Development of a Triple-Coincidence Positron Lifetime Spectrometer for Nuclear Materials Research

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Outline

- What is positron lifetime spectroscopy and to what purpose it can be used?
- Why do we need to study lattice point defects in nuclear materials with positrons?
- What problems are detected when measuring medium-to-high-activity materials with the conventional two detector setup?
- How does a new coincidence detector improve the activity tolerance of the spectrometer?

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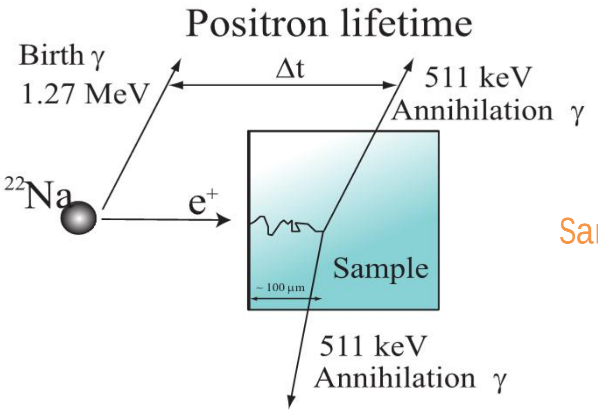
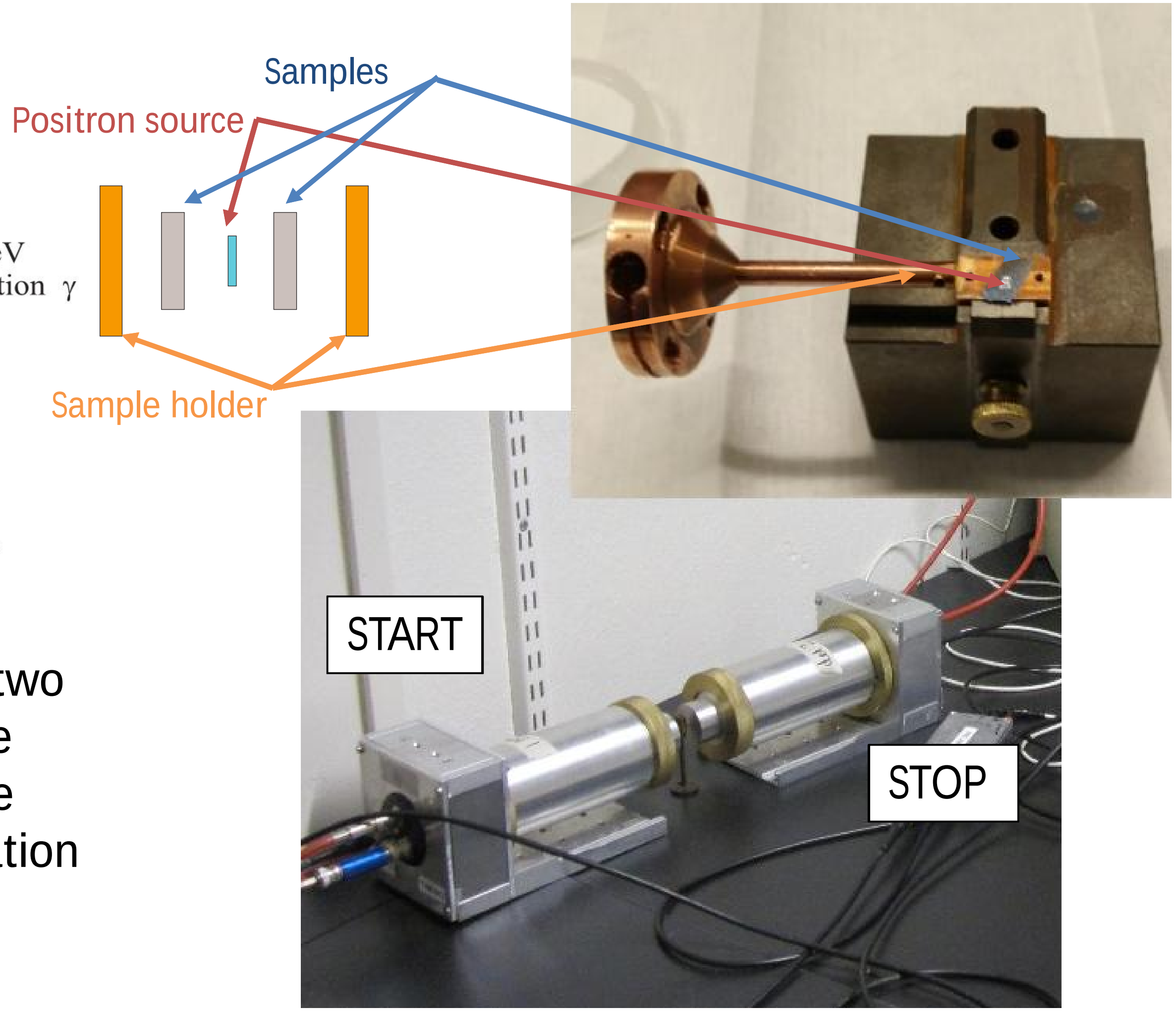
What is positron lifetime spectroscopy?





- Conventional setup: two detectors, one for the birth photons and the other for the annihilation photons

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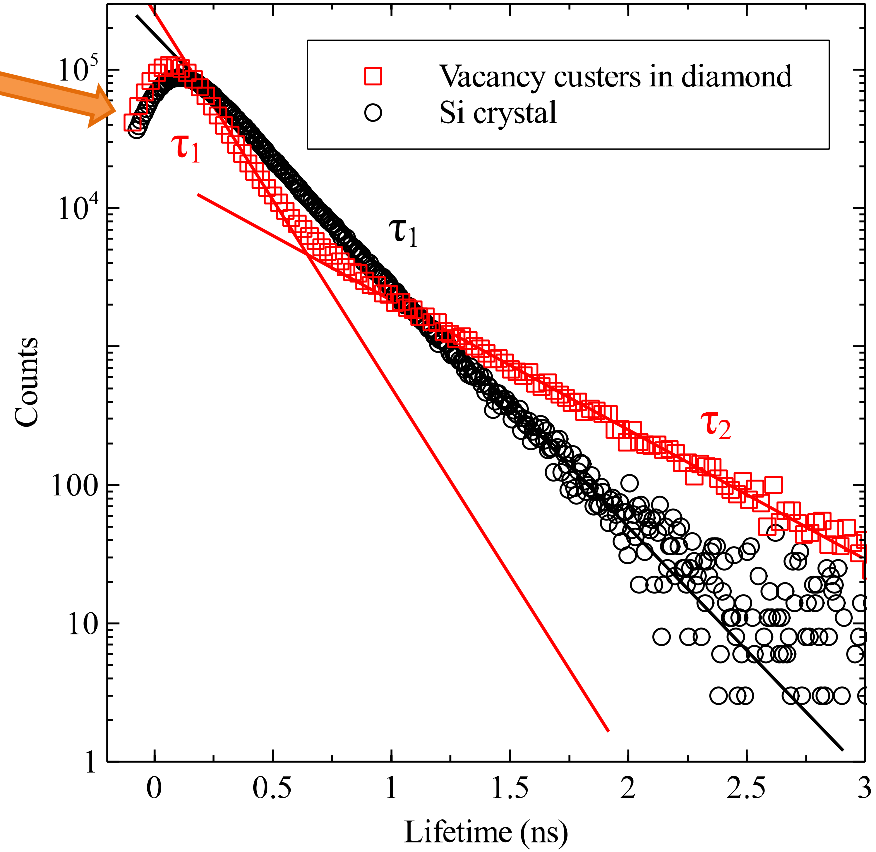
What is positron lifetime spectroscopy?

Positron lifetime spectra after background reduction and source corrections



- Positrons trap easily to vacancy type defects starting at 10^{16} 1/cm^3 vacancy densities (~ 1 ppm) in crystalline material
- Positrons have characteristic decay time in point or nanometer-scale vacancy clusters

Why do we need to study defects in nuclear materials with positrons?

- Nuclear materials are exposed to challenging environment: high temperature, high temperature gradient, actinides, neutron/alpha/beta/gamma irradiation
  - It is difficult to predict the behavior of the nuclear materials in extreme or non-standard conditions
  - It is difficult to predict the behavior of new type of nuclear materials
- Nanoscale defects are in important role in nuclear materials affecting, for example, their mechanical and diffusion properties
- Positron lifetime spectroscopy
  - Could complement TEM results
  - Is sensitive to smaller defect densities than TEM
  - Is much faster to measure than TEM
  - Doesn't allow direct observation of the defect structure (change in the positron lifetime components)
- Recently applied to microstructural defect studies, for example, in UO_2 and structural steels

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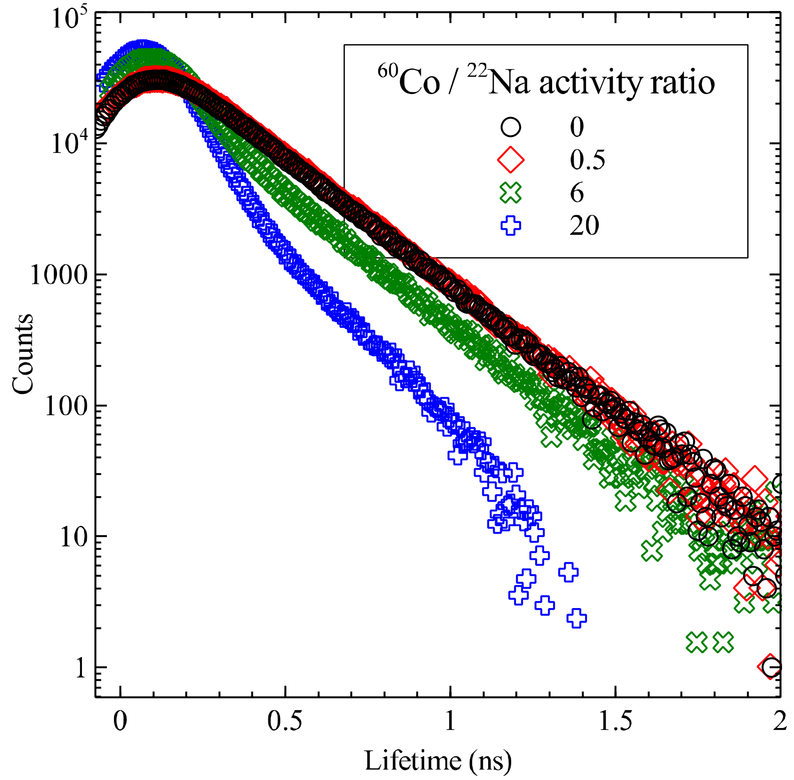
What problems are detected when measuring medium-to-high-activity materials with the conventional two detector setup?

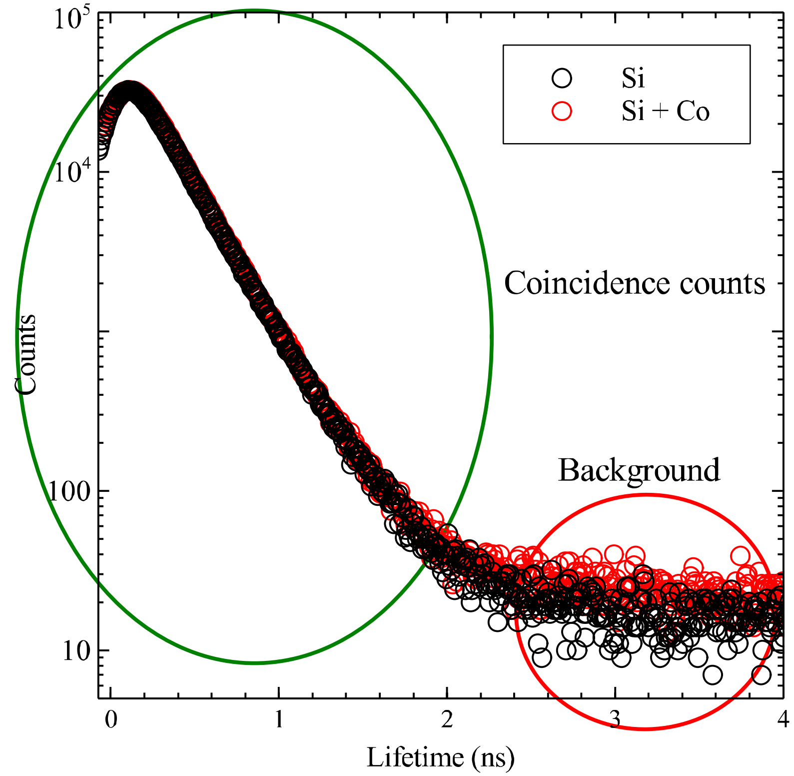
- Adding ^{60}Co in between the detectors: two fast successive gamma photons with 1.17 and 1.33 MeV energies
- Excess coincidence events distort the lifetime spectrum
- Limits for a regular two-detector setup
  - ➢ Coincidence activity in the samples < 1 MBq



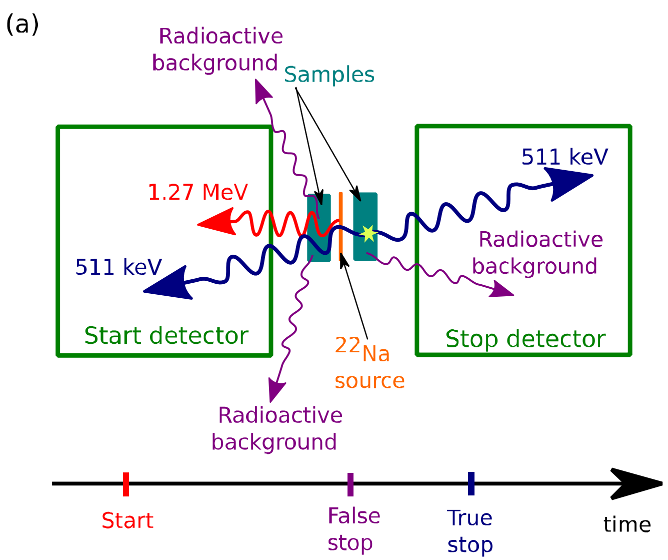
What problems are detected when measuring medium-to-high-activity materials with the conventional two detector setup?

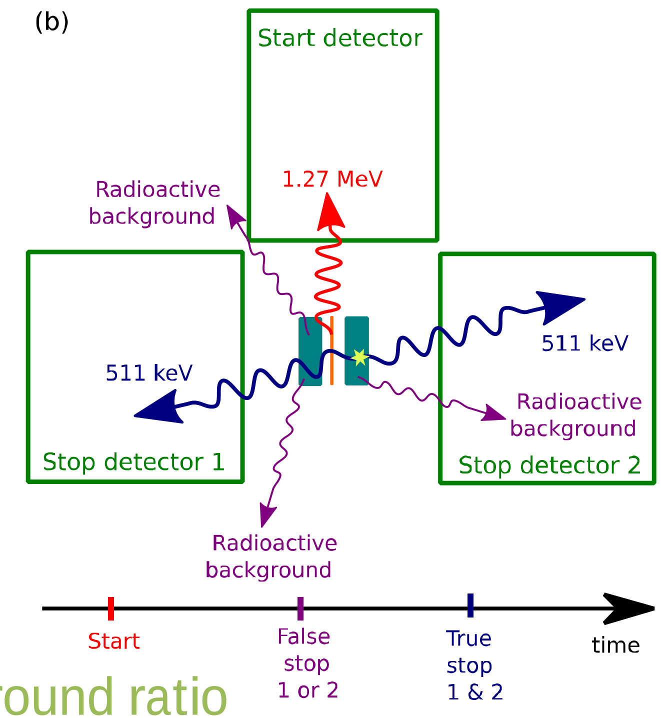
- Excess activity decreases peak-to-background ratio
- Background origins from random coincidence counts inside the spectrometer's time window τ
- Random coincidence count rate:

$$R_R \approx (\varepsilon A)^2 \tau$$



How does a new coincidence detector improve the tolerance of the spectrometer?





- ✓ Improved peak-to-background ratio
- ✓ No two-coincidence distortion
- ✓ Smaller count rate due to geometrical restrictions

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How does a new coincidence detector improve the tolerance of the spectrometer?

Two detectors

$$\frac{R_R}{R_C} = A\tau$$

Three detectors

$$\frac{R_R}{R_C} = (A\tau)^2$$

POSITRON SOURCE

➡ Positron source could be 10 x more active in the three-detector setup

SAMPLE ACTIVITY, NO COINCIDENCE, EFFECT TO PEAK-TO-BACKGROUND < 0.001

Two detectors

$$R_R \approx (\varepsilon A)^2\tau \qquad A_R = \frac{\sqrt{R_R}}{\varepsilon\sqrt{\tau}} \approx 16\text{ MBq}$$

$\varepsilon \approx 2\text{x}10^{-4}$ $R_R \approx 0.1$ c/s $\tau = 10$ ns

Two samples (a 500 mg): 16 GBq/kg

Three detectors

$$R_R \approx (\varepsilon A)^3\tau^2 \qquad A_R = \frac{\sqrt[3]{R_R}}{\varepsilon\sqrt[3]{\tau^2}} \approx 900\text{ MBq}$$

$\varepsilon \approx 5\text{x}10^{-5}$ $R_R \approx 0.01$ c/s $\tau = 10$ ns

Two samples (a 500 mg): 900 GBq/kg

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Conclusions

- In a three detector setup one can increase the sodium source activity to compensate worse count rate, compared to the conventional setup
- Adding a third coincidence detector to the setup can increase the activity tolerance of the spectrometer even 50 times higher
- In the future:
  - Experimental tests and simulations for finding the optimal parameters for the setup
  - Design for operating and measuring samples inside a glove box
  - Possible collaboration with VTT (Finland) and JRC (Karlsruhe, Germany)

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