CRITICAL BEHAVIOR OF POSITRONS IN LOW-TEMPERATURE GASEOUS HELIUM

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The time-decay spectra of positrons annihilating in helium gas from 4.6 to 30°K have been obtained and it is found that the spectra exhibit a large variation with respect to a small change in temperature. Many-body effects are discussed in connection with the data.

In this Letter we report a new and large effect of temperature on the annihilation of positrons in low-temperature helium gas.

We obtained the time-decay spectra of positrons in helium gas over the temperature range 4.6 to 30°K using a variable-temperature cryostat. Temperature was measured with a calibrated germanium-crystal temperature sensor. The reported temperatures have an absolute accuracy of 0.4%, a relative accuracy of 0.2%, and were maintained constant to within 0.05% during the running time. The gas sample was contained in a copper cylinder having an inside diameter of 1.7 cm and a height of 5 cm.[1] Measurement of extraneous heat input assured us that the gas temperature was spatially uniform to at least 5 mdeg K. We obtained our data at the gas densities 0.016, 0.023, and 0.030 g/cm^3. The densities were determined by a fit to existing thermodynamic data for helium,[2] yielding a maximum absolute error of 5% and a maximum relative error of 2%. By staying below 30°K we were assured of the total gas impurity being less than 0.1 ppm. The annihilation spectra were obtained using conventional delayed coincidence techniques. The full width at half-maximum of our prompt resolution curve was 1.2 nsec.

The time-decay spectrum of positrons in helium gas at 4.2°K near the saturated vapor density is characterized by a broad shoulder followed by a large peak having an exponential tail.[3] We have found that this peak can also exist above the critical temperature of helium, 5.2°K. Figure 1 shows that an increase in temperature with the density held constant results in a decrease in the decay rate following the peak and causes the peak to occur at a later time. The peak height also decreases but this is in part due to the decrease in the decay rate following the peak.[3] Figure 2 shows the temperature dependence of the equilibrium decay rate following the peak. Note that the decay rate undergoes a

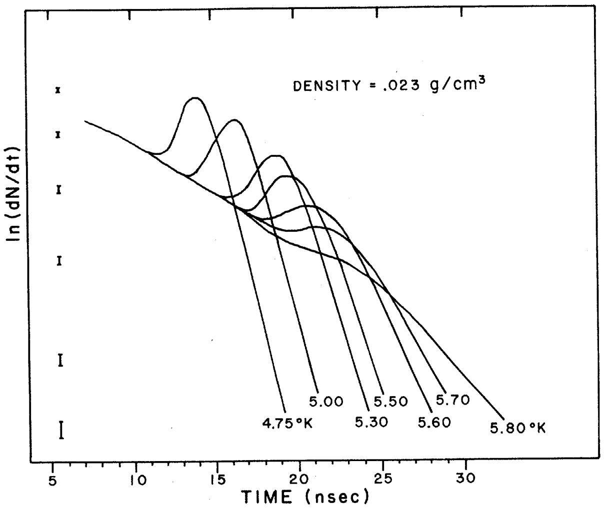

FIG. 1. Smoothed fits to the experimental annihilation spectra of positrons in helium gas. The orthopositronium component and background have been subtracted. Similar sets are also obtained at the other two densities investigated – 0.016 and 0.030 g/cm^3. The representative error bars at the left indicate the extent that the smoothing is to be taken as being meaningful.

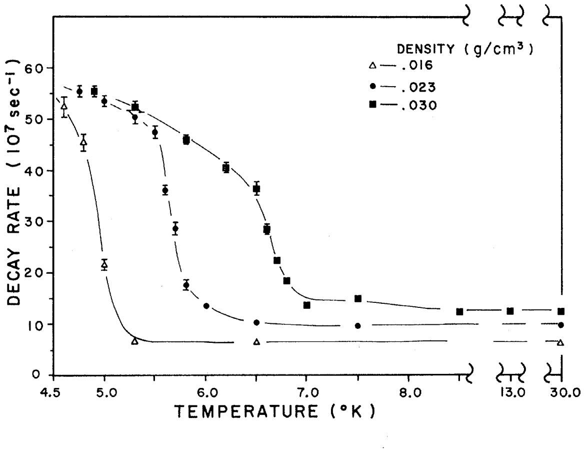

FIG. 2. Equilibrium decay rates of positrons in helium gas versus temperature for three different densities. The error bars have been omitted where they fall within the size of the plotted points. As the decay rates approach their high-temperature limits, the peak in the spectra vanishes and the decay rates are taken as the logarithmic slope of the spectra following the shoulder which remains. Lines through the data points have been included as a visual aid only.

very rapid and large decrease within a small temperature interval of 0.3°K. It should further be noted that the critical temperature of helium plays no apparent role in the behavior of the data.

At each of the three densities investigated we observed a temperature T_H above which an increase in temperature has no detectable effect on the data. The values of T_H are approximately 5.3, 6.5, and 8.0°K at the densities 0.016, 0.023, and 0.030 g/cm^3, respectively. The spectra observed by others at 77 and 300°K,[4] extrapolated to the densities reported in this Letter, are in agreement with the data at 30°K. It is therefore quite likely that temperature has a negligible effect on the annihilation spectra throughout the range from T_H to 300°K.

The high-temperature (i.e., above T_H) spectra are characterized by a shoulder followed by the onset of exponential decay. A typical high-temperature spectrum is shown in Fig. 3. The width of the shoulder is temperature independent and inversely proportional to density. Leung and Paul[4] have demonstrated quite conclusively that the high-temperature spectra can be accounted for using a semiclassical description of free positrons slowing down, via elastic collisions, to thermal energies. Using Drachman's annihilation and momentum-transfer cross sections,[5,6] Leung and Paul found that the shoulder and onset of exponential decay arises from a gradual increase of about 30% in the energy-dependent decay rate coupled with a minimum at 1.7 eV in the momentum-transfer cross section for positron–helium-atom scattering.

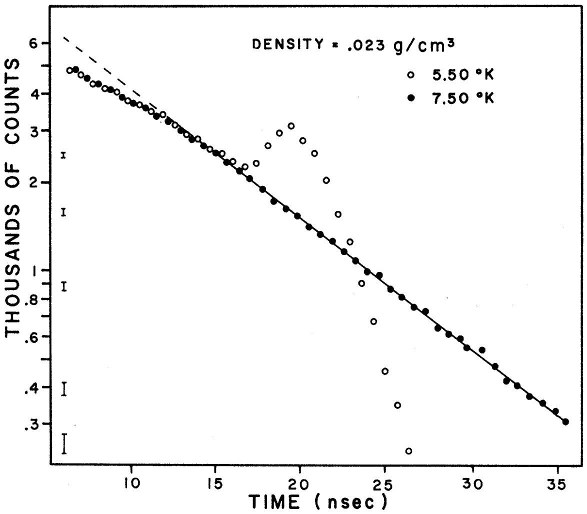

FIG. 3. Two annihilation spectra in helium gas with the orthopositronium component and background subtracted. The 7.5°K spectrum is typical of all high-temperature spectra and is characterized by a shoulder followed by the onset of exponential decay. The dashed-line extrapolation of the equilibrium exponential decay emphasizes the nonexponential shoulder region of the spectrum. The shoulder width (here 12 nsec) multiplied by the gas density was found to be 1400± 150 nsec amagat for all densities and temperatures investigated. Superimposing the 5.5°K spectrum illustrates the way in which the shoulder of the high-temperature spectra coincides with the same region of a typical low-temperature spectrum. Representative Poisson error bars are shown at the left.

In order to account for the peak in the low-temperature spectra, however, one must artificially introduce a sudden increase of up to 600% in the energy-dependent decay rate at some particular energy, E_R.[7] The location of the resulting peak in the calculated spectrum is then determined by the value of E_R. We have used E_R as a parameter to match the location of the peak in our calculated and experimental spectra. The momentum-transfer cross sections calculated by Drachman yielded values of E_R close to thermal energies. Since we did not use the full diffusion theory,[8] no attempt was made to match the actual shape of the peak in the calculated and experimental spectra. We did include, however, the thermal Doppler shift in the first-order analysis of Leung and Paul.

We summarize the results of the above analysis as follows: (1) E_R is very sensitive to the near-zero-energy behavior of the momentum-transfer cross section. (2) The use of any of Drachman's theoretical cross sections yields values of E_R much less than 0.01 eV. This means that the peak in the low-temperature spectra is preceded by the same shoulder and onset of exponential decay occurring in the high-temperature spectra. Figure 3 shows this to be experimentally verified. (3) A particular choice of Drachman's cross sections results in E_R being so close to thermal energies that all the peak positions in the data can be accounted for by a single value of E_R, $(1.3\pm0.1)\times10^{-3}$ eV. The shift in the peak with increasing temperature then results simply from the fact that it takes longer for a positron to slow down to a given energy, via elastic collisions, when the gas atoms are moving faster.

A most important feature of the data shown in Fig. 2 is that the decay rate divided by the gas density is strongly dependent on density in the low-temperature region. Also this dependence is very sensitive to changes in temperature. This makes it virtually impossible to account for the equilibrium decay rate following the peak without resorting to a many-body model. One such model we considered in detail was the electrostricted cluster model[9] which would produce a higher-than-ambient density of helium atoms in the neighborhood of the positron. In addition such a model would have the attractive feature of predicting an increase in decay rate with decreasing temperature and an increase in the stability of the cluster with increasing gas density. It is understood that for the onset of cluster formation the positron must be initially localized since otherwise its velocity, even at thermal energies, would be too great for the helium atoms to collect about it. We can show, using a Born-Oppenheimer approximation, that it is also necessary for the positron to be localized by some mechanism, other than the potential well presented by the cluster, after the cluster has been formed in order to arrive at a self-consistent solution to the problem.[10]

We thus find that in order to make any quantitative use of the cluster model we would have to postulate either attachment of the positron to a single helium atom or a sudden reduction of the mobility of the positron which could result from fully taking into account the quantum mechanical aspects of the positron in a system of many atoms. Such an effect has been predicted for electrons in a random system of hard-core scatterers in a recent paper by Neustadter and Coopersmith.[11] Although the positron–helium-atom interaction cannot be represented by hard-core repulsion, two main features of the Neustadter-Coopersmith calculation (the inclusion of multiple scattering to all orders and making use of the randomness of the spatial distribution of the scatterers) would be retained if a similar calculation for positrons in gaseous helium were made.

In conclusion, the observed critical behavior of the annihilation spectra of positrons appears to require the consideration of many-body effects for an understanding of the phenomena reported in the paper.

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[1] A combination source holder and moderator with cylindrical geometry instead of the conventional foil sandwich for the Na^{22} positron source made measurements with such a small sample cylinder feasible. At a density of 0.016 g/cm^3, for example, 25% of the positrons annihilated in the gas—a factor of 2 to 4 times the fraction of positrons stopped in the gas when a foil sandwich is used.

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[7] S. J. Tao and T. M. Kelly, Phys. Rev. 185, 135 (1969).

[8] As the positron slows down in the gas via elastic atomic collisions, there is a distribution of energies available to the positron after each collision. The full diffusion theory takes this into account and results in a nonseparable, second-order partial differential equation in two variables. W. R. Falk, P. H. R. Orth, and G. Jones, Phys. Rev. Lett. 14, 447 (1965).

[9] L. O. Roellig, *Positron Annihilation,* edited by A. T. Stewart and L. O. Roellig (Academic, New York, 1967), p. 127.

[10] A full discussion of this problem will appear in a later paper.

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DISCONTINUITIES OF IONIC MOBILITIES IN SIMPLE LIQUIDS

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This Letter reports the results of ionic-mobility measurements in the four simple liquids He I, N_2, Ar, and CCl_4. Periodic steps in the mobility, like those found earlier in liquid helium II, were found also in these four liquids. We found also a simple relation connecting the critical velocities to the temperatures of the investigated liquids.

Periodic steps in ionic mobilities have been reported to exist in liquid helium II[1-5] and in liquid argon and nitrogen.[6] The models proposed for the superfluid helium[7,8,3] have not been confirmed by the experiments performed thereafter,[4,5,9] while no models have been proposed for argon and nitrogen.

Because this effect is at present completely unexplained, we decided to investigate several liquids by a technique which enables us to mea-