

Search for C-violating, P-conserving interactions and observation of 2^3S_1 to 2^1P_1 transitions in positronium

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Possible C-forbidden transitions between 2^3S_1 and 2^1P_1 states of positronium are investigated. Limits are placed on the CP-violating state-mixing matrix element: $|\langle 2^1P_1 | H_{CP} | 2^3S_1 \rangle| < 65$ MHz. Zeeman induced transitions yield the first observation of 2^1P_1 states and measurement of the 2^3S_1 to 2^1P_1 transition frequency, $\nu_0 = 11181 \pm 13$ MHz, verifying QED calculations.

1. Introduction

The observation [1] in 1964 of CP violation (charge conjugation–parity) in neutral kaons is still not theoretically understood [2]. The subsequent experimental data on CP violation are limited to positive results only with neutral kaon decay and many negative results in other systems [3], including (assuming CPT) equivalent searches for T violation (time reversal). Among the most precise tests are the searches for static electric dipole moments (EDM) of the neutron [4] and the electron [5]. The EDM experiments have direct sensitivity to a P-odd, T-odd interaction, denoted \mathcal{PT} (where a slash indicates an interaction is odd under the corresponding symmetry operation, see ref. [6]). It is not clear from the positive neutral kaon results if the \mathcal{PT} form for the CP-violating interaction as with EDMs is correct. In fact, the observed CP violation could be a manifestation of a solely \mathcal{CP} mixing of the neutral kaon states K^0 – \bar{K}^0 . The possibility of a long-range, weakly-coupled \mathcal{CP} interaction has not been experimentally excluded [7]. The experiment described

in this paper is the first direct test for a \mathcal{CP} -state-mixing interaction beyond the neutral kaon system^{#1}.

Our experiment (described as type A in ref. [6]) used positronium (Ps) in the $n=2$ excited state; Ps states are not only P eigenstates but also C eigenstates, as shown in fig. 1 of ref. [6]. The experimental design uses the metastable 2^3S_1 state, with a 3γ annihilation lifetime of 1.1 μ s, as the initial state. All of the other $n=2$ states decay in a few ns, either by a Lyman- α (L_α) decay to the ground state (P_J states, $\tau=3.2$ ns), or by annihilation to 2γ (1S_0 state). We stimulate microwave-single-photon electric-dipole transitions (P conserving [6]) between the 2^3S_1 and 2^1P_1 states. In the absence of other external fields, this transition would be strictly forbidden by C since both of these $n=2$ states have the same C eigenvalue and the proton has $C=-1$.

An attractive feature of the $n=2$ Ps system is that the 2^3P_1 state is separated from the 2^1P_1 state by only $E_1=1.826$ GHz. A \mathcal{CP} interaction that mixes these two states is characterized by the matrix element $\mathcal{M}_{CP} = \langle 2^1P_1 | H_{CP} | 2^3P_1 \rangle$. For sufficiently small \mathcal{M}_{CP} , the single-photon electric-dipole transition amplitude between 2^3S_1 and 2^1P_1 would be

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^{#1} The Ps atom in the $n=1$ level has been used for tests of \mathcal{CP} [8] and \mathcal{C} alone (most recently, ref. [9]). The decays of π^0 and η have also been tested for \mathcal{C} .

$$A_{QP} = \frac{\langle 2^1P_1 | H_{QP} | 2^3P_1 \rangle \langle 2^3P_1 | e\epsilon \cdot r | 2^3S_1 \rangle}{E_1}, \quad (1)$$

where $\epsilon(t) = \epsilon_0 \hat{z} \cos(2\pi\nu t)$ is the RF electric field. An externally applied magnetic field $\mathbf{B} = B\hat{z}$ also produces a 2^3S_1 to 2^1P_1 electric-dipole transition amplitude A_B . By observing this magnetically induced effect, we have detected the 2^1P_1 state for the first time, checked the QED prediction for the energy of the 2^1P_1 state, and calibrated our instrument for the measurement of \mathcal{M}_{QP} at $B=0$.

If \mathcal{M}_{QP} is CPT conserving, it is purely imaginary with respect to the CP conserving matrix elements and interference terms between A_{QP} and A_B are negligible. Thus the square of the transition amplitude in the rotating wave approximation [10] for $m=0, \pm 1$ becomes

$$K_m^2 = A\epsilon_0^2 [(B/B_m)^2 + \frac{1}{2}m^2(\mathcal{M}_{QP}/E_1)^2], \quad (2)$$

where $A = (6ea_0/\hbar)^2$, $B_0 = 2034$ G, and $B_{\pm 1} = 761$ G. For sufficiently small ϵ_0 and B , the transition probability can be approximated by $P_m = K_m^2 T \tau L(\delta_m)$ where $T = w/v \cos\theta$ is the transit time of positronium of speed v across the waveguide of width w , and $L(\delta_m)$ is a Lorentzian lineshape for detuning δ_m (approximately $2\pi(\nu - \nu_0)$, where ν_0 is the zero ϵ_0 and B -field center frequency for the transition) and a natural linewidth $1/2\pi\tau = 50$ MHz. In the small field case, the transition probability would exhibit a quadratic dependence on B and ϵ_0 . However, for some ϵ_0 and B used in these measurements substantial saturation and power broadening occur. To accurately model the lineshape and magnetic field dependence of P_m we use eq. (2) of ref. [11] with the complex Rabi frequency $a+ib \equiv [(\delta_m - i/2\tau)^2 + K_m^2]^{1/2}$.

2. Experimental technique and apparatus

The basic arrangement of this experiment is shown in fig. 1 and is similar to that in ref. [11]. A 100 eV slow e^+ beam [12] of up to 10^5 e^+ /s enters the waveguide through a 2 cm diameter, Cu-mesh-covered hole and strikes the back wall of the waveguide where an Al or Mo target foil [13] is positioned. Two percent of the e^+ form excited-state Ps [13,14] that is emitted back into the waveguide. Microwaves in

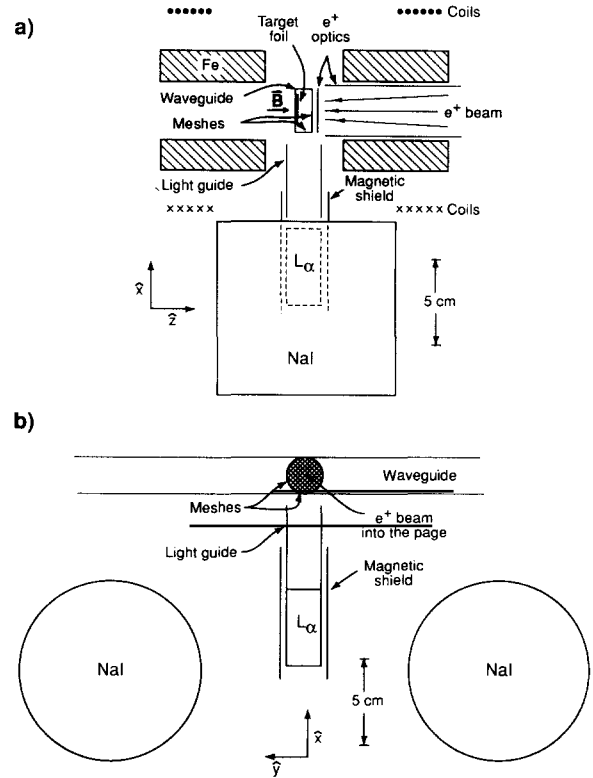


Fig. 1. Experimental apparatus. The apparatus to drive transitions in $n=2$ Ps is shown in (a) the side view and in (b) the e^+ beam's view. A slow e^+ beam enters the microwave waveguide through meshes, strikes a foil and forms $n=2$ Ps. Transitions from 2^3S_1 to 2^1P_1 are driven by 11.2 GHz microwaves and in the presence of a magnetic field produced by the coils. Detectors for the L_α and γ ray annihilation radiation (NaI) are below the waveguide.

the TE_{10} mode, tuned near the transition frequency of 11.2 GHz, propagate in the waveguide and overlap with the $n=2$ Ps atoms defining the interaction region.

The interaction region (typical pressure 10^{-7} Torr) is viewed, through another Cu-mesh-covered hole in the bottom of the waveguide, by a thin quartz end window Hamamatsu R821 solar-blind photomultiplier tube with a CsTe photocathode. This detector is sensitive to Ps L_α photons at 243 nm and operates in the single-photon-counting mode [13]. The L_α transition of interest, $2^1P_1 \rightarrow 1^1S_0 + L_\alpha$, occurs with a 3.2 ns lifetime, but its signal is diluted by L_α transitions of initially formed 2^1P_1 states and other types

of noise. The 1^1S_0 final state decays with a lifetime of 125 ps into two back-to-back 511 keV γ rays, one of which is detected in either of two 10 cm \times 10 cm diameter NaI crystals coupled to Hamamatsu R1307 photomultiplier tubes.

Our experimental signal is a fast timing L_α - γ coincidence as observed in a standard time-to-amplitude converter (TAC) spectrum, with L_α start and γ stop. Further, we require that the NaI signal fall in the 511 keV photopeak of the γ ray energy spectrum. The average NaI energy resolution is about 10% FWHM at 511 keV, the best observed L_α -NaI time resolution is roughly 4 ns FWHM.

The L_α - γ (511 keV) coincidence signal is modulated with the application of 11.2 GHz microwaves to the interaction region. A programmable multi-channel analyzer, Nuclear Data ND-62, alternately turns the microwaves on and off in 60 s intervals, acquiring the L_α - γ (511 keV) TAC spectra in separate memories for the microwave on and off configurations over the course of a day. Daily, the run is stopped, the data are recorded, detector gains monitored and adjusted, and a new run is started. Using the random background-corrected count rate for prompt L_α - γ (511 keV) coincidences with microwaves on (N_{on}) and off (N_{off}), we define the ratio

$$\Delta \equiv \frac{N_{on} - N_{off}}{N_{off}} \quad (3)$$

related to the probability for S to P transitions induced by the microwaves (see below).

A maximum B field of 100 G, uniform to a few percent, is applied to the interaction region with an external pair of current-driven coils and iron pole pieces placed in the vacuum system near the interaction region. A non-zero value for Δ is expected at high B fields. However, Δ is required to be zero at $B=0$ if CP is a good symmetry. Conversely, a non-zero Δ at $B=0$ would be a clear signal of the effects of a $\not{C}P$ interaction [6].

The detector geometry used for this experiment is shown in fig. 1b. The L_α detector is 5 cm below the bottom of the waveguide and magnetically shielded to isolate its electronic gain from magnetic fringing field effects. The NaI detectors are on the same lower side of the waveguide as the L_α detector. This arrangement of detectors differs from that of ref. [11] and is chosen to minimize the dominant source of

noise. This noise is due to γ rays that Compton-scatter from the quartz window of the L_α phototube into a NaI crystal [11]. Scintillations in the phototube coincident with γ detection mimic our experimental signal and dilute the observed values for Δ by the ratio of false to true events. A special thin-window phototube was obtained for these measurements. In addition, the geometry and energy selection in the NaI detectors sufficiently suppresses the γ ray contributions to the noise event rate.

3. Data and data analysis

Figure 2 shows a scan of Δ versus the microwave frequency in the 11.2 GHz region for $B=100$ G and RF electric field of $\epsilon_0=36$ V/cm corresponding to a traveling wave RF intensity of 1.7 W/cm². The resonant nature of the magnetically induced 2^3S_1 to 2^1P_1 transition is evident. This resonance peak constitutes the first observation of the 2^1P_1 state in Ps. A model for Δ (described below) is fit to the data and shown as a solid line in fig. 2. The vast majority of the events in the resonance peak are due to transitions involving the $m=\pm 1$ substates, the peak transition probability due to the $m=0$ substates is expected to be at least an order of magnitude below that of the $m=\pm 1$ substates.

The velocity distribution of $n=2$ Ps has two distinct components [13,14]. Motional Stark effects

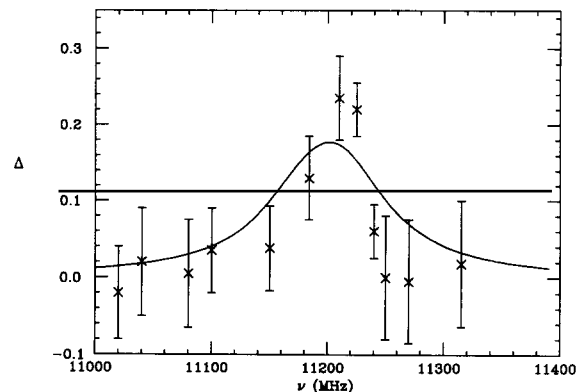


Fig. 2. Resonance structure of magnetically induced 2^3S_1 to 2^1P_1 transitions. A model is fit (solid curve) to a series of measurements of Δ (eq. (3)) scanning the microwave frequency in the region 11.2 GHz using $B=100$ G and $\epsilon_0=36$ V/cm.

broaden the resonance curve for the high velocity component ($KE \approx 30$ eV [13]) beyond the scale of fig. 2; also, since transit times across the waveguide are less than 5 ns, the transition probabilities for this component are small. Only the low velocity component contributes to the sharp, slightly broadened, peak shown in fig. 2. Motional Stark shifts as great as 20 MHz occur at the largest magnetic fields.

There is sizeable uncertainty ($\pm 15\%$) in the scaling of the RF electric field ϵ_0 averaged over the relevant population of $n=2$ Ps atoms. This uncertainty in ϵ_0 is due in part to the presence of standing waves with nodes centered on the mesh-covered holes in the waveguide. Slotted line measurements were performed with our entire RF apparatus to quantify the effect of standing waves.

Table 1 displays the results of a series of near-resonance runs, taken under differing conditions. Variations were made in ϵ_0 , B field, coincidence resolving time and, in one case, the type of γ ray detector. The Δ ($B=0$) values in table 1 are consistent with zero, indicating that no CP violation is being observed in this experiment.

To obtain the most accurate limits of \mathcal{M}_{QP} and the best estimate for the center frequency (ν_0), a multi-parameter model for Δ , based on the expression for P_m from ref. [11], was fit to the data. Perturbation

Table 1

Summary of on-resonance runs. A series of on-resonance runs measuring Δ (eq. (3)) were taken under differing conditions of B field, RF electric field (ϵ_0), coincidence resolving time, and the type of γ ray detector used. A microwave frequency $\nu = 11210$ MHz is used with the $\epsilon_0 = 36$ V/cm runs and $\nu = 11205$ MHz with the $\epsilon_0 = 27$ V/cm runs.

B (G)	ϵ_0 (V/cm)	γ -detector	Δ
100	36	NaI	$+0.271 \pm 0.062$
70	36	NaI	$+0.112 \pm 0.046$
50	36	NaI	$+0.064 \pm 0.016$
30	36	NaI	-0.050 ± 0.100
0	36	NaI	$+0.043 \pm 0.045$
73	27	NaI	$+0.102 \pm 0.043$
0	27	NaI	$+0.040 \pm 0.041$
73	27	NaI ^{a)}	$+0.098 \pm 0.028$
50	27	NaI ^{a)}	$+0.048 \pm 0.026$
0	27	NaI ^{a)}	-0.041 ± 0.025
73	27	Ge	$+0.315 \pm 0.119$
0	27	Ge	-0.062 ± 0.111

^{a)} Slow-timing on NaI instead of fast.

theory is used to correct δ_m for Doppler, motional Stark, induced Zeeman, and AC Stark shifts. The results of the fit of the model are shown as solid curves in fig. 2, the resonance curve, and in fig. 3, a plot of Δ versus B for all the NaI data in table 1. Parameterization of the model includes: (1) angular distribution of Ps velocities and (2) backgrounds which dilute the observed Δ . A $\cos \theta$ distribution is assumed, independent of v . An averaged transition probability \bar{P}_m is obtained from a weighted integration of P_m from $\theta=0^\circ$ to 45° . With the assumption that $n=2$ Ps is formed equally in all sublevels [11,15], background dilution is modeled by

$$\Delta = \frac{\frac{2}{3}\bar{P}_{\pm 1} + \frac{1}{3}\bar{P}_0}{1+b}. \quad (4)$$

The 1 in the denominator represents the background from the three originally formed 2^1P_{1m} substates and b accounts for all other backgrounds. This model is fit to all the data (table 1 and fig. 2) with four free parameters \mathcal{M}_{QP} , ν_0 , v , and b , and one partially free parameter ϵ_0 which is allowed to vary within its error bar.

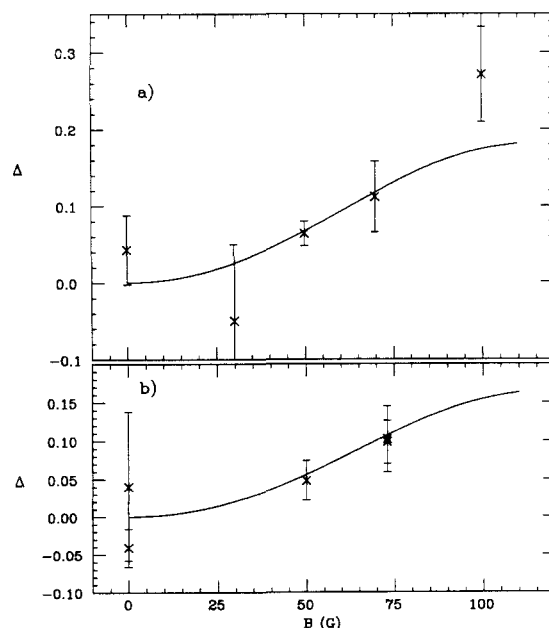


Fig. 3. B field dependence of 2^3S_1 to 2^1P_1 transitions. As the B field is reduced, the signal Δ goes to zero, in accordance with CP conservation. (a) Data with $\epsilon_0 = 36$ V/cm from table 1. (b) Data with $\epsilon_0 = 27$ V/cm NaI. The solid line is a fit to a transition model.

The best fit to the data gave a minimized $\chi^2=19.6$ for 17 degrees of freedom with parameters $|\mathcal{M}_{\mathcal{CP}}|=0\pm 65$ MHz, $\nu_0=11181\pm 13$ MHz, $b=1.9\pm 0.5$, $v=(5.7\pm 0.7)\times 10^7$ cm/s, and $\epsilon_0=(0.84\pm 0.16)\epsilon_0$ (value in table 1) i.e., the fitted ϵ_0 is lower than our estimate. The error quoted for $|\mathcal{M}_{\mathcal{CP}}|$ is obtained by the rescaling prescription of Huber [16]. The value obtained for ν is in excellent agreement with that obtained in ref. [11]. Further, a model with distribution of Ps velocities was also fit with no significant effect upon $|\mathcal{M}_{\mathcal{CP}}|$ and ν_0 .

The results for $|\mathcal{M}_{\mathcal{CP}}|$ and ν_0 are limited primarily by statistics, but systematics of the random-background correction and other systematic effects have been investigated. In one systematic test, the NaI γ ray detectors are replaced by a high resolution, 28% efficiency Ge detector in the same position as one of the NaI detectors. An order-of-magnitude tighter energy window on the 511 keV photopeak in the energy spectrum is achieved. Assuming that the values of the parameters $\mathcal{M}_{\mathcal{CP}}$, v , ϵ_0 , and ν_0 from the fit to the NaI data hold for Ge at 73 G, the value of Δ from table 1 implies that the background for Ge, $b_{\text{Ge}}=0_{-0.5}^{+0.5}$, is also smaller than b . This scaling confirms that the background events stem from γ scintillations in the L_α detector and can be rejected by the superior Ge detector energy resolution. At $B=0$, the Ge data ($|\mathcal{M}_{\mathcal{CP}}| < 140$ MHz) are consistent with the NaI results.

Another systematic test, using almost an order-of-magnitude worse coincidence time resolution and significantly different electronics, gave substantially the same result as the fast coincident timing studies, both using the same energy selection afforded by NaI detectors (see table 1). The consistency indicates that 2^3P_J states, which would appear as delayed coincidence events, contribute negligibly to b . Similarly, no effect is observed when the width of the timing coincidence window in the fast-timing studies is increased.

4. Conclusion

We have observed for the first time the 2^1P_1 state

in Ps^{#2}. The resonance frequency, $\nu_0=11181\pm 13$ MHz, is in good agreement with the theoretical frequency of 11184 MHz [18] and constitutes a new test of quantum electrodynamics with uncertainty only a factor of five worse than the worse precise $n=2$ Ps intervals [11,19]^{#3}. This transition is uniquely sensitive to the 2^1P_1 energy level, but an order of magnitude improvement in the measurement of ν_0 is necessary to test the -3 MHz, order $\alpha^3\text{Ry}$, 2^1P_1 term [18].

We have also extended for the first time the direct experimental search for \mathcal{CP} mixings beyond the neutral kaon system and found none at the level of $|\mathcal{M}_{\mathcal{CP}}| < 65$ MHz. Most currently popular models of CP violation are hadronic and short ranged by construction and predict extremely small effects in Ps [21]. Recently, another type of interaction with derivative couplings [7], relevant to $\mathcal{M}_{\mathcal{CP}}$ in Ps, has been introduced, but more stringent constraints are placed on this particular interaction by atomic-EDM measurements [7]. Consider also that the limit set here on \mathcal{CP} state mixing $|\mathcal{M}_{\mathcal{CP}}/E_1|$ in Ps is

$$\left| \frac{0.065 \text{ GHz}}{1.826 \text{ GHz}} \right| = 0.036 ,$$

within an order of magnitude of the analogous mixing

$$\left| \frac{\langle K_1 \bar{K}_2 \rangle}{\Delta m - \frac{1}{2}i\Delta\Gamma} \right|$$

observed in kaons

$$\left| \frac{0.0027i \text{ GHz}}{(0.85 + 0.89i) \text{ GHz}} \right| = 0.0023 .$$

Since the kaons are a more tightly bound system than Ps, most models would require much smaller CP violating effects in Ps. However, possible long-range, purely leptonic interactions could yield observable effects in Ps, consistent with the kaon data. Comparison of this experiment to other measurements, such as EDMs, is highly model dependent. Interference experiments to measure \mathcal{CP} mixing in Ps at the

^{#2} It is interesting to note that a recent publication [17] reports first observation of the 1^1P_1 state of charmonium, analogous to our first observation of the 2^1P_1 state in Ps reported here.

^{#3} Reference [20] reports an improved uncertainty of 3.2 MHz for the $1^3S_1-2^3S_1$ interval in Ps.

10^{-3} level of accuracy are being actively developed [6].

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