NEW LIMITS ON THE SINGLE- γ DECAY OF ORTHOPOSITRONIUM

U. Amaldi, G. Carboni¹, B. Jonson² and J. Thun³

CERN, Geneva, Switzerland

ABSTRACT

We have searched for the exotic annihilation of orthopositronium, $o\text{-Ps} \rightarrow a^0 + \gamma$, where a^0 denotes a neutral particle of mass $m_a < 2m_e$. For the ratio of this decay mode to the 3γ decay mode, upper limits have been derived in the range $5 \times 10^{-6} - 1 \times 10^{-6}$ (for m_a varying from 100 to 900 keV). This result excludes the hypothesis that this exotic decay is responsible for the discrepancy between the theoretical and experimental values of the orthopositronium lifetime.

(Submitted to Physics Letters B)

-
- 1) On leave from INFN, Pisa, Italy
 - 2) On leave from Dept. of Physics, Chalmers University of Technology, Gothenborg, Sweden
 - 3) CERN Summer Student 1984

1. INTRODUCTION

The existence of light neutral bosons with semiweak interaction has been repeatedly suggested, in the past few years, in the context of the gauge theories incorporating the standard model. Examples are the Higgs [1,2], the axion [3], and the Fayet U-boson [4]. Their interaction is semiweak in the sense that their coupling g_0 to fermions is small, i.e. of the order of $g_0 \approx [\sqrt{2} G]^{1/2} m_f$, where m_f is the fermion mass, so that for an electron $\alpha^* = g_0^2/4\pi \approx 3 \cdot 10^{-13}$.

Because the coupling increases with the fermion mass, the a^0 has been searched for in heavy quark annihilation processes, e.g. $\Psi \rightarrow a^0 + \gamma$ or $\Upsilon \rightarrow a^0 + \gamma$ [5], or in nuclear decays [6]. Other experiments have been looking for a^0 's produced in hadron [7] and electron [8] collisions with nuclei. At present there is no evidence for the existence of such a particle.

It was noticed by several authors [2,4,9-11] that if the mass $m_a < 2 m_e$, the a^0 could be emitted in the annihilation of orthopositronium (o-Ps):

$$\text{o-Ps} \rightarrow a^0 + \gamma \quad (1)$$

This decay mode is particularly interesting if the a^0 is coupled only to leptons or even only to the electron, or if the coupling is mass-independent. In this case, the negative results of the searches performed until now are much less significant. The purpose of the present experiment was to improve the existing limits on the coupling of this kind of particle to the electron.

The single- γ annihilation [Eq. (1)] would result in the appearance of a monochromatic γ line at the energy $\omega = m_e(1 - m_a^2/4m_e^2)$ superimposed on the continuum spectrum due to the 3γ decays of o-Ps [12]. Since the a^0 is penetrating and relatively long-lived no recoiling particle will be visible in the decay¹. The ratio $R = \Gamma_{a\gamma}/\Gamma_{3\gamma}$ is enhanced in o-Ps by a factor $\approx 10^3$ with respect

¹ A light U-type particle could have a short lifetime, but since it would decay into a neutrino pair, it could not be detected.

to the "natural" ratio (semiweak interaction/electromagnetic interaction) $\approx \alpha^*/\alpha$, because of phase space and vertex factors. In a previous experiment on positronium, Carboni and Dahme [13] have set a limit $R < 7 \times 10^{-5}$ (99.7% C.L.) using a Ge(Li) detector. An improvement of this limit of almost two orders of magnitude has recently been obtained with the Heidelberg Crystal Ball [14], but with a limited detector energy resolution. Here we present the results of a new high-resolution measurement, done with an apparatus improved along the lines indicated by Amaldi et al. [15].

2. EXPERIMENTAL TECHNIQUE

The detector used for the search of single γ -rays in the decay of orthopositronium is schematically illustrated in Fig. 1. The basic idea of this set-up is the same as the one already described by Carboni [8]. The positron source was ^{68}Ge ($T_{1/2} = 275$ days) with an activity of $3.7 \mu\text{Ci}$. This isotope is in secular equilibrium with ^{68}Ga ($T_{1/2} = 68$ min) and the γ lines in the decay spectrum are weak and above 577 keV. The source was deposited onto a Ni disk, 0.05 mm thick, in order to minimize the number of annihilations inside the source support. The disk was sandwiched between two 0.5 mm thick NE102 plastic scintillators. Two light guides brought the light to a pair of Philips PM2232B photomultipliers, the coincidence of these signalling the emission of a positron. The positrons traversing the scintillator were stopped in two blocks of silica aerogel ($\rho \approx 0.3 \text{ g/cm}^3$) where about 20% of them formed orthopositronium.

Gamma rays were recorded in an intrinsic Ge detector, placed directly in front of the source assembly. With our geometry the detection efficiency was about 5×10^{-3} at 500 keV. Regular calibrations during the whole data-taking period were made with a ^{133}Ba source. The 511 keV annihilation line also served as an internal calibration. The signal from the Ge detector was used both for pulse-height analysis (energy spectrum) and for timing and lifetime measurement (time spectrum).

In order to reject the 2γ events due to the decay of the singlet state of positronium ($\tau_s = 0.12 \text{ ns}$) and to annihilation in flight, the γ rays were recorded

with the condition of being delayed at least 15 ns with respect to the time of positronium formation (defined by the signal from the plastic scintillators). The time window for the recording of γ -rays was 200 ns to allow for the decay of the major part of o-Ps. Some 2γ events due to quenching of o-Ps and to randoms were also present in this time window (see Section 3).

To suppress the background, where more than one γ -ray was emitted, the source assembly and the Ge detector were placed inside the well (8.4 cm diameter, 9 cm deep) of a large anti-Compton shield. This was a NaI(Tl) crystal (Harshaw, 9 in x 9 in) equipped with six PM tubes. A VETO signal was defined by demanding at least two PM signals above the threshold: this allowed a minimum detectable energy as low as 15 keV, while it reduced the random VETO rate considerably.

A CAMAC system interfaced to a Hewlett-Packard 21MX computer and tape drive was used for data acquisition. The TRIGGER signal was given by a positron traversing one of the thin scintillators, and it opened the 200 ns wide gate. A DELAYED ANNIHILATION was defined as a signal from the Ge detector falling within this gate. The gate was reset and the event discarded if there was a second TRIGGER signal arriving before the Ge one. This condition removed 85% of the random DELAYED ANNIHILATION events. If no VETO signal was present in the NaI chain, the event was a CANDIDATE for a single- γ annihilation. In that case (i) the Ge detector pulse-height and (ii) the time interval between the TRIGGER signal and the Ge signal were recorded on magnetic tape. Time and pulse-height spectra for the DELAYED ANNIHILATION events were recorded for normalization. Scaler contents were printed at the end of each run, in order to monitor the performances of the apparatus. The duration of each run was 2-3 days.

3. RESULTS

The data-taking period lasted about two months. A summary of the results is given in Table 1. For the analysis, spectra from different runs were added together. Shifts of the energy scale never exceeded 0.2% , and were corrected for on the basis of the calibration runs. Figure 2 shows the energy and time spectra for the DELAYED ANNIHILATION events which were used for normalization. By fitting the time spectrum (inset of Fig. 2) with the function $A \exp(-t/\tau) + B$, where the exponential described the o-Ps decay and B represented the random background, we found $\tau = 70.3 \pm 0.4$ ns for the lifetime of o-Ps in aerogel. The lifetime τ is shorter than the triplet lifetime, $\tau_t \approx 140$ ns, because o-Ps in aerogel undergoes collisional quenching in about 50% of the cases [16]. The 511 keV peak in the energy spectrum came mainly from this effect, the rest being random 2γ events (singlet decays and annihilations in flight). The random events in the 511 keV peak were calculated by using the fitted B value, and subtracted from the raw peak to obtain the number of delayed 2γ annihilations, $n_{2\gamma}$ (see Table 1).

Figure 3 shows the energy spectrum for the single- γ CANDIDATES, i.e. after the VETO request. The shape is different with respect to Fig. 2 because of the effect of the NaI veto. The efficiency of the anticoincidence was lowest for the 2γ decays, because the recoiling photon travelled along the crystal axis and traversed a comparatively small NaI thickness. 3γ decays were rejected more efficiently, since (i) it was more unlikely that both recoiling γ 's escaped detection , (ii) the γ 's traversed, on the average, more NaI thickness than those from the 2γ decays, and , (iii) they had larger photoelectric cross-section because of the lower energy.

The search for possible peaks in the spectrum of Fig. 3 was performed in the following way: for every energy, ω , the region around it in the spectrum was fitted with a Gaussian line shape centred at ω , superimposed over a polynomial background. The width of the Gaussian was measured in the calibration runs. This analysis showed that there were no significant peaks in the spectrum. The 1σ limit on the number of single- γ decays, $N_{a\gamma}$, was obtained from

the error $\Delta N(\omega)$ on the area of the fitted Gaussian, and the limit on the ratio R then was

$$R(\omega) = N_{a\gamma}/N_{3\gamma} = [\Delta N(\omega)/\epsilon_{1\gamma}(\omega)]/N_{3\gamma}, \quad (2)$$

where $N_{3\gamma}$ was the total number of 3γ decays and $\epsilon_{1\gamma}(\omega)$ was the efficiency of detecting one γ of energy ω . Equation (2) was conveniently rewritten as

$$R(\omega) = [\Delta N(\omega)/n_{2\gamma}][\epsilon_{2\gamma}/\epsilon_{1\gamma}(\omega)](N_{2\gamma}/N_{3\gamma}), \quad (3)$$

where $n_{2\gamma}$ was the number of 511 keV γ -rays detected in the normalization spectrum (Table 1), $\epsilon_{2\gamma}$ was the efficiency for detecting both photons from the 2γ decay, and $N_{2\gamma} = n_{2\gamma}/\epsilon_{2\gamma}$. The ratio $\epsilon_{2\gamma}/\epsilon_{1\gamma}$ was obtained from the efficiency calibration of the detector, performed with a set of standard sources. It was well approximated by the expression $\epsilon_{2\gamma}/\epsilon_{1\gamma} = 2 (\omega/m_e)^{-0.6}$. The factor $N_{2\gamma}/N_{3\gamma} = \tau_t/\tau - 1 = 1.02$ was obtained using the measured lifetime, τ , and $\tau_t = 141.8 \pm 0.4$ ns from the measurement by Gidley et al. [17].

The final result of this analysis is displayed in Fig. 4, where the limit on R (at 90% C.L.) is given as a function of the a^0 mass. The present limit is about one order of magnitude lower than the previous result obtained by Carboni and Dahme [13], also shown in the figure, and two orders of magnitude lower than the $(g-2)$ limit [13,18,19], except in the region below 100 keV, where there is no sensitivity, because of the presence of the 511 keV line.

For completeness, also shown in Fig. 4 are the predictions for the "classical" axion as computed from Bernreuther and Nachtmann [11] assuming three quark doublets. These have only an academic interest, since several experiments have ruled the classical axion out [5-8]. It is seen that our limit becomes marginally significant in the high-mass region, at least if the upper branch of the curve is considered.

By assuming a pseudoscalar coupling of the a^0 to the electron, the limit on R in Fig. 4 can be transformed into a limit on the coupling α^* , using Eq. (3) of Ref. [13]. The present results for this quantity are given in Table 2 (90% C.L.).

Recently, improved calculations of the o-Ps lifetime [20], have shown a significant discrepancy between the theoretical and the measured values. These are all [17,21] shorter than the computed τ_t by about 0.1-0.01%. It has been suggested [19] that process (1) could be at least partially responsible for the effect. Our limit indicates that the possible discrepancy in the triplet lifetime cannot be attributed to this mechanism, at least if the a^0 mass lies in the region 100-900 keV.

ACKNOWLEDGEMENTS

This experiment was preceded by preliminary tests in which we gratefully acknowledge the participation of W. Dahme and D. Lloyd Owen. We warmly thank A. Donnet for help in setting up the experiment. Finally, we are grateful to A. Baechli of Baechli Instruments for making the NaI detector available to us.

REFERENCES

1. P.W. Higgs, Phys. Rev. Lett. 12, 132 (1964)
P.W. Higgs, Phys. Rev. Lett. 13, 508 (1964)
P.W. Higgs, Phys. Rev. 145, 1156 (1966)
S. Weinberg, Phys. Rev. Lett. 19, 1264 (1967)
2. L. Resnick, M.K. Sundaresan and P.J.S. Watson, Phys. Rev. D8, 172 (1973)
3. S. Weinberg, Phys. Rev. Lett. 40, 223 (1978)
F. Wilczek, Phys. Rev. Lett. 40, 279 (1978)
4. P. Fayet and M. Mezard, Phys. Lett. 104B, 226 (1981)
5. C. Edwards et al., Phys. Rev. Lett. 48, 903 (1982)
M. Sivertz et al., Phys. Rev. D26, 717 (1982)
B. Niczyporuk et al., Z. Phys C - Particles and Fields 17, 197 (1983)
M.S. Alam et al., Phys. Rev. D27, 1665 (1983)
6. J.L. Vuilleumier et al, Phys. Lett. 101B, 341 (1981)
A. Zehnder, Phys. Lett. 104B, 494 (1981)
G.D. Alekseev et al., JETP Letters 36,116 (1982)
V.M. Datar et al., Phys. Lett. 114B, 63 (1982)
P. Lehmann et al., Phys. Lett. 115B, 270 (1982)
A. Zehnder et al., Phys. Lett. 110B, 419 (1982)
H. Faissner et al., preprint PITHA 82-10 (1982)
J.F. Cavaignac et al., Phys. Lett. 121B, 193 (1983)
7. E. Bellotti et al., Phys. Lett. 76B, 223 (1978)
P. Alibrant et al., Phys. Lett. 74B, 134 (1978)
T. Hansl et al., Phys. Lett. 74B, 139 (1978)
C. Bosetti et al., Phys. Lett. 74B, 143 (1978)
P. Coteus et al., Phys. Rev. Lett. 42, 1438 (1979)
P.F. Jacques et al., Phys. Rev. D 21, 1206 (1980)

- H. Faissner et al., Phys. Lett. 103B, 234 (1981)
C.M. Hoffman et al., Phys. Rev. D 28, 660 (1983)
H. Faissner et al., Phys. Rev. D 28, 1198 and 1787 (1983)
F. Bergsma et al., CHARM Collaboration, to be published.
8. T.W. Donnelly et al., Phys. Rev. D 18, 1607 (1978)
D.J. Bechis et al., Phys. Rev. Lett. 42, 1511 (1979)
J.D. Bjorken, preprint FERMILAB-Conf-84/33-T (1984)
 9. K.O. Mikaelian, Phys. Lett. 77B, 214 (1978)
 10. G. Carboni, Phys. Lett. 101B, 444 (1981)
 11. W. Bernreuther and O. Nachtmann, Z. Phys. C - Particles and Fields 11, 235 (1981)
 12. A. Ore and J.L. Powell, Phys. Rev. 75, 1696 (1949)
 13. G. Carboni and W. Dahme, Phys. Lett. 123B, 349 (1983)
 14. R.S. Simon, talk given at Workshop on Nuclear Structure at High Spin, Niels Bohr Institute, Risø, 1983, and private communication.
 15. U. Amaldi, G. Carboni, W. Dahme and D. Lloyd Owen, preprint CERN-EP/83-120 (1983)
 16. For a discussion of quenching, see, for example, H.S.W. Massey, E.H.S. Burhop and H.B. Gilbody, "Electronic and ionic impact phenomena" (Oxford University Press, London, 1974) Vol.5
 17. D.W. Gidley et al., Phys. Rev. Lett. 49, 525 (1982)
 18. T. Kinoshita and W.B. Lindquist, Phys. Rev. Lett. 47, 1573 (1981)
 19. J. Cleymans, P.S. Ray, Lett. Nuovo Cimento 37, 569 (1983)
 20. W.E. Caswell and G.P. Lepage, Phys. Rev. A 20, 36 (1979)

G.S. Adkins, UCLA Ph.D. Thesis (1982)

21. D.W. Gidley et al., Phys. Rev. Lett. 40, 737 (1978)
D.W. Gidley et al., Phys. Lett. 69A, 97 (1978)
T.C. Griffith et al., J. Phys. B 11, L743 (1978)

Table. 1

Summary of results

Total time	4.9×10^6 s
Total triggers	5.3×10^{11}
Total annihilations	6.7×10^{11}
$n_{2\gamma}$, 2γ normalization peak	4.4×10^8
Total 1γ CANDIDATES	7.1×10^7
τ , o-Ps lifetime	70.3 ± 0.4 ns

Table 2

Limits on the coupling constant α^* (see text)

m_a (keV)	α^* (90% C.L.)
100	5.3×10^{-11}
200	4.1×10^{-11}
400	3.2×10^{-11}
600	3.6×10^{-11}
800	4.7×10^{-11}

FIGURE CAPTIONS

- Fig. 1: Schematic view of the detector: 1) NaI(Tl) anticoincidence crystal; 2) intrinsic Ge detector (volume 94.4 cm³, resolution 1.8 keV FWHM at 356 keV); 3) 3.7 μ Ci ⁶⁸Ge source; 4) NE102 scintillators; 5) light-guides; 6) blocks of silica aerogel; 7) Ge detector housing; 8) Photomultiplier tubes.
- Fig. 2: Energy spectrum of orthopositronium decay (DELAYED ANNIHILATIONS) measured in a time interval of 200 ns starting 15 ns after the formation of orthopositronium. The 511 keV peak is mainly due to 2 γ annihilations from o-Ps quenching. The region below 511 keV has contributions both from the Compton-scattered 511 keV γ -rays (shoulder around 340 keV) and from the continuum of 3 γ decays. The inset shows the time spectrum, consisting of an exponential ($\tau = 70.3 \pm 0.4$ ns) due to o-Ps decay, plus a constant background (see text).
- Fig. 3: Energy spectrum of orthopositronium decay with the VETO request (single- γ CANDIDATES). The inset shows all the data. The part used for the search of single- γ peaks, from the exotic decay $o\text{-Ps} \rightarrow a^0 + \gamma$, is shown enlarged and with double bin width.
- Fig. 4: Limits on the ratio of the single- γ to 3 γ decay of orthopositronium, as a function of the a^0 mass from this and other experiments. All the data are displayed at a 90% C.L. The theoretical curve corresponds to the predictions for a "classical" axion as computed in Ref. [11].

Fig. 1

Fig. 2

Fig. 3

Fig. 4