EXPERIMENTAL BEC OF DILUTE GASES

<u>chronology</u>

- Late 70's – Stwalley pointed out that since H_2 triplet molecule has no bound states, gas of spin-polarized H should be (meta) stable

- Early 80's – attempts at H BEC using spin-polarized H & high pressure (Walraven, Silvera...)

  - got within factor of 50, but were stymied by recombination & sticking to LHe-coated walls

- 1986 H. Hess (MIT) proposes evaporative cooling of magnetically trapped gas – no wall problem

- 1991 MIT H group (Kleppner / Greytak) to within a factor of 5 of BEC – but again progress stopped

\- - - - - - -

mid 80's – laser cooling starts

1988 – sub-Doppler temperatures discovered (NBS)

early 90's – it was realized one did not necessarily need a molecule with no bound states, just sufficiently slow inelastic processes

- early 1995 - 3 groups (JILA/MIT/Rice) report
  significant evaporative cooling at DAMOP meeting

June 1995 - BEC at JILA
soon after - "evidence for BEC"* at Rice
- later retracted, then retraction of retraction...
and MIT

... Nobel Prize 2001 Cornell & Wieman (JILA)
Ketterle (MIT)

---

laser cooling - densities ~ 10^{11} cm^{-3} - limited by
rescattering of photons

$T \sim 50\ \mu K$ (not as low as possible
due to density effects)

$\Rightarrow \lambda_{dB} \sim 100$ nm $= 10^{-5}$ cm

$n\lambda_{dB}^3 \sim 10^{-4} \Rightarrow$ still far away from BEC

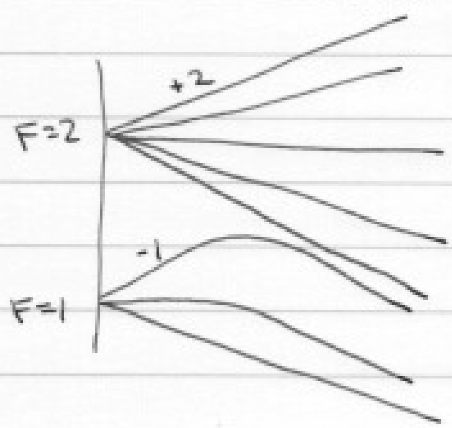
$\Rightarrow$ about as good as one can do with a MOT

— get rid of light - reduces loss due to collisions, an
[illegible]

– use Magnetic trap

since $\vec{\nabla} \cdot \vec{B} = 0$ (Maxwell's eqs.)
$\Rightarrow$ cannot have a field maximum in vacuum

– must trap weak-field seeking states (energy increases with increasing field

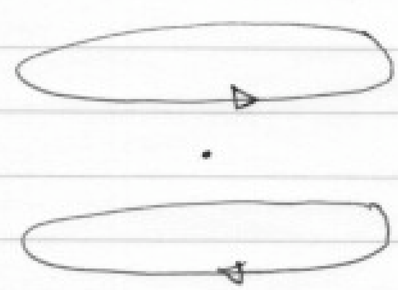


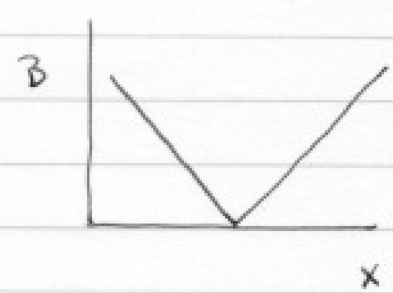
Breit-Rabi for ^{23}Na, ^{87}Rb

use $|1,-1\rangle$ or $|2,+2\rangle$ – weak field seeking states at low field.

– simplest magnetic trap – quadrupole

$$B = B'\vec{\rho} + 2B'\vec{z}$$





field is zero at center (symmetry) and must increase in all directions.

- problem – magnetic trapping relies on adiabatic following of atomic spin and field

$$F_{ad} = \mu \nabla |\vec{B}|$$

- at center of trap, field goes to zero, and adiabaticity breaks down

$$\left[\frac{d\omega_L}{dt} << \omega_L^2 \quad \text{is not satisfied as } \omega_L \to 0 \right]$$

- becomes problematic when atoms ~~cant~~ sample center of trap (i.e. when they are cold]

solns.

1) optical plug (MIT) – use blue-detuned laser (repulsive light shift potential) to prevent atoms from reaching $B=0$ region
   - difficult alignment / vibration issues

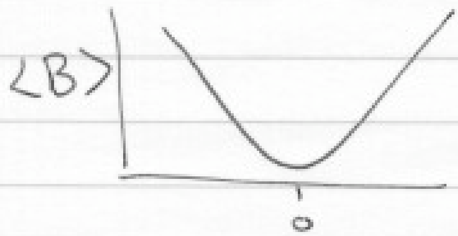
2) TOP trap (JILA) (time orbiting potential)

add rotating uniform field to quadrupole potential

$$B = B_0' \vec{x} + B_0' \vec{y} + 2B_0' \vec{z} + B_r [\cos \omega_t t \, \hat{x} + \sin \omega_t t$$

choose $\omega_{[illegible]} < \omega_{[illegible]} < \omega_{[illegible]}$

- atoms see time-averaged potential



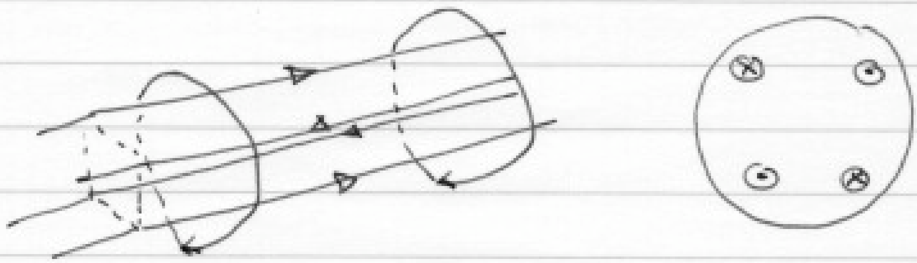
$$U \sim \frac{\mu B_0'^2}{4B_r}\left[x^2 + y^2 + 8z^2\right]$$

typical $\omega_t/2\pi \sim 1-20$ kHz

$B_r \sim 10-200$ Gauss

$B_0' \sim 100-1000$ G/cm

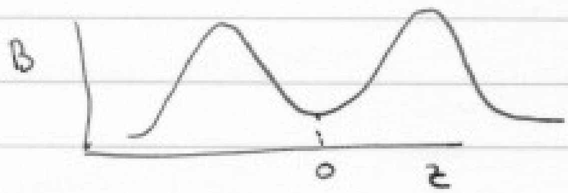
3) Joffe-Pritchard trap



linear quadrupole $B'\hat{x} + B'\hat{y}$

+

"pinch" coils



- many variations of this basic geometry are used to load the magnetic trap, suddenly turn on fields (after turning off light - optical pumping is a <u>very</u> bad thing in the trap)

– we want to preserve phase space density

$$\frac{1}{2} m v_i^2 + \frac{1}{2} K \sigma_i^2 = \frac{1}{2} m v_f^2 + \frac{1}{2} K \sigma_f^2$$

K = mag. trap spring constant

σ_i, σ_f = size before and after trap (inc. therm eq.)

v_i, v_f ~ velocities

using equipartition thm.

$$v_f^2 \sigma_f^2 = \frac{1}{2}\left[\frac{m v_i^4}{K} + 2 v_i^2 \sigma_i^2 + \frac{K \sigma_i^4}{m}\right]$$

differentiate w.r.t. K to find optimum mag. trap

yields $K_{opt} = \frac{m v_i^2}{\sigma_i^2}$

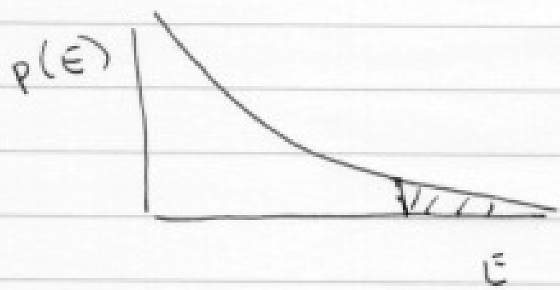
for the phase space density this yields

$$v_i \sigma_i = v_f \sigma_f$$

$\Rightarrow$ p.s.d. is preserved, even though we did something sudden!

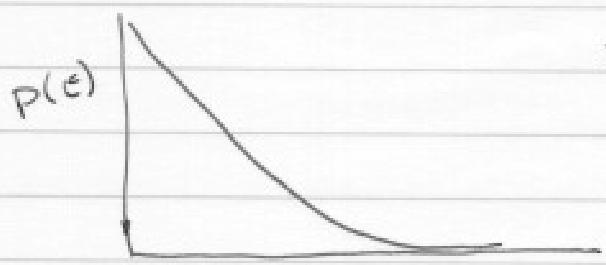
— we now have ~ same p.s.d. in a magnetic trap — need now to cool, without light.

Evaporative cooling:



1) truncate Boltzmann distribution

⋮



2) rethermalise thru elastic collisions

⋮

3) repeat

for cold gases, we are in the s-wave scattering limit, and for identical particles,

$$\sigma = 8\pi a_s^2 \qquad a_s = \text{scattering length}$$

$$\Gamma_{therm} = \gamma n \sigma v$$

$\gamma = 2.7$ (determined by Monte Carlo calcs.)

— sets the time scale for

- optimize evaporation with a parameter defining the truncation energy E_t, $\eta = E_t/kT$

since we want to optimize p.s.d. $\propto nT^{-3/2}$, we want to minimize atom loss

$\Rightarrow$ limiting case ~~E~~ set $\eta = N$, so one particle carries off all the energy

- but - inelastic (loss) processes set limits

a) collisions with background gas atoms $\Gamma_b \sim R$

(10^{-11} Torr ~ 100 sec

b) inelastic loss from 2 ; 3 body collisions

$\Gamma_2 \sim K_2 n N \quad \Gamma_3 \sim K_3 n^2 N$

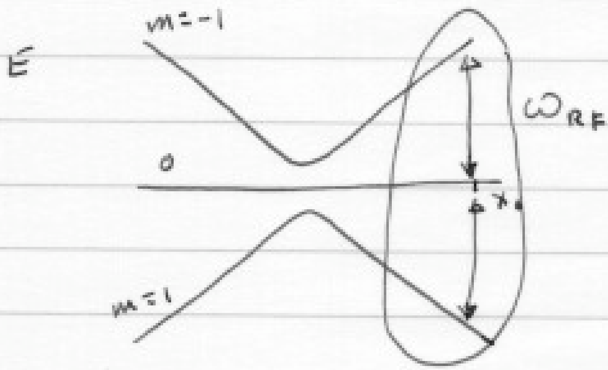
typically, $\eta \sim 4-6$

[ideal - optimize efficiency $\gamma = -\dfrac{d \ln n}{d \ln N}$ at each step]

$\Rightarrow$ we want "run-away" evaporation

- Γ_{therm} increasing as fn. of time

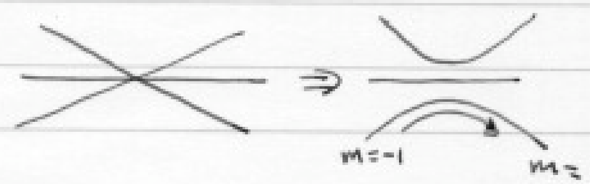
(requires n increasing faster than v decreases to truncate the distribution, use RF spin flips



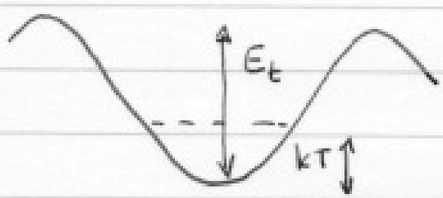
apply ω_{RF} so $\hbar\omega_{RF} = \mu B(x_0)$

where x_0 determines η

dressed picture



atoms undergo spin flip from $m=-1$ to $m=1$
by adiabatic following of dressed states



can adjust E_t (and η) by ramping ω_{RF} as
the atoms cool $\Rightarrow$ "forced" evaporative cooling

Detection - absorption imaging

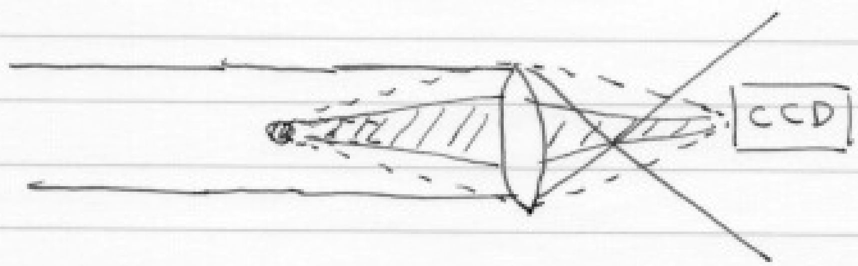


image shadow cast by cloud of atoms onto camera $I(x,y) = I_0\, e^{-\int n\sigma_0\, dz}$ $\sigma_0 \sim \lambda^2/2\pi$

- advantage - detect "absence" of photons with 100% solid angle
- disadvantage - background of laser photons which contribute noise

[absorption better than fluorescence if $n\sigma l >$ S.A.]
(usually the case for BECs)

- but - expect BEC $T_c \sim 100\,nK$, so size will be quite small

gd. state wave fn. $\sim 1\,\mu m$, hard to image with any resolution.

final ingredient ~ "time-of-flight" imaging

- turn off trap

- atoms ballistically expand

$$X(t) \sim \sqrt{x_0^2 + v_0^2 t^2}$$

if $v_0 t \gg x_0$ $\quad X(t) \sim v_0 t$

and spatial distribution is a map of the momentum distribution (and it is big enough to image)

M. H. Anderson, et al. Science 269 198 (1995).

^{87}Rb

- 300 s collect into MOT $\quad 10^7$ atoms, $20\,\mu K$

- optically pump to $|2,2\rangle$ state

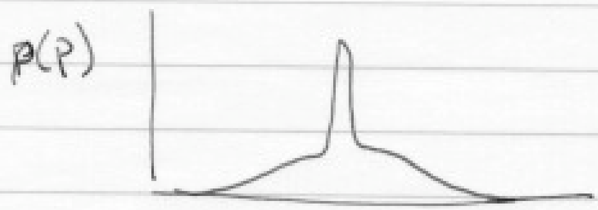
- TOP trap (40, 40, 120 Hz) $\quad 4\times10^6$, $90\,\mu K$ (compression)

$$(n \sigma_{el} v \sim 3\,s^{-1})$$

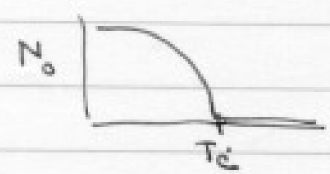
- evaporatively cool for 70 s

signatures of BEC:

- condensation in momentum space
  - expect 2 component momentum distribution



- expect sharp transition at T_c $\quad N_0 \sim 1-(T/T_c)^3$



- expect <u>anisotropic</u> momentum distribution

  $\Rightarrow$ by equipartion, for a thermal cloud,

  $$\langle v_x^2\rangle = \langle v_y^2\rangle = \langle v_z\rangle^2$$

  $\Rightarrow$ spherical expansion

- a condensate should reflect the wave fn. of the trap

$$\omega_x = \omega_y = \frac{1}{\sqrt{8}}\,\omega_z$$