Positron Annihilation: Using Anti-particles for Materials Characterization

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Outline

- Positron Fundamentals
- Positron sources
- Applications
  - Defect Studies by Positron Annihilation Spectroscopy (PAS)
    - Positron lifetime spectroscopy
    - Doppler broadening spectroscopy
- Summary and Conclusions

What is a Positron ?

The positron is the anti-particle of the electron

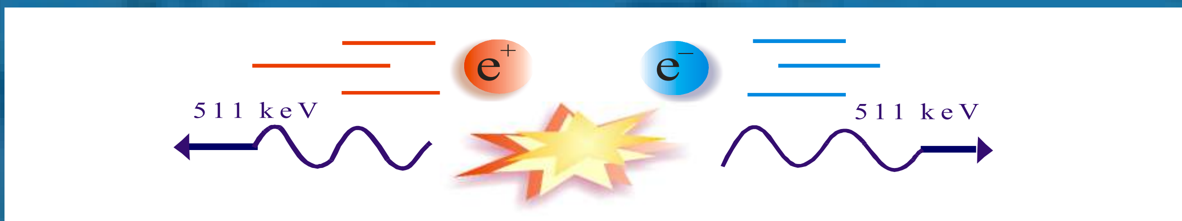
- Identical to the electron in mass

  $m = 511\ keV/c^2 = 9.11*10^{-31}\ kg$

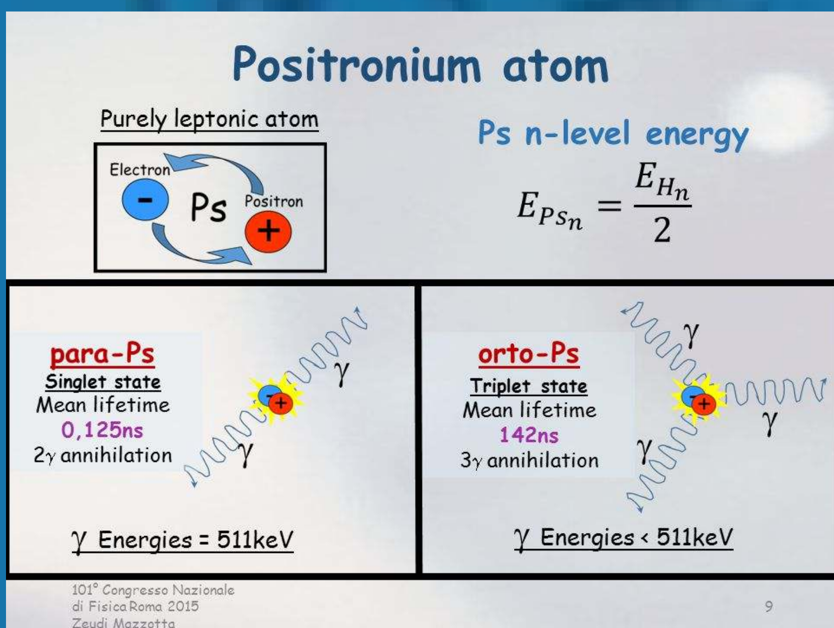
- Spin 1/2
- Opposite charge of $+1.602*10^{-19} C$

http://livefromcern.web.cern.ch/livefromcern/antimatter/history/AM-history01.html

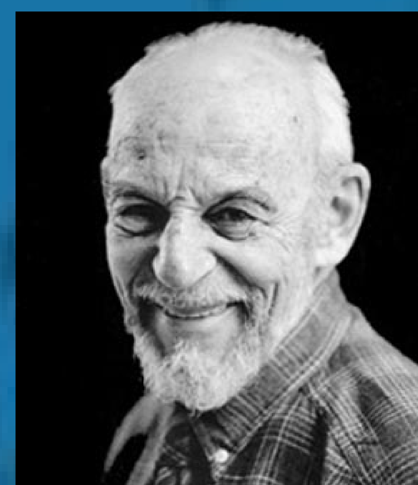
The Fate of the Positron



Annihilation



Positronium



Discovered in 1951 by Martin Deutsch

Nominated for Nobel Prize 1956

This photograph was published on Sunday, August 25, 2002
in: The Tech, Vol. 122, No. 31

Anti-Hydrogen

letters to nature Sep 2002

Production and detection of cold antihydrogen atoms

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¶ *Instituto de Fisica, Universidade Federal do Rio de Janeiro, Rio de Janeiro 21945-970, and Centro Federal de Educação Tecnologica do Ceara, Fortaleza 60040-531, Brazil*
\# *Department of Physics, University of Wales Swansea, Swansea SA2 8PP, UK*
☆ *Istituto Nazionale di Fisica Nucleare, Sezione di Pavia, and ** Dipartimento di Fisica Nucleare e Teorica, Università di Pavia, 27100 Pavia, Italy*
†† *Department of Physics, University of Tokyo, Tokyo 113-0033, Japan*

If we consider cold mixing data only in the range $\cos(\theta_{\gamma\gamma}) < -0.95$, we have detected 131 ± 22 events with a reconstructed vertex and a pair of back-to-back, 511-keV photons above a conservatively scaled antiproton-only background. With an upper limit of the detection and reconstruction efficiency of 2.5×10^{-3}, on the basis of Monte Carlo analysis, we estimate that at least 50,000 antihydrogen atoms were created during cold mixing. This can be compared with the total number of antiprotons mixed, about 1.5×10^{6}.

PRL 93, 263401 (2004) PHYSICAL REVIEW LETTERS week ending 31 DECEMBER 2004

First Laser-Controlled Antihydrogen Production

C. H. Storry,[1] A. Speck,[1] D. Le Sage,[1] N. Guise,[1] G. Gabrielse,[1,*] D. Grzonka,[2] W. Oelert,[2] G. Schepers,[2] T. Sefzick,[2] H. Pittner,[3] M. Herrmann,[3] J. Walz,[3] T.W. Hänsch,[3,4] D. Comeau,[5] and E. A. Hessels[5]

(ATRAP Collaboration)

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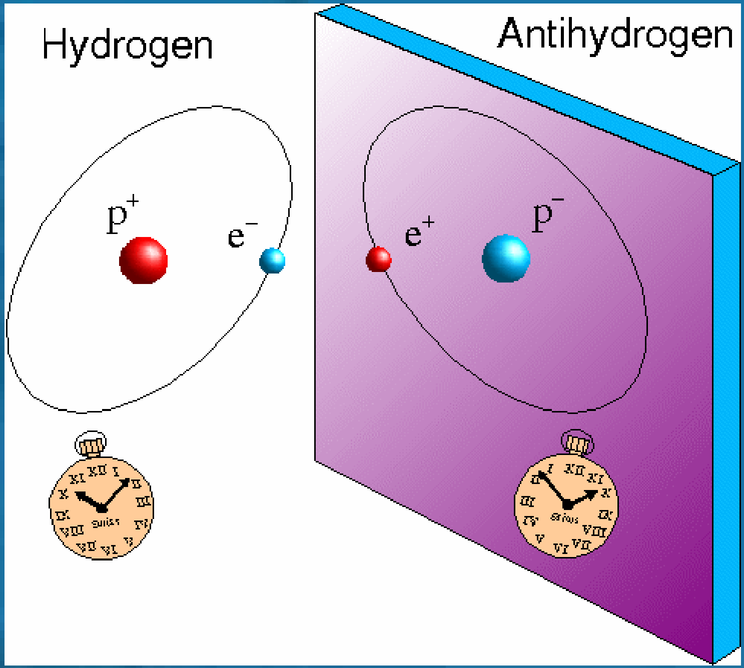
[2]*IKP, Forschungszentrum Jülich GmbH, 52425 Jülich, Germany*
[3]*Max-Planck-Institut für Quantenoptik, Hans-Kopfermann-Strasse 1, 85748 Garching, Germany*
[4]*Ludwig-Maximilians-Universität München, Schellingstrasse 4/III, 80799 München, Germany*
[5]*York University, Department of Physics and Astronomy, Toronto, Ontario M3J 1P3, Canada*

(Received 17 August 2004; published 21 December 2004)

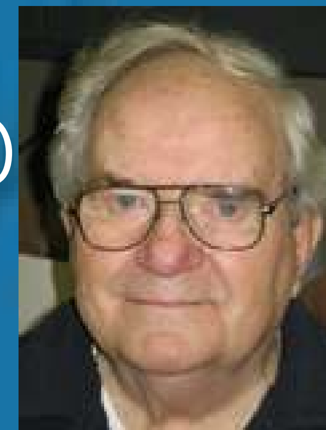
http://www.mpq.mpg.de/~haensch/antihydrogen/introduction.html



Positron Annihilation in Canada

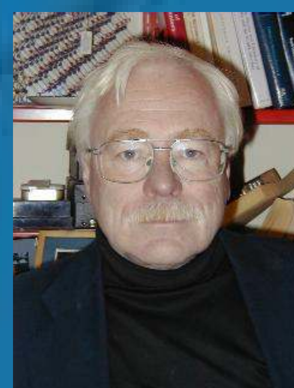
The Pioneers

Ben Hogg (Winnipeg, †)
Innes K. MacKenzie (Guelph, †)



Barry McKee (Queens, †)
Alec T. Stewart (Queens, †)

Jules Carbotte (McMaster, †)



Steen Dannefaer (Winnipeg)

The (Still) Active Annihilators

Western University (P.J. Simpson)
McMaster University (A.P. Knights, P. Mascher)

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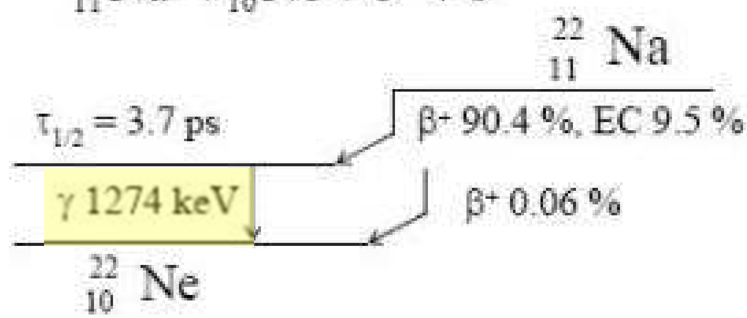
Positron Sources

β^+-decay of radioactive isotopes

Radionuclide	half-life	Maximum energy	γ-rays intensity
^{22}Na	2.6 years	545 keV	100 %
^{58}Co	71 days	470 keV	99 %
^{64}Cu	12.8 hours	1340 keV	0.5 %

$$^{22}_{11}Na \rightarrow ^{22}_{10}Ne + e^+ + \upsilon$$



Positrons originate from the radioactive decay of radioactive nuclides, e.g., ^{22}Na,

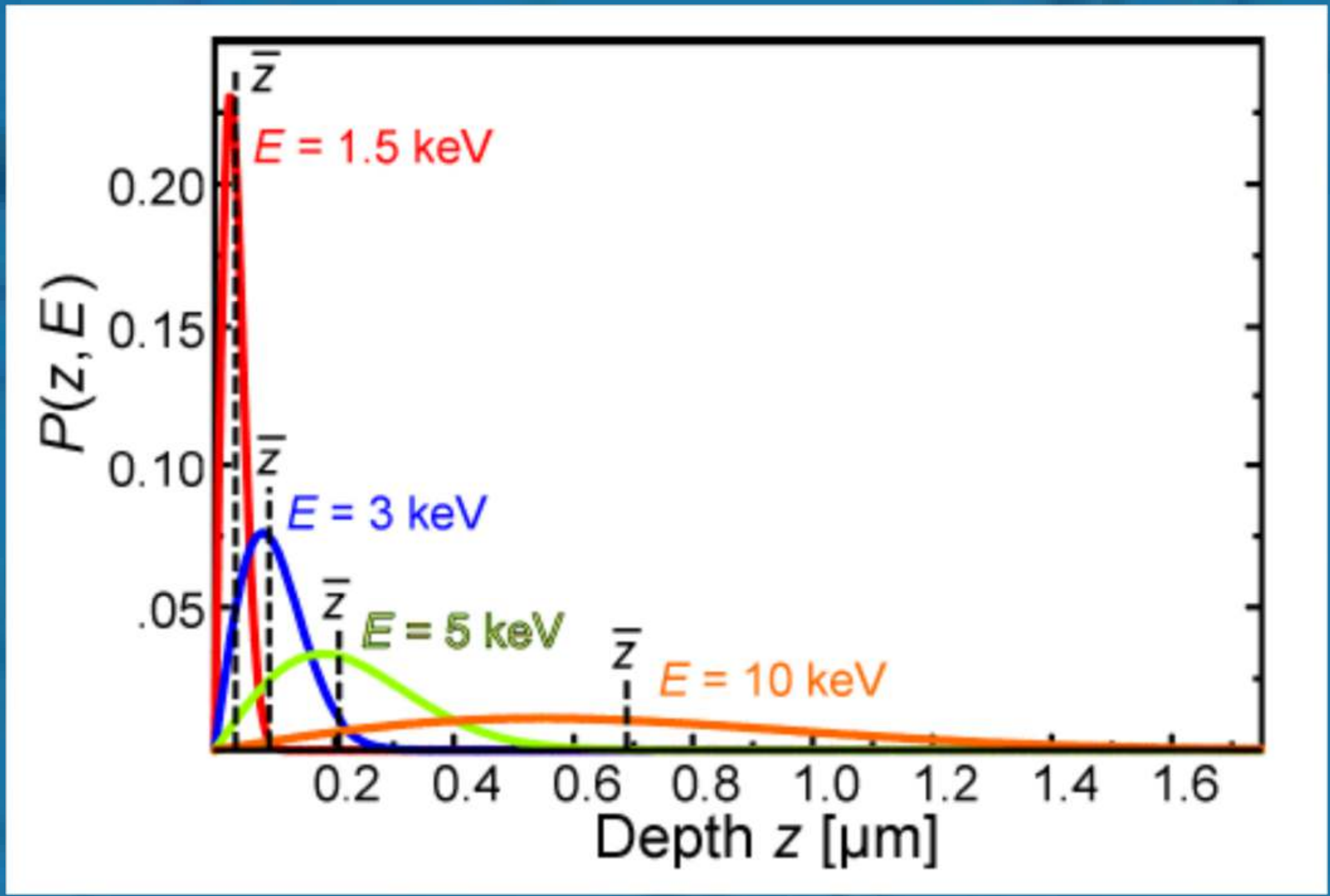
or from pair production ($\gamma \rightarrow e^+ e^-$)

Implantation Profile

$$P(z,T) = \frac{mz^{m-1}}{z_0^m} \exp\left[-\left(\frac{z}{z_0} \right)^m \right],$$

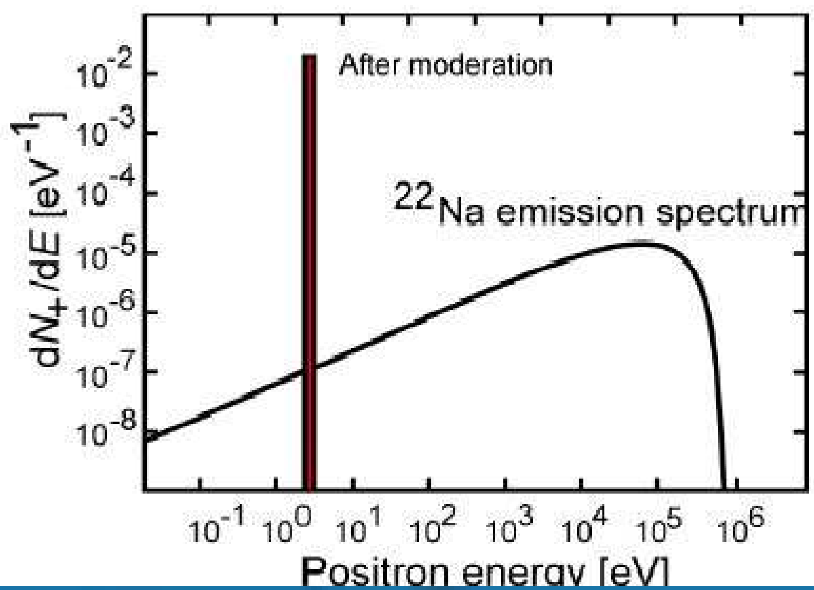
$$z_0 = \frac{AT^r}{\rho \Gamma(1 + 1/m)}.$$

The parameters *r*, *m*, and *A* are empirical values commonly taken to be $r = 1.6$, $m = 2$, and $A = 4.0$ μg cm^{-2} keV^{-r} for Si.

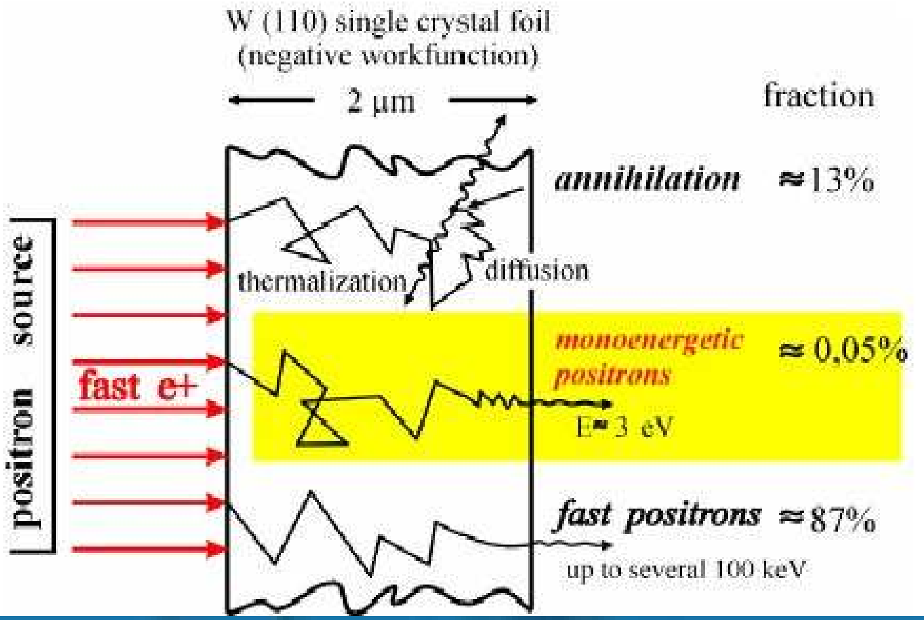


Monoenergetic Positrons for the Study of Thin Layers

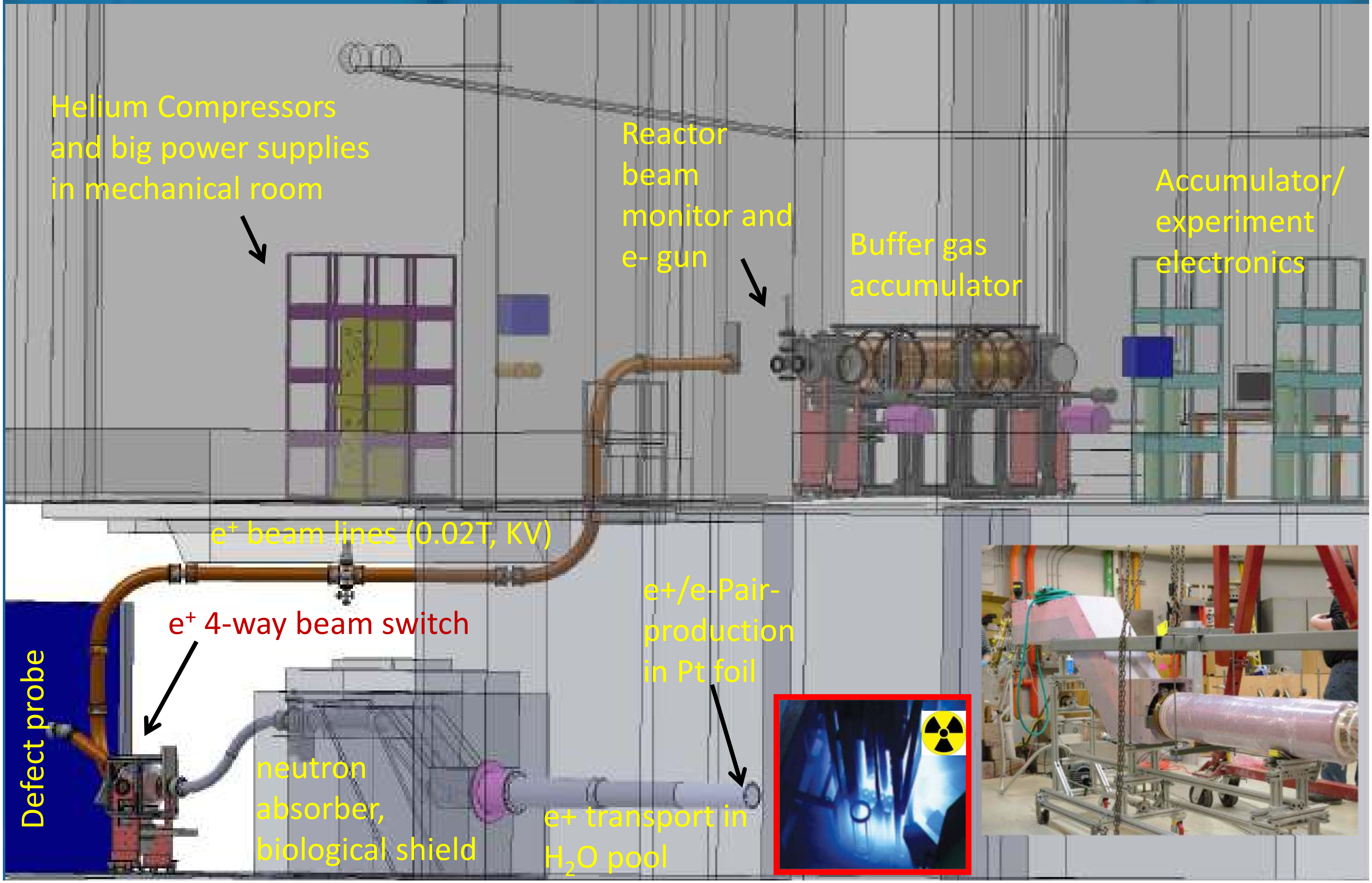
Energy distribution after β^+-decay



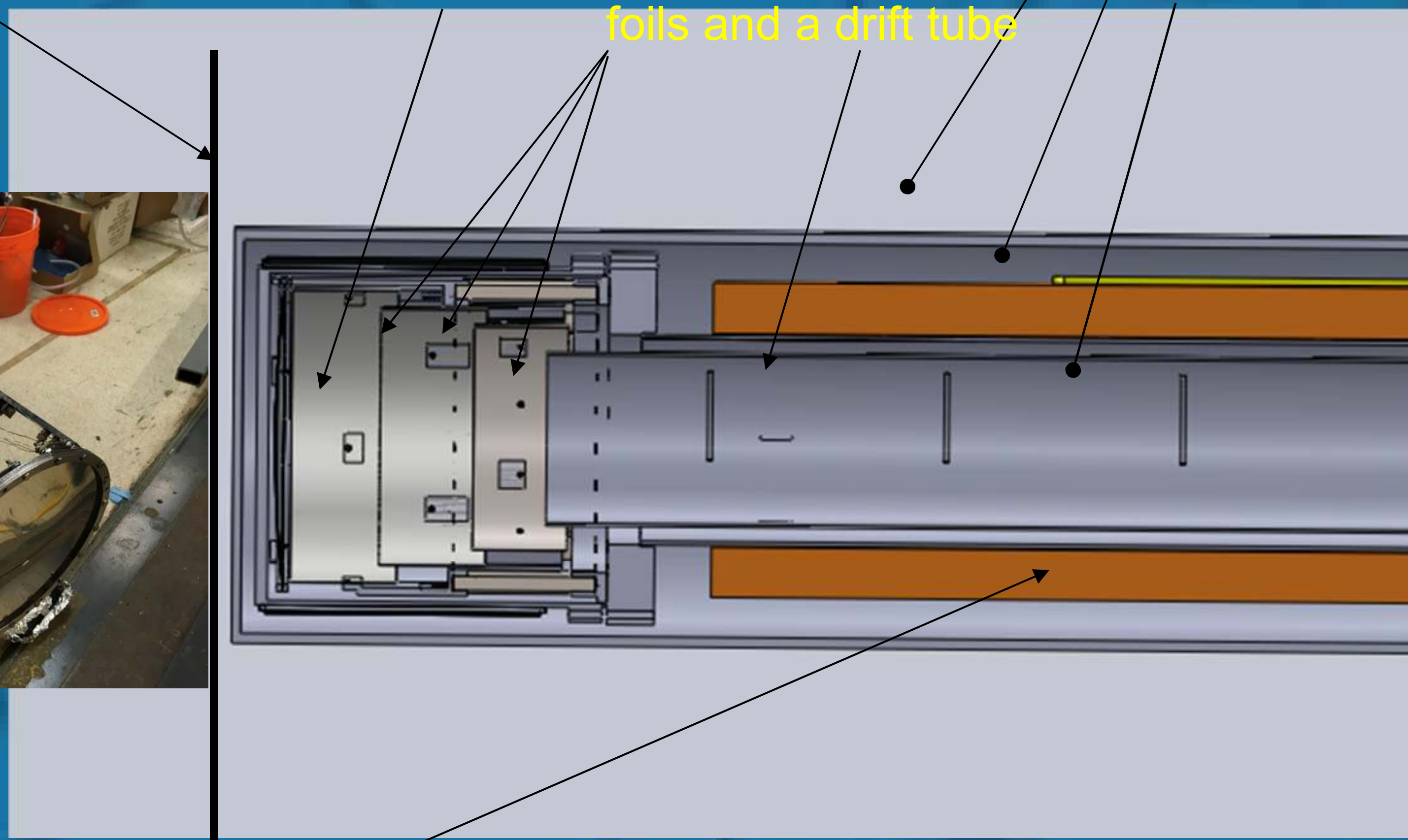
Moderation



McMaster Intense Positron Beam Facility (MIPBF)



e^+ Production Foils Near Reactor Core



Solenoid (>0.01 Tesla) to guide low energy e^+ out of pool
Passively cooled by air (requirements at the reactor)

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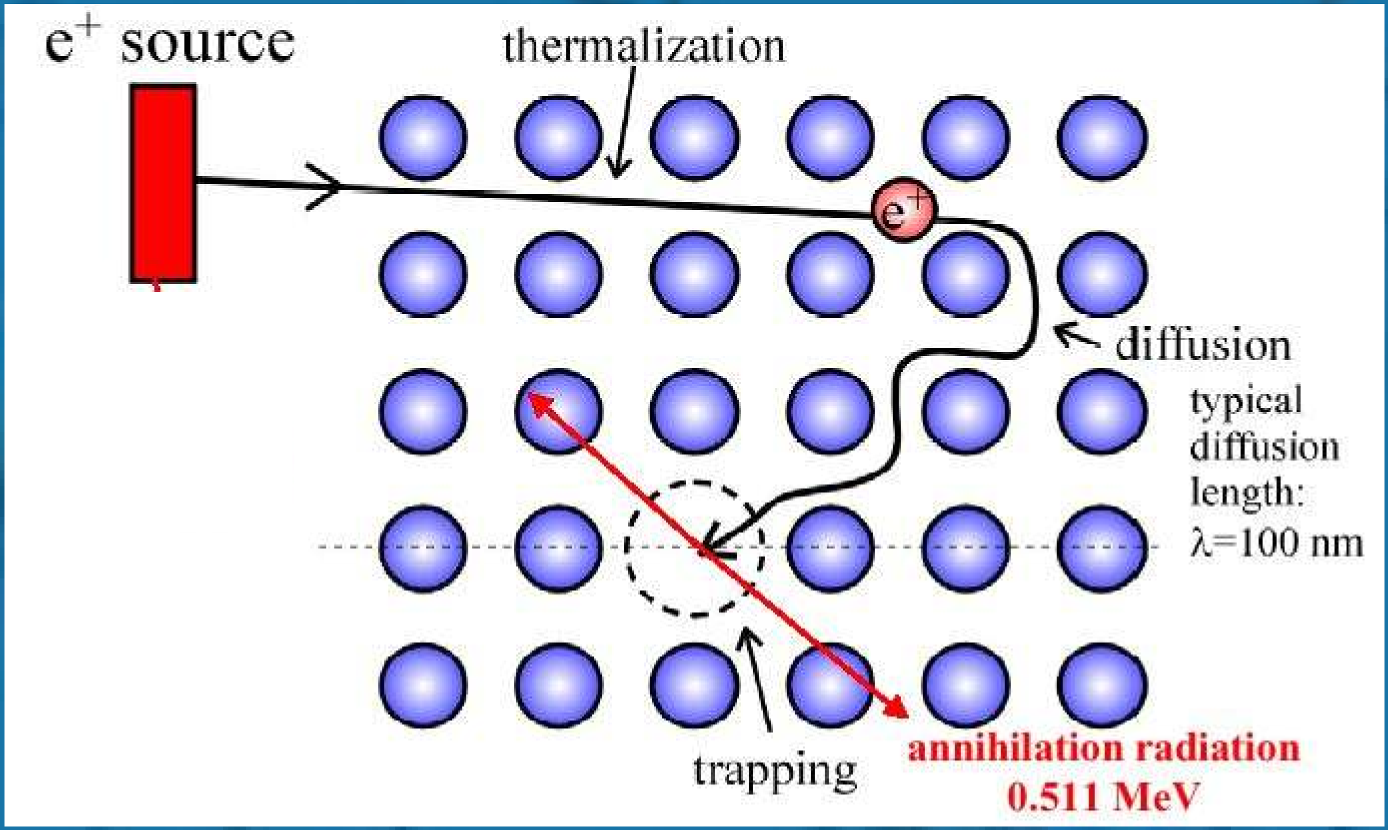
Positrons in Condensed Matter

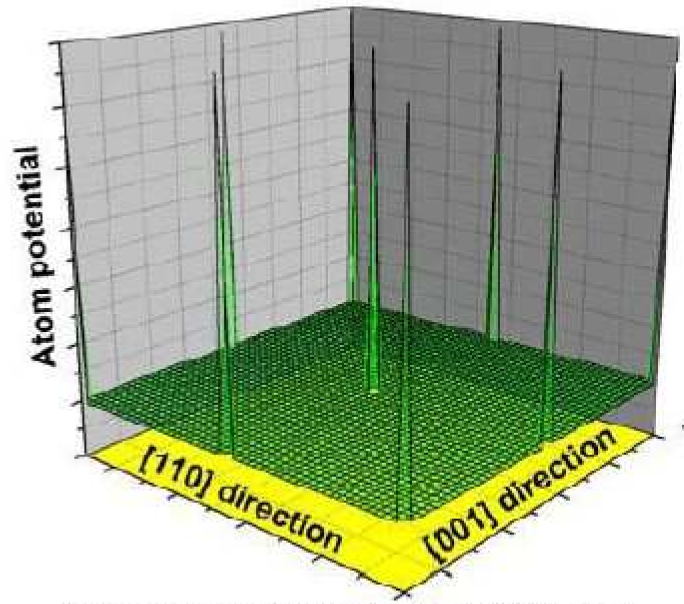


Annihilation parameters change in the localized state

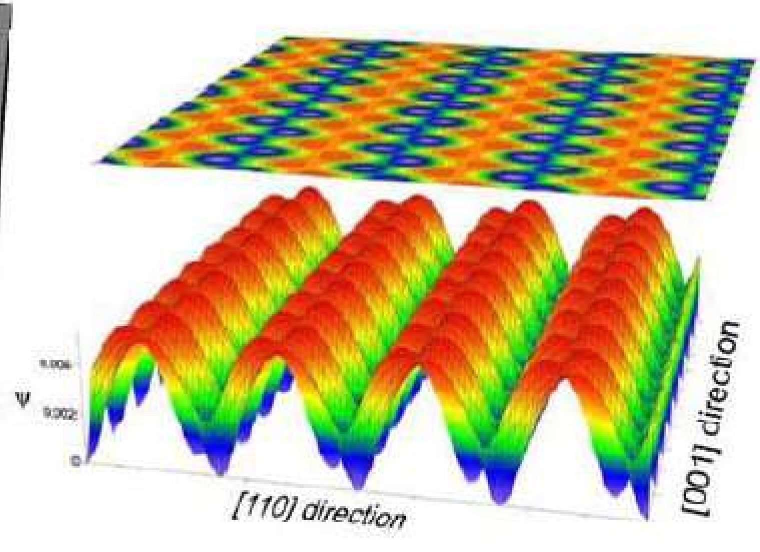
- defects can be detected (size and concentration)

Delocalized Bloch State of Free Positrons

Perfect Lattice

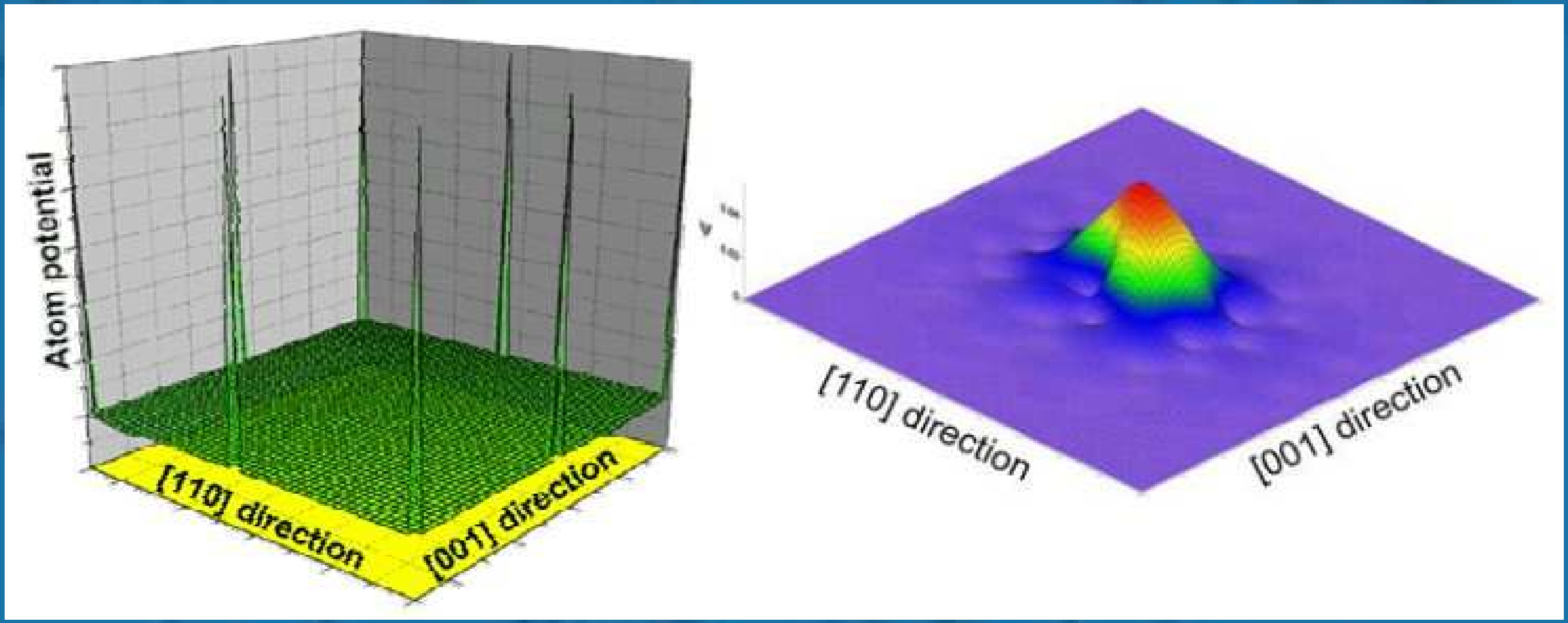


Atom potential in GaAs (110) plane



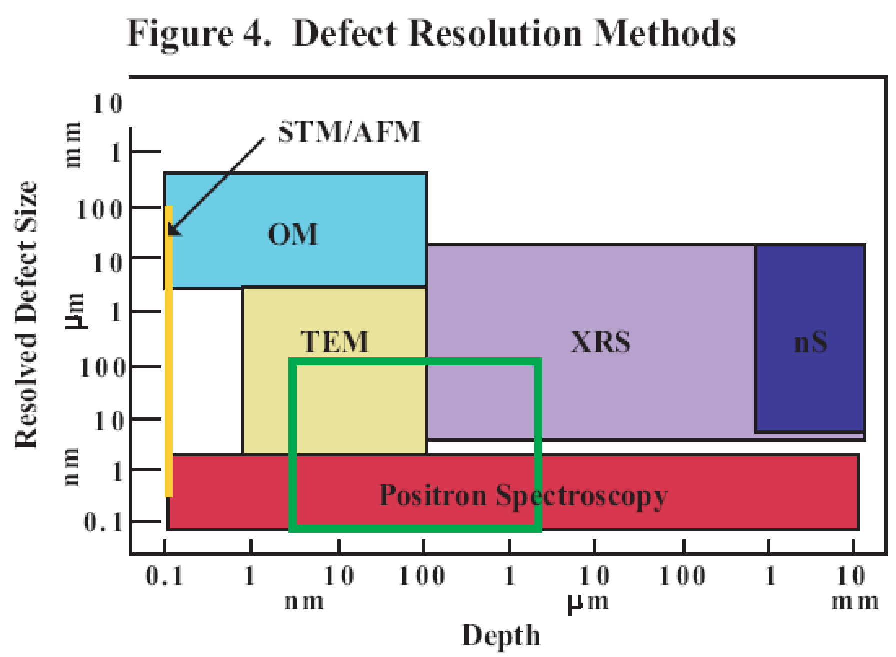
Positron wave function in GaAs (110) plane

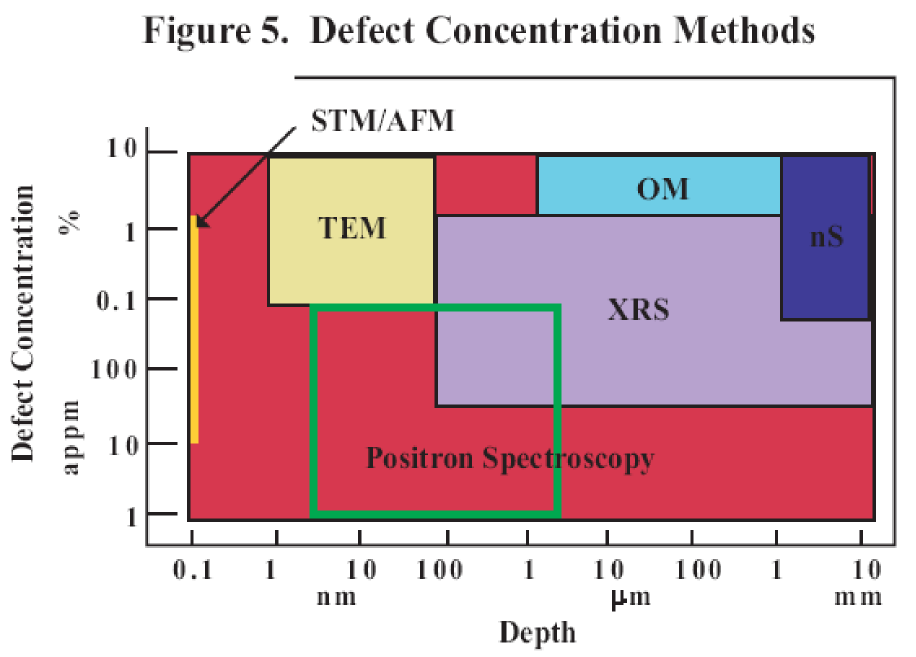
Positron Trapped in a Monovacancy



A vacancy represents a positron trap due to the missing ion core (potential well for a positron)

Positron Annihilation Spectroscopy is a Unique Technique

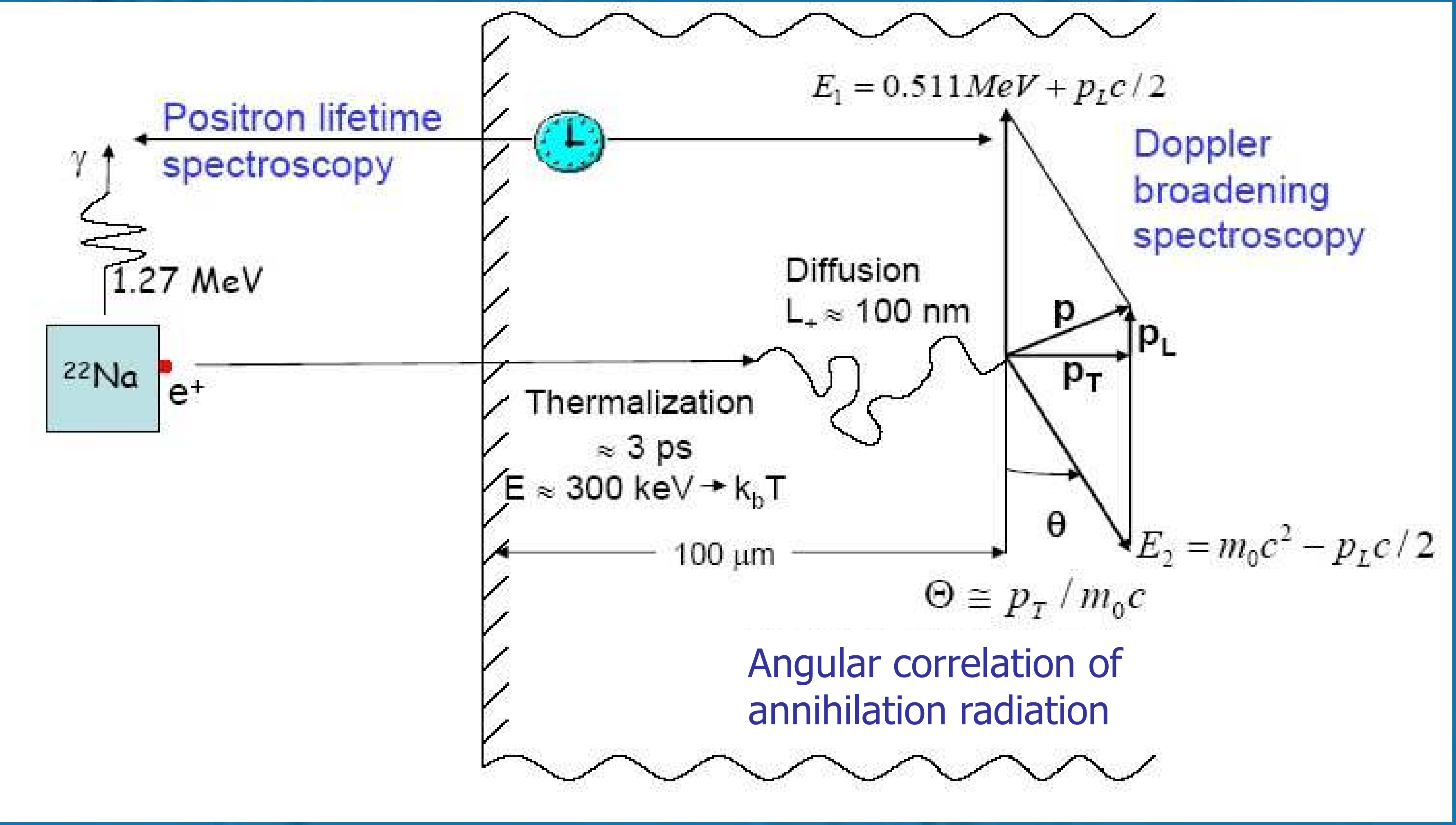




PAS can resolve size and concentration of open volume defects

R.H. Howell et al., 14th International Conference on the Application of Accelerators in Research and Industry, Denton, TX November 6-9, 1996

Methods of Positron Annihilation Spectroscopy

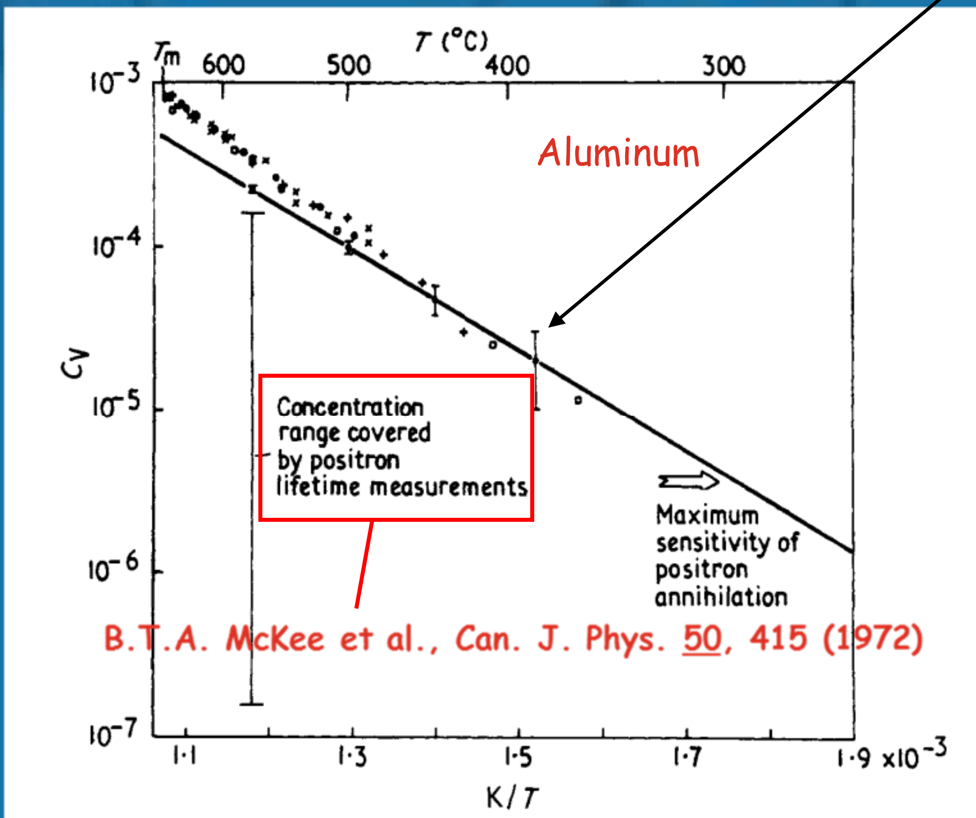


Vacancy Formation Enthalpies - Metals

J. Phys. F: Metal Phys., Vol. 3, February 1973. Printed in Great Britain. © 1973.

Investigation of point defects in equilibrium concentrations with particular reference to positron annihilation techniques

Alfred Seeger
Max Planck Institut für Metallforschung, Institut für Physik and Institut für theoretische und angewandte Physik der Universität Stuttgart, Stuttgart, Germany



<u>Calorimetric Measurements</u>:

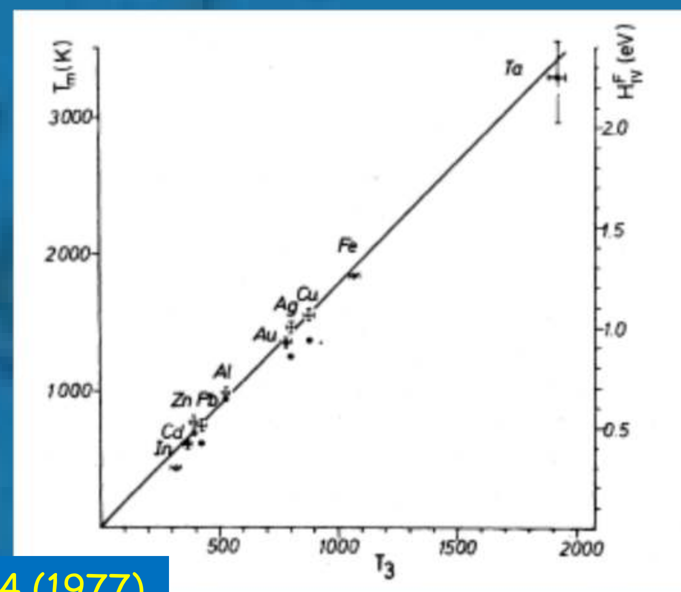
Guarini and Schiavini 1966 *Phil. Mag.* **14** 47-52

<u>Length vs. X-ray Measurements</u>:

Simmons and Balluffi 1960 *Phys. Rev.* **117** 52-61

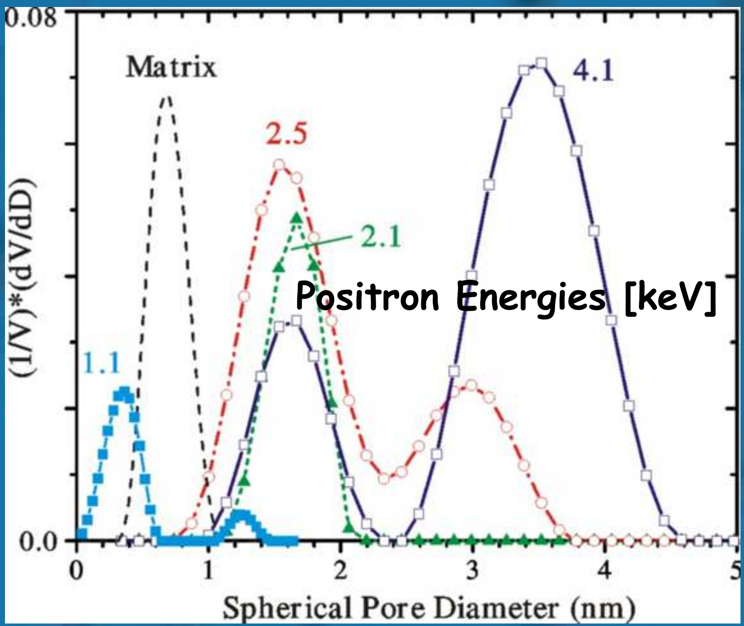
Bianchi, Mallejac, Janot, and Champier 1966 *Compr. Rend. Acad. Sci., Paris* **263** 14047

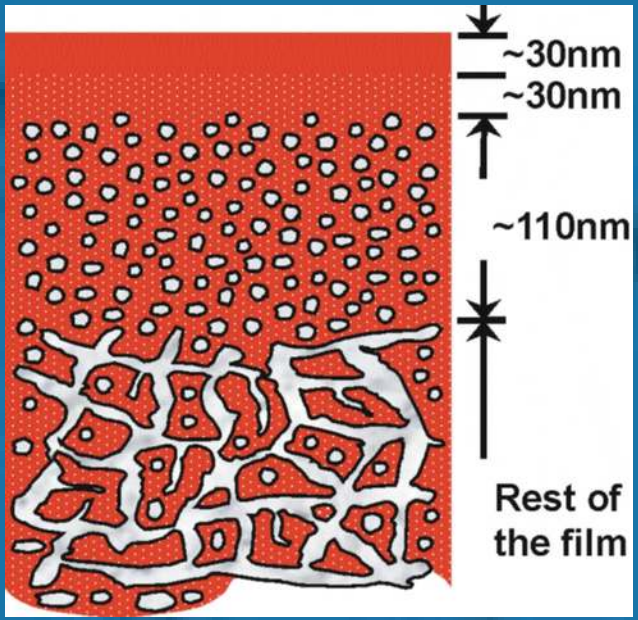
Heigl and Sizmann 1972 *Crystal Lattice Defects* **3** 13-27



K. Maier et al., PRL 39, 484 (1977)

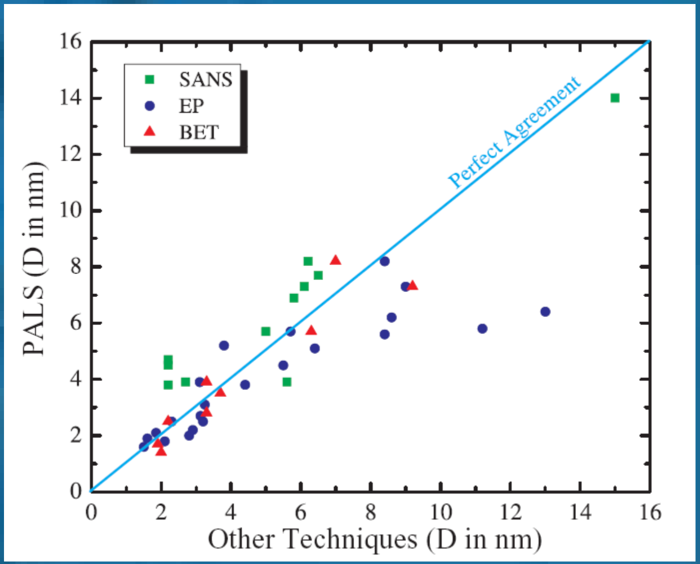
Pore Size Distribution in Low-k Dielectrics





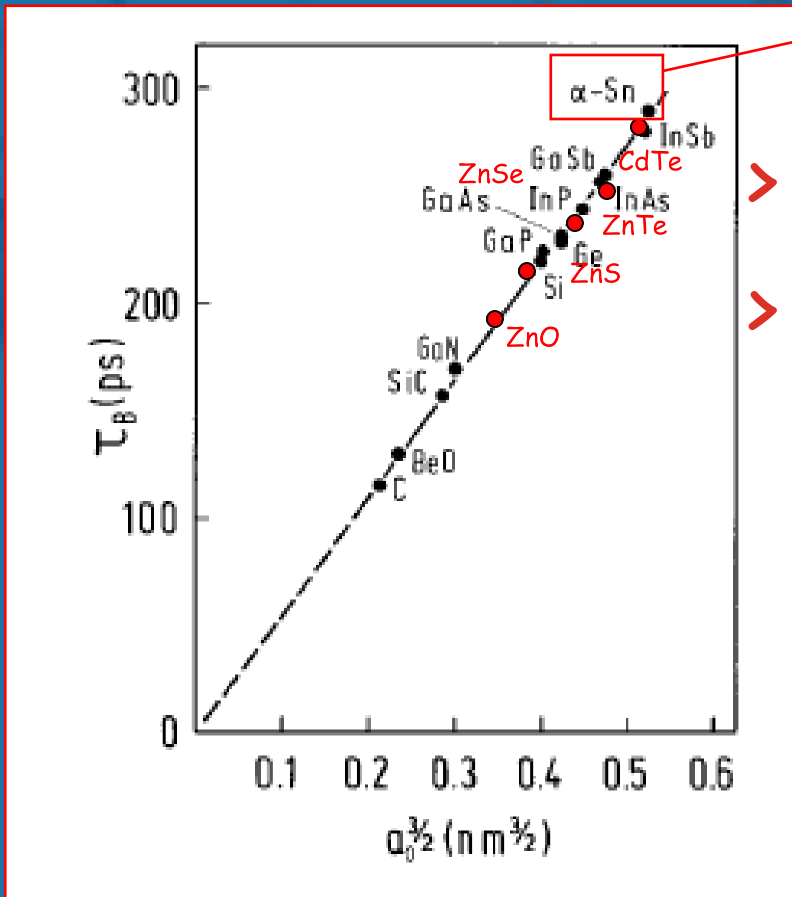
PECVD SiCOH

Peng H.-G. et al., Appl. Phys. Lett. 86, 121904 (2005)



D.W. Gidley et al., Annu. Rev. Mater. Res. 36, 49 (2006)

Lifetimes in Semiconductors

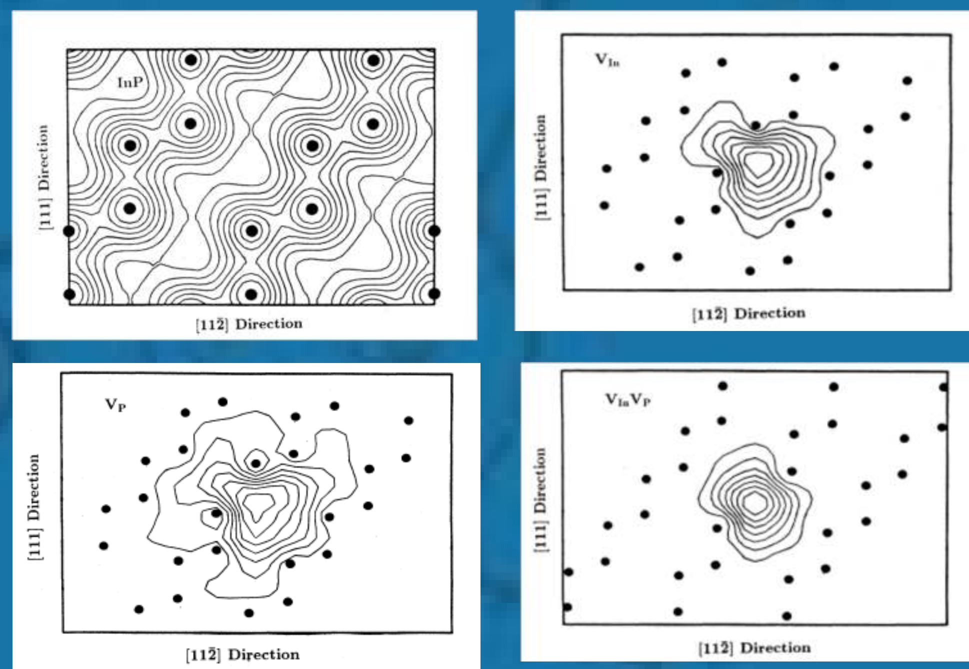


H. Siethoff, phys. stat. sol. (b) 205 R3 (1998)

W. Puff and P. Mascher, J. Phys. F 14, L231 (1984)

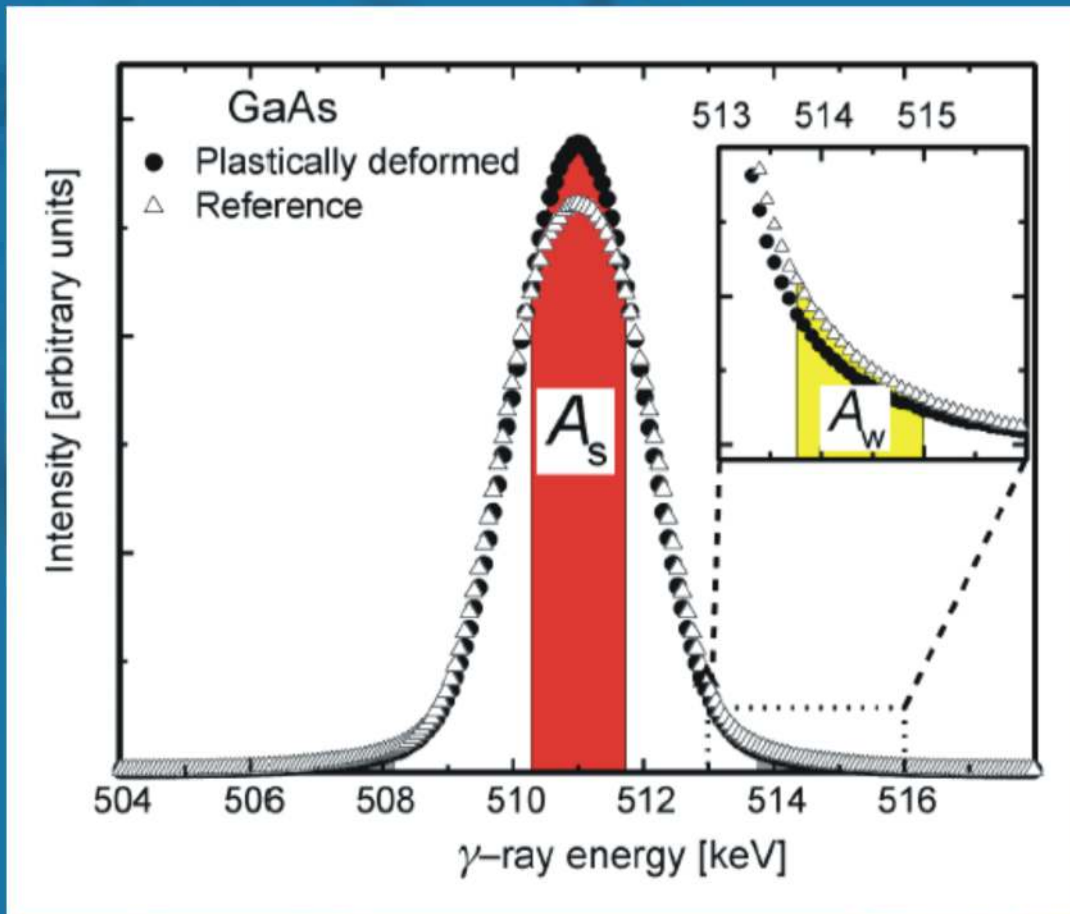
M. Martyniuk and P. Mascher, Physica B 308-310, 924 (2001)

G. Tessaro and P. Mascher, J. Cryst. Growth 197, 581 (1999)



M. Puska et al., PRB 39, 7666 (1989)

Doppler Broadening Spectra



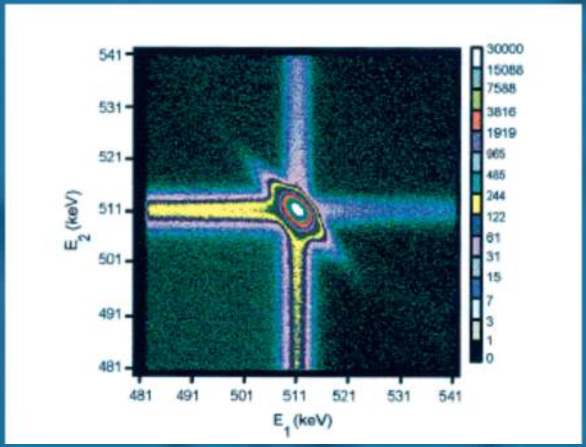
The line shape parameters

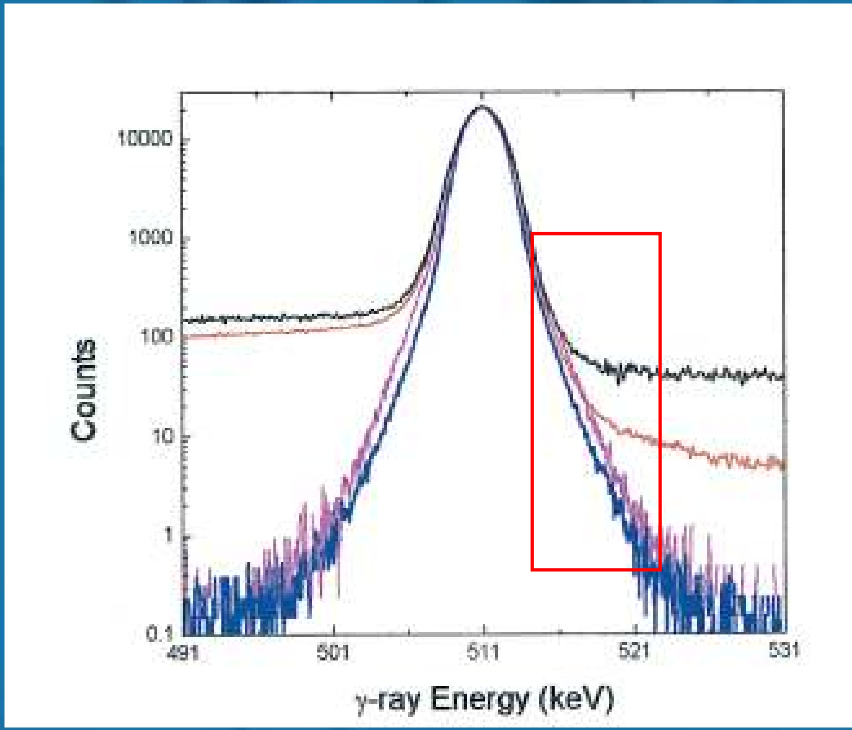
S parameter:
$S=A_s/A_o$

W parameter:
$W=A_w/A_o$

The curve of defect-rich material is higher and narrower than that of a defect-free reference material

Background Reduction



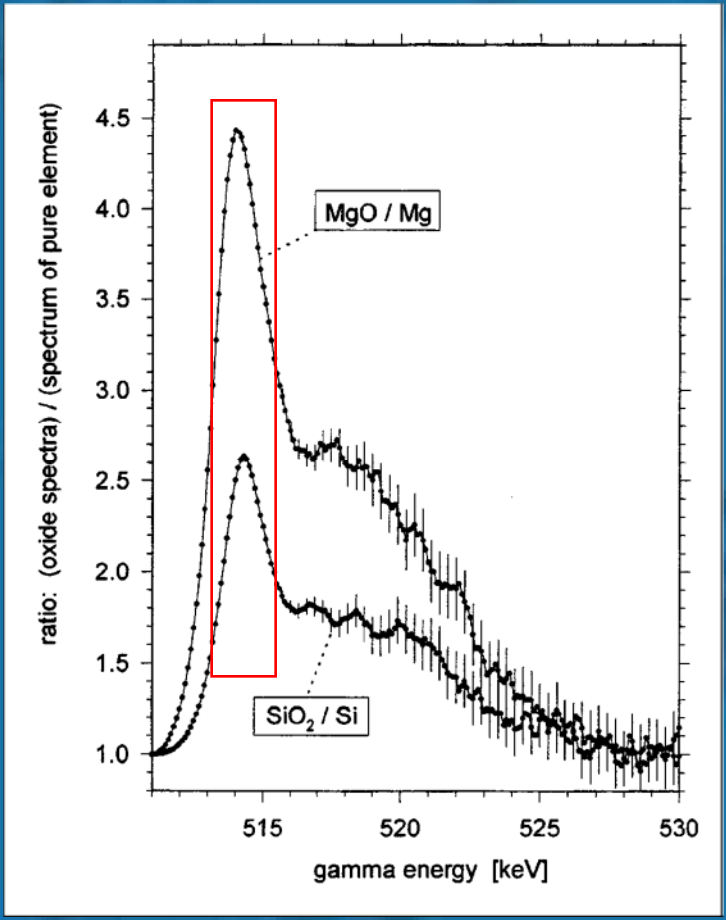


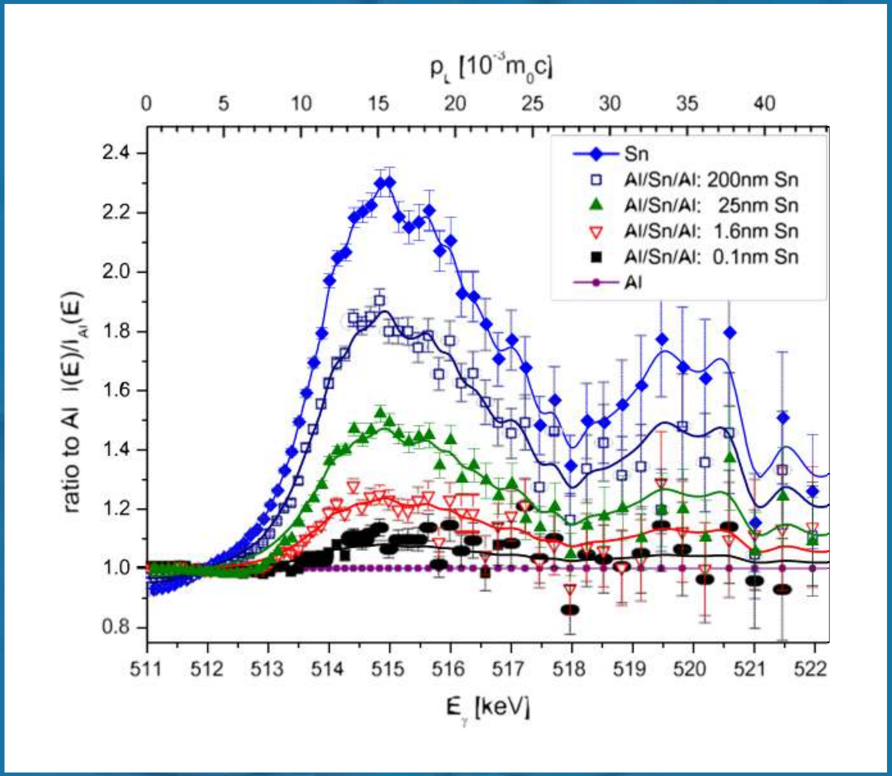
- Investigation of the high momentum part of the energy spectrum is possible, e.g. *annihilation with core electrons of the atoms*
- Thus the *chemical surrounding* of a positron trap can be studied

Asoka-Kumar et al. PRL 77, 2097 (1996)

Doppler Broadening Spectra

Elemental Sensitivity

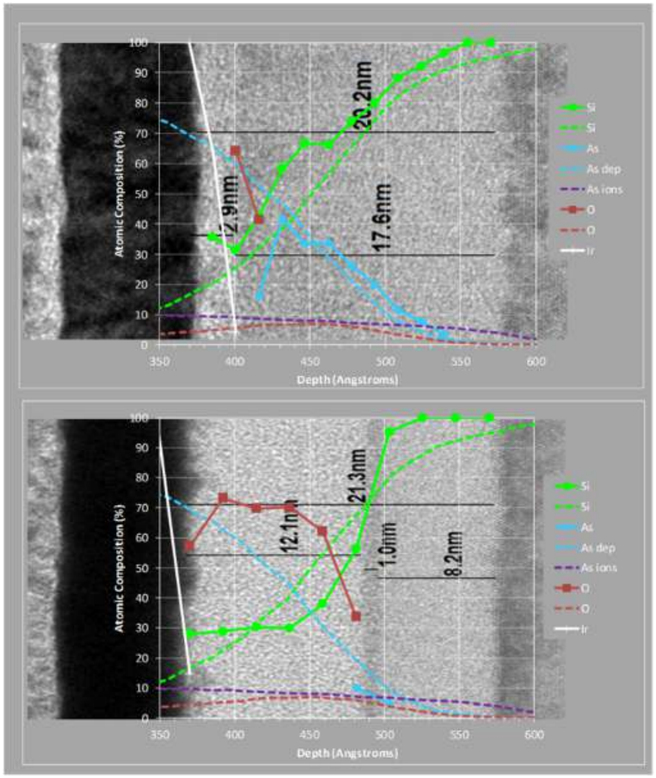


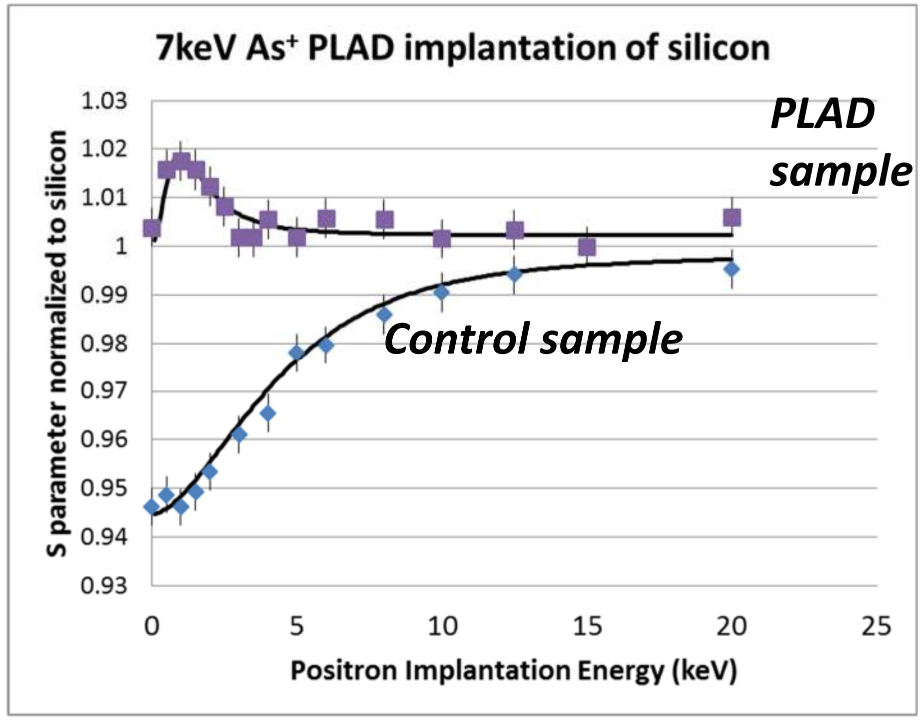


C. Hugenschmidt et al., PRB 77, 092105 (2008)

U. Myler et al., PRB 56, 14303 (1997)

First Results using the Defect Characterization Chamber – Plasma Doping of Silicon (A.P. Knights et al.)





- Plasma Doping (PLAD) is a promising alternative to traditional beamline ion implantation
- Current collaboration with AMAT includes PAS in a round robin experiment to determine differences in the two doping technologies
- Preliminary data (first data taken on Defect Characterization chamber) shows defect formation at near-surface region of PLAD exposed wafer
- Fits to data indicate void formation in a thin layer (work on-going).

The McMaster Intense Positron Beam Facility (MIPBF) Project Team

Peter Mascher	Project Leader (McMaster University)
Simon Day, Scott McMaster	Beam Delivery System (McMaster Nuclear Reactor 50, 1959-2009)
Andrew P. Knights, Peter J. Simpson	Defect Probe (Western; McMaster University)
Peter Kruse	Surface Analysis (McMaster University)
Cody Storry	Positron Storage and Interaction (York Université University)

Ontario
MINISTRY OF RESEARCH & INNOVATION

Canada Foundation for Innovation
Fondation canadienne pour l'innovation

Summary and Conclusions

- Anti-particles provide unique and useful information about the "real world"
- Positron annihilation spectroscopy is a sensitive tool for the investigation of open-volume defects in semiconductors and other materials
- Information on the type, concentration, and chemical surroundings of defects can be obtained