Positron cooling and annihilation in noble gases

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Observation of lifetime spectra for positrons annihilating in a gas was one of the first sources of information on positron interaction with atoms and molecules [1]. In particular, measurements of the normalised annihilation rate $Z_{\rm eff}(t)$ during positron thermalization provided information on the energy dependence of the scattering cross sections and $Z_{\rm eff}$. Understanding the dynamics of positron cooling, including the fraction of positrons surviving to thermalization, is critical for accurate interpretation of such experiments. Incomplete thermalization was suspected to be responsible for the lack of consensus among the $Z_{\rm eff}$ data in Xe [2], while modelling of $Z_{\rm eff}(t)$ [3] revealed deficiencies in the theoretical data for the heavier noble-gas atoms. Understanding of positron kinetics is also crucial for the development of efficient positron cooling in traps and accumulators [4], and for a cryogenically cooled, ultra-high-energy-resolution, trap-based positron beam [5].

Many-body theory (MBT) calculations provide an accurate description of the whole body of data on low-energy positron scattering and annihilation rates on noble-gas atoms [6]. In this work we use our MBT calculated elastic scattering cross sections, $Z_{\rm eff}$ and γ-spectra to study positron cooling and annihilation in noble gases via Monte-Carlo simulation and numerical solution of the Fokker-Planck equation. Both methods yield the positron probability density in momentum space $f(p,t)$ (see Fig. 1), from which we calculate the time-varying annihilation rate $Z_{\rm eff}(t) = \int Z_{\rm eff}(p) f(p,t) dp / \int f(p,t) dp$ and γ-spectra, and compare these with experiment, where available.

We find that a strikingly large fraction of positrons annihilate before thermalising: $\sim$90% in He (see right panel of Fig. 1), $\sim$100% in Ne (due to cooling effectively stalling in the relatively deep momentum-transfer cross section minimum), $\sim$85% in Ar, $\sim$95% in Kr and $\sim$99.97% in Xe, owing to the larger mass. For Ar, Kr and Xe, we find that $Z_{\rm eff}(t)$ is sensitive to the depletion of the distribution due to loss of annihilated particles. This is most notable in Xe, for which the vigorous increase in $Z_{\rm eff}$ at low positron momenta leads to a quasi-steady-state distribution whose low-momentum tail is suppressed relative to the Maxwell-Boltzmann distribution, and a steady-state 'thermal' annihilation rate $\bar{Z}_{\rm eff} \sim 370$ that is smaller than the true thermal $Z_{\rm eff} \sim 450$, thus explaining the discrepancy between gas-cell and trap-based measurements. Overall, the use of the accurate atomic data gives $Z_{\rm eff}(t)$ in better agreement with experiment for all noble gases except Ne, the experiment for which is proffered to have suffered from incomplete knowledge of the fraction of positrons surviving to thermalisation and/or the presence of impurities. We also show that the γ spectrum shape parameters are sensitive probes of the positron energy and cooling times, and thus provide an alternative and complementary probe to positron lifetime spectroscopy.

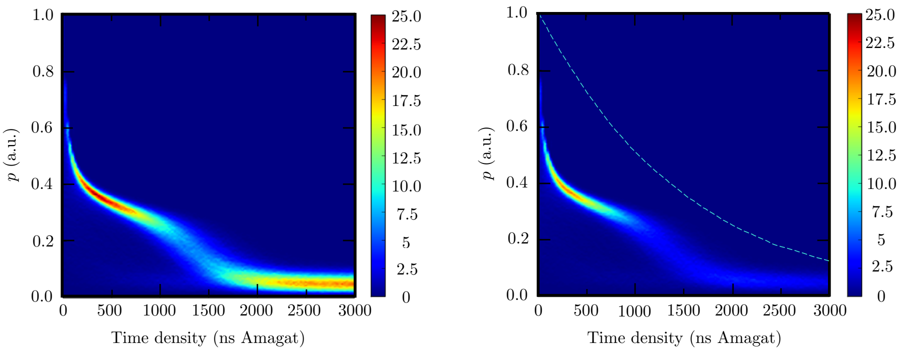

Fig. 1: $f(p,t)$ for positrons in He at 293K, initially distributed uniformly in energy up to the Ps-formation threshold: excluding (left) and including (right) annihilation. The latter distribution is normalized as $\int f(p,t) dp = F(t)$, where $F(t)$ is the fraction of positrons surviving at time t (shown by the dashed line on the right panel).

References

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