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Ice and Atoms: experiments with laboratory-based positron beams

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Abstract. This short review presents results of new positron and positronium (Ps) experiments in condensed matter and atomic physics, as an illustration of the satisfying variety of scientific endeavours involving positron beams which can be pursued with relatively simple apparatus in a university laboratory environment. The first of these two studies – on ice films - is an example of how positrons and Ps can provide new insights into an important system which has been widely interrogated by other techniques. The second is an example of how simple positron beam systems can still provide interesting information – here on a current interesting fundamental problem in positron atomic physics.

1. Introduction

Over the past forty years experimental positron beam investigations have developed from beginnings in atomic collision physics, in which for many years beam intensities of less than one positron per second were common [1], to a huge variety of studies in many fields using beams of up to 10^8 positrons per second – sometimes in large reactor or LINAC-based facilities [2-3]. Notwithstanding this impressive development, there still remain many interesting experiments which can be performed with what are today relatively standard laboratory-based positron beams. In this review two examples of such experiments are described, one with a simple beam system using a particle detector, and one with a standard medium-intensity magnetic-transport beam [4]. These are presented in the hope that science will continue to benefit from numerous small-scale endeavours as well as the ambitious, large-scale projects planned for the future.

2. Positron beam studies of ice films

While other techniques have provided insights into surface changes and pore properties of ice [5,6], VEPAS constitutes a sensitive method for studying the depth profile and evolution with temperature of both atomic and pore structure [7]. The annihilation of positrons in ice (either in the bulk or trapped in small open volume defects) is characterised by the lineshape parameter *S*, whereas the formation of Ps, which can be trapped in larger (meso-) pores or find its way to the surface via a pathway of interconnected pores, is characterised by the parameter *F*, a measure of the probability that Ps survives to decay into 3γ as ortho-Ps. The larger or more interconnected the pores are, the larger *F* will be.

2.1 Experimental method: ice films

By installing a simple copper cold finger attached to the head of a closed-cycle He refrigerator unit in the sample chamber of the magnetic-transport positron beam at the University of Bath [8], amorphous

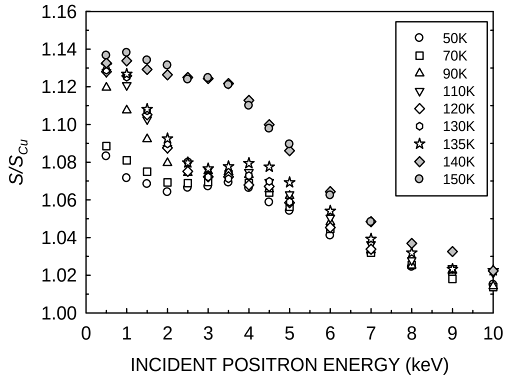

Figure 1. $S(E)/S(\mathrm{Cu})$ for a 700nm thick amorphous ice film at 50-150K.

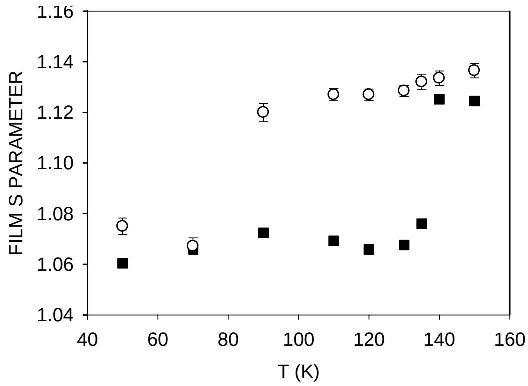

Figure 2. Fitted S for the 'bulk' film (■) and near-surface layer (o). Changes are irreversible.

solid water (ASW) films could be grown under controlled conditions by leaking vapour into the sample chamber via a needle valve from a side chamber containing pure water initially subjected to several freeze–pump–thaw cycles.

The parameter S was deduced from the 511 keV photopeak and the 3γ:2γ parameter R from the ratio of annihilation events in the 'valley' region between about 475-505 keV and in the photopeak.

2.2 Positron results: phase changes

S for an ASW film are shown in Fig. 1 as a function of sample temperature. By fitting the data assuming two layers (from 0 - 80 and 80 - 800nm) characteristic S values could be extracted [9]; these are plotted in Fig. 2. These data provide clear evidence of the sensitivity of the S parameter to the amorphous-crystalline phase transition at just below 140K. Unexpectedly, however, they also suggest that in the top 80nm region crystallisation occurs between 70-130K. This is corroborated by the S-W plot of Fig.3; the large circles represent annihilation in Cu (Cu), ASW (A), the surface (S) and crystalline ice (C). The low-E values tend towards the point C at temperatures above ~70K.

2.3 Positronium results: pore structure

The parameter F, proportional to the probability that the implanted positrons will be annihilated as ortho-Ps, was calculated from the measured ratios R. F for the film featured in Figs. 1-3 is shown in Fig. 4. The decrease of F with T is interpreted as indicating a reduction in pore size and interconnectivity until, at ~120K, almost no Ps survives to decay into three gammas- indicative of pore collapse. Over the same temperature range the effective ortho-Ps diffusion length L_{Ps} falls from ~ 120 to 12 nm, consistent with a decrease in pore interconnectivity. Above 135K F increases irreversibly when the film undergoes crystallization, associated with an increase in the Ps diffusion length.

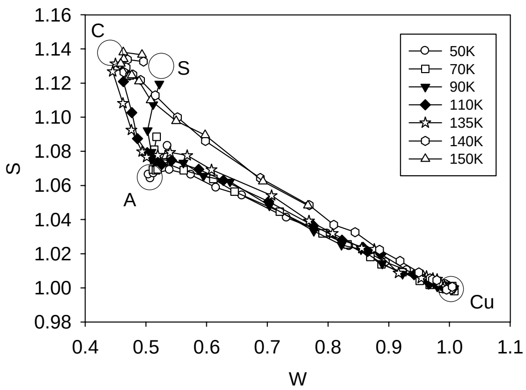

Figure 3. S-W plots at 50-150K.

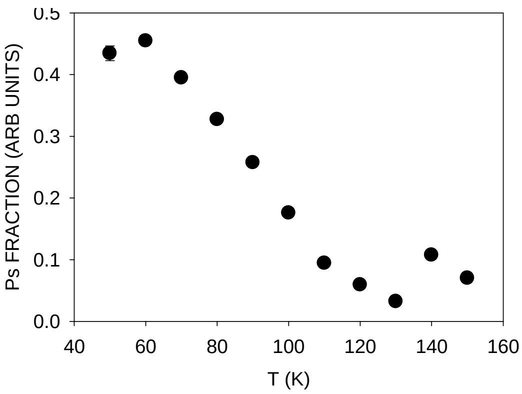

Figure 4. Fitted Ps fractions $F(T)$.

3. Elastic positron scattering above the Ps formation threshold

On the other side of the laboratory, a simple solenoid-guided positron beam system was constructed for final year undergraduate projects from hardware gathering dust on storage shelves. The simplicity of the system lent itself to straightforward positron-atom scattering measurements. However, this area of research is mature [10] and measurements have to be selected which are both possible with older technology but which are still able to add something meaningful to the field.

A candidate for such an experiment is the behaviour with positron energy of the elastic scattering cross section (Q_{el}) for positron-atom collisions in the energy range just above the Ps formation threshold. The early paper of Campeanu et al [11] proposed the existence of a cusp-like feature in Q_{el} at the Ps threshold energy in He. In an experiment in which both Q_{tot} (the total cross section) and Q_{Ps} were measured using the same apparatus, however, no significant cusp was observed [12]. A series of papers from UCL [13] concluded that there should be coupling between Q_{el} and Q_{Ps} in the noble gases near threshold, with cusps becoming more prominent with increasing Z.

3.1 Experimental method: elastic scattering

The source/moderator produced a 4mm-diameter beam of ~300 positrons s^{-1}. The energy spread of the beam was reduced to ~0.4eV FWHM by applying 2V above the moderator potential to a double 92%-transmission mesh held immediately in front of the moderator (Fig.5). This cut-off mesh also serves as an efficient reflector for back-scattered positrons. The positrons then pass through a 70mm-long gas cell, under the influence of a 5mT magnetic field. They pass through a cylindrical retarding field analyzer in the evacuated volume between gas cell and CEM detector; the total path length is approximately 400mm.

An example of the measured CEM count rate with and without as in the cell is shown in Fig. 6. The signal attenuation A_0 at V_{RFA} = 0V is due only to Ps formation events, and A_{tot} at V_{RFA} =7V is due to both elastic scattering and Ps formation). Therefore, in the limit of a thin gas cell, $Q_{el} = Q_{tot}$ (1-A_0/A_{tot}). This procedure was followed for He, Ne, Kr, Ar and Xe.

3.2 Results: elastic scattering

The results for He and Kr are shown in Fig. 7. In He and Ne there is a small but discernable cusp-like feature, the first in reasonable agreement with that seen by Caradonna et al [14]. In Ar, Kr and Xe Q_{el} rises significantly after the Ps threshold, levelling or falling slightly after a few eV [15]. This is not the expected cusp-like feature, in which the maximum is at the threshold energy.

Thus, once again, we have obtained an intriguing and unexpected result. One possible explanation is that there exists a virtual Ps state which enhances the branching into the final elastic channel. Another possibility is that the results of Fig. 8 are actually cusp-like features superimposed on a generally increasing cross section – but this requires that the energy calibration be in error by an unlikely 1eV or more. Recently Buckman et al [16] have reported measurements which suggest that cusps exist in all five gases; it will be interesting to probe why the results differ, but both groups agree

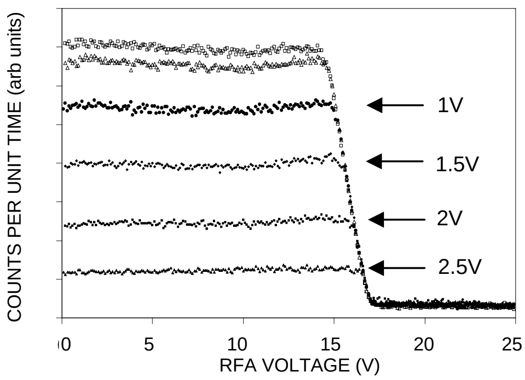

Figure 5. CEM count rate vs RFA voltage for cut-off potentials 1 - 2.5V.

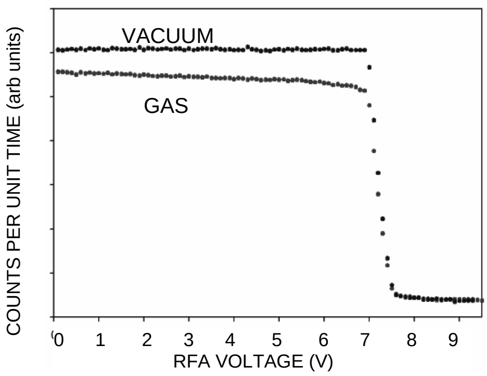

Figure 6. CEM count rate vs RFA voltage in vacuum and gas.

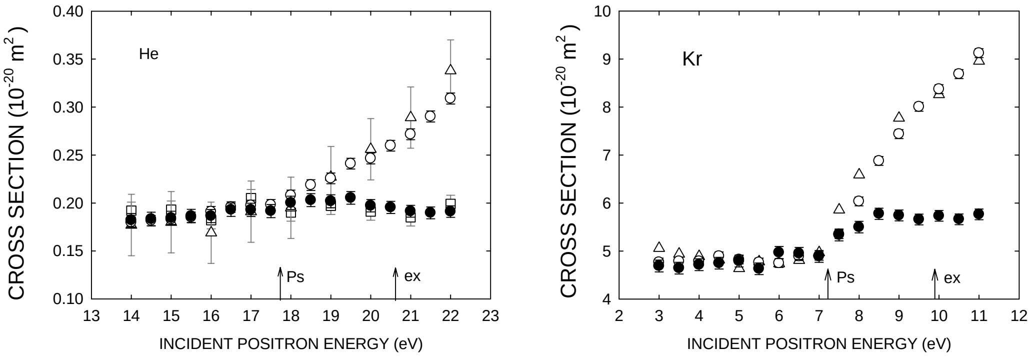

Figure 7. ●: Q_{el} for positron scattering. O: Q_{tot}. Δ: Q_{tot} from earlier measurements. □ (He): Q_{el} from ref [23]. Threshold energies for atomic excitation and ionisation are shown.

that there is an interesting energy dependence of Q_{el} in the region of the Ps formation threshold.

4. Conclusions

The purpose of this short review is to underline the potential of simple positron beam measurements to have a significant research impact. The results of the ice film measurements are likely to be of considerable interest to physical chemists, astrophysicists, cryobiologists and modellers. In the case of atomic collisions, there are clearly still interesting current questions which can be answered – or at least illuminated - by using relatively simple positron beam systems. May laboratory-based positron beam systems long continue to play a useful and important role in developing our understanding of scientific and technological problems of the day.

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