Radiological
Laboratory
in Warsaw
(1934)

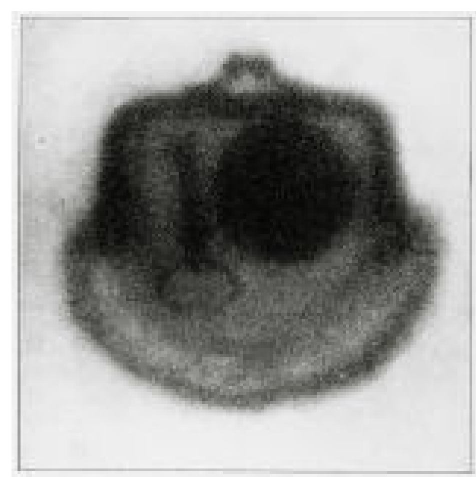
Marian Danysz

$$^{4}He + ^{14}N \rightarrow ^{17}F + n$$

$$^{17}F \rightarrow ^{18}O + e^{+} + \nu$$

Formal leader of the Radiological Laboratory in Warsaw

A girl from Warsaw

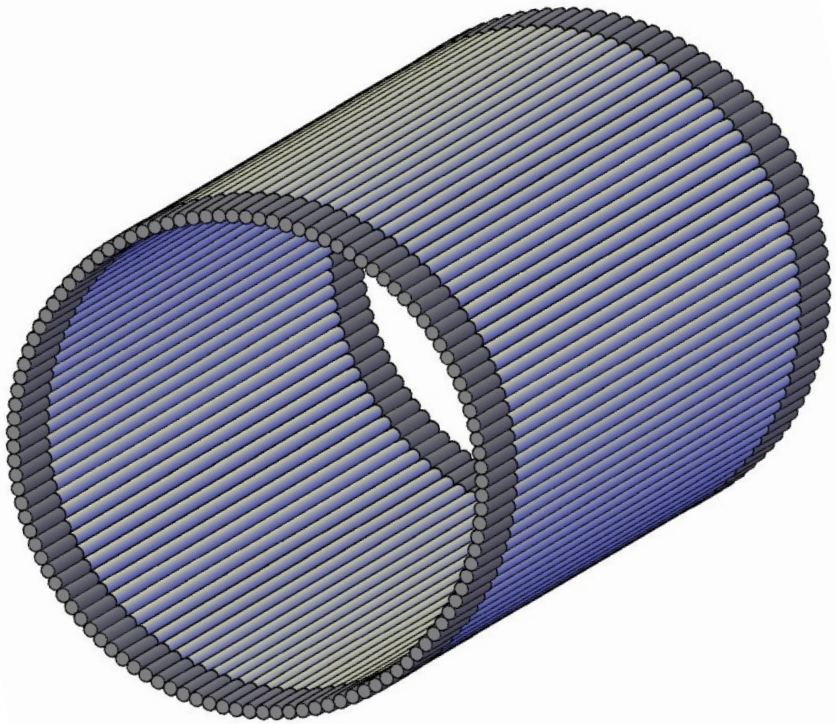


„Radiograph" taken by Maria Curie by exposing a purse to radium.

http://www.galloimages.co.za/

R.F. Mould, The British Journal of Radiology, **71**, 1229 (1998)

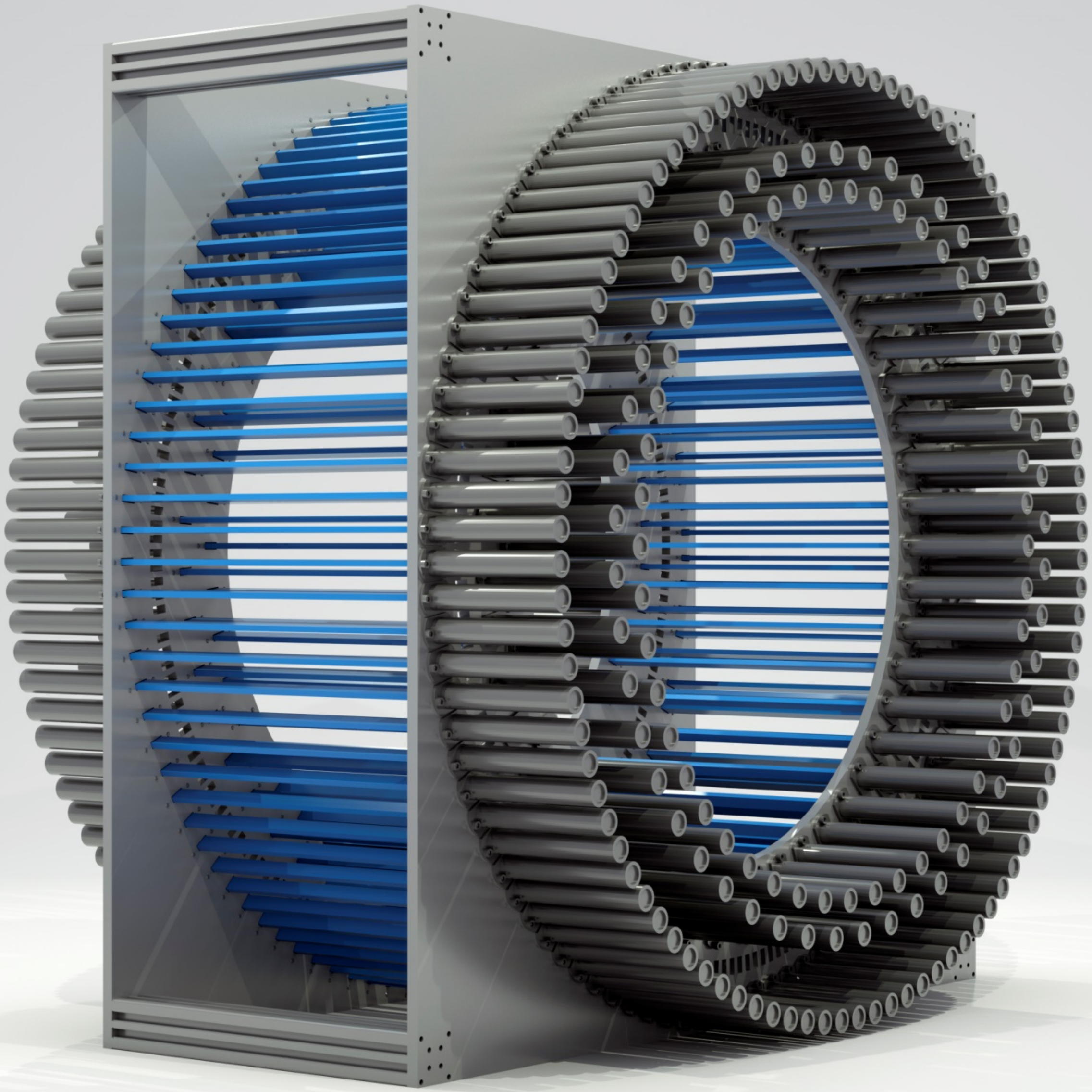
Investigations of morphology and discrete symmetries with positronium



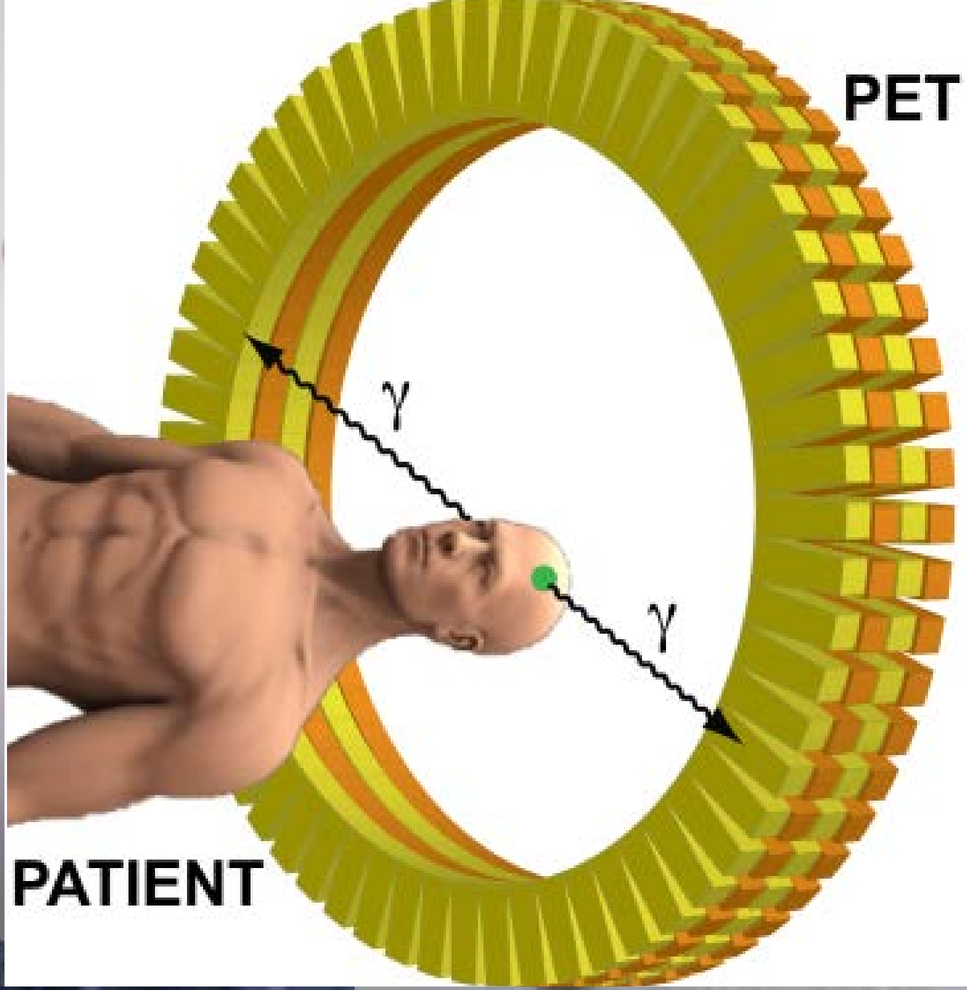
II Symposium on Applied Nuclear Physics and Innovative Technologies
Cracow, 24-26 September 2014

Pawel Moskal
Jagiellonian University, Cracow, Poland

J-PET (Jagiellonian PET)



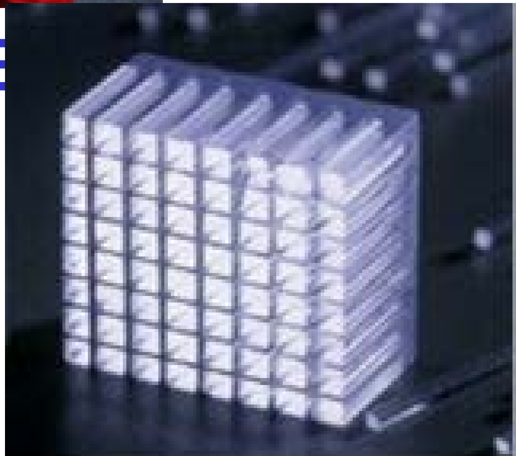
crystals → plastics

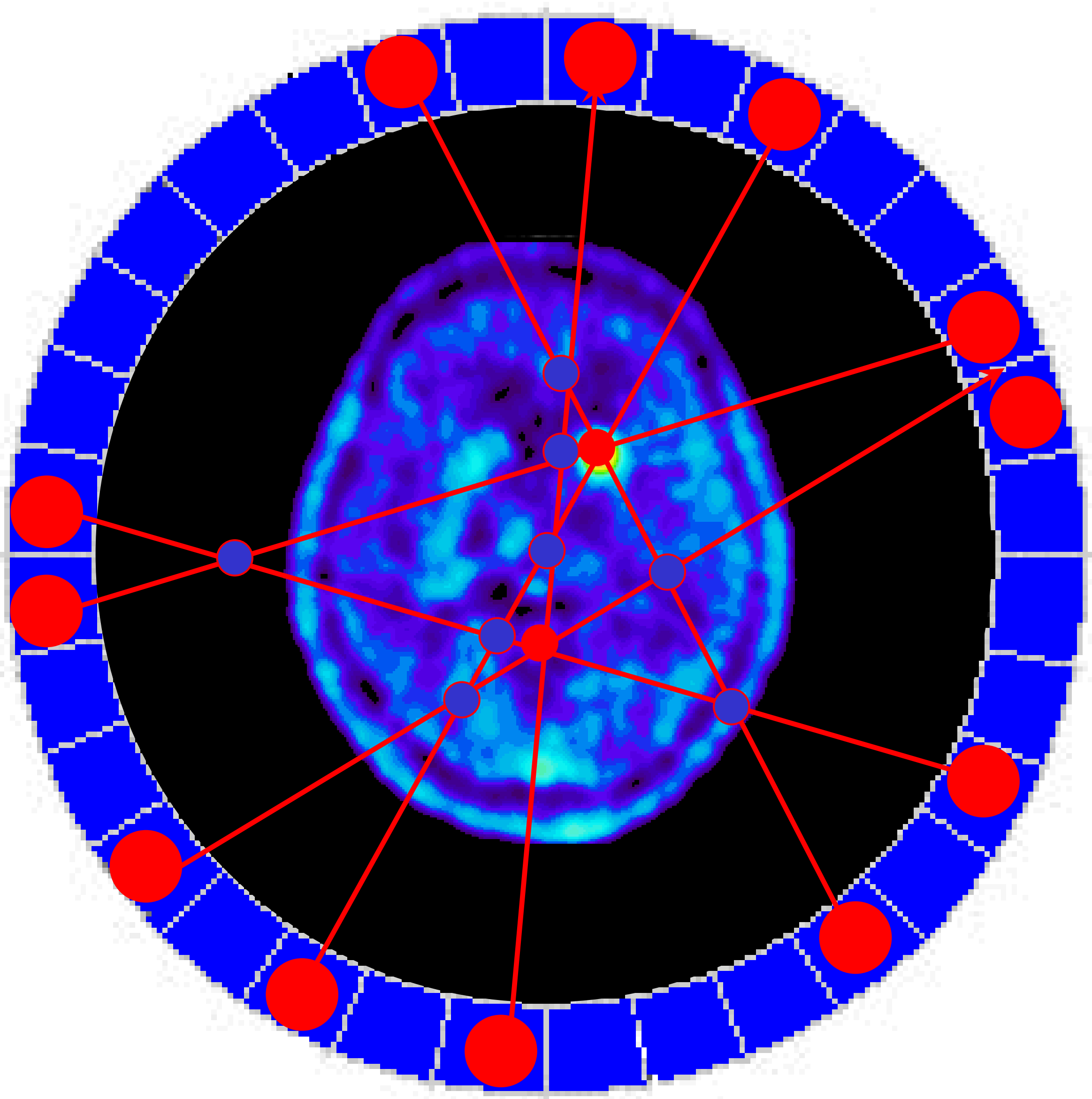


RADIOACTIVE SUGE

Fluoro–deoxy-glucose (F-18 FDG)

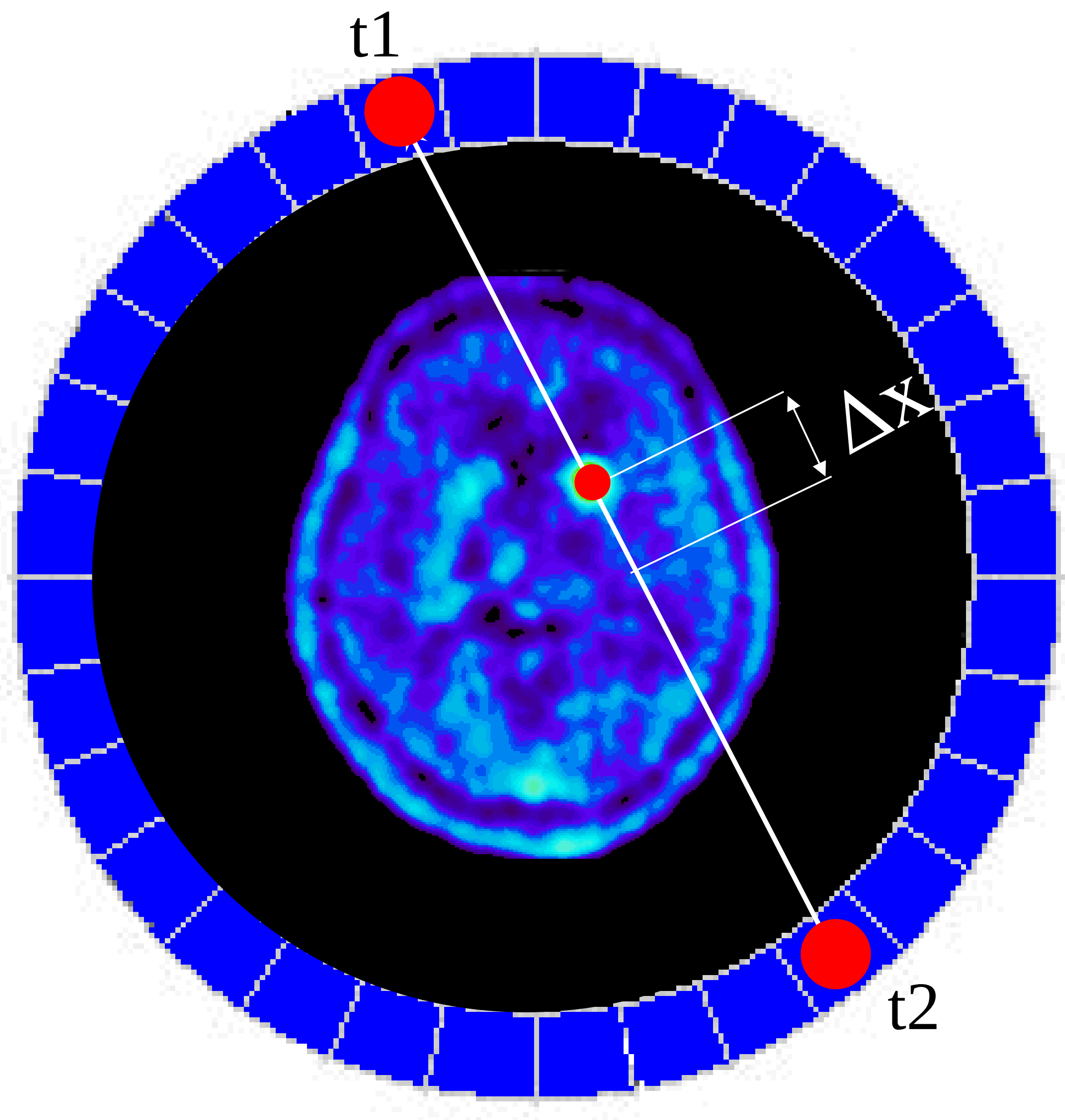
~200 000 000 gamma per second

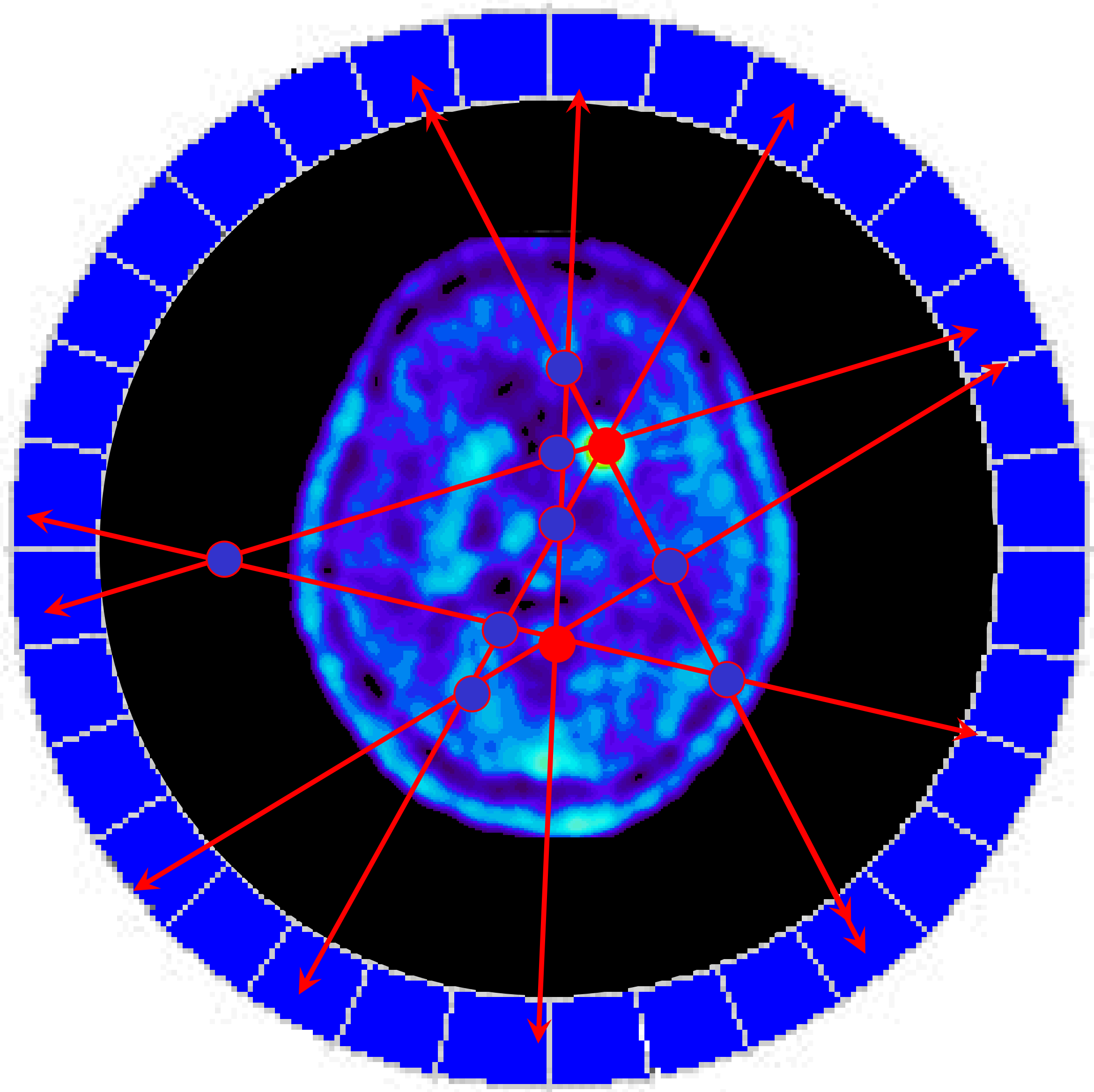




PET-TOF

$$\Delta x = (t2 - t1)\, c / 2$$





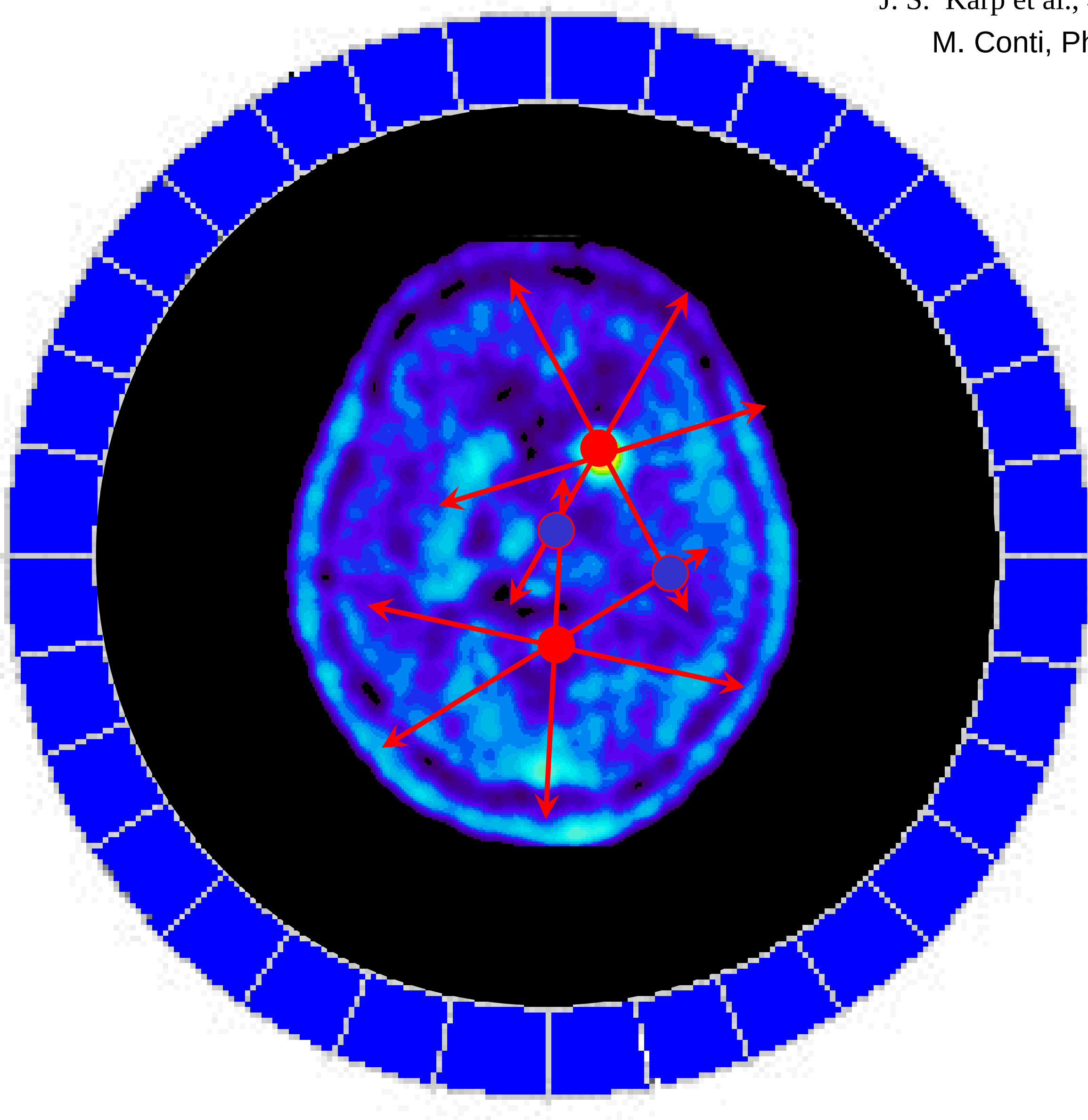
signal/background

~ D / Δt

40cm/600ps improvement by factor of 4

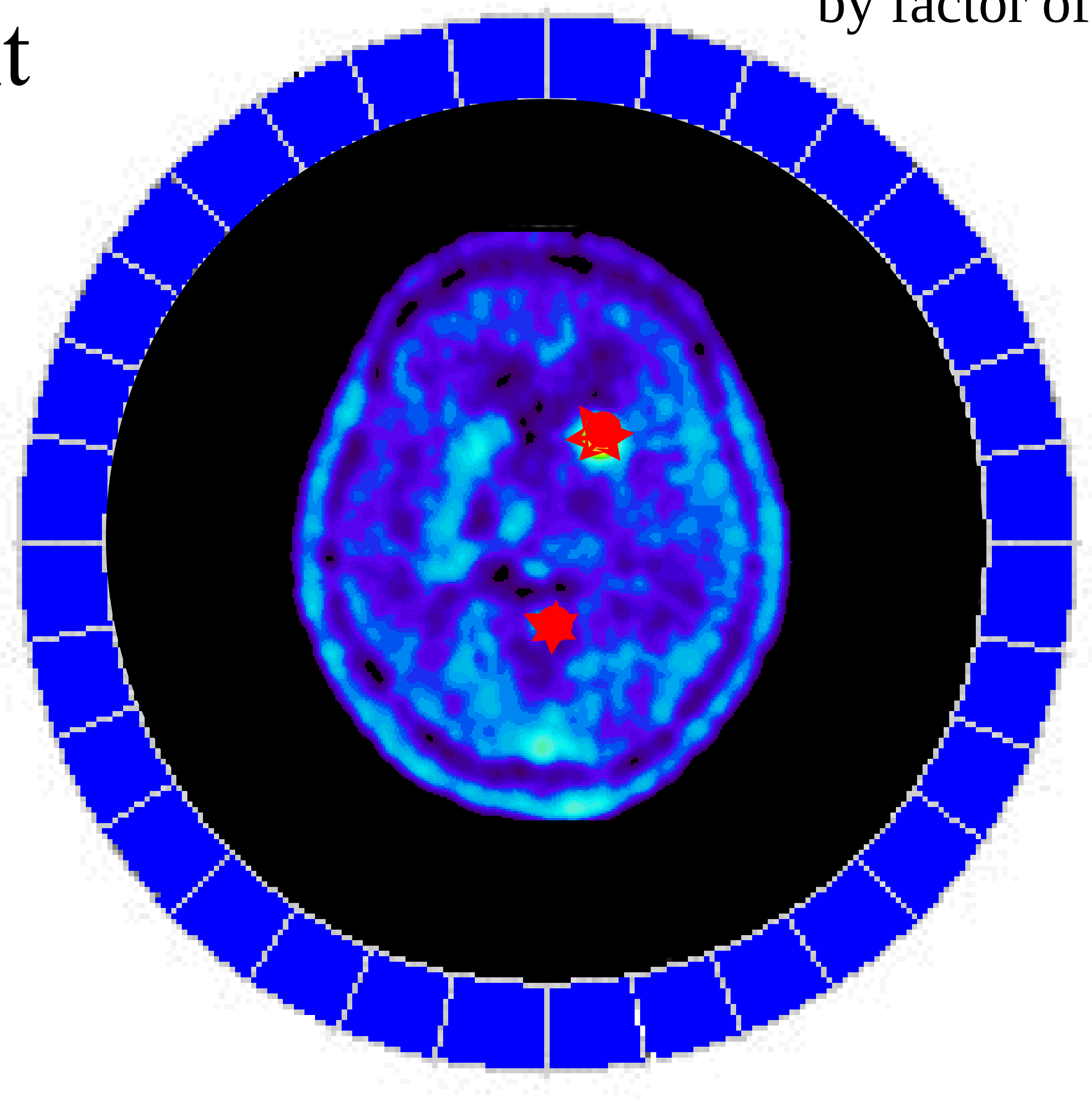
J. S. Karp et al., J Nucl Med 2008; 49: 462

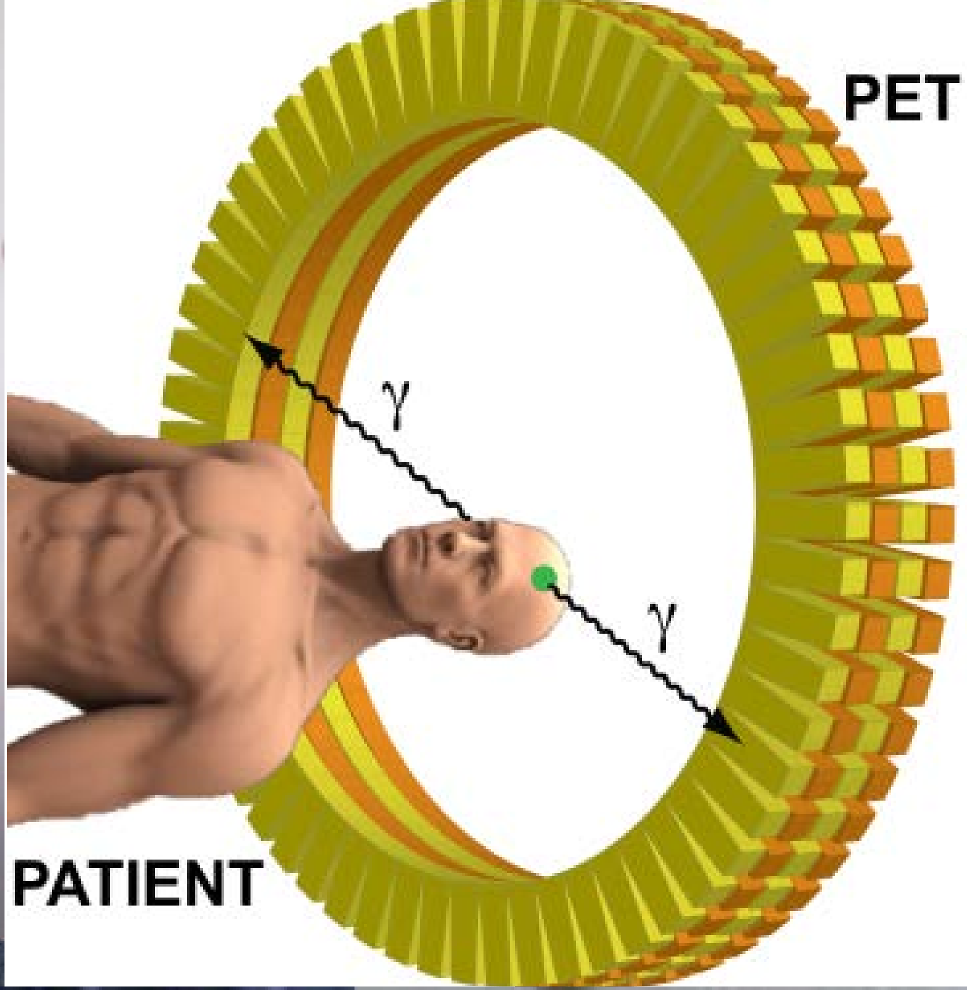
M. Conti, Physica Medica 2009; 25: 1.



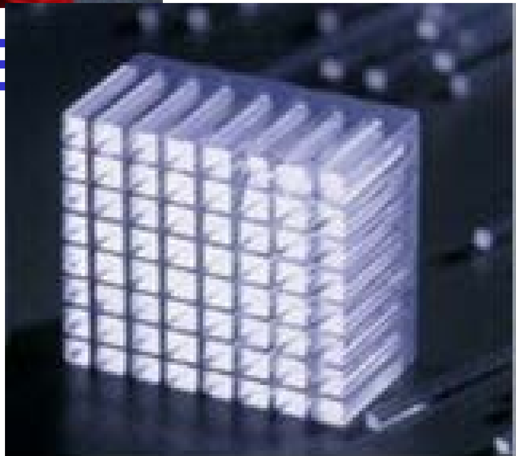
signal / background
~ D / Δt

40cm/70ps improvement
by factor of 30



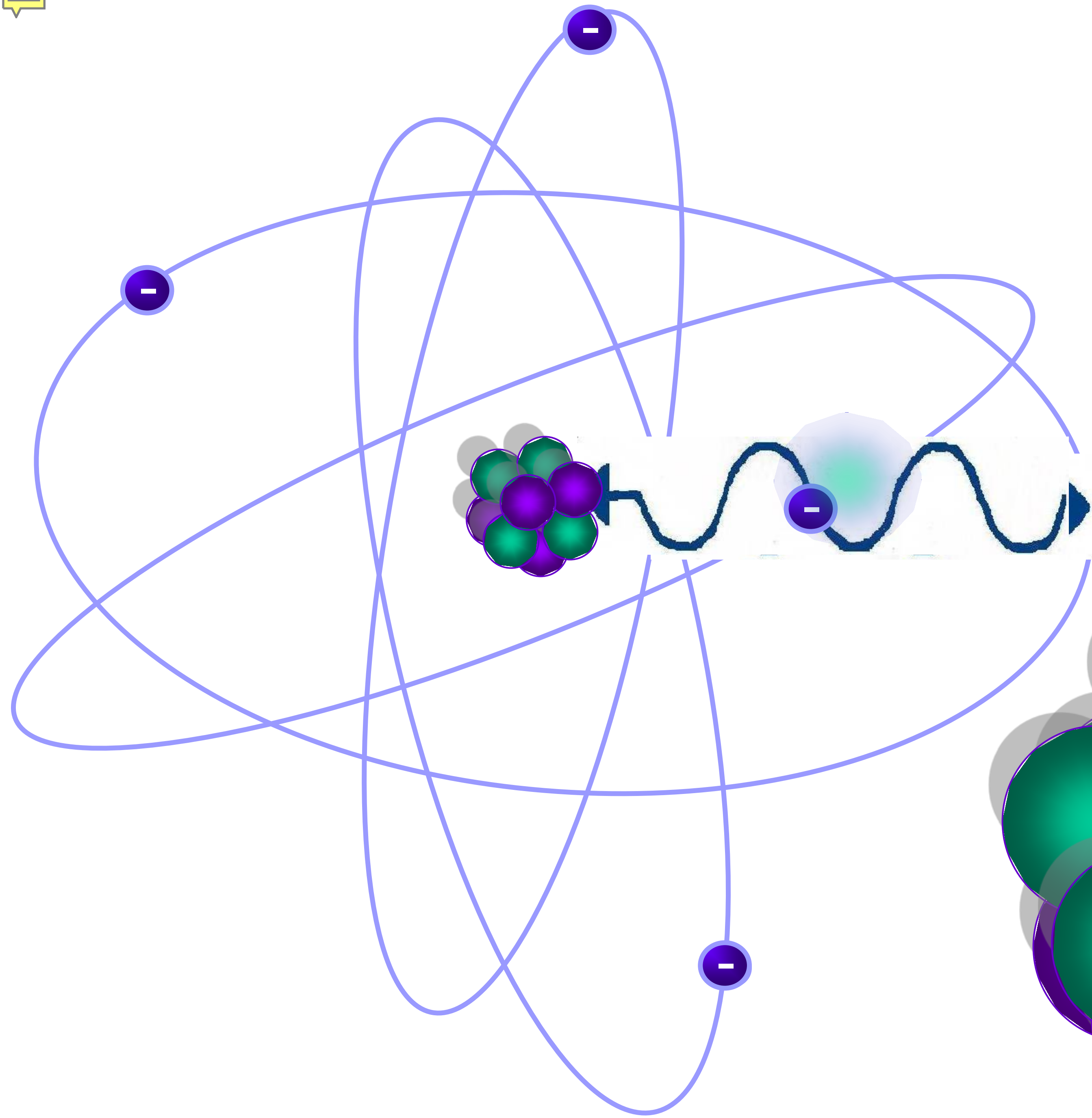


RADIOACTIVE SUGE



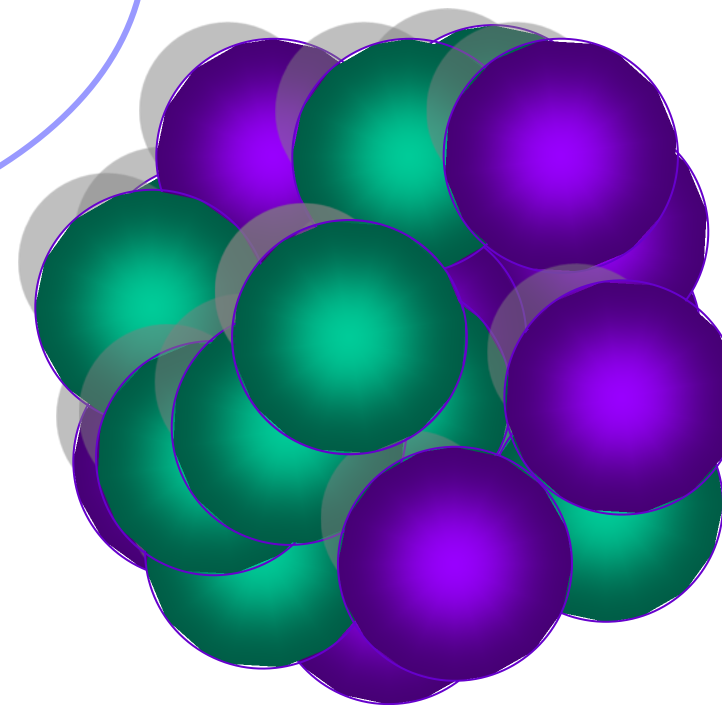
Fluoro–deoxy-glucose (F-18 FDG)

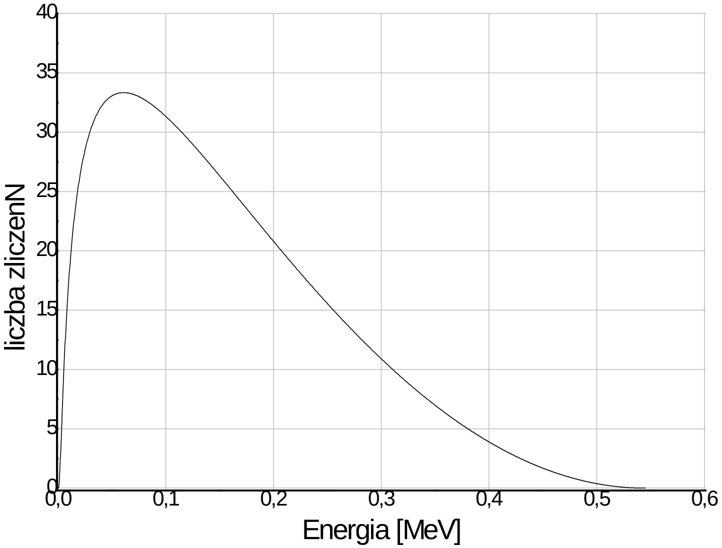
~200 000 000 gamma per second

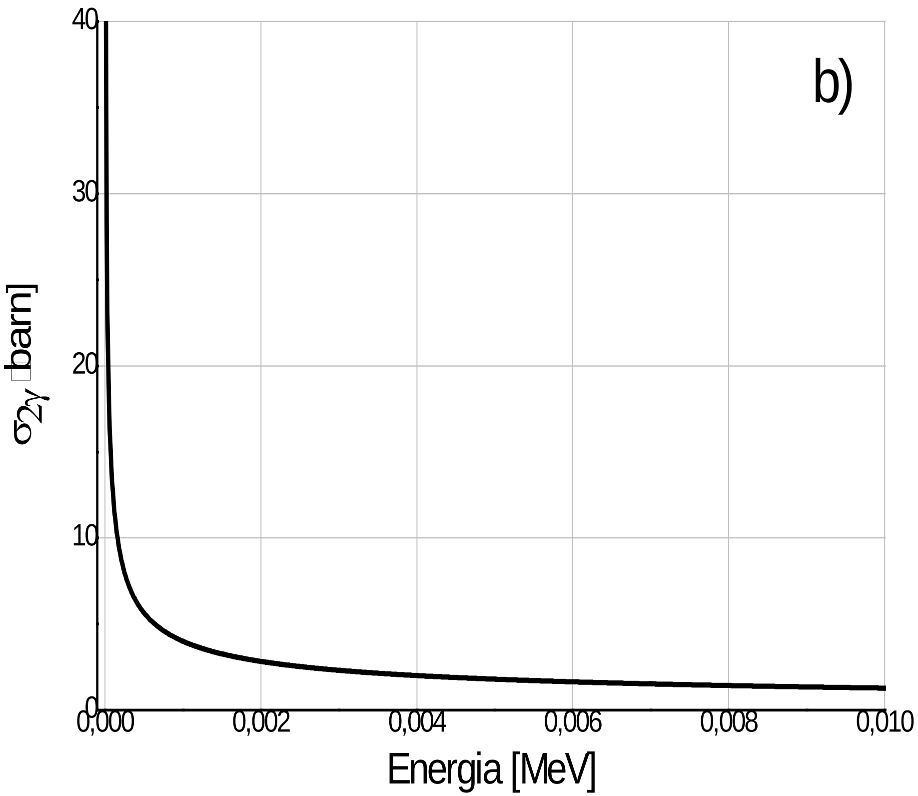


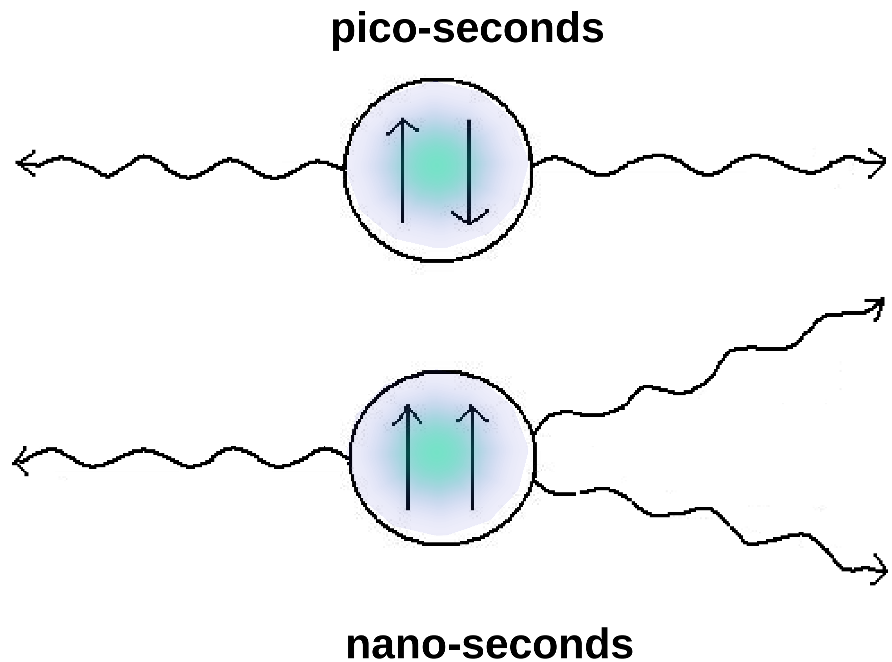
promieniowanie
beta plus

$$^{18}F \longrightarrow {}^{18}O + e^{+} + \nu_e$$

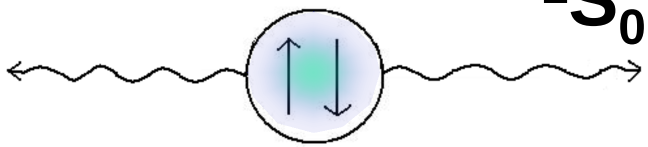



liczba zliczenN
Energia [MeV]
0
5
10
15
20
25
30
35
40
0,0
0,1
0,2
0,3
0,4
0,5
0,6

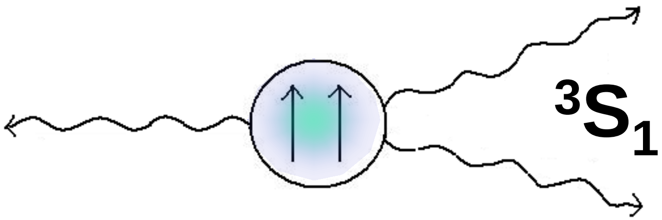

b)
σ2γ barn]
Energia [MeV]
0
10
20
30
40
0,000
0,002
0,004
0,006
0,008
0,010


pico-seconds
nano-seconds

L=0



$^1S_0$ **Para-positronium tau(p-Ps) ≈ 125 ps**



$^3S_1$ **Ortho-positronium tau(o-Ps) ≈ 142 ns**

		$^1S_0$	$^3S_1$
	S	0	1
	J	0	1
L=0 ->	P	-	-
	C	+	-
	CP	-	+

$$C\,|Ps> \;=\; (-1)^{L+S}\,|Ps>$$

$$C\,|n\gamma> \;=\; (-1)^{n}\,|n\gamma>$$

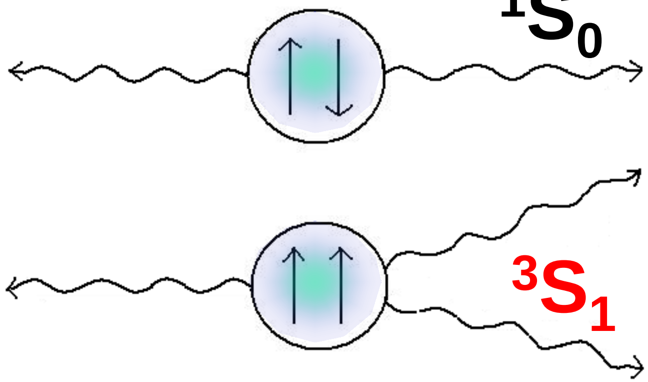
Production rate

¼   m = 0

m = +1

¾   m = 0

m = -1



$^1S_0$ tau(p-Ps) ≈ 125 ps

$^3S_1$ tau(o-Ps) ≈ 142 ns

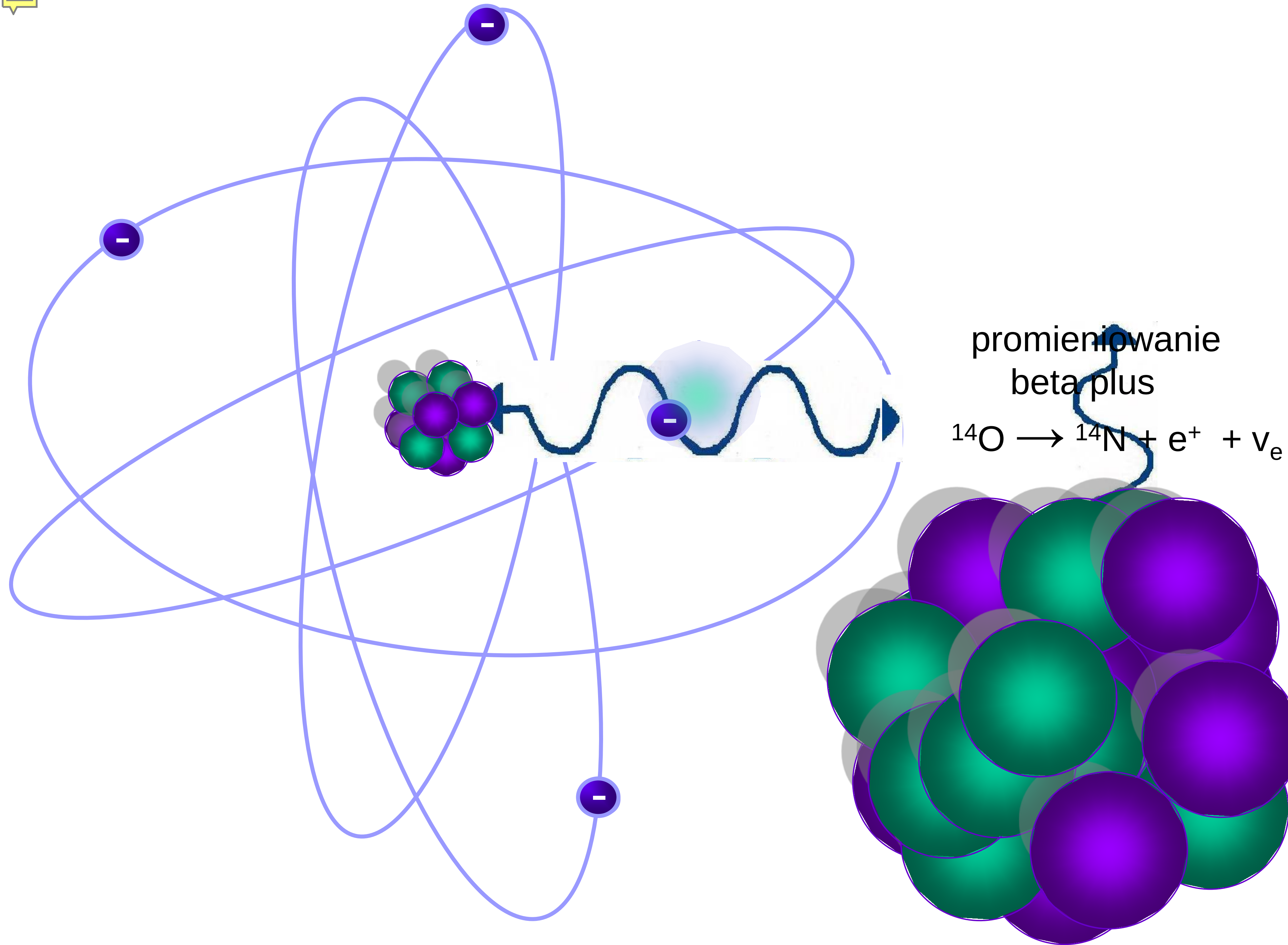
But
e+e- may undergo a direct annihilation:

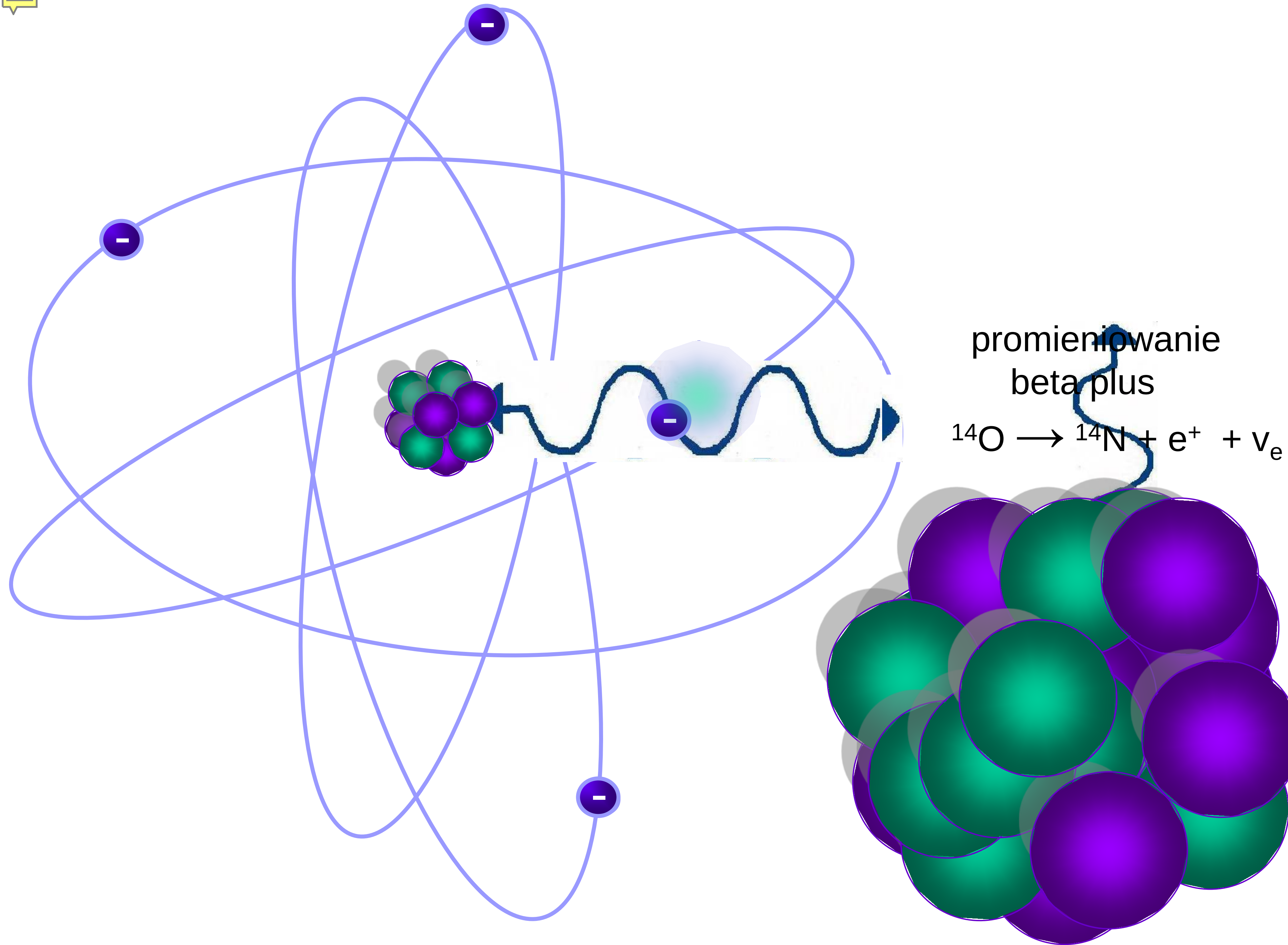
e+ e- --> γ γ / e+ e- --> γ γ γ / e+e- --> γ γ γ γ ≈ 1 / 370 / 1000000

positron „life time" in matter depends on the material properties ≈ **300-400 ps**

tau(o-Ps) strongly depends on the size of the free volumes between molecules…

$$N(\Delta t) = N_o P_{ps} \tfrac{3}{4} e^{-\Delta t/\tau o\text{-}Ps} + N_0 \tfrac{1}{4} P_{ps} e^{-\Delta t/\tau p\text{-}Ps} + N_0 (1-P_{ps}) e^{-\Delta t/\tau b}$$


promieniowanie
beta plus
$^{14}O \longrightarrow {}^{14}N + e^{+} + \nu_e$


promieniowanie
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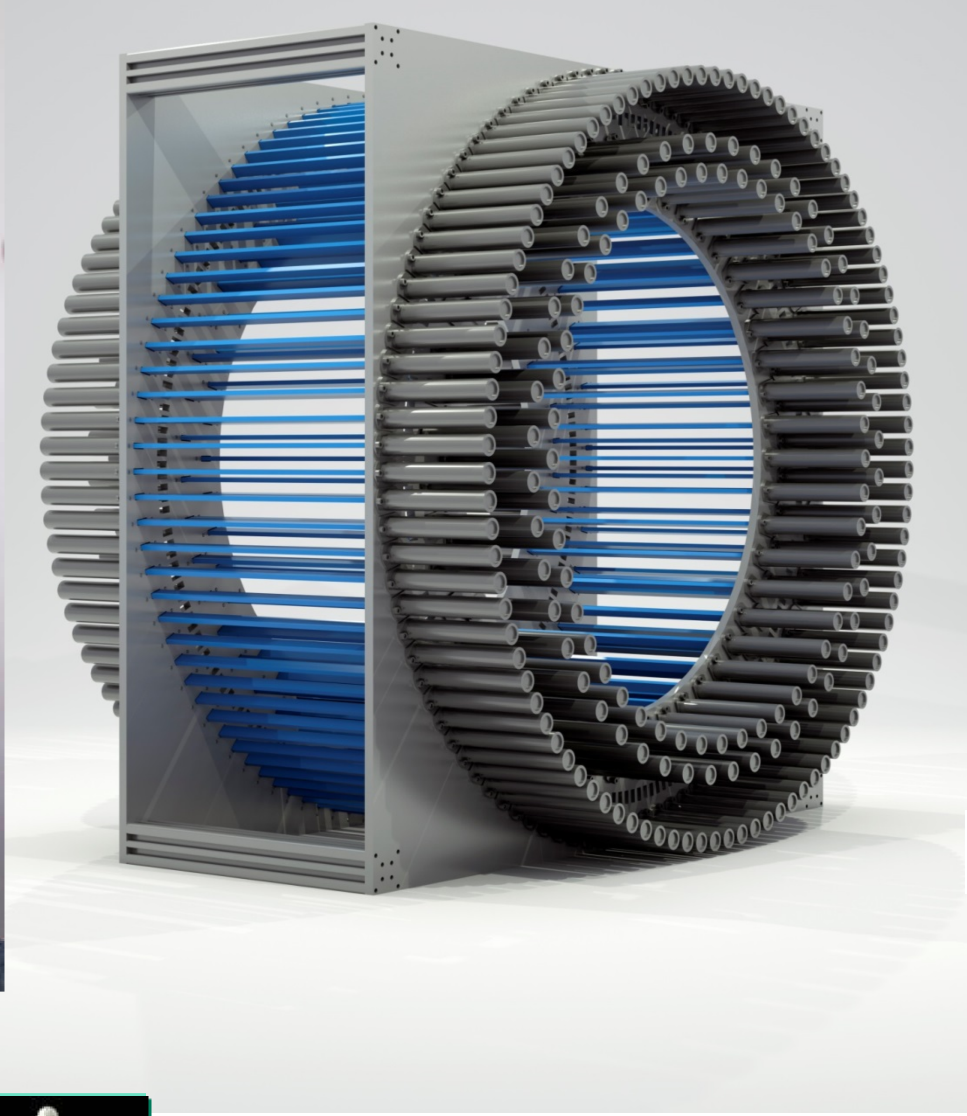

RADIOACTIVE SUGER

Fluoro–deoxy-glucose (F-18 FDG)

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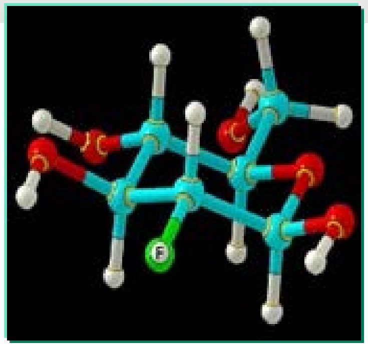
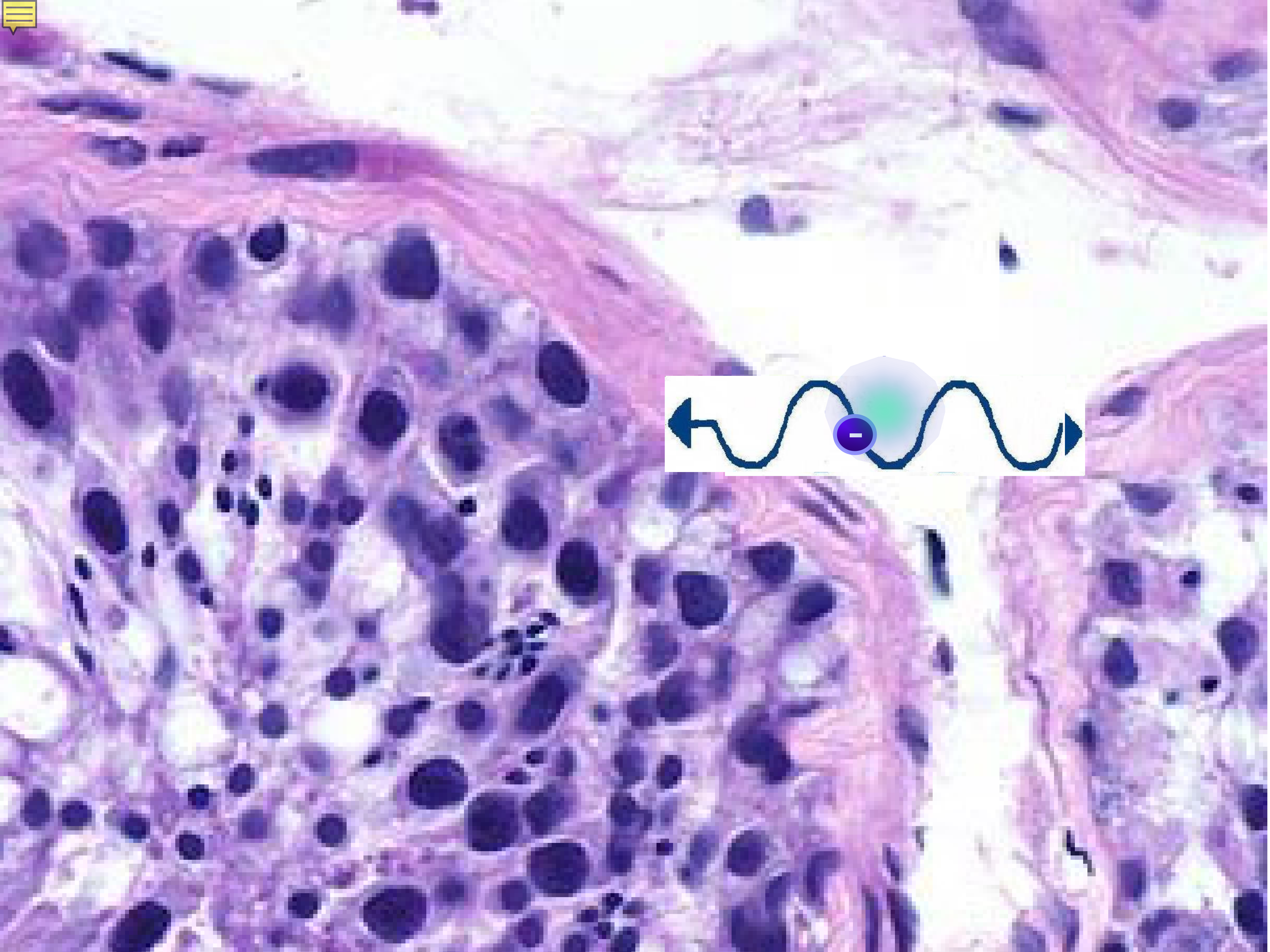
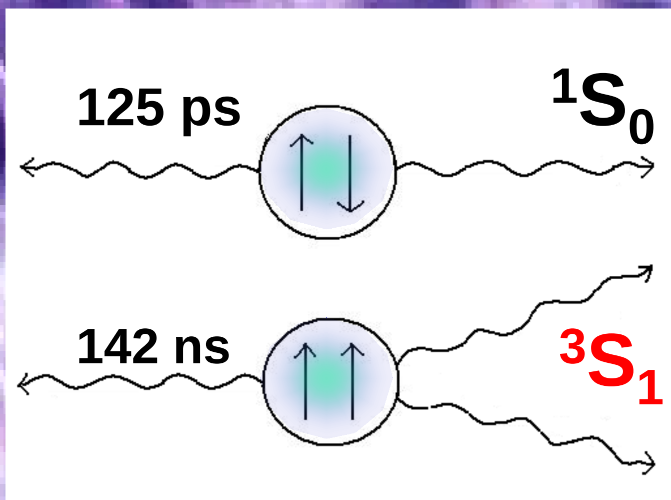
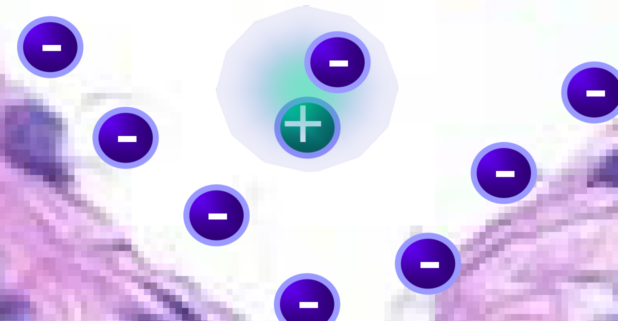








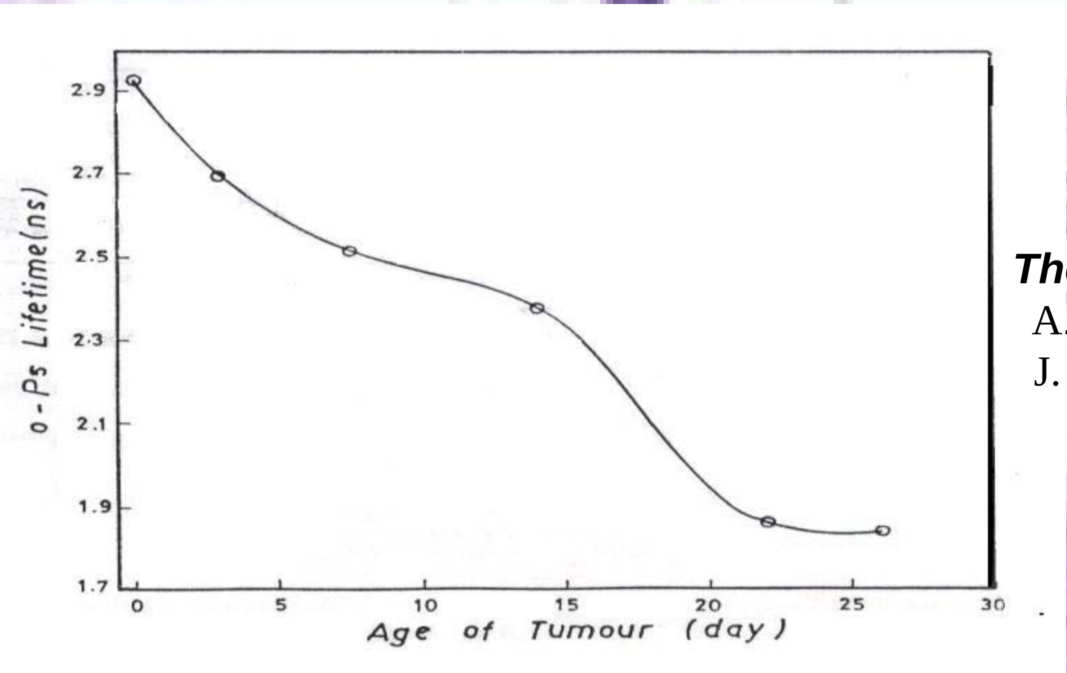
$M_0 = mM/(M+m)$

$E=E_H/2 = 6.8$ eV;

Radius $= 2\ r_B = 0.1$ nm

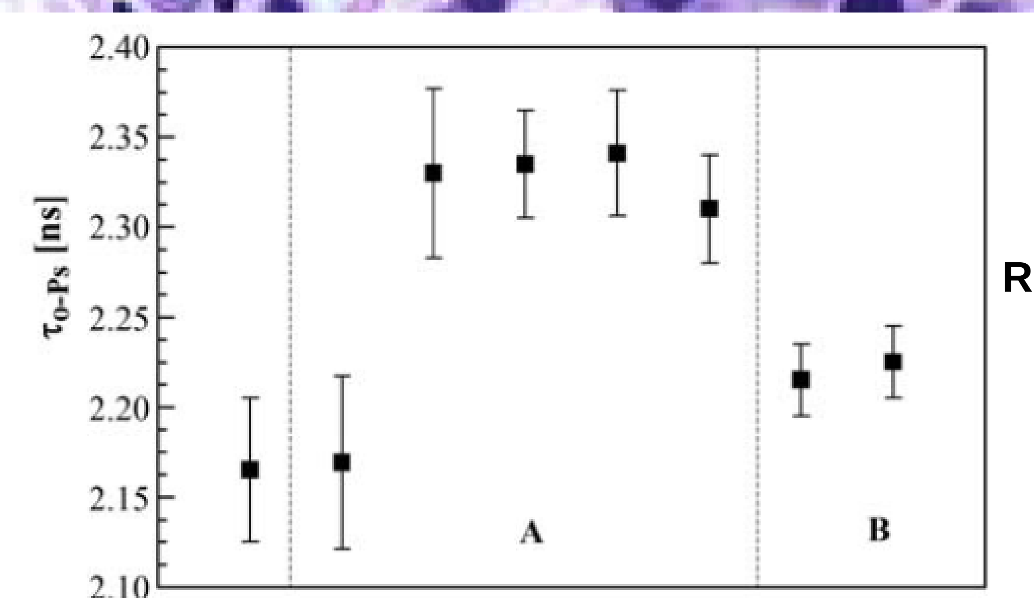
(hyperfine splitting) 8.4×10^{-4} eV

Patent application: Morphometric imaging (2013) P.405185

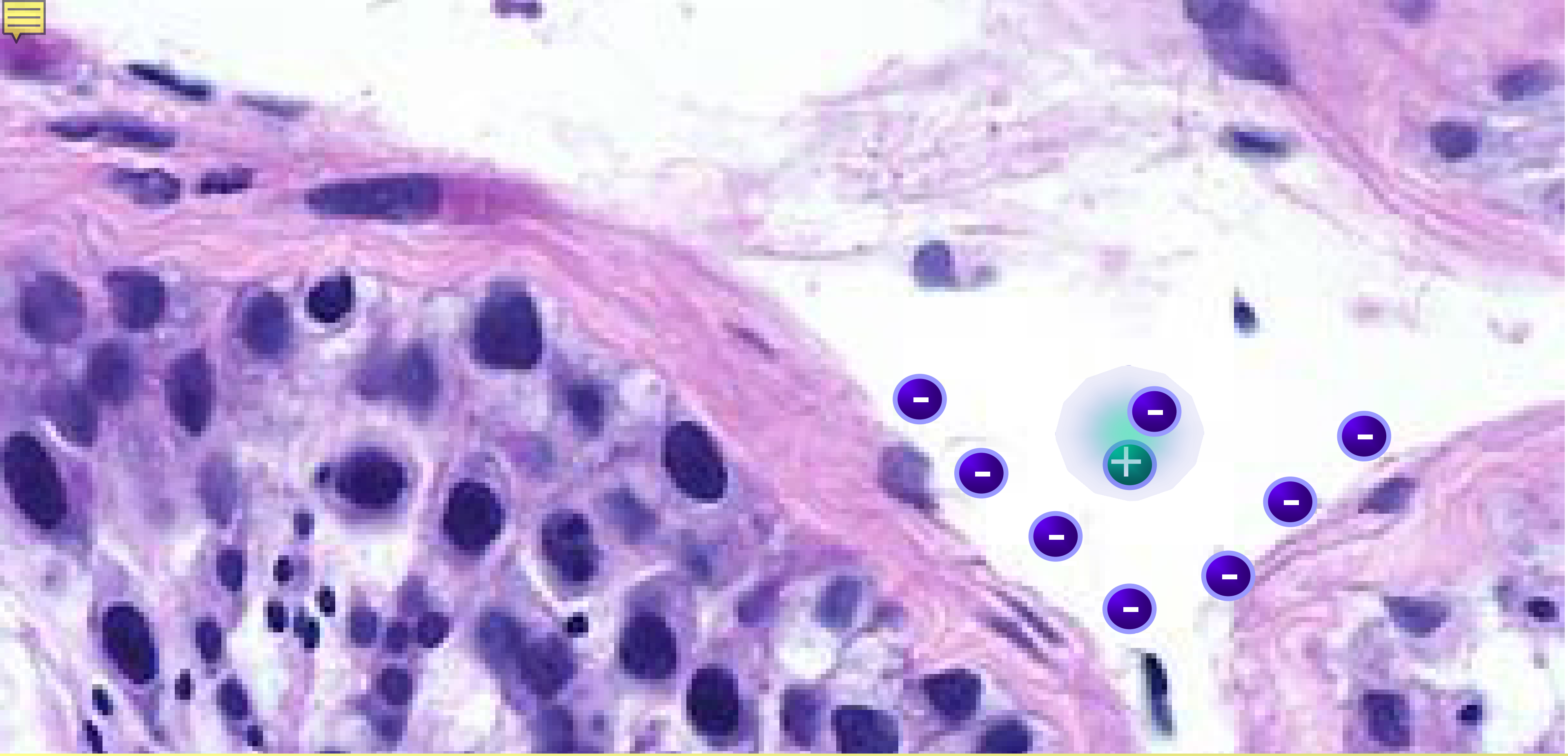


The age of mice's tumour with o-Ps lifetime

A.H. Al-Mashhadani et al., Iraqi J. Sci. 42C, 60 (2001) 3.



R. Pietrzak et al., NUKLEONIKA 58 (2013) 199

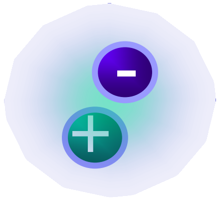


$$N(\Delta t) = N_o P_{ps} \tfrac{3}{4} e^{-\Delta t/\tau_{o\text{-}Ps}} + N_0 \tfrac{1}{4} P_{ps} e^{-\Delta t/\tau_{p\text{-}Ps}} + N_0 (1-P_{ps}) e^{-\Delta t/\tau_b}$$

$$(\tau_{o\text{-}Ps} \cdot P_{poz})^{-1} \quad W = SUV / (\tau_{o\text{-}Ps} \cdot P_{poz})$$

Patent application:

Morphometric imaging PCT/EP2014/068374 (2013)



Eigen-state of Hamiltonian and P, C, CP operators

The lightest known atom and at the same time anti-atom which undergoes self-annihilation as flavor neutral mesons

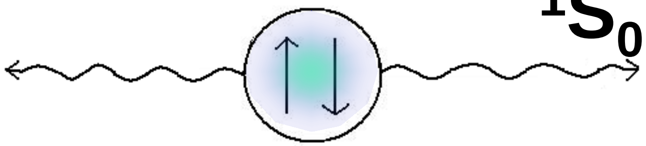
The simplest atomic system with charge conjugation aigenstates.

Electrons and positron are the lightest leptons so they can not decay into lighter partilces via weak interactiom ..

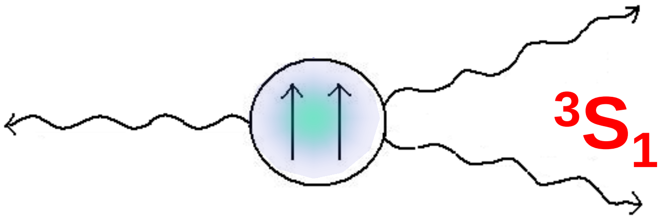
No charged particles in the final state (radiative corrections very small 2 * 10^{-10})
Light by light contributions to various correlations are small
B. K. Arbic et al., Phys. Rev. A 37, 3189 (1988).
W. Bernreuther et al., Z. Phys. C 41, 143 (1988).

Purely Leptonic state !

Breaking of P, T, C, CP, observed but only for processes involving quarks
So far breaking of these symmetries was not observed for purely leptonic systems.



$^1S_0$ **Para-positronium** tau(**p-Ps**) ≈ **125 ps**



$^3S_1$ **Ortho-positronium** tau(**o-Ps**) ≈ **142 ns**

	$^1S_0$	$^3S_1$	2γ	3γ	4γ	5γ	…
C	+	-	+	-	+	-	

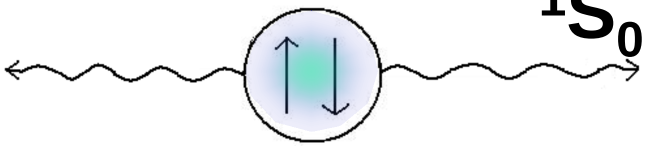
bound state mixing is not possible because there are
no positronium states with opposite *C*-parity and the same J^P

BR ($^3S_1 \to 4\gamma$ / $^3S_1 \to 3\gamma$) < 2.6 10^{-6} at 90%CL

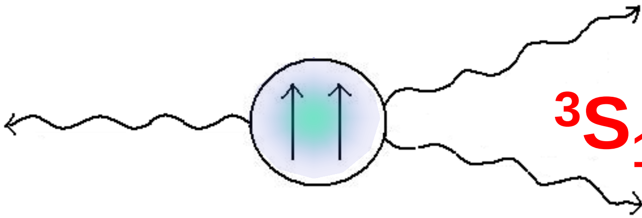
J. Yang et al., Phys. Rev. A54 (1996) 1952

BR ($^1S_0 \to 3\gamma$ / $^1S_0 \to 2\gamma$) < 2.8 10^{-6} at 68%CL

A. P. Mills and S. Berko, Phys. Rev. Lett. 18 (1967) 420



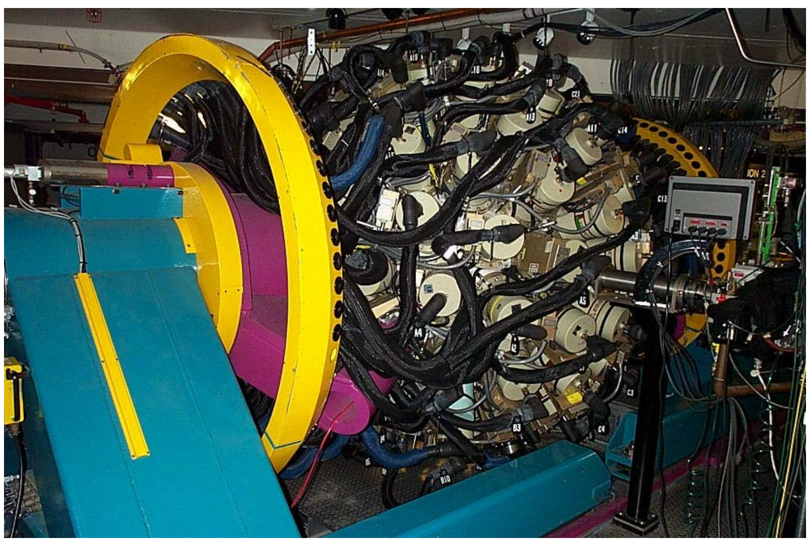
$^1S_0$ **Para-positronium tau(p-Ps) ≈ 125 ps**

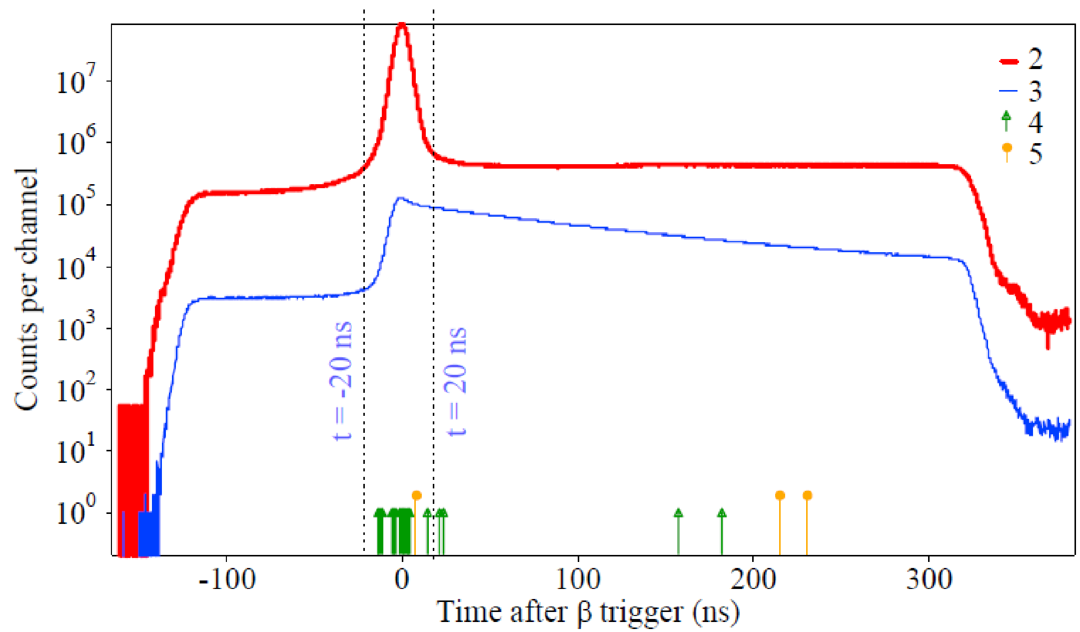


$^3S_1$ **Ortho-positronium tau(o-Ps) ≈ 142 ns**

BR ($^1S_0$ --> 5γ / $^1S_0$ --> 2γ) < $2.7\ 10^{-7}$ at 90%CL

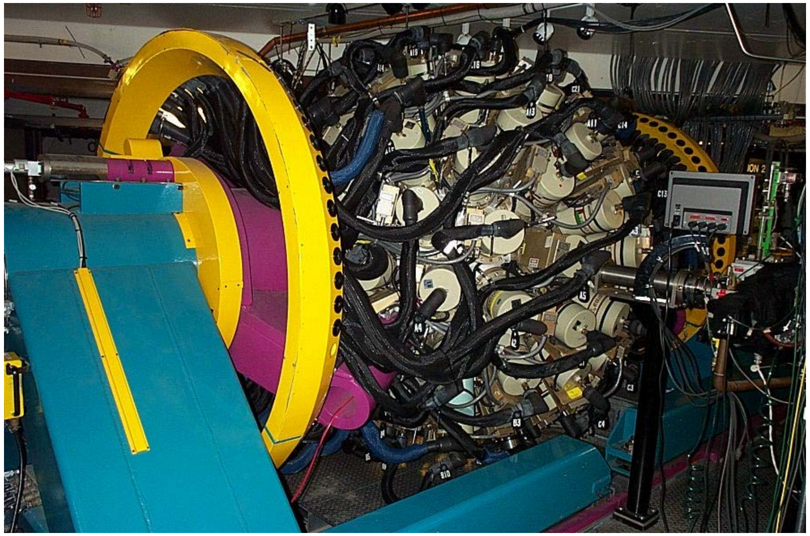
P. A. Vetter and S. J. Freedman Phys. Rev. A 66 (2002) 052505

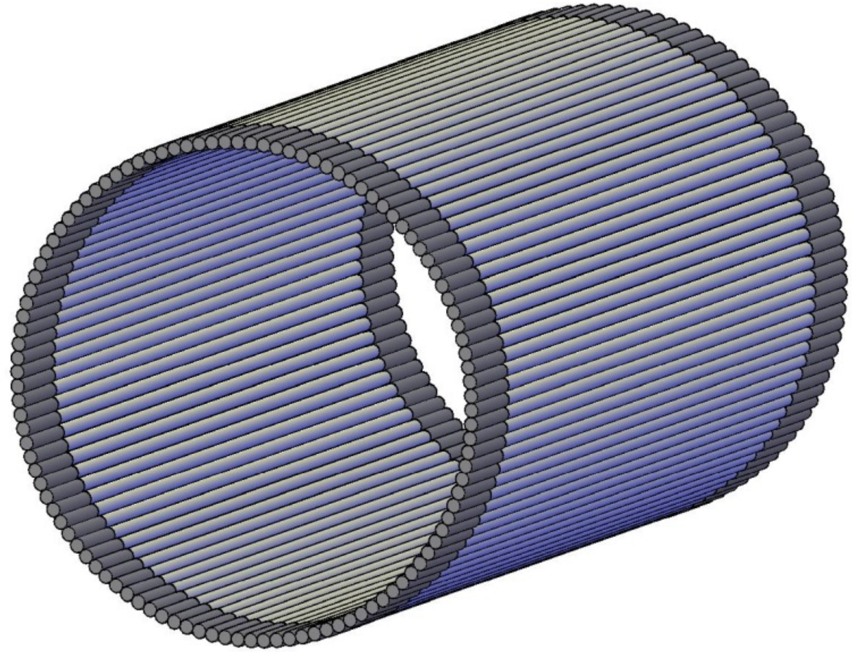




Result from: P. A. Vetter and S. J. Freedman Phys. Rev. A 66 (2002) 052505

Figure taken form the presentation of A. O. Macchiavelli, Nuclear Structure, Oak Ridge, 2006





Sigma(Delta_T) > 4.6 ns

Sigma(Delta_T) < 0.1ns

$N(\Delta t) = N_o^0 (1+C\ldots) e^{-\Delta t/\tau o\text{-}Ps}$ + $N_{direct} e^{-\Delta t/\tau b} + N_p^0 (1+C\ldots) e^{-\Delta t/\tau p\text{-}Ps}$

Efficiency + cuts 0.15 per gamma

Source activity 0.04 MBq

Acceptance x efficiency: 0.1 per gamma

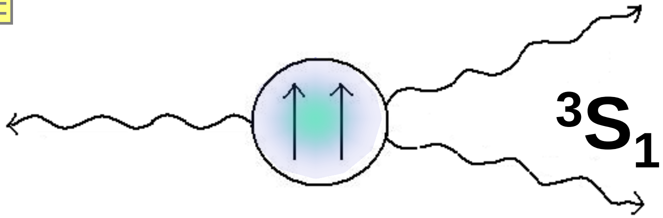
Activity > 20 MBq

pile-ups t_crystal / t_plastic_scintillator ~= 100

Angular resolution

detector 7cm(dia) / 25cm (radius)

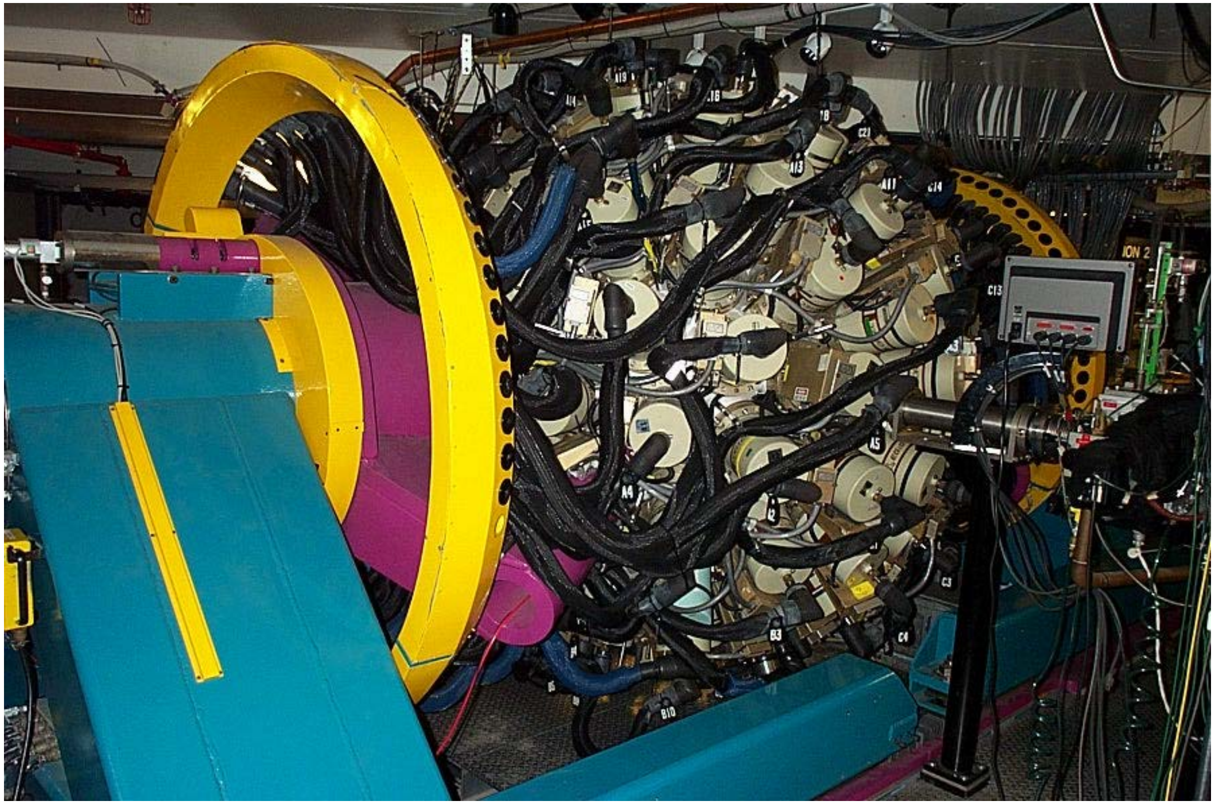
1cm / 40cm (radius)



$^3S_1$ **Ortho-positronium tau(o-Ps) ≈ 142 ns**

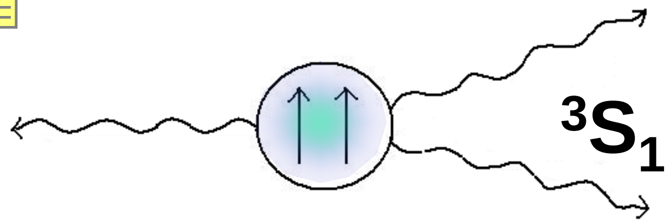
Operator	C	P	T	CP	CPT
$\vec{S} \cdot \vec{k}_1 \times \vec{k}_2$	+	+	-	+	-
$(\vec{S} \cdot \vec{k}_1)\,(\vec{S} \cdot \vec{k}_1 \times \vec{k}_2)$	+	-	-	-	+

P.A. Vetter and S.J. Freedman,
Phys. Rev. Lett. 91, 263401 (2003).
C_CPT = 0.0071 ± 0.0062



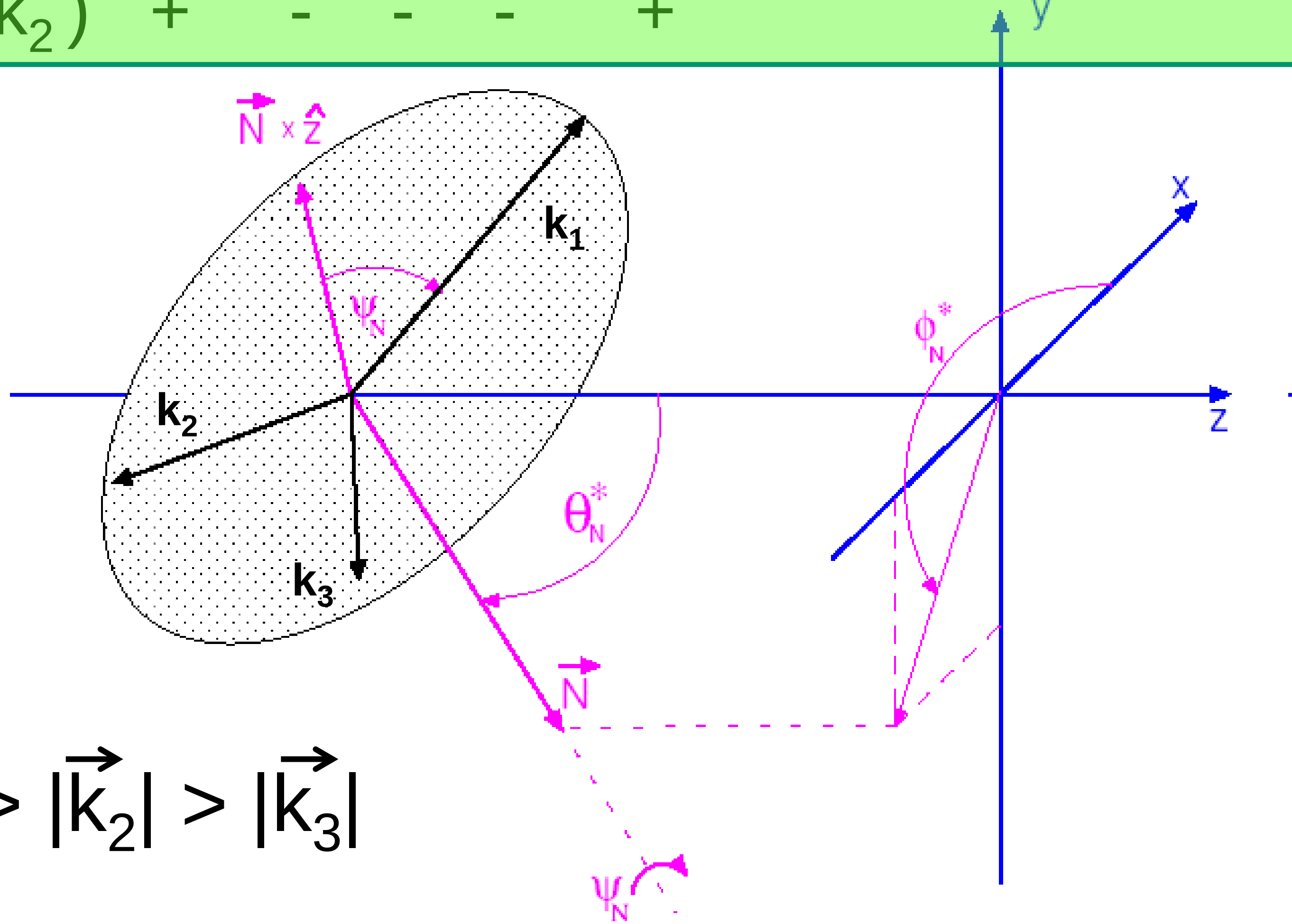
SM 10^{-10} – 10^{-9}
photon-photon interactions

Figure taken form the presentation of P. Vetter, INT UW Seattle, November, 2002

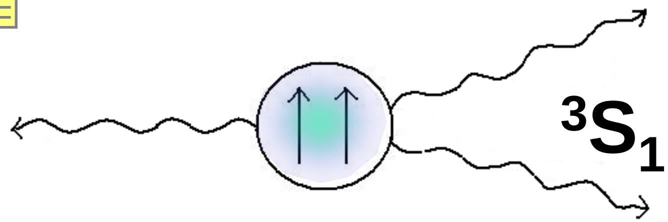


$^3S_1$ Ortho-positronium tau(o-Ps) ≈ 142 ns

Operator	C	P	T	CP	CPT
$\vec{S} \cdot \vec{k}_1 \times \vec{k}_2$	+	+	-	+	-
$(\vec{S} \cdot \vec{k}_1)(\vec{S} \cdot \vec{k}_1 \times \vec{k}_2)$	+	-	-	-	+

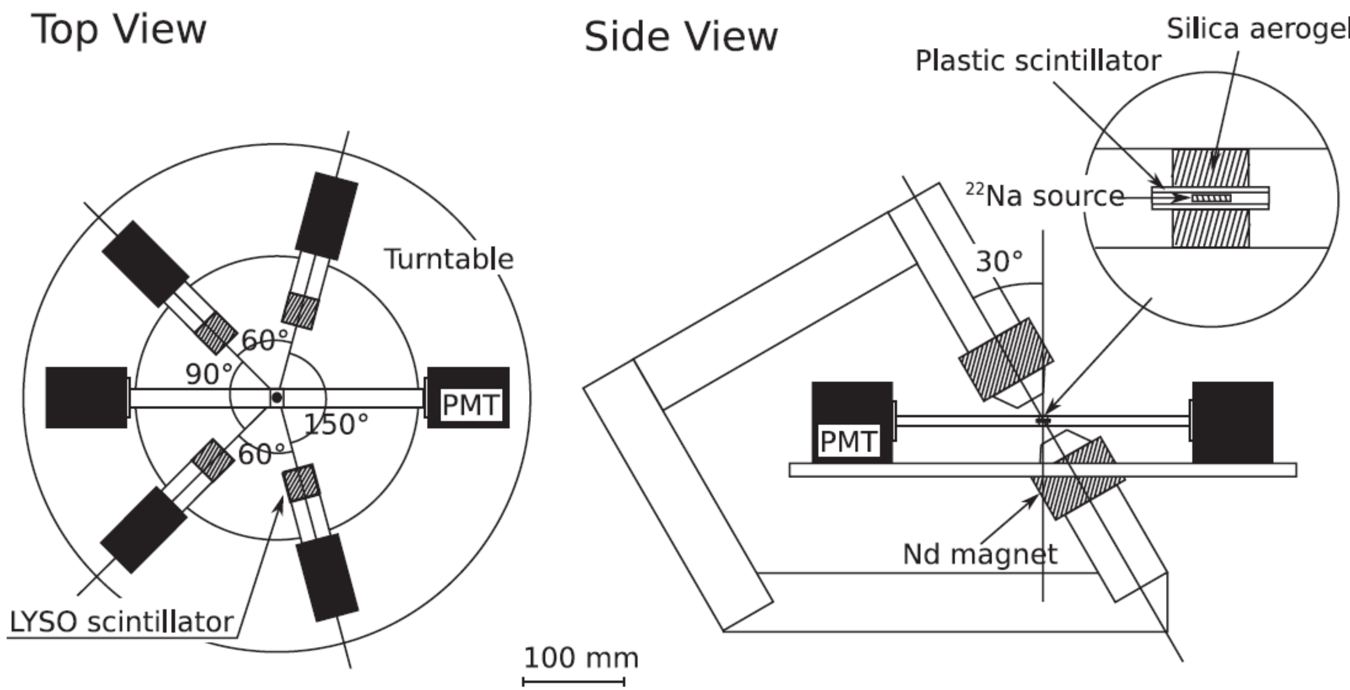


$$|\vec{k}_1| > |\vec{k}_2| > |\vec{k}_3|$$



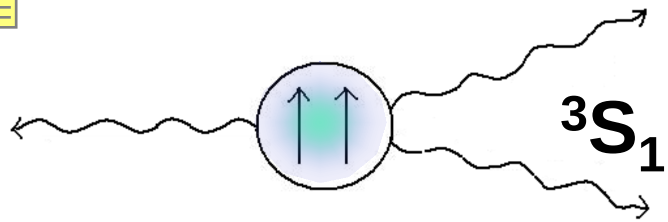
$^3S_1$ Ortho-positronium tau(o-Ps) ≈ 142 ns

So far best accuracy for **CP violation** was reported by
T. Yamazaki et al., Phys. Rev. Lett. 104 (2010) 083401



$$N = N_0[1 + C_{CP}(\vec{S}\cdot\vec{k}_1)(\vec{S}\cdot\vec{k}_1\times\vec{k}_2)]\exp(-t/\tau)$$

$$Q = (\vec{S}\cdot\vec{k}_1)(\vec{S}\cdot\vec{k}_1\times\vec{k}_2) = P_2\sin 2\theta\sin\psi\cos\phi$$



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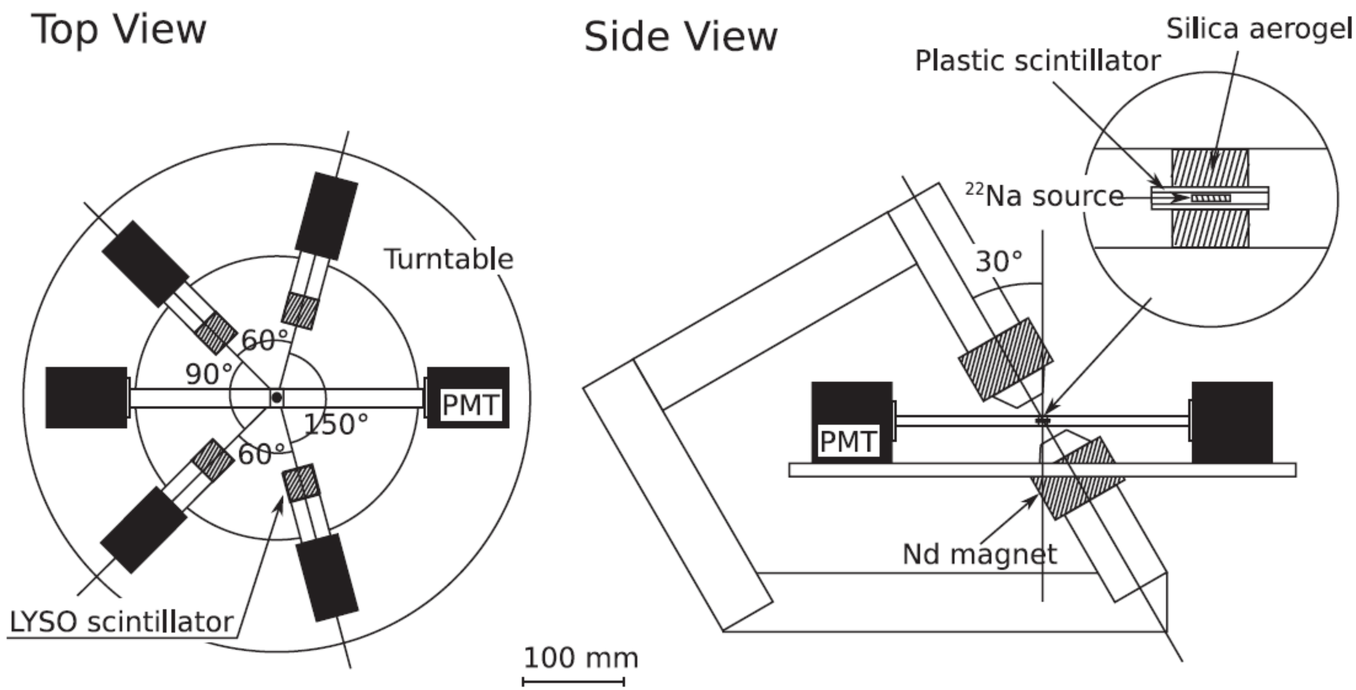
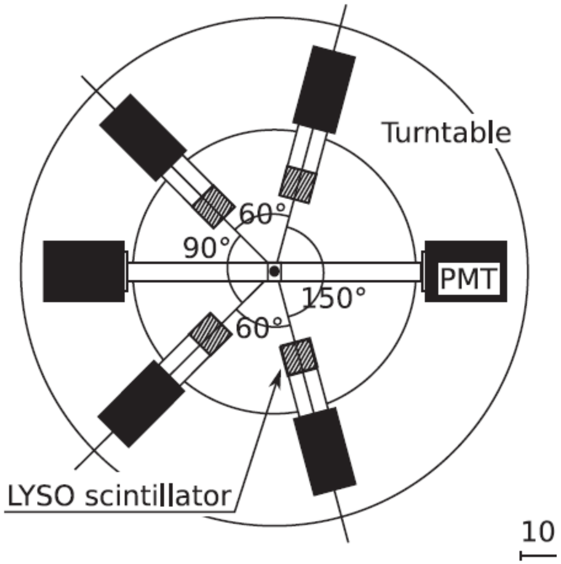
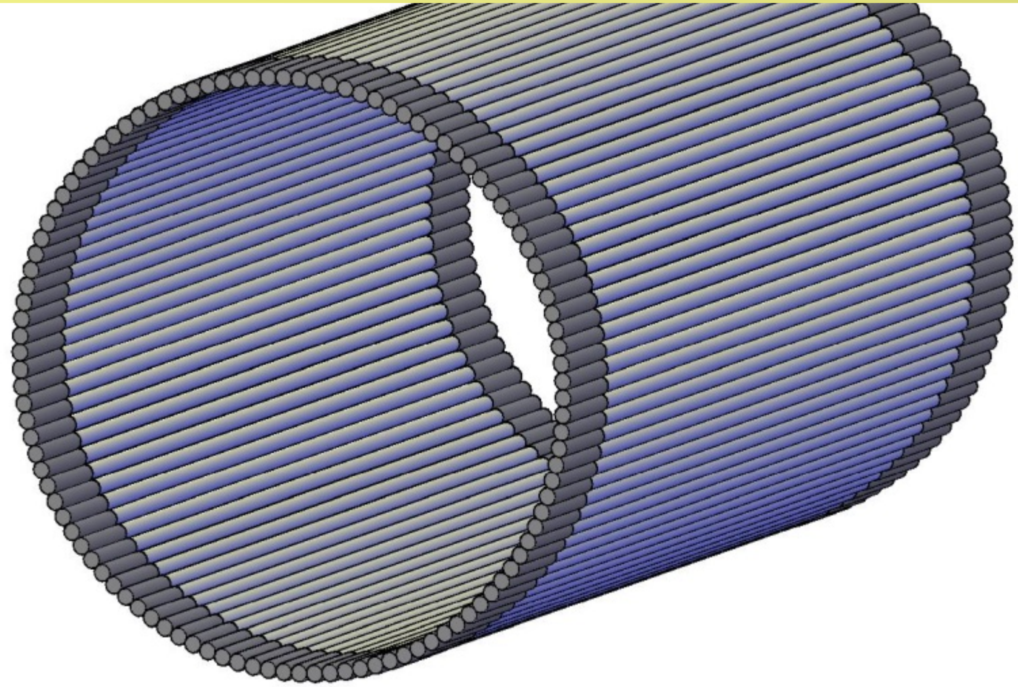


-0.0023 < C_CP < 0.0049 at 90% CL

J-PET (**J**agiellonian **PET**)





Sigma(Delta_T) ≈ 0.9ns — Sigma(Delta_T) < 0.1ns

N(psi) — N(theta, psi, phi) simultaneously, psi and psi+180

Magnet inside — Electromagnet outside

pile-ups t_crystal/t_plastic_scintillator ~= 100

Source activity 1 MBq — Activity > 20 MBq

Coincidence gate: 700ns — none (1ns … offline)

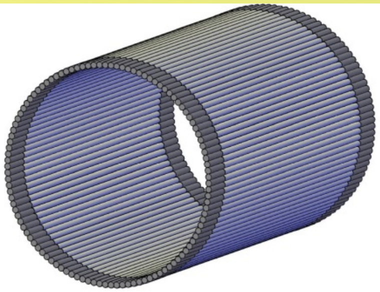
2gamma — 3gamma

Acceptance 3* 10^{-5} for 2γ — Acceptance x efficiency: 10^{-4} for 4 γ

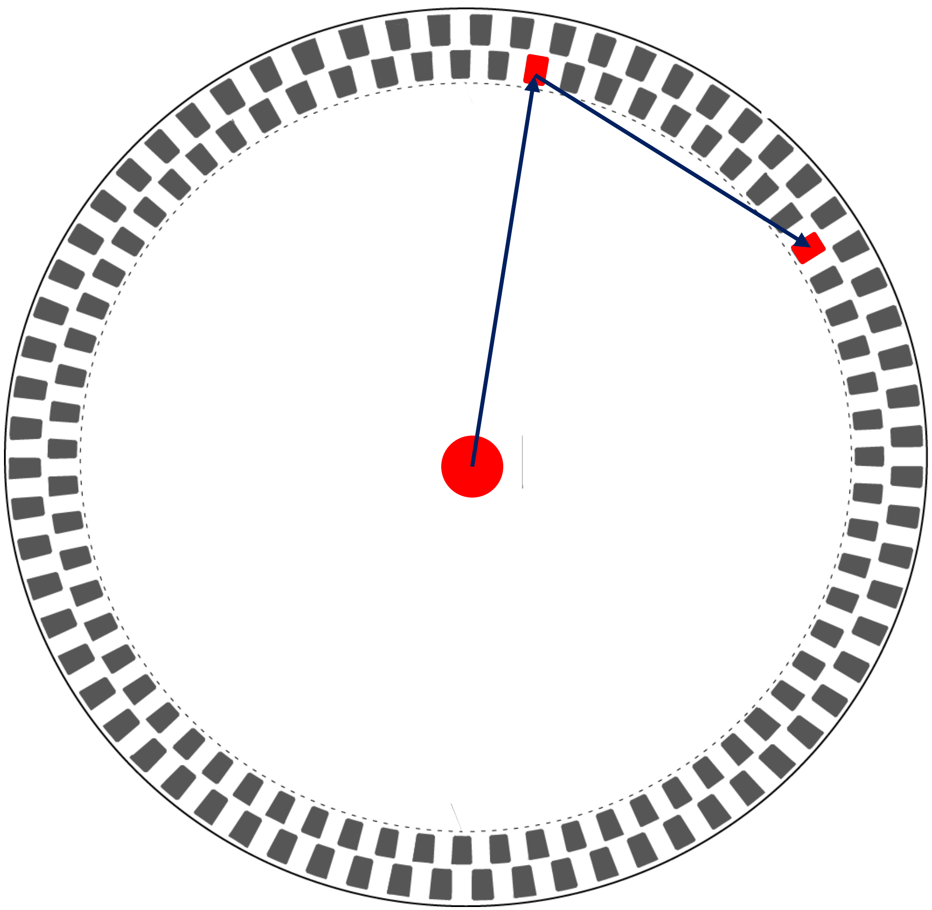
Angualar resolution

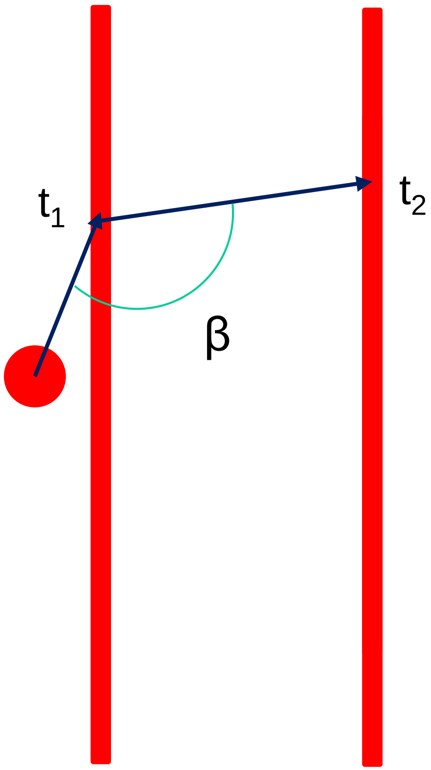
detector 3cm / 10cm (radius) — 1cm / 40cm (radius)

J-PET --> polarization of γ



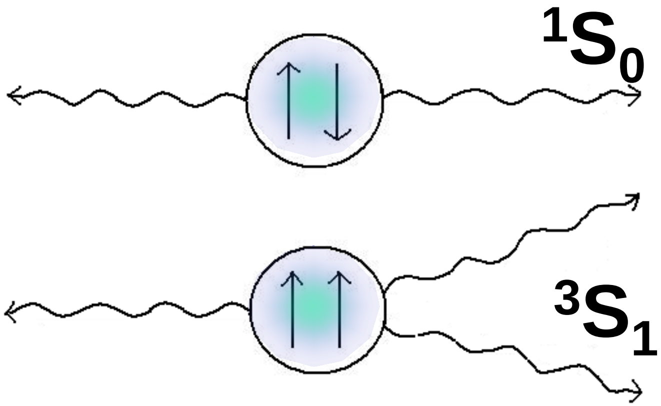
$\sigma(t_1 - t_2) < 100\text{ps}$





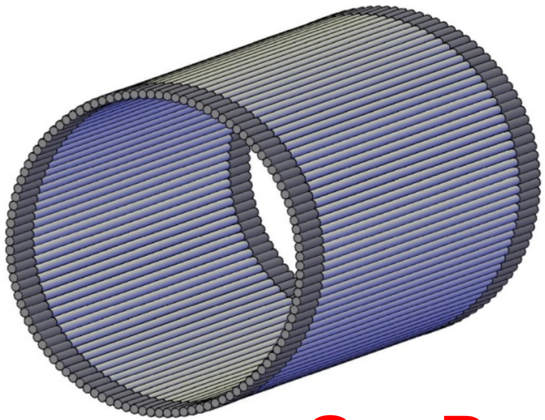
Compton scattering:

β correlated with $\vec{E}$



$^1S_0$ **Para-positronium tau(p-Ps) ≈ 125 ps**

$^3S_1$ **Ortho-positronium tau(o-Ps) ≈ 142 ns**



	T	P
$\vec{S}$	-	+
$\vec{k}$	-	-
$\vec{E}$	+	-

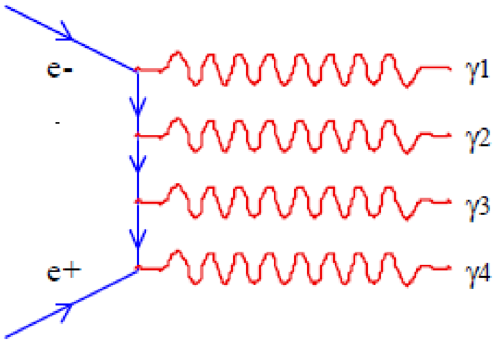
$^3S_1$ --> 3γ -->

Operator	C	P	T	CP	CPT
$\vec{S} \cdot \vec{k}_1 \times \vec{k}_2$	+	+	-	+	-
$(\vec{S} \cdot \vec{k}_1)(\vec{S} \cdot \vec{k}_1 \times \vec{k}_2)$	+	-	-	-	+

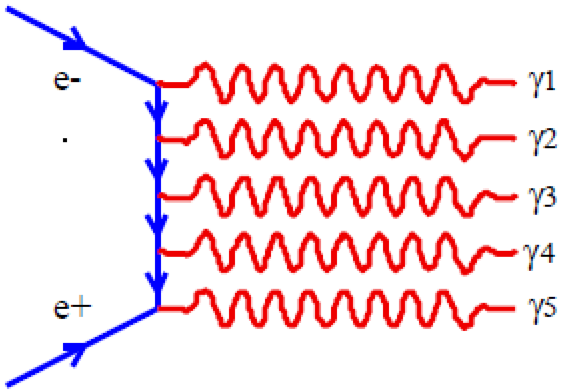
$^1S_0$ --> 2γ -->

Operator	C	P	T	CP	CPT
$\vec{S} \cdot \vec{E}_1 \times \vec{E}_2$	+	+	-	+	-
$\vec{S} \cdot \vec{E}_1$	+	-	-	-	+

Tests of QED

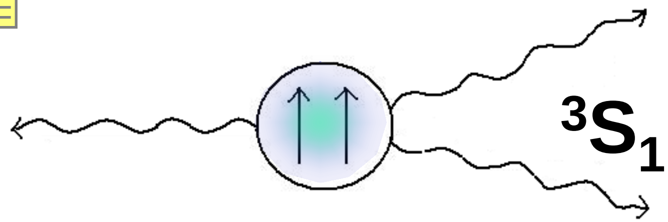


$$\Gamma(\mathrm{Ps} \to 4\gamma) \approx \alpha^7 = 1.43\ 10^{-6}$$



$$\Gamma(\mathrm{Ps} \to 5\gamma) \approx \alpha^8 = 0.959\ 10^{-6}$$


THANK YOU
FOR YOUR ATTENTION



$^3S_1$ **Ortho-positronium tau(o-Ps) ≈ 142 ns**

Operator	C	P	T	CP	CPT
$\vec{S} \cdot \vec{k}_1 \times \vec{k}_2$	+	+	-	+	-
$(\vec{S} \cdot \vec{k}_1)(\vec{S} \cdot \vec{k}_1 \times \vec{k}_2)$	+	-	-	-	+

T. Yamazaki et al., Phys. Rev. Lett. 104 (2010) 083401

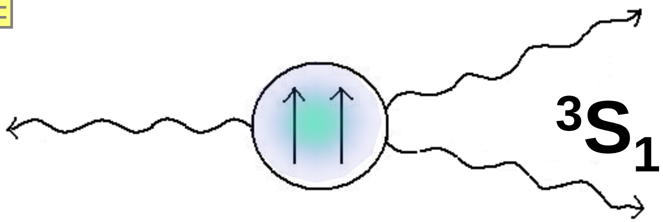
-0.0023 < C_CP < 0.0049 at 90% CL

P.A. Vetter and S.J. Freedman, Phys. Rev. Lett. 91, 263401 (2003).

C_CPT = 0.0071 ± 0.0062

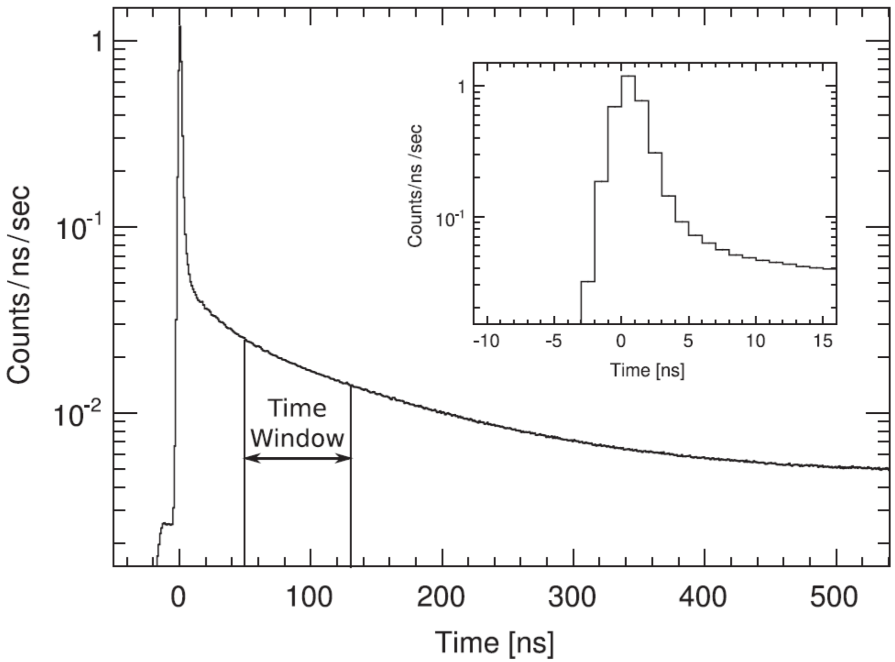
SM 10^{-10} – 10^{-9} W. Bernreuther et al., Z. Phys. C 41, 143 (1988)

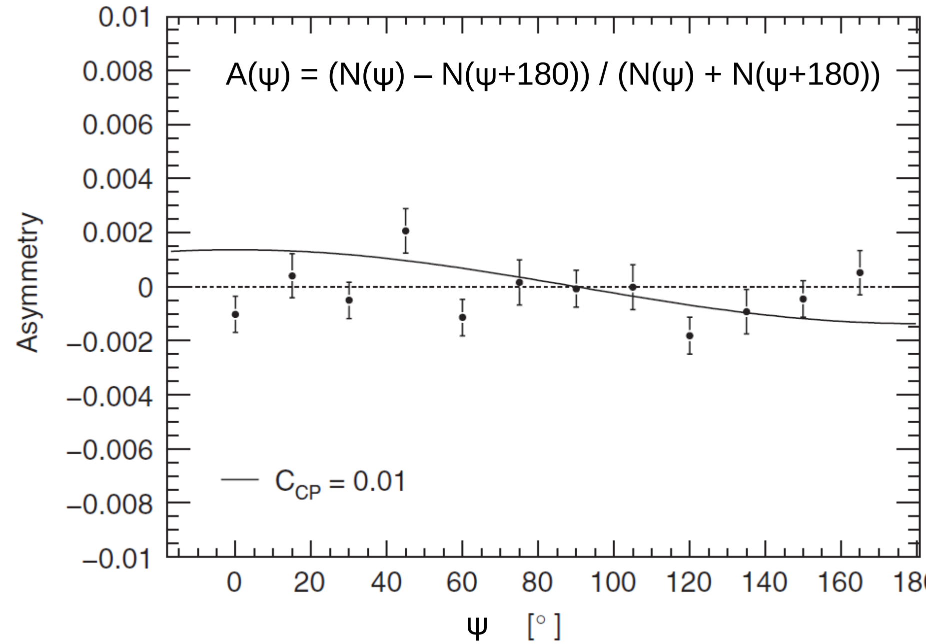
This is due to photon-photon interactions in the final state caused by the creation of virtual charged particle pairs.



$^3S_1$ Ortho-positronium tau(o-Ps) ≈ 142 ns

T. Yamazaki et al., Phys. Rev. Lett. 104 (2010) 083401





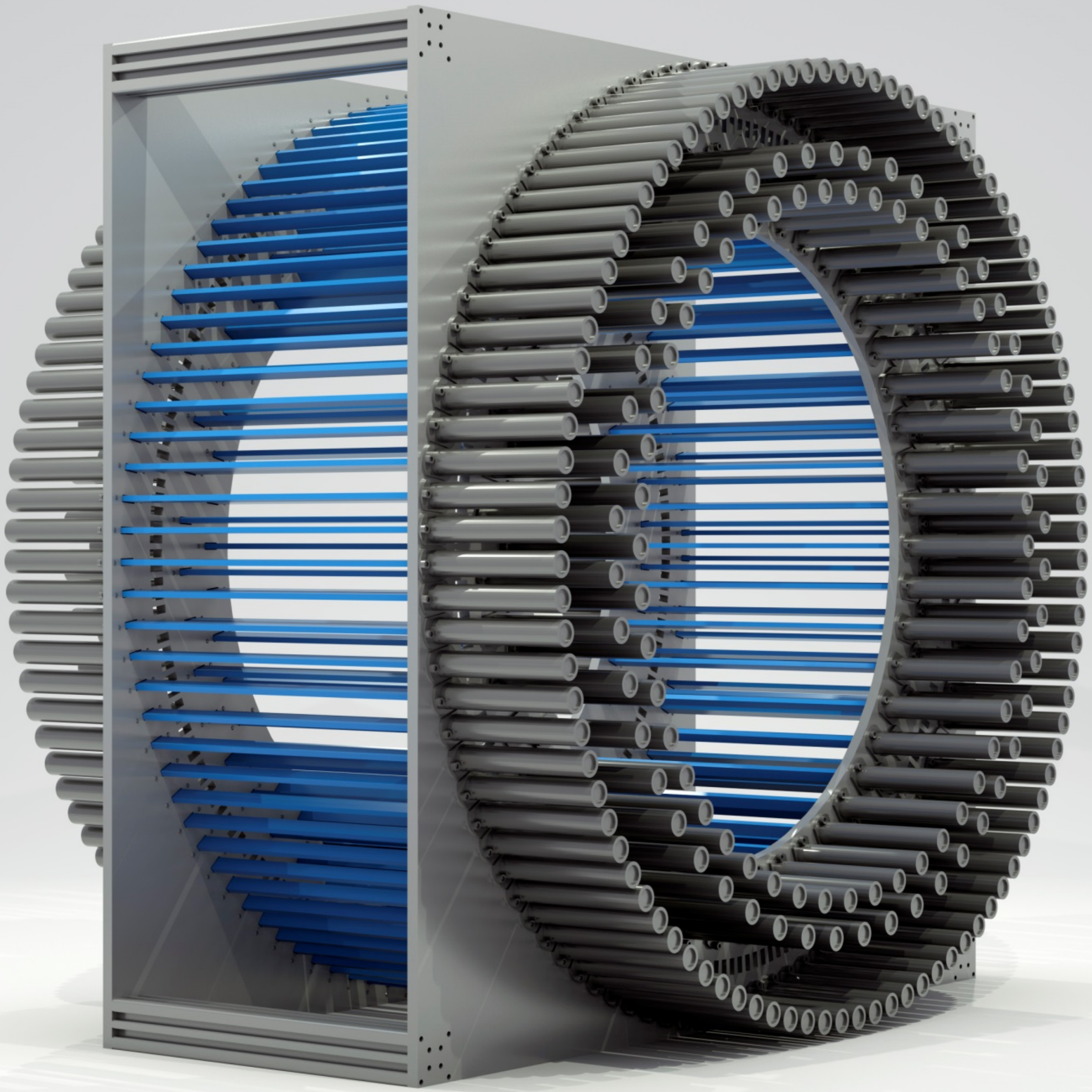
-0.0023 < C_CP < 0.0049 at 90% CL

SM 10^{-10} – 10^{-9}

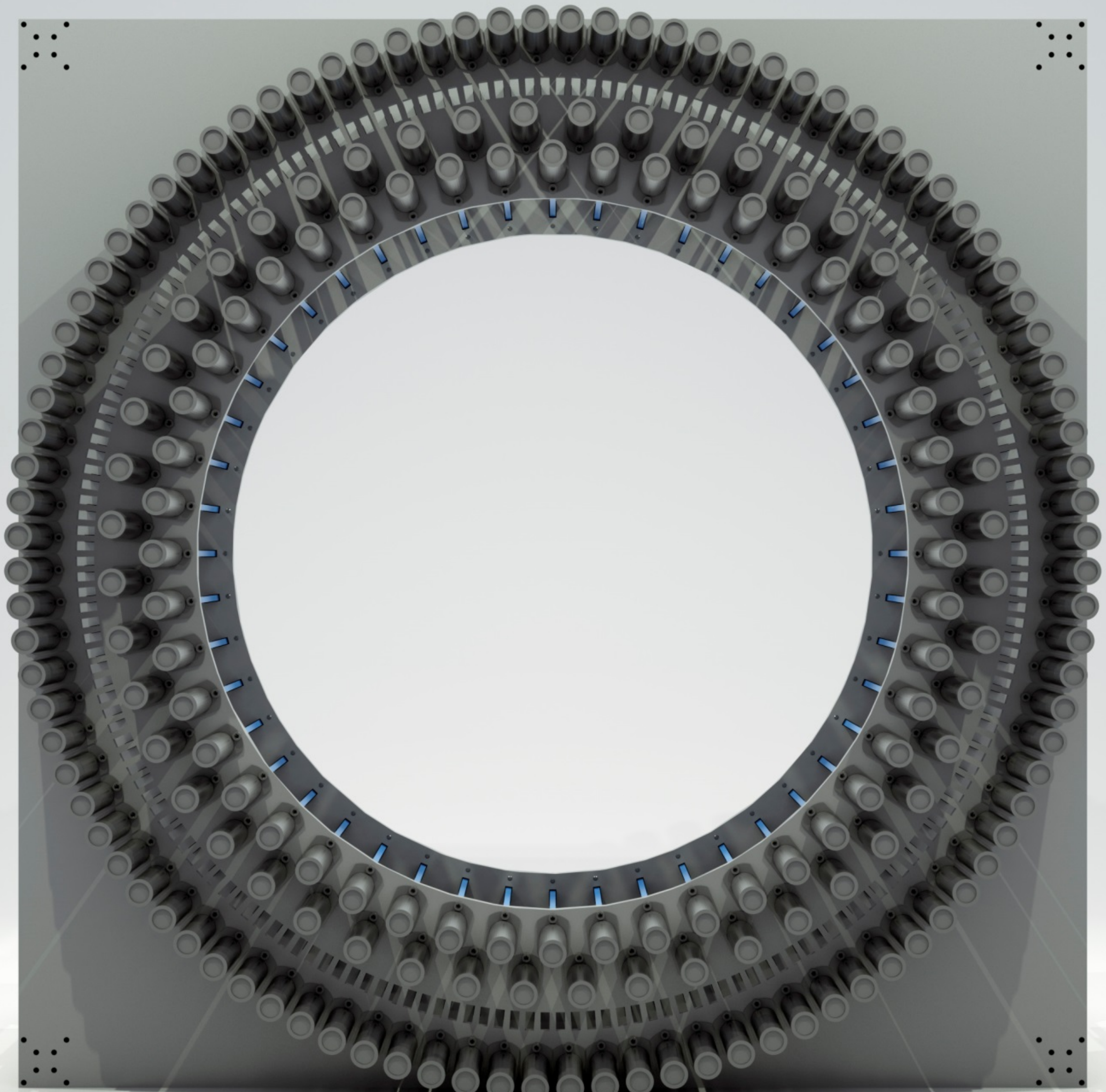
W. Bernreuther et al., Z. Phys. C 41, 143 (1988)

This is due to photon-photon interactions in the final state caused by the creation of virtual charged particle pairs)

$$P_2 = \frac{N_{+1} - 2N_0 + N_{-1}}{N_{+1} + N_0 + N_{-1}}$$



crystals → plastics




THANK YOU
FOR YOUR ATTENTION