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Can we measure the gravitational free fall of cold Rydberg state positronium?

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Abstract

In this paper we examine the possibilities for detecting the free fall of Rydberg positronium atoms. In our scheme, cold positronium atoms are emitted from a "point" source and excited to the $n = 25$ circular Rydberg state with $L = n - 1$. The positronium atoms are allowed to travel horizontally 10 m in a field free vacuum and focused onto a detector using an elliptical Van der Waals mirror. A free fall distance of order 50 μm and a few detected atoms per hour are anticipated. Various extraneous influences on the positronium, such as collisions with residual gas atoms, Stark mixing in stray electric and magnetic fields, photoionization due to thermal radiation, and accelerations due to patch potentials are estimated.

1. Introduction

Notwithstanding the conventional point of view that antigravity is impossible within the established framework of modern physics, the hypothesis that antimatter is attracted to matter has not been the subject of a direct test. Attempts by Fairbank [1] and his group to measure the gravitational free fall of electrons and positrons were not conclusive and work is in now progress to prepare antihydrogen atoms for free fall measurements in vacuum [2]. A measurement of the free fall of neutral positronium atoms would be much simpler than for its constituent charged particles. However, the positronium must be in a high Rydberg state in order to have a sufficiently long lifetime to result in an observable free fall distance. In such a state the positronium is highly polarizable and the free fall region must be nearly as free of stray electric and magnetic fields as would have been needed for observations on free electrons and positrons. Nevertheless, the experiment appears feasible with current technology.

The proposal is to produce a "point" source of positronium [3] of 1-μm vertical extent and to excite it via Doppler-free techniques to an $n \approx 25$ state. There are now several possibilities for a free fall experiment. The simplest perhaps is to allow the positronium in the low energy tail of its energy distribution to travel a few meters in the horizontal direction, be focused by a mirror and then travel a few more meters to converge on a 1-μm spot on a position sensitive detector, as shown in Fig. 1. Deflections of the spot as large as 50 μm should be observable at the longest positronium time of flight delay.

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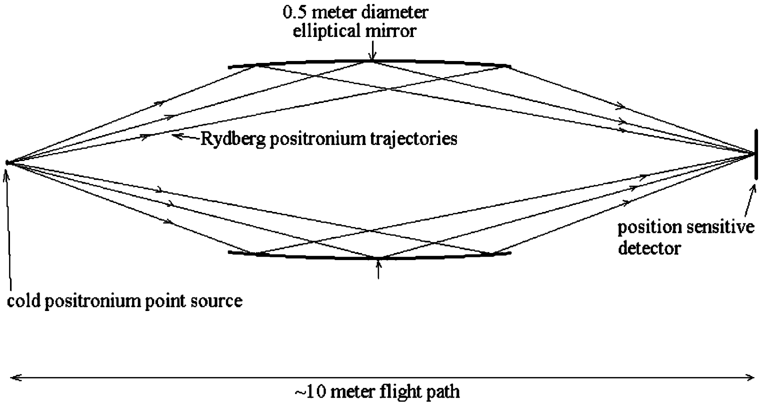

Fig. 1. Experiment to measure the gravitational free fall of $n = 25$ Rydberg positronium.

A second possibility using lasers to make an atom interferometer and a third to use transmission gratings to make a Mach–Zender interferometer [4] need to be evaluated and compared to the mirror experiment.

2. Cold positronium production

Positrons from the final brightness enhancement remoderator of an intense slow positron beam source are accelerated to 3 keV and brought to a line focus of vertical width equal to 1 μm and horizontal width 300 μm on an aluminum sample. The sample is a single crystal Al(1 1 1) surface at a temperature of 186 K that has been treated by exposure to oxygen. It is found that such a sample will emit thermal positronium with an efficiency of about 12% and a beam-Maxwellian velocity distribution [5]

$$\mathrm{d}N/\mathrm{d}E_\perp\,\mathrm{d}E_\parallel = N_0(k_\mathrm{B}T)^{-2}\exp\{-(E_\perp + E_\parallel)/k_\mathrm{B}T\}, \tag{1}$$

where $E_\perp$ and $E_\parallel$ are the components of the positronium energy perpendicular and parallel to the surface respectively, k_B is Boltzmann's constant and T is the sample temperature. The total number of cold positronium atoms emitted from the horizontal line source is taken to be $N_0 = 7 \times 10^5$. The number of atoms emitted in a nearly normal direction to the surface within a solid angle $\mathrm{d}\Omega$ and having a maximum perpendicular energy $E_\perp$, is for small $E_\perp$,

$$N(E_\perp, \theta) = \tfrac{1}{2}N_0(E_\perp/k_\mathrm{B}T)^2\,\mathrm{d}\Omega = (v/3\ \mathrm{m/ms})^4\,\mathrm{d}\Omega \times 3.6\ \text{atoms per pulse}, \tag{2}$$

where the perpendicular component of the positronium velocity is v and the positronium kinetic energy is

$$E_\perp = (v/3\ \mathrm{m/ms})^2 \times 51.1\ \mu\mathrm{eV}. \tag{3}$$

In a 0.5-mm region near the Al target, the slow positronium atoms are to be excited to the 2S-state using first-order Doppler-free two photon excitation [6]. These atoms would then live about 1.1 μs and travel about 3 mm, during which time they would be excited to a high Rydberg d state with principle quantum number $n \approx 25$ by first-order Doppler-free resonant absorption of pairs of circularly polarized infrared photons. With correctly aligned cw laser beams, no momentum will be imparted to the Ps by the two-photon absorption. By appropriate curvature of the two-photon wave front, the positronium could be slowed to increase the density of its low energy component. The positronium is then to be spun up to the maximum orbital angular momentum state with $L = n - 1$ by circularly polarized microwave radiation.

3. Free fall

We allow the positronium atoms to fall for q times the lifetime of the Rydberg state of the atoms which is (see Fig. 2 and [7])

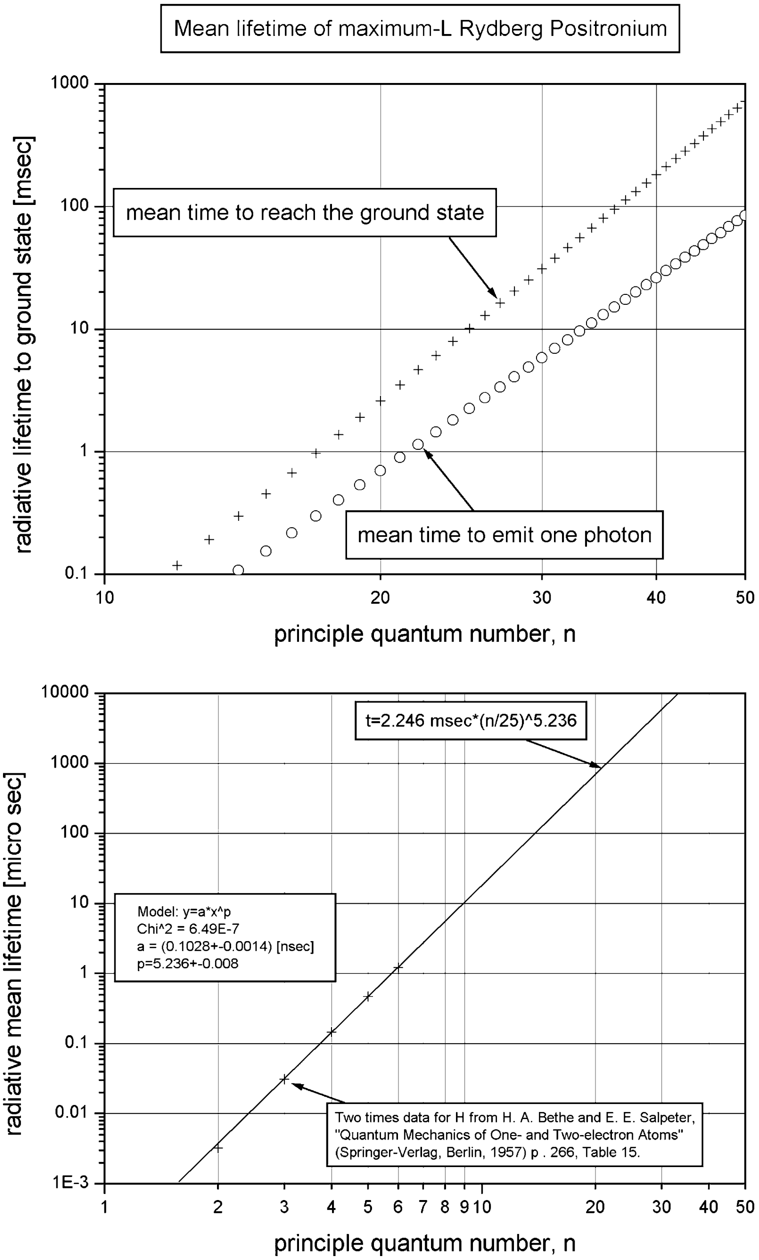

Fig. 2. Radiative lifetimes of positronium excited states.

$$(n/25)^{5.236} \times 2.25 \text{ ms}. \tag{4}$$

The total Ps flight path is then

$$(n/25)^{5.236}(v/3 \text{ m/ms})q \times 6.75 \text{ m}. \tag{5}$$

The gravitational free fall is

$$\Delta x = \tfrac{1}{2}gt^2 = q^2(n/25)^{10.47} \times 24.8 \text{ µm}. \tag{6}$$

Note that the deflection of the positronium due to emission of a photon from the transition $n \to n-1$, $L \to L-1$ is

$$\Delta p/p = (1/4)\alpha^2(c/v)n^{-3} = 8.52 \times 10^{-5}(25/n)^3(3\ \mathrm{m/ms}/v), \qquad (7)$$

which is so great as to preclude the emission of even a single photon during the free fall.

4. Van der Waals mirror

The cold Rydberg Ps atoms could be focused by quantum mechanical reflection at a grazing angle θ from an elliptical dielectric mirror subtending a half angle θ and solid angle $\mathrm{d}\Omega \approx \frac{1}{4}\sin^2\theta$. One possibility is to illuminate the dielectric by a totally internally reflected wave so that an evanescent wave is present in the vacuum just outside the mirror. Appropriate choice of the frequency and intensity of the radiation would result in reflection of the positronium. Reflection will also occur for an unilluminated dielectric when the perpendicular component of the Ps wavelength is sufficiently greater than the length scale of the Van der Waals potential, i.e. when [8]

$$|\mathrm{d}k_\perp/\mathrm{d}x| \geqslant k_\perp^2, \qquad (8)$$

where $\hbar^2 k_\perp^2/4m_\mathrm{e} = E_0 - V(x)$ is the perpendicular component of the positronium center of mass kinetic energy, and $E_0 = E_\mathrm{T}\sin^2\theta$ is its value at very large x. The Van der Waals potential $V(x)$ for a Rydberg Ps atom, with principle quantum number n and $L = n-1$, in vacuum a distance x from a flat surface with a dielectric constant ε is approximately given by

$$V(x) = -(\varepsilon - 1)(\varepsilon + 1)^{-1}(1/6) \times (n^4 + 3n^3/2 + n^2/2)e^2a_\mathrm{B}^2/x^3, \qquad (9)$$

provided $x > 2n^2a_\mathrm{B}$, the mean radius of the Rydberg Ps atom defined by the expectation value of $1/r$. Here r is the radial separation of the electron and positron and a_B is the Bohr radius of the infinite mass hydrogen atom. We have also assumed the orbital angular momentum state is the one for which $m = L$, with the axis of quantization normal to the surface. The inequality $|\mathrm{d}k_\perp/\mathrm{d}x| \geqslant k_\perp^2$ cannot be satisfied for

$$\begin{aligned} E_0 &> (2^{15}/3^{10})Ry(n^4 + 3n^3/2 + n^2/2)^{-2} \\ &\quad \times (\varepsilon+1)^2(\varepsilon-1)^{-2} \\ &= (25/n)^8(\varepsilon+1)^2(\varepsilon-1)^{-2} \\ &\quad \times (1 + 3/2n + 1/2n^2)^{-2} \times 49.5\ \mathrm{peV}. \end{aligned} \qquad (10)$$

We thus require

$$E_\mathrm{T} < (0.03/\sin\theta)^2(25/n)^8(\varepsilon+1)^2(\varepsilon-1)^{-2} \times (1 + 3/2n + 1/2n^2)^{-2} \times 55\ \mathrm{neV}. \qquad (11)$$

For a material like solid glass with $\varepsilon \approx 3$, the necessary kinetic energy of the positronium atoms will be unattainably small without laser cooling and phase space compression of the positronium. For a mirror surface made from a very low density material such as aerogel or liquid He with $\varepsilon = 1.04$, we then have

$$E_\mathrm{T} < (0.03/\sin\theta)^2(25/n)^8 \times (1 + 3/2n + 1/2n^2)^{-2} \times 138\ \mu\mathrm{eV}, \qquad (12)$$

well within the velocity limit originally decided upon, i.e. 3 m/ms:

$$(v/3\ \mathrm{m/ms}) < (0.03/\sin\theta)(25/n)^4 \times (1 + 3/2n + 1/2n^2)^{-1} \times 1.64. \qquad (13)$$

5. Count rate

The total count rate calculated from Eq. (2) is now

$$N = (v/3\ \mathrm{m/ms})^4(\sin\theta/0.03)^2\mathrm{e}^{-(q-1)}(\eta/0.01) \times 3.0 \times 10^{-4}\ \text{counts per second}, \qquad (14)$$

with η being the product of the net optical excitation probability, the probability of reflection from the elliptical mirror and the detection efficiency. The positron pulse repetition rate has been taken to be 100 s^{-1}. Given the careful optimization of η, this rate would be sufficient to allow for focusing, alignment and systematic tests, most of which however would be done using the faster positronium atoms. Note that the trajectories of the fast positronium atoms defines the zero of deflection. From Eq. (6), the magnitude of the largest deflection will be of order 50 μm for $q = 1.5$ and $n = 25$. This should be readily measured using a channel plate detector having channels of diameter 10 μm.

6. Extraneous influences

There are many perturbations that can disturb a measurement on a single atom falling under the influence of gravity [9]. The gravitational force on a positronium atom in the earth's field is

$$F_G = 5.1 \times 10^{-13}\ \text{eV/cm}. \tag{15}$$

The image potential of a metal surface a distance x from Rydberg Ps will produce a force

$$F_I = (Ry/a_B)(na_B/x)^4, \tag{16}$$

which will exceed the gravitational force for $x <$ 300 μm.

The polarizability of the Ps is approximately equal to r^3, and its potential energy in an electric field E is $U = r^3E^2$. The patch potential variations [10] a distance x from a surface having uniformly distributed patches of size δ with work function variations $\Delta\phi$ will be $\Delta\phi\ (\delta/x)$ due to the averaging of the fluctuations. The electric fields will be of order $E \approx \Delta\phi\delta/ex^2$. The patch potential force will then be of order

$$\begin{aligned} F_P &= (\Delta\phi\delta/ex^2)^2 r^3/x \\ &= (\Delta\phi/0.5\ \text{eV})^2(\delta/0.1\ \mu\text{m})^2(n/25)^6 \\ &\quad \times (300\ \mu\text{m}/x)^5 \times 2 \times 10^{-14}\ \text{eV/cm}, \end{aligned} \tag{17}$$

which will be negligible compared to F_G except in the vicinity of the mirror. How to maintain low stray fields near the mirror is an unsolved problem since it must have a low dielectric constant. Possibly it could be made from aerogel with a thin coating of colloidal graphite.

The stray electric fields will cause Stark mixing and thus quenching and ionization of the Rydberg states. Also to be avoided are effectively time varying electric fields due to the motion of the Ps through spatially varying fields. Excitations with $\Delta n = 1$ for $n = 25$ will occur at roughly 80 GHz due to spatial variations of about $3 \times 10^5\ \text{cm}^{-1}$ that are only present within a few hundred nm of a surface. Transitions with $\Delta n = 0$ will require much slower variations and need to be examined closely.

Collisions with residual gas atoms in a 10-m flight path at 10^{-11} Torr, for which the density is 3×10^5 molecules/cm^3, would be just negligible for a cross-section of $4\pi r^2 \approx 10^{-9}\ \text{cm}^2$. Magnetic fields will mix the orbital substates, introduce motional Stark quenching and also deflect the atoms.

Thermal radiation from the walls of the vacuum container can photoionize the positronium or induce transitions. Liquid He temperature has k_BT just the same as the $\Delta n = 1$ transition energy for $n = 25$. The transition rates need to be calculated.

7. Conclusion

We can hardly claim at this point that a free fall measurement would be practical, given the possibility of unanticipated systematic effects and the difficulty of accounting for some of the known disturbances. However the experiment seems promising enough to warrant further calculations and preliminary experiments.

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