Status of electron EDM experiments

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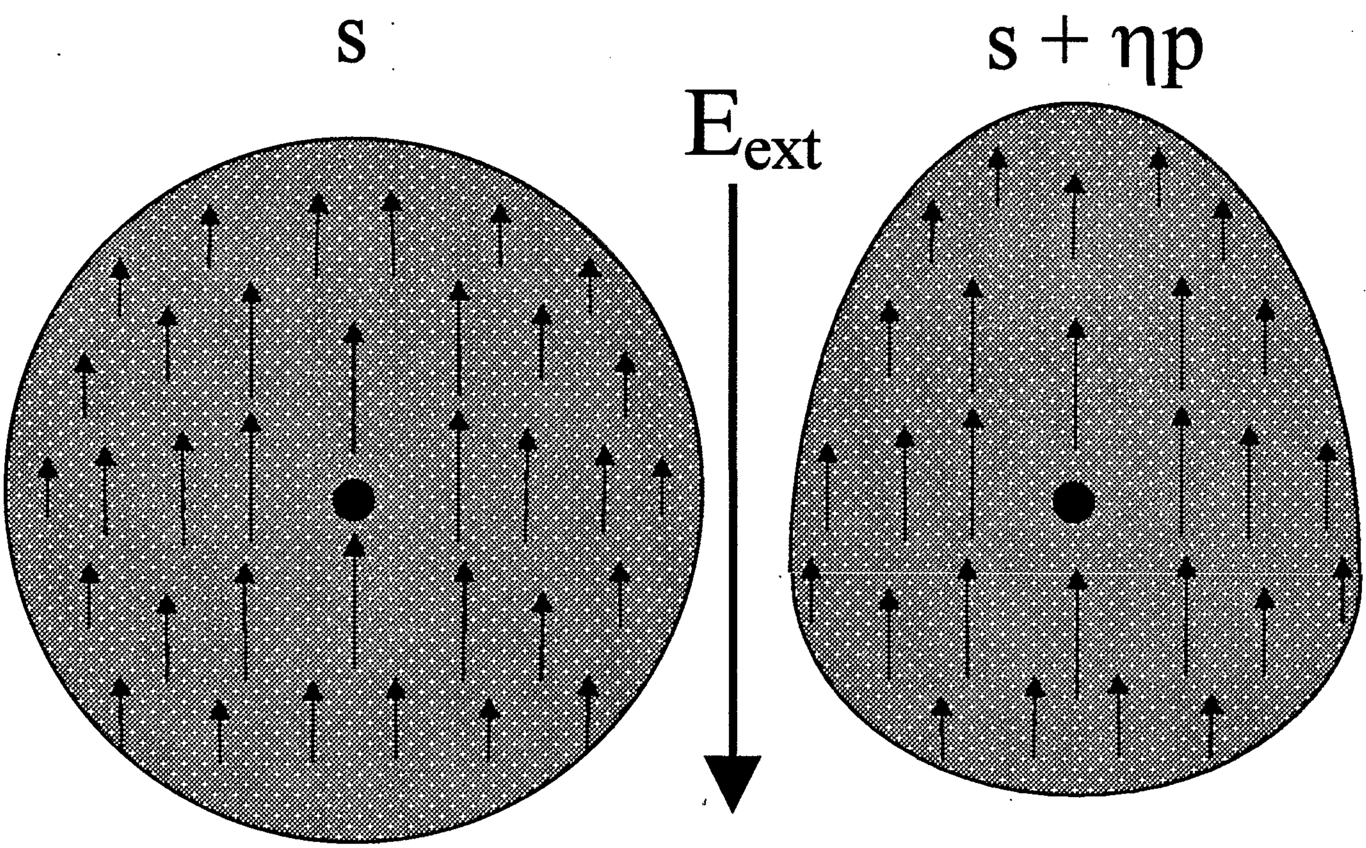
- Electron EDM vs. atom/molecule EDM
- Berkeley Tl experiment
- Yale/Amherst PbO experiment
- Status and future prospects

General method to detect an EDM:

	<u>Geometric picture</u>	**<u>Energy-level picture</u>**
State preparation	Polarize particles with spin $\mathbf{S} \perp \mathbf{E}$	Create superposition of spin states $\pm\mathbf{S} \parallel \mathbf{E}$
Optional magnetic field $\mathbf{B} \parallel \mathbf{E}$:	Precession $d\theta/dt = \mu B/\hbar$ (absent in co-rotating frame)	Frequency offset $\omega_0 = \mu B/\hbar$
Observation after time τ	Precess for time τ through angle $\theta = dE\tau/\hbar$	Frequency shift $\Delta\omega = dE/\hbar$ w/resolution $\delta\omega = 1/\tau$
Shot-noise limited sensitivity	$\partial\theta = 1/\sqrt{\dot{N}T}$; $1/\delta d = E\tau\sqrt{\dot{N}T}$	$\partial\omega = \delta\omega/\sqrt{\dot{N}T}$; $1/\delta d = E\tau\sqrt{\dot{N}T}$

Q. Can an electron in a neutral atom/molecule feel a net E-field?



A. No! (Classically)

Schiff's Theorem: $\langle \vec{E}_{tot} \rangle = \langle \vec{E}_{ext} + \vec{E}_{int} \rangle = 0!$

Simple proof: $\langle E_{tot} \rangle \propto \langle F_{tot} \rangle = 0$

Evasion of Schiff's Theorem:

d_e induces d_{atom} because of <u>magnetic</u> forces

$$\langle \vec{F}_{tot} \rangle = \langle \vec{F}_{el} + \vec{F}_{mag} \rangle = 0,$$
$$\text{so } \langle \vec{F}_{el} \rangle = \langle \vec{F}_{mag} \rangle$$

$$\vec{F}_{mag} = e(\vec{v}/c)\times(\vec{E}\times\vec{v})/c = e\vec{E}_{eff}$$

Dominant effect near nucleus, where v and $E_{internal}$ both large

$$|\langle \vec{E}_{eff} \rangle| = (v^2/c^2)\cdot E_{internal}\cdot \mathcal{P}$$

$$\propto (Z\alpha)^2 \cdot Ze/a_0^2 \cdot \mathcal{P}$$

atomic polarization in external E-field unbalances vector sum

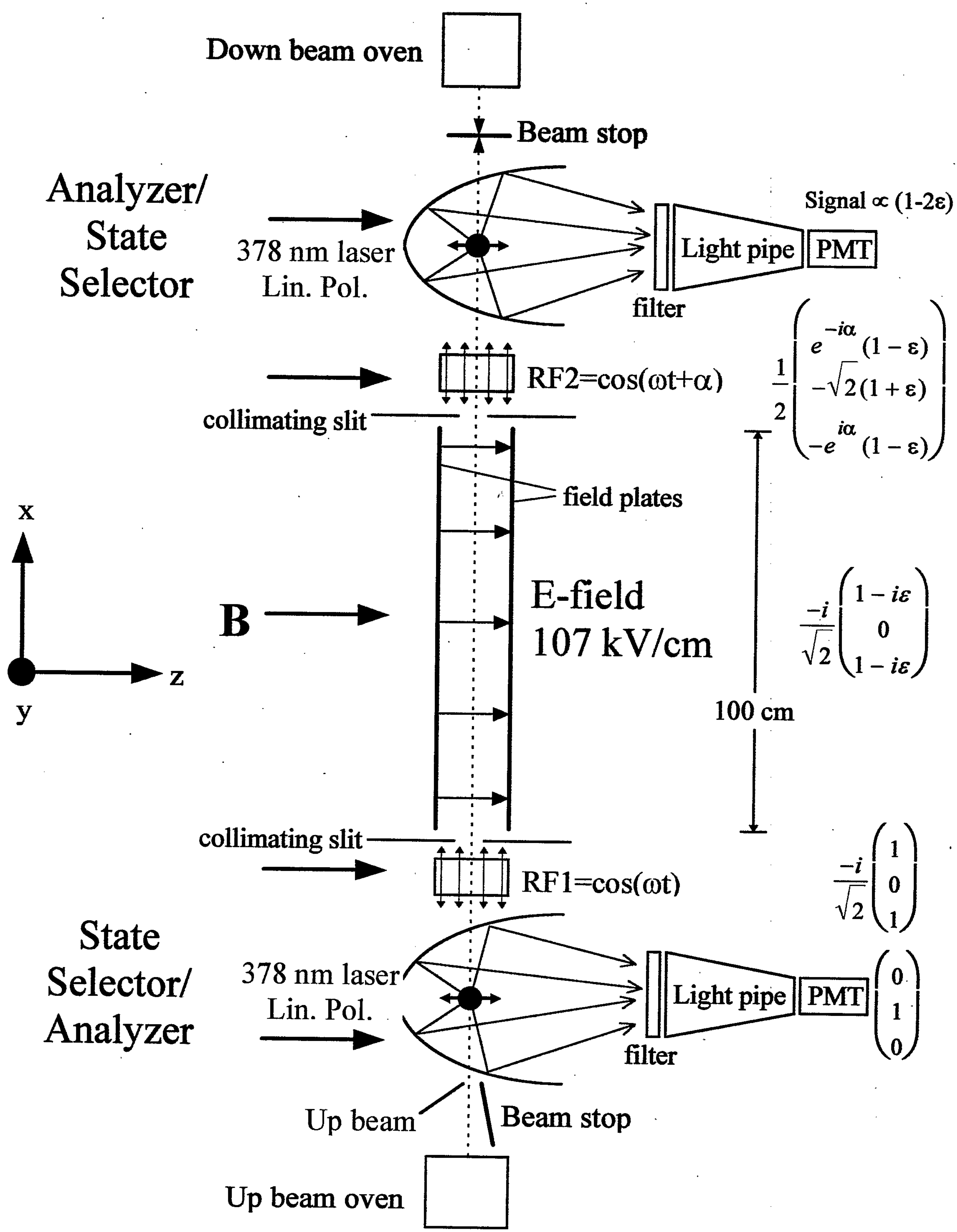
$$\sim \mathcal{P}\cdot 10^{11}\ \text{V/cm @ } Z\sim 80$$

$$(\sim 10^3 \cdot E_{external} \text{ for } \mathcal{P} \ll 1)$$

The Berkeley EDM experiment in atomic thallium:

Principal Investigator:	E. D. Commins
Previous Collaborators:	H. Gould C. Carlberg K. Abdullah
Published Results: Phys. Rev. A 50(4), 2960 (1994).	E.D.C. S. Ross B. C. Regan D. D.
New Version (1994-2001)	E.D.C. B.C.R. D.D. C. Schmidt

$|E_{eff}| \sim 600 \times E_{ext}$.

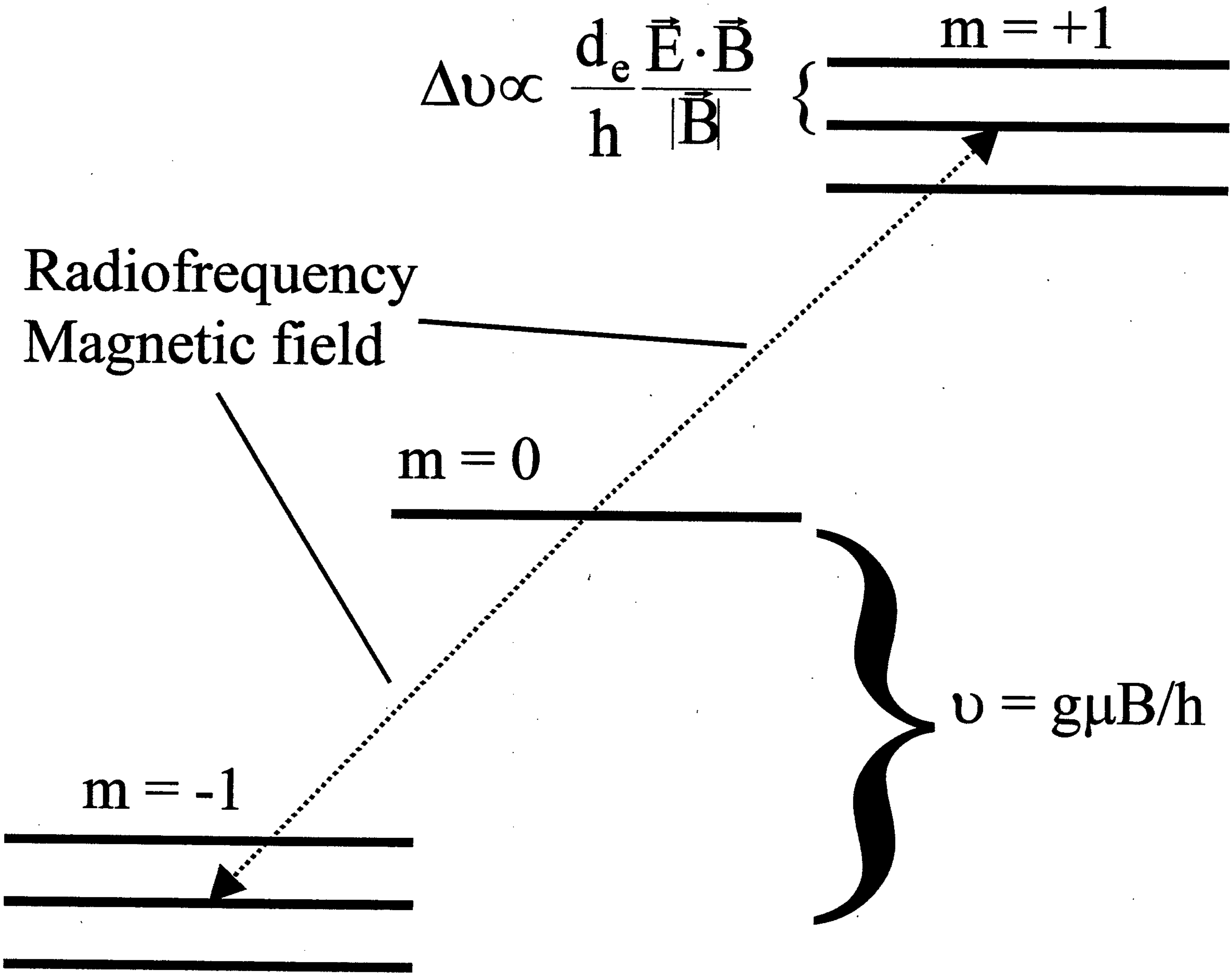


Down beam oven
Beam stop
Analyzer/ State Selector
378 nm laser Lin. Pol.
Light pipe
PMT
Signal ∝ (1-2ε)
filter
RF2=cos(ωt+α)
$\frac{1}{2}\begin{pmatrix} e^{-i\alpha}(1-\varepsilon) \\ -\sqrt{2}(1+\varepsilon) \\ -e^{i\alpha}(1-\varepsilon) \end{pmatrix}$
collimating slit
field plates
x
z
y
B
E-field 107 kV/cm
$\frac{-i}{\sqrt{2}}\begin{pmatrix} 1-i\varepsilon \\ 0 \\ 1-i\varepsilon \end{pmatrix}$
100 cm
collimating slit
RF1=cos(ωt)
$\frac{-i}{\sqrt{2}}\begin{pmatrix} 1 \\ 0 \\ 1 \end{pmatrix}$
State Selector/ Analyzer
378 nm laser Lin. Pol.
Light pipe
PMT
$\begin{pmatrix} 0 \\ 1 \\ 0 \end{pmatrix}$
filter
Up beam
Beam stop
Up beam oven

The signature of an EDM:

$$H = -\vec{\mu}\cdot\vec{B} - \vec{d}\cdot\vec{E} = -(\mu B + dE)m_F$$

A shift in the magnetic resonance frequency

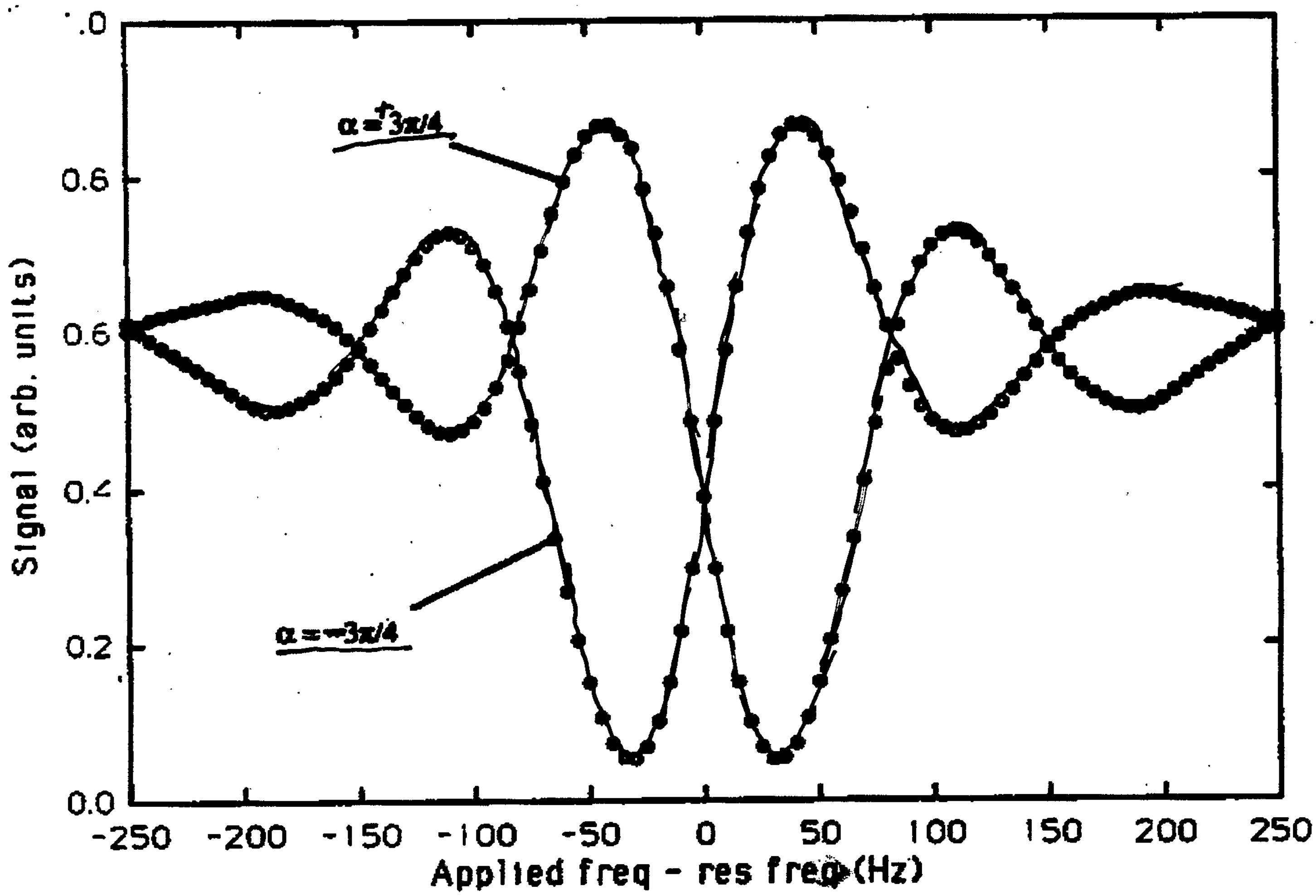


Frequency resolution $\delta\nu \approx 1/(2\pi T\sqrt{N})$

Typical observed Ramsey fringes:

$T \sim 3\,ms$

$\Delta\nu \approx 1/(2\pi T) \approx 50$ Hz

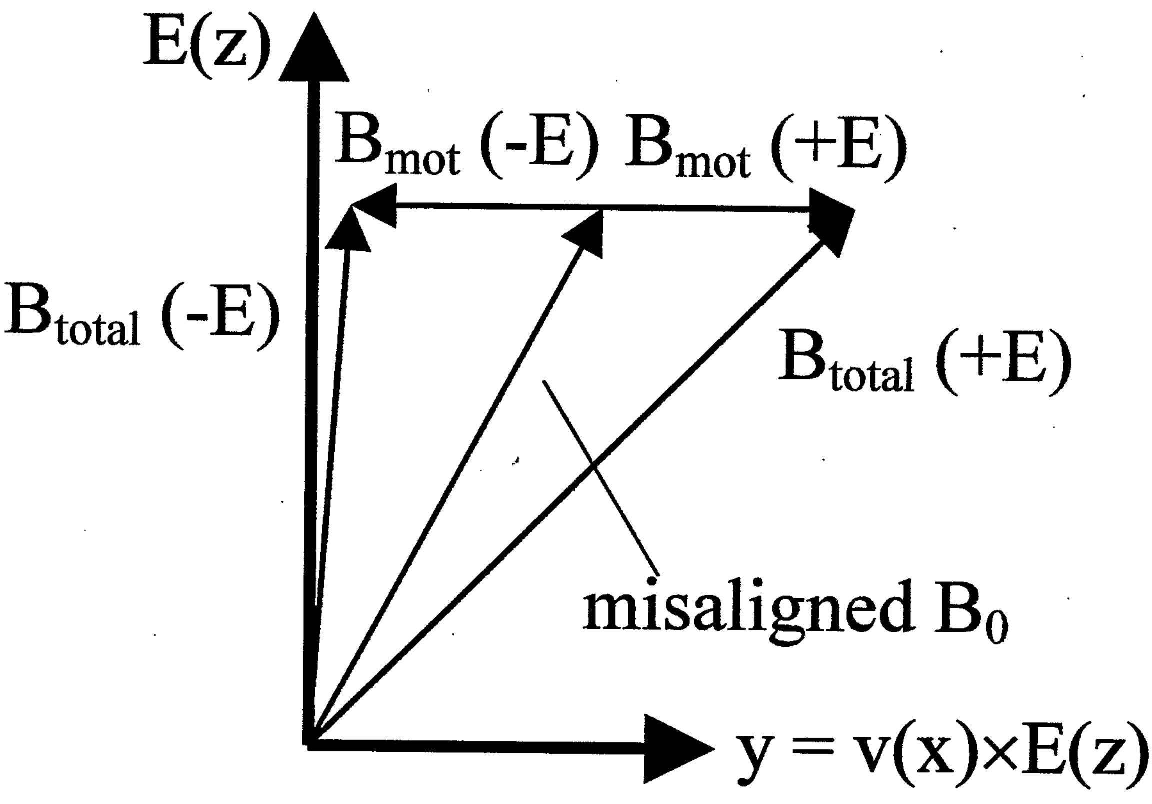


Range of observed frequencies:
10 kHz (.02 G) to 300 kHz (.64 G)

$\dot{N} \sim 10^8/s$ on resonance

Systematic effects due to the motional magnetic field $\vec{B}_{mot} = \vec{E} \times \vec{v} / c$:

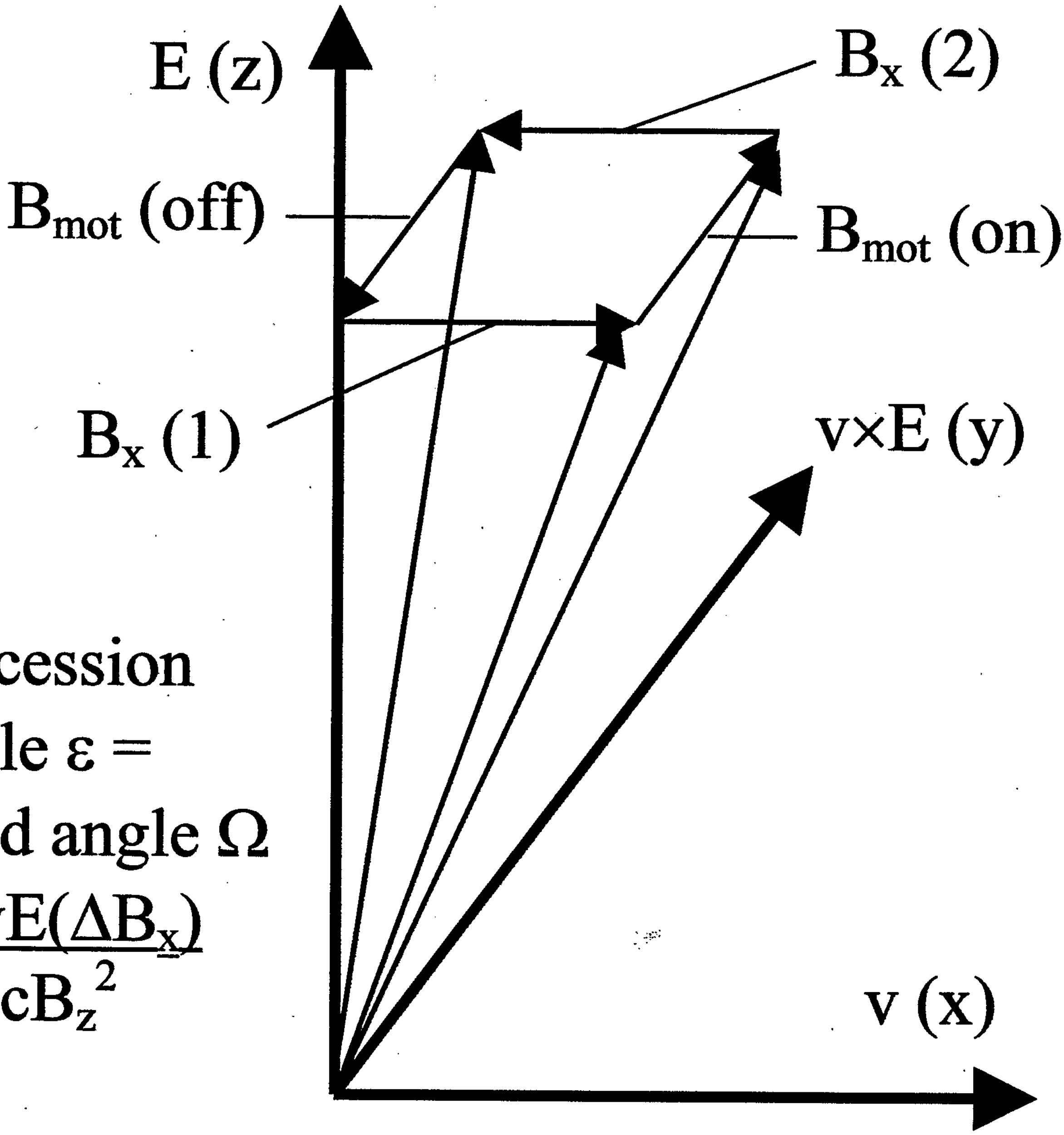
1. If $\vec{B}_0$, $\vec{E}$ are not exactly parallel, $\nu \propto |\vec{B}_{total}| = |\vec{B}_0 + \vec{B}_{mot}|$ reverses with $\vec{E}$:



Solution: average over counterpropagating beams
⇒ residual effects are product of two imperfections (i.e., one v-mismatch × one wrong B-component)

Systematic effects due to $\vec{B}_{mot} = \vec{E} \times \vec{v} / c$:

2. In combination with a gradient in B_0, B_{mot} can lead to a **geometric phase**:



Precession angle ε = solid angle Ω $= \dfrac{vE(\Delta B_x)}{cB_z^2}$

Solution:

Compare effect at different values of B_z

The results:

Best limit on the electron EDM:

$$d_e = [1.8 \pm 1.2\ (\text{stat.}) \pm 1.0\ (\text{syst.})] \times 10^{-27}\ e\cdot\text{cm}$$

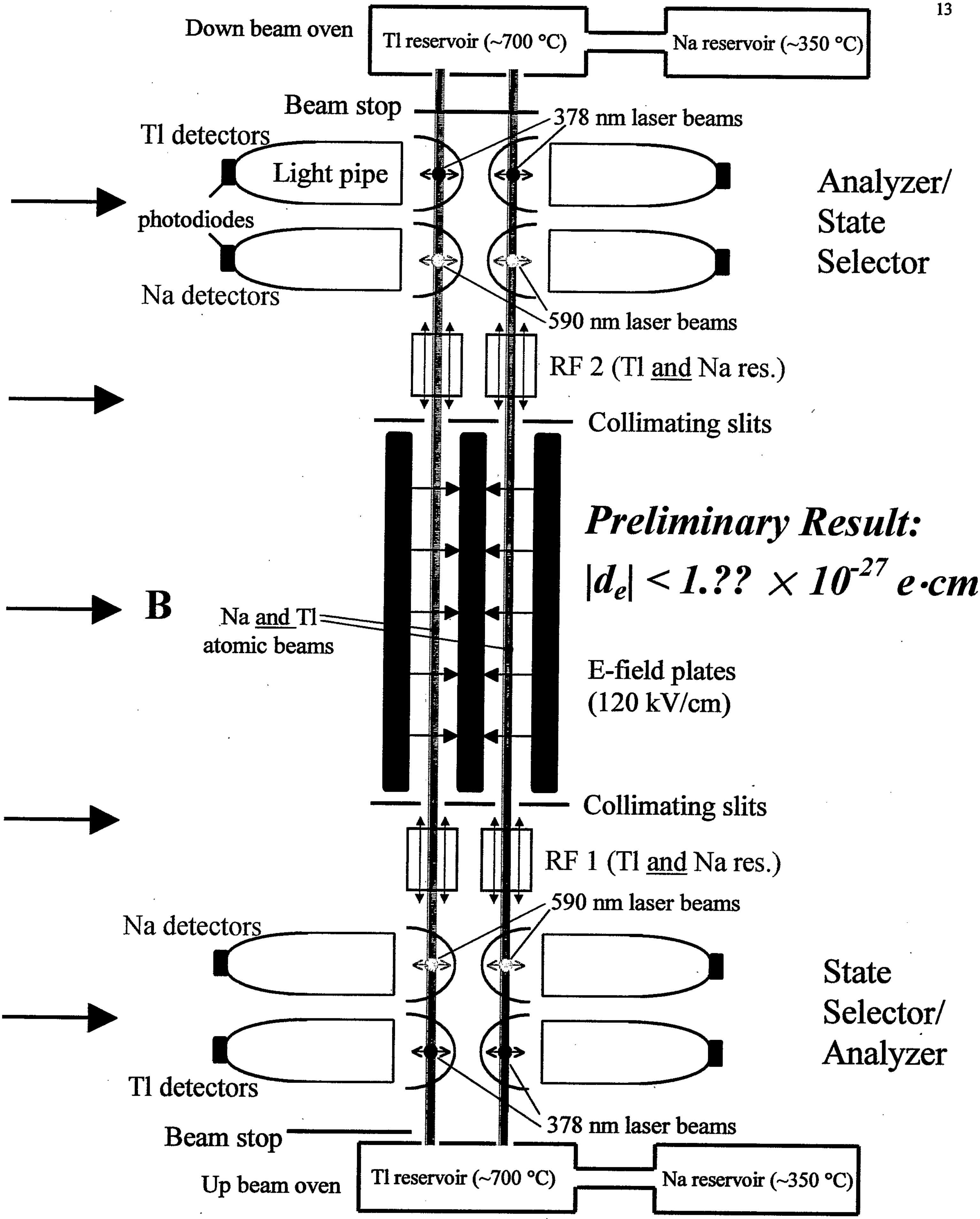
[E.D. Commins, S.B. Ross, D. DeMille, and B.C. Regan, Phys. Rev. A **50**(4), 2960 (1994).]

Recently completed improvements:

- Copropagating beams of **thallium and sodium**: Na is sensitive to all systematic effects, but not to P-,T- odd effects because of low Z (11)

- Side-by-side beams in opposite E-fields: reduction of noise due to fluctuations in B-field

***Achieved*: ~4× improvement in sensitivity**


Down beam oven
Tl reservoir (~700 °C)
Na reservoir (~350 °C)
Beam stop
378 nm laser beams
Tl detectors
Light pipe
photodiodes
Na detectors
590 nm laser beams
Analyzer/
State
Selector
RF 2 (Tl and Na res.)
Collimating slits
Preliminary Result:
|d_e| < 1.?? × 10^-27 e·cm
B
Na and Tl
atomic beams
E-field plates
(120 kV/cm)
Collimating slits
RF 1 (Tl and Na res.)
590 nm laser beams
Na detectors
State
Selector/
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Tl detectors
Beam stop
378 nm laser beams
Up beam oven
Tl reservoir (~700 °C)
Na reservoir (~350 °C)

Search for the electric dipole moment of the electron using metastable PbO

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Yale University

L. Hunter, S. Maxwell, D. Krause, K. Aulmer
Amherst College

- Why is the electron EDM interesting?
- How to detect an EDM
- The "enhancement factor"
- Why PbO?
- Current status and plans

$ Research Corp., Sloan Found., Packard Found., NSF, NIST

A new direction in EDM searches: using molecules to search for d_e

↑ ***Extremely*** large effective E-field with lab-size external field:

$\mathcal{P} \sim 1 \Rightarrow \mathbf{E_{eff}} \sim \mathbf{10^{11}}$ **V/cm** possible

(For atoms, $\mathcal{P} \sim 10^{-3}$ @ $E_{ext} \sim 100$kV/cm)

~10^3 Relative gain in sensitivity with molecules

↓ Smaller signals due to thermal distribution over rotational levels (~10^{-4})

↓ Molecules with unpaired electron spins are thermodynamically disfavored

⇒ high temperature chemistry, even smaller signals

Addressing some problems with molecules: the metastable a(1)[$^3\Sigma^+$] state of PbO

- PbO is thermodynamically stable (routinely purchased and vaporized) a(1) populated via laser excitation (replaces chemistry)

- a(1) has very small Ω-doublet splitting (like any $|\Omega|=1$ state) $\Rightarrow$ complete polarization with very small fields (~10 V/cm), Equivalent to E ~ 10^8 V/cm on an atom!

$\Rightarrow$ can work in vapor cell

PbO Cell	***vs.***	**Tl Beam**
$N = nV \sim 10^{16}$		$N = nV \sim 10^8$

Figure of merit for statistical sensitivity:

$$\mathcal{E}_{int} \times \tau \times \sqrt{\frac{dN}{dt}}$$

internal E-field → $\mathcal{E}_{int}$; coherence time → τ; count rate → $\sqrt{dN/dt}$

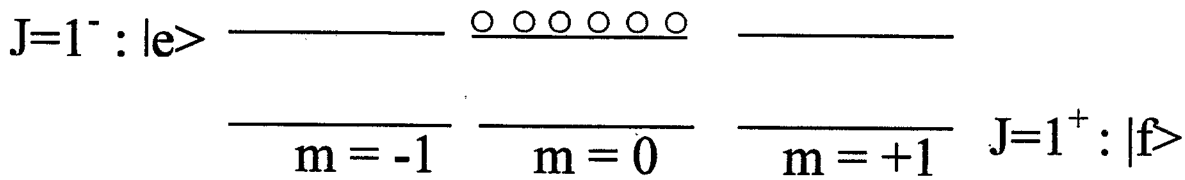
Atom/Molecule	Thallium	PbO
Group	Berkeley (Ongoing final version)	Yale/ Amherst
Applied field (V/cm)	100,000	>10
Internal field (V/cm)	6×10^{7}	6×10^{9} ***
Relaxation time τ (ms)	3	0.1
Counting rate (1/s)	$< 2\times10^{9}$	10^{11} / 10^{15}
Figure of merit	1.0	24 / 2400
EDM sensitivity (e·cm)	$>2\times10^{-28}$	**10^{-29} / 10^{-31}**
Present limit (e·cm)	$<4\times10^{-27}$	

→ 2 stages of complexity, with $\varepsilon \sim 10^{-5} / 10^{-1}$, and shot-noise limited detection

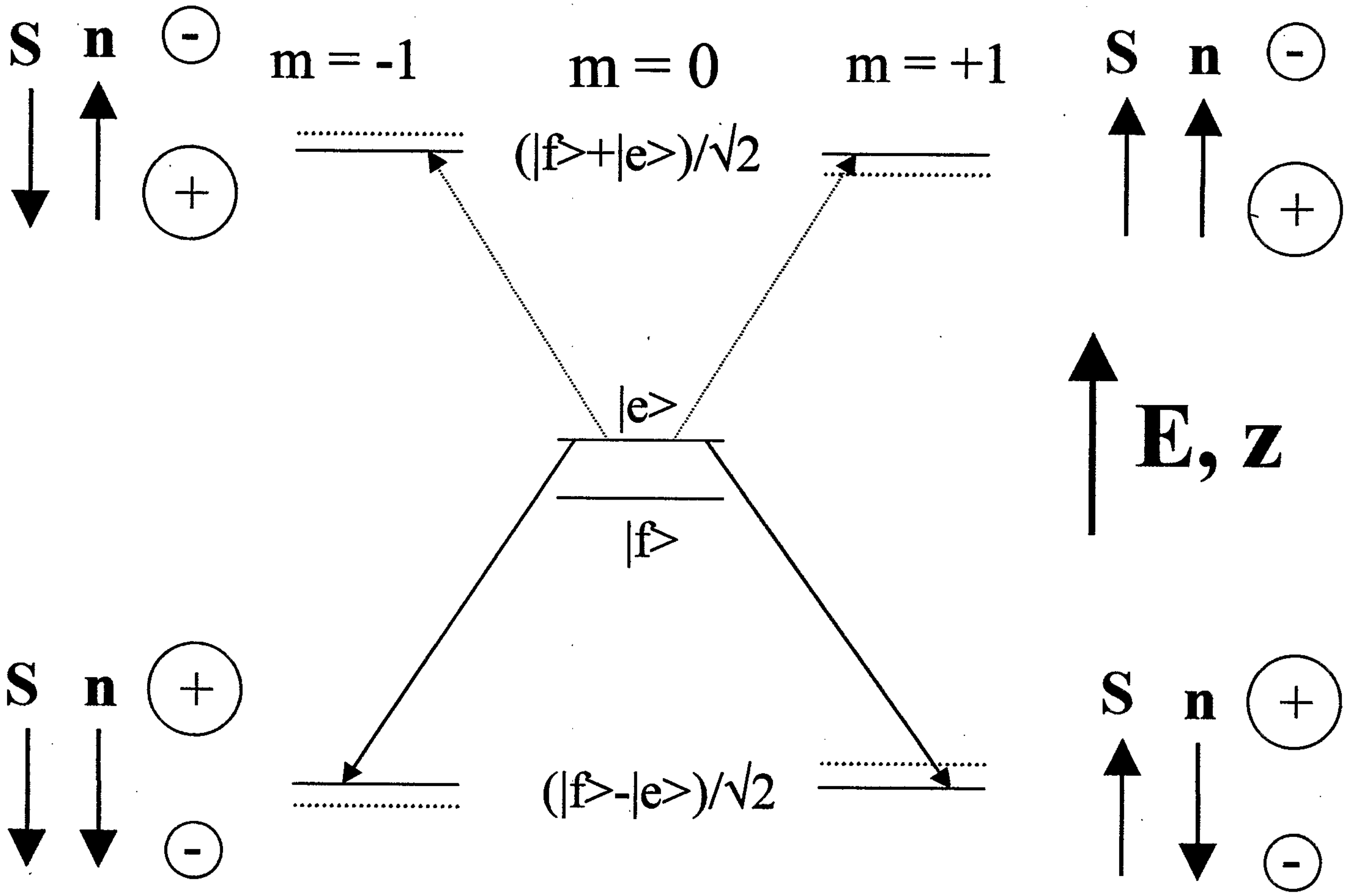
*** New data suggests E_{int} is 5–10x larger than naive estimate here!

Ω-doublet levels = comagnetometer

No E-field:

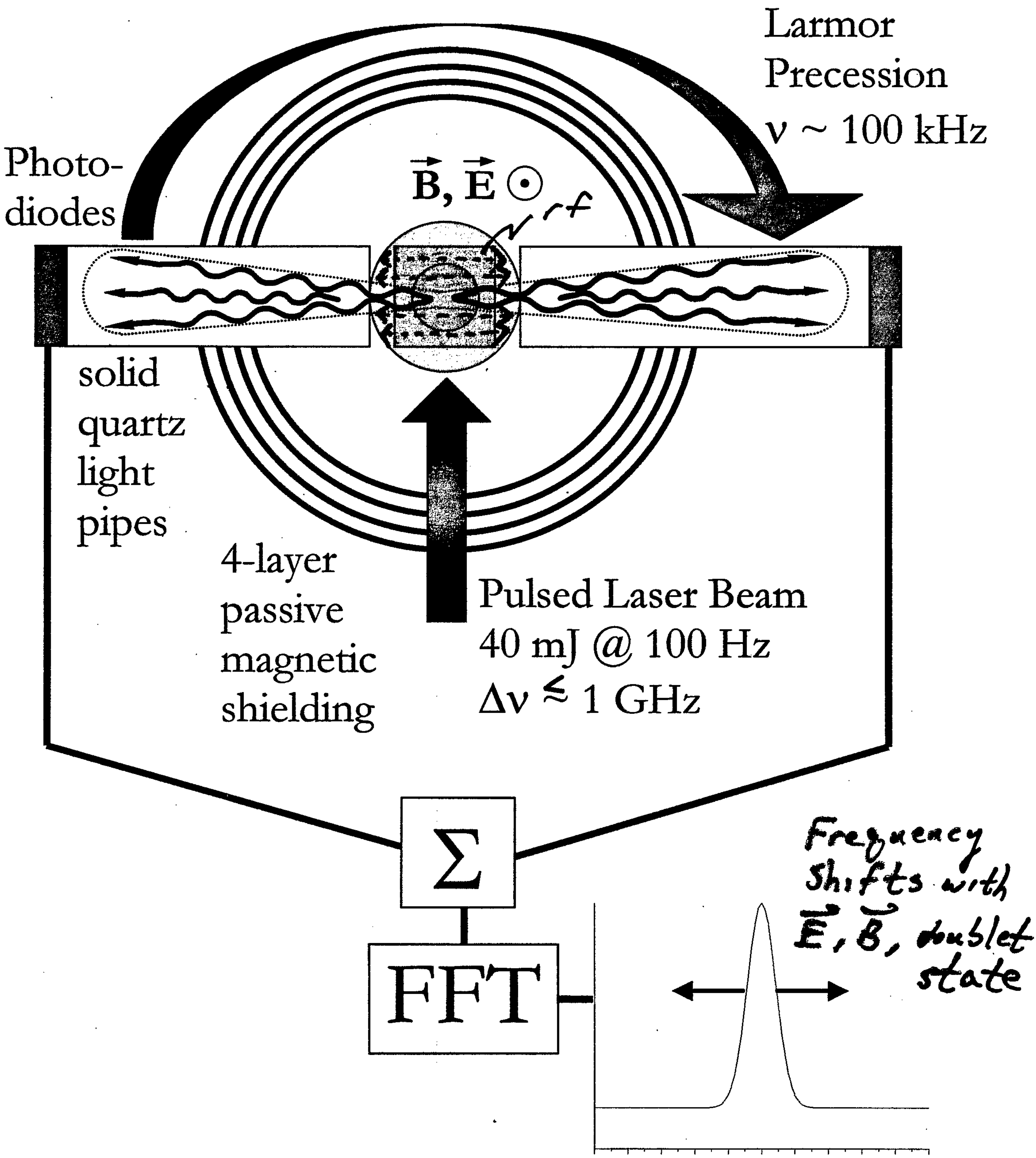


Structure and transitions in E-field:



Quadratic Stark splitting eliminates v×E effects!

Anticipated Experimental Setup



Current status of EDMs:

3 experiments give best limits on fundamental quantities:

	n (ILL, PNPI)	**Hg** (Seattle)	**Tl** (Berkeley) (preliminary)
EDM	$<7\times10^{-26}$	$<2\times10^{-28}$	$\lesssim7\times10^{-25}$
d_n	7×10^{-26}	2×10^{-25}	
d_e		1×10^{-26}	$\sim1\times10^{-27}$
θ_{QCD}	4×10^{-10}	2×10^{-10}	
$\varepsilon_{q/l,\,SUSY}$	1×10^{-2}	2×10^{-3}	$\sim6\times10^{-3}$
ε_{Higgs}	$3/\tan\beta$	$0.4/\tan\beta$	$\sim0.2/\tan\beta$
$x_{q/l,\,LR}$	1×10^{-2}	1×10^{-3}	$\sim2\times10^{-2}$

Future electron EDM searches:

- PbO ($\times 10^2$-10^4): Yale + Amherst *(Ongoing)*

- Laser-cooled/trapped Cs ($\times 100$): Stanford, Berkeley' *(Detailed proposal published by Stanford group)*

- Other developmental work: *Cold molecules, Cs in helium, etc...*