Fe - Foil Møller at 100 μA

Professor Sick made some excellent arguments this morning which should be examined seriously. I believe the stumbling point is **BEAM LOSS**:

$$\Theta_{ms} \simeq \frac{13.6\ \mathrm{mrad}}{E} \sqrt{\frac{X}{X_0}}$$

For 4μm Fe foil and 1 GeV,

$$\Theta_{ms} \simeq 0.2\ \mathrm{mrad}$$

Assuming 100m drift to the Hall C pivot,

$$\Delta r = 100\mathrm{m} \cdot 10^{2} \cdot 0.2\,\mathrm{mrad} = 2\mathrm{cm}$$

or comparable to the beam pipe radius.

This is consistent with my one observation that ~$\frac{1}{3}$ of the beam can be lost in transport. Sustained, this would be intolerable at 100μA.

Modified optics and a thinner foil may help. But this is a key issue.

Dave Mack

Alkali Atom Møller Polarimeter

D. Mack
TJNAF
June 9, 2003

Polarimetry Workshop

Polarimeter FOM vs E

Potential Expts

Alkali beams

Depopulation Polarization

Zeeman Cooling

Outlook

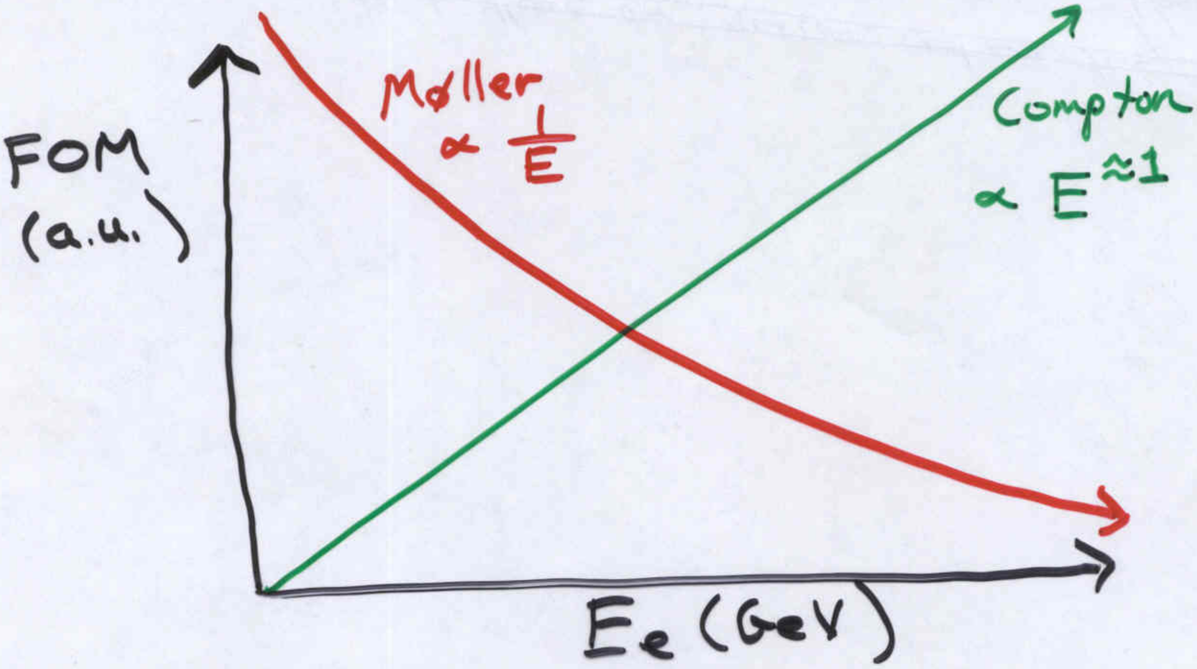
Relative Figures of Merit

Møller $A = \frac{7}{9}$

$$\frac{d\sigma}{d\Omega_{cm}} = \frac{\alpha^2}{2mE_e} \cdot \frac{(3+\cos^2\theta_{cm})^2}{\sin^4\theta_{cm}}$$

Assuming $\Delta\theta_{cm}$ independent of E_e,

$$\mathrm{FOM} \equiv \sigma A^2 \propto \frac{1}{E_e}$$



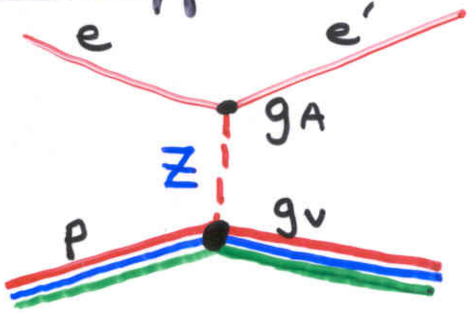
The comparison is somewhat apple vs orange, but

- * Møller polarimeters rule at low E
- * Compton polarimeters rule at high E

is inescapable.

Potential Application

PV in ep → ep
Qweak (proton)



For $\theta \to 0$, $\tau \ll 1$,

$$A_{PV} \propto G_F Q^2 \left\{ g_A^e \sum_q g_V^q \right\} = G_F Q^2 \cdot 1 \cdot (1-4\sin^2\theta_W)$$

$\simeq .3$ ppm at $Q^2 \simeq .03$

- Asymmetry is small
- EW radiative corrections significant ($\simeq 25\%$) but uncertainties small
- Hadronic dilutions large ($\simeq 40\%$)

Excellent way to measure $\sin^2\theta_W$ at low Q^2.

OR

Search for new vector couplings to quarks.

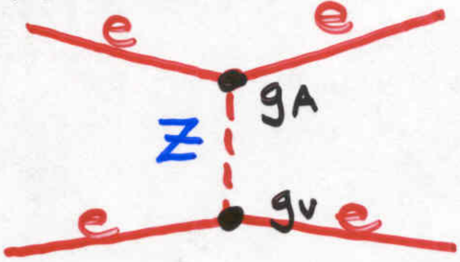
$$\boxed{\text{Need } \frac{\Delta P_e}{P_e} \lesssim 1\%}$$

$E_e \simeq 1$ GeV $I_e \simeq 170\,\mu A$

* Low E problematical for Compton.
  " Fe-foil Møller.
* High I "

Potential Application

PV in ee → ee
Qweak (electron)
@ 12 GeV



$$A_{PV} \propto G_F Q^2 g_A^e g_V^e = G_F Q^2 \cdot 1 \cdot (1 - 4\sin^2\theta_W)$$

$$\approx .3 \text{ ppm at } Q^2 \simeq .03$$

- Asymmetry is small (even smaller at 12 GeV!)
- Radiative corrections are large (≃ 40%) uncertainties need reduction
- No hadronic dilutions

Good way to measure $\sin^2\theta_W$ at low Q^2.

OR

Search for new vector couplings to electrons.

$$\boxed{\text{Need } \frac{\Delta P_e}{P_e} \simeq 1\%}$$

$E_e \simeq 12$ GeV $\quad$ $I_e \simeq 100\,\mu A$

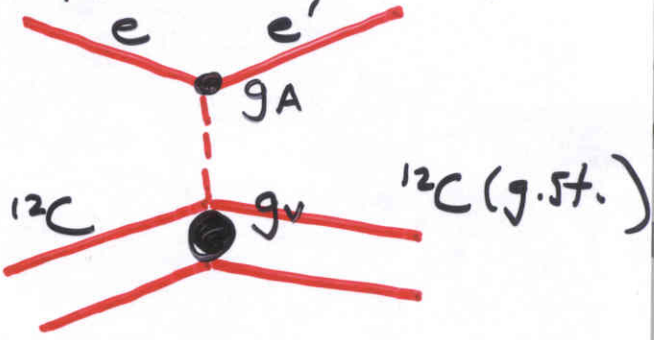
* Compton outlook is good.

* High I problematic for Fe-foil Møller.

Potential Application

PV in $0^+ \to 0^+$

$e + {}^{12}C \to e' + {}^{12}C$ (g.st.)



For $\tau \ll 1$,

$$A_{PV} \propto G_F Q^2 g_A^e \sum g_V^q = G_F Q^2 * 1 * (-4\sin^2\theta_W)$$

≈ 2.5 ppm at $Q^2 \simeq .03$

- Asymmetry relatively large
- EW radiative corrections probably manageable
- Hadronic dilutions vanish as $Q^2 \to 0$
- Xsect is BIG (as $Q^2 \to 0$, $\sigma \to 36 * \sigma_{proton}$)
- FOM $\propto \sigma A^2$ is enormous ($\to 3600 * \text{FOM}_p$)

Sadly, no longer a competitive $\sin^2\theta_W$ measurement, and has roughly same sensitivities as Cs APV which may have a ± 0.5% error.

However,

$0^+ \to 0^+$ Continued

Important because it measures a different

$$A * g_v^{up} + B * g_v^{down}$$

than Qweak (proton), and it may be the best low Q^2 test of CC-NC universality of G_F. and only check on APV!

$$\boxed{\text{Need } \frac{\Delta P_e}{P_e} \lesssim 0.5\%}$$

$I_e \simeq 100\,\mu A$

$E_e \simeq .25 - 1.0$ GeV

* Low E problematic for Compton.

* High I " " Fe-foil Møller.

Accurate Polarimetry at Low E, High I: One Strategy

Specifications:

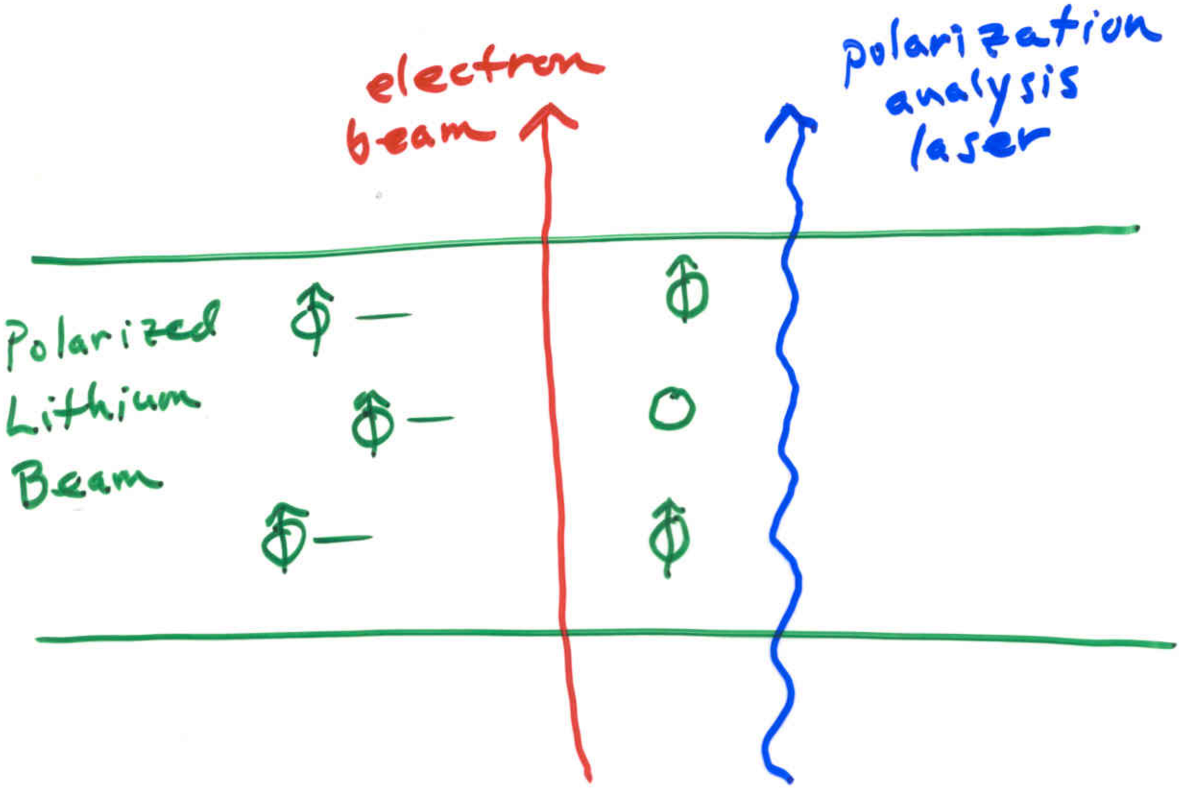
- Dilute target for continuous measurement at high currents
- Target polarization ≈ 100%, continuously and accurately measured.
- Acceptable rate
- Lightest possible atom preferred to minimize Fermi momentum and dilution.

Today I consider a beam of alkali atoms, emphasizing Lithium. However, Sodium may work/fail equally well.

${}^{1}H$
${}^{3}Li$
${}^{11}Na$
${}^{19}K$
${}^{37}Rb$
${}^{55}Cs$
yuck

Why a Beam?

Why not bottle it for higher density?

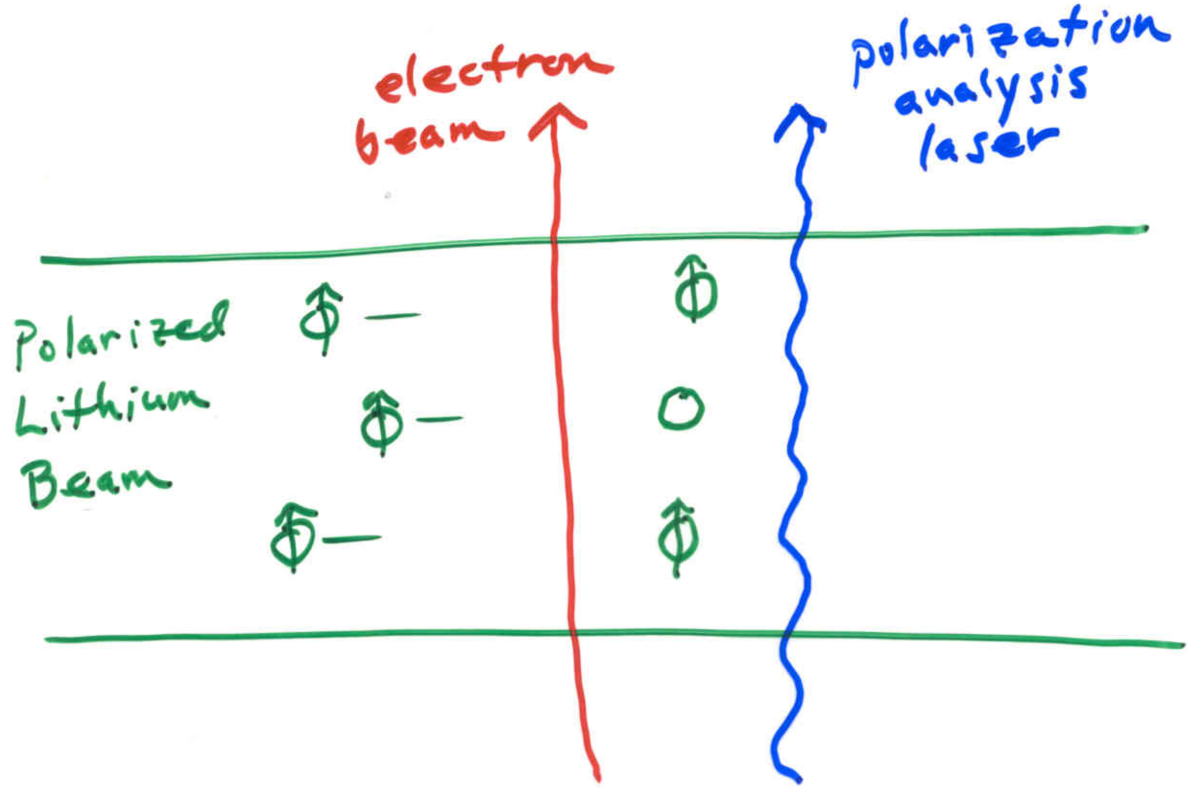


Answer: With a beam,

- It's easy to measure the polarization
- It's easy to measure any de polarization
- If needed, one can trade off density vs refresh-rate

Why a Beam?

Why not bottle it for higher density?



Answer: With a beam,

- It's easy to measure the polarization
- It's easy to measure any de polarization
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The Alkali Period

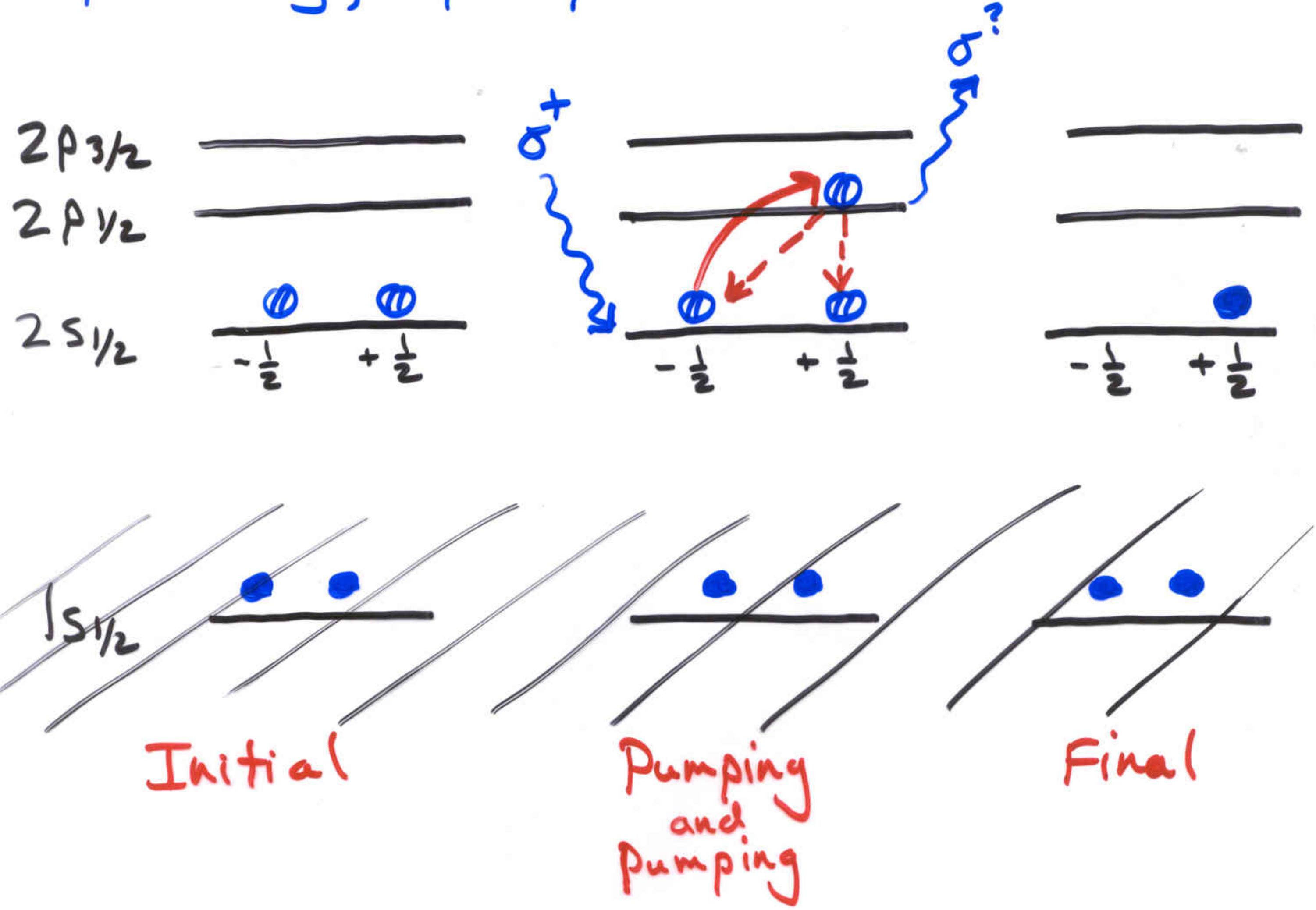
Element	A	1st Excited Transition	Abundance	Nuclear Spin	Dilution ≡ $\frac{pol}{tot}$
^{1}H	1 2	1s→2p 10.2eV!	99.99% .01%	$\frac{1}{2}$+ 1+	100%
^{3}Li	6 7	(He)2s→2p	7.5% 92.5%	1^{+} $3/2^{-}$	33.3%
^{11}Na	23	(Ne)2s→2p	100%	$3/2^{+}$	9.1%
^{19}K	39 41	(Ar)4s→4p	93.3% 6.7%	3/2+ 3/2+	< 5.3%
(^{26}Fe	56 etc.	(Ar)$3d^{6}4s^{2}$→?	91.8% etc.	0^{+}	7.7%)
^{37}Rb	85 86m	(Kr)5s→5p	72.2% 27.8%	$5/2^{-}$ 6^{-}	2.7%
^{55}Cs	133	(Xe)6s→6p	100%	$\frac{7}{2}$+	1.8%

Nuclear and Radiochemistry   Friedlander © 1981

Depopulation Polarization in ^{3}Li

Ignore nuclear spin for the moment.

Pumping $2s_{1/2} \rightarrow 2p_{1/2}$ with σ^+ light, selection rules are $\Delta L = 1$, $\Delta m = +1$. For decay, in principle $\Delta m = 0, \pm 1$.

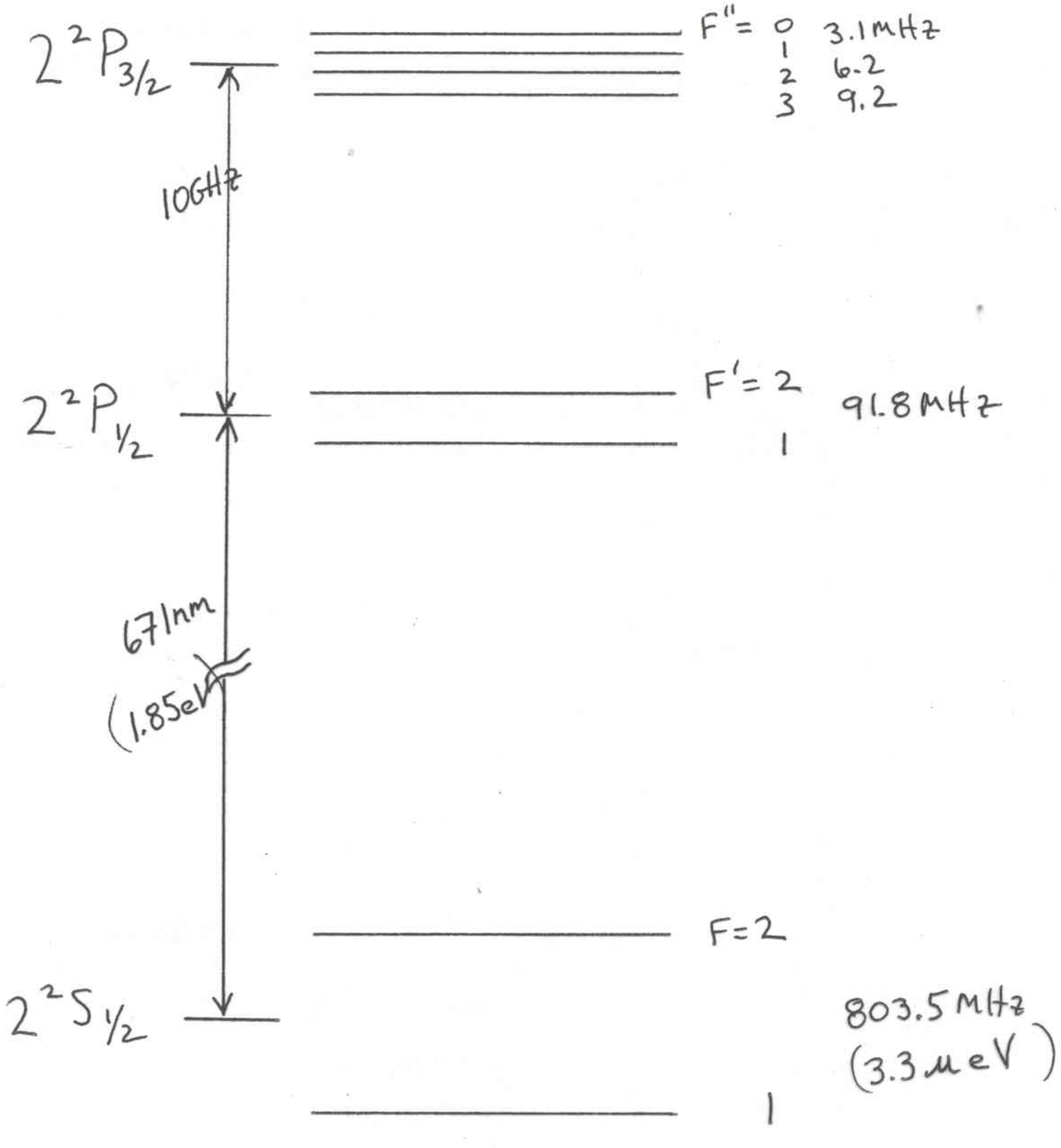


- Polarization approaches 100% after 10 cycles of absorption and decay.
- Depolarization mechanisms are few in atomic beams - dominant is reabsorption of unpolarized fluoresence

Lithium-7

Abundance 92.5%

Nuclear Spin$^{\pi}$ · $\frac{3}{2}^{-}$

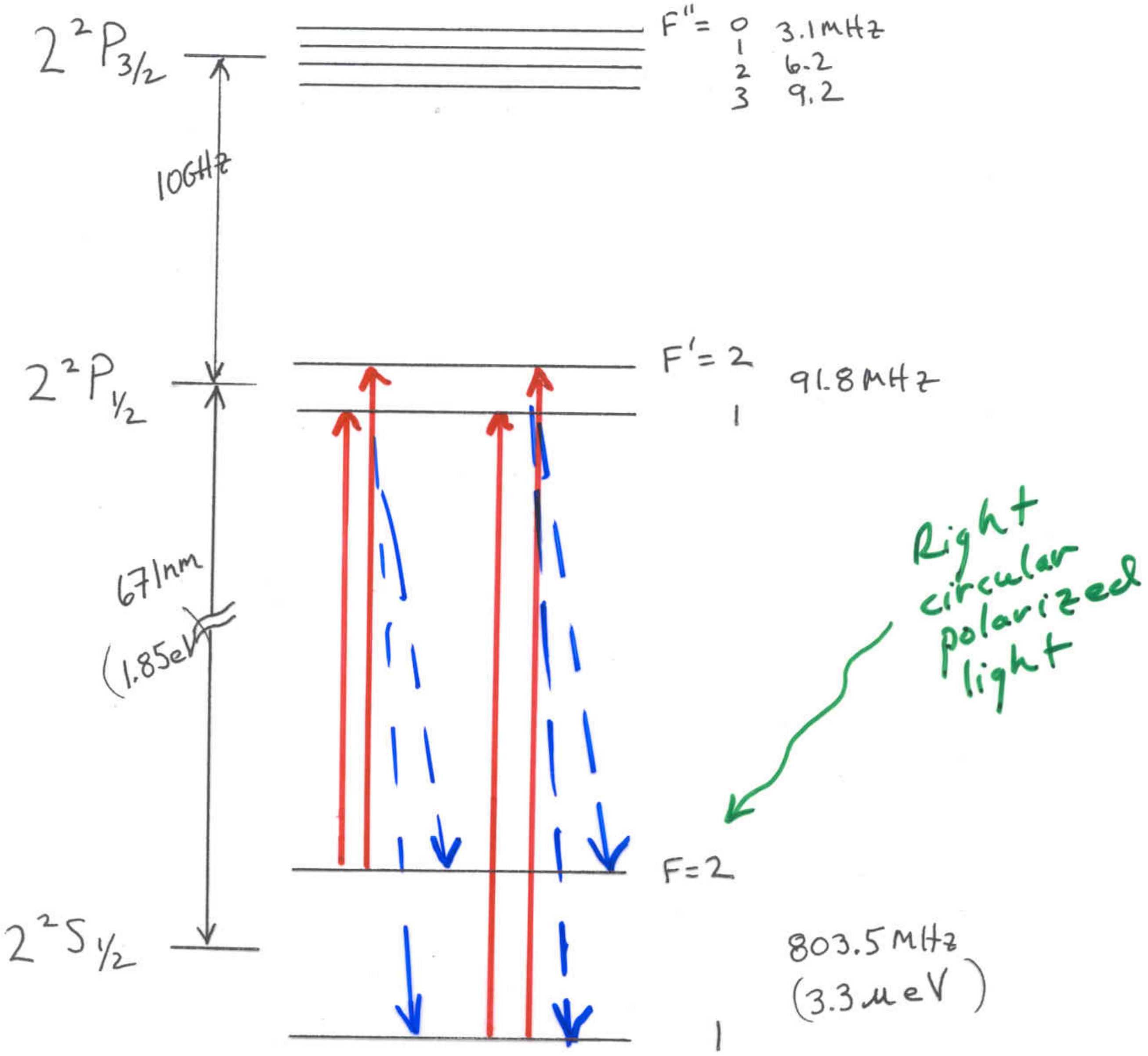


The hyperfine structure complicates things, but much of it is unresolved by either the laser line width or the absorption width due to Doppler.

Important: Don't leave anything "stuck" in an unwanted hyperfine state by selection rules.

Polarizing Lithium-7

Anderson and Nimmo PRL 42, 1520 (1979)



* Ground state converges to F=2, m=+2

* Once completely polarized, the g.st. is "bleached" (cannot absorb σ^+ photons)

Minimum Li Areal Density Required

Hall C Møller Benchmark

1.4 minutes for 1% statistics @ 1 µA, 1 GeV, with 4 µm Fe foil

$$\text{time}\,(?\%\ \text{statistics}) = 1.4 * \frac{E\,(\text{GeV})}{I\,(\mu A)} * \left(\frac{1\%}{?\%}\right)^2$$

$$\rho t = 3.1\,\text{mg/cm}^2 \quad (.02\%\ X_0)$$

$$n^{Fe}_{\text{atoms}} = 3.4 \cdot 10^{19}\ \text{atoms/cm}^2$$

$$n^{Fe}_{e} = 8.8 \cdot 10^{20}\ e^-/\text{cm}^2$$

Minimum Lithium Areal Density

Assume 100 µA, 1000 x longer, $\overset{\approx 1\ \text{day}}{}$ 1% statistics, include dilutions :

$$n^{Li}_e \geq n^{Fe}_e * \left(\frac{1\,\mu A}{100\,\mu A}\right)\left(\frac{1.4\,\text{min.}}{1400\,\text{min.}}\right) * \left(\frac{.077}{.33}\right)^2 =$$

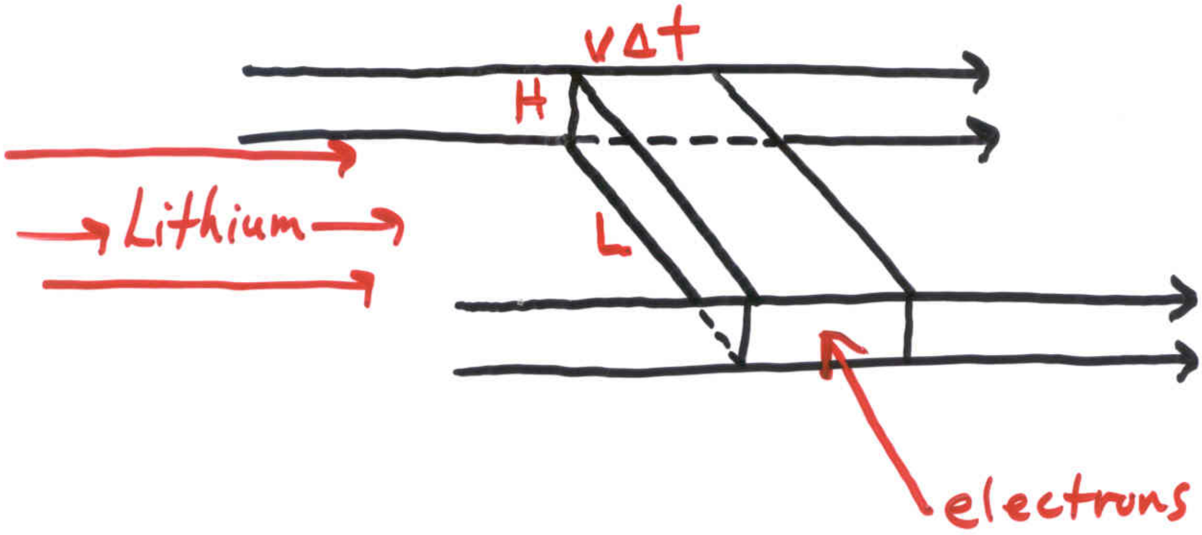
$$4.8 \cdot 10^{14}\ \frac{e^-}{\text{cm}^2}$$

$$\boxed{n^{Li}_{\text{atoms}} \geq \frac{n^{Li}_e}{3} = 1.6 \cdot 10^{14}\ \frac{\text{atoms}}{\text{cm}^2}}$$

$$\rho t \geq 1.9\ \text{ngrams/cm}^2 \quad (2.3 \cdot 10^{-12}\ X_0)$$

Lithium Beam Specifications

Assume a ribbon beam



Define $R \equiv \frac{\#\text{ atoms}}{\text{sec}}$

then

$$\rho L = \frac{R}{H\,v} \geq 1.6 \cdot 10^{14}\ \frac{\text{atoms}}{\text{cm}^2}$$

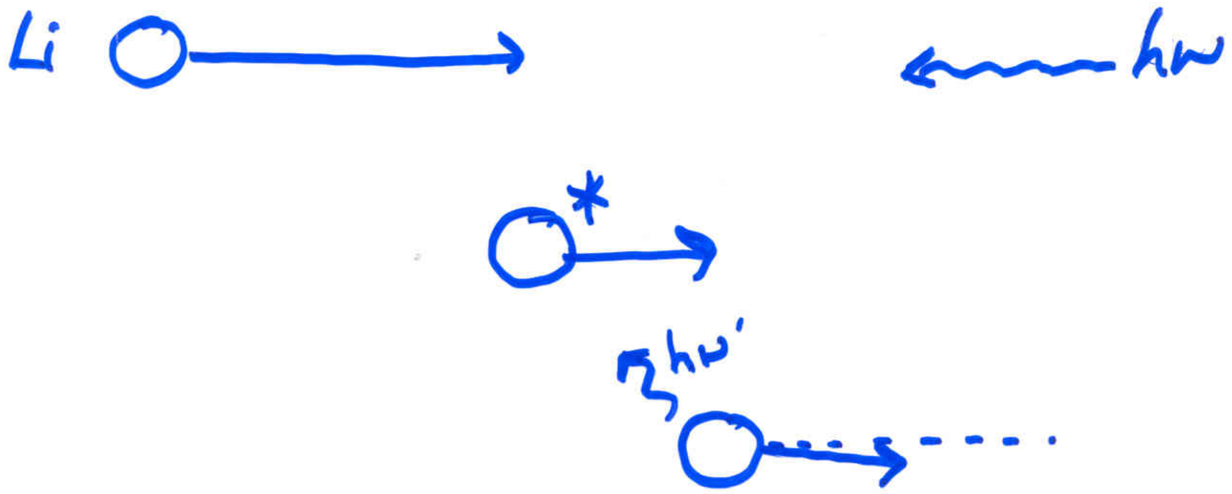
previous slide

- L doesn't matter
- H should be small (good "focus")
- Want large R (lots of atoms/sec)
- Want <u>small</u> velocity v (aka <u>cooling</u>)

Let H = .2 cm

$$\frac{R\ [\text{atoms/sec}]}{v\ \left[\frac{\text{cm}}{\text{sec}}\right]} \geq 3.2 \cdot 10^{13}$$

One Dimensional Laser Cooling



$$\Delta p_{Li}^{z} = \Delta p_{\gamma}^{z}$$

$$M \Delta v = \frac{h\omega}{c}$$ <u>on average</u>

$$\Delta v = \frac{h\omega}{Mc} \simeq 8.5 \text{ cm/sec}$$

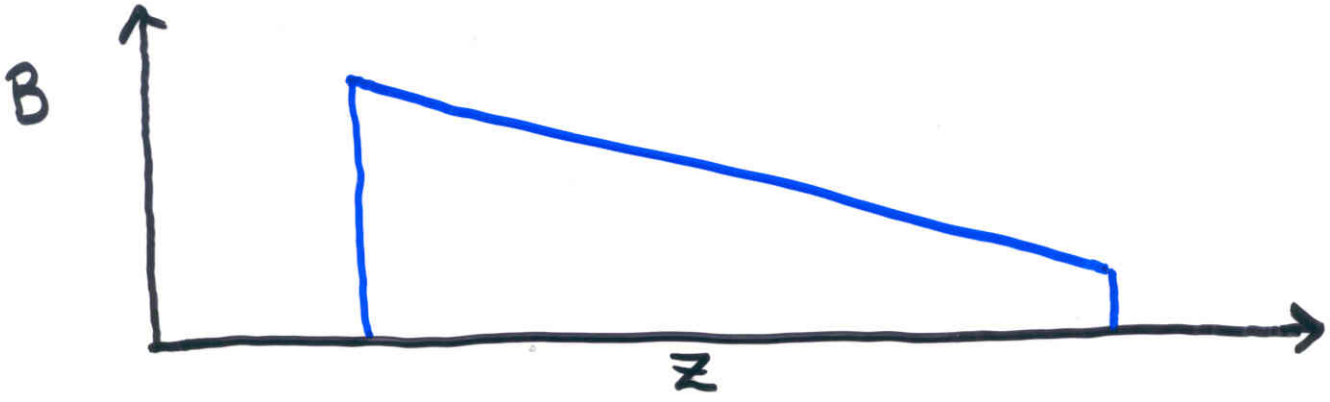
Since $v_{Li} \gg \Delta v$ we need **lots** of γ's:

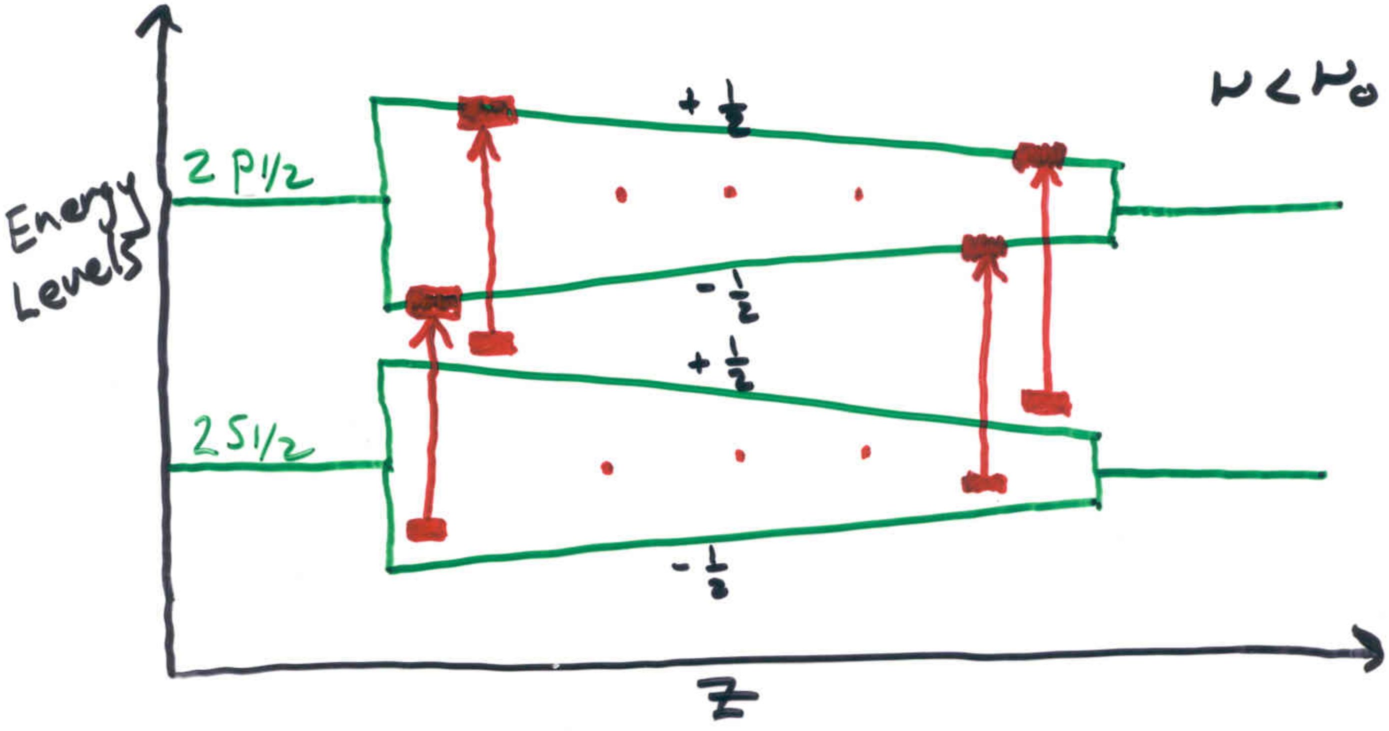
$$N_{\gamma} = \frac{10^{5} \text{ cm/sec}}{8.5 \text{ cm/sec}} \simeq 12{,}000.$$

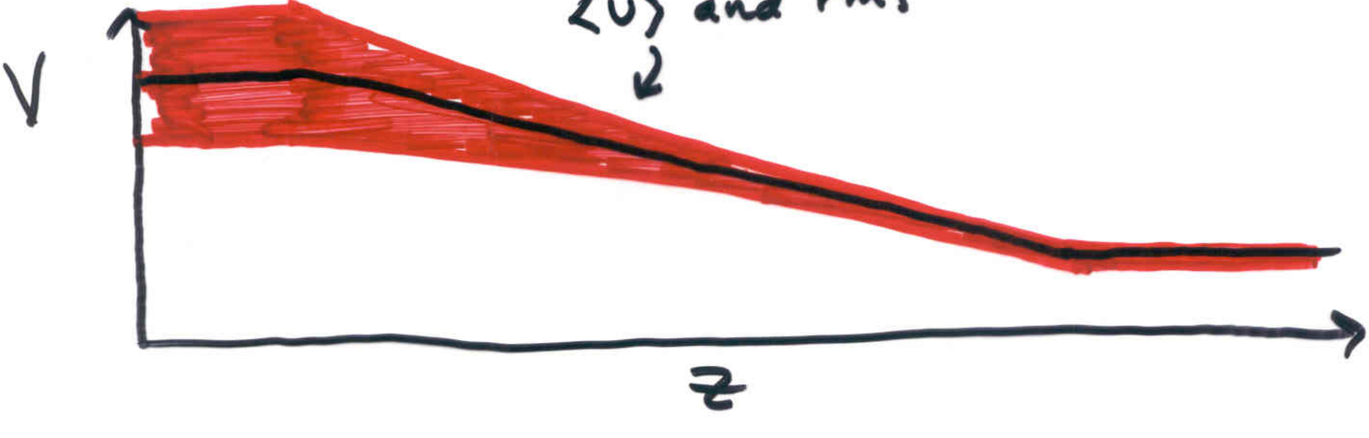
Special techniques are needed to keep the absorption on resonance in spite of the slowing (changing Doppler shift).

Zeeman Cooling
($S_N = 0$ Example)

Phillips & Metcalf
PRL **48**, 596 (1982)

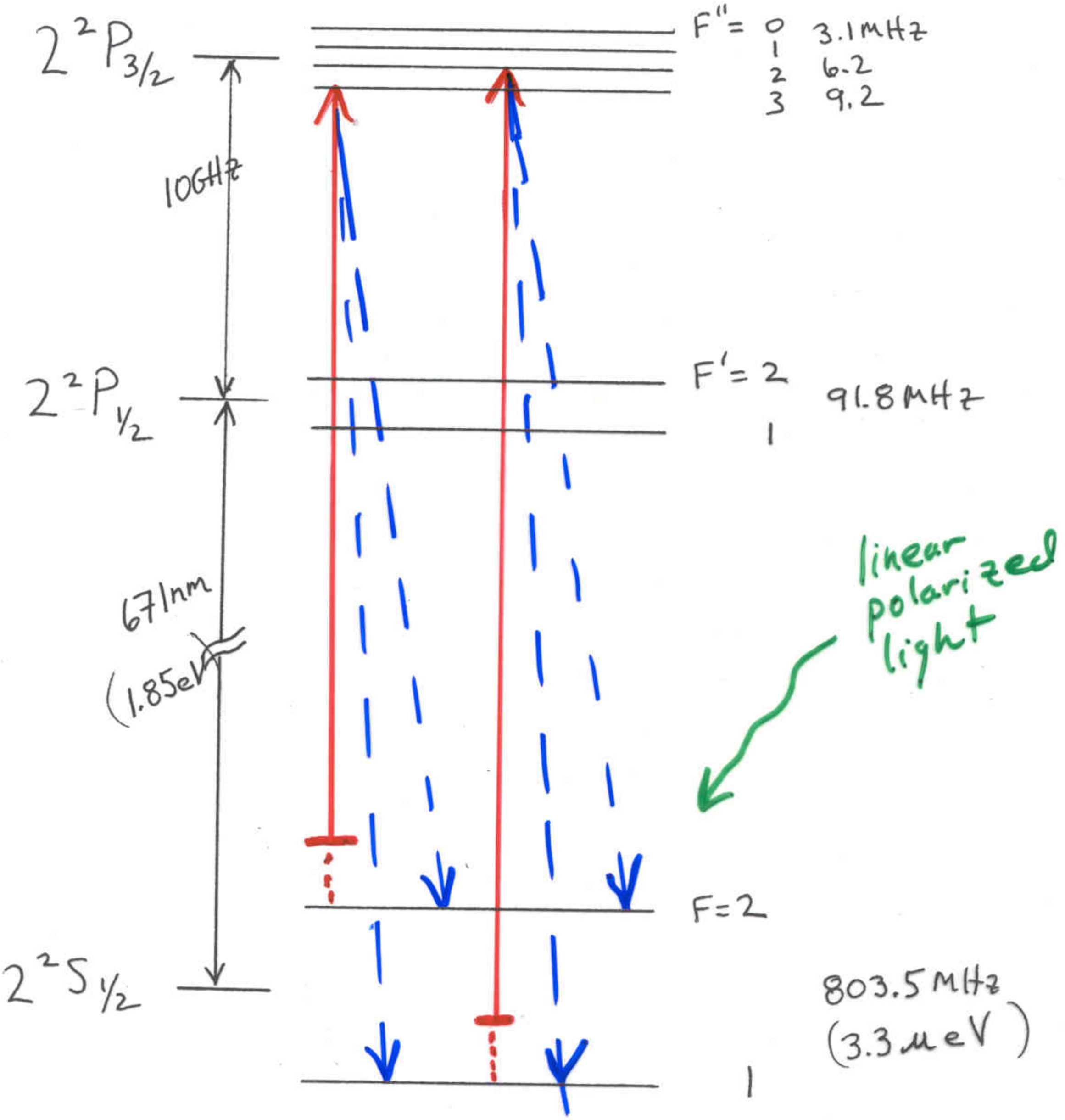






Cooling Lithium-7

M.-O. Mewes et al, PRA 61 011403(R) 1999



* All ground state hyperfine levels coll

* Ground state absorption does not bleach asymptotically - pulsed operation should increase transparency

Idiot Check:

How much cooling is needed and does that violate any laws?

$V\left(\frac{cm}{sec}\right)$	T	$R_{min}\left(\frac{atoms}{sec}\right)$	Mass Flow	Cooling Laser Power Output
1000	84mK	$3.2 \cdot 10^{16}$	32 mg/day	114 Watts
100	.84mK	$3.2 \cdot 10^{15}$	3.2 mg/day	11.4 Watts
10	8.4μK	$3.2 \cdot 10^{14}$	.32 mg/day	1.14 Watts

This suggests the goal for V_{group} to be $O\left(100 \frac{cm}{sec}\right)$.

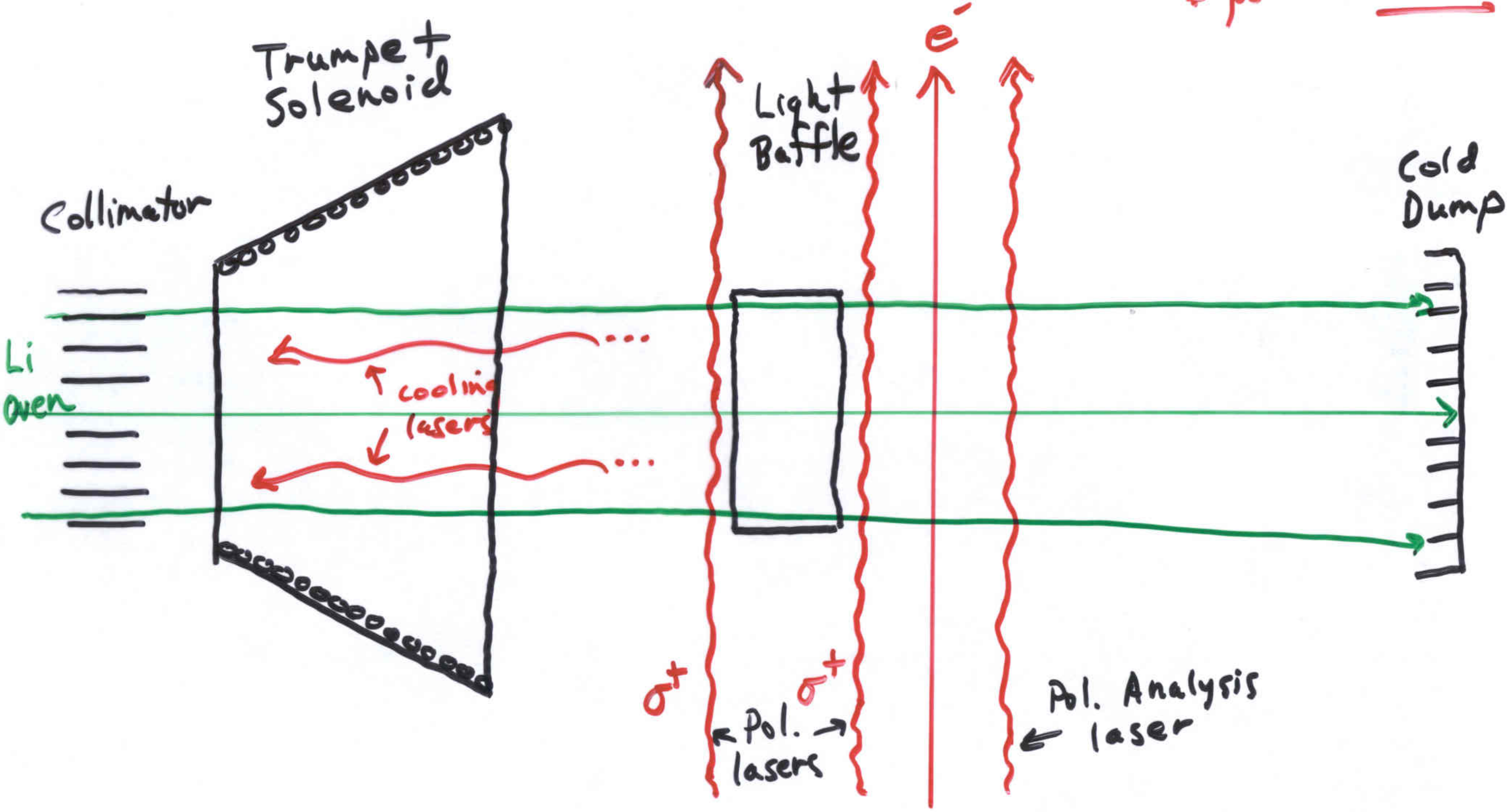
A x10 increase in $\Delta\Omega_{moller}$ would yield at $100 \frac{cm}{sec}$

$$R_{min} \rightarrow 3.2 \cdot 10^{14} \frac{atoms}{sec}$$

$$P_{cool} \rightarrow 1.14 \text{ Watts}$$

Schematic – Top View

* cool first
* polarize second



Cooling lasers are above and below the plane.

Summary

- Several important expts require high accuracy polarimetry at $E \lesssim 1$ GeV.
- Polarizing warm beams of $R \geq 10^{15} \frac{\text{atoms}}{\text{sec}}$ to $\simeq 100\%$ is probably feasible
- Laser cooling $R = 10^{15} \frac{\text{atoms}}{\text{sec}}$ is very agressive.

  Further work must focus on cooling.
- Polarizing a cooled beam should not cause undue heating provided $\langle v \rangle \geq 100 \frac{\text{cm}}{\text{sec}}$.