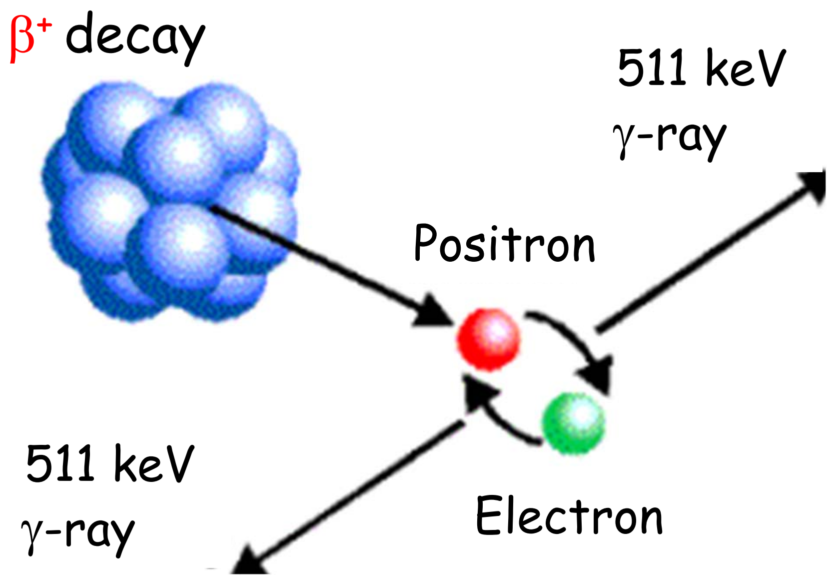
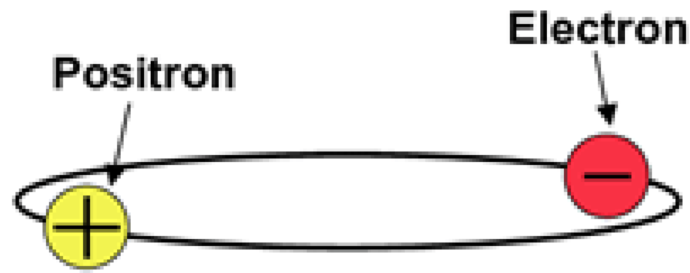
# Positronium decay (Ps)

The positronium is a bound state of the electron and positron similar to a Hydrogen atom. The positronium can be produced from positrons emitted from $\beta^+$ decays.




The energy levels of the positronium are similar to the one of the Hydrogen atom.

The energy spacing is smaller by a factor of 2 because the reduced mass of the positronium is lower by a factor 2.

Positronium

$$m_{ee} = \frac{m^2}{2m} = \frac{m}{2}$$

Hydrogen

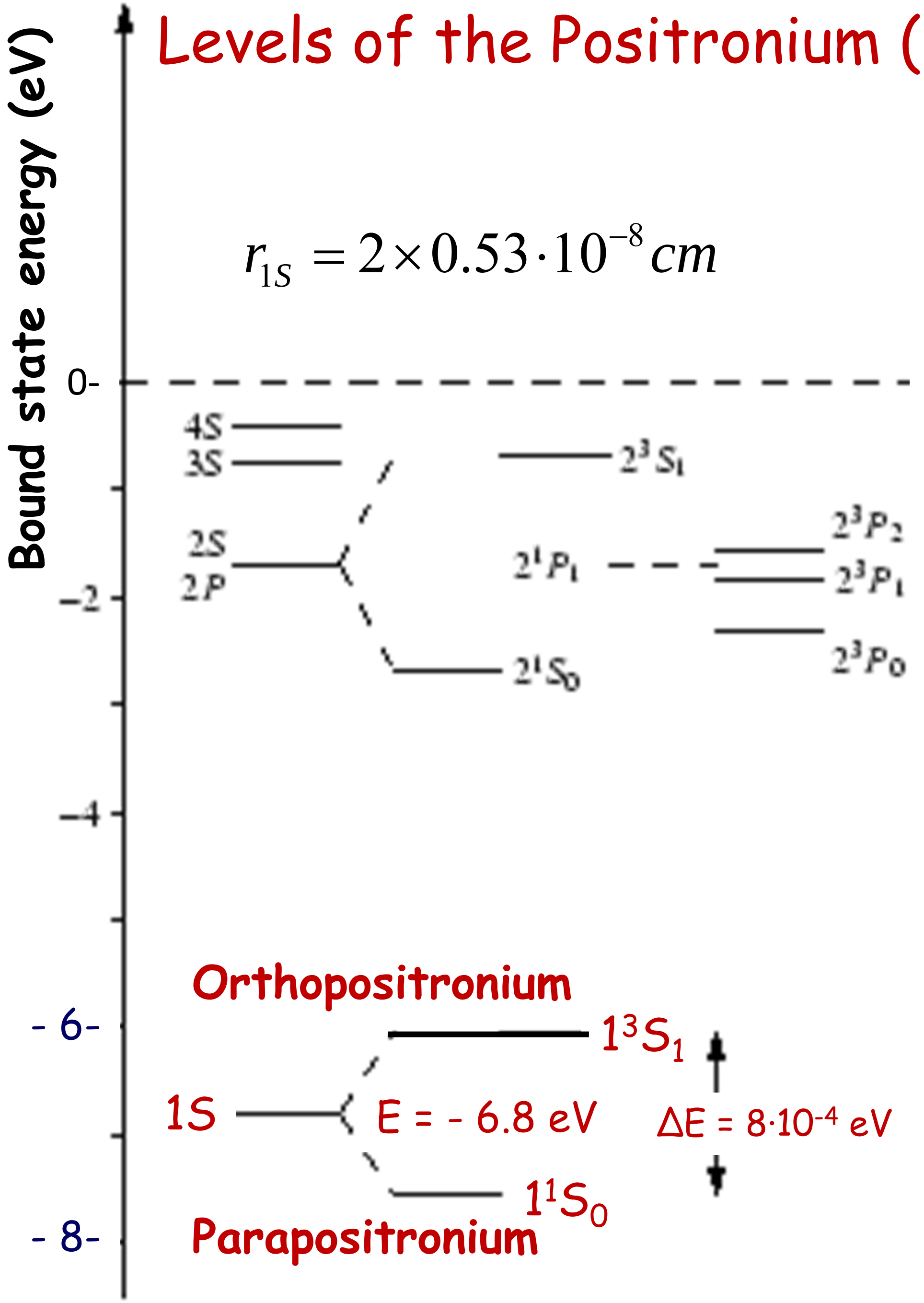
$$m_{ep} = \frac{M \cdot m}{M + m} \approx m$$

# Levels of the Positronium (Ps)

$$r_{1S} = 2 \times 0.53 \cdot 10^{-8}\, cm$$

$$E_n = -\frac{\mu \cdot e^4}{8 \cdot h^2 \varepsilon_0^2} \frac{1}{n^2} = -\frac{6.8}{n^2} \;\; eV$$

$\mu$ = reduced mass
n = principal quantum number



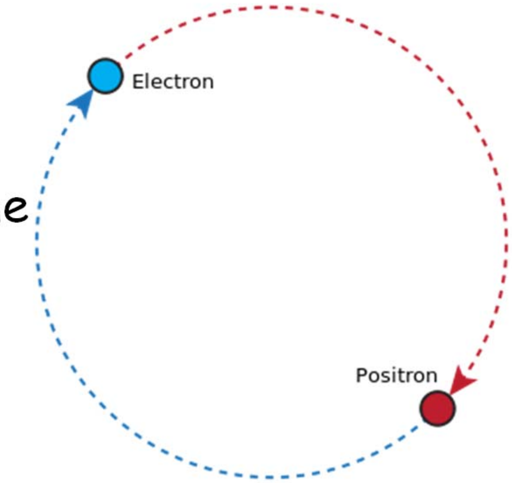

The lowest lying level splits in two states:

- *parapositronium* (lifetime 125 ps), the electron and the positron have antiparallel spin, coupled to S=0. This state annihilates mainly in **two photons** with opposite directions, each one having energy 511 keV.

- *orthopositronium* (lifetime 142 ns), the electron and the positron have parallel spin, coupled to S=1. This state annihilates in **three photons** with energies and directions satisfying conservation of energy and momentum.

In vacuum, one forth of the bound states of Ps are formed in a state with S=0, while three forth are formed in a triplet state with S=1

In order to preserve angular momentum and respect CP (Charge and Parity) invariance, a positronium in a state of spin S and orbital momentum L annihilates according to the following **selection rule**:




$$(-1)^{n_\gamma} = (-1)^{L+S}$$

Parapositronium $n_\gamma$ =2,4,...

Orthopositronium $n_\gamma$ =3,5,...

The ratio between the decay channel in three photons and that one in two photons is 1/373. It is a consequence of the ratio between the lifetimes of the two states and of their phase space

125 ps for the Parapositronium

142 ns for the Orthopositronium

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# The Three-Photon Annihilation of Positrons and Electrons*

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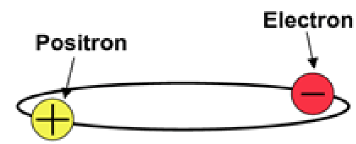
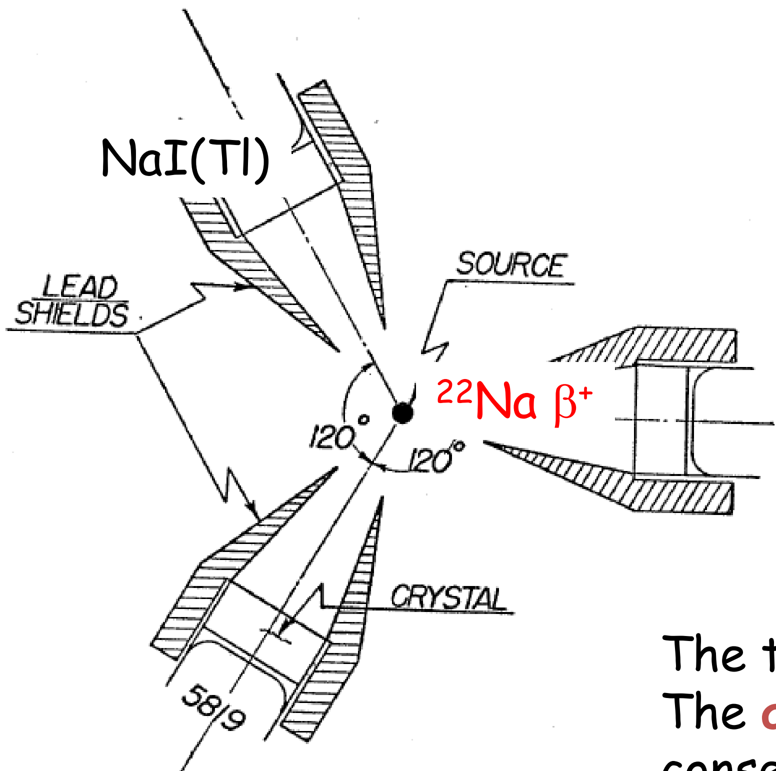
(Received January 22, 1954)

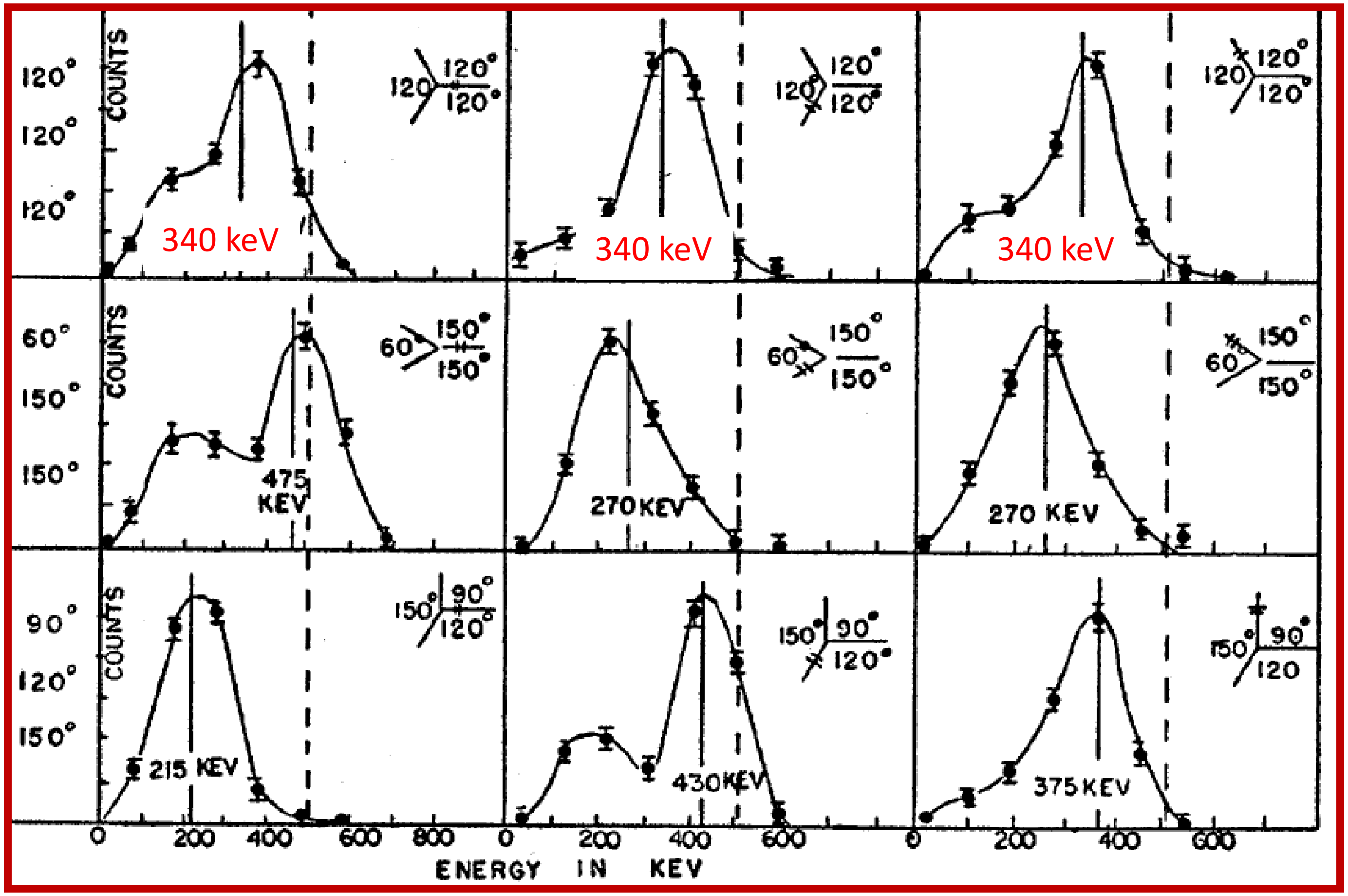


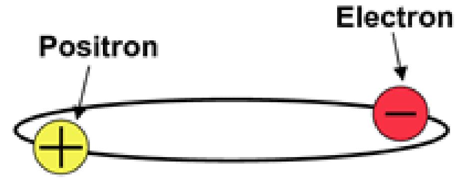




| Angles between counters 2–3 | 3–1 | 1–2 | Energy in each counter (kev) $E_1$ | $E_2$ | $E_3$ |
|---|---|---|---|---|---|
| *120° | 120° | 120° | 341 | 341 | 341 |
| *90° | 120° | 150° | 430 | 215 | 375 |
| *60° | 150° | 150° | 475 | 272 | 272 |

The three NaI(Tl) detectors lay on the same plane. The **annihilation takes place at rest** and as a consequence the total momentum is negligible. The sum of the momenta of the two (or three) photons must be negligible.

2γ decay in line
3γ decay in the same plane




The expected energies for each of the detectors are reported. Their sum must be 1022 keV

As a consequence of the **conservation of linear momentum and energy**, the energies of the three photons depend on the emission angles. If the three detectors have a symmetrical configuration with 120 deg in between them, the three photons must have the same energy, i.e. 340 keV.

Suggestion for data analysis: distance between source and detector is ~15cm and therefore the solid angle subtended by the detectors (10cm wide) is not always 120º

The ratio (~1/370) between the annihilation events in 3$\gamma$ and that one in 2$\gamma$ has been verified to have a slight dependence on the material where the positronium annihilates

## Lifetime of the positron decay in matter

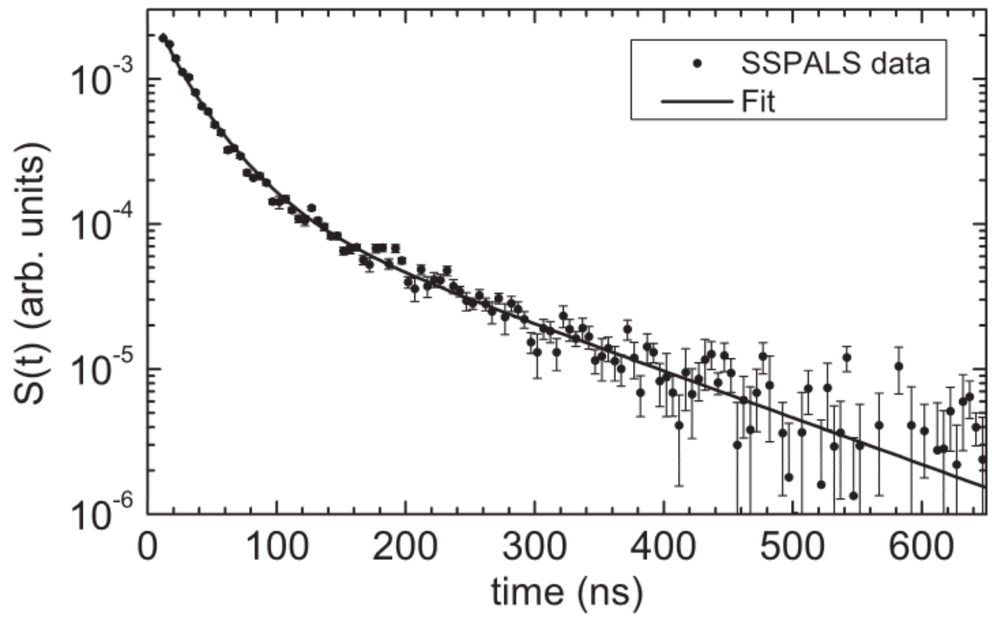
In vacuum the orthopositronium decays with $\tau$ = 142 ns. In matter the lifetime depends on the type of material.

In this experiment with mesoporous silicon two components were measured, one with

$\tau_1$ = 25.03±0.3 ns

The other with

$\tau_2$ = 140 ±7 ns

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**Delayed emission of cold positronium from mesoporous materials**

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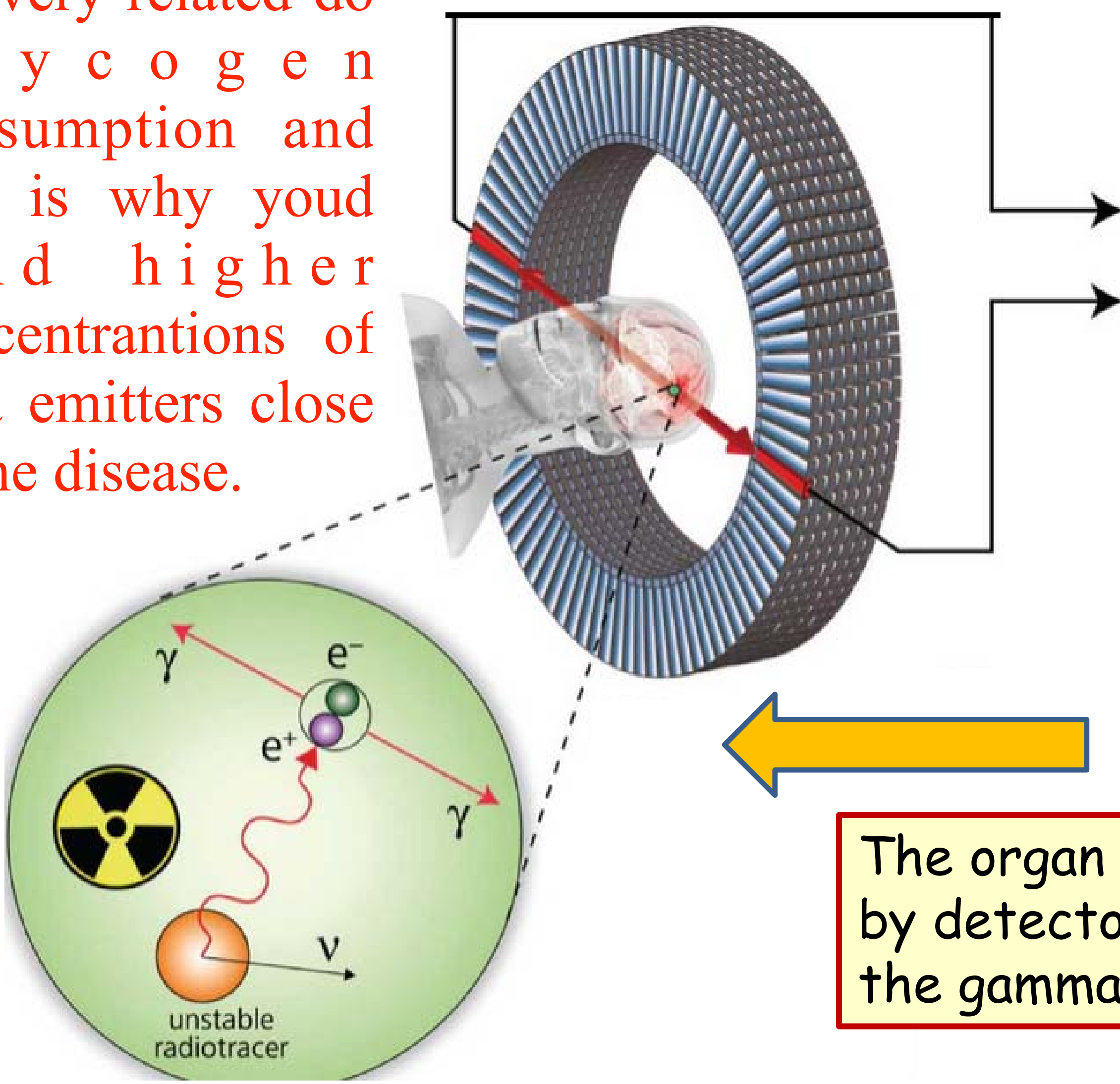
Check the lifetimes of orthopositronium and parapositronium

Positrons have a wide use in nuclear medicine, for example in

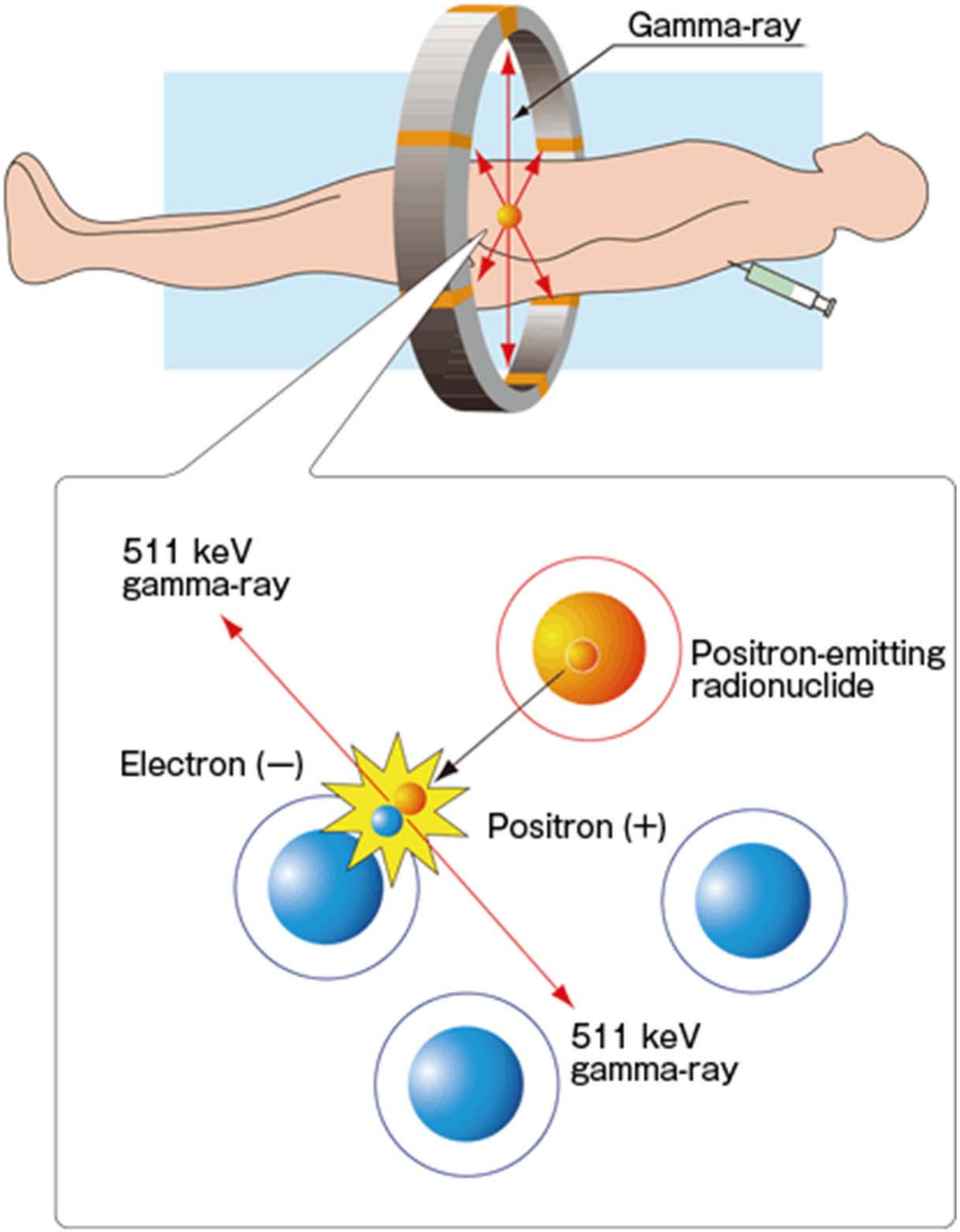
# Positron Emission Tomography (PET)

The radioisotopes are very related do glycogen consumption and this is why youd find higher concentrantions of beta emitters close to the disease.




Compounds with a small contents of radioisotopes with short lifetime such as the nuclei $^{11}C$ or $^{18}F$ ( $\beta^+$ emitters) can be injected and can be traced till they concentrate in specific tissues or organs.
It is possible to trace them because they decay by positron emission that annihilates with the electrons and yield two gammas of 511 keV in opposite direction.

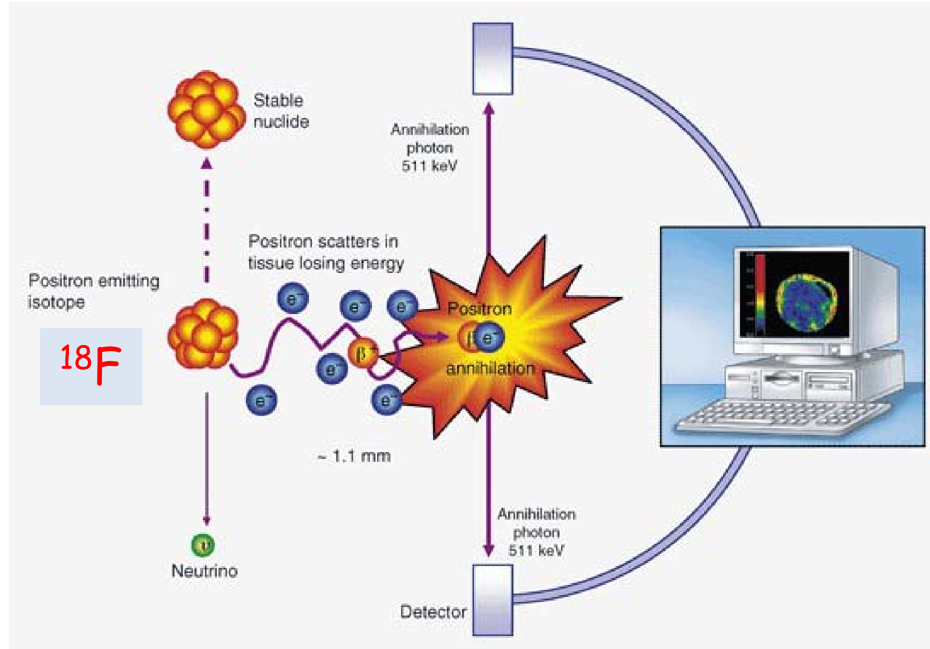
The organ has to be surrounded by detectors that can detect the gamma radiation emitted

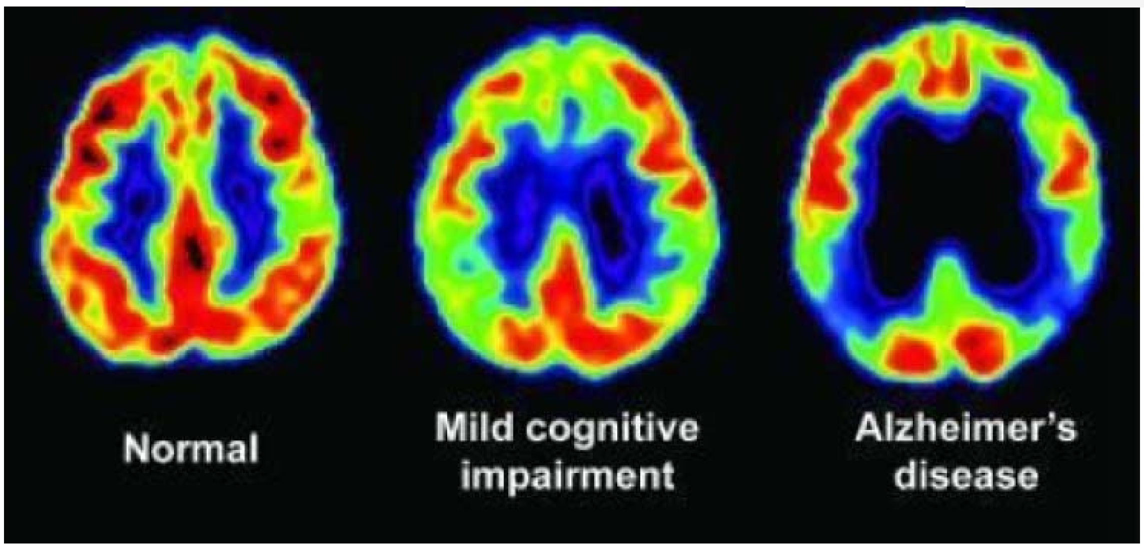



When two detectors detect the arrival of two photons in time coincidence it is reasonable that the two photons were emitted by the same annihilation decay.
The position where there was the decay of the $^{11}C$, $^{13}N$ or $^{18}F$ must be along the line connecting the detectors that fired.

Identifying many couples of photons, exploiting many crossings, it is possible to guess the position or distribution of the radioactive elements.

<u>Following the processes</u> for a proper amount of time it is possible to obtain a <u>map of the changes in concentration of the elements.</u>
This paves the way to a functional study of the heart, the brain or other organs, with the possibility of diagnosing their functional problems.



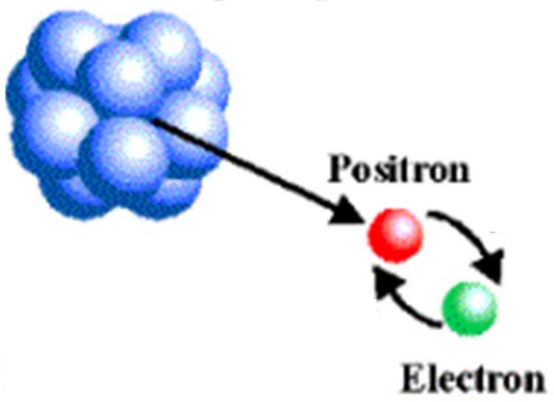




PET images shows a <u>lowering of the consumption of glycogen</u> associated to a weaken cognitive capacity as a consequence of the Alzheimer disease.
The fluorodeoxyglucose [$^{18}$F]FDG is commonly used.

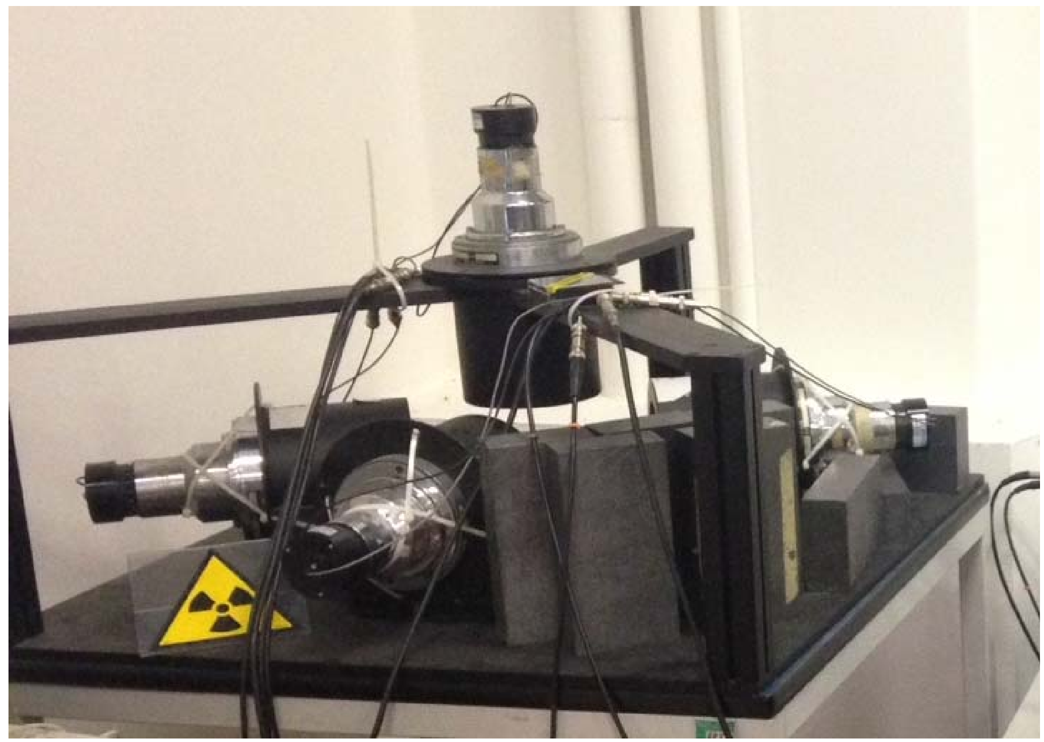
Goals of the experience are a) measurement of the ratio between positron decay in two photons and decay in three photons

b) measurement of the time distribution of the events

$^{22}$Na source

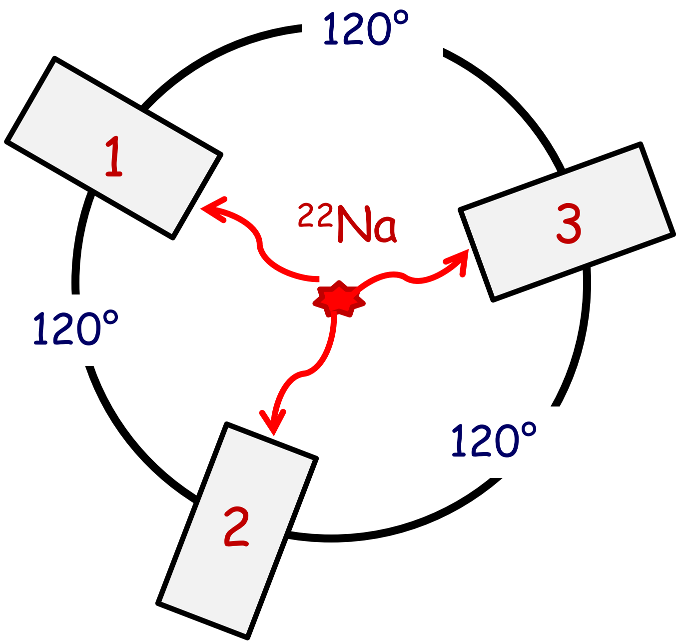



The two or three gammas emitted in coincidence will be measured by three scintillator detectors NaI(Tl) 4" x 4"
laying in the same plane. A forth NaI(Tl) is positioned on top, in an orthogonal direction to that plane.

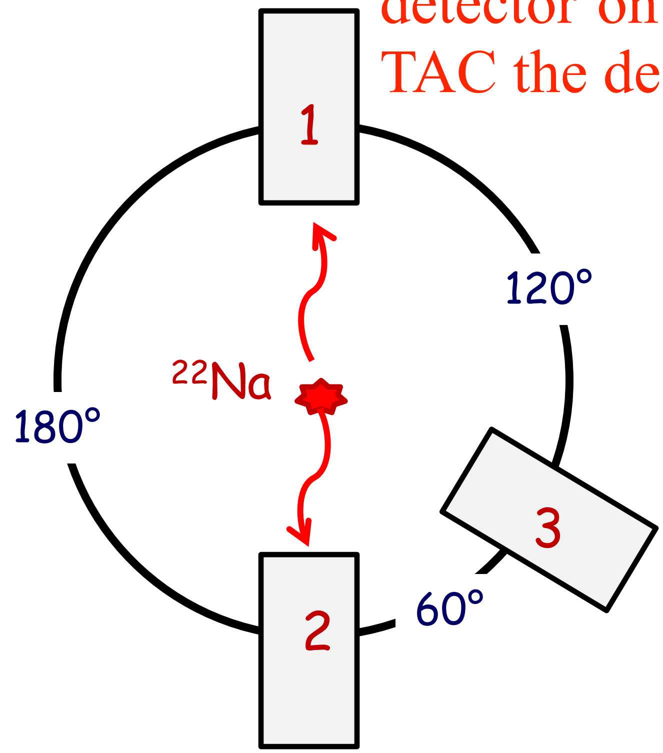


The three detectors are mounted on a rotating arm that allows the variation of the angle in between them.
Two configurations will be used:

One of the three detectors is not used. With the fourth detector on the top to TAC the decay



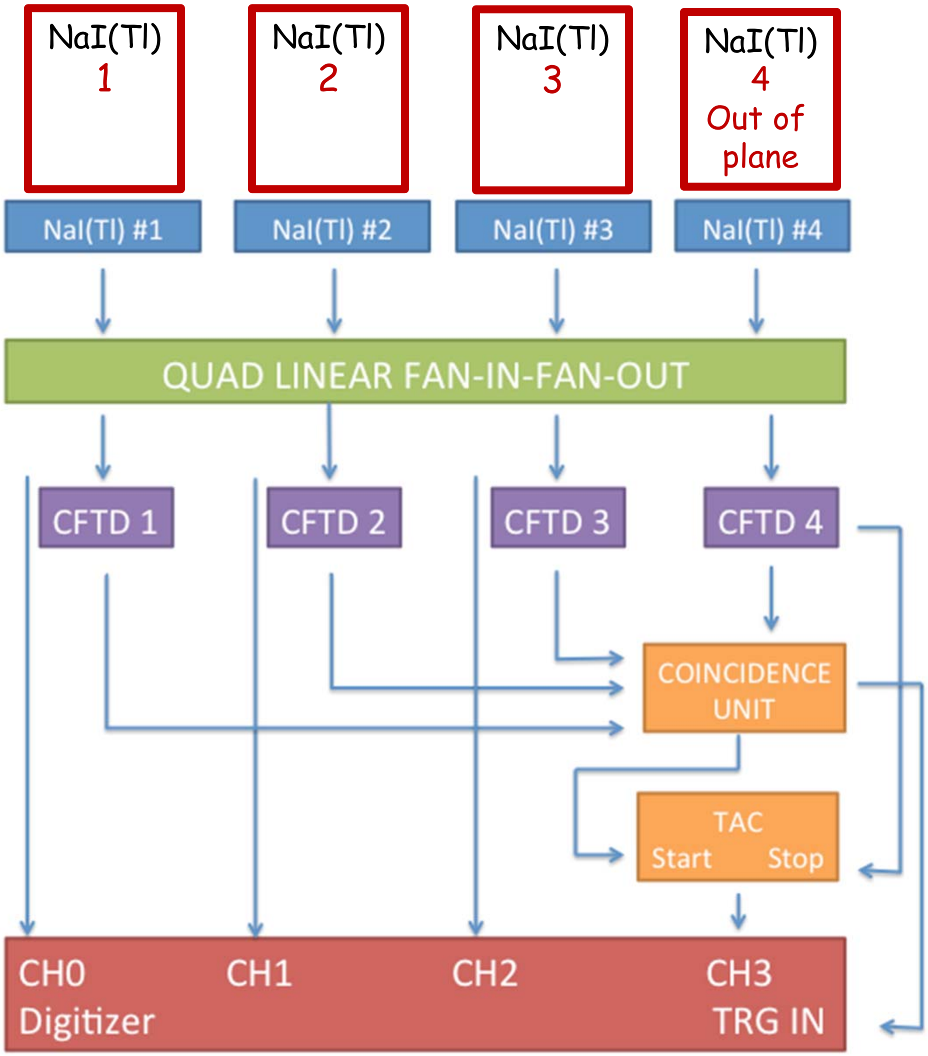

Three-gammas decay




Two-gammas decay

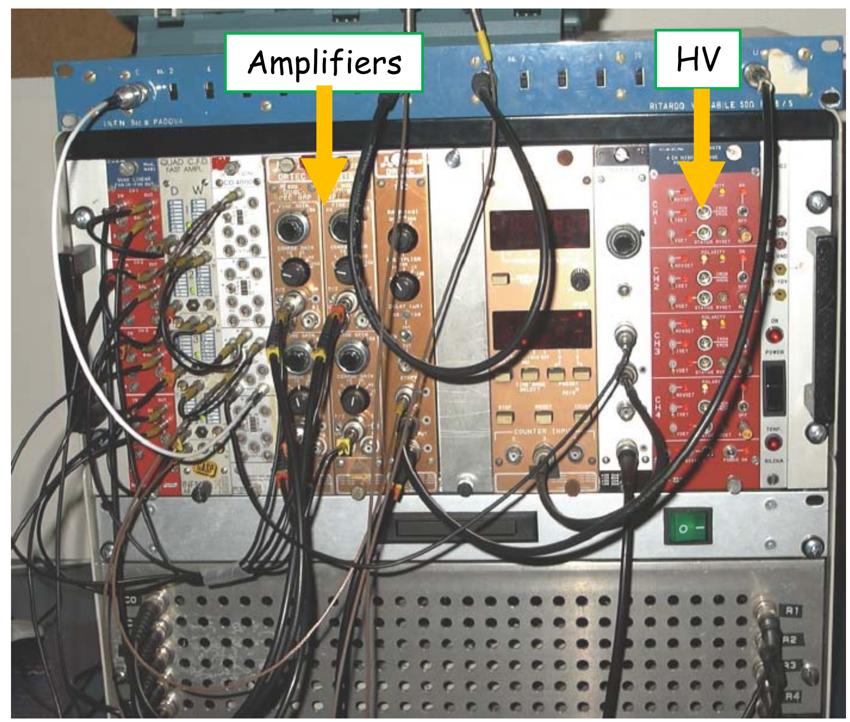
We can measure the 1.2 MeV gamma as the time start where the positronium has been created.

# Electronics layout

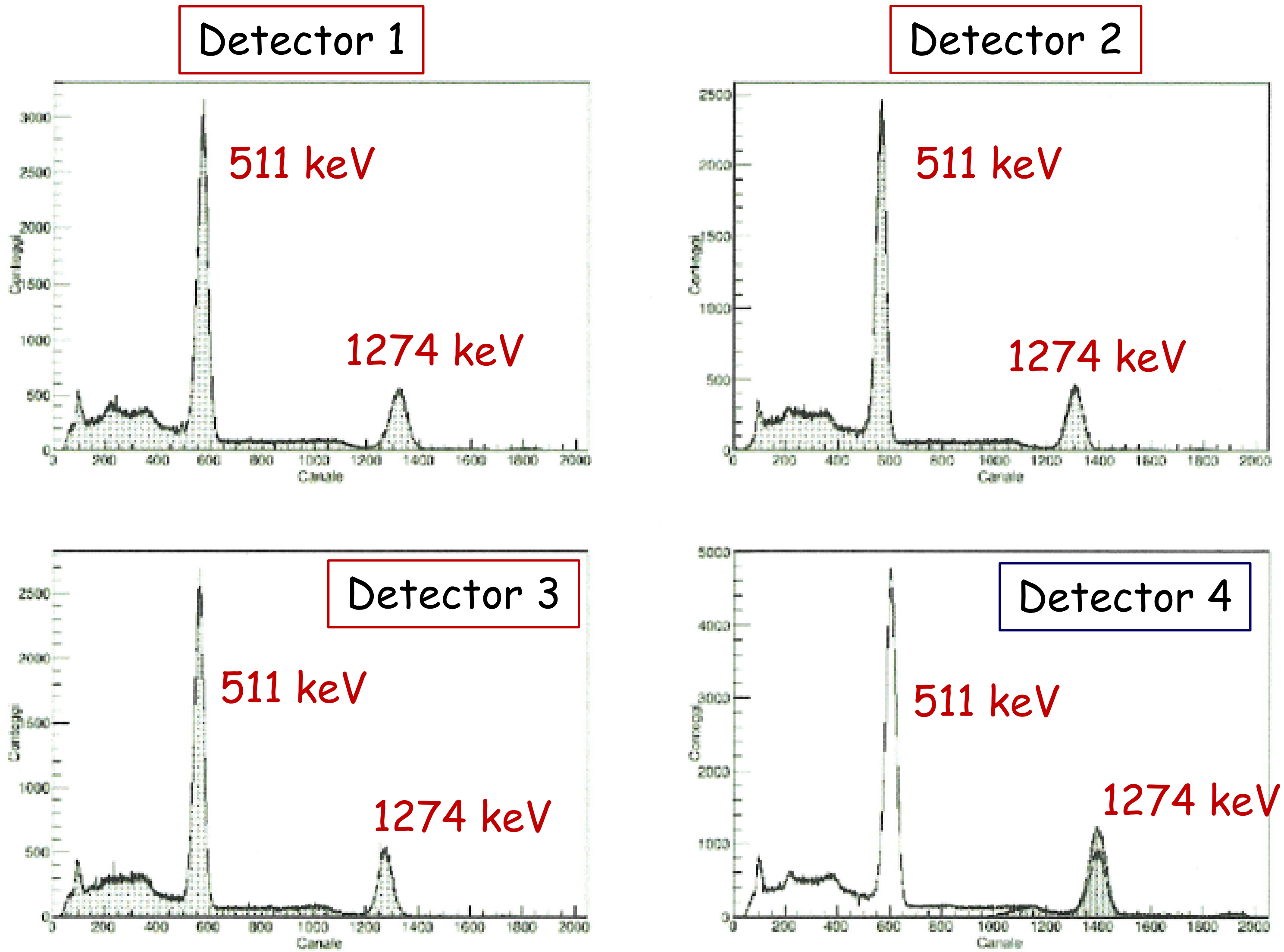



Time to amplitude converter: measure the decay time of the positronium

The three detectors 1, 2 and 3 are taken in coincidence in between them and also in coincidence with the 1274 keV gamma in detector 4 out of plane.



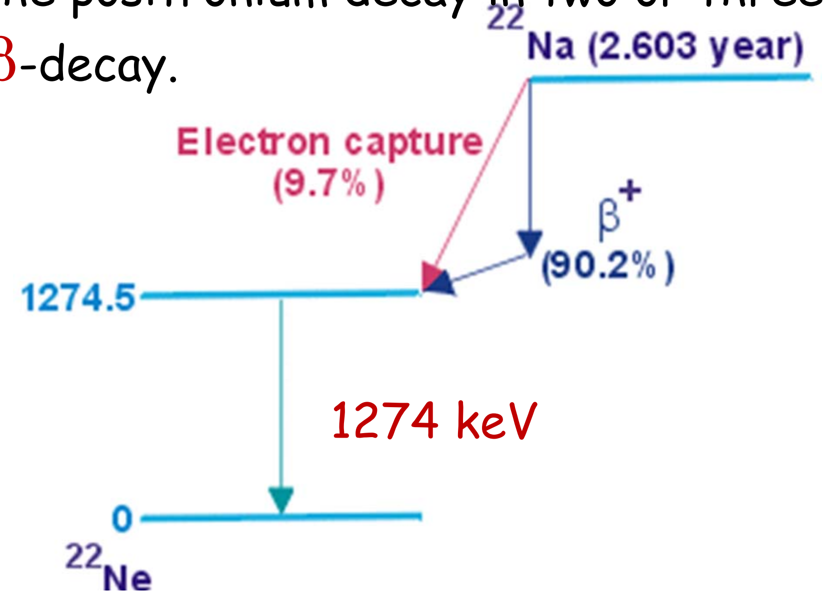
# Energy calibration of the 4 NaI(Tl) detectors

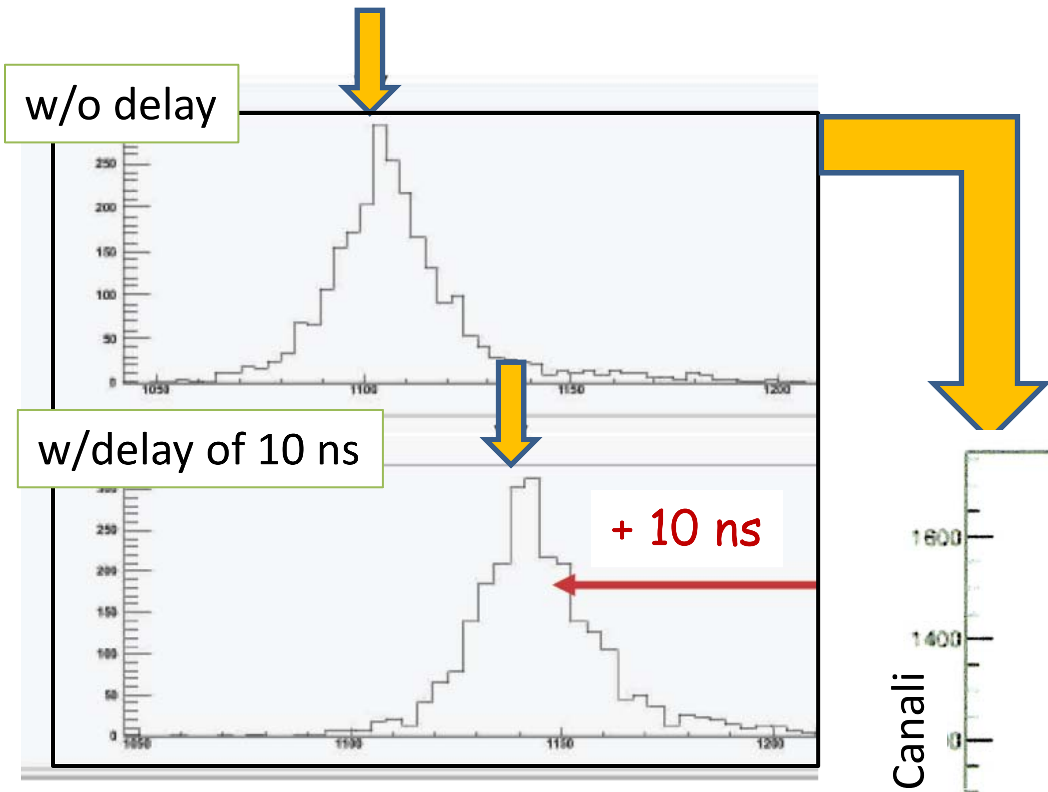



Use best the 1274 peaks, setting the threshold maybe at ~600 keV

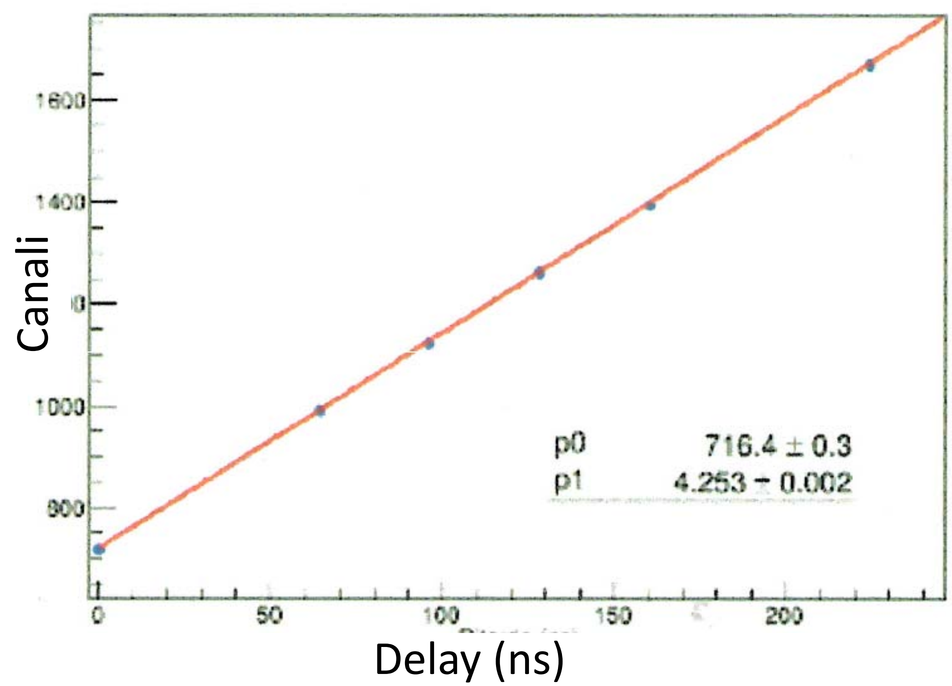
# TAC calibrations (Time to Amplitude Converter)

In order to measure the coincidence between the positronium decay in two or three photons and the $\gamma$ decay of $^{22}Ne$ populated by $\beta$-decay.



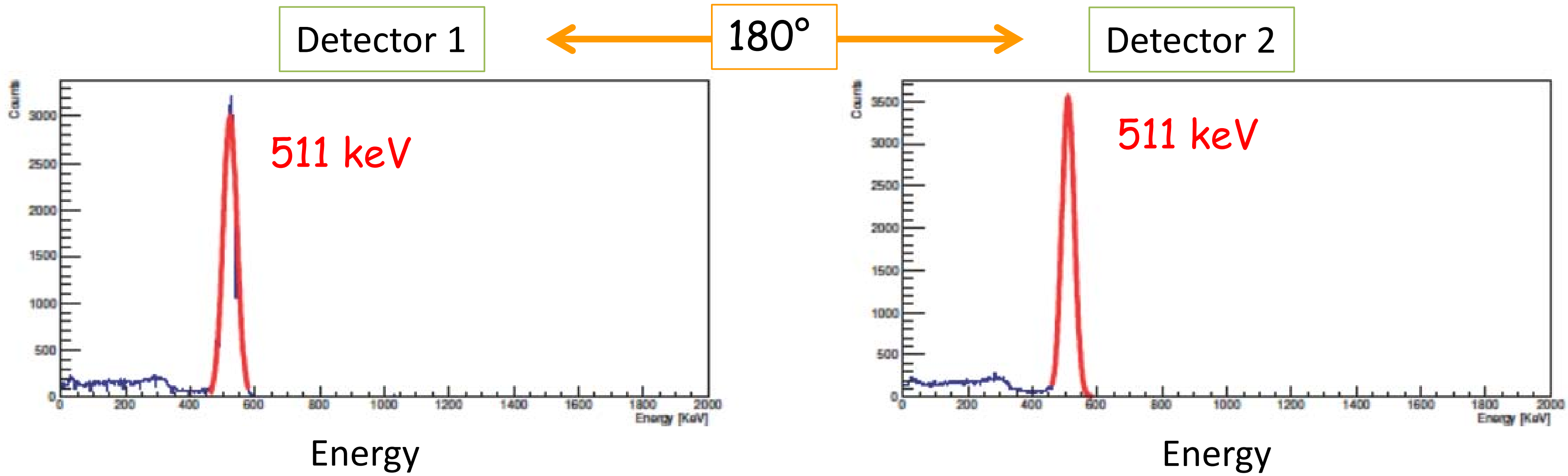




TAC calibration

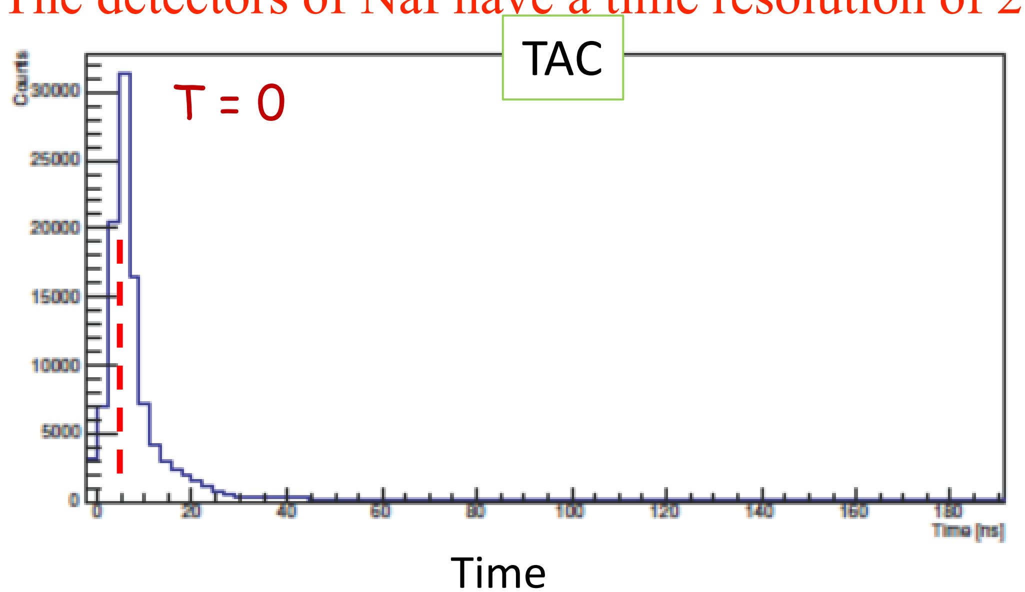


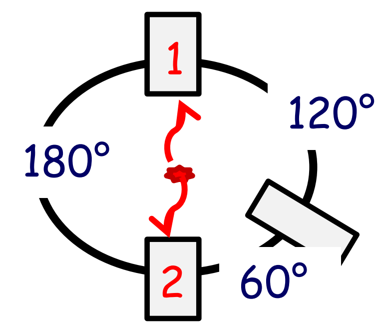

Calibration of the channels and delay.

# Results: two photons decay



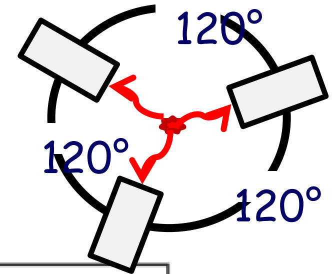

The detectors of NaI have a time resolution of 2 ns

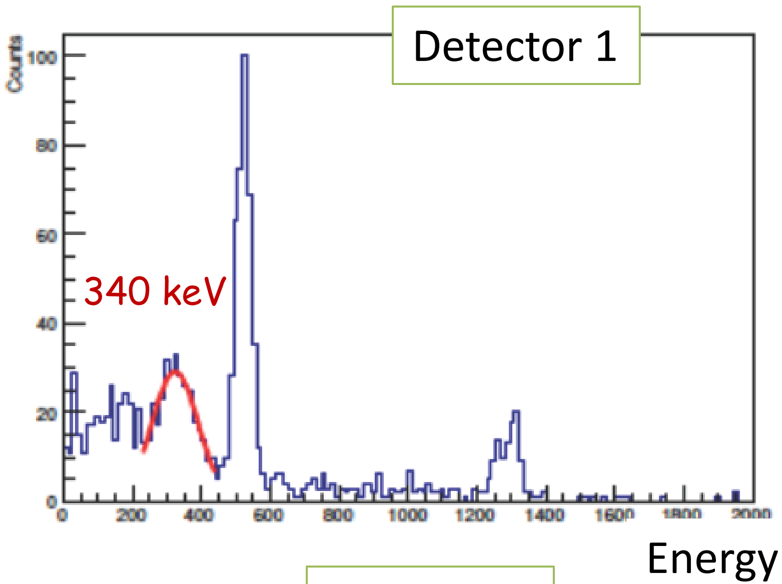


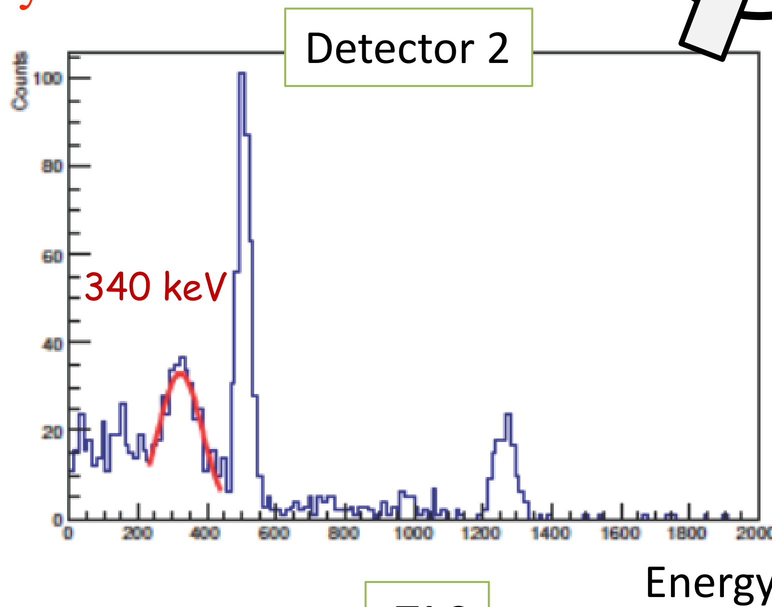



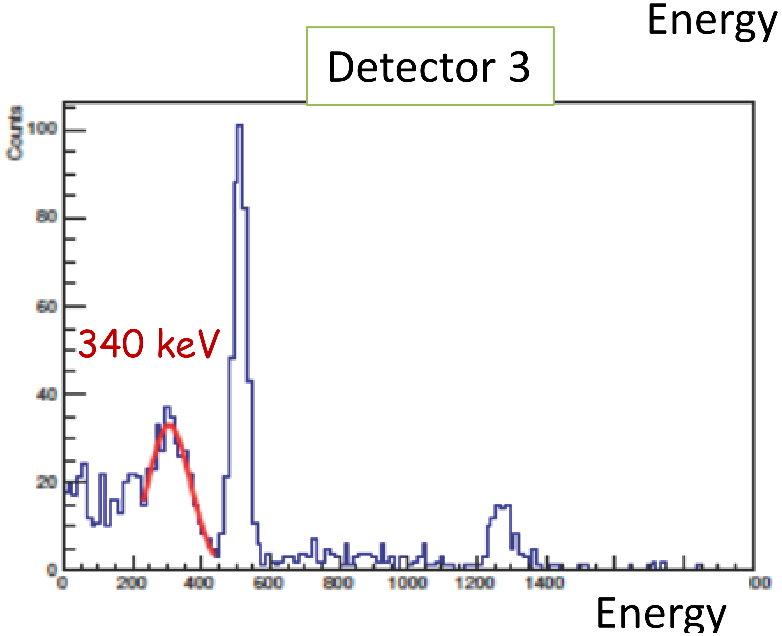
# Results: three photons decay

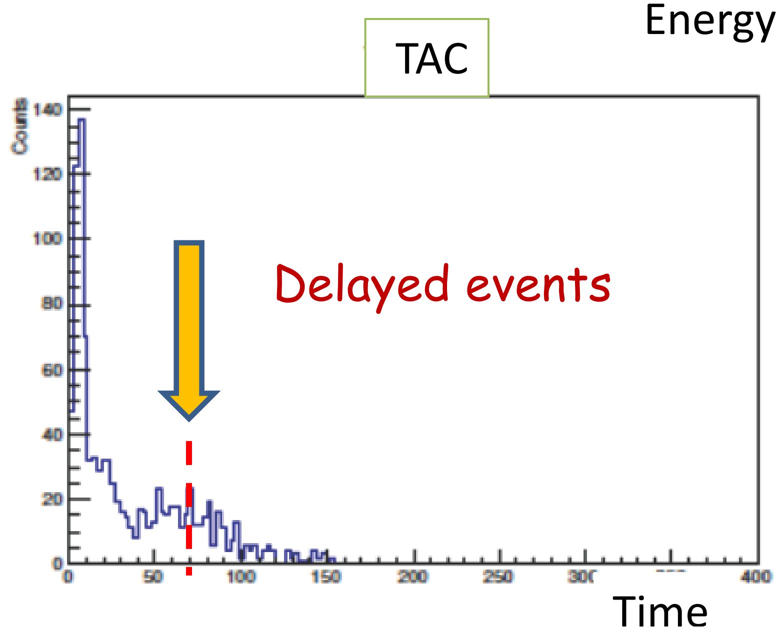
Were always going to find peaks at 511 keV and 1.2 MeV. The probabilities are greater for two photon decay.



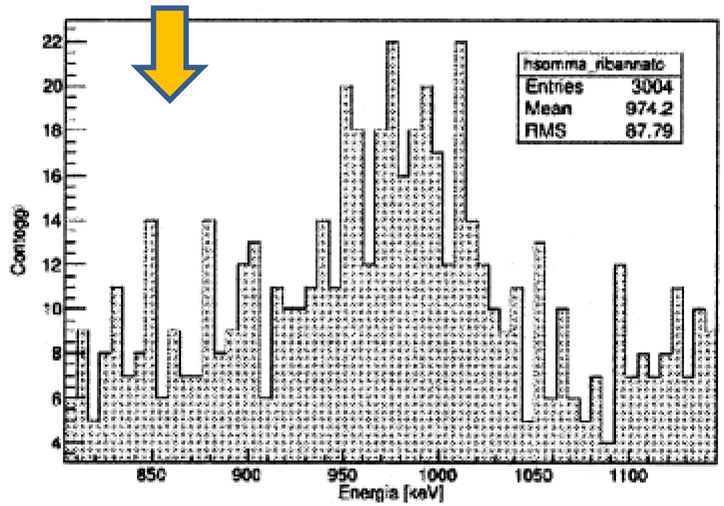



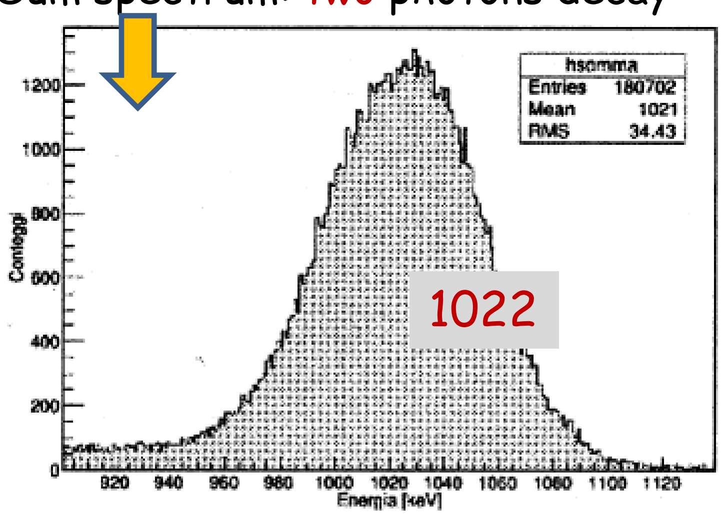



Sum gamma spectra: the energies measured by each detector are summed and incremented in a spectrum → $\Sigma$ = 1022 keV

Sum spectrum: three photons decay




Sum spectrum: two photons decay




In order to measure the three gamma decay we have to wait for a long time!!

Summarizing, the goals of the Positronium experiment are'

a) to verify the ratio in between the two photons decay and the three photons decay of the positronium

b) to measure the timing distribution of the events for the two tyoes of decay

- First session: preparation and calibration of the scintillators
- Second session: setup of the coincidences and measurement of the decay in two gammas (short) and three gammas (full night)
- Third session: measurement of the time distribution of the events