The decay rate of o-Ps with the J-PET detector

K. Dulski, S. Sharma

on behalf of the J-PET collaboration

November 2nd, 2022

The Hitchhiker's Advanced Guide to Quantum Collapse Models and their impact in science, philosophy, technology and biology

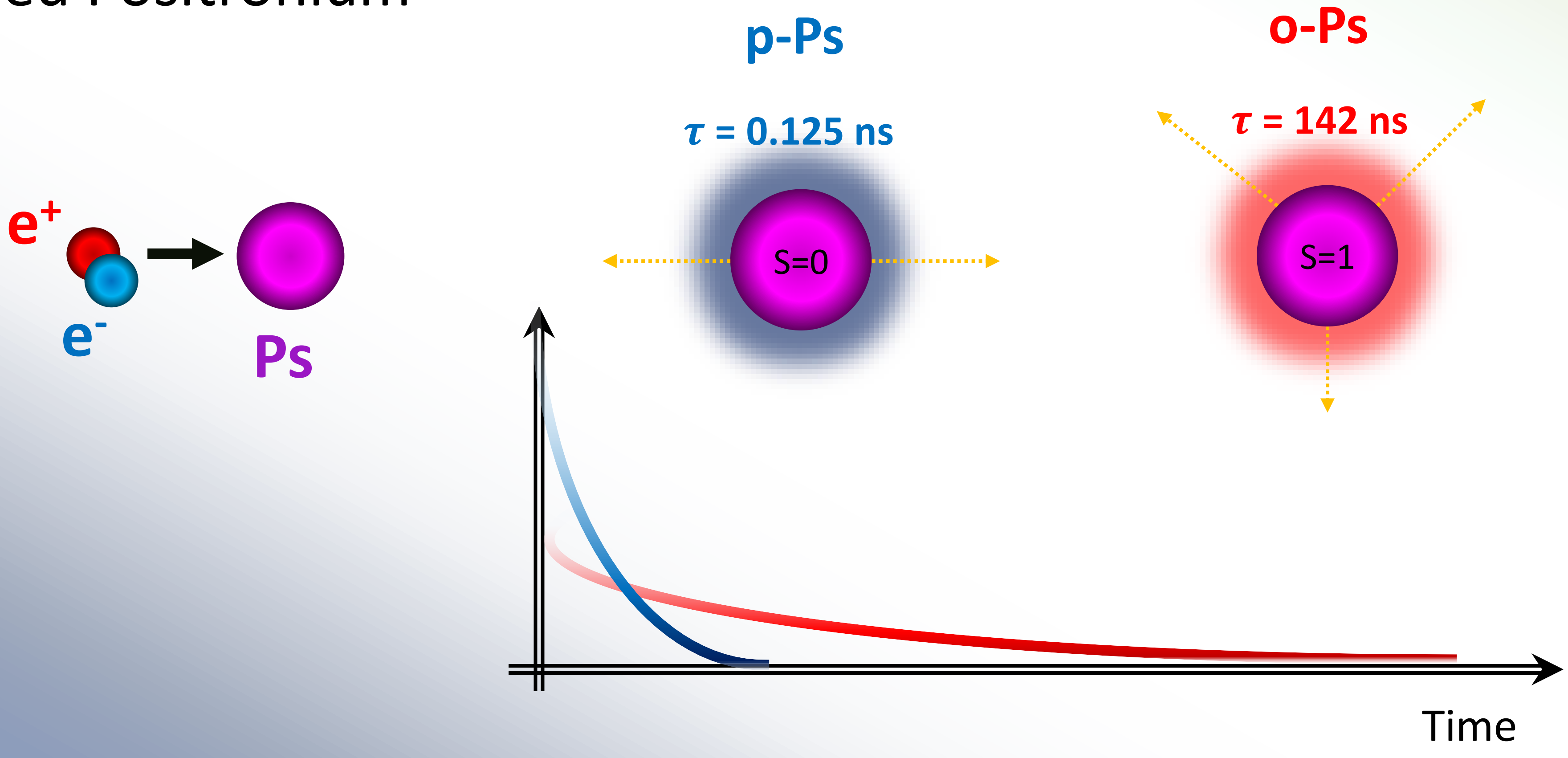
J-PET

Outline

- Positronium
- Previous experiments
- Experimental details
- Analysis procedure
- Final result and comparison
- Conclusions

Positronium

Positron (e^+) and electron (e^-) can form a quasi-stable bound state called Positronium



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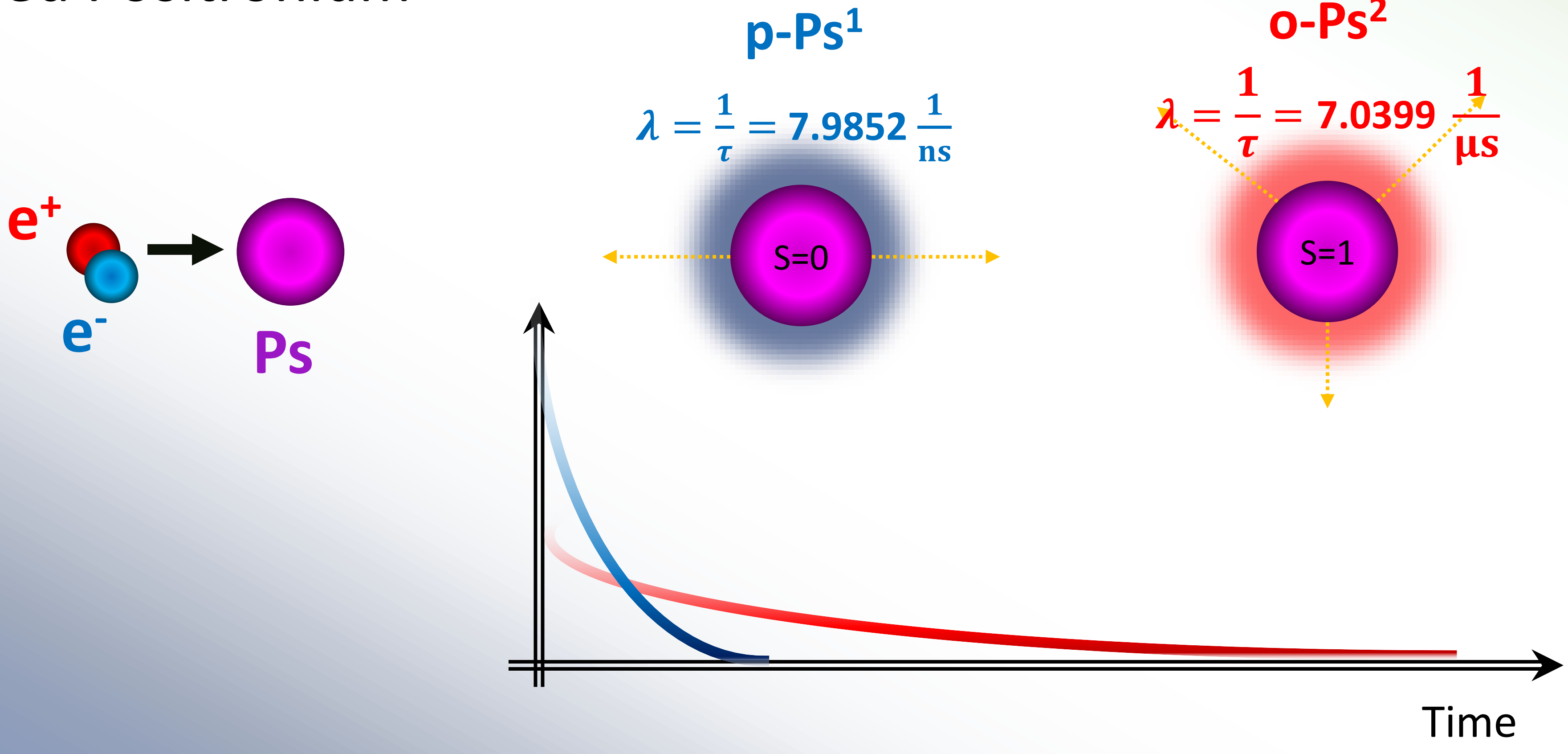
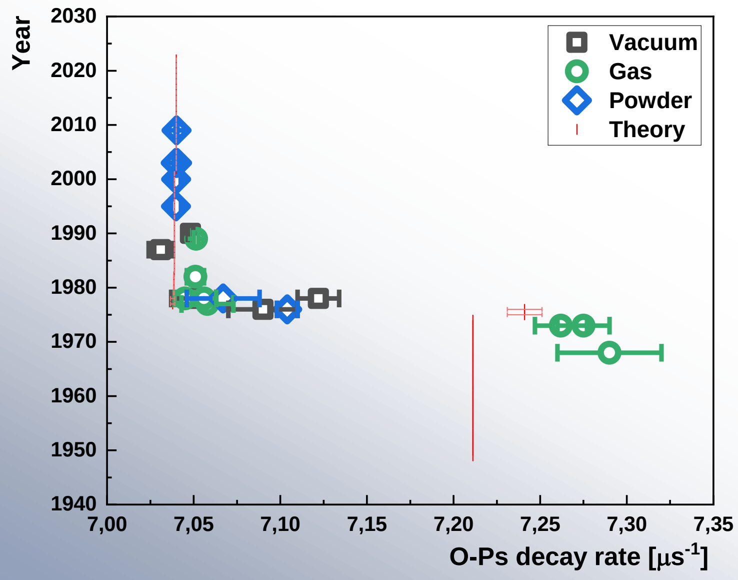
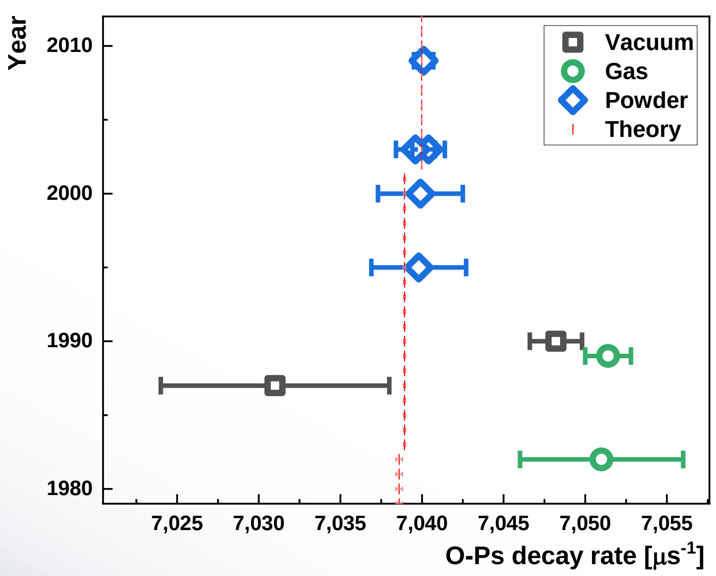


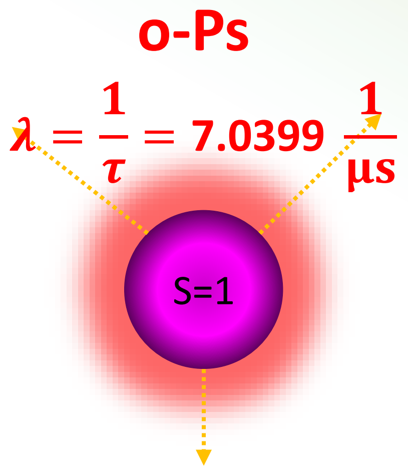
[1]Adkins, Ann. Phys. 1983 | [2]Adkins, Fell, Sapirstein Ann. Phys. 2002

Ortho-Positronium

Ortho-positronium decay rate was determined experimentally in various media







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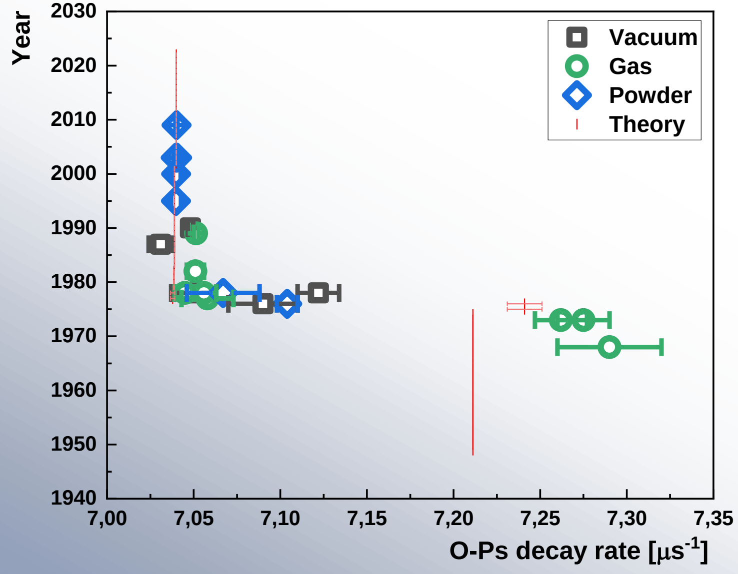
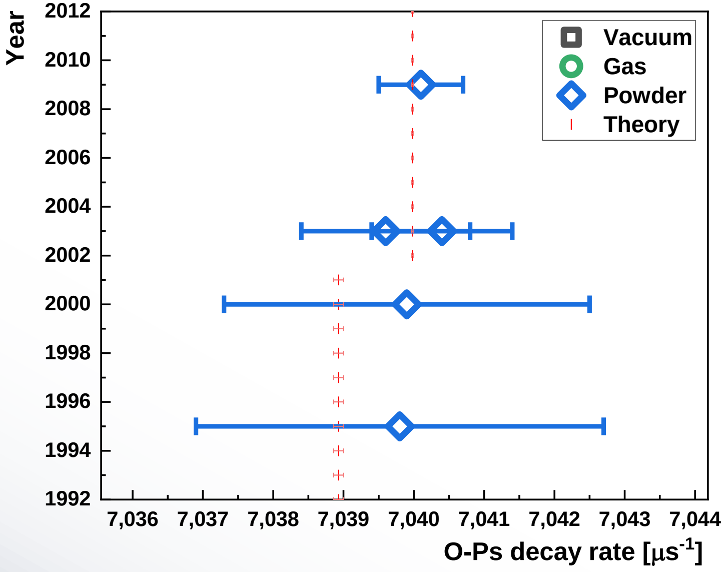
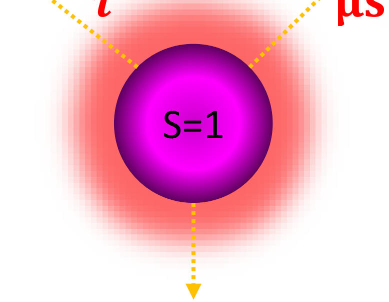


Theoretical prediction[2]
7.039979(11) μs^{-1}



o-Ps

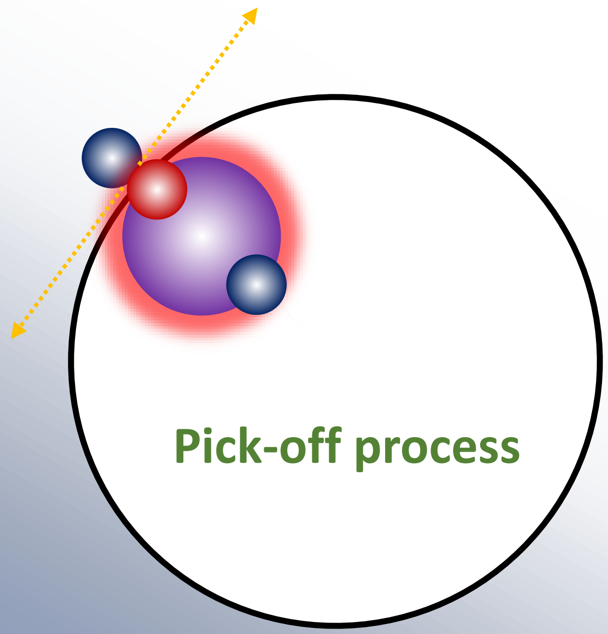
$$\lambda = \frac{1}{\tau} = 7.0399\ \frac{1}{\mu s}$$

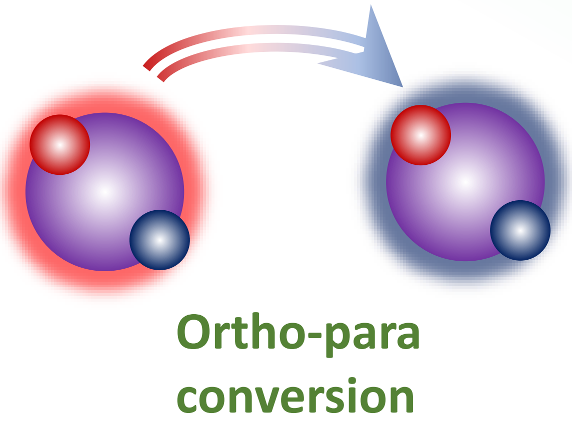


[2]Adkins, Fell, Sapirstein Ann. Phys. 2002

Ortho-positronium lifetime in matter

Interaction with matter can lead to the reduction of the o-Ps mean lifetime

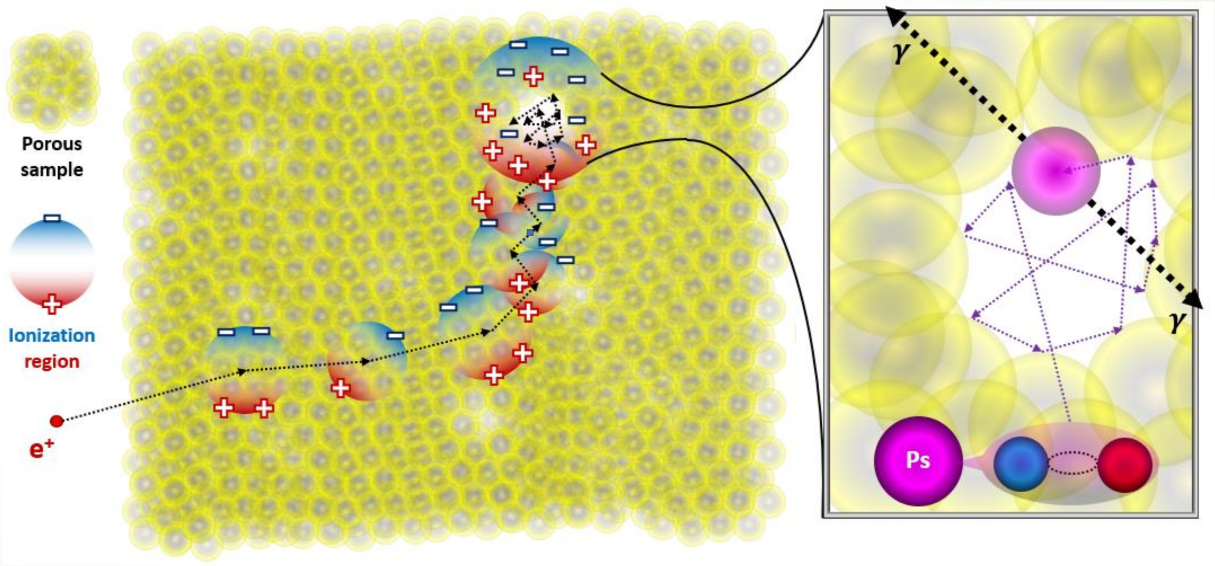




Ortho-positronium decay rate determination in matter

However, the decay rate of o-Ps can be determined also in the matter after applying some corrections

$$\lambda_{exp} = \lambda_{o-Ps} + \lambda_{pick-off}$$



Ortho-positronium decay rate determination in matter

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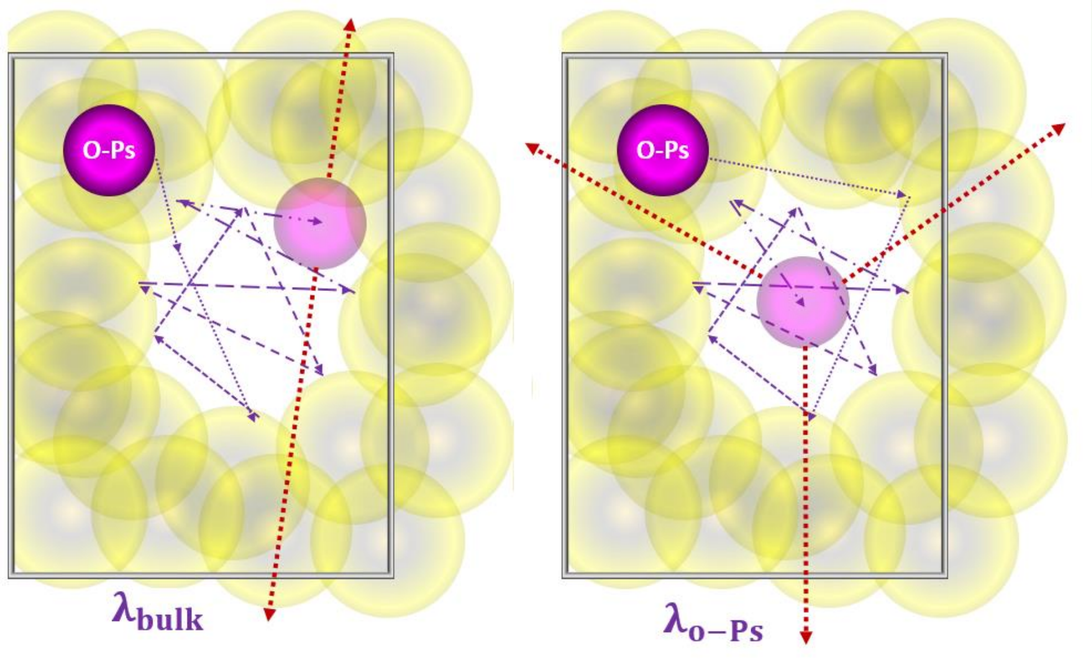
$$\lambda_{exp} = \lambda_{o-Ps} + \lambda_{pick-off}$$

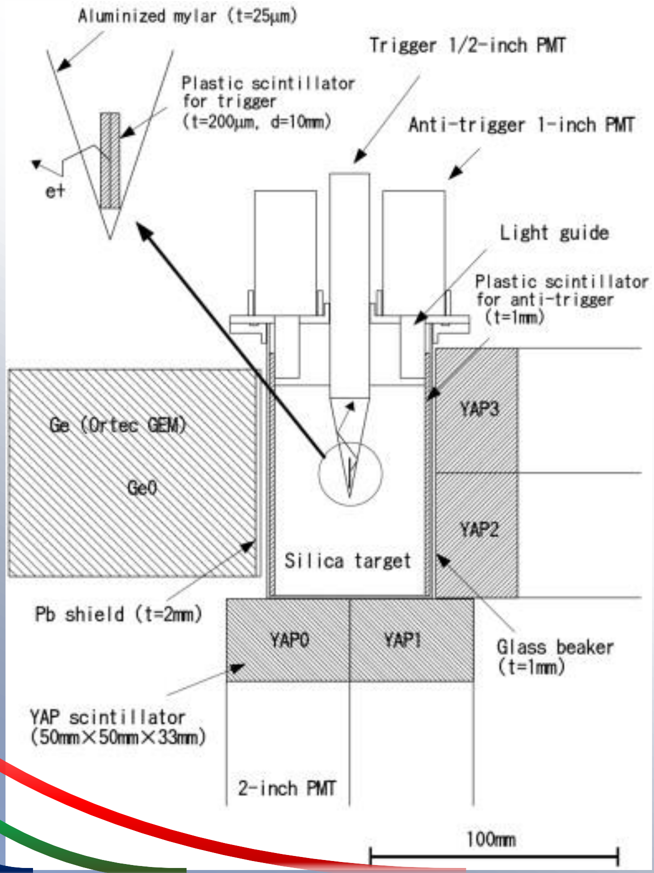
Inelastic collisions of o-Ps

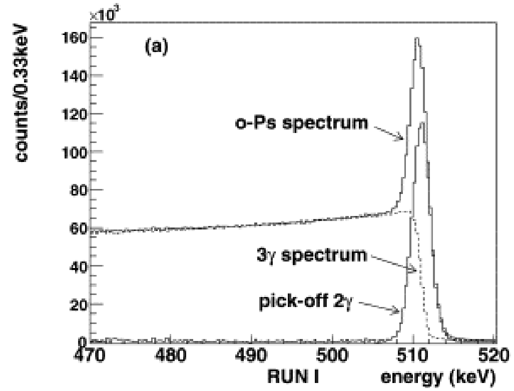
$$\lambda_{exp}(t) = \lambda_{o-Ps} + \lambda_{pick-off}(t)$$

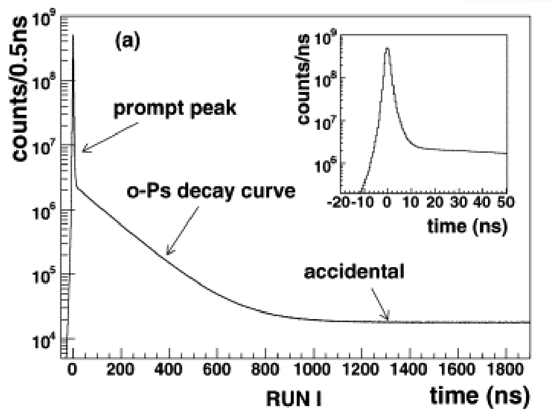


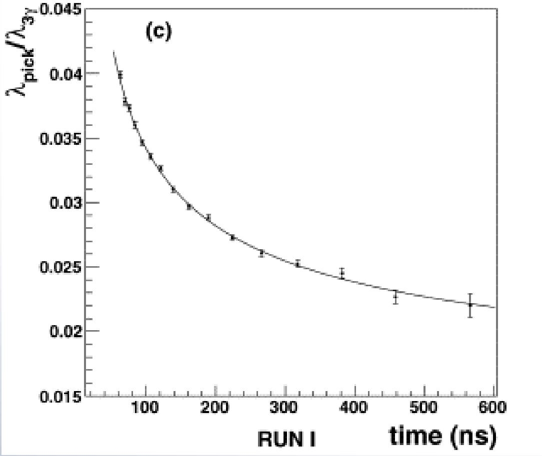
Previous experiment

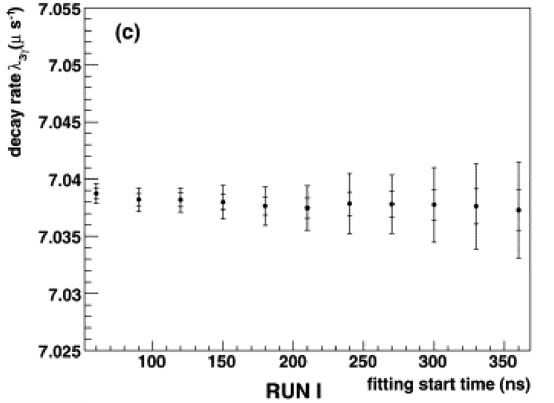
In the most recent experimental result[3] following procedure was applied











[3]Y .Kataoka, S. Asai, T. Kobayashi, Phys. Lett. B 671 (2009)

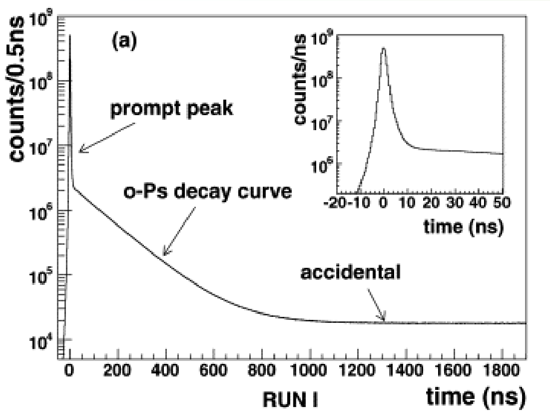
Previous experiment

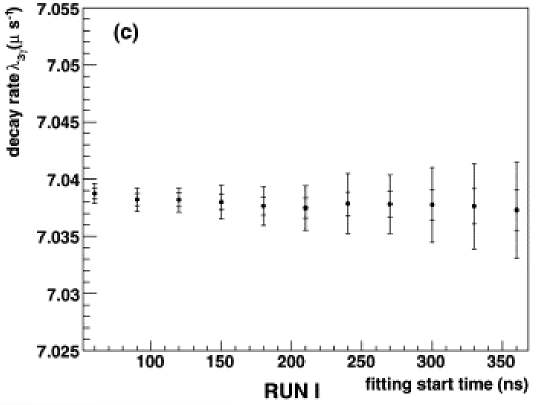
In the most recent experimental result[3] following procedure was applied

$$N_{\text{obs}}(t) = \exp(-R_{\text{stop}}t)\left[\left(1+\frac{\epsilon_{\text{pick}}}{\epsilon_{3\gamma}}\frac{\lambda_{\text{pick}}(t)}{\lambda_{3\gamma}}\right)N(t)+C\right]$$

an experimental random counting rate representing the fact that time interval measurement always accept the first γ as a stop signal

The relative value of the detection efficiency is estimated with the monochromatic γ-rays emitted from ^{152}Eu, ^{85}Sr, and ^{137}Cs.





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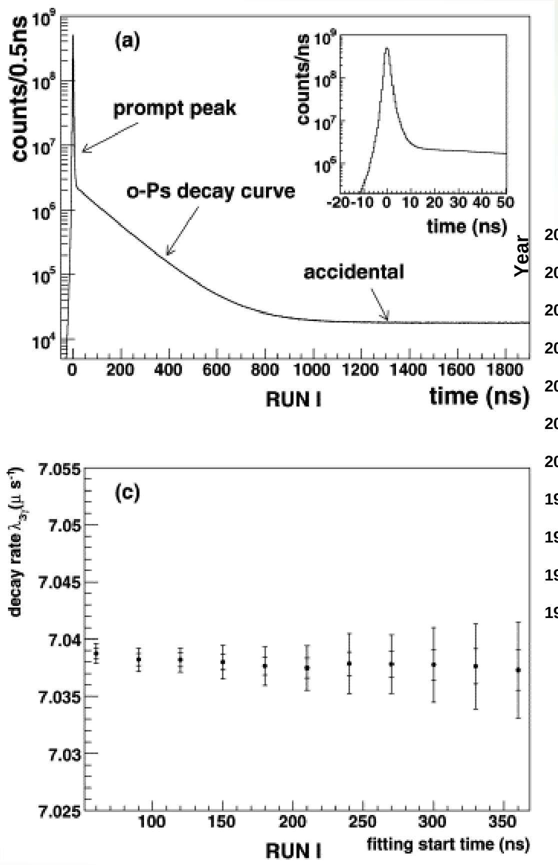
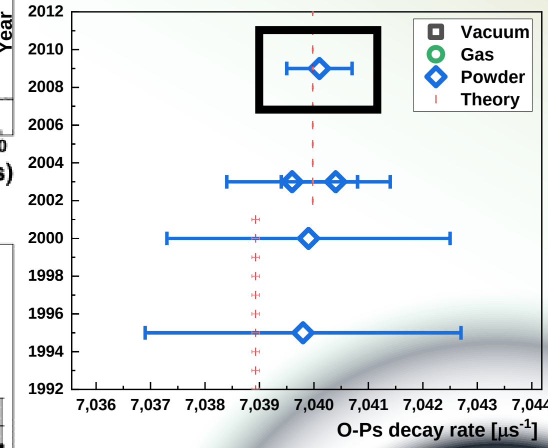


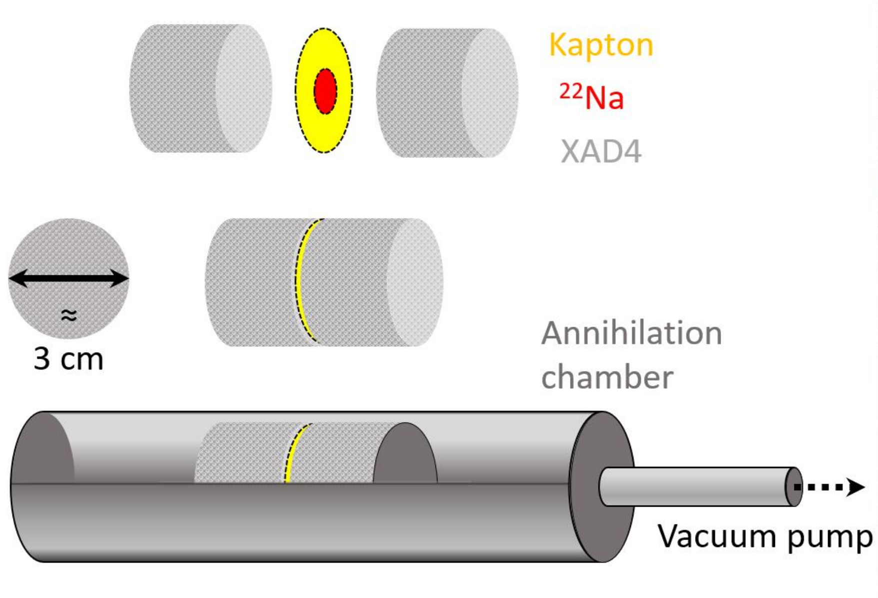
Combined result from Run I + Run II

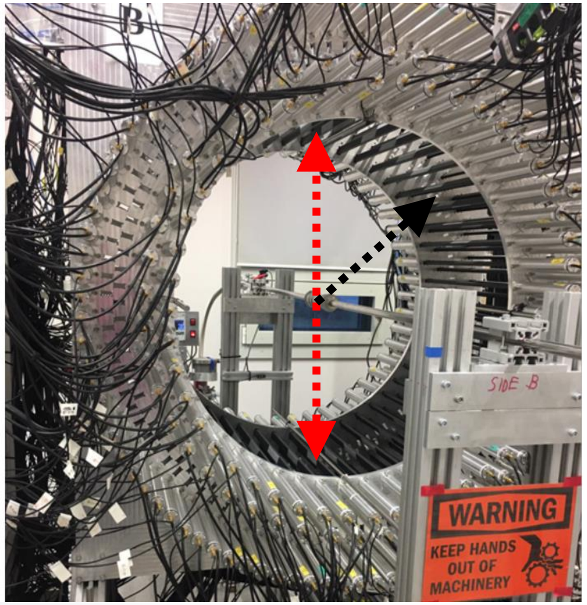


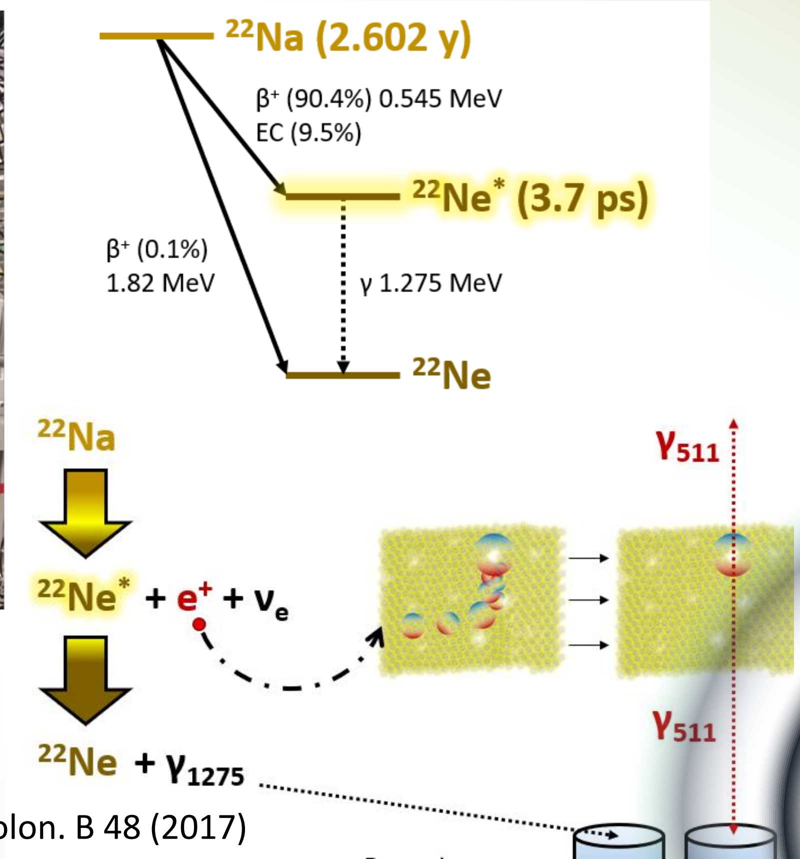
[3]Y .Kataoka, S. Asai, T. Kobayashi, Phys. Lett. B 671 (2009)

Jagiellonian-PET

The experimental setup for the measurement of the decay rate with the J-PET detector was as following[4,5]:



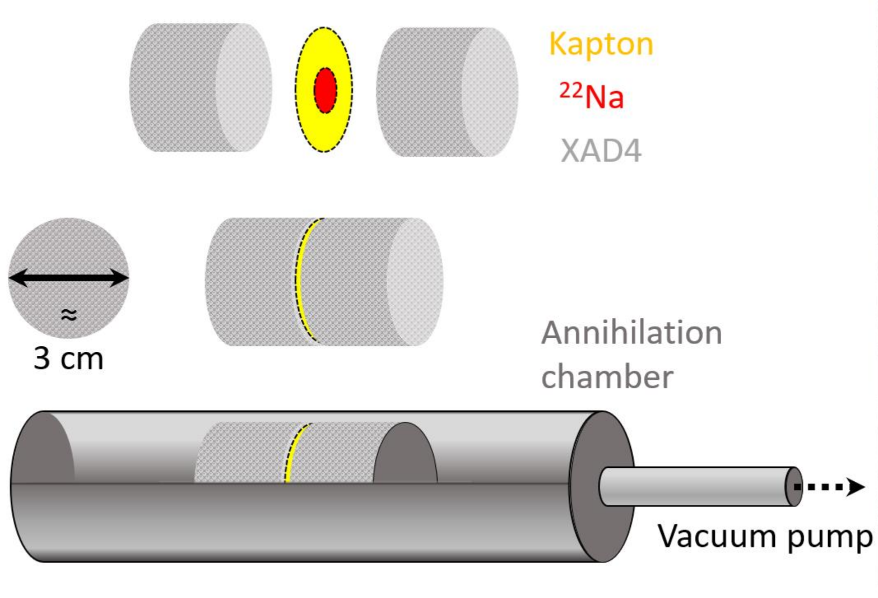


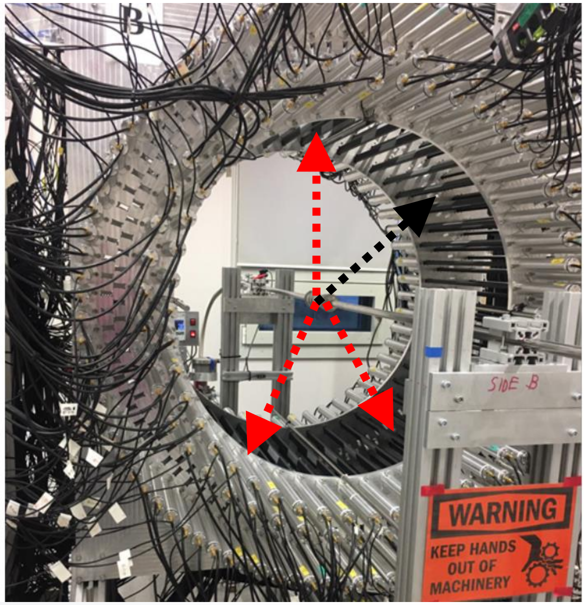


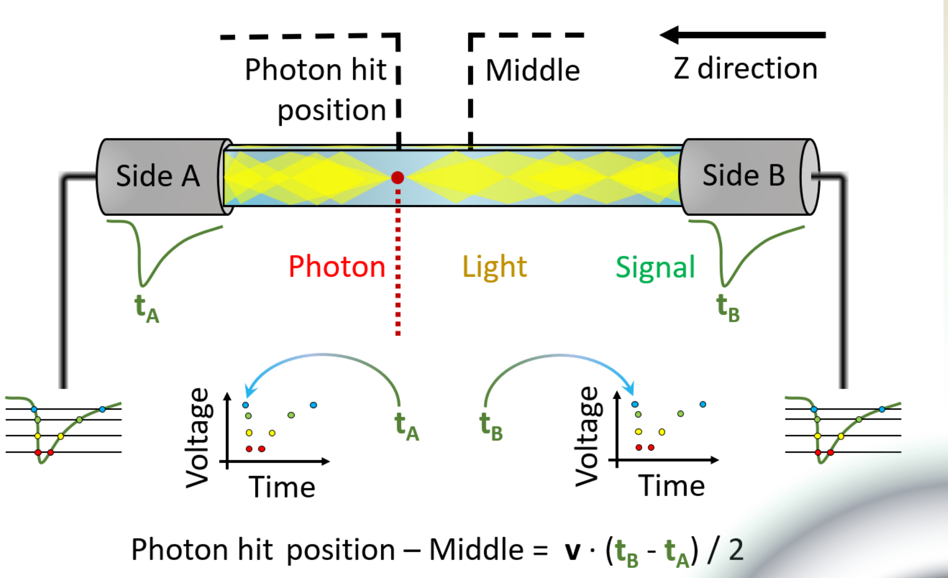
[4]K. Dulski, PhD thesis | [5]S. Niedźwiecki et al., Acta Phys. Polon. B 48 (2017)

J-PET detector

The J-PET detector consists of 192-strip plastic scintillators (EJ-230) connected on both sides with vacuum photomultipliers[4,5]







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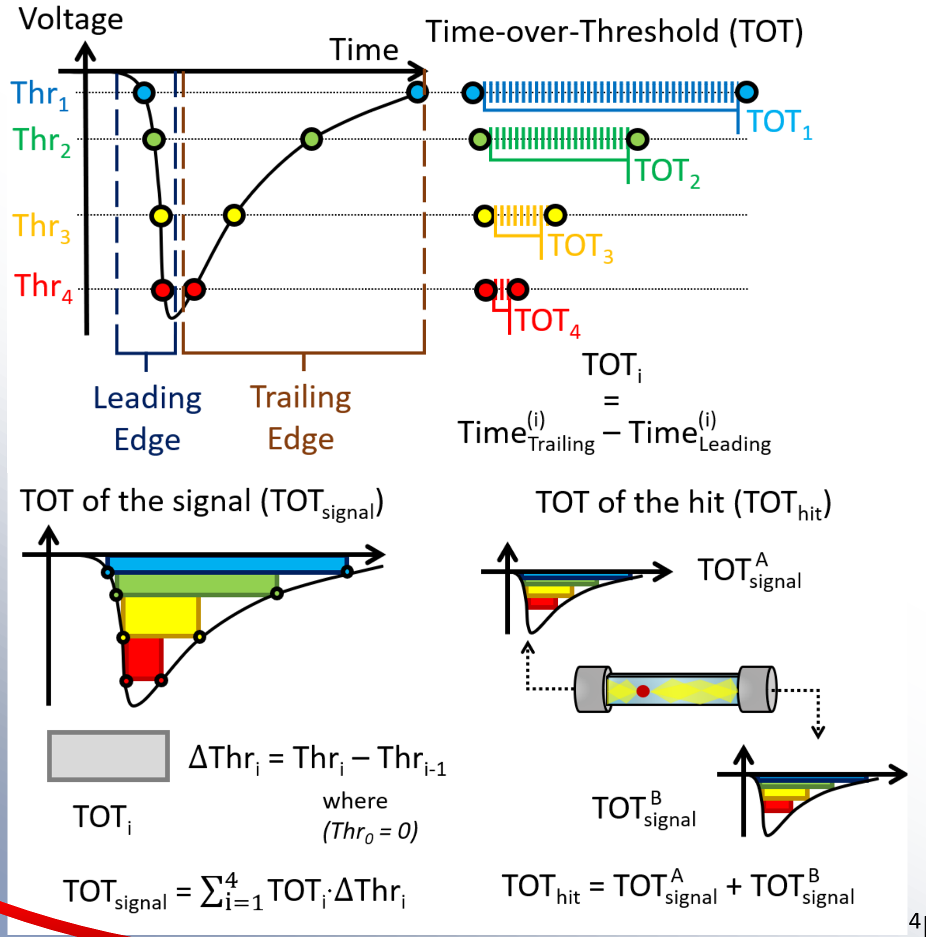
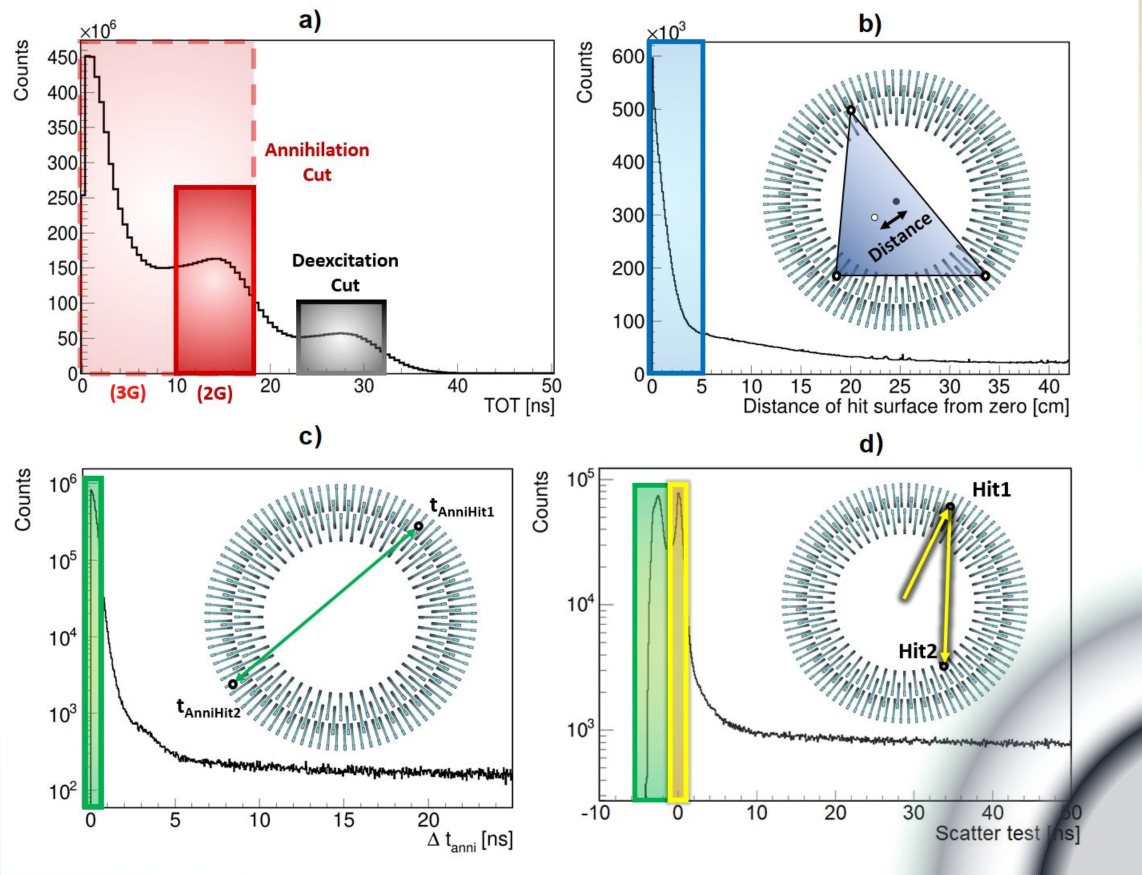
Analysis procedure – selection

Following analysis procedure was applied to select events to analysis[4,6]

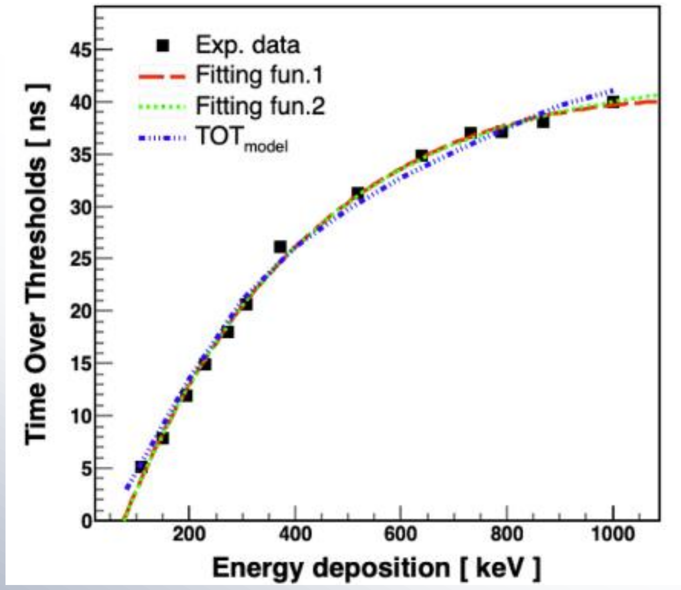


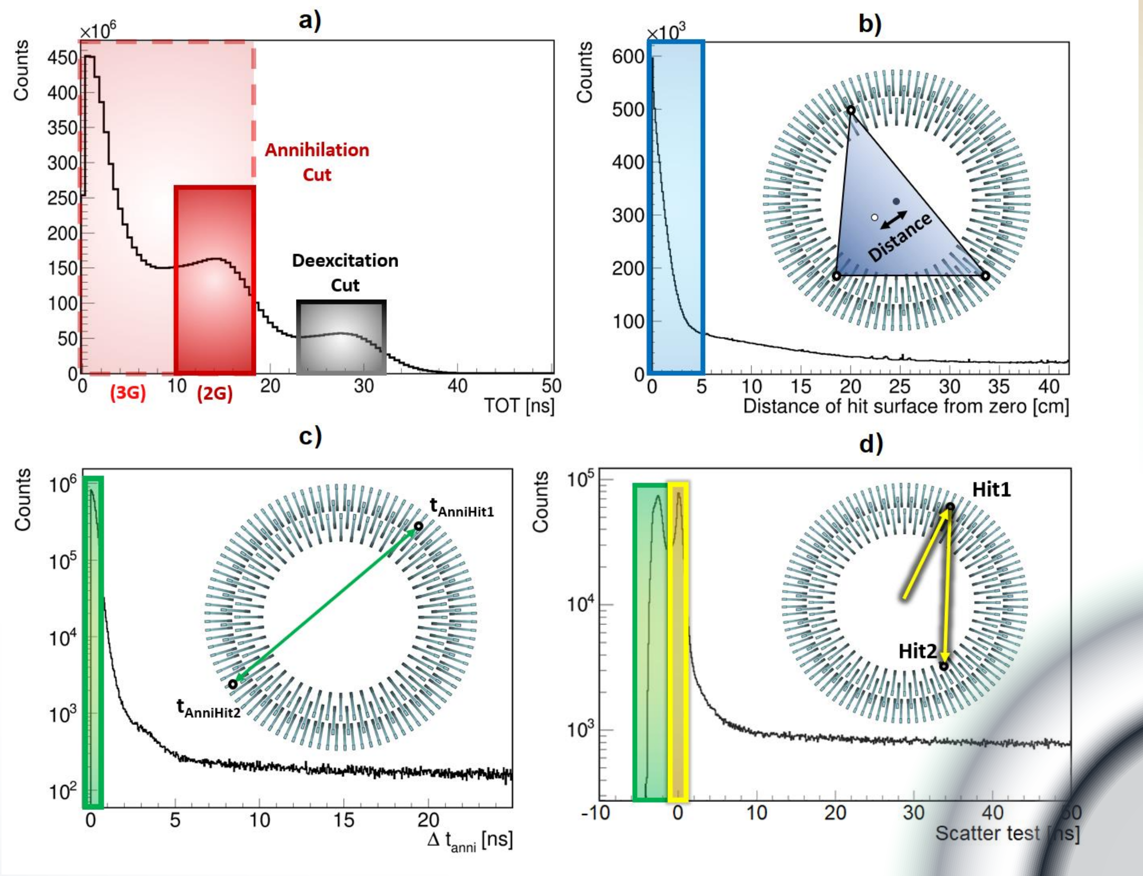


[4]K. Dulski, PhD thesis | [6]K. Dulski et al., NIM A 1008 (2021)

Analysis procedure – selection

TOT was checked as a valid measure of the energy deposition[7]





[7]S. Sharma et al., EJNMMI Phys. 7 (2020)

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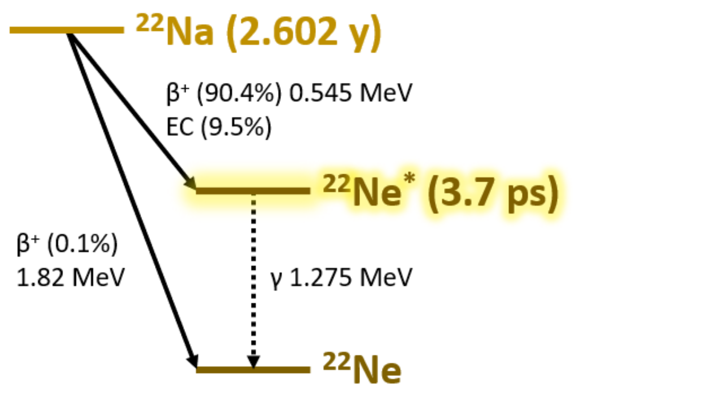

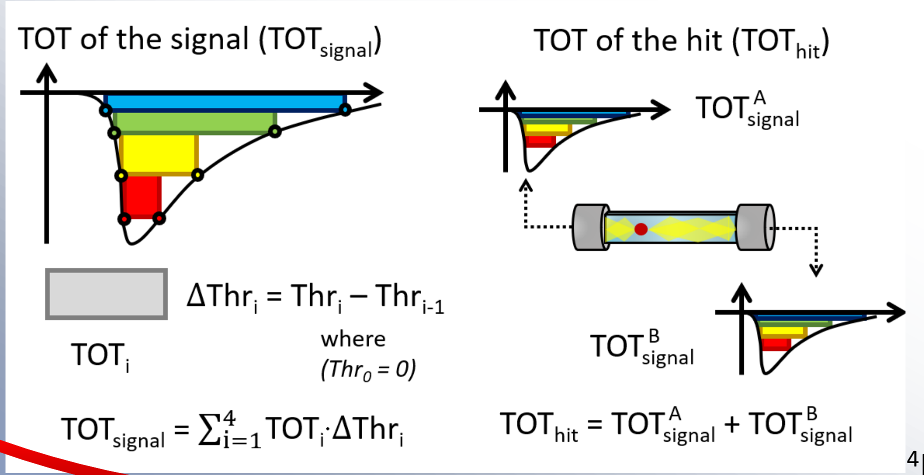

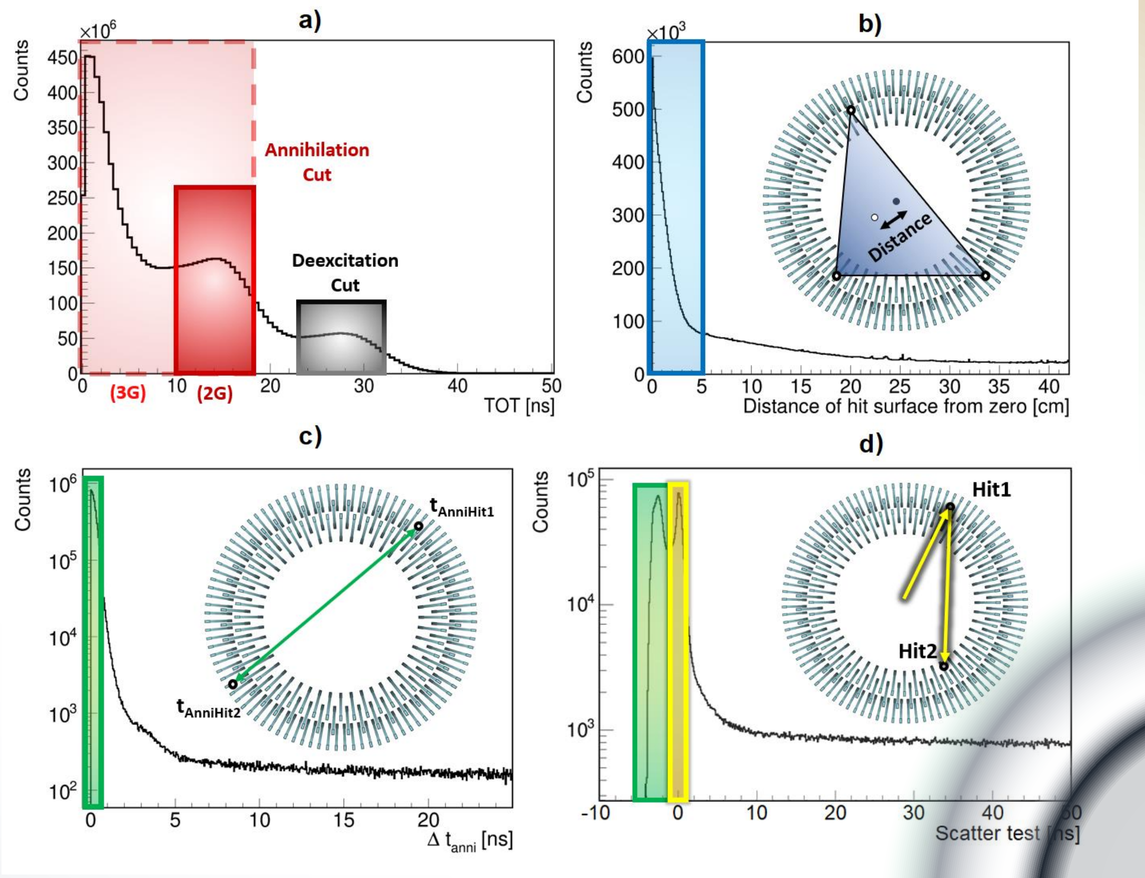

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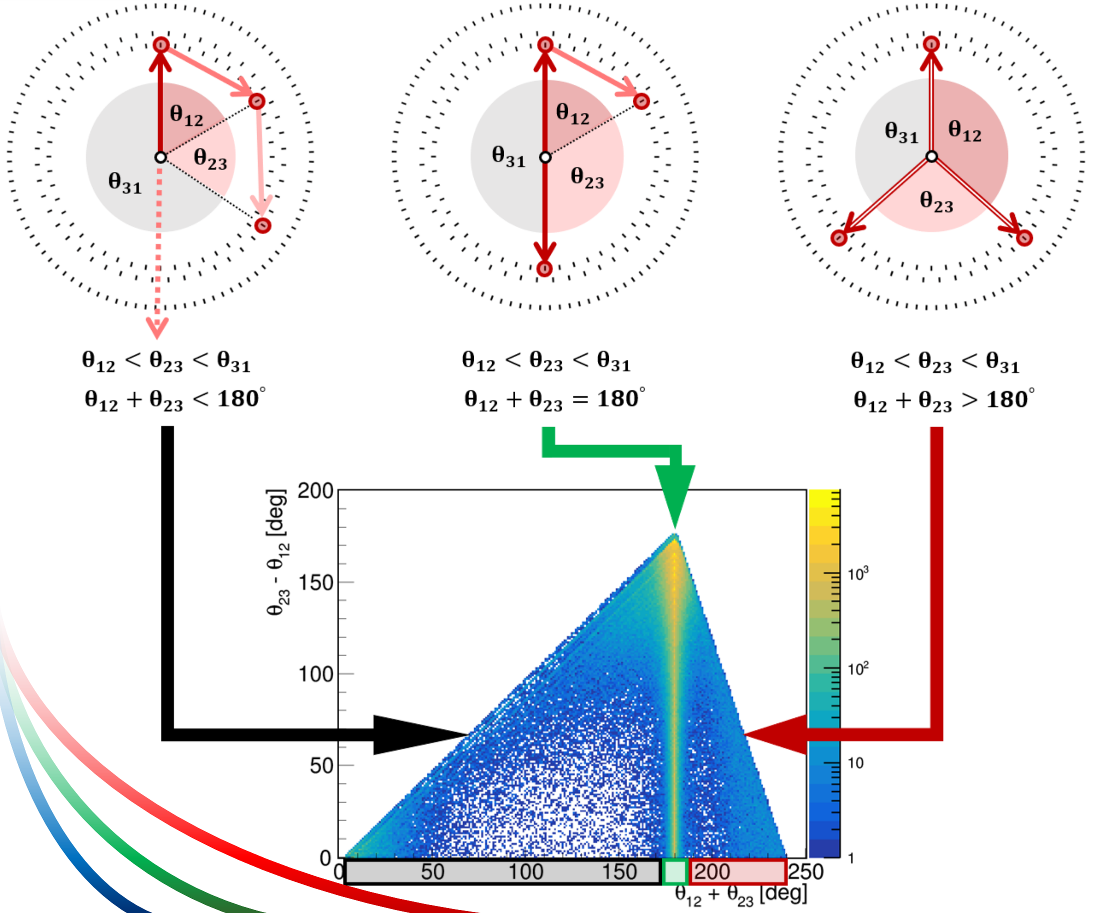

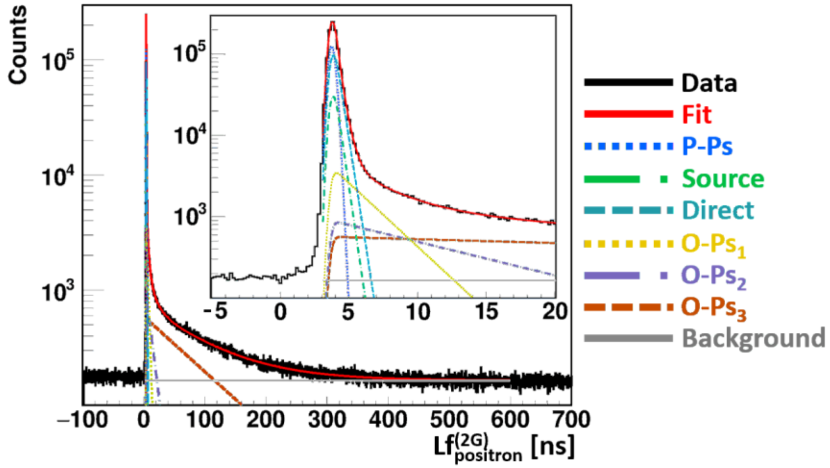

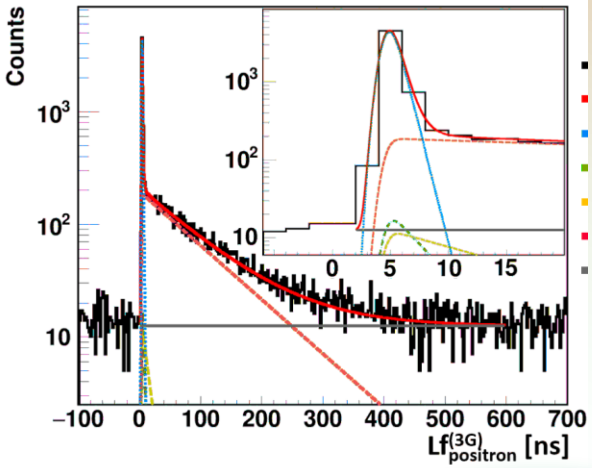

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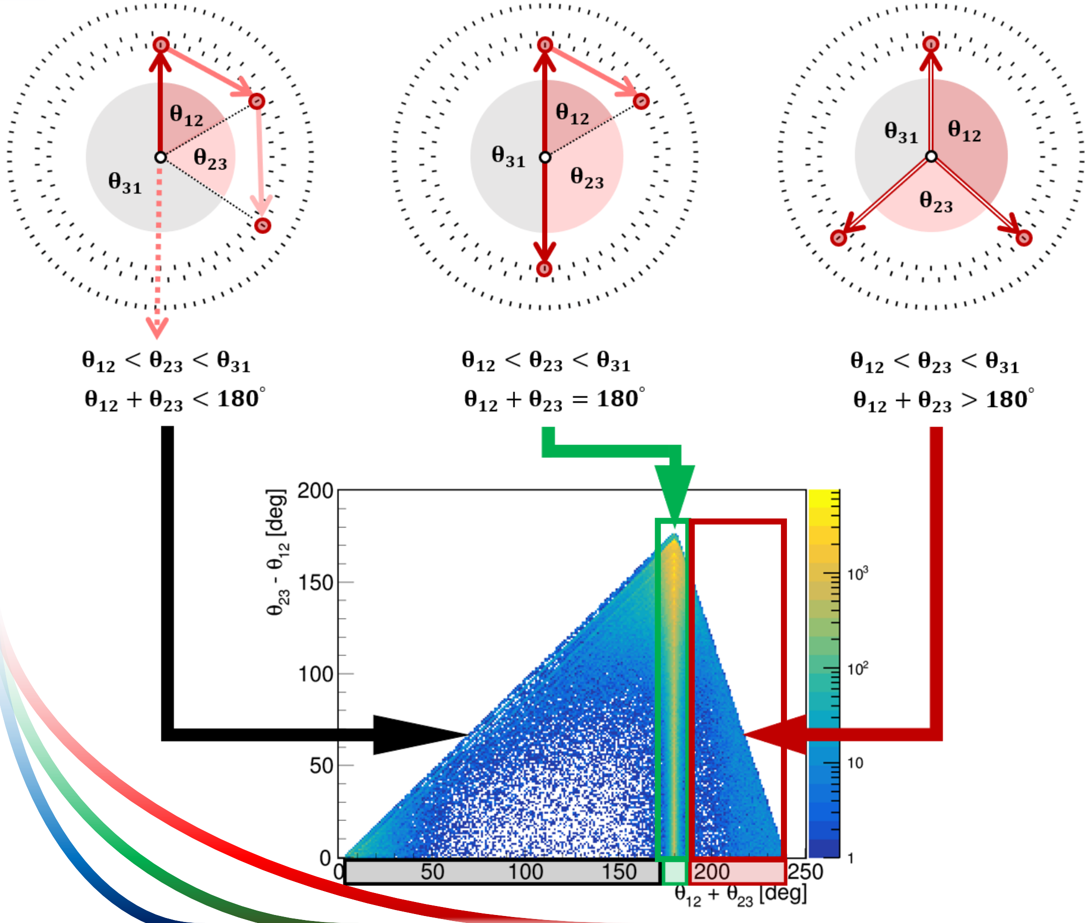
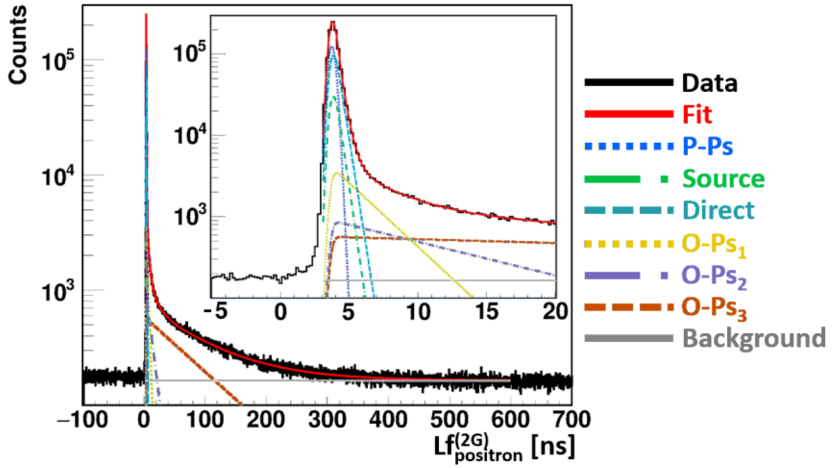
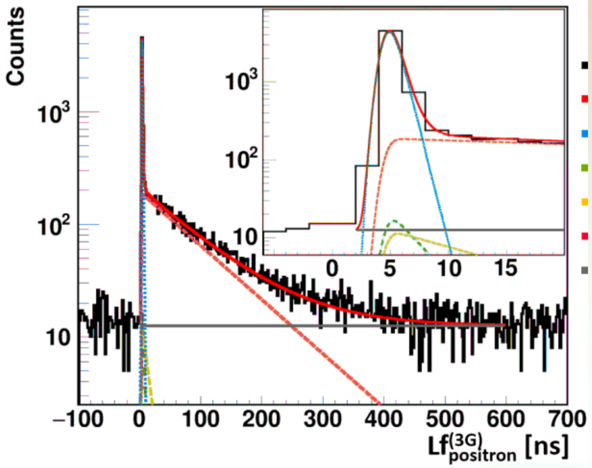




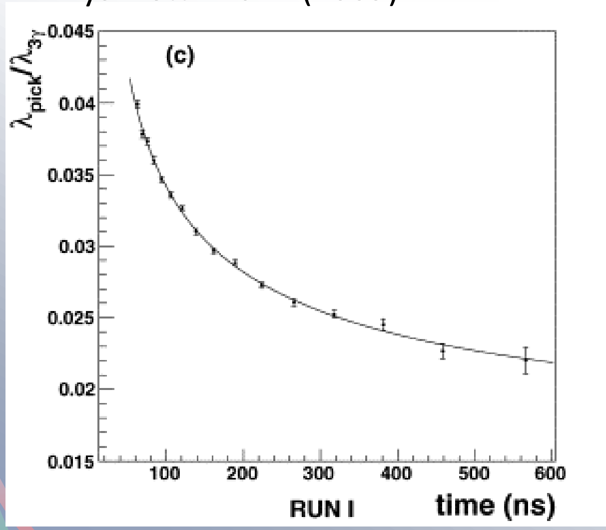


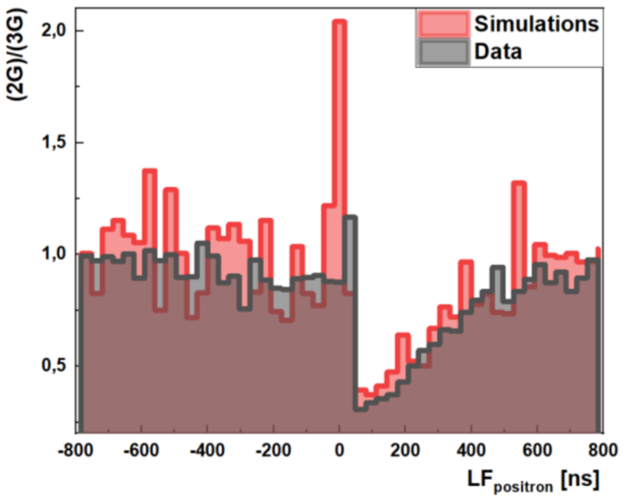
[4]K. Dulski, PhD thesis | [6]K. Dulski et al., NIM A 1008 (2021)

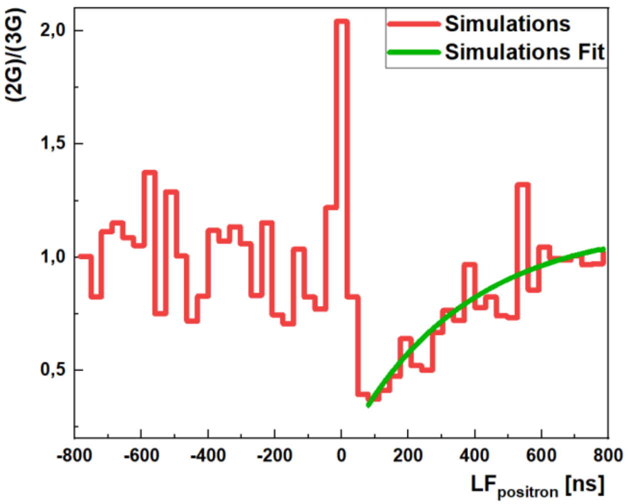
Analysis procedure – fitting

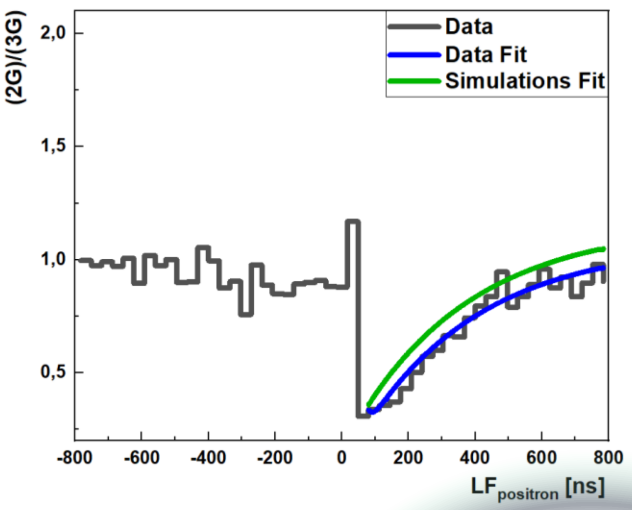
Simulations were conducted to estimate the pick-off dependence over time[4]

[3]Y .Kataoka, S. Asai, T. Kobayashi, Phys. Lett. B 671 (2009)

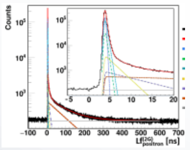


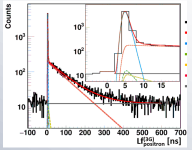






$$\frac{(\mathbf{2G})}{(\mathbf{3G})} =$$





Model:
exponential decay

[4]K. Dulski, PhD thesis

Analysis procedure – fitting

Run4 - 30 days measurement

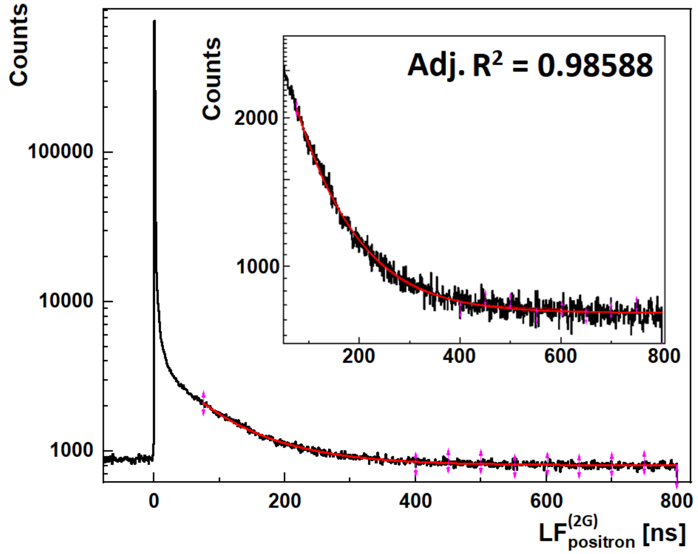
Next, the (2G) spectrum was fitted with the following model[4]

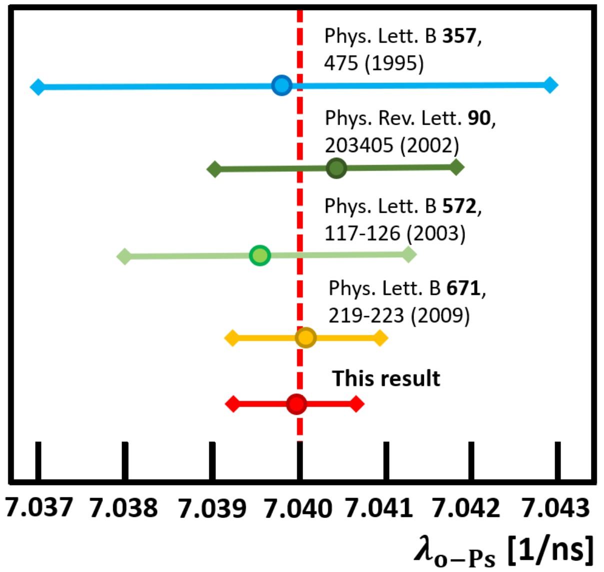
$$\lambda_{\text{o-Ps}}^{\text{matter}} \overset{\text{Eq. 5.9}}{=} \lambda_{\text{o-Ps}} + \lambda_{\text{pick-off}}^{0}$$

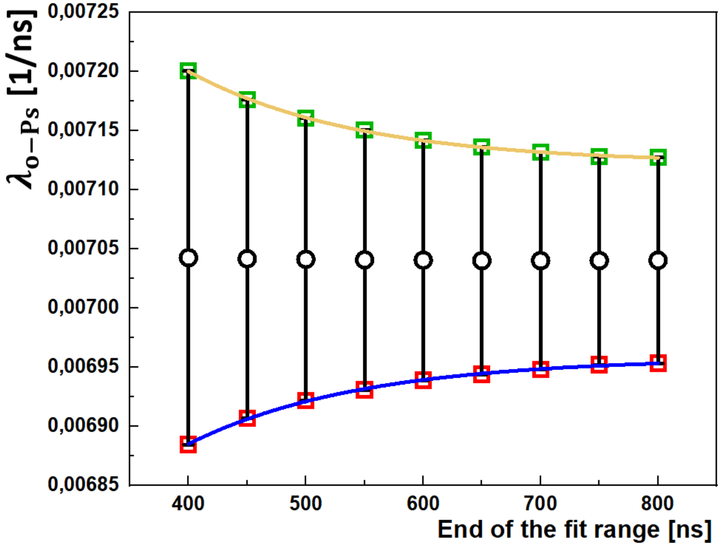
$$\lambda_{\text{pick-off}}(\mathrm{t}) = \lambda_{\text{pick-off}}^{\mathrm{v}}(\mathrm{t}) + \lambda_{\text{pick-off}}^{0} = \lambda_{\text{o-Ps}}\left(\mathrm{F}_{\frac{(2\mathrm{G})}{(3\mathrm{G})}}(\mathrm{t}) + \mathrm{C_b}\right)$$

$$f\left(\mathrm{LF_{positron}}\right) = f(0)\cdot\exp\left(-\lambda_{\text{o-Ps}}\left(1+\frac{\lambda_{\text{pick-off}}\left(\mathrm{LF_{positron}}\right)}{\lambda_{\text{o-Ps}}}\right)\cdot\mathrm{LF_{positron}}\right)$$

$$= f(0)\cdot\exp\left(-\lambda_{\text{o-Ps}}\left(1+\mathrm{C_b}+\mathrm{F}_{\frac{(2\mathrm{G})}{(3\mathrm{G})}}\left(\mathrm{LF_{positron}}\right)\right)\cdot\mathrm{LF_{positron}}\right).$$







0.00712114 (94) 1/ns

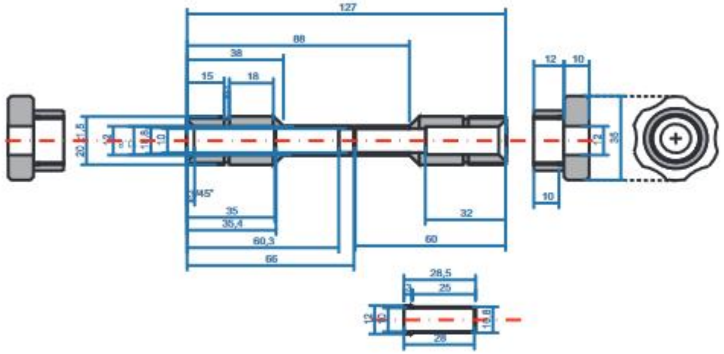
0.00703996 (71) 1/ns $= \lambda_{o-Ps}$

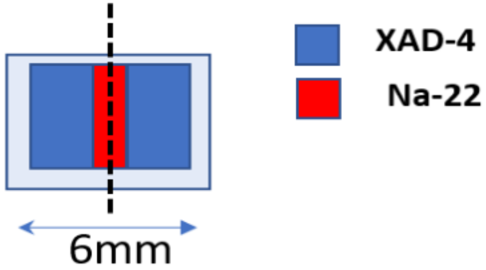
0.00695778 (105) 1/ns

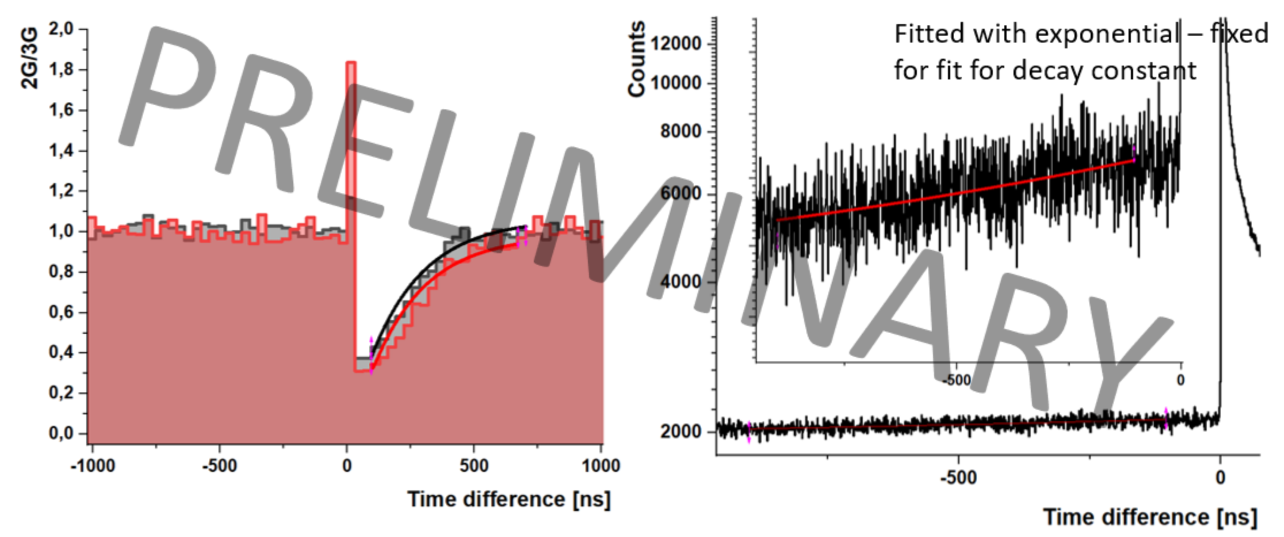
$1/\lambda_{o-Ps} = \tau_{o-Ps}$ = 142.046 (14) ns

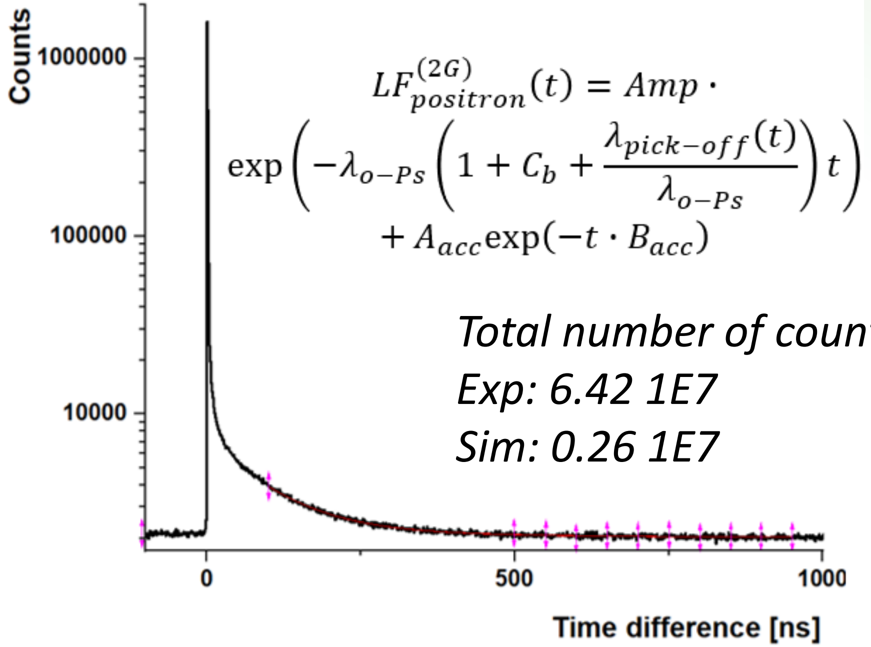
[4] K. Dulski, PhD thesis

Next step improvement









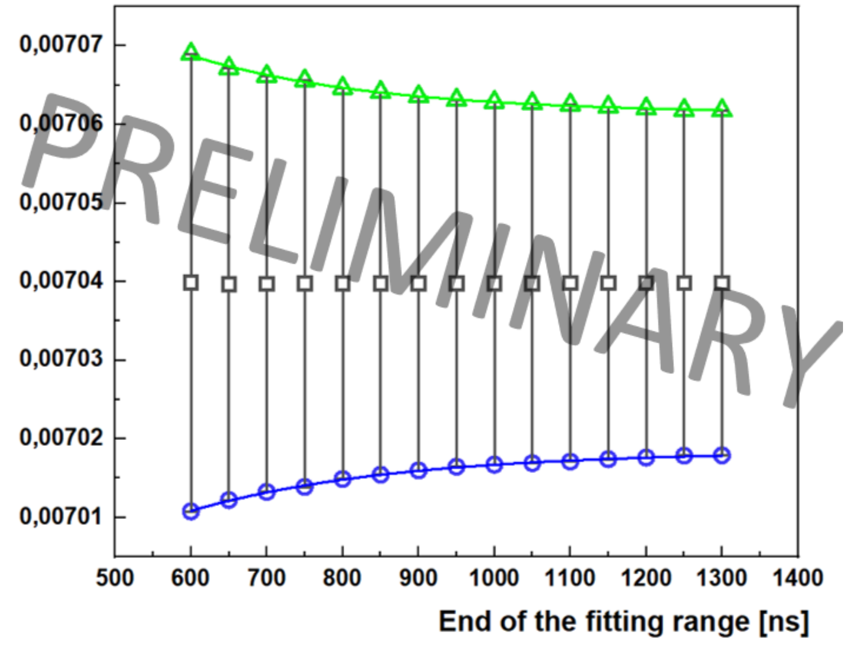
$$LF^{(2G)}_{positron}(t) = Amp \cdot \exp\left(-\lambda_{o-Ps}\left(1 + C_b + \frac{\lambda_{pick-off}(t)}{\lambda_{o-Ps}}\right)t\right) + A_{acc}\exp(-t \cdot B_{acc})$$

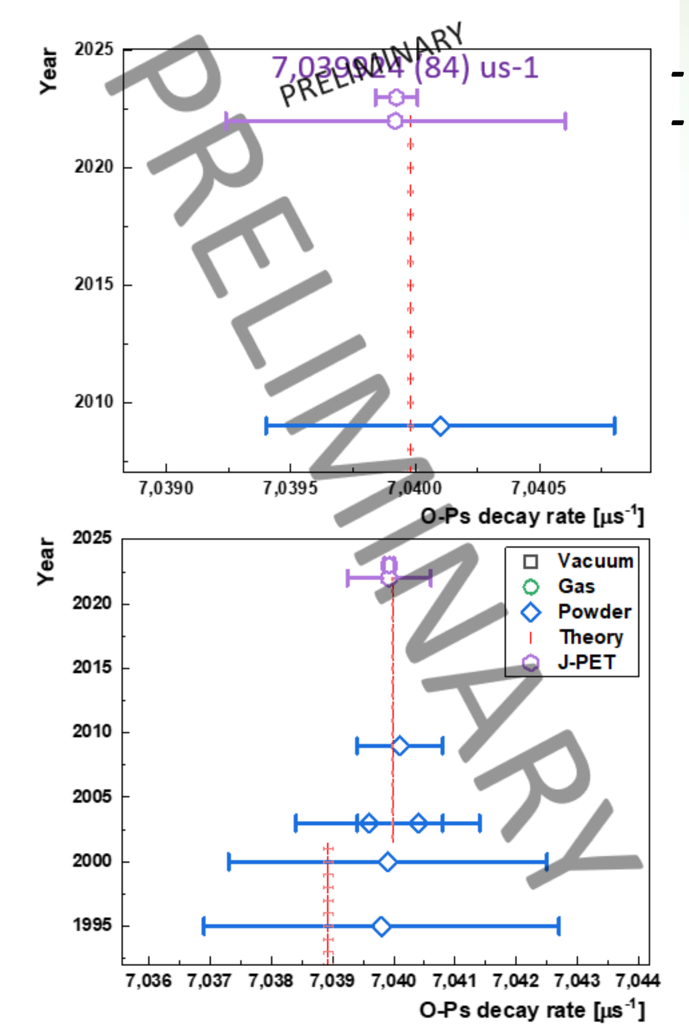
Total number of counts for (2G) spectrum
Exp: 6.42 1E7
Sim: 0.26 1E7

Data from 50 days measurement of Run11 (Still plenty of data to analyze ~years of measurement)

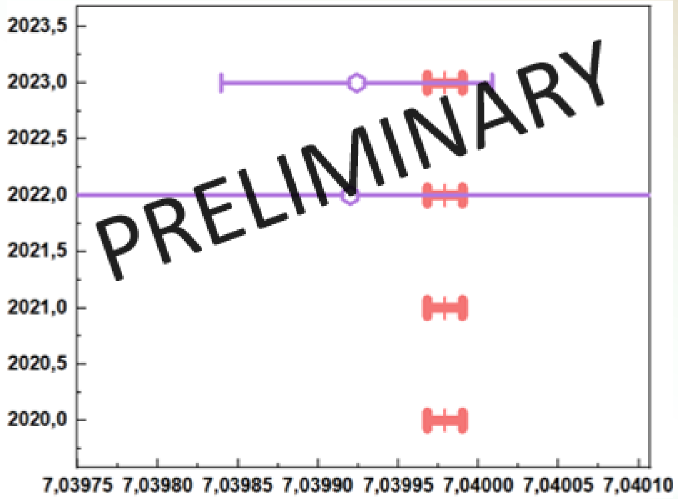
Final result and comparison

Theoretical prediction
7.039979(11) μs^{-1}





- Part of Run11
- Run4



Still to do

Obtained uncertainty is purely statistical. The first estimation of some of the sources of the systematic uncertainty was done:

- the activity of the source assumed in the simulations (10^{-5} μs-1)
- data selection criteria (10^{-6} μs-1)

In addition, the analysis of the rest of the Run11, and the potential inclusion of the data from different runs are considered. At the same time, the statistic for the simulated data is still increasing.

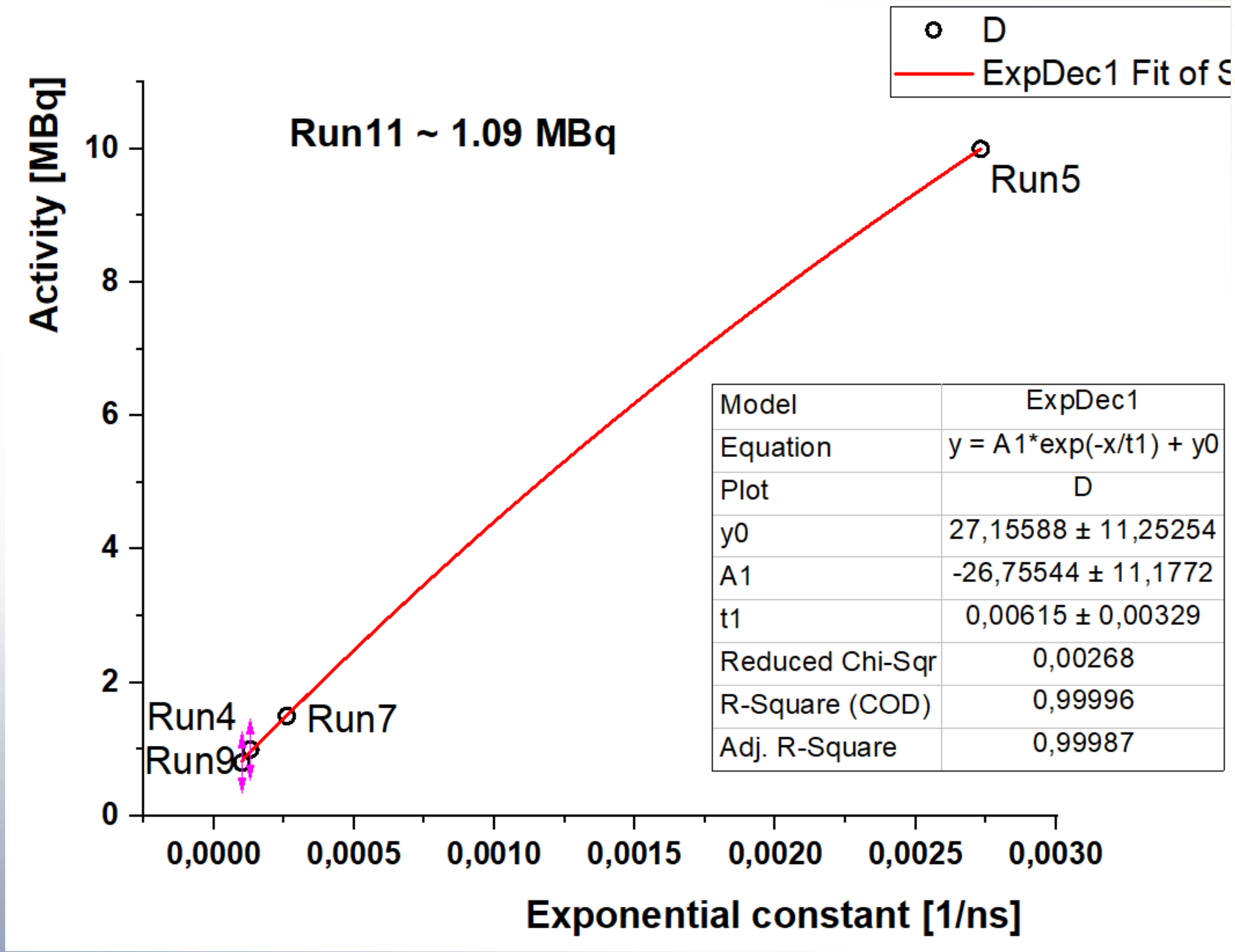
Conclusions

The J-PET detector serves as a highly sensitive detector with potential applications in fundamental studies.

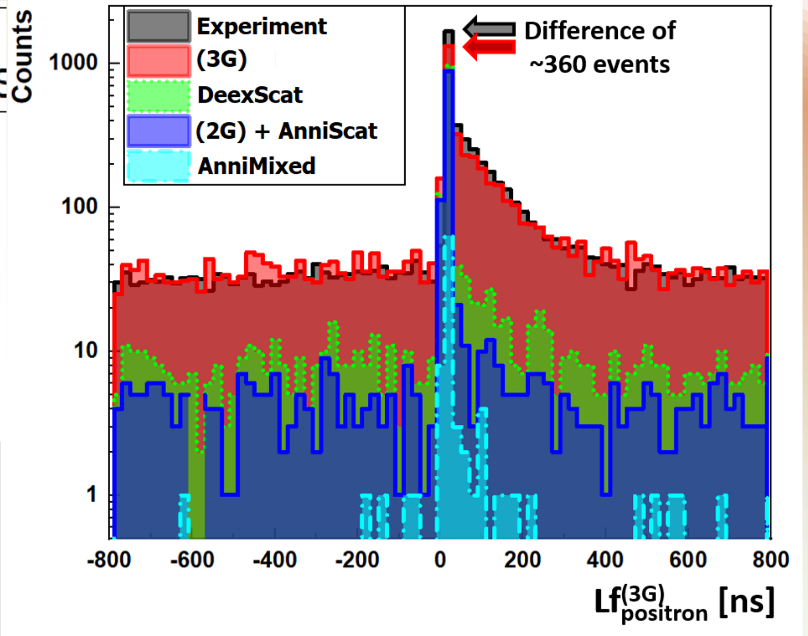
Positron-electron annihilations in the porous sample were measured in order to estimate the o-Ps decay rate in a vacuum.

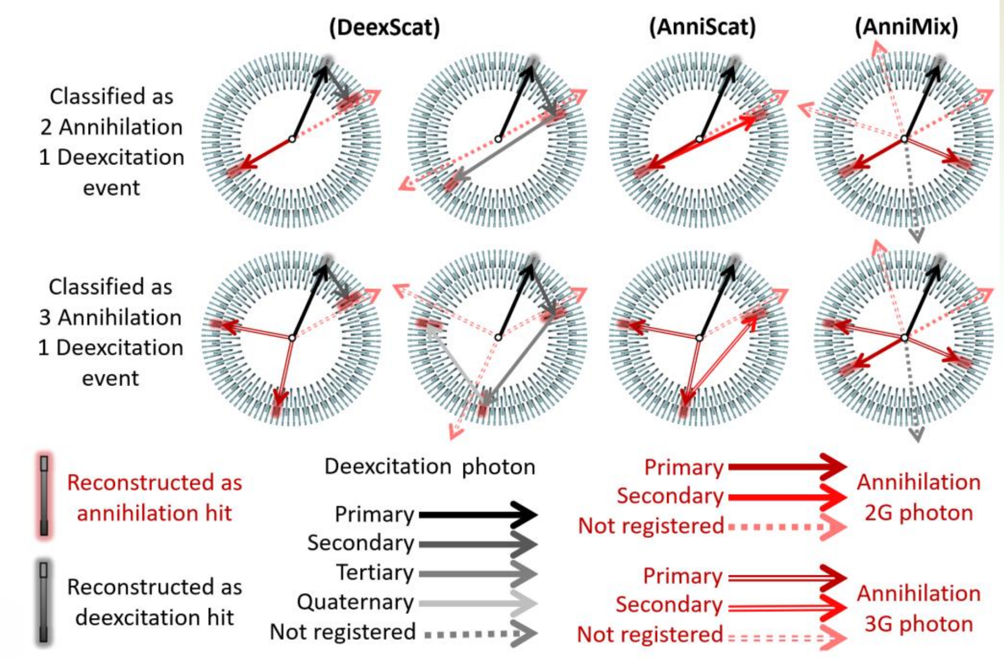
The uncertainty of the obtained value of the o-Ps decay rate is greater than in the previous experiments, additionally with the possibility of its improvement even to a level close to the precision of theoretical considerations, by increasing the statistics both for the experimental and simulated data.

Thank you for your attention



Model	ExpDec1
Equation	y = A1*exp(-x/t1) + y0
Plot	D
y0	27,15588 ± 11,25254
A1	-26,75544 ± 11,1772
t1	0,00615 ± 0,00329
Reduced Chi-Sqr	0,00268
R-Square (COD)	0,99996
Adj. R-Square	0,99987





Returning to the experimental decay rate of the o-Ps:

$$\lambda_{exp} = \lambda_{o-Ps} + \lambda_{pick-off}(R)$$

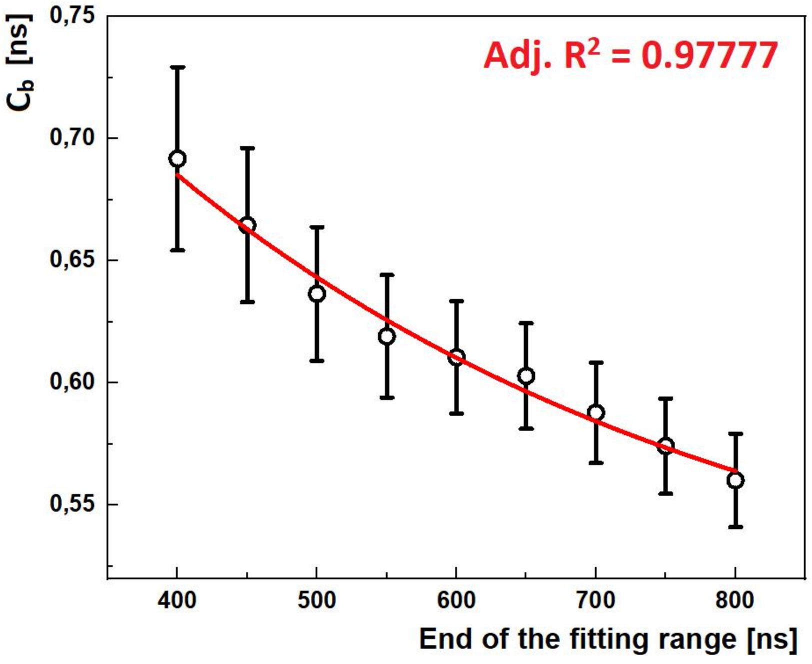
Here $\lambda_{pick-off}$ will depend on the radius of the free volume R

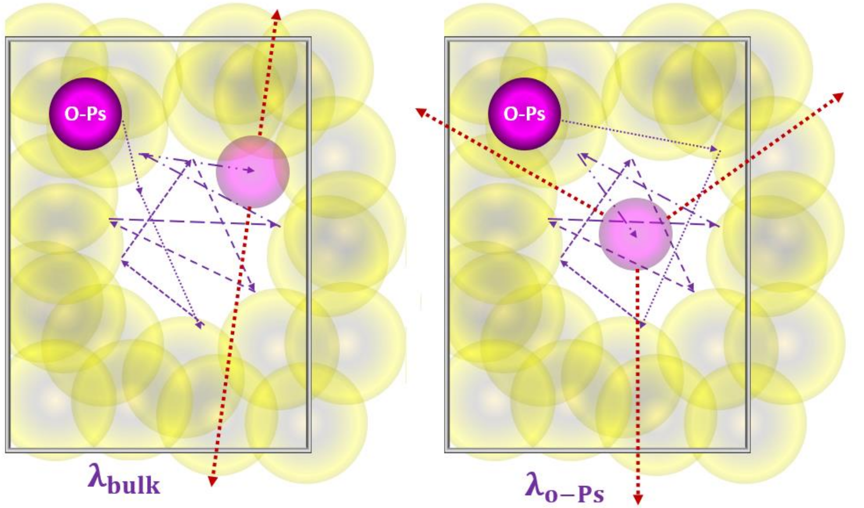
However, decay rate can be expressed also as a function of two decay rates: λ_{o-Ps} - o-Ps self annihilation; λ_{bulk} - o-Ps annihilation by pick-off

$$\lambda_{exp} = (1-P)\lambda_{o-Ps} + P\lambda_{bulk},$$

where P is the Probability of the o-Ps to annihilate by pick-off proces and this is the only function of R. One can additionally show that

$$\lambda_{pick-off} = P(R) \cdot (\lambda_{bulk} - \lambda_{o-Ps})$$





Model: A·Exp(-EndFitRange/B) + C_0

A = 0.513(86), B = 417.0 (1.5) ns

C_0= 0.489 (45) ns ➡ λ_{bulk} = 1.986 (18) 1/ns

Transforming the last form of the o-Ps decay rate to the model fitted

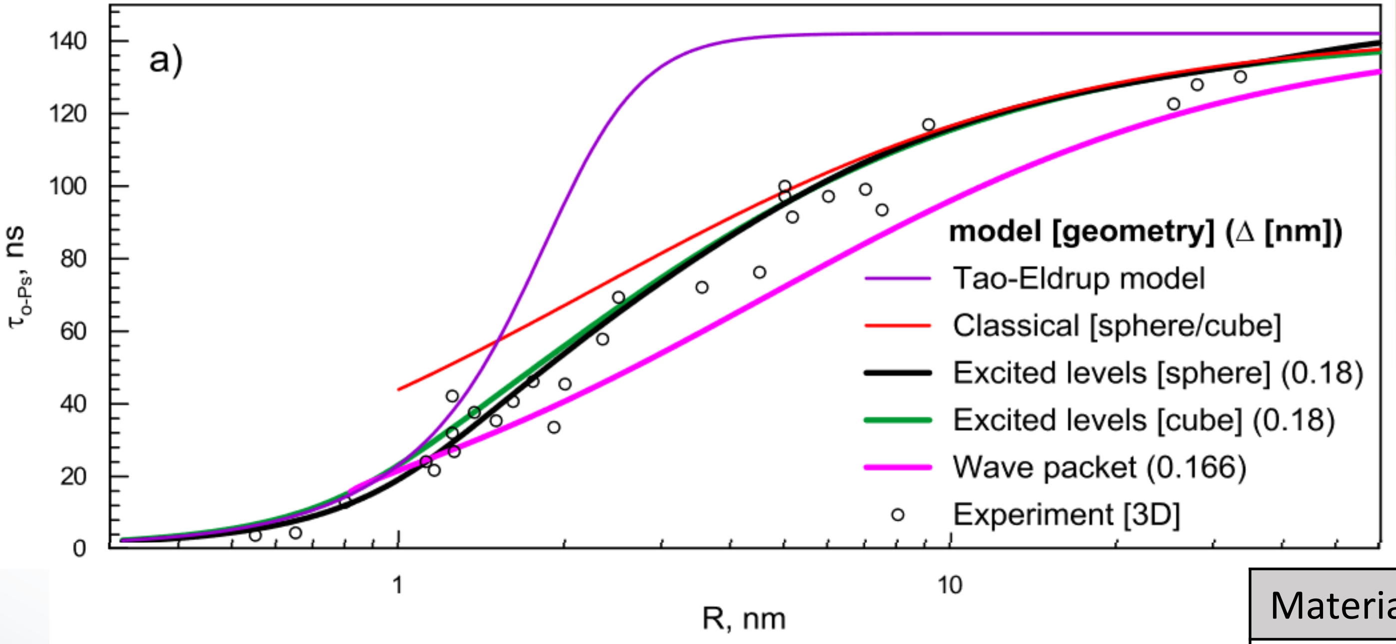
$$\lambda_{exp} = \lambda_{o-Ps}\left(1 + \frac{\lambda_{pick-off}(t)}{\lambda_{o-Ps}} + C_b\right)$$

$$\lambda_{exp} = (1-P)\lambda_{o-Ps} + P\lambda_{bulk} = \lambda_{o-Ps}\left(1 + P\frac{(\lambda_{bulk} - \lambda_{o-Ps})}{\lambda_{o-Ps}}\right)$$

allow to express C_b as a function of the decay rates (not considering influence of $\lambda_{pick-off}(t)$)

$$C_b = 0.489 = P\frac{(\lambda_{bulk} - \lambda_{o-Ps})}{\lambda_{o-Ps}}$$

In order to estimated λ_{bulk} value of P needs to be determined



R. Zalewski, J. Wawryszczuk, T. Goworek, Rad. Phys. Chem. 76 (2007), 243-247

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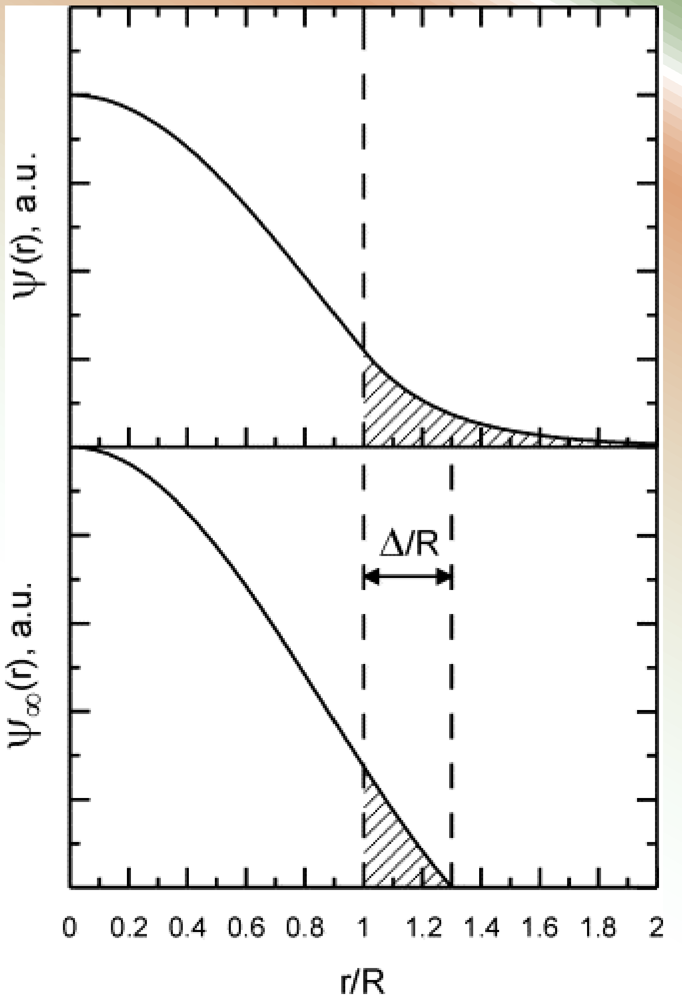

Parameter C_b can be expressed as

$$C_b = P\frac{(\lambda_{bulk} - \lambda_{o-Ps})}{\lambda_{o-Ps}}$$

On the other hand radius of the pores for the material used in the measurement is equal to 5 nm. P(5 nm) according to the Goworek-Gidley model

$$P_{G-G}(5\,nm) = 0.001738$$
$$\lambda_{o-Ps} = 0.00704\ \text{ns}^{-1}$$
$$C_b = 0.489\ (45)$$
$$\lambda_{bulk} = 1.986\ (18)\ \text{ns}^{-1}$$

Material	λ_{bulk} [ns^{-1}]
Biphenyl	1,524013
Naphthalene	1,64433
n-Octadecane	1,243274
Silica	1,403696
NaCl	0,842218
KCl	0,64169
KBr	0,842218

Theoretical value

$$\lambda_{bulk} = \lambda_{p-Ps}/4 + 3\lambda_{o-Ps}/4 = 2.005\ \text{ns}^{-1}$$