CORRELATION BETWEEN DECAY LIFETIME AND ANGULAR DISTRIBUTION OF POSITRON ANNIHILATION IN THE PLASTIC SCINTILLATOR NATON*

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Positron annihilations in amorphous materials show anomalous features in the results of both lifetime and angular correlation experiments. A complex lifetime spectrum[1] has been observed in the former and a "narrow component"[2] in the latter. The existence of some correlation between these two has been suggested[3] and an experimental attempt to illustrate such a correlation was reported recently[4]; however, the results suffered from a rather poor time resolution.

The present experiment has succeeded in resolving the connection between lifetimes and angular distributions. This was done by measuring the lifetime spectra at different angles between the annihilation gamma rays, using a better time resolution. The plastic scintillator Naton was chosen as a sample of amorphous material because it can be used both as the material in which annihilation is produced and as the detector (detector No. 1, 1.3 cm diam × 0.2 cm) to signal the arrival of a positron. A second Naton crystal (detector No. 2, $1\frac{3}{4}$ in. diam × 1 in.) and a NaI scintillator (detector No. 3, $1\frac{3}{4}$ in. diam × $1\frac{1}{4}$ in.) were placed 3 meters apart at opposite sides of the annihilation source, sitting behind a slit system with an angular resolution of 2.1 mrad. Detectors 1 and 2 performed the usual lifetime measurement by means of a time-to-pulse-height converter (TPC), and simultaneously detectors 2 and 3 performed the angular correlation measurement. The output pulses from the TPC were stored in a 512-channel analyzer which was gated by the triple coincidence of all three detectors, each with proper energy selection. In doing this, the lifetime spectra would depend on the angular distribution of the two annihilation gamma rays. A pulse-height compensator[5] was used to correct the time jitter caused by the wide window openings in the single-channel analyzers (SCA's) for detectors 1 and 2. With the fast photomultipliers of type XP 1020, the optimum time resolution [full width at half-maximum (FWHM) of the prompt curve obtained with β-γ coincidences from Co^{60}] of our electronic system was 0.3 nsec. When a larger Naton crystal was substituted for detector 2 and the SCA windows were opened widely in the low-energy regions to fulfill present experimental requirements, the time resolution was 0.7 nsec.

At the final setting, the triple coincidence rate was about one count per minute. In order to accumulate enough counts, 25 to 30 days were used to take data at each position of detector 3. The experimental conditions were checked constantly. The data were printed out every day and only the runs that were measured without noticeable drift were summed as the final results.

A typical set of results, after careful subtraction of background, is shown in Fig. 1a. The spectra were then resolved into two or three components by a least-squares fitting program. Due to the poor statistics of the present experiment, the following procedures were used to analyze the data:

(1) A lifetime spectrum was obtained, using coincidences between the two plastic scintillators only, to get good statistics.

(2) This complex lifetime spectrum was fitted by a least-squares program with two lifetimes and then with three lifetimes. The χ^2 of a three-lifetime fit was about the same as that of a two-lifetime fit.

(3) The lifetimes so obtained were used as known parameters in least-squares fit to the lifetime curves obtained at different angles between the annihilation gammas. In this way, the relative contribution of each lifetime was obtained at each angle, giving the angular distribution of each lifetime component.

If the lifetime spectra are resolved into two components, we obtain the following lifetimes:

$$\tau_1 = 0.37 \pm 0.01 \text{ nsec } (77 \pm 2\,\%),$$

$$\tau_2 = 1.98 \pm 0.04 \text{ nsec } (23 \pm 1\,\%).$$

These two components have the following angular distributions [Fig. 1(b)]:

τ_1: narrow (6.3 mrad FWHM),

τ_2: broad (10.5 mrad FWHM).

This establishes the fact that the τ_2 component is due to the formation of triplet positronium which annihilates by picking off an outer atomic electron. The momentum associated with this annihilation is expected to reflect the momentum distribution of the available electrons and hence to show a rather broad distribution. All other annihilation processes remain unresolved in the τ_1 component.

The above conclusion has been confirmed by the measurements using a Ge(Li) detector. The momentum of the annihilating pair manifests itself in a broadening of the 0.511-MeV linewidth due to the Doppler effect. With the advent of the Ge(Li) detector of high energy resolution, the broadening can be measured with considerable accuracy. The annihilation spectrum was fed into a SCIPP-1600 multichannel analyzer which was gated by the coincidence between the pulses from the TPC and the pulses from the Ge(Li) detector. The single-channel analyzer, after the TPC, was adjusted to accept most of the long-lifetime component [in the region between channels 110 and 140 in Fig. 1(a), where $I_2 > I_1$] or most of the short lifetime component [in the region between channels 80 and 100 in Fig. 1(a), where $I_2 > I_1$]. With this arrangement, the annihilation gamma-ray lines corresponding to different ratios of I_2/I_1 were then obtained. A set of the results is shown in Fig. 2. The annihilation photopeak corresponding to a larger contribution from the I_2 component is broader than that corresponding to a larger contribution from the I_1 component. The

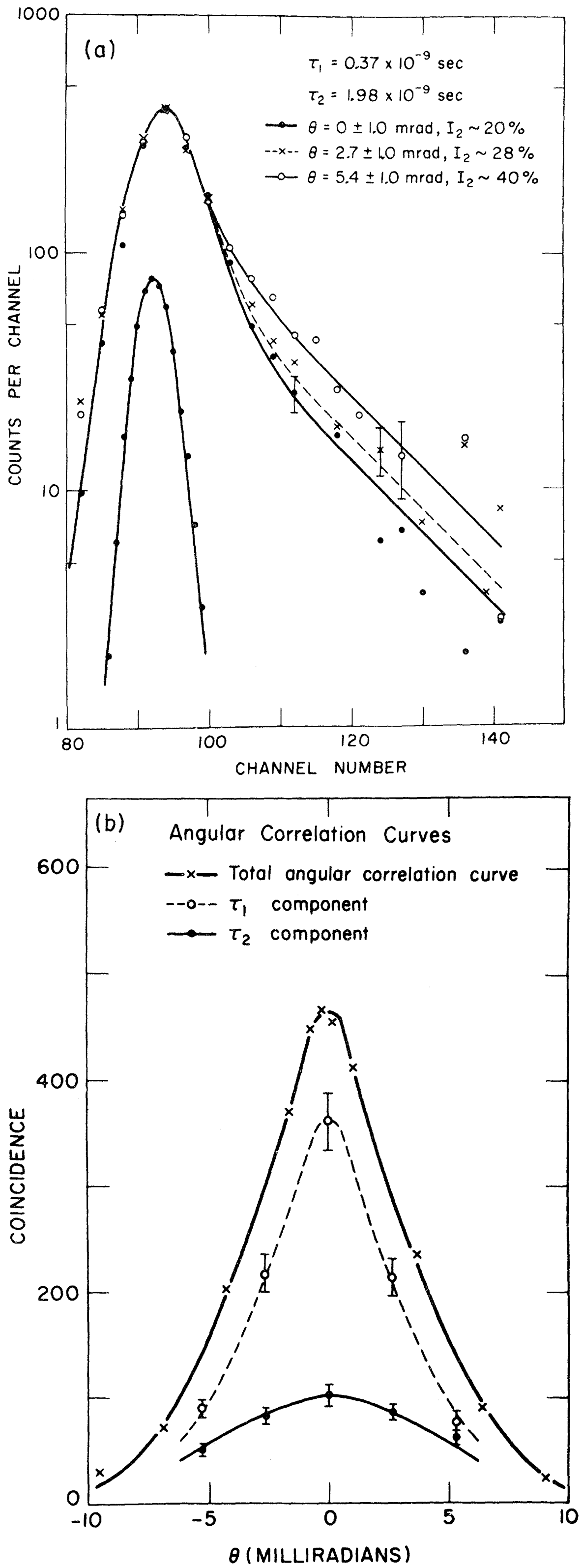

FIG. 1. (a) Lifetime spectra corresponding to different angles between the annihilation gamma rays. (b) Angular correlation curve resolved into two components.

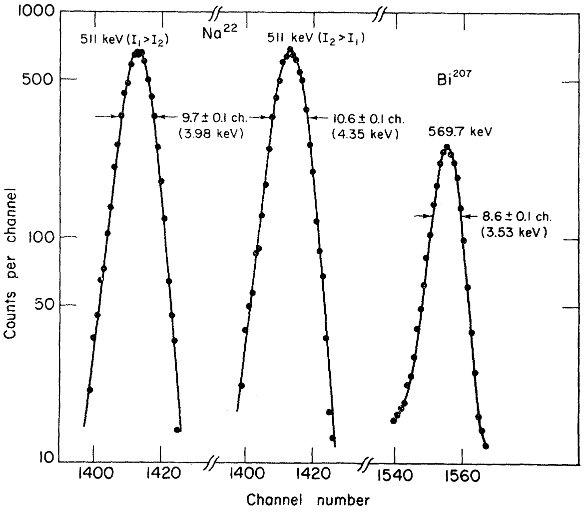

FIG. 2. Annihilation photopeaks corresponding to different contributions from various lifetimes. The 569.7-keV line from Bi^{207} taken in the same conditions is shown for comparison.

average energy of the electrons, calculated from the Doppler broadening of the $I_2 > I_1$ peak (4.35 keV FWHM) compared to the 569.7-keV peak from Bi^{207} (353 keV FWHM), is 6.3 eV. That of the $I_1 > I_2$ peak (3.98 keV FWHM) is 3.3 eV.

If the lifetime spectra are resolved into three components, we obtain the following results:

(1) The long-lifetime component ($\tau_L = 2.01 \pm 0.04$ nsec, ~20%) has a broad angular distribution.

(2) The intermediate-lifetime component ($\tau_I = 0.64 \pm 0.10$ nsec, ~13%) has an angular distribution narrower than that of the long-lifetime component. It is believed that this component is due to free-positron annihilations with outer atomic electrons.[6] The extra momentum contribution in the long-lifetime component may be due to the orbital momentum of the positron bound in positronium.

(3) The short-lifetime component ($\tau_S = 0.33 \pm 0.02$ nsec, ~67%) has a complex origin; besides a narrow component due to the annihilation of singlet positronium, there is some other decay mechanism with large momentum but short lifetime.

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DISPERSION IN SECOND SOUND AND ANOMALOUS HEAT CONDUCTION AT THE LAMBDA POINT OF LIQUID HELIUM*

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The absence of a characteristic length at the lambda temperature T_λ of liquid helium is used to determine the wave-number dependence of the phase fluctuations and the second-sound dispersion relation $\omega = ak^{3/2}$ where ω and $\vec{k}$ are the frequency and wave number and $a \approx 0.1$ cm$^{3/2}$ sec^{-1}. Further predictions are $|T - T_\lambda|^{-1/3}$ singular temperature variation for second-sound damping ($T < T_\lambda$) and the thermal conductivity ($T > T_\lambda$).

The purpose of this note is to point out some dynamical consequences of the absence of any characteristic length beyond the atomic dimensions in an extended homogeneous system at its phase transition. This similarity property holds neither below nor above the transition temperature, where a temperature-dependent correlation length, which becomes much greater than atomic dimensions, is manifested. It is precisely at the transition temperature that this length becomes infinite and is no longer relevant as a characteristic unit. The similarity property then provides a useful means of connecting the critical behavior of the system above the transition with that below. In this way we predict an anomalous dispersion of second sound at the liquid-helium lambda temperature, T_λ, of the form $\omega \propto k^{3/2}$ (where ω and k are the frequency and wave number, respectively), and a relation between second-sound damping and the heat conductivity, for temperatures T below and above T_λ, respectively. Both of these quantities are predicted to vary as $|T - T_\lambda|^{-1/3}$, and recent experimental data are consistent with this singular behavior.[1,2]

A complete description of the hydrodynamics of the superfluid helium at long wavelengths entails the kinetically conjugate variables of quantum mechanical phase and mass density for the superfluid, and the corresponding variables of normal-fluid velocity and entropy density for the normal fluid. But because of the