STARK AND ZEEMAN EFFECTS ON LASER COOLING OF POSITRONIUM

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ABSTRACT

Theoretical work on laser cooling of Positronium (Ps), including effects of external magnetic and electric fields, is reviewed and extended.

INTRODUCTION

Laser cooling of Positronium (Ps) was proposed in Ref. [1]. Cold Ps would benefit precision spectroscopy, production of a Bose-Einstein condensate of Ps, and the development of an annihilation gamma-ray laser. It could also be important in forming antihydrogen through the reaction $\bar{p} + Ps \rightarrow \bar{H} + e^-$ [2].

Saturation of the 1s-2p transition is a necessary condition for producing cold Ps through the technique of laser cooling. Optical saturation of this transition was recently demonstrated through observations of enhanced annihilation radiation during resonant laser excitation [3]. The enhancement of annihilation radiation results from Zeeman mixing in n=2 states of Ps [4]. External fields could, however, counteract laser cooling by trapping and/or mixing Ps into other substates. Here, detailed numerical simulations of Ps laser cooling in one-dimension are used to obtain limits on the strength of external fields for which laser cooling of Ps can be achieved.

n=1 ↔ n=2 RADIATIVE TRANSITIONS IN POSITRONIUM

Fig. 1 shows an energy level diagram for the n=1 and n=2 levels of Ps. In the absence of external fields, the energy difference ΔE_{nl} between fine structure states ~ (α^2/n^3) Ryd ~ 200 GHz/n^3. Because of the presence of ΔE_{nl} in the denominator of Stark- and Zeeman-effect corrections to the Ps wave functions in first-order perturbation theory, the magnitude of the correction is greater for states with larger values of n. Hence magnetic mixing is appreciable in n=2 Ps when B ~ 100 Gauss, whereas it is important in n=1 Ps only when B >> 1 kGauss.

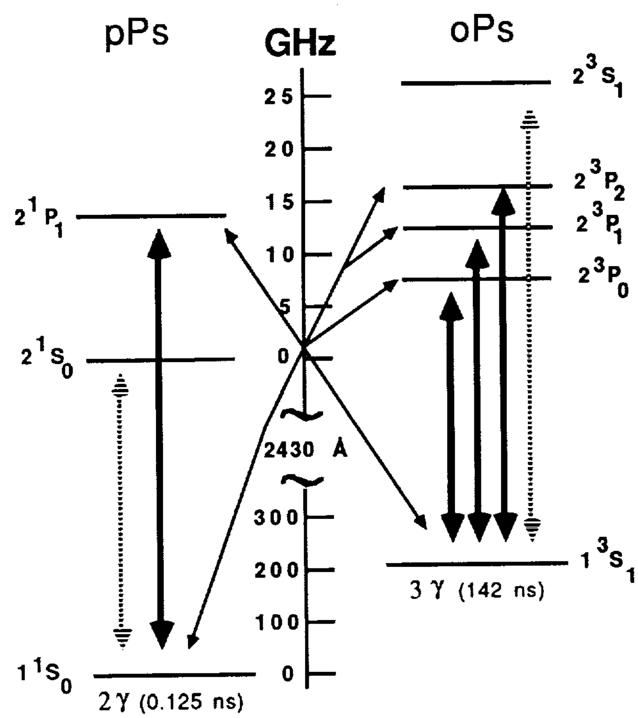


Fig. 1. Fine structure energy-level diagram of n=1 and n=2 positronium. Heavy solid lines show allowed electric dipole transitions; light solid lines and shaded lines show radiative transitions permitted in the presence of external magnetic and electric fields, respectively.

The heavy solid lines in Fig. 1 show allowed electric dipole transitions in the absence of external fields. Light solid lines show n=1↔n=2 transitions permitted in the presence of a magnetic field. A pathway between the 1^3S_1 and 1^1S_0 levels therefore exists via radiative transitions to and from the 2^1P and 2^3P levels when a magnetic field is present [4]. Because of the short annihilation lifetime of Ps in the 1^1S_0 state, an increase in the annihilation rate, depending on magnetic field strength, laser power and polarization, can be produced from resonant excitation of Ps. This signal was used to monitor optical saturation of the 1^3S-2^3P transition in Ps [3]. Also shown in Fig. 1 by the shaded lines are radiative transitions possible in the presence of an external electric field, in which case transitions between states with the same value of orbital angular momentum are possible.

LASER COOLING OF POSITRONIUM

Laser cooling of Ps to temperatures below 1 K is possible using a broadband laser negatively detuned to the 1^3S-2^3P transition [1]. For Ps, the minimum achievable temperature is determined by the photon recoil energy $R = h^2/2m_{Ps}\lambda^2$, so that $T_{min} \sim R/k_B \approx 150$ mK for the $1s \leftrightarrow 2p$ transition. Laser cooling depends on spontaneous emission to rid the atom of one unit of photon momentum. The fastest cooling allowed by this technique thus corresponds to a recoil velocity $v_R = h/m_{Ps}\lambda \cong 1.5\times10^5$ cm s^{-1} per spontaneous lifetime $\tau_{1s\leftrightarrow2p} \cong 3.2$ ns. Successful cooling of a substantial fraction of the Ps made at high temperatures must compete with the $t_{oPs} = 142$ ns annihilation lifetime of ortho-Positronium (oPs). Approximately 50 spontaneous emissions occur during the average lifetime of an oPs atom, implying that laser cooling will be successful if Ps are produced with characteristic temperatures no greater than ~ 700 K.

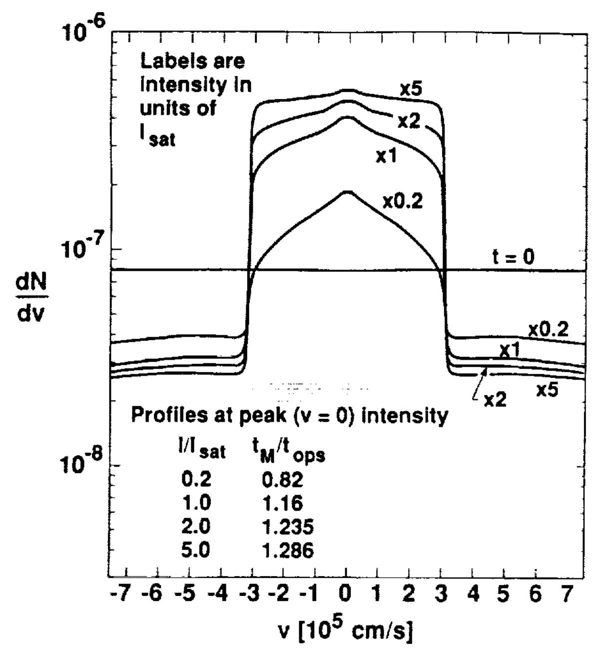
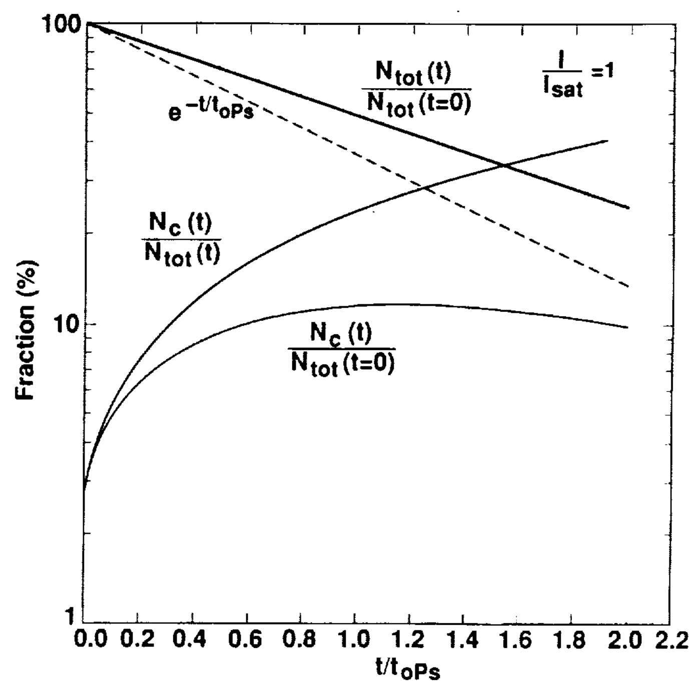


Fig. 2 (above). Positronium velocity distribution resulting from laser cooling by broadband laser light negatively detuned to the $1s\rightarrow2p$ transition frequency of Ps. Distributions for different laser intensities are shown at the time of the maximum Ps population at zero velocity. Initial Ps velocity distribution is shown by the t=0 curve.

Fig. 3 (right). Time dependences of $N_{tot}(t)$, the total number of positronium atoms remaining at time t, and $N_c(t)$, the number of Ps with velocities within one recoil velocity ($v_R \cong 1.5\times10^5$ cm s^{-1}) of zero velocity, for saturation laser intensity of the Ps $1s\rightarrow2p$ transition.

A rate equation treatment of laser cooling of Ps was used to investigate the various processes in detail. Fig. 2 shows the oPs velocity distribution dN/dv as a function of laser intensity I in units of I_{sat}, the saturation laser intensity. (I_{sat} is here defined such that the induced rate is $\pi/4$ times the spontaneous rate; cf. Ref.[4]). A laser profile with uniform intensity redward of the $1s \leftrightarrow 2p$ transition frequency was used in this simulation, and the original oPs velocity distribution was assumed to be a one-dimensional Maxwellian at room temperature. The oPs velocity profiles are plotted when dN(v=0)/dv reaches its maximum value, representing the point at which further cooling of the remaining warm oPs no longer compensates for losses due to annihilation. The peaks of the velocity profiles have roughly similar shapes irrespective of I/I_{sat}, corresponding to an effective temperature $T_{eff} \sim 0.6$ K. The amplitudes of the peak profiles approach an asymptotic value with increasing laser intensity; this again reflects the fact that only spontaneous emissions are effective in cooling.

The dependences on time t of the fraction $N_{tot}(t)$ of oPs that have not annihilated, and the fraction $N_c(t)$ of oPs with $-v_R \le v \le +v_R$, are plotted in Fig. 3 for $I = I_{sat}$. Because the oPs spend an appreciable amount of time in n=2 states with a long annihilation lifetime (≥ 0.1 ms), the average lifetime of an oPs atom is greater than t_{oPs} in the absence of fields. This is not necessarily the case when external fields are present, as we discuss in the next section.



STARK AND ZEEMAN EFFECTS ON LASER COOLING OF POSITRONIUM

External magnetic and electric fields counteract laser cooling. Magnetic fields cause mixing into S=0 para-Positronium (pPs) states from which annihilation of Ps occurs on a time scale short compared to t_{oPs}. Electric fields permit Ps to make transitions to states whose long radiative lifetimes slow the cooling rate.

Fig. 4 shows the effects of a magnetic field on laser cooling of Ps. The rate equations describing cooling were supplemented with a loss term $\propto B^2/\delta E$, representing Zeeman mixing from oPs to pPs. The term δE is an average over the energy differences between the various Zeeman-mixed states in the n=2 level, and corresponds in this simulation to linearly polarized laser light with photon propagation vector $\mathbf{k} \perp \mathbf{B}$.

Define the cooling efficiency as the ratio of the number of Ps with velocities in the range $-v_R \leq v \leq +v_R$ at time $t = t_{oPs}$, to the number of Ps in this same velocity interval at t=0. Both the cooling efficiency and the fraction of total Ps remaining at $t = t_{oPs}$ decrease rapidly with increasing magnetic field when B > 100-200 G, for $I=I_{sat}$ [Fig. 4(a)]. If B = 200 G, the cooling efficiency is greatest when $I \cong I_{sat}$, as shown in Fig. 2(b). The cooling efficiency decreases at larger values of I because faster transition rates lead to increased Zeeman mixing and loss of oPs from the system which is not compensated for by the marginally increased cooling rate.

An external electric field interferes with cooling by providing a pathway between the 1^3S_1 and the 2^3S_1 states which, having a slower radiative lifetime, therefore slows cooling. The magnitude $\mathcal{E}$ of the electric field above which this effect is important can be estimated by recalling that ~ 50 absorptions and spontaneous emissions are required for cooling. If each radiative cycle is accompanied by a loss to the 2^3S_1 state of magnitude η^2, then the electric field will affect cooling when $(1-\eta^2)^{50} \approx 1/2$. In the perturbation limit $\eta \approx 6ea_0\mathcal{E}_{||} / \delta E_S$ [4], where $\delta E_S \approx 12$ GHz (Fig. 1). Thus when the parallel electric field $\mathcal{E}_{||} \gtrsim 200$ V/cm, laser cooling of Ps is impeded. Detailed numerical simulations, including spontaneous emission from 2^3S_1 to 1^3S_1, are required to assess the Stark effect on laser cooling of Ps in detail.

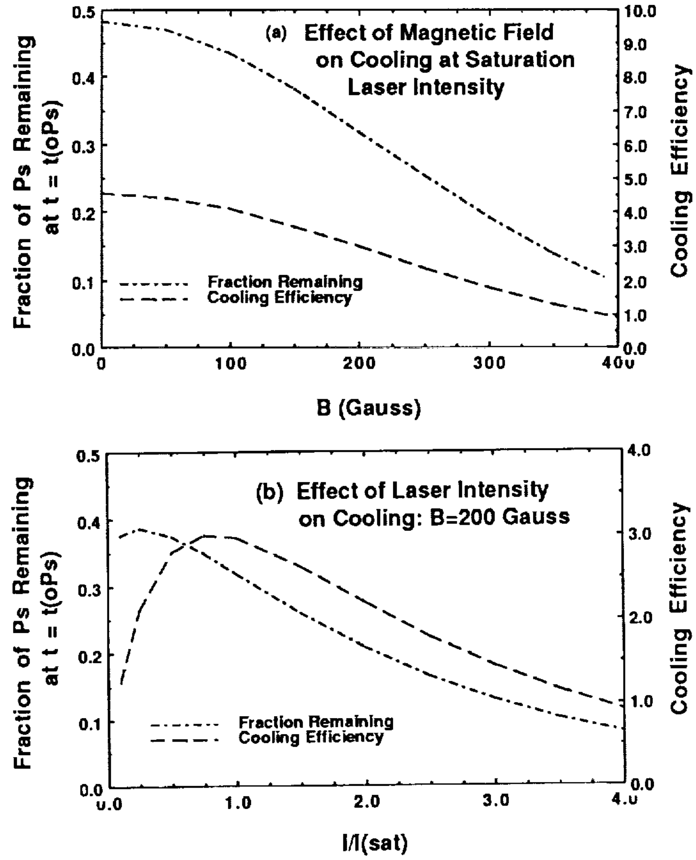


Fig. 4. Effects of an external magnetic field on laser cooling of positronium. The cooling efficiency and the fraction of Ps remaining after one oPs lifetime are shown as a function of the magnetic field at saturation laser intensity in Fig. 4(a), and as a function the laser intensity for a 200 Gauss magnetic field in Fig. 4(b).

In summary, laser cooling of Positronium can be achieved if the strengths of external magnetic and electric fields are < 100-200 Gauss and $\lesssim$ 200 V/cm, respectively.

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