coherent amplification in laser cooling and trapping

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Optical scattering forces, such as for Doppler cooling and magneto-optical trapping, may be **amplified** without further spontaneous emission using the state-dependent deflection by a pulsed or chirped laser field. Amplified forces allow more **compact deceleration** of beams with **reduced transverse heating**, and suit species with **open level schemes** where losses due to spontaneous emission and re-pumping would otherwise dominate the cooling process itself.

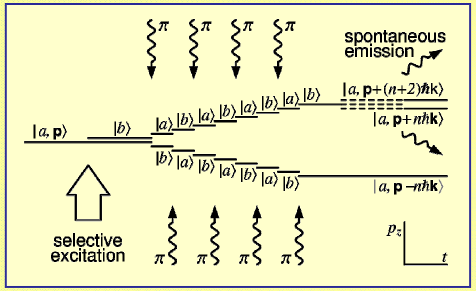
OPTICAL SCATTERING FORCES

MOT and Doppler cooling forces use the photon impulse accompanying position/velocity-dependent absorption

	scattering	amplified	
max impulse	$\hbar k$	$2n\hbar k$	per lifetime
spont. emission	one	one	per lifetime

AMPLIFIED FORCES

By separating the selective excitation from the impulse, the interaction with counter-propagating, interleaved trains of population-inverting π-pulses has been used[1,2] or proposed to give a significant enhancement to the scattering force. Applications include efficient momentum transfer for beam deflection[3,4], increasing the path separation in atom interferometers[5], and an amplified cooling mechanism[6].



References

1 B. Nölle et al., Europhys. Lett. 33, 261 (1996).
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3 M. Cashen et al., J. Opt. B. 4, 75 (2002)
4 M. Cashen and H. Metcalf, J. Opt. Soc. Am. B. 20, 915 (2003)
5 D. S. Weiss, B. C. Young and S. Chu, Appl. Phys. B. 59, 217 (1994)
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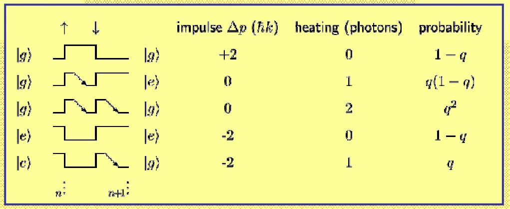
ANALYSIS

We divide the sequence into pairs of counter-propagating pulses. Depending upon the atomic state at the start of the period, and whether spontaneous emission occurs, there are five possible outcomes, shown below:



	↑ ↓		impulse Δp ($\hbar k$)	heating (photons)	probability
$\|g\rangle$		$\|g\rangle$	+2	0	$1-q$
$\|g\rangle$		$\|e\rangle$	0	1	$q(1-q)$
$\|g\rangle$		$\|g\rangle$	0	2	q^2
$\|e\rangle$		$\|e\rangle$	-2	0	$1-q$
$\|e\rangle$		$\|g\rangle$	-2	1	q
	n ⋮ n+1 ⋮				

This ultimately gives a mean impulse after *n* pulse pairs

$$I_n = 2\left\{\frac{1-q}{2-q} - e_0\right\}\frac{(1-q)^{2n}-1}{(1-q)^2-1}(2-q)$$

where q is the spontaneous emission probability and e_0 the initial excitation. The variance is given by

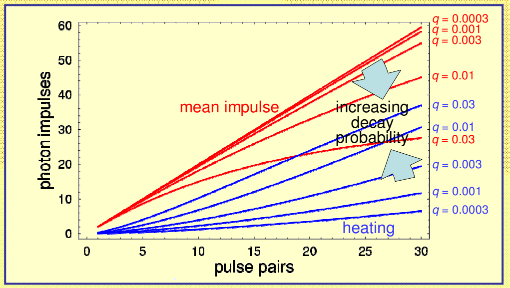
$$\begin{aligned}\Delta_n^2 = \Delta_0^2 &- \frac{4}{q^2}\left\{\frac{1-q}{(2-q)^2}[q^2-3q+3] - \frac{q^2-2q+2}{2-q}e_0 + e_0^2\right\}\\ &+\frac{8(1-q)}{q(2-q)}n + \frac{4(1-q)^{2n}}{q^2}\left\{1-q-(2-q)e_0+2e_0^2\right\}\\ &-\frac{4(1-q)^{4n}}{q^2}\left\{\frac{(1-q)^2}{(2-q)^2} - 2\frac{1-q}{2-q}e_0 + e_0^2\right\}.\end{aligned}$$

and the probable number of spontaneous decays is

$$D_n = \frac{2q}{2-q}n + q^2\left(\frac{1-q}{2-q} - e_0\right)\frac{(1-q)^{2n}-1}{(1-q)^2-1}.$$

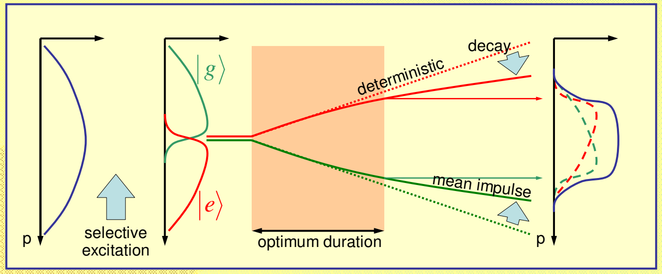
giving a combined heating term

$$\Delta_n^{(T)2} = \Delta_n^2 + \alpha D_n^2$$



OPTIMUM COOLING STRATEGY

For a given initial velocity distribution, we may use our results to determine the optimum duration of pulse sequence with which to amplify a velocity-selective excitation: a combination of best overlap and minimum heating.



For the regime in which spontaneous emission may be neglected, the optimum sequence length reduces an initially Gaussian distribution **to 36% of its initial temperature within a single excited state lifetime**.

LOGARITHMIC COOLING SERIES

A series of sequences, each tailored to the starting temperature, can thus reduce the number of lifetimes required for a given cooling impulse to its logarithm: a distribution with a width of 10,000 $\hbar k$ can be cooled to its recoil limit in as few as **10 sequences**. The number of **spontaneous decays** is reduced by the same **factor of 1000**.

APPLICATIONS

- **amplified force** – faster **deceleration** of atomic beams
  – cooling on **intercombination** lines
- **reduced transverse heating**
  – atomic beams
- **reduced spontaneous emission**
  – **molecules** and open level schemes