7/4/25.

Optical cooling / Laser cooling

Scattering rate (r) : 10^8/sec.

$\lambda = 500\,nm$.

Scattering force =

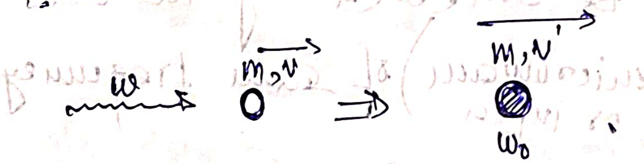
$$= \frac{6.626 \times 10^{-34} \times 10^{8} \times \cancel{\;}}{500 \times 10^{-9}}$$

$$-34+16+9-8$$

$$= \frac{3.9756 \times 10}{3}$$

$$\cancel{= 1.3\ldots \times 10^{-17}}$$

$$= \boxed{1.32 \times 10^{-17}\ m s^{-2}}.$$



we follow energy conservation.

$$\hbar\omega + \tfrac{1}{2}mv^2 = \hbar\omega_0 + \tfrac{1}{2}mv'^2 \quad \text{------ (1)} \quad [\text{energy}].$$

$$\frac{\hbar\omega}{c} - mv = mv' + \cancel{\frac{\hbar\omega_0}{c}} \quad [\text{internal will cancel out}] \quad \text{--- (2)} \quad [\text{momentum}]$$

$$\frac{\hbar^2\omega^2}{m^2c^2} + \frac{m^2v^2}{m} - \frac{2mv\hbar\omega}{mc} = m^2 v'^2 . m.$$

$$\hbar\omega + \cancel{\tfrac{1}{2}mv^2} = \hbar\omega_0 + \tfrac{1}{2}\left[\frac{\hbar^2\omega^2}{mc^2} + \cancel{mv^2} - \frac{2v\hbar\omega}{c}\right]$$

$$\hbar\omega = \hbar\omega_0 + \frac{\hbar^2\omega^2}{2mc^2} - \frac{\cancel{2}\hbar\omega v}{c}.$$

neglect $\frac{1}{c^2}$ term.

$$\therefore \cancel{\hbar}\omega = \cancel{\hbar}\omega_0 - \cancel{\hbar}\frac{\omega v}{c}.$$

$$\boxed{\omega_0 = \omega\left(1 + v/c\right)}.$$

$$\therefore \omega = \frac{\omega_0}{1+v/c} = \omega_0\left(1 - v/c + \frac{1}{2}(v/c)^2 \dots\right).$$

linear doppler shift: $\frac{\omega_0 v}{c}$.

Quadratic " " $= \frac{\omega_0 v^2}{2c^2}$ $\boxed{\left(+\frac{\hbar\omega^2}{2mc^2}\right)}$ $\rightarrow$ shift due to photon recoil

without ignoring $1/c^2$ term:

$$\omega = \omega_0 + \frac{\hbar\omega^2}{2mc^2} - \frac{\omega v}{c}$$

$$\omega\left[1 + v/c - \frac{\hbar\omega}{2mc^2}\right] = \omega_0.$$

$$\omega = \frac{\omega_0}{1+\left(v/c - \frac{\hbar\omega}{2mc^2}\right)}$$

Q) consider a beam of ions:

$$\boxed{\begin{aligned} v_0 &= 3\times10^5 \text{ m/s.} \\ \lambda_0 &= 500 \text{ nm.} \\ M &= 100 \text{ amu} \end{aligned}}$$

$K = \frac{\omega_0}{c} = \frac{2\pi}{\lambda_0}$.

$\omega_0 = \left(\frac{2\pi c}{\lambda_0}\right)$.

Linear doppler shift

$$\frac{2\times3.14\times\cancel{3\times10^8}}{500\times10^{-9}} \times \frac{3\times10^5}{\cancel{3\times10^8}} = \boxed{3.76\times10^{12}\ \text{Hz}}$$

Quadratic doppler shift:

$$\frac{2\times3.14\times\cancel{3\times10^8}}{2\times500\times10^{-9}} \times \frac{3\times10^5\times\cancel{3}\times10^5}{\cancel{3\times10^8}\times\cancel{3}\times10^8}$$

$$= 18.84\times10^{10-8+9-8}$$

$$= 1.884\times10^{10-11} = \boxed{1.88\times10^9}.$$

photon recoil:

$$\frac{\hbar\omega^2}{2mc^2} \approx 10^{-16}\ Hz.$$

Optical cooling

4/25

Q) Beam of atom: $v = 500\,ms^{-1}$.
width of beam: 2 mm.
lifetime of transition $= 10^{-8}$ s
How many absorption/emission the atom undergoes?

~~beam velocity → $250 \times 10^{3}\,s^{-1} \times 10^{-8}$~~

~~2.5×10^{-3}~~

$$\frac{2 \times 10^{-3}}{5 \times 10^{2}}\ s$$

$= 4 \times 10^{-5}$ s.
4×10^{-6} s.

(*) Time required to pass the beam

⇒ 4×10^{-6} s = 4 μs → এই সময়ে থাকে

$$\frac{\boxed{4 \times 10^{-6}}}{10^{-8}} \times 10^{8} = \boxed{400 \text{ cycles}}$$ → $\boxed{\text{of absorption/emission}}$

→ per second এত গুলো transition হয়।

Q) How much energy will be transferred by photon recoil if emitted freq is ω. → (n cycles)

Momentum transfer → $n(\hbar k)$

velocity → $n\frac{\hbar k}{m}$

Total energy per atom → $\frac{1}{2} m \times \left(\frac{n\hbar k}{m}\right)^2 = \frac{n^2\hbar^2 k^2}{2m}$

cycles

(*) $\boxed{\Delta E_{recoil}}$

Q) Na atoms

Mass = 23 amu. $= 23 \times 1.67 \times 10^{-27}$ kg

absorb a photon of energy $= 2\,eV = 2 \times 1.6 \times 10^{-19}$ J.

$\Delta u =$ ~~$\frac{2 \times 1.6 \times 10^{-19} \times 2}{23 \times 1.67 \times 10^{-27}}$~~

$= 1.08 \times 10^{4}$

$= 1.08 \times 10$

$\Delta v = \dfrac{h\nu}{Mc}$ = (should be) → $\boxed{3\ m/s}$.

v_0 = 600 m/s থেকে v = 20 m/s.

per photon কমবে 3 m/s.

$\dfrac{600 - 20\ m/s}{3\ m/s} = \dfrac{580}{3} = \boxed{194} \approx \boxed{200}$ emissions/absorptions

lifetime for sodium → 16 ns = 16×10^{-9} s.
minimum cooling time → 200 × lifetime.

$= 200 \times 16 \times 10^{-9}$

$= 3.2 \times 10^{-6}$ = 3.2 μs.

initial velocity → 600 m/s থেকে 20 m/s.

$\dfrac{\Delta v}{\text{cooling time}} = \dfrac{580}{3.2} = 181.25 \times 10^{+6}\ m s^{-2}$

$= \boxed{1.8 \times 10^{8}\ m s^{-2}}$ → accelaration cooling

path travelled by Atom $= ut + \frac{1}{2} f t^2$.

$= 600 \times 3.2 \times 10^{-6} + \cancel{\frac{1}{2}} \times \cancel{1.8}\,.9 \times 10^{8} \times 3.2 \times 10^{-6} \times 3.2 \times 10^{-6}$.

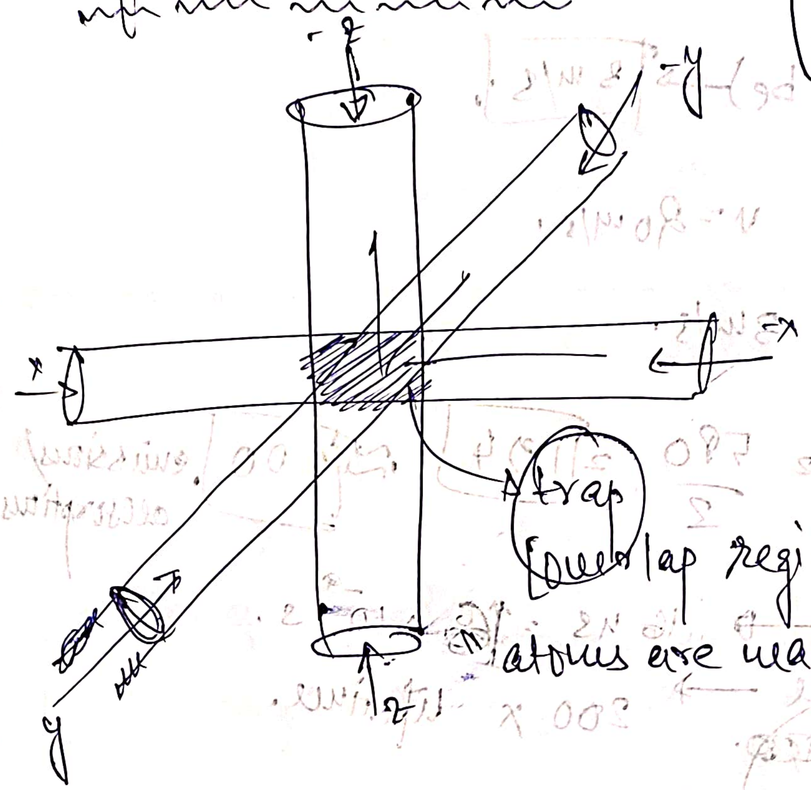
$= 1.92 \times 10^{-3} + 9.216 \times 10^{-4}$.

$= (1.92 + .92) \times 10^{-3}$.

$= 2.84 \times 10^{-3}$ m. $\approx \boxed{3\ mm}$.

Minimum beam length.

Optical molasses



[six counter propagating laser beams]

Pump-probe spectroscopy

10 marks (Line shape)

10 mark (raman scatter) [graphene etc].

10 mark (rabi osc) [weak + strong field].

10 mark (optical cool)

10 mark. (non linear spectro)