Positron Annihilation in Helium*

THOMAS BRUCE DANIEL† AND ROBERT STUMP
Physics Department, University of Kansas, Lawrence, Kansas
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Positron mean lives were measured in helium gas over a wide temperature range at densities from 4.6 to 534 times the STP density and in liquid helium at 4.2 and 5.1°K. The orthopositronium mean life in the liquid at 5.1°K was found to be $(9.4\pm0.6)\times10^{-8}$ sec which differs little from the lifetime in liquid at 4.2°K. Except at very low temperatures, the pick-off rate in gas agreed moderately well with theory. The low pick-off rate associated with orthopositronium in liquid was observed also in the gas at temperatures below 9°K for densities greater than 250 times the STP density.

INTRODUCTION

THE discovery of orthopositronium in liquid helium[1,2] raised the question of why its mean life (10^{-7} sec) is so much longer than would be expected on the basis of the liquid density. Ferrell has pointed out[3] that it is energetically favorable for a positronium atom to be in a region where the local helium density is less than average. He postulated that once in this region, the positronium creates a little bubble in the liquid. The pick-off rate, and thus the observed mean life, then should be characteristic of the density of the saturated vapor in the bubble. A sensitive test of the bubble theory is provided by a measurement of orthopositronium mean life in liquid helium near the critical point where the calculated mean life is about $\frac{1}{3}$ the mean life in the liquid at 4.2°K.

A twofold experimental program naturally suggested itself. First, the orthopositronium mean life was measured as a function of gas density to see if the pick-off rate corresponded to Ferrell's calculation. Second, the mean life was measured in liquid helium near the critical point to check the bubble theory.

EXPERIMENTS

Positrons from a $Na^{22}Cl$ source sandwiched between thin aluminum foils passed into helium confined in an annihilation chamber. The size of the chamber was chosen to facilitate the lifetime measurement at the pressure and temperature being investigated. In all, five different chambers were employed. They ranged in size from 6 inches diameter and 7 inches long for low pressures at room temperature down to $\frac{1}{2}$ inch diameter and $1\frac{1}{2}$ inches long for high pressures at liquid nitrogen and liquid helium temperatures. The chamber for experiments in the temperature region 4 to 50°K was isolated from the liquid helium bath by a vacuum wall and provided with an electric heater. By regulating the current through the heater, the heat leak to the bath could be compensated thus controlling the temperature of the helium inside the chamber. Before each experiment, the chamber was repeatedly exhausted to a fore pump vacuum and flushed with helium.

Mean lives were measured in the usual way from a plot of coincidence rate *versus* the delay time between the 1.28-Mev nuclear gamma ray emitted simultaneously with a positron and one of the subsequent annihilation photons. Gamma rays were detected by plastic scintillators mounted on photomultiplier tubes whose signals were fed into a delay time to pulse-height converter. A 256-channel pulse-height analyzer recorded the converter pulses. Signals from the last dynode of the photomultiplier tubes were sent to discriminator circuits for identification. The discriminators were set so that if a nuclear gamma ray was detected by one photomultiplier and an annihilation gamma ray by the other, then pulses were sent to a 2-way slow coincidence circuit which controlled a gate between the converter and the pulse-height analyzer.

RESULTS

The coincidence rate *versus* delay time curves usually indicated the presence of three components in the decay of positrons. First, there was a short-lived ($\sim10^{-10}$ sec) component attributed to the decay of positronium in the ^1S state. Second, there was an intermediate life due to the annihilation of free positrons. Third, there was a long-lived ($\sim10^{-7}$ sec) component due to positronium in the ^3S state (orthopositronium). The latter two components of positron decay are plotted as a function of helium density in Fig. 1. The unit of density used is the amagat, the density of the helium gas under STP conditions. Near the critical point it was not possible to make a straightforward density calculation from p, T data. It was possible, however, to assign limits to the density for these data. To avoid crowding the figure, typical standard deviations are shown for only a few points.

The group of points (between light parallel lines) which are in inverse proportion to the helium density with no temperature dependence being evident is identified as belonging to the annihilation of free positrons. Of the remaining data in Fig. 1, those taken

* Part of Ph.D. thesis submitted by T. B. D. to the University of Kansas.
† Present address: Midwest Research Institute, Kansas City, Missouri.
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[3] R. Ferrell, Phys. Rev. **108**, 167 (1957).

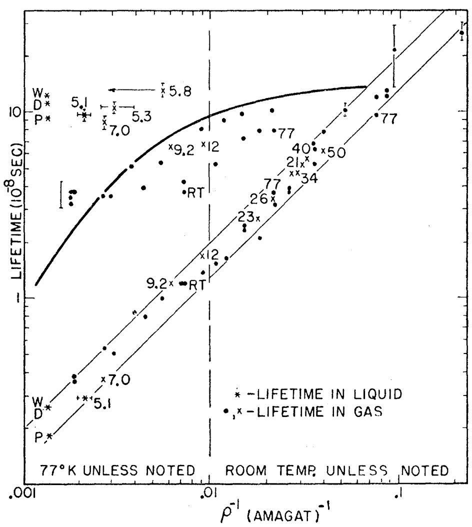

FIG. 1. Lifetimes in helium *vs* density^{-1}. Heavy curve indicates calculated values for picked-off orthopositronium. Points P and W are from references 1 and 2, respectively, and are included for comparison with points D, the data taken in liquid helium at 4.2°K.

in gas at temperatures from 9°K up to room temperature appear to agree moderately well with Ferrell's calculated values (heavy curve) for picked-off orthopositronium. For temperatures below 9°K, the data do not agree with the theoretical values but are about the same as for the liquid.

The mean life τ_2 of orthopositronium measured in liquid helium at 4.2°K is $(11.2\pm0.6)\times10^{-8}$ sec, in good agreement with previous experiments.[1,2] The mean life in the liquid just below the critical point at 5.1°K is $(9.4\pm0.6)\times10^{-8}$ sec which does not agree with the prediction of the bubble theory.

The annihilation cross section σ is defined by $\lambda = n\sigma v$, where λ is the annihilation rate, n is the number of helium atoms per unit volume, and v is the average relative velocity of positron and helium atoms. From the experimental values of n and λ, the volume cross section σv may be found. For free positrons, the average value of $\sigma_1 v = 2.4\times10^{-14}$ cm^3 sec^{-1} over the whole range of p and T investigated. The observed annihilation rate for orthopositronium is $\lambda_2 = \lambda_{\text{vacuum}} + \lambda'$, where $\lambda_{\text{vacuum}} = 7.14\times10^6$ sec^{-1} and λ' is the pick-off annihilation rate. The volume cross section for pick-off $\sigma_2 v$ found from the experimental values of λ' is approximately 2.4×10^{-15} cm^3 sec^{-1} for temperatures down to 9°K.

It must be remembered that if the orthopositronium were not picked off appreciably by the helium and instead a quenching agent were present as a contaminant, τ_2 would still vary in much the same way with increasing density. However, a calculation showed that to give the observed effect the contamination of the helium, even if it were all oxygen, would need to have been 10 times the maximum impurity content claimed by the supplier. Experimental tests for contamination were run at $\rho = 534$ amagats. This was the highest density at which data were taken in the gas and thus where the effect of any contamination would be most pronounced. The test consisted of four experiments, two done with gas straight from the bottle and two performed with gas which had been allowed to seep into the chamber through a liquid helium cold trap which would have frozen out any impurity. The cold trap had no perceptible effect on the results, indicating that the orthopositronium was indeed being picked off by helium and not being quenched by a contaminant.

Although the immediate goal of this inquiry was to settle the questions posed by Ferrell's explanation of the low pick-off rate in liquid helium, the most interesting result was the discovery that a low pick-off rate is not a property of the liquid phase exclusively but is also associated with the gas at sufficiently low temperatures.