

RELATIVISTIC ENHANCEMENT of ELECTRON EDM IN A PARAMAGNETIC ATOM

- ONE-ELECTRON CENTRAL FIELD APPROXIMATION:

Hamiltonian before EDM perturbation:

$$H = c \alpha \cdot p + mc^2\gamma_0 - e(\Phi_i + \Phi_e)$$

$$\Phi_e = -\mathbf{E}_e \cdot \mathbf{r}$$

- $|\psi\rangle$ are the eigenstates of H
- EDM perturbation: Choosing $\mathbf{B} = 0$, we have:

$$H_{\text{EDM}} = -d_e \gamma_0 \Sigma \cdot \mathbf{E} \quad (\mathbf{E} = \mathbf{E}_i + \mathbf{E}_e)$$

- Separate into two parts:

$$H_{EDM} = -d_e \Sigma \cdot E - d_e(\gamma_0 - 1) \Sigma \cdot E$$

SURVIVES IN N.R. LIMIT VANISHES IN N.R. LIMIT

CONTRIBUTES NOTHING
TO FIRST ORDER ENERGY SHIFT
(SCHIFF'S THEOREM)

$$\Delta E = \langle \psi | -d_e(\gamma_0 - 1) \Sigma \cdot E | \psi \rangle$$

$$H = H_0 - |e| \Phi_e$$

$$|\psi\rangle = |\psi_0\rangle + |e| \sum_n' \frac{|\psi_n\rangle \langle \psi_n| E_e z |\psi_n\rangle}{E_0 - E_n}$$

$$= |\psi_0\rangle + |e| E_e |\eta\rangle$$

$$\begin{aligned}\therefore \Delta E &= \langle \psi | -d_e(\gamma_0 - 1) \Sigma \cdot \mathbf{E} | \psi \rangle = \\ &= -d_e E_e \langle \psi_0 | (\gamma_0 - 1) \Sigma_z | \psi_0 \rangle \\ &\quad - d_e E_e [\langle \eta | (\gamma_0 - 1) \Sigma \cdot \mathbf{E}_i | \psi_0 \rangle + \langle \psi_0 | (\gamma_0 - 1) \Sigma \cdot \mathbf{E}_i | \eta \rangle]\end{aligned}$$

$$R \approx 2|e| \sum \frac{\langle \psi_0 | (\gamma_0 - 1) \Sigma \cdot \mathbf{E}_i | \psi_n \rangle \langle \psi_n | z | \psi_0 \rangle}{E_0 - E_n}$$

$$\langle \psi_n | z | \psi_0 \rangle \approx a_0$$

$$E_0 - E_n \approx .1 e^2/a_0$$

$$|e| \langle \psi_0 | (\gamma_0 - 1) \Sigma \cdot \mathbf{E}_i | \psi_n \rangle \approx Z^2 \alpha^2 \cdot \frac{Z|e|^2}{a_0^2}$$

$$\therefore R \approx 10 Z^3 \alpha^2$$

ENHANCEMENT FACTORS

$$|R| \equiv \left| \frac{d_a}{d_e} \right| \approx 10 Z^3 \alpha^2$$

ATOM	Z	STATE	R
<hr/>			
Na	11	$3^2S_{1/2}$	0.3
Rb	37	$5^2S_{1/2}$	30
Cs	55	$6^2S_{1/2}$	114
Fr	87	$7^2S_{1/2}$	1100
Tl	81	$6^2P_{1/2}$	-585
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Very large enhancement factors for certain paramagnetic molecules...

YbF, CdF, PbO,

CONTRIBUTIONS TO d_a

DIAMAGNETIC ATOMS (^{199}Hg , ^{129}Xe)

- NUCLEONIC EDM
- P,T- ODD N-N INTERACTION
- P,T- ODD e-N INTERACTION
(TENSOR-PSEUDOTENSOR)

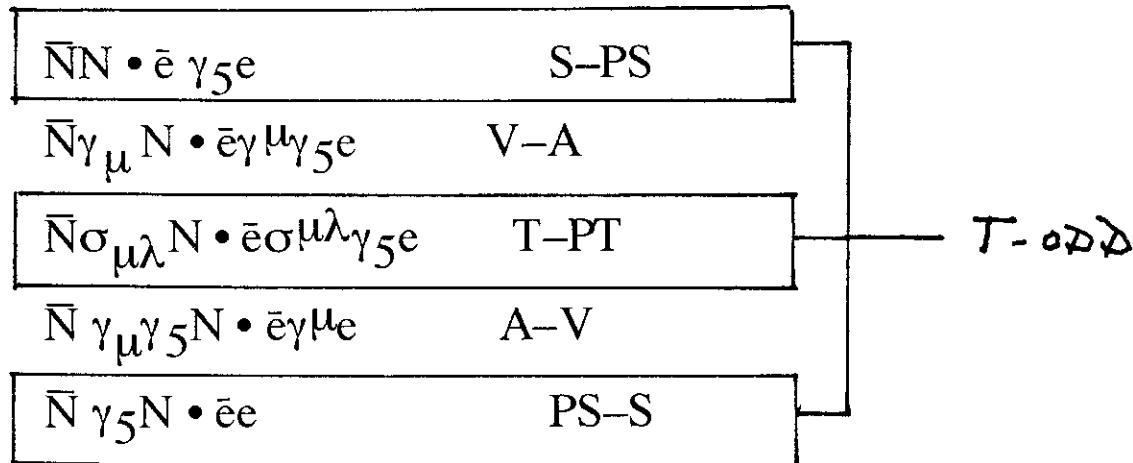
PARAMAGNETIC ATOMS (^{133}Cs , ^{205}Tl)

- ELECTRON EDM
- P,T -ODD e-N INTERACTION
(SCALAR - PSEUDOSCALAR)
- EFFECTS INDUCED BY RADIATIVE CORRECTIONS FROM STANDARD WEAK INTERACTIONS:

C,T ODD e-e, e-N COUPLINGS
T- ODD BETA DECAY COUPLINGS

P,T -ODD e-N INTERACTION

P-ODD NON-DERIVATIVE COUPLING FORMS:



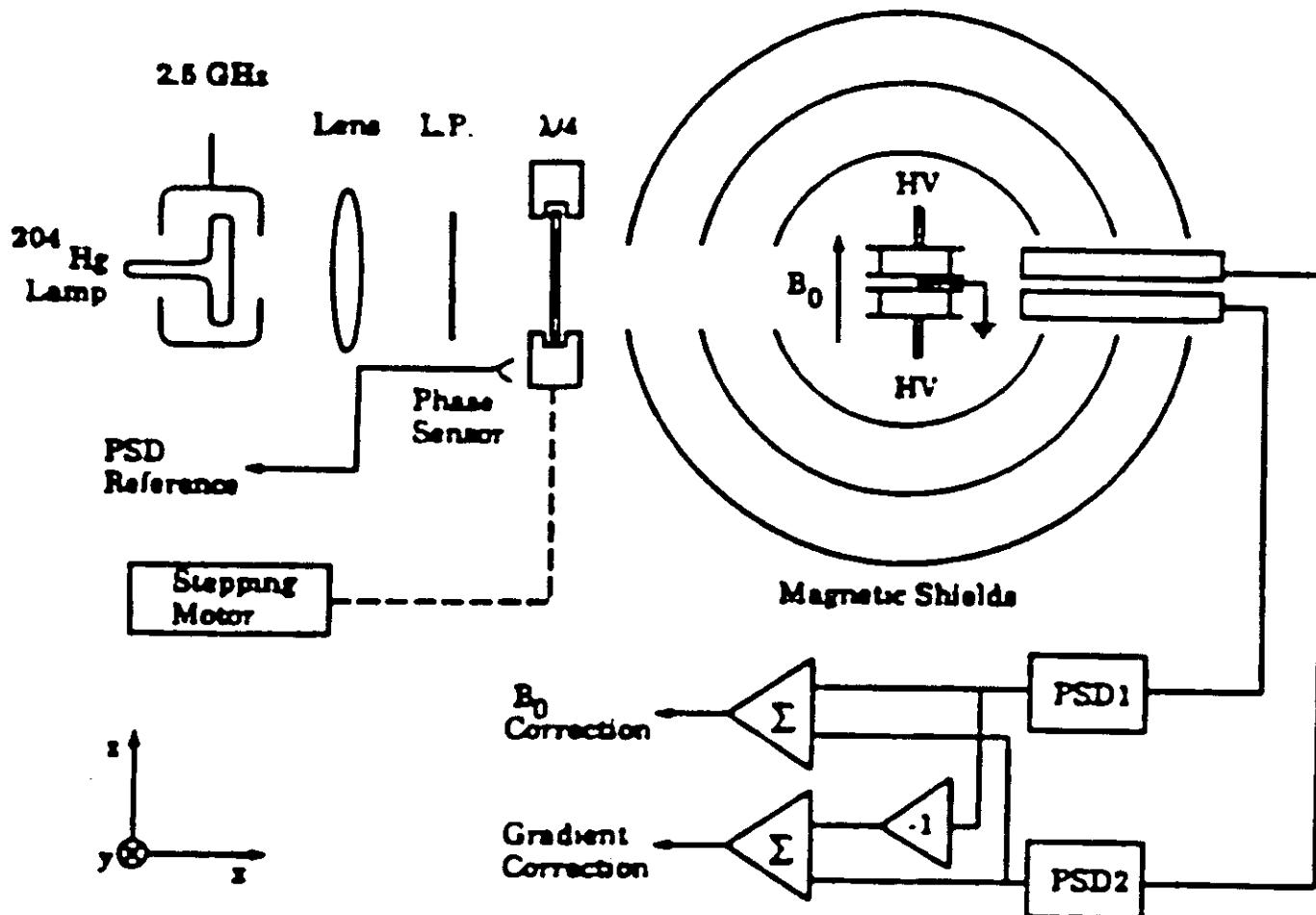
$$\begin{aligned}
 H_{e-N} &= i \frac{G_F}{\sqrt{2}} \\
 \sum_i^A \left(C_S \bar{N}_i N_i [\bar{e}\gamma_5 e] + C_T \bar{N}_i \sigma^{\mu\lambda} N_i [\bar{e}\sigma_{\mu\lambda}\gamma_5 e] + C_P \bar{N}_i \gamma_5 N_i [\bar{e}e] \right)
 \end{aligned}$$

DIAMAGNETIC ATOMS

• ^{199}Hg

E.N. Fortson and co-workers
Univ. of Washington, Seattle

[J. Jacobs et al Phys. Rev. A 52, 3521 (1995)]



$$|d(199\text{Hg})| < 8.7 \cdot 10^{-28} \text{ e cm.}$$

DIAMAGNETIC ATOMS (continued)

- NEW ^{199}Hg Experiment: (E.N. Fortson and co.)

Discharge lamp → Laser source
 Higher Hg densities
 Better control of systematics (2 cells → 4 cells)

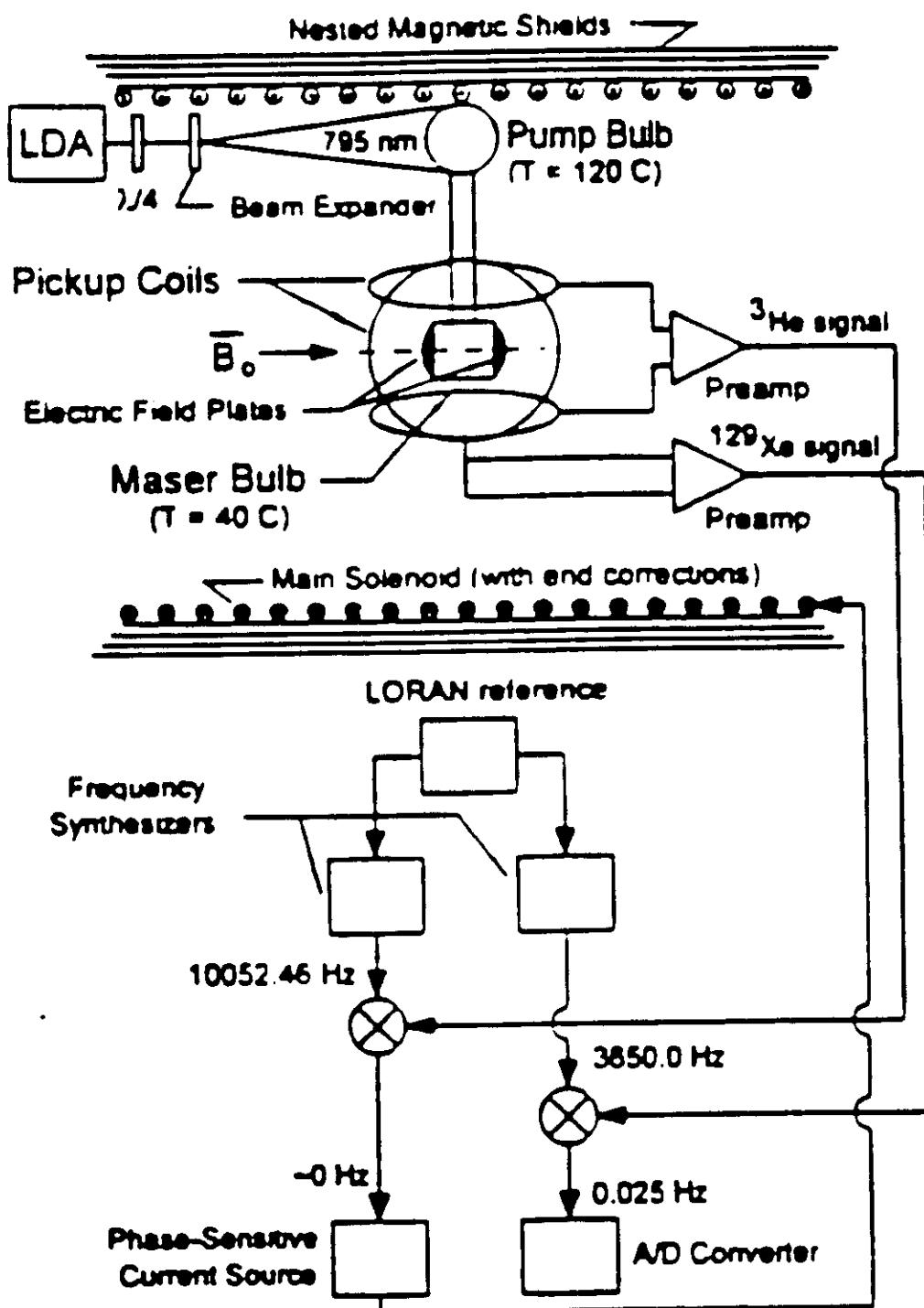
Hopes for improvement by factor of ≈ 30

- $^{129}\text{Xe} + ^3\text{He}$ Dual MASER

R. Walsworth (Harvard-Smithsonian),
 T. Chupp (Michigan) and co-workers

[R.E. Stoner et al Phys. Rev.Lett. 77, 3971 (1996)]

HOPES FOR 10^{-28} e·cm SENSITIVITY
 IN
 $d(^{129}\text{Xe})$



ELECTRON EDM SEARCHES

RECENT PAST, PRESENT, AND NEAR FUTURE

- CELL OPTICAL PUMPING (^{133}Cs)

L. Hunter (Amherst, 1989)

- ATOM TRAPPING IN SOLID HELIUM (^{133}Cs)

S. Kanorsky et al (Munich)

- ATOM VAPOR COOLING, TRAPPING (^{133}Cs)

S. Chu (Stanford)

D. Weiss (Berkeley)

- PARAMAGNETIC MOLECULES

E. Hinds (Brighton, U.K.)

(Yb F)

D. DeMille (Yale)

(Pb O *)

SEARCH FOR THE ELECTRON ELECTRIC DIPOLE MOMENT

1999

B.C. Regan (graduate student)

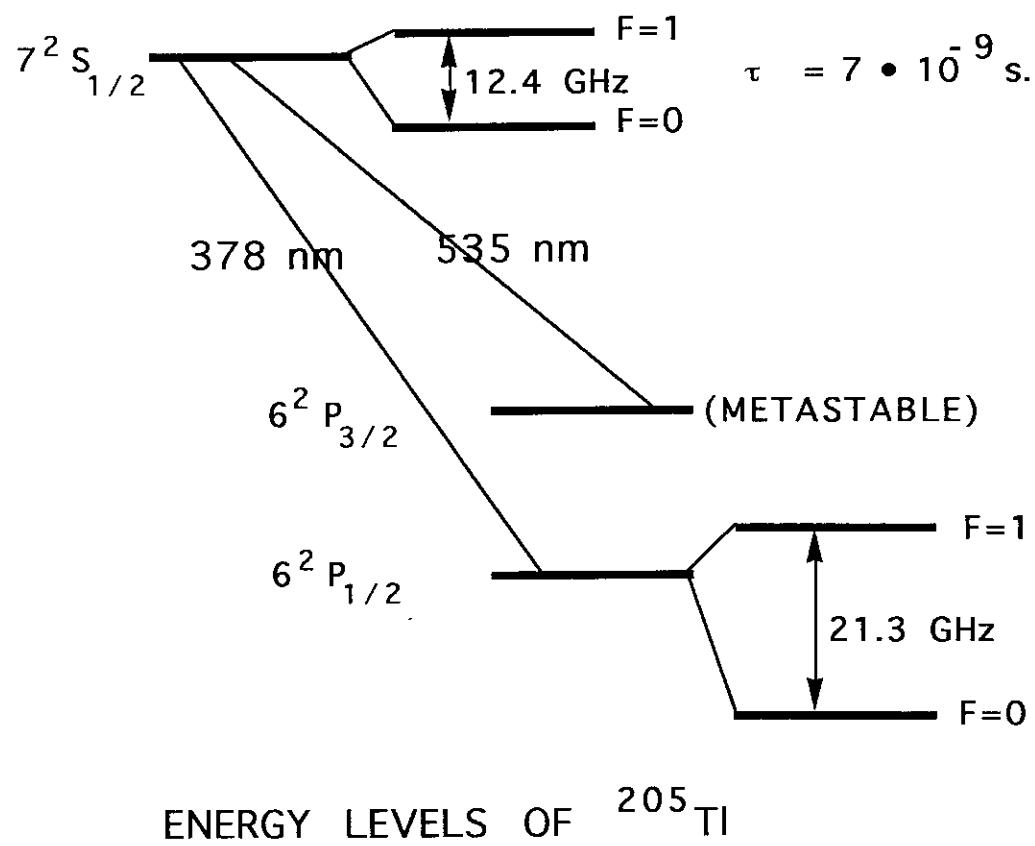
D.P. DeMille (former post-doc, now at Yale)

Christian Schmidt (post doc)

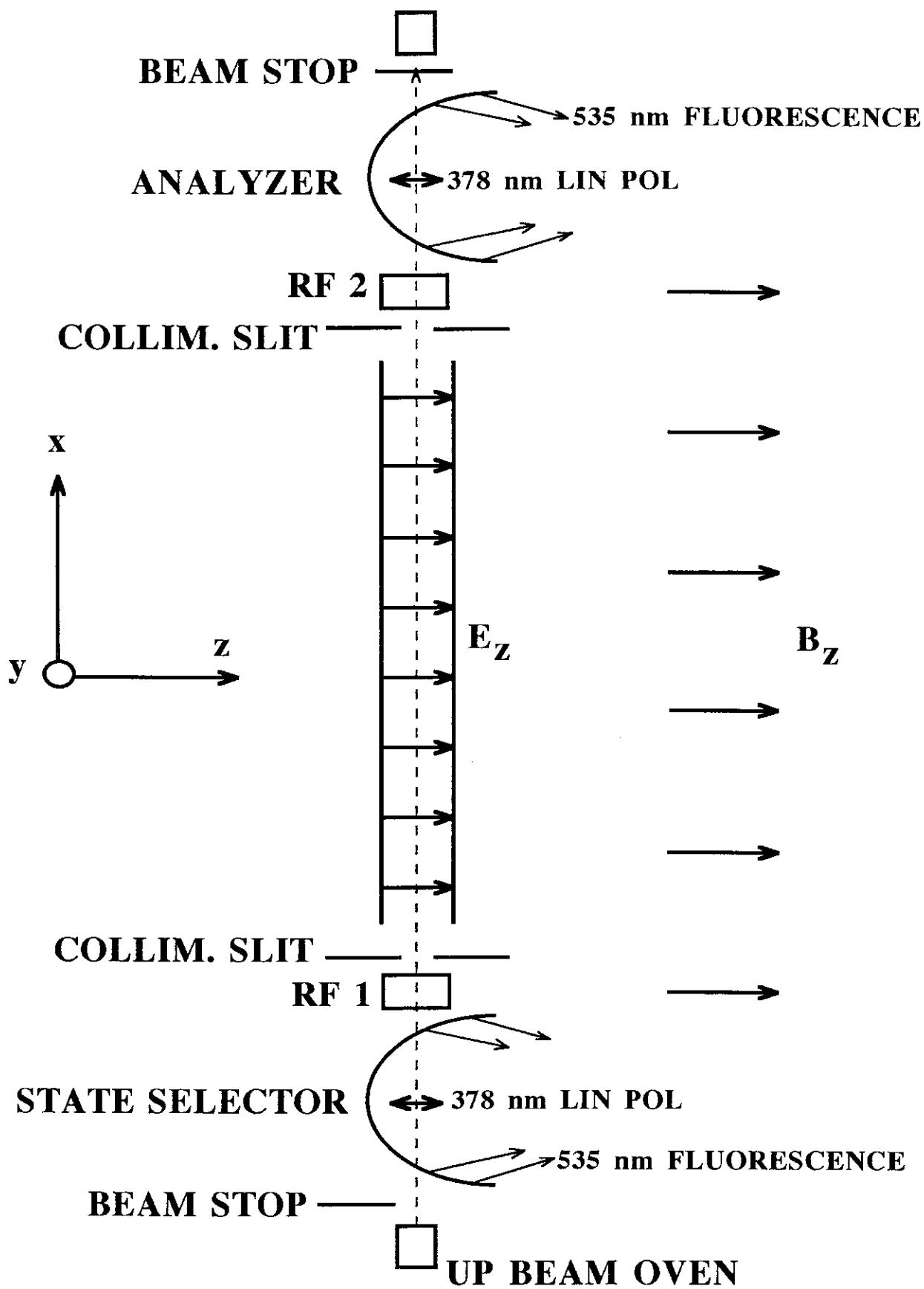
E.D. Commins

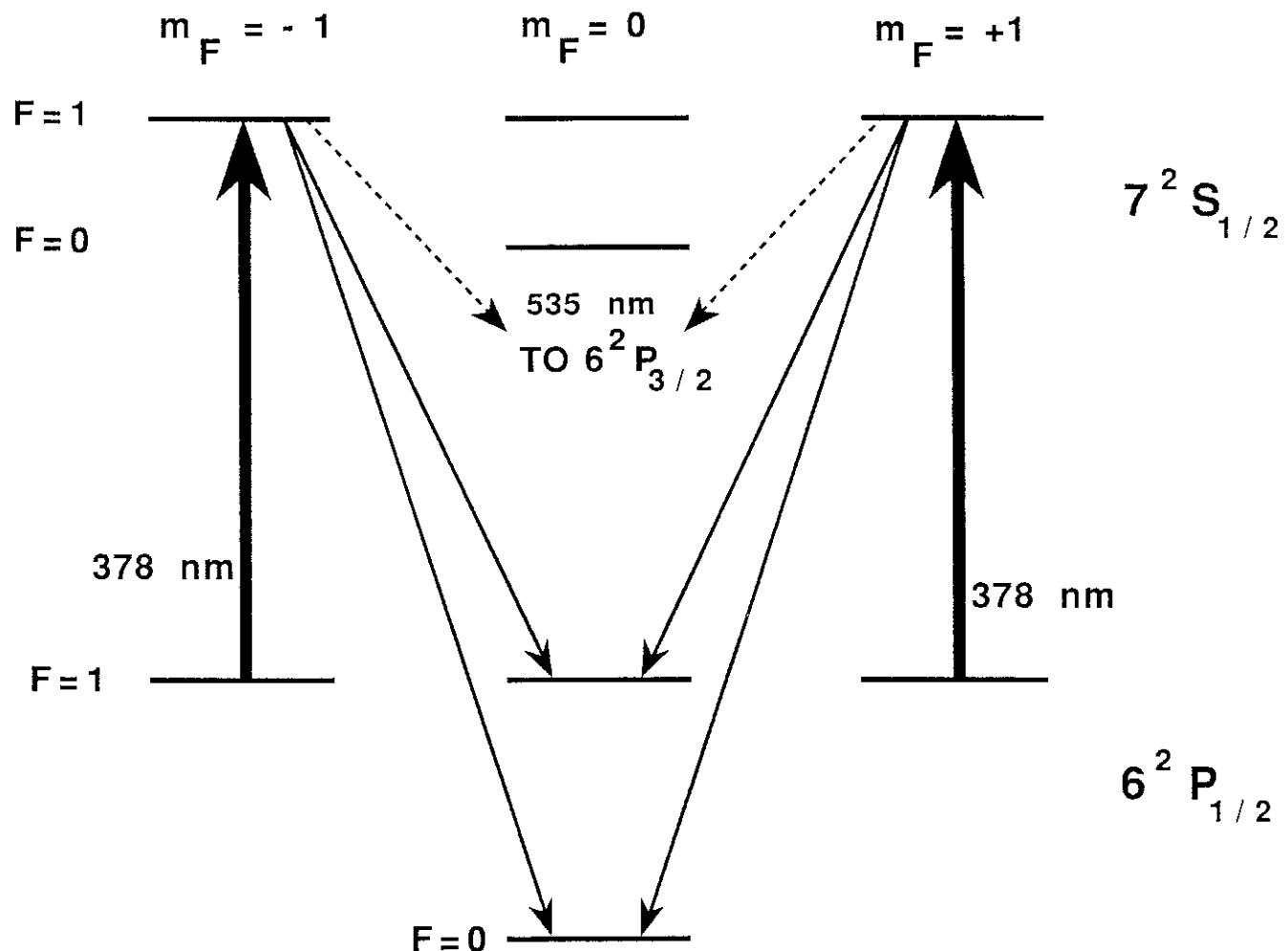
University of California, Berkeley and L.B.N.L.

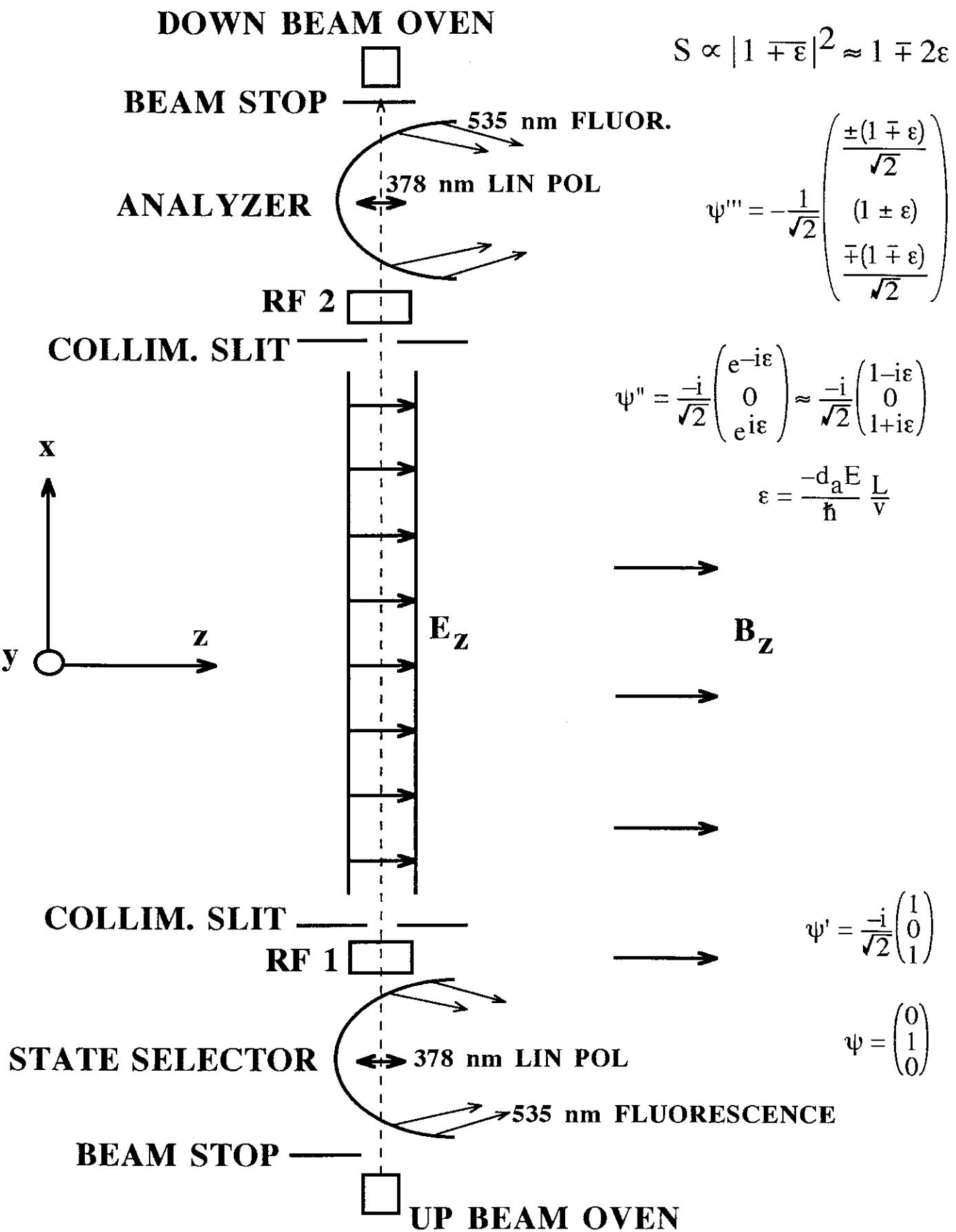
ATOM	Z	gnd config	State
...			
Gold (Au)	79	...5d ¹⁰ 6s	² S _{1/2}
Mercury (Hg)	80	...5d ¹⁰ 6s ²	¹ S ₀
Thallium (Tl)	81	...5d ¹⁰ 6s ² 6p	² P _{1/2}
Lead (Pb)	82	... 5d ¹⁰ 6s ² 6p ²	³ P ₀
...			



DOWN BEAM OVEN







THE E x v EFFECT

$$\mathbf{B} = \mathbf{B}_0 + \frac{1}{c} \mathbf{E} \times \mathbf{v}$$

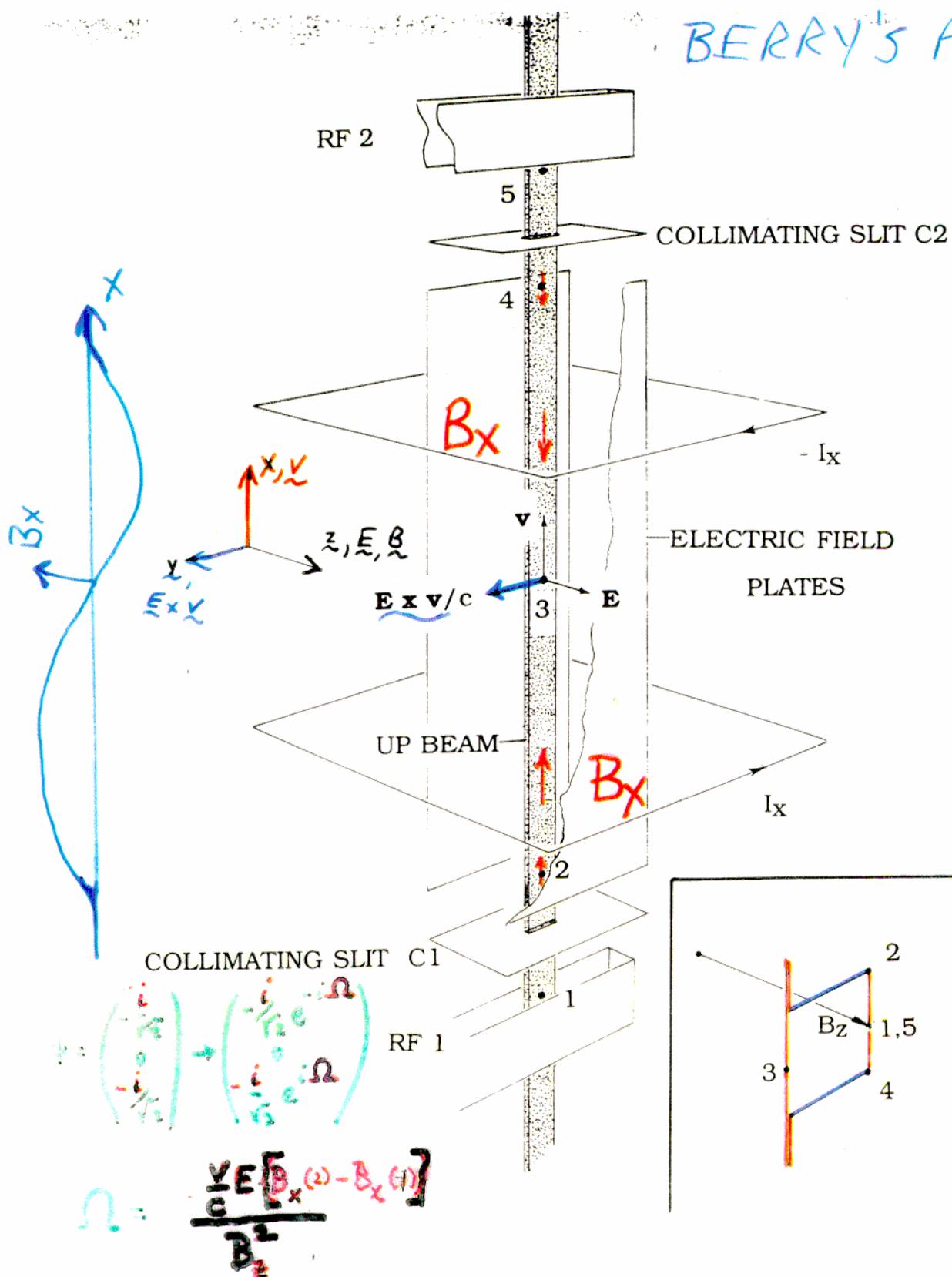
$$\begin{aligned}\gamma |\mathbf{B}| &= \gamma \sqrt{\mathbf{B}_0^2 + 2 \mathbf{B}_0 \cdot \frac{\mathbf{E} \times \mathbf{v}}{c} + \left(\frac{\mathbf{E} \times \mathbf{v}}{c}\right)^2} \\ &\approx \gamma \left(|\mathbf{B}_0| + \mathbf{B}_0 \cdot \frac{\mathbf{E} \times \mathbf{v}}{c |\mathbf{B}_0|} \right)\end{aligned}$$

THE TROUBLESONME TERM IS:

$$\gamma \mathbf{B}_0 \cdot \frac{\mathbf{E} \times \mathbf{v}}{c |\mathbf{B}_0|}$$

$\vec{E} \times \vec{v}$ can change direction of \vec{B} :

BERRY'S PHASE



ELECTRON EDM SEARCH

1994 RESULT

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

E.D. Commins, S.B. Ross, D.DeMille, and B.C. Regan

Phys. Rev. A **50**, 2960, 1994

CONTRIBUTIONS TO UNCERTAINTIES

STATISTICAL

SYSTEMATIC

“Magnetic” noise	$E \times v$
Laser freq fluctuations	Geometric phase
Laser power fluctuations	Leakage, charging currents
Atomic beam fluctuations	
Shot noise	

ELECTRON EDM SEARCH

MAJOR IMPROVEMENTS

- PAIRED ATOMIC BEAMS**

- NOISE REDUCED BY FACTOR OF 10**

- SODIUM - THALLIUM**

- E x v**

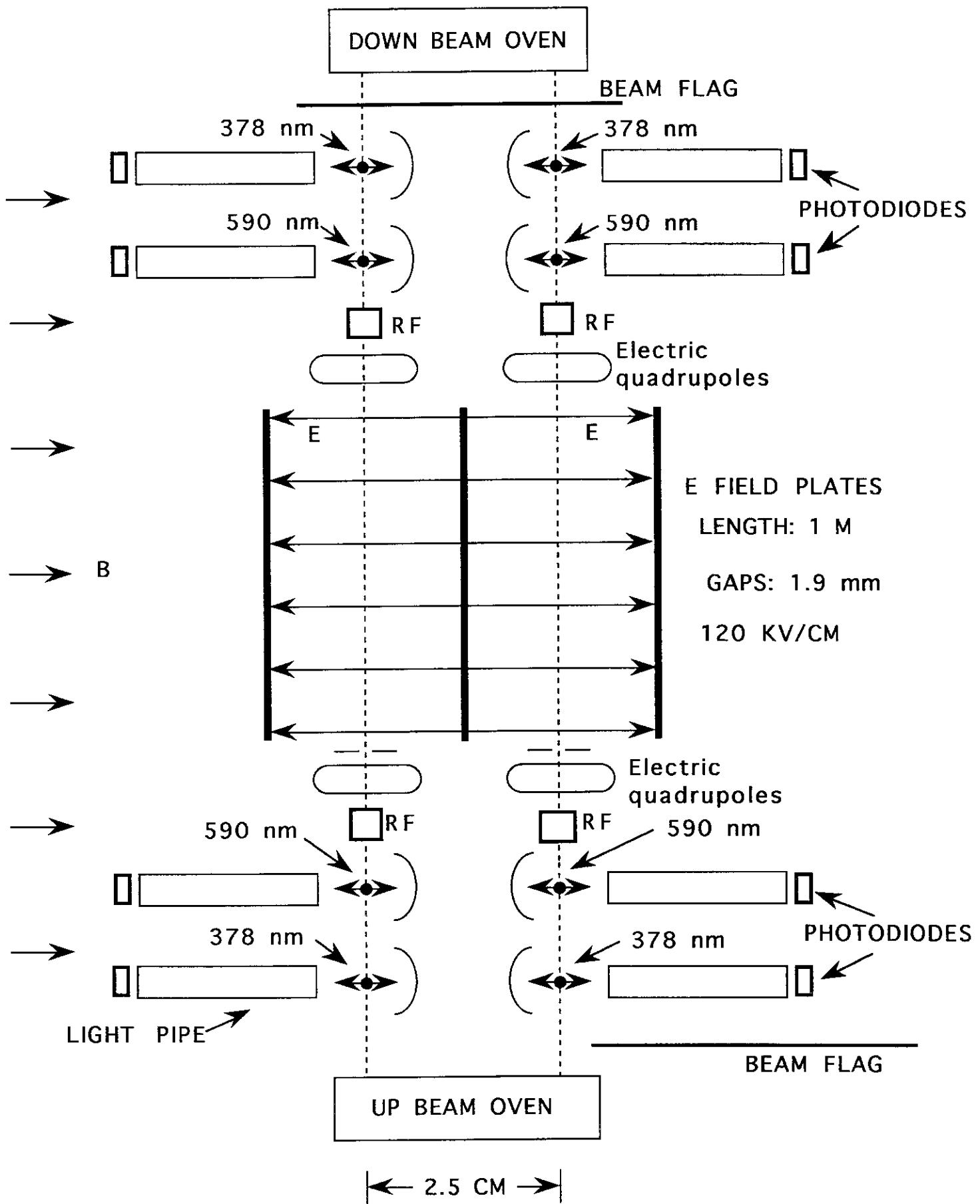
- Geometric Phase**

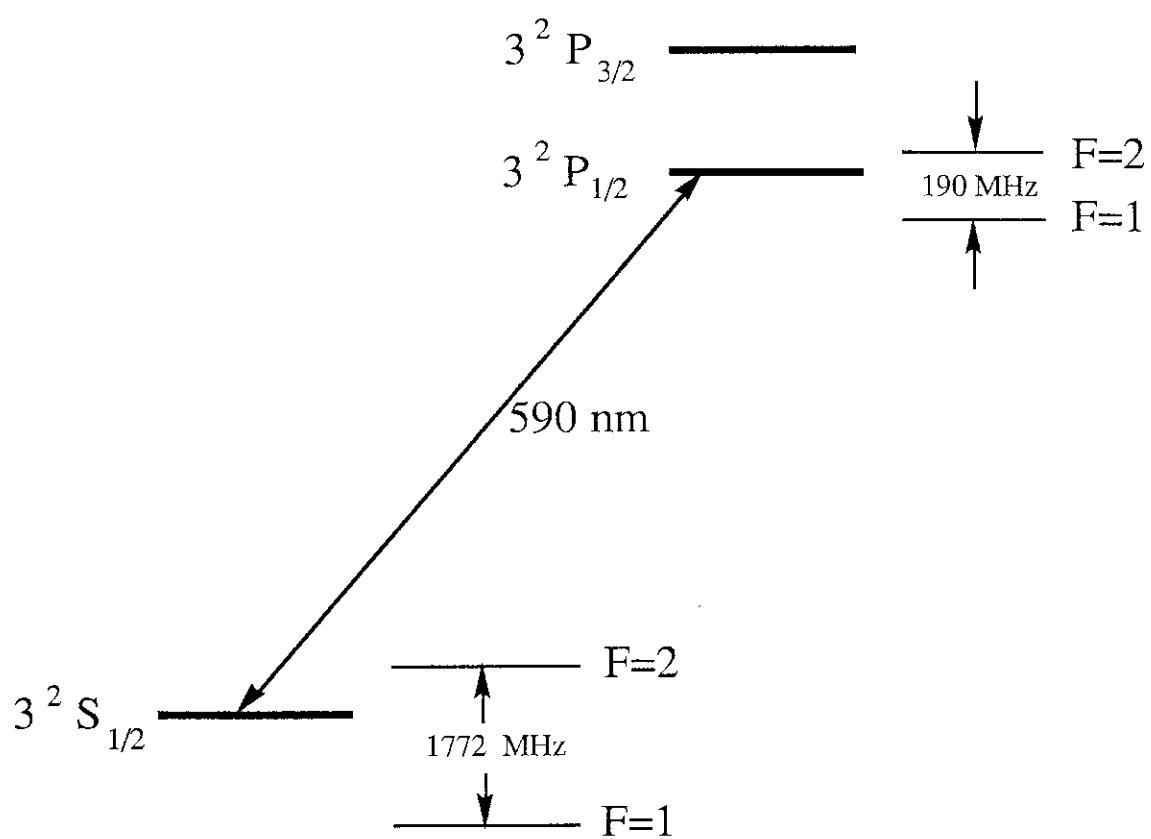
- Charging and Leakage currents**

- MISCELLANEOUS**

- More efficient detection**

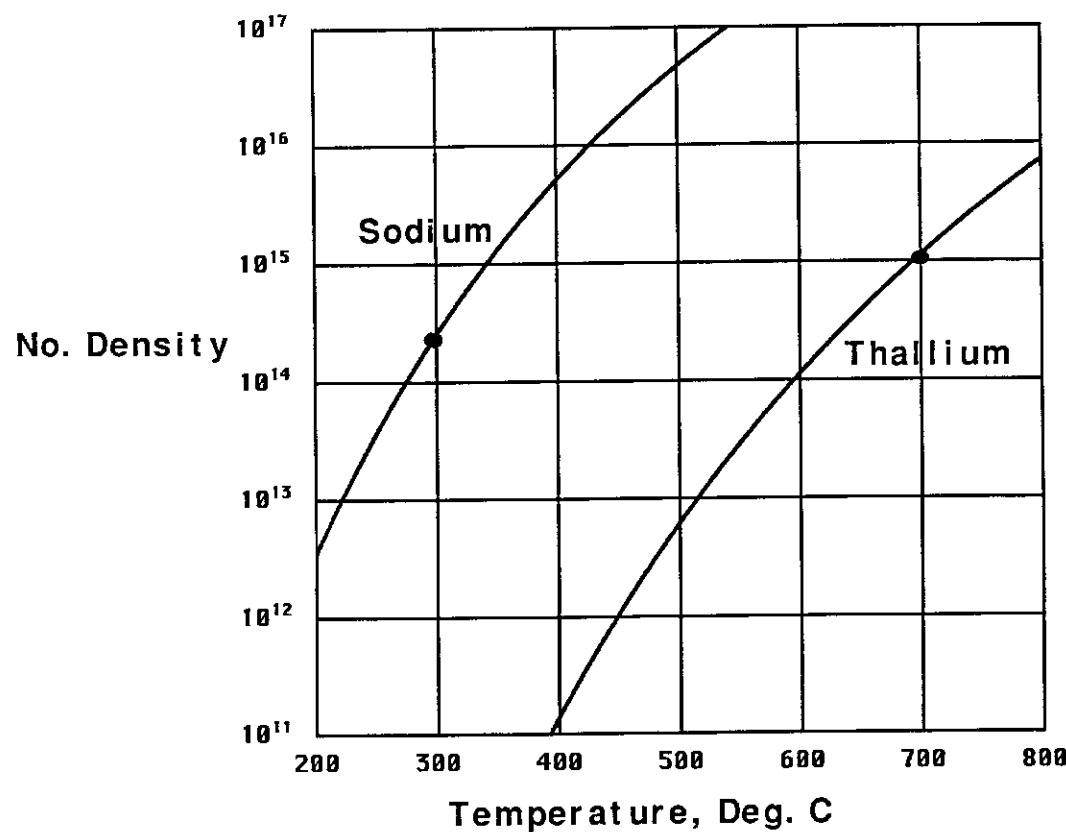
- Higher oven fluxes**

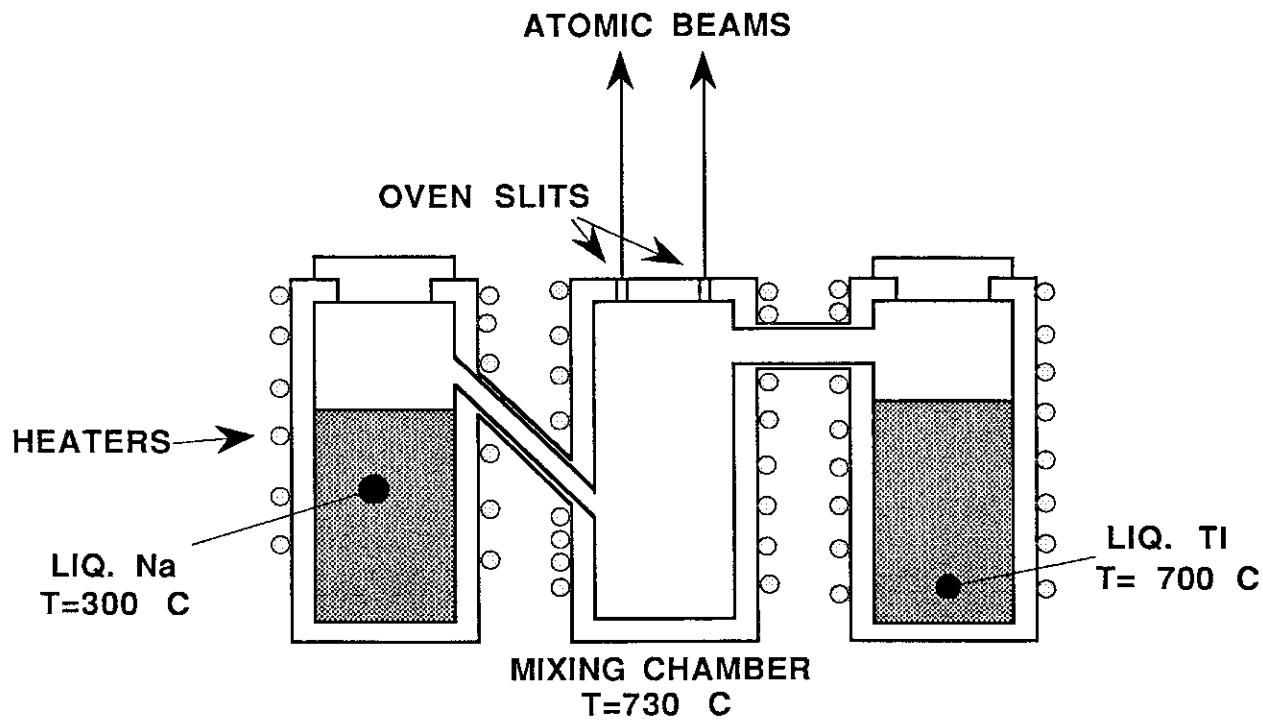




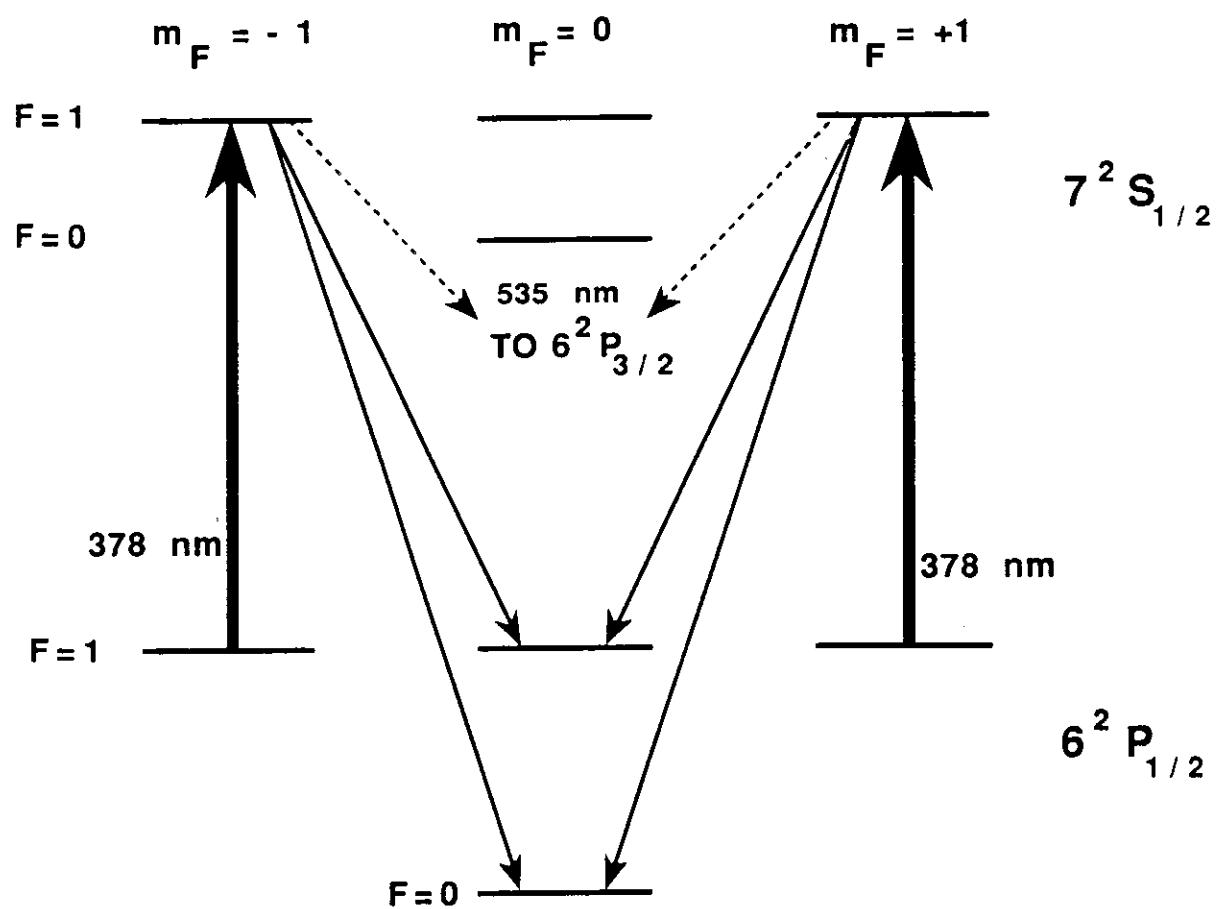
SODIUM [NA] Z = 11

LOW -LYING LEVELS





UP BEAM OVEN



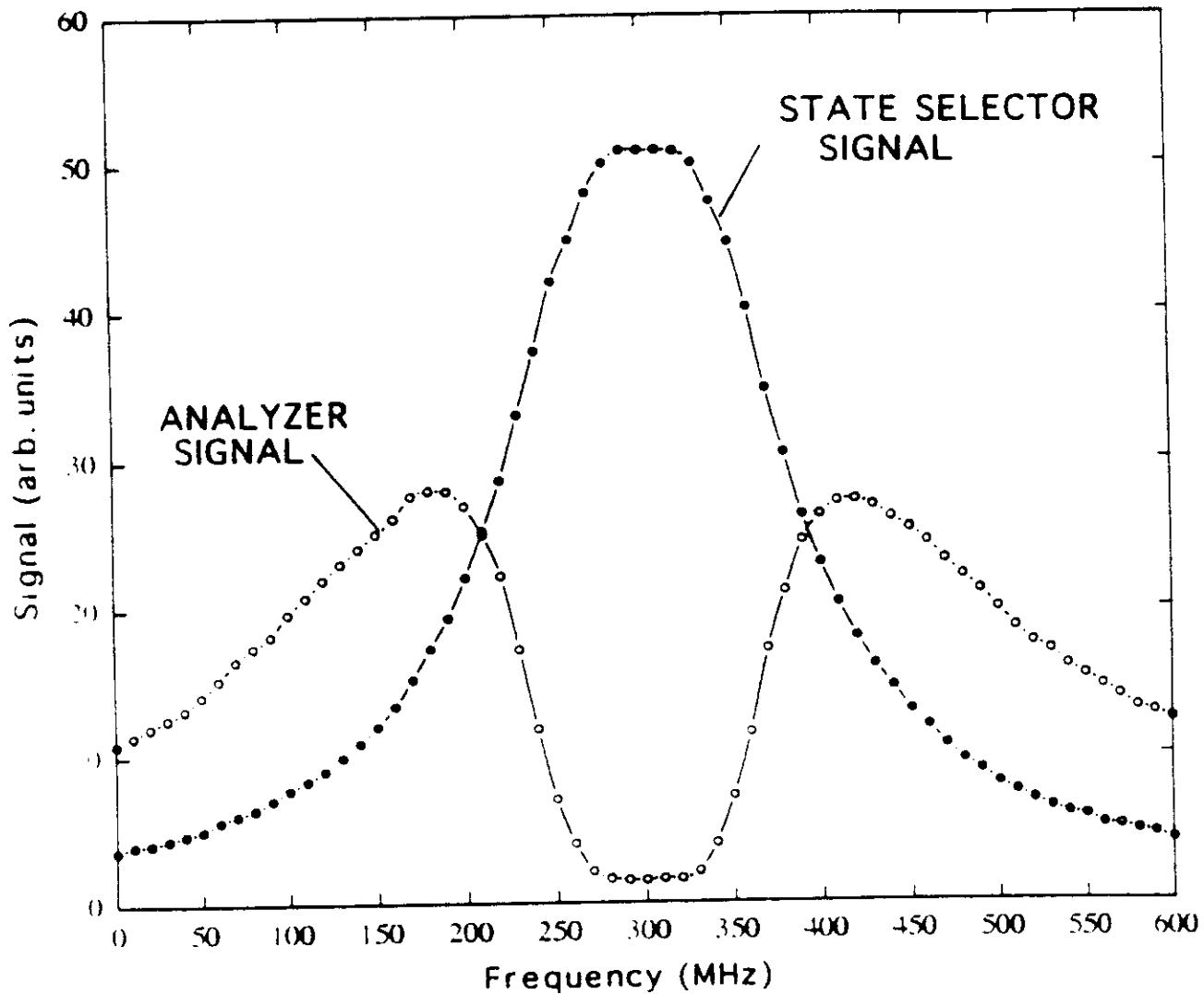
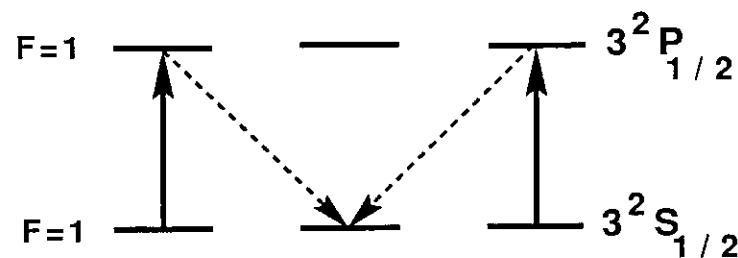
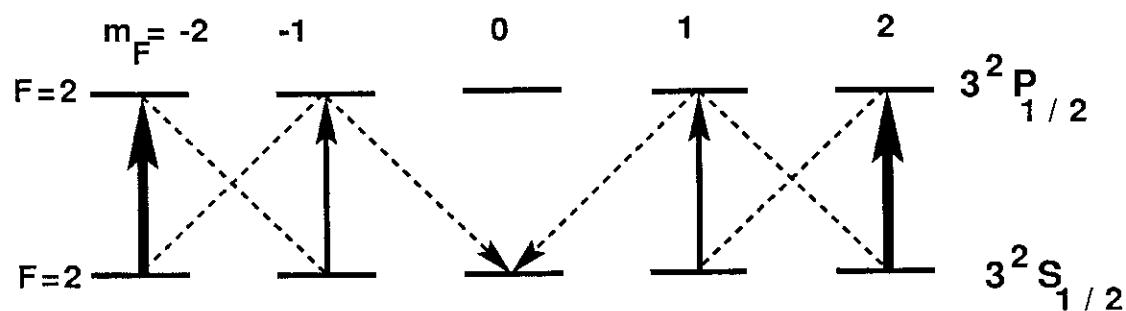
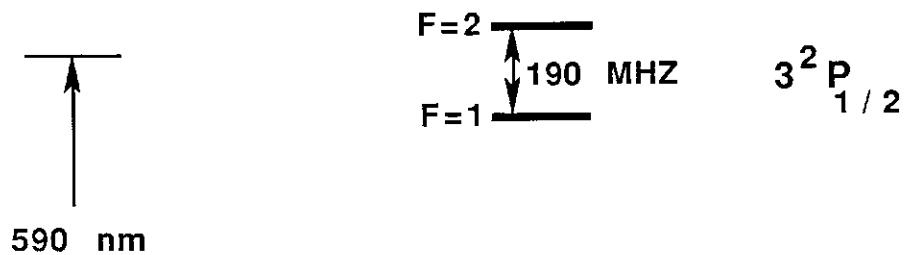
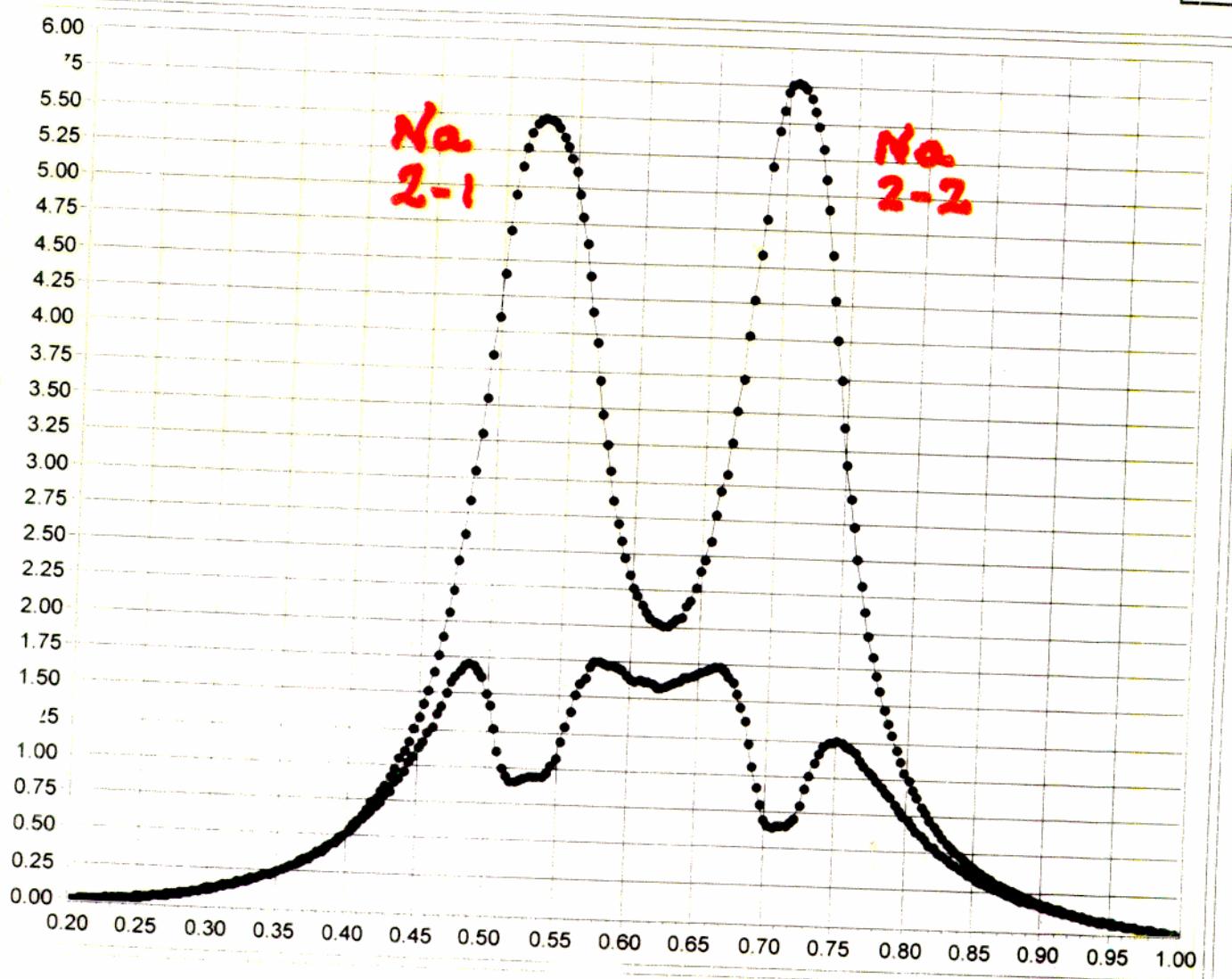


FIG. 5. Typical optical resonances observed with 535-nm fluorescence in the state selector and analyzer. *Tl 1-1*



SODIUM OPTICAL PUMPING

Optical Pumping Data f ~~Day~~ vi
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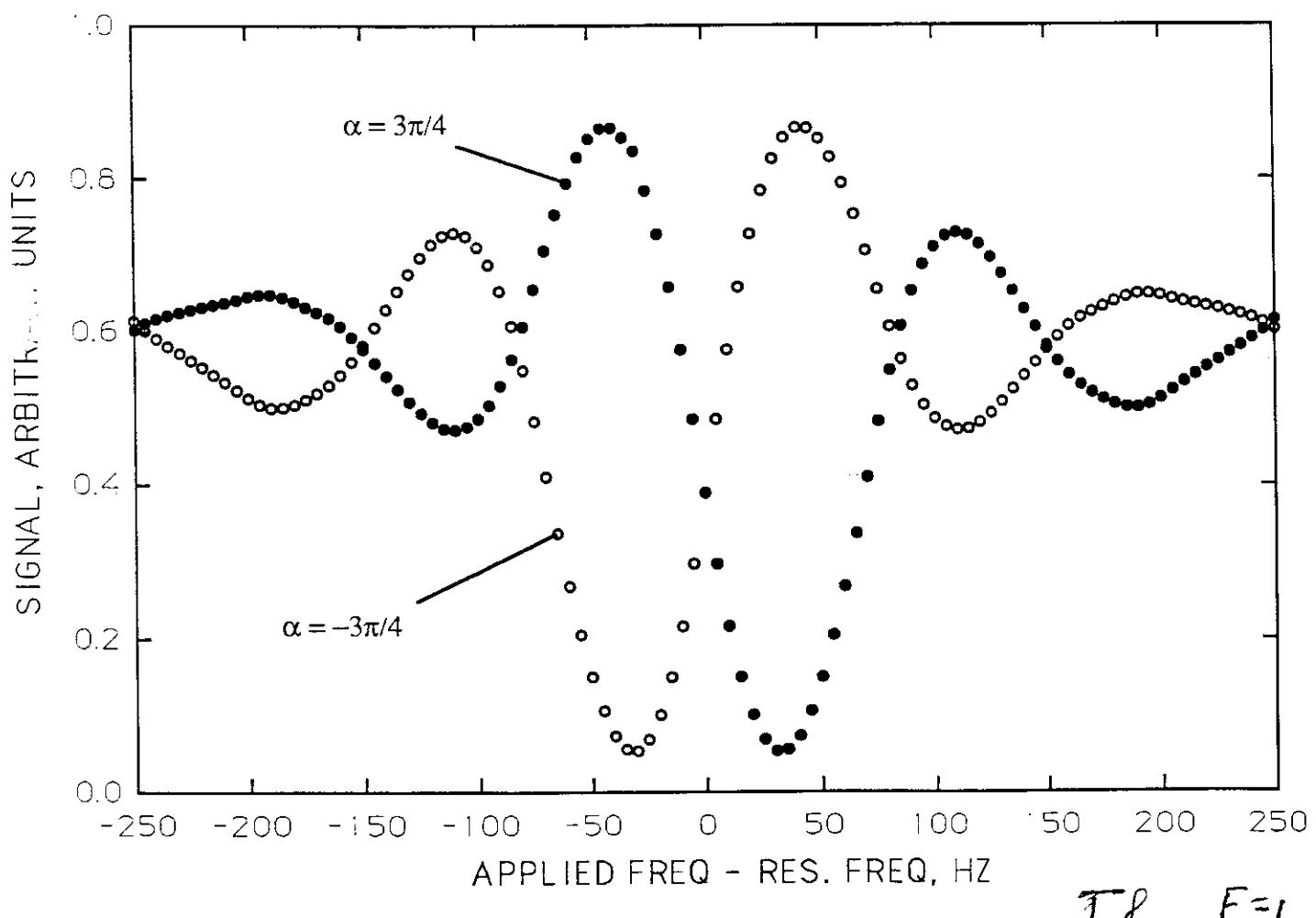
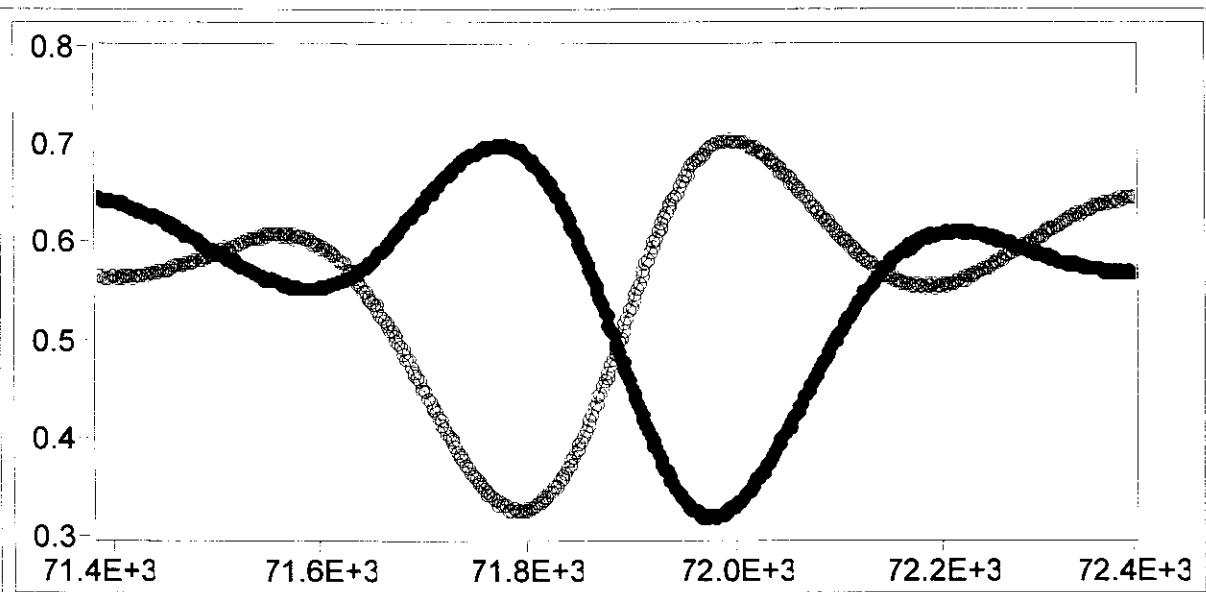


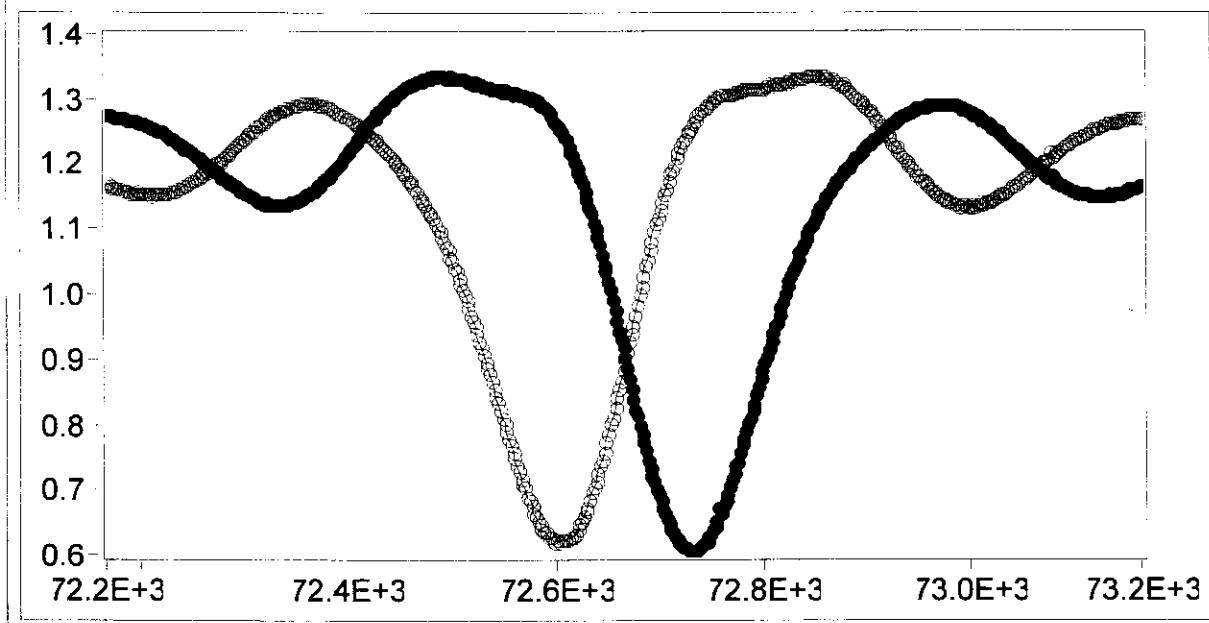
Fig. 9

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Na 11



Na 22

COMPARISON OF SODIUM AND THALLIUM

	THALLIUM	SODIUM
ATOMIC NO. Z	81	11
AV BEAM VEL	$4 \cdot 10^4$ cm/s	$1 \cdot 10^5$ cm/s
ENHANCEMENT R	-585	0.3
OBSERVED STATES	$6^2P_{1/2}$, F=1	$3^2S_{1/2}$, F=2 F=1
g_F	$g_{F=1} = 1/3$	$g_{F=2} = 1/2$
		$g_{F=1} = -1/2$
E x v EFFECT, LEAKAGE CURRENTS		SAME SIGN FOR F=2 , F=1
GEOMETRIC PHASE		OPPOSITE SIGN FOR F=2 , F=1

PRESENT STATUS:

- Statistics:

At present:

$$1.8 \cdot 10^{-27} \text{ e cm in 1 hour}$$

Previous published result:

$$1.8 \cdot 10^{-27} \text{ e cm in 150 hours}$$

- Vastly improved control over systematics from double beam system, Na-Tl comparison, more sophisticated magnetic field system.

WE ARE TAKING DATA

SUMMARY OF EDM RESULTS

SYSTEM	UPPER LIMIT
d_n	$6 \cdot 10^{-26} \text{ e cm}$
QCD PHASE $\bar{\Theta}_{\text{QCD}}$	$4 \cdot 10^{-10}$
<hr/>	
$d_{\text{mol}}(\text{Tl F})$	$4.6 \cdot 10^{-23} \text{ e cm}$
d_{proton}	$1 \cdot 10^{-23} \text{ e cm}$
<hr/>	
$d_a(^{199}\text{Hg})$	$8.7 \cdot 10^{-28} \text{ e cm}$
Schiff moment Q_S	$2.2 \cdot 10^{-11} \text{ e cm}^3$
η (nucleon-nucleon)	$1.6 \cdot 10^{-3}$
η_q (quark-quark)	$3.4 \cdot 10^{-6}$
$\varepsilon_q(\text{SUSY})$	$7 \cdot 10^{-3}$
C_T (electron-nucleon)	$1.3 \cdot 10^{-8}$

SUMMARY, CONTINUED

SYSTEM	UPPER LIMIT
$d_a(^{205}\text{Tl})$	$2.3 \cdot 10^{-24} \text{ e cm}$
d_e	$4 \cdot 10^{-27} \text{ e cm}$
C_S (electron-nucleon)	$4 \cdot 10^{-7}$
$\varepsilon_e \text{SUSY}$	$4 \cdot 10^{-2}$