Determining the asolute fraction of emitted positronium by GEANT4 supported analysis of gamma ray spectra

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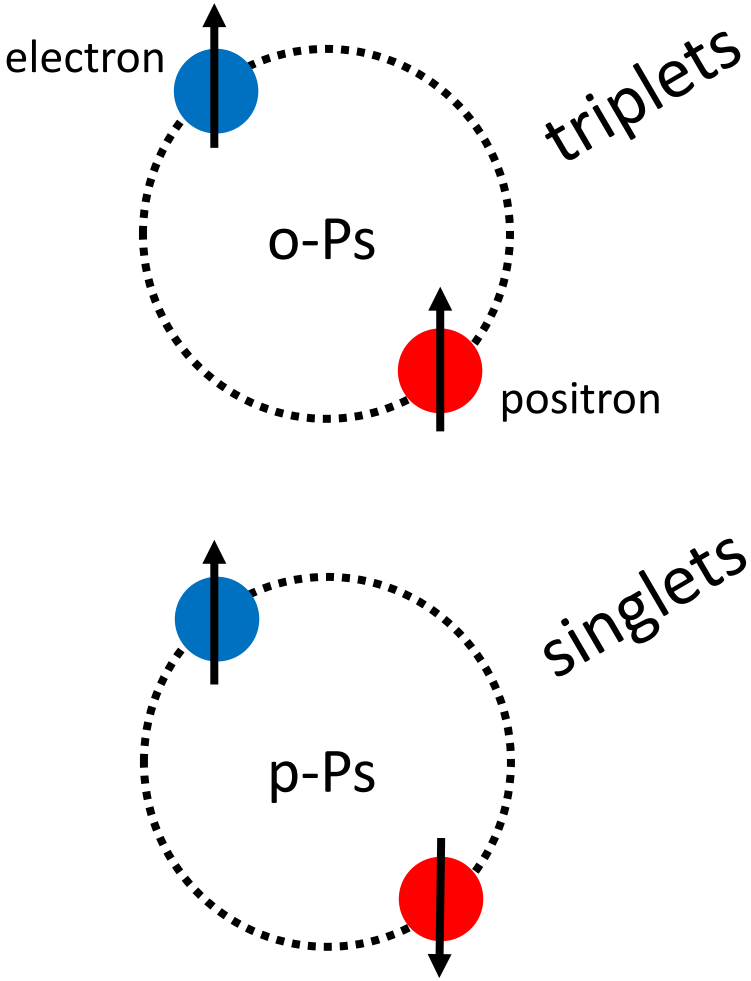
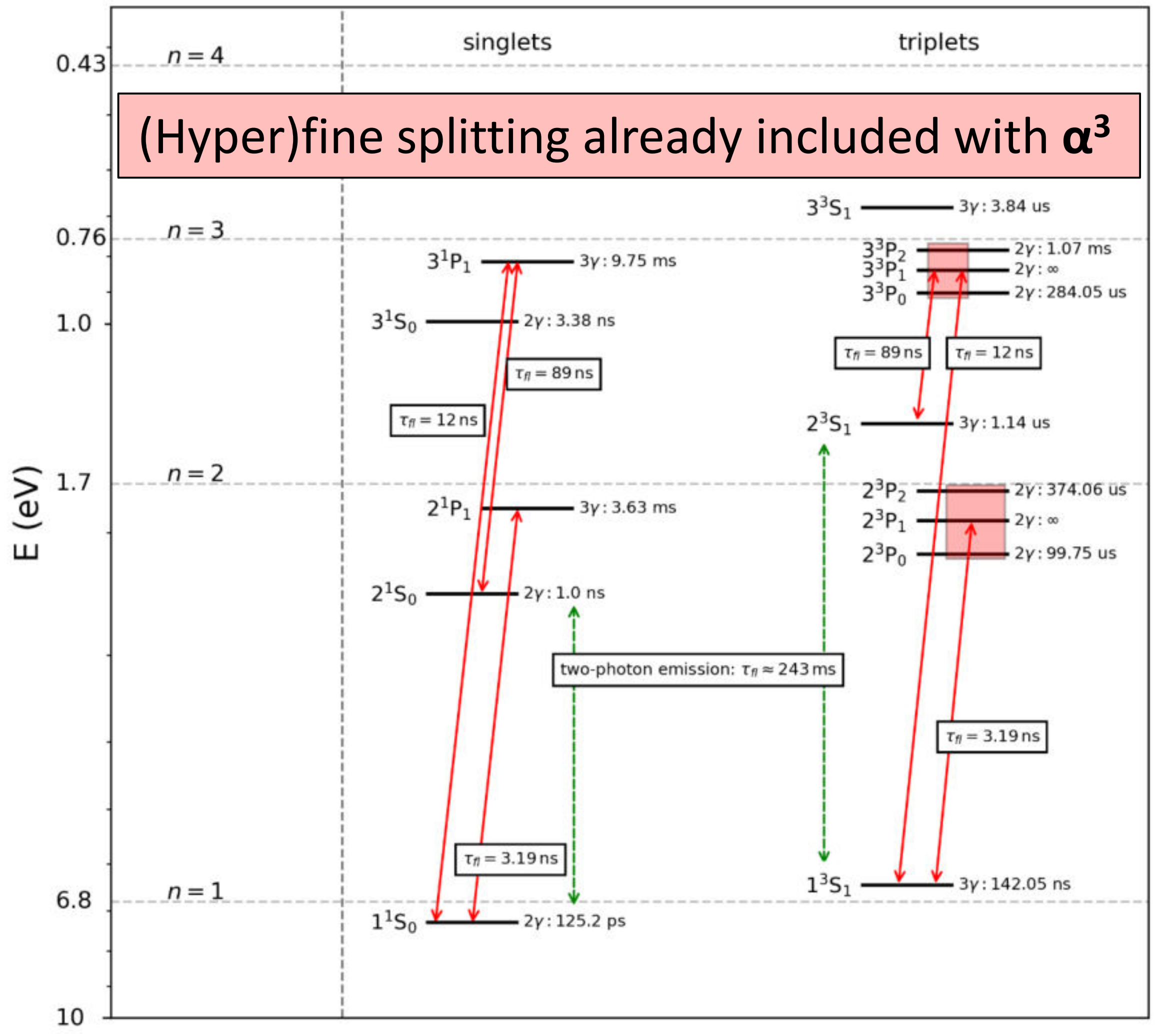
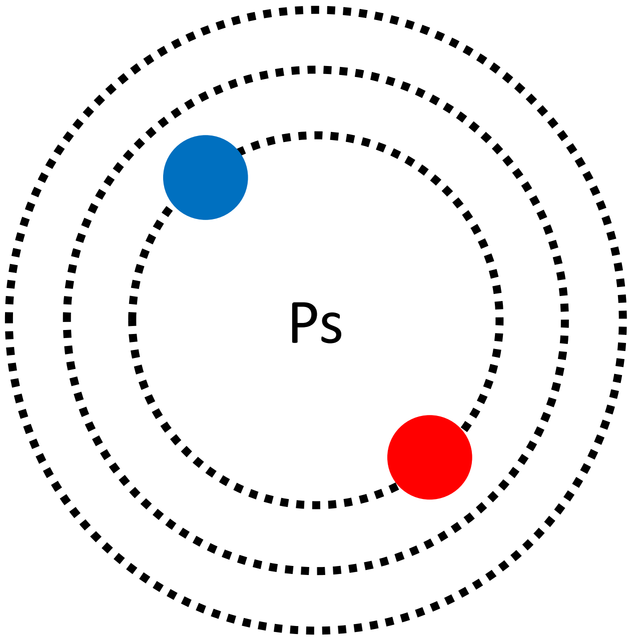
FRM II
Forschungs-Neutronenquelle
Heinz Maier-Leibnitz

Ps level scheme up to n=3





Range of physics with Ps



Ps is a great experimental test ground for QED

- precision tests via Ps laser excitation
- Ps laser cooling
- quenching and photoionization

Ps is also interesting for

- gravitational measurements
- Bose-Einstein condensates (gamma ray lasers?)
- catalyst for antimatter (charge exchange)
- material science, porosimetry

Hot experimental topics

Routes of Ps emission

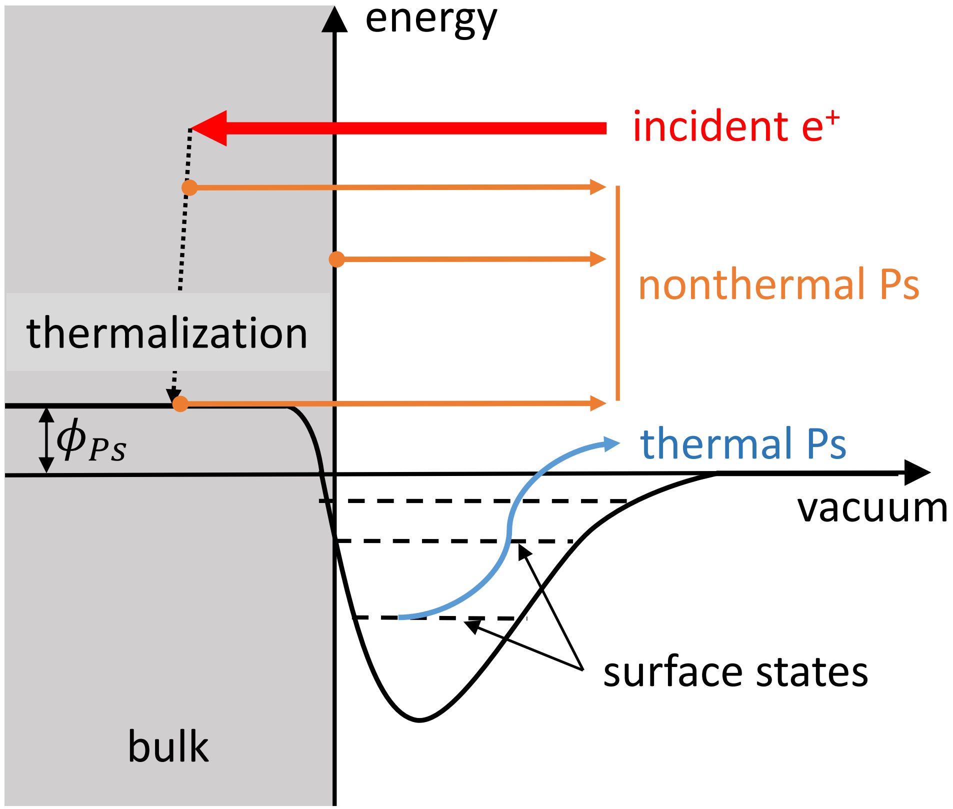
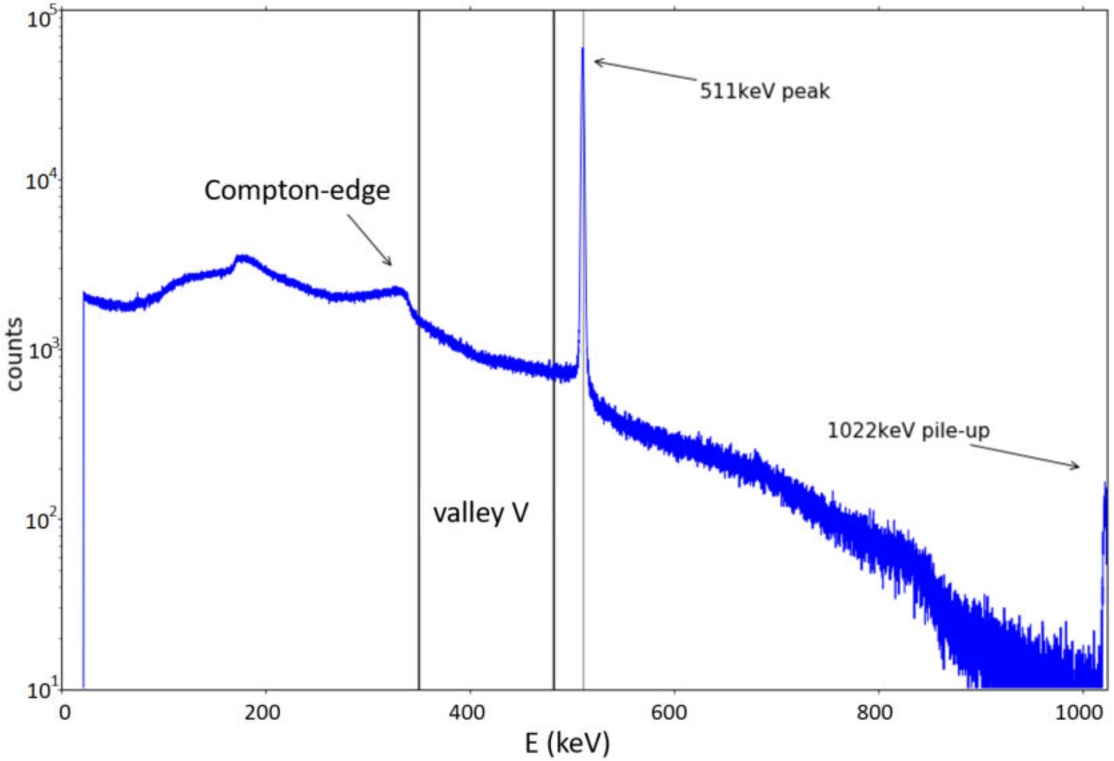


Image after Schultz and Lynn (1988)

Incident e+:	up to keV
Nonthermal Ps:	few eV
Thermal Ps:	<100 meV

Ps detection with HPGe

High purity Ge detector with high energy resolution



Define the valley-to-peak ratio *R*

$$R = \frac{V}{P}$$

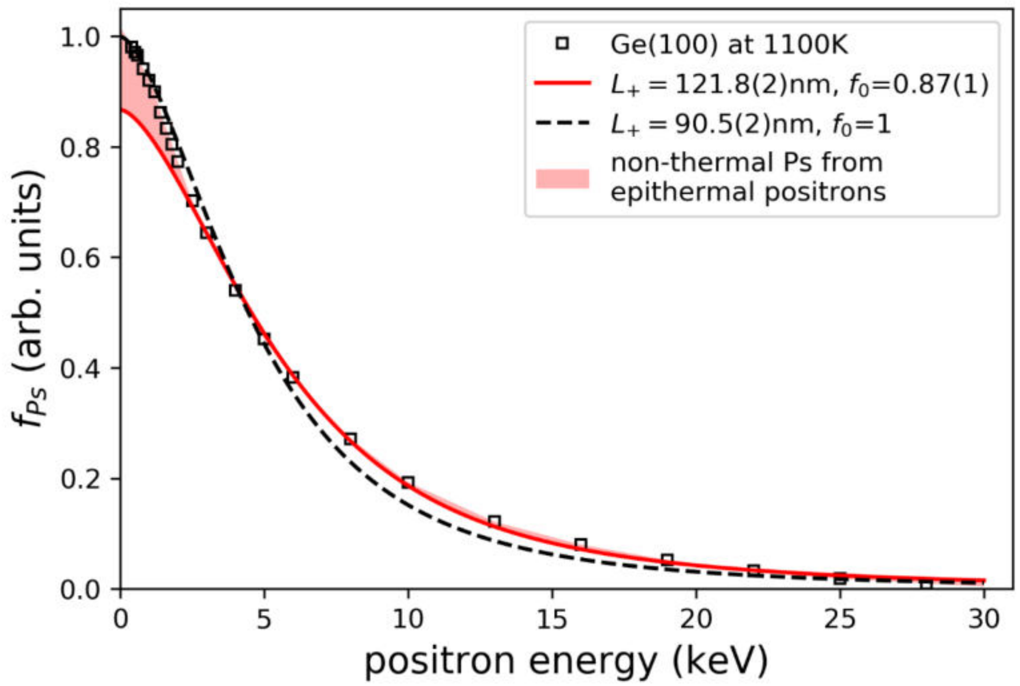
Compare this to a 0% and a 100% Ps measurement and scale R in between:

$$f_{Ps} = \left\{1 + \frac{P_1}{P_0}\frac{[R_1 - R]}{[R - R_0]}\right\}^{-1}$$

- R_1 from Ge at 1100K with e^+ at ≈0eV
- R_0 from Ge at RT with e^+ at 30keV
- P_1/P_0 (Peak 100% / Peak 0% ≈ 0.4)

Ps fraction $f_{Ps}(E)$ from common method

$$f_{Ps} = \left\{1 + \frac{P_1}{P_0}\frac{[R_1 - R]}{[R - R_0]}\right\}^{-1}$$



Positron diffusion model for Ge(100):

P(z) : Makhov implantation profile

- m = 1.68
- n = 1.6
- B = 7.48 nm keV^{-n}

J. Dryzek and P. Horodek, Nucl. Instr. Meth. B, 266 (2008)

L_+: positron diffusion length

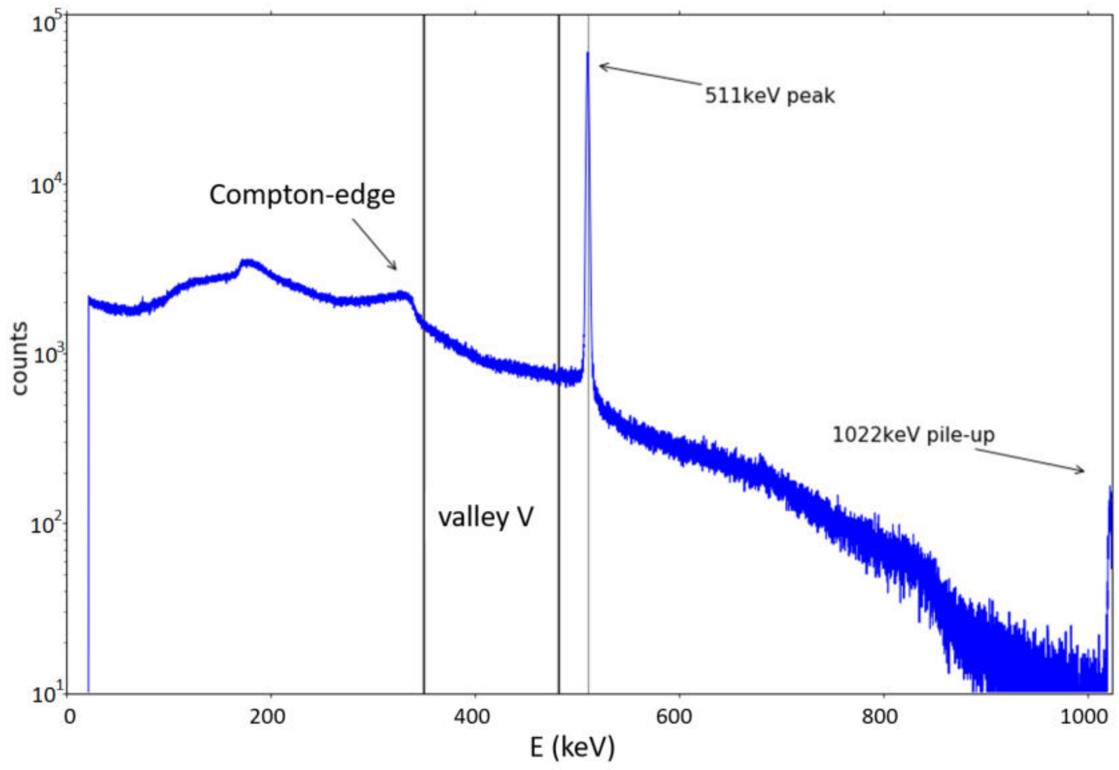
J_0: Fraction of thermal positrons escaping through the surface

f_0: Fraction of J_0 forming Ps

$$f_{Ps} = f_0 J_0 \int_0^\infty P(z) e^{-\frac{z}{L_+}} dz$$

Ps detection

High purity Ge detectors with high energy resolution (as for CDBS)



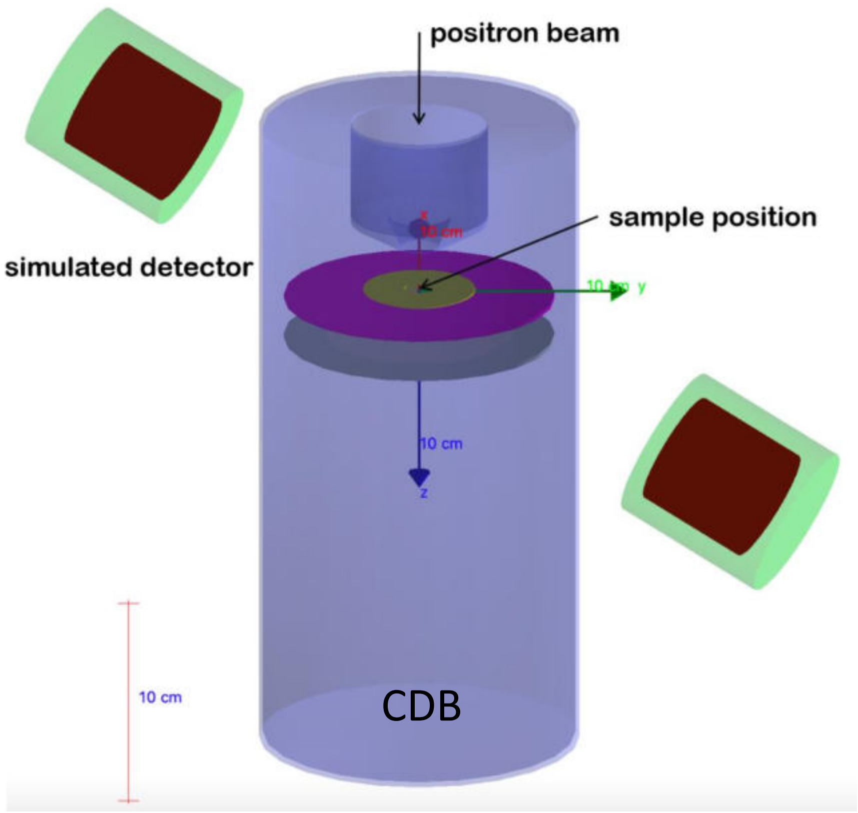
$$f_{Ps} = \left\{1 + \frac{P_1}{P_0}\frac{[R_1 - R]}{[R - R_0]}\right\}^{-1}$$

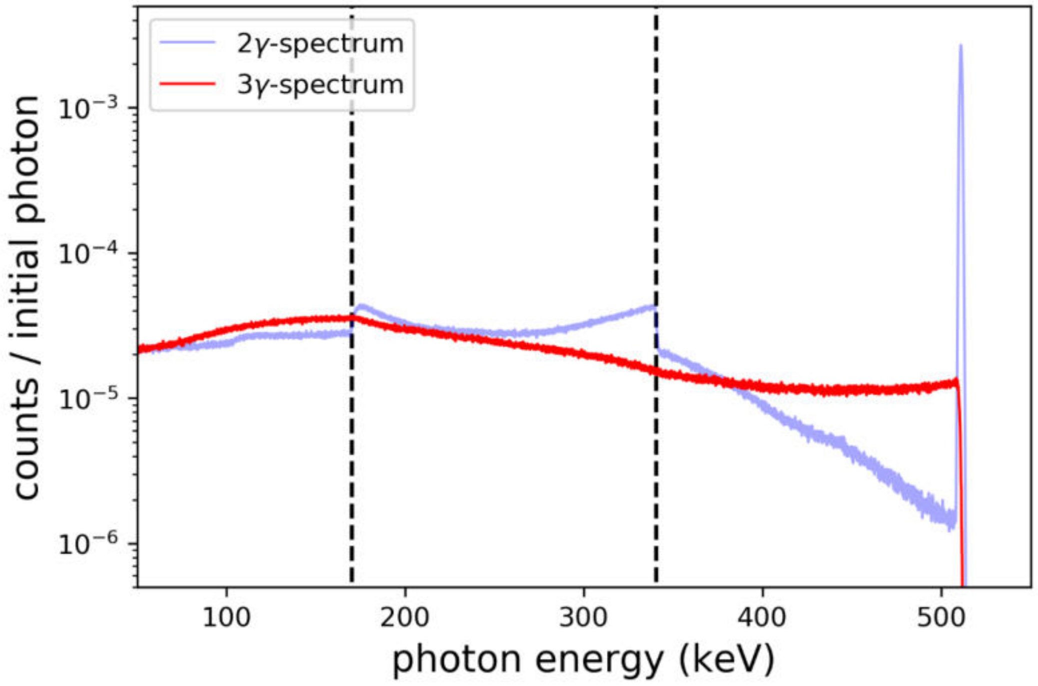
Uncertainties:

- R_1 really 100% Ps? (surface contamination, reemission)
- different 2ɣ and 3ɣ detection efficiencies
- background due to Compton scattering, pile-up, photon absorption: all subsumed in R_0 (lower limit)
- possible fluctuations in the count rate (P_1/P_0)
- Ps velocity: a fraction of Ps hits an obstacle -> 2ɣ

New method

GEANT4 simulation of one HPGe detector

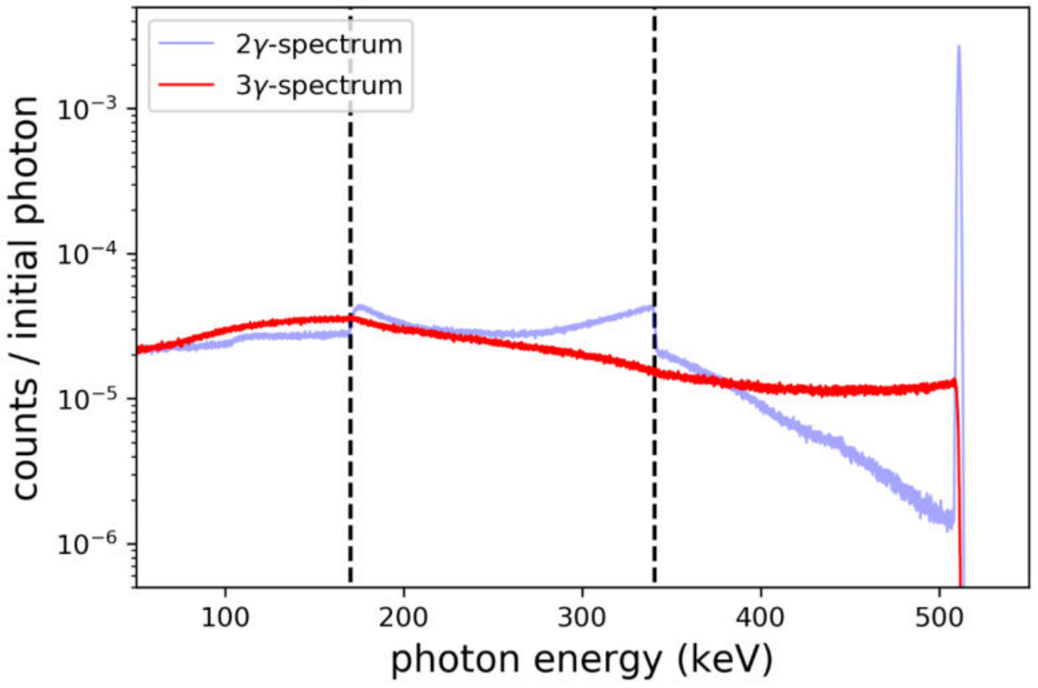




B. Rienäcker, T. Gigl, G. Nebbia, F. Pino, and C. Hugenschmidt, Phys. Rev. A 102, 062212 (2020)

New method

$$C_{meas}(E) = N_{2\gamma}C_{2\gamma} + N_{3\gamma}C_{3\gamma} + C_{BG}$$



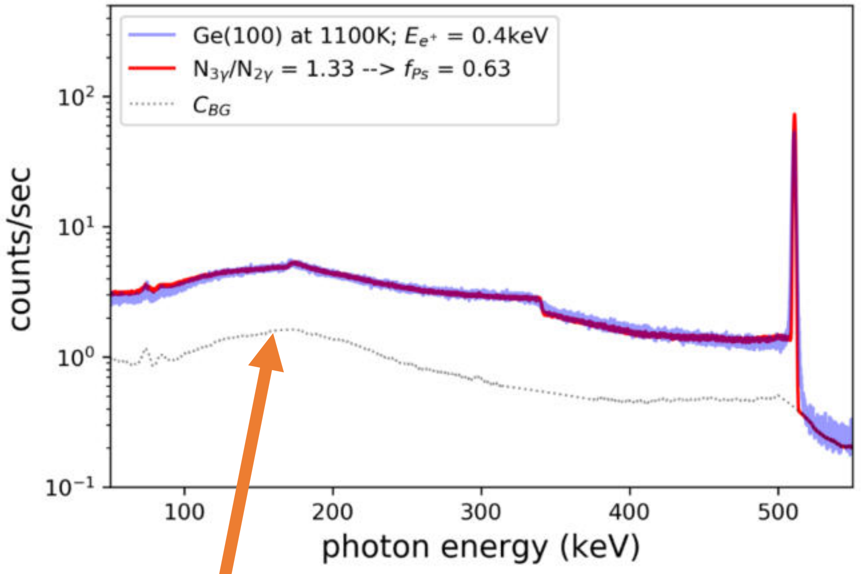
Uncertainties:

- ~~R_1 really 100% Ps? (surface contamination, reemission)~~
- ~~different 2ɣ and 3ɣ detection efficiencies~~
- background due to ~~Compton scattering~~, **pile-up**, ~~photon absorption~~: subsumed in C_{BG}
- ~~possible fluctuations in the count rate (P_1/P_0)~~
- **Ps velocity**: a fraction of Ps hits an obstacle -> 2ɣ

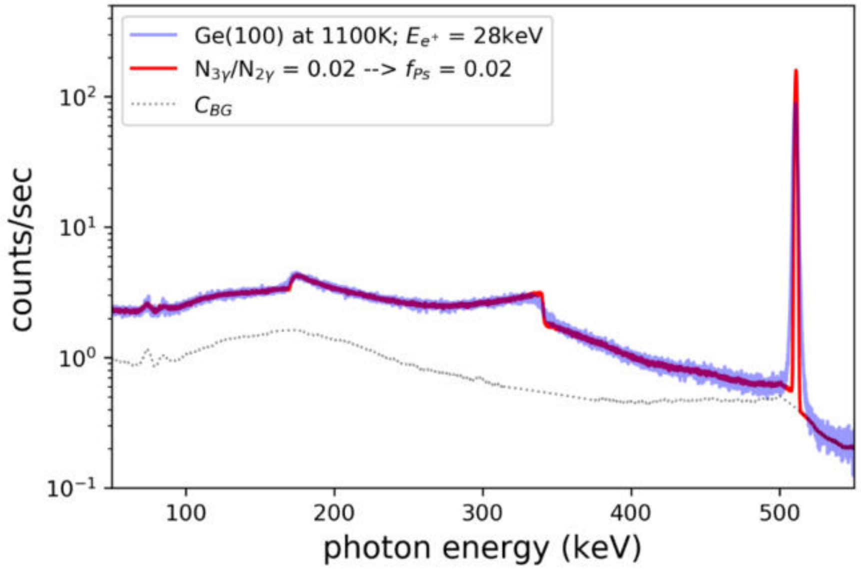
$$f_{Ps} = \frac{amount\ of\ Ps}{total\ number\ of\ e^+} = \frac{\frac{4}{3}N_{3\gamma}}{N_{3\gamma} + \frac{3}{2}N_{2\gamma}}$$

New method

"100% Ps reference"



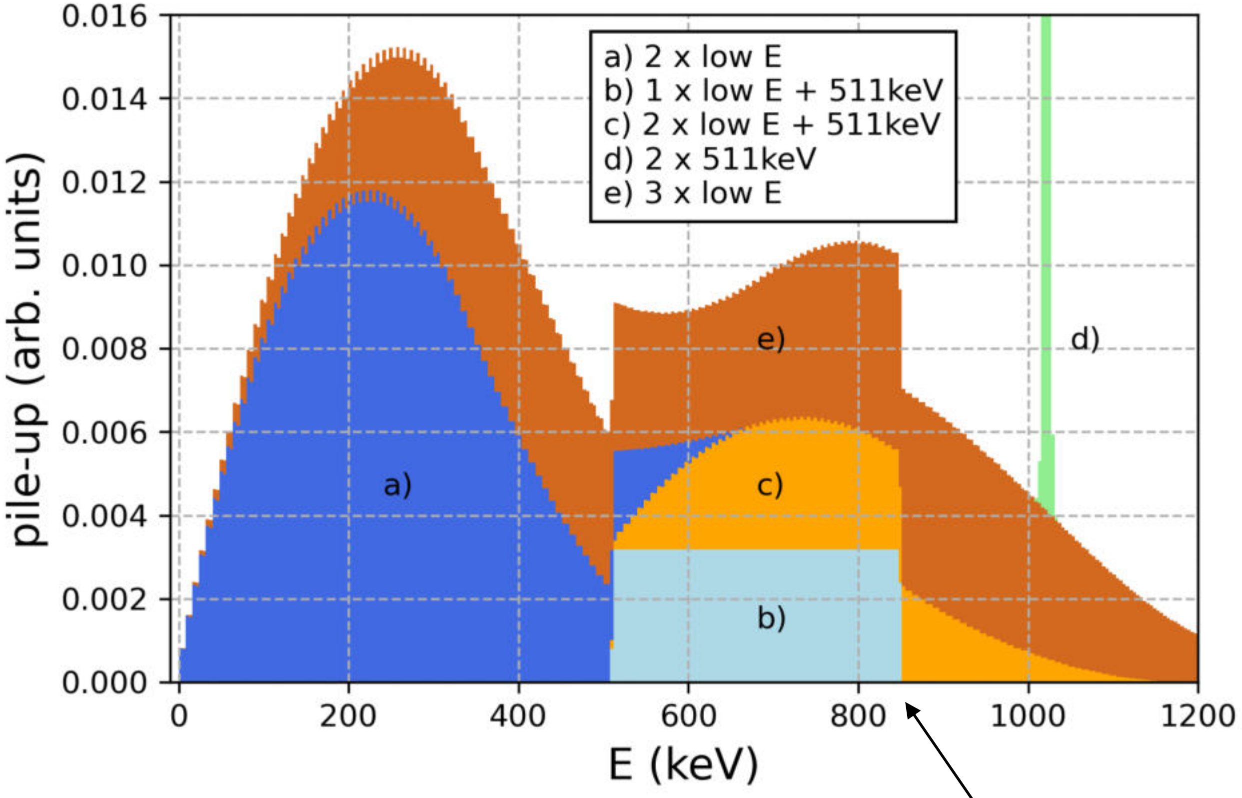
"0% Ps reference"



Mainly pile-ups

$$C_{meas}(E) = N_{2\gamma}C_{2\gamma} + N_{3\gamma}C_{3\gamma} + C_{BG}$$

Pile-ups (qualitative check)

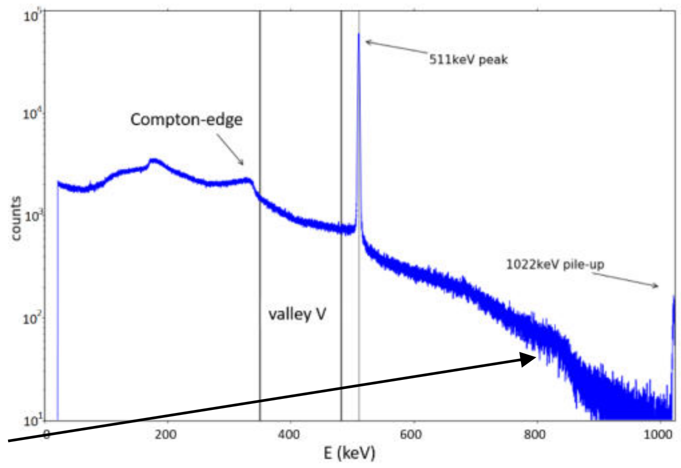


Low energy range (low E) from 0 to 500 keV

Peak range (511 keV) from 510 to 512 keV

Measured ratio:

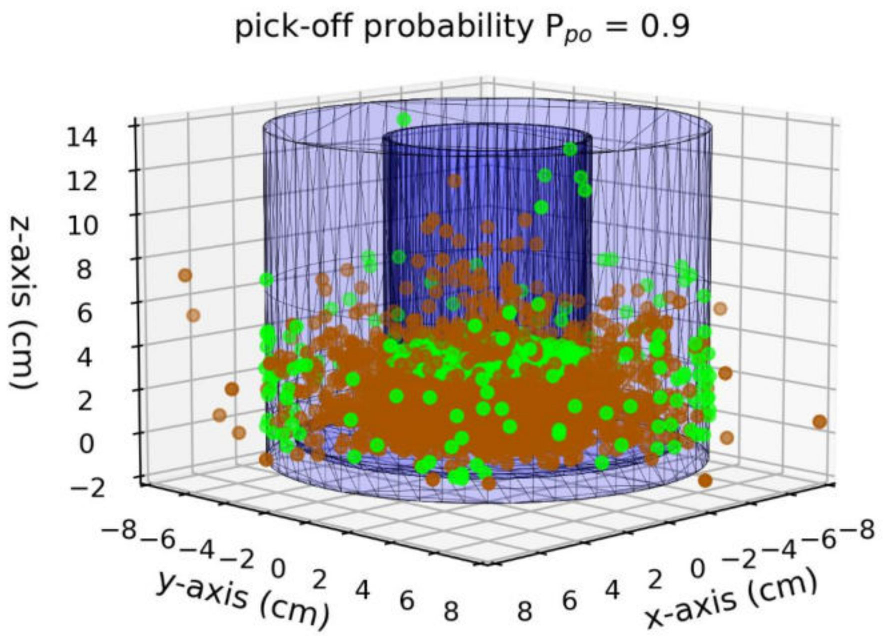
$$\frac{\text{Counts in } 0 \ldots 500 \text{ keV}}{\text{Counts in } 510 \ldots 512 \; keV} = \frac{3}{1}$$



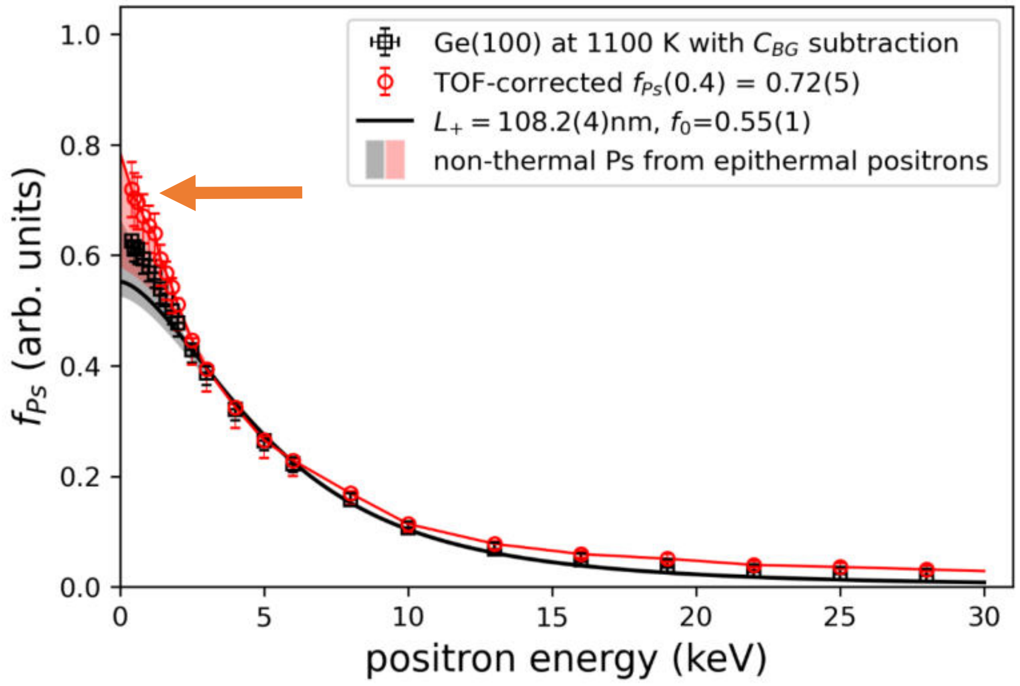
Edge at 840 keV

Influence of the Ps velocity

Dealing with the Ps velocity: Monte Carlo



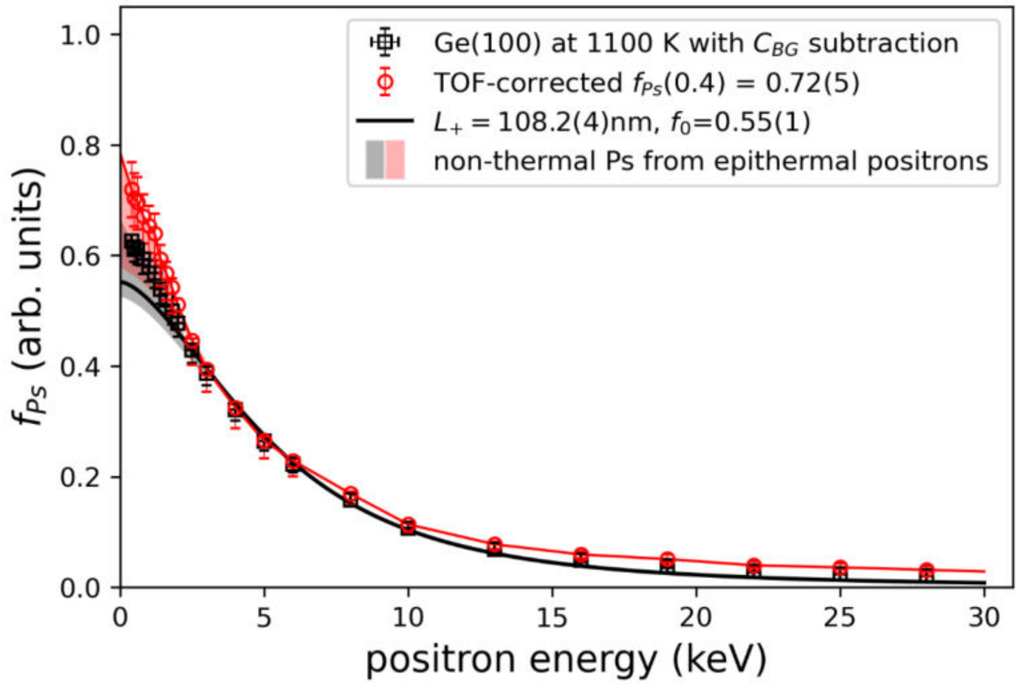
10.000 o-Ps atoms in real detector geometry



95% of thermal Ps and **46%** of non-thermal Ps annihilate in flight, the rest touches a wall

Summary

- Many interesting experiments use Ps
- HPGe detectors are commonly used to detect Ps annihilation radiation
- Absolute fraction of emitted Ps strongly depends on systematic uncertainties and calibration
- new, direct method based on simulation has only few systematic error sources left (that can be tackled)
- The Ge(100) calibration target at 1100 K as used here had an efficiency for Ps production of less than 0.80(5) at 0 keV positron implantation energy



Questions?

Thank you!