Precise Measurement of $n=2$ Positronium Fine-Structure Intervals

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(Received 11 June 1993)

The $n=2$ fine-structure transitions in positronium have been measured by observation of increased Lyman-α radiation at microwave induced resonances. We used an accelerator based slow positron beam to produce positronium in the 2^3S_1 excited state inside a waveguide. Our results are $\nu_0=18\,499.65 \pm 1.20 \pm 4.00$ MHz, $\nu_1=13\,012.42\pm0.67\pm1.54$ MHz, and $\nu_2=8624.38\pm0.54\pm1.40$ MHz for the $2^3S_1\rightarrow 2^3P_{0,1,2}$ transition frequencies, respectively. The first error is statistical and the second is systematic. This is in agreement with recent bound state QED calculations.

PACS numbers: 36.10.Dr, 12.20.Fv

Positronium (Ps), as a bound system of a lepton and its antiparticle, is an excellent testing ground for quantum electrodynamics (QED). Other than muonium and hydrogen, positronium is an eigenstate of the C operator leading to analogies with bound quark states ($c\bar{c}$, $b\bar{b}$) and QCD calculations. To date, several high precision measurements that test higher order radiative corrections to the energy levels and decay rates have been performed [1,2].

The only serious discrepancy (6.2σ) between theory and experiment is established in the orthopositronium ($1\,^3S_1$) decay rate [3]. To clarify the situation, improved measurements on other Ps properties seem appropriate. The fine-structure intervals in $n=2$ positronium (Ps*) are particularly important since they are very sensitive to higher order radiative corrections.

The energy levels are generally written as a power series in the fine-structure constant α:

$$\frac{E}{h}=cR_\infty(a+b\alpha^2+c\alpha^3+d\alpha^3\ln\alpha^{-1}+e\alpha^4\ln\alpha^{-1}+\cdots),$$

where $R_\infty=109\,737.315\,682\,7(48)$ cm^{-1} is the Rydberg constant and the coefficients $a,b,c,d,e,\ldots$ depend on the quantum numbers n,S,L,J. For the triplet $n=2$ state, which is of interest here, the coefficients a,b,c,d were calculated some time ago [4]. More recently, the calculation of the three fine-structure intervals $2^3S_1\rightarrow 2^3P_J$ ($J=0,1,2$) has been extended in two independent approaches [5,6] to the order $R_\infty\alpha^4\ln\alpha^{-1}$ resulting in an upward shift of 0.96 MHz for all three transitions. The yet uncalculated higher order corrections are estimated to contribute less than 1 MHz.

The slow positron facility TEPOS at the University of Giessen uses an electron linear accelerator (36 MeV, 160 μA) to produce positrons by bremsstrahlung and pair production [7]. After moderation in tungsten vanes a slow positron beam of typically 5×10^7 e^+/s with 1 cm diameter is available. The positrons are transported with a kinetic energy of 100 eV inside a 0.01 T solenoid over a distance of 9 m. The low transport energy reduces the transmission of the beam line to 20%, but is necessary for an efficient production of Ps* [8]. In the detection region the slow positrons are extracted out of the magnetic guiding field and focused by an electrostatic lens system through a grid covered circular entrance hole (inner diam of 20 mm) into a waveguide (type WR 90, 23×10 mm^2). About 5×10^6 e^+/s are implanted in a molybdenum foil mounted to the rear inner wall of the waveguide. The correct position of the beam is monitored by a NaI-scintillation detector placed behind a 10 cm thick lead collimator having a channel diameter of 1 cm. We estimate that about 2×10^4 Ps*/s are formed. Assuming equal population of all 16 sublevels in $n=2$, a fraction of 3/16 is in the metastable state 2^3S_1 (annihilation lifetime 1.1 μs) and 12/16 is in the $2P$ states which decay by spontaneous emission of Lyman-α photons ($\lambda=243$ nm) within 3.2 ns. The 2^1S_0 state annihilates into two γ quanta within 1 ns and does not contribute to Lyman-α radiation. The Lyman-α photons are observed by a solar blind photomultiplier (Hamamatsu R2078) through a grid covered rectangular opening (10×20 mm^2) in the upper wall of the microwave guide perpendicular to the e^+ beam direction. The photomultiplier is located outside the vacuum housing and separated from the waveguide by a 25 cm long light guide consisting of a strainless steel tube with an inner diameter of 20 mm whose surface is polished and covered with evaporated aluminum before each beam time. The interaction region of the Ps* is shown in Fig. 1. The approximate detection efficiency of the optical system is 0.004, given by solid angle (0.06), transmission of the light guide and quartz window (0.5), and the quantum efficiency of the photomultiplier (0.14). According to the time structure of the accelerator, the positrons arrive in pulses containing about 10^4 e^+, with a duration of 2 μs and a repetition rate of 600 Hz. Therefore, coincidence experiments are not feasible, but the dark counting rate of the photomultiplier (10/s) is suppressed by the duty factor of the accelerator by applying a delayed gate to the counter. A microwave induced resonance transition $2^3S_1\rightarrow 2^3P_J$

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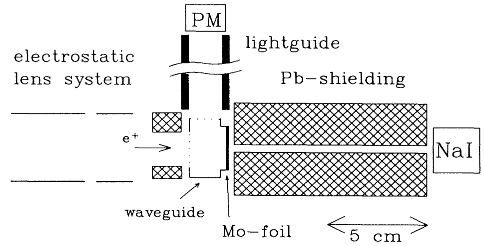

FIG. 1. Interaction region of Ps* atoms ($n=2$) and microwave radiation.

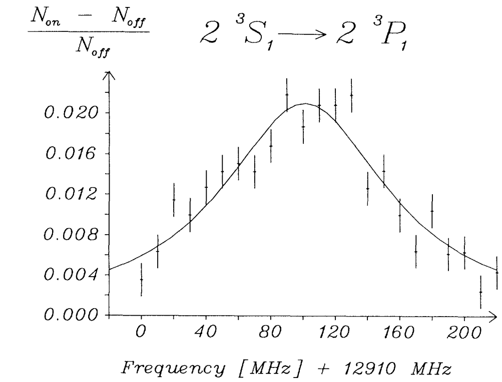

FIG. 3. Example spectrum of a $2^3S_1 \rightarrow 2^3P_1$ transition. The center frequency is $\nu_1 = 13011.0 \pm 2.2$ MHz. The experimental points are fitted by a Lorentzian line shape (microwave power 4 mW/cm^2).

($J=0,1,2$) is detected by an increase in the Lyman-α counting rate (at most $25\% = 3/12$ for complete depopulation and equal detection efficiency for spontaneous and microwave induced emission). In the present case, the molybdenum foil for the Ps* production was positioned inside a 2 mm deep rectangular extension in the rear wall of the waveguide. In this way we obtained a partial screening of the annihilation radiation and of spontaneous Lyman-α photons. The typical counting rate observed without microwaves is $N_{\rm off} = 400$/s resulting mainly from scintillation events (≈ 360/s) induced by 10^7 annihilation quanta/s and an estimated contribution of 40 spontaneous Lyman-α photons/s. The counting rate with high microwave power was typically $N_{\rm on} = 420$/s at the center of a resonance. We define our signal as $(N_{\rm on} - N_{\rm off})/N_{\rm off}$, which is about 0.05 for a complete depopulation of the 2^3S_1 state. To minimize the influence of instabilities other than counting statistics, we measured $N_{\rm on}$ and $N_{\rm off}$ for 5 s each and stepped the frequency forward and backward over the line profile. To obtain the signal-to-noise ratio shown in Figs. 2, 3, and 4 we summed about 200 scans for each line corresponding to a measurement time of 12 h during which all parameters like positron intensity and microwave power were well controlled. A total number of 1.3×10^{13} positrons were used for the 60 measurements on all three resonances.

The microwaves were generated by a frequency synthesizer (Systron-Donner 1720B) providing at least 10 mW power from 2 to 18.9 GHz. For higher power levels, we used a traveling-wave tube amplifier (Hughes 8010H) which was equipped with a built-in insulator. The spectral bandwidth after amplification was narrower than 30 kHz and the frequency accuracy better than 10^{-8}. The frequency and power settings (resolution 0.1 dB) were remotely controlled by a personal computer. For all measurements, a WR 90 waveguide was used in the interaction region. For the 18.5 GHz line, a transition from WR 62 (16×8 mm^2) to WR 90 was used at the power input side. We measured the power-standing-wave ratio (PSWR) for all used frequencies yielding values of 1.12 for the 8.6 and 13 GHz and 2.0 for the 18.5 GHz transition, respectively.

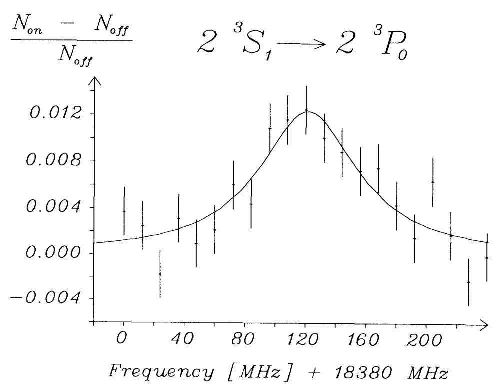

FIG. 2. Example spectrum of a $2^3S_1 \rightarrow 2^3P_0$ transition. The center frequency is $\nu_0 = 18501.4 \pm 4.1$ MHz. The experimental points are fitted by a Lorentzian line shape (microwave power < 150 mW/cm^2).

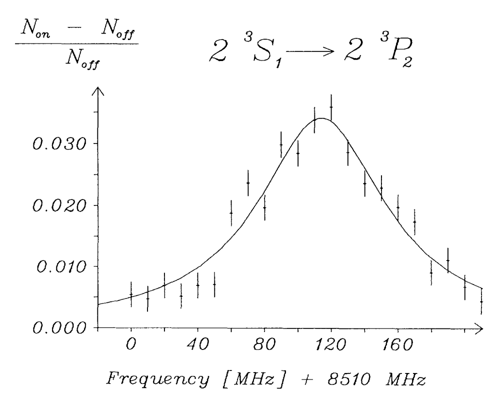

FIG. 4. Example spectrum of a $2^3S_1 \rightarrow 2^3P_2$ transition. The center frequency is $\nu_2 = 8624.1 \pm 1.5$ MHz. The experimental points are fitted by a Lorentzian line shape (microwave power 4 mW/cm^2).

Particular care was taken to have constant microwave power at the position of the Ps* atoms over the whole sweep range of about 200 MHz for one line. Variations in microwave power would induce asymmetries in the line which lead to a systematic shift in the line center. Behind the interaction region our waveguide was terminated by a matched load and the transmitted power was monitored with a calibrated power sensor via a 12 dB directional coupler (Fig. 5). To check the effect of power variations, we changed the microwave power by a factor of 2 for the left and right side of a resonance and observed a shift in the fitted frequency of 9 MHz for all transitions. In an actual run we kept the input power to the waveguide constant. The transmitted power at the output did not vary by more than 5% over the sweep range of a resonance line for the $2^3S_1 \rightarrow 2^3P_{1,2}$ transitions. Since this variation was not systematic in one direction over the line profile, we deduce an upper limit of 0.60 MHz for a possible shift in the line center under our experimental conditions. This value was confirmed by a simulation using the known dependence of the transition probability on the microwave power at each frequency step. For the $2^3S_1 \rightarrow 2^3P_0$ transition, the power varied as much as 50% over the whole line profile. When we measured the resonance frequency for constant input and constant output powers, respectively, the observed shifts were smaller than 2 MHz in all cases. We assign this value as a systematic uncertainty in our measured resonance frequency.

During the experiment, we used two different versions of the waveguide setup (I and II). The first was equipped with two vacuum windows made of 1 mm polyethylene slices (spaced by 151 mm). A central part 110 mm in length containing the interaction region was removable and plugged together with the rest of the waveguide. This allowed propagation of the microwaves in the $+\mathbf{x}$ and $-\mathbf{x}$ direction, respectively, and we observed slightly different transition frequencies for each direction. We attribute this to a first order Doppler shift due to an asymmetry in the detection efficiency for different Ps* velocities. This asymmetry is caused partly by a misalignment of 1.8 mm between the axis of the lightguide with respect to the center of the entrance and observation hole and partly by nonuniform excitation efficiency for the three transition frequencies. The observed frequency shifts are in agreement with an effective velocity component of $v/c = 3\times10^{-4}$ for those Ps* that are seen by the photomultiplier. The Doppler corrected transition frequency was obtained by averaging the forward and backward values. As a possible systematic error of the corrected value we used the quadratically added uncertainties of the two individual measurements, resulting in 1.27, 1.41, 3.46 MHz for the ν_2, ν_1, ν_0 transitions, respectively.

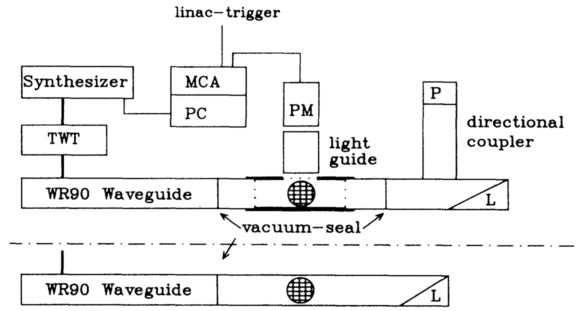

FIG. 5. Schematic diagram of the microwave system and data handling. P is a power meter and L is a matched load (upper part setup I and lower part setup II).

To check our results, we used a second waveguide setup (II) which was carefully machined to be symmetric with respect to the axis of the lightguide. We then found transition frequencies which were in agreement with the corrected forward-backward value of the first waveguide (I). As our results for each transition frequency, we quote the weighted average from the measurements with the two different waveguides. A correction, which is only necessary for the ν_2 transition at 8.6 GHz, arises from the fact that the relation between the electrical field strength E and the power P in a waveguide differs from free space: $E^2 \sim P[1 - \nu_c^2/\nu^2]^{-1/2}$, where $\nu_c = 6.6$ GHz is the cutoff frequency. For our measurements with constant power P, a correction of $+(0.30\pm0.10)$ MHz to the center fre-

TABLE I. Example for the data analysis of the transition $\nu_2 = 2^3S_1 \rightarrow 2^3P_2$. (a) Systematic error due to uncorrelated variations in the transmitted power. (b) Systematic error due to the quadratic sum of Doppler shift correction error and error (a). The final result includes a correction $+(0.30\pm0.10)$ MHz due to the nonproportionality of E^2 and P (see text). All frequencies are in MHz.

Waveguide version	Propagation direction	Number of lines	Transition frequency	Statistical error	Systematic error
I	$+\mathbf{x}$	10	8626.81	±0.90	±0.60 (a)
I	$-\mathbf{x}$	10	8621.85	±0.90	±0.60 (a)
Average		20	8624.33	±0.65	±1.40 (b)
II	$+\mathbf{x}$	5	8623.60	±0.90	±0.60 (a)
Weighted average		25	8624.08	±0.53	±1.40 (b)
Final result		25	8624.38	±0.54	±1.40 (b)

TABLE II. Fine-structure transitions in Ps* ($n=2$). All frequencies are in MHz. The first of the quoted errors is statistical and the second is systematic.

	Calculations Ref. [5]	Experiments Ref. [9]	Experiments This work
$2^3S_1 \rightarrow 2^3P_0$	18497.10	$18504.1 \pm 10.0 \pm 1.7$	$18499.65 \pm 1.20 \pm 4.00$
$2^3S_1 \rightarrow 2^3P_1$	13011.86	$13001.3 \pm 3.9 \pm 0.9$	$13012.42 \pm 0.67 \pm 1.54$
$2^3S_1 \rightarrow 2^3P_2$	8626.21	$8619.6 \pm 2.7 \pm 0.9$	$8624.38 \pm 0.54 \pm 1.40$
		8618.4 ± 2.8[a]	

[a]From Ref. [10], measured in a magnetic field of 54 G.

quency of the ν_2 transition is included in our final result. Table I shows, as an example, the data analysis of the ν_2 transition. Further corrections arising from the following effects are negligibly small (<10 kHz): second order Doppler shift, ac Stark shift, Zeeman, and motional Stark effect in the residual magnetic field of 0.15 mT. The improved signal/noise ratio compared to previous measurements allowed us to perform further systematic checks: (a) variation of the beam position, (influence on the first order Doppler shift), (b) applying magnetic fields (observation of Zeeman and motional Stark effect), and (c) tuning of electronics (gate width, delay time, discriminator levels). However, none of these checks provided any evidence that systematic line shifts occurred outside our quoted error limits. Table II compares the final results of our experiment with prior experimental results and theoretical calculations.

The theoretical line shape, as given in Ref. [9], is symmetric around the center frequency and depends on the natural linewidth, the transit time of Ps* inside the waveguide, and the microwave power. A Lorentzian line shape is a good approximation and does not affect the fitted value for the center frequency. The observed linewidths (FWHM) varied with the microwave power P as $\Delta\nu=[a^2+b^2P]^{1/2}$ as expected from the theoretical line shape formula. The fitted value $\Delta\nu=88$ MHz for $P=0$ is composed of the quadratic sum of the natural linewidth, the Doppler broadening and the transit time broadening. The saturation intensities for the ν_0, ν_1, ν_2 transitions at high power levels scaled approximately as 1:2:3 as predicted by the Clebsch-Gordan coefficients.

From our experimental results, a value can be deduced for the higher order terms in the power series of the energy levels. If we write $\nu_{\text{exp}}=\nu^{(0)}+A$, where $\nu^{(0)}=18496.14$ MHz, 13010.90 MHz, and 8625.25 MHz, respectively, are the lower order theoretical values for the ν_0, ν_1, and ν_2 lines [5], then we obtain $A(\nu_0)=3.51 \pm 4.18$ MHz, $A(\nu_1)=1.52 \pm 1.68$ MHz, $A(\nu_2)=-0.87 \pm 1.50$ MHz. The weighted average of these values is $A=0.41 \pm 1.08$ MHz. The upper limit of $A=1.49$ MHz confirms the 0.96 MHz value calculated for the $R_\infty \alpha^4 \ln\alpha^{-1}$ term and the estimate that higher order corrections would contribute less than 1 MHz.

We thank the Deutsche Forschungsgemeinschaft for financial support. We are grateful to R. S. Conti and T. Steiger for stimulating discussions and turning our attention to the relation $E^2 \not\propto P$.

[1] A. P. Mills, Jr. and S. Chu, in *Quantum Elektrodynamics*, edited by T. Kinoshita (World Scientific, Singapore, 1990), Vol. 7, p. 774.
[2] M. S. Fee *et al.*, Phys. Rev. Lett. **70**, 1397 (1993).
[3] J. S. Nico, D. W. Gidley, A. Rich, and P. W. Zitzewitz, Phys. Rev. Lett. **65**, 1344 (1990).
[4] T. Fulton and P. C. Martin, Phys. Rev. **95**, 811 (1954).
[5] R. N. Fell, Phys. Rev. Lett. **68**, 25 (1992).
[6] I. B. Khriplovich, A. I. Milstein, and A. S. Yelkhowsky, Phys. Lett. B **282**, 237 (1992), an initial disagreement with Ref. [5] has been resolved [R. N. Fell (private communication)].
[7] W. Faust *et al.*, Nucl. Instrum. Methods Phys. Res., Sect. B **56/57**, 575 (1991).
[8] R. Ley *et al.*, J. Phys. B **23**, 3437 (1990).
[9] S. Hatamian, R. S. Conti, and A. Rich, Phys. Rev. Lett. **58**, 1833 (1987).
[10] A. P. Mills, Jr., S. Berko, and K. F. Canter, Phys. Rev. Lett. **34**, 1541 (1975).