

Characterization of pore filling of mesoporous host systems by means of positronium annihilation lifetime spectroscopy (PALS)

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Positronium annihilation lifetime spectroscopy (PALS) is an alternative method for the determination of pore sizes and pore size distributions. It is a measuring methodology which shows no limitations in the lower nanometer region and works, besides, without destruction of the sample material. It can be used for the characterization of open and closed pores. Additionally, this technology offers the possibility to obtain pore filling ratios of gases, liquids and solids precisely. Polymorphous medicaments, like acetaminophen, show different crystallization behavior within a pore system, depending on the pore size. This property can be used to control the crystalline state of the medicament and to optimize therefore the pharmaceutical use of the active substance. In this study, acetaminophen (C₈H₉NO₂), also known as Paracetamol, is incorporated into different porous systems. The filling of the pores is realized by an acetaminophen melt at 453 K. The silica membranes are dipped into the melt, subsequently removed and cooled. Information concerning the filling ratio of the pores with the pharmaceutical was received with the help of PALS. The extended Tao–Eldrup model forms the theoretical base, taking into account the pore size sensitive annihilation properties of the ortho-positronium in matter.

Keywords: porous glasses, host–guest chemistry, positronium annihilation lifetime spectroscopy (PALS).

1. Introduction

Porous glasses are, due to their properties, ideally suited as matrix in the host–guest chemistry. These properties include a good chemical, mechanical and thermal resistance. In addition, porous glasses are characterized by adjustable pore sizes throughout the whole nanometer range (1–1000 nm), associated with a narrow pore size distribution. Another advantage is the surface of these glasses, which could be functionalized easily by the existing silanol groups [1].

Porous glasses in the form of ultra-thin plates were used, for example, to study the crystallization behavior of acetaminophen in pore systems with different pore sizes [2]. A relation between the crystallization behavior and the corresponding size of the pore system could be shown. The knowledge and the ability to manipulate the polymorphic crystalline state of pharmaceuticals are very interesting for different application fields [3]. Hence, it is possible to optimize the properties of the pharmaceuticals selectively [4, 5].

Filling the pores of porous materials with host substances can easily result in the generation of isolated and closed pores. Then standard methods, like nitrogen sorption and mercury intrusion, are unsuitable for the characterization of such materials. An alternative is the positronium annihilation lifetime spectroscopy (PALS). With this technique nanoporous materials can be investigated non-destructively. Another advantage is the possibility to characterize closed pore systems. Thus it is possible to make statements about the degree of pore filling. It could be shown, that PALS is a useful technique for the characterization of mesoporous pore systems [6].

2. Experiment

2.1. Preparation of the mesoporous host systems

In this study, a sodium borosilicate glass with the composition 70 wt% SiO₂, 23 wt% B₂O₃ and 7 wt% Na₂O was used. Porous glasses with pore diameters of 2.2 nm, 9.3 nm and 22 nm were prepared in the form of ultrathin plates with dimensions 20 mm×20 mm×0.3 mm. The production procedure of these porous glasses has been described in detail in previous papers [7, 8].

The loading of the porous glass plates with acetaminophen was performed using a 453 K melt of this pharmaceutical. The glass plates were immersed into the melt and after removal they were cooled. The acetaminophen crystallized inside the pore system and excess of it on the surface of the specimen was carefully removed with a scalpel.

2.2. Positronium annihilation lifetime spectroscopy

The PALS measurements were done using a fast–fast coincidence system [9–11] (for experimental construction see Fig. 1) with a time resolution of 250 ps (FWHM, ²²Na source), an analyzer channel width of 121.5 ps, and a number of 8000 channels corresponding to a maximum delay time of 972 ns. The activity of the used positron source was 1.2×10⁵ Bq (3.2 μCi). To avoid crycondensation effects, the sample chamber was evacuated to 10⁻⁸ mbar. The calibration curve was recorded at a temperature of 300 K. By default the statistics were collected with 4 million counts. For analysis of the lifetime spectrum the routine LifeTime [12] in its version 9.0 was used [13]. The dependence of the positronium lifetime on the pore size was described by the extended Tao–Eldrup model [14, 15]. Most of the lifetime spectra consist of four components. The two shorter lifetimes are due to positron annihilation which shows single exponential behavior. The third component is caused by positronium

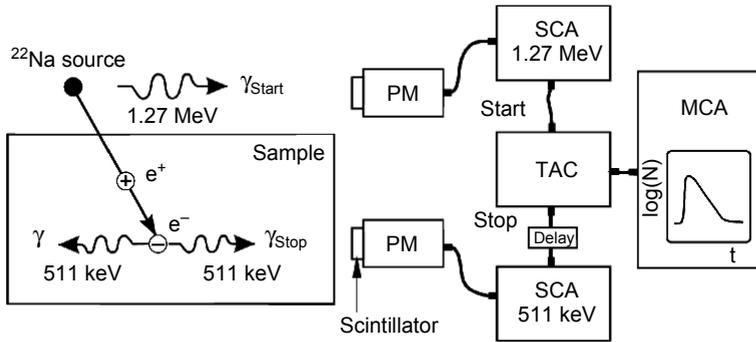


Fig. 1. The positronium lifetime is measured as time difference between the appearance of the 1.27 MeV start γ -quantum and the registration of one of the 511 keV stop γ -quanta originating from annihilation of the positronium at the pore walls. The γ -quanta are converted into an electric signal by a scintillator and photomultiplier (PM). The amplitude of this signal is proportional to the respective energy. The differentiation of a start and stop signal is accomplished by a single-channel-analyzer (SCA). The time-to-amplitude-converter (TAC) changes the time difference into a tension pulse and the impulse height is proportional to time. These pulses are stored in a multi-channel-analyzer (MCA) in the form of the lifetime spectrum $N(t)$.

annihilation inside the glass volume. This component can be satisfactorily fitted by a single exponential lifetime component. This has been confirmed by measurements of glass samples before they were processed to become a porous system. Only the longest component must often be fitted as an exponential component having a distribution of the lifetimes. This distribution is caused by the distribution of the pore size, which shows a broad variety around the mean pore size. This distribution can be fitted by the analysis program LifeTime 9.0. In this program, the probability density function of this distribution is a logarithmic Gaussian. Detailed information on spectra and measurements can also be obtained from [16].

3. Results

The ortho-positronium pick-off lifetime τ_4 illustrates the relationship between the loading of acetaminophen and the pore dimensions. It is the intensity I_4 of this lifetime revealing the degree of filling. A linear relationship between the degree of filling and intensity of the lifetime τ_4 was required. The intensity I_4 of the unloaded

T a b l e 1. Positronium lifetimes and intensities for loaded and unloaded glass membranes with different pore sizes.

Sample	Unloaded membrane		Loaded membrane	
	Lifetime [ns]	Intensity [%]	Lifetime [ns]	Intensity [%]
22 nm membrane	121	6.2	111	0.5
9.3 nm membrane	98	7.8	58	0.9
2.2 nm membrane	31	14.3	20	4.0

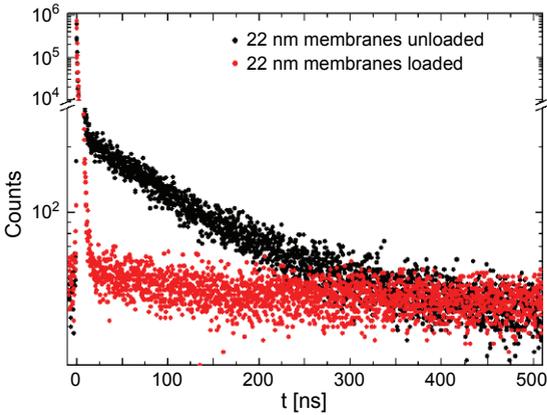


Fig. 2. Lifetime spectra of a porous glass membrane with a mean pore diameter of 22 nm before (black) and after (red) loading with acetaminophen.

sample corresponds to a degree of filling of 0%. When the pores are filled completely, the intensity is at 0% accordingly.

Lifetime spectra were taken for the samples under investigation before and after loading with acetaminophen. The resulting data are shown in Table 1. As an example Fig. 2 shows the lifetime spectra of the sample with a mean pore diameter of 22 nm.

For the loaded sample, the long lifetime component nearly disappeared from the spectrum. The analysis results in a reduced lifetime τ_4 of 111 ns with an intensity of only 0.5%. This means the pores of this material were filled up to 92% with acetaminophen. The remaining amount of unfilled pores can be explained by pores, which were inaccessible for a filling with acetaminophen. The second sample tested (9.3 nm) has a higher intensity of the lifetime after loading compared to the first one (22 nm). Nevertheless, 88% of the pores are filled. The reduction of lifetime also

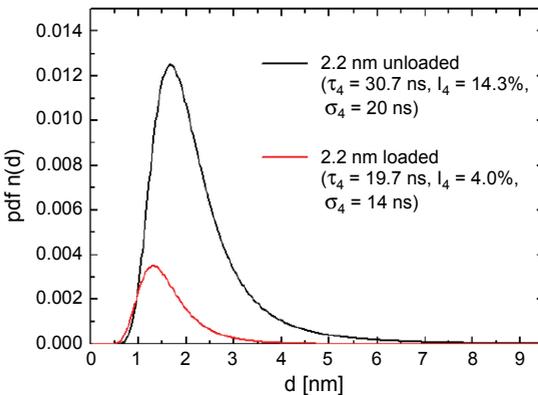


Fig. 3. Pore size distribution of the sample with a mean pore diameter of 2.2 nm before (black) and after (red) loading with acetaminophen.

points to partially filled pores. For the last sample with 2.2 nm pore size, the pore size distributions before and after loading are shown in Fig. 3. To compare the distributions directly, the intensities of the ortho-positronium lifetimes were normalized. It can be seen that the filling of the membrane, despite the very small pore size, is still relatively good (72%). After loading, the fraction of large pores is extremely low and the maximum of the distribution is shifted to smaller pores.

4. Conclusions

Porous glasses are, due to their specific properties, suitable as matrix for pharmaceuticals. So it is possible to investigate the different crystallization behavior of pharmaceuticals in bulk and under confinement. Additionally it can be concluded that positronium annihilation lifetime spectroscopy (PALS) is an alternative method for the characterization of nanoporous materials. The advantage of this technique, that also isolated and closed pores can be investigated, offers the possibility to determine the different degrees of pore filling of loaded nanoporous systems.

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