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ASYMMETRY IN EXPERIMENTS TESTING CPT IN ORTHO-PS DECAY[*]

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Abstract. *Atom of positronium (Ps) – the bound state of an electron and a positron, has two ground states: singlet (para-Ps) and triplet (ortho-Ps). In this paper we consider* asymmetry *in the CPT test experiments performed using polarized ortho-Ps decay. Ortho-Ps annihilates dominantly into three gamma rays with the continuous energy spectrum in the range (0-511) keV. In searching for decays of ortho-Ps which violate CPT symmetry, the correlation* $\vec{S}\cdot(\vec{k}_1 \mathrm{x} \vec{k}_2)$ *was tested, where* $\vec{S}$ *is the ortho-Ps spin, and* $\vec{k}_1$, $\vec{k}_2$ *are the momenta of the two most energetic annihilation photons* ($E_{\gamma 1}>E_{\gamma 2}>E_{\gamma 3}$)*. The experimental tests consisted in comparing the number of asymmetric decays of polarized ortho-Ps in two identical reflection-symmetric geometries, and the angular correlation coefficient was calculated from the* asymmetry *(A). Using our previous results, as well as the results of other researchers, we particularly discuss the tests carried out at the three and seven-detector system (A = 0.0017 ± 0.0017 and A = 0.0008 ± 0.00091, respectively), together with their measuring errors.*

Key words: *CPT test, ortho-positronium, asymmetry*

1. INTRODUCTION

The fundamental discrete symmetries C (charge-conjugation), P (parity), T (time-reversal) – alone or in a combination, have been tested using the bound state of an electron and a positron, i.e., atom of positronium (Ps) (see, for example, [1-3]). As discussed in [4], Ps is an eigenstate of the C, and its states are parity eigenstates (since it is bound by a central potential). The states of this atom, i.e. fully lepton system (singlet and triplet – para-Ps and ortho-Ps, respectively) have different properties, resulting in a different number of sub-states in regard to the magnetic quantum moment (m=0 and m=0,±1, respectively), annihilation type (i.e., number of annihilation photons), the mean lifetime in vacuum (~120 ps and ~140 ns, respectively), etc. [5]. They are sensitive to violation effects [1], and consequently – suitable candidates for the mentioned symmetries testing. For example, due to the C conservation, the para-Ps decays into even, whilst ortho-Ps – into odd number of photons. Therefore, the searches for the evidence of the C violation in Ps decays were based on searching for the C-forbidden number of annihilation photons (e.g., 3 annihilation photons from para-Ps decay) [6,7].

The ortho-Ps (with parallel e^--e^+ spins) has the three sub-states regarding the magnetic quantum moment (0,±1), it dominantly annihilates through 3γ-decay and the spectrum is known to have a continuous energy distribution ranging from 0 to 511 keV [5].

Ways how to test CP, T, and CPT invariance in the 3γ-decay of polarized ortho-Ps have been discussed in [1], then followed by a number of experiments performed in this regard (e.g. [2,4,8,9]).

Evidently, multidetector systems were needed, and the standard facility used for measuring γ-coincidences from ortho-Ps decay (three detectors lying in the same plane, 120° among the detector axes, photon energies of 340 keV [5]) could not be applied for these purposes. The discrete symmetry violation was then studied by the means of the ortho-Ps spin and angular correlations of the photon momenta (in order of decreasing energy: $E_{\gamma 1}>E_{\gamma 2}>E_{\gamma 3}$; $|\vec{k}_1|>|\vec{k}_2|>|\vec{k}_3|$), and taking $\hat{k}=\vec{k}/|\vec{k}|$, the possible evidence for a violation was searched for in a value of the forbidden correlations C_{CPT} and C_{CP} (see, for example, [10])

$$\vec{S}\cdot(\hat{k}_1 \mathrm{x} \hat{k}_2), \qquad (1)$$

and

$$(\hat{S}\cdot\hat{k}_1)\cdot(\hat{S}\cdot\hat{k}_1 \mathrm{x} \hat{k}_2), \qquad (2)$$

respectively.

The authors of ref. [10], denoting forbidden correlations with “minus”, considered dependency between angular correlation operators (Eqs. 1 and 2) and discrete symmetries (C, P, T, CP and CPT) as: +, +, -, + and -, respectively (operator from Eq. 1), and +, -, -, - and +, respectively (operator from Eq. 2).

The angular correlation (Eq. 1) in ortho-Ps 3γ-decay is CPT odd (and that in Eq. 2 – CP odd). Therefore, γ-

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rays should be measured precisely, as well as the spin (in CP violating parameter spin term appears twice – tensor polarization). As a consequence, magnets have been used for the spin alignment. Namely, in the magnetic field, ortho-Ps sub-state with m=0 mixes with the para-Ps one, without changing its lifetime component (m=±1) [5], i.e., in delayed timing window m=0 would be eliminated.

It is clear that the angular correlations cannot be directly measured, and that they should be determined through a measurable observable, which is in fact – the asymmetry, associated with violation parameters (C_{CPT}, C_{CP}) in the following way

$$C = \frac{A}{S_{sp}}, \tag{3}$$

where C is C_{CPT} or C_{CP}, S_{sp} is the corresponding analyzing power built on the operator $\vec{S}\cdot(\hat{k}_1 x \hat{k}_2)$ or $(\hat{S}\cdot\hat{k}_1)\cdot(\hat{S}\cdot\hat{k}_1 x \hat{k}_2)$, respectively [10], depending on the background conditions as well, while A is the asymmetry

$$A = \frac{N_+ - N_-}{N_+ + N_-}. \tag{4}$$

The asymmetry is determined by counting the numbers of decays (N) when the normal (to the decay plane) is parallel (+) and antiparallel (-) to the spin direction.

In this way, for example, a 90% confidence interval of the CP violation parameter (C_{CP}) has been recently found to be $-0.0023 < C_{CP} < 0.0049$ [2].

Since many of fundamental questions still need answers (the Lorentz invariance violating effects, the Universe's predominance matter/antimatter, etc.) precise QED tests are highly topical. In this paper, we focus on the CPT tests in ortho-Ps decay, i.e. on asymmetry as the measured observable.

It is important to point out that the theory of the CPT odd term (Eq. 1) is given in [1], and three experiments (of those which have searched for such a correlation) are selected for a presentation [8,9,3] – resulting in $C_{CPT}=0.020\pm0.023$ [8], $C_{CPT}=0.014\pm0.019$ [9], $C_{CPT}=0.0071\pm0.0062$ [3].

2. EXPERIMENTAL CONDITIONS

2.1. *Spectrometers*

In the system of three detectors described in [8], angles between the axis of two detectors were around 145° (based on the QED of phase space), and the best "signal/background" ratio was estimated to be in the triple coincidences mode of counting, in the energy windows of $\Delta E_{\gamma1}\approx(400\text{-}500)$ keV, $\Delta E_{\gamma2}\approx(300\text{-}400)$ keV and $\Delta E_{\gamma3}\approx(200\text{-}300)$ keV. This mode gave a low counting rate, so the mode of double coincidences was preferred and a registration of one of annihilation photons from the ortho-Ps 3γ-decay was excluded (with the energy of (200-300) keV, i.e., <300 keV; because it was not clear whether it is a Compton-scattered photon or the photon with energy $E_{\gamma3}$). In this experiment, the target has been placed in the centre of the circle circumscribed around the triangle (three NaI(Tl) detectors were located at the triangle vertices). The centres of the detectors (with a vertex at the centre of the mentioned circle) made the angles of $\theta^{12}=145^\circ, \theta^{23}=70^\circ, \theta^{13}=145^\circ$.

A slow-positron beam polarized perpendicularly to the decay plane has been used, and the true events were those when the first detector registered a photon with the energy of $\Delta E_{\gamma1}$ and the second or third – a photon with the energy of $\Delta E_{\gamma2}$. The spin of the beam was periodically reversed (for 180°).

The CPT odd angular (triple) correlation $\vec{S}\cdot(\vec{k}_1 x \vec{k}_2)$ was tested, and the coincidences $(\vec{k}_1 x \vec{k}_2)$ of gamma rays, delayed by (20-200) ns in regard to the emergence of a positron (an average coincidence counting rate – 0.5 s^{-1}, measuring time – around 200 h) were registered (the events number – $3.5\cdot10^5$) and the asymmetry were then calculated using Eq. 4, and found to be $A=0.0017\pm0.0017$ [8].

It was clear from the above experiment that the measuring accuracy and the counting rate of the ortho-Ps asymmetric decays can be improved in an experiment with a multidetector gamma coincidence spectrometer, containing the detector pairs at the angle of 145°.

Our spectrometer, i.e., the seven-detector system, was described in [11, 12]. In brief, it consists of 7 NaI(Tl) detectors (15 cm x 10 cm) – five in the horizontal and two in the vertical plane, CAMAC electronics and PC. The system in the stage of construction is presented in Fig. 1, while its block diagram and work principle – in [12].

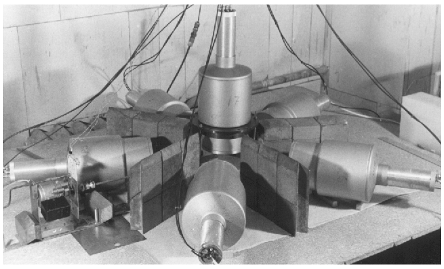


Figure 1. The seven-detector (NaI(Tl)) system – in the stage of construction

The resolution time was 8 ns, and ^{22}Na with the activity of $3.2\cdot10^5$ Bq was used as a positron source (e^+ followed by the emission of the 1275 keV nuclear photon), together with "Ps-forming" substance SiO_2, in which the life-time of ortho-Ps was found to be (91±4) ns [12]. This source-target arrangement enabled the degree of positron polarization ≥0.32. As it is known, positrons are polarized along their momentum, and a degree of polarization depends on the ratio: positron's velocity and the light velocity (i.e., v/c) [3]. Usually, an average polarization is calculated from an average velocity of positrons from the source (β emitter) and, in the case of ^{22}Na, it is around 67 %, with a correction of ~1 % [3]. So, averaged over the whole ^{22}Na energy spectrum, the degree of e^+ polarization had been found to be ≈65 % [13].

In the glass bulb, with the pressure of $(1\pm0.2)\cdot10^{-4}$ mm Hg, in Al (to assure "not-forming" Ps outside of SiO_2), ^{22}Na and SiO_2 were arranged to lie along the central axis, and this system was located in the geometric centre of the system (i.e., along the axis of a computer-controlled motor). The construction is shown in Fig. 2.

The acquisition time for the determined positron direction (1000 s) was driven by the software CPT-TEST, and after each bulb rotation by 180°, the spectrometric data acquisition started again. The ambient temperature during the experiment was (18±1) °C.

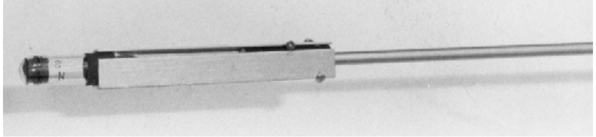


Figure 2. Construction containing system "positron source-target"

The detectors located in the vertical plane registered the 1275 keV nuclear photon, while the other five detectors (from the horizontal plane) registered double coincidences.

The total measuring time was 640 000 s, and the asymmetry of A=0.0008±0.00091 was obtained [12], i.e., twice better than in the previous experiment (ref. [8]).

Using the Gammasphere array of Compton-suppressed HPGe detectors, the authors of ref. [3] registered $2.65\cdot10^7$ events of ortho-Ps annihilation, obtaining in such way the amplitude of a CPT violation asymmetry of 0.0026±0.0031 that is smaller (by a factor of six) than in the two mentioned experiments. The spectrometer consisting of 110 HPGe detectors which surrounded an 18 cm radius target chamber [3], and polarized ortho-Ps produced by using ^{68}Ge and ^{22}Na, under the other conditions described in the same reference, allowed the calculation of an asymmetry ("of each data histogram about θ=0" [3])

$$A = \frac{N_\theta - N_{-\theta}}{N_\theta + N_{-\theta}}, \qquad (5)$$

where N_θ represented "the number of counts in the bin for $\theta=\cos^{-1}[\vec{S}\cdot(\vec{k}_1 x \vec{k}_2) W_i(\vec{k}_1,\vec{k}_2)]$", with $W_i(\vec{k}_1,\vec{k}_2)$ as a weighting factor for the decay plane normal vector depending on the momenta of annihilation photons [3]. In this way, series of measurements of the mentioned ratio N_+ and N_- (Eq. 4), for all the possible θ orientations of the decay plane, were generated, and the asymmetry (in dependence on θ) was then compared to the Monte Carlo simulation of a CPT-odd signal [3], and resulted in C_{CPT}=0.0071±0.0062. Two additional correlation amplitudes for each weighting factor averaged over spin orientations are also given in [3] presenting "a more substantial improvement in a limit to a potential CPT-violating decay asymmetry".

Further, we focus on two experiments with the same approach [8,12], i.e., the asymmetry defined by Eq. 4.

2.2. Background: three- and seven- detector system

In a mentioned experiment, the background from external sources can be neglected, and its main sources are related to two- and three-photon positron annihilation, para- and ortho-Ps decay (into two and three photons), ortho-para Ps conversion and pickoff annihilation (i.e., ortho-Ps quenching), as well as the Compton-scattering of annihilation radiation, all resulting in – true, true-random and random background gamma coincidences (see, for example, [12]). True background coincidences in two mentioned experiments [8,9], were mainly associated with the coincidence registration of the Compton scattered 511 keV photon originated from so called ortho-para (Ps) conversion and pickoff annihilation (described in [5]). The true-random background originated from a delayed (coincidences) registration of the photon from the true ortho-Ps decay, and the Compton scattered photon with a random energy of 511 keV (which could have originated from the decay of another Ps atom, as well). Random background coincidences were associated with the registration of two photons not caused by the starting positron (i.e., not "genetically" related).

It is important to note that the background in the case of the three-detector system was theoretically evaluated [8], while during the experiment performed by the seven-detector system – directly measured, using the two time windows. One (the first) gate signal was delayed by 30 ns admitting the elimination of the background from scattered photons originating from para-Ps and free positron annihilation, and it was the first time window. Using the second time window, random coincidences were taken into account, since this window was gated by the signal of the same length, but delayed by 2 μs from the first one [12].

3. ASYMMETRY

As is given in Eq. 3, the violation parameter C_{CPT} is calculated from the measured asymmetry and the corresponding analyzing power. The second one is calculated [8] taking into consideration background events, detector solid angles, size/volume of the Ps annihilation region, average angle of the Ps-spin direction with the normal (to its decay plane), polarization, ortho-Ps annihilation with m=0 and m=±1 (spin projections), energy range coverage (degree) – detectors energy resolution. All these factors also contributed to the analyzing power of the seven-detector system, but some of them were taken into account in the asymmetry measurements.

Namely, according to the notable background, the asymmetry (Eq. 4) should be

$$A = \frac{(N_+^t - N_+^B) - (N_-^t - N_-^B)}{(N_+^t - N_+^B) + (N_-^t - N_-^B)}, \qquad (6)$$

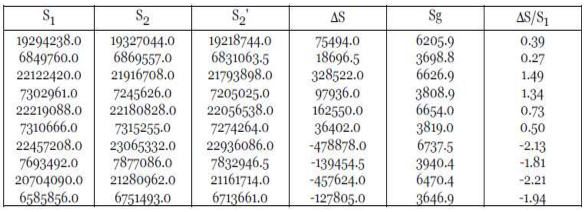
where, N_+^t and N_-^t are total numbers of registered events with parallel and antiparallel orientation (the positron spin and the normal to the decay plane) respectively; N_+^B and N_-^B are corresponding background events.

In the experiment [8], background random coincidences are neglected (being only ~10^{-5} of the desired ones). It was concluded that the contribution of true and true-random background coincidences made 8 % of the total counted [8]. This was due to the chamber (12 cm^3) inside which Ps annihilated, allowing the direct registration of two photons (511 keV) from one annihilation act. So, taking into consideration the authors' analysis, but also the background and statistical errors, the asymmetry should be A=0.00185±0.00191, as discussed in [12]. In addition, the applied assumption that $N_+^B = N_-^B$ could be insufficiently correct.

The statistical and systematic errors in experiments of this kind should be carefully considered and discussed. It can be done for the experiment with the seven-detector system [12], where two time windows have been used. Therefore, our data – obtained during the experiment [9], considered and presented here in more details, could help to clarify sources and contribution of such errors.

For example, in the seven-detector system experiment, the spectra acquired by five detectors in the integral mode of counting (some data are reported in Table 1) were used to rate registration efficiencies. The live measuring time for one spin direction was t_1=4330 s, and for the other t_2=4354.4 s. The S_1s are photopeak areas at the energies of 511 keV and 1275 keV for the first, and S_2s – for the second spin direction. Rating to the same live time (S_2') was realized by $(S_2/t_2)t_1$, while $\Delta S = S_1 - S_2'$. The S_g represents the dispersion of results.

Table 1. Spectra of five detectors



S_1	S_2	S_2'	ΔS	Sg	$\Delta S/S_1$
19294238.0	19327044.0	19218744.0	75494.0	6205.9	0.39
6849760.0	6869557.0	6831063.5	18696.5	3698.8	0.27
22122420.0	21916708.0	21793898.0	328522.0	6626.9	1.49
7302961.0	7245626.0	7205025.0	97936.0	3808.9	1.34
22219088.0	22180828.0	22056538.0	162550.0	6654.0	0.73
7310666.0	7315255.0	7274264.0	36402.0	3819.0	0.50
22457208.0	23065332.0	22936086.0	-478878.0	6737.5	-2.13
7693492.0	7877086.0	7832946.5	-139454.5	3940.4	-1.81
20704090.0	21280962.0	21161714.0	-457624.0	6470.4	-2.21
6585856.0	6751493.0	6713661.0	-127805.0	3646.9	-1.94

To measure the asymmetry, for the one spin direction, spectrum had been acquired for 1000 s, the spin was then inverted for 180° and spectrum again acquired over 1000 s. In that way, 320 spectra were obtained for one, and the same number of spectra for the other positron-spin direction (the total acquisition time was 640 000 s, as mentioned above).

All the data was reduced to the same live time using the coefficient

$$r = C_1(sd)\cdot C_2(sd,i)\cdot \exp\left[(-\ln 2\cdot t/T_{1/2})\right]\cdot 1000/t, \tag{7}$$

where C_1 is the coefficient dependent on sd (i.e., the spin direction) (and *i* – detector combination), different for S_1 and S_2; C_2 is the coefficient also dependent on the spin direction and the combination of detectors – *i* (5 pairs, and 10 values of the coefficient C_2), $T_{1/2}$ is the half-life of the positron source (^{22}Na), and t is the time from the exposition beginning to the moment of recording the spectrum.

The asymmetry and error of its determination (A and ΔA, respectively) were calculated using the software CPT-TEST

$$A = \frac{\sum_{i=1}^{10} A_i \frac{1}{\Delta A_i^2}}{\sum_{i=1}^{10} \frac{1}{\Delta A_i^2}}, \tag{8}$$

$$\Delta A = \sqrt{\frac{1}{\sum_{i=1}^{10} \frac{1}{\Delta A_i^2}}}, \tag{9}$$

where index *i* is related to the individual results from registering double coincidences.

It is important to note that the background was determined experimentally – by the second time window (w2), and Table 2 contains a number of data as an illustration. N_1' is the number of events for 1000 s, averaged on 320 spectra for the first spin direction (going to N_+ or N_-), N_2' is the number of events for 1000 s also averaged on 320 spectra for the second spin direction, S_g is the dispersion of results averaged on all spectra for a given spin direction.

Table 2. Second time window (w2) – experimental data

i	N_1'	Sg_1	N_2'	Sg_2
13	- 346.2	1.0	+ 344.1	1.4
14	+ 343.0	1.1	- 341.0	1.5
24	- 312.2	1.0	+ 319.5	1.0
25	+ 337.7	1.0	- 345.9	3.0
31	+ 249.1	0.8	- 245.6	1.1
35	- 268.1	0.9	+ 272.3	0.9
41	- 336.2	1.0	+ 334.5	1.1
42	+ 360.2	1.1	- 358.9	2.7
52	- 304.7	1.0	+ 298.8	1.1
53	+ 349.1	1.0	- 344.5	1.0

4. MEASURING ERRORS

4.1. Statistical errors

All the background coincidences (true, true-random and random) were present in the experiment [9], with an increased (in regards to the experiment [8]) probability of registration of true-random and random coincidences (due to the 1275 keV photon scattering). This, as well as the twice worse resolution time, broader interval in the time decay spectra – increased the background counting rate. In addition, the lifetime of ortho-Ps decay component in our experiment was (91±4) ns, as mentioned above.

On the other hand, the background was determined experimentally, by the second time window, and was taken into account immediately in calculating the asymmetry. As noted in [9], a start signal was generated by the detectors in the vertical plane (registration of the 1275 keV photon), and the spectra for each positron polarization were collected by using the others five detectors. The first time window gave the total spectra. Since a contribution of all background components was the same in both time windows (excepting those caused by Ps-quenching), desired events could be obtained by subtracting the two spectra. This procedure completely corresponded to the experimental conditions and there was no need to make additional corrections based on theoretical analysis – either of its particular components or of the total background. Additionally, the experiment's geometry allowed the exclusion of the direct registration of two annihilation photons emerged at an angle of 180°.

As abovementioned, the second time window did not show processes related to ortho-Ps-quenching, only. However, an analysis of such processes for given experimental conditions showed that the most probable background event was – coincidence registration of the Compton-scattered 511 keV photon in the energy window of (300-400) keV and the other annihilation photon (511 keV) also scattered – but in the target material, Al and glass bulb (in the energy window of (400-500) keV). A probability of this process registration did not exceed 1 % of the desired events counting rate [12], and could be neglected together with its contribution to the total background.

Integral spectra (from the detectors in the horizontal plane) in the first and second time window, without the energy selection, can be seen in [12].

The sum spectra of the first and second time window, with the energy selection of ($\Delta E_{\gamma 1}\approx$(400-500) keV and $\Delta E_{\gamma 2}\approx$(300-400) keV), with the counting rate of 8.65 s^{-1} and 3.20 s^{-1}, respectively, are shown here, in Fig. 3.

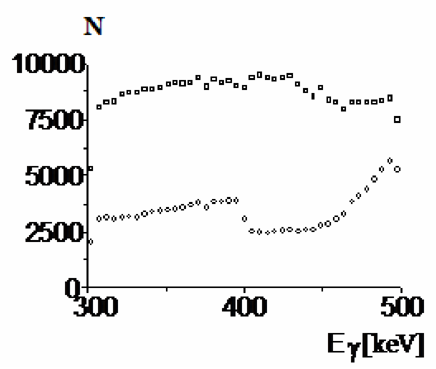


Figure 3. Counting rates in the first ( ) and second (O) time window – upon introducing the energy selection of events

The statistical error in determination of the asymmetry (ΔA), estimated from measured counting rates of n in the first and second time window, in dependence of the acquisition time, using [12]

$$\Delta A=\frac{\sqrt{2\left[(n_+^t-n_+^B)^2+(n_-^t-n_-^B)^2\right](n_+^t+n_+^B+n_-^t+n_-^B)}}{\left[(n_+^t-n_+^B)+(n_-^t-n_-^B)\right]^2\sqrt{\dfrac{t}{2}}}, \quad (10)$$

is given in Table 3.

Table 3. Statistical error in determination of the asymmetry

Acquisition time, s	ΔA
10 000	0.0063
100 000	0.0020
700 000	0.00075

For comparison, based on data from [9], for 700 000 s, ΔA=0.00191.

4.2. Systematic errors

The systematic errors are related to the long-term instability of the detector amplitude analyzers during measurements (I), drift of the instantaneous coincidences peak (II), inaccuracy in matching and fixing the region where ortho-Ps decays – to the system geometric centre, as well as a possible displacement of the decay point after the spin inversion (III).

In our experiment, the abovementioned drift (II) was less than 0.5 ns [12].

The first ones (I) were reduced in off-line data processing, using all integral spectra acquired for 1000 s, and performing the energy calibrations. From these calibration data, the time dependences for each of five detectors lying in horizontal plane and registering annihilation events were obtained, and correction factors of energy calibration were then used in the processing of experimental data. As an illustration, such time dependences for five detectors are shown in Fig. 4.

To control the accuracy of the calibration time dependence, in the total integral spectrum (during the whole experiment) the calibration peak widths were determined and found to coincide with the peak widths in individual (1000 s) integral spectra.

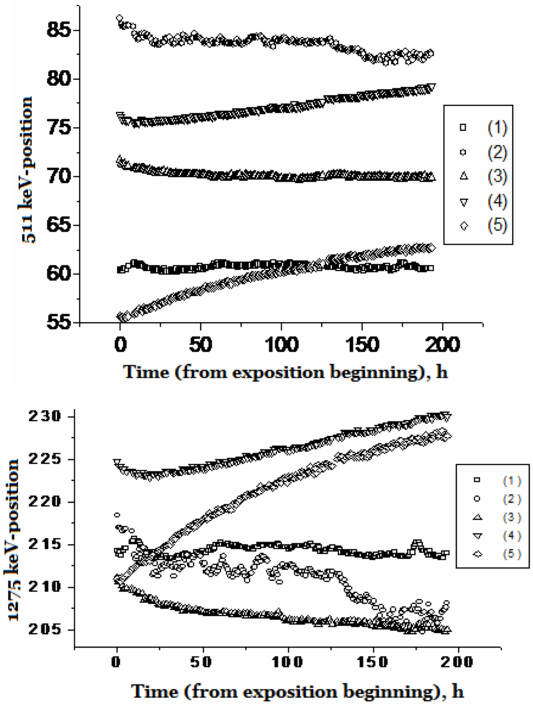


Figure 4. The time dependences for each detector

Therefore, the main sources of the systematic errors were those marked as (III). In general, the other errors, mostly caused by the instability of equipment are much smaller and mainly eliminated by multiple positron-spin inversions.

In the experiment with a three-detector system [8], the place of ortho-Ps forming was located with a high accuracy, three-photon annihilation occurred in a chamber of 12 cm^3, the accuracy in focusing position of the positron-beam centroid was 0.02 mm, with a less than 0.1 mm displacement upon spin inversion; all together introducing a systematic error in the asymmetry value of around $\pm 10^{-3}$ [8].

In the seven-detector system experiment, ortho-Ps atoms annihilated in the sample with volume which was smaller by a factor of 600. An inaccuracy of the system geometric centre determination and matching it to the system "positron source-target" did not exceed 0.5 mm [12]. In order to reduce the systematic errors due to the variation of the positron beam centroid position upon the spin inversion, a pair of detectors at the angle of 144° was considered in the following way. One of them (i) registered photon from the ortho-Ps decay $E_{\gamma 1} \approx (400\text{-}500)$ keV, and the other (j) – photon with an energy of $E_{\gamma 2} \approx (300\text{-}400)$ keV (or *vice versa*). There were 10 such combinations in the experiment, and taking two possible spin directions (↑,↓) probabilities of photon registration by one of the detectors, counting rates have been evaluated and the systematic error, due to displacement of the centroid upon the spin inversion, was defined as the ratio of the solid angles $\Omega_i^{\uparrow}\Omega_j^{\uparrow}/(\Omega_i^{\downarrow}\Omega_j^{\downarrow})$. The energy spectra for two positron-spin directions, from the five detectors in the horizontal plane, after a slight correction of the positron source-target positions, were compared using the 511 keV photopeak for each detector, and showed a variation for two spin directions not exceeding 1 % [12].

5. CONCLUSIONS

Increasing the number of detector combinations which registered desired events in a test of the CPT-invariance in the decay of polarized ortho-Ps, the test accuracy was significantly improved. The asymmetry determined in the seven-detector system experiment was found to be twice better than in the tree-detector one. The setup analyzing the capacity was also better – taking into consideration background events, solid angles – 1.9 % of 4π sr, the size of the Ps annihilation region, and the same degree of the energy window coverage.

The spectrometer of 110 HPGe detectors later used resulted in the amplitude of CPT violation asymmetry many folds smaller.

However, it does not mean that spectrometers with a smaller number of detectors cannot be further used in the CPT testing, i.e., in searching for decays of ortho-Ps which violate the CPT symmetry. This is particularly because experimental tests basically consist of comparing the number of its asymmetric decays in two identical reflection-symmetric geometries.

The accuracy of experiments of this type could be improved, not only by increasing the number of annihilation planes (perpendicular to the Ps-orientation), but also using slow polarized positrons from a high-intensity beam, for example, and a target with ortho-Ps lifetime comparable with that in a vacuum. A proper event selection and considering/eliminating all the background coincidences could also help the accuracy improvement.

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