

Slow positrons in gases

While they share many of the properties of negative electrons, positrons exhibit other phenomena—such as annihilation or positronium formation in collisions with atoms or molecules—that are all their own.

Sir Harrie Massey

The study of the behavior of slow positrons in gases has recently become a very lively field. New fast counting techniques are making it possible to enlarge much further the base already established in earlier work, as well as bringing into practical possibility measurements that previously seemed unattainable. (Typical of the recent experimental systems is the apparatus shown in the photograph, figure 1, and diagrammatically in figure 2.) For collisions with helium atoms at energies below the positronium formation threshold the position appears very well established, and the prospect is now opened for interpreting, in more detail, positron collisions with more complex systems.

The experimental verification of the existence of positrons by Carl Anderson,¹ following the theoretical predictions of P. A. M. Dirac² and of J. Robert Oppenheimer,³ was a major event in physics. Of particular importance was the confirmation of the concept of antiparticles, from which followed the possibility of annihilation of positrons in collisions with electrons. While these discoveries were of very fundamental significance, the existence of positrons—

which have now become part of the stock-in-trade of experimental physics—opens up possibilities for atomic and solid-state physics that are being exploited with considerable success.

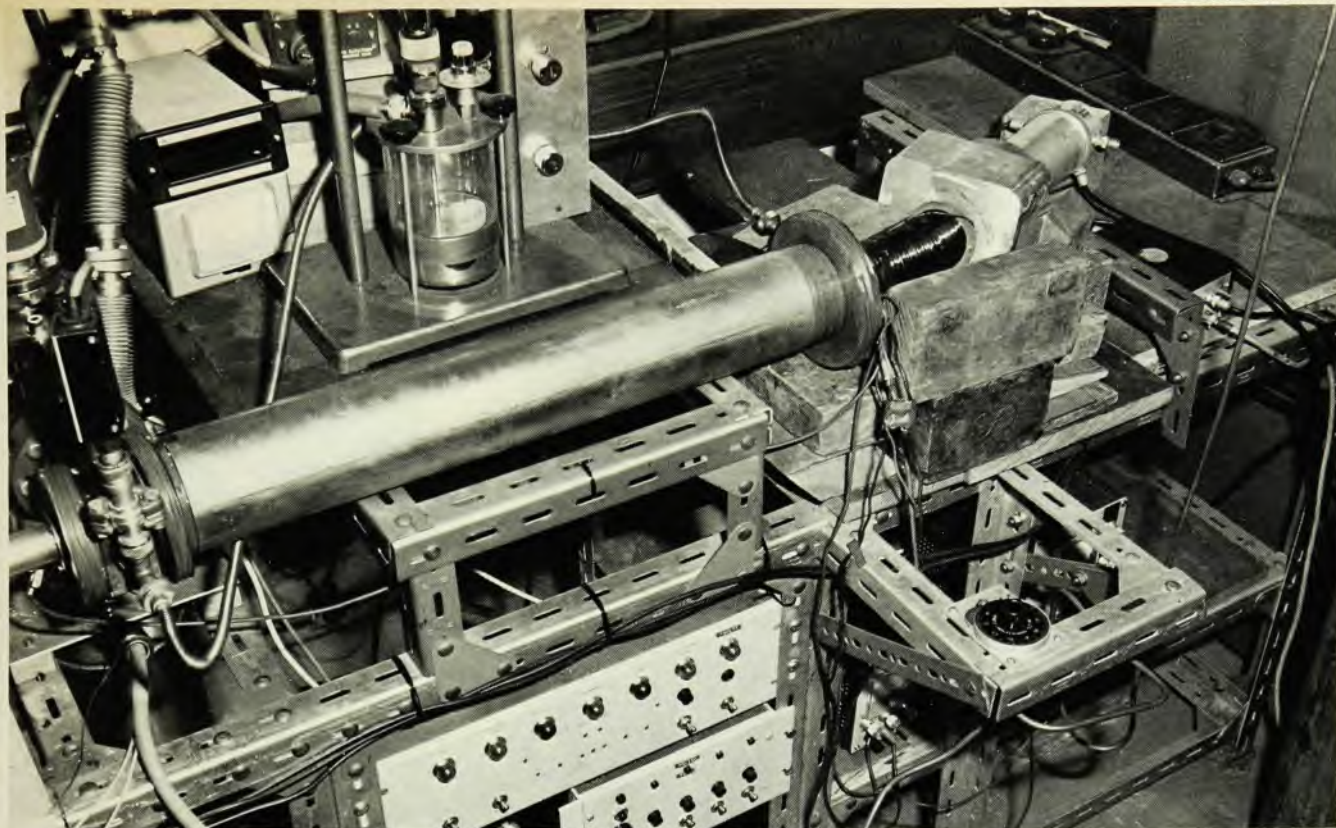
Apart from the simplest cases it is still only possible to develop approximate theories for the scattering of slow electrons by atoms and molecules. A very severe test of such theories is to apply them to the corresponding case of scattering of slow positrons by merely reversing the sign of the charge. Such reversal may make a very marked difference in the convergence of the approximation used, changing a series of terms of one sign into an alternating series in which successive terms tend to cancel, for example. In addition new phenomena may be studied. Thus, unlike electrons, slow positrons may suffer annihilation in collisions with atoms and molecules. The prediction of the relevant cross sections provides a further very severe test (which has no analogue for electrons) of any approximate theory.

A positron and electron can form a bound system, positronium (Ps), with allowed energies (apart from fine-structure effects) one half of the corresponding values for the hydrogen atom. The study of the formation and properties of positronium provides, on the one hand, further information about the validity of quantum electrodynamics and, on

the other, it leads to fresh ideas about chemical reactions in which the active positive particle is of very small mass.

At first sight it would seem difficult to carry out quantitative measurements for slow positrons in gases, because we have no sources of such positrons comparable in strength with those for slow electrons. Furthermore, in gases at a pressure of an atmosphere or so, the lifetime of a positron against annihilation with an electron is only of the order of a few nanoseconds. Nevertheless, because of the advanced state of development of coincidence-counting techniques with high time resolution, advantage may be taken of the gamma radiation produced in positron annihilation to detect and locate in time the decay of individual positrons. By sophisticated application of these techniques we now possess a considerable amount of data on cross sections for collision phenomena involving slow positrons and positronium that are of sufficient accuracy to make severe demands on theory. Indeed, in the last few years, the equivalent of the classical Ramsauer experiment for electrons has been carried out for positrons, yielding results of much interest and importance. Precision measurements have even been made⁴ of the fine-structure separations in the ground 1s and excited 2p states of positronium. We shall, however, confine ourselves in this arti-

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Time-of-flight apparatus for measuring the total cross section of positrons in gases. In this photograph of the equipment in use at University College London the main cylindrical flight compartment is in the

foreground with the source at the left end. On the right is the curved portion of the path, followed by the detector and photomultiplier. Part of the lead shielding is removed in this photograph. Figure 1

cle to a discussion of the latest experiments, together with the relevant theory, concerned with the basic collision phenomena. We will begin by recalling some of the main features of positron annihilation and of positronium, but refer the reader to Chapter 26 of *Electronic and Ionic Impact Phenomena* by H. S. W. Massey, E. H. S. Burhop and H. B. Gilbody, 2nd edition, Vol. 5, for details of earlier work.

Annihilation of free positrons

According to relativistic quantum theory a positron and an electron, with opposite spins, may annihilate each other on collision to produce two quanta of gamma radiation. If the mean concentration of these electrons at the position of the positron is $n_s \text{ cm}^{-3}$, the chance of annihilation per second is given by

$$\lambda_s = 4\pi r_0^2 c n_s \quad (1)$$

where c is the velocity of light and r_0 , the so-called radius of the free electron is equal to e^2/mc^2 where e and m are respectively the electron charge and mass. On the other hand, if the positron and electron have parallel spins this mode of annihilation is not possible. Instead, the fastest annihilation process allowed is one involving emission of three gamma quanta, and it is about 400 times slower than for the case in which the spins are antiparallel.

If n is the total number of electrons present at the position of the positron, $n_s = n/4$ so that the total chance of annihilation per second is

$$\lambda = \frac{1}{4} \lambda_s = \pi r_0^2 c n \quad (2)$$

We may specify the annihilation rate in a gas in terms of an effective annihilation cross section Q_a , where, in terms of the positron velocity v ,

$$Q_a = \pi r_0^2 c Z_a / v \quad (3)$$

Z_a being the effective number of annihilation in electrons per atom or molecule in the gas.

The measurement of Q_a as a function of v for different gases would provide valuable information about positron-atom interactions that has no counterpart for electrons. In fact, all that can be done is to measure a mean annihilation cross section $\langle Q_a \rangle$, for positrons possessing a distribution of velocities, as a function of the root-mean-square velocity—but this still provides data of much value.

Positronium

Because the relative motion of a positron and electron is the same as that of a particle of mass $\frac{1}{2} m$ moving under the same interaction due to a fixed center of force, the allowed energies for positronium when no allowance is made for fine structure are one half the corre-

sponding values that arise for atomic hydrogen.

There is a fine structure separation between the singlet and corresponding triplet states, but the most significant difference between them is in the mean lifetime before mutual annihilation of electron and positron occurs. As in the free positron case, the single S states may decay through emission of two gamma quanta. For the ground singlet state, referred to as "para Ps," the lifetime is given by

$$\tau_p = 1.25 \times 10^{-10} \text{ sec} \quad (4)$$

This is to be contrasted with the much longer mean life τ_0 of the ground triplet state (ortho Ps), which decays through emission of three gamma quanta. Thus

$$\tau_0 = 1.41 \times 10^{-7} \text{ sec} \quad (5)$$

which is long enough for the behavior of ortho Ps in gases to be studied experimentally. Any collision that converts ortho Ps to para Ps will lead very quickly to annihilation, and this property makes practicable the measurement of rates of processes that lead to the ortho-para conversion.

Life history of a positron in a gas

Positrons are produced with relatively high energies of some keV, usually from a radioactive source such as Na^{22} . They slow down rapidly in a gas through inelastic collisions in which ex-

citation or ionization of a gas atom occurs. At these energies there is little difference between the inelastic cross sections for electron and for positron impact. For either particle at an energy of around 100 eV the ionization cross section is about 10^{-16} cm^2 ; compare this with the cross section for annihilation which, according to equation 3, is $1.2 Z_a \times 10^{-23} \text{ cm}^2$. Because Z_a is of the order of the number of electrons per atom it is clear that the energy of the positrons will be reduced to a value below the ionization energy E_i of the atoms before they will have any appreciable chance of suffering annihilation. Once the positron energy has been reduced below the threshold energy for excitation, E_{ex} , which is not much less than E_i , further moderation of positron energy can only occur in elastic collisions with the gas atoms, of mass M . In such collisions a positron loses a fraction $2m/M$ of its initial energy and the cross section to be compared with Q_a is now $2mQ_d/M$, where Q_d is the momentum-transfer cross section for positron-atom collisions and is of the order of atomic dimensions. For 1 eV positrons in argon, taking $Q_d = 10^{-15} \text{ cm}^2$, we find that

$$2mQ_d/M = 2.5 \times 10^{-20} \text{ cm}^2$$

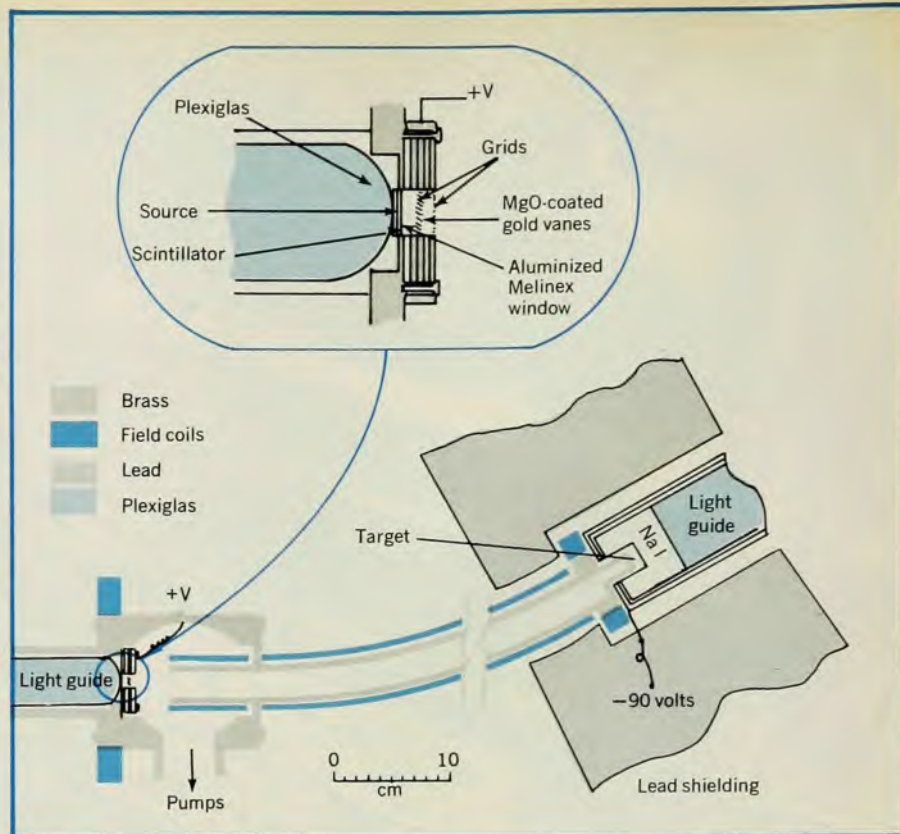
$$Q_a = 1.2 Z_a \times 10^{-22} \text{ cm}^2$$

Even though the cross sections are now becoming comparable it is to be expected that a considerable fraction of positrons will come to thermal equilibrium in the gas before annihilation. This will be even more probable in polyatomic gases, in which energy moderation below the electronic excitation threshold can occur through excitation of vibration and rotation.

In an analysis of this kind we must also allow for the possibility of positronium formation. As Aadne Öre⁵ pointed out, it will largely occur in a comparatively small positron energy range known as the "Öre gap." Thus, to capture an electron, a positron must have an initial kinetic energy greater than $E_i - E_{ps}$ where E_{ps} is the binding energy, 6.8 eV, of the ground state of positronium. However, if the positrons possess an initial kinetic energy greater than E_i , the positronium atom will be formed with a kinetic energy greater than E_{ps} and so will rapidly break up in further collisions with gas atoms. Furthermore, positrons with energy E such that $E_i > E > E_{ex}$ will be likely to suffer inelastic collisions, which will degrade their energy below that required for Ps formation. We can therefore say that, to a good approximation, positronium will only be produced permanently by positrons with energies in the range

$$E_{ex} > E > E_i - E_{ps}$$

—the so-called Öre gap. With the assumption that the energy distribution



Schematic drawing of the positron time-of-flight apparatus shown also in the photographs of figure 1 and on the cover of this issue. The detail shows the source region. Figure 2

of the positrons after the last ionizing collision is roughly uniform, we find that the fraction ϕ of positrons forming positronium satisfies the inequality

$$\frac{E_{ex} - (E_i - E_{ps})}{E_{ex}} < \phi < \frac{E_i - (E_i - E_{ps})}{E_i} = \frac{E_{ps}}{E_i} \quad (6)$$

For atomic gases ϕ can be expected to be a significant fraction. The situation is less clear for molecular gases, because of energy loss through excitation of vibration and rotation. In many cases, however, these latter processes occur so infrequently that equation 6 applies quite well with E_{ex} taken as the excitation energy of the first excited electronic state.

Slow positron collisions

Consider a beam of positrons of uniform velocity v passing through a gas containing N atoms per cm^3 . In passing a small distance δx through the gas, a fraction δf of the beam will be lost in collisions with the gas atoms, either through deflection or energy loss or both. The fraction δf is given by

$$\delta f = NQ_t(v)\delta x \quad (7)$$

where $Q_t(v)$ is the total cross section of a gas atom for collision with positrons of velocity v . At positron energies less than the excitation threshold for the gas

atoms, Q_t will be equal to the total elastic cross section Q_{el} . This may be written in the form

$$Q_{el} = 2\pi \int_0^\pi I_{el}(\theta) \sin \theta d\theta \quad (8)$$

where $I_{el}(\theta)d\omega/Q_{el}$ is the probability that, in an elastic collision, the positron will be deflected into a direction within the solid angle $d\omega$ making an angle θ with the initial direction of motion. $I_{el}(\theta)d\omega$ is usually referred to as the differential elastic cross section.

Carl Ramsauer, in his classic experiments⁶ with the slow electrons, measured Q_t as a function of v by almost direct use of the relation in equation 7. However, for positrons, the problem is much more difficult. This is primarily because of the difficulty of producing a primary beam of low-velocity positrons that is sufficiently well defined geometrically as well as being reasonably homogeneous in energy. Even with particle-counting techniques the beam intensity that can be obtained is so low that contributions to the measured signals from background effects may easily dominate. Nevertheless, by a combination of good luck in obtaining a relatively strong source of slow positrons and of experience in the introduction of elaborate methods for removing random background signals, total cross sections have been measured over a positron energy range from 2.0 eV to a few hundred eV with accuracy not much less than in

Ramsauer's initial experiments with electrons.

The momentum-transfer cross section, which is the significant cross section for calculating rates of energy loss through elastic collisions, is given in terms of $I_{el}(\theta)$ by

$$Q_d =$$

$$2\pi \int_0^\pi (1 - \cos \theta) I_{el}(\theta) \sin \theta d\theta \quad (9)$$

Information about Q_d , as distinct from Q_t , comes from experiments on the time spectrum of annihilation events of positrons in gases and will be described later. We first proceed to describe the experiments that yielded values for Q_t and their relation to theory.

Total cross section measurements

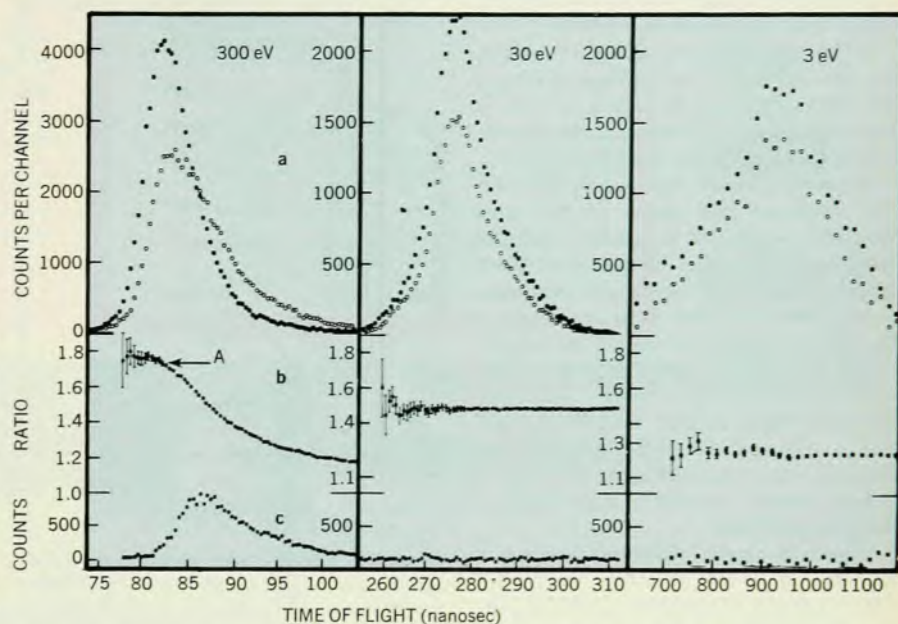
In principle the total cross section measurements are made by a time-of-flight method, the time elapsing between emission of a positron from a source and its detection after passage along a prescribed path being measured for a large number of positrons. With no scattering gas present the resulting spectrum is determined by the velocity distribution of the positrons issuing from the source. Introduction of gas will change the spectrum, because positrons undergoing collisions in the gas will suffer changes in the direction or magnitude of their velocity or both. By analyzing the spectra with and without the presence of the gas one can obtain the total cross section defined by equation 7. The simplest situation is one in which only elastic collisions are possible, and in such collisions the positrons are deflected through such large angles that they never reach the detector. In such a case the spectrum with gas present will be similar to that when it is absent, but the peak intensity for a given total initial flux will be reduced simply by the fraction δf of equation 7 with δx given by t/v , where t is the time of flight at the peak. When either small-angle deflections or inelastic collisions (or both) occur, the situation is more complicated. We will defer further consideration of this matter until after we have discussed the form of the actual results obtained.

The first preliminary measurements of a total cross section for slow positrons of fairly well-defined energy were made by D. G. Costello, D. E. Groce, D. F. Herring and J. William McGowan⁷ for helium. These measurements were only possible because the slow positron source was of a novel type. Karl Canter, Paul Coleman, Ceiri Griffith and George Heyland⁸ found that this source could be modified so as to provide a usable flux of positrons of quite well-defined energy for time-of-flight experiments. Since then a number of measurements of total cross sections have

been carried out for positrons in rare gases^{9,10} and in certain molecular gases.¹¹

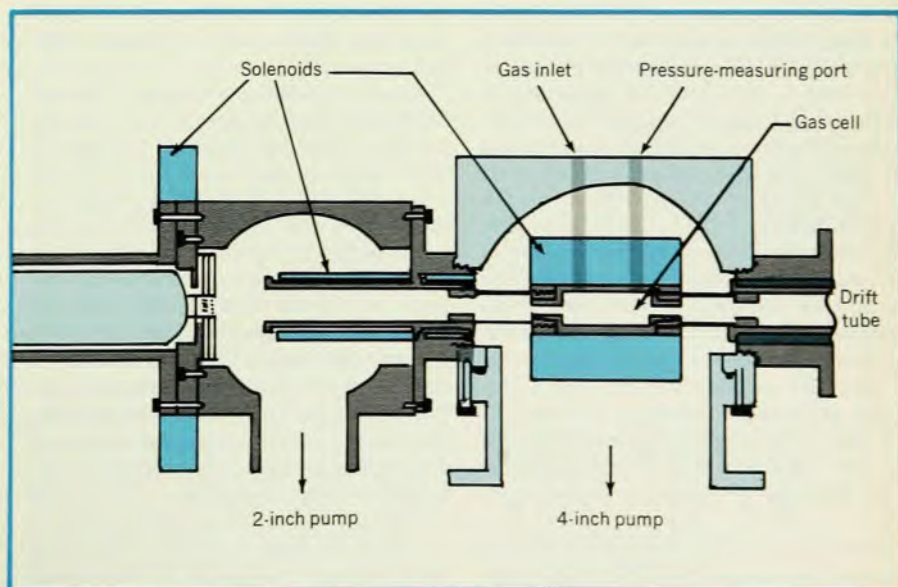
Figures 1 and 2 illustrate the typical arrangement used in these experiments. Positrons from a Na^{22} radioactive source are detected in a thin plastic scintillator, which provides a "start" pulse to the timing sequence. They then pass through a thin aluminized Melinex window followed by a thin aluminum foil. The issuing positrons then fall on a system of gold vanes, as in a

photomultiplier, coated with a thin layer of magnesium oxide. The emergent positrons have energies between 1.5 and 0.5 eV and are accelerated to the required energy by application of a dc potential. They then enter the time-of-flight tube that consists of a straight section 70 cm long followed by a section 15 cm long curved in an arc of 25 cm radius. By means of a suitable magnetic field they are confined to paths close to the axis throughout the full flight path and are detected



Spectra observed in helium for three positron energies, 300, 30 and 3 eV. Top curves (a) show time-of-flight spectra, without gas present (black dots) and in the presence of helium (open circles). Ratios of the count rate with and without gas present are plotted (curves b), and the bottom curves (c) show the spectra of positrons either inelastically scattered or scattered through angles less than 90°; these curves are obtained by subtracting the vacuum spectrum (after scaling by an attenuation factor as described in the text) from the spectrum obtained with gas present in the scattering chamber.

Figure 3



Modified time-of-flight apparatus in which about 80% of the scattering is confined to a limited scattering region (about 8 cm) to gain improved resolution.

Figure 4

through the annihilation radiation produced in an aluminum foil, which activates a sodium-iodide counter to give the "stop" pulse. Roughly 1 in 10^5 of the positrons emitted from the source enter the flight tube as the slow positron "beam." Small as this ratio may be, it is much greater than that obtained previously and is large enough to make the experiments practicable. Even so the total counting times required to give adequate statistics are still very long.

The time-of-flight spectrum is obtained with a time-to-amplitude converter and multichannel analyzer.

Although the slow positron source has proved to be very effective we are far from understanding how or why it works as it does. Without it the experiments could not have been carried out.

We have already referred to the relation between the shape of the time spectrum when gas is present and the angular distribution of scattered positrons. With the longitudinal magnetic field present all positrons scattered in the forward direction should eventually reach the detector at the end of the flight path—only those scattered through angles greater than 90 deg will fail to do so. It might be expected therefore that the spectrum when gas is present would exhibit a long "tail" of delayed positrons.

Figure 3 shows observed spectra in helium for three positron energies.¹⁰ The situation is simplest at 30 eV, the spectrum being of the same shape with and without gas present. The absence of a "tail" in the former case implies that the scattering is very largely in the backward direction. Under these circumstances the nearly constant ratio of the signals, with and without gas, should give a reliable measure of the attenuation factor of equation 7.

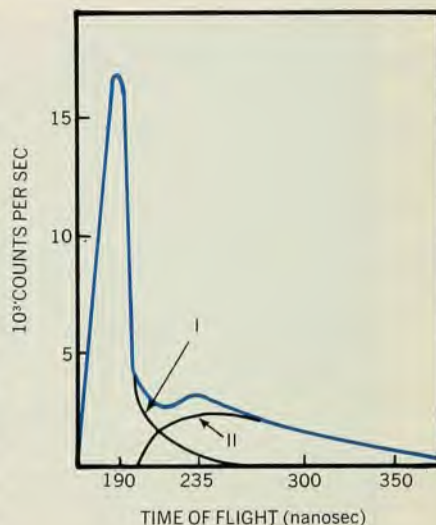
At 300 eV a marked "tail" is present at long flight times due to positrons scattered in the forward direction. In this case $1 - \delta f$ may be taken as the ratio of the signals on the short-time side of the peak, which is independent of flight time within experimental error.

The shape of the spectrum at the lowest energy, 3 eV, is likely to depend markedly on the energy distribution of the positrons leaving the source as well as on the differential scattering cross section. Because of this effect, results at these energies are less reliable.

(We will see later that the theory predicts, for energies between 4 eV and 11 eV, that most of the elastic scattering is in the backward direction, consistent with the type of spectrum shown at 30 eV.)

Apart from its importance in determining the way in which the total cross section is obtained it is clear that additional information about the nature of the scattering process can be derived

from the shape of the time-of-flight spectrum. To exploit these possibilities further, Coleman, Griffith, Heyland and T. L. Killeen¹² are now using a modified time-of-flight apparatus in which about 80% of the scattering is confined to a short section (about 8 cm) of the flight path. Figure 4 illustrates the arrangement of the scattering chamber in their equipment. The chamber, 80 mm long, is inserted directly after the source assembly. Positrons enter and leave the chamber through



Smoothed time-of-flight spectrum for 61-eV positrons in helium obtained with the apparatus of figure 4. Curve I is the extension of the spectrum of unscattered positrons obtained by multiplying the vacuum spectrum by the factor $(1 - \delta f)$. Curve II, the difference between I and the gas spectrum, represents inelastically scattered positrons and forward elastically scattered positrons. Figure 5

cylindrical apertures 6 mm in diameter and 20 mm long. Gas admitted into the chamber leaks out through the apertures and is pumped by a 4-inch diffusion pump.

Figure 5 shows a typical time-of-flight spectrum observed with this apparatus in helium for 61-eV positrons.¹² With the improved resolution obtained a second peak is observed at a time-of-flight from the scattering section that corresponds to positrons of energy 31 ± 1 eV. It appears very probable that the peak is due to inelastically scattered positrons that have lost about 30 eV in a single collision. The contribution to the spectrum from unscattered positrons may be obtained by subtracting the spectrum observed in the absence of gas multiplied by $1 - \delta f$ where δf is obtained as described above. When this is done the residual is as shown in figure 5. This includes positrons that have been scattered elastically in the forward direction as well as inelastically scattered positrons. It is expected that, with still further improvements in tech-

nique, it will be possible to separate these two contributions and perhaps even distinguish between ionizing collisions and those that have involved excitation of discrete levels. The early results shown in figure 5 indicate that the sum of the cross sections for forward elastic scattering and for inelastic collisions is about $0.6 \pi a_0^2$ for 61 eV positrons.

Results of measurements

Figure 6a shows the observed total cross sections¹⁰ for the rare gases as functions of the positron energy. For comparison, figure 6b shows corresponding results for electron collisions.

In all cases the positron cross sections are falling with decreasing energy at the lowest observable energy, raising the possibility that a Ramsauer-Townsend minimum, such as is found for electrons in argon, krypton and xenon, occurs at still lower energies. There is strong additional evidence, to be discussed below, that this is indeed the case of helium. From quite different arguments it appears very probable that it is also true for argon.

At first sight it might seem remarkable that a Ramsauer-Townsend effect could occur for positrons. In general terms it arises when the incident particle is acted on by an attractive field, which at some low energy so contracts the wavelength of incident particles with zero angular momentum about the scattering center (the s waves), that an integral number of additional wavelengths is introduced. No phase shift and hence no scattering will be observed at infinity.

It is true that scattering of particles with non-zero angular momentum can occur, but at sufficiently small energies, this will be very small; therefore the total cross section will also be very small, even if non-zero. If the scattering field is repulsive, the incident wavelength is increased by the field, but an integral number of wavelengths cannot be eliminated from the s waves except at such incident energies that the contributions from particles of high angular momentum is not small. No minimum is therefore expected in the cross section.

For electrons the mean interaction with an undistorted atom is attractive, whereas for positrons it is repulsive. On this basis the observed behavior of the cross sections appears strange. However, a slowly moving charged particle will polarize the atom with which it is interacting. This introduces a long-range attractive interaction, independent of the sign of the charge, which has the form $-\frac{1}{2}\alpha e^2/r^4$ at large separation r , where α is the polarizability of the atom. At low energies this is the dominant interaction, the same for both electrons and positrons. Under these cir-

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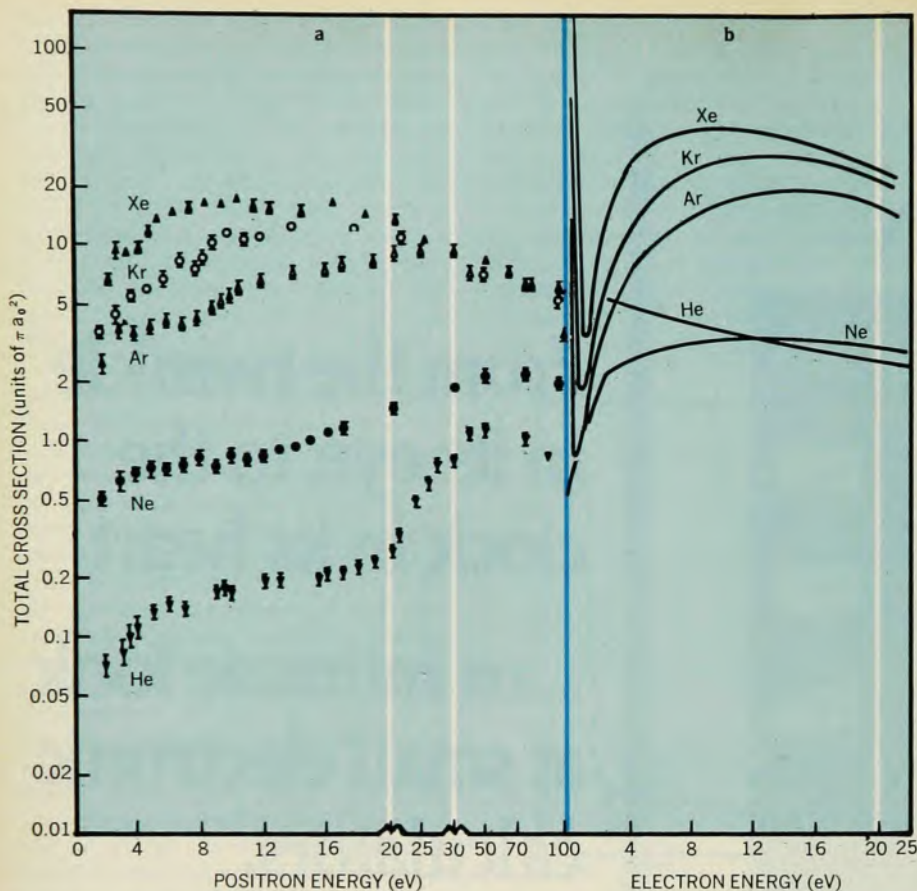
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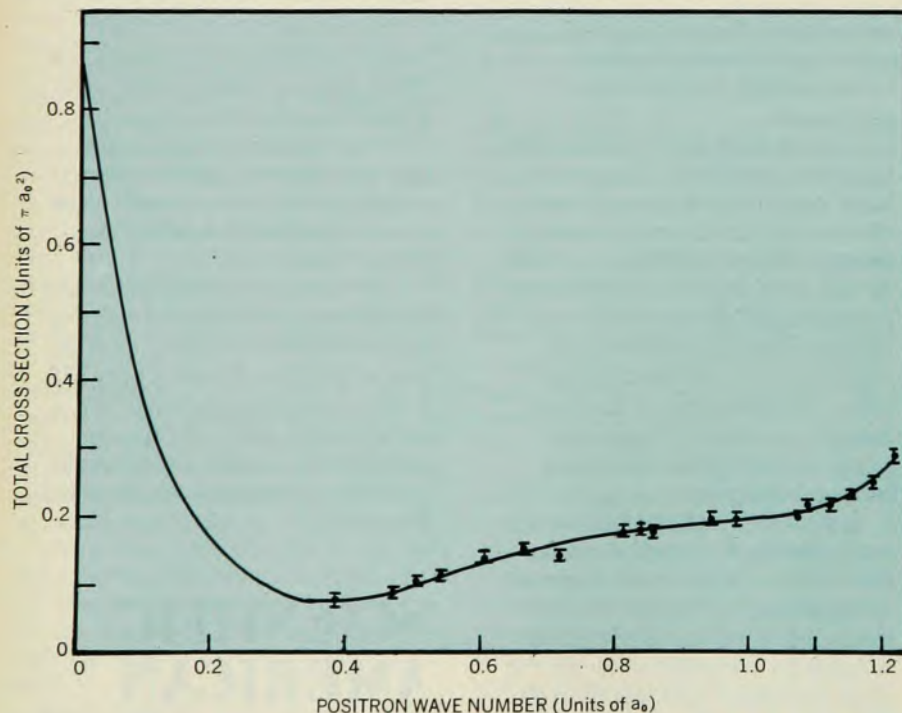
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Positrons and electrons compared. Curves (a) on the left are total cross sections of the rare gases for collisions with slow positrons, as measured by Coleman, Griffith, Heyland and Killeen. On the right (curves b) are shown for comparison the corresponding total cross sections for collisions with slow electrons. (The factor a_0^2 in the cross-section unit is the square of the first Bohr orbit in hydrogen, $2.8 \times 10^{-17} \text{ cm}^2$. Note the changes in abscissa scales indicated by the three vertical white lines.)

Figure 6



Cross sections for positrons in helium plotted as a function of positron wavenumber k . The solid line is the calculation discussed in the text, and the points are observations by Coleman, Griffith, Heyland and Killeen. (If k is the wavenumber measured in units of a_0 , the positron energy is $13.5 k^2 \text{ eV}$.)

Figure 7

cumstances there is no difficulty in understanding the occurrence of a Ramsauer-Townsend effect in slow positron collisions with atoms.

Theoretical analysis of the observed results for helium can be carried out in considerable detail at energies below the threshold for positronium formation. At these energies Q_t is equal to the elastic cross section Q_{el} which is given in terms of the phase shifts η_l for scattering of particles of velocity v and mass m with quantized angular momenta by

$$Q_{el} = (4\pi/k^2) \sum_{l=0}^{\infty} (2l+1) \sin^2 \eta_l \quad (10)$$

where k is the wave number $mv/\hbar$. As described qualitatively above, at low energies the η_l are all small for $l \neq 0$ and converge rapidly as l increases. J. W. Humberston and R. I. Campeanu have calculated η_0^{13} and η_1^{14} , using the Kohn variational method with trial wave functions for the combined system (positron + atom) that depend explicitly on the distances between the positron and the atomic electrons. In this way full allowance is made for the important correlation effects. The variation of Q_{el} with positron wave number k , calculated with these phases together with a less accurate but quite good approximation for η_2 , is shown in figure 7 in comparison with the observed data. The agreement is excellent and there appears little doubt that the theory gives accurate results over the energy range in which comparison is possible. Furthermore, as we will see, it also gives very good results for the effective number of annihilation electrons. It may therefore be confidently expected to be equally accurate at lower energies, providing strong evidence for the existence of a rather shallow minimum near $ka_0 = 0.38$ (1.9 eV).

If we know the phase shifts η_l , we can calculate the angular distribution of scattered positrons without difficulty. Figure 8 shows the calculated angular distributions per unit angle for positrons with energies between 2 eV and 11 eV. Note that over this range the scattering is mainly backward, which is consistent with the absence of a "tail" in the observed time-of-flight spectra.

The relatively rapid rise of the total cross section in helium above the positronium threshold to a maximum at a positron energy near 50 eV is quite striking. Analysis into the three separate contributions from elastic scattering, positronium formation and inelastic scattering involving excitation and ionization would be very interesting. If the relation of the cross sections for inelastic scattering to the corresponding ones for electron impact could be determined quantitatively, valuable evidence would be afforded about the relative importance of the different factors that determine the inelastic scattering of

electrons as well as positrons. This is the aim of further experiments, with improved resolution, on the shape of time-of-flight spectra as described earlier.

Annihilation-time spectra

So far we have been describing experiments that yield quantitative information on positron scattering cross sections. Quantitative information about annihilation cross sections may be obtained from experiments in which the rate of annihilation of positrons in a gas at a suitable pressure is measured as a function of the elapsed time t since emission from the source. Historically, experiments of this kind were the first to be carried out, and for some years they were the most effective means of obtaining information not only about annihilation but also momentum-transfer cross sections. (See Chapter 26 of *Electronic and Ionic Impact Phenomena* by Massey, Burhop and Gilbody, 2nd edition, Vol. 5 for an account of this work.) Recently the measurement technique has been improved to yield results of much higher accuracy. At the same time the new quantitative data available on total cross sections makes interpretation of the annihilation-time spectra more definite and reliable.

The general shape of an annihilation time spectrum is illustrated in figure 9. At very short time there is a sharp peak known as the "prompt" peak due to positrons annihilating in the walls of the experimental gas chamber, in the

source and via para-positronium production in the gas. This peak is followed by a gradually changing region known as the "shoulder," which persists while the positrons are slowing down (due to collisions with gas atoms) until they come to thermal equilibrium. With molecular gases the shoulder is much briefer, because of the increased rate of energy loss by excitation of inner molecular motion.

Once thermal equilibrium is reached the free positrons decay in collisions with the gas atoms at a rate λ_1 proportional to the gas density. This is given by

$$\lambda_1 = \pi n \langle Z_a(T) \rangle r_0^2 c \quad (11)$$

(see also equation 3) where n is the number of gas atoms per unit volume. $\langle Z_a(T) \rangle$ is the mean number of annihilation electrons per atom at the temperature T .

In addition to the free positrons there will also be present a number of ortho-positronium atoms which have sufficiently long lives to provide a significant proportion of annihilation events. The rate λ_2 at which the ortho-positronium atoms decay with consequent positron annihilation can be written

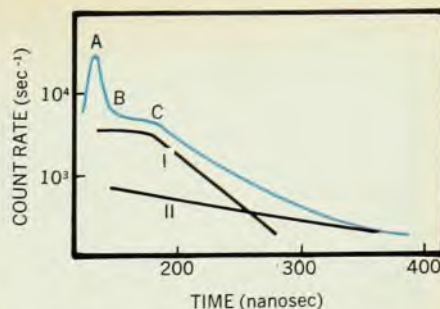
$$\lambda_2 = \frac{1}{\tau_0} + n \langle Q_{qv} \rangle \quad (12)$$

where τ_0 is the lifetime of free ortho Ps and $\langle Q_{qv} \rangle$ is the mean value of the product of the ortho Ps velocity v and the so-called "quenching" cross section Q_q . This is the cross section for any collision process involving ortho Ps that leads to positron annihilation. For example, the positron in the ortho Ps may annihilate with an atomic electron—this effect is known as "pick-off" quenching. Again, in an atomic collision an electron in the atom with spin opposite to that of the electron in ortho Ps may exchange places with it, so converting the ortho Ps to para Ps, which annihilates rapidly. It is also possible for a chemical reaction to occur, producing a compound involving ortho Ps in which the electron density and hence the annihilation rate is increased.

As a result of the annihilation of thermalized positrons and of ortho Ps the annihilation time spectrum beyond the shoulder is a combination of two exponential decay curves of the form

$$ae^{-\lambda_1 t} + be^{-\lambda_2 t} \quad (13)$$

with, in general, $\lambda_1 > \lambda_2$. If the two components can be separately determined the mean number of annihilation electrons for thermalized positrons $\langle Z_a(T) \rangle$ may be obtained and, from λ_2 , the lifetime τ_0 of free ortho Ps as well as the mean value of Q_{qv} . An important, necessary (but not sufficient) check on the validity of the analysis is that λ_1 should be proportional to the gas pressure and λ_2 , while varying linearly with



Annihilation time spectrum. The "prompt peak" is lettered "A," and "BC" is the gradually changing "shoulder region." Curve I is the contribution from free positron annihilation; curve II is the contribution from ortho-positronium annihilation. Figure 9

gas pressure should tend to a constant value in the limit of zero pressure.

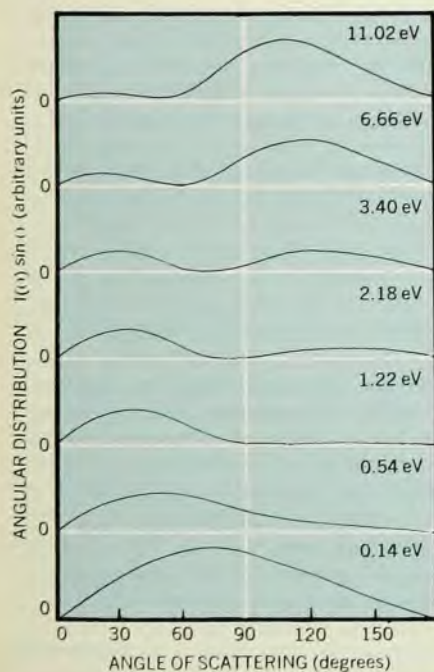
Experimental method

To effect an accurate separation of the decay curve into two exponentials a high statistical accuracy is required. Coleman, Griffith, Heyland and Killeen¹⁵ have developed a simple apparatus with a fast rate of data accumulation so that ageing and thermal drift of the electronics is not serious. This has only been effective because, at the same time, they have introduced a sophisticated procedure for elimination of background signals.

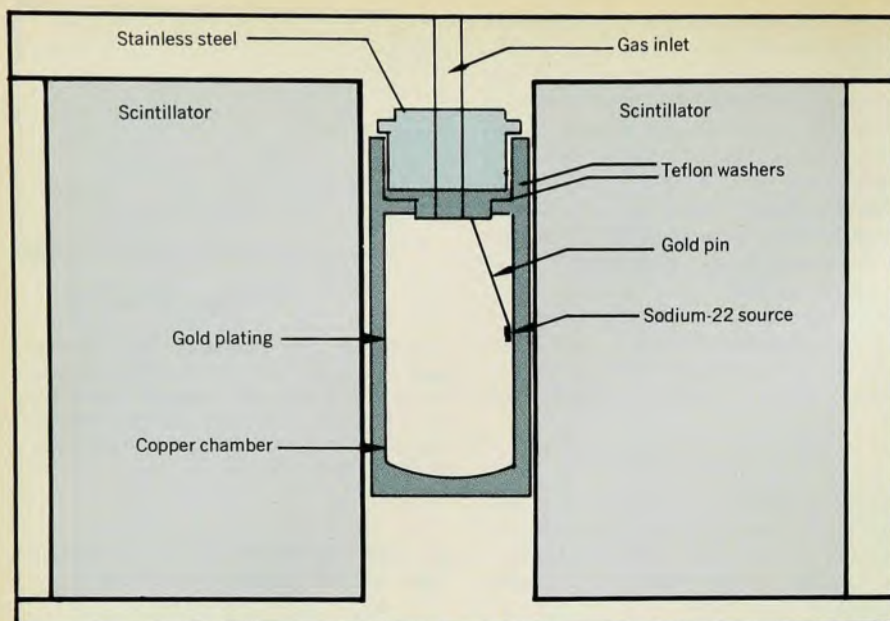
Figure 10 illustrates the general arrangement of their equipment. Gas at pressures up to 60 atmospheres is contained in a small pressure vessel machined from a drawn copper rod, the inner surface being electroplated with gold. Positrons are emitted from a Na²² source of 5 Ci strength deposited on a thin gold spatula mounted in contact with the wall of the vessel. The "start" pulse detector is a large-diameter plastic scintillator set to detect the 1.28-MeV gamma ray emitted with negligible delay after the positron. A similar scintillator mounted opposite the first provides the "stop" pulses. Spectra with a resolution of 1.5 nanoseconds are obtained and the coincidence rate is 1200 events per second.

The gold plating and gold backing of the source increase the backscattering of positrons into the gas and help to maximize the proportion of annihilation occurring there.

Figure 11 shows results obtained for helium at a density of 43.6 amagat at room temperature. [The density of an atomic gas is 1 amagat when 1 cm³ of the gas contains 2.7×10^{19} (Loschmidt's number) of atoms.] To indicate the accuracy involved, raw data are shown as well as those obtained when the procedure for removal of random coincidences is applied. The figure also shows an analysis into two exponentials, beyond the shoulder region.

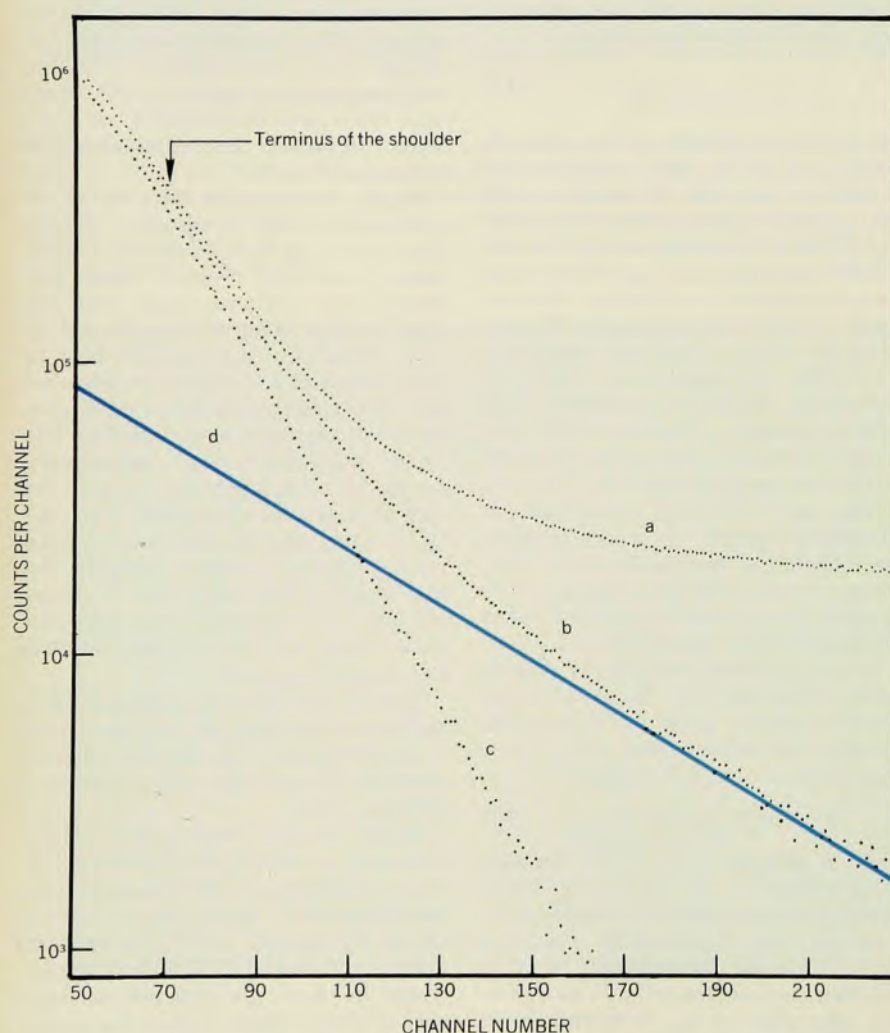


Calculated angular distributions $I(\theta) \sin(\theta)$ for scattering of positrons of different energies by helium atoms. Note the concentration of scattering in the backward direction at the higher energies. Figure 8



Apparatus for measuring annihilation time spectra developed by Coleman, Griffith, Heyland and Killeen. The copper pressure vessel contains gas at up to 60 atmospheres pressure and a sodium-22 source. The two plastic scintillators provide "start" and "stop" pulses from which spectra with resolution of 1.5 nanosec are obtained.

Figure 10



Annihilation spectrum observed with the apparatus of figure 10, for pure helium at a density of 43.6 amagat at room temperature. Each channel corresponds to 1.94 nanosec. Curve a is unprocessed data; curve b has the background subtracted; curve c is the free positron component, and curve d is the ortho-positronium component.

Figure 11

From experiments such as these, λ_1 and λ_2 may be determined as functions of gas pressure; they both behave as expected. Least-squares fitting gives

$$\lambda_1 = 0.793 \pm 0.001\rho \text{ per microsec} \quad (14)$$

and

$$\lambda_2 = 7.24 + 0.1006 \pm 0.003\rho \text{ per microsec} \quad (15)$$

where ρ is the gas density in amagats.

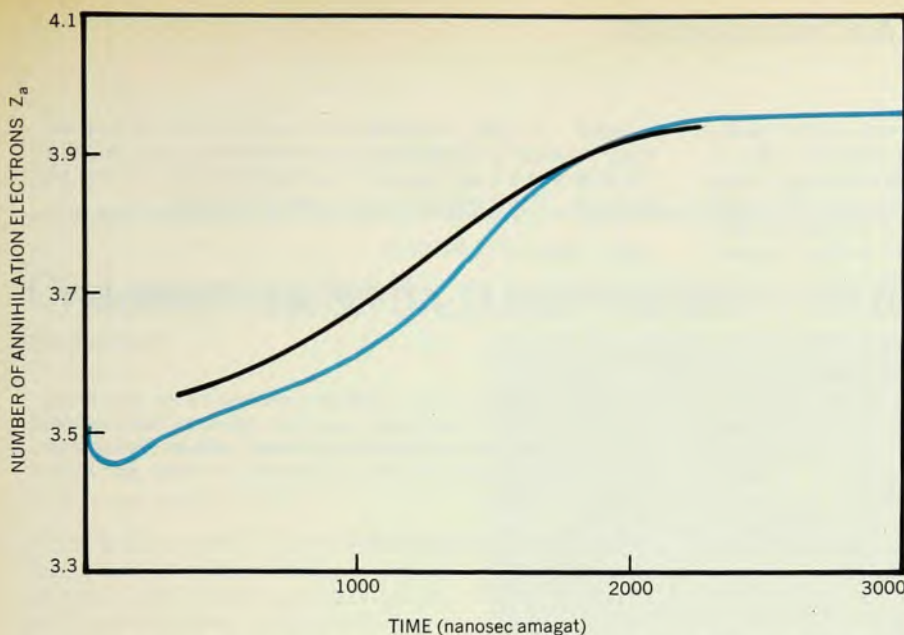
From λ_1 , $Z_a(T)$ is found to be 3.94 ± 0.02 for helium at room temperature. Knowing the wave function for the motion of a positron in the field of a helium atom as a function of velocity at low velocities enables $Z_a(T)$ to be calculated. Using the same variational wave function that was so successful in reproducing the observed elastic scattering, Humberston¹⁶ calculated Z_a as 3.9 in excellent agreement with observation.

It is possible to go further and predict theoretically the form of the annihilation spectrum in the shoulder region. For this it is necessary to calculate the velocity distribution of the positrons as it varies with time over the region. This may be done if we assume that, on passing through the Öre gap, the positrons emerge with a velocity distribution that is either isotropic in energy or momentum space, provided both the momentum transfer and the annihilation cross sections for positrons in the gas are known as a function of positron velocity. Campeanu and Humberston¹⁷ have carried through a theoretical program of this kind in which they derive the two positron cross sections from their variationally determined wave functions. Figure 12 shows the remarkably good agreement they obtain with the observed results of Coleman, Griffith, Heyland and Killeen¹⁵ for the variation of the number of annihilation electrons Z_a with time t over the shoulder region. The theoretical results depend very little on the initial velocity distribution assumed for the positrons.

The good agreement obtained is a very severe and convincing test of the accuracy of the wave functions calculated by Humberston and Campeanu. A still further test is to investigate again, with the improved statistical accuracy, the effect of an electric field on the annihilation spectrum. This will change the value of λ_1 by modifying both the shape and root-mean-square value of the equilibrium distribution in a way depending once again on the annihilation and momentum transfer cross sections as function of positron velocity.

Results of similar accuracy have been obtained for the other rare gases and are being analyzed to provide information on the cross sections concerned.

With the accuracy now available the natural lifetime τ_0 of ortho Ps which appears in equation 12 may be measured with some precision. With this end in



Effective number of annihilation electrons, Z_a , in helium plotted as a function of the time t since production of the positrons from the source. The black line represents observations by Coleman, Griffith, Heyland and Killeen, while the colored curve shows a calculation by J. W. Humberston and R. I. Campeanu. Figure 12

view it is an advantage to work in Freon, for which λ_1 is so large that most of the annihilation spectrum has the form of a single exponential only. In this way Coleman and Griffith¹⁸ obtained

$$1/\tau_0 = 7.262 \pm 0.015 \text{ per nanosec}$$

which agrees well with earlier measurements of R. H. Beers and V. W. Hughes¹⁹ who found

$$1/\tau_0 = 7.275 \pm 0.015 \text{ per nanosec}$$

Recent calculations,²⁰ which include corrections up to order e^8 , give

$$1/\tau_0 = 7.241 \pm 0.010 \text{ per nanosec}$$

Further experiments are being carried out to improve the accuracy.

Much can be done from observation of annihilation spectra to study quenching cross sections for ortho positronium, but a discussion of this work would go beyond the scope of the present article.

* * *

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