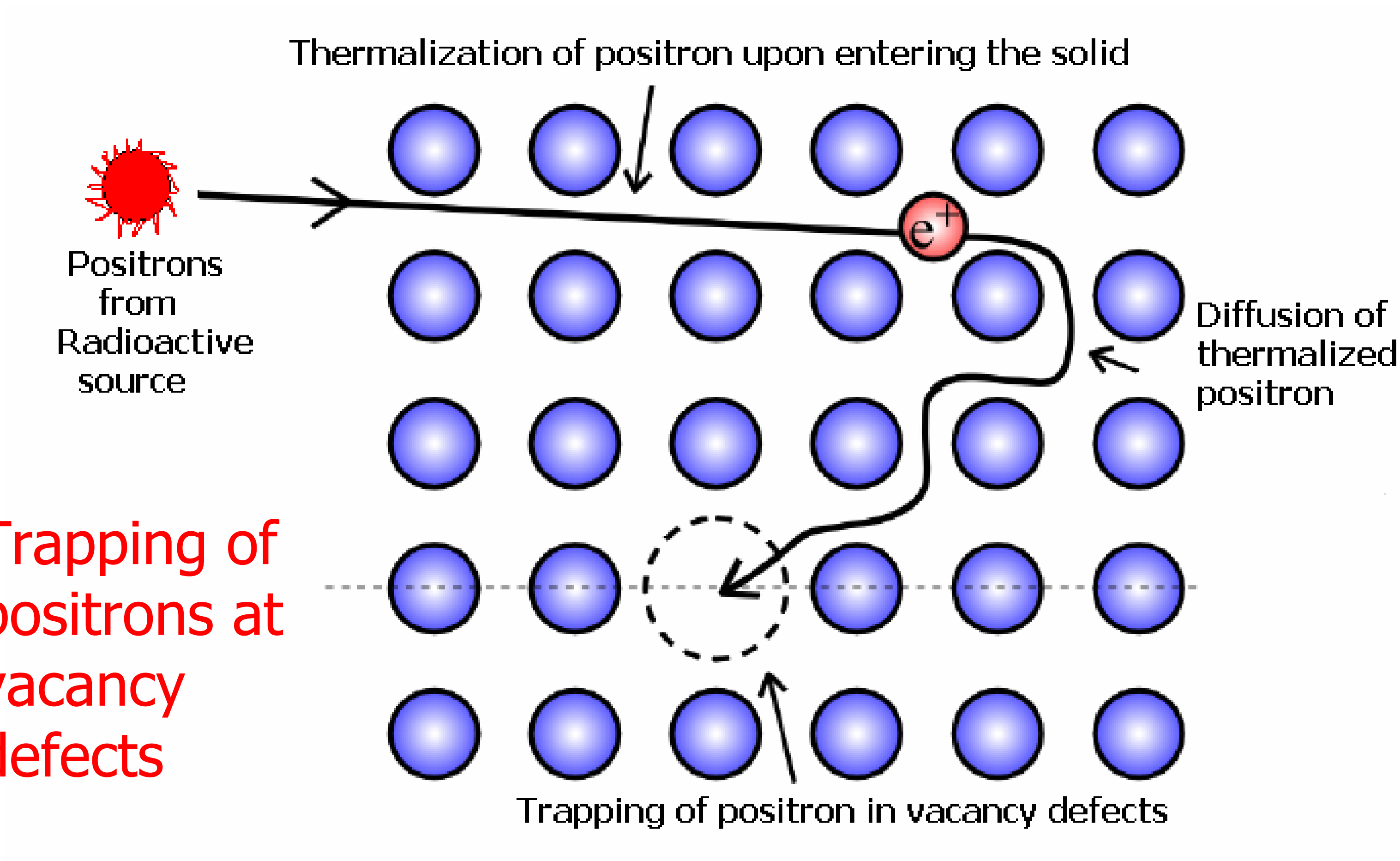
Positron lifetime spectroscopy

Application of positrons in materials research



Trapping of positrons at vacancy defects

Using positrons, one can get defect information.

R. Krause-Rehberg and H. S. Leipner, *Positron annihilation in Semiconductors*, (Springer Verlag, Berlin, 1998).

How positrons are produced?

- Positrons are emitted as a result of β^+ decay of radioactive isotopes such as Na^{22}, Cu^{64} and Co^{58}. These positron sources are used for laboratory applications.

- Another way to produce high flux of positrons is to bombard electrons on an absorber of high atomic number creating Bremsstrahlung γ-rays, thereby generating electron-positron pairs.

- Positrons can also be produced from nuclear reactors using Cu^{63} (n,γ) Cu^{64} reaction.

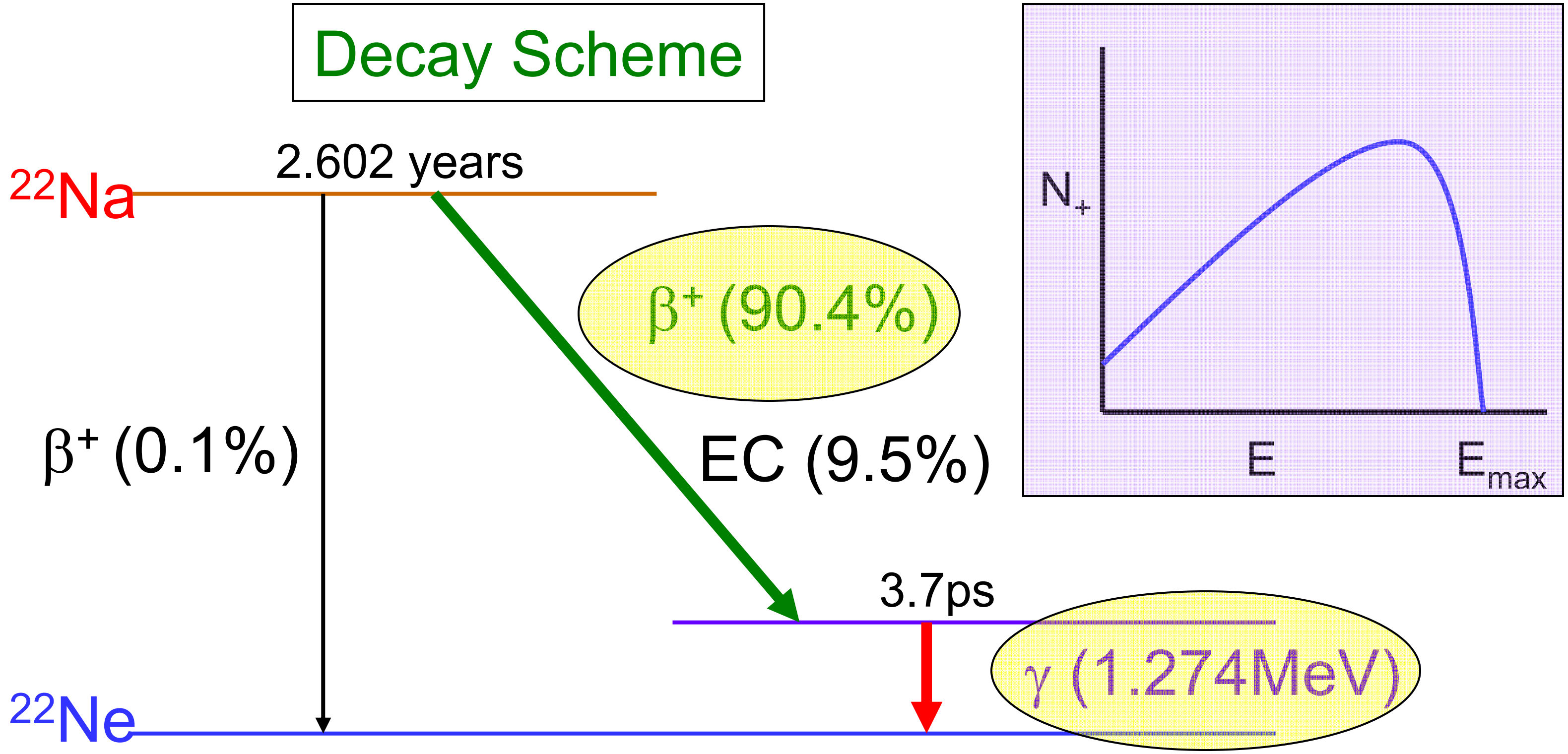
Conventional positron sources – isotope sources

^{22}Na, ^{64}Cu, ^{58}Co, $^{68}Ge(^{68}Ga)$....

Work horse

$$^{22}Na \longrightarrow {}^{22}Ne + \beta^+ + \nu + \gamma$$

Decay Scheme



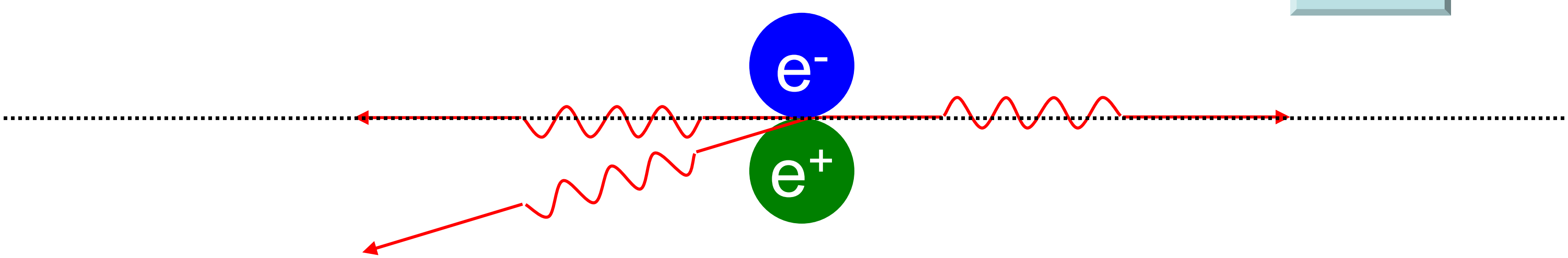
Positron–electron annihilation

Mass → Energy

$2m_0$ → $2m_0c^2$

- One gamma emission – needs third particle – recoil
- **Two 511 keV gamma emission – most probable**
- Three gamma emission – negligible (0.3%)

Conserve Energy & momentum



Annihilation? Not always!

Bound state of positron-electron pair - **Positronium**

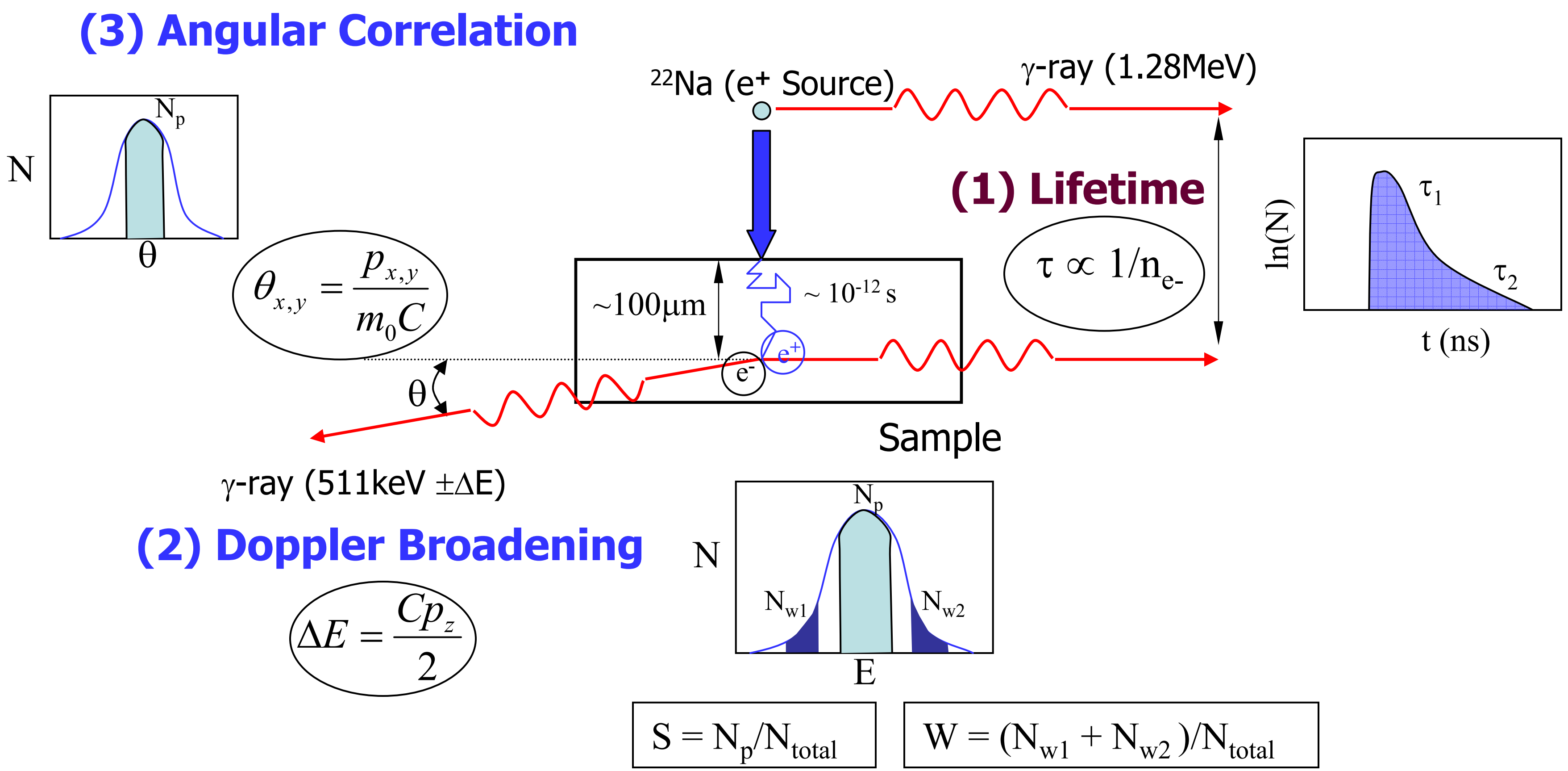
↑↓ Para-positronium (125ps)

↑↑ Ortho-positronium (142ns)

Ps is formed in

- ✓ Polymers
- ✓ Ionic crystals
- ✓ Liquids
- ✓ Gases

Positron annihilation spectroscopy



Positron Annihilation Spectroscopy consists of three techniques viz., (1) Positron lifetime (2) Doppler Broadening and (3) Angular Correlation of annihilation radiation.

Positron lifetime in Solids

- The positron lifetime τ is determined by the local electron density at the annihilation site. The annihilation rate λ (inverse of positron lifetime) is proportional to the local electron density at the site of positron annihilation.

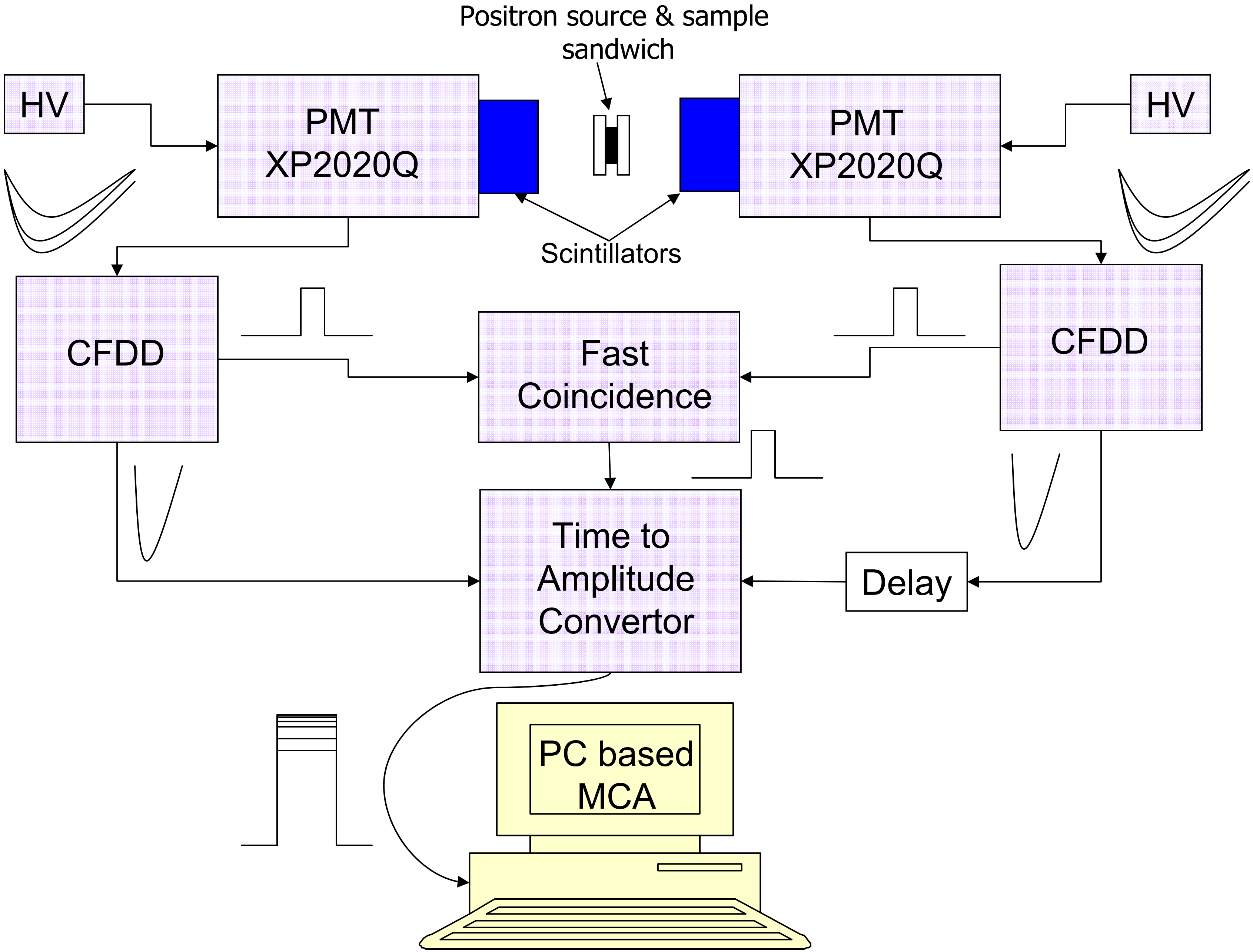
- Since the birth of the positron is accompanied by the immediate emission of 1.28 MeV photon and the death of the positron by the emission of two 511 keV photons, positron lifetime can be measured using nuclear timing spectroscopy techniques.

- Experimentally, positron lifetime in a sample is deduced by measuring the time delay between the birth signal of a positron (1.28 MeV) and annihilation signal (511 keV) of positron.

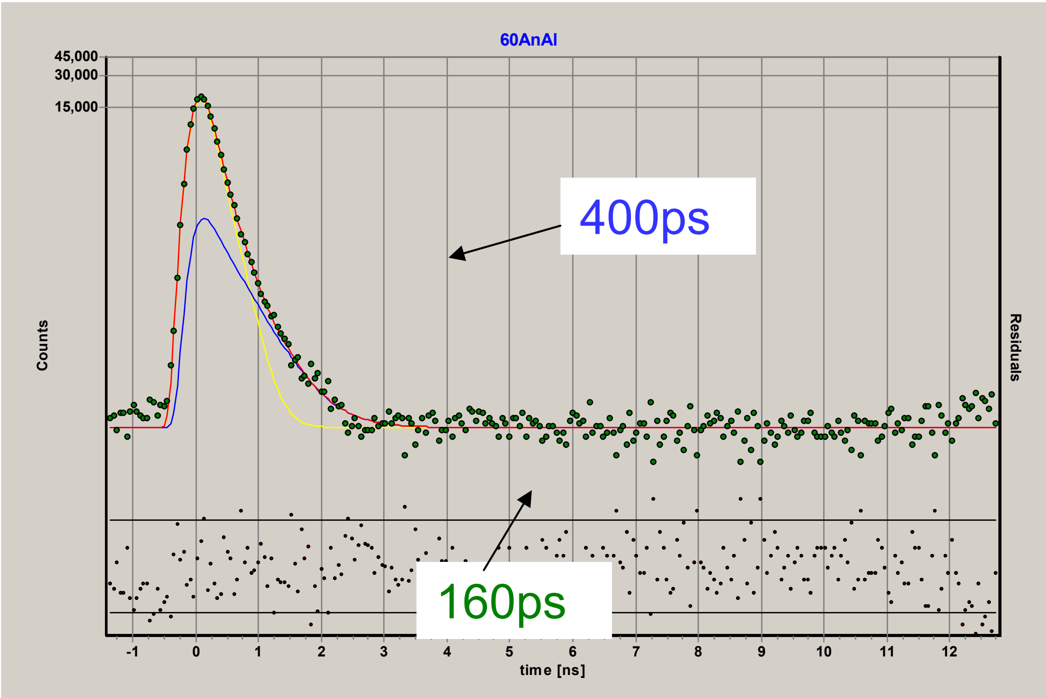
- Typically positron lifetimes range from a few hundred picoseconds to a few nanoseconds in materials (metal, semiconductors, insulators, polymers).

- Hence, researchers use custom-built timing spectrometers to measure such short lifetimes.

Experimental positron lifetime spectrometer



Experimental lifetime spectrum with fitting



- The lifetime spectrum is a convolution of instrumental resolution, source lifetime and the sample lifetime.

- Each lifetime component represents annihilations from a specific defect.

- Size and concentration of vacancy-defects can be obtained from the lifetime value and its intensity.

$$N(t) = BG + G(t) \otimes \sum_i I_i e^{-t/\tau_i}$$

Analysis and extraction of useful information from positron lifetime spectra

- From the experimental curve, the positron lifetime is extracted using a program. In an annealed metal, all positrons annihilate as free particle with a well-defined annihilation rate λ. The lifetime measurement then produces a single exponential spectrum of the form exp $(-\lambda t)$. The corresponding mean lifetime τ is the inverse of λ.

- If the positrons annihilate from different states in the sample, the result is an multi exponential lifetime spectrum.

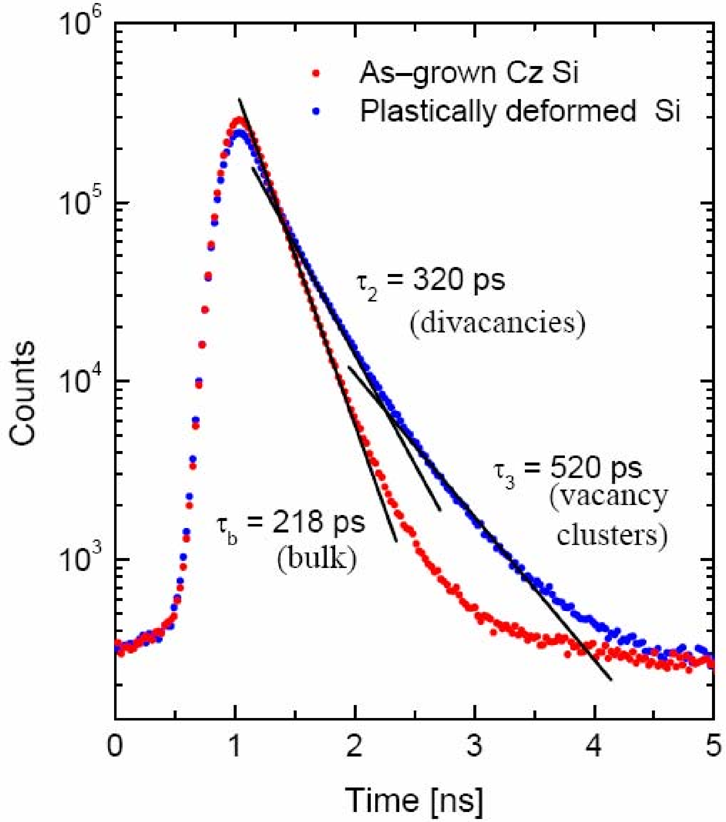
$$\text{Average } \tau = \Sigma_i I_i \tau_i \qquad - (1)$$

- This is normally analyzed using a program to extract lifetime values τ_i and relative intensities I_i associated with the different components.

- τ_i gives information on the kind of defects present and the I_i is related to the defect concentration.

- So, both the nature of defect and its concentration are obtained using positron lifetime measurement.

Positron lifetime spectroscopy



- positron lifetime spectra consist of exponential decay components
- positron trapping in open-volume defects leads to long-lived components
- longer lifetime due to lower electron density
- analysis by non-linear fitting: lifetimes t_i and intensities I_i

positron lifetime spectrum:

$$N(t)=\sum_{i=1}^{k+1}\frac{I_i}{\tau_i}\exp\left(-\frac{t}{\tau_i}\right)$$

trapping coefficient

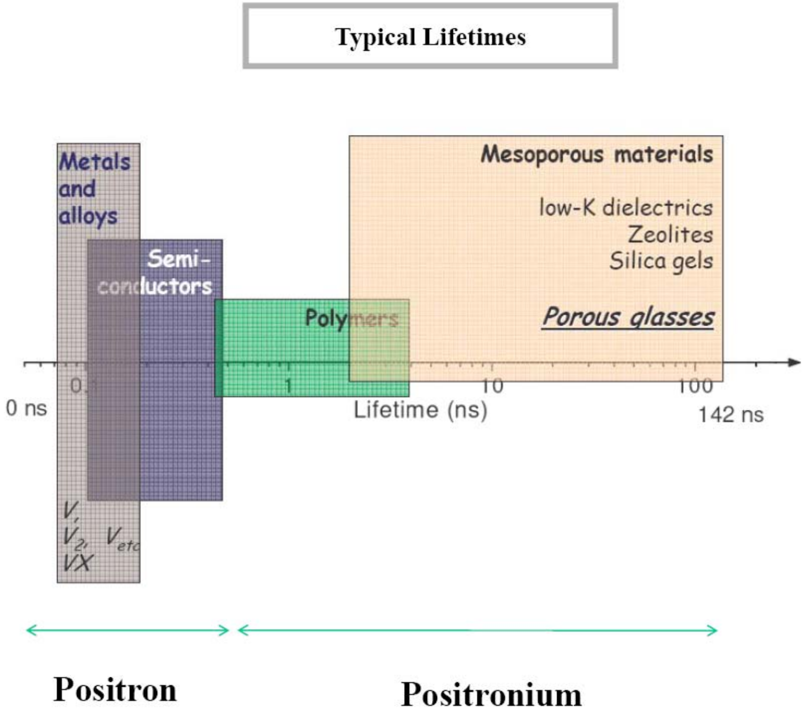
$$\kappa_d=\mu C_d=\frac{I_2}{I_1}\left(\frac{1}{\tau_b}-\frac{1}{\tau_d}\right)$$

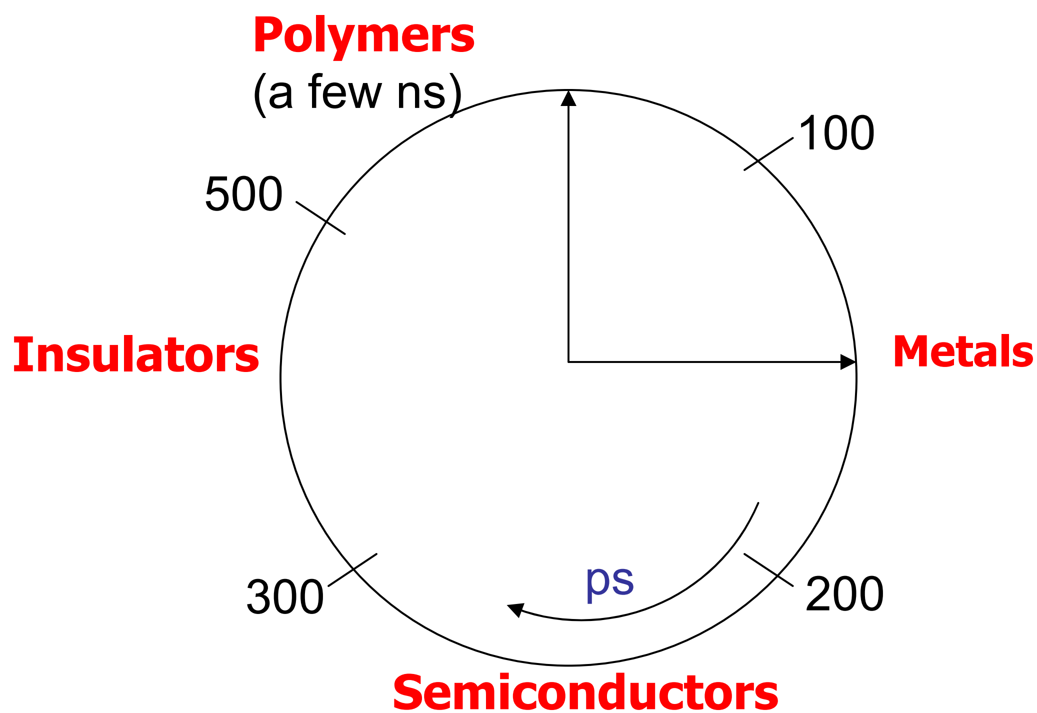
trapping rate **defect concentration**

Using positron spectroscopy, one can identify and quantify vacancy defects

R. Krause-Rehberg and H. S. Leipner, *Positron annihilation in Semiconductors*, (Springer Verlag, Berlin, 1998).

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





Application of PAS for defect studies

- Positron lifetime is sensitive to the local electron density.
- Due to relative decrease of the local electron density at the site of vacancy, positron lifetime increases due to the presence of vacancy-defects.
- Further, as the vacancy cluster size increases, positron lifetime initially increases upto some cluster size and saturates at higher sizes.
- Thus, positrons can be used as a probe to any process aided by vacancy-defects, with sensitivity starting from atomistic vacancy defect onwards upto a large vacancy cluster or void.