COMMENTS AND ADDENDA

The Comments and Addenda section is for short communications which are not of such urgency as to justify publication in Physical Review Letters and are not appropriate for regular Articles. It includes only the following types of communications: (1) comments on papers previously published in The Physical Review or Physical Review Letters; (2) addenda to papers previously published in The Physical Review or Physical Review Letters, in which the additional information can be presented without the need for writing a complete article. Manuscripts intended for this section may be accompanied by a brief abstract for information-retrieval purposes. Accepted manuscripts will follow the same publication schedule as articles in this journal, and galleys will be sent to authors.

Annihilation of Positrons in Argon at High Densities

S. J. Tao
The New England Institute, P.O. Box 308, Ridgefield, Connecticut 06877
(Received 24 October 1969)

The annihilation of positrons in argon as a function of argon density at densities from 10 to 65 amagats has been investigated at room temperature. The direct annihilation rate, the reciprocal of shoulder width, and the quenching rate of *o*-positronium are found to be linearly dependent on argon density in the density range investigated within the range of the experimental error. The value of Z_{eff} of the direct annihilation rate is found to be 26.2 for an argon density up to 50 amagats.

I. INTRODUCTION

In a recent paper[1] (I), Orth and Jones investigated the annihilation of positrons in argon as a function of argon density at densities less than 20 amagats. They have also compared their results with the results obtained by many previous workers,[2–7] in which the densities of the argon investigated were all below 20 amagats.

Recently, we have investigated the annihilation of positrons in argon as a function of argon density at densities from 10 up to 65 amagats. The results will be briefly described here.

II. EXPERIMENTAL

The pressure chamber is a spherical vessel with a 5 in. diam, made from stainless steel with a polished surface. The whole gas system, including the gas inlet and the vacuum side for the evacuation of the system, is made from stainless steel. All joints are either welded or sealed by metal packings. The system is designed to sustain a maximum pressure of 1500 psia. The argon gas used in this experiment is the "ultra pure" grade supplied by Matheson. The maximum amounts of impurities certified by them are (in ppm): CO_2, 1; O_2, 5; H_2, 1; CO, 1; N_2, 5; H_2O, 2.1; and CH, 2. The filling of the gas chamber was done by evacuation, followed by purging. The purging was performed by filling to a pressure of more than 500 psia, and then discharging to a pressure of about 20 psia. This procedure was repeated five or more times. No purification of the gas was made since we have learned[8] that certain ordinary methods of purification, such as passing the gas over melted calcium, may introduce more impurities into the argon gas. The experiments were carried out at a room temperature of about 22 °C.

The lifetime spectra were measured by a sophisticated system of time-to-amplitude converters. The details of the system will be described elsewhere.[9] The timing pulses produced by the photomultipliers are split into two pairs and are fed into two time-to-amplitude converters of different ranges: a short-range one with a linear region of 32 nsec, and a long-range one with a linear region of 320 nsec. These two time-to-amplitude converters are gated by a single gate pulse which is controlled by a fast side-channel energy selection system. The outputs of these two time-to-amplitude converters are accepted by a ND2200 multi-channel analyzer and put in separate halves of the memory using a digiplex and two analog-to-digital converters. One of the outputs of the time-to-amplitude converters is delayed in order to allow the memory to receive the two outputs at real time. This system, when it serves a pair of 56AVP photomultipliers coupled with NATON136 phosphors having a $1\frac{1}{2}$ in. diam and 2 in. length, gives a resolution that is better than 0.6 nsec full width half-maximum.

The positron source is 5-μC Na22 deposited on a very thin mica sheet that is centered in the gas chamber. A pair of the lifetime spectra is shown in Figs. 1 and 2 as examples. The spectrum in Fig. 2 actually is an enlarged portion of the peak and shoulder of the spectrum in Fig. 1. The data in the portion of the spectrum below the shoulder are fitted with a curve of two-component exponential decay by using a standard procedure.[10] The mean life of the short-lifetime component represents the direct annihilation of thermalized or nearly thermalized positrons; and the mean life of the long-lifetime component, the annihilation of *o*-positronium.

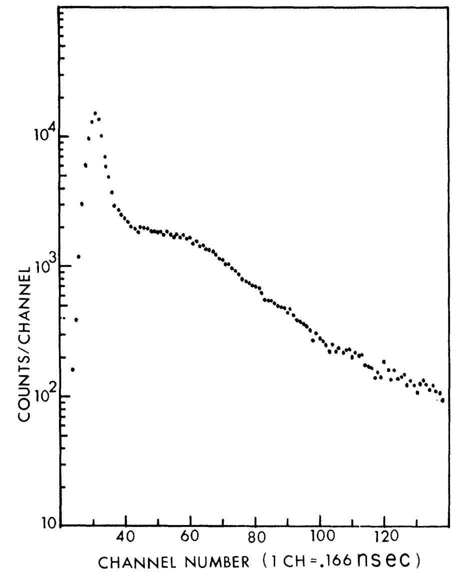

FIG. 2. Positron annihilation lifetime spectrum in argon at a density of 63.8 amagats (from the short-range time-to-amplitude converter).

III. RESULTS AND DISCUSSION

A. Direct Annihilation Rate

Figure 3 shows the dependence of the direct annihilation rate (λ_1) on argon density. The densities of the argon were calculated based on a correction formula.[11] The deviation of the density due to various causes was estimated to be less than 3%.

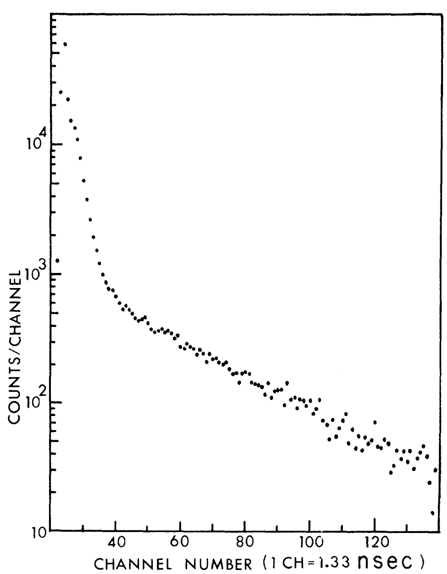

FIG. 1. Positron annihilation lifetime spectrum in argon at a density of 63.8 amagats (from the long-range time-to-amplitude converter).

The data were fitted with a simple linear function of

$$\lambda_1 = (5.09 \pm 0.24)D \, , \qquad (1)$$

where the units of λ_1 are $(\mu\text{sec})^{-1}$ and D, are amagats.

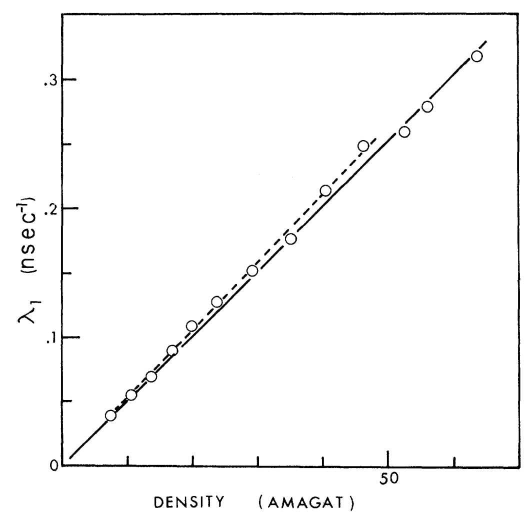

FIG. 3. Dependence of the direct annihilation rate of positrons on argon density. The solid line represents the line $\lambda_1 = 5.09 \times 10^6 D$ sec^{-1}. The dashed line represents the line $\lambda_1 = 5.27 \times 10^6 D$ sec^{-1}.

The confidence level from which the deviation 0.24 was calculated is 0.05.[12] The same confidence level is used for the rest of the straight-line fits. The formula (1) is represented by the solid line in Fig. 3. The rate constant 5.09×10^6 sec^{-1} amagat^{-1} is lower than the averaged value of 5.27×10^6 sec^{-1} amagat^{-1} of the formula (3) in I.

However, if the three points representing the data for densities greater than 50 amagats are excluded, the data can be fitted with a function of

$$\lambda_1 = (5.27 \pm 0.23)D \quad , \tag{2}$$

where the units of λ_1 and D are the same as the ones used in formula (1). This rate constant agrees very well with the value formula (3) in I. The formula (2) is represented by the dashed line in Fig. 3.

No attempts were made to improve the goodness of fit by using a more complicated function. However, the nonlinear dependence of the direct annihilation rate on argon density for densities lower than 20 amagats, as represented by formula (4) in I, is not observed for argon densities greater than 20 amagats. It is reasonable to say that the formula (2) or the formula (3) in I is good for argon with density in the range from 15 to 50 amagats.

B. Shoulder Width

Figure 4 shows the dependence of the shoulder width on argon density. The criterion for the determination of the shoulder width is similar to the one used by Paul and Leung.[13] The reciprocal of the shoulder width is actually plotted against the argon density. The data were fitted with a linear function of

$$1/(\text{S. W.}) = (2.73 \pm 0.23)D$$

where the units of $1/(\text{S. W.})$ and D are the same as the ones in formula (1). The formula (3) is represented by the solid line in Fig. 4. From the slope of the formula (3) the width-density product was calculated to be 366 nsec amagat. This value is slightly greater than the rather large value of 340 nsec amagat reported in I. Impurities generally do reduce the thermalization time of positrons in argon, and hence the shoulder width in the annihilation lifetime spectrum; thus the greater width-density product may be due to the fact that a purer gas was used in this experiment.

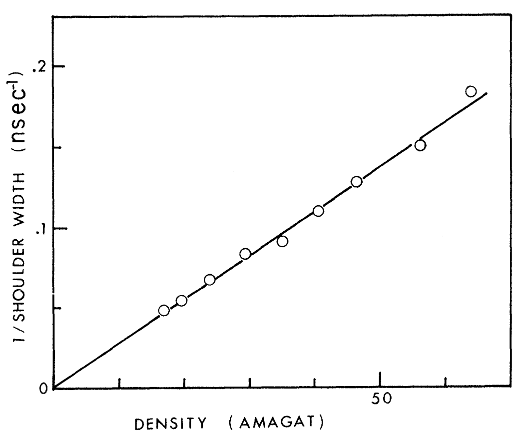

FIG. 4. Dependence of the shoulder width on argon density. The solid line represents the line $1/(\text{S.W.}) = 2.73\times10^6 D$ sec^{-1}.

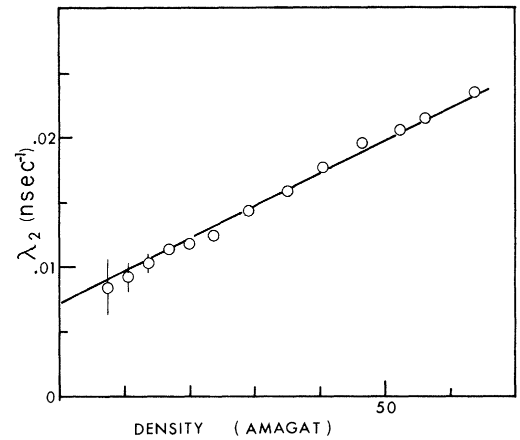

FIG. 5. Dependence of the o-positronium annihilation rate on argon density. The solid line represents the line $\lambda_q = 0.255\times10^6 D$ sec^{-1} with intersect at $\lambda_2 = 0.72\times10^6$ sec^{-1}.

C. Quenching of o-Positronium

Figure 5 shows the dependence of the o-positronium annihilation rate (λ_2) on argon density. If the annihilation rate of the o-positronium in a free space is assumed to be the theoretical value 7.2×10^6 sec^{-1},[14] the data fits a linear function of

$$\lambda_q = (0.255 \pm 0.015)D \quad , \tag{4}$$

where λ_q is the o-positronium quenching rate and the units of λ_q and D are the same as the ones in formula (1). The formula (4) is represented by a solid line in Fig. 5.

When the data of the o-positronium annihilation rate are fitted directly to a function of $\lambda_2 = a_0 + a_1 D$, the corresponding values of the coefficient are found to be

$$a_0 = (6.7 \pm 0.4) \times 10^6 \text{ sec}^{-1} ,$$

$$a_1 = (2.7 \pm 0.5) \times 10^5 \text{ sec}^{-1} \text{ amagat}^{-1} ,$$

provided the three points representing the data displaying large deviations at argon densities lower than 15 amagats are neglected. If these three poor points are included, the calculated value of a_0 will be too small to be meaningful.

The results agree well with the values obtained in I:

$$a_0 = (7.53 \pm 0.18) \times 10^6 \text{ sec}^{-1} ,$$

$$a_1 = (2.4 \pm 0.2) \times 10^5 \text{ sec}^{-1} \text{ amagat}^{-1} ;$$

and with the values obtained by Beers and Hughes[15]:

$$a_0 = (7.29 \pm 0.03) \times 10^6 \text{ sec}^{-1} ,$$

$$a_1 = (2.36 \pm 0.16) \times 10^5 \text{ sec}^{-1} \text{ amagat}^{-1} .$$

D. Effect of High Density

The above results suggest that the direct positron annihilation rate, the reciprocal of shoulder width, and the quenching rate of o-positronium are linearly dependent on argon density and can be represented by a function of $\lambda = aD$ up to a density of at least 50 amagats.

This implies that at the high density of 50 amagats the effect of multicollision, i.e., the interaction of the positron or the o-positronium with more than one argon atom at a time, is negligible. If it is present, it does not change the linear dependence of the direct annihilation rate, the o-positronium quenching rate, or the momentum transfer cross section which is related to the shoulder width on argon density.

Certainly the nonlinearities present at lower densities, such as the one for direct annihilation reported in I and the one for the o-positronium quenching rate,[16] require further study and explanation.

ACKNOWLEDGMENTS

This work is partially supported by AEC grant AT(30-1)3661. The author is grateful to the Dow Chemical Company for their assistance in the construction of the pressure system. Thanks are also due to Dr. John Lee, Dr. T.M. Kelly, and Dr. S.Y. Chuang for their assistance and valuable discussions.

---

[1]P. H. R. Orth and G. Jones, Phys. Rev. 183, 7 (1969), hereafter called I.

[2]S. J. Tao, J. Bell, and J. H. Green, Proc. Phys. Soc. (London) 83, 453 (1964).

[3]D. A. L. Paul, Proc. Phys. Soc. (London) 84, 563 (1964).

[4]P. E. Osmon, Phys. Rev. 138, B216 (1965).

[5]W. R. Falk and G. Jones, Can. J. Phys. 42, 1751 (1964).

[6]D. A. L. Paul and L. Saint-Pierre, Phys. Rev. Letters 11, 493 (1963).

[7]W. R. Falk, P. H. R. Orth, and G. Jones, Phys. Rev. Letters 14, 447 (1965).

[8]S. J. Tao and J. Bell, in Proceedings of the Positron Annihilation Conference, 1965, edited by A. T. Stewart and L. O. Roelling (Academic Press Inc., New York, 1967), p. 371.

[9]S. J. Tao (to be published).

[10]S. J. Tao, IEEE NS-15, 1, 175 (1968).

[11]G. A. Cook, Argon, Helium, and the Rare Gases (Wiley-Interscience Publishers, New York, 1961), Vol. 1, pp. 265–303.

[12]F. S. Action, Analysis of Straight-Line Data (Dover Publications, New York, 1966), Chap. 2.

[13]D. A. L. Paul and C. Y. Leung, Can. J. Phys. 46, 2779 (1968).

[14]A. I. Alekseev, Zh. Eksperim. i Teor. Fiz. 36, 1839 (1959) [English transl.: Soviet Phys. – JETP 9, 1312 (1959)].

[15]R. H. Bears and V. W. Hughes, Bull. Am. Phys. Soc. 13, 633 (1968).

[16]G. J. Celitens, S. J. Tao, and J. H. Green, Proc. Phys. Soc. (London) 83, 833 (1964).