Observation of the Positronium Negative Ion

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A beam of 400-eV positrons is partially transmitted through a 40-Å C film in vacuum. Measuring the γ-ray energy spectrum with a downstream Ge(Li) detector, a new γ-ray peak is observed, the energy of which can be changed by applying a voltage to a grid behind the film. Attributing the new peak to a Doppler-shifted annihilation γ implies a mass-to-charge ratio $3.011(14)m/e$, thus signaling the presence of the $e^-e^+e^-$ positronium negative ion, Ps^-. The Ps^- conversion efficiency of the C film is $(2.8\pm0.3)\times10^{-4}$.

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The stability of a bound system of two electrons and one positron was first demonstrated theoretically in a pioneering paper on "polyelectrons" by Wheeler.[1] The binding energy of the positronium negative ion $e^-e^+e^-$ (Ps^-) against breakup into positronium (Ps) and a free electron is computed[2,3] to be 0.3266 eV, somewhat less than half the binding energy of the H^- ion. The 2γ annihilation rate of Ps^- is predicted[4] to be $\Gamma=(0.502\text{ nsec})^{-1}$, very close to the spin-averaged Ps decay rate. The branching ratio for 3γ annihilation is the same as for a positron in a metal ($\approx 2.6\times10^{-3}$); the branching ratio for annihilation into a single photon of energy $\frac{4}{3}mc^2$ and an energetic electron of energy $\frac{2}{3}mc^2$ would be about $\alpha^4\approx10^{-9}$. Autoionizing excited S states of Ps^- are predicted[5] with lifetimes of about 10^{-12} sec. It is not known whether the metastable[6] $2p^2\,{}^3P$ state of H^- has a long-lived analog in the Ps^- system. Such a state would have fine structure, whereas there is none in the $J=\frac{1}{2}$ Ps^- ground state where the two electron spins are paired in a relative singlet.

The production of H^- ions by slow-proton bombardment of thin foils is well known.[7] Conclusive evidence that the same technique allows us to form Ps^- with slow positrons is presented in this Letter. Besides demonstrating the existence of a new exotic entity, this experiment makes it possible to measure the properties of Ps^- and, by photoionization, to produce high-velocity Ps for the first time. Fast Ps beams would be useful for measuring Ps-atom cross sections and could conceivably be used to study surfaces[8] via Ps diffraction.

The method for forming Ps^- is based on the slow-positron techniques which enabled Canter, Mills, and Berko[9] to form Ps in vacuum with high efficiency and to observe and measure the properties of the $n=2$ state of Ps. The apparatus used in the present experiment is shown schematically in Fig. 1. A beam of positrons from a 15-mCi source of ^{58}Co and a Cu(111)+S moderator[10] is guided by a magnetic field B to a thin carbon target in a $\sim10^{-9}$-Torr vacuum. The energy of the incident positrons is adjusted so that some of them penetrate entirely through the carbon film. Upon emerging from the carbon, there is some probability that the positrons will be bound to two electrons as Ps^-. A grid located 2.5 mm from the carbon film is biased positive with respect to the film so that any Ps^- will be accelerated, whereas transmitted positrons will return to the film. The annihilation photons are counted by a Ge(Li) detector which would see the Ps^- coming towards it. The unambiguous signature of Ps^- is thus a blue-shifted annihilation line, the energy of which is directly determined by the voltage difference W between the grid and the carbon film. The Doppler shift of the annihilation γ's emitted at an angle θ from the direction of the Ps^- veloci-

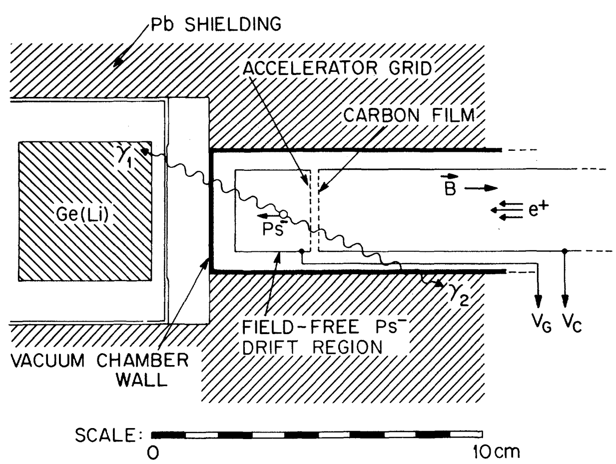

FIG. 1. Apparatus for observing Ps^-, the negative ion of positronium. Ps^- formed at the back of the carbon film is accelerated by the voltage difference $W=V_G-V_C$, resulting in a blue-shifted annihilation photon γ_1 being detected by the Ge(Li) detector.

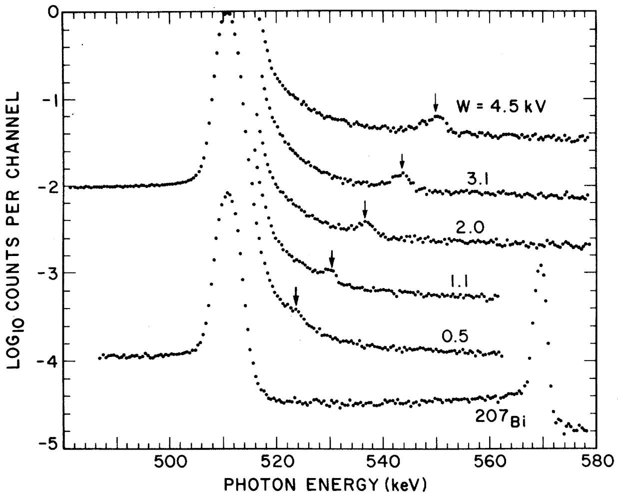

FIG. 2. Annihilation γ-energy spectra obtained for five different Ps^- acceleration voltages W. Each curve is a composite of four 12-h spectra obtained at incident e^+ energies E between 300 and 500 eV. The total number of counts per channel at the 511-keV peak is $\sim 4 \times 10^6$. The arrows indicate the peak positions predicted by Eq. (1). The background is mostly associated with scattered annihilation γ's which have been partly removed by a graded Pb-Sn-Cu shield in front of the detector. The ^{207}Bi calibration line shows the energy resolution at 569.63(8) keV.

ty is

$$\Delta E = [\lambda + (2\lambda + \lambda^2)^{1/2} \cos\theta] mc^2, \qquad (1)$$

where $\lambda = eW/3mc^2$ and m is the mass of the electron. For $W = 1000$ V and $\theta = 0°$, $\Delta E = 18.79$ keV, a shift which can be easily observed in the presence of a large background of unshifted annihilation γ's.

The carbon film was made by evaporating C onto a mica substrate in vacuum. The carbon was floated off the mica onto water and picked up on a 333-line/in. Ni mesh. The C film was found to transmit 50% of an incident positron beam when the energy was 470 ± 20 eV. Other measurements[11] have shown that the median penetration depth for positrons in Al is 8.0 ± 1.8 $\mu g/cm^2$ at 2.1 keV and is proportional to E^n, with $n = 1.60 \pm 0.15$. From this, I infer that the carbon thickness is 37 ± 13 Å, using a density of 2 g/cm^3 for the carbon.

Figure 2 shows annihilation photon energy spectra obtained with acceleration voltages from 500 to 4500 V. Above the unshifted 511-keV photopeak, we see a low-intensity peak that moves in energy as the acceleration voltage changes. The arrows denote the Doppler shifts predicted by Eq. (1) with use of an appropriately averaged value of $\langle \cos\theta \rangle$ for the geometry of Fig. 1. The agreement between the expected and the observed energy shifts makes one confident that the shifted peaks can be attributed to the detection of Doppler-shifted γ rays from the 2γ annihilation of Ps^- in flight.

Since the Ps^- is being accelerated during a significant portion of its lifetime, the blue-shifted annihilation γ-ray spectrum will not be monoenergetic. More precisely, only a fraction $\zeta \approx \exp(-3\Gamma \Delta E d/eWc)$ of the Ps^- will emerge from the acceleration region of width d before annihilating. Ignoring the instrumental resolution, the complete Doppler-shifted energy spectrum is

$$dN/d\epsilon = \epsilon_0^{-1} \exp(-\epsilon/\epsilon_0)\theta(\Delta E - \epsilon) + \zeta\delta(\epsilon - \Delta E), \qquad (2)$$

where $\epsilon_0 = ecW\cos\theta/3\Gamma d$, θ is the unit step function, and the energy ϵ is measured relative to the

TABLE I. Ps^- line-shape parameters (obtained by least-squares fitting a Gaussian plus cubic background line shape to the shifted photopeaks in Fig. 2), the mean value of $\cos\theta$ calculated for the geometry of Fig. 1, the mass-to-charge ratio M/Q calculated from ΔE, and the Ps^- yield f^- implied by the relative Ps^- photopeak area A^-/A^+. ΔE = 58.63(8) keV and 2.35σ = 1.8(1) keV for the ^{207}Bi calibration line.

W (V)	ΔE (keV)	$10^6 A^-/A^+$	2.35σ (keV)	$\langle\cos\theta\rangle$	$(M/Q)(m/e)^{-1}$	$10^6 f^-$
501[a]	no fit	⋯	⋯	0.970[b]	⋯	⋯
1130[a]	19.3(2)	47(8)	~2.5	0.968[b]	3.022(38)	102(17)
2011[a]	26.0(2)	63(8)	3.3(3)	0.966[b]	2.992(28)	111(14)
3144[a]	32.6(2)	84(8)	3.8(3)	0.964[b]	3.003(24)	132(13)
4529[a]	39.1(2)	88(8)	4.2(3)	0.961[b]	3.028(21)	129(12)

[a] Uncertainty is ± 0.1%. [b] Uncertainty is ± 0.005.

unshifted energy mc^2.

To examine the energy shifts in more detail, the shifted peaks obtained for different values of E and W have been fitted by a line shape

$$A^-(2\pi\sigma^2)^{-1/2}\exp[-(\epsilon-\Delta E)^2/2\sigma^2]+\sum_{n=0}^{3}a_n\epsilon^n.$$

The best-fit parameters for the data of Fig. 2 are listed in Table I; the areas A^- have been normalized to the unshifted 511-keV photopeak areas A^+. The full widths at half maximum $[2\sqrt{2\ln 2}]\sigma$ are broader than the ^{207}Bi calibration line because of the dispersion in $\cos\theta$. The fraction f^- of positrons yielding Ps^- is obtained from A^-/A^+ after correcting (1) for solid-angle changes due to the mean Ps^- forward displacement $d+(6eW/m\Gamma^2)^{1/2}$, (2) for the Ps^- that hits the forward wall of the drift region, (3) for the λ^3 dependence of the photoelectric absorption cross section of the Ge(Li) detector, and (4) for the fraction, ζ, of Ps^- which should be monoenergetic (calculated with use of $d=2.5$ mm and $\Gamma=2\times10^9$ sec^{-1}). I assume that the Ps production at the C grid is negligible (<10%) and have made no correction for the 66(5)% of the positrons and the 75(5)% of the Ps^- that is intercepted by grid wires. Under the assumption that the peaks arise from positrons annihilating bound in an object with mass M and charge Q, I derive $M/Q=(m/e)(2eW/mc^2)(mc^2/\Delta E)^2(\cos^2\theta+\Delta E/mc^2)$ and compute values in Table I for M/Q from the best-fit ΔE's. The average $M/Q=3.011(14)m/e$ is in accord with the value $3m/e$ expected for Ps^-.

The measured dependence of f^- on the energy E of the positrons incident on the carbon film is shown in Fig. 3. The fraction, η, of the positrons transmitted through the carbon film as a function of E is plotted in the same figure. After correcting for grid losses, $f^-(E)\approx(0.1\text{ V})\,\partial\eta/\partial E$, which may be interpreted to mean that the Ps^- is formed by a small fraction (~1%) of the positrons leaving the film with the typical atomic velocities ($E\approx10$ eV, $v\approx\alpha c$) which would be favorable for capturing two electrons. H^- is similarly formed with several-percent efficiency[7] by protons emerging from solid foils with $v\approx\alpha c$. This suggests that an improved Ps^- conversion efficiency would be obtained by using a smaller film thickness d to increase $\partial\eta/\partial E$. Because the thickness for half-transmission is proportional to E^n, it appears that $\partial\eta/\partial E\propto d^{-1/n}\approx d^{-0.6}$. If this is true, f^- will only double for a film one-quarter of the thickness used in the present experiment. Since the H^--formation probability is dependent on the choice of the material for the foil converter, it would be interesting to measure f^- for different films. For example, it becomes energetically favorable to form Ps^- if we lower the electron work function of a surface by coating it with Cs, although there might not be a dramatic change in f^- because of the small density of electrons of appropriate energy.

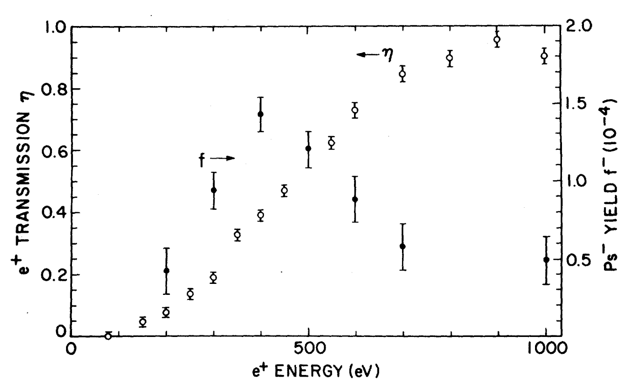

FIG. 3. Positron transmission probability η and Ps^- formation fraction f^- plotted vs e^+ incident energy E. There is no noticeable dependence of the peak shift ΔE on the energy E. To account for grid losses, f^- should be multiplied by 2.0 ± 0.2.

Besides its mass of $3m$, charge of e, spin of $\frac{1}{2}$, and its binding energy, the positronium negative ion has an annihilation lifetime, a 2γ-angular correlation, a $1\gamma/2\gamma$-branching ratio, a magnetic moment, a photoionization cross section, and autoionizing excited states, all of which are sensitive to the details of its wave function and which can now be measured given a sufficiently strong source of slow positrons.[12] Furthermore, it should be feasible to measure the total scattering cross sections for Ps^- colliding with electrons or atoms.

It is interesting to note that field ionization does not appear to preclude accelerating Ps^- to relativistic energies. The annihilation in flight of Ps^- provides a tunable source of γ rays of precisely known relative energy shift. To use these annihilation γ's as an absolute standard, we need to know the average kinetic energy T of the Ps^- at the moment it leaves the foil.[13] One might expect that $T\approx10$ eV as the Ps^- is being formed by only the low-velocity positrons. The spin of the electron which remains after 2γ annihilation is the same as that of the positron in the Ps^-. Since positrons preserve their large β-decay polarization while slowing down,[14] the formation and annihilation of Ps^- allows the positron and Ps^- polarization to be measured via Mott scattering of the spectator electron.

In conclusion, I have observed the positronium negative ion, thus making available for study a new purely leptonic system with many interesting measurable properties.

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Range and Spectral-Density Measurements of Very Slow Muons

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Range and spectral density of very slow negative muons have been measured with novel techniques. The intensity around and below 1 keV agrees with semiclassical calculations but contradicts some quantum-mechanical theories of the Coulomb capture.

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The slowing down and Coulomb capture of negative mesonic particles has found widespread interest since the pioneering work of Fermi and Teller.[1] The per-atom capture rate at energies W between W_0 and W_1 with $W_0 > W_1$ is given by

$$R(W_0, W_1) = \int_{W_1}^{W_0} n(W)\sigma(W)\,dW, \qquad (1)$$

where $n(W)$ is the spectral flux density, that is, the number of particles per unit energy and unit time entering a small sphere divided by the cross section of the sphere, and $\sigma(W)$ is the capture cross section. With neglect of capture, scattering, and straggling at $W > W_1$, $n(W_1)$ is correlated to $n(W_0)$ by

$$n(W_1)S(W_1) = n(W_0)S(W_0), \qquad (2)$$

where $S(W)$ is the stopping power.[2] Straggling is, in our experiment, compensated for by the spread of the energy spectrum at any value taken for W_0. Scattering can be corrected for. Hence $S(W)$ can be measured with the help of $n(W)$ for energy values W_1 high enough that capture is negligible. Particles captured between W_0 and W_1 will be missing at W_1; hence, given a way to calculate $S(W)$, one can measure $R(W_0, W_1)$ and, with $W_0 \approx W_1$, also $\sigma(W_1)$.

Both slowing down and capture can be treated either semiclassically or quantum mechanically. The spectral flux density $n(W)$ was semiclassically calculated to be proportional[3] to W or to be constant[4] at low energy W. Most semiclassical calculations predict capture from energies of the order of 100 eV, depending on the atomic number Z of the capturing element, while most quantum-mechanical calculations predict capture predominantly from substantially higher energies which rise strongly with Z; for example, in Li at 240 eV[5] and in C at 8 keV.[6] The subject is reviewed in Refs. 7 and 8.

No direct experimental information on $n(W)$ and $\sigma(W)$ at very low energies has been available up to now. It is the aim of this Letter to report on the first measurement of the two quantities for μ^- down to energies of some hundred electronvolts.