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Measurement of the Decay Rate of the Positronium Negative Ion

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Positronium negative ions Ps^- are formed by a beam of 420-eV positrons impinging on a thin carbon film in vacuum. Measurements of the number of ions reaching a grid under different acceleration conditions are used to determine both the Ps^- decay rate $\Gamma = 2.09(9)$ $nsec^{-1}$ and its initial kinetic energy $T = 13^{+19}_{-10}$ eV. The decay rate is in good agreement with a recent calculation by Ho.

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Atoms with few electrons are relatively simple systems for testing many-electron calculation schemes. The classic variational method developed by Hylleraas[1] for He and extended[2,3] to H^- and Ps^- (the negative ions of hydrogen and positronium) gives very precise theoretical values for the binding energies of these two-electron objects. The reason for this success is that the ground-state energy depends only quadratically on the difference between the amplitudes of the exact and calculated wave functions. There is therefore interest in the measurement of properties which depend linearly on the wave functions. In the Ps^- system[4] ($e^+e^-e^-$) the annihilation rate Γ depends fairly strongly on electron-positron correlation and thus probes a particular aspect of the wave function.

In lowest order, the decay of Ps^- is via two photons and Γ is proportional to the density of electrons at the positron,[5]

$$\Gamma = (1+\sum\eta_i)2\pi r_0{}^2 c\int\psi(\vec{r}_+,\vec{r}_1,\vec{r}_2)^2\,\delta^3(\vec{r}_+-\vec{r}_1)\,d^3r_+\,d^3r_1\,d^3r_2,$$

where $\psi(\vec{r}_+,\vec{r}_1,\vec{r}_2)=\psi(\vec{r}_+,\vec{r}_2,\vec{r}_1)$ is the Ps^- wave function, $\vec{r}_+$ is the positron coordinate, and $\vec{r}_1,\vec{r}_2$ are the coordinates of the two relative singlet-state electrons. The small quantities η_i account for radiative corrections to the free-particle annihilation cross section[6] $[\eta_i = -\alpha(5/\pi - \pi/4)+\dots]$, 3γ annihilation[7] $[\eta_2 = 4\alpha(\pi/3 - 3/\pi)+\dots]$, and bound-state and relativistic wave-function effects (η_3). The correction η_3 has not been calculated to my knowledge. A recent calculation[8,9] of Γ by Ho gives $\Gamma = (1+\sum\eta_i)\times 2.0908\times 10^9\ sec^{-1}$ and should be accurate to about one part in 10^3. In an effort to confront this theory with an experimental test, the first measurement of the Ps^- decay rate has been made and is reported here.

The apparatus is shown in Fig. 1. A beam of 4-eV positrons ($10^6\ sec^{-1}$) produced by a ^{58}Co β^+

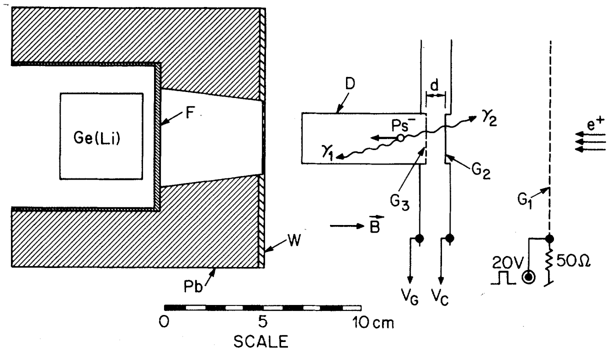

FIG. 1. Apparatus for measuring the Ps^- decay rate. e^+, beam of positrons guided by a 100-G axial magnetic field B; G_1, pileup-reducing grid; G_2, Ps^--forming carbon film; G_3, acceleration grid; D, zero-electric-field drift region; W, vacuum chamber wall; F, graded Pb, Sn, Cu, Al scattered-γ-ray filter for the Ge(Li) spectrometer.

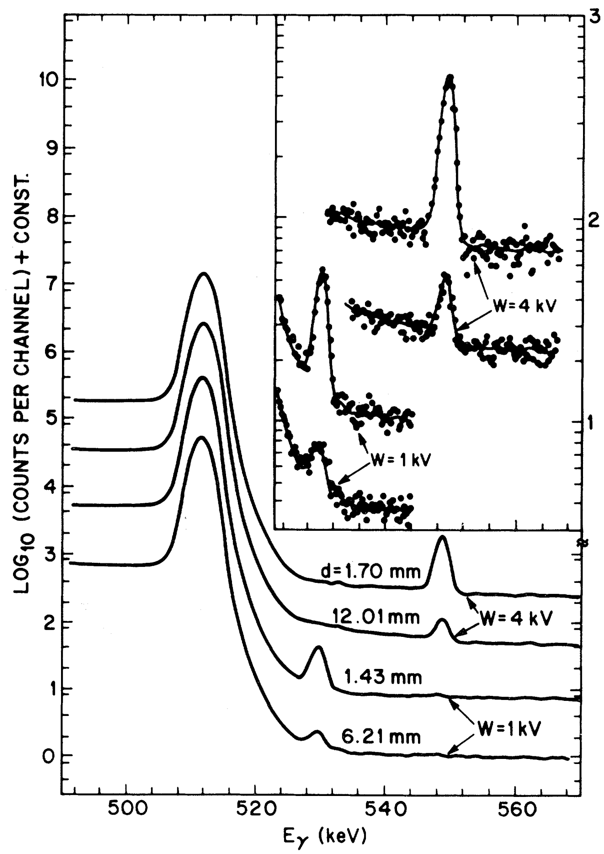

FIG. 2. γ-ray energy spectra obtained at various G_2-G_3 distances d and two acceleration potentials W.

source (initial activity 150 mCi) and W(110) moderator[10] is guided by a solenoidal magnetic field to a thin (~50-Å) carbon film supported on a Ni grid G_2 (333 lines per in., 65% transmission) biased at a potential $V_C = -416$ V. About half the positrons are transmitted by the film and roughly one positron in 10^4 emerges from the film bound to two electrons as a Ps^- ion.[11] The ions are accelerated towards a second Ni grid G_3 (70 lines per in., 80% transmission) biased at a potential V_G and separated from the carbon film G_2 by a distance d. Annihilation photons are detected by a Ge(Li) γ-ray spectrometer. The Ps^- is traveling toward the Ge(Li) detector with velocities a few percent of the speed of light. Thus the annihilation photons from the decay of the Ps^- in flight are blue-shifted and are easily distinguished from the many 511-keV γ's from positrons annihilating in the carbon film.

In the region D beyond the grid G_3 the electric field vanishes and any Ps^- in this region will have a constant velocity. The intensity A^- of the Doppler-shifted annihilation γ-ray peak resulting from motion with this velocity is proportional to the probability that the Ps^- reaches G_3. The proper time interval between the emission of the Ps^- and its arrival at G_3 is proportional to the distance traveled d for a given potential difference $W = V_G - V_C$. This implies that the intensity A^- will have an exponential dependence on d that may be used to determine the Ps^- lifetime.

The total elapse of proper time during which the Ps^- is moving from $z=0$ to $z=d$ in an electric field W/d is

$$t = \frac{1}{c}\int_0^d \frac{dz}{\beta\gamma} = \frac{d}{\lambda c}\ln[1+\lambda+(2\lambda+\lambda^2)^{1/2}]g(\lambda,\epsilon), \quad (1)$$

where $\lambda = eW/3mc^2$ and $\epsilon = T/3mc^2$. The function $g(\lambda,\epsilon)$ is the correction for the nonzero initial Ps^- kinetic energy T, and may be expanded as follows:

$$g(\lambda,\epsilon) = 1 - (T/W)^{1/2} + \tfrac{1}{2}(T/W) + \dots \quad (2)$$

The Ps^- annihilation γ's emitted in the direction of the z axis have a Doppler-shifted energy $E = mc^2(\gamma + \gamma\beta)$. The time spent by the Ps^- in traveling from point a to b in the constant electric field may also be written $t_{ab} = (d/\lambda c)\ln(E_b/E_a)$. Using $dN \propto e^{-\Gamma t}dt$ we find that the energy spectrum of γ's detected in the forward direction should be

$$dN = N_0 \exp\left[-\frac{d\Gamma}{\lambda c}\ln\left(\frac{E}{E_0}\right)\right]\left(\frac{d\Gamma\theta(E_m - E)}{\lambda c E} + \delta(E_m - E)\right)dE, \quad (3)$$

where E_m is the maximum γ-ray energy.

Figure 2 shows γ-ray energy spectra representative of the data obtained over a period of 60 d at different distances d and two applied potentials W. The signal-to-noise ratio has been improved over that of Ref. 11 by turning off the positron beam with a 20-μsec 20-V pulse on G_1 whenever the Ge(Li) detector starts to record an event. The spectra are fitted by linear least squares with use of the line shape of Eq. (3) [with independent amplitudes for the terms in $\theta(E_m - E)$ and $\delta(E_m - E)$] folded with a Gaussian resolution function having a 2.13 keV full width at half maximum (FWHM). Added to the theoretical line shape is a background spectrum obtained with $V_G = +13$ V and $d = 15.87$ mm. Under these conditions, the amount of Ps^- and fast positronium formed and the number of positrons annihilating in the carbon film are unchanged. However, the low electric field between the carbon film and the grid gives us a spectrum having a negligible number of Ps^- annihilation photons with energies in the region of the spectrum where the fits are made. The background spectrum was smoothed by folding it with a Gaussian having a 1.0 or 1.5 keV FWHM for $W = 1$ or 4 keV. The value of χ^2 for the fits to the line shape (see Table I) is not very sensitive to Γ, which was taken to be 2.0×10^9 sec^{-1} in Eq. (3). The areas of the monoenergetic $Ps^- \to 2\gamma$ photopeaks A^- are divided by the areas of the 511-keV photopeaks to obtain the relative monochromatic Ps^- photopeak areas f^-. The inset in Fig. 2 shows the Ps^- photopeaks on an expanded scale with curves fitted over the ranges 522–542 and 530–570 keV at $W = 1$ and 4 keV, respectively.

The lower left inset in Fig. 3 is a plot of the relative 511-keV photopeak area count rate R versus grid separation d. The count rate changes with d because the solid angle subtended by the Ge(Li) detector decreases as d increases. The data shown in the inset are well represented by a curve $R = d_0^2/(d_0 + d - d_1)^2$ ($d_1 = 2.99$ mm, $d_0 = 180.3 \pm 3.7$ mm, $\chi^2/\nu = 5.05/5$) which has been used to correct the 511-keV photopeak areas to a common distance d_1. It is important to note that since G_3 is fixed, the Ps^- photopeak areas A^- need no such correction.

The position of the carbon film was controlled by micrometers on a long vacuum manipulator. The micrometers were read with a 10^{-3}-mm precision and these readings were used to compute the manipulator displacement Δ. The actual distance d between G_2 and G_3, $d = c_1 + c_2\Delta$, in-

TABLE I. Results of line-shape fits. N, run number; d, grid separation; t/g, computed delay time; f^-, relative monochromatic Ps^- photopeak area; χ^2/ν, chi square per degree of freedom for fit; W, acceleration potential; A, total 511-keV photopeak area.

N	d (mm)	t/g (psec)	f^- (10^{-6})	χ^2/ν	W (volts)	A (10^6)
21	1.43	263	53.03±1.16	100.25/77	1000	71.26
13	1.70	315	49.24±1.72	87.38	"	30.88
19	2.35	433	37.12±1.42	77.70	"	37.99
6	2.47	457	37.29±1.77	82.96	"	25.70
11	2.99	552	32.14±1.62	54.63	"	27.13
12	4.28	790	19.05±1.43	76.42	"	26.41
17	4.92	909	15.77±0.99	105.57	"	51.53
10	5.56	1028	11.85±1.24	75.02	"	29.24
20	6.21	1147	11.37±0.76	72.49	"	74.79
8	8.14	1505	4.36±0.88	84.95	"	45.97
23	1.70	158	78.68±1.44	158.14/158	3936	52.82
14	2.17	202	73.47±1.90	145.00	"	28.68
2	2.99	278	63.65±1.78	174.74	"	29.53
25	4.28	398	49.23±1.66	169.72	"	28.78
4	5.56	518	40.25±1.48	166.28	"	30.08
1	8.14	759	25.50±1.24	129.48	"	32.31
5	10.72	998	16.00±1.17	169.11	"	28.90
15	12.01	1118	12.40±0.62	168.96	"	92.52
3	13.30	1238	9.23±0.97	181.19	"	31.30
24	14.58	1358	6.09±0.54	179.03	"	99.89
7	15.87	1477	5.78±0.71	151.63	"	48.50
9,16,18,22		background runs			429	136.19

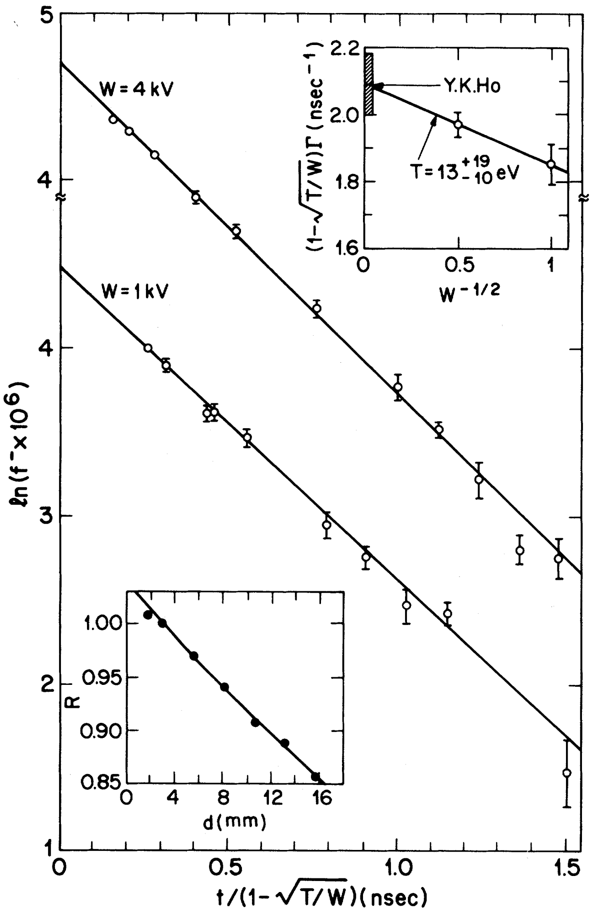

FIG. 3. Logarithm of the relative amount of Ps$^-$ surviving for a time $t/g = t/[1-(T/W)^{1/2}]$ computed from Eqs. (1) and (2). Lower inset: the relative 511-keV photopeak count rate R vs grid separation d. (R = 250 sec^{-1} at the start of the experiment.) Upper inset: the extrapolation of the measured Ps$^-$ decay rate to infinite acceleration potential W.

volves two constants which were determined by traveling microscope observations of the two grids through a vacuum window. The additive constant has no effect on the measurement of Γ. The multiplicative constant is $c_2 = 0.906 \pm 0.004$.

The logarithms of the relative $\text{Ps}^- \to 2\gamma$ photopeak areas f^- are plotted in Fig. 3 versus the time t computed from Eqs. (1) and (2). The data are linear-least-squares fitted by straight lines $\ln(10^6 f^-) = a - (g\Gamma)(t/g)$ [where g is from Eq. (2)] with the following results. At $W = 1$ kV (1000 ± 1 V), $a = 4.48 \pm 0.03$, $g\Gamma = (1.851 \pm 0.058)$ nsec^{-1}, and $\chi^2/\nu = 6.22/8$; at $W = 4$ kV (3936 ± 4 V), $a = 4.70 \pm 0.02$, $g\Gamma = (1.971 \pm 0.034)$ nsec^{-1}, and $\chi^2/\nu = 8.47/9$. The values of a are not the same for the two sets of data because at $W = 4$ kV the Ps$^-$ decays closer to the Ge(Li) detector than at 1 kV. The fitted values of $g\Gamma$ are unaffected by this because the spatial distribution of Ps$^-$ contributing to the monoenergetic peak does not depend on d for a given value of W. It is to be noted that although the angular distribution of annihilation γ's depends on W, this does not affect the fitted values of $g\Gamma$ because the angular distribution is independent of d. The two decay rates are plotted versus $W^{-1/2}$ in the upper right inset of Fig. 3. As shown by Eq. (2), $g\Gamma$ should depend approximately linearly on $W^{-1/2}$, $g\Gamma = \Gamma[1-(T/W)^{1/2}]$. The straight line through the two measurements of $g\Gamma$ gives the extrapolated value $\Gamma = (2.09 \pm 0.09)$ nsec^{-1} and a mean value (actually the square of the mean of the square root) of the Ps$^-$ kinetic energy at the time of formation of $T = 13^{+19}_{-10}$ eV. At the present level of precision, the errors are completely dominated by counting statistics.

In conclusion, the first measurement of the decay rate of the positronium negative ion has been made and is in good agreement with the calculation by Ho. An order-of-magnitude increase in the experimental precision appears feasible and would allow us to test the radiative corrections and bound-state contributions to the decay rate.

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