尋找電子電偶極
Search for electron's EDM

Using slow atomic beam of thallium
And
Dipolar molecule

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A man called S. Weinberg ever said, at XXVIth ICHEP, Dallas :

…..it may be that the next exciting thing to come along will be the discovery of a neutron or atomic or electron electric dipole moment. These electric dipole moments ….seem to me offer one of the most exciting possibility for progress in particle physics.

The Grail of AMO physics
-----EDM-----

- Dose it exist?-------------Is there an EDM?
- How dose it look like? How large will it be?

基本粒子電偶極與物理定律的對稱守恆

C: 電荷 **(q→-q) P:** 宇稱**(r →-r) T:** 時間**(t →-t)**

P 不守恆**:** 李、楊、吳→

CP守恆

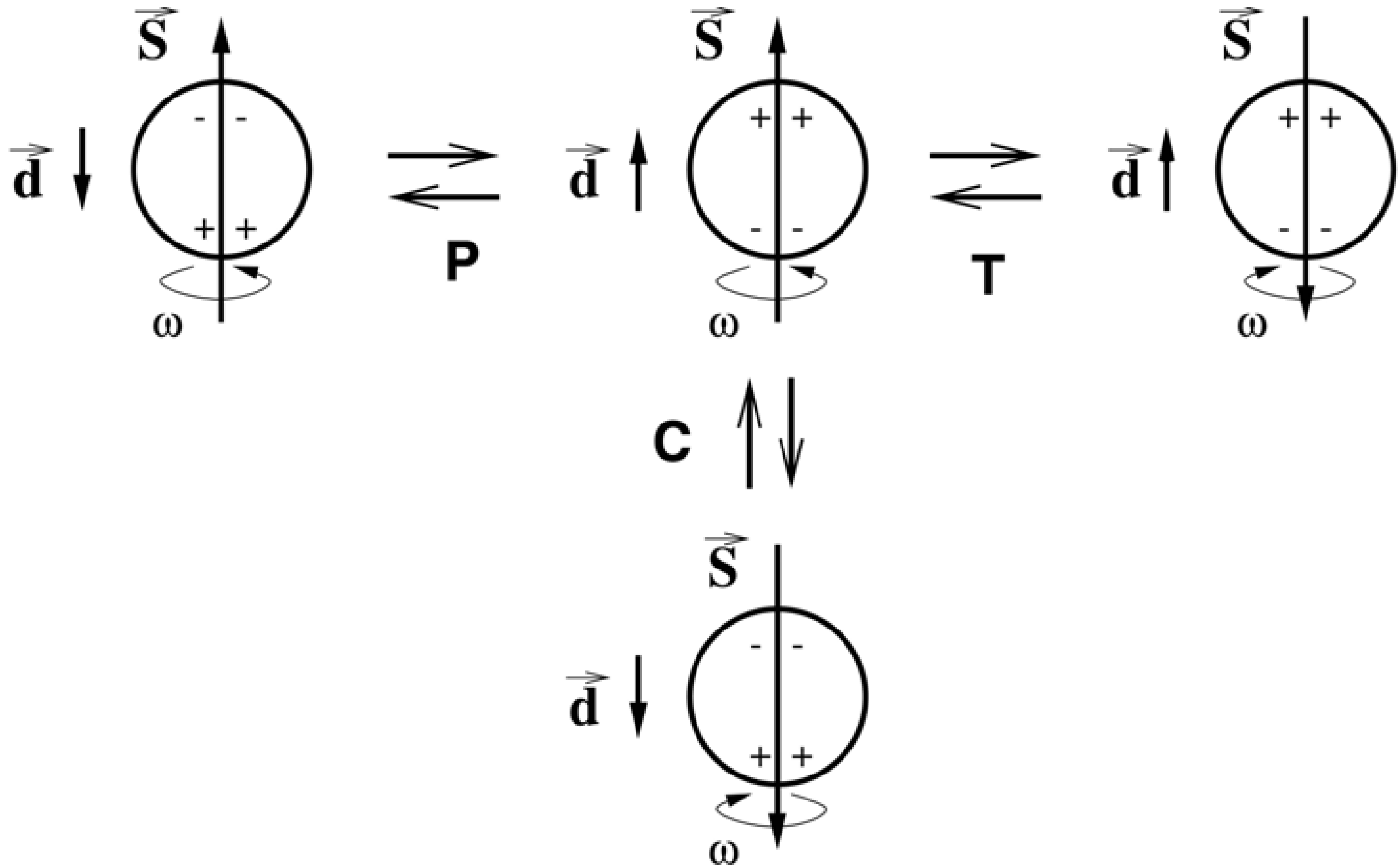
$K^0_L \rightarrow 2\pi$ → **CP** 不守恆

目前確實觀察到的**CP violation** 的物理現象

B

35 year later…..The new one, from B factory(Belle, BABAR)

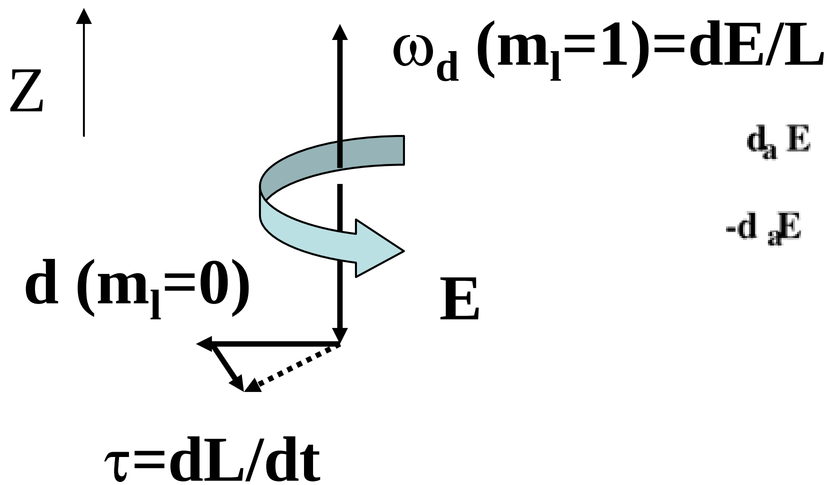
根據**CPT theorem** ，等同於 **T violation**



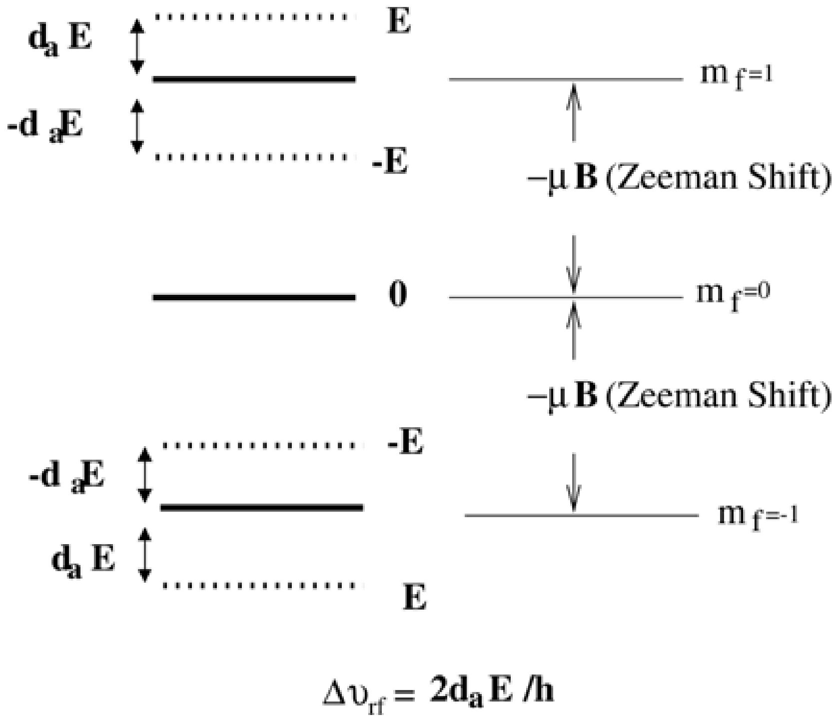
若是基本粒子具有永久電偶極→P-odd, T-odd

或是 具有內部結構→基本的粒子?

EDM 的基本量測方法



同時外加一個平行與反平行的磁場 可使極微小的ω較易量到 $\omega = \omega_z \pm \omega_d$



Linear stark effect

Who is good for EDM?

- Neutron------by Ramesy 50’s
- Proton?
- Electron?

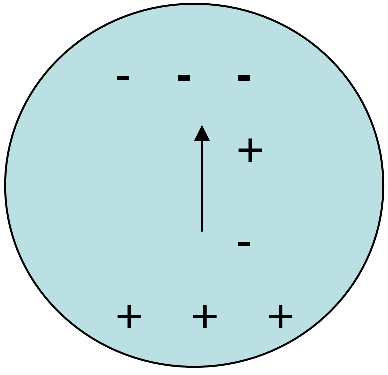
Charged particles will go out of apparatus by applied electric field!!!

→neutral system: atom? Molecule?

(lately, the ion storage ring can also solve the problem-----muon)

Schiff's argument

- From a classical picture, at equilibrium , charge distribution will be re-arranged to E=0, therefore, E·d=0.



Atom just like a metal shielding!!!

The story is not the end

- There are spin dependent contributions
- There are relativistic correction
- The particle spin direction is correlated to the electric field

(Schiff 1963 & Sandars 1965)

→ EDM could be **enhanced** within atomic or molecular system

Enhance factor

In a paramagnetic system, unpaired electron.

If $d_e \neq 0$, atomic system will be induced a

$$d_a = \text{enhance} \times d_e$$

Enhance factor:考慮相對論效應在電偶極與外加電場間的交互作用後產生的. 與原子的**Z^3**約成正比.(60s, P. Sandars)

(700 for thallium, 200 for ceasium→ larger is better!!!!)

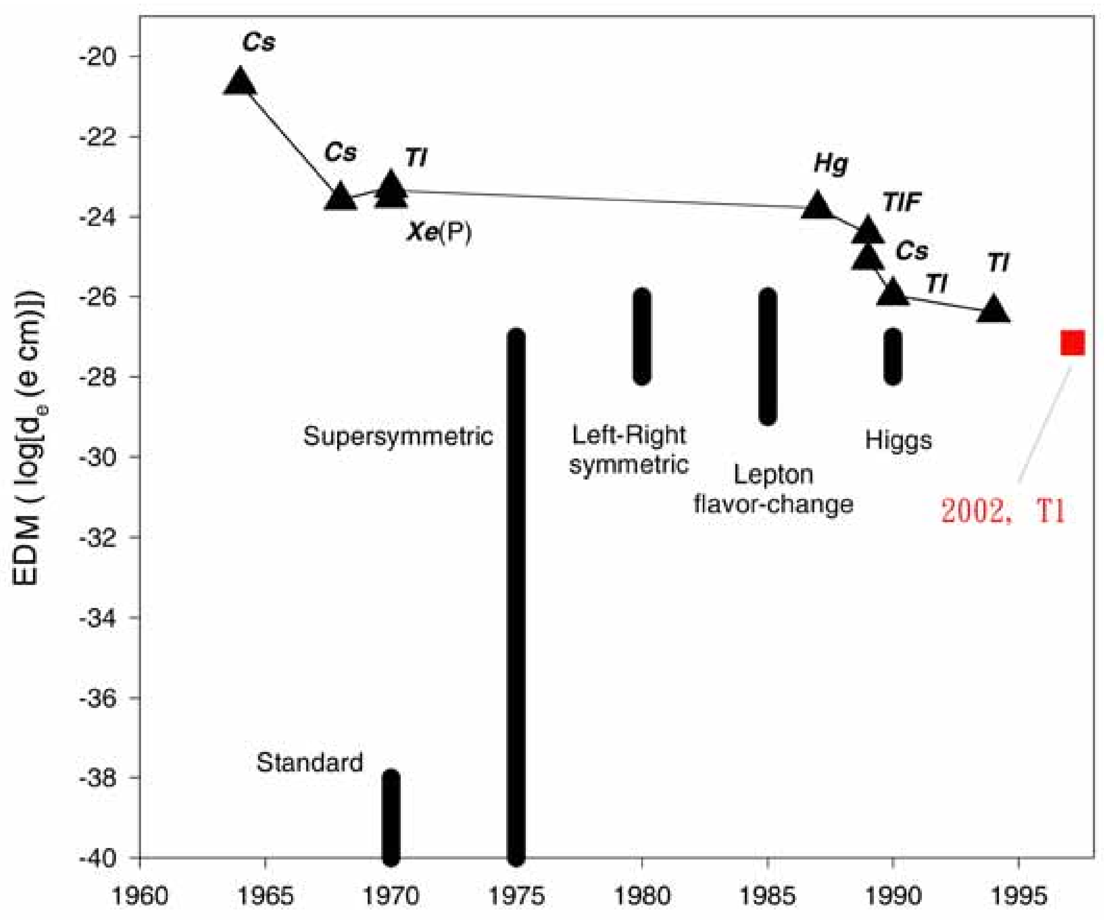
Line them up!!!

- Atoms must be aligned (prepared in m=0), and with a long relaxation time

Old method: A Stern-Gerlach magnet to select atoms with a proper polarization (m=0) →Very poor efficiency.

New method: using **optical pumping** to prepare atom in a proper Zeeman sublevel.

電子EDM的理論預測與實驗進展

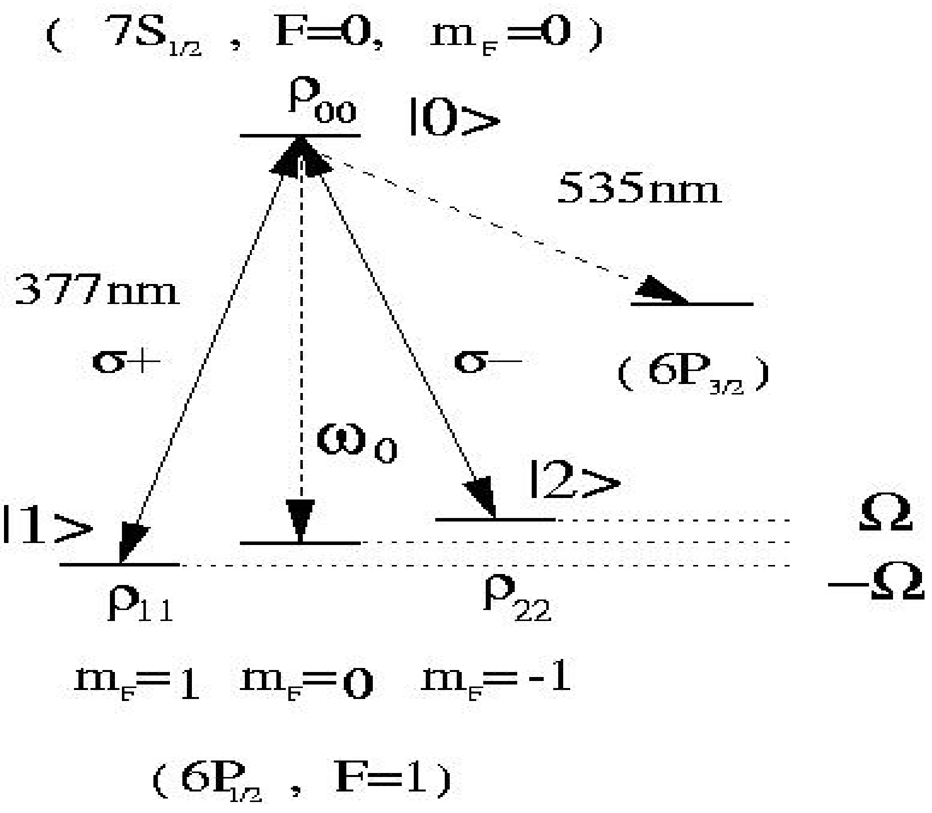


Thallium: enhance factor=700

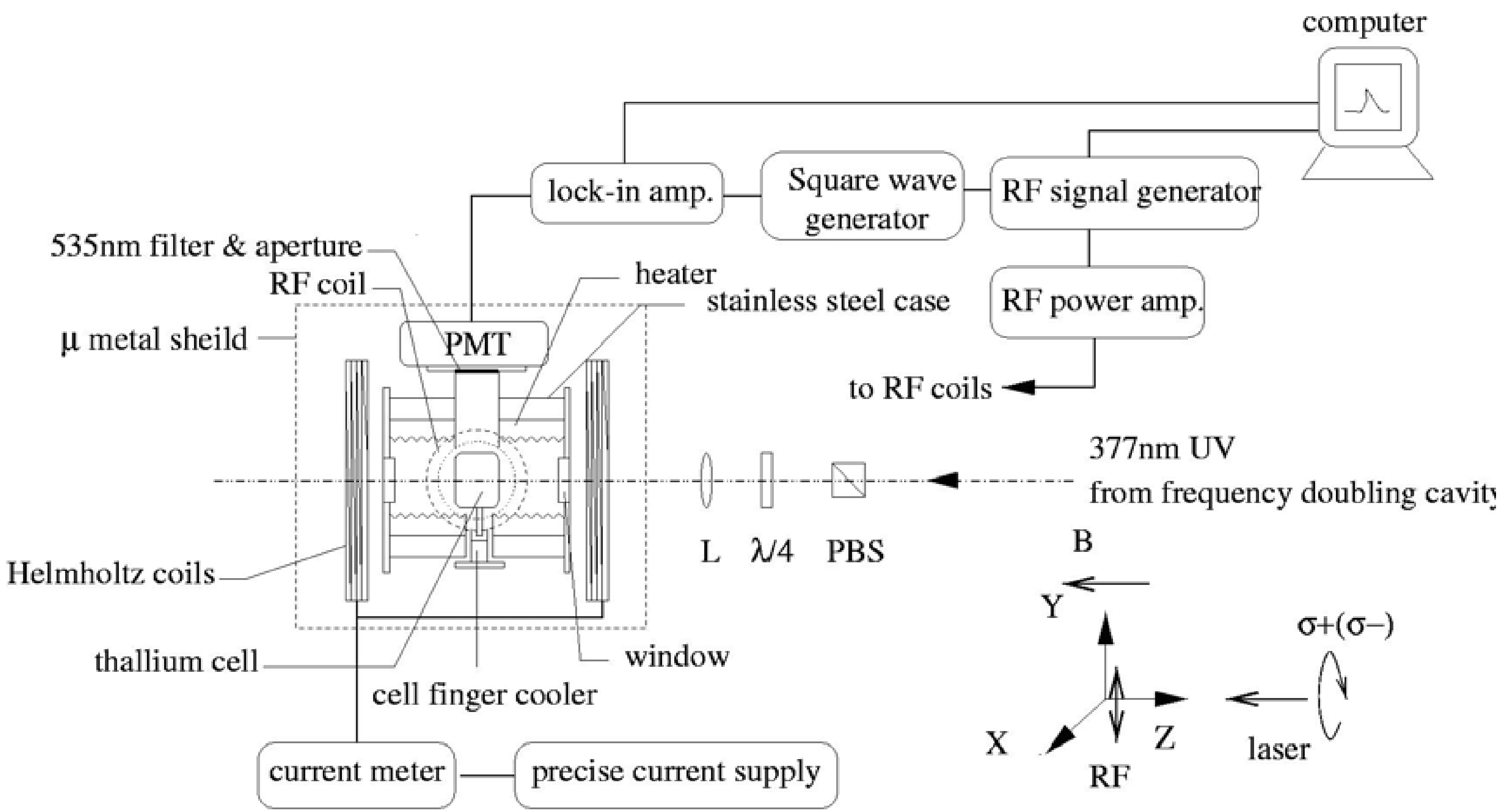
•Prepare Tl in m_f=0 state using optical pumping

•Drive Zeeman sub-levels with RF radiation.

•For EDM experiment, RF resonance must narrow→long relaxation time

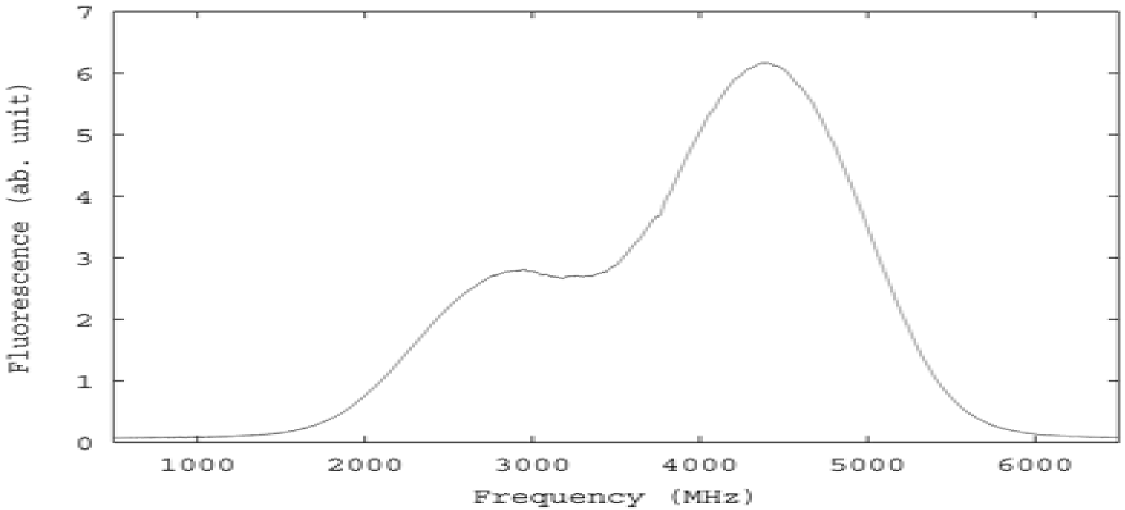


Optical pumping atomic thallium in a sealed cell

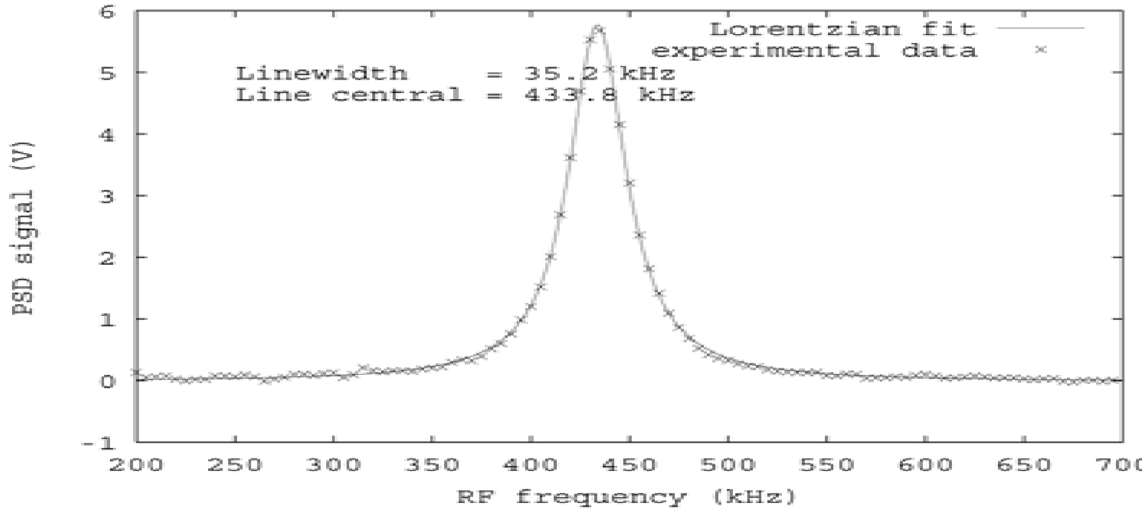


Result

Doppler broadened spectrum



RF resonance



Comparison of cell- and beam- type experiment

beam

- ☹原子在電場中飛行, 產生額外的B_{eff}= v×E
- ☺ 原子碰撞機率小, **relaxation time**長
- ☹原子數目少, 信號微弱

cell

- ☺原子沒有固定的飛行方向, 無**v×E**效應
- ☹原子相互碰撞,產生**collision relaxation (large RF resonance width)**
- ☺原子密度高, 信號大

→ **The way out :**

slow atomic beam!!!!

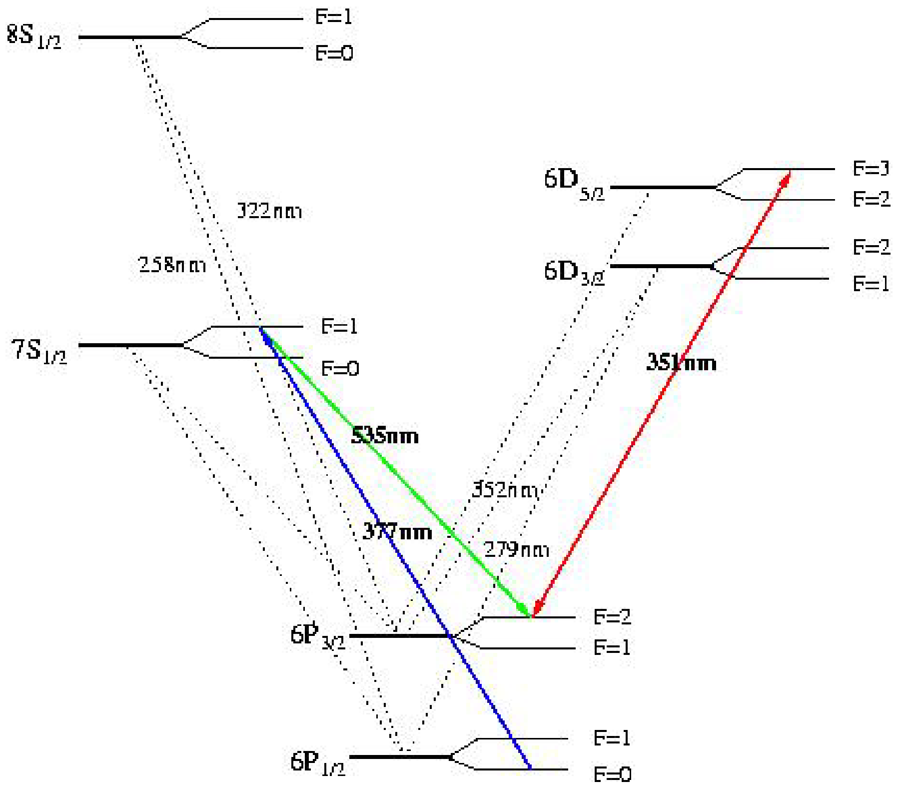
How is cooling thallium possible ?

- Find a closed cooling cycle:

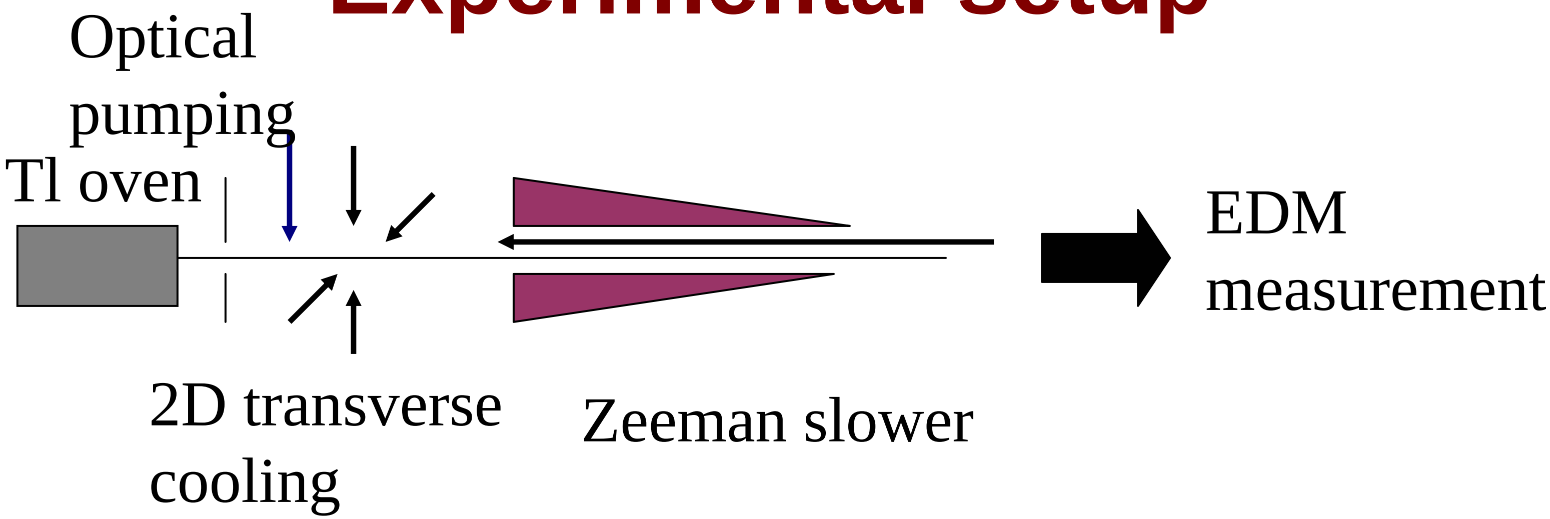
$6P_{3/2}(F=2) \rightarrow 6D_{5/2}(F=3)$

- Proper laser sources: 351nm, 377nm

  Al (AIII group) was cooled successfully by U. Colorado



Experimental setup

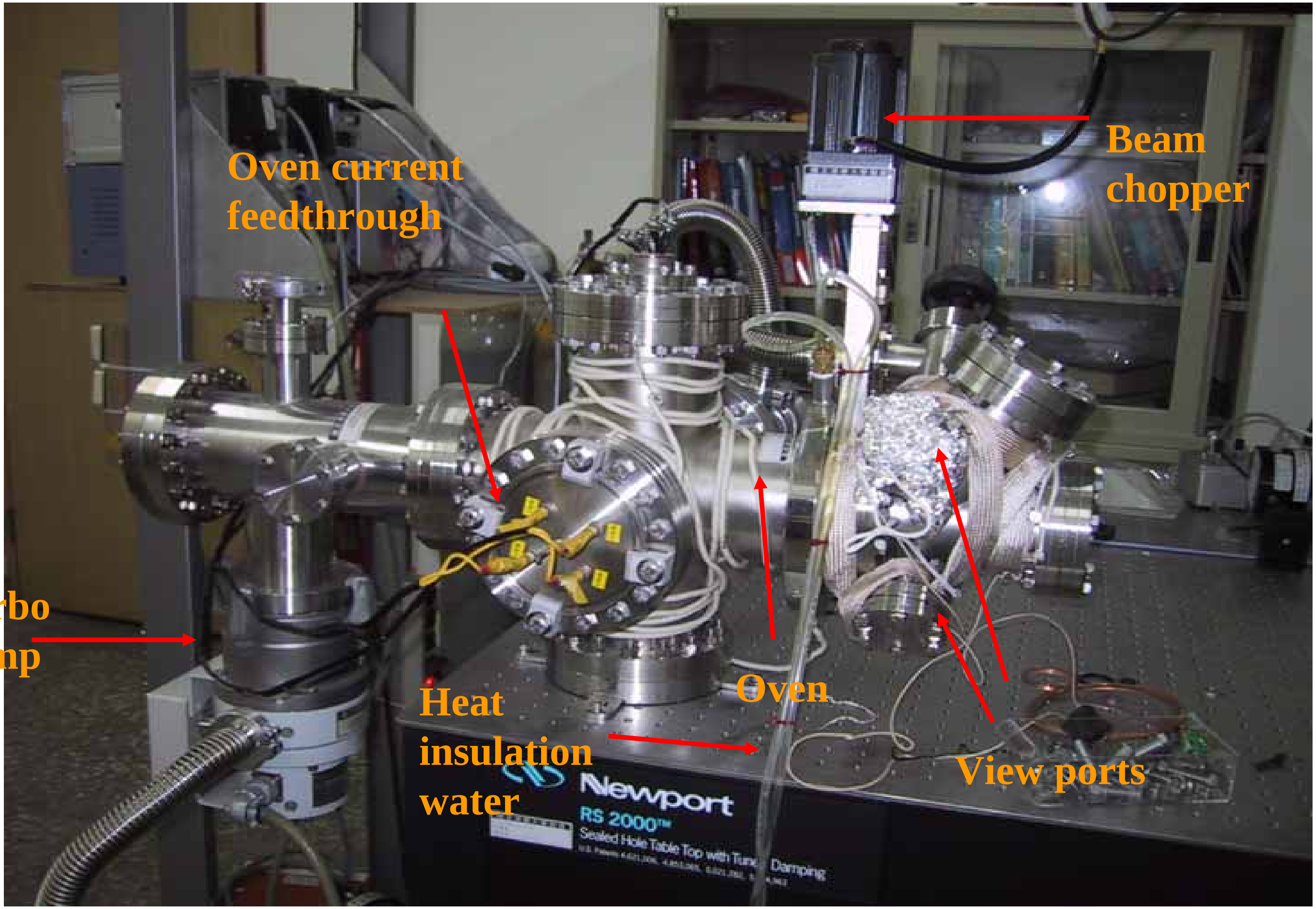


- Hot atomic beam source (700ºC)
- Laser source:

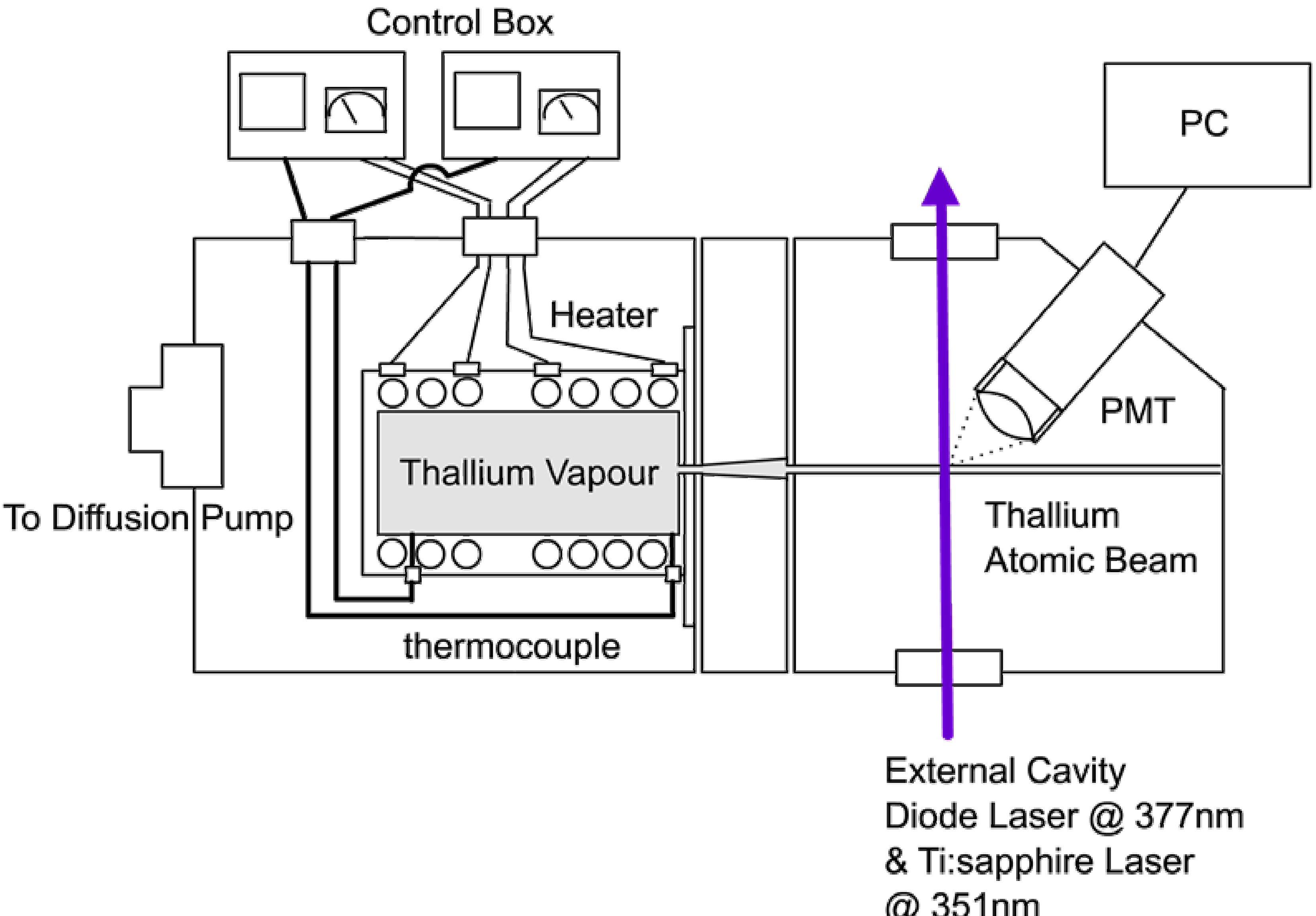
377nm: frequency-doubled diode laser(760nm)

351nm: frequency-doubled Ti:Sapphire laser

Thermal atomic thallium beam source



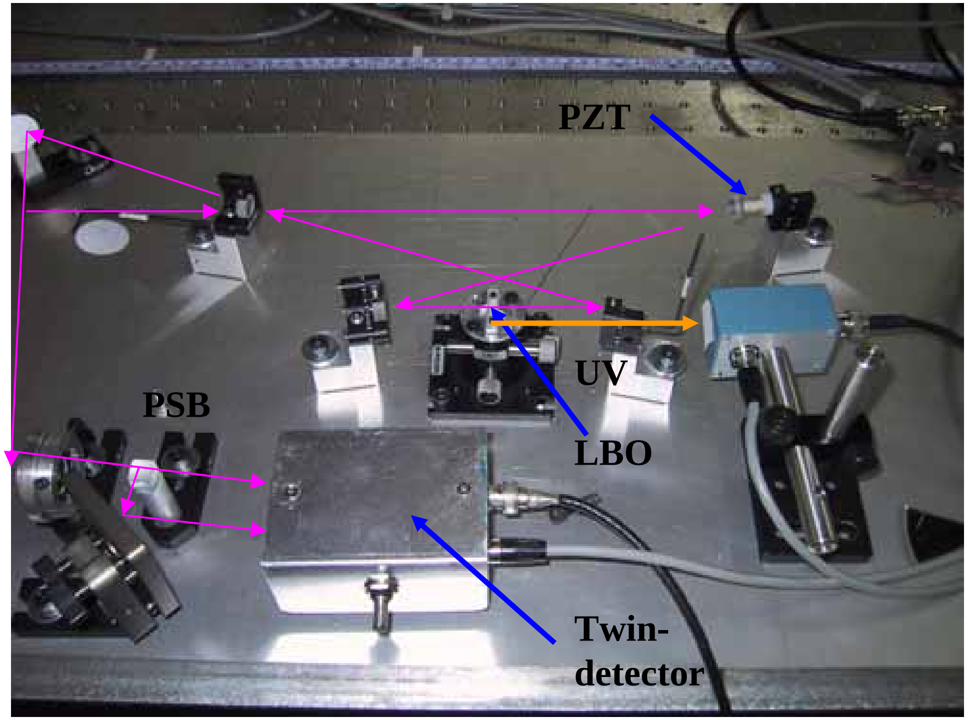
Green fluorescence



Frequency doubling of mid-power diode laser

- LBO, ring cavity enhanced with 97% input coupler
- Cavity locked using polarization error signal

- UV light observed
- Cavity ready to be locked



The number of energy state

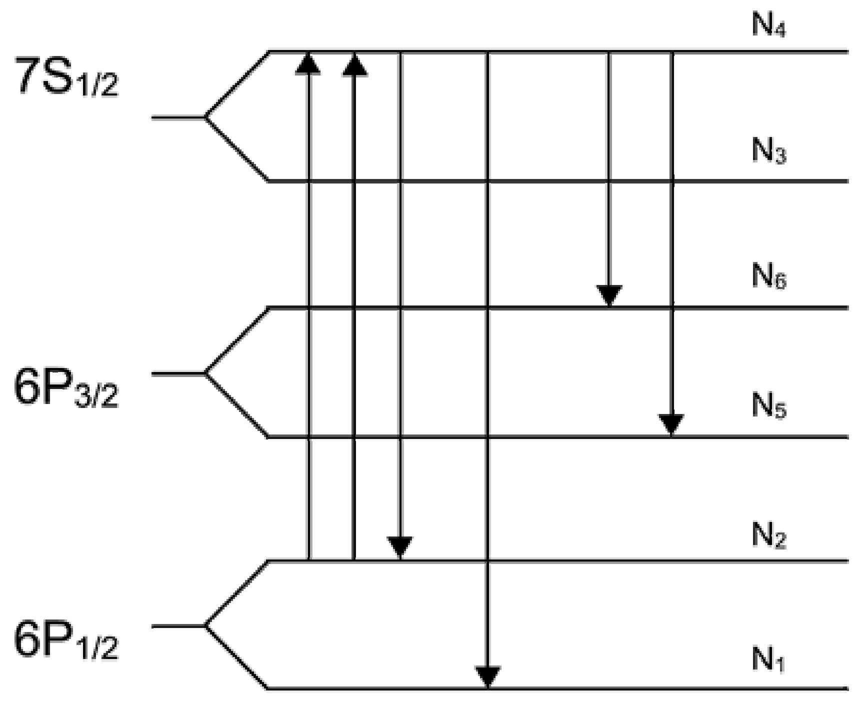
$$\frac{dN_2}{dt} = -B_{24}N_2 I + B_{42}N_4 I + A_{42}N_4$$

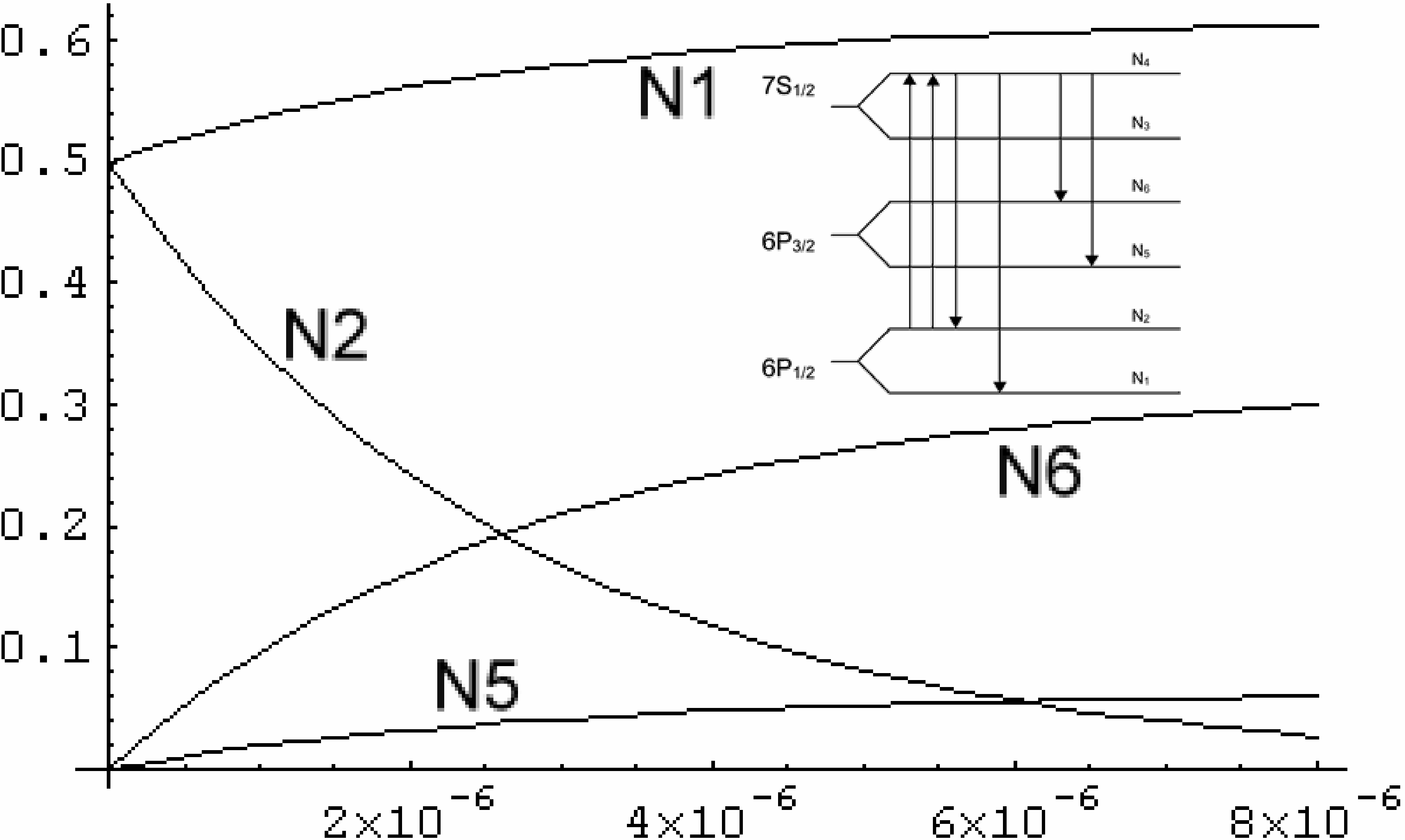
$$\frac{dN_4}{dt} = B_{24}N_2 I - B_{42}N_4 I - A_{42}N_4 - A_{46}N_4 - A_{45}N_4 - A_{41}N_4$$

$$\frac{dN_6}{dt} = A_{46}N_4$$

$$\frac{dN_5}{dt} = A_{45}N_4$$

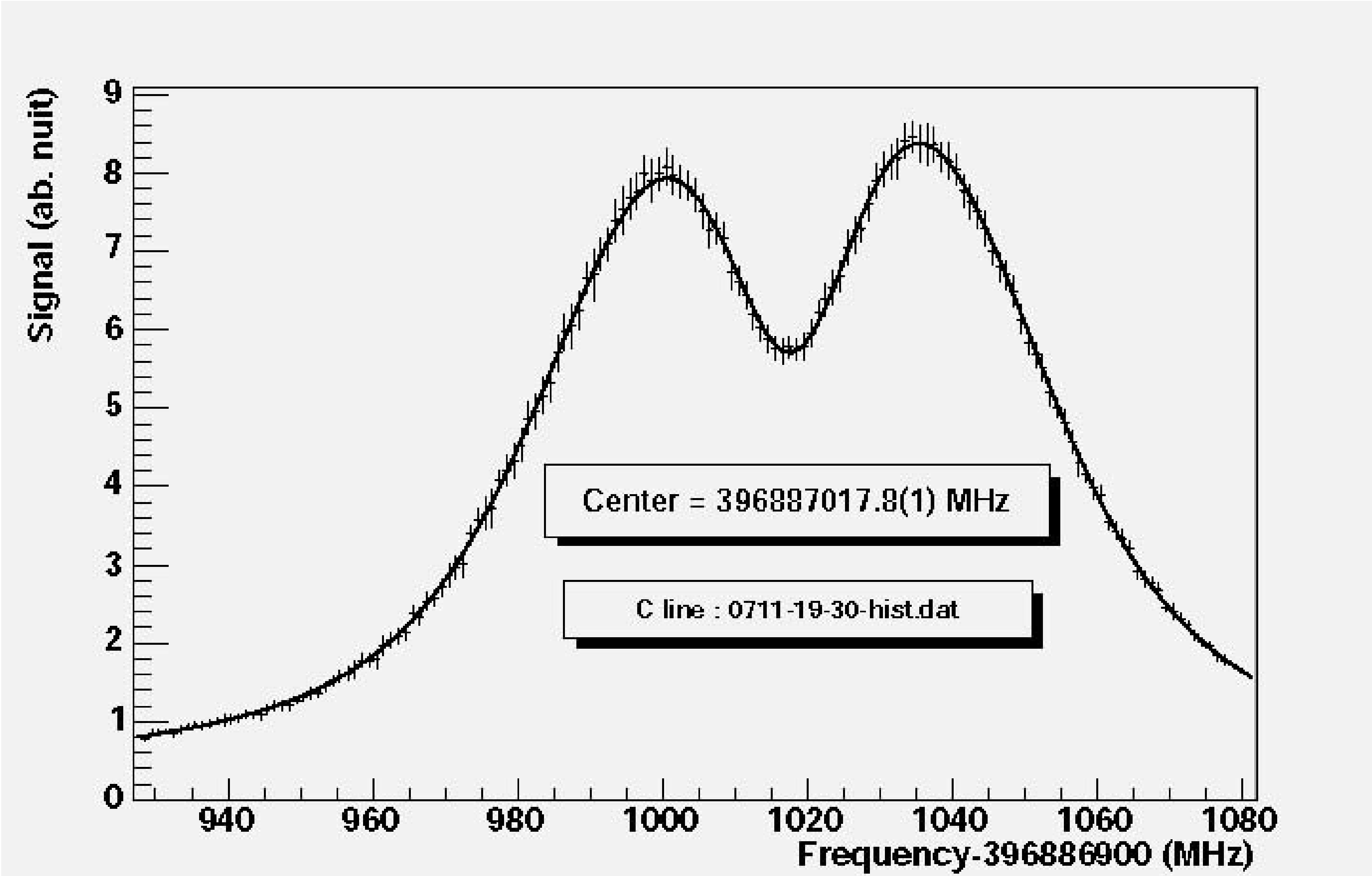
$$\frac{dN_1}{dt} = A_{41}N_4$$



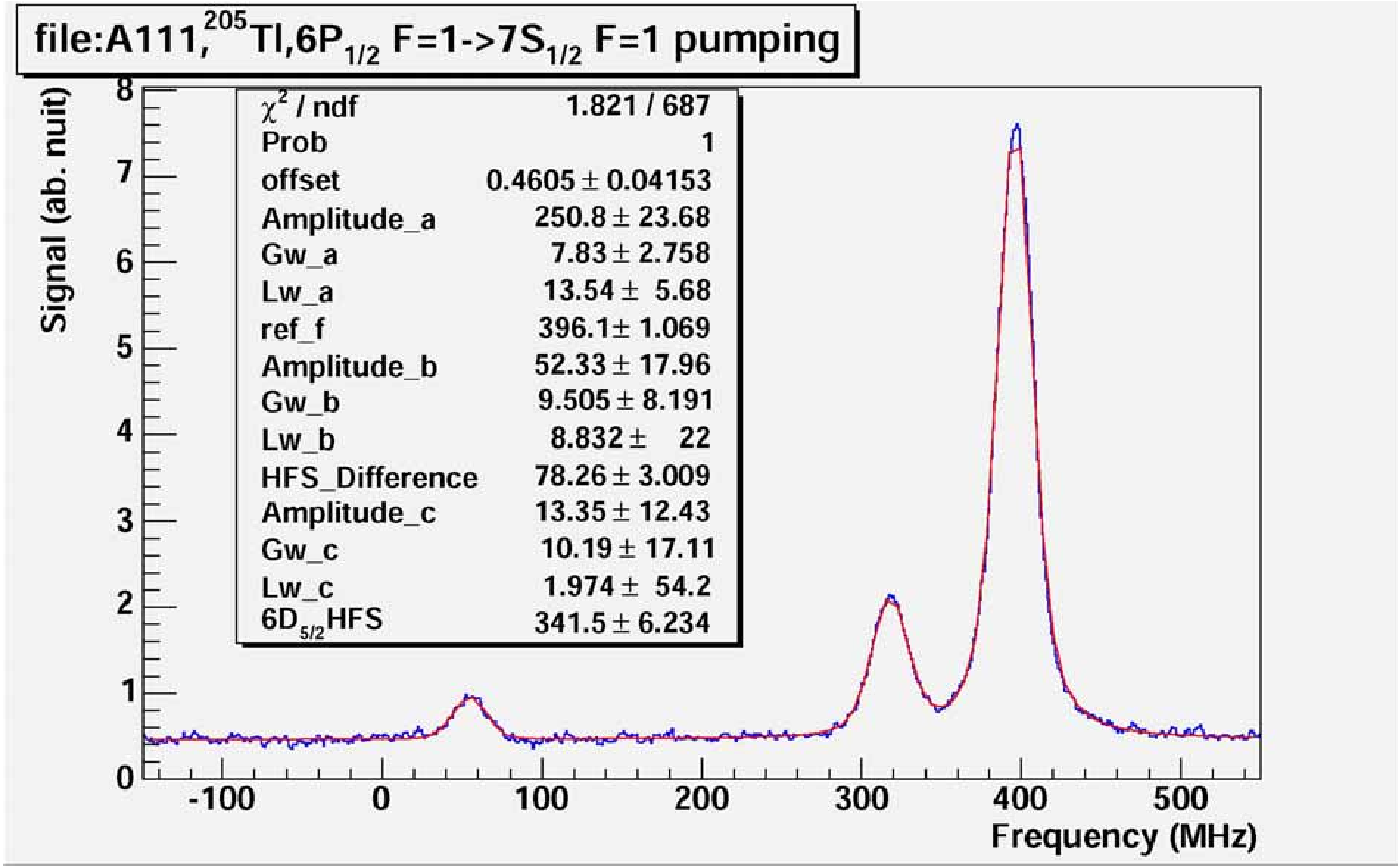


0.6
0.5
0.4
0.3
0.2
0.1
N1
N2
N5
N6
7S1/2
6P3/2
6P1/2
N4
N3
N6
N5
N2
N1
2×10-6
4×10-6
6×10-6
8×10-6

Atomic thallium 6P(1/2)->7S(1/2)



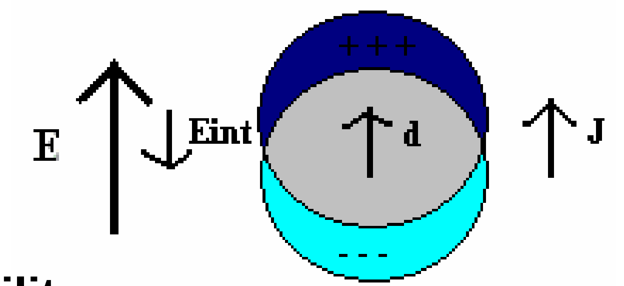
6P(3/2)-6D(5/2)



file:A111,205Tl,6P1/2 F=1->7S1/2 F=1 pumping
χ2 / ndf 1.821 / 687
Prob 1
offset 0.4605 ± 0.04153
Amplitude_a 250.8 ± 23.68
Gw_a 7.83 ± 2.758
Lw_a 13.54 ± 5.68
ref_f 396.1 ± 1.069
Amplitude_b 52.33 ± 17.96
Gw_b 9.505 ± 8.191
Lw_b 8.832 ± 22
HFS_Difference 78.26 ± 3.009
Amplitude_c 13.35 ± 12.43
Gw_c 10.19 ± 17.11
Lw_c 1.974 ± 54.2
6D5/2HFS 341.5 ± 6.234
Signal (ab. nuit)
Frequency (MHz)
0
1
2
3
4
5
6
7
8
-100
0
100
200
300
400
500

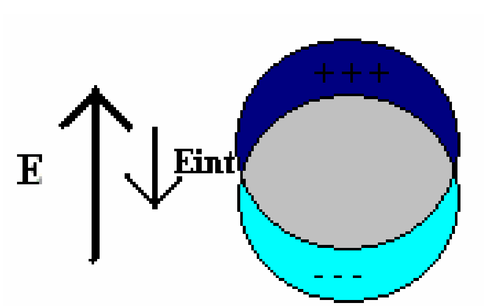
Atomic and Molecular system

Enchance=q P
=atomic structure x polarizability

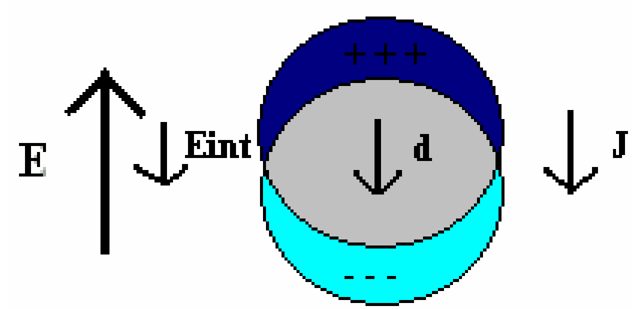


U=Eint.d

In **atomic** **system, the polarizability is** **small****, because of the large energy gap between fine structure**



Atom is polarized due to external E
→Stark mixing (S + P)
→Internal effective Eint



U=-Eint.d

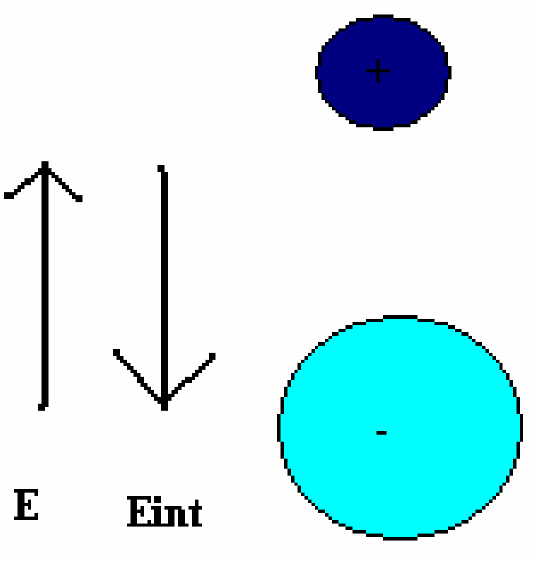
Dipolar molecule

- High polarizability

→very high enhance factor R

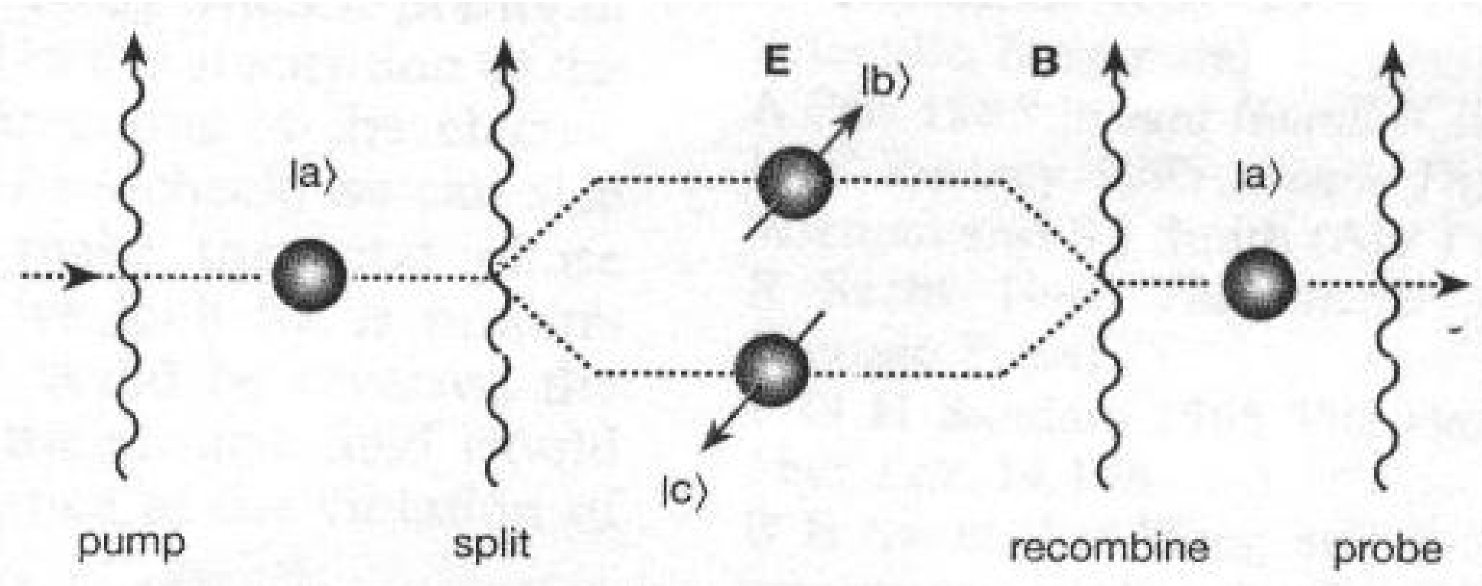
→ No need magnetic field to align system, only E field

YbF: E=30 GV/cm



$$\Delta d_e = \frac{\Delta d_{atom}}{\Re} = \frac{\hbar \Delta\omega}{E\Re} = \frac{\hbar}{E\Re}\frac{1}{\tau\sqrt{N}}$$

Typical molecular EDM experiment



$$| m = 0 >$$

$$\frac{1}{2}(| +1 > + | -1 >)$$

$$A | 0 >$$

$$\frac{1}{2}(| +1 > e^{i\phi} + | -1 > e^{-i\phi})$$

$$\phi = \frac{(E \cdot d_a)\Delta t}{\hbar}$$

Early and recent EDM experiment with molecular system

- First molecule EDM experiment TlF

→No unpaired electron. Nuclear EDM

(Sandars 1980, Ramsey 1984, Hinds 1987)

- **YbF ---Sussex, electron** $4\times10^{-25}e\cdot cm$
- **PbO ---Yale, electron, aim to** $5\times10^{-32}e\cdot cm$
- **current limit by atomic thallium** $4\times10^{-27}e\cdot cm$

The difficulties in conventional scheme

- Low number density, low distribution in suitable J level
- Paramagnetic dipolar molecule is aggressive ----The chemistry……..
- Collision and interaction time still the problem

Toward the realization of KRb dipolar molecule

- Laser cooled Rb + Laser cooled K

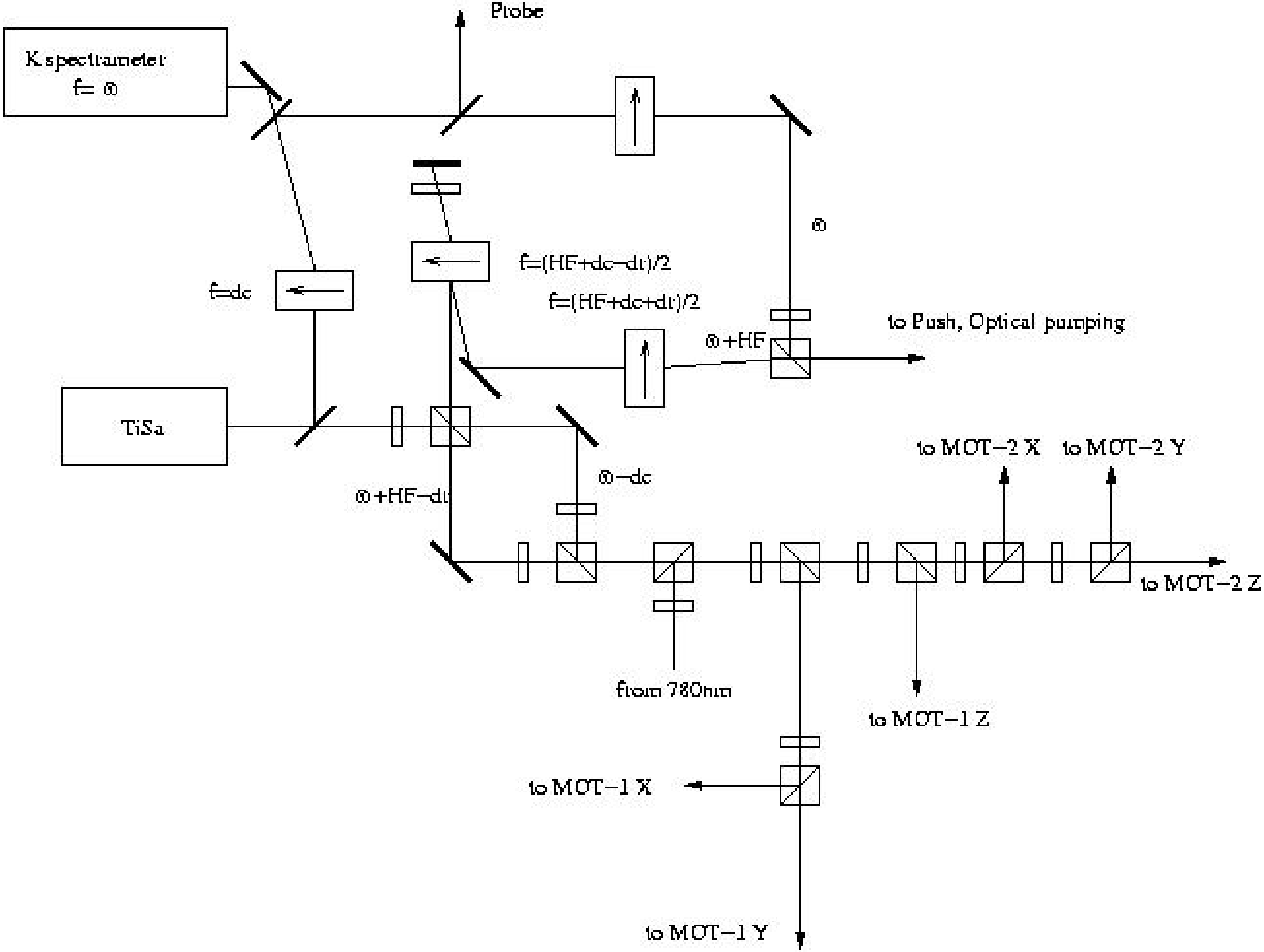
→cold KRb mixture

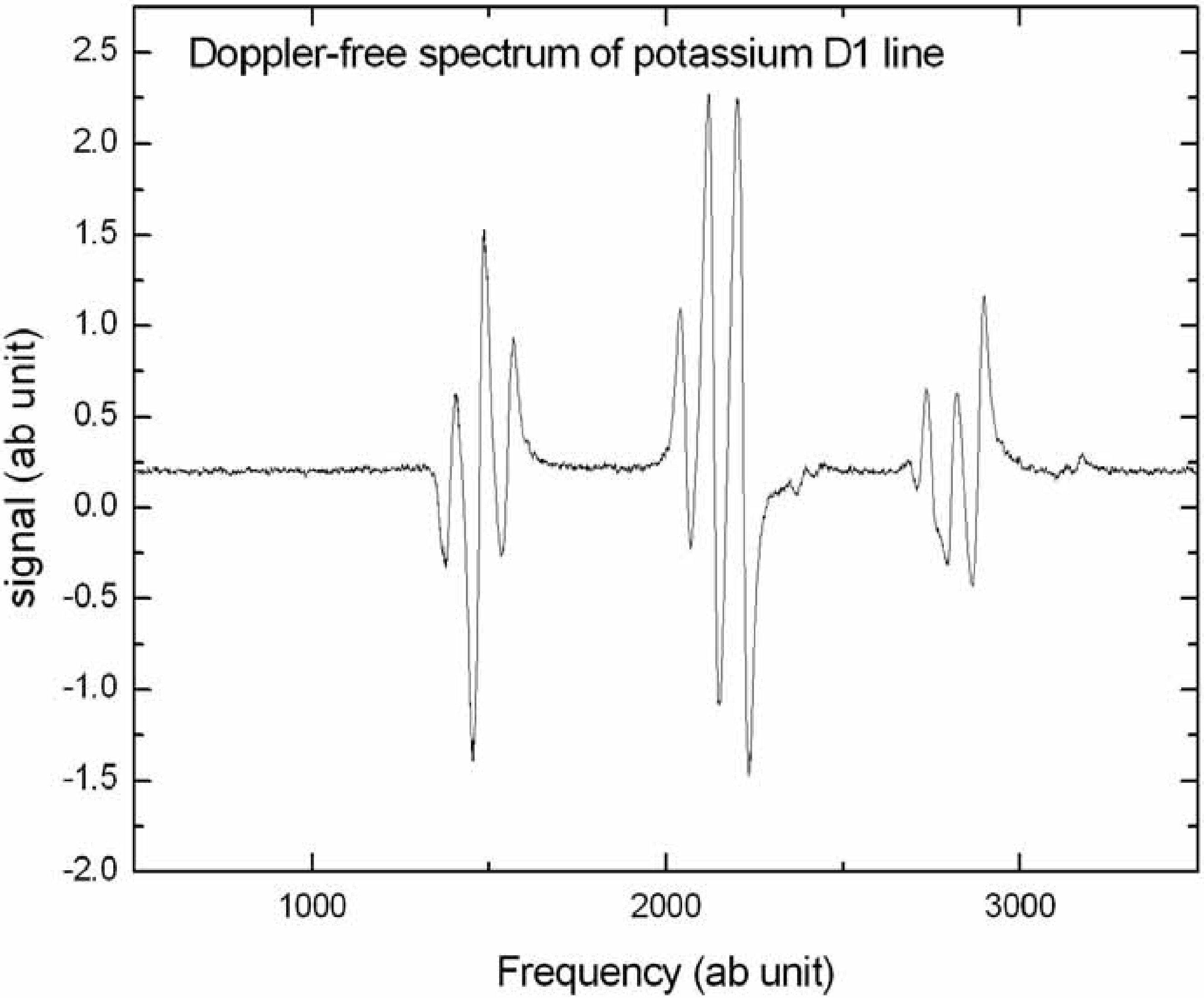
→photo-association or Feshbach resonance

→Cold polar molecule

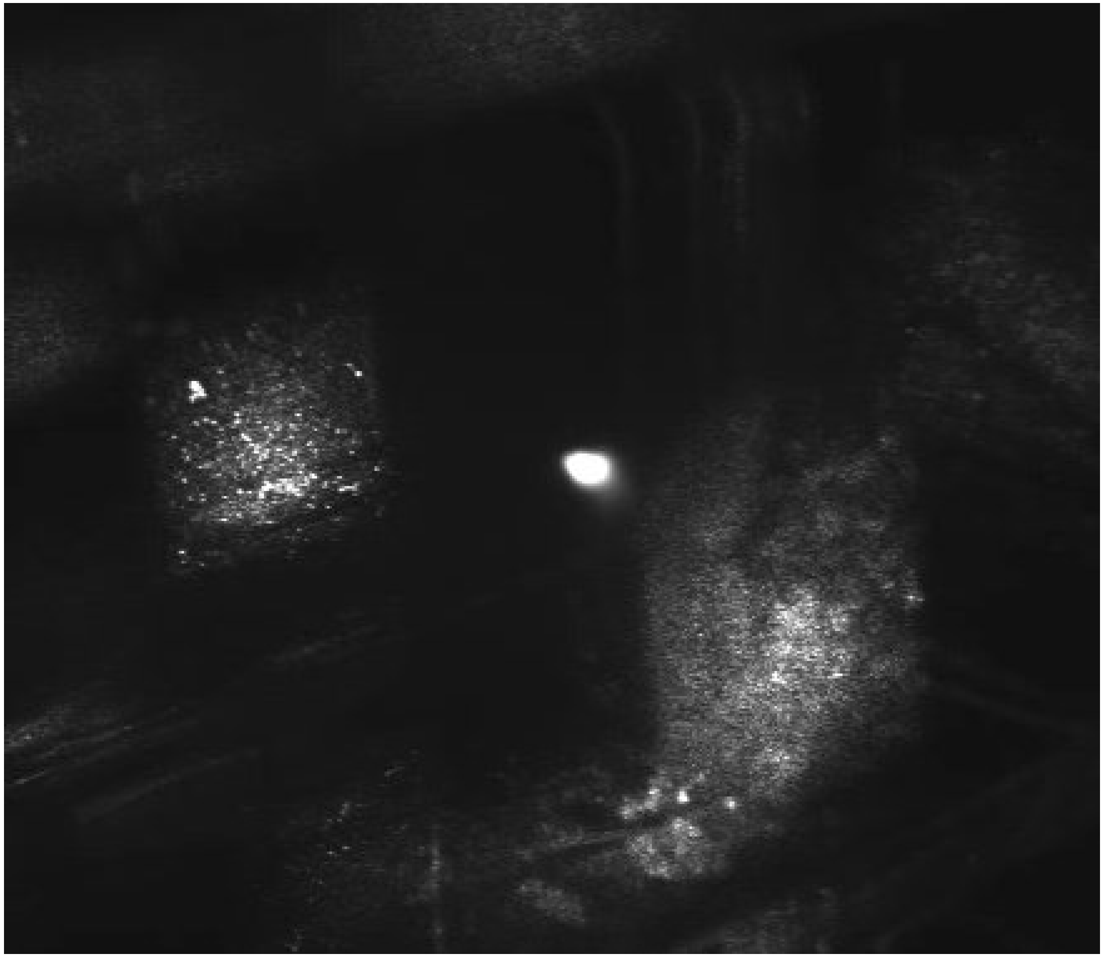
Yes, very naïve. But it works!!

KRb: Brazil, Connecticut, LENS
RbCs: Yale


Probe
K spectrometer
f= ®
®
f=dc
f=(HF+dc−dr)/2
f=(HF+dc+dr)/2
®+HF
to Push, Optical pumping
TiSa
®−dc
®+HF−dr
to MOT−2 X
to MOT−2 Y
to MOT−2 Z
from 780nm
to MOT−1 Z
to MOT−1 X
to MOT−1 Y



Doppler-free spectrum of potassium D1 line
2.5
2.0
1.5
1.0
0.5
0.0
-0.5
-1.0
-1.5
-2.0
signal (ab unit)
1000
2000
3000
Frequency (ab unit)



Conclusions

- Current EDM upper bond set by experimental results has been very close to some theory.
- The simple and clean atomic thallium system may still the best candidate for EDM experiment.
- Laser cooled dipolar molecule could bring the EDM experiment to a new era.

Review articles

- “Test of Time-Reversal Invariancein Atoms, Molecules, and Neutron” L.R. Hunter, Science Vol. 252, P.73(1991)
- “Electric dipole moments of charged particles” P.G.H. Sandars, Contempory Physics Vol 42,P.97(2001)
- “Electron dipole moments” E.D. Hinds and Ben Sauer, Physics World, April 1997,P.37