Cesium atoms embedded in cryogenic argon for electron EDM measurement

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Outline

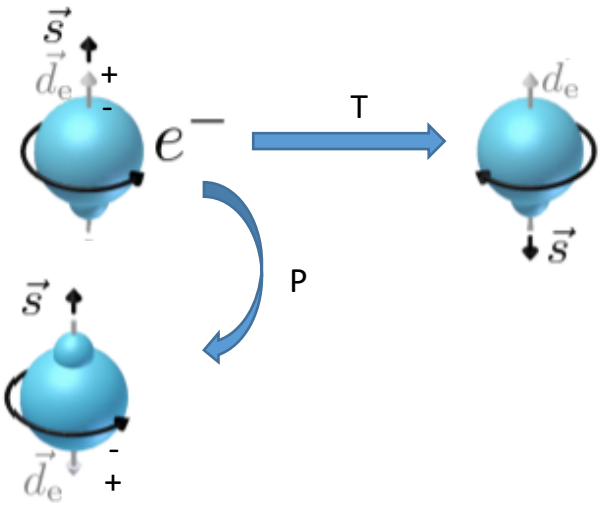
- EDM worldwide → why EDM
- Why in cryogenic solid: EDMMA project (Cs in Ar)
- Experimental setup: Cs absorption spectra
- Possible trapping sites: stability study
- Line position
- Line broadening
- Possible improvement

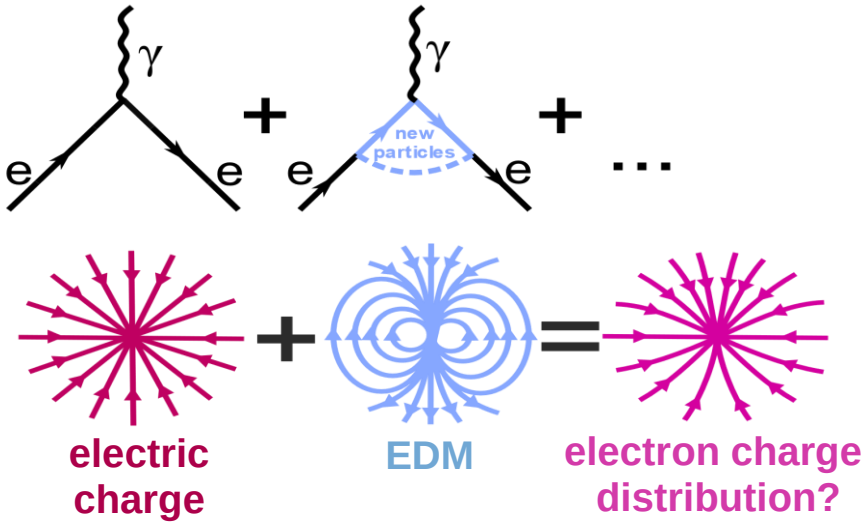
electron-EDM: P and T violation

CPT→ CP violation (can explain matter/antimatter asymmetry: Sakharov)

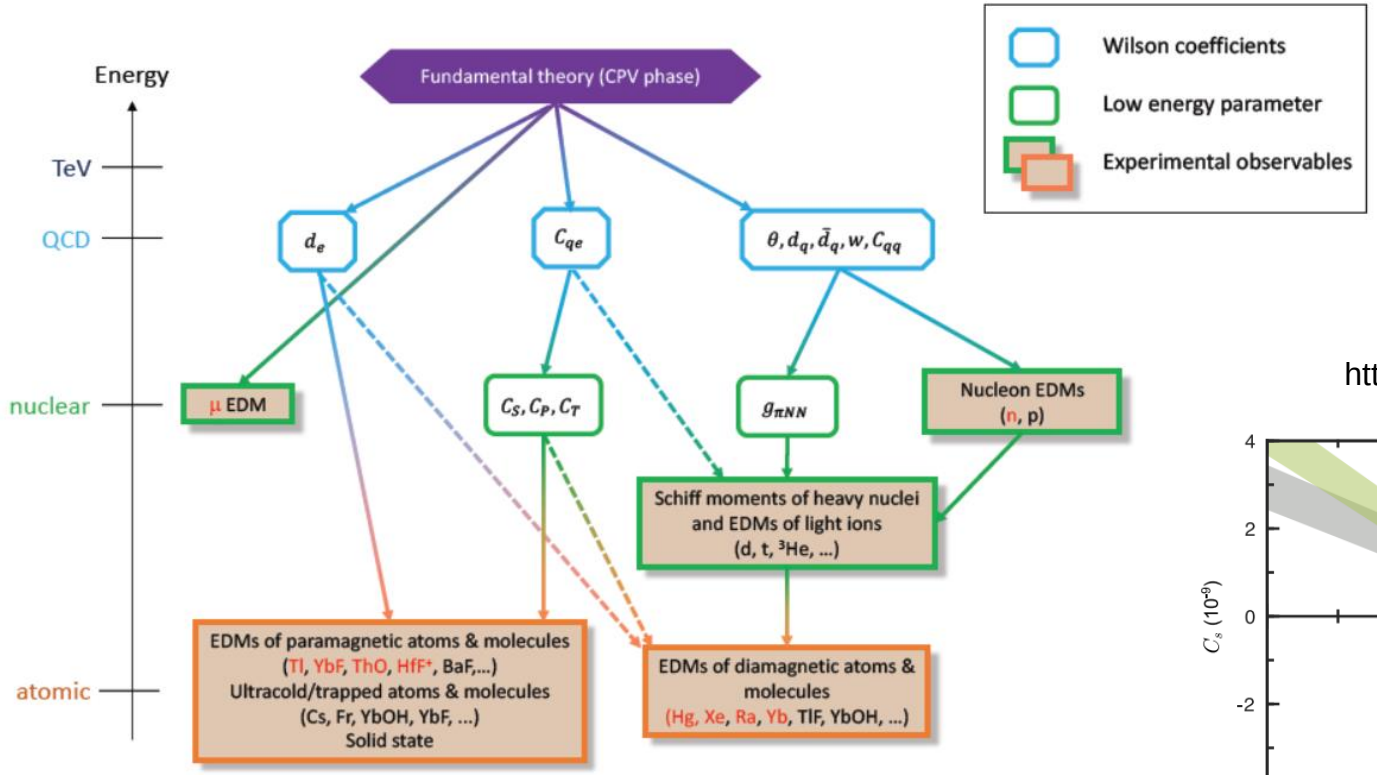
$$H = H_0(\frac{q_i q_j}{4\pi\varepsilon_0 \|\boldsymbol{r}\|}, p^2)$$

Conserved parity	P (r → -r)
Time reversal	T (t→ -t)
Charge conjugaison	C (q→-q)





Link between high energy and (very)low energy physics



https://arxiv.org/pdf/2212.11841.pdf

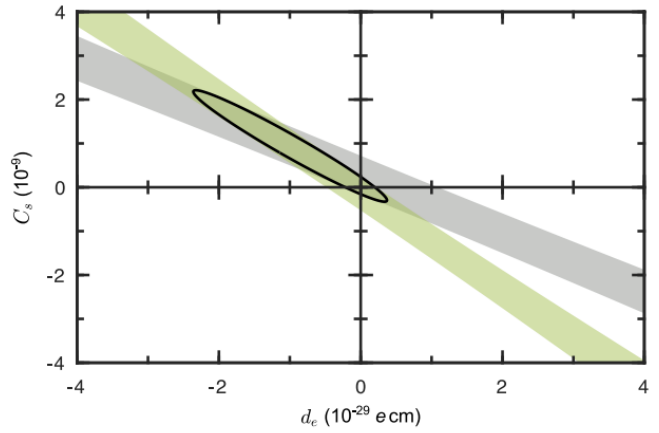
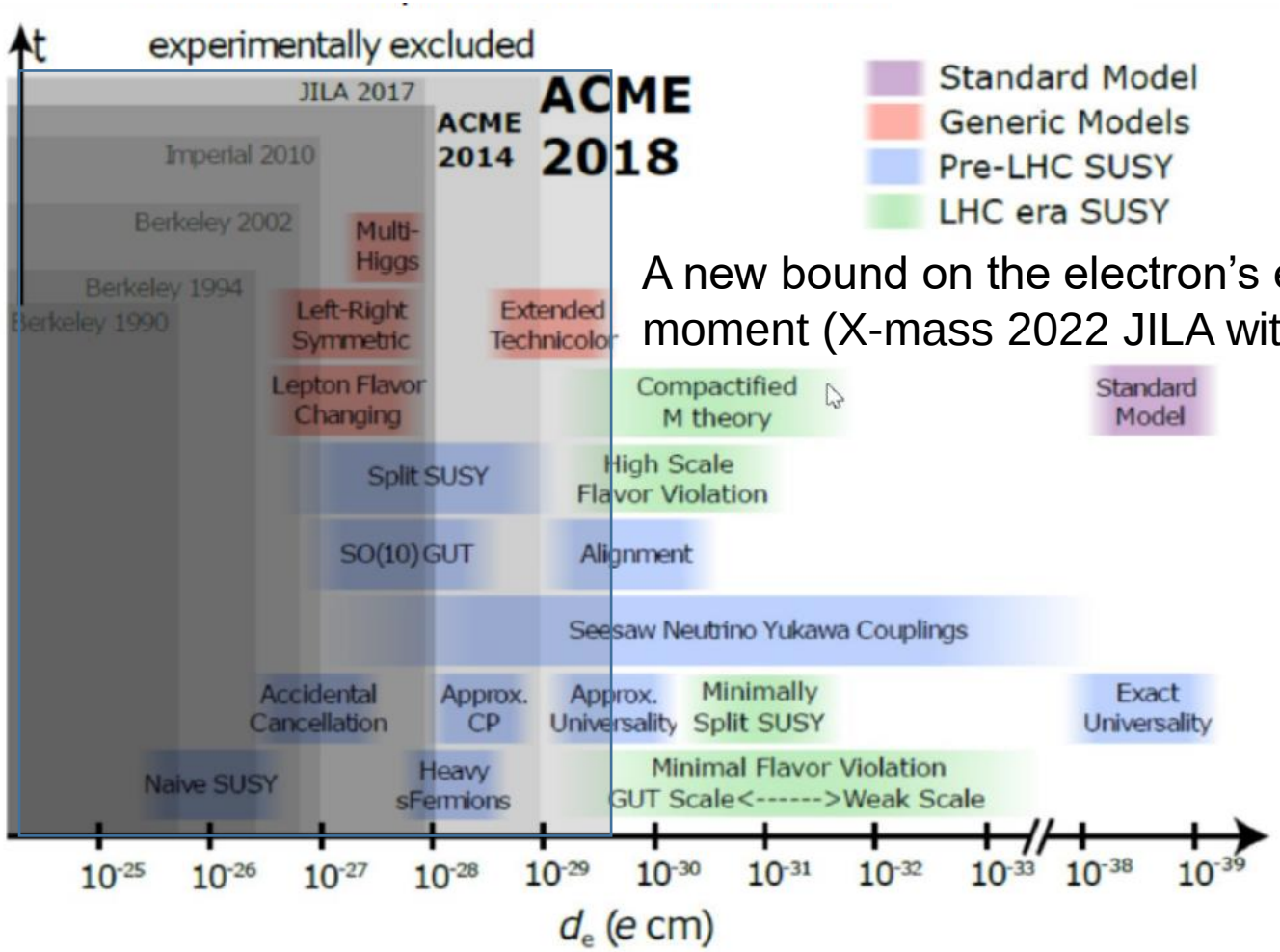


FIG. 5. Fit to results of this work and Ref. [5]. Green and grey shaded regions show 90% confidence bands for HfF^+ and ThO respectively. Ellipse shows 90% confidence limit for global fit. Parameters used in fits are from Ref. [29].

Blum, T., Winter, P., Bhattacharya, T., Chen, T. Y., Cirigliano, V., DeMille, D., ... & Semertzidis, Y. K. Fundamental Physics in Small Experiments. *arXiv preprint arXiv:2209.08041*.

Predicted electron electric dipole moments (compiled by D. DeMille)



A new bound on the electron's electric dipole moment (X-mass 2022 JILA with HfF^+)

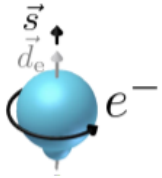
Super high energy physics with table top experiments

$$m \approx \sqrt{\frac{10^{-26} e \cdot cm}{d_e}}\, TeV$$

0.5 5 50 500 5000 One loop (TeV)

5 0.05 0.5 5 50 500 Two loops (TeV)

EDM status and project



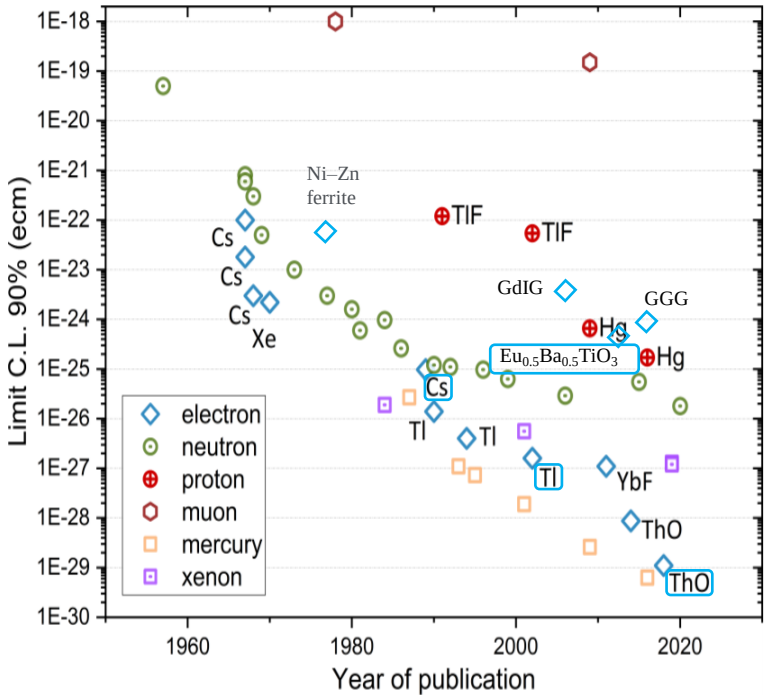
$$\Delta H = \langle\psi|\mathbf{d}.\mathbf{E}|\psi\rangle = d_{\text{eff}}.E_{\text{eff}}\cos(\hat{dE}) \approx \hbar/\tau$$

$$d.E_{\text{eff}} = \frac{\hbar}{\epsilon_{\text{polar}}\tau\sqrt{N}}$$

Ideal

N big
τ long

Some EDM history



Kirch, K., & Schmidt-Wellenburg, P. Search for electric dipole moments.

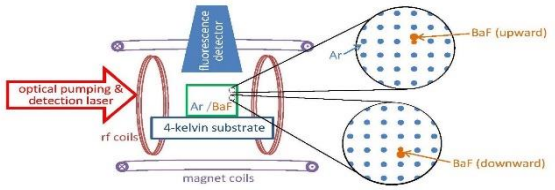
Electron EDM predictions

Particle	N_T time integrated	Time τ [s]	Polarization ε	Eff. Field E_{eff} (V/cm)	EDM e.cm
Cs	10^{14}	0.015	0.7	$5\ 10^{5}$	$1\ 10^{-26}$
ThO	10^{13}	0.002	0.1	10^{11}	10^{-29}
HgF^+	10^{17}	3	0.8	$2\ 10^{10}$	$4\ 10^{-30}$

Particle	N_T time integrated	Time τ [s]	Polarization ε	Eff. Field E_{eff} (V/cm)	EDM e.cm
Atoms (Cs) in matrix	10^{16}	0.01	0.1	10^{6}	$6\ 10^{-27}$
	10^{20}	1	1	10^{9}	$6\ 10^{-35}$
Molecule in matrix	10^{18}	0.1	0.1	10^{10}	$6\ 10^{-33}$
	10^{21}	1	1	10^{11}	10^{-37}

Beyond Standard Models

Standard Model ~10^{-38} ecm



http://www.yorku.ca/edmcubed/

H=-d.E_{eff} (laboratory field E_{lab} 10kV/cm)

$$\mathcal{L}_{\rm d} = -i\frac{d}{2}\,\bar{\psi}(\boldsymbol{x})\sigma^{\mu\nu}\gamma_5\psi(\boldsymbol{x})F_{\mu\nu}(\boldsymbol{x}) \quad \Rightarrow \quad H_{\rm d} = -d\,[2\,\gamma_0\boldsymbol{S}\cdot\boldsymbol{E} + i\gamma_0\boldsymbol{\alpha}\cdot\boldsymbol{B}]$$

$$H_{\rm d} = H_{\rm d}^{\rm clas} + H_{\rm d}^{\rm rel} = \begin{pmatrix} -2d\,\boldsymbol{S}\cdot\boldsymbol{E} & 0 \\ 0 & -2d\,\boldsymbol{S}\cdot\boldsymbol{E} \end{pmatrix} + \begin{pmatrix} 0 & 0 \\ 0 & 4d_e\,\boldsymbol{S}\cdot\boldsymbol{E} \end{pmatrix}$$

Schiff's theorem

$$\Delta\mathcal{E} = \langle\psi|H_{\rm d}|\psi\rangle = \langle\psi|H_{\rm d}^{\rm rel}|\psi\rangle = \langle\psi|\begin{pmatrix} 0 & 0 \\ 0 & 4d_e\,\boldsymbol{S}\cdot\boldsymbol{E} \end{pmatrix}|\psi\rangle = \boxed{4d_e\langle\psi_L|\boldsymbol{S}\cdot\boldsymbol{E}|\psi_L\rangle}$$

Need mixed state $|\psi\rangle = \varepsilon_s|s\rangle + \varepsilon_p|p\rangle$ $\Rightarrow$ $\boxed{\langle\psi|H_e|\psi\rangle \sim d_e(100\,\mathrm{GV/cm})(Z/80)^3\epsilon_s\epsilon_p}$

Ex: Atoms 1st order (Perturbation Stark effect) with $\varepsilon_s \approx 1$ and $\varepsilon_p \approx \dfrac{\langle s\,|ez|\,p\rangle}{\mathcal{E}(s)-\mathcal{E}(p)}E_{\rm lab}$

$\langle\psi|H_e|\psi\rangle \sim 125 d_e E_{\rm lab}$ Cs

Ex: Molecule aligned on field $\epsilon_s \approx \epsilon_p \approx 1/\sqrt{2}$

$\langle\psi|H_e|\psi\rangle \sim d_e(100\,\mathrm{GV/cm})$

EDM – worldwide (gas phase)

https://www.psi.ch/en/nedm/edms-world-wide
In 2020

Neutrons: (~ 200 ppl.)
- Beam EDM @ Bern
- LANL nEDM @ LANL
- nEDM @ PSI
- nEDM @ SNS
- PanEDM @ ILL
- PNPI/FTI/ILL @ ILL
- TUCAN @ TRIUMF

Storage rings: (~ 400 ppl.)
- CPEDM/JEDI
- muEDM @ PSI
- g-2 @ FNAL
- g-2 @ JPARC

Atoms: (~ 60 ppl.)
- Cs @ Penn State
- Fr @ Riken
- Hg @ Bonn
- Hg @ Seattle
- Ra @ Argonne
- Xe @ Heidelberg
- Xe @ PTB
- Xe @ Riken

Molecules: (~ 55 ppl.)
- BaF (EDM^3) @ Toronto
- BaF (NLeEDM) @ Groningen/Nikhef
- HfF+ @ JILA
- ThO (ACME) @ Yale
- YBF @ Imperial

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- Possible improvement

Using cryogenic matrix: An old idea

"ARTIFICIAL VACUUM" FOR *T*-VIOLATION EXPERIMENT 1987

Craig PRYOR
Department of Physics, University of California, Santa Barbara, CA 93106, USA
and
Frank WILCZEK
Institute for Theoretical Physics, University of California, Santa Barbara, CA 93106, USA

PHYSICS LETTERS B

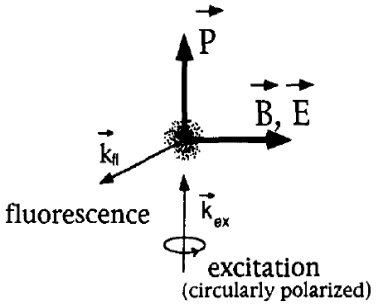


Fig. 4. Geometry of the proposed EDM experiment.

Can paramagnetic atoms in superfluid helium be used to search for permanent electric dipole moments?

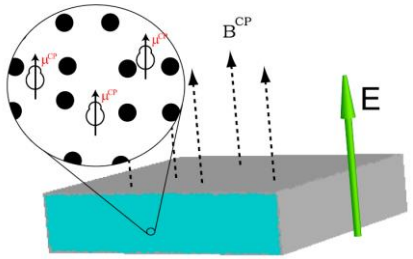
Physics Letters A 174 (1993) 298–303

M. Arndt, S.I. Kanorsky, A. Weis and T.W. Hänsch

Proposal for a Sensitive Search for the Electric Dipole Moment of the Electron with Matrix-Isolated Radicals

PRL **97,** 063001 (2006)

M. G. Kozlov
Petersburg Nuclear Physics Institute, Gatchina 188300, Russia
Andrei Derevianko



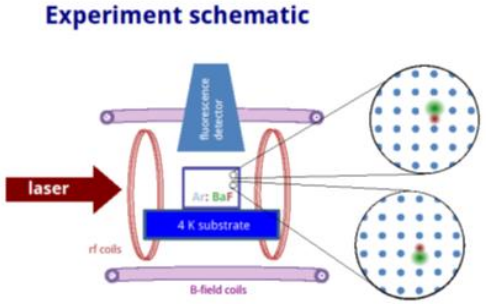
atoms MDPI

Article

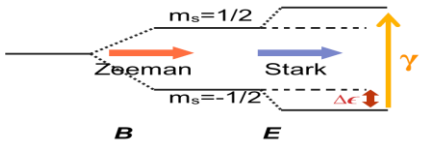
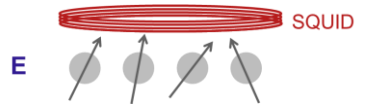
Oriented Polar Molecules in a Solid Inert-Gas Matrix: A Proposed Method for Measuring the Electric Dipole Moment of the Electron

A. C. Vutha [1,*], M. Horbatsch [2] and E. A. Hessels [2]

BaF
YbF
...



eEDM in solid state systems

year	sample	eEDM limit in e·cm	method	$H = d_e E + \mu B$ d_e // μ
1961	KCr- & NH_4-$(SO_4)_2$ $12H_2O$	$d_e < 10^{-13}$	EPR spectroscopy	Δ Energy = -d.E_{eff} 
1963	Al_2O_3:Cr & MgO:Cr	$d_e = (1 \pm 4.6) \times 10^{-16}$	EPR spectroscopy	
1979	Nickel-Zink-Ferrite	$d_e = (8.1 \pm 11.6) \times 10^{-23}$	Magnetometry	
2004	GdIG	$d_e = (2 \pm 3) \times 10^{-24}$	Voltage measurement	B field, align spin → dipole → Create +/- charges
2011	GGG	$d_e = (-5.57 \pm 7.98_{stat} \pm 0.12_{syst}) \times 10^{-25}$	Magnetometry	E field, align dipole→ Spin → Create B field 
2012	$Eu_{0.5}Ba_{0.5}TiO_3$	$d_e = (-1.07 \pm 3.06_{stat} \pm 1.74_{syst}) \times 10^{-25}$	Magnetometry	

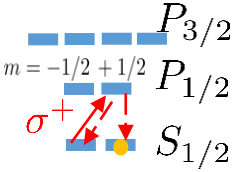
Broken symmetry -> magnetoelectric

$$E_i^{\text{int}} = E_i^* + \frac{1}{\varepsilon_0} P_i^{\text{stat}} + \chi_{ij} E_j^* + \alpha_{ij} B_j^* + \frac{1}{2}\beta_{ijk} B_j^* B_k^* + \frac{1}{2}\gamma_{ijk} B_j^* E_k^* + \frac{1}{2}\chi_{ijk}^{(2)} E_j^* E_k^*$$

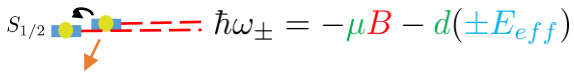
$$B_i^{\text{int}} = B_i^* + \frac{1}{\mu_0} M_i^{\text{stat}} + \bar{\chi}_{ij} B_j^* + \alpha_{ij} E_j^* + \frac{1}{2}\beta_{ijk} E_j^* B_k^* + \frac{1}{2}\gamma_{ijk} E_j^* E_k^* + \frac{1}{2}\bar{\chi}_{ijk}^{(2)} B_j^* B_k^*$$

Spin precession
align by optical pumping + coherence

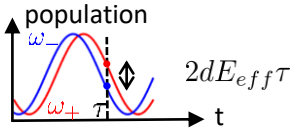
1) Optical pumping (alignement)

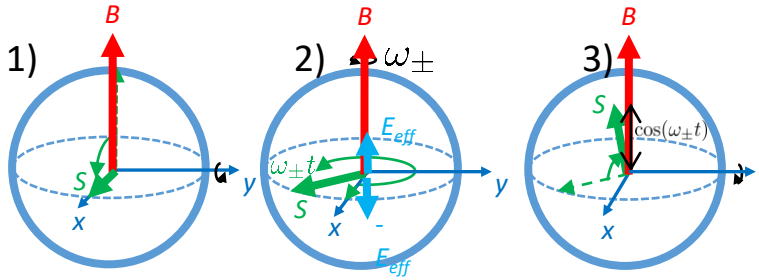


2) Precession



3) Readout





USE ATOMS
(circular)

PHYSICAL REVIEW A VOLUME 54, NUMBER 2 AUGUST 1996

Millihertz magnetic resonance spectroscopy of Cs atoms in body-centered-cubic ^{4}He

S. I. Kanorsky,* S. Lang, S. Lücke, S. B. Ross,† T. W. Hänsch, and A. Weis

Max-Planck-Institut für Quantenoptik, Hans Kopfermann Strasse 1, D-85748 Garching, Germany

PHYSICAL REVIEW A 88, 063404 (2013)

Optical pumping of rubidium atoms frozen in solid argon

T_1 (population) ~1 s

T_2 (coherence, phase) ~0.1 s (for Cs)

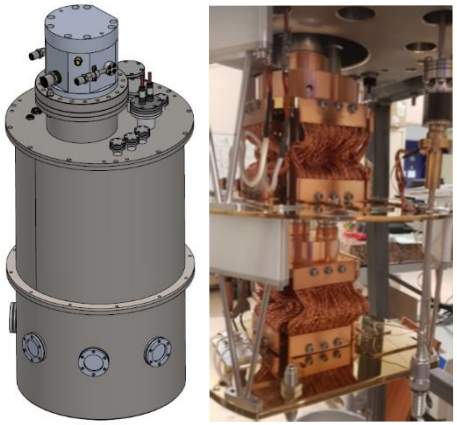
Spin coherence and optical properties of alkali-metal atoms in solid parahydrogen

Sunil Upadhyay,[1] Ugne Dargyte,[1] Vsevolod D. Dergachev,[2] Robert P. Prater,[1] Sergey A. Varganov,[2] Timur V. Tscherbul,[1] David Patterson,[3] and Jonathan D. Weinstein[1,*]

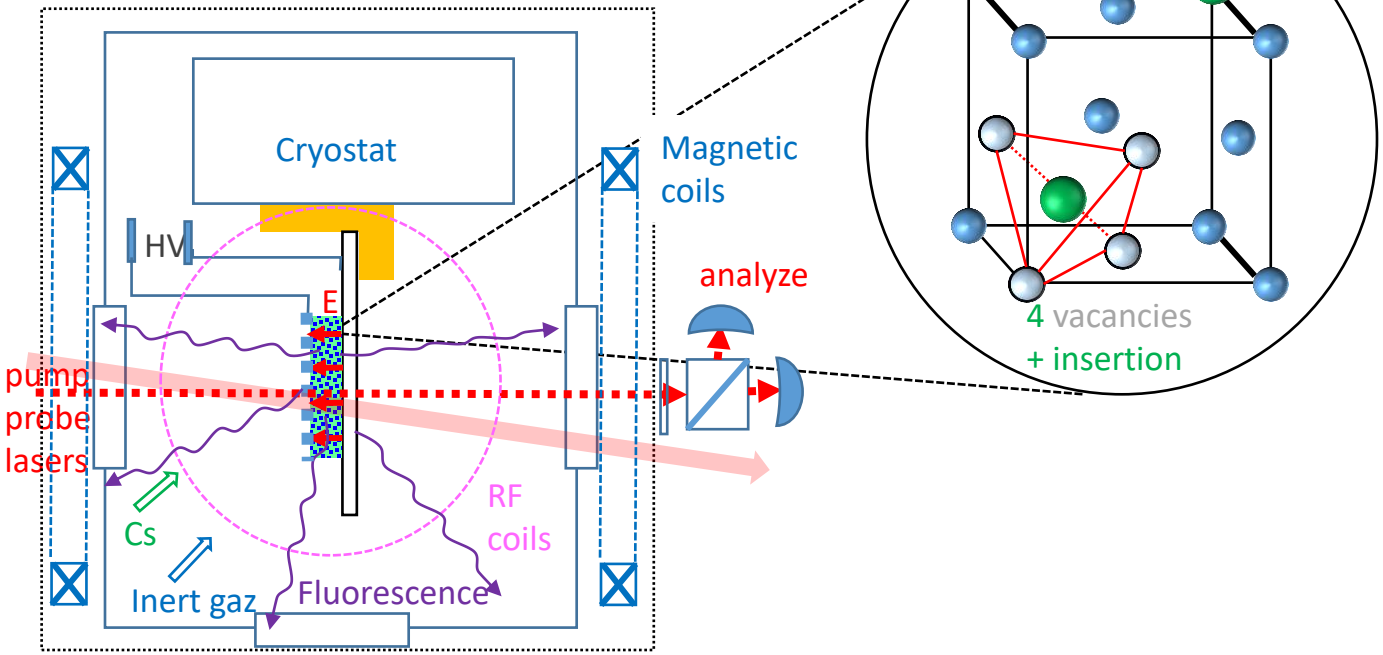
[1]*Department of Physics, University of Nevada, Reno NV 89557, USA*

Phys. Rev. A 100, 063419 (2019)

LAC
ISMO (cryogenic matrix)
LPL (RF metrology)
CIMAP (theory matrix)



mycryofirm



More particles N,
Trapped long time τ

$$d.E_{\text{eff}} = \frac{\hbar}{\epsilon_{\text{polar}} \tau \sqrt{N}}$$

Spin : aligned, polarised + optical manipulation (diagnostics)

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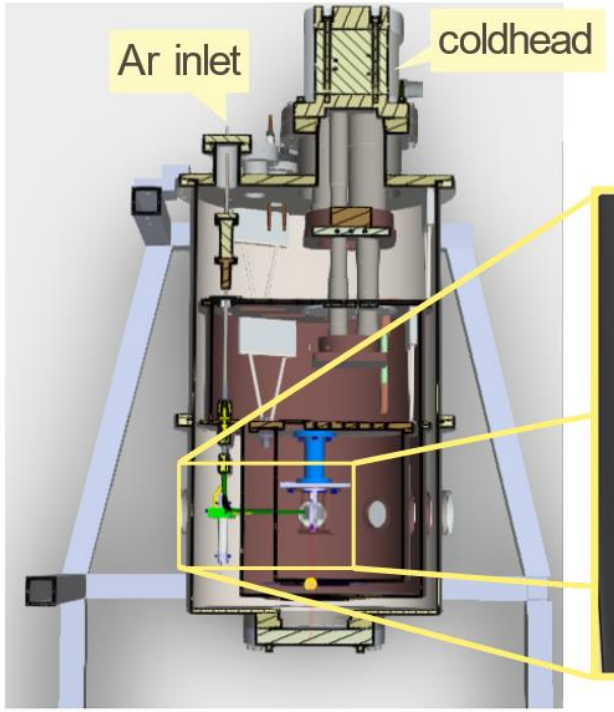
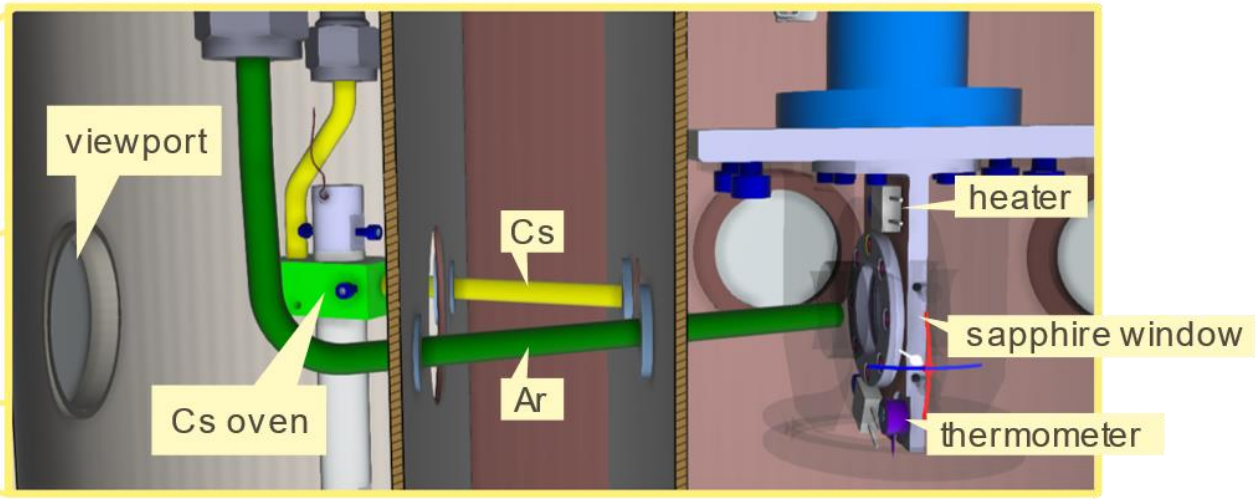
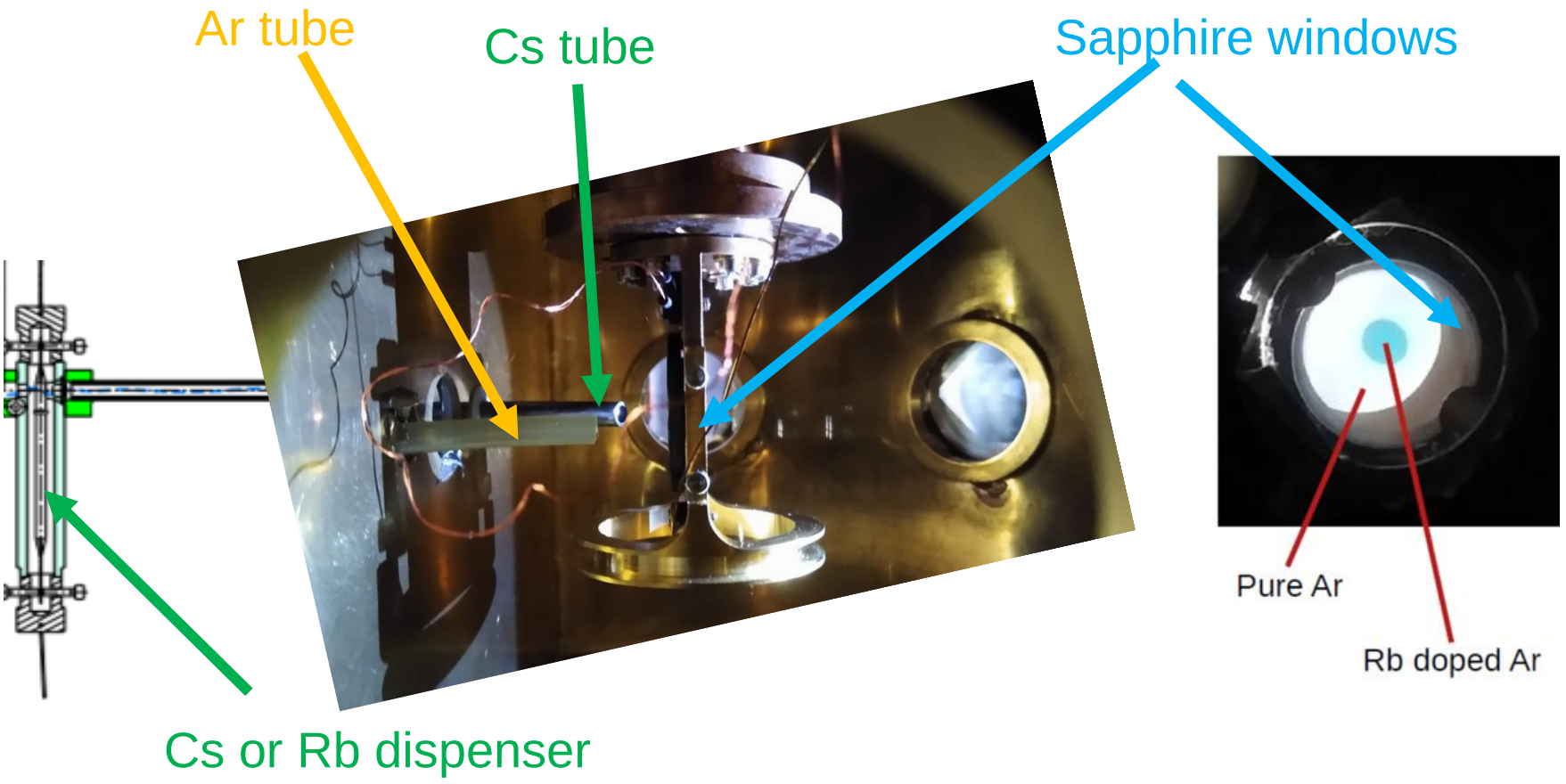
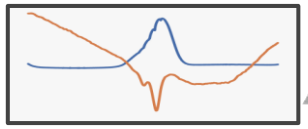
Experimental setup






Ar tube
Cs tube
Sapphire windows
Cs or Rb dispenser
Pure Ar
Rb doped Ar



Oscilloscope

Cs flux measurement

$\rightarrow N_{Cs} \approx 10^{18}$

Cs doped
Ar crystal

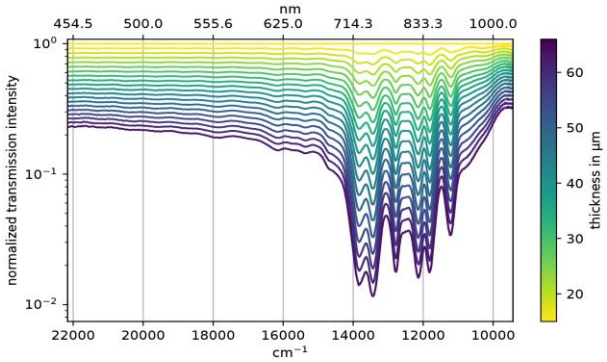
light source

Cs

laser

spectrometer

Transmission
Cs in argon

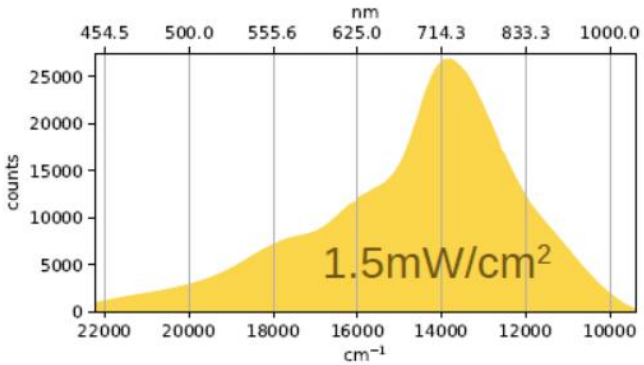


Ar

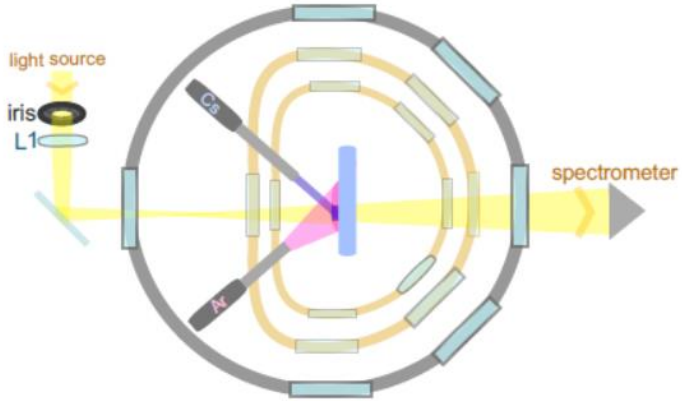
camera

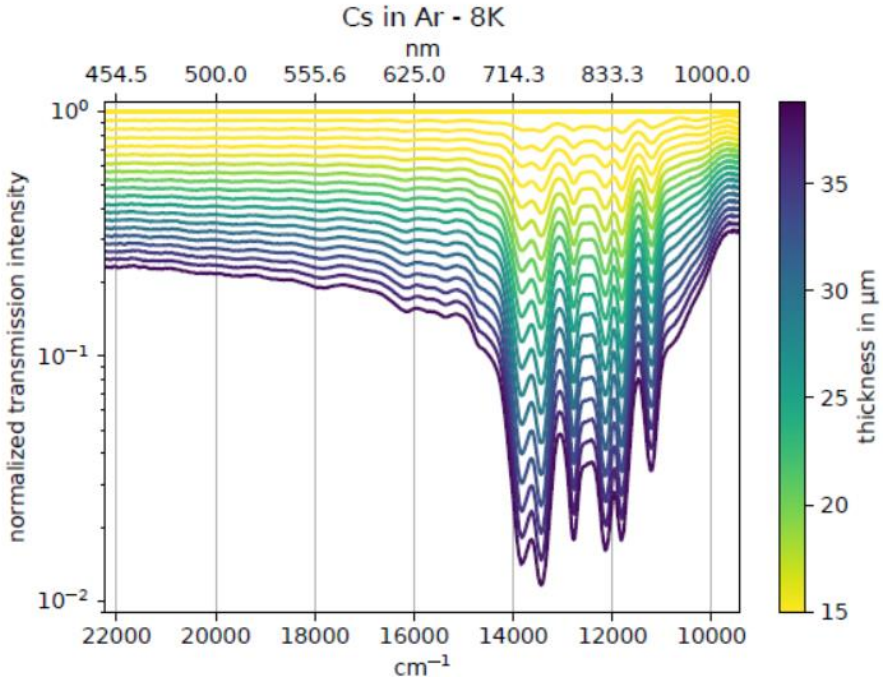
Fizeau interferometer
Matrix growth
$\lambda/2$ every fringes

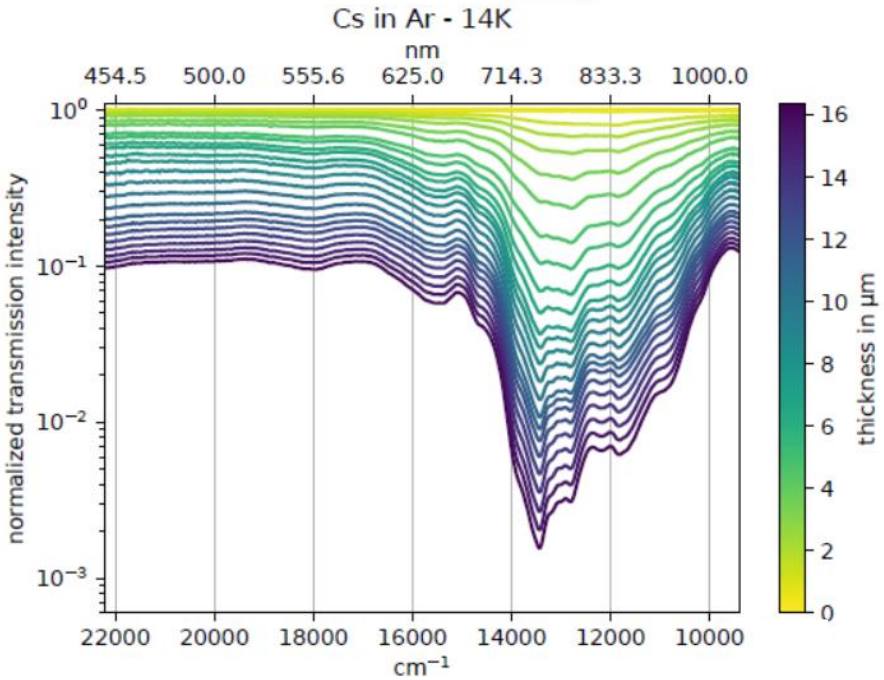
laser



Transmission Specroscopy





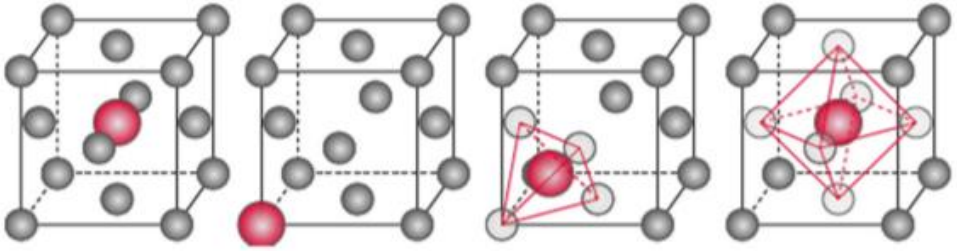


Interpretation of Cs spectrum

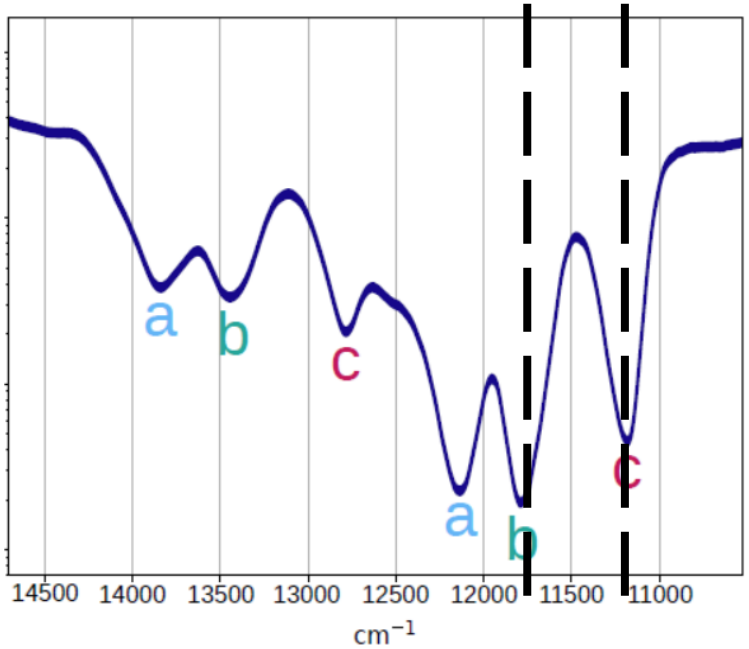
Optical Absorption Spectra of Alkali Atoms in Rare-Gas Matrices

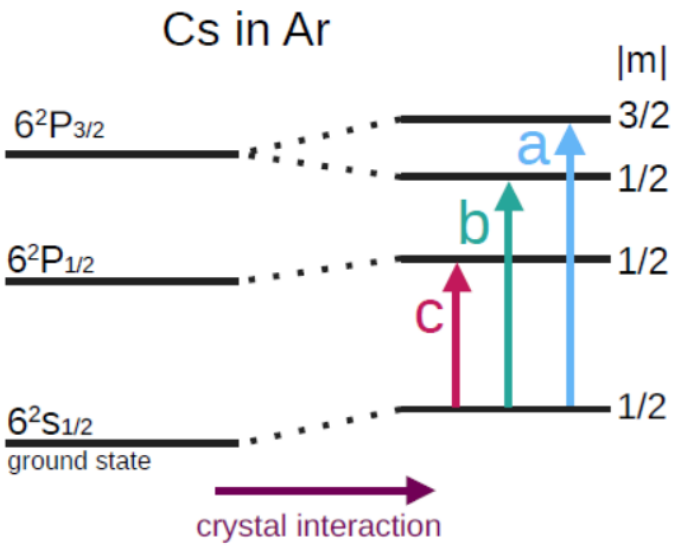
W. Weyhmann‡ and F. M. Pipkin
Lyman Laboratory of Physics, Harvard University, Cambridge, Massachusetts
(Received 19 August 1964)

Probably 2 different Trapping sites



Gas phase Cs(6s)—Cs($6p_J$)
852nm 894nm





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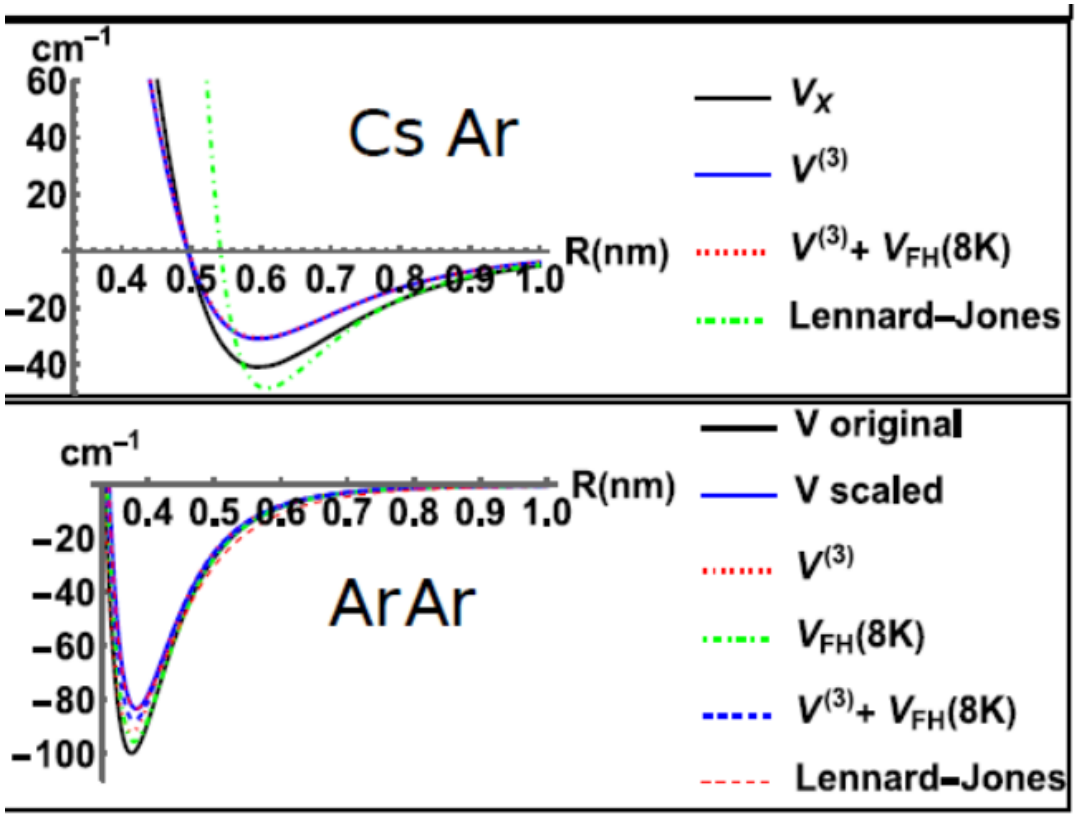
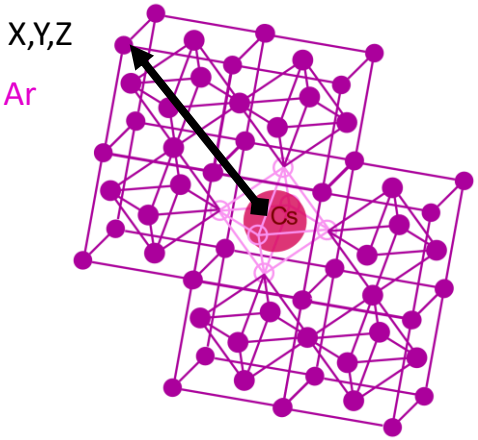
Ar-Ar and Cs-Ar Pair wise potential approximation

$$V = E_{\mathrm{Cs}}(n, N)$$

$$V = \sum_{i=1}^{N-n} V_{\mathrm{Ar-Cs}}(\boldsymbol{r}_{Cs-Ari}) + \sum_{1 \le i < j \le N-n} V_{\mathrm{Ar}}(\boldsymbol{r}_{ij})$$



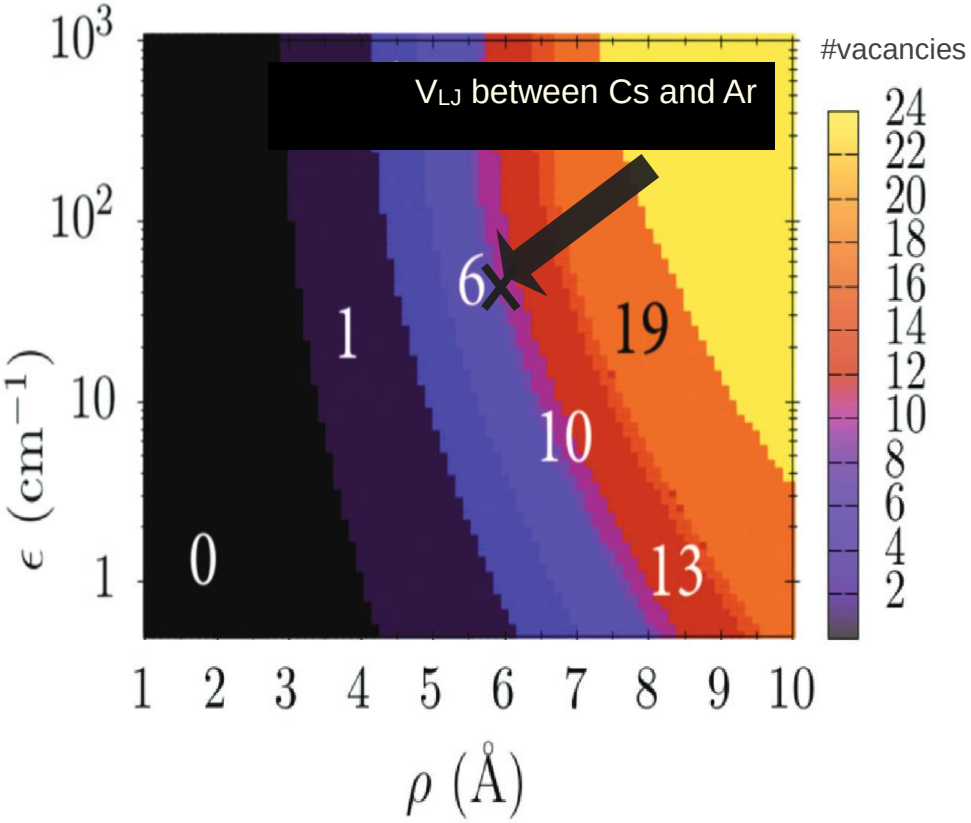


N ~ 1000 atoms

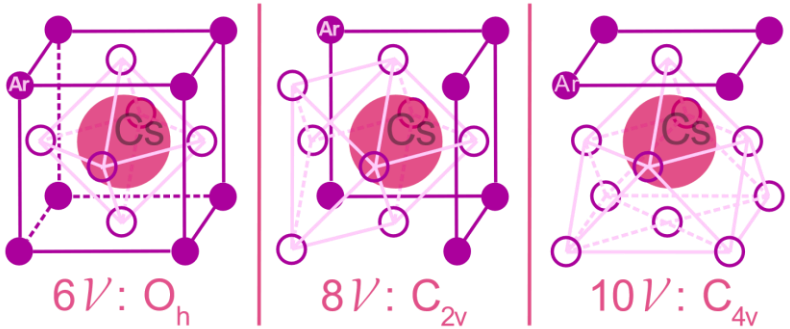
n vacancies

Most probable trapping sites (n=6,8,10 vacancies)?

Free energy of trapping sites in fcc argon for different Lennard-Jones-potentials $V_{LJ}(r) = \varepsilon\left[\left(\frac{\rho}{r}\right)^{12} - 2\left(\frac{\rho}{r}\right)^{6}\right]$



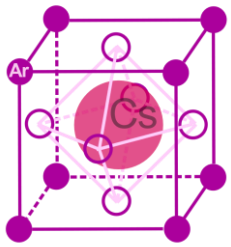
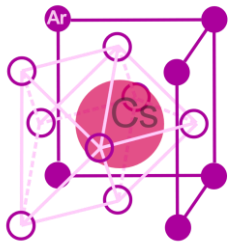
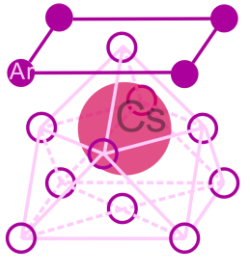
G. K. Ozerov, D. S. Bezrukov, and
A. A. Buchachenko, Phys. Rev. B 103, 184110 (2021)



Different magneto-electric couplings

$$E_i^{\mathrm{int}} = E_i^* + \frac{1}{\varepsilon_0} P_i^{\mathrm{stat}} + \chi_{ij} E_j^* + \alpha_{ij} B_j^* + \frac{1}{2}\beta_{ijk} B_j^* B_k^* + \frac{1}{2}\gamma_{ijk} B_j^* E_k^* + \frac{1}{2}\chi^{(2)}_{ijk} E_j^* E_k^*$$

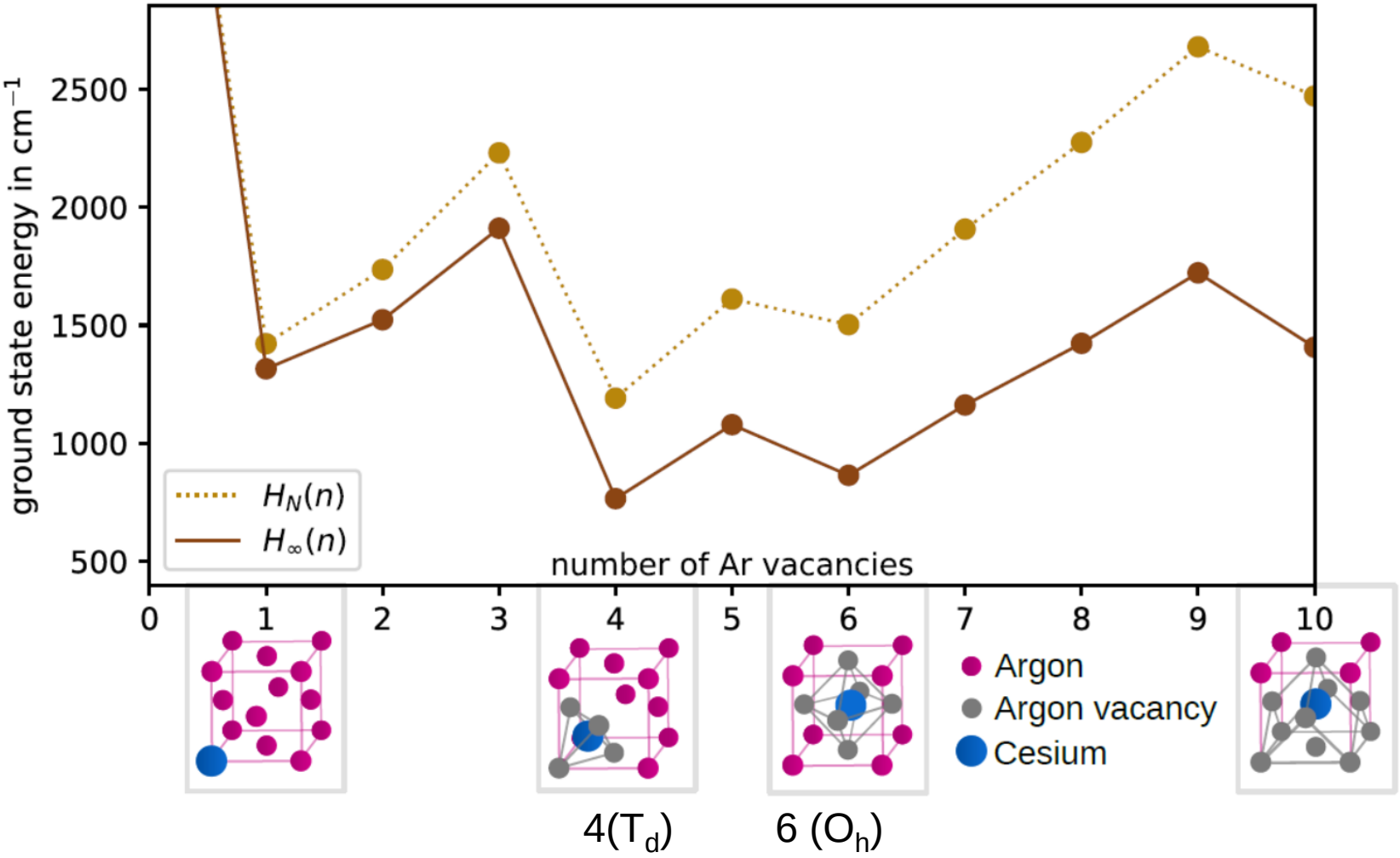
$$B_i^{\mathrm{int}} = B_i^* + \frac{1}{\mu_0} M_i^{\mathrm{stat}} + \bar{\chi}_{ij} B_j^* + \alpha_{ij} E_j^* + \frac{1}{2}\beta_{ijk} E_j^* B_k^* + \frac{1}{2}\gamma_{ijk} E_j^* E_k^* + \frac{1}{2}\bar{\chi}^{(2)}_{ijk} B_j^* B_k^*$$

	 $6\mathcal{V}$: O_h	 $8\mathcal{V}$: C_{2v}	 $10\mathcal{V}$: C_{4v}
α:	$\boldsymbol{\alpha}^{O_h} = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix}$	$\boldsymbol{\alpha}^{C_{2v}} = \begin{pmatrix} 0 & \alpha_{12} & 0 \\ \alpha_{12} & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix}$	$\boldsymbol{\alpha}^{C_{4v}} = \begin{pmatrix} 0 & \alpha_{12} & 0 \\ -\alpha_{12} & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix}$
β & γ:	zero	Orthogonal ***E*-*B***-mixing	Orthogonal ***E*-*B***-mixing

Stability diagram

Accomodation energy: system (Cs+Ar) energy – energy of the pure Ar crystal

$$\Delta E_N(n) = E_{\mathrm{Cs}}(n, N) - E_{\mathrm{Ar}}(N)(N-n)/N$$



Convex stability (ex: 5+5 → 4 +6) → **4 vacancies or 6 vacancies**

Optimizing the Ar and Cs positions to minimize the energy → frozen shell

First order

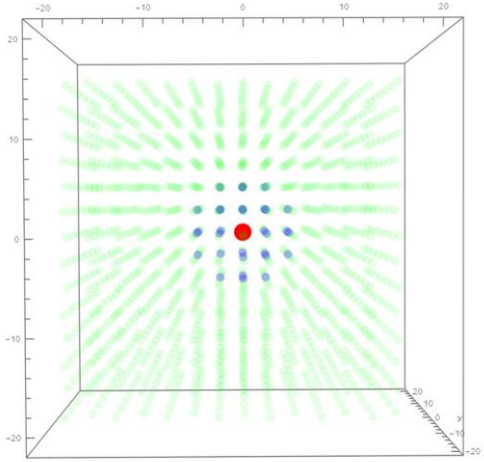
$$\text{Taylor expansion of the energy : } V = V(0) + \sum_k \left(\frac{\partial V}{\partial x_k}\right) x_k$$

Derivative calculated by finite difference

GRADIENT DESCENT

Adam: A **method** for **stochastic optimization**
DP Kingma, J Ba - arXiv preprint arXiv:1412.6980, 2014 - arxiv.org

Cité 135878 fois



Second order

$$\text{Taylor expansion of the energy : } V = V(0) + \sum_k \left(\frac{\partial V}{\partial x_k}\right) x_k + \frac{1}{2}\sum_{j,k} x_j H_{j,k} x_k$$

$x_j = q_j\sqrt{(m_j)}$ where m_j is the mass of the atom on which the j^{th} cartesian coordinate reside

ibrational modes $\boldsymbol{Q}^{\text{normal}} = \boldsymbol{P}(\boldsymbol{X} - \boldsymbol{X}_0)$ with P an orthonormal matrix

leading to $V = \sum_k \left(\frac{\omega_k Q_k^{\text{normal}}}{\sqrt{2}}\right)^2 + (V^{(1)}\boldsymbol{P}^{\text{T}})_k Q_k^{\text{normal}}$.

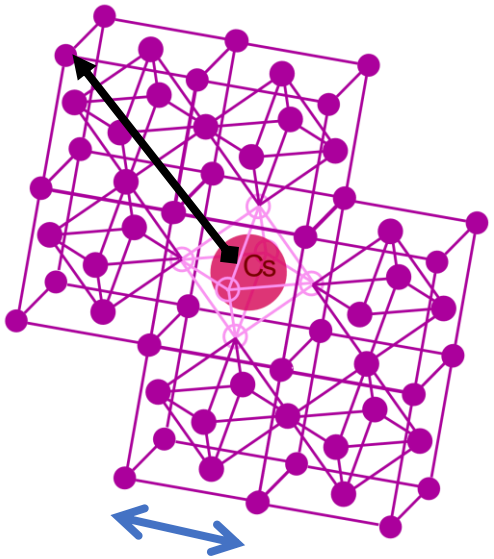
New positions

Outline

- EDM worldwide → why EDM
- Why in cryogenic solid: EDMMA project (Cs in Ar)
- Experimental setup: Cs absorption spectra
- Possible trapping sites: stability study
- Line position
- Line broadening
- Possible improvement

Cs(6s and 6p) - Ar potential approximation

Cs(6s) - Ar $$V = \sum_{i=1}^{N-n} V_{\mathrm{Ar-Cs}}(\boldsymbol{r}_{Cs-Ari}) + \sum_{1 \le i < j \le N-n} V_{\mathrm{Ar}}(\boldsymbol{r}_{ij})$$

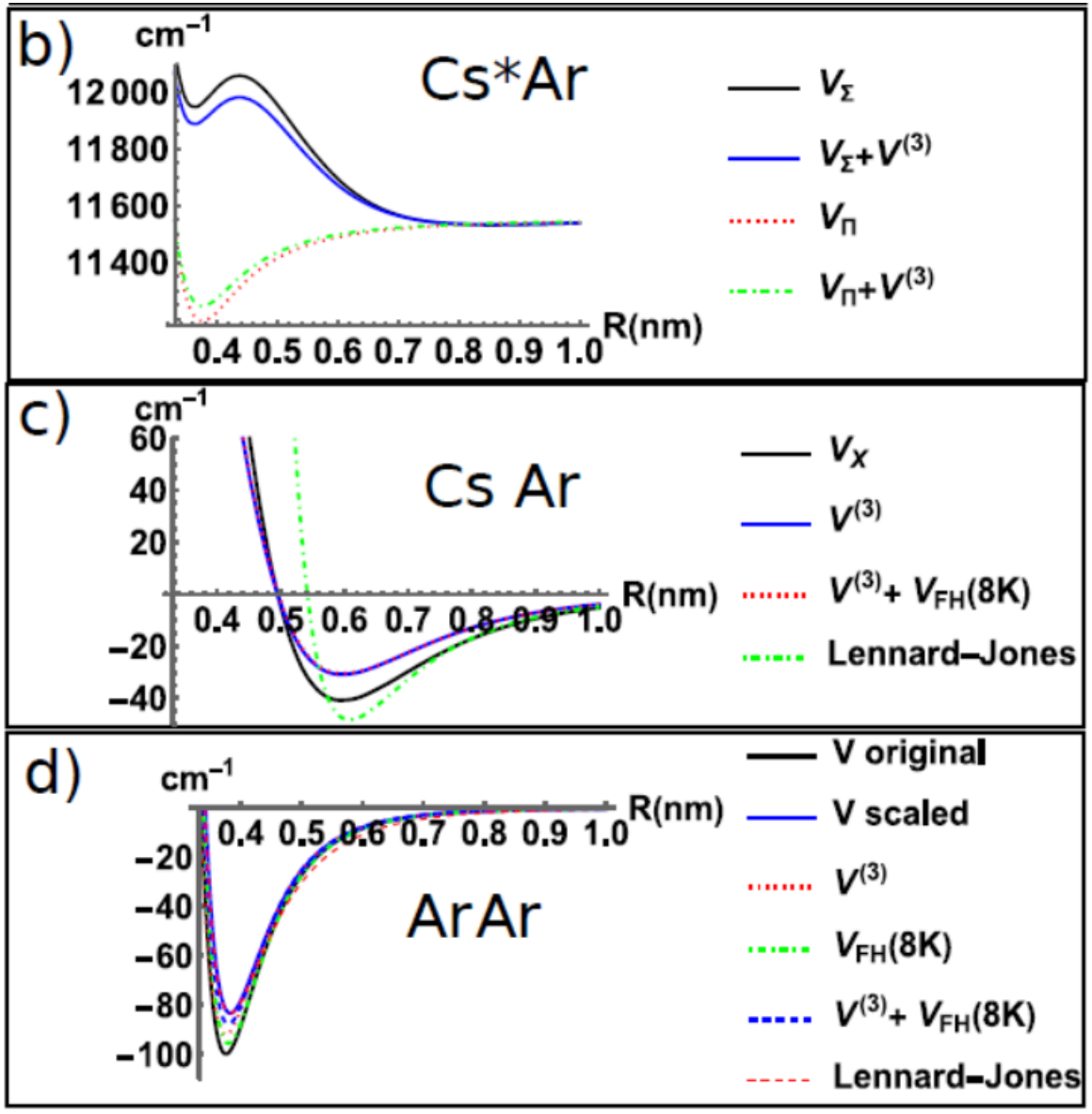


Cs(6p m) - Ar $$\langle L'M' | \hat{V}_{Cs,Ar}(\boldsymbol{R}_{Cs,Ar} = \{X, Y, Z\}) | LM \rangle$$

$$\frac{1}{3}(2V_{\Pi}(R) + V_{\Sigma}(R))\boldsymbol{I}_3 + \frac{1}{6}\frac{V_{\Sigma}(R) - V_{\Pi}(R)}{R^2} \begin{array}{c} \\ |M=-1\rangle \\ |M=0\rangle \\ |M=1\rangle \end{array} \begin{array}{c} \begin{array}{ccc} |M=-1\rangle & |M=0\rangle & |M=1\rangle \end{array} \\ \begin{pmatrix} X^2+Y^2-2Z^2 & 3\sqrt{2}(X+iY)Z & -3(X+iY)^2 \\ 3\sqrt{2}(X-iY)Z & -2(X^2+Y^2-2Z^2) & -3\sqrt{2}(X+iY)Z \\ -3(X-iY)^2 & -3\sqrt{2}(X-iY)Z & X^2+Y^2-2Z^2 \end{pmatrix} \end{array}$$

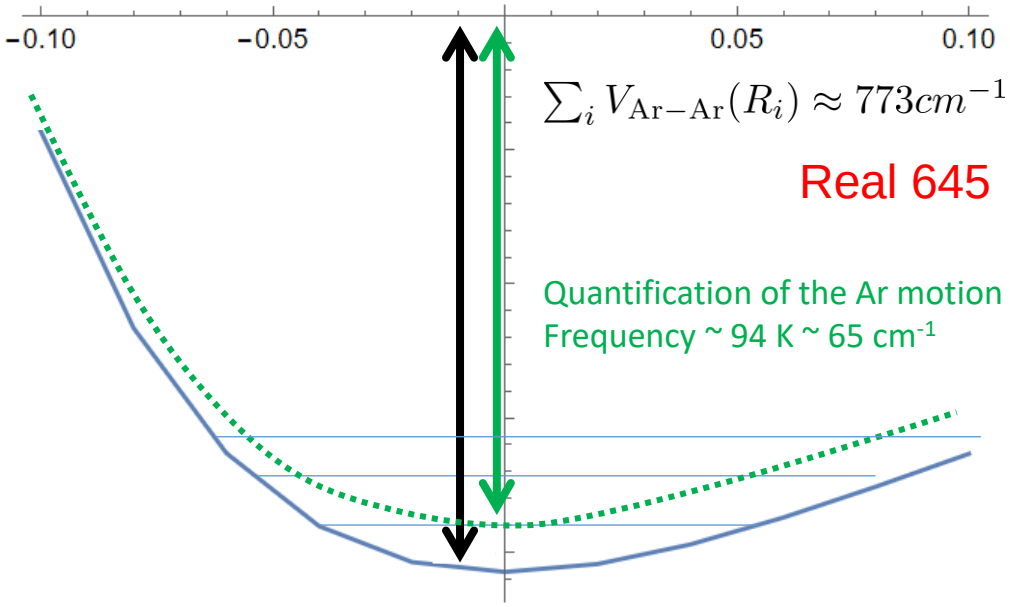
Potential curves

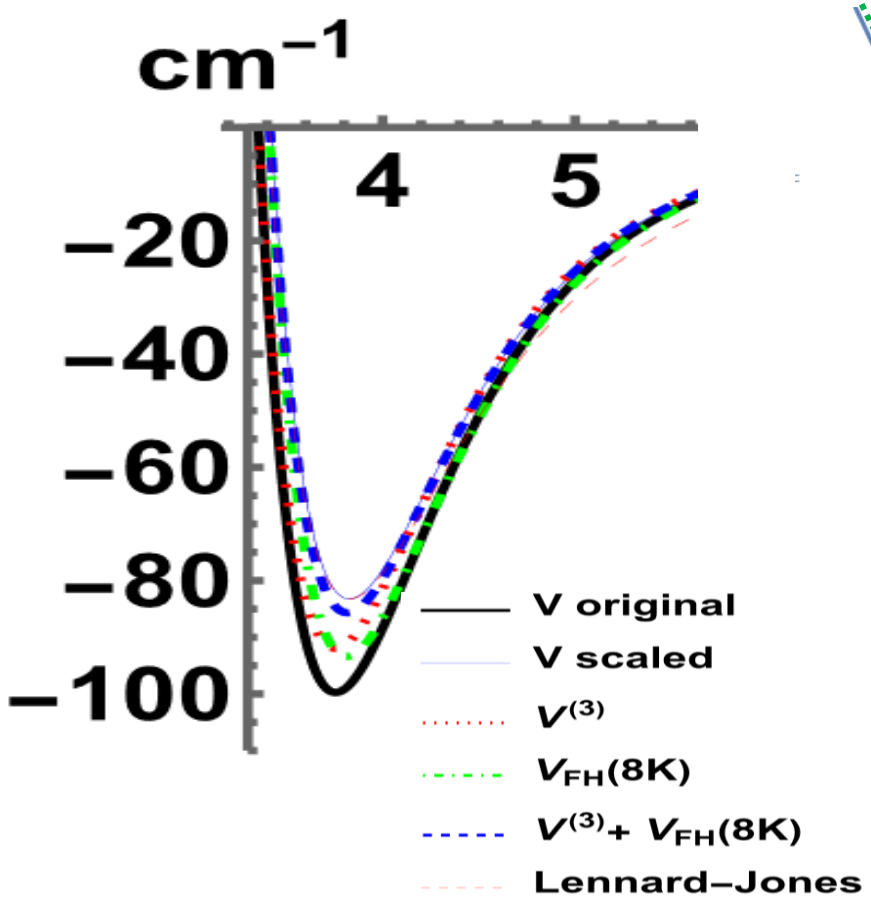
Zero point energy, Third order correction



Zero point energy

5.21 + δ a (Angström) real 5.31





Feynman-Hibbs effective correction to a pair potential between ground state atoms:

$$\Delta V_{FH}(R) = \sigma_0^2 (V''(R) + 2V'(R)/R)$$

$$\sigma_0 = \sqrt{\frac{\hbar^2}{24 \mu k_B T}}$$

Is the Gaussian width of quantum particles

Third order (triple atom interaction)

$$H = \sum_i H_0(i) + \frac{1}{2}\sum_{i\neq j} V_{ij}(elec, R_i, R_j).$$

Ar (4p)

Ar (4s) $|m_i\rangle$

Ar ($3p^6$) $|0_i\rangle$

the first order is zero, the second order leads to a shift depending on atom A given by $\sum_B E^{(2)}_{AB}$

So up to second order E= Sum_ij E(i,j) = pair-wise (two body) approximation

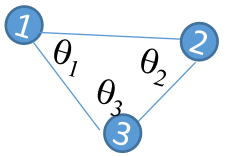
long-range $V_{12} = \frac{e^2}{4\pi\epsilon_0 R_{12}^3}\boldsymbol{r}(1).(1 - 3\boldsymbol{e}_{12}\boldsymbol{e}_{12}).\boldsymbol{r}(2)$

$$E^{(2)}_{12} = \sum_{m_1,m_2} -\frac{|\langle 0_1 0_2|V_{12}|m_1 m_2\rangle|^2}{\Delta_{m_1}(1)+\Delta_{m_2}(2)} \text{ where } \Delta_{m_i}(i) = E_{m_i} - E_{0_i}.$$

$$E^{(2)}_{12} = -\frac{C_6}{R^6_{12}}$$
$$C_6 = \frac{1}{3}\frac{r(Ar)^4}{E_{SP}(Ar)}$$
$$r(Ar) = \langle P||r||S\rangle$$

Third order

$$E^{(3)}_{123} = \sum_{\sigma\in S_3, m_1, m_2, m_3} \frac{\langle 0_{\sigma(1)} 0_{\sigma(2)}|V_{\sigma(1)\sigma(2)}|m_{\sigma(1)} m_{\sigma(2)}\rangle\langle m_{\sigma(2)} 0_{\sigma(3)}|V_{\sigma(2)\sigma(3)}|0_{\sigma(2)} m_{\sigma(3)}\rangle\langle m_{\sigma(3)} m_{\sigma(1)}|V_{\sigma(3)\sigma(1)}|0_{\sigma(3)} 0_{\sigma(1)}\rangle}{(\Delta_{m_{\sigma(1)}}(\sigma(1))+\Delta_{m_{\sigma(2)}}(\sigma(2)))(\Delta_{m_{\sigma(1)}}(\sigma(1))+\Delta_{m_{\sigma(3)}}(\sigma(3)))}$$



Axilord-Teller-Muto (1943)
Bell 1970 for different ground state atoms

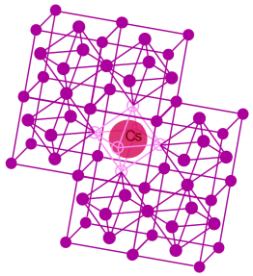
long-range

$$E^{(3)}_{123} = \frac{C_9}{R^3_{12}R^3_{23}R^3_{31}}\frac{1 - 3(\cos(2\theta_1) + \cos(2\theta_2) + \cos(2\theta_3))}{4}$$

$$C_9 = \frac{4}{9}r^2_{SP}(Cs)r^4_{SP}(Ar)\frac{E_{SP}(Cs) + 2E_{SP}(Ar)}{2(E_{SP}(Cs) + E_{SP}(Ar))^2 E_{SP}(Ar)}$$

Effective 2-body potentials

Marcelli-Wang-Sadus



the full crystal energy is $\frac{1}{2}\sum_{AB} E^{(2)}_{AB} + \frac{1}{6}\sum_{ABC} E^{(3)}_{ABC}$ can be written as sum of two body terms $E^{\text{eff}}_{AB} = \frac{1}{2}\sum_{AB}(E^{(2)}_{AB} + \frac{1}{3}\bar{E}^{(3)}_{AB})$.

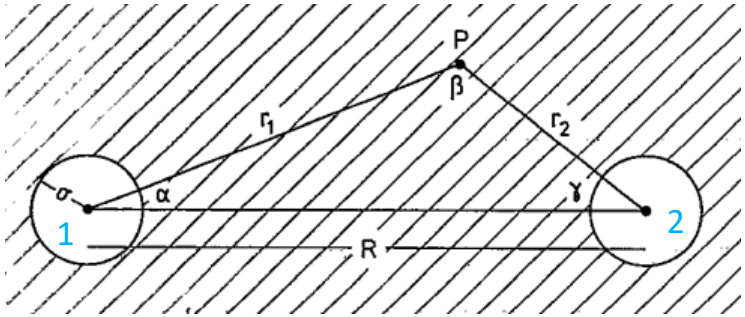
Effective Axilrod–Teller interaction in van der Waals gases and liquids

Herbert Stenschke
Freie Universität Berlin, Institut für Theoretische Physik, Arnimallee 14, 14195 Berlin, Germany

+ Yoshi muto 1943 !

V= $$E^{(3)}_{123} = \frac{C_9}{R^3_{12}R^3_{23}R^3_{31}} \frac{1 - 3(\cos(2\theta_1) + \cos(2\theta_2) + \cos(2\theta_3))}{4} \quad (B10)$$

Sum over atom 3



we replace the sum by an integral assuming Ar atoms uniformly distributed with the Ar solid density

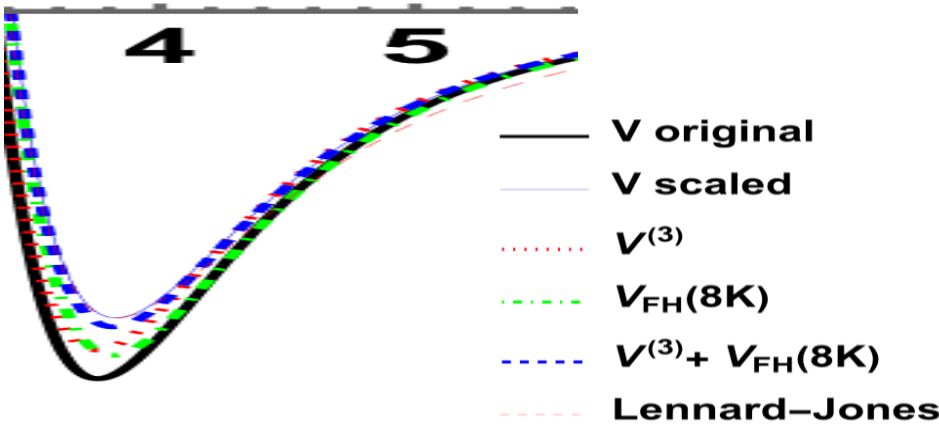
$$\bar{V} = 2\pi\rho \int V r^2 \sin\theta \mathrm{d}r\mathrm{d}\theta$$

$$\bar{V} = E^{(3)}_{12} = 2\pi\rho \frac{C_9}{R^6}\frac{4}{3} = E^{(2)}_{AB}(R)\left(1 - \frac{8\pi\rho}{9}\frac{C_9}{C_6}\right)$$

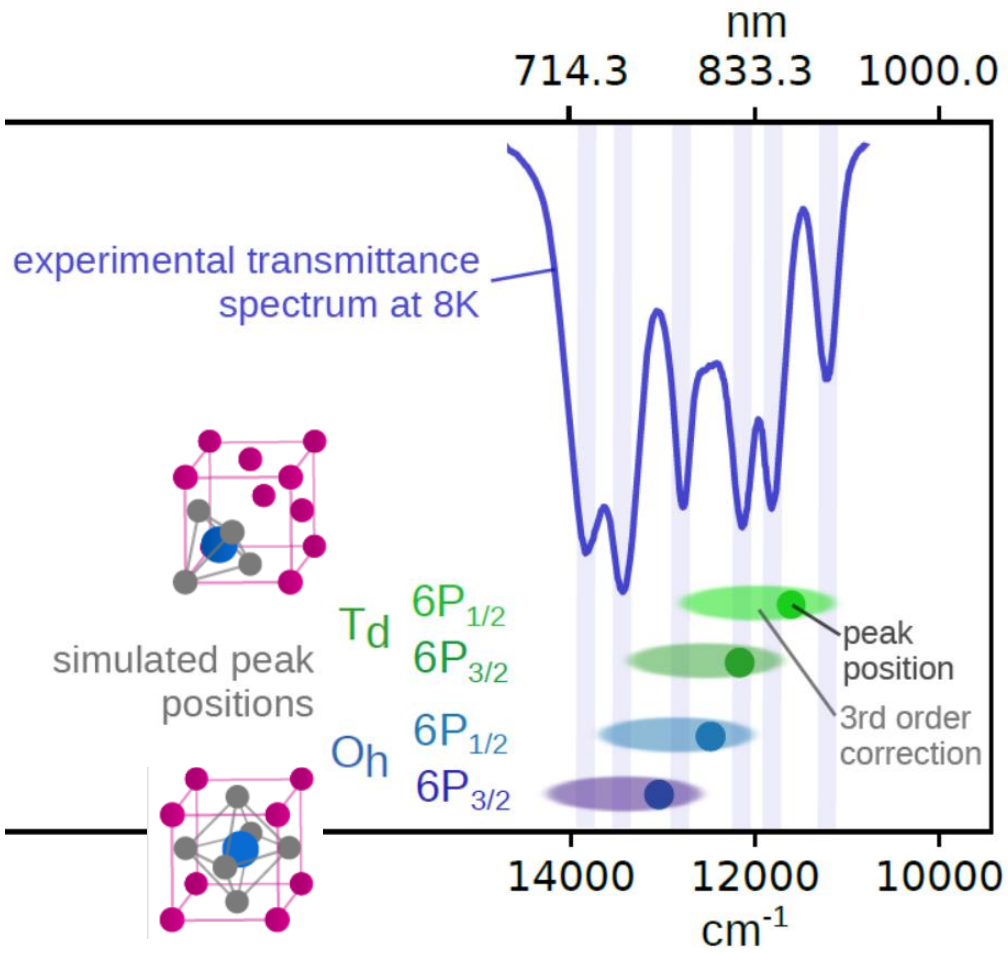
Miracle:
the cut off parameter does not enter the result
The final result is proportional to the two-body potential

For the liquid noble gases the correction is 1%, 3.5%, 7.5%, 10%, and 12% for He, Ne, Ar, Kr, and Xe, respectively.

→ **OK for Ar-Ar (same as scaled potential) . I generalze for Cs-Ar**



Reasonable line positions for 4(T_d) – 6 (O_h)
Sensitive to potentials + third order correction



Oh(6) blue shift

Td(4)~0 shift

Outline

- EDM worldwide → why EDM
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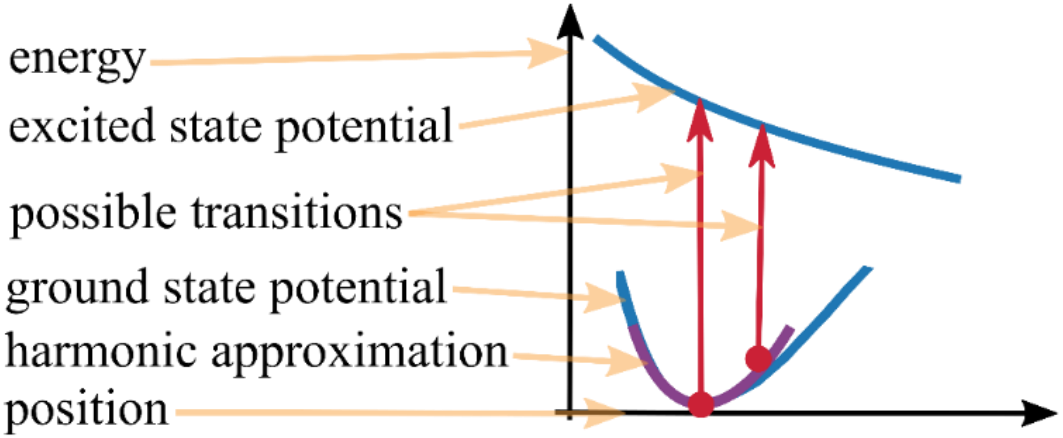
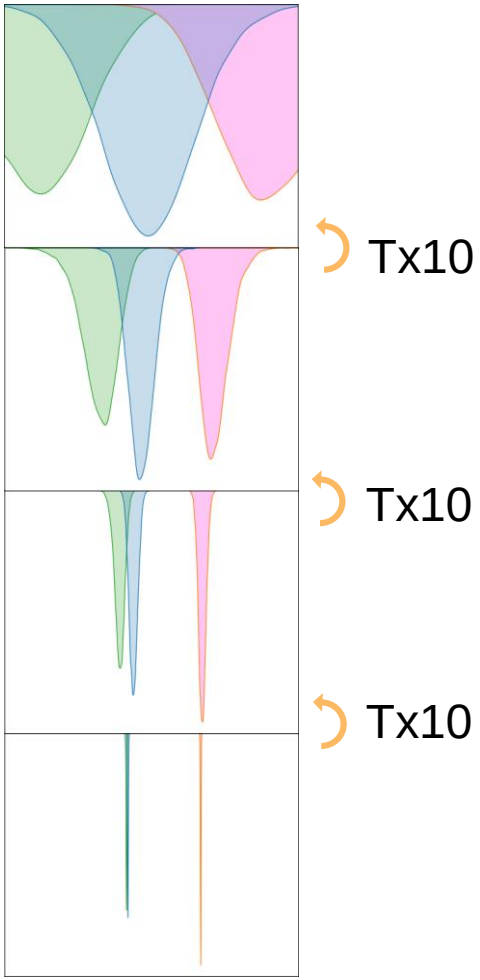
- Line broadening
- Possible improvement

Jahn-Teller Dynamical (thermal) effect
→ Broadening and splitting



Semi-classical Franck-Condon approximation

Crystal field
1st order in excited state



Crystal Field theory: effectif coupling parameters

JOURNAL OF THE PHYSICAL SOCIETY OF JAPAN, Vol. 25, No. 5, NOVEMBER, 1968

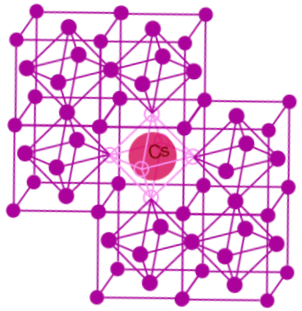
Optical Absorption Line Shapes Due to Transition from Orbital Singlet to Triplet States of Defect Centers with Cubic Symmetry

Kikuo CHO

Sum over Ar

$$\begin{pmatrix} X^2+Y^2-2Z^2 & 3\sqrt{2}(X+iY)Z & -3(X+iY)^2 \\ 3\sqrt{2}(X-iY)Z & -2(X^2+Y^2-2Z^2) & -3\sqrt{2}(X+iY)Z \\ -3(X-iY)^2 & -3\sqrt{2}(X-iY)Z & X^2+Y^2-2Z^2 \end{pmatrix}$$

$$\begin{pmatrix} V_{A_1}Q_{A_1} - \frac{V_E Q_{E,2}}{\sqrt{3}} & V_{T_2}\frac{iQ_{T_2,1}+Q_{T_2,2}}{\sqrt{2}} & -V_E Q_{E,1} - iV_{T_2}Q_{T_2,3} \\ V_{T_2}\frac{-iQ_{T_2,1}+Q_{T_2,2}}{\sqrt{2}} & V_{A_1}Q_{A_1} + 2\frac{V_E Q_{E,2}}{\sqrt{3}} & V_{T_2}\frac{-iQ_{T_2,1}-Q_{T_2,2}}{\sqrt{2}} \\ -V_E Q_{E,1} + iV_{T_2}Q_{T_2,3} & V_{T_2}\frac{iQ_{T_2,1}-Q_{T_2,2}}{\sqrt{2}} & V_{A_1}Q_{A_1} - \frac{V_E Q_{E,2}}{\sqrt{3}} \end{pmatrix}$$



The A_1 mode (Q_{A_1} varying as $X^2+Y^2+Z^2$) is a symmetrical radial one that preserves the symmetry, the E_g mode

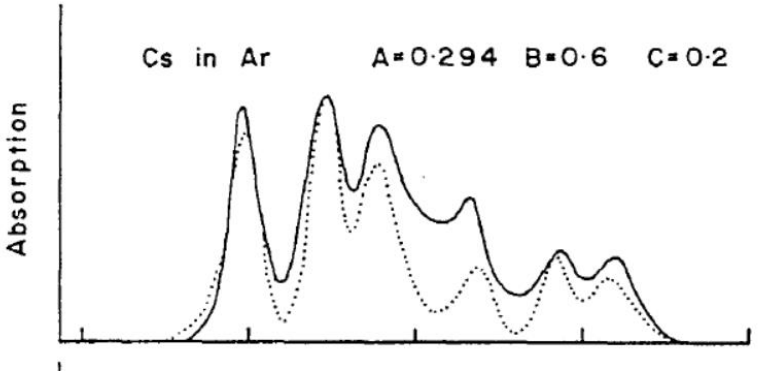
($Q_{E,1}$ varying as X^2-Y^2 and $Q_{E,2}$ as $2Z^2-X^2-Y^2$) is a tetragonal distortion that for instance modify the O_h symmetry into D_{4h}

T_2 ($Q_{T,1}, Q_{T,2}, Q_{T,3}$ varying respectively as XZ, YZ or XY)) bends the crystal to D_{3d} or C_{3v}.

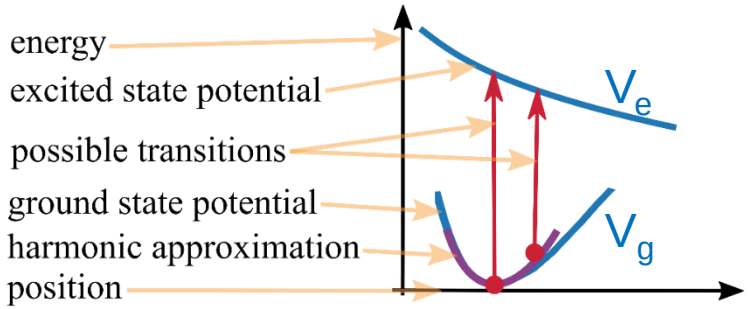
J. PHYS. SOC. JAPAN 31 (1971) 957~958

Optical Absorption Spectra of Cesium Atoms in Rare-Gas Matrices

Teinosuke KANDA and Takeo EBISU

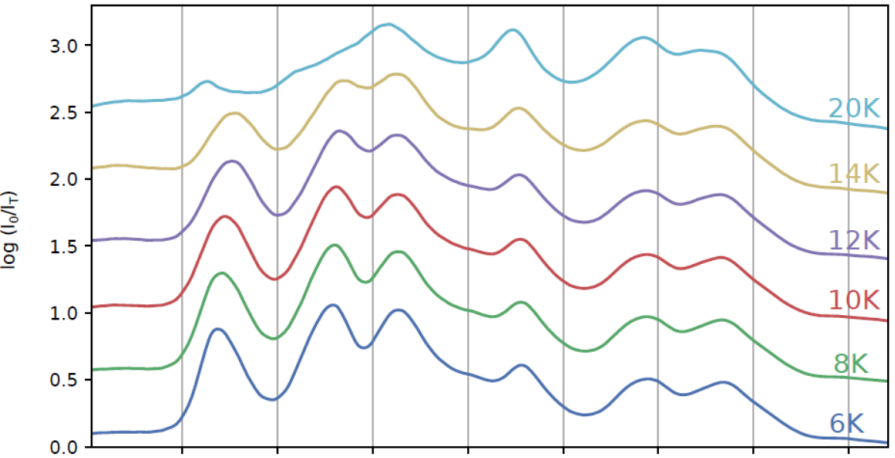


Classical (Mulliken) Simulation

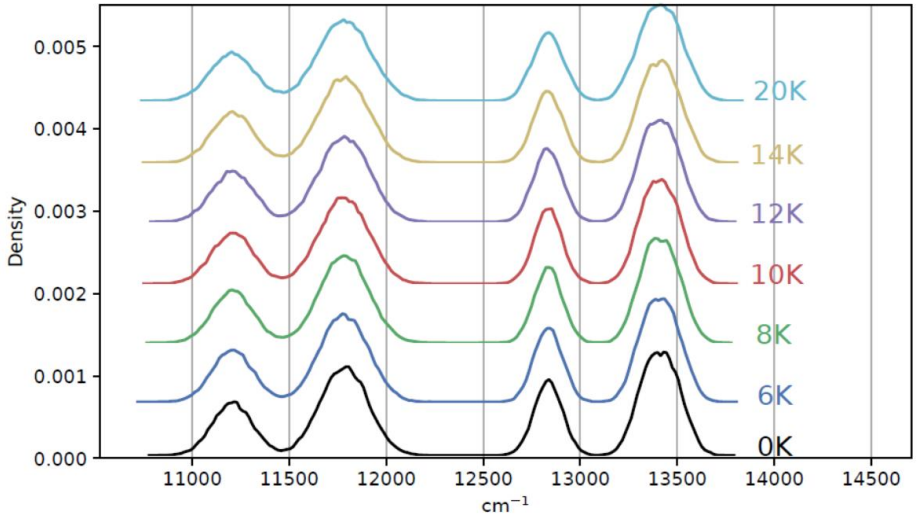


$$A(E) \propto \int P_{\mathrm{g}}(\boldsymbol{Q})\delta[E - (V_{\mathrm{e}}(\boldsymbol{Q}) - V_{\mathrm{g}}(\boldsymbol{Q}))]\mathrm{d}\boldsymbol{Q}$$

Experiment



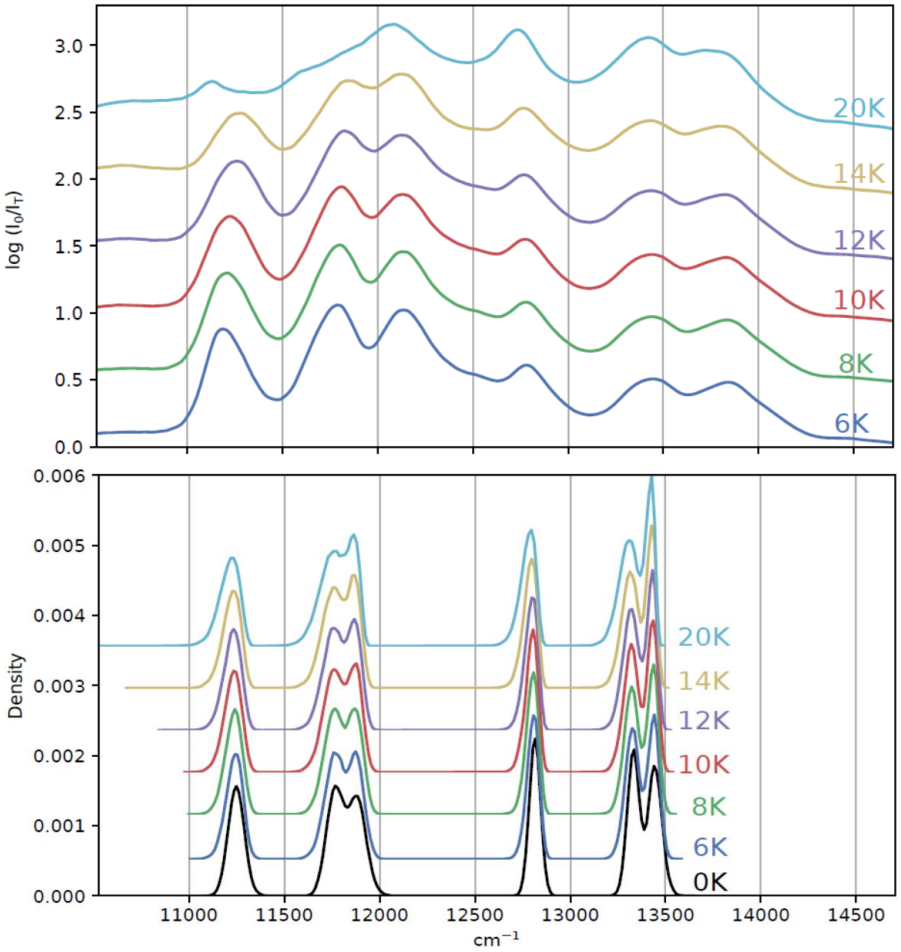
Theory for 4 and 6 vacancies

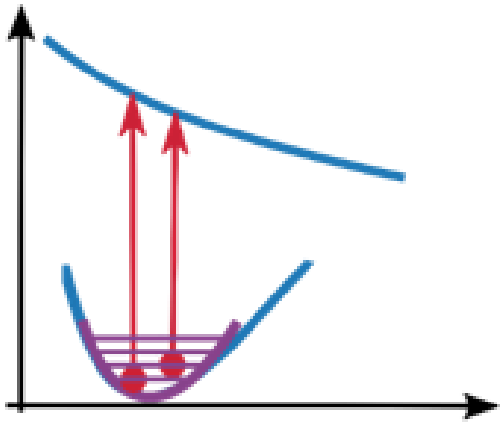


Semi-Classical (Reflexion approximation)

$$A(E) \propto \sum_i P_i \int |\Psi_i(\boldsymbol{Q})|^2 \, \delta[E - (V_e(\boldsymbol{Q}) - E_i)] \mathrm{d}\boldsymbol{Q}$$

Experiment



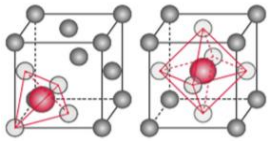


Theory

Outline

- EDM worldwide → why EDM
- Why in cryogenic solid: EDMMA project (Cs in Ar)
- Experimental setup: Cs absorption spectra
- Possible trapping sites: stability study
- Line broadening simulation
- Possible improvement

Conclusion

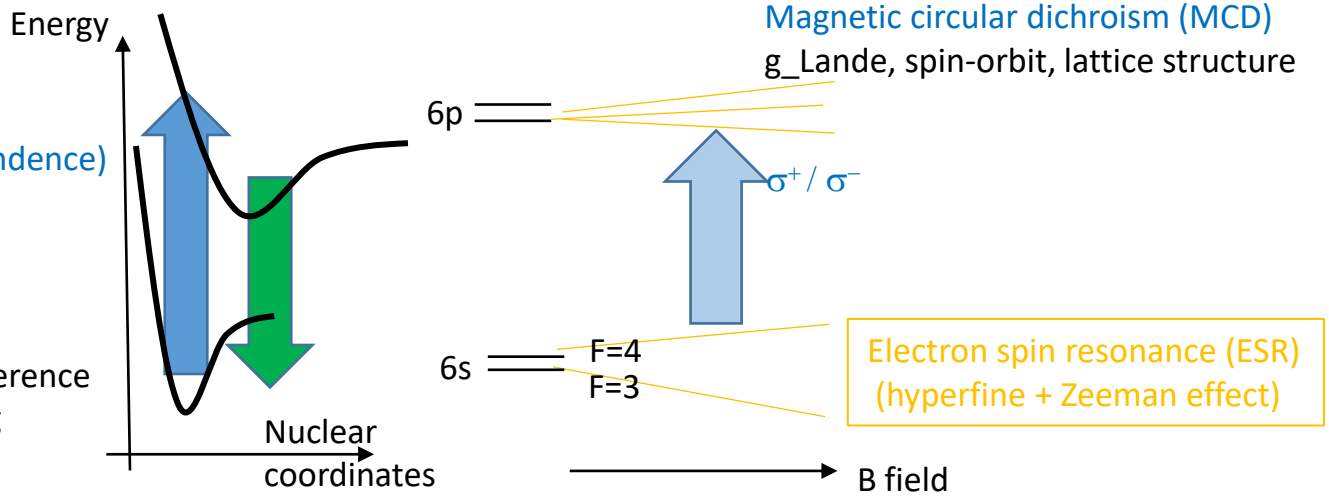


- Cs in Ar seems promising for EDM measurment below 10^{-30} e.cm → new physics
- In solid state systems, there can be dangerous mixing terms. But not present in O_h(6 vacancies)
- Absorption spectra shows that multiple trapping sites are present at the same time. Is it Td (4 vacnacies) + Oh (6 vacancies) chat about hcp phase ?

Next steps

More absorption (temperature dependence)
Fluorescence measurment
Temperature dependance
Magnetic circular dichroisme
Optical pumping
Electron Spin Resonance → Spin coherence
Magneto electric effects E/B coupling

Other atoms (Li, Na, K, Rb, Cs)
Other gaz (Kr, Xe, para-H_2) → move to EDM, axions



That’s it for now

http://www.lac.universite-paris-saclay.fr/Data/Stages/2022/1

•Sébastian LAHS (Master thesis, Germany): *Cs in a cryogenic matrix*

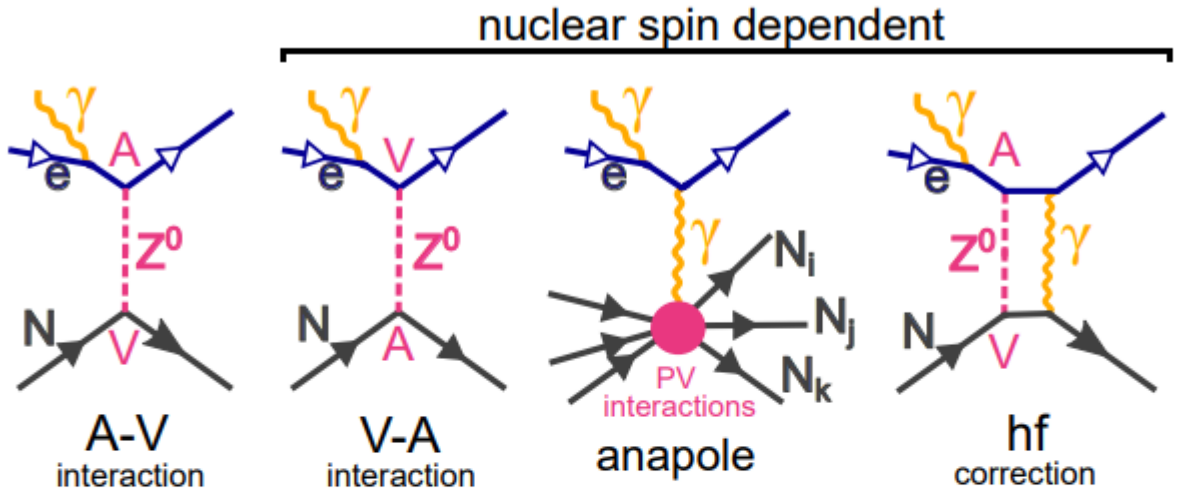


Figure 24: Leading order Feynman diagrams of the most significant parity violating electron-nucleon interactions. From left to right: nucleus-vector to electron-axial-vector (A-V) weak neutral current, nucleus-axial-vector to electron-vector (V-A) weak neutral current, Nuclear anapole moment to electron electromagnetic interaction, weak correction to the hyperfine (hf) coupling.

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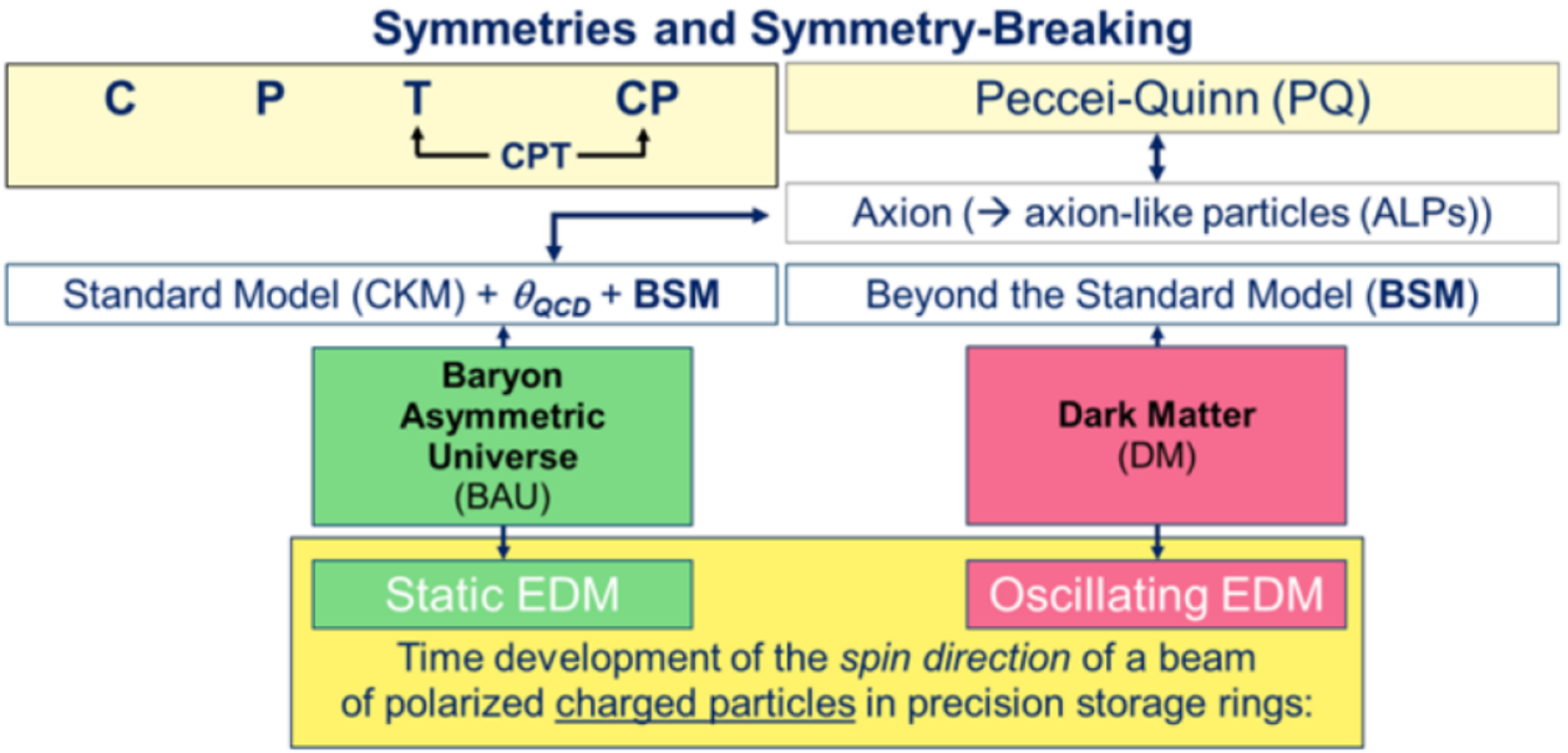
Article

Precision Storage Rings for Electric Dipole Moment Searches: A Tool En Route to Physics Beyond-the-Standard-Model

Hans Ströher [1,*], Sebastian M. Schmidt [2,3], Paolo Lenisa [4] and Jörg Pretz [1,3]



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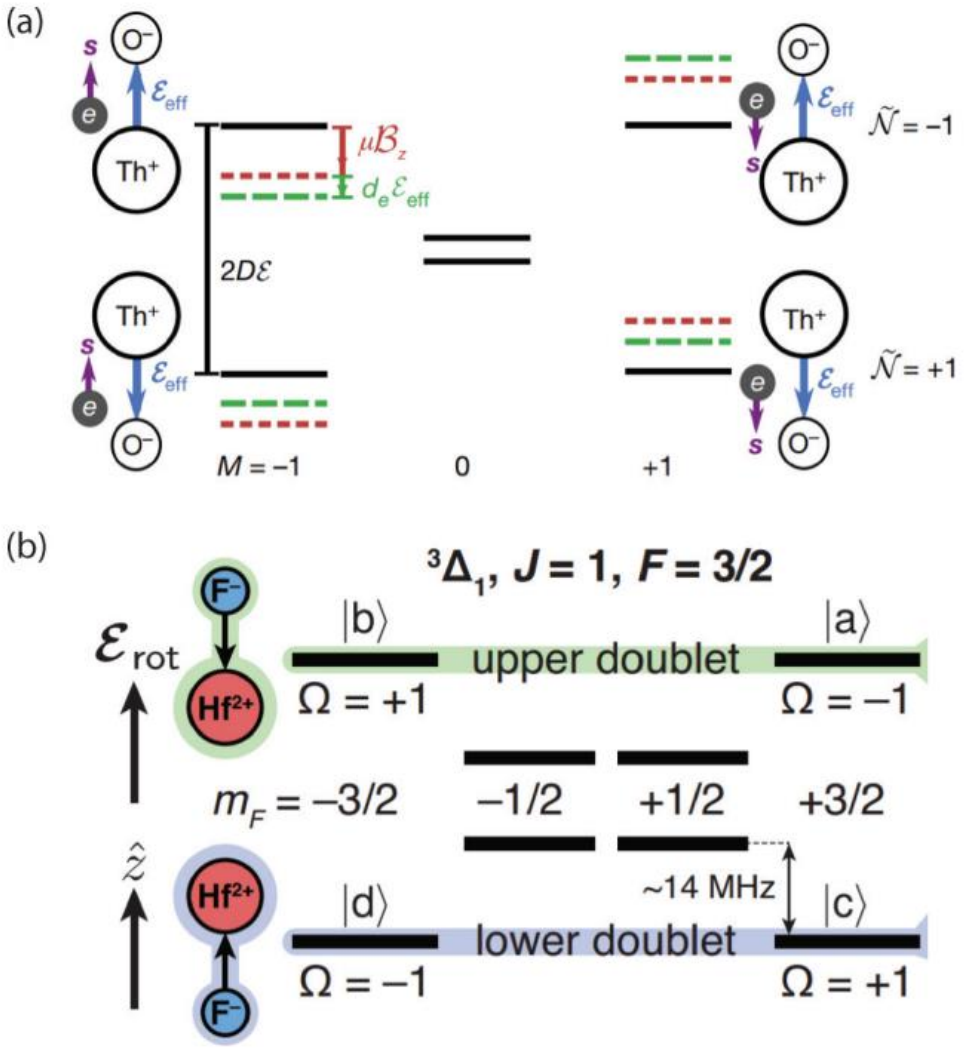
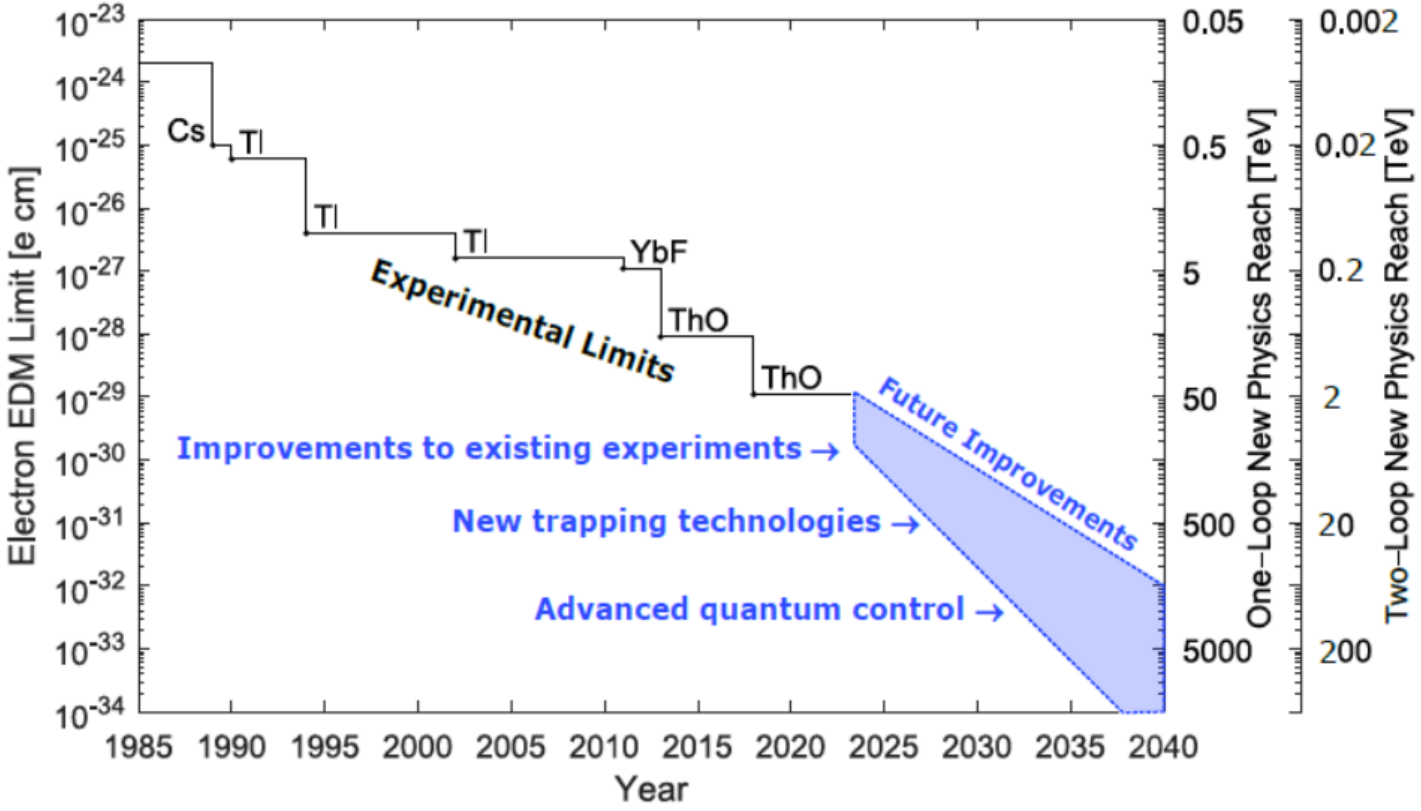


Blum, T., Winter, P., Bhattacharya, T., Chen, T. Y., Cirigliano, V., DeMille, D., ... & Semertzidis, Y. K. (2022). Fundamental Physics in Small Experiments. *arXiv preprint arXiv:2209.08041*.



B. Searches for electric dipole moments

A permanent electric dipole moment of a particle or system would imply the presence of a new source of CP violation, which could explain the matter-antimatter asymmetry in the Universe.

- The nEDM@SNS experiment, which will use unique cryogenic techniques to make the most precise search for the neutron's EDM, moved from R&D to construction of the apparatus, starting with the cryostats and the magnetic field system. Assembly and testing has now begun at ORNL's SNS [38].
- The LANL nEDM experiment achieved the polarized UCN density required for goal sensitivity [39, 40]. A magnetically shielded room was installed and the magnetic fields characterized. Precession chambers, electrodes, and UCN valves are ready and magnetometers are under development.
- Numerous atomic EDM experiments, using methods ranging from vapor cells to optical lattices, improved sensitivity to hadronic CP-violation via nuclear Schiff moments in atoms such as ^{199}Hg [41], ^{225}Ra [42, 43], and ^{129}Xe [44, 45], and a new experiment reported a limit on the ^{171}Yb EDM [46].
- Work with radioactive pear-shaped nuclei, which are extremely sensitive to hadronic CP violation, has made major progress [47]: the Ra EDM work mentioned above, the first spectroscopy on a radioactive molecule, RaF [48], and the first control of radium-containing molecular ions [49, 50].
- Limits on the electron EDM were improved by an order of magnitude by the ACME [51] and JILA [52, 53] experiments, which leverage internal molecular electric fields. The YbF [54] and NL-EDM eEDM [55] experiments made major improvements in laser-cooling [56] and trapping [57].
- Atomic electron-EDM experiments with Cs [58] and Fr [59] continued their push to leverage quantum science methods. Several new molecular approaches are under development, including laser-cooled polyatomics [60, 61] and matrix-isolated diatomics [62].
- Molecular eEDM methods are being expanded to search for hadronic CP violation, both through nuclear Schiff moments and magnetic quadrupole moments, in several active experiments, including CeNTREX [63], YbOH [60, 64], and YbF [65] and several others in initial stages of development.
- The phenomenology of EDMs was connected with physics at the energy frontier [66–69]. The ways in which the EDM program and LHC complement each other in exploring the origin of CP violation and the Universe's matter-antimatter asymmetry are now much better understood [70–72].
- Lattice QCD calculations of the nucleon EDM have appeared [73–81], paving the way for results with quantified uncertainties. At the nuclear level, we have new Schiff moment computations [82–84]. Progress in *ab initio* techniques promises *ab initio* calculations of Schiff moments soon [85].