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WINTER COLLEGE ON
HIGH RESOLUTION SPECTROSCOPY

(8 January - 2 February 1990)

OPTICAL MOLASSES

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OPTICAL MOLASSES,

NEW LASER-COOLING MECHANISMS and THE COLDEST GAS IN THE UNIVERSE

National Institute of Standards and Technology (Formerly NBS)

P. Lett
C. Westbrook
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H. Metcalf S.U.N.Y.
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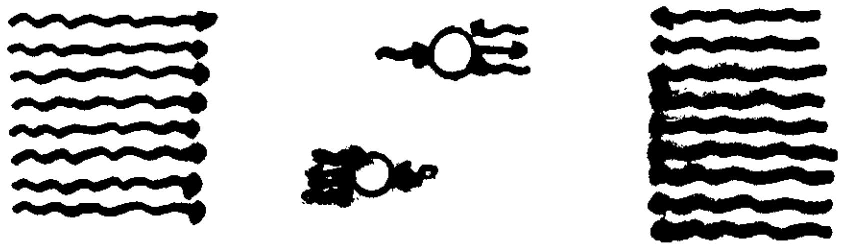
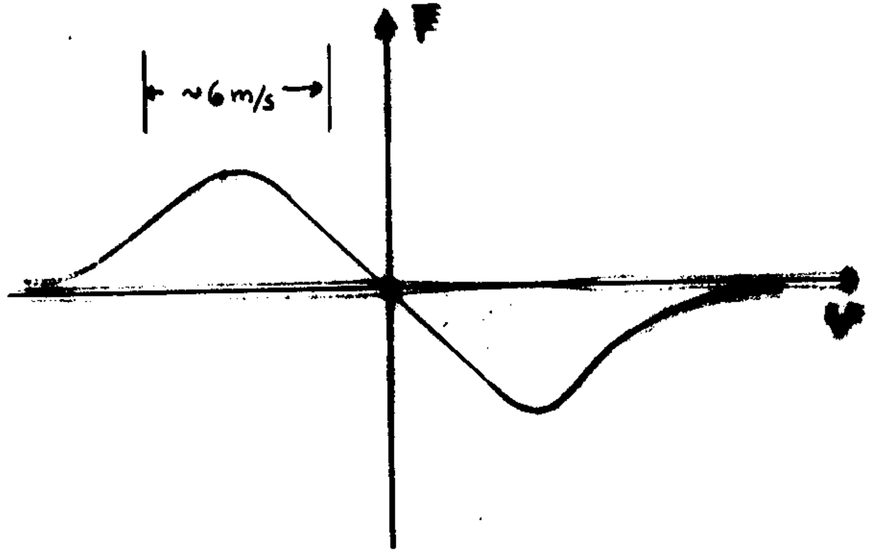
J. Dalibard
ENS
A. Clairon
C. Cohen-Tannoudji

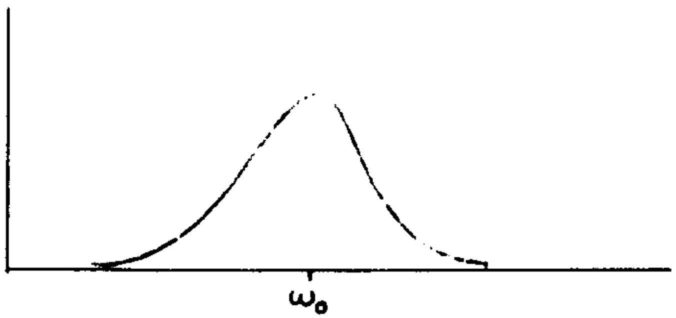
"Balanced" Cooling

(Hansch + Schawlow 1975)





Excitation Lineshape



at rest

2-level atom, fraction in excited state

$$f = \frac{1}{2} \frac{I/I_0}{1 + I/I_0 + \left(\frac{2\Delta}{\Gamma}\right)^2}$$

$\Delta = \omega - \omega_0$

$\Gamma = 1/\tau_N$

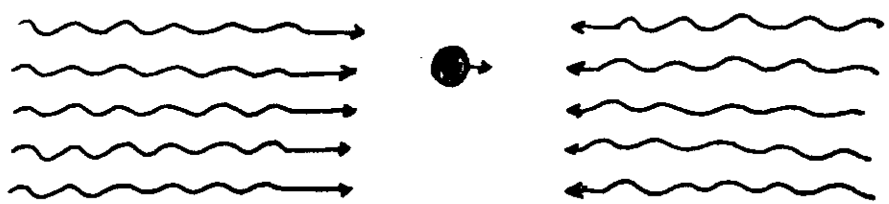
oving atom: $\Delta \rightarrow \Delta - \vec{k}\cdot\vec{v}$

absorption rate $R = f \cdot \Gamma$

$I/I_0 \rightarrow 0$

$$R = \frac{\Gamma}{2} \frac{I/I_0}{1 + \left[\frac{2(\Delta - k \cdot v)}{\Gamma}\right]^2}$$

OPTICAL MOLASSES 1-D



for $I << I_0$:

$$F_l = \frac{\hbar k \Gamma}{2} \frac{I/I_0}{1 + \left[\frac{2(\Delta - kv)}{\Gamma}\right]^2} \qquad F_r = -\frac{\hbar k \Gamma}{2} \frac{I/I_0}{1 + \left[\frac{2(\Delta + kv)}{\Gamma}\right]^2}$$

for $kv \ll \Delta, \Gamma$

$$F(v) = F_l + F_r \approx \underbrace{F_l(0) + F_r(0)}_{0} + v\left(\frac{dF_l}{dv} + \frac{dF_r}{dv}\right)$$

$$\frac{dF_{l,r}}{dv} = \mp \frac{\hbar k \Gamma}{2} \frac{(I/I_0)\left[\mp 4\left(\frac{\Delta \mp kv}{\Gamma}\right)\frac{2k}{\Gamma}\right]}{\left[1 + \left(\frac{2\Delta}{\Gamma}\right)^2\right]^2} \approx \frac{2\hbar k^2 (I/I_0)\cdot\left(\frac{2\Delta}{\Gamma}\right)}{\left[1 + \left(\frac{2\Delta}{\Gamma}\right)^2\right]^2}$$

$$F(v) = \frac{4\hbar k^2 \left(\frac{2\Delta}{\Gamma}\right)\frac{I}{I_0} v}{\left[1 + \left(\frac{2\Delta}{\Gamma}\right)^2\right]^2} = -\alpha v \qquad \alpha > 0 \text{ for } \Delta < 0$$

$$F \cdot v = -\alpha v^2 = \dot{E}_{cool}$$

(cooling rate)

1-D Cooling Limit

heating rate in "mythical" 1-D case $(I/I_0 \ll 1)$

$$\dot{E}_{heat} = \frac{\dot{p^2}}{2M} .$$

Now p, the atomic momentum, random walks
one step = $\hbar k$ for every absorption
<u>and</u> emission.

$$\langle p^2 \rangle = 2N(\hbar k)^2 \qquad N = \text{absorbed photons}$$

$$\frac{\dot{p^2}}{2M} = \frac{\hbar^2 k^2}{2M} 2 R_{abs}^{(z\text{-beam})} = \frac{\hbar^2 k^2}{M} \Gamma \frac{I/I_0}{1+\left(\frac{2\Delta}{\Gamma}\right)^2} = \dot{E}_{heat}$$

$$\text{set} \quad \dot{E}_{heat} - \dot{E}_{cool} = 0$$

$$\frac{\hbar^2 k^2 \Gamma}{M} \frac{I/I_0}{[\quad]} = \frac{4\hbar k^2 \left(\frac{2\Delta}{\Gamma}\right) v^2 \, I/I_0}{[\quad]^2}$$

$$\frac{1}{2} M v^2 = \frac{\hbar\Gamma}{8} \frac{1+\left(\frac{2\Delta}{\Gamma}\right)^2}{\left(\frac{2\Delta}{\Gamma}\right)} \cong \frac{1}{2} k_B T$$

$$k_B T_{min} = \frac{\hbar\Gamma}{2} \qquad \Delta = -\Gamma/2 \qquad (I/I_0 \ll 1)$$

240 μK for Na

The Doppler Cooling Limit

$$k_B T = \frac{-\hbar\Gamma}{4} \frac{1+(2\Delta/\Gamma)^2}{2\Delta/\Gamma}$$

minimize at $\Delta = -\Gamma/2$

where $k_B T_D = \dfrac{\hbar\Gamma}{2}$

T_D = 240 μK for Na
120 μK for Cs

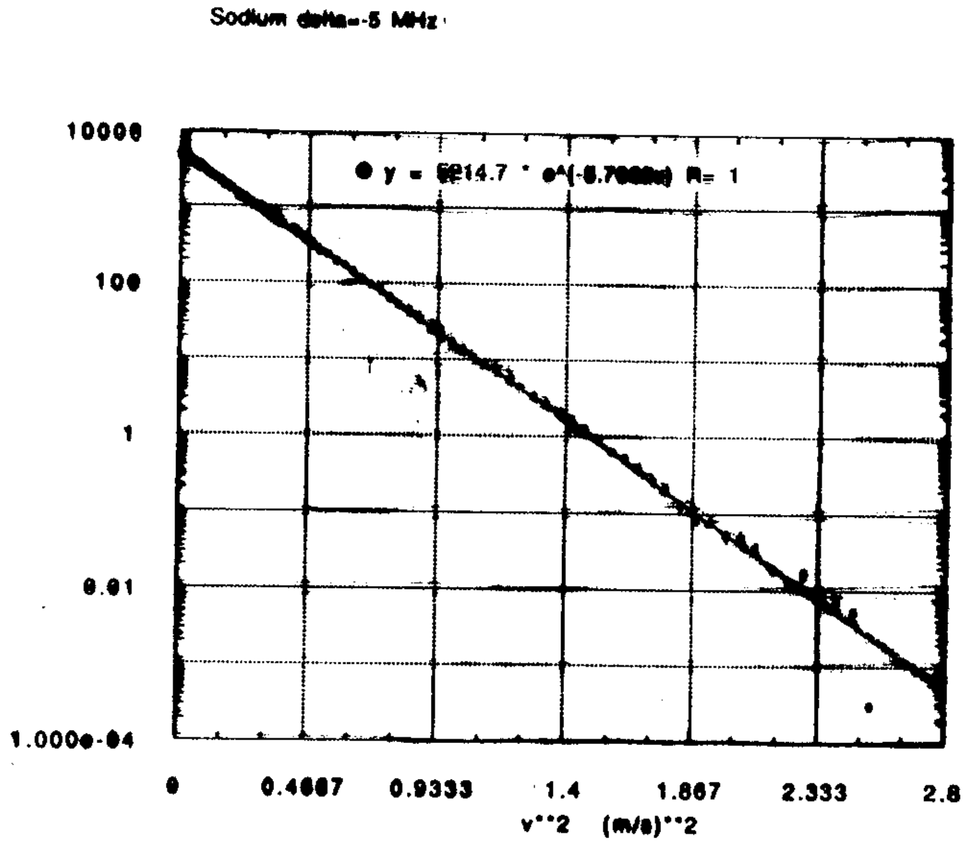
Cooling Limit in 3-D ($I \ll I_0$)

- Consider each component of $\vec{v}$
- Each is damped exactly as in 1-D
- Emissions can go off in all directions (less heating for a given component)
- <u>But</u> other directions contribute to this direction with <u>their</u> emissions
- So: heating is the same.

so $\frac{1}{2} m v_x^2 = \frac{\hbar\gamma}{4} = \frac{1}{2} k_B T_{min}$

$$\frac{1}{2} m |\vec{v}|^2 = \frac{3\hbar\gamma}{4} = \frac{3}{2} k_B T_{min}$$

$$k_B T_{min} = \frac{\hbar\gamma}{2} \quad \text{in 3-D as in 1-D}$$



$\vec{F} = -\alpha \vec{v}$

$\dot{E}_{cool} = \vec{F}\cdot\vec{v} = -\alpha v^2 \propto E_{KINETIC}$

$\frac{E_{KIN}}{-\dot{E}_{cool}} \sim 20\,\mu s$ (optimum cond. for Na)

but !

The momentum takes a random walk

$\dot{p}^2 \propto R_{SCATT} \propto \dot{E}_{HEAT}$

$\dot{E}_{HEAT} = \dot{E}_{COOL} \Rightarrow k_B T = \frac{\hbar\gamma}{2}$

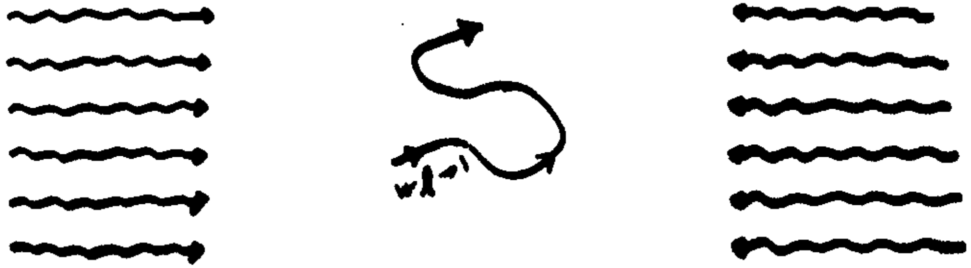
$\langle v^2 \rangle \propto \frac{R}{\alpha}$

$\langle v^2 \rangle^{1/2} \sim 50$ cm/s (cooling limit)

$T = 240\,\mu K$

OPTICAL MOLASSES

(the "molasses effect")



For Na $1/\gamma \sim 40\,\mu s = \tau$

and $\langle v^2 \rangle^{1/2} \sim 0.5$ m/s

$l = v\tau \sim 20\,\mu m$

random walk: $\langle x^2 \rangle^{1/2} = l\left(\frac{t}{\tau}\right)^{1/2}$

for $t = 1$ sec, $\langle x^2 \rangle^{1/2} \sim 3$ mm

(compare to 500 mm for ballistic motion)

Bell Labs 1985 theory + expt

NBS 1985 theory (Dalibard)

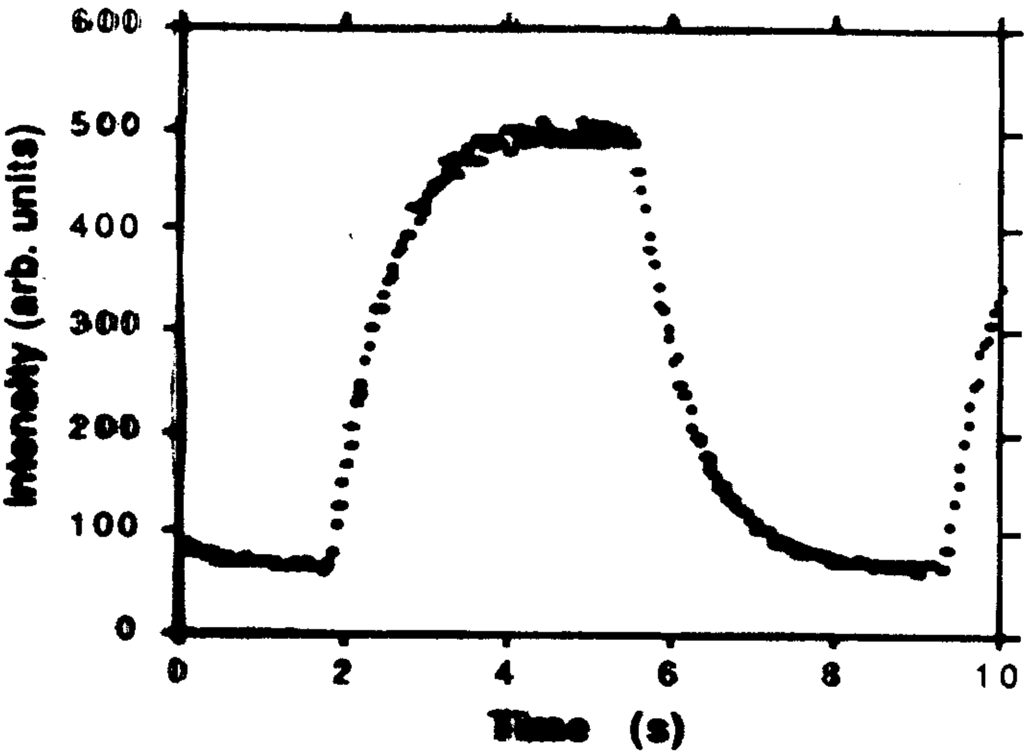
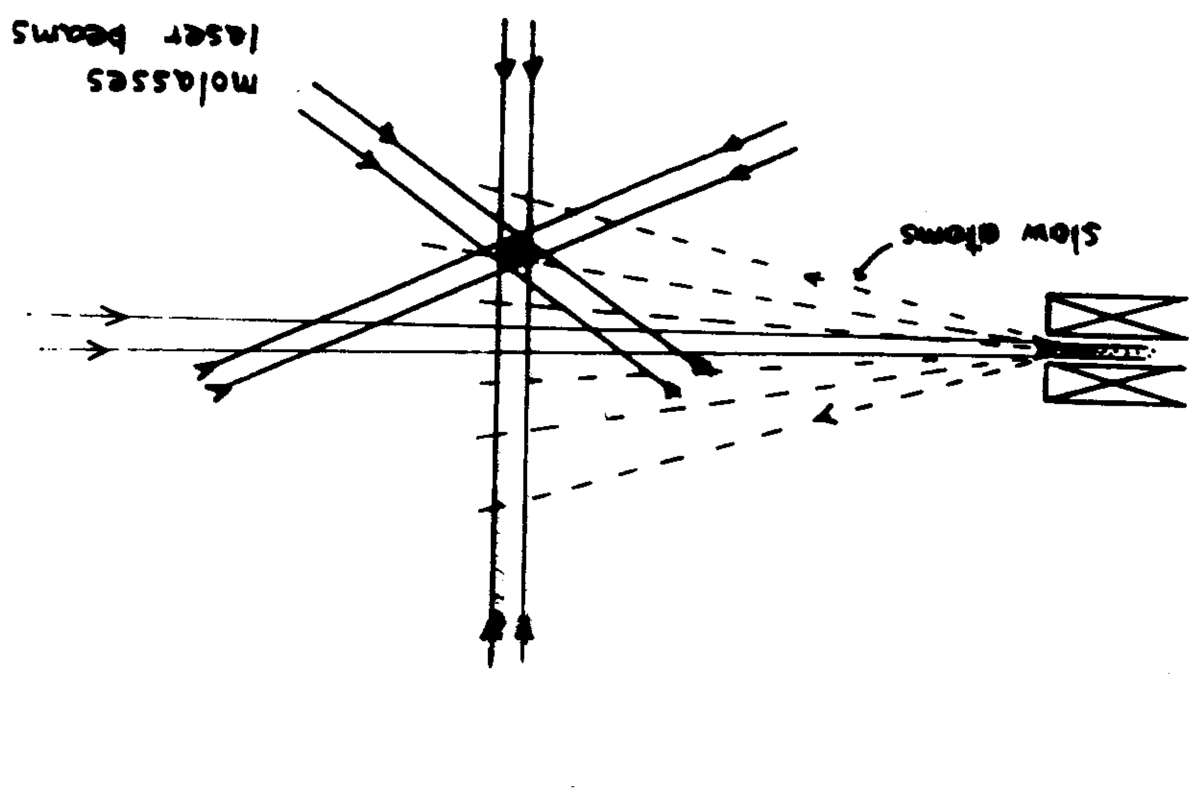
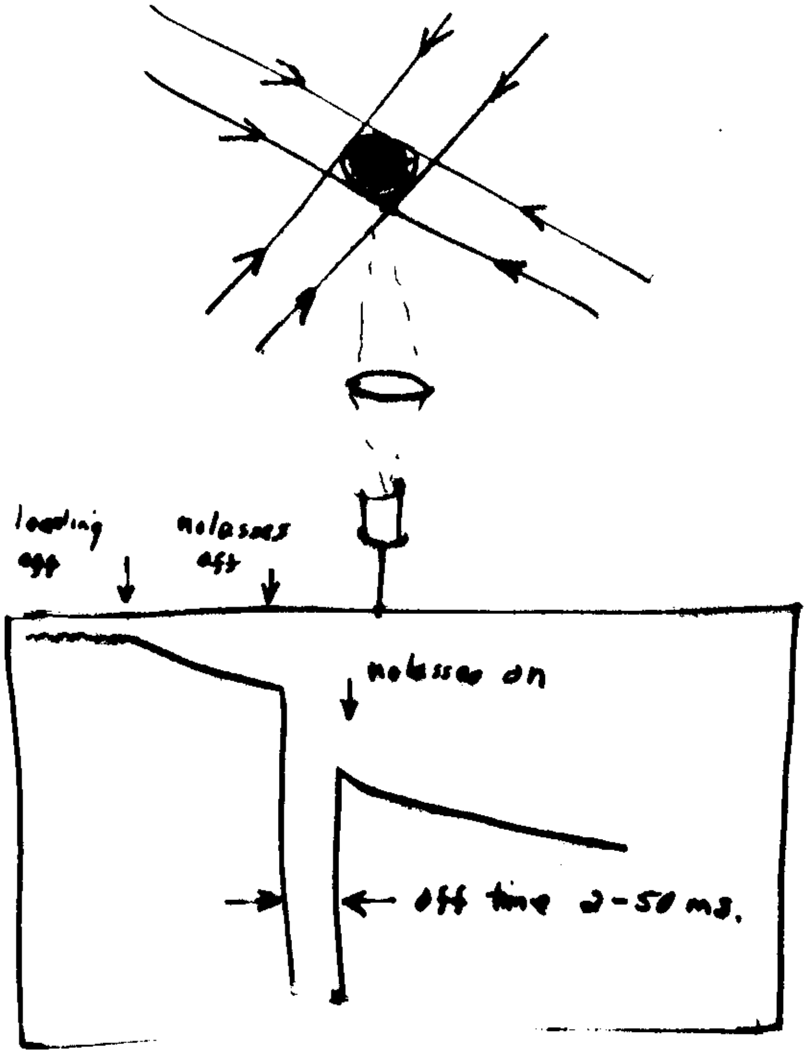

Intensity (arb. units)
0
100
200
300
400
500
600
0
2
4
6
8
10
Time (s)

FIG 11


molasses
laser beams
slow atoms

Release + Recapture



Molasses Temperature

- AT+T Bell Labs 1985

  $T = 240^{+200}_{-60}\ \mu K$

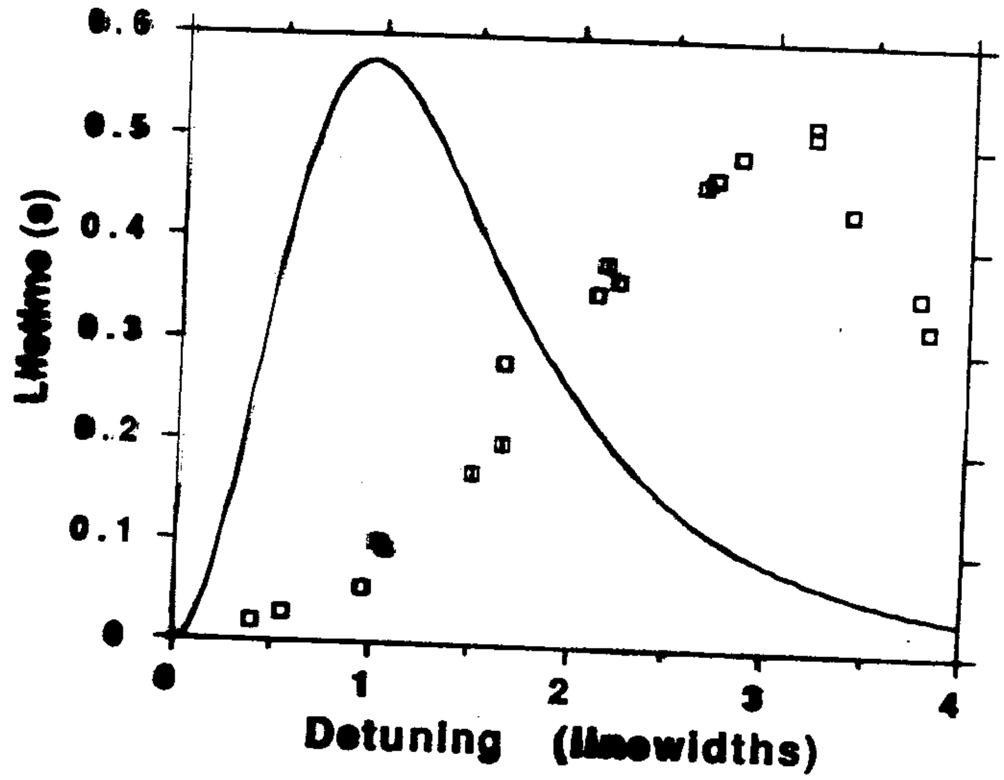
- NBS Gaithersburg 1987

  $T \sim 240\ \mu K$

- JILA 1988

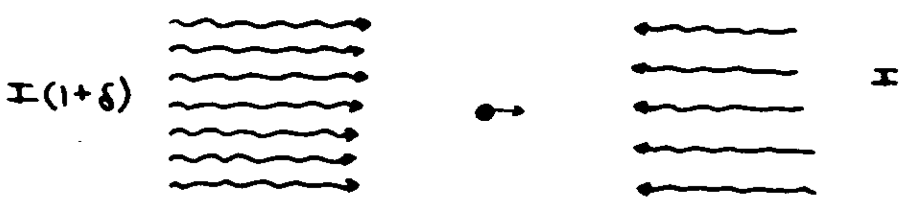
  (Cesium: $T_{MIN} = 125\ \mu K$)

  $T = 100^{+100}_{-30}\ \mu K$



OPTICAL MOLASSES III.

Effect of Imbalance on Molasses

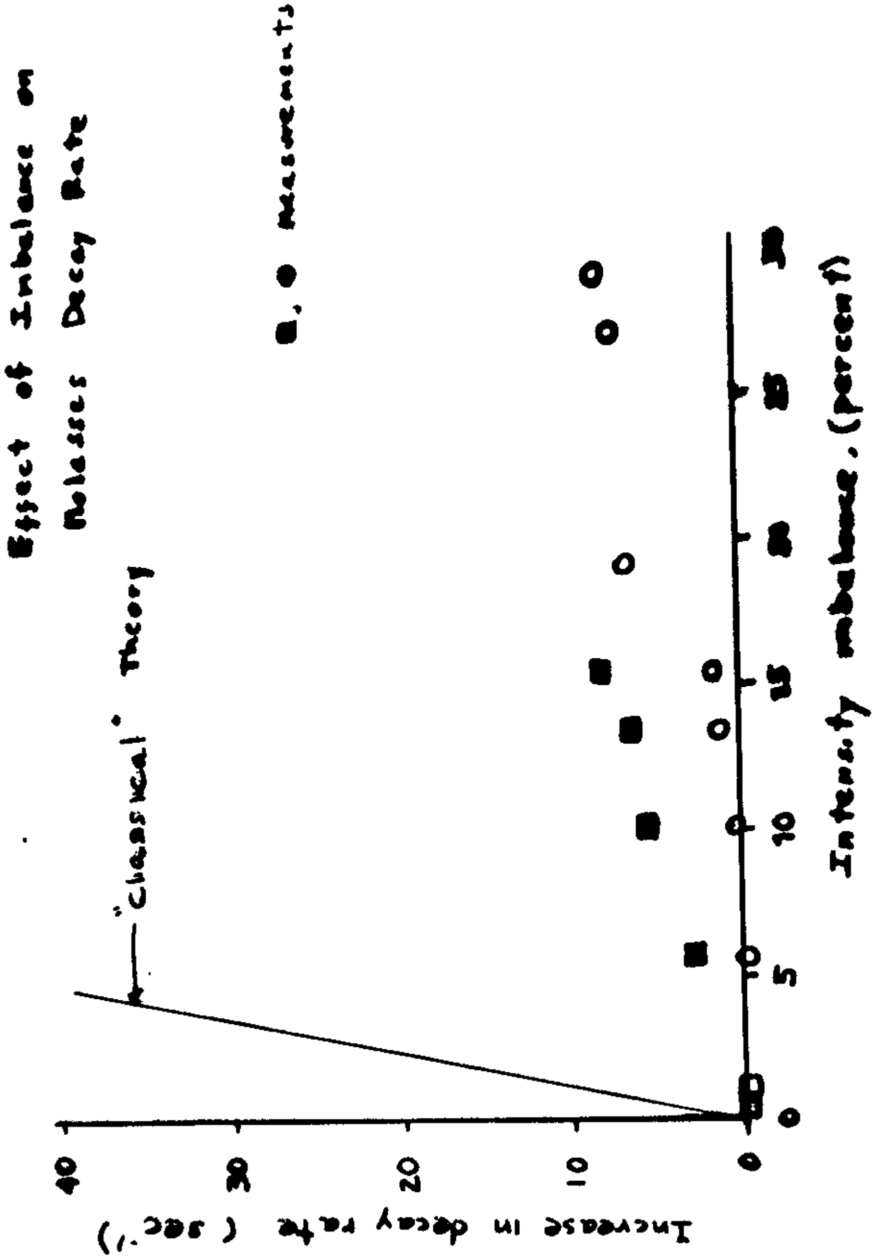


$$v_{drift} = \frac{\delta\left(\Delta^2 + \frac{\Gamma^2}{4}\left[1 + I/I_s\right]\right)}{4k\Delta} \approx 35\,\mathrm{cm/s} \quad \text{with } \delta = 0.1$$

and best molasses

($\tau \approx 15$ ms)

Molasses Temperature



- AT+T Bell Labs 1985

  $T = 240^{+200}_{-60}\ \mu K$

- NBS Gaithersburg 1987

  $T \sim 240\ \mu K$

- JILA 1988 (Cesium, $T_{min} = 125\ \mu K$)

  $T = 100^{+100}_{-30}\ \mu K$

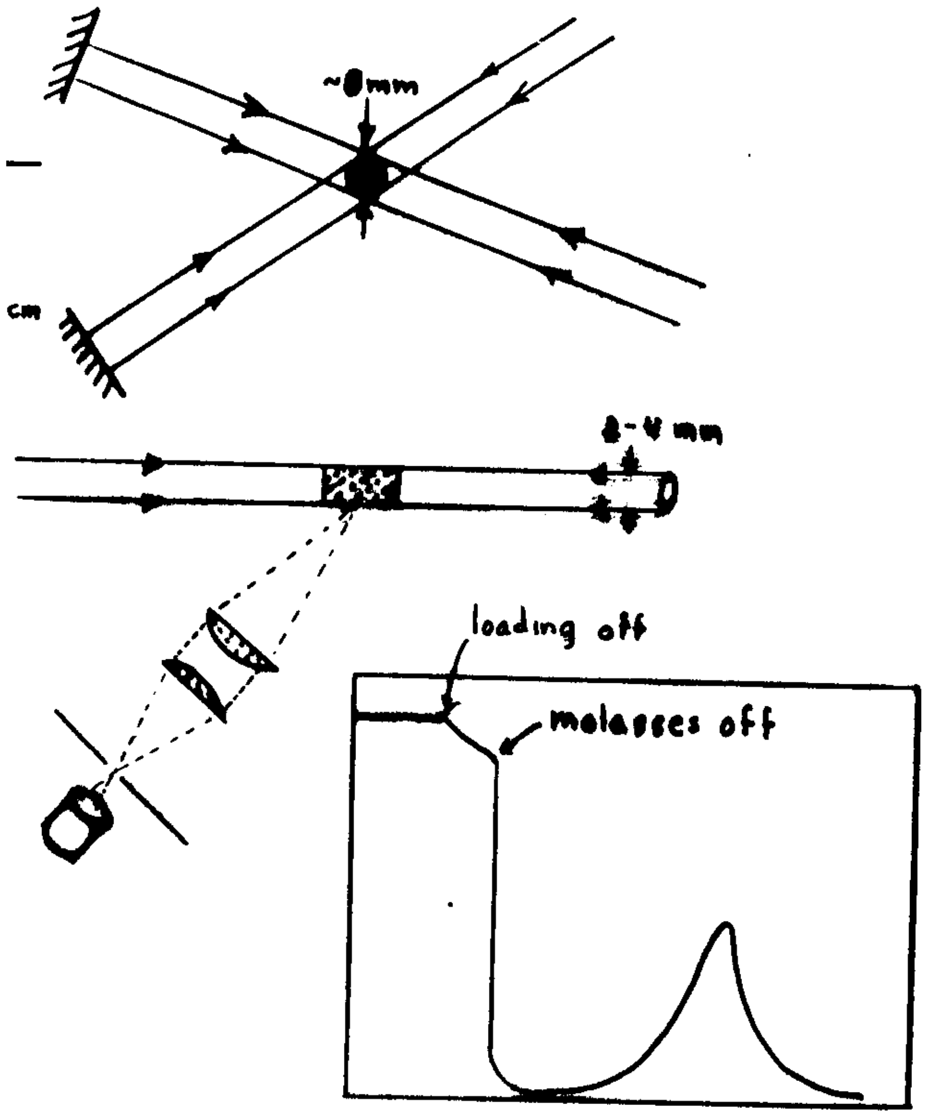
i.e. $k_B T \approx \frac{\hbar\gamma}{2}$ in each case

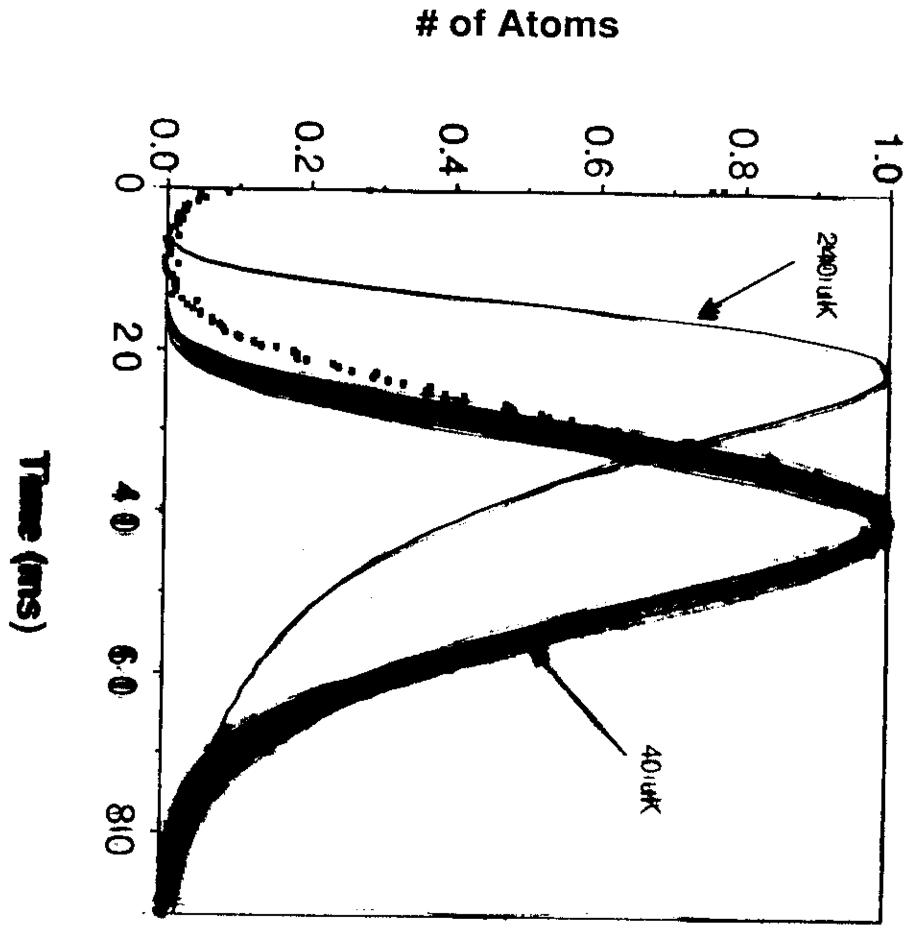
<u>But</u>: $k_B T = \frac{\hbar\gamma}{2}$ only for $I \ll I_0$ and $\Delta = -\gamma/2$

$$k_B T = \frac{\hbar\gamma}{4} \cdot \frac{1 + I/I_0 + \left(\frac{2\Delta}{\gamma}\right)^2}{2\Delta/\gamma}$$

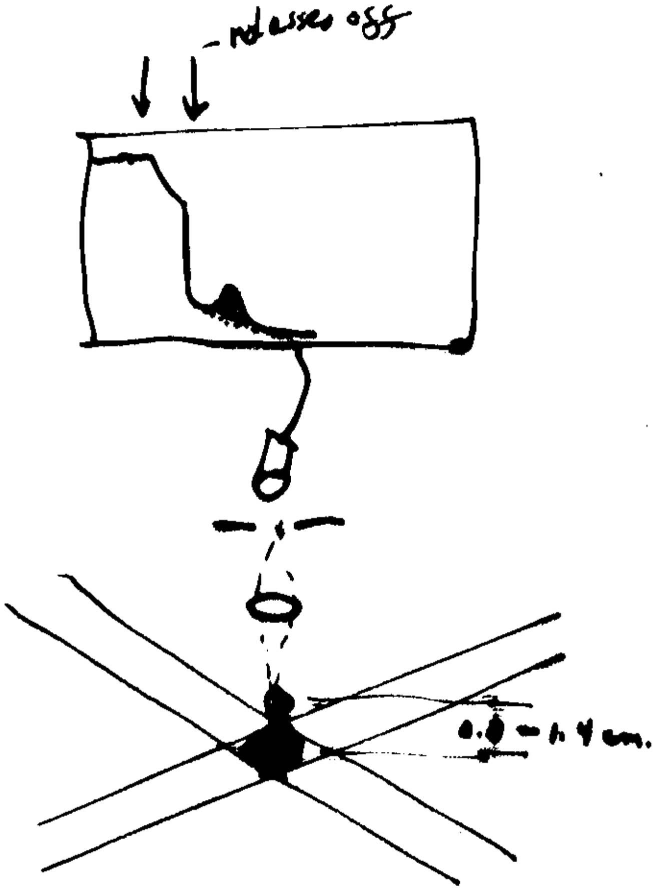
and $I/I_0 \sim 1$, $2\Delta/\gamma > 1$ for NBS expts.

Time of Flight

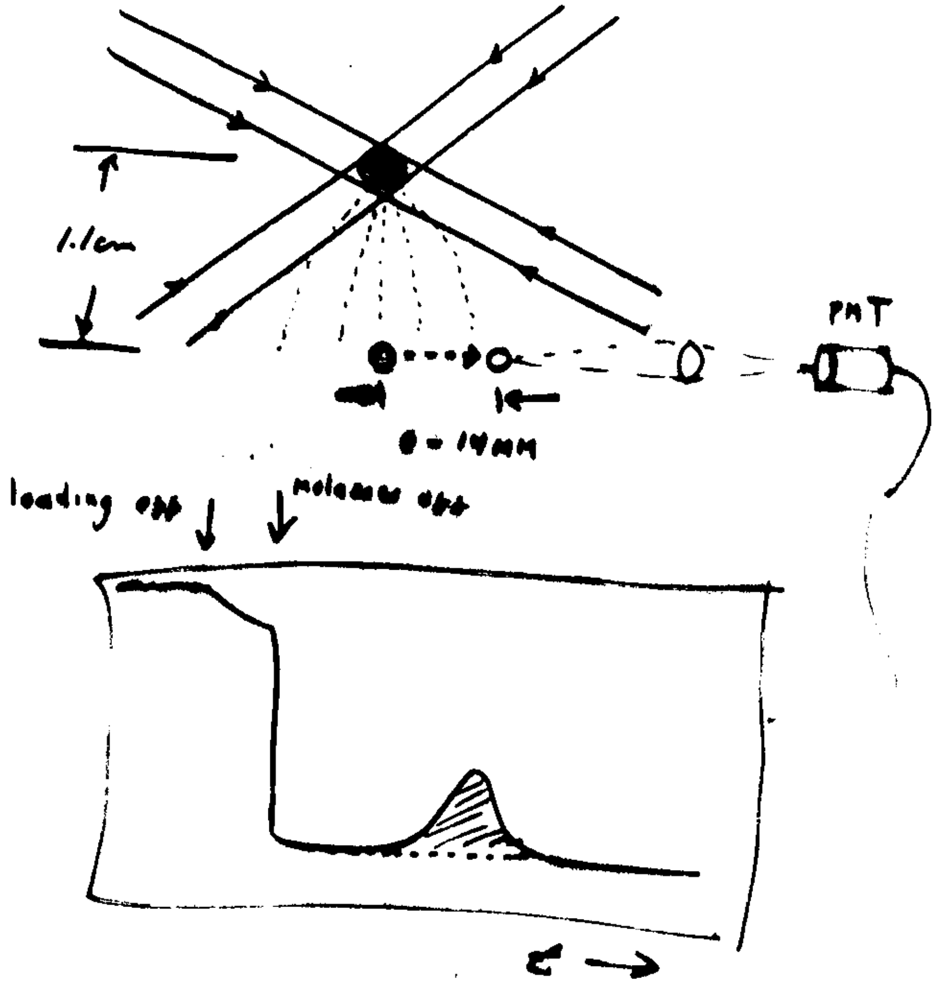


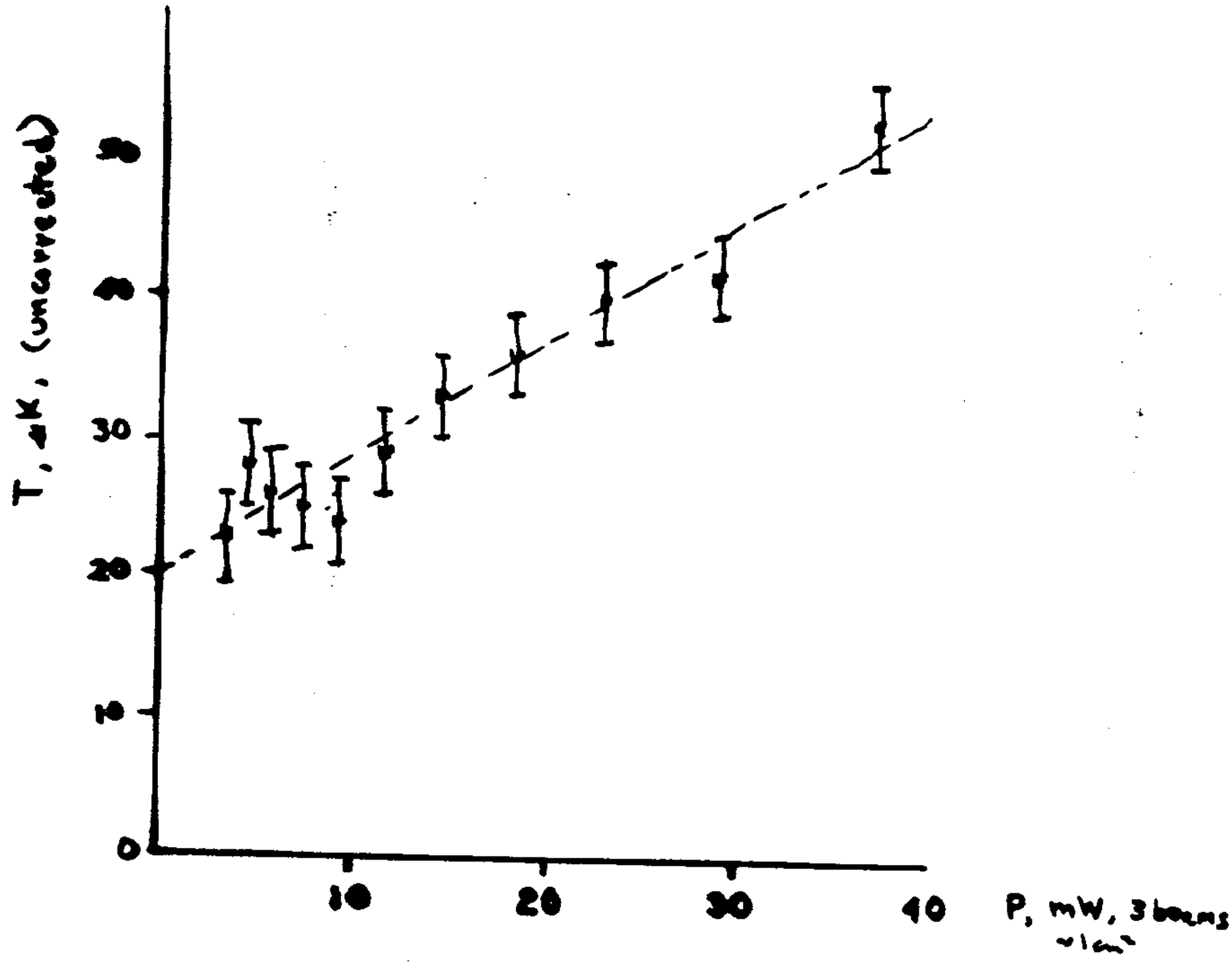


Fountain

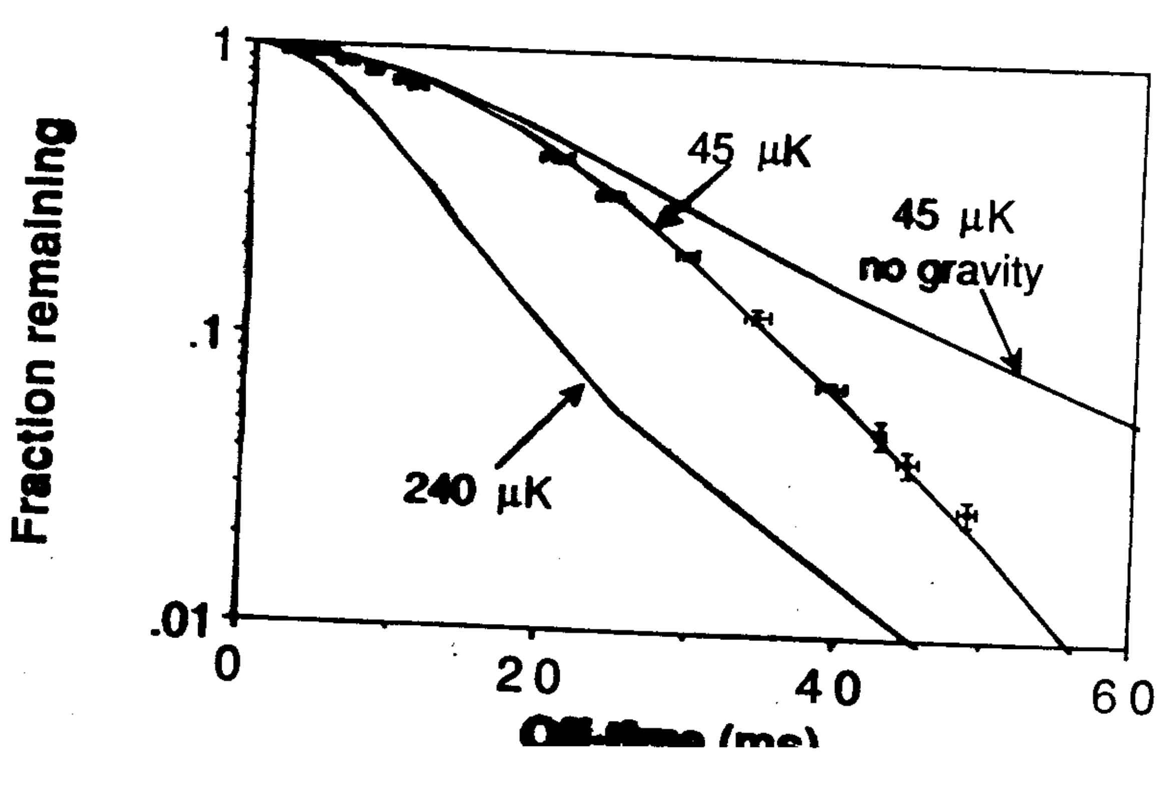


SHOWER




T, µK, (uncorrected)
0
10
20
30
40
50
10
20
30
40
P, mW, 3 beams
~1cm²

+ Recapture


Fraction remaining
1
.1
.01
0
20
40
60
45 µK
45 µK
no gravity
240 µK

Properties of ultra-cold Molasses

- $T << T_D$
- $T \sim 1/I$
- T sensitive to polarization
- T very sensitive to magnetic field

(Na is not a 2-level atom)
(Note that ion traps see T_D even for non-2-level ions)

THE COLDEST GAS IN THE UNIVERSE?

What is the vapor pressure of Na at equillibrium, at $T = 20\,\mu K$?

Classical Thermodynamics, assume constant heat of vaporization:

$$P = P_0\, e^{-\frac{\Delta E_V}{k_B T}}$$

for Na $\frac{\Delta E_V}{k_B} = 12400$

so $P(20\,\mu K) = P_0 \cdot e^{-6.2 \times 10^8}$

or $n(20\,\mu K) = 10^{-2.7 \times 10^8}$ $\frac{\text{atoms}}{\text{cubic whatevers}}$

$V_{universe} \approx 10^{85}\ cm^3$