eEDM searching experiments using new molecular systems

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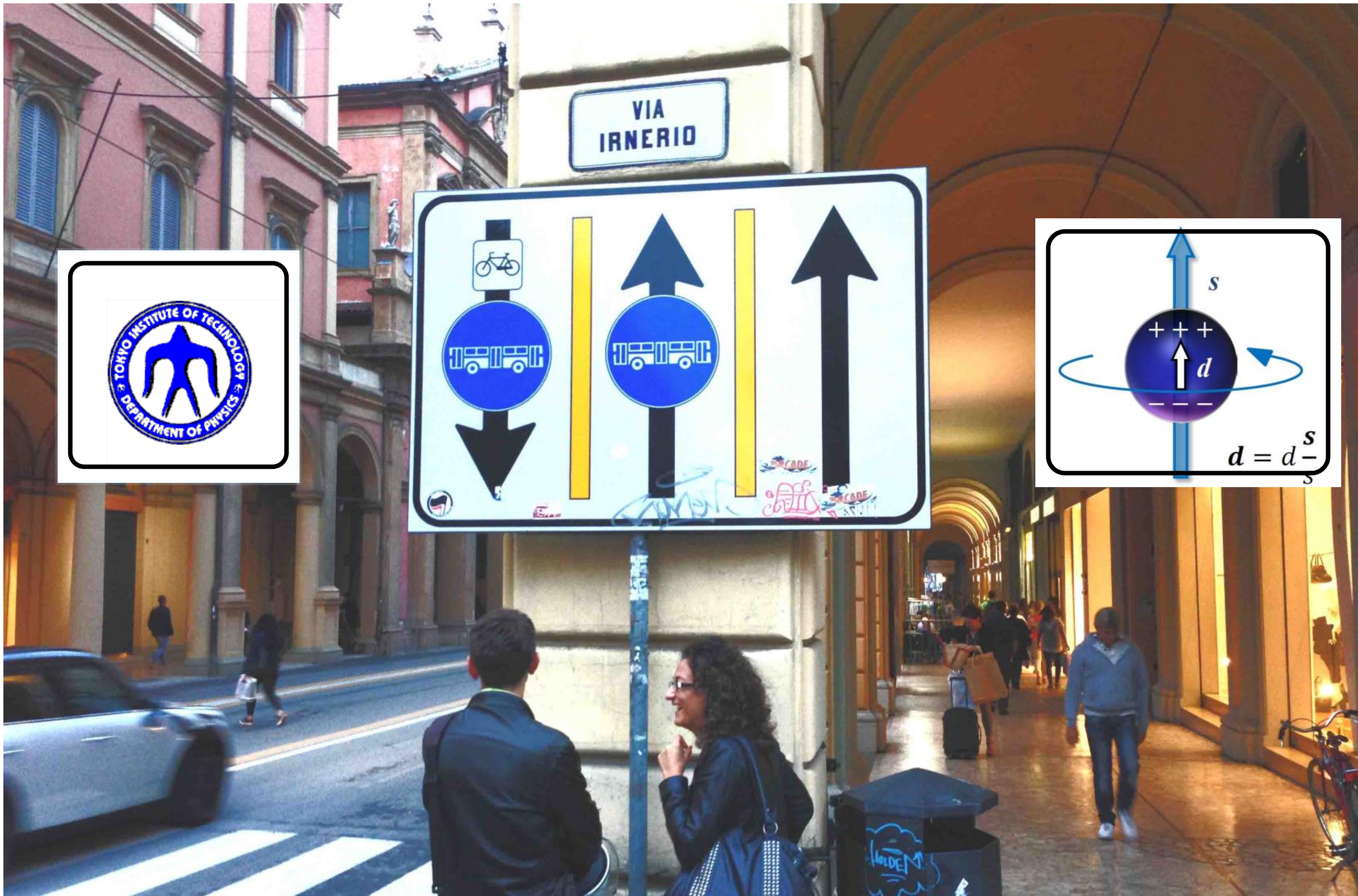


Contents

○ Short history of eEDM searching experiments

○ Requirements on the molecules for eEDM measurement

○ Strategy of eEDM measurement using molecules

１）direct measurement of small Stark energy shift.

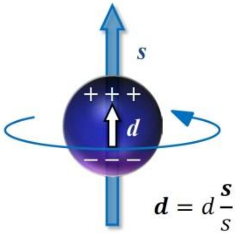
２）indirect measurement of change in thermal distribution

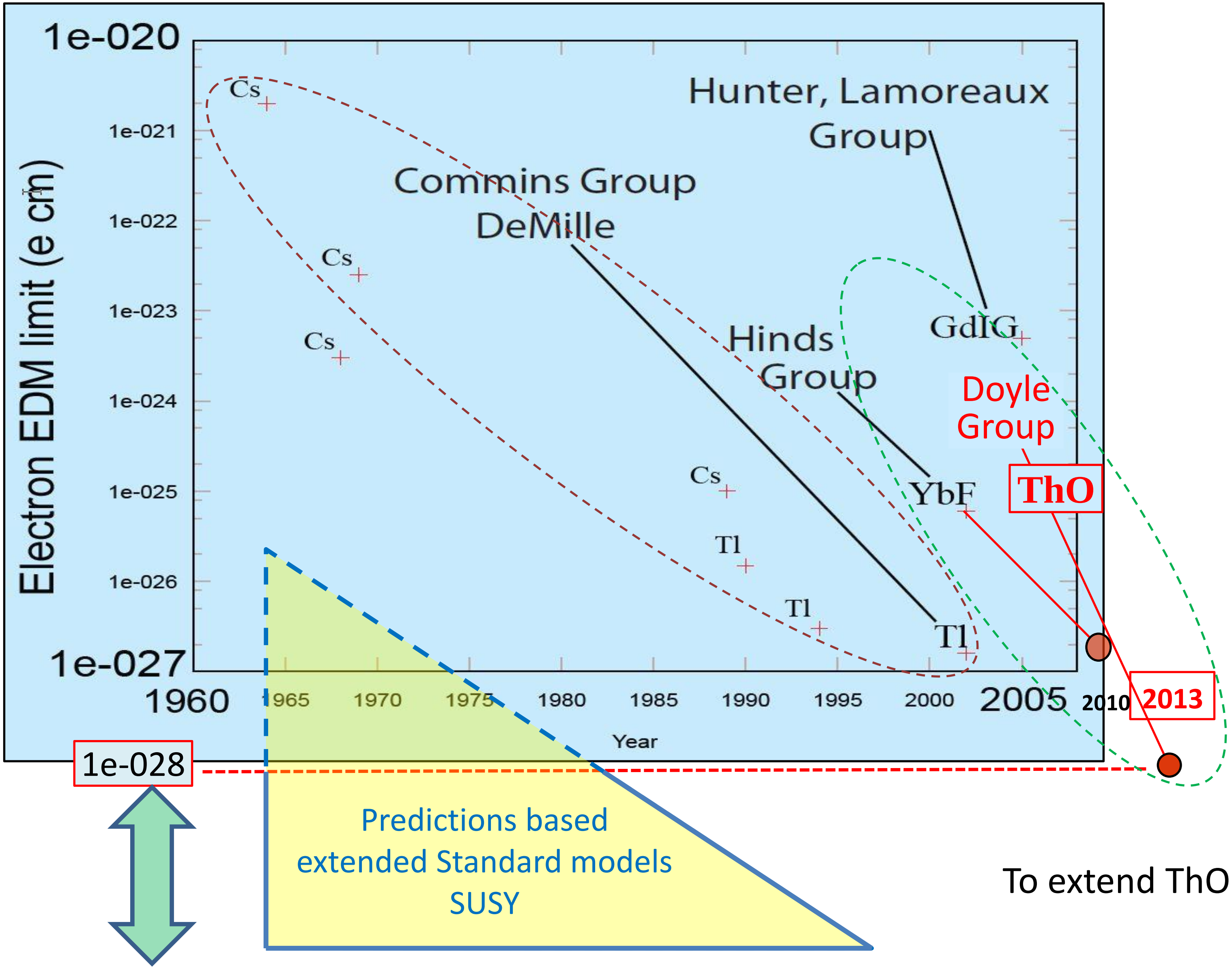
○ Proposal of the direct and indirect measurements using new molecule system and recent experimental results.

１） BiO

２） HgH/*p*-H_2

eEDM searching experiments





1e-038 Prediction based Standard model

To extend ThO

Requirements on the molecules for eEDM measurement

	subject	reason, comment
1	Polar molecule	Internal electric field : $\boldsymbol{E}_{\mathrm{in}}$
2	Unpaired electron	un-cancelation of $\boldsymbol{d_e}$
3	Heavy element	Large relativistic effect gives an enhancement of $\boldsymbol{E}_{\mathrm{in}}$
4	Large $\boldsymbol{E}_{\mathbf{in}}$	Depends on not only the nucleus but SOMO
5	Close parity states	Easy to molecular orientation
6	*g*-factor	Smaller is better because of immune on ***B***-fluctuation
7	Isotope	Larger natural abundance
8	nuclear spin	Smaller is better because of hyperfine splitting
9	Number of mol.	Large is better, but not easy to prepare a big amount of radicals at the observing state.
10	Lifetime of state	Upper limit on observation time
11	Relaxation time	T_1, T_2
12	Easy and safe material to handle at laboratory. Non-toxic. Non-radio active	

3-D mapping of detection sensitivity

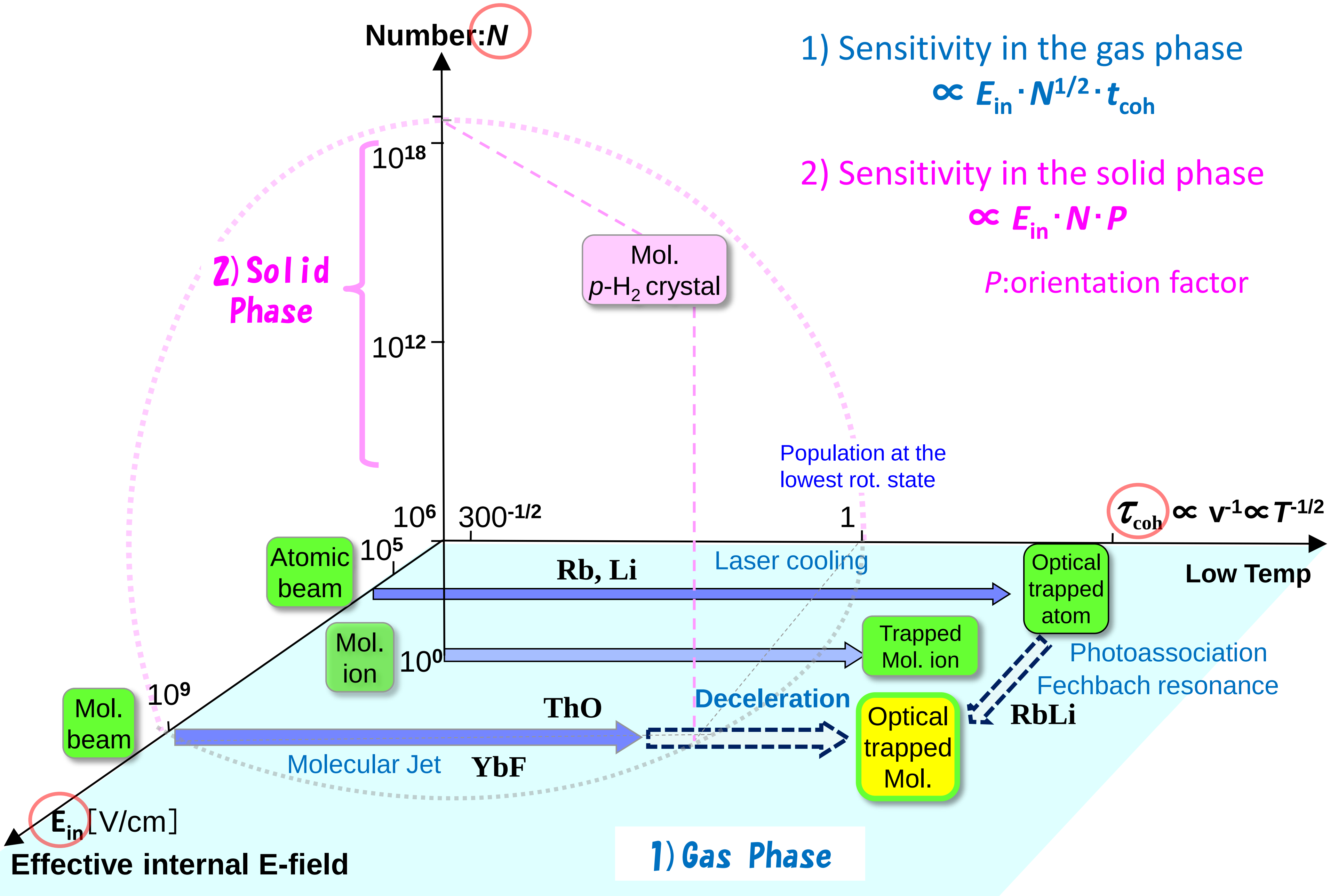
1) Sensitivity in the gas phase

$\propto E_{in} \cdot N^{1/2} \cdot t_{coh}$

2) Sensitivity in the solid phase

$\propto E_{in} \cdot N \cdot P$

P:orientation factor



Strategies for eEDM measurement using molecules

Direct measurement

$$\Delta\varepsilon = \boxed{d_e E_{eff}}$$

= $1e^{-28}$ [e・cm] x 100 [GV/cm]
~ 10^{-3}[Hz]

Ultra high resolution spectroscopy

Cold molecules in the gas phase

Phase (time developing) measurement
Ramsay Resonance
YbO, ThO **BiO** beam/trap
HfF^+ trap

Indirect measurement

Change in thermal population

$$\Delta n = n \frac{\boxed{d_e E_{eff}}}{kT}$$

~ 10^{19} → d_e
~ 10^{-13}[K] → $d_e E_{eff}$
~ 10^{6}
~ 1[K] → kT

Non-spectroscopic measurement
Metric of physical quantity except energy
ex.)Magnetization

Solid phase in *para*-H_2 crystal

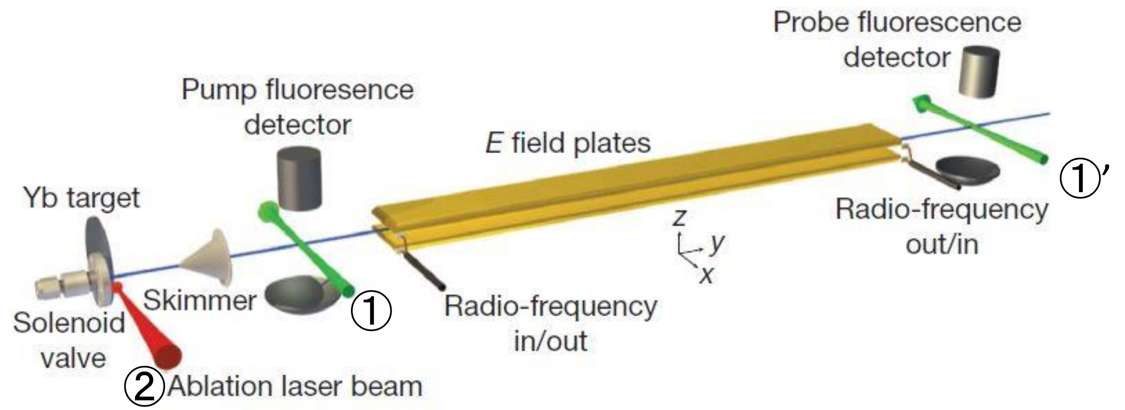
Ultra high-sensitive
Magnetometry of
HgH/*p*-H_2 crystal

Comparison among the candidate molecular system

	molecule	Electronic State	N-spin	Isotope Abundance	N	P Polar factor	E_{eff} [GV/cm]	τ_{coh} [s]	$E_{\mathrm{eff}} \cdot \tau_{\mathrm{coh}} \cdot N^{1/2}$	g-factor [μ_B]	$\lvert D_e \rvert$ [e·cm]	Method	Improvement by optical lattice [s]	Group
Gas Phase	$^{180}\mathrm{Hf}^{19}\mathrm{F}^{+}$	$a^3\Delta_1$	F 1/2	0.35	10^1	1	90	(1)	(280)	0.004	($5\mathrm{x}10^{-28}$)	trap	-	Cornell
Gas Phase	$^{174}\mathrm{Yb}^{19}\mathrm{F}$	$X^2\Sigma^+$	F 1/2	0.31	10^7	0.6	26	T_2 $>10^{-3}$	24	1.002	$< 1.\mathrm{x}10^{-27}$	Beam	~1000	Hinds
Gas Phase	$^{232}\mathrm{ThO}$	$a^3\Delta_1$	0	1	10^5	1	104	T_1 $<10^{-3}$	33	0.004	$< 1\mathrm{x}\ 10^{-28}$	Beam	1	Doyle
Gas Phase	$^{209}\mathrm{BiO}$	$X^2\Pi_{1/2}$	9/2	1	(10^7)	1	116	T_2 $>10^{-3}$	(260)	0.002	-	Beam	~1000	*This proposal*
Gas Phase	$^{204}\mathrm{HgH}$	$X^2\Sigma^+$	H 1/2	0.3	(10^7)	(10^{-5})	150	T_2 $>10^{-3}$	(1)	1.002	-	Beam	~1000	*This proposal*
									$P \cdot N \cdot E_{\mathrm{eff}}/k_B T$					
Solid Phase	$^{209}\mathrm{BiO}$ /*p*-H_2	$X^2\Sigma^+$	All	All	(10^{14})	(1)	116	T_1 $<10^{-7}$	(10^{16})	1.002	-	Thermal population	-	*This proposal*
Solid Phase	$^{\mathrm{All}}\mathrm{HgH}$ /*p*-H_2	$X^2\Sigma^+$	All	All	(10^{19})	(10^{-5})	150	T_1 $<10^{-7}$	(10^{16})	1.002	-	Thermal population	-	*This proposal*

1) eEDM searching experiments using BiO beam

Molecular beam experiment used in **YbF** by Hinds group (2011)



1)Radical generation	2)Preparing initial state	3)Interaction region	4)Detecting final state
	$\|-1\rangle + \|+1\rangle$		$\|-1\rangle + e^{i\Delta\phi}\|+1\rangle$

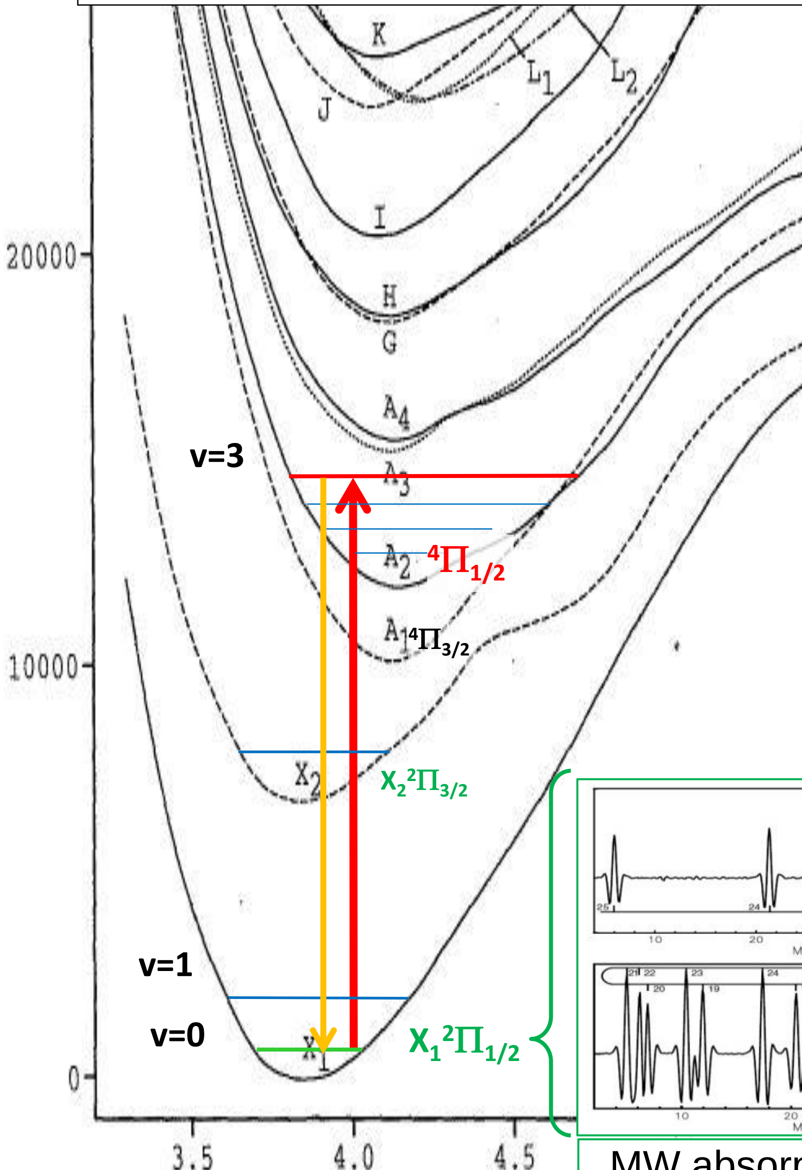
Selecting the hyperfine-resolved single quantum state for the measurement.
Choosing the electronic transition for manipulating the initial state.

①Laser Spectroscopy

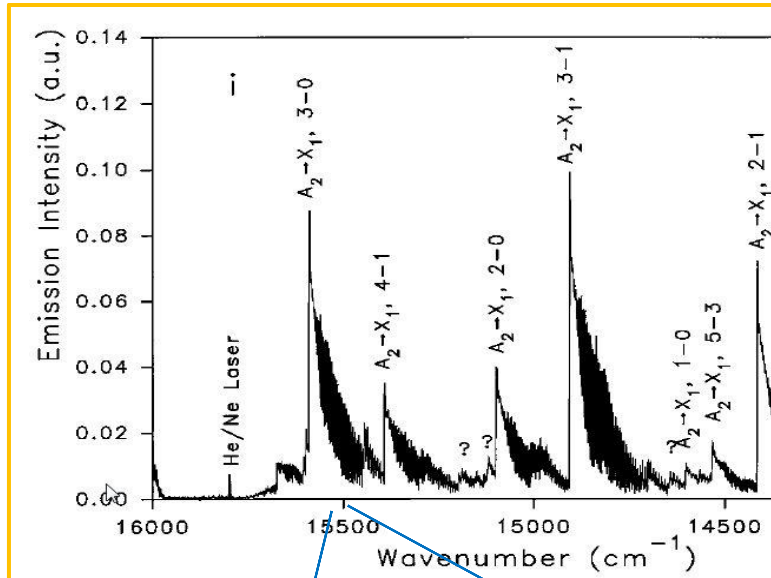
② How to generate the BiO radical beam

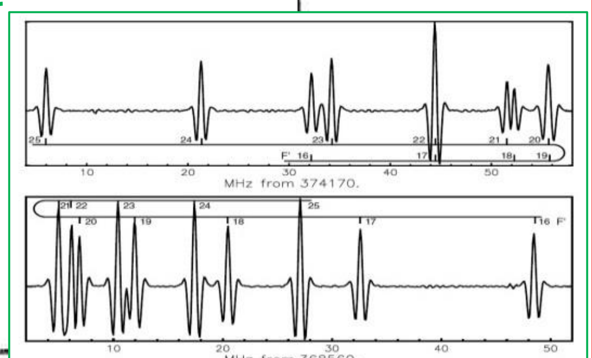
Spectroscopic Studies on BiO

ab initio potentials
Alekseyev, *et.al.*, JCP, 100, 8956(1994)

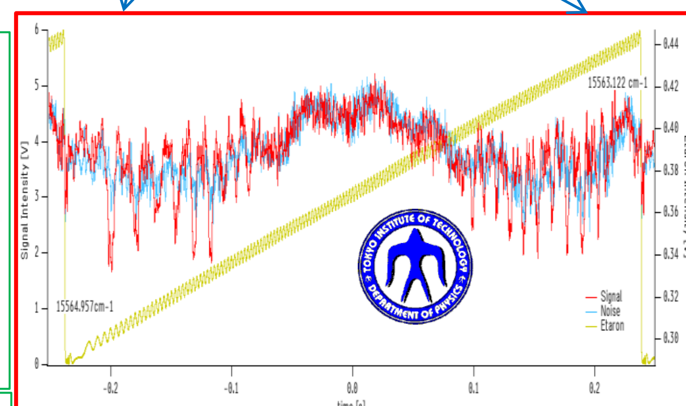


FTIR emission spectroscopy
Shestakov, *et.al*., JCP, 190, 28 (1998)





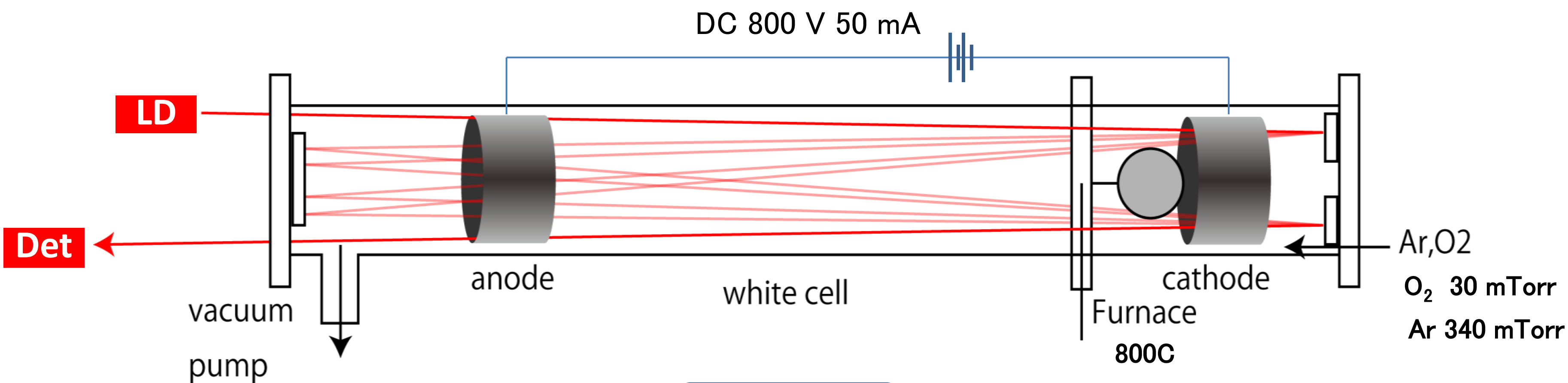
MW absorption spectroscopy
Cohen, *et.al.*,JMS, 239,16 (2006)



Laser absorption spectroscopy (This)

Producing and detection of the **BiO** radicals in a cell@T=300K

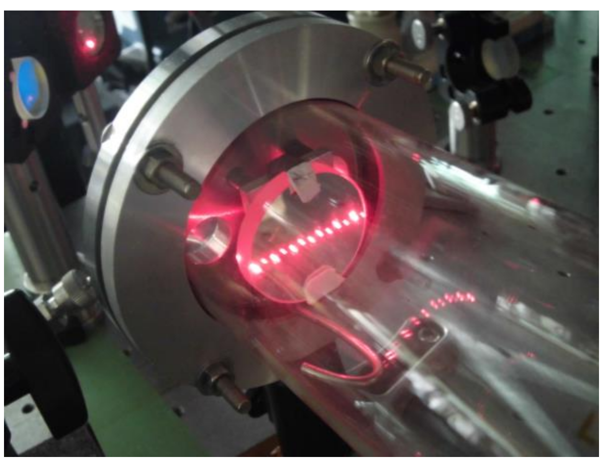
$$\mathrm{Bi} + \mathrm{O_2}^* \rightarrow \mathrm{BiO} + \mathrm{O}$$

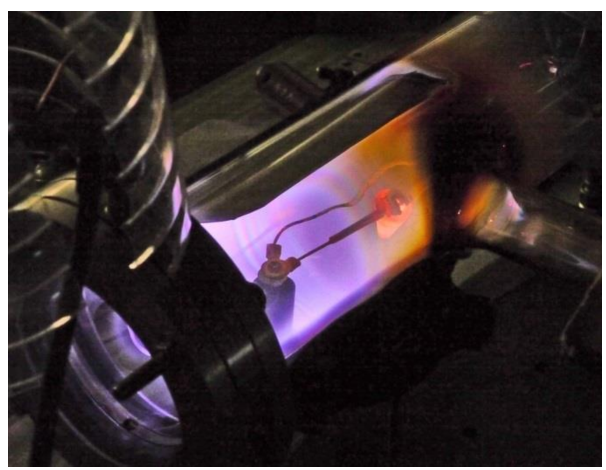


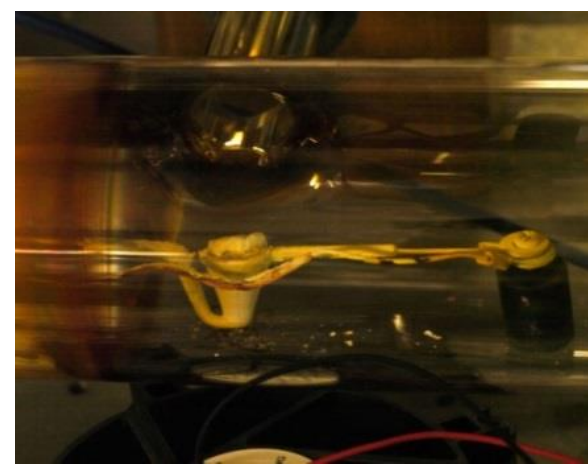
Discharge

Furnace

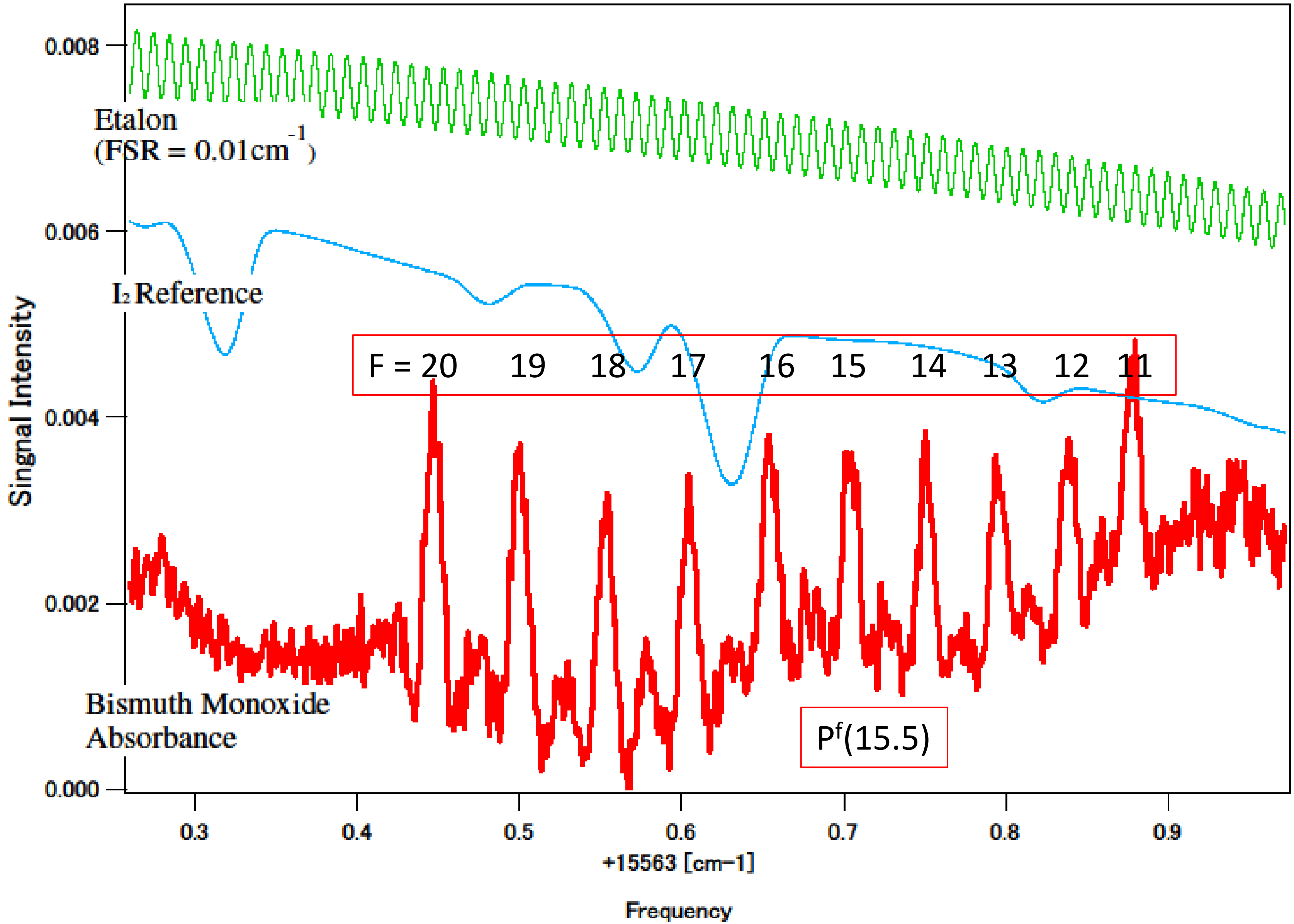
multi-pass absorption cell





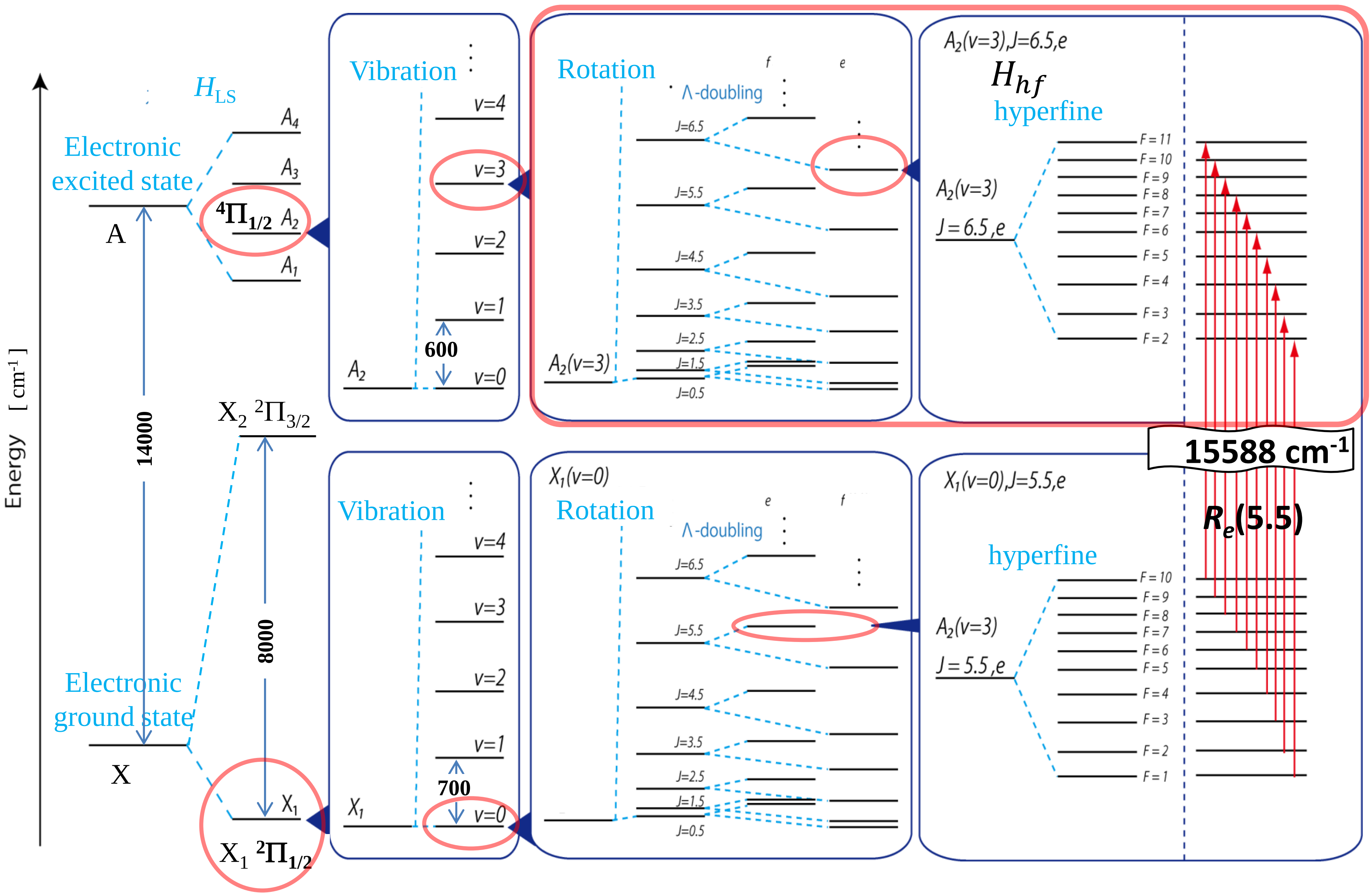


Observed Spectrum of BiO in the visible region



Energy levels of **BiO**

Hyperfine resolved rotational analysis of the A_2 electronic excited state



Hyperfine analysis for the A_2 state

$$\mathrm{H} = \mathrm{H}_{\mathrm{rot}} + \mathrm{H}_{\mathrm{hf}}$$

$$H_{hf} = aI_zL_z + b_F\boldsymbol{I}\cdot\boldsymbol{S} + c\,I_zS_z + \frac{1}{2}d(\Lambda_+^2\,I_-S_- + \Lambda_-^2\,I_+S_+) + eQq(3I_z^2 - \boldsymbol{I}^2)/4I(2I-1)$$

n.spin – e.orbit

Fermi contact

e.spin – n.spin diag.

e.spin – n.spin off-diag.

n.Q-pole diag.

Basis function : Hund's case $\boldsymbol{a}_\beta$: $|\,J, \Lambda, \Sigma, I, F\,\rangle$ ⟹ 20 x 20 matrix elements for a F state

Molecular constants determined [cm^{-1}]

Constants	$A_2\,{}^{(4)}\Pi_{1/2}(v=3)$	$A_2(v=3)$ ※1	$X_1\,{}^2\Pi_{1/2}(v=0)$ ※2
T_v	15588.54880(8)[a]	15588.24	-
B	0.241156(4)	0.2415(2)	.30408148(1)
$D \times 10^{-7}$	2.49(4)	3.01 (42)	2.36428(3)
p	-0.03798 (3)	-0.051(34)	+0.185372(9)
$q \times 10^{-6}$	-	-3.67 (398)	- 13(50)
$a/2-(b+c)/4$	0.025(1)	-	0.04544(1)
d	0.02408 (2)	-	0.118836(1)
eQq	-0.019 (3)	-	+0.141(5)

A = -2666 fixed※2

Perturbing Σ state?

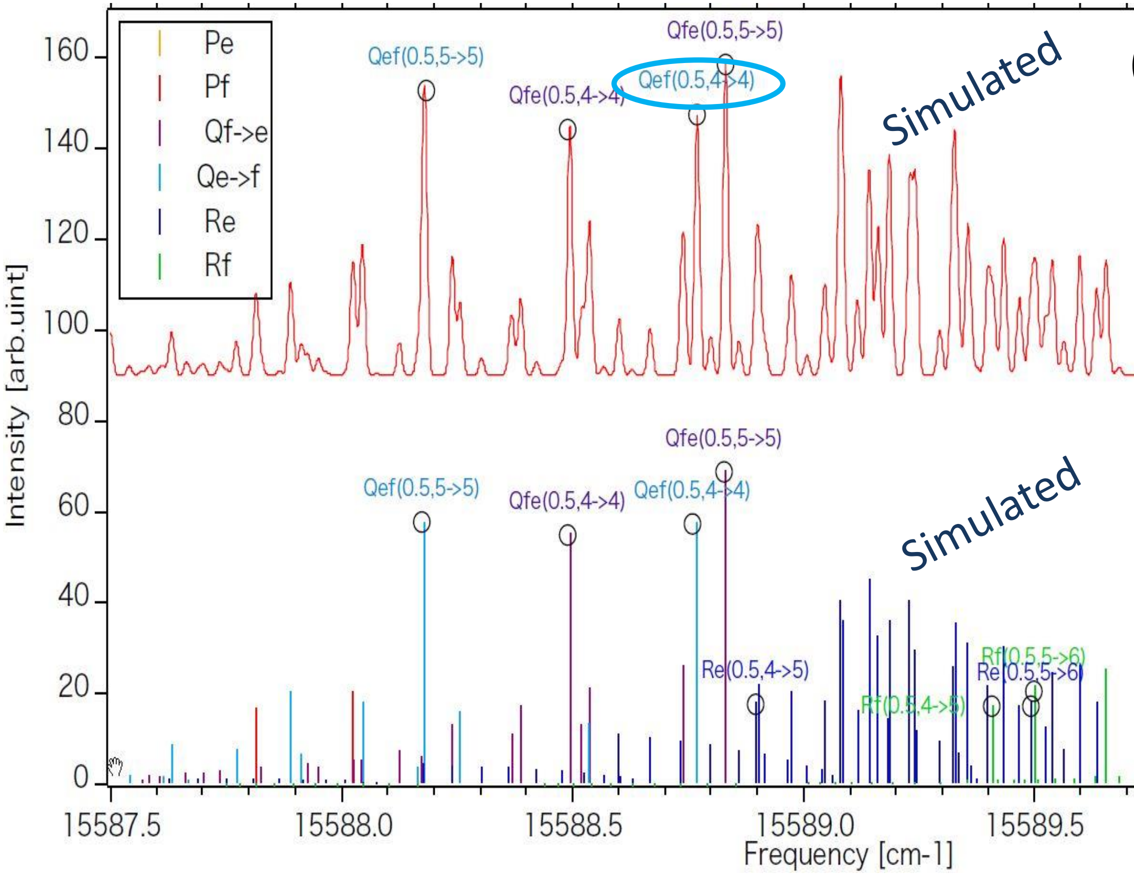
$\frac{dE}{dz}$ is inverted

※1 R. F. Barrow, W. J. M. Gissane and D. Richards, *Proc. R. Soc. Lond. A* (1967)

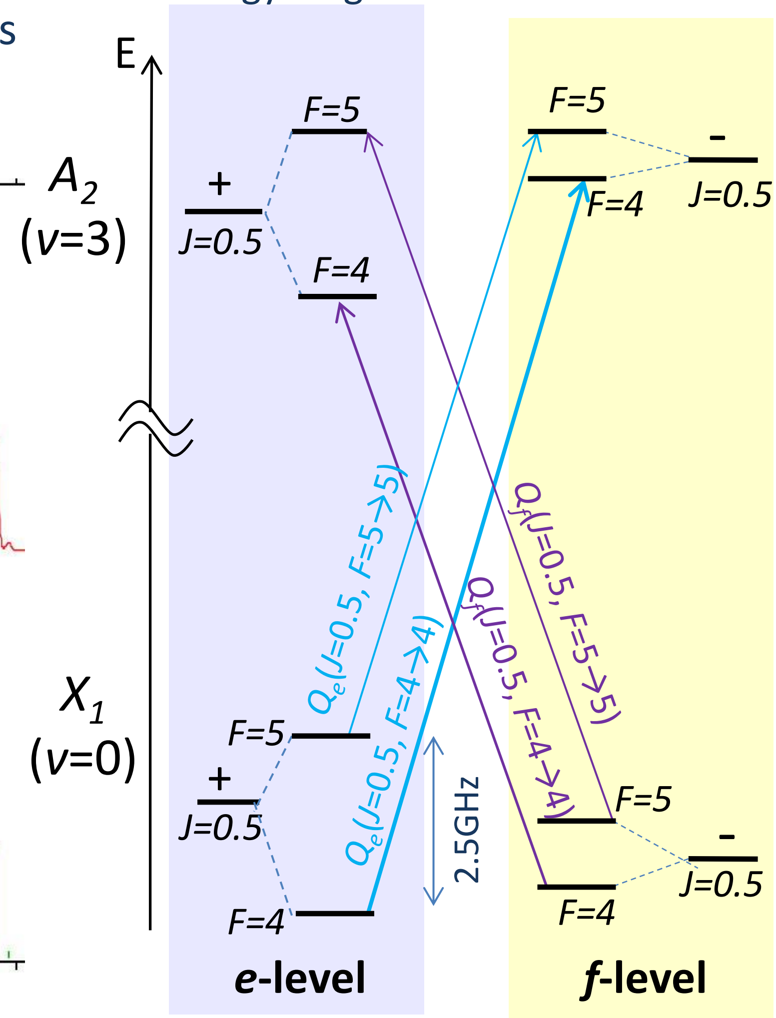
※2 E.A. Cohen, et. al . Mol. Spectrosc (2006)

Candidate transition for the eEDM measurement

Simulated spectrum of the lowest rotational transitions in $A_2(v=3)$ - $X_1(v=0)$ at T = 5 K



Energy diagram of the lowest state

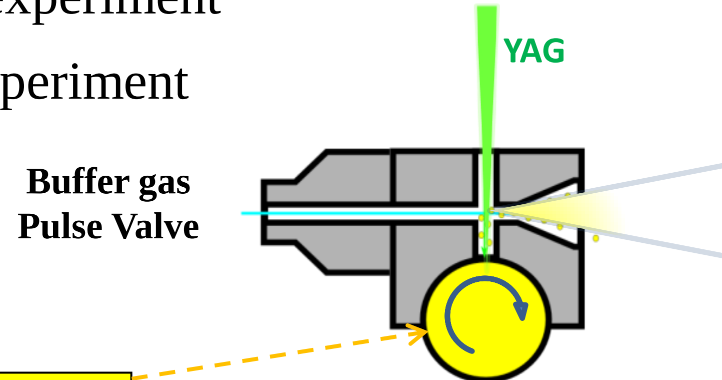


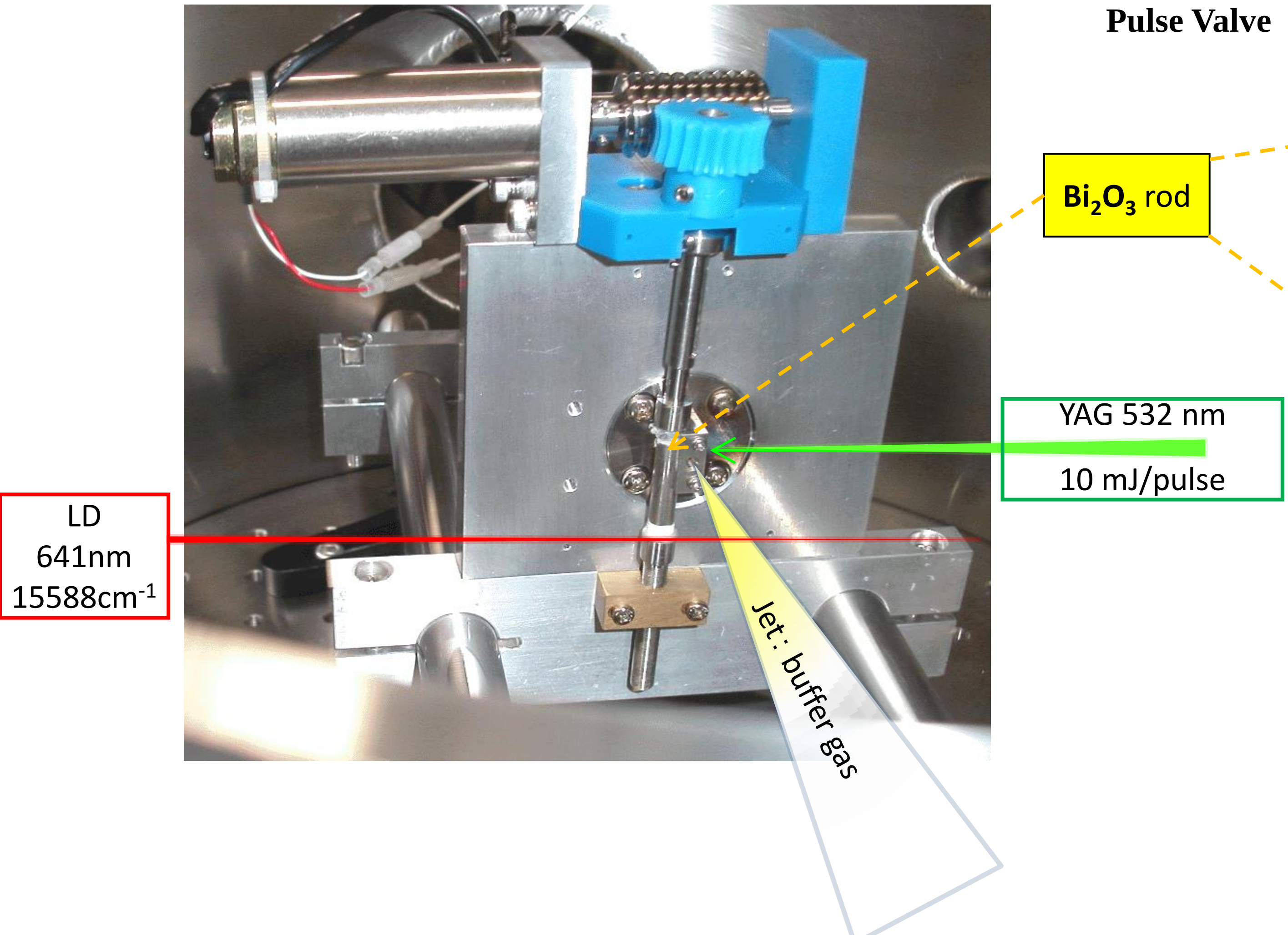
Only 2 hyperfine components at the lowest J=0.5

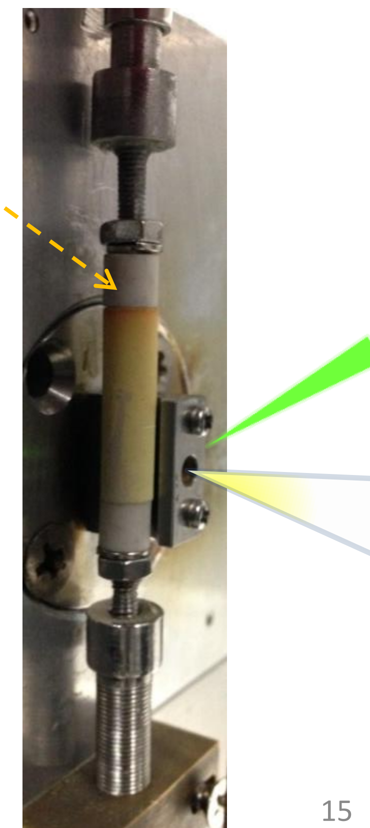
Current status : LIF detection in a supersonic jet with laser ablation

Bi/O_2 buffer gas → BiO for the beam experiment

Bi_2O_3/H_2 buffer gas → BiO for the *p*H_2 experiment







2) eEDM searching experiments using HgH in *p*-H_2 crystal

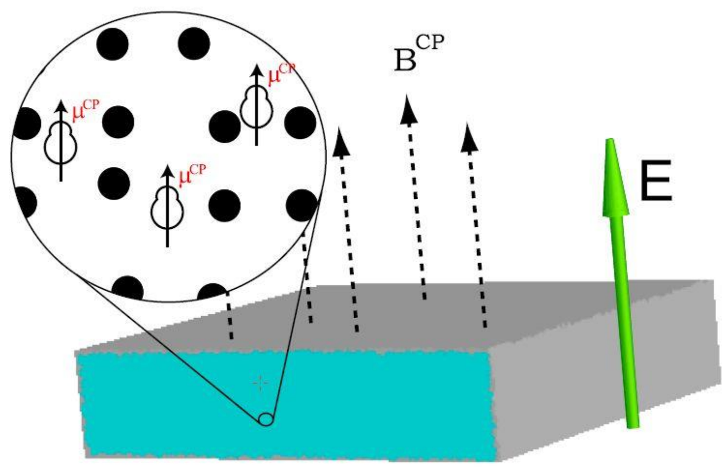


FIG. 1 (color online). Scheme of searching for EDM of an electron with diatomic radicals embedded in a matrix of rare-gas atoms. A polarizing electric field E is applied to the matrix. As a result, molecular CP-violating magnetic moments μ^{CP} become oriented and generate ultraweak magnetic field B^{CP}. By measuring B^{CP}, one places constraints on eEDM.

HgH/Ar Kozlov, *et.al.*, PRL,97,063001(2006)

HgH/*p*-H_2 Sushkov Theoretical proposal

Change in thermal distribution

10^{-28}[e·cm]

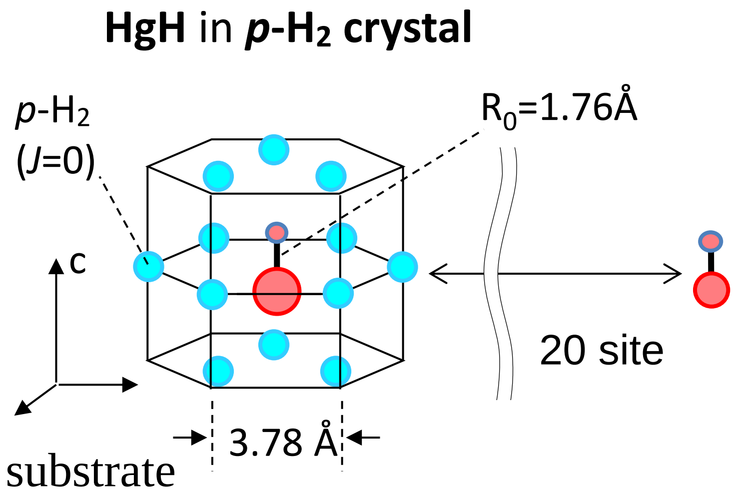
$$\Delta n = \boldsymbol{n}_0 \frac{\boldsymbol{p} \cdot \boxed{d_e \cdot E_{\mathrm{in}}}}{kT}$$

~10^{-13} [K]

~1[K]

~ 10^{6} ⬅ ~ 10^{19}

Realization of n=10^{19} radicals in a matrix isolation ; HgH/p-H_2



p-H_2 crystal : $(1cm)^3$ $n_{pH2}=10^{23}$

1) Doping of Hg atom ; [Hg] = 100 ppm ; $n_{Hg} = 10^{-4} \times 10^{23} = 10^{19}$

2) Photo-chemical reaction in the crystal

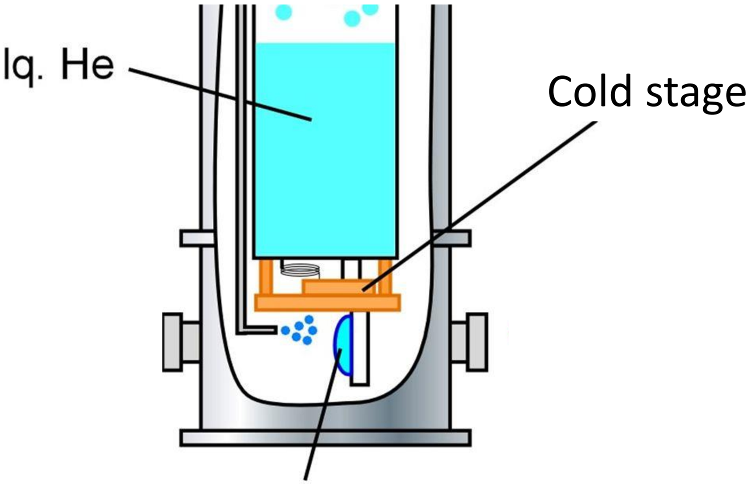
$$Hg(^1S) + h\nu(253nm) \rightarrow Hg^*(^3P)$$

$$Hg^*(^3P) + H_2 \rightarrow HgH\ (X^2\Sigma) + H(^2S) \quad (\eta\sim100\%\ \text{in the gas phase})$$

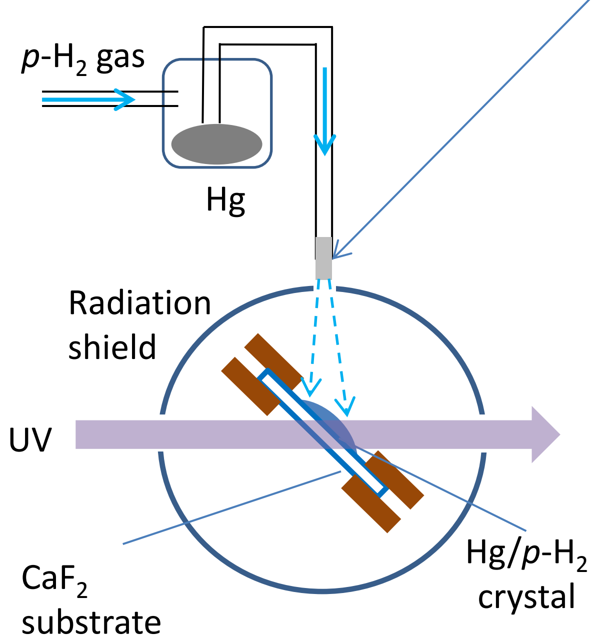
$$H(^2S) + H(^2S) \rightarrow p\text{-}H_2(X^1\Sigma) + o\text{-}H_2(X^1\Sigma) < 100\ \text{ppm}$$

$n_{Hg} = n_{HgH} = 10^{-4} \times 10^{23} = 10^{19}$

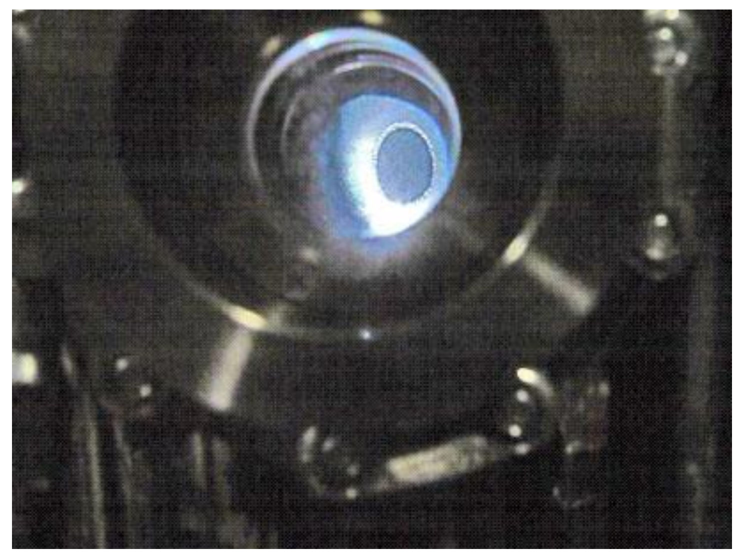
Hg/p-H_2 crystal generation



sample/p-H_2 generated on substrate
by blowing of p-H_2 gas



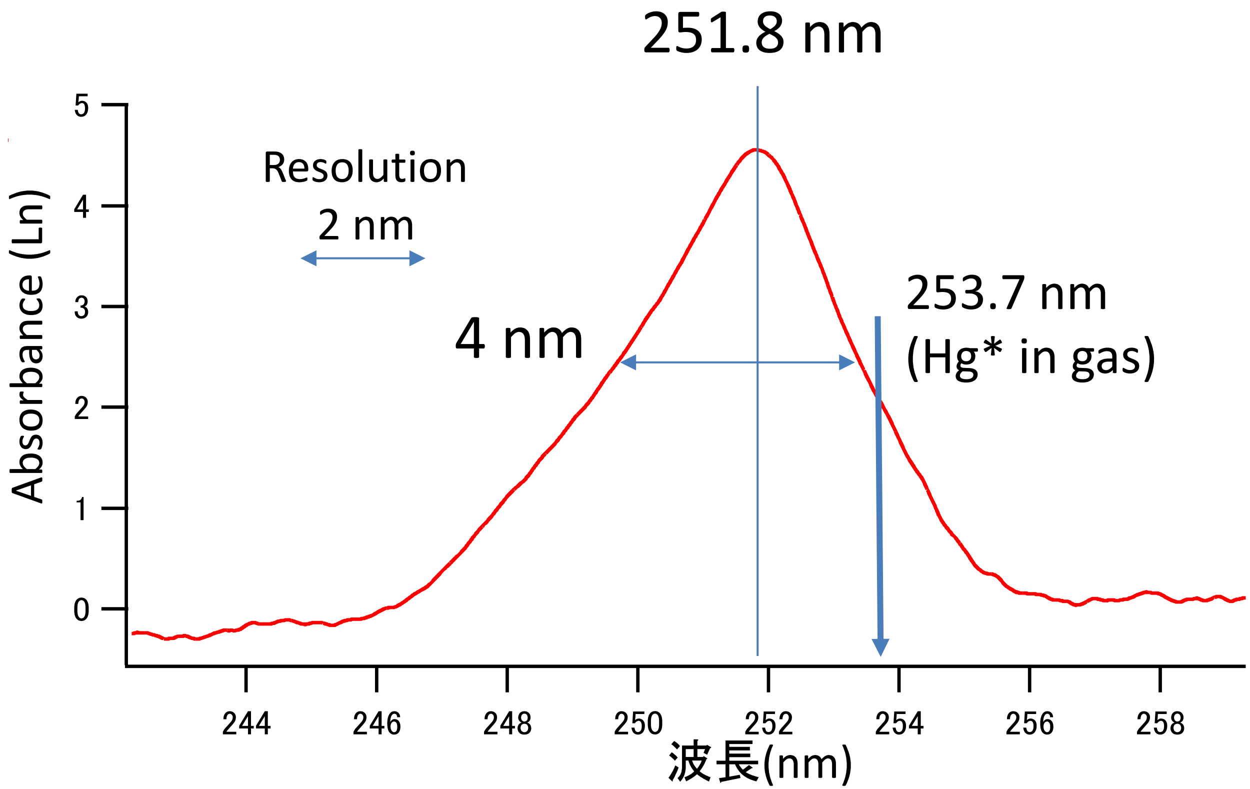
Multi-capillary



Crystal through the window

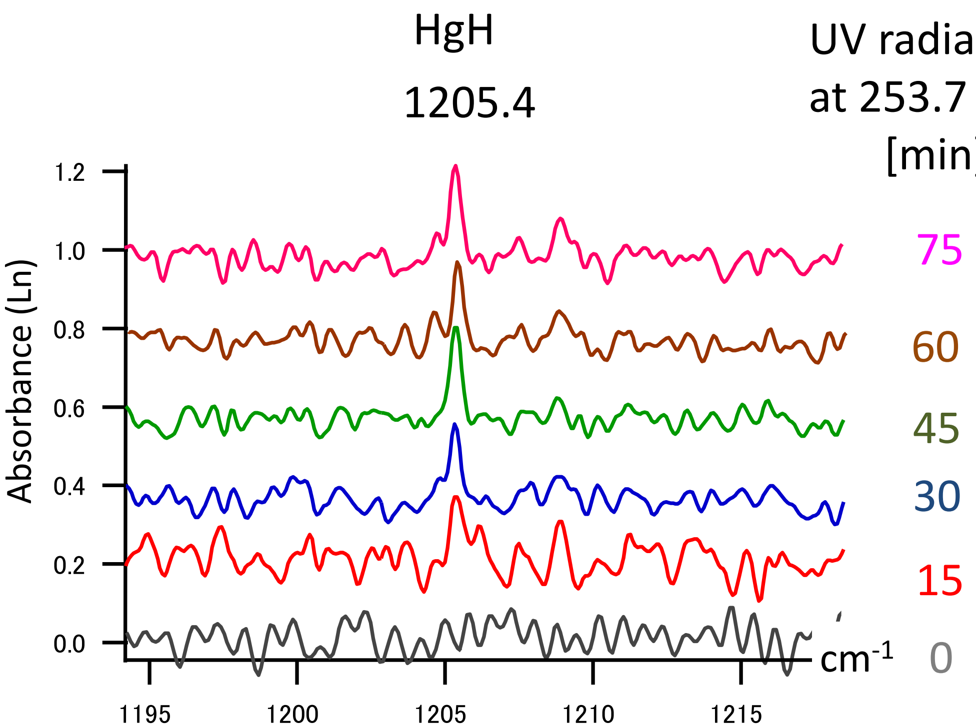
UV absorption spectrum of Hg/p-H_2 crystal

Hg/p-H_2 crystal
thickness=0.5 mm



Column density $\mathbf{nL} = \dfrac{\mathrm{L}\int \alpha(\nu)\,\mathrm{d}\,\nu}{\int \sigma\,(\nu)\,\mathrm{d}\,\nu} \sim 4.6 \times 10^{17}\mathrm{cm}^{-2} \sim 10^{19}\ /\mathrm{cc}$

IR absorption spectrum of HgH and HgH_2 /*p*-H_2



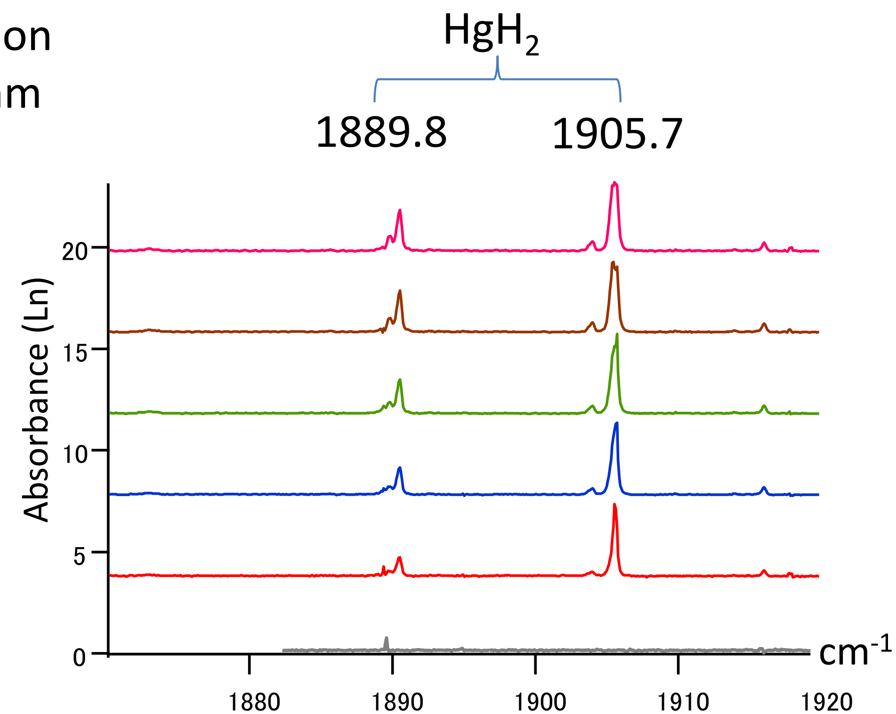
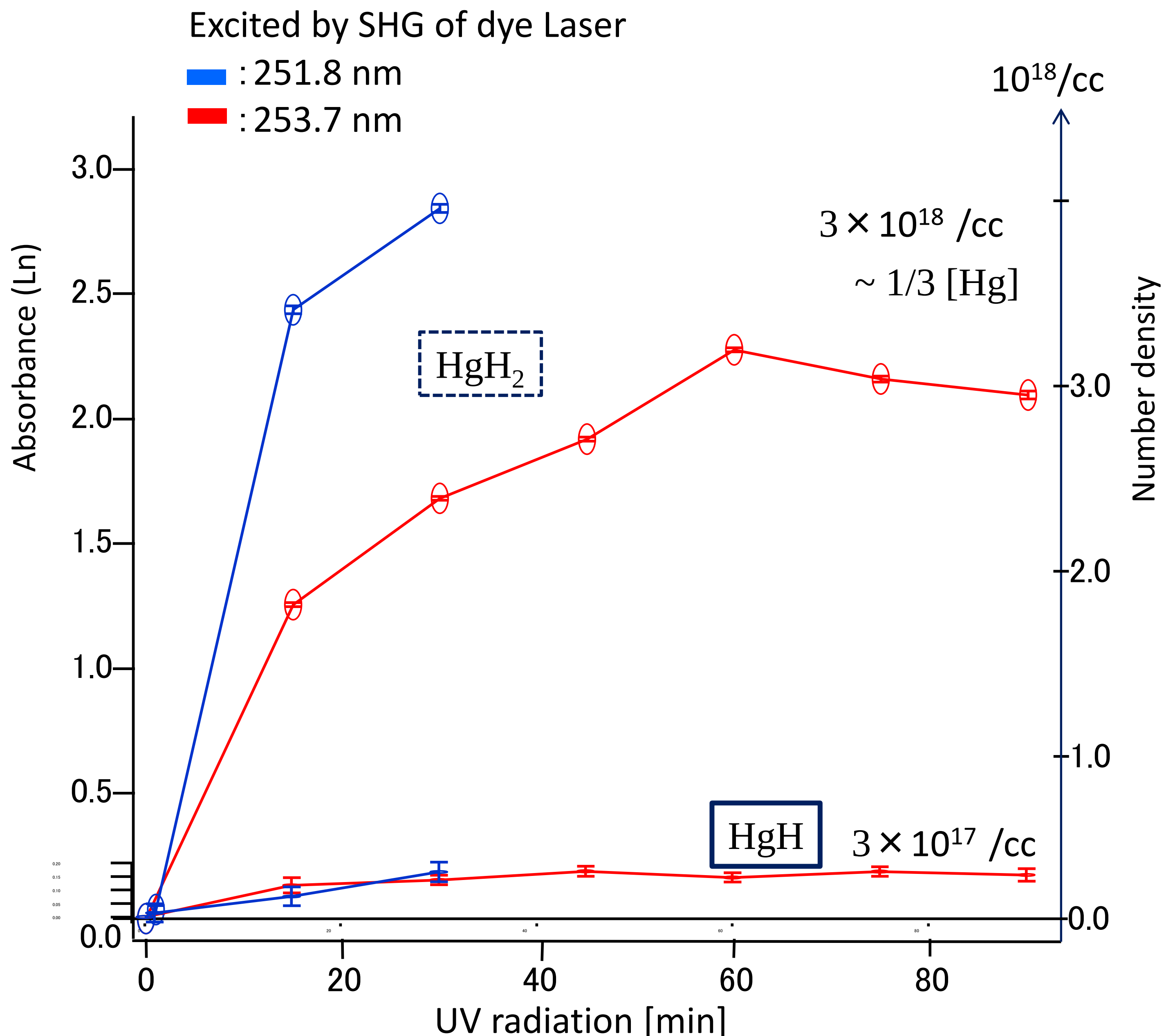
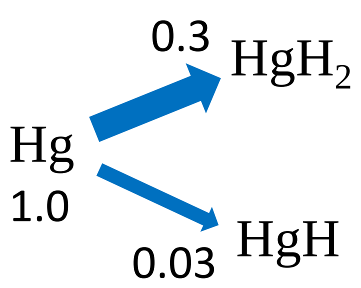


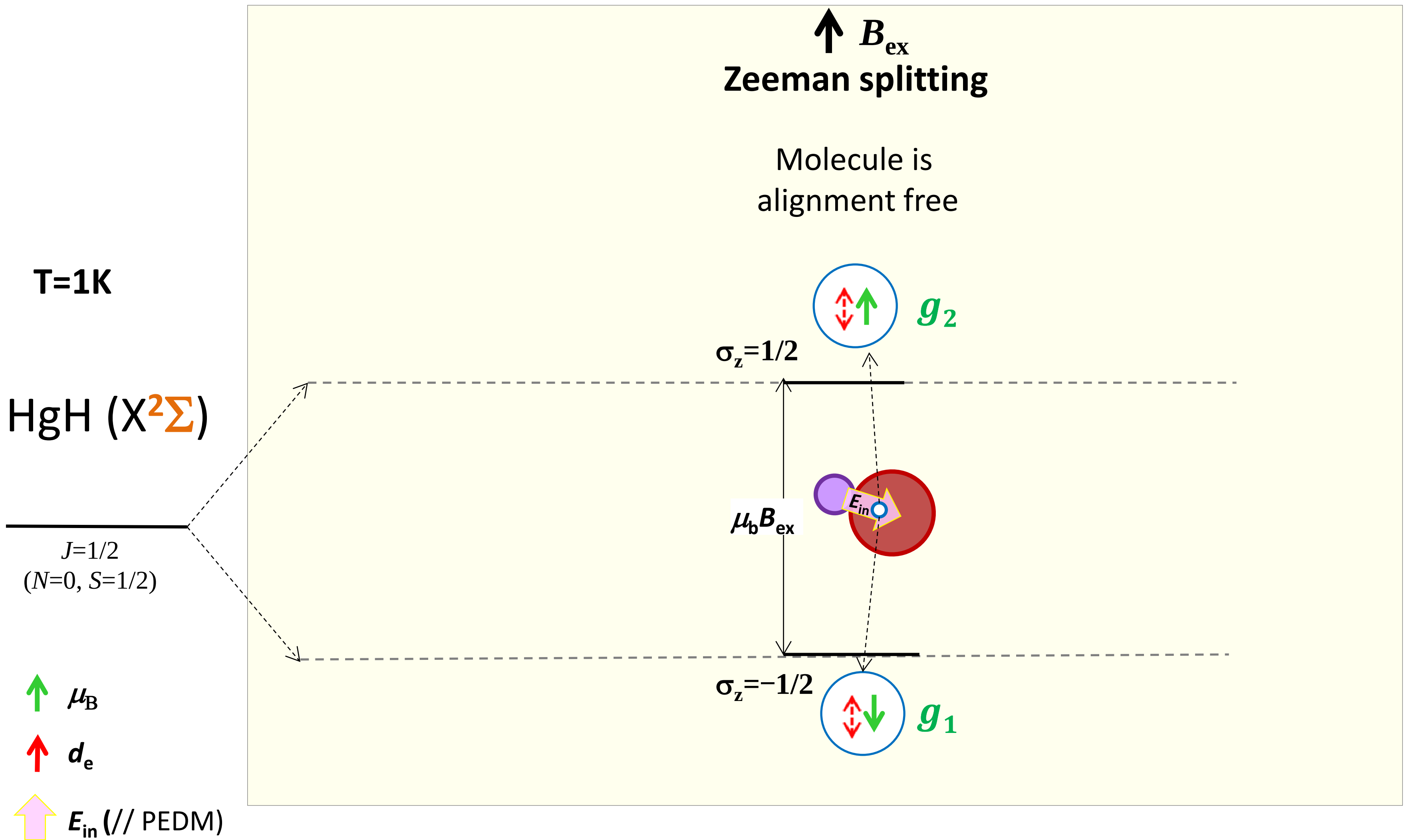
Photo-chemical production of HgH and HgH_2/p-H_2 by UV radiation



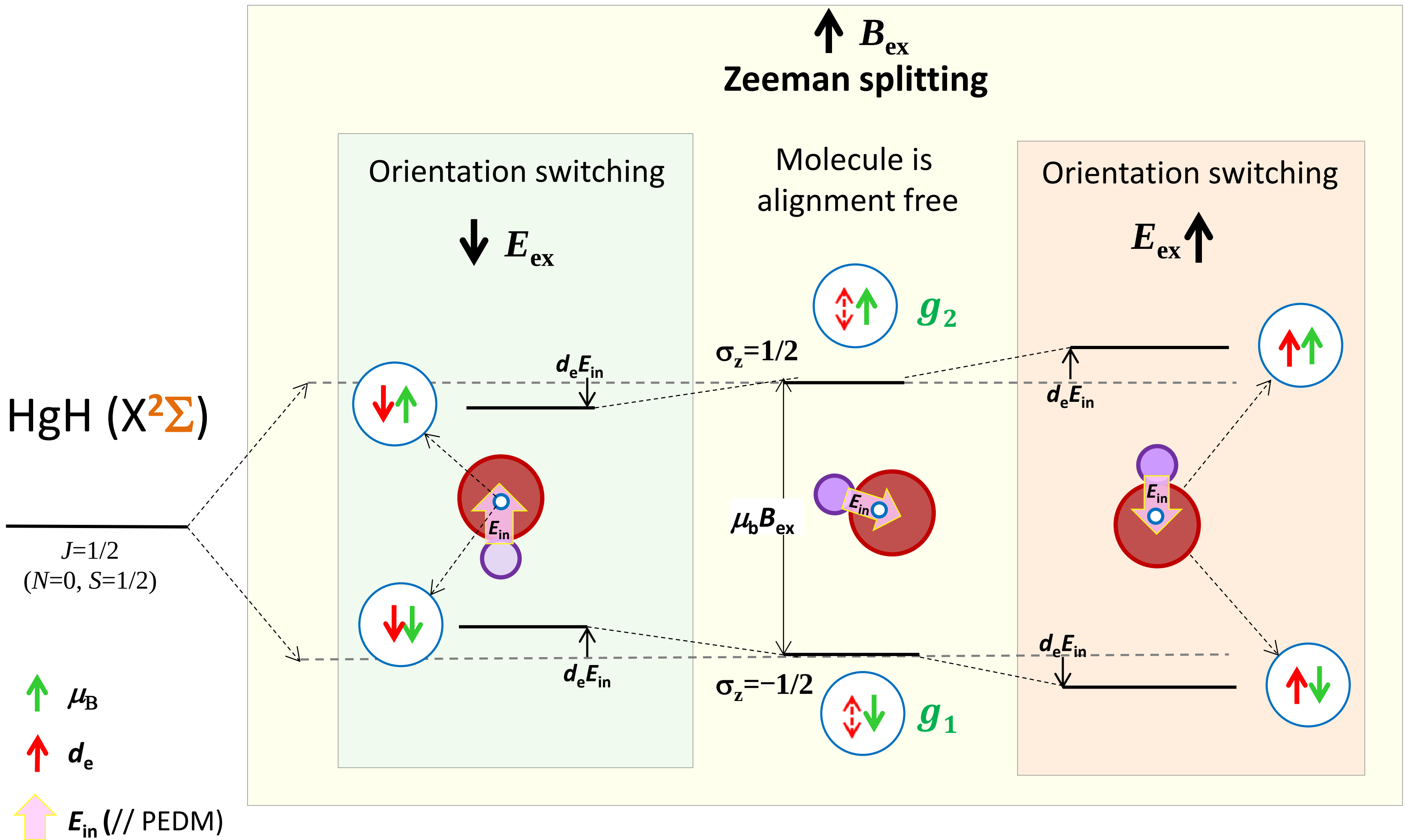
Assuming vibrational
Transition moment
μ = 0.1 Debye



Energy shift due to eEDM and change in thermal distribution

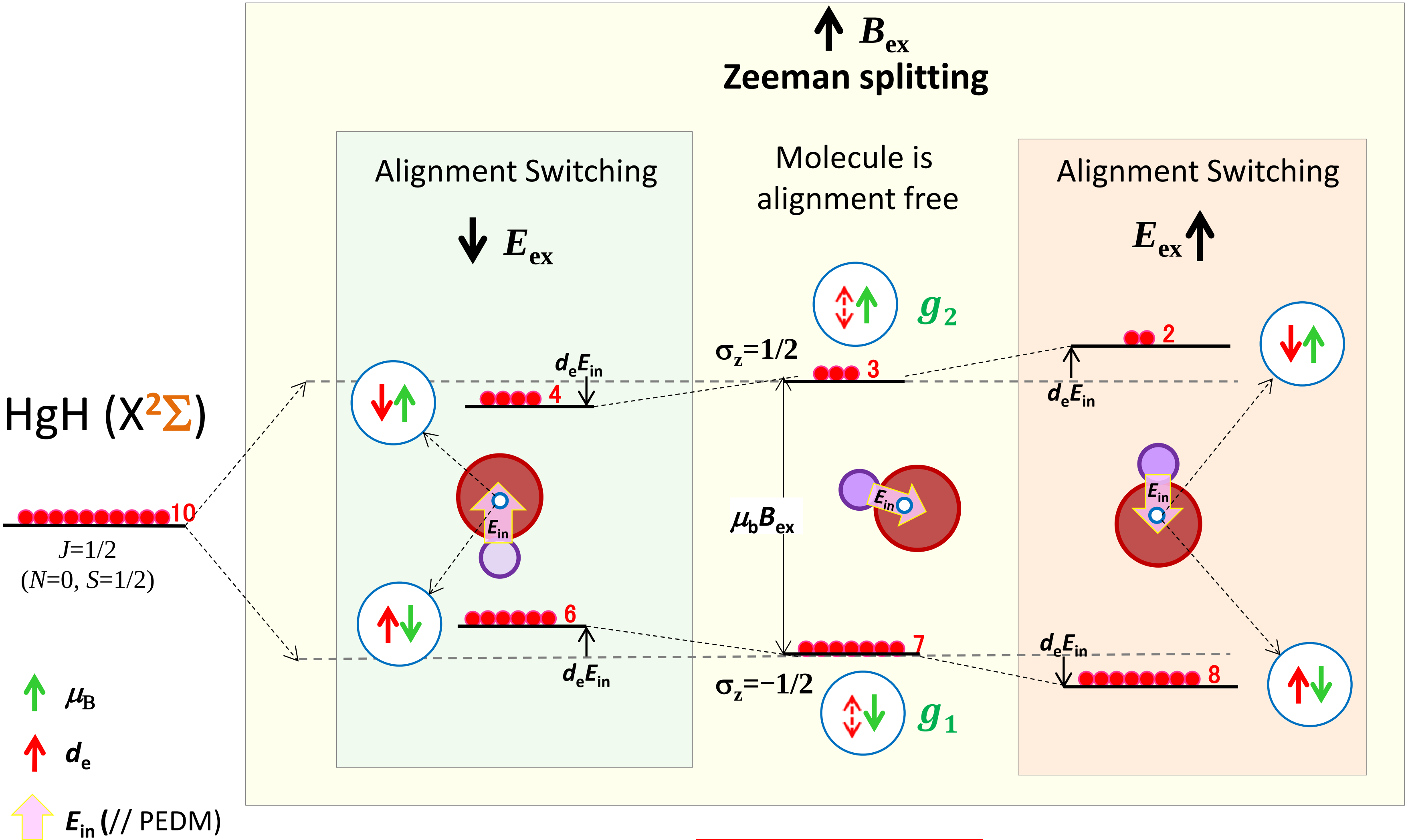


Energy shift due to eEDM and change in thermal distribution



$$\Delta\varepsilon = \ d_e \cdot \sigma_z \cdot E_{\text{in}}$$

Energy shift due to eEDM and change in thermal distribution



Boltzmann distribution

$$\Delta n = n_0 \frac{4 p d_e E_{in}}{kT}$$

$$\Delta M = (g_2 - g_1)\Delta n$$

Quick relaxation by spin-phonon interaction

p:orientation ratio

Change in magnetization
$= 2\mu_B \Delta n$

eEDM detection beyond 10^{-28}[e･cm]using the change in thermal distribution

Magnetmetory

$$\Delta\Phi \propto (g_2 - g_1)\Delta n$$

$$= 2\mu_B \Delta n$$

$$= 2 \times 10^{-23} \Delta n \text{ [T]}$$

$$\Delta n = \frac{4pd_e E_{\text{in}}}{kT} = 4\text{x}10^6$$

$n_0 = 10^{19}$

T=1K

$d_e = 10^{-28}$ (Doyle's limit)

$$\sim 1 \times 10^{-16} \text{ [T]}$$

1) SQUID sensitivity 10^{-15} [T/Hz$^{1/2}$]

p:orientation factor	1	10^{-5}
S/N@1[s]	~0.1	10^{-6}
Time for S/N=1[s]	100	10^{12}

2) Faraday effect's sensitivity 10^{-17} [T/Hz$^{1/2}$] ? (Sushkov)

Summary with a staff and students

1) BiO experiment

The candidate state for EDM experiment
and laser transition is determined

S. Yamaguchi (M grad.)

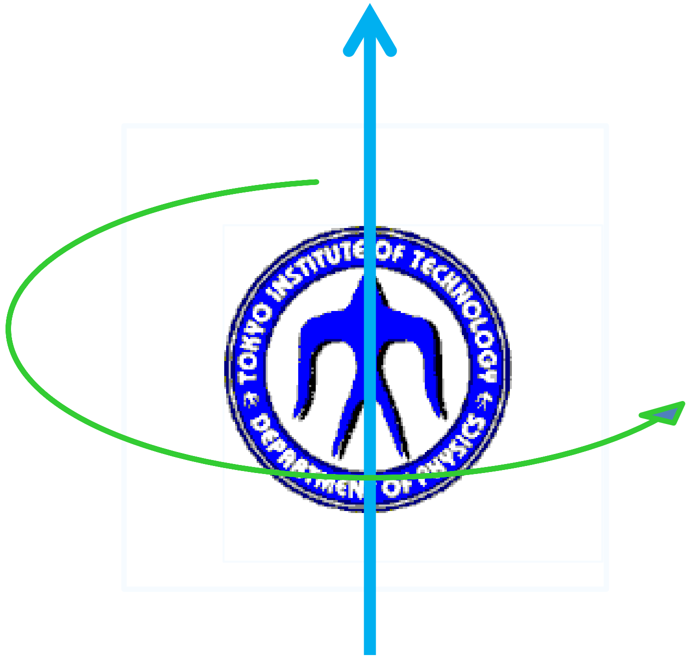
Y. Suematsu(M2)

2) Hg/*p*-H_2 experiment

10^{17}/cc of HgH radical is created in solid *para*-H_2

A. Mizoguchi(assistant prof.)

T. Ohono (M grad.)



Thank you