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Citation: American Journal of Physics **67**, 880 (1999); doi: 10.1119/1.19142
View online: https://doi.org/10.1119/1.19142
View Table of Contents: https://aapt.scitation.org/toc/ajp/67/10
Published by the American Association of Physics Teachers

Positronium in the undergraduate laboratory

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(Received 12 October 1998; accepted 9 March 1999)

Positronium is an exotic atom formed by an electron and its antiparticle, the positron. Orthopositronium, which is the state with total spin 1, has a decay constant of about 7.05 μs^{-1} and decays primarily into three gamma rays. A relatively simple experiment is described which will allow students to detect and measure the lifetime of orthopositronium in gases using apparatus often found at undergraduate institutions. Other effects, such as parapositronium decay, pick-off, and thermalization, can also be demonstrated. © *1999 American Association of Physics Teachers.*

I. INTRODUCTION

Positronium was the first ''exotic atom'' to be predicted and later discovered. Shortly after the prediction of the existence of the anti-electron,[1,2] or positron, and its subsequent discovery in 1933,[3] there was speculation about the existence of a bound system consisting of a positron and electron, called positronium. Several calculations followed[4,5] predicting the general characteristics of positronium. It was not until 1951, however, that positronium was produced[6] in such a way that its fundamental properties could be studied.

The structure of positronium is very similar to that of hydrogen. In calculating the energy levels, however, a reduced mass of $m_e/2$ rather than m_e must be used, which leads to a ground state energy of half that of hydrogen, or -6.8 eV. As in the case of hydrogen, the ground state can be a singlet state with spins antiparallel and total spin $s=0$ $(m=0)$ called parapositronium, or it can be in the triplet state with spins parallel and total spin $s=1$ $(m=-1,0,1)$ called orthopositronium. The difference in magnetic moment between the proton and positron results in hyperfine splitting of these states that is 200 times greater than in hydrogen. The greatest difference between hydrogen and positronium, however, is that in ground state positronium, the electron and positron wave functions have significant overlap and annihilation can occur. The number of gamma rays emitted in the decay process is governed by the charge-conjugation selection rule[7]

$$(-1)^{l+s}=(-1)^n, \tag{1}$$

where l is the orbital angular momentum, s is the total spin of the positronium atom, and n is the number of gamma rays emitted. Clearly, since $l=0$ for ground state positronium, parapositronium with $s=0$ must decay into an even number of gamma rays, while orthopositronium must decay into an odd number. However, it is not possible to conserve both momentum and energy for decays into a single gamma ray. Hence, the most likely decay channel for parapositronium is into two gamma rays, while for orthopositronium it is into three. Because of this multi-photon decay requirement, para- and orthopositronium have relatively long lifetimes, with inverse decay rates λ^{-1} of about 0.1 and 140 ns, respectively.

The study of positronium is of current interest for many different reasons, probably the most important of which is as a test of quantum electrodynamics (QED). Positronium is an ideal testing ground for the predictions of QED because the interactions between the electron and positron are purely leptonic, as opposed to many other systems in which the strong interaction also plays a role. The most precise measurements to date[8,9] of the decay rate of orthopositronium disagree with the order-α QED predictions[10–13] by several standard deviations. However, there has been one recent experiment,[14] designed to minimize systematic uncertainties due to extrapolation to zero density, the results of which are consistent with QED. A number of experiments[15–23] have been performed seeking ''exotic'' decay modes for positronium in an attempt to explain this discrepancy. Recently measurements[24–26] of positronium excited states have become possible and are being compared with QED predictions. Another topic of interest is using positronium to test time-reversal, parity, and charge-conjugation (TCP) invariance by looking for forbidden decay modes.[27–31] The decay of positronium formed in deep space has been detected and used to study our galaxy,[32–34] as well as set limits on exotic positronium decay channels.[35] Several reviews exist dealing with positronium[36,37,7] and positronium theory.[38,39]

Considering the interest that has been generated by positronium over the past 50 years, and the relative ease with which it can be produced and studied, it is dismaying that there has been little published about undergraduate experiments involving positronium. Most students are very interested in the topic of antimatter, and are enthusiastic about studying the properties of such an exotic material as positronium. As far as can be determined, the only published experiments[40–44] for undergraduates involving positrons or positronium have to do with measuring the angular correlation of the two gamma rays produced in parapositronium decay. The purpose of this paper is to describe a simple apparatus that can be constructed out of commonly available off-the-shelf parts which will allow students to measure the decay rate of orthopositronium in gases as well as observe several other interesting effects.

II. QUALITATIVE THEORY OF POSITRONIUM FORMATION AND SUBSEQUENT DECAY

The formation of positronium in a gas can be understood qualitatively, especially for the case of monatomic gases, using what is known as the ''Ore Gap'' theory.[45,46] In this model, positrons entering a gas are slowed by collisions with gas molecules until they reach an energy low enough that they can capture an atomic electron. Clearly, if the energy of the positronium after formation E_{ps} is much larger than the energy required to disassociate positronium I_{ps} (about 6.8 eV), any positronium that forms will quickly dissociate, so for positronium to form, $E_{ps}<I_{ps}$. This restriction on the positronium energy is equivalent to a restriction on the maxi-

mum energy of the slowed-down positron, since E_{ps} is related to E_p, the kinetic energy of the incident positron after slowing, by conservation of energy:

$$E_{ps}=E_p-I_M+I_{ps}, \tag{2}$$

where I_M is the amount of energy required to separate the electron from the gas molecule (the ionization potential), and the final kinetic energy of the molecule is neglected. According to Eq. (2), therefore, $E_{ps}<I_{ps}$ implies $E_p<I_M$. There is also a minimum energy below which the positron is unable to capture an electron from the molecule, implying that for positronium to form, $E_p>I_M-I_{ps}$. This range of positron energies, $I_M>E_p>I_M-I_{ps}$, for which positronium may be formed in a gas is often called the ''Ore Gap.'' If the positrons are spread evenly in energy after slowing in the medium, one might expect the maximum fraction $f_{\max}$ of incident positrons which form positronium to be about

$$f_{\max}=\frac{I_M-(I_M-I_{ps})}{I_M}=\frac{I_{ps}}{I_M}, \tag{3}$$

which in the case of nitrogen is about $6.8\,\text{eV}/14.5\,\text{eV}=0.47$. Typically the fraction of positrons forming positronium is in the range of 25%–50%.[47] A more modern approach to positronium formation is the ''Spur'' theory,[47] in which the positron is bound coulombically to one of the ionization electrons in the ''spur,'' or path of the positron. This theory has yielded satisfactory results for liquids and insulating solids, but is less successful for polyatomic gases.

The amount of time it takes for the positron to slow down in the gas until it reaches an energy low enough to form positronium is typically only a few nanoseconds. Neglecting relativistic effects and assuming constant acceleration, this time can be estimated using $R=vt/2$, where R is the range of the positrons in the gas, and v is their velocity. For 0.15 MeV (0.63c) positrons the range in nitrogen gas at one atmosphere and room temperature is about 24 cm,[48] yielding a time of 2.5 ns. Since the vacuum half-life of orthopositronium is roughly 100 ns, the amount of time required for the positron to slow can be neglected.

Once the positrons have slowed until their energy is in the ''Ore Gap,'' there is a good chance that positronium will be formed. It will then decay according to the exponential decay law. The decay rate in a gaseous medium, however, is always larger than the vacuum decay rate, because of the possibility that the bound positron may annihilate with an atomic electron. For low gas densities, this effect is linear with the number density (and therefore the pressure) of the gas.[49,8] Typically, to measure the vacuum decay constant, experimenters must measure the decay constant at several gas pressures and extrapolate to zero.

Several processes can distort the shape of the decay curve. For example, it is possible for the positrons to continue to slow until their energy is below the ''Ore Gap.'' Once the energy of the positrons is low enough, they can only lose further energy by scattering elastically, and thus may take a relatively long time to reach thermal energies, after which they decay with a lifetime much longer than for orthopositronium. The decay spectrum therefore often exhibits a ''shoulder'' due to annihilation of these nonthermalized positrons. Depending on the gas, the annihilation of these positrons may tend to decrease the apparent measured decay constant. Since the thermalization time for positrons in polyatomic gases is much less than for monatomic gases, polyatomic gases exhibit this effect to a much smaller degree, or not at all.

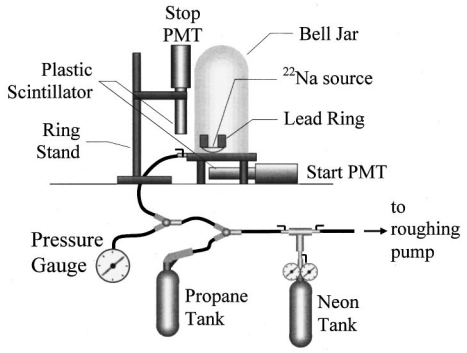

Fig. 1. A schematic diagram of the experimental apparatus. A 1.27 MeV gamma ray detected by the ''start'' scintillator indicates that a positron has been emitted into the gas in the bell jar. The positron may form orthopositronium, which decays into three gamma rays, one of which may be detected by the ''stop'' scintillator.

Spin-exchange can also affect the shape of the decay spectrum. Due to the fact that molecular oxygen has two unpaired spins, it very efficiently converts ortho- to parapositronium. The parapositronium then decays almost immediately, causing an apparent increase in the decay rate. This so-called ''pick-off'' rate has been measured to be about 35 μs^{-1}/atm for oxygen.[50,51] Thus, for an accurate measurement of the decay rate in a gas, one must be very careful to avoid contamination by atmospheric oxygen.

III. DESCRIPTION OF THE EXPERIMENT

The apparatus used to produce positronium and detect its decay is similar to that used in the original discovery of positronium.[52] Figure 1 is a schematic diagram of the apparatus. A bell jar contained a gas sample and a source of positronium. Plastic scintillator detectors were placed outside the bell jar to detect gamma rays that signaled the formation and decay of the positronium. The interval between the formation and decay of the positronium was digitized and stored in a multichannel analyzer.

The gas chamber was a large glass bell jar, 17 cm in diameter and 30 cm high, of the type normally used for classroom demonstrations. It is not necessary that it be glass; in fact, the less expensive bell jars made of plastic might work better because they would reduce gamma ray attenuation and increase the signal-to-noise ratio. Using silicone vacuum grease to form a seal with the iron base, the chamber was evacuated with a roughing pump down to a pressure of about 2 torr according to a mercury manometer. The chamber was then sealed and the pressure was found to increase about 2 torr per hour. It is important that this rate be as low as possible, since, as was discussed in Sec. II, oxygen entering the chamber will increase the decay constant. Several gases, including air, neon, and propane, could be introduced into the evacuated bell jar by a system of valves and rubber tubing. The neon we used was research grade, while the propane was the type sold at hardware stores as fuel for blowtorches. The pressure of the gas in the chamber was measured using an automotive fuel pump pressure gauge. Decay curves were measured for each of the gases at various pressures between about 380 and 760 torr. Higher pressures in-

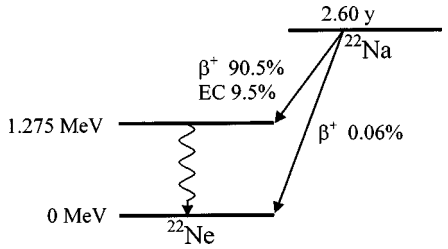

Fig. 2. The nuclear decay scheme for ^{22}Na. About 90.5% of the time, emission of a 1.275 MeV gamma ray signals the emission of a positron (see Ref. 54).

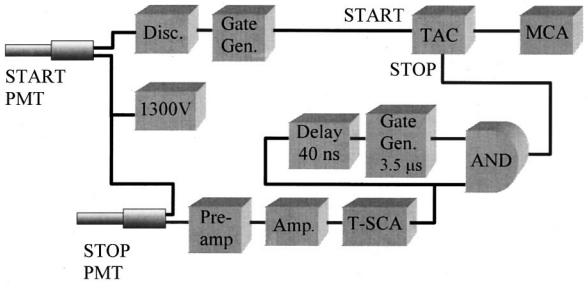

Fig. 3. A block diagram of the electronics. Pulses from the ''start'' and ''stop'' detectors are discriminated and then input to a TAC whose output is proportional therefore to the time between the formation and the decay of the positronium.

crease the rate of positronium formation because of the increased number density of gas molecules. The positronium lifetime, however, is slightly pressure dependent[8] so that higher pressures also increase the decay rate. For data acquisition runs longer than one day, for each gas, except obviously air, the chamber was reevacuated and refilled with gas every 24 h to minimize oxygen contamination.

Inside the bell jar was a positronium source constructed by evaporating 1 μC of ^{22}Na in a salt solution[53] onto a small glass dish. As shown in Fig. 2, ^{22}Na decays to the 1.27 MeV excited state of ^{22}Ne by the emission of positrons with a branching ratio of about 90.5%.[54] The endpoint energy of the emitted positrons is 0.546 MeV. The excited ^{22}Ne nucleus then decays with a half-life of 3.7 ps to the ground state by emitting a 1.27 MeV gamma ray. In this experiment, detection of a 1.27 MeV gamma ray indicated that a positron had been emitted. This positron may enter the gas, slow down, and form positronium. A lead ring with wall thickness of 15 mm and a length of 65 mm was used to keep gamma rays coming directly from the source from reaching the ''stop'' detector. A colinear detector arrangement was avoided so as to reduce the number of two-gamma annihilation background events.

The detectors were rods of plastic scintillator (Bicron BC-400) 5.1 cm in diameter and 15.2 cm long. The ''start'' detector was placed under the iron base to detect the 1.27 MeV gamma rays indicating the emission of a positron and subsequent possible formation of positronium. The ''stop'' detector was placed against the glass of the bell jar to detect the gamma rays (of energy 0.511 MeV or less) from the orthopositronium decay. Attached to each scintillator was a Thorn-EMI 9266KB04FL photomultiplier tube. The type of detector should not be critical as long as it is relatively fast. Sodium iodide detectors commonly used in undergraduate laboratories should also perform well.[55]

The signals from the detectors were processed by standard NIM electronics as shown in Fig. 3. The output from the ''start'' detector immediately entered a discriminator adjusted to produce a negative NIM logic pulse for gamma rays above the 0.511 MeV annihilation energy. This threshold was set by placing a ^{22}Na source directly on the detector and adjusting the discriminator threshold while examining the output of the phototube with an oscilloscope triggered on the discriminator output. A timing single channel analyzer (TSCA) could have been used instead of the discriminator, had one been available. The ''stop'' signal was amplified and a logic pulse was produced by a TSCA for pulses between about 0.1 and 0.7 MeV. These ''start'' and ''stop'' logic pulses controlled a time to amplitude converter (TAC), set to a 1 μs maximum timing interval, whose output was recorded and histogrammed by a Nucleus PCA-II multichannel analyzer (MCA) card in a PC-compatible computer. Since the ''start'' signal arrived much earlier than the ''stop'' signal, a gate generator was used to align the pulses. The ''start'' and ''stop'' rates were about 800 cps, while the coincidence rate, that is, the rate of events where a ''start'' pulse was followed within about 0.75 μs by a ''stop'' pulse, was only about 3 cps. The coincidence unit was used to disable the start input of the TAC for a period of 3.5 μs in order to correct for the internal reset time of the TAC at high count rates. Since the rates in this experiment were quite low, this part of the circuit had a minimal effect and could probably be eliminated.

The TAC was calibrated using a LeCroy 2323A gate generator to delay a pulse by a specified amount. The original pulse was used to start the TAC, while the delayed pulse stopped the conversion. The timing resolution of the system was measured by adjusting the TSCA on the ''stop'' detector to detect gamma rays of about 1 MeV. A ^{60}Co source was then used as a source of coincident gamma rays to trigger both detectors simultaneously. The FWHM spread in the coincidence peak was about 10 ns. In addition, the linearity of the TAC was checked by removing the two detectors about 1 m from each other, surrounding them with lead shielding, and placing a ^{60}Co source on each detector, aligned so that the pulses were totally uncorrelated. The resulting spectrum was found to be very flat.

IV. DISCUSSION OF EXPERIMENTAL RESULTS

Figure 4 is a plot of the time difference between the ''start'' and ''stop'' signals for neon (data collection time of 19 h) and air (data collection time of 6.4 h). In both cases there is a large peak around zero which is caused by the fast decay of parapositronium and by the annihilation of positrons in the gas and surrounding vessel. Following the prompt peak is a long tail due to the decay of orthopositronium. On the log scale shown in the figure, this exponential decay becomes a downward sloping linear function whose slope is the decay constant λ. The background events in these spectra are accidental coincidences, that is, they arise when the detectors trigger on random events within the 1 μs window of the TAC. Neon, since it is a monatomic gas, has a much longer thermalization time, as evidenced by the presence of a ''shoulder'' in the spectrum immediately following the large parapositronium peak at $t=0$. Air has an oxygen fraction of about 21%, and would therefore be expected to have a much larger decay constant due to ''pick-off.'' This is

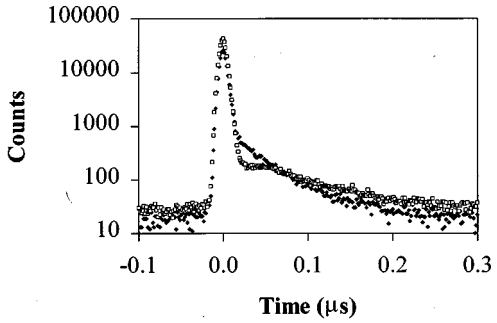

Fig. 4. A plot of the time difference between the ''start'' and ''stop'' detectors for air at one atmosphere (solid diamonds) and neon at about 0.5 atmosphere (open squares) in the bell jar.

indeed seen, in fact, for the spectrum in Fig. 4 the fitted decay constant is approximately 16 μs^{-1}, which would correspond to a pick-off rate of about 43 μs^{-1}/atm.

An exponential decay function was fit to each decay spectrum using the fitting code MINUIT.[56] The function had the form

$$N = Ae^{-\lambda t} + B, \tag{4}$$

where N is the decay rate for time bin t, A is a constant related to the formation rate of orthopositronium, B is the background accidental coincidence rate, and λ is the decay constant. The quality of a typical fit can be seen in Fig. 5, which is a plot of the decay spectrum after collecting events for about 4 days with one atmosphere of propane. One difficulty encountered when fitting this function to the measured spectrum is determining the starting time bin for the fit. For times less than a certain value, the parapositronium decay as well as thermalization effects can distort the exponential decay curve. Figure 6 shows the fitted value of λ for propane at one atmosphere as a function of the first time bin used in the fitting procedure. Clearly, after about the first 50 ns the value of λ becomes relatively constant at about 7.4 μs^{-1}. This is higher than the vacuum decay rate of $7.038\,236 \pm 0.000\,010\ \mu s^{-1}$ as calculated using QED[12,13] or the best measurements to date of $7.0514 \pm 0.0014\ \mu s^{-1}$ and $7.0482 \pm 0.0016\ \mu s^{-1}$,[8,9] most likely because of the pressure-dependent effects discussed in Sec. II. For comparison, Fig. 6 also shows the decay constant obtained by Westbrook *et al.*[8] for isobutane at 800 torr, which is slightly greater than our value for propane at 760 torr.

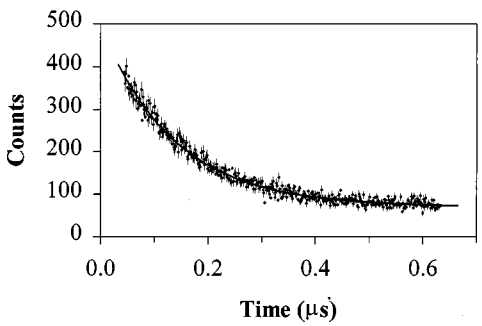

Fig. 5. A fit of an exponential decay plus flat background $Ae^{-\lambda t} + B$ (line) to the measured decay spectrum (points) for propane at one atmosphere for points after about 0.05 μs.

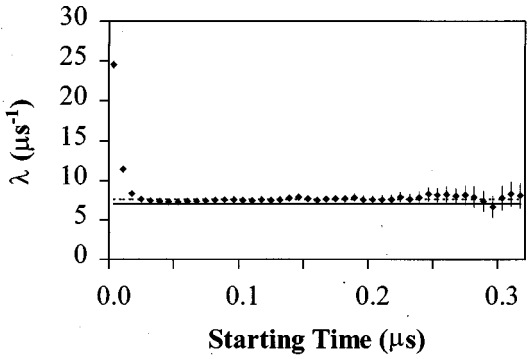

Fig. 6. A plot of the fitted value of the decay constant λ (points) as a function of the first time bin for which data were included in the fit. The best vacuum decay rate theoretical prediction of 7.038 μs^{-1} (Ref. 12) and experimental measurements of 7.051 and 7.048 μs^{-1} (Refs. 8 and 9) appear as one line at this scale (solid line). The decay rate for isobutane at 800 torr (dashed line) is 7.63 μs^{-1} (Ref. 8).

V. CONCLUSION

The decay of orthopositronium is currently of great interest because the measured decay constants do not agree with the predictions of QED, as well as for a host of other lesser reasons. An apparatus has been presented which will allow undergraduate students to measure this decay constant in different gases, as well as observe several effects which can distort the shape of the orthopositronium decay spectrum. The results obtained by this technique should be limited primarily by the purity of the gases used, the ability of the vacuum system to keep out atmospheric oxygen, and the data collection time.

ACKNOWLEDGMENTS

This material is based upon work supported by the National Science Foundation under Grant No. DUE-9550949 and by the M.J. Murdock Charitable Trust, Vancouver, WA.

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WHICH ARE THE RIGHT QUESTIONS?

The task of physics is not to answer a set of fixed questions about nature, such as deciding which particles are elementary. We do not know in advance what are the right questions to ask, and we often do not find out until we are close to an answer.

Steven Weinberg, ''The first elementary particle,'' Nature **386**, 213–215 (20 March 1997).