New Schemes for the Production and Spectroscopy of Positronium

G. Werth

Institut für Physik, Universität Mainz,
D-6500 Mainz, Fed. Rep. of Germany

The rate of positronium formation has been increased by 2-3 orders of magnitude using recently developed accelerator based slow positron sources. This opens the possibility of improvements of precision experiments on the Ps atom as well as new experiments on excited states. First evidence for enhanced metastable Ps formation is presented and future possibilities are discussed.

1. Introduction

Thirty-six years after the first production of positronium by Deutsch it seems somewhat surprising that our experimental knowledge of this system is restricted to the states of principal quantum numbers n=1 and n=2. Table I summarizes the present most precise data.

Table I Presently known values of energy differences and decay rates in positronium

	Experiment			Theory	
1^1S_0 decay rate	7.944(11)	ns^{-1}	/1/	7.9842	ns^{-1}
1^3S_1 decay rate	7.0516(13)	μs^{-1}	/2/	7.0383	μs^{-1}
Ground state Hfs	203 388.7(7)	MHz	/3/	203 404.0	MHz
$1^3S_0-2^3S_1$	1 233 607 185(15)	MHz	/4/	1 233 607 197	MHz
$2^3S_1-2^3P_2$	8 619.6(3.6)	MHz	/5/	8625.2	MHz
	8 628.4(2.8)	MHz	/6/		
$2^3S_1-2^3P_1$	13 001.3(4.8)	MHz	/5/	13 010.9	MHz
$2^3S_1-2^3P_0$	18 504.1(11.7)	MHz	/5/	18 496.1	MHz

The Hydrogen Atom Editors: G.F. Bassani · M. Inguscio · T.W. Hänsch

There exist no experiments at all for states above n=2, which would be an interesting test case for a relativistic two-body system.
In view of the fundamental nature of the system more extensive and more precise data would be highly desirable as a test for bound state QED calculations. With the exception of the 1S-2S energy difference measurement, which is limited in precision by the laser wavelength measurement, all present experiments suffer from low statistics due to the small number of Ps atoms. It seems therefore worthwile discussing recent advances of increased Ps production and in particular methods to populate the metastable 2^3S_1 state, which could serve as a basis for excited state spectroscopy. While laser excitation of states above n=2 from the ground state requires wavelengths between 205 nm (L_β) and 182 nm (ionization limit), which are very difficult to obtain with sufficient power, the corresponding wavelengths range from 2^3S_1 is 1310 nm (H_α) to 728 nm (ionisation limit). Lasers with such wavelengths are commercially available.

2. Slow Positron Production

Positronium atoms are formed in collision of low energy positrons in gases or on surfaces. The most obvious way to enhance the Ps formation rate is to increase the number of low energy positrons. Conventional sources use radioactive e^+-emitters like ^{22}Na or ^{58}Co. The high energy positrons from these sources are stopped in thin metal foils. A small number of them diffuses to the surface before annihilation and is released into the vacuum with an energy of about 1 eV due to the negative work function of metals for positron emission. Extensive work has been done by different groups to improve on the moderator efficiency. Using carefully cleaned single crystal surfaces, about 1 out of 10^3 fast positrons is re-emitted at low energies having an energy spread of about 0.2 eV. The total amount of slow positrons depends on the radioactive source strength. Taking up to 100 mCi, which can be handled decently in the laboratory, low energy positron rates up to 10^6 s^{-1} are obtained routinely. Apart from safety requirements the source strength is limited by self-absorption inside the source material unless one uses extended surfaces, which in turn reduces the beam brightness. The main characteristics of such beams are that they are continuous in time and have a spin polarization due to the natural helicity of the particles. Higher intensities of slow positron beams require the use of high flux reactors or of electron accelerators. The first approach has been made by LYNN et al. /7/, who used a neutron activated ^{64}Cu source with half-life of 12.8h to obtain a high specific activity of 600 Ci/g and produced a slow positron beam of 4 x 10^7 e^+/s. The moderation of high energy positrons appearing in the bremsstrahlung of electron accelerators has been investigated at first in Mainz /8/ and Livermore /9/. A picture of the present setup at Mainz is shown in Fig. 1.

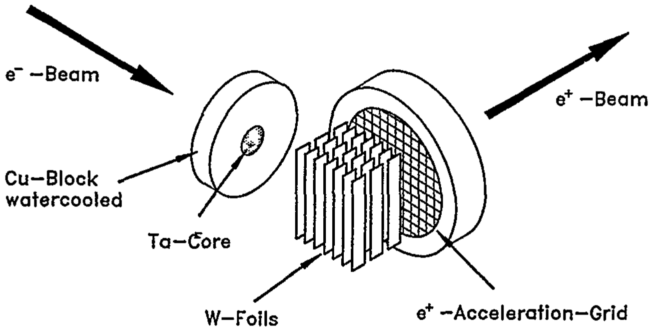

Fig. 1 Target and moderator setup for slow positron production at the Mainz Linear Accelerator

While the moderation process does not differ from that of radioactive sources, the number of particles as well as the time structure of the beam depends on the accelerator. Since the intensity of the bremsstrahlung is approximately proportional to the atomic number Z and the cross-section for pair production scales as Z^2, high Z materials of high melting points like tantalum are suited best as targets. The maximum efficiency of a target-moderator combination, defined as the number of slow positrons per fast electron, depends on the electron energy and the target's thickness: if for a given energy the target is too thin, only a fraction of the beam is used for positron production. On the other hand in thick targets many of the positrons annihilate before they reach the surface. The optimum thickness is roughly two radiation lengths, which is the distance in which a relativistic electron beam energy is reduced to 1/e of its initial value. Data from different groups (Mainz, Livermore, Tsukuba, Gießen) indicate that total slow positron fluxes of more than 10^8 e^+/s are obtained almost routinely.

Equally important as the source strength is the time structure. Accelerators may be continuous in time or may have a pulse structure, which sometimes can be varied according to the requirements of the experiment. Figure 2 shows as an example the time structure of the 400 MeV LINAC at Mainz.

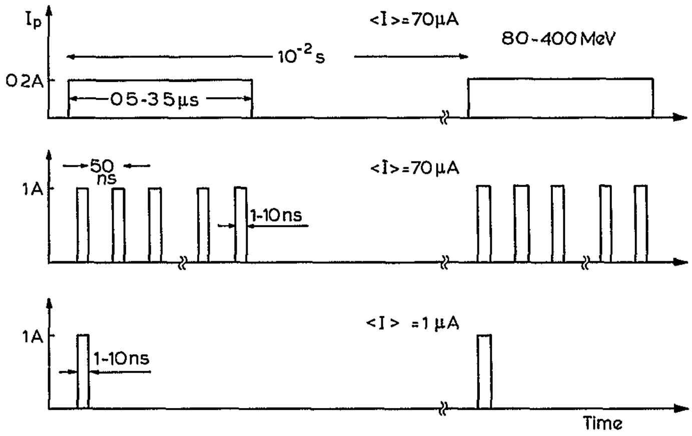

Fig. 2 Possible modes of operation of the Mainz LINAC

Long pulses of up to 3.2 µs as well as single shot operations with pulse duration ranging from 1 to 10 ns are possible. In particular the single pulse mode with 100 Hz repetition rate is very similar to the time structure of commercially available high power lasers. This can be of advantage in laser excitation of positronium atoms as discussed below. It should be pointed out that the time structure is only partially preserved in slow positron beams. Slow positron beam transport over distances of several meters is a necessary requirement because of the high radiation and background level at accelerator targets. Due to the initial energy spread, short pulses are spread out in time, in particular if the transport system uses magnetic guidance fields and contains bends. In practice we have obtained 40 ns e^+-pulses, starting from 10 nsec accelerator pulses after a beam transport over 20 meters.

3. Ground State Positronium Production

Slow positrons impinging on metal or metal-oxide surfaces at energies ranging up to a few hundred eV may form positronium atoms. The probability depends strongly on the surface temperature. While in experiments using radioactive sources as positron emitters, in general clean and well defined crystal surfaces have been used to obtain a maximum positronium yield, the high flux of slow positrons at electron accelerators facilitate substantially the experimental setup. Untreated metal surfaces show the same temperature dependence of positronium formation as previously observed with single crystals (Fig. 3), and even with somewhat reduced efficiency compared to single crystals positronium intensities of several 10^7 s^{-1} are obtained.

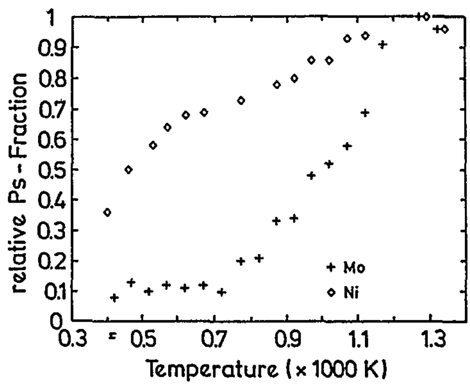

Fig. 3 Temperature dependence of Ps formation on untreated metal surfaces (from ref. 16)

The energy distribution of positronium atoms emitted from metal surfaces has been investigated by MILLS /10/. The main part has a mean kinetic energy of about one eV and is formed when a positron diffuses from the inside of the target material to the surface, is emitted into the vacuum by the negative work function of the metal, and catches a surface electron. A second part of the Ps atom has lower energies and arises from thermal desorption of positrons bound in a potential well at the surface by the image force. The activation energy E_a for this process is a delicate balance between the binding energy E_b of the positron at the surface, the work function ϕ_- of the target material and the binding energy 1/2 Ry of the Ps atom /11/:

$$E_a = E_b + \phi_- - 1/2\ \mathrm{Ry}.$$

Typical values for E_b are 2-4 eV, while E_a ranges from 0.2 eV to 1 eV depending on the crystal face and the surface contamination.

4. Excited State Positronium Formation

In 1975 CANTER et al. /12/ discovered that about 1 out of 10^4 Ps atoms emitted from solid surfaces is in the metastable 2^3S_1 state. Although this number is small it was sufficient to allow first experiments on the fine structure of the n=2 state /5,6/. The stronger sources now available at accelerators may lead to intensities of metastable Ps atoms which are comparable to the number of ground state Ps in earlier experiments. In a first attempt our group has tried to observe fine structure transitions on n=2 Ps in a setup at an electron accelerator and found a good signal-to-noise ratio in the observed L_α count rate following a microwave induced fine structure transition /13/ (Fig. 4,5).

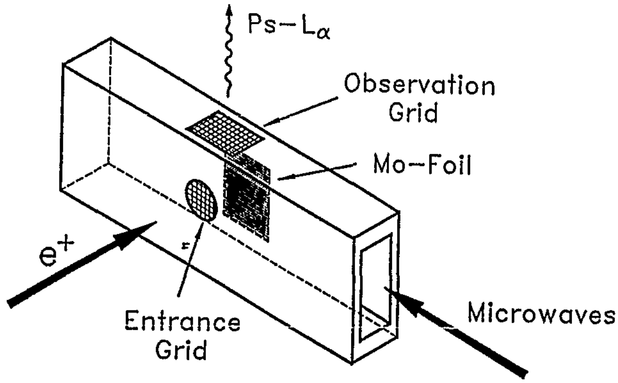

Fig. 4 Experimental setup to observe L_α photons after microwave induced fine structure transitions of n=2 Ps

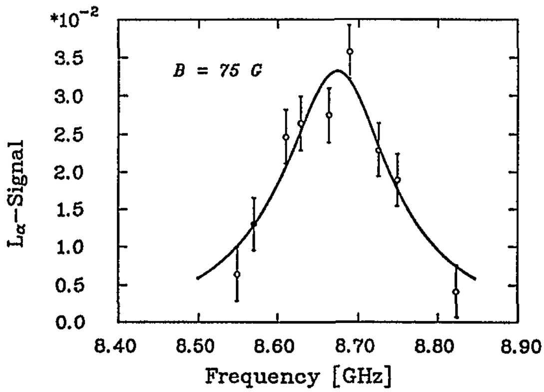

Fig. 5 2^3S_1 - 2^3P_2 resonance. The L_α-detector count rate difference with and without microwaves, normalized to the total count rate, is plotted against the microwave frequency. Running time was 5 min per data point

Although the resonance is shifted by Zeeman- and motional Stark-effects due to a residual magnetic field of about 75 G in the transition region, the results are promising and lead to the expectation of improved precision in future excited state experiments.

A disadvantage of this simple approach to create n=2 Ps is the fact that thermal activation from surface states, as in the case of ground state Ps, is energetically not possible because of the small binding energy of n=2 Ps. Thus only the fast component (about 1 eV) of n=2 Ps exists, which may lead to transient time problems in spectroscopy.

A different approach, which could further increase the number of n=2 Ps and at the same time preserve the slow velocity component is the optical excitation from the ground state into 2^3S_1. A direct two-photon 1^3S_1 - 2^3S_1 transition at 243 nm does not lead to n=2 population since the strong required laser power immediately leads to ionisation of n=2 Ps by a third photon. It should be possible, however, to excite the allowed transitions to the n=3 and n=4 levels from the ground state at 205 nm and 194 nm, respectively. From the branching ratio of the excited states one finds that 12% of the excited atoms end up in the 2^3S_1 state in each case. The required wavelengths are commercially available with the kW output power from Raman shifted excimer-pumped dye lasers, e.g. The time structure of many accelerators of several ns pulse width and 100-1000 Hz repetition rate fits particularly well to the time structure of those lasers (see Fig. 2). Although the short pulse width of accelerators is not completely preserved in the positron time structure, as mentioned above; one can anticipate intensities of about 10^5 n=2 Ps atoms per second in the near future.

5. Possible Experiments

Accelerator based slow positron sources, which produce 2-3 orders of magnitude higher intensities of Ps atoms than radioactive sources, could be used to improve earlier experiments on Ps and could make possible the spectroscopy of higher excited states. Most obvious would be a remeasurement of the fine structure splitting in n=2 Ps. The good signal-to-noise ratio should allow to reduce the microwave power to avoid power broadening and to obtain the natural linewidth of 50 MHz. Although it is difficult to estimate the final precision of those experiments, the need for higher-order corrections above the presently calculated $\alpha^3 R$ correction is indicated.

Increased metastable n=2 Ps rates should allow laser excitation to higher states, in particular highly excited Rydberg states. The signature of such a transition could be the reduction of L_α counts, if a n=2 fine structure transition is driven simultaneously.

The specific feature of short pulses of slow positrons could be used to make a new determination of the Ortho-Positronium lifetime. At present the most accurate experimental determination of this quantity differs by 10 standard deviations from the theoretical value, which represents the only serious discrepancy in low energy QED (see Table I). A new experiment, which uses short pulses of many Ps-atoms and observes the decay of the ensemble, would differ substantially in Ps rate and consequently in the electronic setup from earlier single-event experiments and could help to decide whether the discrepancy is due to so far unobserved systematic effects in the experiments or whether the theory needs improvement.

Finally the high Ps rate could be used to improve on the search for rare or forbidden decays of ground state Ps. Table II summarizes the present values of such decay modes and theoretical predictions.

A serious drawback in precision spectroscopy on Ps is the high velocity of $2 \cdot 10^6$ cm/s at initial energies of about 1 eV, which easily leads to transient time broadening. Thus finally laser cooling of Ps may be required to obtain smaller uncertainties. A rough estimate indicates that such experiments are in fact possible: The scattering of a 243 nm photon from the Ps atom reduces its velocity by an amount of $\Delta v = h\ k/m = 10^5$ cm/s. Thus about 20 scattering processes are needed to cool a 1 eV Ps atom to very low temperatures. The minimum time required for this process is 20 times the average lifetime of the first excited 2^3P state, which is 3.2 ns. The total cooling time of 64 ns takes about half the lifetime of the Ps ground state (142 ns). Although the recoil limited final temperature will be by a factor of $(M(\text{atom})/m\ (Ps))^{1/2} \sim 200$ higher than that obtained in heavy atom cooling, it would be a substantial progress to high precision experiments.

Search Hits Help

Table II Experimental and theoretical values of rare decay modes of Singlet (λ_S) and Triplet (λ_T) positronium

Decay	Experiment	Theory
$\frac{\lambda_T(3_\gamma)}{\lambda_S(2_\gamma)}$	$\frac{1}{1133(20)}$	$\frac{\alpha(\pi^2-9)\cdot 4}{9\pi} = \frac{1}{1115}$
$\frac{\lambda_S(4_\gamma)}{\lambda_S(2_\gamma)}$		$0.274(\alpha/\pi)^2 = 1.5 \cdot 10^{-6}$
$\frac{\lambda_T(5_\gamma)}{\lambda_T(3_\gamma)}$		$0.177(\alpha/\pi)^2 = 0.96 \cdot 10^{-6}$
$\frac{\lambda_S(3_\gamma)}{\lambda_S(2_\gamma)}$	$<2.8\cdot 10^{-6}$ /14/	0, if C conserved
$\frac{\lambda_T(4_\gamma)}{\lambda_T(3_\gamma)}$	$<8\cdot 10^{-6}$ /15/	0, if C conserved

6. Acknowledgements

The experiments of the Mainz group were performed by R. Ley, K.D. Niebling and A. Schwarz and were supported by the Deutsche Forschungsgemeinschaft. The author enjoyed conversations about the subject with A. Rich, V. Telegdi and C. Westbrook during the symposium on "The Hydrogen Atom" at Pisa, 1988.

References

/1/ D.W. Gidley, A. Rich, E. Sweetman and D. West: Phys.Rev.Lett. 49, 525 (1982)

/2/ C.I. Westbrook, D.W. Gidley, R.S. Conti and A. Rich: Phys.Rev. Lett. 58, 1328 (1987)

/3/ W.M. Ritter, P.O. Egan, V.W. Hughes and K.A. Woodle: Phys.Rev. A30, 1331 (1984)
A.P. Mills: Phys.Rev. A27, 262 (1983)

Search Hits Help

/4/ S. Chu, A.P. Mills and J.L. Hall: Phys.Rev.Lett. 52, 1689 (1984)

/5/ S. Hatamian, R.S. Conti and A. Rich: Phys.Rev.Lett. 58, 1833 (1987)

/6/ A.P. Mills, S. Berko and K.F. Canter: Phys.Rev.Lett. 34, 1541 (1975)

/7/ M. Weber, K.G. Lynn et al.: In Electron and Atomic Collisions, ed. by D.C. Lorents, W.E. Meyerhof and J.C. Peterson (North-Holland, Amsterdam 1986), p. 227

/8/ M. Begemann, G. Gräff, H. Herminghaus, H. Kalinowski and R. Ley: Nucl.Instr.Meth. 201, 287 (1982)

/9/ R.H. Howell, R.A. Alvarez and M. Stanek: Appl.Phys.Lett. 40, 751 (1982)

/10/ A.P. Mills and L. Pfeiffer: Phys.Rev.Lett. 43, 1961 (1979)

/11/ A.P. Mills: Solid State Comm. 31, 623 (1979)

/12/ K.F. Canter, A.P. Mills and S. Berko: Phys.Rev.Lett. 33, 7 (1975)

/13/ K.D. Niebling: Thesis, Mainz 1988 (unpublished)

/14/ A.P. Mills and S. Berko: Phys.Rev.Lett. 18, 420 (1967)

/15/ K. Marco and A. Rich: Phys.Rev.Lett. 33, 980 (1974)

/16/ J. Dahm, K.D. Niebling, R. Ley and G. Werth: Appl.Phys. A44, 105 (1987)