Thursday, April 18, 2024

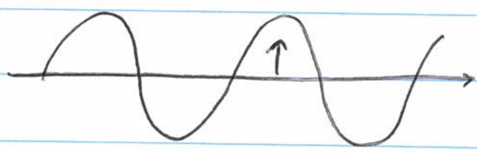
Laser cooling below the Doppler cooling limit

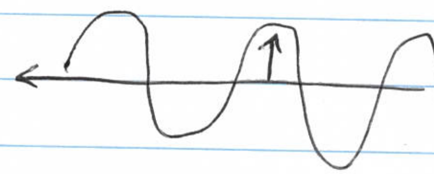
Sisyphus cooling

A_ Review of optical standing waves

1 – Counter-propagating with identical polarizations

(and identical frequencies)





$\vec{E}_{left} = E_0 \cos(kx - \omega t)\hat{y}$ $\qquad$ $\vec{E}_{right} = E_0 \cos(kx + \omega t + \cancel{\phi})\hat{y}$

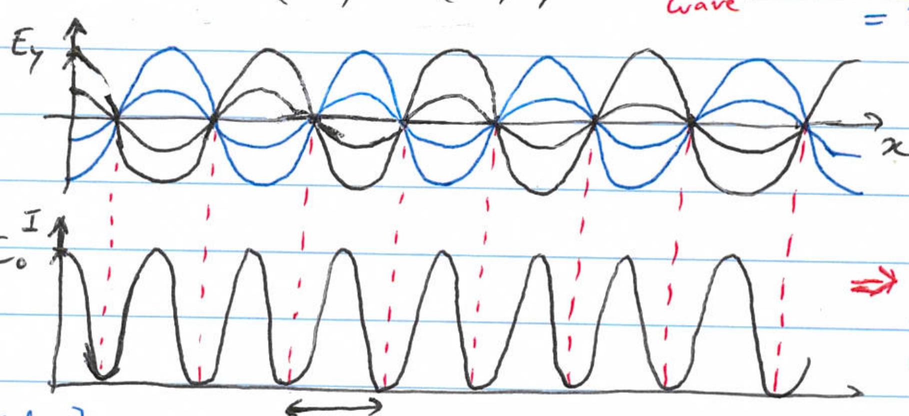
ignore (important, but not for today's physics)

$\Rightarrow \vec{E}_{total} = \vec{E}_{left} + \vec{E}_{right}$

$= E_0 \left[\cos(kx - \omega t) + \cos(kx + \omega t) \right] \hat{y}$

$= 2E_0 \cos(kx) \cos(\omega t)\, \hat{y}$ ← standing wave

trigonometric identity $\cos a + \cos b = 2\cos\left(\frac{a+b}{2}\right)\cos\left(\frac{a-b}{2}\right)$



$I = 4E_0^2 \frac{\varepsilon_0}{2} \cos^2(kx)$

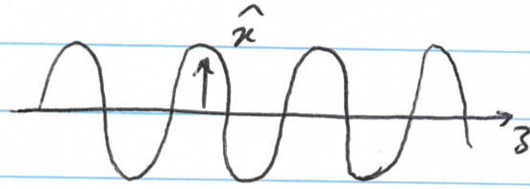
$= 4I_0 \left[\frac{1}{2} + \frac{1}{2}\cos(2kx)\right]$

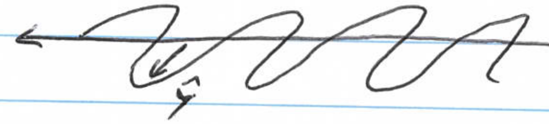
1D optical lattice

⇒ If used as a far off-resonance optical dipole potential, then it is a "crystal" of light for atoms.

2. Counterpropagating perpendicular polarizations

(called "Lin ⊥ Lin" or "lin-perp-lin")





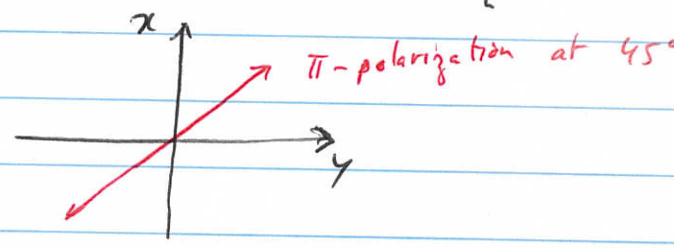
$$\vec{E}_{left} = E_0 \cos(kz - \omega t)\hat{x} \qquad \vec{E}_{right} = E_0 \cos(kz + \omega t + \cancel{\phi})\hat{y}$$

ignore again

$$\vec{E}_{total} = E_0 \cos(kz - \omega t)\hat{x} + E_0 \cos(kz + \omega t)\hat{y}$$
$$= E_0 \left\{ \cos(\omega t - kz)\hat{x} + \cos(\omega t + kz)\hat{y} \right\}$$

$\boxed{\text{reminder: } k = \frac{2\pi}{\lambda}}$

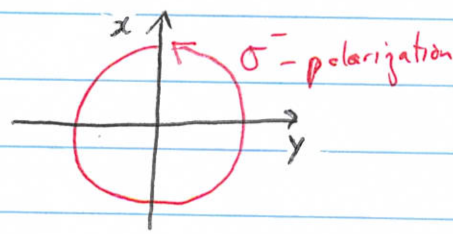
<u>case 1</u>: $kz = 0 \Rightarrow z = 0$ and $\vec{E}_{total} = E_0 \left[\cos(\omega t)\hat{x} + \cos(\omega t)\hat{y} \right]$



<u>case 2</u>: $kz = \pi/4 \Rightarrow z = \frac{\lambda}{8}$ and $\vec{E}_{total} = E_0 \left[\cos(\omega t - \pi/4)\hat{x} + \cos(\omega t + \pi/4)\hat{y} \right]$

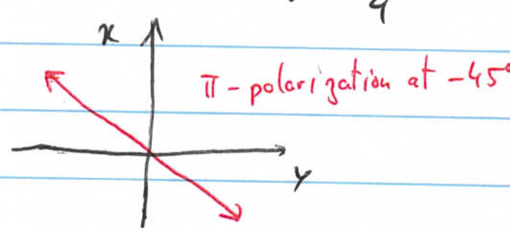
time origin shift: $t = t' + \frac{\pi}{4\omega}$

$$= E_0 \left[\cos(\omega t')\hat{x} + \cos(\omega t' + \pi/2)\hat{y} \right]$$
$$= E_0 \left[\cos(\omega t')\hat{x} - \sin(\omega t')\hat{y} \right]$$



<u>case 3</u>: $kz = \pi/2 \Rightarrow z = \frac{\lambda}{4}$ and $\vec{E}_{total} = E_0 \left[\cos(\omega t - \pi/2)\hat{x} + \cos(\omega t + \pi/2)\hat{y} \right]$

$$= E_0 \left[\sin(\omega t)\hat{x} - \sin(\omega t)\hat{y} \right]$$

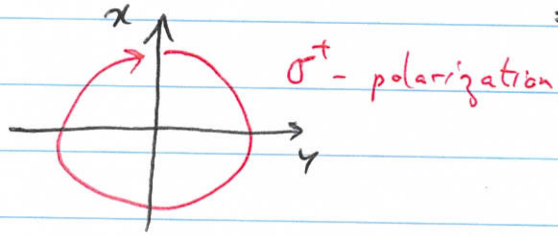


<u>Case 4</u>: $kz = \frac{3\pi}{4} \Rightarrow z = \frac{3\lambda}{8}$ and $\vec{E}_{total} = E_0\left[\cos\left(\omega t - \frac{3\pi}{4}\right)\hat{x} + \cos\left(\omega t + \frac{3\pi}{4}\right)\hat{y}\right]$

time origin shift: $t = t' + \frac{3\pi}{4\omega}$

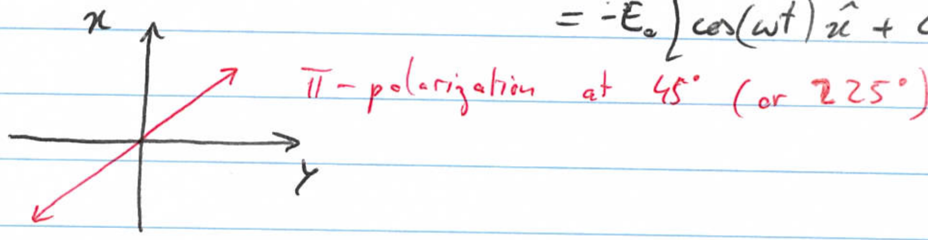
$$= E_0\left[\cos(\omega t')\hat{x} + \cos\left(\omega t' + \frac{3\pi}{2}\right)\hat{y}\right]$$

$$= E_0\left[\cos(\omega t')\hat{x} + \sin(\omega t')\hat{y}\right]$$

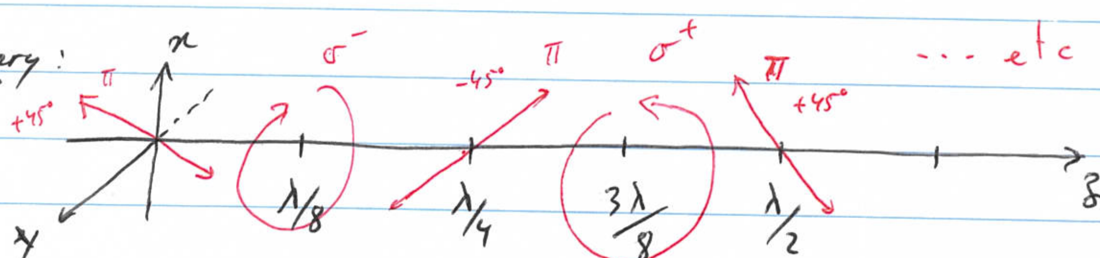


<u>Case 5</u>: $kz = \pi \Rightarrow z = \frac{\lambda}{2}$ and $\vec{E}_{total} = E_0\left[\cos(\omega t - \pi)\hat{x} + \cos(\omega t + \pi)\hat{y}\right]$

$$= -E_0\left[\cos(\omega t)\hat{x} + \cos(\omega t)\hat{y}\right]$$



<u>Summary</u>:



$\Rightarrow$ we get a standing wave, but with a periodic gradient in the polarization

Show Powerpoint slides on Sisyphus Cooling

<u>Sisyphus cooling temperature</u>: $kT_{sisyphus}\Big|_{theory} \simeq \frac{(\hbar k)^2}{2m} \gg \Delta E_{stark}$

$^{87}Rb \Rightarrow T_{sisyphus\ theory} = 370\,nK$

$$kT_{sisyphus}\Big|_{practical} \simeq \genfrac{}{}{0pt}{}{10}{100}\, kT_{sisyphus}\Big|_{theory}$$

Magnetic Traps

(I) Hamiltonian

The Hamiltonian for an atom in an external B-field is given by

$$H = \frac{P_{cm}^2}{2M} + \underbrace{H_{atom}}_{\frac{p^2}{2m} + \frac{q^2}{R}} + \underbrace{H_{Zeeman}}_{= -\vec{\mu}\cdot\vec{B} = \mu_B g_F m_F |\vec{B}|}$$

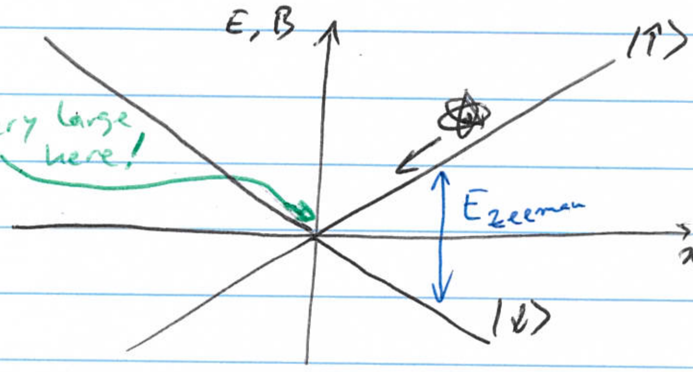
note: potential energy = internal energy level shift

quantization axis given by direction of local magnetic field.

semiclassical criterion for adiabatic motion:

$$\frac{H_{Zeeman}}{\hbar} \gg \frac{1}{B}\left(\frac{dB}{dt}\right)$$

$\frac{dB}{dt}$ is very large here!



you don't want the Fourier frequency components of a frequency/energy ramp to include ω_{Zeeman} $[E_{Zeeman} = \hbar\omega_{Zeeman}]$

If adiabaticity is satisfied, then the "angle" between $\vec{\mu}$ & $\vec{B}$ stays the same, and the atoms stay in their m_F-level/state defined by the local magnetic field quantization axis.

$$H_{Zeeman} = -\vec{\mu}\cdot\vec{B} = -|\vec{\mu}|\,|\vec{B}|\underbrace{\cos\theta}_{\text{constant}}$$ ← classical expression

$$= \underbrace{m_F\, g_F\, \mu_B}_{\text{constant}}\,|\vec{B}|$$ ← quantum expression (if motion is adiabatic)

positive

magnitude of $|\vec{B}|$ determines the potential energy

with $\mu_B = \dfrac{|e|\hbar}{2m_e} = 9.27408\times10^{-24}$ J/Tesla

$= h \times 1.4$ MHz/G

$\Rightarrow$ $\boxed{\text{Magnetic potential energy is proportional to } |\vec{B}|.}$