Frequency Independent Laser Cooling of Atoms and Molecules

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For many atoms, laser-cooling techniques can routinely provide ensembles with temperatures down to the mikrokelvin regime [1]. The simplest laser cooling scheme is Doppler cooling, which occurs when a two-level atom is irradiated by counterpropagating laser beams tuned a few linewidths below the frequency of an absorption line [2]. At very low velocities, more subtle cooling mechanisms, as polarization gradient cooling, come into play. All these laser cooling techniques have in common, that they depend critically on the detuning from the atomic resonance. This implies, that only single atomic species and isotopes can be cooled with one optical frequency. Moreover, systems with a richer internal structure, such as more complex atoms and all molecules with their vibrational and rotational structure have yet resisted laser cooling. Cold molecules have so far been produced indirectly by photoassociation of atoms and cooling with a buffer gas [3].

Here, a novel mechanism for laser-cooling is proposed which is based on a sequence of four short laser pulses designed to realize a matter wave interferometer [4]. The key point is that with the proposed scheme the probability of transferring photon momenta to a particle depends on its velocity, but not on the relative detuning of the optical frequency from an absorption line. This detuning independence allows the simultaneous laser-cooling of several different species or isotopes of atoms with similar transition wavelengths, and has prospects for the laser-cooling of molecules. In a two-level configuration, the optical pulses induce transitions between an electronic ground state $|g\rangle$ and an excited state $|e\rangle$, as shown in Fig. 1. When the excited state is populated after the pulses, it relaxes into the ground state after a spontaneous lifetime τ (assume $\tau > 4T$, where $4T$ is the total length of the pulse sequence). As in the case of Doppler cooling, an average momentum of a photon recoil, $\hbar k$, is transferred to the particle if the excited state is populated, since the spontaneously emitted photon has a random direction.

An insensitivity to the relative detuning has long been observed both in spin and photon echo experiments. For the internal particle quantum numbers, the proposed scheme resembles a double spin echo sequence. In contrast to echo experiments the fringe signal here is sensitive to the particle velocity, as the proposed interferometer does not form a closed loop. The velocity dependence of the fringe signal can be intuitively understood by considering the spatial phase dependence of a plane matter wave $\psi \propto e^{i p_z z / \hbar}$ propagating along the z-axis with velocity p_z/m. With a separation $\Delta z = 8T\hbar k/m$ between paths at the interferometer output, one derives a velocity dependent phase $\Delta \phi = 8Tkp_z/m$. The excitation rate into the upper state, and also the net momentum transfer, varies sinusoidally with the particle velocity. The velocity resolution is determined by the time between the pulses, and requires a typical pulse spacing T of a

nanosecond for a Doppler resolution of a few hundred MHz. The proposed scheme allows the simultaneous laser cooling of samples of (effective) two-level systems with different resonance frequencies, as e.g. different atomic species or isotopes.

Let us now discuss the application of this cooling scheme to diatomic molecules with their broad multitude of transitions. For molecules, the pulse length should be chosen so short that the pulse frequency bandwidth exceeds the vibrational splitting. With a sufficiently short optical pulse, an excitation from all substates of the electronic ground state is possible. As such short optical pulses prepare superpositions of several substates of the electronic levels, the generated rovibrational wavepackets evolve with time. The fringe contrast expected for molecules has been estimated using a density matrix approach [4]. It is found, that a clear interference signal is obtained from probability contributions that are in the same sublevels of the electronic states in both interfering paths. A more realistic theoretical model of the cooling process for molecules should also account for optical pumping, a distribution of Franck-Condon factors and effects as photoionization. An application of the proposed scheme towards a laser cooling of molecules seems sufficiently promising that further model calculations and experimental studies appear worthwhile.
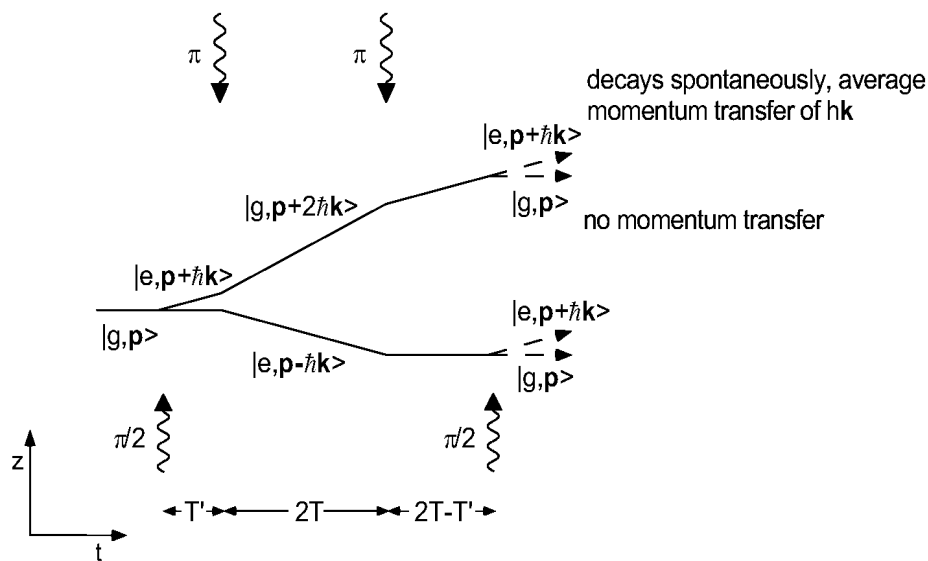

Figure 1: Scheme of a frequency independent matter wave interferometer for laser cooling.

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