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MEASUREMENT OF THE BRANCHING RATIO FOR THE π^0-MESON DECAY INTO A PHOTON AND A POSITRONIUM ATOM

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1. INTRODUCTION

A time-like photon can be converted into a fermion-antifermion pair with positive energy or into a bound state of the same particles. If the photon energy in the radiative process $a \rightarrow b + \gamma$ is much greater than the positronium mass, then the branching ratio for the atomic decay $a \rightarrow b + A_{2e}$ is almost independent of the masses and kinds of particles a, b and equals[1]:

$$\rho_A = \frac{W(a \rightarrow b + A_{2e})}{W(a \rightarrow b + \gamma)} = 0.30\,\alpha^4 = 0.84 \cdot 10^{-9}. \qquad (1)$$

The radiative correction for the ρ_A value has been calculated[2].

The special case of a time-like photon conversion to an atom is realized in the π^0-meson decay into a photon and a positronium:

$$\pi^0 \rightarrow \gamma + A_{2e}. \qquad (2)$$

Since two photons are emitted in the π^0 decay,

$$\rho_\pi = \frac{W(\pi^0 \rightarrow \gamma + A_{2e})}{W(\pi^0 \rightarrow \gamma + \gamma)} = 2\rho_A = 1.69 \cdot 10^{-9}. \qquad (3)$$

The positron in decay (2) is emitted mainly in the ground state ($\rho_\pi(1S) = 1.40 \cdot 10^{-9}$), its spin equals 1.

The possibility of ultrarelativistic A_{2e} detection and of quantitative measurements with them was proved in refs.[3,4]. In those works and in the present experiment positronia were produced in the reaction $p + C \rightarrow A_{2e} + X$ at 70 GeV proton energy. Calculations using the Lund model show that 91% of the atoms are produced in decay (2); 6%, in the $\eta \rightarrow \gamma + A_{2e}$ decay; and the remaining 3%, in the decays of other particles. The photon and positronium energy spectra are practically the same in any of these decays. Therefore the measurement of A_{2e}

to photons ratio at some momentum and angle range allows one to determine the ρ_A value and hence the branching ratio decay (2).

The bound state system emitted in decay (2) is ultrarelativistic: the positronium has $\gamma \approx 67$ in the π^0-meson rest frame. The production rate for such processes has not been measured previosly. In the only hitherto investigated atomic decay $K^0_L \to \nu + A_{\pi\mu}$[5,6] the bound state of a pion and a muon is emitted with $\gamma \approx 1.3$ in the K^0_L rest frame.

In the present experiment the A_{2e} atoms to photons ratio has been measured in the 800-2000 MeV/c momentum range and the ρ_A value has been obtained.

2. APPARATUS

Measurements were carried out at the relativistic positronium channel[7,8] of the IHEP proton synchrotron (Serpukhov). The scheme of positronium production and detection (Fig.1) was described in ref.[4]. A target made of 0.4 μm carbon film was inserted into the internal proton beam. Ultrarelativistic positronia resulting from proton-target interactions came into the channel at an angle of 8.4° to the proton beam.

The 40 m long channel is connected to the accelerator vacuum pipe without any partition in order to eliminate disintegration of positronium atoms in matter. The channel acceptance angle is $3.8 \cdot 10^{-5}$ sr. The target and the initial part of the channel are protected against the dissipated magnetic field of the accelerator.

A uniform, horizontally directed, magnetic field (clearing field) is applied along 23 m of the channel in order to remove charged particles from the the channel, the field being normal to the channel axis and equal to 56 E. The ground state positronium atoms passed the clearing field without dissociation into e^+ and e^- if their momenta were less than 2.5 GeV/c. Excited atoms dissociated in this field and were not detected.

The channel ended in a vacuum chamber placed between the poles of the spectrometric magnet SM (H = 4600 E).

The SM fringing field destroyed the positronium atoms, the electrons and positrons being detected by two telescopes consisting of drift chambers (DC), scintillation (S) and gas threshold Cherenkov (C) counters. These electrons and positrons have a small effective mass and approximately equal momenta. For background suppression the multilevel hardware-software processor of ref.[4] was used. It selected e^+e^- pairs by imposition of restrictions on the difference between coordinates of the e^+ and e^- at the magnet entrance, on track deviations from the target direction in the vertical plane and on the particle momentum difference.

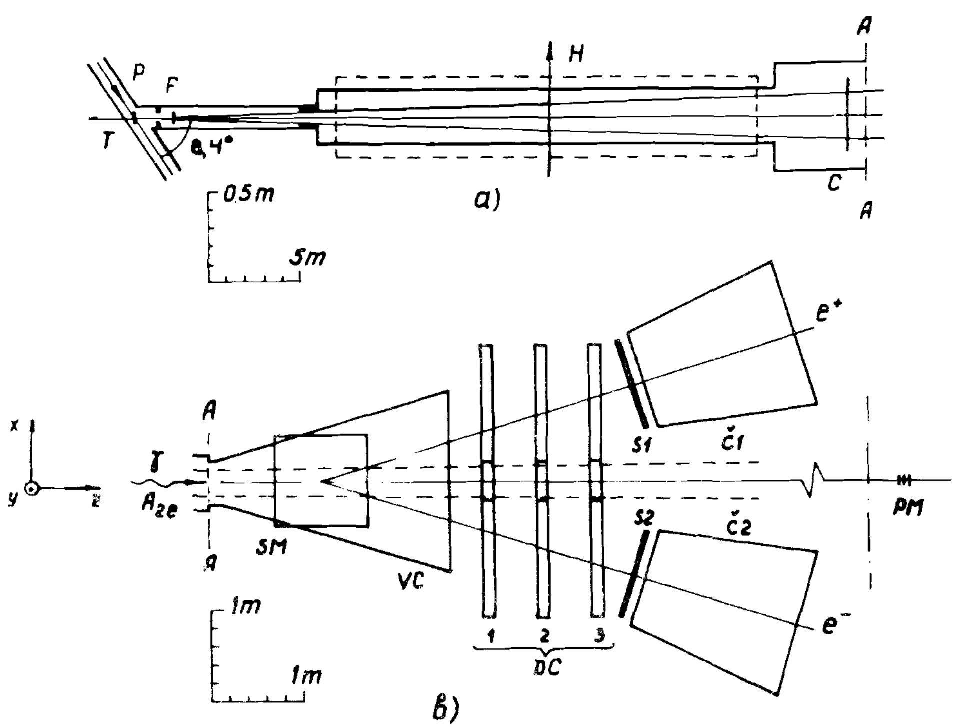

Fig.1. The experimental layout: p - internal proton beam, T - film target, C - convertor, SM - spectrometric magnet, VC - vacuum chamber, DC - drift chambers, S_1, S_2 - scintillation counters, C_1, C_2 - gas threshold Cherenkov counters, PM - photon monitor.

A plexiglas convertor ≈0.6 mm thick ($1.8 \cdot 10^{-3}$ radiation length) was inserted in the channel while measuring the photon flux. The convertor overlapped the channel cross section and served as source of e^+e^- pairs produced by beam photons. The photon flux in the channel was determined using the number of detected e^+e^- conversion pairs. Having measured the ratio of the number of A_{2e} to this flux normalized to the photon monitor (PM) readings one can obtain the branching ratio of decay (2). The scintillation counter telescope placed at the channel axis was used as a PM. The photon beam intensity in the energy range 800-2000 MeV was $2 \cdot 10^7$ sec^{-1}.

3. IDENTIFICATION OF A_{2e} DISSOCIATION PAIRS

The absence of track detectors before the spectrometric magnet is a specific feature of the experiment. Therefore all detected particles are assumed to be emitted from the target placed at the channel axis. This assumption was adopted in spatial reconstruction and momentum calculation.

In the data processing a restriction was imposed on the quantity

$$r = \left(\sum_{i=1}^{4}\left(\frac{\xi_i}{\sigma_i}\right)^2\right)^{1/2} ,$$

where $\xi_1 = \Delta X = X_1 - X_2$ is the difference between the positron and electron X-coordinates at the magnet entrance, $\xi_2 = \Delta Y = Y_1 - Y_2$ is the difference between the Y-coordinates at the exit membrane of the vacuum chamber, $\xi_3 = \Delta\theta_1$ ($\xi_4 = \Delta\theta_2$) is the positron (electron) deviation in the vertical plane from the target direction, σ_i is the ξ_i distribution parameter equal to a half of the interval containing 68% of events. The ξ_i values for pairs from A_{2e} dissociation differ from zero because of e^- and e^+ multiple scattering in the elements of the experimental apparatus, the finite precission of coordinate measurements in the drift chambers and errors in evaluating the magnetic field topography. The difference between the Y-coordinates is calculated at the exit of magnet for excluding errors caused by multiple scattering in the vacuum chamber membrane. The σ_i values characterizing the resolution of the experimental setup were obtained by Monte-Carlo simulation /4/ of the corresponding ξ_i distributions.

The e^+e^- pair emission point was also required to be located in the beam cross section at the magnet SM entry.

The distributions of events over ε defined as $\varepsilon = 2(p_1 - p_2)/(p_1 + p_2)$ are shown in Fig. 2 for different criteria imposed on the value of r, here p_1 and p_2 are the e^+ and e^- momenta in the lab frame. The pairs from the A_{2e} dissociation in the SM field should form a narrow peak near $\varepsilon = 0$ with the standard deviation $\sigma_\varepsilon = 0.014$ in accordance with the Monte-Carlo calculation. To obtain the number (N_A) of positronium atoms an interval of 0.06 over ε containing an excess of events over the background was chosen. The quantity N_A represented the difference between the total number of events in this interval and the number N_f of background events under the peak. The value of N_f was calculated by a quadratic polynomial approximation of the distribution over ε in two intervals of ε near the peak, each being 0.10 wide. The obtained number of atoms was stable against changes in the histogram bin width, the polynomial power adopted in the background fitting, and the interval widths used for the background approximation.

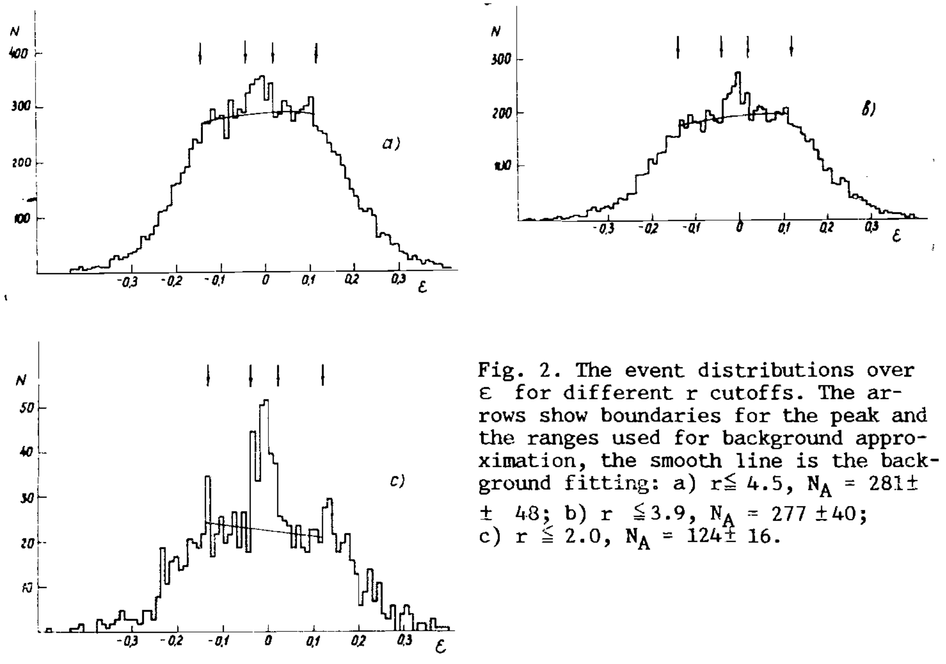

Fig. 2. The event distributions over ε for different r cutoffs. The arrows show boundaries for the peak and the ranges used for background approximation, the smooth line is the background fitting: a) r ≦ 4.5, $N_A = 281 \pm 48$; b) r ≦ 3.9, $N_A = 277 \pm 40$; c) r ≦ 2.0, $N_A = 124 \pm 16$.

N_A, as a function of r, is shown in Fig. 3. In subsequent calculations the value $N_A = 277 \pm 40$ ($\sigma_\varepsilon = 0.015 \pm 0.003$) obtained for $r < 3.9$ was used; the positronium losses should be less than 1%.

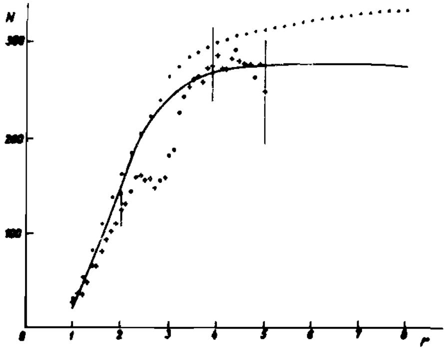

Fig. 3. The number of detected positronium atoms and photons as function of r; + - number of atoms, · - number of photons, solid line - number of photons with the background substraction. The last two bulks of the data were normalized in order to make the photon data comparable with the data for atoms.

The distribution of the number of atoms over the beam cross section was checked to be uniform and the momentum spectra of atoms and photons were shown to be identical within the measurement accuracy. The procedure of calculation of the number of atoms has revealed no event excess where there should be none, for example: in the distribution over ε of the number of e^+e^- pairs from the photon conversion during the run with the inserted convertor and in the event distribution used for the search for atoms, if any one of the ξ_i values exceeded $3\cdot\sigma_i$.

4. MEASUREMENT OF THE PHOTON FLUX

For measuring the photon flux a run with the inserted convertor was performed. To select the conversion pairs the quantities ξ_i were used in the same manner as for A_{2e} identification. The corresponding values of σ_i were obtained by the Monte-Carlo method, and they were in agreement with experimental ones[4].

Unlike the pairs from the A_{2e} dissociation, the conversion pairs exhibit a wide distribution over ε and, hence, another probability of hitting the detectors. However these probabilities are equalized by imposing the $|\varepsilon| \leq 0.1$ cutoff. The number (N_0) of detected e^+e^- pairs was obtained as a function of r for this cutoff (see Fig. 3). In the $r > 4$ region the number of converted photons should be constant. The observed small increase in this number was caused by conversion of secondary photons on the channel pipe. To exclude this addition to a primary photon flux the function $N_0(r)$ was approximated by a straight line in the $r > 5$ region and then the $N_0(r)$values were correspondingly decreased within the whole range of r. The obtained values were used for calculations of the photon flux I_γ.

To calculate I_γ the coherent and incoherent cross sections of pair production were computed in the high energy approximation for different photon energies and the ε cutoff in accordance with ref.[9]. Nonrelativistic Hartree-Fock form factors and incoherent scattering functions[10] were used. The calculation accuracy reached about 1%. The total cross section was weighted over the photon spectrum in the 800-2000 MeV energy range. The conversion probability was found to be equal to $(5.73 \pm 0.17)\cdot 10^{-5}$ at $|\varepsilon| \leq 0.1$ cutoff.

5. RESULTS

To calculate the positronium atoms-to-photons ratio the quantities N_A and N_0 were used under the condition that r=3.9 (see the Table).

Table. Results of measurements

Kind of event	Number of events	Monitor counting
A_{2e}	277 ± 40	$(6.76 \pm 0.21)\cdot 10^9$
protons	1366 ± 42	$3.85\cdot 10^5$

The following corrections should be made to these numbers in order to obtain the branching ratio ρ_π.

Some of the produced positronia are broken up by interaction in the target matter[4]. Taking into account the formation time of the positronium[11] one finds that $(99.2\pm0.4)\%$ of the atoms leave the target. If the formation time is neglected, this value would decrease by 17%.

When atoms pass the clearing magnetic field, oscillations[7] occur between the singlet and triplet state of the atoms. Some of the positronia annihilate because the singlet state decay length is comparable with the channel length, $(89.3 \pm 0.8)\%$ of the atoms reach the spectrometric magnet.

For additional background supression a beam intensity criterion was imposed, $(96 \pm 3)\%$ of the atoms survived subsequently.

The ratio of the probabilities for the detectors being hit by a conversion pair and by a positronium dissociation pair is (0.98 ± 0.02). The detectors efficiency in recording e^+e^- pairs cancels out in the N_A/I_γ ratio.

The measured, and corrected in this way, N_A/N_γ ratio normalized to the monitor data allows one to obtain the branching ratio $\rho_\pi(1S)$ for positronium atom production in the 1S state for radiative decays of elementary particles: $\rho_A(1S) = (0.76 \pm 0.12)\cdot 10^{-9}$. Only 83% of the positronia are produced in the ground state and hence the total relative probability of a time-like photon conversion into a positronium is $\rho_A = (0.92 \pm 0.14)\cdot 10^{-9}$, which coincides with the theoretical value (1). Using the obtained ρ_A and relation (3) for the branching ratio of decay (2) one has

$$\rho_\pi = (1.84 \pm 0.29)\cdot 10^{-9}.$$

This value is in good agreement with earlier experimental estimation[3].

In conclusion the authors wish to thank the beam department and accelerator staff, our colleagues from the Serpukhov department of JINR for their help in carrying out the experiment, and the staff of the Computer Center of the LNP of the JINR for technical assistance.

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Афанасьев Л.Г. и др. E1-89-593
Измерение вероятности распада π^0-мезона
на гамма-квант и атом позитрония

В pC-взаимодействиях при E_p = 70 ГэВ под углом 8,4° в лабораторной системе измерено отношение числа ультрарелятивистских позитрониев /A_{2e}/ к числу гамма-квантов в интервале импульсов 800-2000 МэВ/с. Определена относительная вероятность $\rho_\pi(1S) = (1,84 \pm 0,29)\cdot 10^{-9}$ распада π^0 на γ-квант и A_{2e}. Параметр ρ_π определяется вероятностью ρ_A перехода времениподобного фотона в A_{2e} при радиационных распадах элементарных частиц.

Работа выполнена в Лаборатории ядерных проблем ОИЯИ.

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Afanasyev L.G. et al. E1-89-593
Measurement of the Branching Ratio for the π^0 Meson
Decay into a Photon and a Positronium Atom

The ratio of the positronium ultrarelativistic atoms (A_{2e}) number to the photon number in the momentum interval 800-2000 MeV/c has been measured in pC-interactions at E_p = 70 GeV and at the angle of 8.4° in the lab frame. The branching ratio $\rho_\pi = (1.84 \pm 0.29)\cdot 10^{-9}$ for the π^0 decay into a photon and A_{2e} has been obtained. The parameter ρ_π is determined by the conversion probability ρ_A of a time like photon into A_{2e} in radiative decay of elementary particles.

The investigation has been performed at the Laboratory of Nuclear Problems, JINR.

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