Temperature Dependence of Microstructure of Biological Tissues Probed Via the Positronium Method

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ABSTRACT

Positron annihilation technique (PAT) has been applied for the first time to investigate the positronium (Ps) lifetime parameters those related to the microstructure of biological tissues (cow's liver and rabbit's muscles) as a function of temperature in the range of 257–383 K.

A fast, high-efficiency timing spectrometer was constructed and used to measure the lifetime spectra. They were easily resolved into three components. The long-lived one (of lifetime 2.0 to 2.6 ns and intensity 6.5 to 13.3%) was attributed to the annihilation of Ps formed in open volumes in the tissues. The nature of changes suggests that small temperature variations caused detectable changes in the free volume size of atomic scale (sub-nanometer) in which Ps is localized, and thereby, Ps lifetime and its formation probability is found to be sensitive to small changes in the tissue's microstructure.

The results indicate that PAT opens up additional possibilities of using the positronium as a sensitive probe in various fields of biology and medical physics.

INTRODUCTION

Various modern techniques for direct observation, analysis and testing of the microstructure of biological tissues have been developed, e.g., the nuclear magnetic resonance, fluorescence spectroscopy, differential scanning and electron microscopy. Each has certain application and limitation. Recently, the Positron Annihilation Technique (PAT) has found its role as spectroscopic tool to study the microstructural changes in materials in atomic scale (Mogenson, 1995).

Positrons emitted from a radioactive β^+ source lose their energy quickly in solids through inelastic collisions, and finally annihilate with electrons emitting mostly two 0.511 MeV gamma photons for each annihilated pair. In molecular substances, a significant fraction of these positrons forms positronium (Ps) before their annihilation. Ps is a bound electron-positron pair which can exist in two spin states, a short-lived para-Ps (p-Ps) with anti-parallel spins which decays into two photons with lifetime of 125 ps, and a long-lived ortho-Ps (o-Ps) with parallel spins, three photons emission and lifetime of 140 ns in free space. The positron of the o-Ps may annihilate with an electron in the surrounding medium possessing opposite spin and subsequently two gamma photons are emitted. This so-called pick-off annihilation process often dominates and reduces the mean lifetime of o-Ps to a few nanoseconds. The annihilation rate of o-Ps is then sensitive to the electron density and therefore molecular density of its environment. The details of positron and Ps annihilation processes are described elsewhere (Jean and Schrader, 1988; Hautojarvi and Corbel, 1995).

In conventional PAT measurements, the positrons injected into the investigated material can penetrate a distance of 10 -1000 μm in solids before annihilation depending on the material density; hence, the positrons probe bulk material in such measurements.

This work was performed in order to test the sensitivity of Ps (as a nuclear probe) to sub-microstructural changes in biological tissues which has not previously been reported. The temperature dependence of microstructure of biological tissues via positronium method is investigated.

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EXPERIMENTAL DETAILS

The lifetime measurements were employed using an efficient fast timing spectrometer (Elias et al., 1999) constructed for the present work. The time resolution of better than 0.38 ns was achieved at 50% of sodium-22 energy windows.

The positron source, about 285 kBq (7.7 μCi) of sodium-22 from an aqueous $^{22}NaCl$ solution was deposited between two identical aluminum foils, each of 4.5 μm thickness, glued together and inserted between the two samples in the usual "sandwich" configuration.

Tissues used to investigate the effect of temperature were cows' liver and rabbits' abdominal muscles. Pieces of 0.6 cm thickness were dissected out from these tissues, then exposed to different temperatures between 257 and 383 K (−14 to 100°C). The thickness of the investigated samples was chosen to stop all positrons emitted from the sodium-22 source.

The positron lifetime spectra were processed using modified versions of PFPOSFIT (Puff, 1983) and RESOLUTION (Kirkegaard and Eldrup, 1981) computer codes. Necessary corrections for the annihilations in the source (0.45 ns, 2.7%) and in its windows (0.25 ns, 12%) were employed during analysis.

RESULTS AND DISCUSSION

All unfolded lifetime spectra were resolved with good variance in three components each corresponds to a certain annihilation state: the shortest lifetime τ_1 varies between 0.14 to 0.22 ns, is attributed mainly to p-Ps annihilations; the intermediate lifetime τ_2 = 0.3–0.5 ns is mainly due to the annihilation of positrons in the bulk; and the long lifetime τ_3 = 2.0–2.6 ns is due to o-Ps annihilation.

The o-Ps lifetime and intensity are parameters which vary as functions of tissue's composition. They are used to evaluate the free volume hole properties. The hole size (V_h) values were determined using the following formula (Elias and Al-Bayati, 1999):

$$V_h\,(nm^3) = (0.5\,\tau_3^4 - 7.61\,\tau_3^3 + 47.31\,\tau_3^2 - 19.72\,\tau_3 - 1) \times 10^{-3}$$

where τ_3 represents the o-Ps lifetime in ns. The intensity of this component represents the o-Ps formation probability which is an indicator to the number of holes in which the Ps atoms are confined. The temperature dependence of o-Ps lifetime parameters is listed in Tables (1 and 2) for both types of tissues.

The temperature dependence of hole sizes is plotted in Figs. (1 and 2). The maximum change in hole size at the investigated range of temperature was 38% and 32% for cow's liver and rabbit's muscle tissues respectively.

The biological cell contains about 80% water which exists either as a common medium or as a solvent for many molecules, or as a bound or hydrate water associated with certain molecules. The remaining 20% are proteins, lipids, and carbohydrates. Therefore, the high water content should be considered in the interpretation of the temperature effect.

Table (1) shows that o-Ps lifetime decreases moderately between 0.5°C and 50°C. In this range, the hole size was decreased from 0.156 to 0.113 nm^3 (Fig. 1). In liquid water, there is a little space between the closely packed molecules, and the molecular rotation period is of the order of 10^{-11}s, considerably shorter than the p-Ps lifetime; hence, there will be relatively few open spaces of sufficient size and duration for Ps to form and to annihilate in before being drastically distorted by the neighboring water molecule.

As the temperature increases from 35°C to 50°C, the influence of lattice vibration and density fluctuations became important. The thermal fluctuations cause a smearing of the electron density distribution in the lattice, effectively raising the electron density in the free volume. This shortens the o-Ps lifetime and thereby reduces the hole size. Above 50°C, the tissue's structure begins to break down, probably due to the trans-gauch interconversions, i.e. rotations about a single carbon atom are increased. These kinks in the carbon chains (proteins and lipids) produce defects as the result of rearrangement in packing of carbon chains due to the increased mobility. Moreover, degradation of DNA may occur at high temperatures, and the water starts to evaporate. These events lead to reduce the o-Ps intensity (i.e., the total number of holes is decreased), and to increase o-Ps lifetime (i.e., the hole size is increased).

Below 0°C, a dramatic change is observed in o-Ps parameters (Tables 1 and 2, and Figs. 1 and 2), indicating the freezing of tissue's water and the most

striking effect here is the separation of ice from solutions and suspensions within and around the cell. Ice crystals formed in the intercellular space grow by withdrawing water from within the cell. The protoplast of the frozen cell is contracted due to the water being extracted from the cell vacuoles and ice forming in the intercellular space. Rapid freezing was thought (Smith, 1961) to cause the dehydration of the protoplasm, so that the order structural arrangement of the cell is disturbed. These rearrangements and the presence of ice will increase the o-Ps intensity (i.e. formation probability) with increasing temperature.

In ice, the relatively open hexagonal structure allows a larger fraction of positrons to form Ps, and since the period of the molecular motion in ice is about 10^{-6}s, considerably longer than that of o-Ps, the Ps can annihilate without being distorted by collisions with the molecules. The hole size values decrease sharply upon freezing as shown in Fig. (2).

CONCLUSION

The present study indicates that the positronium annihilation parameters in biological tissues are sensitive to temperature changes. The nature of changes in these parameters suggests that small temperature variations cause detectable changes in the free volume size of the tissue on atomic scale. The results indicate that PAT opens up additional possibilities of using the positronium as a sensitive probe in various fields of biology and medical physics.

Table 1: Temperature dependence of o-Ps lifetime parameters for cows' liver tissues.

Temperature K	Temperature C	o-Ps Lifetime ns	o-Ps Intensity %
259	-14	2.233 ± 0.03	7.56 ± 0.18
270	-3	2.263 ± 0.03	7.16 ± 0.10
273.5	0.5	2.594 ± 0.05	7.65 ± 0.20
290	17	2.231 ± 0.04	7.76 ± 0.20
298	25	2.235 ± 0.03	7.79 ± 0.13
310	37	2.198 ± 0.02	8.89 ± 0.10
323	50	2.178 ± 0.02	9.59 ± 0.10
363	90	2.329 ± 0.04	7.82 ± 0.20
383	110	2.400 ± 0.04	6.50 ± 0.80

Table 2: Temperature dependence of o-Ps lifetime parameters for rabbits' muscle tissues.

Temperature K	Temperature C	o-Ps Lifetime ns	o-Ps Intensity %
257	-16	2.017 ± 0.02	13.34 ± 0.19
270	-3	2.164 ± 0.03	9.56 ± 0.17
272	-1	2.185 ± 0.04	7.98 ± 0.16
275	2	2.337 ± 0.02	8.75 ± 0.18
279	6	2.290 ± 0.03	8.81 ± 0.18
283	10	2.158 ± 0.02	9.57 ± 0.17

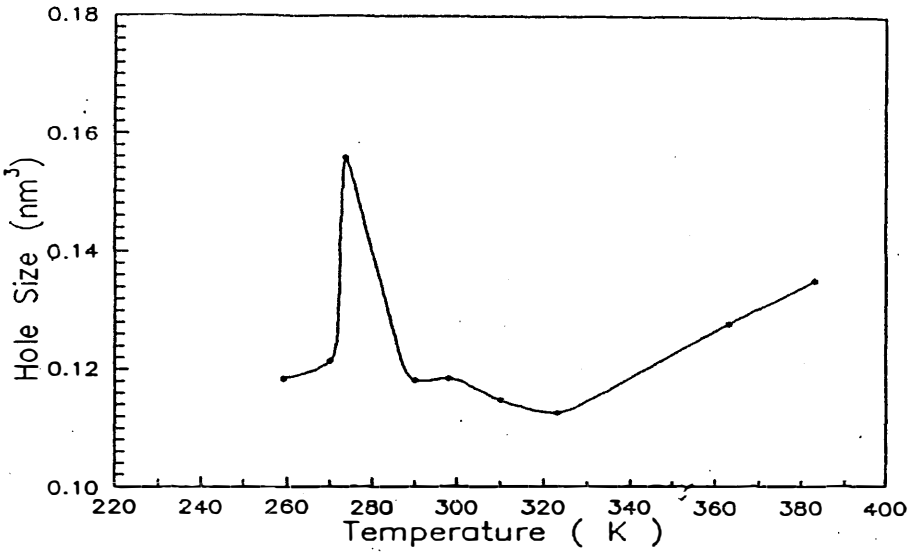

Fig. 1: Temperature dependence of the hole size for cows' liver tissues.

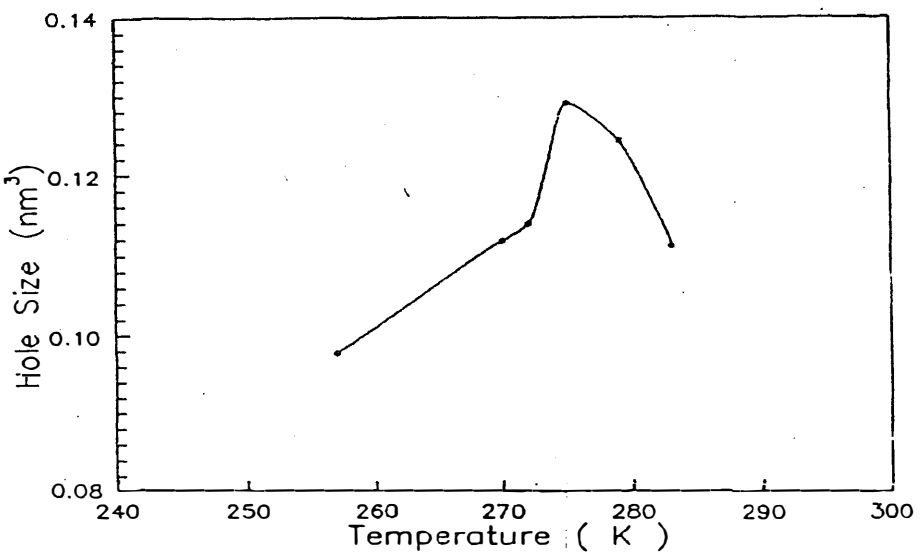

Fig. 2: Temperature dependence of the hole size for rabbits' muscle tissues.

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دراسة تأثير درجة الحرارة على التركيب المجهري للأنسجة البايولوجية باستخدام طريقة البوزترونيوم

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ملخـص

تم استخدام تقنية فناء البوزترون لأول مرة لدراسة أعلومات زمن عمر البوزترونيوم المتعلقة بالتركيب المجهري لبعض الأنسجة البايولوجية كدالة لدرجة الحرارة في المدى ٢٥٧ – ٣٨٣ كلفن. استخدمت منظومة زمنية سريعة وكفؤة بنيت لقياس الأطياف الزمنية. أمكن تحليل هذه الأطياف الى ثلاثة مركبات زمنية، عزيت المركبة الطويلة (٢.٠ – ٢.٦ نانوثانية وشدة ٦.٥ – ١٣.٣٪) الى فناء البوزترونيوم المتكون في الحجوم الحرة في النسيج.

ان طبيعة التغيرات تدل على ان التغيرات البسيطة في درجة الحرارة تؤدي الى تغيرات محسوسة في ابعاد الحجم الحر بالأبعاد الذرية (أجزاء النانوثانية) والتي يوجد فيها البوزترونيوم.

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