Light shifts induced by atomic parity nonconserving transitions in ultracold Fr for probing physics beyond the Standard Model

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   - New Physics beyond the Standard Model

3. Nuclear Spin dependent Parity Nonconservation effect
   - Nuclear Anapole Moment

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Introduction

Particle Physicist

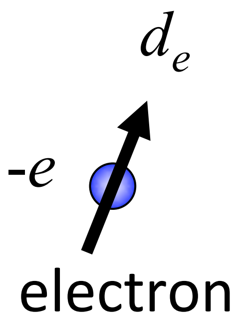
Atomic Physicist

Spectroscopy
Precise Measurement
to detect the frequency shift

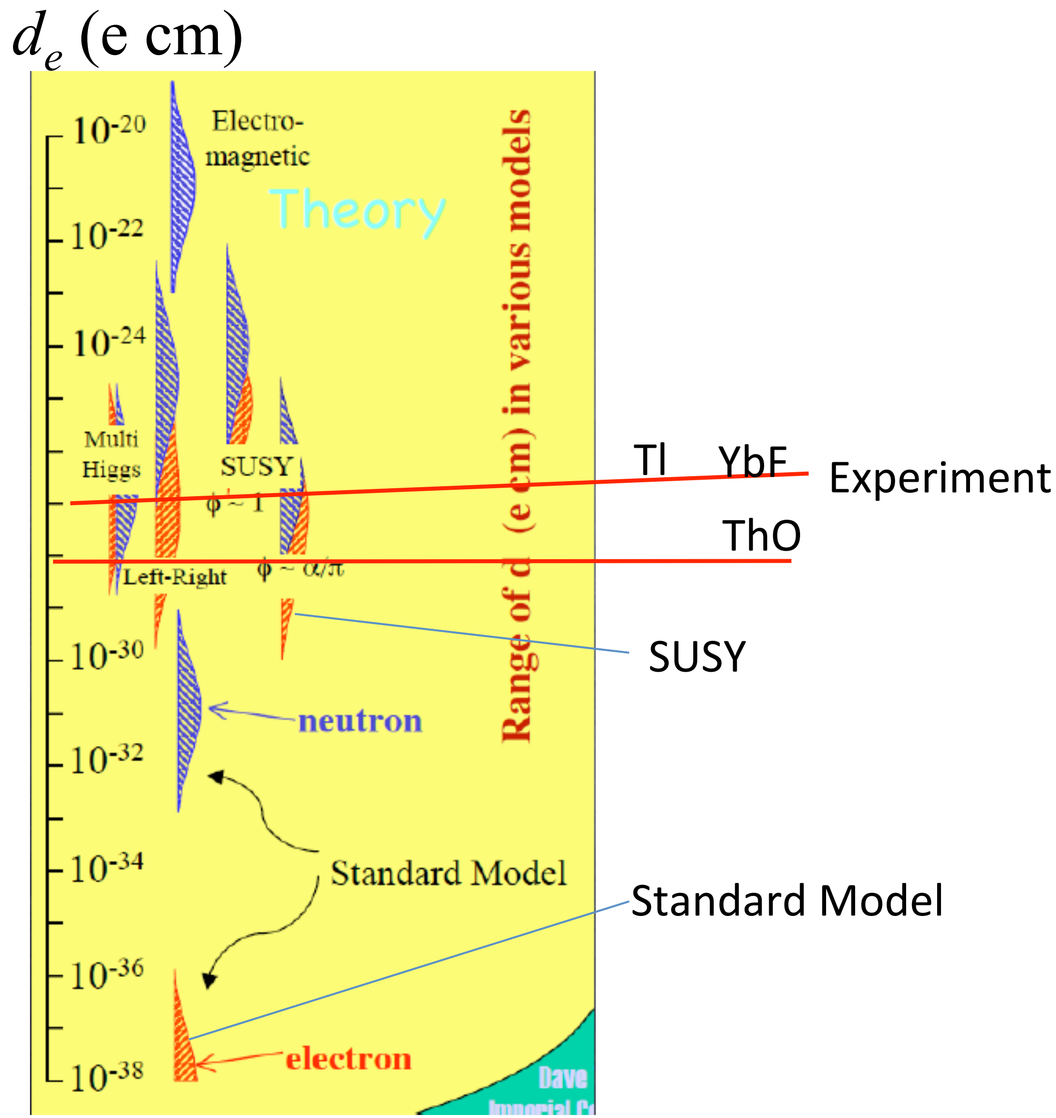
New Physics
beyond the Standard Model

electron's electric dipole moment (e-EDM)

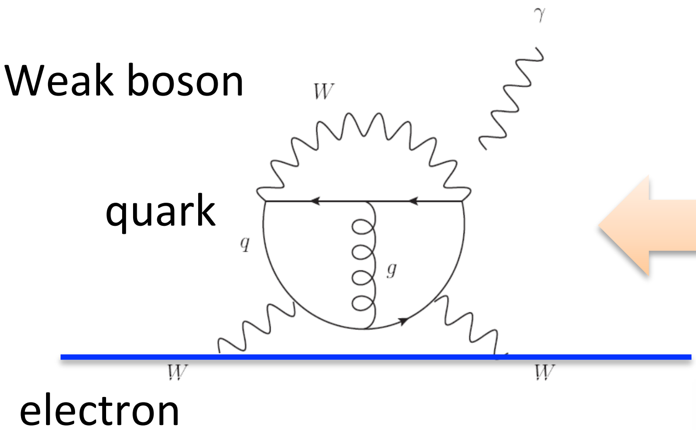
electric dipole moment (EDM)

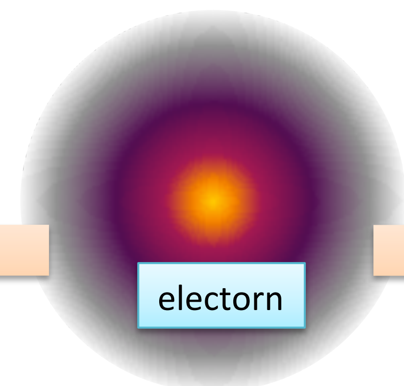


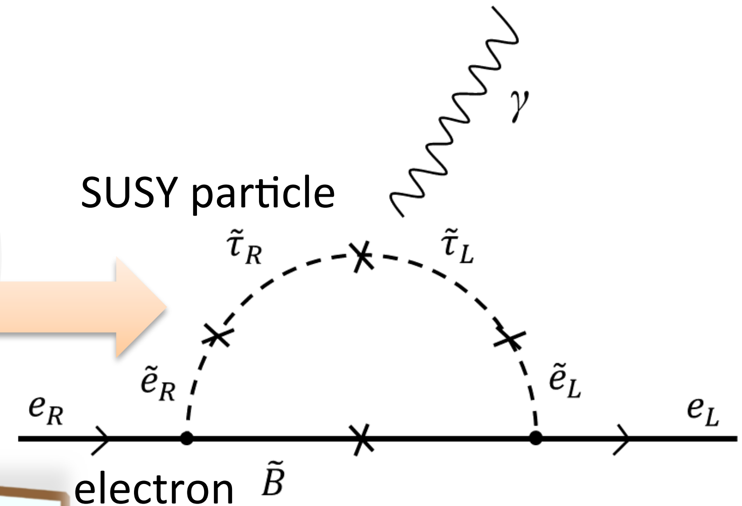
T- Violation

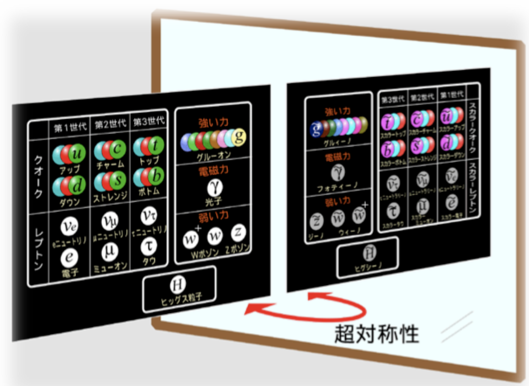


EDM induced by New Physics









Standard Model

$$d_e < 10^{-37} e \cdot cm$$

SUSY

split SUSY

$$d_e \sim \frac{\alpha}{4\pi} \frac{m_\tau}{M_{\tilde{l}}^2} \frac{\mu m_{\tilde{B}}}{M_{\tilde{l}}^2} \sin\theta_\mu \tan\beta$$

$$M_i \sim \mathrm{TeV}$$

Probe for New Physics beyond the Standard Model

Our approach:

electron EDM

- Laser cooling of Fr atoms -> A. Uchiyama today's talk
- Ultracold FrSr molecuels

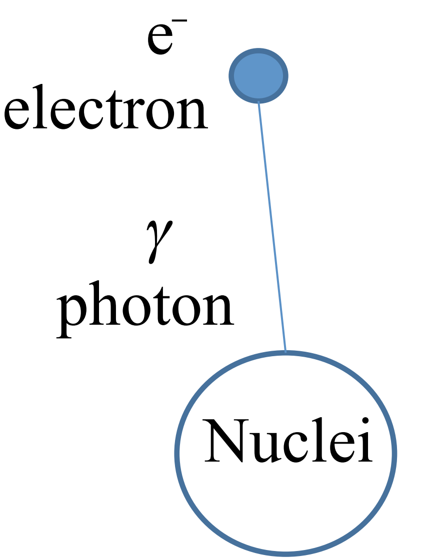
Parity Nonconservation (PNC)

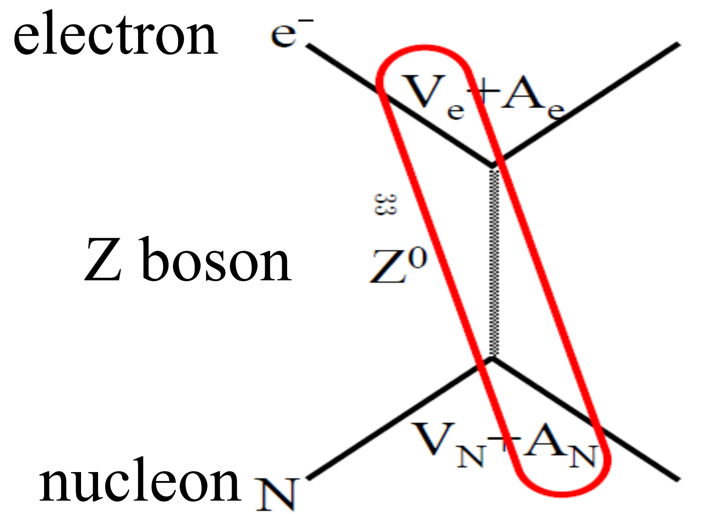
- Laser cooling of Fr atoms -> My talk

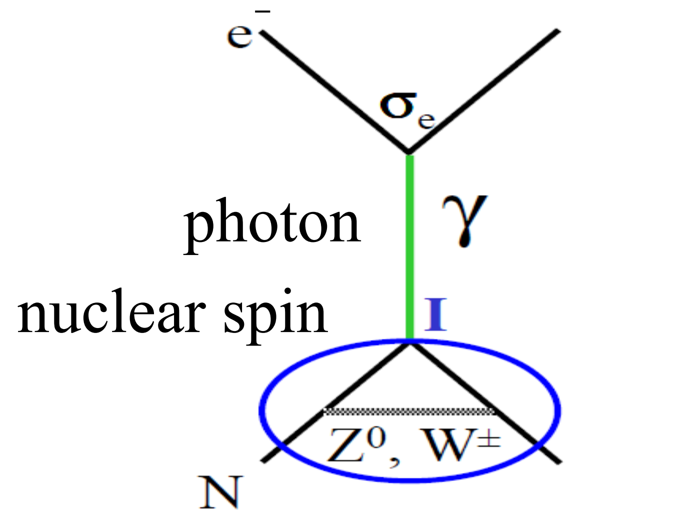
Weak interaction in atom

Laser induced transition → Excitation of electron's energy

Weak interaction -> Parity Nonconservation (PNC) in atom







electromagnetic force (Coulomb's law)

①Neutral Current Weak
(nuclear spin independent)
(nuclear spin dependent)
New Physics

②Anapole moment
(nuclear spin dependent)
information about
PNC in Nuclei

Contents

① Nuclear Spin independent PNC

Nuclear Spin Independent (NSI)

$$H_W^{\text{s.i.}} = \frac{G_F}{2\sqrt{2}} Q_W \gamma_5 \rho(\vec{r})$$

G_F: Fermi constant
ρ : nucleon density

weak charge

$$Q_W = Z(1 - 4\sin^2\theta_W) - N$$
$$= (2Z+N)C_u + (2N+Z)C_d$$

$$Q_W^{\text{Exp.}} = Q_W^{\text{SM}} + Q_W^{\text{New Physics}}$$

$$\Delta Q_W \equiv Q_W^{\text{Exp.}} - Q_W^{\text{SM}}$$

↑

Atomic Physics

① Nuclear Spin independent PNC

Nuclear Spin Independent (NSI)

$$H_W^{\text{s.i.}} = \frac{G_F}{2\sqrt{2}} Q_W \gamma_5 \rho(\vec{r})$$

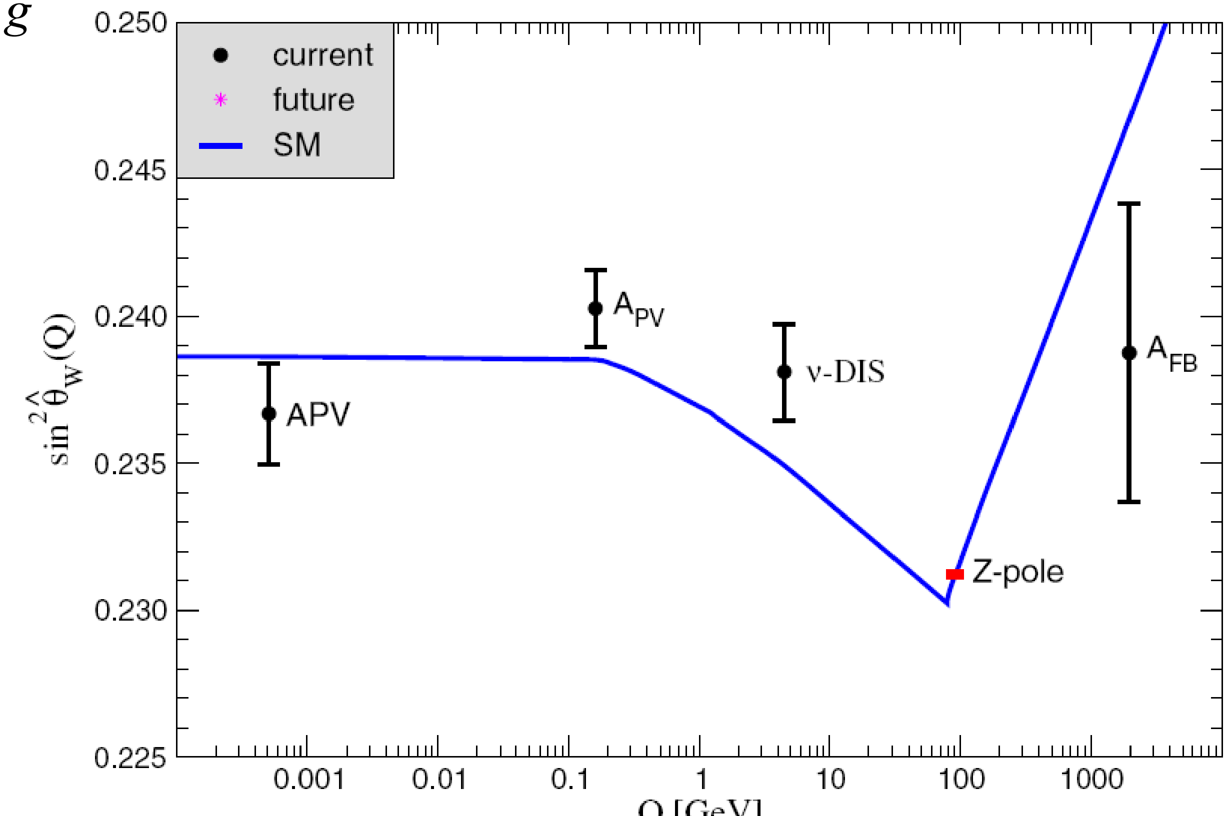
weak charge

$$Q_W = Z(1 - 4\sin^2\theta_W) - N$$
$$= (2Z+N)C_u + (2N+Z)C_d$$

$$M_{fi} \propto g \cdot \frac{1}{Q^2c^2 + M^2C^4} \cdot g$$

W ~ 80 GeV
Z ~ 91 GeV

No evidence of difference from SM



New Physics beyond the Standard Model

M.J. Ramsey-Musolf, Phys.Rev. C **60**, 015501(1999).
Jens Erler, Andriy Kurylov, and Michael J. Ramsey-Musolf, Phys. Rev. D **68**, 016006(2003).

$$\mathcal{L} = \mathcal{L}^{PV}_{S.M.} + \mathcal{L}^{PV}_{NEW}$$

SM $$\mathcal{L}^{\rm PV}_{\rm SM} = -\frac{G_F}{\sqrt{2}} \bar{e}\gamma_\mu\gamma_5 e \sum_q C_{1q}\ \bar{q}\gamma^\mu q$$

New Physics $$\mathcal{L}^{\rm PV}_{NEW} = \frac{g^2}{4\Lambda^2} \bar{e}\gamma_\mu\gamma_5 e \sum_f h^q_V\ \bar{q}\gamma^\mu q,$$

Mass scale

$$\frac{\Lambda}{g} \geq \frac{1}{\sqrt{\sqrt{2}G_F\left|\Delta Q_W\right|}} \approx 4.6\ \mathrm{TeV}$$

$@\ \Delta Q_W / Q_W = 4\ \%$

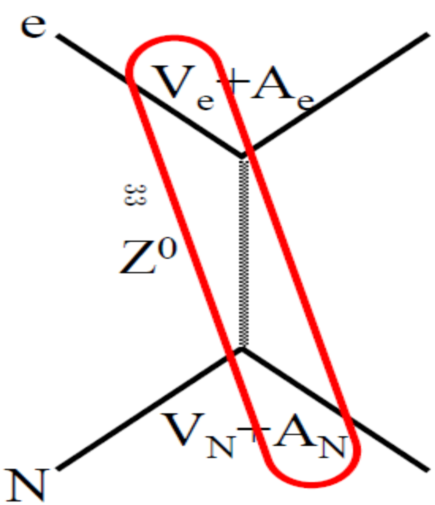
(1) Z' Boson : SO(10), technicolor models to SUSY and E6 (string theories) — g=0.45 -> Λ = 2.1 TeV

(2) technicolor, models of composite fermions, or other strong coupling dynamics — g=2π -> Λ = 29 TeV

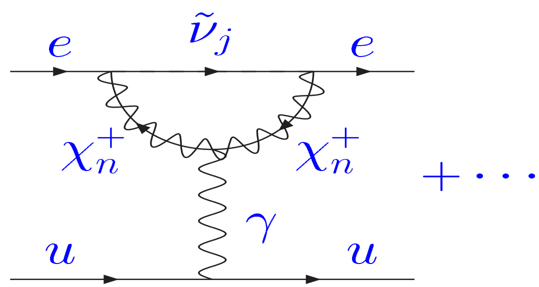
Examples of SUSY loop corrections to Q_W

Jens Erler, Andriy Kurylov, and Michael J. Ramsey-Musolf, Phys. Rev. D **68**, 016006(2003).

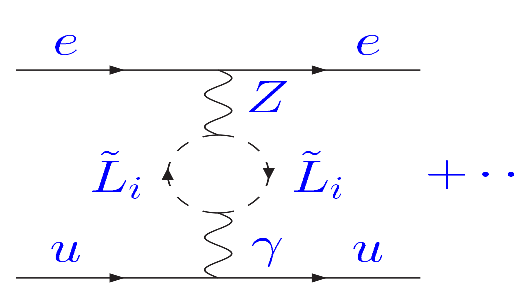
SM



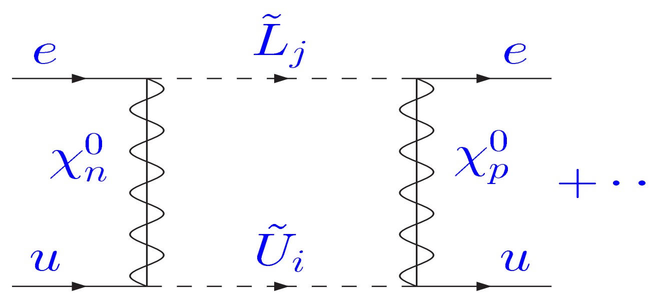
SUSY



(a)



(b)

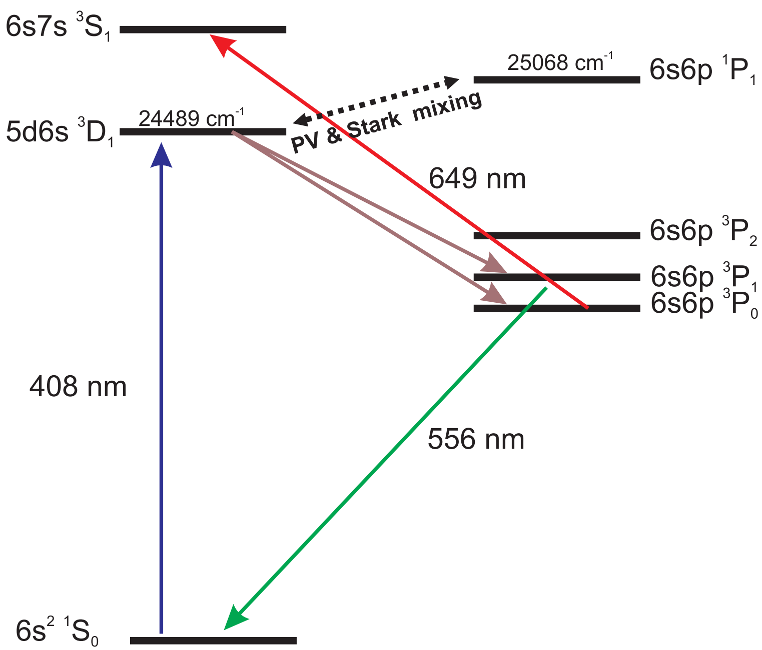


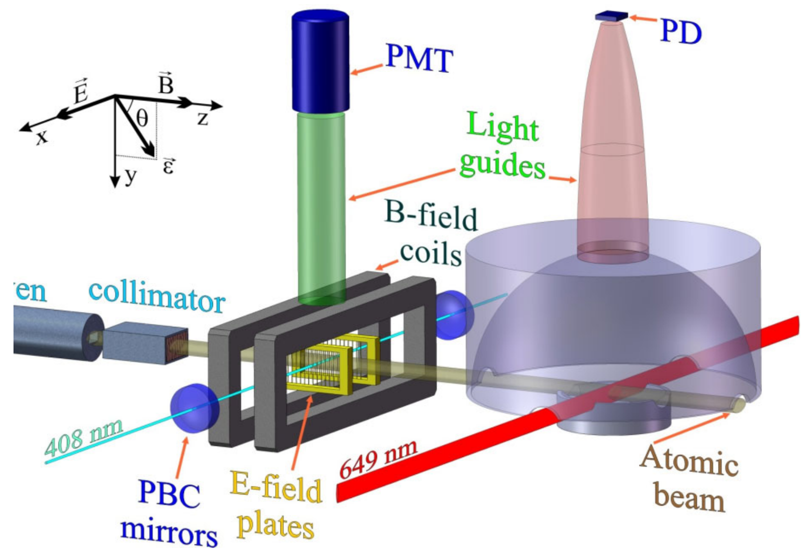
(c)

$$\Delta Q_W \equiv Q_W^{\text{Exp.}} - Q_W^{\text{SM}}$$

Yb atom experiment

K. Tsigutkin, D. Dounas-Frazer, A. Family,
J. E. Stalnaker, V. V. Yashchuk and D. Budker,
Phys. Rev. Lett. **103**, 071601(2009).





$$|\zeta| = 8.7 \pm 1.4 \times 10^{-10} e a_0$$

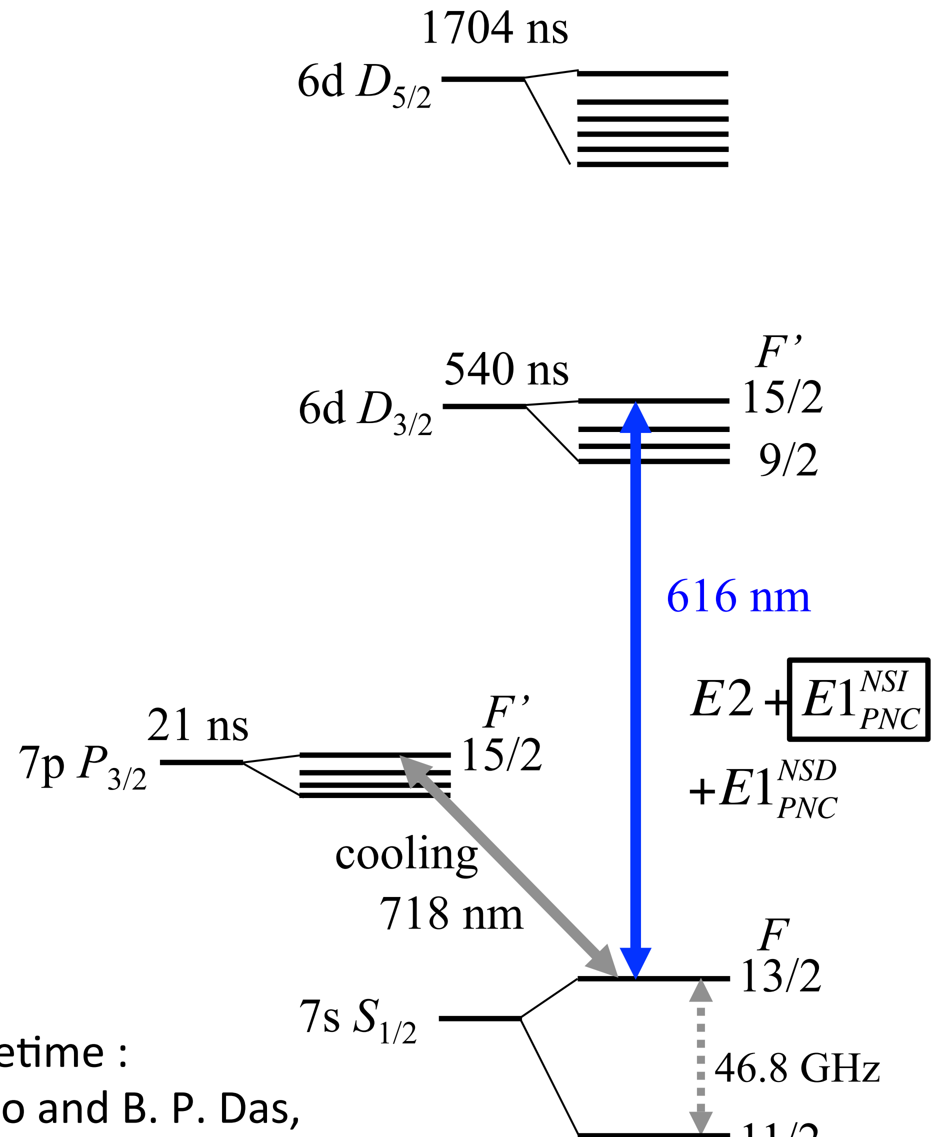
Nuclear Spin Independent (NSI) weak interaction using ^{210}Fr atom

$$H_{PNC}^{NSI} = \frac{G_F}{2\sqrt{2}} \mathcal{Q}_W \gamma_5 \rho_{nuc}(r)$$

NSI PNC-induced E1 amplitude given by

$$E1_{PNC}^{NSI} = (-1)^{J_f - M_f} \begin{pmatrix} J_f & 1 & J_i \\ -M_f & q & M_i \end{pmatrix} \mathcal{X}$$

$$\mathcal{X} = \sum_{k \neq i} \frac{\langle J_f || D || J_k \rangle \langle J_k || H_{PNC}^{NSI} || J_i \rangle}{\sqrt{2J_i + 1}(E_i - E_k)} + \sum_{k \neq f} \frac{\langle J_f || H_{PNC}^{NSI} || J_k \rangle \langle J_k || D || J_i \rangle}{\sqrt{2J_f + 1}(E_f - E_k)}$$



Ref. of Lifetime :
B. K. Sahoo and B. P. Das,
PRA **92**, 052511 (2015)

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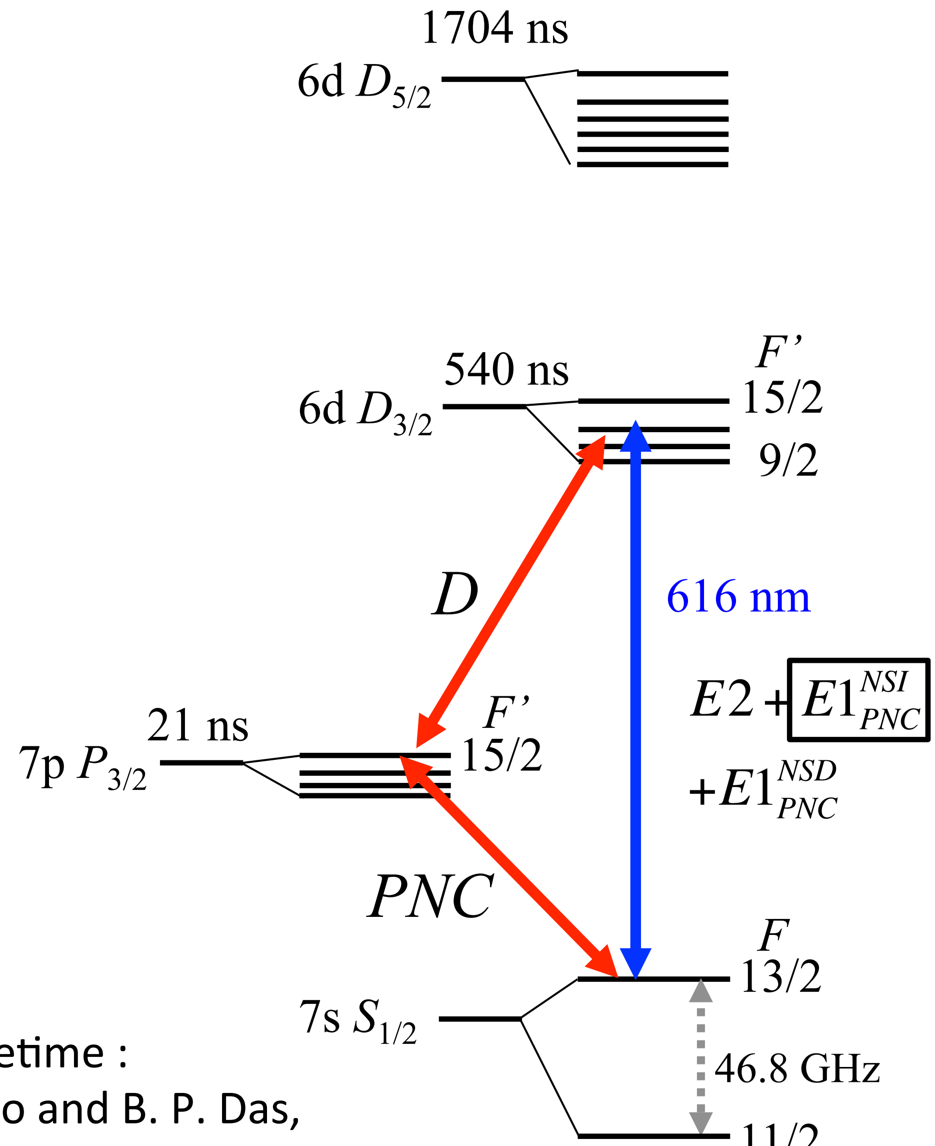

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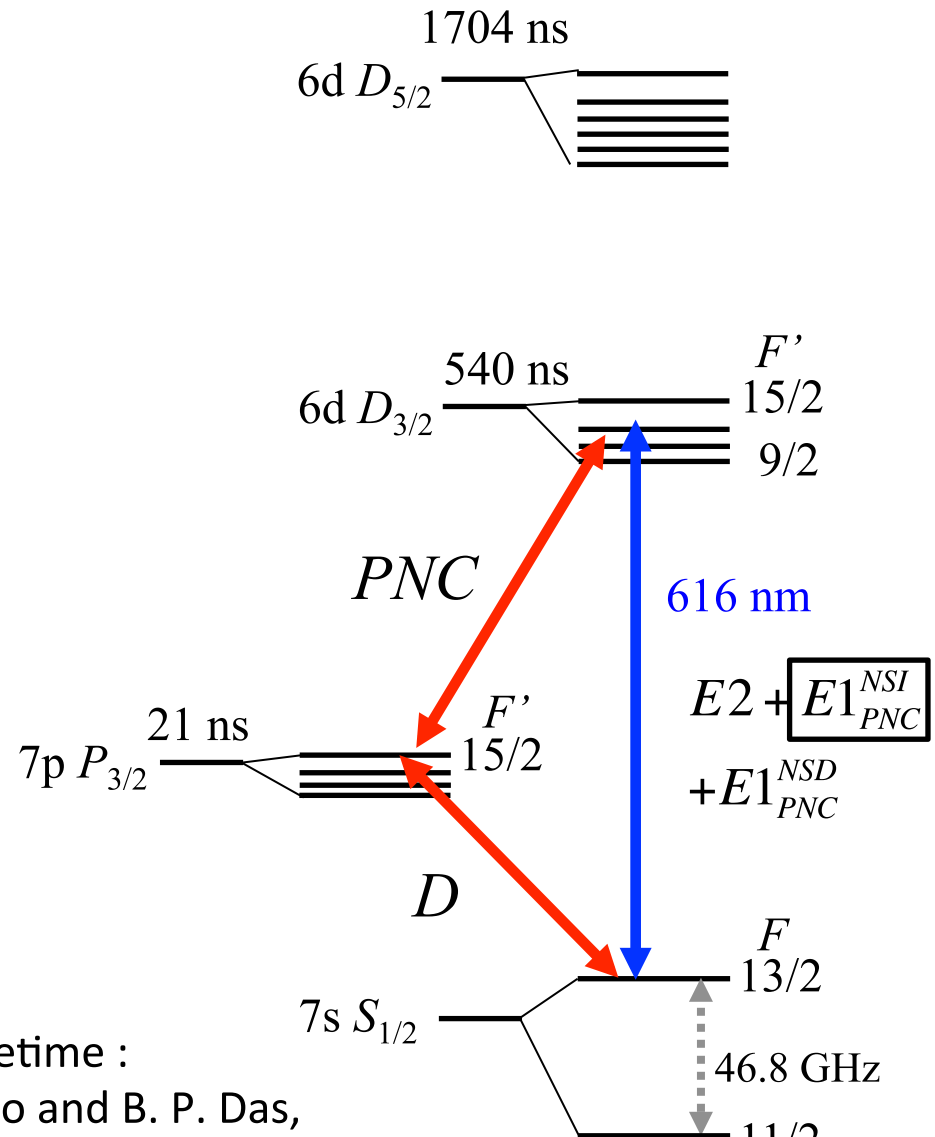


Ref. of Lifetime :
B. K. Sahoo and B. P. Das,
PRA **92**, 052511 (2015)

Matrix element operators of odd parity operators.

J_f state	J_i state	$\langle J_f \| D \| J_i \rangle$	$\langle J_f \| H_{PNC}^{NSI} \| J_i \rangle$	$\langle J_f \| K^1 \| J$
$7p\ ^2P_{1/2}$	$7s\ ^2S_{1/2}$	4.26	10.52	25.03
$8p\ ^2P_{1/2}$	$7s\ ^2S_{1/2}$	0.34	5.98	14.64
$9p\ ^2P_{1/2}$	$7s\ ^2S_{1/2}$	0.11	4.03	9.93
$10p\ ^2P_{1/2}$	$7s\ ^2S_{1/2}$	0.06	2.98	7.39
$11p\ ^2P_{1/2}$	$7s\ ^2S_{1/2}$	0.04	2.38	5.92
$7p\ ^2P_{3/2}$	$7s\ ^2S_{1/2}$	5.96		2.54
$8p\ ^2P_{3/2}$	$7s\ ^2S_{1/2}$	0.95		1.02
$9p\ ^2P_{3/2}$	$7s\ ^2S_{1/2}$	0.44		0.61
$10p\ ^2P_{3/2}$	$7s\ ^2S_{1/2}$	0.28		0.45
$11p\ ^2P_{3/2}$	$7s\ ^2S_{1/2}$	0.18		0.33
$8s\ ^2S_{1/2}$	$7p\ ^2P_{1/2}$	4.27	4.83	12.96
$8s\ ^2S_{1/2}$	$8p\ ^2P_{1/2}$	10.08	2.74	6.60
$8s\ ^2S_{1/2}$	$9p\ ^2P_{1/2}$	1.00	1.85	4.54
$8s\ ^2S_{1/2}$	$10p\ ^2P_{1/2}$	0.41	1.37	3.38
$8s\ ^2S_{1/2}$	$11p\ ^2P_{1/2}$	0.24	1.09	2.71
$8s\ ^2S_{1/2}$	$7p\ ^2P_{3/2}$	7.52		0.73
$8s\ ^2S_{1/2}$	$8p\ ^2P_{3/2}$	13.32		0.60
$8s\ ^2S_{1/2}$	$9p\ ^2P_{3/2}$	2.26		0.36
$8s\ ^2S_{1/2}$	$10p\ ^2P_{3/2}$	1.09		0.26
$8s\ ^2S_{1/2}$	$11p\ ^2P_{3/2}$	0.63		0.18
$6d\ ^2D_{3/2}$	$7p\ ^2P_{1/2}$	7.45		2.60
$6d\ ^2D_{3/2}$	$8p\ ^2P_{1/2}$	2.75		0.48
$6d\ ^2D_{3/2}$	$9p\ ^2P_{1/2}$	0.82		0.22
$6d\ ^2D_{3/2}$	$10p\ ^2P_{1/2}$	0.45		0.14
$6d\ ^2D_{3/2}$	$11p\ ^2P_{1/2}$	0.28		0.09
$6d\ ^2D_{3/2}$	$7p\ ^2P_{3/2}$	3.44	0.23	0.18
$6d\ ^2D_{3/2}$	$8p\ ^2P_{3/2}$	0.88	0.16	0.45
$6d\ ^2D_{3/2}$	$9p\ ^2P_{3/2}$	0.28	0.12	0.35
$6d\ ^2D_{3/2}$	$10p\ ^2P_{3/2}$	0.15	0.09	0.28
$6d\ ^2D_{3/2}$	$11p\ ^2P_{3/2}$	0.09	0.07	0.21
$6d\ ^2D_{5/2}$	$7p\ ^2P_{3/2}$	10.52		5.10
$6d\ ^2D_{5/2}$	$8p\ ^2P_{3/2}$	2.83		2.01
$6d\ ^2D_{5/2}$	$9p\ ^2P_{3/2}$	0.90		1.27
$6d\ ^2D_{5/2}$	$10p\ ^2P_{3/2}$	0.42		0.91
$6d\ ^2D_{5/2}$	$11p\ ^2P_{3/2}$	0.28		0.68

Nuclear Spin Independent (NSI) PNC amplitude ($7S_{1/2}$ to $6D_{3/2}$)

$-iea_0 \times 10^{-11}$

Isotope	$8s\ ^2S_{1/2} \rightarrow 7s\ ^2S_{1/2}$ Main	Core	Final	$6d\ ^2D_{3/2} \rightarrow 7s\ ^2S_{1/2}$ Main	Core	Final
^{210}Fr	13.49	−0.03	13.53	45.31	1.84	47.84
^{211}Fr	13.60	−0.03	14.64	45.68	1.86	47.71
^{223}Fr	14.91	−0.03	14.96	50.10	2.04	52.91

E2 amplitude ($7S_{1/2}$ to $6D_{3/2}$)

$$(E2_{MM'})_{ij} = \left\langle 6D_{3/2}, M' \middle| \frac{e}{6}\left(3x_i x_j - r^2\delta_{ij}\right) \middle| 7S_{1/2}, M \right\rangle$$

The electric quadrupole amplitude ea_0^2

J_f state	J_i state	$\langle J_f, 1/2 \| E2 \| J_i, 1/2 \rangle$
$7p\ ^2P_{3/2}$	$7p\ ^2P_{1/2}$	62.06
$6d\ ^2D_{3/2}$	$7s\ ^2S_{1/2}$	34.06
$6d\ ^2D_{5/2}$	$7s\ ^2S_{1/2}$	41.96
$6d\ ^2D_{5/2}$	$6d\ ^2d_{3/2}$	31.49
$8s\ ^2S_{1/2}$	$6d\ ^2D_{3/2}$	56.83
$8s\ ^2S_{1/2}$	$6d\ ^2D_{3/2}$	72.88
$8s\ ^2S_{1/2}$	$7s\ ^2S_{1/2}$	

Nuclear Spin Dependent (NSD) PNC amplitude
($7S_{1/2}$ to $7S_{1/2}$, $8S_{1/2}$, $6D_{3/2}$, and $6D_{5/2}$)

Contributions to the reduced matrix elements of Y in $iea_0K_W \times 10^{-11}$ from the final perturbed state (Final) and initial perturbed state (Initial) considering intermediate states up to the 11P states in the corresponding transitions of ^{210}Fr, ^{211}Fr, and ^{223}Fr.

			This work				
$J_f \to J_i$	F_f	F_i	Final	Initial	Core	Tail	Total
^{210}Fr ($I = 6$)							
$7s\ ^2S_{1/2} \to 7s\ ^2S_{1/2}$	11/2	13/2	−2.907	−2.414	−0.172	−0.035	−5.529
$8s\ ^2S_{1/2} \to 7s\ ^2S_{1/2}$	11/2	11/2	1.284	−0.545	−0.002	0.008	0.745
	13/2	11/2	2.029	0.893	−0.077	−0.063	1.847
	11/2	13/2	2.321	0.401	−0.077	−0.062	2.026
	13/2	13/2	1.389	−0.589	−0.002	−0.008	0.789
$6d\ ^2D_{3/2} \to 7s\ ^2S_{1/2}$	9/2	11/2	−0.089	3.341	0.127	−0.085	3.294
	11/2	11/2	−0.480	−3.205	−0.118	0.078	−3.725
	13/2	11/2	0.905	2.631	0.093	−0.062	3.568
	11/2	13/2	−0.853	−1.832	−0.063	0.042	−2.706
	13/2	13/2	0.700	2.800	0.102	−0.068	3.531
	15/2	13/2	0.096	−3.622	−0.138	0.092	−3.572
$6d\ ^2D_{5/2} \to 7s\ ^2S_{1/2}$	9/2	11/2	−1.555	0.233	∼0.0	∼0.0	−1.323
	11/2	11/2	1.929	−0.288	∼0.0	∼0.0	1.641
	13/2	11/2	−1.652	0.247	∼0.0	∼0.0	−1.405
	11/2	13/2	−1.209	0.181	∼0.0	∼0.0	−1.028
	13/2	13/2	2.090	−0.312	∼0.0	∼0.0	1.777
	15/2	13/2	−2.503	0.374	∼0.0	∼0.0	−2.129

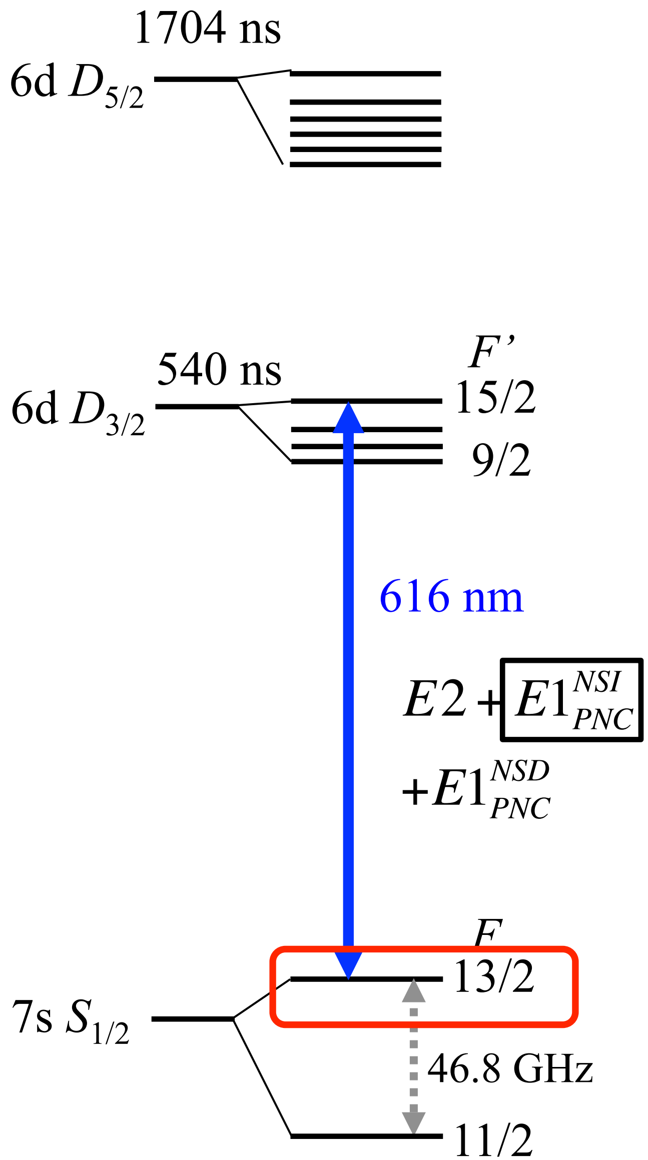
How to detect the E1 NSI PNC amplitude?

$$H_{PNC}^{NSI} = \frac{G_F}{2\sqrt{2}} Q_W \gamma_5 \rho_{nuc}(r)$$

Conventional: (Cs, Yb..)
Detection of the direct transition

Our approach:
Detection of the Light shift induced by the NSI PNS effect.

Original proposal
for NSI PNC of Ba ion
N. Fortson, PRL **70**, 2383(1993).



Light shift induced by interference of E1 PNC and E2 transitions

Original proposal
for NSI PNC of Ba ion
N. Fortson, PRL **70**, 2383(1993).

Laser field

$$E(r,t) = \frac{1}{2} E(r)\left[e^{-i\omega t} + c.c.\right]$$

Rabi frequency

$$\Omega_{MM'}^{PNC} = -\frac{1}{2\hbar}\sum_i \left(E1_{MM'}^{PNC}\right)_i E_i(0)$$

$$\Omega_{MM'}^{E2} = -\frac{1}{2\hbar}\sum_i \left(E2_{MM'}\right)_{ij} \left.\frac{\partial E_i(r)}{\partial x_j}\right|_0$$

$$\left|\Omega_{MM'}\right|^2 = \left|\Omega_{MM'}^{E2} + \Omega_{MM'}^{PNC}\right|^2$$

$$\cong \left|\Omega_{MM'}^{E2}\right|^2 + 2\,\mathrm{Re}\left(\Omega_{MM'}^{PNC*}\Omega_{MM'}^{E2}\right)$$

The light shift (the complex level shift)

$$\alpha_M = \Delta\omega_M - i\,\Gamma_M / 2$$

The field dependent solution to the set of two-level equations connecting M to the various M' sublevels is

$$\alpha_M = \frac{1}{2}\left(\omega_0 - \omega - i\,\Gamma_{6D3/2}\right) \pm \frac{1}{2}\sqrt{\left(\omega_0 - \omega - i\,\Gamma_{6D3/2}\right)^2 + 4\Omega_M^2}$$

$$\Omega_M^2 = \sum_{M'} \left|\Omega_{MM'}\right|^2 \qquad \hbar\omega_0 = W_{6D3/2} - W_{7S1/2}$$

It will be assumed that $\left|\Omega_M\right| \gg \left|\omega_0 - \omega - i\,\Gamma_{6D3/2}\right|$

$$\Delta\omega_M \rightarrow \left(\omega_0 - \omega\right) \pm \Omega_M$$

$$\sqrt{\left|\Omega_M^{E2}\right|^2 + 2\,\mathrm{Re}\left(\Omega_{MM'}^{PNC*}\Omega_{MM'}^{E2}\right)} = \left|\Omega_M^{E2}\right|^2 \sqrt{1 + \frac{2\,\mathrm{Re}\left(\Omega_{MM'}^{PNC*}\Omega_{MM'}^{E2}\right)}{\left|\Omega_M^{E2}\right|^2}}$$

$$\Delta\omega_M^{PNC} \approx -\mathrm{Re}\sum_{M'} \frac{\mathrm{Re}\left(\Omega_{MM'}^{PNC*}\Omega_{MM'}^{E2}\right)}{\left|\Omega_M^{E2}\right|}$$

$$\Delta\omega_M^{E2} \approx \left(\omega_0 - \omega\right)/2 - \Omega_M^{E2}$$

total light shift due to E2 transition

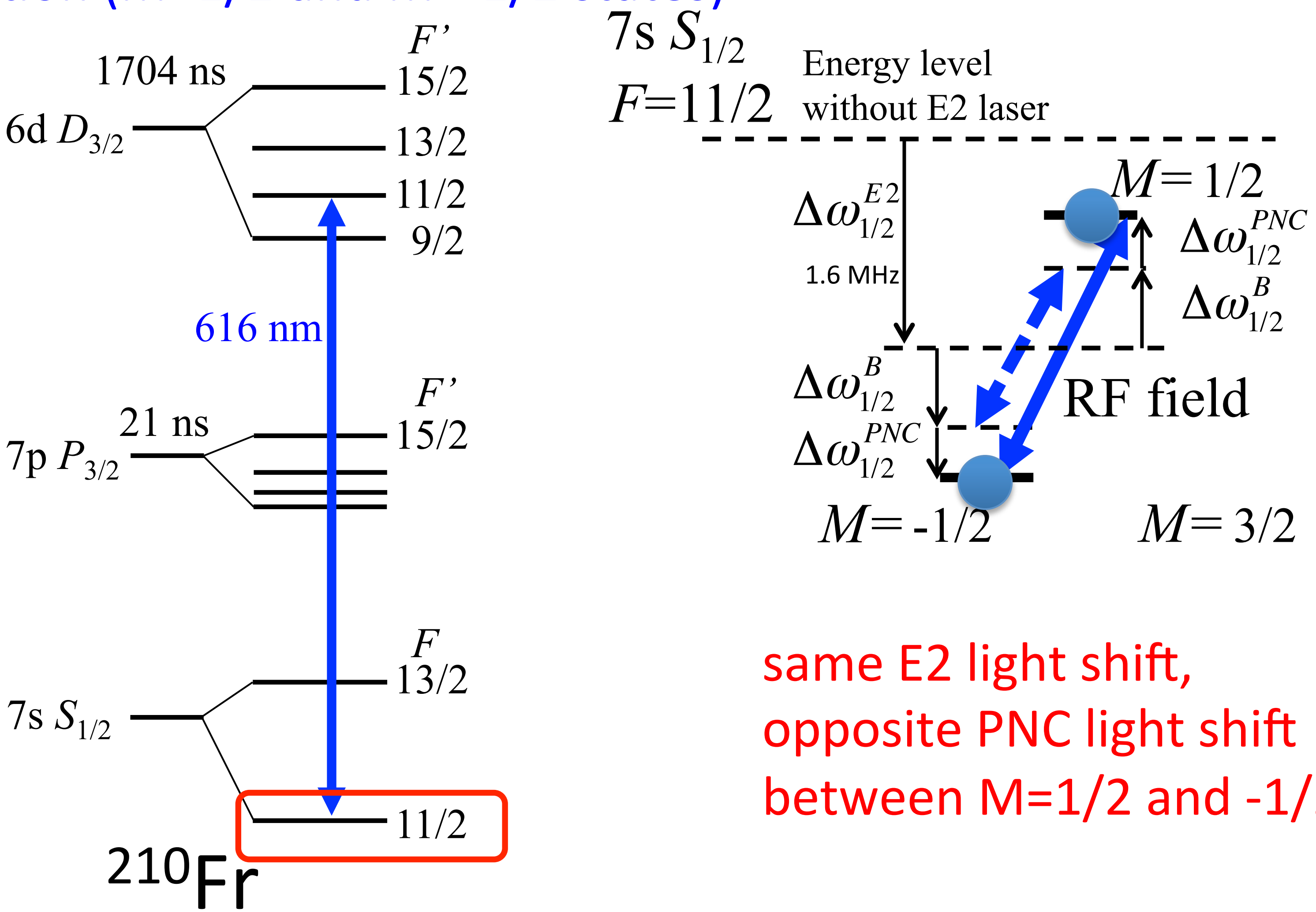
$$\left|\Omega_M^{E2}\right|^2 \equiv \sum_{M'} \left|\Omega_{MM'}^{E2}\right|^2$$

Calculation results of Light shifts

J_f	J_i	F_f	F_i	m_F	$\Delta\omega^{E2}/2\pi$ (MHz)	$\Delta\omega^{NSI}/2\pi$ (Hz)	$\Delta\omega^{NSD}/2\pi$ (mHz)
^{210}Fr (I=6)		9/2	11/2	1/2	3.89	0.217	2.2
		11/2	11/2	1/2	1.64	-4.444	-54.5
6d $D_{3/2}$ -> 7s $S_{1/2}$		13/2	11/2	1/2	6.90	-0.145	-2.2
		11/2	13/2	1/2	8.69	-0.085	-1.2
		13/2	13/2	1/2	1.77	4.126	48.1
		15/2	13/2	1/2	4.99	0.170	1.5

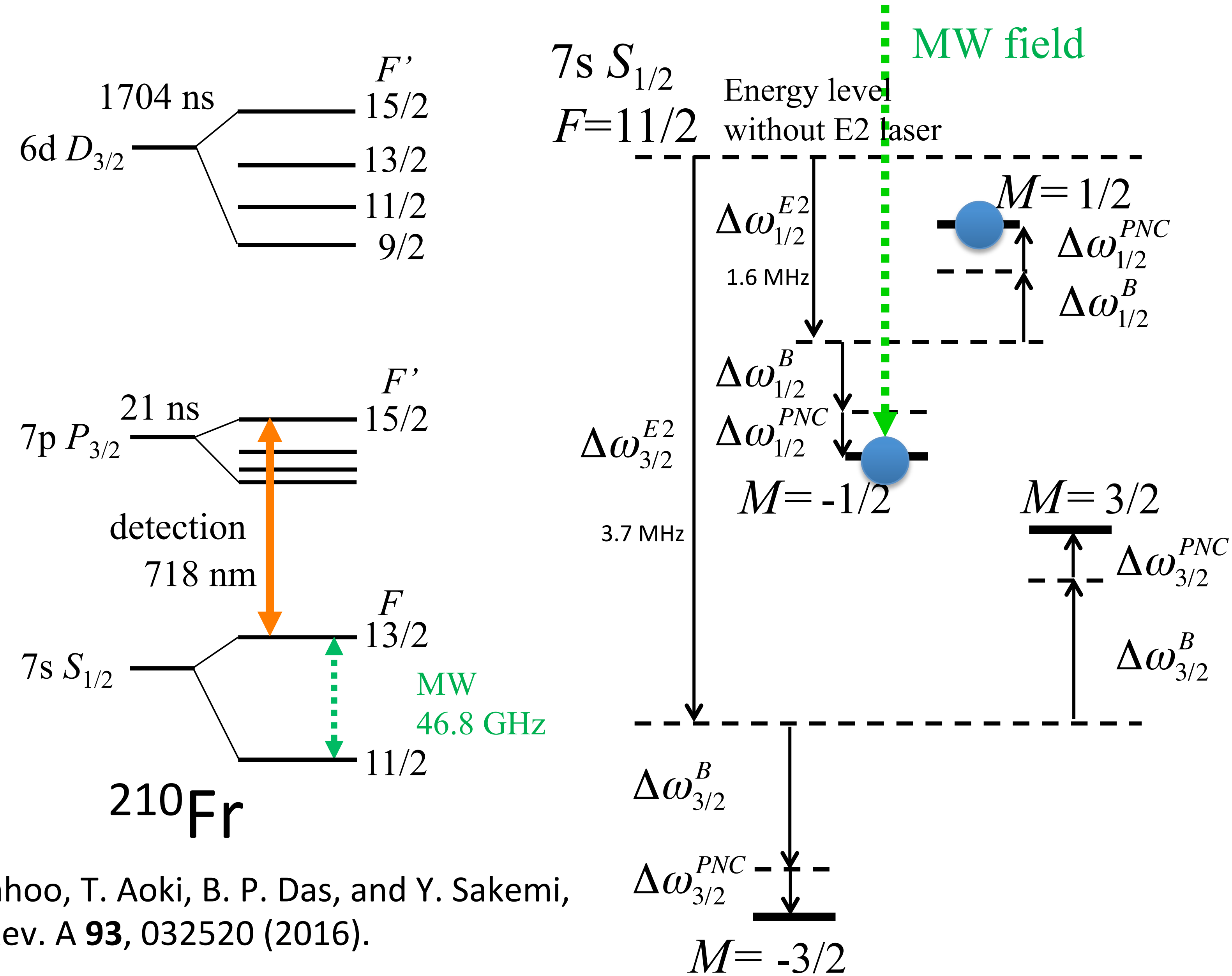
T. Aoki *et al.*, to be submitted.

Measurement method for the Light shift due to F=11/2 to F'=11/2 transition (M=1/2 and M=-1/2 states)



same E2 light shift,
opposite PNC light shift
between M=1/2 and -1/2 state

State selective detection of F=13/2, M=-1/2 state



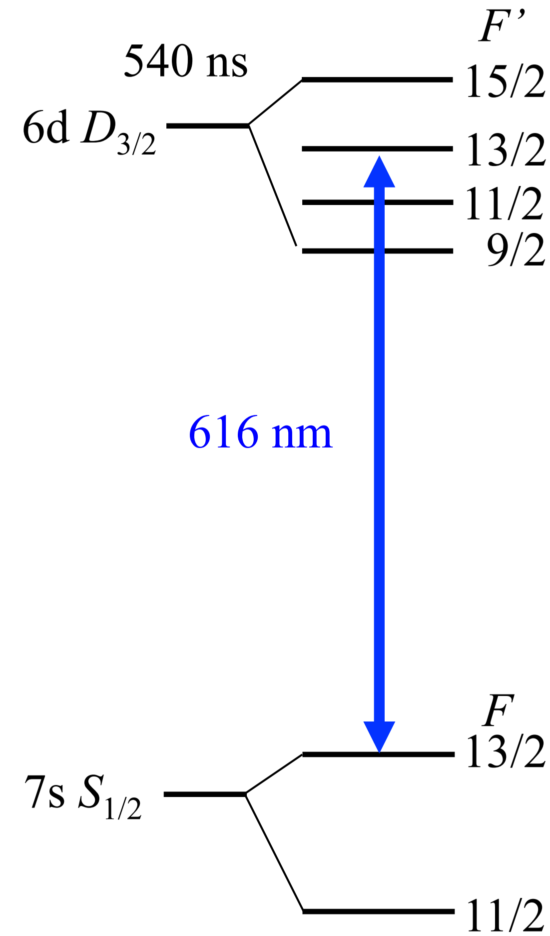
B. K. Sahoo, T. Aoki, B. P. Das, and Y. Sakemi, Phys. Rev. A **93**, 032520 (2016).

Calculation of light shifts for all magnetic sublevels in the F=13/2 state

$E = 2 \times 10^6$ V/m

	F_f	F_i	m_F	$\Delta\omega^{E2}/2\pi$ (MHz)	$\Delta\omega^{NSI}/2\pi$ (Hz)	$\Delta\omega^{NSD}/2\pi$ (mHz)
$\Delta M = \pm 1$	13/2	13/2	1/2	1.77	4.126	48.1
	13/2	13/2	3/2	3.86	5.443	63.4
	13/2	13/2	5/2	5.94	5.382	62.8
	13/2	13/2	7/2	7.62	5.037	58.7
	13/2	13/2	9/2	8.60	4.469	52.1
	13/2	13/2	11/2	8.37	3.608	42.1
	13/2	13/2	13/2	5.54	2.147	25.0
$\Delta M = 0$	13/2	13/2	1/2	6.14	-0.421	-4.9
	13/2	13/2	3/2	5.38	-1.263	-14.7
	13/2	13/2	5/2	3.84	-2.106	-24.6
	13/2	13/2	7/2	1.54	-2.948	-34.4
	13/2	13/2	9/2	1.54	3.790	44.2
	13/2	13/2	11/2	5.38	4.633	54.0
	13/2	13/2	13/2	9.98	5.475	63.8

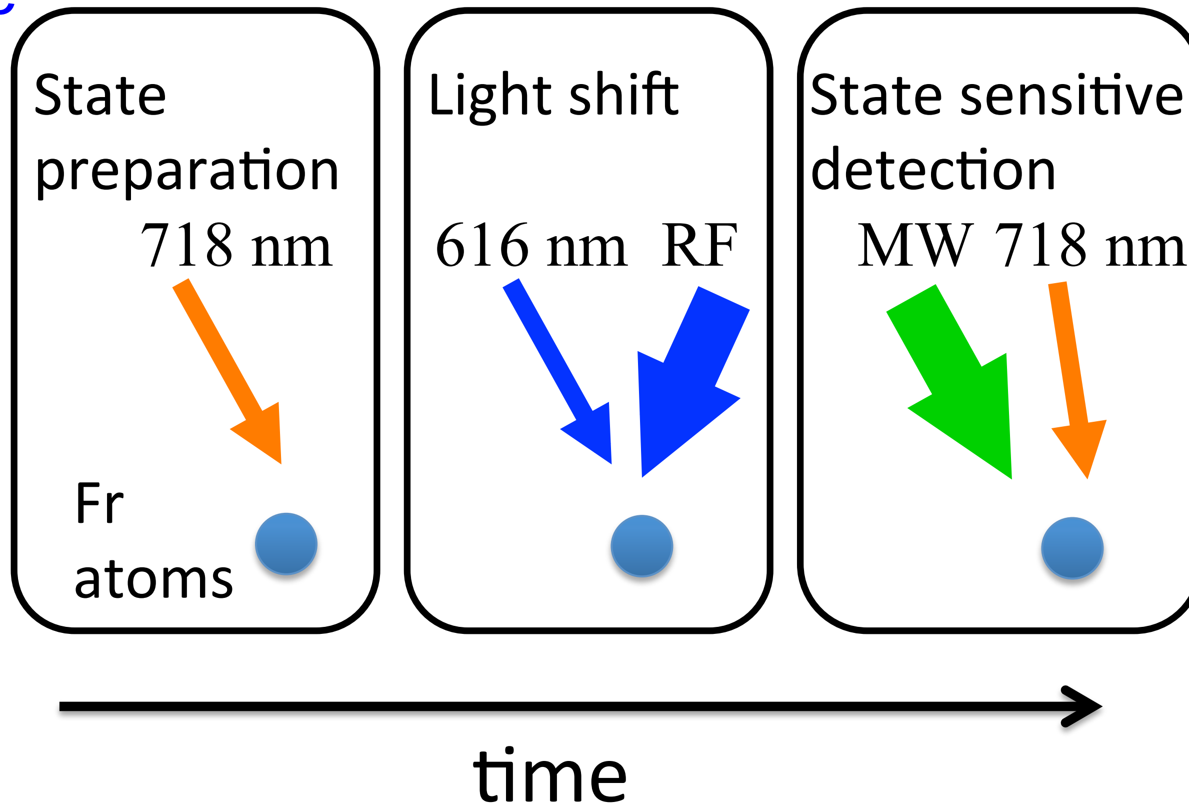
same E2 light shift



T. Aoki *et al.*, to be submitted.

Experimental procedure

Laser Cooling



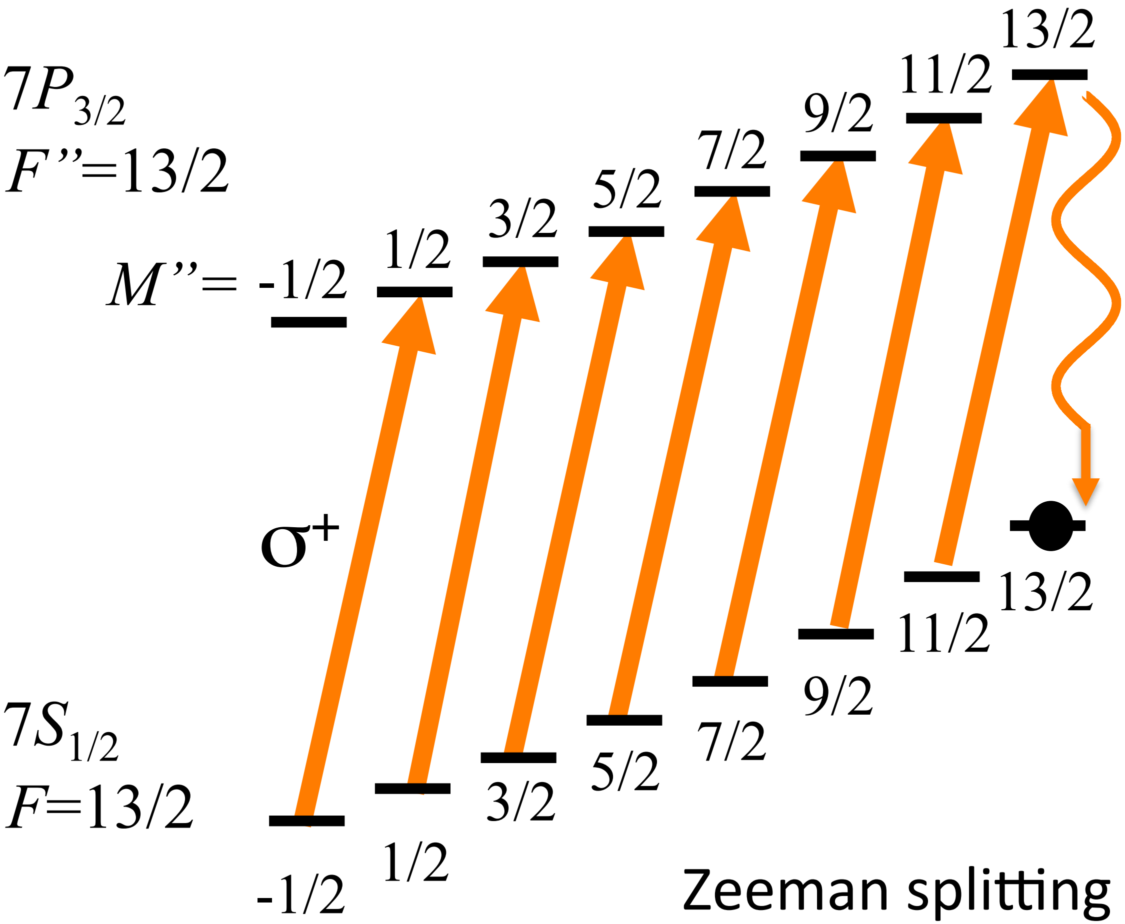
Polarization Gradient Cooling

T = 10-50 μK

Loaded into Optical Lattice

State preparation

Optical pumping to F=13, M=13/2 (Spin Polarized)
under magnetic field

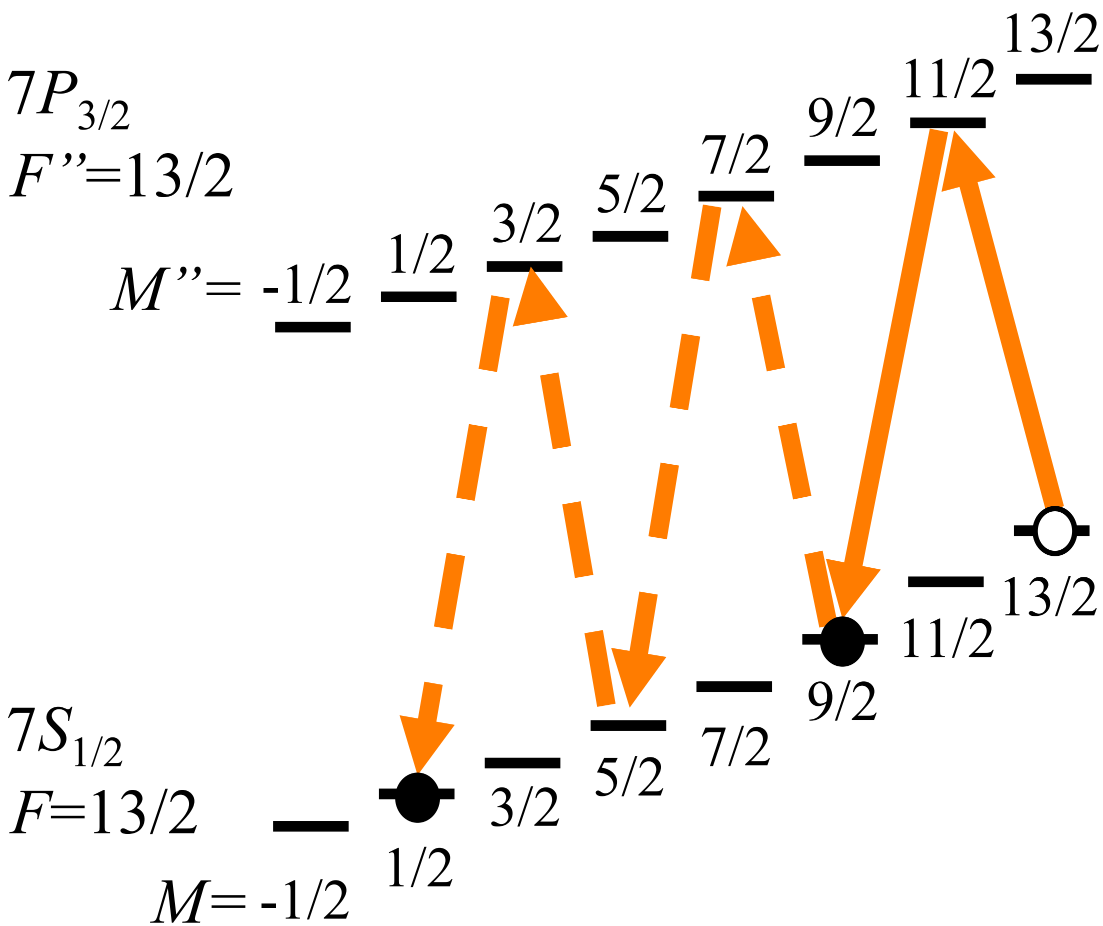


Zeeman splitting of magnetic sublevels
in hyperfine structure

+ repumping beams

State preparation

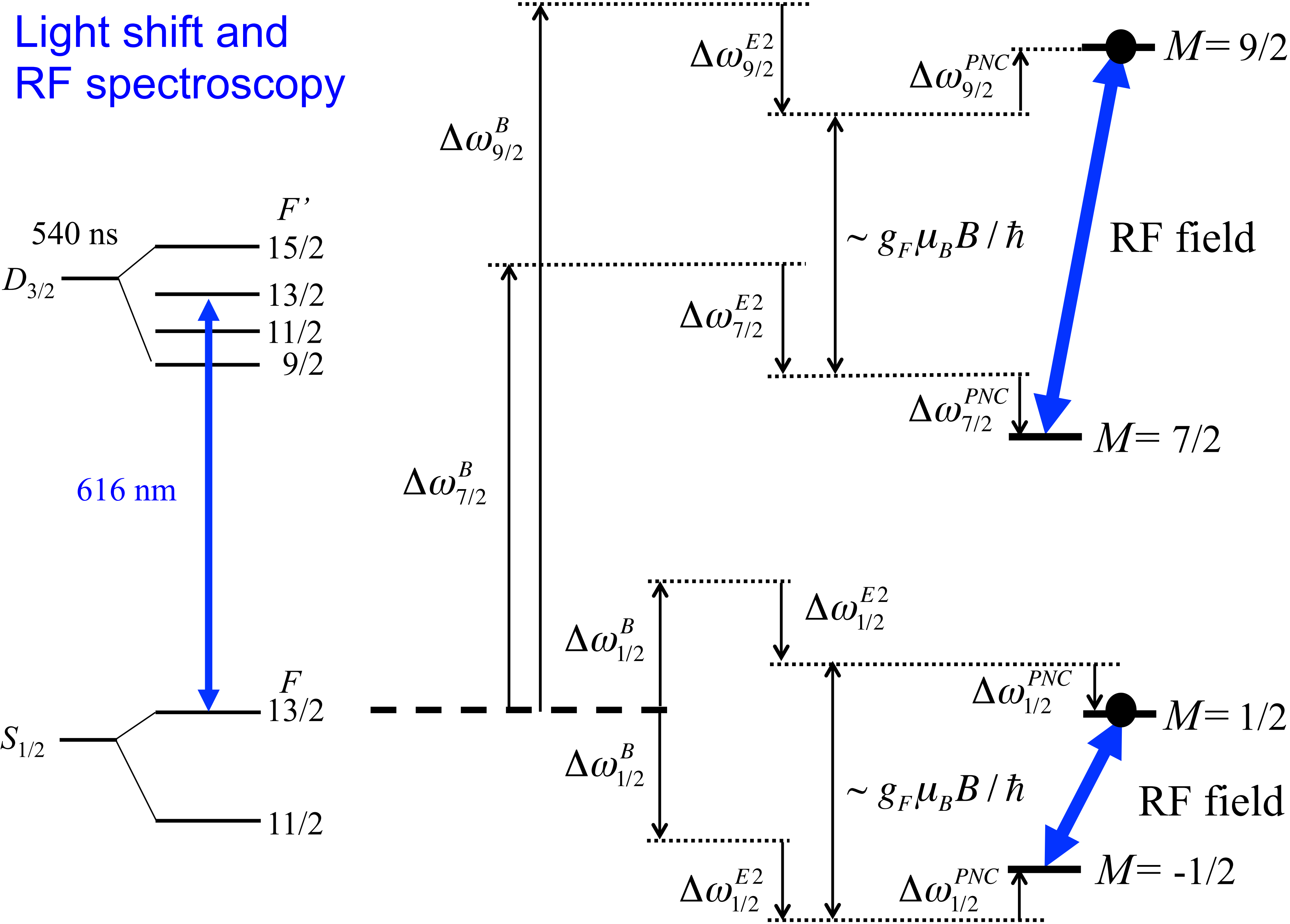
STIRAP process to prepare the atom in M=9/2 and 1/2 state



Stimulated Raman Adiabatic Passage (STIRAP)

M. Weitz, B. C. Young, and S. Chu, Phys. Rev. A **50**, 2438 (1994).
T. Nakajima, Phys. Rev. A **59**, 559 (1999).

Light shift and RF spectroscopy



1st order Zeeman shift is cancelled

2nd order Zeeman shift is reduced

$$\delta\omega = \delta\omega_{\frac{1}{2},-\frac{1}{2}} - \delta\omega_{\frac{9}{2}\frac{7}{2}}$$

$$= \boxed{-7580\ (\mathrm{NSI})} + \ 1\,073\,090\ \ (\mathrm{Zeeman@}\ 11.62\ \mathrm{G}) + \ 21\left(\frac{\delta B}{0.1162\ \mathrm{mG}}\right)\ \mathrm{mHz}$$

$$-88.4\ (\mathrm{NSD})$$

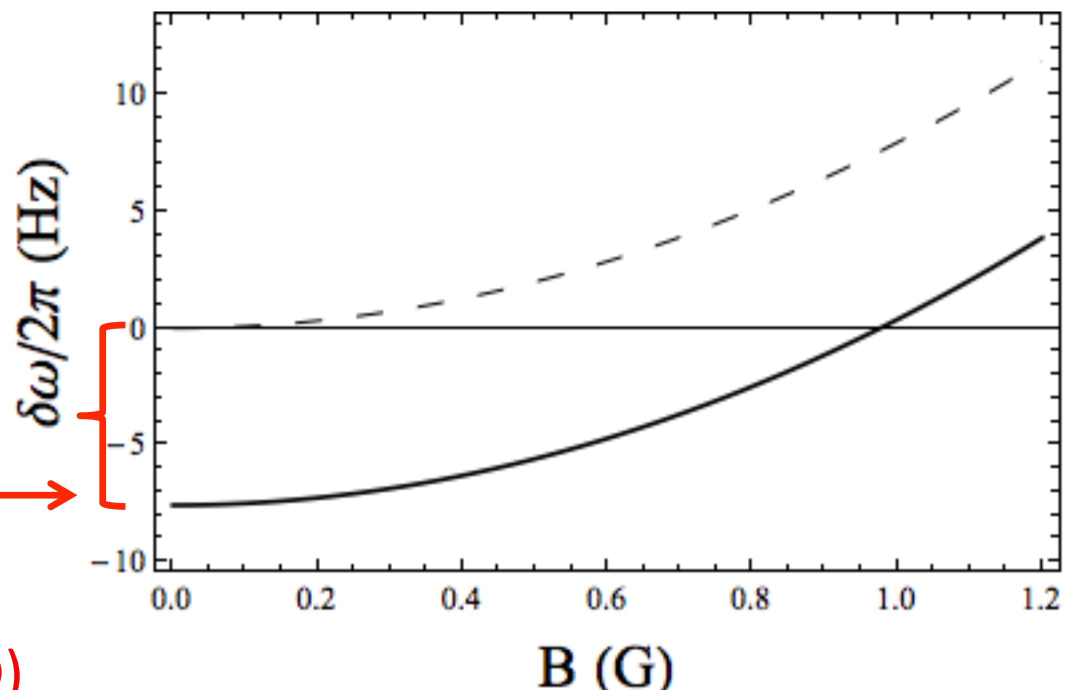
Magnetic shield of 1/3000

Breit-Rabi formula

$$\hbar\Delta\omega^{B} = -\frac{h\Delta\nu}{2(2I+1)} - g^{I}\mu_{\mathrm{B}}BM \pm \frac{h\Delta\nu}{2}\sqrt{1+\frac{4M}{2I+1}x+x^{2}}$$

$$x \equiv (g_J + g_I)\frac{\mu_{\mathrm{B}}B}{h\Delta\nu}, \qquad \Delta\nu \equiv A(I+1/2)$$

Dependence of magnetic field



PNC induced light shift

-7.580 Hz (NSI)

-0.088 Hz (NSD)

Estimation of measurement time

[1] B. K. Sahoo et al., PRA 83, 030502(R) (2011).

shot noise limit $\delta\nu = \dfrac{1}{2\pi\sqrt{\tau N T}}$

$\tau = 540$ ns
$N = 10^4$ → $T = 2\text{x}10^4$ s
0.015 Hz

↑

$\Delta Q_W / Q_W = 0.2\,\%$

Atom	$\delta\omega_{\mathrm{NSI}}$ (Hz)	
Ba+	-0.47	[1]
Ra+	9.97	[1]
Fr	-7.580	this work

insensitive to magnetic fluctuation

Our scheme

Mass scale

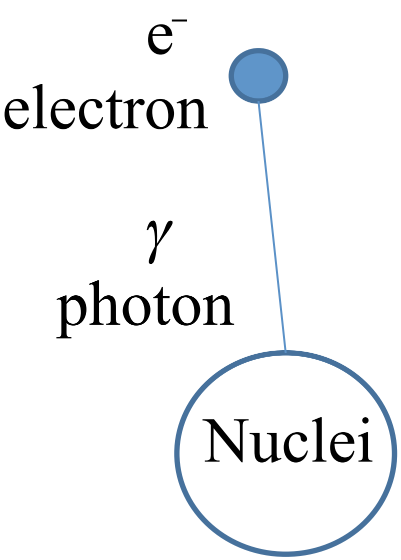
$$\frac{\Lambda}{g} \geq \frac{1}{\sqrt{\sqrt{2}G_F\left|\Delta Q_W\right|}} \approx 20.6\ \mathrm{TeV}$$

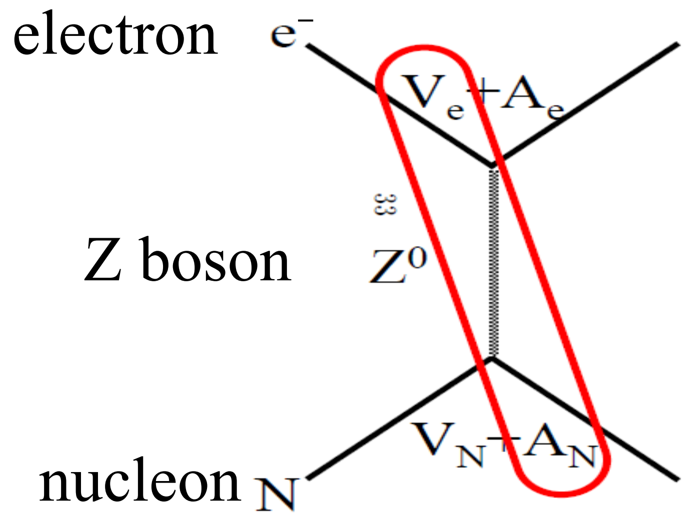
Contents

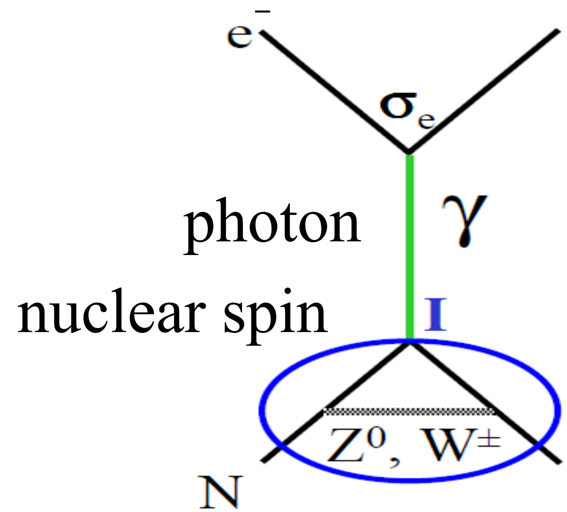
Weak interaction in atom

Laser induced transition ➡ Excitation of electron’s energy

Parity Nonconservation (PNC) in atom







electromagnetic force (Coulomb's law)

①Weak Neutral Current (nuclear spin independent)

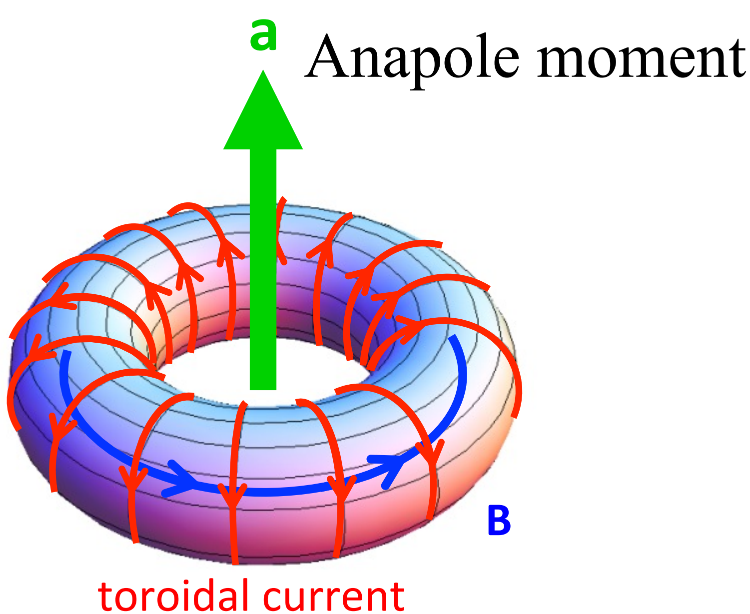
②Anapole moment (nuclear spin dependent)

②Anapole moment

Anapole moment

$$\mathbf{a} = -\pi \int d^3 r r^2 \mathbf{J}(\mathbf{r})$$

electromagnetic current density



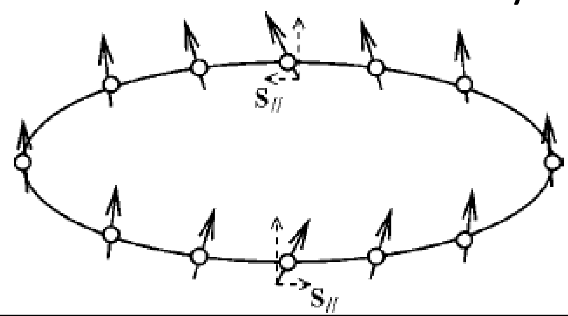
NSD Weak interaction

$$\hat{W} = \frac{G}{2\sqrt{2}m_p} g[\boldsymbol{\sigma}\cdot\mathbf{p}\rho(r) + \rho(r)\boldsymbol{\sigma}\cdot\mathbf{p}]$$

perturbed wave function of nucleon

$$\psi = \mathrm{e}^{i\theta\boldsymbol{\sigma}\cdot\mathbf{r}}\psi_0 \qquad \theta = -gG\rho/\sqrt{2}$$

spin of the unperturbed wave function will be rotated around the vector r by an angle of 2θr.



I : Nuclear Spin

$$\mathbf{a} = \frac{1}{e}\frac{G}{\sqrt{2}}\frac{(I+1/2)}{I(I+1)}\kappa_a \boldsymbol{I}$$

Atom with nuclear spin involves the nuclear anapole moment

J.S.M. Ginges, V.V. Flambaum, Physics Reports **397**, 63 (2004).

Cs experiment

C. S. Wood, S. C. Bennett, D. Cho, B. P. Masterson, J. L. Roberts, C. E. Tanner, and C. E. Wieman, Science **275**, 1759 (1997).

6S – 7S transition

Nuclear Spin Independent (NSI)

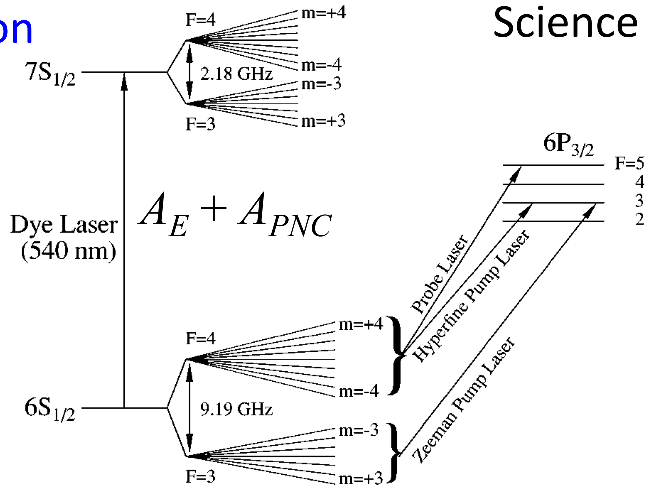
$$H_W^{\mathrm{s.i.}} = \frac{G_F}{2\sqrt{2}} Q_W \gamma_5 \rho(\vec{r})$$

$Q_W = Z(1 - 4\sin^2\theta_W) - N \sim -N$

weak charge

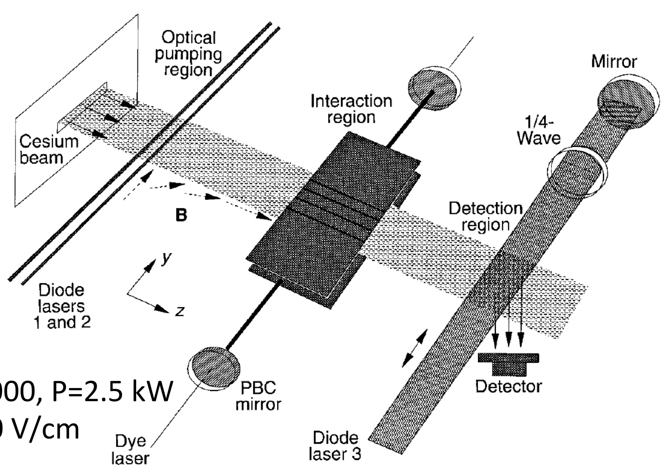
Nuclear Spin dependent (NSD)

$$H_W^{\mathrm{s.d.}} = \frac{G_F}{\sqrt{2}} \kappa \vec{\alpha} \cdot \vec{I} \rho(\vec{r})$$



A_E: “Stark-induced” $E1$ transition amplitude

Fig. 2. Schematic of the apparatus. In the interaction region, **B** is along the *z* axis, **E** is along the *x* axis, and the 540-nm dye laser beam defines the *y* axis.



F=100,000, P=2.5 kW

E_x = 500 V/cm

$$\epsilon_z \hat{z} + pi\ \mathrm{Im}(\epsilon_x)\,\hat{x}$$

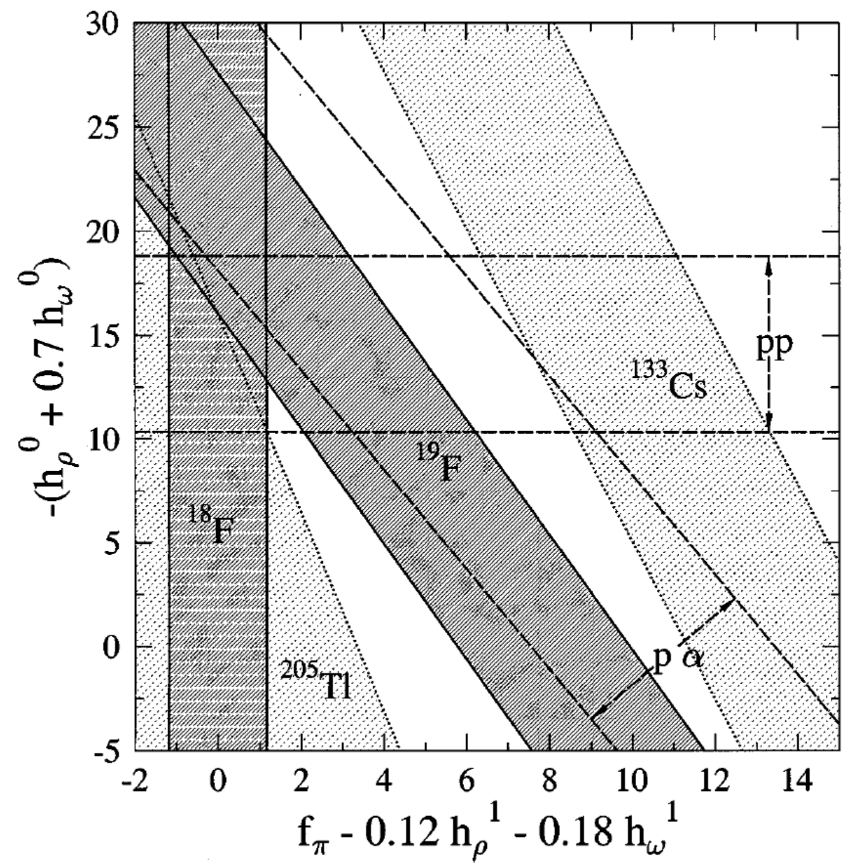
$$R = |A_E + A_{\mathrm{PNC}}|^2 \sim \beta^2 E_x^2 \epsilon_x^2 C_1(F, m_F; F', m'_F) + 4\beta E_x \epsilon_x p \mathrm{Im}(\epsilon_x) \mathrm{Im}(E1_{\mathrm{PNC}}) C_2(F, m_F; F', m'_F)$$

β: tensor transition polarizability

$$\kappa(^{133}\mathrm{Cs}) = 0.112 \pm 0.016$$

$$\mathrm{Im}(E1^{\mathrm{s.d.}}_{\mathrm{PNC}})/\beta = 0.077 \pm 0.011\ \mathrm{mV/cm}$$

Constraints on the PNC meson couplings (x10^7)



W. C. Haxton and C. E. Wieman, Annu. Rev. Nucl. Part. Sci. **51**, 261(2001).

Nuclear Spin Dependent (NSD) weak interaction

$$H_{\rm PNC}^{\rm NSD} = \frac{G_F}{\sqrt{2}} \mathcal{K}_W \boldsymbol{\alpha} \cdot \mathbf{I}\, \rho_{\rm nuc}(r) \longrightarrow H_{\rm PNC}^{\rm NSD} = \frac{1}{|I|} \sum_q (-1)^q I_q^1 K_{-q}^1$$

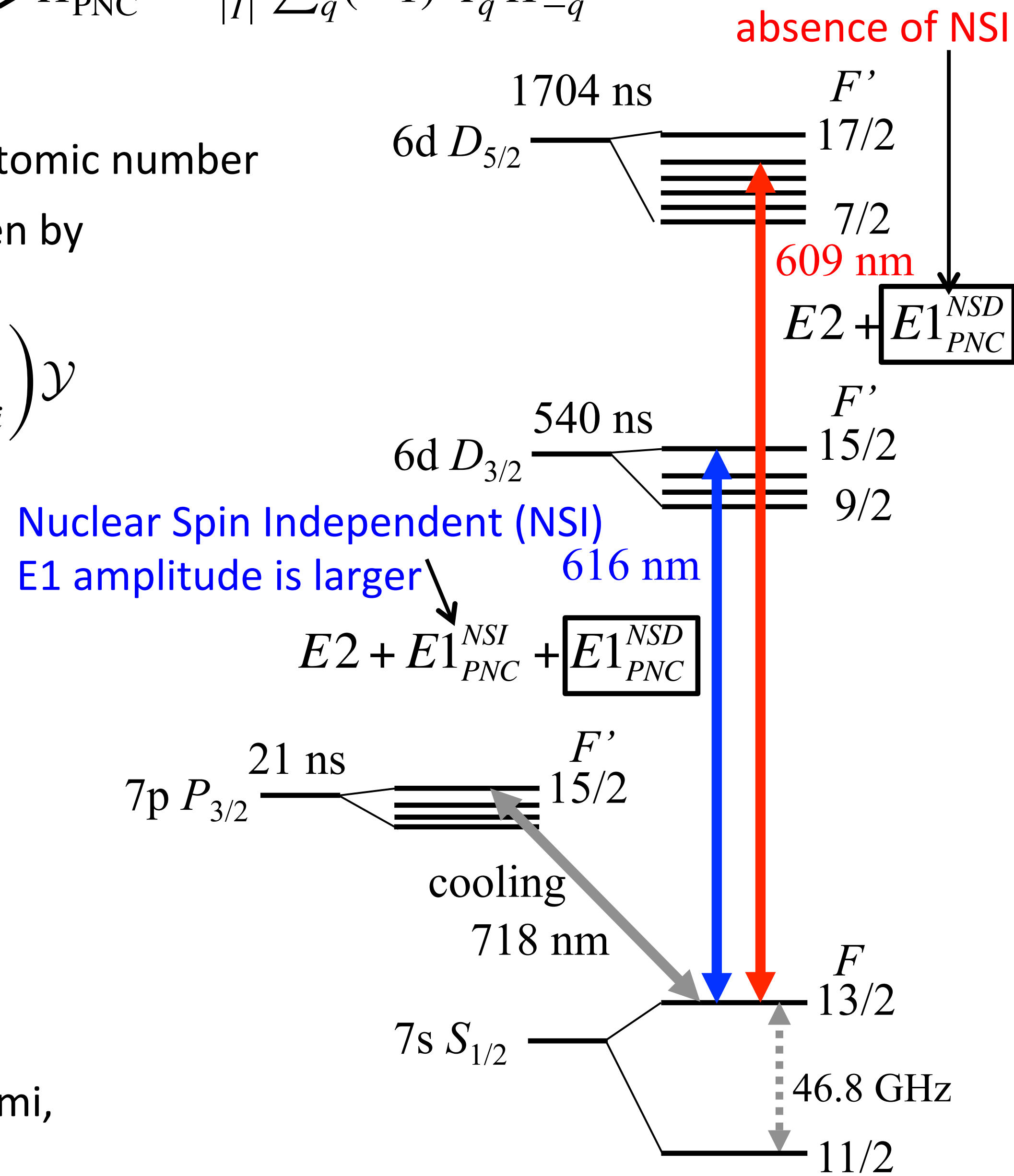
$$\mathcal{K}_W \approx \frac{9}{10} g_p \mu_p \frac{\alpha A^{2/3}}{M_p r_0}$$

A: the atomic number

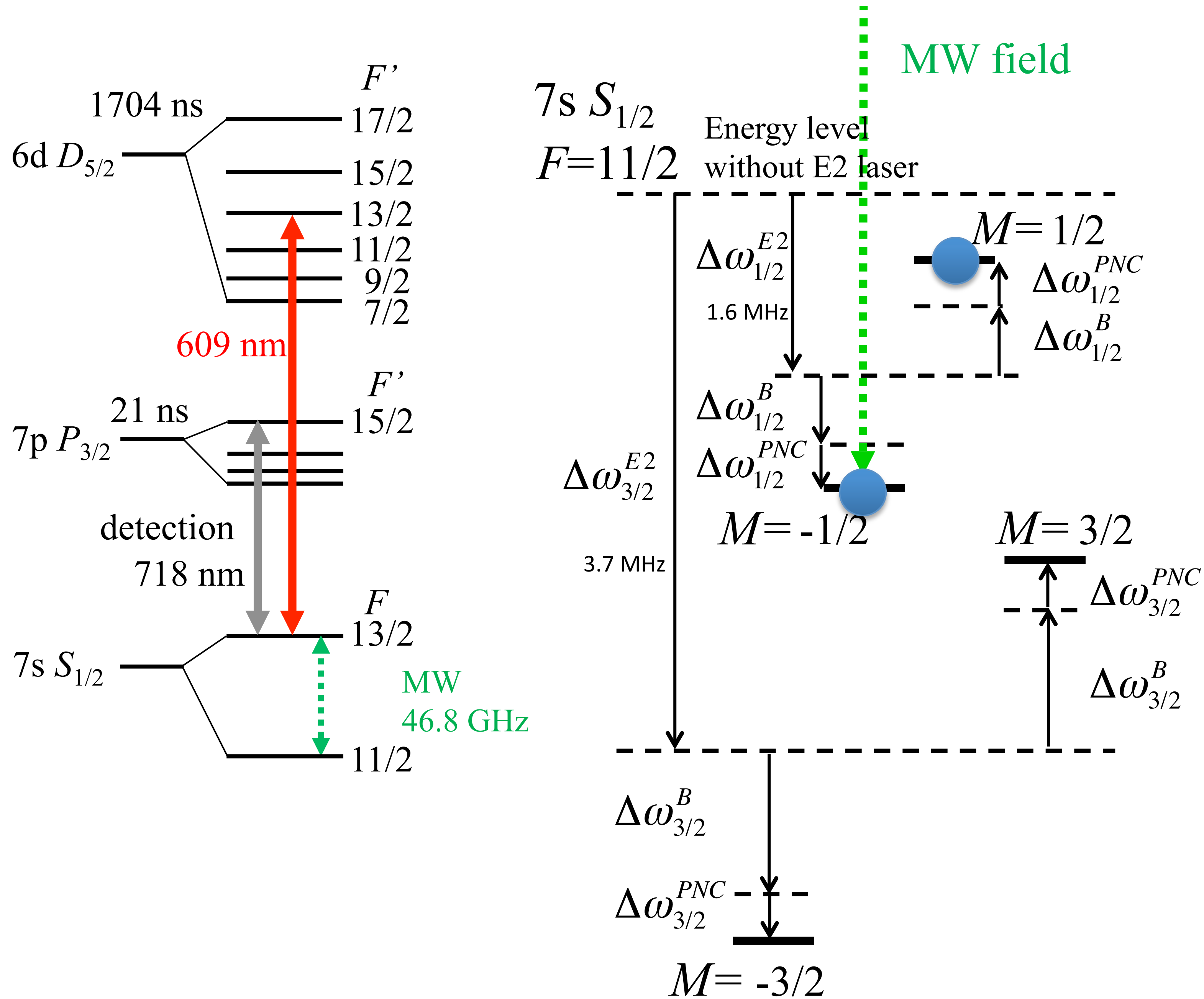
A small NSD PNC-induced E1 amplitude given by

$$E1_{M_f M_i}^{\rm PNC} = (-1)^{F_f - M_f} \begin{pmatrix} F_f & 1 & F_i \\ -M_f & q & M_i \end{pmatrix} \mathcal{Y}$$

$$\mathcal{Y} = \eta \left(\sum_{k \neq i} (-1)^{j_i - j_f + 1} \frac{\langle J_f || D || J_k \rangle \langle J_k || K^1 || J_i \rangle}{E_i - E_k} \times \begin{Bmatrix} F_f & F_i & 1 \\ J_k & J_f & I \end{Bmatrix} \begin{Bmatrix} I & I & 1 \\ J_k & J_i & F_i \end{Bmatrix} + \sum_{k \neq f} (-1)^{F_i - F_f + 1} \frac{\langle J_f || K^1 || J_k \rangle \langle J_k || D || J_i \rangle}{E_f - E_k} \times \begin{Bmatrix} F_f & F_i & 1 \\ J_i & J_k & I \end{Bmatrix} \begin{Bmatrix} I & I & 1 \\ J_k & J_f & F_f \end{Bmatrix} \right),$$



B. K. Sahoo, T. Aoki, B. P. Das, and Y. Sakemi,
Phys. Rev. A **93**, 032520 (2016).



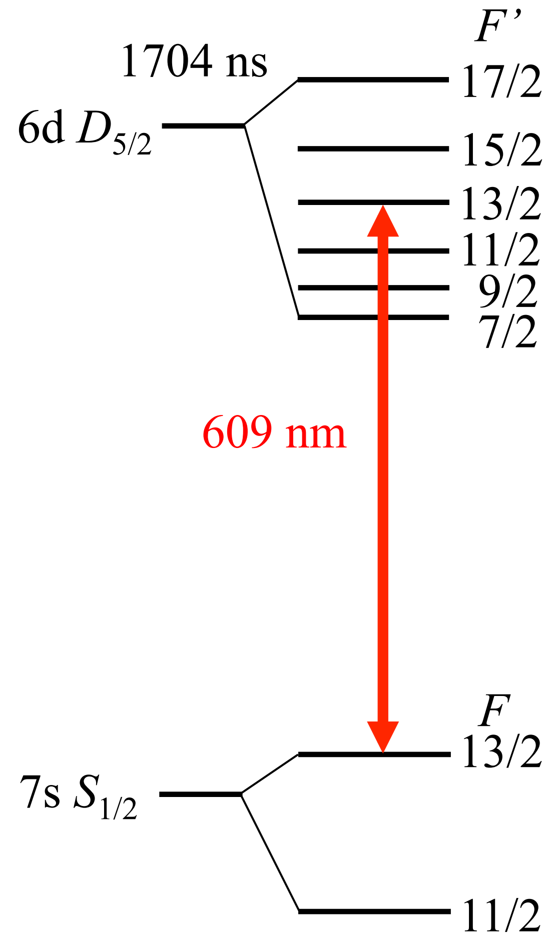
F'
1704 ns
17/2
6d $D_{5/2}$
15/2
13/2
11/2
9/2
7/2
609 nm
F'
21 ns
15/2
7p $P_{3/2}$
detection
718 nm
F
13/2
7s $S_{1/2}$
MW
46.8 GHz
11/2
MW field
7s $S_{1/2}$
F=11/2
Energy level
without E2 laser
M= 1/2
$\Delta\omega_{1/2}^{E2}$
1.6 MHz
$\Delta\omega_{1/2}^{PNC}$
$\Delta\omega_{1/2}^{B}$
$\Delta\omega_{1/2}^{B}$
$\Delta\omega_{1/2}^{PNC}$
$\Delta\omega_{3/2}^{E2}$
M= -1/2
M= 3/2
3.7 MHz
$\Delta\omega_{3/2}^{PNC}$
$\Delta\omega_{3/2}^{B}$
$\Delta\omega_{3/2}^{B}$
$\Delta\omega_{3/2}^{PNC}$
M= -3/2

Calculation of light shifts for all magnetic sublevels in the F=13/2 state

E=2 × 10^6 V/m, $K_W \approx 0.568$, E2 = 39.33 ea_0^2

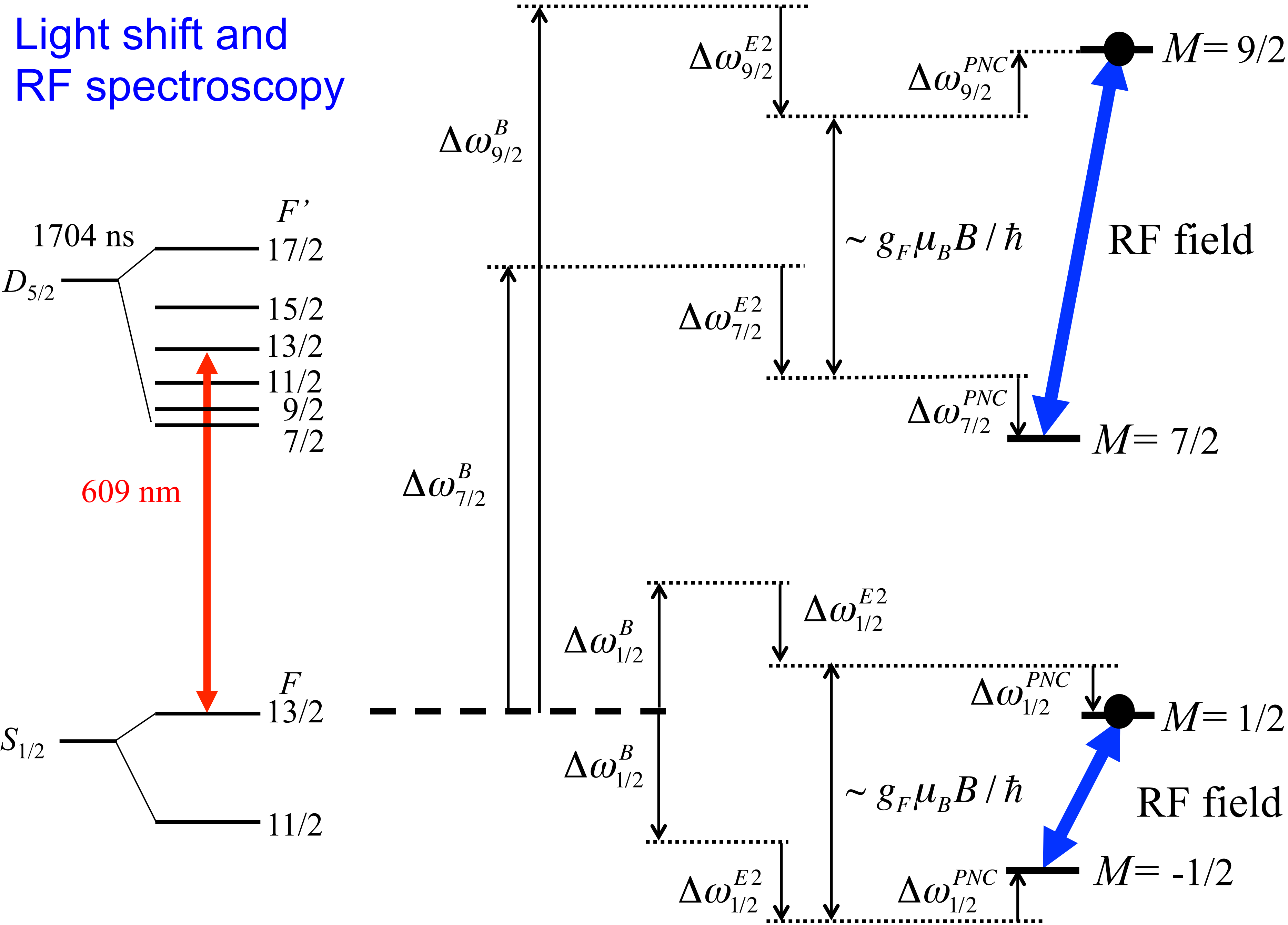
	F_f	F_i	m_F	$\Delta\omega^{E2}/2\pi$ (MHz)	$\Delta\omega^{NSI}/2\pi$ (Hz)	$\Delta\omega^{NSD}/2\pi$ (mHz)
$\Delta M = \pm 1$	13/2	13/2	1/2	1.70	0	24.22
	13/2	13/2	3/2	3.70	0	31.95
	13/2	13/2	5/2	5.70	0	31.59
	13/2	13/2	7/2	7.30	0	29.56
	13/2	13/2	9/2	8.23	0	26.23
	13/2	13/2	11/2	8.01	0	21.18
	13/2	13/2	13/2	5.30	0	12.60
$\Delta M = 0$	13/2	13/2	1/2	5.88	0	-2.41
	13/2	13/2	3/2	5.15	0	-7.41
	13/2	13/2	5/2	3.68	0	-12.36
	13/2	13/2	7/2	1.47	0	-17.30
	13/2	13/2	9/2	1.47	0	22.24
	13/2	13/2	11/2	5.15	0	27.19
	13/2	13/2	13/2	9.56	0	32.13

same E2 light shift



T. Aoki *et al.*,
Asian J. Phys. (accepted)

Light shift and RF spectroscopy



1st order Zeeman shift is cancelled

2nd order Zeeman shift is reduced

$$\delta\omega = \delta\omega_{\frac{1}{2},-\frac{1}{2}} - \delta\omega_{\frac{9}{2},\frac{7}{2}}$$

$$= -44.5\ (\mathrm{NSD}) + 1\ 414\ 0700\ (\mathrm{Zeeman@13.34\ G}) + 21\ \left(\frac{\delta B}{0.1334\ \mathrm{mG}}\right)\ \mathrm{mHz}$$

Magnetic shield of 1/3000

Breit-Rabi formula

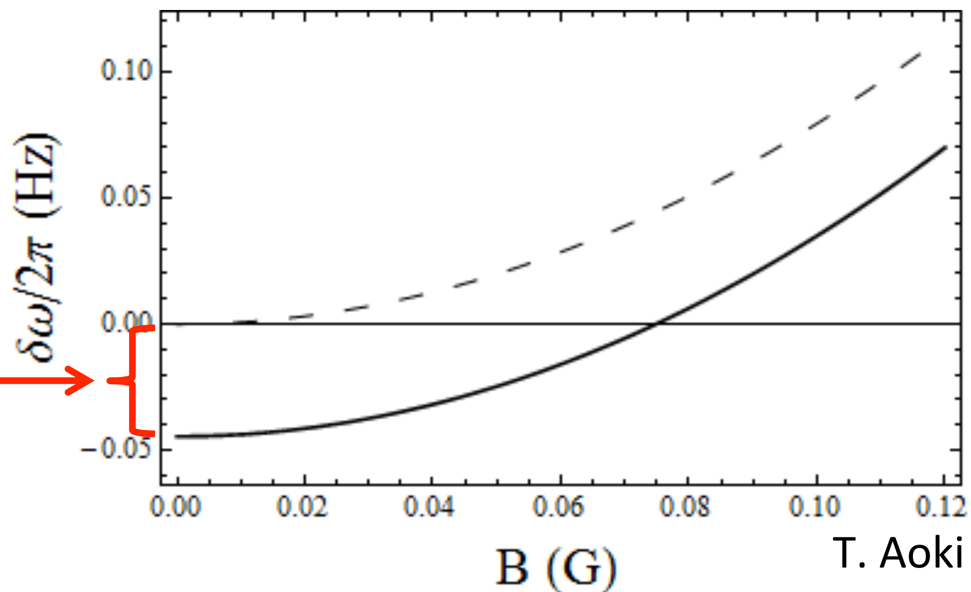
$$\hbar\Delta\omega^{B} = -\frac{h\Delta\nu}{2(2I+1)} - g^{I}\mu_{\mathrm{B}}BM \pm \frac{h\Delta\nu}{2}\sqrt{1 + \frac{4M}{2I+1}x + x^{2}}$$

$$x \equiv (g_J + g_I)\frac{\mu_{\mathrm{B}}B}{h\Delta\nu}, \qquad \Delta\nu \equiv A(I + 1/2)$$

Dependence of magnetic field

PNC induced light shift

44.5 mHz



T. Aoki *et al.*,
Asian J. Phys. (accepted)

Estimation of measurement time

[1] B. K. Sahoo et al., PRA 83, 030502(R) (2011).

shot noise limit $\delta\nu = \frac{1}{2\pi\sqrt{\tau N T}}$

$\tau = 1704$ ns
$N = 10^4$
0.0445 Hz

$\longrightarrow$ $T = 751$ s

Atom	$\delta\omega_{\mathrm{NSD}}$ (mHz)	
Ba+	0.009	[1]
Ra+	0.11	[1]
Fr	44.5	this work

T. Aoki *et al.*,
Asian J. Phys. (accepted)

Summary

- We investigated light shifts of nuclear-independent (depedent) parity-nonconservation interaction in ultracold ^{210}Fr.
- We found that the magnetic sublevels of M=9/2 and 7/2 have the same E2 light shift and opposite PNC light shift.
- The frequency difference of the transition of M=1/2 to -1/2 and the transition of M=9/2 to 7/2 has no 1st order Zeeman shift and small 2nd order Zeeman shift.

  Measuring this frequency difference enables us to obtain the value of PNC, with being insensitive to magnetic field fluctuation..

- Sensitivity of NSI PNC is estimated to $\Delta Qw/Qw = 0.2\%$, which corresponds to Λ/g = 20.6 TeV for New Physics.

T. Aoki *et al.*,
(to be submitted)

- Sensitivity of NSD PNC is is useful to measure the nuclear anapole moment to resolve the discrepancy between atomic Cs and particle scattering experiments.

B. K. Sahoo, T. Aoki, B. P. Das, and Y. Sakemi,
Phys. Rev. A **93**, 032520 (2016).

T. Aoki *et al.*,
Asian J. Phys. (accepted)