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ORTHOPOSITRONIUM DECAY RESEARCH USING METHOD OF GAMMA-COINCIDENCES

Abstract

The experimental research on asymmetric orthopositronium decays is carried out using the 32-crystal γ-coincidence 4π-spectrometer ARGUS. The angular distribution of the orthopositronium annihilation quanta in a weak magnetic field is also presented in the work, as well as the time distributions obtained by the system based on three detectors included into the delayed coincidence circuit. For observing the angular anisotropy in orthopositronium decay in a magnetic field, the three-detector spectrometer is used. This is the first time that the anisotropy of the 3γ-decay quanta angular distribution - caused by orthopositronium spin oscillations in the magnetic field, has researched by the coincidence method. Moreover, the CPT-invariance test in the polarized orthopositronium decay using the angular correlations, carried out with the seven-detector setup, is demonstrated the absence of the effect at a 1.1 % level of uncertainty in the angular correlation coefficient (C_n = 0.010 ± 0.011).

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ISTRAŽIVANJE RASPADA ORTOPOZITRONIJUMA KORISTEĆI METOD GAMA-KOINCIDENCIJA

Izvod

Eksperimentalno istraživanje asimetričnih raspada ortopozitronijuma ostvareno je pomoću 32-kristalnog 4π-spektrometra γ-koincidencija ARGUS. U radu je takođe predstavljena ugaona raspodjela ortopozitronijumskih anihilacionih kvanata u slabom magnetnom polju, kao i vremenske raspodjele dobijene korišćenjem sistema od tri detektora koji su uključeni u šemu zakašnjelih koincidencija. Za posmatranje ugaone anizotropije pri raspadu ortopozitronijuma u magnetnom polju korišćen je trodetektorski spektrometar. Ovo je prvi put da je koincidentnim metodom istraživana anizotropija ugaone raspodjele kvanata iz 3γ-raspada - uslovljena oscilacijama spina ortopozitronijuma u magnetnom polju. Nadalje, testiranje CPT-invarijantnosti pri raspadu polarizovanog ortopozitronijuma korišćenjem ugaonih korelacija, ostvareno pomoću uređaja sa sedam detektora, pokazalo je odsustvo efekta na nivou nesigurnosti od 1.1 % - u koeficijentu ugaonih korelacija ($C_n = 0.010 \pm 0.011$).

MULTIDETECTOR COINCIDENCE SPECTROMETER ARGUS

The 32-crystal γ-coincidence 4π-spectrometer ARGUS (Fig. 1) was developed in order to research rare cascade and correlative nuclear decays [1].

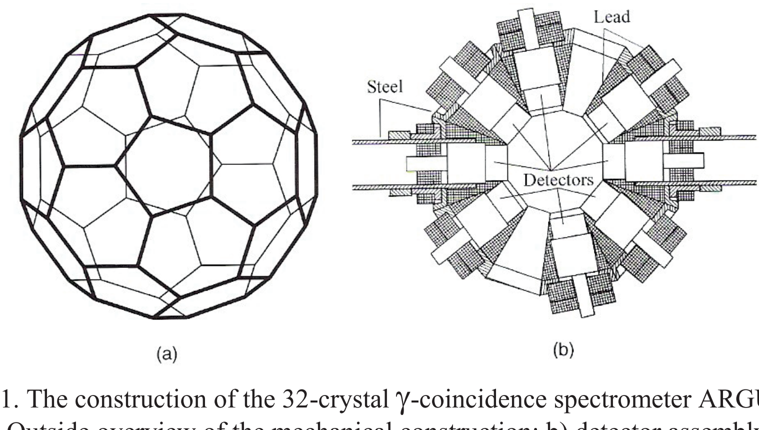


Fig. 1. The construction of the 32-crystal γ-coincidence spectrometer ARGUS. a) Outside overview of the mechanical construction; b) detector assembly of the spectrometer.

The spectrometer load-carrying structure consists of 32 pentahedral and hexahedral steel truncated pyramids, which form a closed honeycomb surface with an inner diameter of ≈ 0.5 m. A detector based on a 150-mm-diameter and a 100-mm-high NaI(Tl) crystal is housed in each pyramid. To reduce the background count rate, the construction is installed in the low-background room, and shielded from the earth background radiation with a 10-cm-thick lead layer. Each detector is encased in a special shielding container, consisting of a pyramid (the lead thickness is up to 6 cm) and a 10-cm-thick lead disk. The spectrometer includes 32 detecting channels (Fig. 2.).

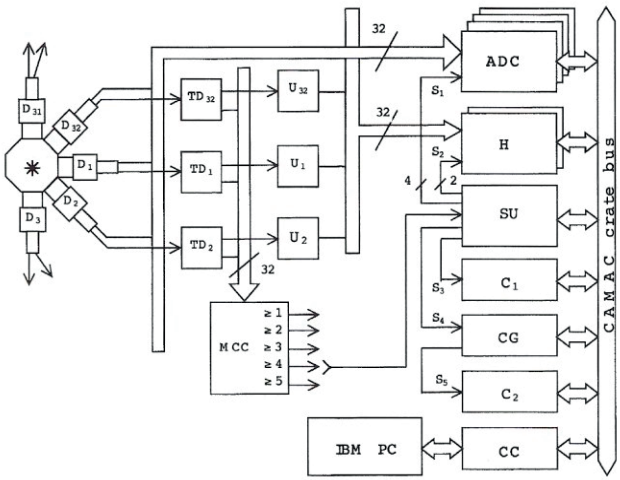


Fig. 2. A block diagram of the spectrometer ARGUS: (D_1 - D_{32}) detectors based on NaI(Tl) of 150-mm diameter and 100-mm thickness; (TD_1 - TD_{32}) time discriminators by the leading edge; (U_1 - U_{32}) delay univibrators; (MCC) majority coincidence circuit; (ADC) 32 8-bit charge-to-code converters; (H) 32-bit hodoscope; (SU) splitter-univibrator; (C_1) counter of events; (CG) clock-pulse generator; (C_2) "live-time" counter; (CC) CAMAC crate controller; (S_1) strobe pulses for the ADC (650 ns); (S_2) strobe pulses for the hodoscope (50 ns); (S_3) signal following the input strobe pulse from the MCC; (S_4) dead-time signal; and (S_5) clock pulses.

The counter-outputs with pulse rise and decay times of $\tau_r \approx 50$ ns and $\tau_d \approx 600$ ns, respectively, follow distinct paths for the time and amplitude analysis. Time discriminators (TD_1 - TD_{32}) derive time markers with a length of (50 ± 10) ns, which then arrive at the majority coincidence circuit (MCC). The MCC operates by pulse overlap and permits selection of a coincidence fold of 1 to 5. Moreover, using the programs for events selection it is possible to extract events with any higher fold.

If an event with a given coincidence fold has occurred, the MCC gate signal initiates the recording of the numbers of detectors participating in the event, and the amplitude analysis of the signals from these detectors. The first operation is carried out with register H, while the amplitude analysis requires 32 8-bit ADCs (256-channels each).

Therefore, information about each detected coincidence event is recorded in the form of detectors numbers, and their output pulse heights (γ-ray energies). The setup operates on line with an IBM PC, and its units are made to CAMAC standard.

The spectrometer software provides (1) data acquisition and readout; (2) assignment of the data-acquisition mode (in real or current time, or by acquisition of the required counting); (3) selection of the coincidence-fold ranges for the detected events; (4) data acquisition in the form of information on each event and total integral spectra; (5) calibration of spectrometric channels in energy, photo-absorption efficiency, and total detection efficiency; (6) separation of the recorded events according to the selection criteria by the coincidence fold, energy, and angular correlations of the emitted γ-rays; (7) conversion of the data on each event into the integral spectra of the detectors and the total spectrum of the whole setup.

In experimental researching rare positronium decays, we undertook additional measures to reduce the probability that γ-rays, which have suffered Compton scattering in one detector, penetrate the other. For this purpose, a leaden collimator is mounted on the surface of each detector. The collimator was a 30-mm-thick disk with a central cone-shaped orifice of 80- and 70-mm diameters on the detector surface and the side of the spectrometer center, respectively. Using the additional collimators it was possible, in particular, to reduce almost by a factor of 3 the background count rate of double coincidences for an energy of (0.15 - 2.0) MeV.

ORTHOPOSITRONIUM ASYMMETRIC DECAYS

The basic experimental methods for researching positron (positronium) annihilation are based mainly on the registration of [2]:

1) the delayed coincidences between the emission of a positron and its following annihilation (or positronium annihilation),
2) the coincidence rate of the two annihilation photons as a function of the angle between detectors (near 180^o, $E_{\gamma 1} \approx E_{\gamma 2} \approx 511$ keV),
3) the energy spectrum of the annihilation quanta,
4) the coincidences of the three annihilation photons.

For the last type of experiments only the specific (the most simple) case of three-photon decay is used: three detectors are placed in a plane, at the angle of 120° one to another, to register photons with energy of 340 keV.

It is well known that the energy spectrum of three-photon annihilation contains quanta from 0 to 511 keV, and the probability of a photon emission is increasing with rising of photon energy. Therefore, it is interesting to research other schemes of detecting orthopositronium (o-Ps) annihilation, where the angles between the centres of detectors differ from 120°. This is important, for example, for the experiments of searching for CP-, and CPT-violation in positronium decay, where the coincidences of $E_{\gamma 1} > E_{\gamma 2} > E_{\gamma 3}$ photons should be registered. In this case, the angles between the centres of detectors (in different triads) can differ from 120°. As a result, the energies of detected photons can significantly differ from $2/3\ mc^2$, where m is an electron mass, c is the light velocity.

The positron annihilation spectrum in Al and SiO_2, obtained using the spectrometer ARGUS and ^{22}Na ($4{\cdot}10^5$ Bq) as a positron source, is researched. The coincidence event is recorded only if $k = 4$, and one of the registered photon falls into the energy range $1100 < E\gamma < 1400$ keV. In that way, the background caused by a Compton scattered nuclear γ-ray (1275 keV) decreases significantly. The average values of detector photo-efficiency, total efficiency and energy resolution for 392 keV photon were $4.3 \cdot 10^{-3}$, $5.6 \cdot 10^{-3}$ and 13.5 %, respectively.

To reduce background and select o-Ps annihilation events from a spectrum of $k = 4$ γ-coincidences, the following filter criteria are used:

1) the nuclear photon of 1275 keV must be present in the coincidence events;
2) the coincidence events must be registered by the detectors, which are not positioned at the angles of 180° between the centres of each two of them (this eliminates the annihilation events

caused by free electron-positron pairs and parapositronium atoms);

3) a sum of energies of the three annihilation quanta must be equal to 1022 keV, taking into account the energy resolution of the detectors;
4) a sum of the annihilation photons momenta on the Dalitz plot must be equal to zero.

In the background spectrum, measured during 10000 s, no one of the events passed four filter criteria.

Table 1 contains the filter criteria efficiency for the annihilation spectra in Al and SiO_2. Only 0.24 % of all events in SiO_2 and 0,026 % in Al have passed these criteria.

Table 1. The relative number of events passed the filter criteria for Al and SiO_2 spectrum.

	Al		SiO_2	
Filter criterion No	Relative number of events with respect to the initial spectrum	Count rate [s^{-1}]	Relative number of events with respect to the initial spectrum	Count rate [s^{-1}]
1)	0.45	91.0	0.43	92.1
2)	0.04	8.2	0.05	10.6
3)	0.0023	0.47	0.0054	1.16
4)	0.00026	0.053	0.0024	0.52

Orthopositronium 3γ-decay for four counting geometries (I - IV) described in Table 2 is researched. Total exposition time in SiO_2-powder was 55000 s.

Beside the experimental research, Monte-Carlo computer simulation of positronium three-photon decay has been also performed, taking into account photon interactions with scintillators and detector-to-detector Compton scattering. Because the mentioned criteria not only filter background events, but also eliminate a part of the positronium three-photon decay events, it is necessary to apply the same filter criteria to the simulation results for comparing them with the experimental spectra.

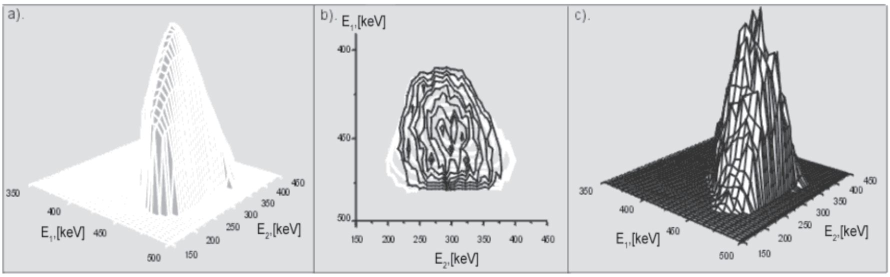
Table 2. The registration geometries and the count rates.

Geometry	Angles between centres of the detectors	Number of detector triads in spectrometer ARGUS	Count rate [s^{-1}]
I	142.6; 142.6; 70.5	60	0.021
II	142.6; 138.2; 79.2	60	0.214
III	142.6; 116.6; 100.8	60	0.260
IV	138.2; 109.5; 109.5	60	0.027

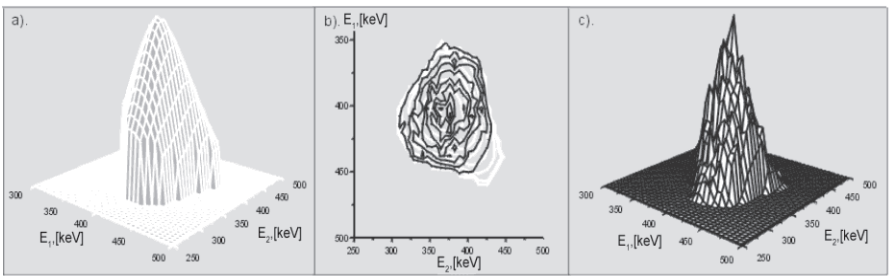
The theoretical and experimental distributions of the o-Ps annihilation quanta for the geometries II and III are given in Fig. 3.

Fig. 3. Simulated with EGS4 (a) and measured (c) distributions of the o-Ps-annihilation quanta, for geometry II (above) and II (below). Topograms of simulated (white lines) and measured (black lines) distributions for these geometries are shown in (b).

Geometry II



Geometry III



It can be seen that the centres of experimental and theoretical distributions coincide, taking into account the experimental accuracy (5 keV). For analysing the resemblance of these distributions, it is appropriate to use a concept of a correlation coefficient. Sampling mean value ρ of the true correlation coefficient can be calculated as

$$\rho = \frac{\sum_{i=1}^{n}(x_i - \bar{x})(y_i - \bar{y})}{\sqrt{\sum_{i=1}^{n}(x_i - \bar{x})^2 \sum_{i=1}^{n}(y_i - \bar{y})^2}}, \qquad (1)$$

where x_i and y_i are the numbers of events in the i-th channel of the simulated and measured spectra; $\bar{x} = \frac{1}{n}\sum_{i=1}^{n} x_i$, and $\bar{y} = \frac{1}{n}\sum_{i=1}^{n} y_i$.

For n = 250 points, $\rho = 0.72$ for geometry II and $\rho = 0.87$ for geometry III are obtained. It means that the true value of the correlation coefficient r, with 95 % confidential probability, is not exacly equal to ρ, but belongs to the interval $0.65 < r < 0.78$ for geometry II, and $0.83 < r < 0.91$ for geometry III [3]. Thus, the experimental and simulated spectra are in a good agreement. A slight discrepancy between the experimental and theoretical distributions (see topograms - Fig. 3b) appears in the both geometries mainly in the low energy region of the third annihilation quantum (< 170 keV). This is because the individual low energy thresholds of photon registration by each detector are not taken into account in the computer simulation program.

POSITRONIUM SPIN ROTATION (PsSR) METHOD

The phenomenon of oscillations of the positronium 3γ-decay quanta angular distribution in a magnetic field was predicted in the works [4, 5], and the idea of realization of the new matter investigating method with the use of positrons was put forward. Polarized positrons are slowed down in matter to form the polarized positronium atom. The anisotropy of the 3γ-decay angular distribution relative to the Ps atom quadrupolarization will bring time oscillations of the count rate, which can be experimentally observed in recording delayed coincidences between the nuclear γ-quantum (^{22}Na) and annihilation quanta.

By analogy with the μSR - method, the new technique was called the positronium spin rotation (PsSR) method [5].

The oscillation frequencies correspond to the differences in energy of Ps atom levels in the magnetic field are

$$\begin{aligned} \Omega_1 &= 1/2\Delta W(\sqrt{1+x^2}-1), \\ \Omega_2 &= 1/2\Delta W(\sqrt{1+x^2}+1), \\ \Omega_3 &= \Delta W\sqrt{1+x^2}, \end{aligned} \quad (2)$$

where ΔW is the value of the Ps ground state hyperfine splitting, $x = 4\mu H/\Delta W = 0.0275\, H$ (kG), H is the external magnetic field strength. The oscillation can be simply detected in a weak ($x << 1$) magnetic field at the frequency Ω_1, since $\Omega_2, \Omega_3 \approx 10^{12}$ s^{-1} and the terms involving Ω_2 and Ω_3, when averaged over the detector time resolution ($\approx 10^{-9}$ s), become zero.

The oscillation modulation depth h_o, equal to the ratio of the oscillation amplitude to the value of the non-oscillating term, is defined by the following expression

$$h_o = 0.213P|\sin\theta \sin 2\beta \sin\alpha|, \quad (3)$$

where (Fig. 4) β, and α are the polar and azimuthal angles specifying the direction towards the detector, θ is the angle between the external magnetic field direction (OZ axis) and the positron average polarization vector (in the plane XZ). P is the degree of polarization of the positrons entering the target.

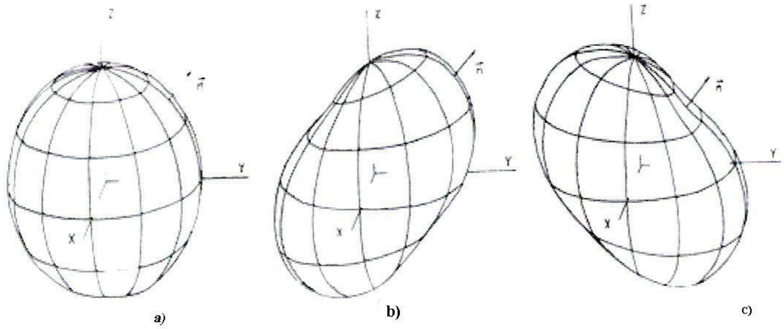


Fig. 4. The angular distribution of the o-Ps annihilation quanta in a weak magnetic field at the time $t = 0$ (a), $t = To/4$ (b) and $t = 3To/4$ (c); To is the oscillation period, n is the vector directed to the center of the detector.

The oscillation amplitude becomes maximum when the positrons entering the target are polarized perpendicular to the external magnetic field direction ($\theta = \pi/2$), and the detector registering decay quanta is placed at the angle $\beta = \pi/4$ to the magnetic field direction in the plane normal to the positron polarization vector ($\alpha = \pi/2$). Oscillation phases ψ, observed at the angles $\beta = \pi/4$ and $\beta = 3\pi/4$ (α = const), and those observed in the case when $\alpha = \pi/2$ and $\alpha = -\pi/2$ (β = const) differ by π.

Thus, the experimentally obtained time distribution is described in the first approximation by the expression

$$N(t) = Ae^{-t/\tau}\{1 + h_o \sin[(2\pi t / To) + \Psi]\} + B, \quad (4)$$

where A is the amplitude of the non-oscillating term, τ is the o-Ps lifetime, $To = 2\pi/\Omega_1$ is the oscillation period, B is the background.

To register the time spectra of o-Ps annihilation, the system based on three NaI(Tl) detectors (∅ 150x100 mm) included into the delayed coincidence circuit is used. One of the detectors is set to register a nuclear γ-quantum of 1275 keV (^{22}Na), and the other two, facing each other and being incorporated into the summation circuit, detect annihilation quanta. The system time resolution was 7.0 ns, and the time range was 500 ns. The “positronium producing” target was a tablet of fine-grained SiO_2, and the SmCo magnets were used in the first experiments.

The positrons are polarized parallel to the direction of their motion to the degree $P = v/c$, where v – is the velocity of a positron at the time of its escape from the source. The value of the positron polarization averaged over the source energy spectrum is $P = 0.65$. Owing the fact that the positrons enter the target (and hence, become polarized) within 2π solid angle the average degree of positron polarization P decreases to one half.

To decrease the background to the positron annihilation ratio, the Ps time spectra were registered during the time interval $t = 25\ldots500$ ns.

The new phenomenon of the time oscillation in the decay of o-Ps in a magnetic field was observed at first in our work [6], and after that was confirmed completely in the experiments of Taiwan group [7].

A new magnetic system type Helmholts coil, characterized by an absence of annihilation γ-quanta absorption and high homogeneity over the target volume was created [8], and in the next our works the phenomenon was researched in details for different types of SiO_2 and $Al_2 0_3$ samples [9-11].

We used the fact that the oscillation phases ψ observed in constant magnetic field H at the angles $\beta = \pi/4$ and $\beta = 3\pi/4$ (α = const) differ from π. The distribution is defined by the following expression (see eq. (4))

$$N(t) = 2Ae^{-t/\tau} h_o \sin[(2\pi t / To) + \Psi]. \qquad (5)$$

The experimentally obtained data are analyzed with the non-linear squares method using the hypothesis that the time distribution is described by equation (5). Theoretical values of ψ, To, A, h_O, τ, estimated with the least squares method, are in a good agreement with the experimental data. Some experimental time distributions are given in Fig. 5, where the solid curve shows the theoretically estimated time distribution (**1.** $To = 58.6 \pm 0.2$ ns, $\psi = \pi$; **2.** $To = 68.6 \pm 0.4$ ns, $\psi = \pi$; **3.** $To = 81.4 \pm 0.4$ ns, $\psi = 0$; **4.** $To = 109.2 \pm 1.2$ ns, $\psi = 0$).

It is important to stress that the exposure time of experimental spectra necessary for obtaining the oscillation parameters is several hours.

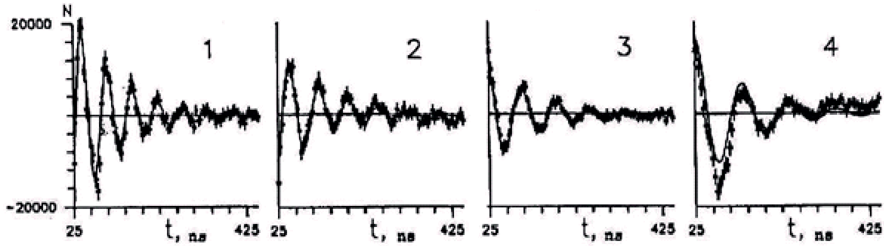


Fig. 5. The time distribution obtained by subtraction of the distributions observed at the angles $\beta = \pi/4$ and $\beta = 3\pi/4$ ($\alpha = \pi/2$).

At present, there is a better opportunity of realizing the PsSR-method, because the new structures with long-lived components of Ps-annihilation (for example, polymers, zeolites and porous glasses) are available [12].

ANGULAR ANISOTROPY IN ORTHOPOSITRONIUM DECAY IN A MAGNETIC FIELD

The direct experimental observation of the o-Ps spin rotation in condensed media is extremely difficult to realize because: the positronium lifetime in condensed media very rarely exceeds the value (1 - 5) ns, and it requires a setup with very high time resolution; 2γ-decay count rate is usually for two or more orders of magnitude higher than 3γ-decay count rate, and for reducing the background related to two-photon coincidences, one or two additional detectors should be used, which reduces the setup time resolution and/or increases the time for collecting necessary statistics. One of possible way to solve this contradiction is to use a spectrometer for coincidence registration of 3γ-decay quanta, when the positronium lifetime is not detected at all.

As it is known, the cross section of o-Ps 3γ-annihilation in a magnetic field is [6]

$$\sigma = E\gamma_1 e^{-\gamma_1(t-\tau)} + F\gamma_2 e^{-\gamma_2(t-\tau)} + K\frac{\gamma_1+\gamma_2}{2} e^{-\frac{\gamma_1+\gamma_2}{2}(t-\tau)} \sin[\Omega(t-\tau)], \quad (6)$$

where, E, F, K are constants depending on the experiment geometry, γ_1, γ_2 are o-Ps decay rates in a magnetic field, and Ω is the oscillation frequency.

In the case when o-Ps-creation is not detected by the setup, it is necessary to integrate equation (6) over all possible times of o-Ps creation (from $-\infty$ to the present time t), and it will be

$$\int_{-\infty}^{t} \sigma(t-\tau)d\tau = E + F + K\frac{\Omega\gamma_3}{\Omega^2+\gamma_3^2}, \tag{7}$$

where $\gamma_3 = (\gamma_1 + \gamma_2)/2$, and $\Omega \equiv \Omega_1$ - from equation (2).

The last component in (7) describes the angular anisotropy of the decay quanta distribution, caused by the Ps-spin rotation in a magnetic field. It is possible to show that it reaches its maximum value $K/2$ in the case when $\Omega \equiv \gamma_3$.

For coherent phenomena research in o-Ps decay in a magnetic field, the multidetector spectrometer is designed [13], and then modernized in our experiment. The setup allows analyzing angular distributions of Ps-decay photons in a magnetic field in the regime of one, two or three-photon coincidences. It is expected the coherent phenomenon influences on the o-Ps decay photons angular distribution in the case when the o-Ps spin frequency is close to the o-Ps decay rate in the target.

A block diagram of the spectrometer is given in Fig. 6. The detector unit includes three NaI(Tl) scintillation detectors (D_1 - D_3) - 150-mm in diameter and 100-mm in height, monitored by low-background photo-multipliers. The detectors are shielded from the magnetic field. The energy resolutions of the detectors for 511 keV photon are 11.5, 11.6, and 12.7 %, respectively. The (D_1 - D_3) output pulses with rise and decay times $\tau_r \approx 70$ ns and $\tau_d \approx 400$ ns undergo the time and amplitude analysis. The signal from the first detector is delayed for 70 ns as compared with the other detectors signals. In the time channels the detector signals come to the time discriminators TD, in the amplitude channels – via delay lines DL to the linear gate LG. TD_1 generates time marks with 500 ns duration, and TD_2 - TD_3 – with 20 ns duration. These signals arrive at the input of the coincidence unit CU, which has capability of selecting events with k-fold coincidences ($1 \le k \le 3$). In order to compensate the different count rate for varies k, the adjustable frequency dividers FD_1 and FD_2 can reduce quantity of the registered events of 1-fold and 2-fold coincidences, respectively. The FDs are based on the decade counters. The logic unit LU forms the control signals for LGs - from FD_1, FD_2 and CB (for $k = 3$) output pulses. The input register IR records the information about the multiplicity of coincidences and the detectors have registered that event. The amplitude analysis requires three 10-bit ADCs, and the setup operates on line with a PC.

The spectrometer software has wide service possibilities. It includes the following procedures: 1) calibration, 2) data acquisition, 3) data processing, presentation and archiving, 4) automatic control of all operations. Complete information about the angular, energy and multiple correlations can be obtained off-line after processing the experimental data.

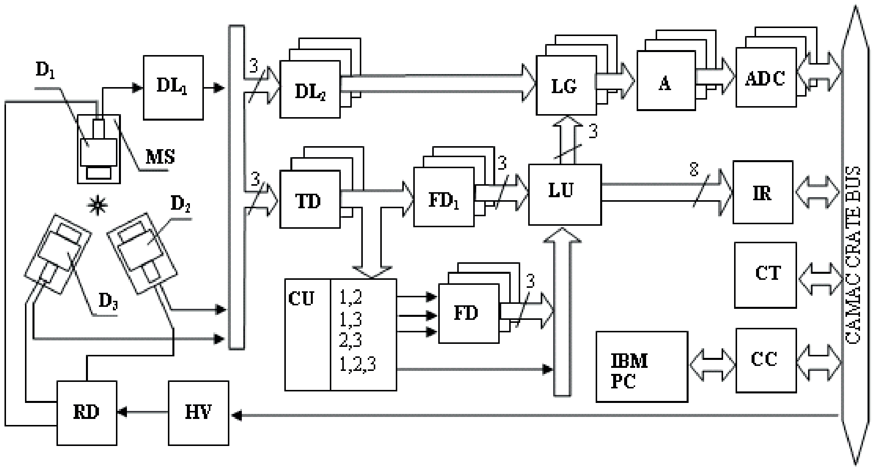


Fig. 6. A block diagram of the spectrometer: (D_1 - D_3) detectors with NaI(Tl); (MS) magnetic shield; (DL_1) additional variable delay line (70 ns); (RD) resistive divider; (HV) high-voltage source; (DL_2) delay lines; (TD) time discriminators; (CU) coincidence unit; (FD_1 and FD_2) frequency dividers; (LG) linear gate; (LU) logic unit; (A) amplifiers; (ADC) charge-to-code converters; (IR) input register; (CT) counter timer; (CC) CAMAC controller.

In the first experimental researching the anisotropy of the o-Ps quanta angular distribution in dependence on the magnetic field, the detectors are located in the same plane with the magnetic induction vector B (Fig. 7), and the specific magnetic system [8] is used. The first detector lies closely to the positron source ^{22}Na (10^5 Bq), and registers 1275 keV γ-quantum. The other two detectors lie symmetrically to the vector B at the distance of 20 cm from the positron source, at the angle of 90° one to another, and register o-Ps annihilation quanta. In this case, in accordance with Fig. 4, maximum effect is achieved. Two-photon coincidences regime is used (i.e. coincidences between signal from the first detector and a signal from the second or the third one). For reducing the background, the following is used: the setup registers γ-quanta from o-Ps decay in the time diapason of (70 – 570) ns after o-Ps-creation; the software package selects events which correspond to registering γ-quanta of (600 – 1400) keV (i.e. 1275 keV quantum) by the first detector and registering annihilation γ-quanta of (100 - 450) keV by the other detectors.

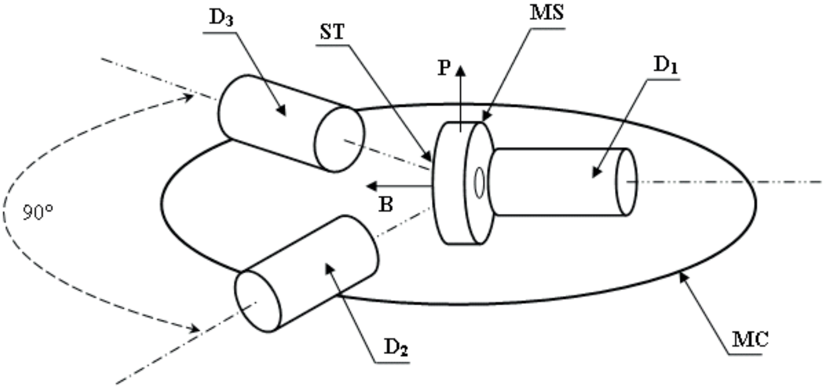


Fig. 7. The experimental diagram: (D_1 - D_3) NaI(Tl) detectors; (B) magnetic field induction; (P) positron polarization vector; (ST) source-target system; (MS) magnetic system; (MC) metallic construction.

The Ps spin direction is periodically (after 600 s) reversed for 180°. For every value of the magnetic field an exposure lasted 12 hours. Total exposure time was 11 days. After changing the Ps spin direction, a position of the 1275 keV peak center in the first detector spectrum is analyzed automatically, and the high voltage is corrected in dependence on this result.

The anisotropy A (with a statistical error in the range of $\pm 3\sigma$) is calculated as

$$A = \frac{n_\uparrow - n_\downarrow}{n_\uparrow + n_\downarrow} \pm 6 \cdot \sqrt{\frac{n_\uparrow \cdot n_\downarrow}{\left(n_\uparrow + n_\downarrow\right)^3 \cdot t}}, \tag{8}$$

where $n_\uparrow$, $n_\downarrow$ are count rates for opposite Ps spin directions, and t is exposure time.

The obtained experimental data are given in Fig. 8. Because the o-Ps decay is not registered for the time shorter than t_d (t_d = 70 ns), it is necessary to change borders in equation (7), and thus it follows

$$\int_{-\infty}^{t-t_d} \sigma(t-\tau)d\tau = E\cdot e^{-\gamma_1 \cdot t_d} + F\cdot e^{-\gamma_2 \cdot t_d} + K\cdot \gamma_3 \cdot e^{-\gamma_3 \cdot t_d} \cdot \frac{\Omega\cdot\cos(\Omega\cdot t_d) + \gamma\cdot\sin(\Omega\cdot t_d)}{\Omega^2+\gamma_3^2}. \quad (9)$$

The last term in (9) describes the anisotropy of the angular o-Ps quanta distribution in the magnetic field. The experimental data with variable decay constant γ3 are fitted. The obtained o-Ps lifetime in the sample of SiO_2 was (102 ± 9) ns, which is in accordance with the value obtained by the delayed coincidences method.

It is important to stress that this experiment is the first one where the anisotropy of the 3γ-decay quanta angular distribution (caused by o-Ps spin oscillations in the magnetic field) is researched by the coincidence method. Further development of this method is very promising for researching the Ps spin relaxation in real media.

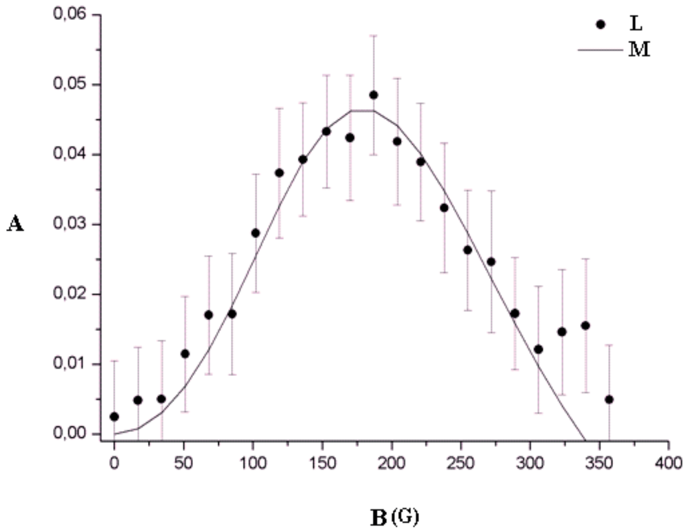


Fig. 8. The anisotropy of the o-Ps decay γ-quanta angular distribution **A** in dependence on the magnetic field **B**. **L** are the experimental data, and **M** – the data from equation (9) fitted by the last term.

CTP TESTING IN THE POLARIZED ORTHOPOSITRONIUM DECAY

The CPT-invariance is one of the most important statements of the modern theoretical physics. Since the proving of the CPT-theorem, the CPT-invariance testing became a vital issue in experimental particle physics. The experiment of CPT-testing with Ps atom was only performed in [14], where a three-detector setup (and polarized slow positron beam) was used. In that experiment the angular correlation $\vec{s}\cdot(\vec{k}_1\times\vec{k}_2)$ was tested, where $\vec{s}$ is the o-Ps spin, and $|\vec{k}_1|>|\vec{k}_2|>|\vec{k}_3|$ are the momenta of decay photons.

In the experiment [14] two of three photons were detected and count rates of two photon coincidences obtained under two opposite orientations of the o-Ps spin where then compared, i.e. that experimental test of CPT-invariance consisted in comparing the number of asymmetric decays of polarized o-Ps atoms, detected in two identical reflection-symmetric geometries. The result for the coefficient of angular correlation in the experiment [14] was $C_n = 0.20 \pm 0.023$. Certainly, the analyzing power and accuracy of CPT-experiments with positronium is much worse than, for example, experiments with neutral K-mesons [15]. Nevertheless there are at least two reasons for an interest in positronium experiments. At first, it is very interesting to test the CPT-invariance using fully leptonic system like positronium. A good example of global symmetries testing using new objects is well known atom P-violating experiment [16]. The second reason is the discrepancy between calculated and measured o-Ps lifetime [17]. The thorough researching o-Ps and looking for new discrepancies are topical.

The seven-detector setup (see Fig. 9) and the new technique for selection of annihilation events to measure the same correlation as in [14] were used in our experiment. Also, as in the experiment [14], two-photon coincidences $k_1 \subset [400, 500]$ keV and $k_2 \subset [300, 400]$ keV with the angle of 145° between detector axes were detected. The setup contains 5 pairs of detectors with the required angles between detector axes: D_1- D_3; D_1- D_4; D_2- D_4; D_2- D_5; D_3- D_5 (not two pairs as in [14]). Additionally, every detector collects data in two energy windows [400 - 500] keV and [300 - 400] keV simultaneously (not only in one window as in [14]). As a result, 10 suitable spectra for every positron polarization are simultaneously collected, and the count rate of useful events were approximately 5 times higher than in the experiment [14] with approximately the same intensity of a positron source. The detailed description of this experimental setup and background conditions can be found in [18].

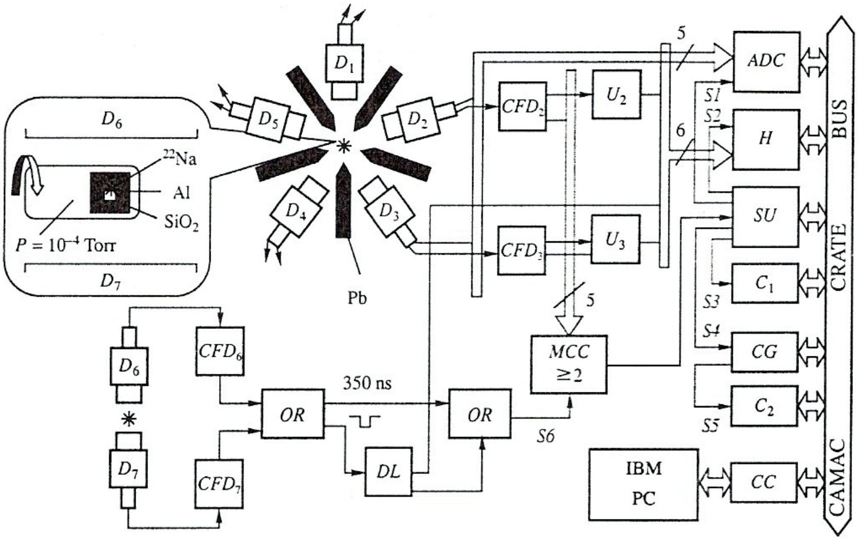


Fig. 9. A block diagram of the spectrometer: (D_1 - D_7) NaI(Tl)-detectors (150 mm x 100 mm); (CFD_1 - CFD_7) constant fraction discriminators; (U_1- U_5) delay univibrators; (MCC) majority coincidence circuit; (ADC) five 8-bit charge-to-code converters; (H) hodoscope; (SU) splitter-univibrator; (C_1) counter of events (triggering from the MCC); (CG) clock-pulse generator; (C_2) real-time counter; (CC) CAMAC crate controller; (S_1) gate signal for the ADC (600 ns); (S_2) gate signal for the hodoscope (40 ns); (S_3) signal following the input gate signal from the MCC; (S_4) dead-time signal; (S_5) clock pulses; (S_6) gate signal for the MCC; (OR) logical adder; (DL) delay line.

The positron source (^{22}Na with the activity of $3.2 \cdot 10^5$ Bq) is located close to a 3-mm-diameter tablet of silica gel SiO_2. The source-target sandwich is arranged in vacuumed glass bulb that lies along the axis of a computer-controlled motor that periodically changes a direction of positron spin during the experiment.

Detector D_6 or D_7 generates a start signal as a result of a registration of the nuclear photon 1275 keV (^{22}Na). Then two spectra for each positron polarization are collected at the same time, and differ only by the time window. The first spectrum contains two photon coincidence events that were delayed by (30 - 350) ns from positron emerging. The second one contains the events in the time window (2000 - 2350) ns that can be considered as a background. The asymmetry degree is calculated by the formula

$$A = \frac{N_+ - N_-}{N_+ + N_-} = \frac{(N_+^\Sigma - N_+^B) - (N_-^\Sigma - N_-^B)}{(N_+^\Sigma - N_+^B) + (N_-^\Sigma - N_-^B)}, \tag{10}$$

where N_+ and N_- are the numbers of events (after background subtraction), measured with parallel (+) and antiparallel (-) orientation of the positron spin to the normal to the decay plane ($\vec{k}_1 \times \vec{k}_2$); indexes Σ and B denote the spectra in the first time window (30 – 350) ns and background spectra (delayed time window) respectively. The total acquisition time in the experiment was $6.4 \cdot 10^5$ s. In view of the statistical and systematical errors, the measured asymmetry was A = 0.0008 ± 0.00091; that is twice better than the result in [14].

To obtain the coefficient of angular correlation we should divide the value of the asymmetry degree on the analyzing power S_{an}, that is calculated as an average value of $\vec{s} \cdot (\vec{k}_1 \times \vec{k}_2)$ over the experiment geometry and over all background conditions. The latter was not taken into account in equation (10). To calculate S_{an} we should:

- calculate a geometric average value of ($\vec{k}_1 \times \vec{k}_2$), taking into account the arrangement and dimensions of detectors and the sample;
- calculate an average value of Ps spin $\vec{s}$;
- take into account the background related to the possible detection of a photon with energy bellow 400 keV into the energy window (400 – 500) keV, a photon with energy bellow 300 keV into the window (300 – 400) keV, and a photon with energy over 400 keV into the window (300 – 400) keV (we calculate this background using average energy resolutions of the detectors).

Finally, it is obtained that the analyzing capacity in our experiment is $S_{an} = 0.082$, and the coefficient of angular correlation $C_n = 0.010 \pm 0.011$. This indicates that our experiment on the direct CPT-invariance test using the angular correlations, carried out with the seven-detector setup, demonstrates the absence of the effect at a 1.1 % level of uncertainty in the angular correlation coefficient.

The accuracy of the experiment on the CPT-invariance testing by analyzing angular correlations in the polarized o-Ps decay can be improved using a high-intensity beam of slow polarized positrons and a target with an o-Ps lifetime equal to that in vacuum (142 ns). Since the geometry of the three-photon annihilation under study is far from being unique, it is also desirable to increase the number of sensor combinations detecting the annihilation events. This can be achieved by increasing the number of annihilation planes under study which make an angle of about 90° with the Ps spin direction.

Our result, mentioned above, is improved later using Gamma-sphere array of Compton-suppressed high-purity germanium detectors. The amplitude of a CPT-violating asymmetry in that experiment is found to be 0.0026 ± 0.0031 [19].

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