Measurements of the Propagation Speed of 511 KeV γ -Rays in Air and other Material Media

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Abstract – The propagation speeds of the 511 KeV γ -Rays were measured in several material media, based in a fast-slow coincidence method. The time-resolution of the instrumental system used to perform the experiments allows to get reliable results in covered distances of ~ 40 cm.

1) Introduction

- The speed of electromagnetic radiation (ER) propagating in vacuum (here simply considered as empty space), taking into account basic postulate of the Relativity Theory, irrespective of any coordinate system, is the highest possible speed at which anything can propagate, the ultimate speed limit of the Universe. In what visible light is concerned, during at least the last four hundred years, many attempts were done, using a great deal of different methods, to find it's value(1), with high precision results being get during the last hundred years(2). It should be emphasized that those experiments were done using visible light and concerned with its propagation in air. Presently, a well accepted value, with very small uncertainty, is **c= 299,792.458 Km/s**(3) (**c** reporting to the latin word *celeritas*: "speed swiftness"). When propagating in material media (MM), such value is always lower when compared to the vacuum value. Beside this, the speed propagation in vacuum is independent of the ER spectral composition, which does not happen when propagation takes place in some MM: in this specific situations the dispersion effect, which is dependent of the ER wavelength as well as of the propagating MM density, plays an important role. The ratio between the values of ER speed propagation in vacuum (in such situation visible light is always mentioned instead ER radiation) and of the speed propagation of any ER (that means, irrespective of it's wavelength and/or frequency) in any MM, $\mathbf{c_{MM}}$, is called *refractive index* of this substance relatively the propagating wavelength. Such *refractive index*, represented by a two speeds ratio, is an abstract number usually bigger than one: $\mathbf{n= c/c_{MM}}$. The value of ER speed propagation in a gas is approximately the same when compared to such number in vacuum, because of the very small ER dispersion in gases. In most cases, therefore, we may admit that ER propagation speeds in air and vacuum have the same value, and so far to consider the air index refraction $\mathbf{n_{air}= 1}$. But this is a specific feature, far of being a general situation: in the case of yellow sodium (Na) light, wavelength $\lambda = \mathbf{10^{-5}}$ **cm**, when propagating in water, **n= 1.333**(4).

Until present, such studies focusing propagation speeds, refractive indexes, dispersions were specially related to visible light, or to ER in wavelengths ranges close to it, and with transparent MM. To our knowledge, the only incursion in this subject dealing with γ -rays was performed already a long time ago using an electronic coincidence counting system, when the value of it's speed propagation was measured in air, $\mathbf{c_{\gamma}}$ **= 298,300.15 Km/s**(5). Incidentally, the use of γ -rays would allow a determination of ER propagation values in non-transparent MM, excludent for visible light; and in such a way better sketching of their structural -or of other nature- properties that may interfere with this propagation.

To perform such measurements the availability of a γ -radiation source in which two γ -rays are emitted simultaneously in opposite directions -as already used(5) as well as applied in the present case- turns out to be essential to the feasibility of the experiment, as far as no reflection techniques could be used. Such suitable source was the positron emitter ^{22}Na placed in a metal container in which the positrons are stopped and annihilated when reacting with the medium electrons, in such way originating -as it is very well established from momentum/energy conservation laws(6)- two γ -rays, energy 511 KeV each, both emitted in opposite directions.

2) Procedure – In the following set of experiments, two photomultiplier tubes with coupled truncated conic BaF_2 scintillation crystals (40 mm height) were attached to a 2 m iron trail, one of them (DET1) fixed at 7 cm distance and a second movable one (DET2) and concerning the interposed MM, at several different distances, on opposite sides of a γ-radiator ~ 8 μCi/^{22}Na. The experiments consisted in the measurements of the transit-time differences of the two oppositly emmitted γ-rays, by displaying the positions of the coincidence spectra built-up by the counts, displayed in a Multi-Channel, as results of the electronically detected coincidences between those γ-rays detected by DET1 and DET2 according the different distances DET2 assumed on the trail, and concerned with the various materials (water, glass, wood, PVC plastic, lucite and, of course, air) interposed between the ^{22}Na radiator and DET2. The instrumental system (IS) (Fig. 1) was an electronic fast-slow coincidence circuit [slow branch: amplifier (AMP), timing single channel (SCA), universal coincidence (COINC); fast branch: constant fraction timing discriminator (CFTD); time to pulse height converter (TAC)]. Finally, the third step slow-fast coincidences were recorded on an analog digital converter/multi-channel (MCA). More detailed explanations about construction and performance of such an IS can be found elsewhere[7,8].

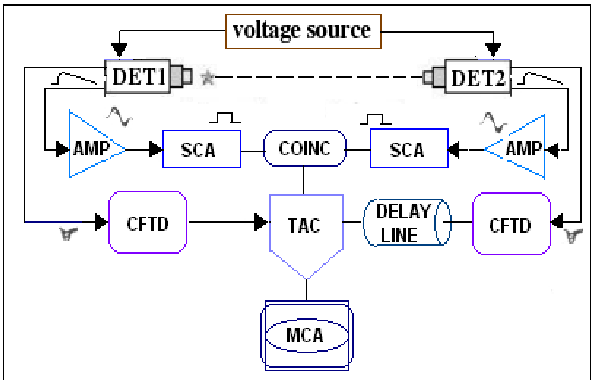

Fig. 1: Instrumental System (IS)

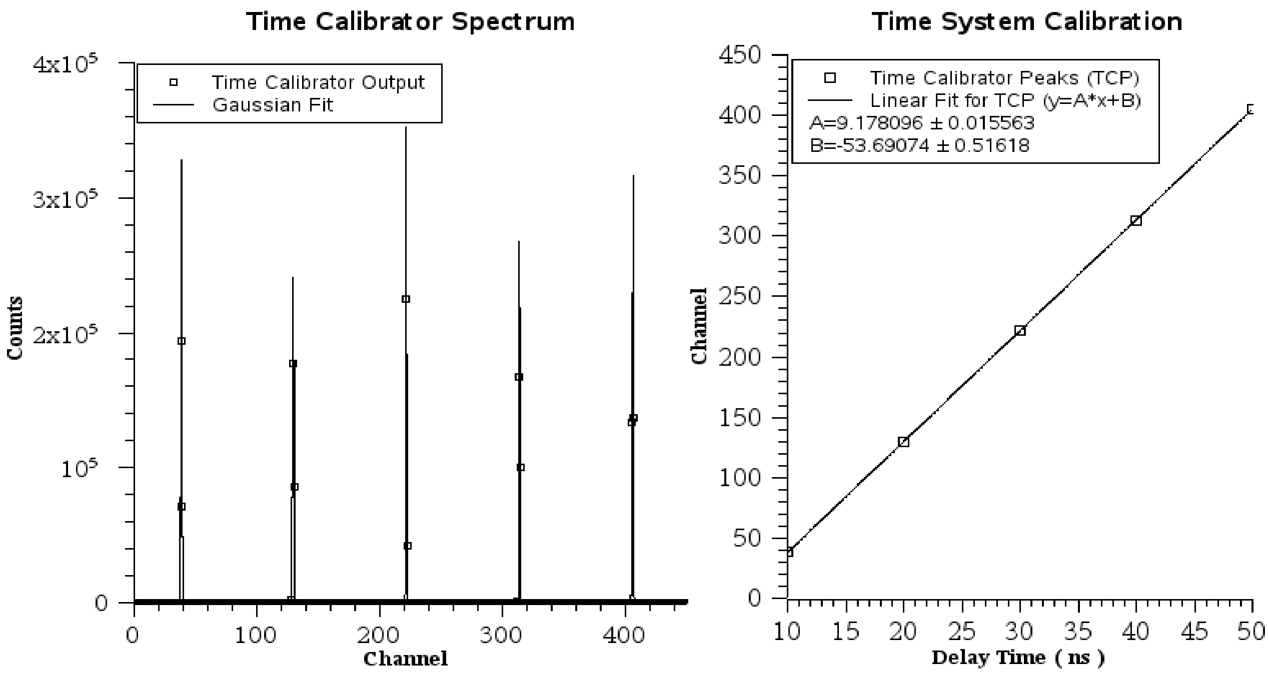

Fig. 2 - IS Time Calibration

Table I: IS Time Calibration

delay (ns)	channel	width
10	38.6287	0.715834
20	129.354	0.901385
30	221.361	0.575204
40	313.413	0.826302
50	405.504	0.767009

As a first step of the experiments, it was measured the time calibration of the IS by using a Time Calibrator (TC) which produces two pulses with highly precise variable delays between their outputs; which, by their way, are feeding the TAC whose amplitude output is related to the delays.

In Fig. 2 and Table I are shown the measured and adjusted parameters. The time/channel calibration result extracted from those data is **.109 ns/channel.**

3) Experimental Spectra Results

Experiment 1 - Calibration of the IS/Speed in Air

a) in the first beginning of these set of experiments there was a first trial to calibrate the "as used in the experiments" IS (Fig. 1): DET2 was aligned with the γ -radiator ^{22}Na in three positions: at 7 cm (ZERO position), 60 cm (from ZERO position) and 120 cm (also from ZERO position). The peaks of the three measured spectra were centered on the channels 230.92, 250.03 and 269.30, respectively; so, 120 cm length is represented by 38.38 channels, which gives a total time propagation of 4.18342 ns, and a propagation speed **c_{air1}= 286,846.64 Km/s**, 95.682% of the CODATA value[3].

b) a second calibration of the IS -also a measurement of the 511 KeV γ -radiation in air- more carefull as far as based in several spectra measured with equalized displacements of DET2, as well as by using a higher precision adjusting spectra process was performed, and also with the measurements performed with DET1 and DET2 aligned to the center of the ^{22}Na source fixed between the two detectors. This set -taking into account their extension may also be taken as a "speed in air experiment"- of measurements started with DET2 at the farthest position, and from where this distance was decreasing by several steps of 20 cm each. The Gaussian adjusted fast-slow coincidence measured spectra, in a "normalized modality"**, are shown in Fig. 3 (adjusted parameters herein). The IS, mainly due to the fast time response of the BaF_2 scintillation crystals, displayed a measuring resolution-time ~ 0.4 ns (~ four channels; half-height width of the Gaussian adjustment to the fast-slow γ - γ coincidence curve). In the average, the 20 cm distance was estimated as being covered in 0.6719227 ns, with a resulting propagation speed **c_{air2}= 297,653.28 Km/s**, 99.287% of the CODATA value[3].

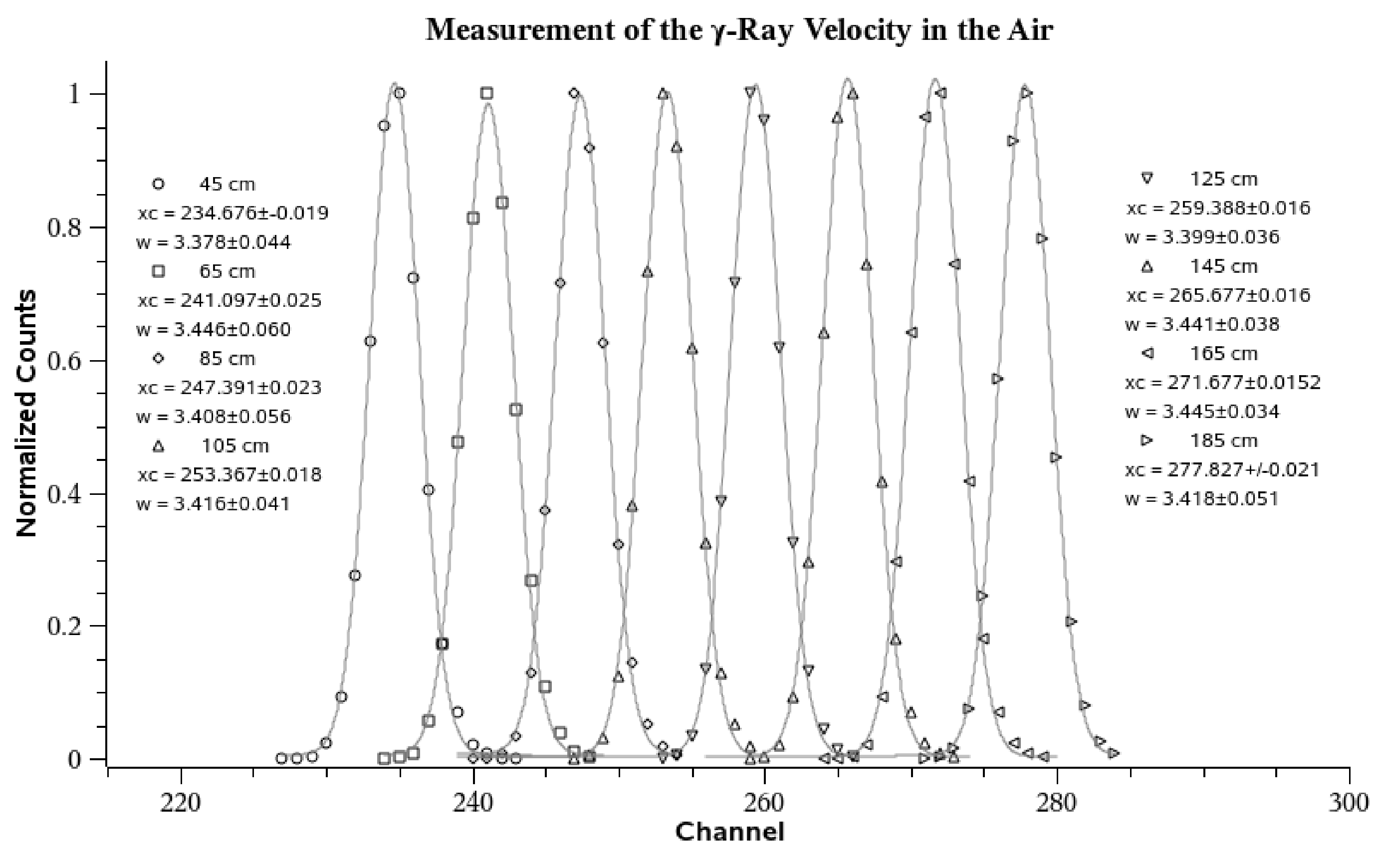

Fig. 3: normalized adjusted calibration spectra of the measurements of the γ -Ray speed in air

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** "normalized modality" - the spectra displayed in this text were built up by taking the ratios of each measured coincidence value divided by the peak measured value of the corresponding experimental curve. As far as the real measured coincidence curves could show quite different numbers (different distances between detectors, different interposed materials, different time measurements), all the Tables show the "central peak channel", it's counting rate and the measured spectra "widths" (number of channels corresponding to the half width of the spectra half height).

The Programs used to fit the measured spectra were QTIPLOT and FITYK.

Experiment 2 - Speed in Air

Table II - Air Parameters			
Length	**Peak**	**Center**	**Width**
60	50,018	253.222	2.058
120	4,370	271.624	2.054

a) this measurement was performed with DET2 shifted away 60 cm from position ZERO.
b) this measurement was performed with DET2 shifted away 120 cm from position ZERO.
Fig. 4 and Table II display the adjusted coincidence measured spectra and average highest coincidence counting channels.

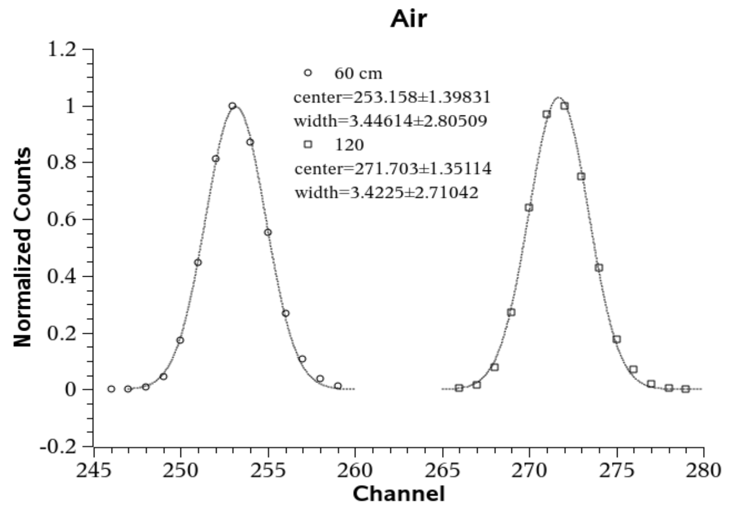

Fig. 4: normalized adjusted spectra of the Air Experiment

The 60 cm distance in air (18.402 channels) was covered in 2.005818 ns, with the resulting propagation speed $\mathbf{c_{air}}$= **299,129.83 Km/s**, 99.779% of the CODATA value[(3)]. This $\mathbf{c_{air}}$ result was taken as the most reliable for comparison to the speed propagations of the next experiments.

Experiment 3 – Speed in Water

Table III - Water Parameters			
Length	**Peak**	**Center**	**Width**
60	2,600	253.598	2.175
120	500	273.250	2.980

a) DET2 shifted 60 cm from position ZERO with the interposition of the 60 cm long glass tube filled with water.
b) DET2 shifted 120 cm from position ZERO with the interposition of a filled with water glass tube 120 cm long. Fig. 5 and Table III display the adjusted coincidence measured spectra and average highest coincidence counting channels.

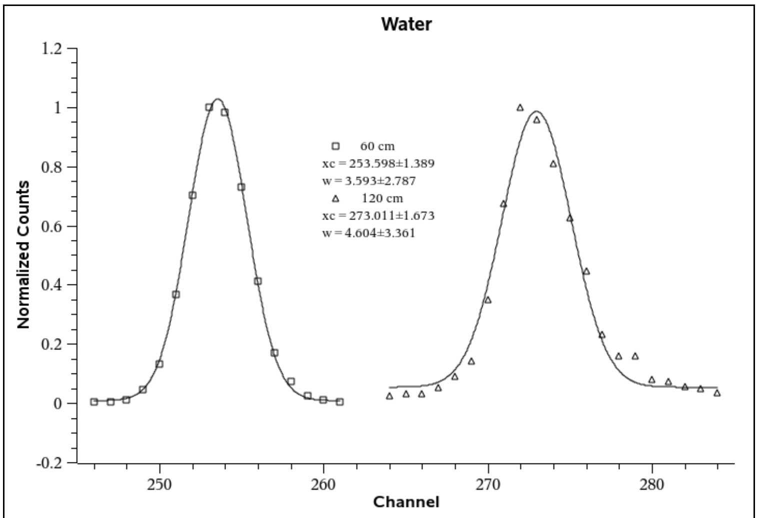

Fig. 5: normalized adjusted spectra of the Water Experiment

The 60 cm distance in water (19.652 channels) was covered in 2.142068 ns, with the resulting propagation speed of $\mathbf{c_{water}}$= **280,103.15 Km/s**, refractive index $\mathbf{n_{water}}$= **1.0679**.

Experiment 4 – Speed in Glass

Table IV - Glass Parameters			
Length	**Peak**	**Center**	**Width**
15	87,743	239.341	3.497
30	6,203	244.237	3.665
45	604	249.458	3.666

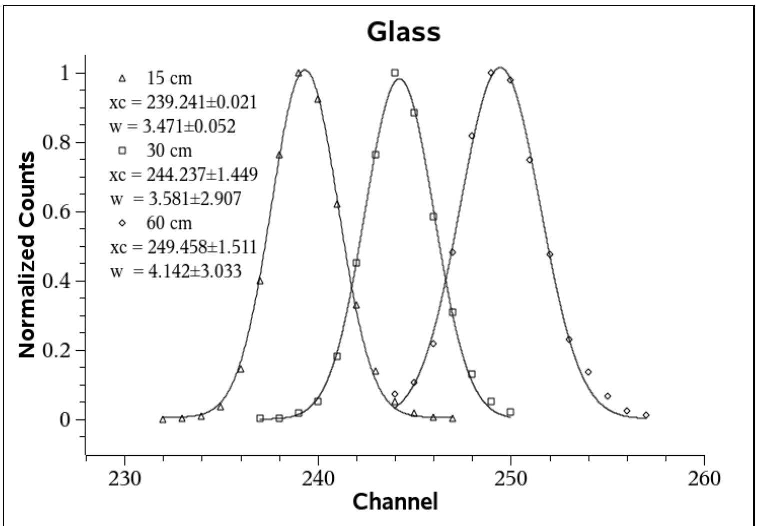

Fig. 6: normalized adjusted spectra of the Glass Experiment

a) DET2 was shifted 15 cm from position ZERO with the interposition of a BK-7 glass rod.
b) DET2 was shifted 30 cm from position ZERO with adding a second 15 cm length BK-7 glass rod .
c) DET2 was shifted 45 cm from position ZERO with the interposition of a third BK-7 glass rod .
Fig. 6 and Table IV display the adjusted coincidence measured spectra and average highest coincidence counting channels.

The 30 cm distance in glass (10.117 channels) was covered in 1.102753 ns, with the resulting propagation speed of $\mathbf{c_{glass}}$= **272,046.41 Km/s**, refractive index $\mathbf{n_{glass}}$= **1.0995**.

Experiment 5 – Speed in Wood

Table V - Wood Parameters			
Length	***Peak***	***Center***	***Width***
20	6,737	241.009	3.771
40	6,568	247.096	3.803
60	5,746	253.339	3.800

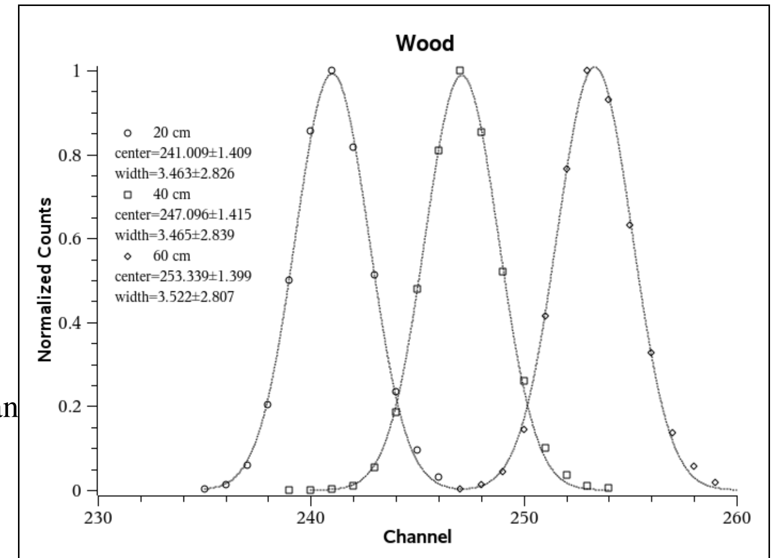

Fig. 7: normalized adjusted spectra of the Wood Experiment

a) the first measurement was performed with the radiation- γ on SIDE2 crossing an interposed 20 cm length wood (nature unknown) rod;
b) a second measurement was done interposing 40 cm length of the same wood.
c) finally, a third measurement was performed interposing 60 cm total length of the wood. Fig. 7 and Table V display the adjusted coincidence measured spectra and average highest coincidence counting channels.

The 40 cm distance in wood (12.33 channels) was covered in 1.34397 ns, with the resulting propagation speed of $\mathbf{c_{wood}}$=**297,625.69 Km/s**, refractive index $\mathbf{n_{wood}}$= **1.0050**.

Experiment 6 – Speed in Plastic PVC

Table VI - PVC Parameters			
Length	***Peak***	***Center***	***Width***
15	6,147	239.147	3.437
30	5,300	244.002	3.455

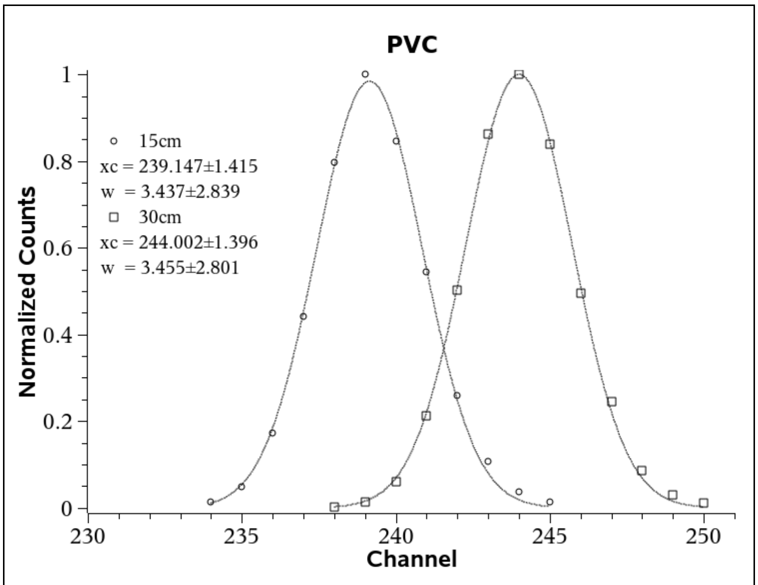

Fig. 8: normalized adjusted spectra of the plastic PVC Experiment

a) in a first measurement it was interposed a 15 cm length.
b) the second measurement was done by adding a second 15 cm length rod.
Fig. 8 and Table VI display the adjusted coincidence measured spectra and average highest coincidence counting channels.

The 15 cm distance in PVC (4.855 channels) was covered in 0.529195 ns, with the resulting speed of $\mathbf{c_{PVC}}$**= 283,449.39 Km/s**, refractive index $\mathbf{n_{PVC}}$**= 1.0553**.

Concluding Remarks –

- All the fast-slow coincidence spectra shown in this work are "normalized adjusted spectra" (see footnote below Fig. 2); this approach was used in order to avoid the discrepancies in height between the measured spectra due to big differences in their coincidence counting rates because of different lenghts of the interposed MM as well as due to the differences in transparency to the 511 KeV γ -rays. Similar heights of those measured spectra, even desirable to better equalize spectra half-widths, all of them with reasonable counting rates, would demand exceedingly high counting times.
- For the refractive indexes calculations, the propagation speed in air was that one extracted from Experiment 2: **299,129.83 Km/**s.
- For the propagation velocities calculations, the covered distances were always taken between adjusted peaks centers; widths spectra curves differences due to different spectra heights were disconsidered.
- In all the experiments, because of the IS resolution-time value, two fast-slow coincidence spectra are allowed to be totally displayed showing a distance between their peak centers not higher than ten channels, that means, **1.09 ns,** equivalent to **~ 40 cm** covered distance; a distance that would fix a minimum to measure, with our IS, propagation velocities of electromagnetic waves in any MM transparent to the 511 KeV γ -rays.

Acknowledgment – The student Carlos Victor Marques da Silva is fully acknowledged for contribution in composing some of the figures.

References

1) "The Speed of Light" - J.H. Rush; Scientific American, August 1955.
2) "The Ether-Drift Experiment and the Determination of the Absolute Motion of the Earth" - Dayton C. Miller; Reviews of Modern Physics 5(1933)203.
3) CODATA – The Commitee on Data for Science and Technology.
4) "Física/Vol. III (Ótica)" – F.W. Sears; Ed. Ao Livro Técnico LTDA., Rio de Janeiro, 1961.
5) "The Velocity of γ -Rays in Air" - M.R. Cleland & P.S. Jastram; Physical Review 84/2(1951)271.
6) "Curso de Física Básica (vol. IV-Ótica/Relatividade/Física Quântica)" - H.M. Nussenzweig; Ed. E. Blücher LTDA; São Paulo, 1998.
7) "Espetroscopia de Radiação-Gama" - LCA/EXP/CBPF; Monografia/CBPF-MO-001/07; março 2007.
8) "Radiation Detection and Measurements" - Glenn F. Knoll; J. Wiley&Sons eds.; 1979-1989.