Optical Society of Korea Summer Meeting (8.17~18, 2000)

# 다준위 원자의 레이저 냉각 및 펌핑

# Laser Cooling and Pumping of Multilevel Atoms

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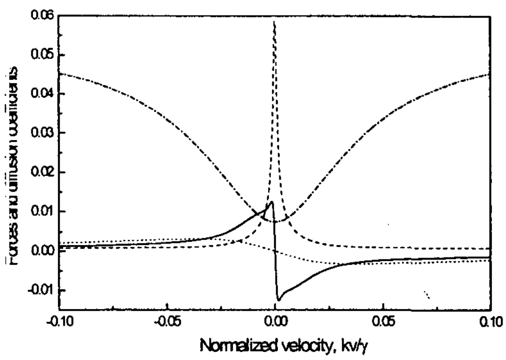
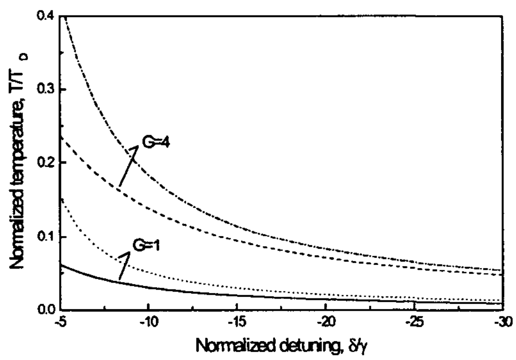
**Theoretical foundations of atom dynamics in laser fields are reviewed in relation with applications to laser spectroscopy, control of atomic motion, atom traps and frequency standards. Quasiclassical kinetic equations are applied to multilevel atomic schemes interacting with counter-propagating laser waves to describe the properties of atomic populations and coherence and the time evolution of atomic distribution function. Basic types of the dipole radiation forces on atoms are discussed for the realistic cases of multilevel dipole interaction schemes such as 3(g)+5(e), 3(g)+3(e), 5(g)+3(e), 5(g)+7(e), 3(g)+3(e)+5(e) and 1(g)+3(g)+3(e)+5(e).**

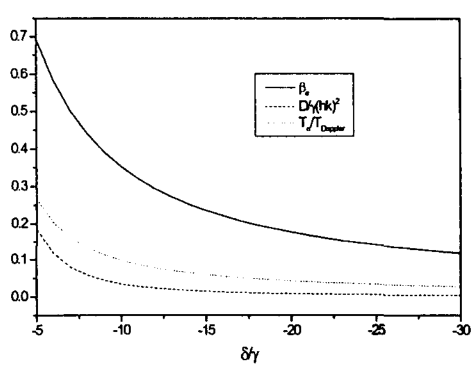
Deep laser cooling of atoms by counter-propagating laser waves is now commonly applied to experiments of atomic and optical physics in two basic laser field configurations, a $\sigma_+ - \sigma_-$ configuration composed of two counter-propagating waves circularly polarized in opposite directions and a Lin-Lin configuration composed of linearly polarized waves with orthogonal polarizations. In typical experimental schemes of deep laser cooling, atoms are excited by the laser waves at the dipole transitions between hyperfine structure magnetic sublevels $|F, m\rangle$ in cases when upper-state degeneracy $2F_e + 1$ exceeds the ground-state degeneracy $2F_g + 1$ These schemes are nowadays of broad use in experiments on laser cooling of atoms in atomic vapors or in magnetic and magneto-optical traps. Earlier studies of laser cooling of atoms in the above two basic field configurations have already given useful estimations for the friction forces and atomic temperature.(1) It is, however, still unclear what is the quantitative difference between the laser cooling processes produced by the two basic field configurations when they are applied to the same atomic scheme under the same conditions. This question is nowadays of importance for applications of laser cooling schemes to microwave and optical frequency standards and high precision spectroscopy. More broad physical interest to comparison of the two basic laser cooling schemes comes from still unclear questions of what is the difference between the elementary excitation processes in two schemes and why the two laser cooling field configurations lead to a very close value of atomic temperature. In the dressed-state picture the cooling processes for the $\sigma_+ - \sigma_-$ and Lin-Lin configurations are attributed to the behavior of the total field polarization in space and described by physically different polarization-gradient cooling mechanisms.(1)

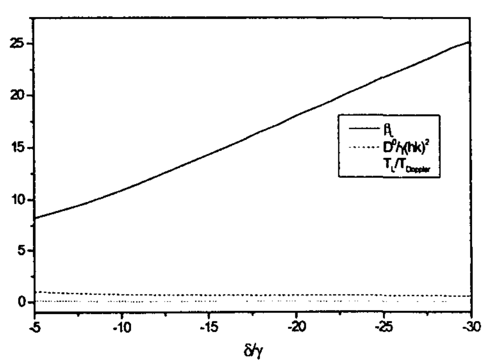
We have recently derived from the kinetic theory approach that the physical mechanism responsible for deep laser cooling in a $\sigma_+ - \sigma_-$ field configuration is based on the two-photon atomic transitions between the ground-state sublevels.(2, 5) In a case of a $\sigma_+ - \sigma_-$ configuration the two-photon processes were found to contribute to the ground-state atomic coherence near zero velocity. The ground-state coherence modifies in turn the ground-state atomic populations and optical coherences near zero velocity. This results in a narrow dispersive structure near zero velocity in the radiation force and a narrow dip in the momentum diffusion coefficient centered at zero velocity. The high friction coefficient due to the radiation force and a low momentum diffusion coefficient were found to be responsible for the sharp narrowing of the velocity distribution of atoms, i.e., for the subDoppler laser cooling of atoms in a $\sigma_{+}-\sigma_{-}$ field configuration.

We have also extended the kinetic theory of laser cooling of multilevel atoms to a case of Lin-Lin field configuration and compared the underlying physical processes and effectiveness of laser cooling of atoms by the two basic field configurations.[6] As before, we have investigated the simplest model of a (3+5)-level atom that includes three ground-state magnetic sublevels ($F_g=1$) and five upper-state sublevels ($F_e=2$). The kinetic theory approach shows that similar to a case of $\sigma_{+}-\sigma_{-}$ field configuration, in a Lin-Lin field configuration the even-order multiphoton processes are responsible for narrow velocity structures in atomic populations, coherences, radiation force and diffusion coefficient at zero velocity. Alongside we find that a physical picture of atomic excitation by a Lin-Lin field configuration is more complicated as compared with that of a $\sigma_{+}-\sigma_{-}$ configuration. While a $\sigma_{+}-\sigma_{-}$ field configuration produces a single two-photon process connecting the ground-state sublevels, a Lin-Lin field configuration induces the four-photon and higher even-order multiphoton processes including stepwise multiphoton processes composed of the two-photon processes. Most important of them is found to be the stepwise four-photon process. This process produces a super-narrow velocity structure that is broadened by the rest even-order processes. The four-photon process produces the increase in the friction due to the radiation force but it simultaneously produce increase in the diffusion coefficient. As a result, the four-photon process as well as other multiphoton processes give a small contribution to the atomic temperature that is found to be asymptotically close to that for a $\sigma_{+}-\sigma_{-}$ field configuration at large detunings. We have thus concluded that the laser cooling mechanism in a Lin-Lin field configuration is based mainly on the stepwise four-photon process while in a $\sigma_{+}-\sigma_{-}$ field configuration it is based on the two-photon process.

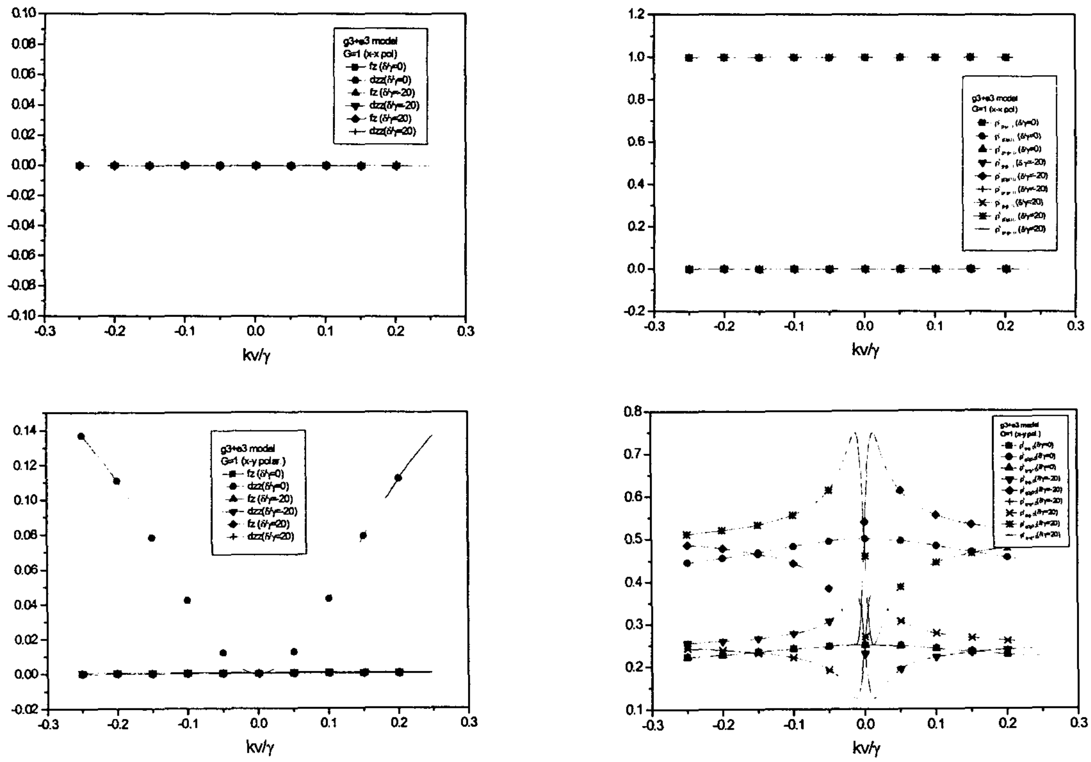


Similar to a case of (3+5)-level scheme, our kinetic theory has been applied to different types of multilevel dipole interaction schemes such as 3(g)+3(e), 5(g)+3(e), 5(g)+7(e), 3(g)+3(e)+5(e) and 1(g)+3(g)+3(e)+5(e) for studying the possibility of laser cooling of the atoms and optical pumping of the atoms to a single ground-state magnetic sublevel that is important in an atomic fountain clock.

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