Beyond standard model using atom in cryogenic matrix: the electron electric dipole moment

Daniel Comparat

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Numerous problem to be solved ☾ New physics

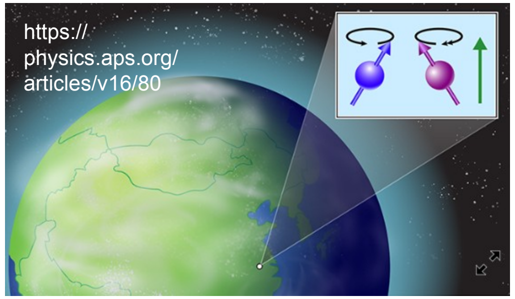
- **Questions in Fundamental Physics**:
  - Nature of dark matter and dark energy.
  - Unification of quantum mechanics (probabilistic, discrete) and general relativity (deterministic, continuous).
  - Neutrino mass existence: Standard Model massless, but neutrino oscillations ☾ they have

Charge (C): e^+ ☾ e^-
Parité (P): r ☾ -r
Temps (T): t ☾ -t

- **Tensions**:
  - Matter-antimatter asymmetry: CP violation predicted is insufficient to explain the
  - Muon g-2 anomaly: measured magnetic moment disagree with theory -> new particles or forces?
  - B meson decay anomalies: decays deviate from Standard Model ☾ new particles leptoquarks?
  - Proton radius puzzle: Value obtained via electron scattering or by muonic hydrogen differs
- **Not happy with:**
  - Strong CP Problem: In quantum chromodynamics no observed CP violation even if possible ($\theta < 1e\text{-}10$) ☾ Axions
  - Hierarchy problem.
    - Vast difference in the strengths of the fundamental forces.
    - Higgs boson's mass contributions due to its interactions with other particle should increase its Higgs mass dramatically but to avoid this require coupling constants values tuned to an extreme precision

AMO Physics can play a (big) role

Gravitation and quantum mechanics



Search for exotic force (spin-gravity)

Search for violation of quantum statistics

Precision test of Quantum electrodynamics

Atomic parity violation

Time reversal violation: electric dipole moments

Charge (C): e^+ ☾ e^-
Parité (P): r ☾ -r
Temps (T): t ☾ -t

Test of CPT theorem: matter-antimatter comparisons

Lorentz symmetry tests

Search for (light) dark matter

Axion as dark matter
→ osc. eEDM

$$(\partial^\mu \partial_\mu - m^2)\, a(x) = 0$$

$$\Rightarrow d_e \propto E\, a_o \sin(m_a t)$$ Axion mass

$$\frac{m_a t}{\hbar = 6.582\times 10^{-16} eV}$$

Search for time variation of fundamental constants

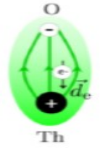
SEARCHES FOR BSM PHYSICS WITH ATOMIC, MOLECULAR, AND OPTICAL PHYSICS

Mariana Safranova

Fundamental symmetries with quantum science techniques

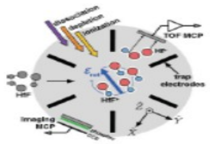
Searches for electron electric-dipole moment (eEDM)

Advanced ACME



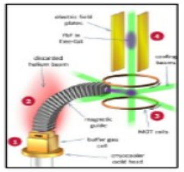
ThO

JILA eEDM



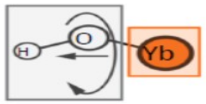
HfF⁺, ThF⁺

Imperial College



YbF

PolyEDM

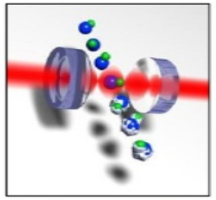


Also NMQM search

YbOH, ...

Searches for hadronic EDMs

CeNTREX

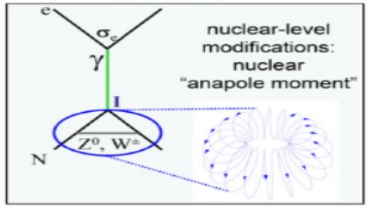


Hg
Xe
Ra
EDMs

TlF (proton EDM)

Enhanced parity violation

ZOMBIES



Also Yb (Mainz), Fr (FRIUMF & Japan)

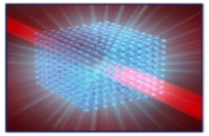
Rapid advances in ultracold molecule cooling and trapping; polyatomic molecules; future: molecules with Ra & "spin squeezed" entangled states

Atomic and Nuclear Clocks & Cavities

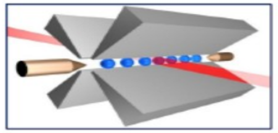
Major clock & cavities R&D efforts below, also molecular clocks, portable clocks and optical links

BSM searches with clocks

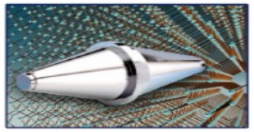
- Searches for variations of fundamental constants
- Ultralight scalar dark matter & relaxion searches
- Tests of general relativity
- Searches for violation of the equivalence principle
- Searches for the Lorentz violation



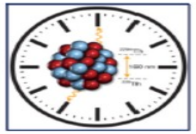
3D lattice clocks



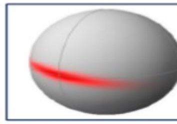
Multi-ion & entangled clocks



Ultrastable optical cavities



Nuclear & highly charge ion clocks



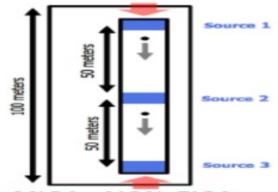
Measurements beyond the quantum limit

Atom interferometry

BSM searches:
Variation of fundamental constants
Ultralight scalar DM & relaxion searches
Violation of the equivalence principle

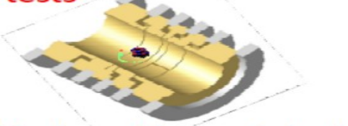
Prototype gravitational wave detectors

MAGIS-100 Fermilab



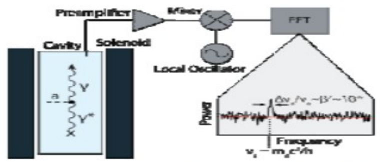
MIGA, AION, ZIGA

QED tests



Highly charged ions and simple systems (H, D, $^3He^+$, He, Li, HD, ...)

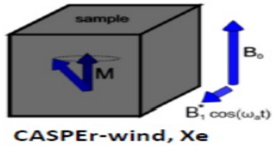
Axion and ALPs searches



Microwave cavities: HAYSTAC

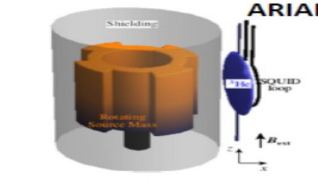
AMO: measurements beyond quantum limits

CASPEr-electric, solids
(coupling to gluons)



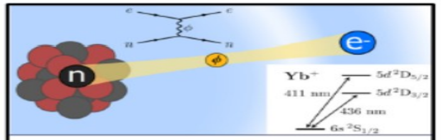
CASPEr-wind, Xe
(coupling to fermions)

ARIADNE

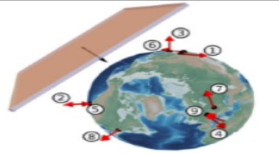


Resonantly detecting axion-mediated forces with NMR

Other dark matter & new force searches

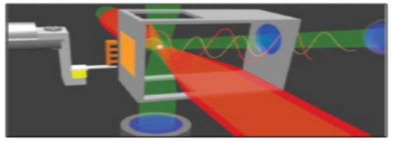


Fifth force searches with precision spectroscopy with atoms and ions



GNOME: network of optical magnetometers for exotic physics

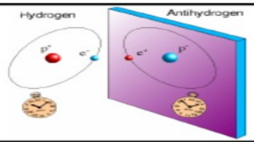
Levitated optomechanics



Also: GW detection and testing the Newtonian inverse square law

CPT tests

$\overline{p}, \overline{H}$



Many other current & future experiments: tests of the gravity-quantum interface, and HUNTER, SHAFT, ORGAN & UPLOAD (axions), solid-state directional detection with NV centers (WIMPs), doped cryocrystals for EDMs, Rydberg atoms, ...

Fundamental Physics in Small Experiments

T. Blum, P. Winter

T. Bhattacharya, T.Y. Chen, V. Cirigliano, D. DeMille, A. Geraci, N.R. Hutzler, T.M. Ito, D. Kaplan, O. Kim, R. Lehnert, W.M. Morse, Y.K. Semertzidis

Springer Handbook of Atomic, Molecular, and Optical Physics

Searches for New Physics

Marianna S. Safronova

nature physics

Review article https://doi.org/10.1038/s41567-024-02499-9

Quantum sensing and metrology for fundamental physics with molecules

Received: 10 August 2023

Accepted: 2 April 2024

David DeMille[1,2], Nicholas R. Hutzler[3], Ana Maria Rey[4,5] & Tanya Zelevinsky[6]

PHYSICAL REVIEW LETTERS **132,** 190001 (2024)

Essay: Quantum Sensing with Atomic, Molecular, and Optical Platforms for Fundamental Physics

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REVIEWS OF MODERN PHYSICS, VOLUME 97, APRIL–JUNE 2025

Spin-dependent exotic interactions

P and T violation —> Good observable for new physics

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

Conserved parity P (r ☾ -r)

Time reversal T (t ☾ -t)

Charge conjugaison C (q ☾ -q)

size of known violating observable

zero

small

- Physicists have been wrong before…
- P violation---Wolfgang Pauli:[1]
  "I do not believe that the Lord is a weak left-hander, and I am ready to bet a very high sum that the experiments will give symmetric results."
- CP violation---Lev Landau:[2]
  "If CP is violated, I will hang myself."

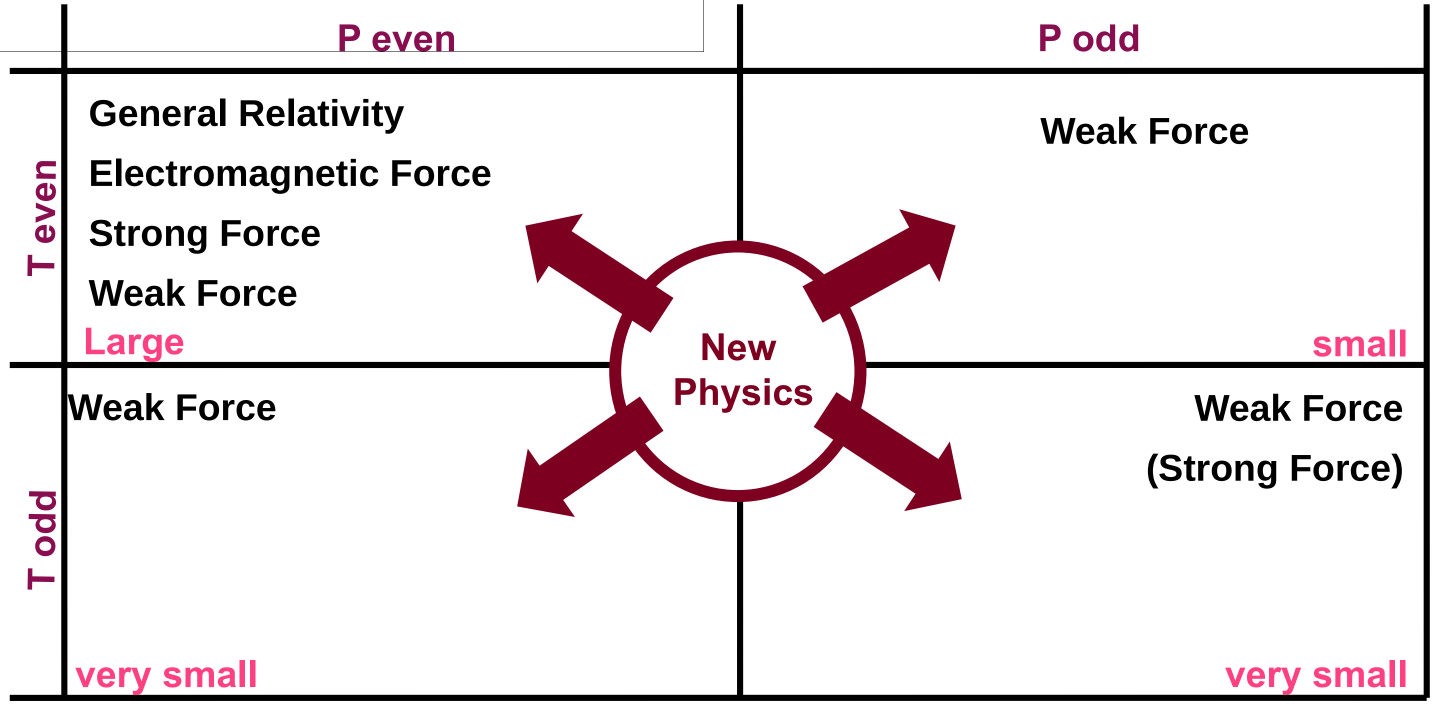
[1] Pauli in a letter to Victor Weisskopf, quoted in the Ambidextrous Universe, by Martin Gardner.
[2] Oral history, as related by Dima Budker.

T violation via CPT ☾ CP violation (can explain matter/antimatter asymmetry: Sakharov)

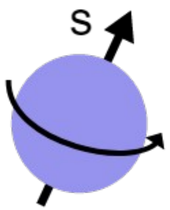
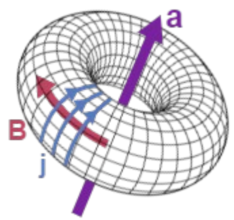
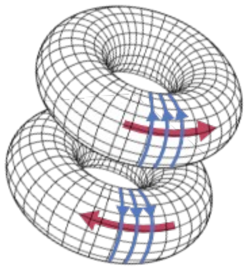
$$H = H^0 + V^{EM} + V^N$$

$$V^N = -V^P - V^{PT} - V^T$$

V^P	V^{PT}	V^T
P-odd *T*-even	*P*-odd *T*-odd	*P*-even *T*-odd



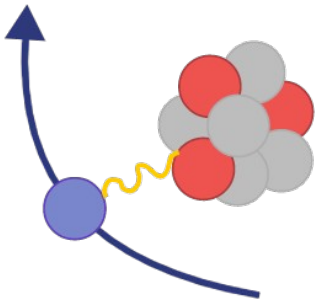
Parity **P** and Time reversal **T**

	P even	**P odd**
T even	Magnetic Dipole moment  Electric Quadrupole, Magnetic Octupole,...	Anapole moment 
T odd	Tetrapole moment 	Electric Dipole moment  Magnetic Quadrupole, Electric Octupole,...

P&T violating moments

8

Atomic Hamiltonians



T-odd, P-odd

$$H_{EDM} = S\boldsymbol{I} \cdot \left[\boldsymbol{\nabla}\delta(\boldsymbol{r})\right]$$

T-even, P-odd

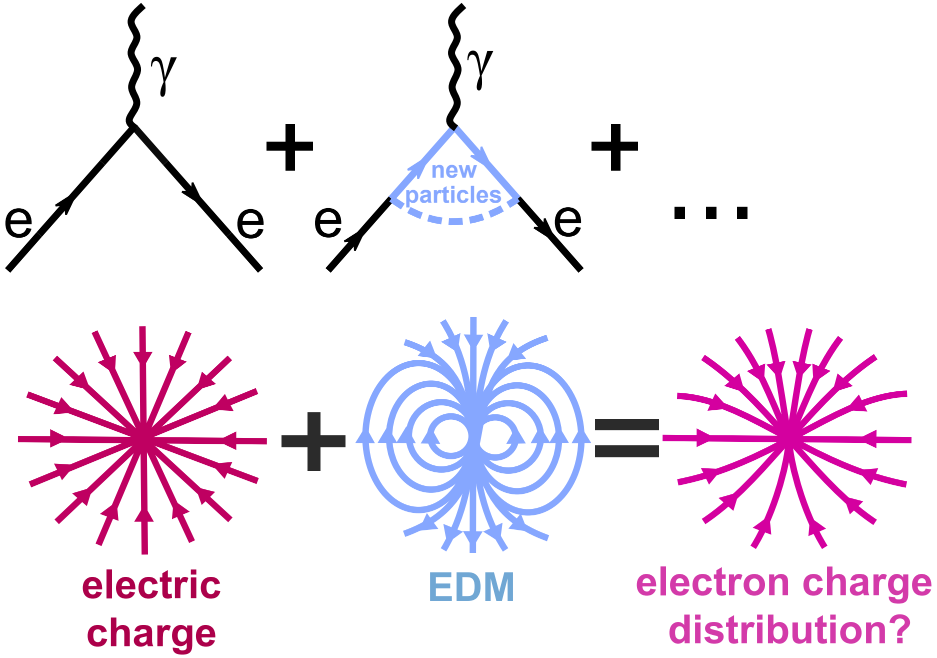
$$H_{\text{anapole}} = \frac{a}{I}\frac{1}{2m}\left[\boldsymbol{I} \cdot \{\boldsymbol{p}, n(\boldsymbol{r})\} + i(\boldsymbol{I} \times \boldsymbol{\sigma}) \cdot \{\boldsymbol{p}, n(\boldsymbol{r})\}\right]$$

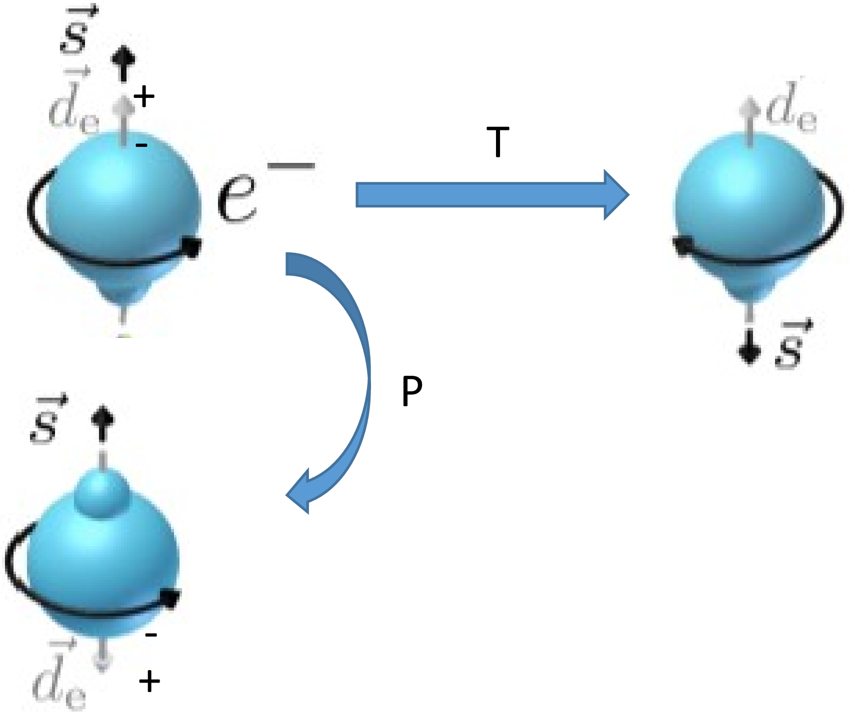
T-odd, P-even

$$H_{\text{tetrapole}} = \frac{t}{2m}\left[iQ_{ij}^{I^2}\left[\partial_i\partial_j, \delta(\boldsymbol{r})\right] + \frac{3\left\{(\boldsymbol{I} \times \boldsymbol{\sigma})_i, I_j\right\}\left[\left[\partial_i\partial_j\delta(\boldsymbol{r})\right] - \delta(\boldsymbol{r})\partial_i\partial_j\right]}{2I(2I-1)}\right]$$

nuclear spin electron spin

P and T violation: Electric Dipole Moment (EDM)





T violation via CPT ☾ CP violation (can explain matter/antimatter asymmetry: Sakharov)

EDM – worldwide

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

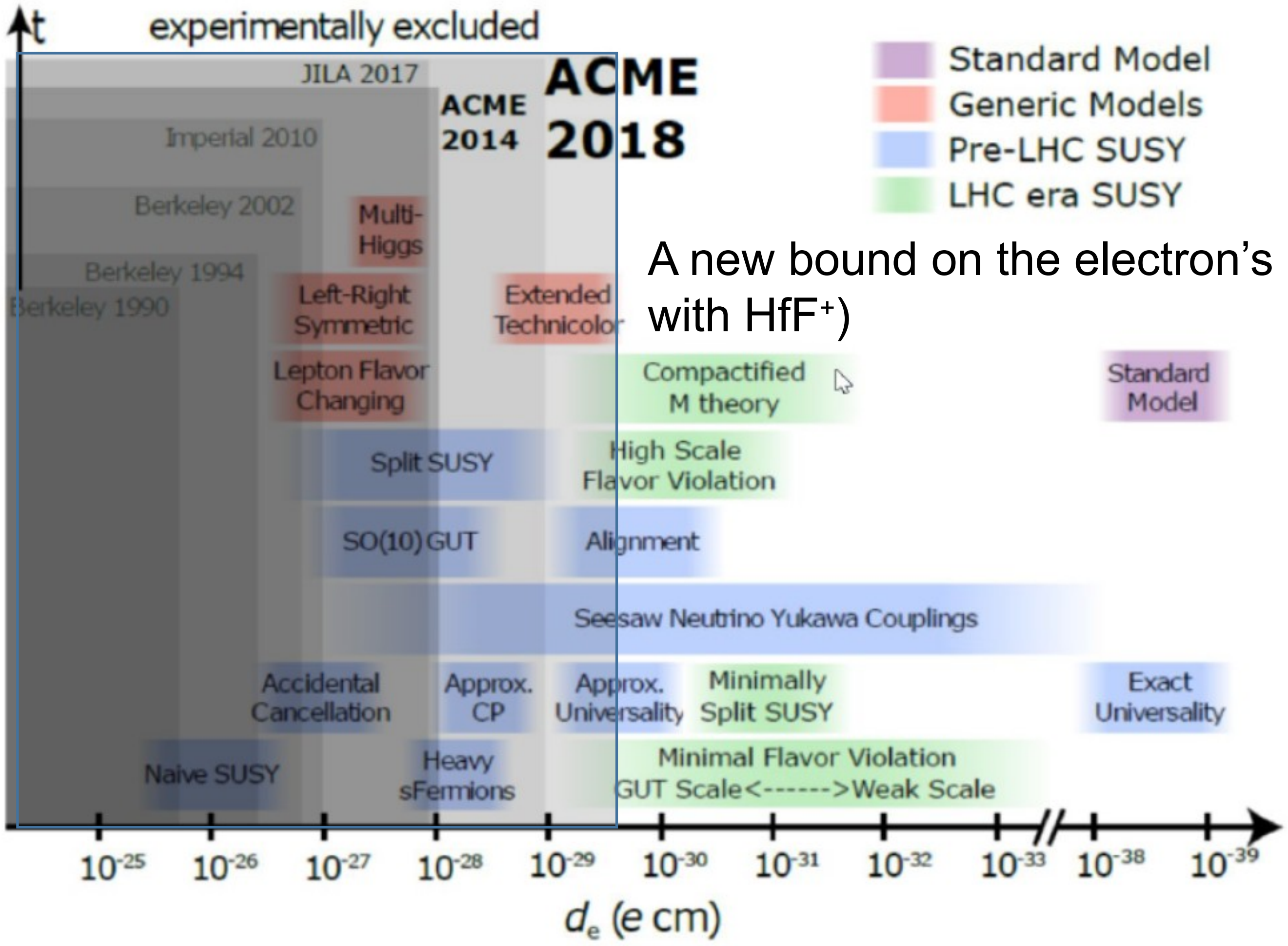
Atoms: (~ 60 ppl.)

- 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

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



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

Super high energy physics with table top experiments

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

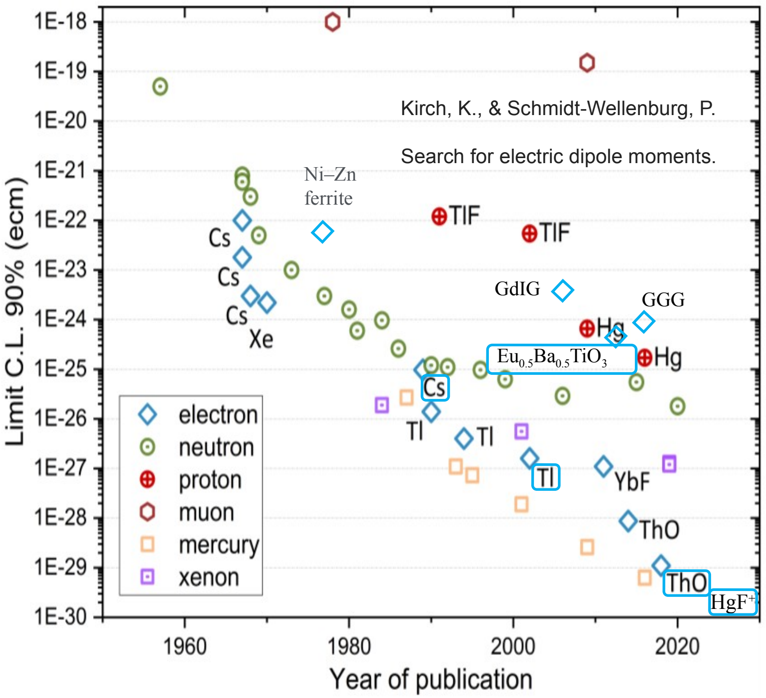
0.05	0.5	5	50	500	5000	One loop (TeV)
0.005	0.05	0.5	5	50	500	Two loops (TeV)

EDM status and project (for electron)

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

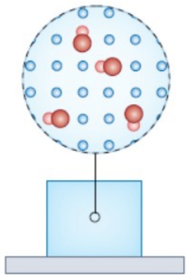
$$d.E_{\text{eff}} = \frac{\hbar}{\epsilon_{\text{polar}}\tau\sqrt{N}}$$

Some EDM history



Particle	N_T time integrated	Time [s]	Polarization Epsilon,	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^{7}	3	0.8	$2\ 10^{10}$	$4\ 10^{-30}$

Ideal



N big

τ long

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

Supersymmetry (SUSY),
Multi-Higgs,
Symmetrical Left-Right
Leptoquarks,
Additional dimensions,
Technicolor and Composite Models,
Axion Models,
Neutrino Mass Models,
Grand Unification Theories (GUT),
CP-Violant QED Sector Extensions,
Mirror Matter Models

Standard Model electron EDM ~10^{-38} e.cm

Which atom/molecule ?

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

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

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

Schiff's theorem

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

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

with $\varepsilon_s \approx 1$ and $\varepsilon_p \approx \frac{\langle s\,|ez|\,p\rangle}{\mathcal{E}(s)-\mathcal{E}(p)}E_\mathrm{lab}$

Ex: Atoms 1st order (Perturbation Stark effect)

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

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

$\langle\psi|H_e|\psi\rangle \sim d_e(100\,\mathrm{GV/cm})$ ThO, HfF^+, ..

How to measure —> Ramsey spectroscopy

PHYSICAL REVIEW VOLUME 108, NUMBER 1 OCTOBER 1, 1957

Experimental Limit to the Electric Dipole Moment of the Neutron

J. H. Smith,* E. M. Purcell, and N. F. Ramsey
Oak Ridge National Laboratory, Oak Ridge, Tennessee, and Harvard University, Cambridge, Massachusetts
(Received May 17, 1957)

An experimental measurement of the electric dipole moment of the neutron by a neutron-beam magnetic resonance method is described. The result of the experiment is that the electric dipole moment of the neutron equals the charge of the electron multiplied by a distance $D=(-0.1\pm2.4)\times10^{-20}$ cm. Consequently, if an electric dipole moment of the neutron exists and is associated with the spin angular momentum, its magnitude almost certainly corresponds to a value of D less than 5×10^{-20} cm.

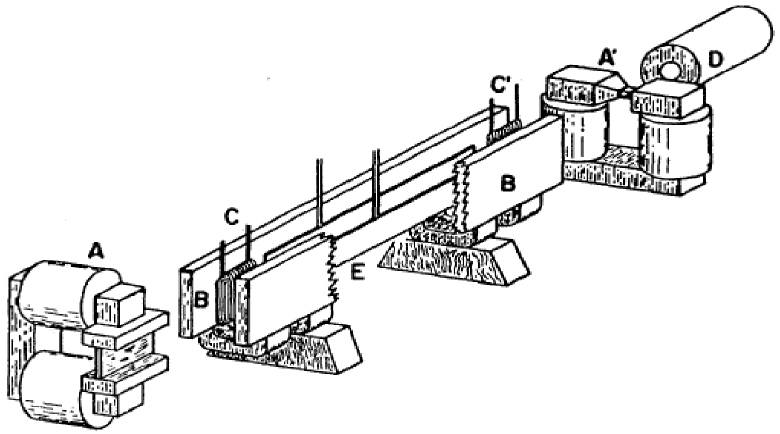
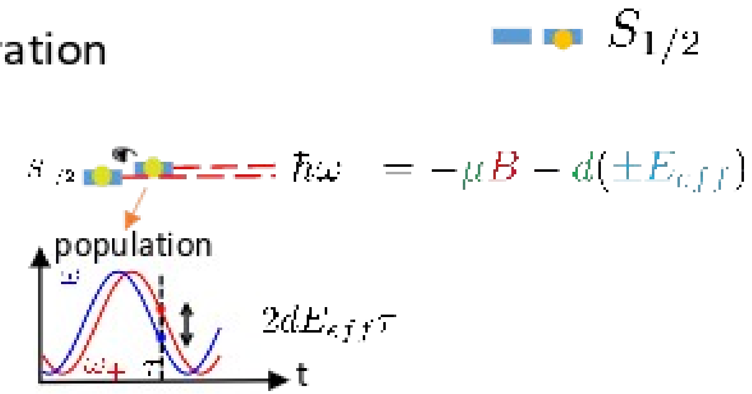


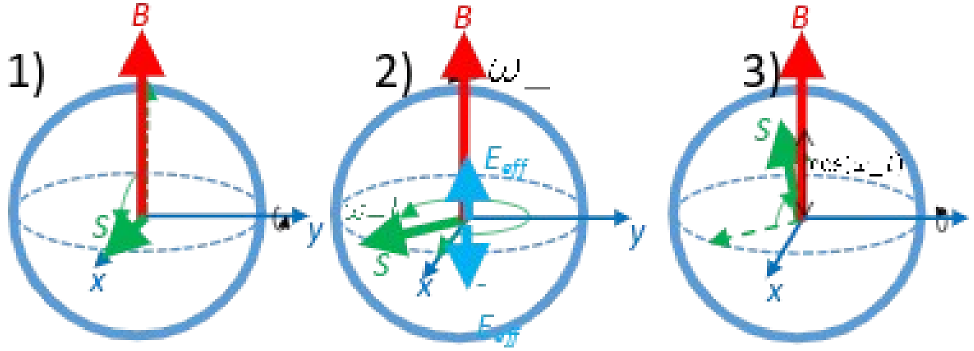
Fig. 1. Schematic diagram of the apparatus. A, the magnetized iron mirror polarizer. A', the magnetized iron transmission analyzer. B, the pole faces of the homogeneous field magnet. Note the horseshoe-like magnets bolted along the bottom. C, C', the coils for the radio-frequency magnetic field. D, the BF_3 neutron counter. The magnetic fields in the polarizing magnet and the homogeneous field magnet are at right angles, and two twisted iron strips were used between them to rotate the neutron spins adiabatically.

1) Spin preparation

2) Precession

3) Readout





EDM in matrix

EDMMA

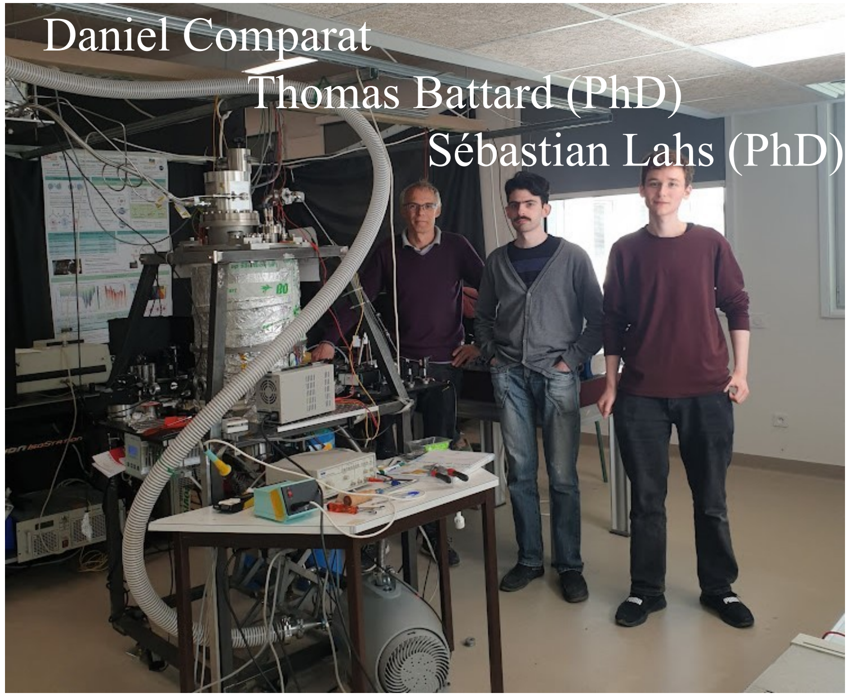
Wutharath Chin, **Claudine Crépin-Gilbert**

Julie Douady, **Benoit Gervais,** Erwan Hochard, Emmanuelle Jacquet, Raphael Photopoulos

Chloé Malbrunot

Benoit Darquié, Mathieu Manceau,

Hemanth Dinesan (Post-Doc)
Subham Mahapatra (M2)

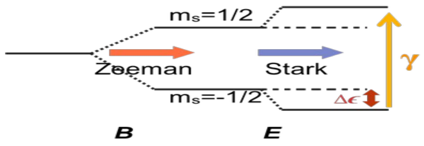
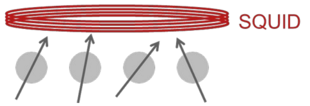


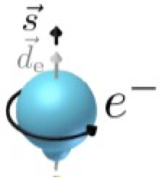
PHYSICAL REVIEW A **108**, 042820 (2023)

Cesium atoms in a cryogenic argon matrix

T. Battard,[1] S. Lahs,[1] C. Crépin,[2] and D. Comparat[1,*]

History of 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	$d_e = (1 \pm 4.6)\mathrm{x}10^{-16}$	EPR spectroscopy	
1979	Nickel-Zink-Ferrite	$d_e = (8.1 \pm 11.6)\mathrm{x}10^{-23}$	Magnetometry	
2004	GdIG	$d_e = (2 \pm 3)\mathrm{x}10^{-24}$	Voltage measurement	B field, align spin ☾ dipole ☾ Create +/- charges
2011	GGG	$d_e = (-5.57 \pm 7.98_{stat} \pm 0.12_{syst})\mathrm{x}10^{-25}$	Magnetometry	E field, align dipole ☾ Spin ☾ Create B field
2012	$Eu_{0.5}Ba_{0.5}TiO_3$	$d_e = (-1.07 \pm 3.06_{stat} \pm 1.74_{syst})\mathrm{x}10^{-25}$	Magnetometry	



d_e aligned along S

Broken symmetry -> magnetoelectric

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

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

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

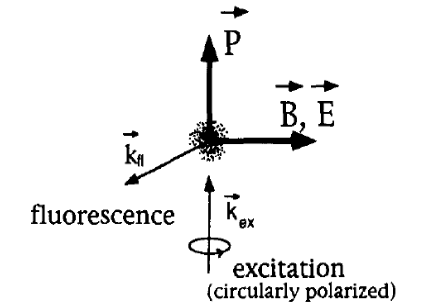


Fig. 4. Geometry of the proposed EDM experiment.

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

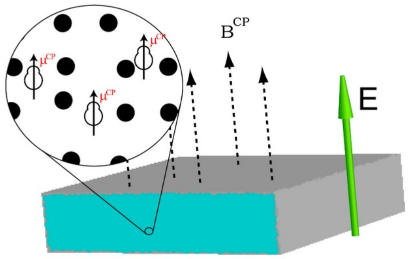
Physics Letters A 174 (1993) 298–303

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

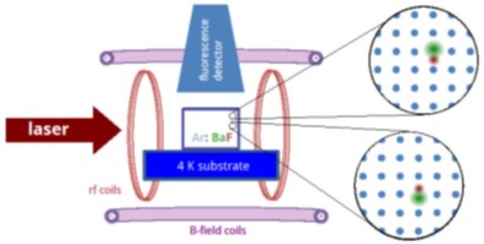
Article

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

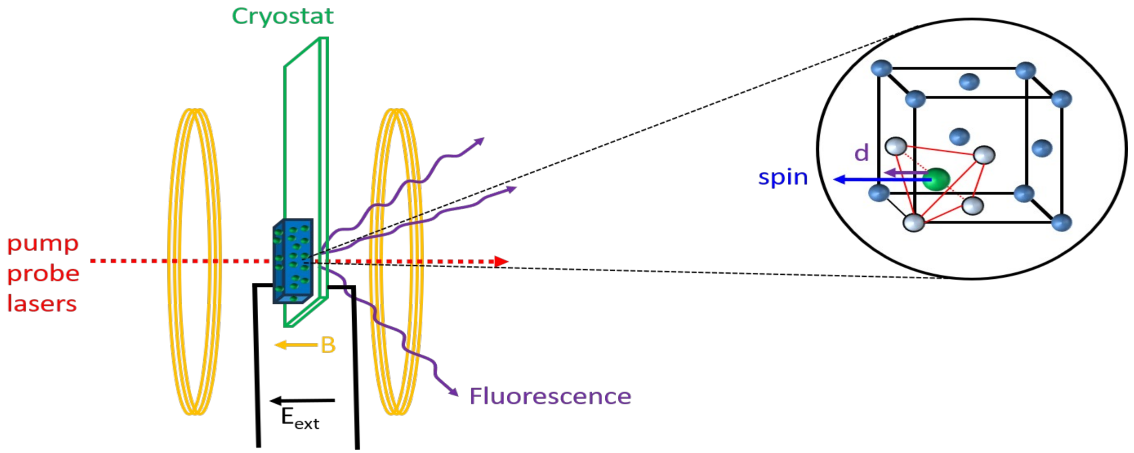
A. C. Vutha [1,*], M. Horbatsch [2] and E. A. Hessels [2]

BaF
…

Experiment schematic



EDM in Matrix



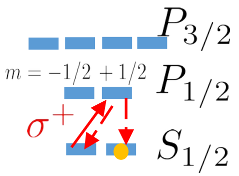
- atoms (Rb, Cs, Tm, Yb, ...)
- molecules (BaF, RaF, ..)
- in rare-gas (Ne,Ar mainly) or parahydrogen

- Lambo R, Xu CY, Pratt S, Xu H, Zappala J, Bailey K, ***Lu ZT***, Mueller P, O'Connor T, Kamorzin B et al.. 2021 High-resolution spectroscopy of neutral **Yb atoms** in a solid Ne matrix. Physical Review A 104, 062809.
- Braggio C, Calabrese R, ***Carugno G***, Fiscelli G, Guarise M, Khanbekyan A, Noto A, Passante R, Rizzuto L, Ruoso G et al.. 2022 Spectroscopy of **Alkali Atoms** in Solid Matrices of Rare Gases: Experimental Results and Theoretical Analysis. Applied Sciences 12, 6492.
- Gaire V, ***Parker C***, Raman C, Li J, Pei Y. 2022 Excitation of magnetic dipole transition of **Thulium** atoms trapped in rare gas crystals. In APS Division of Atomic, Molecular and Optical Physics Meeting Abstracts vol. 2022 pp. H04–009.
- Li S, Ramachandran H, Anderson R, ***Vutha A***. 2023 Optical control of **BaF molecules** trapped in **neon ice**. New Journal of Physics.
- Lambo R, Koyanagi G, Horbatsch M, Fournier R, **Hessels E**. 2023 Calculation of the local environment of a **barium monofluoride** molecule in a **neon** matrix. arXiv preprint arXiv:2305.10667.
- Ballof J, Nusgart N, Lalain P, Au M, Heinke R, Leimbach D, Stegemann S, Schutt M, Rothe S, ***Singh JT***. 2023 Progress towards the FRIB-EDM3-Frontend: A tool to provide **radioactive molecules** from isotope harvesting for fundamental symmetry studies. Nuclear Instruments and Methods in Physics Research Section B: Beam Interactions with Materials and Atoms 541, 224–227.
- Azevedo LO, Costa RJ, Wolff W, Oliveira AN, Sacramento RL, Silveira DM, ***Cesar CL***. 2023 **A platform** for trapped cryogenic electrons, anions and cations **for fundamental physics** and chemical studies. arXiv preprint arXiv:2301.13248.
- Lambo RL, Koyanagi GK, Ragyanszki A, Horbatsch M, Fournier R, ***Hessels EA***. 2023 Calculation of the local environment of a barium monofluoride molecule in an argon matrix: a step towards using **matrix-isolated BaF for determining the electron electric dipole moment**. Molecular Physics 121, e2198044.

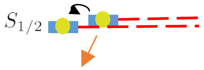
Spin precession
align by optical pumping + coherence

USE ATOMS (circular)

1) Optical pumping (alignement)

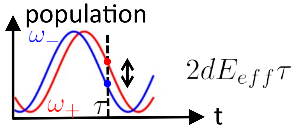


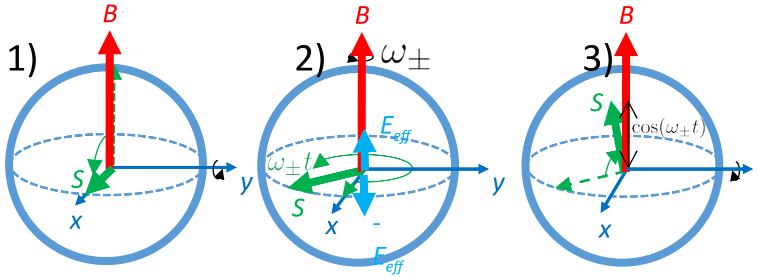
2) Precession



$\hbar\omega_\pm = -\mu B - d(\pm E_{eff})$

3) Readout





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

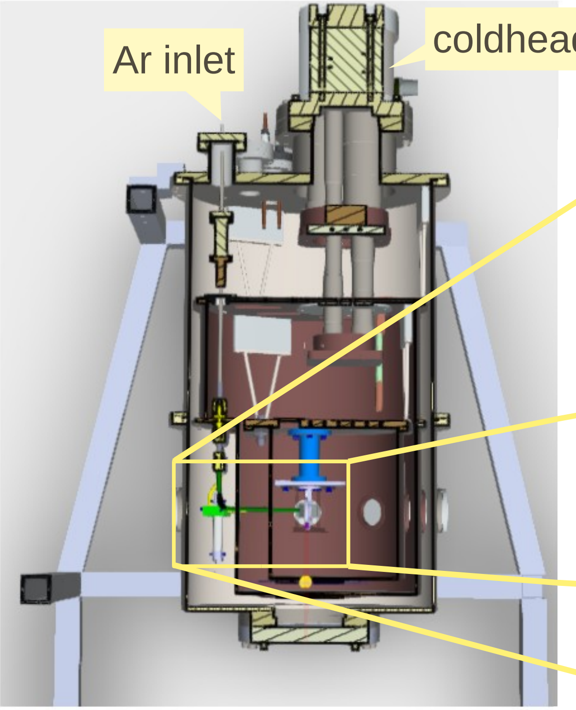
T_2 (coherence, phase) ~0.1 s (for Cs)

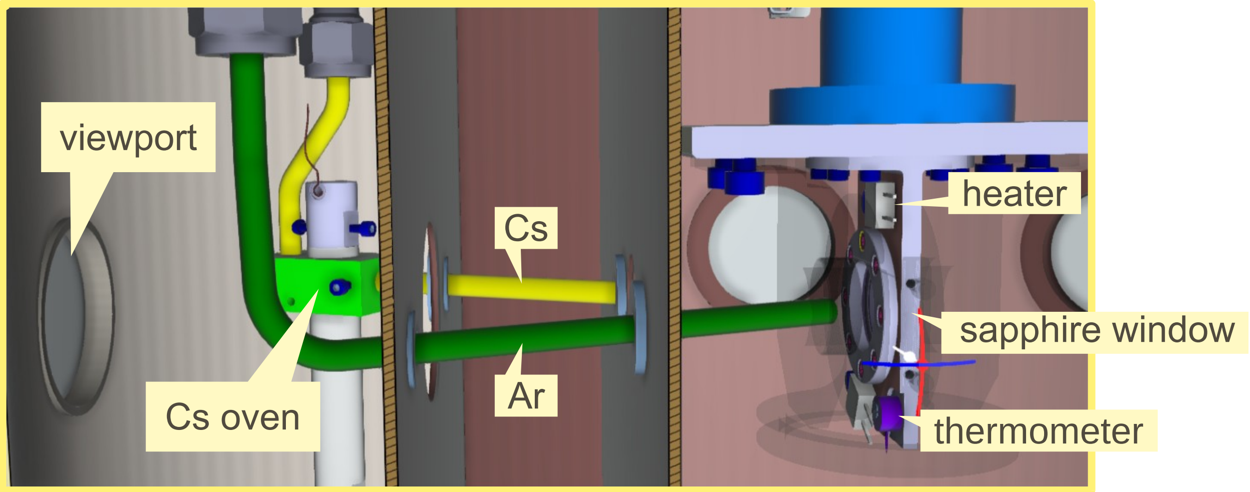
Spin coherence and optical properties of alkali-metal atoms in solid parahydrogen

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)

Experimental setup

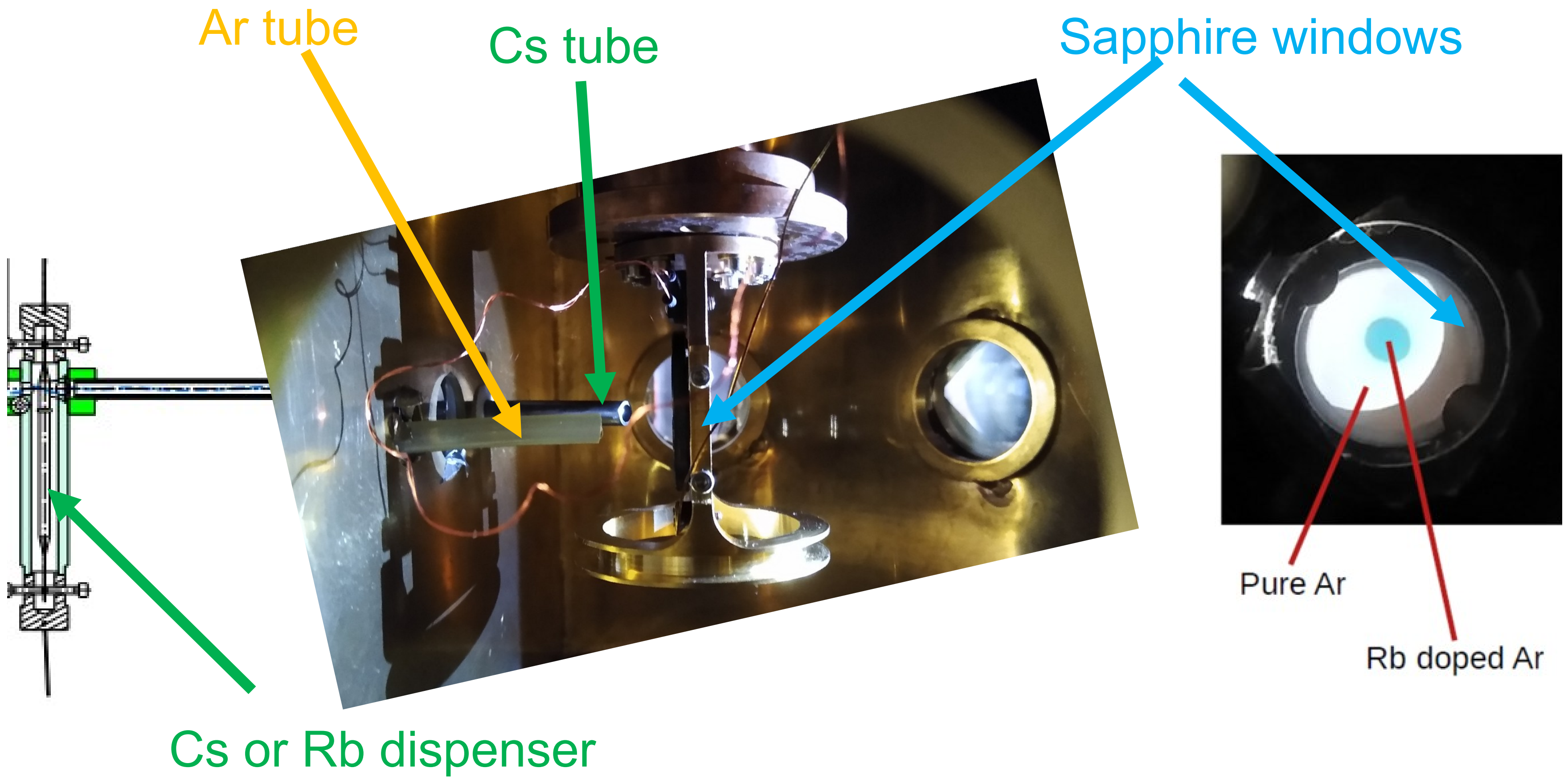


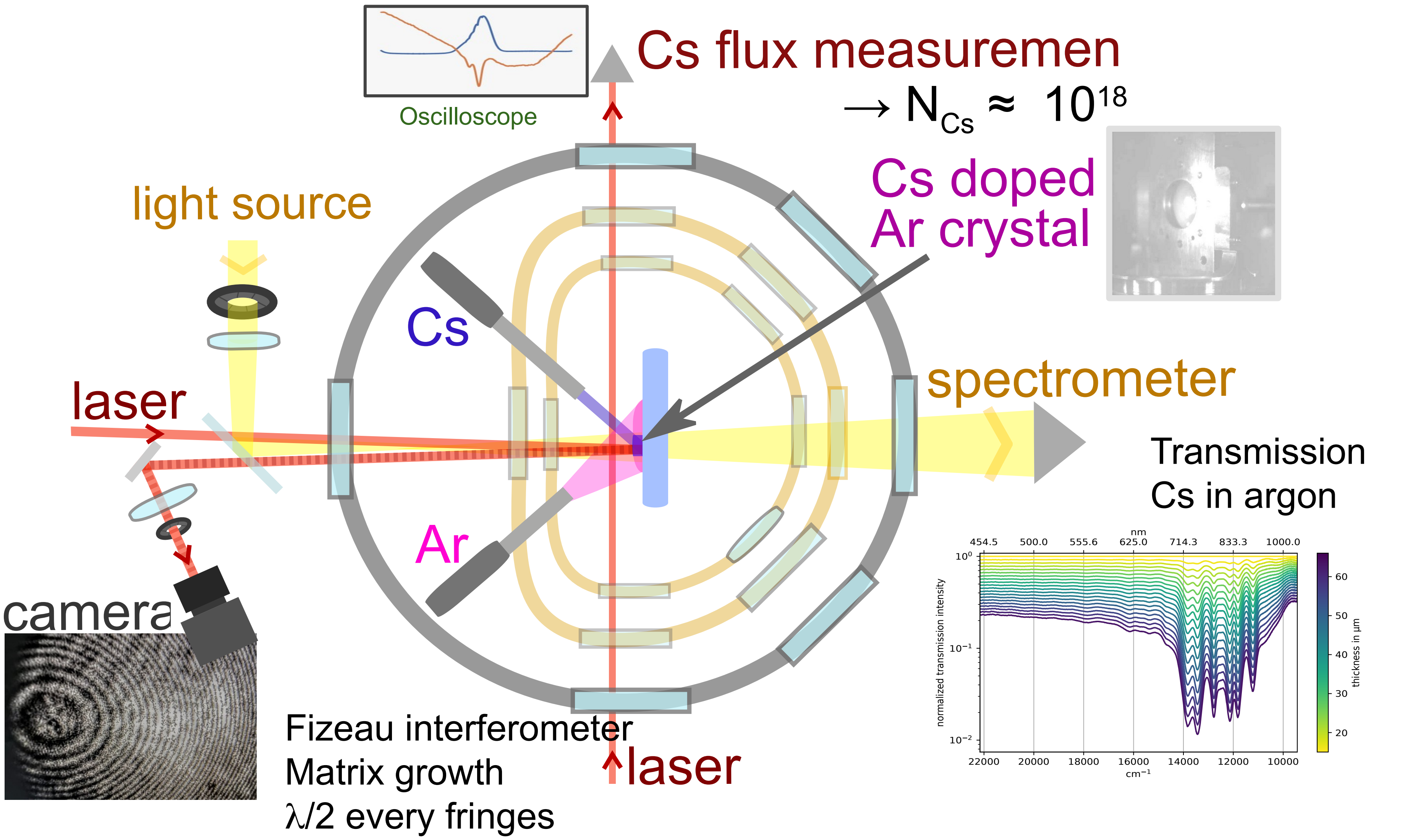


PHYSICAL REVIEW A **108**, 042820 (2023)

Cesium atoms in a cryogenic argon matrix

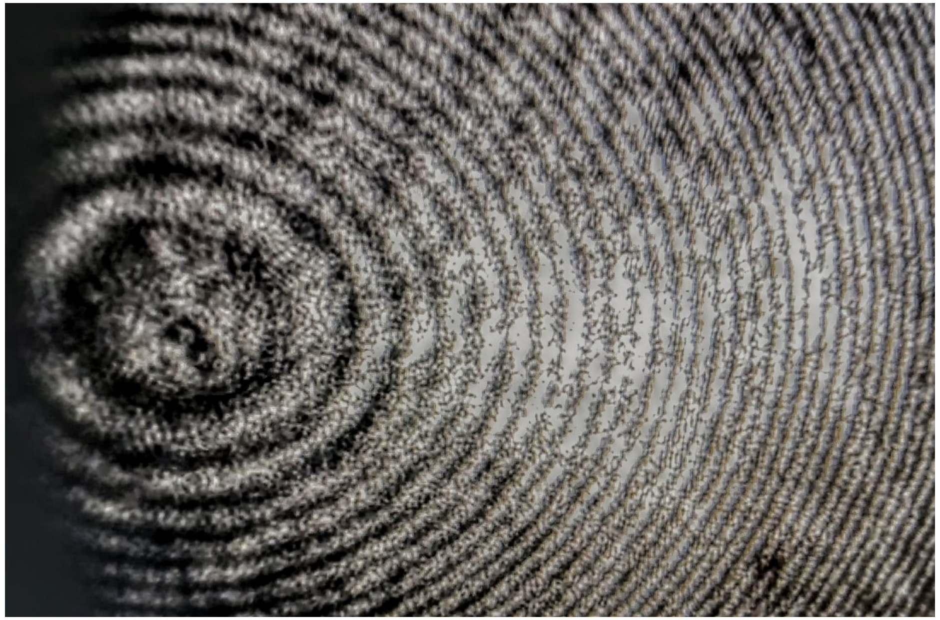
T. Battard,[1] S. Lahs,[1] C. Crépin,[2] and D. Comparat[1,*]

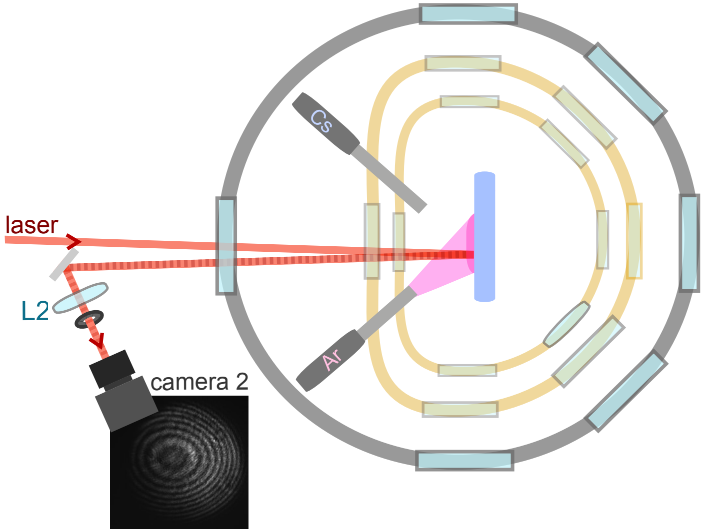

Ar tube
Cs tube
Sapphire windows
Cs or Rb dispenser
Pure Ar
Rb doped Ar

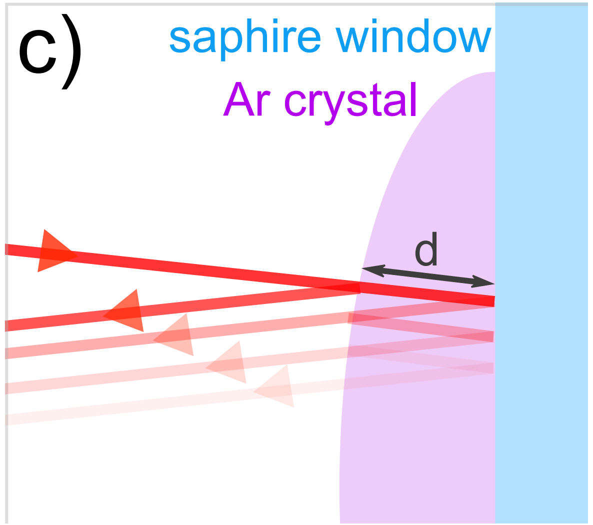


Cs flux measuremen
→ N_Cs ≈ 10^18
Oscilloscope
light source
Cs doped
Ar crystal
Cs
laser
spectrometer
Transmission
Cs in argon
Ar
camera
Fizeau interferometer
Matrix growth
λ/2 every fringes
laser
nm
454.5
500.0
555.6
625.0
714.3
833.3
1000.0
normalized transmission intensity
10^0
10^-1
10^-2
22000
20000
18000
16000
14000
12000
10000
cm^-1
thickness in µm
60
50
40
30
20

Crystal thickness and quality





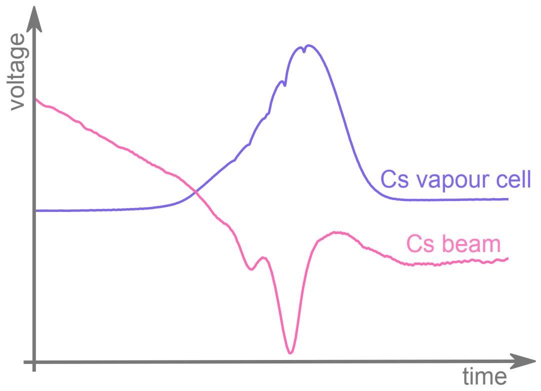


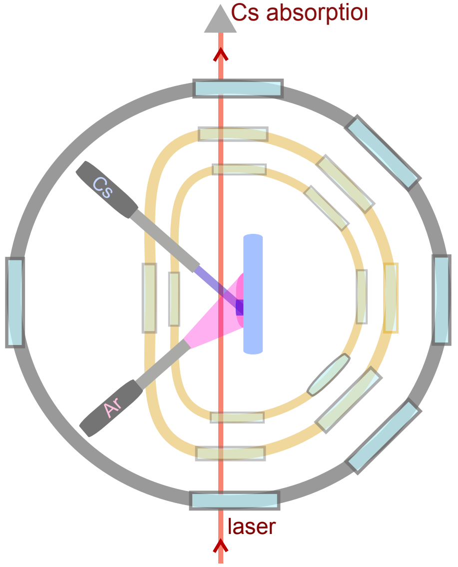
Growth rate ≈ 1µm/min

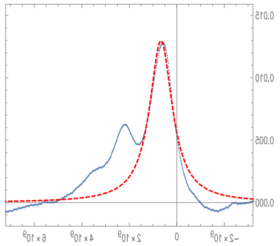
Cs flux measurement

→ In Ar crystal ~10^{18} per cm^3

Cs in Ar at Similar distance (10nm) than dislocations!

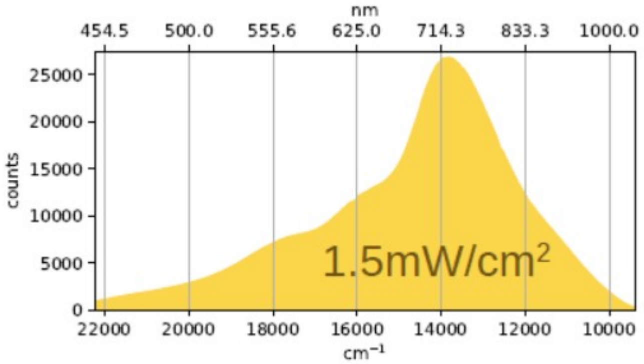


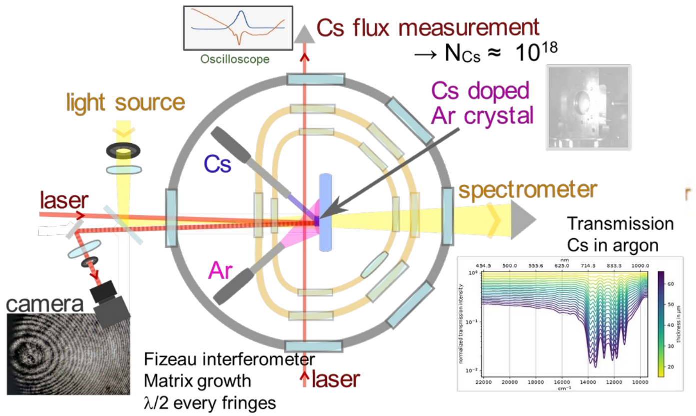


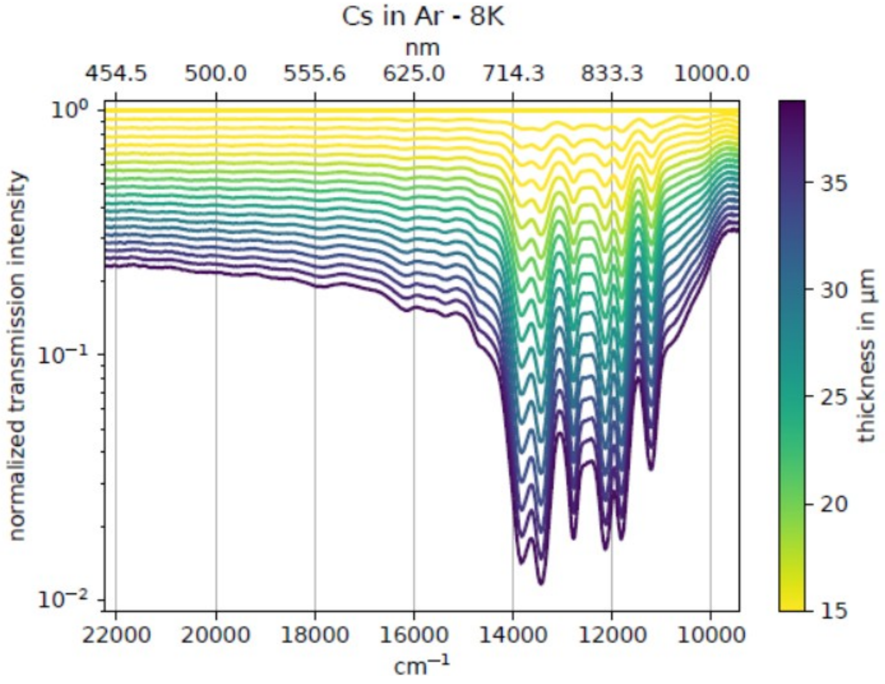


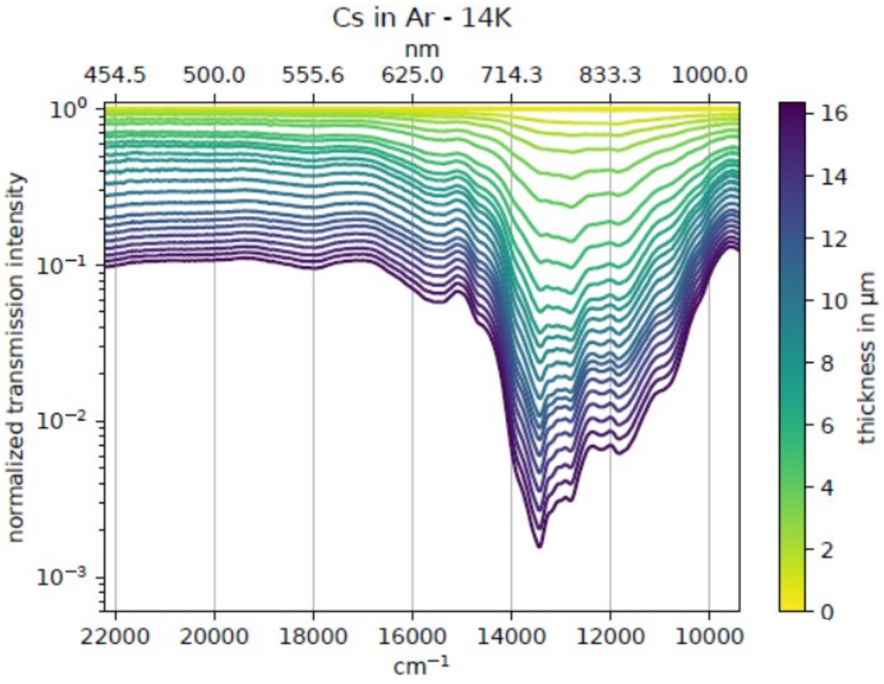
Effusive beam model, broadening by Doppler effect

Transmission Specroscopy







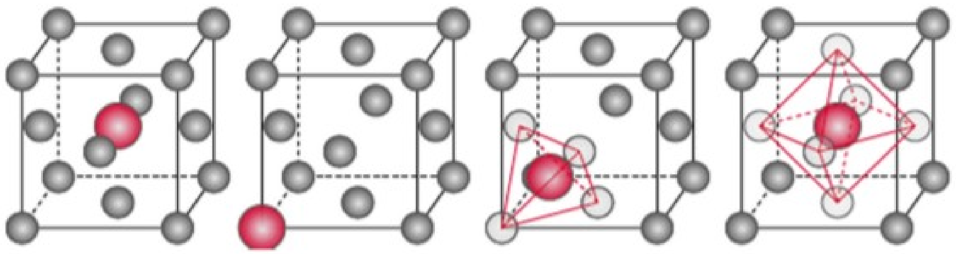


Interpretation of Cs spectrum

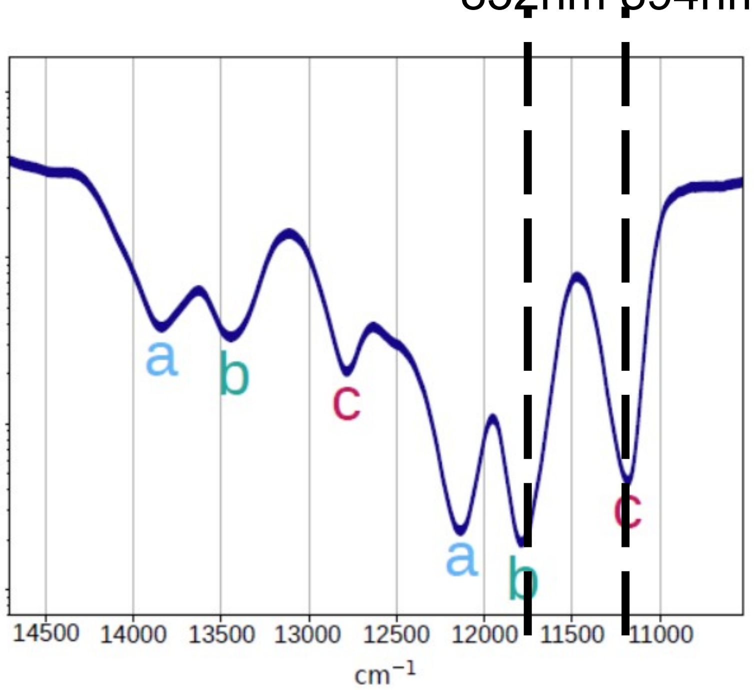
Optical Absorption Spectra of Alkali Atoms in Rare-Gas Matrices

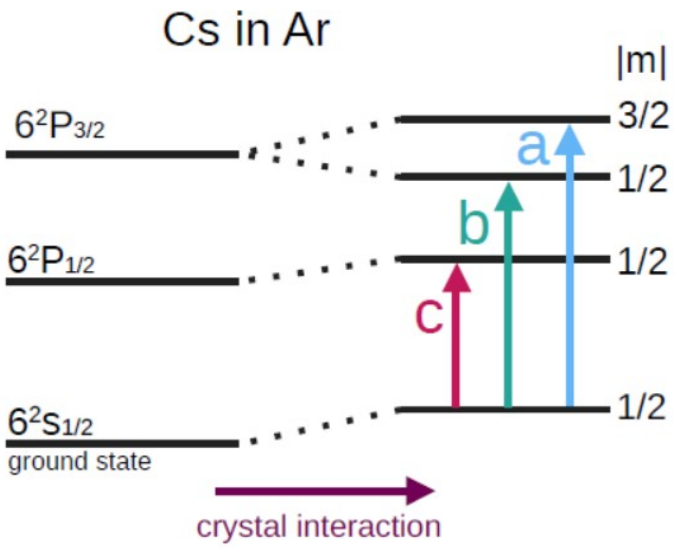
W. Weyhmann‡ and F. M. Pipkin
Lyman Laboratory of Physics, Harvard University, Cambridge, Massachusetts
(Received 19 August 1964)

Probably 2 different
Trapping sites



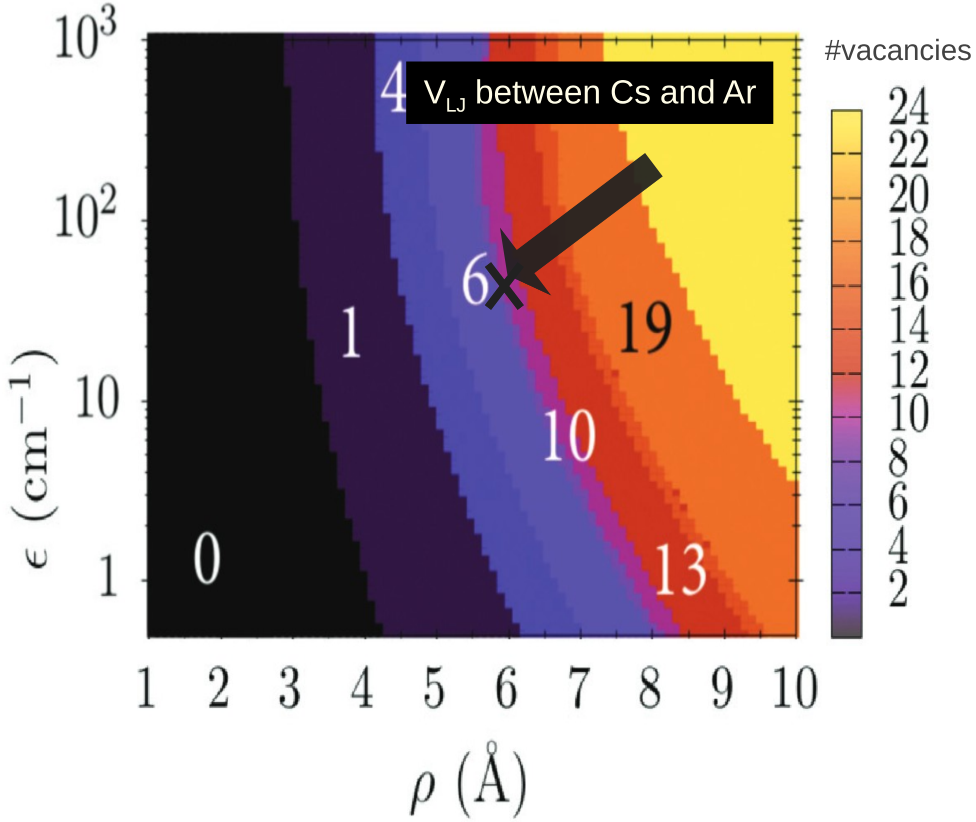
Gas phase Cs(6s)—Cs(6p$_J$)
852nm 894nm



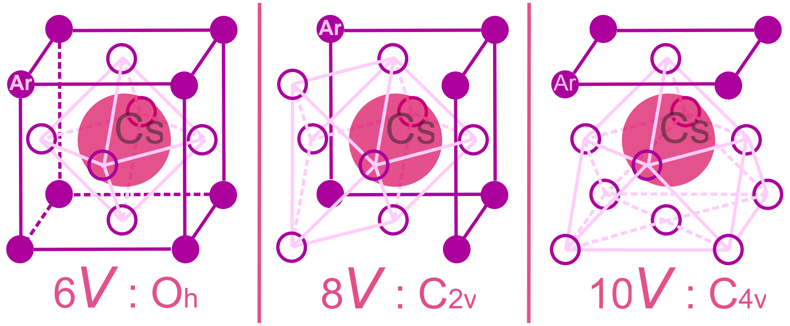


Most probable trapping sites (n=6,8,10 vacancies)?

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



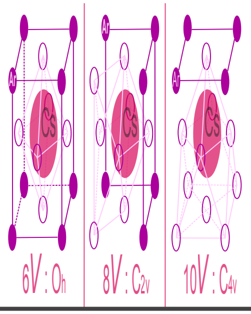
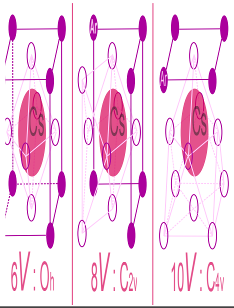
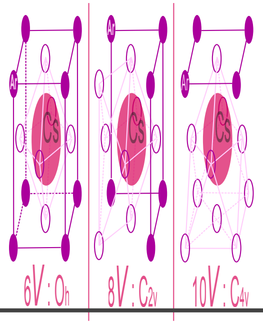
G. K. Ozerov, D. S. Bezrukov, and
A. A. Buchachenko, Phys. Rev. B 103, 184110 (2021)



Different magneto-electric couplings

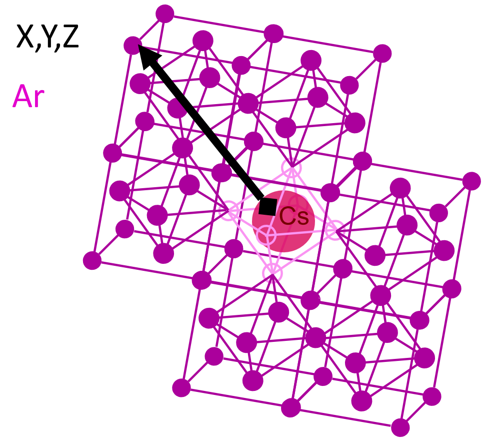
$$E_i^{\mathrm{int}} = E_i^* + \frac{1}{\varepsilon_0} P_i^{\mathrm{stat}} + \chi_{ij} E_j^* + \alpha_{ij} B_j^* + \frac{1}{2}\beta_{ijk} B_j^* B_k^* + \frac{1}{2}\gamma_{ijk} B_j^* E_k^* + \frac{1}{2}\chi_{ijk}^{(2)} E_j^* E_k^*$$

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

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

Ar-Ar and Cs-Ar Pair wise potential approximation

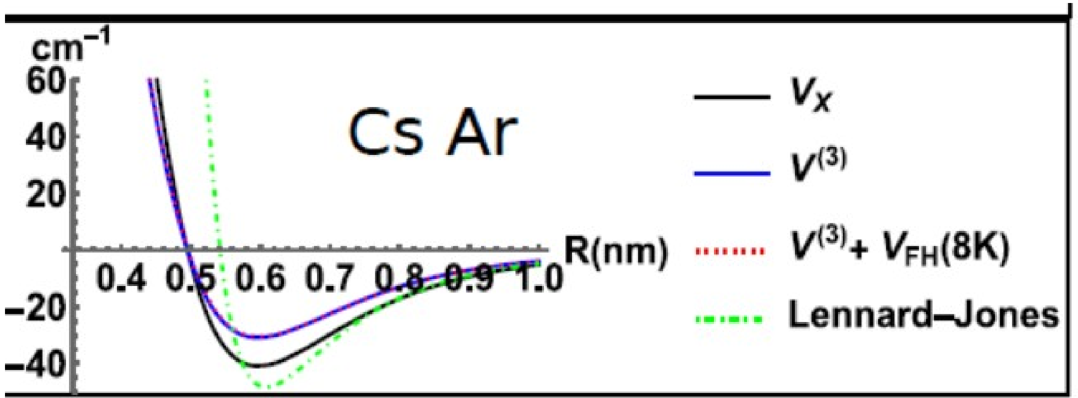
$$V = E_{\mathrm{Cs}}(n, N)$$

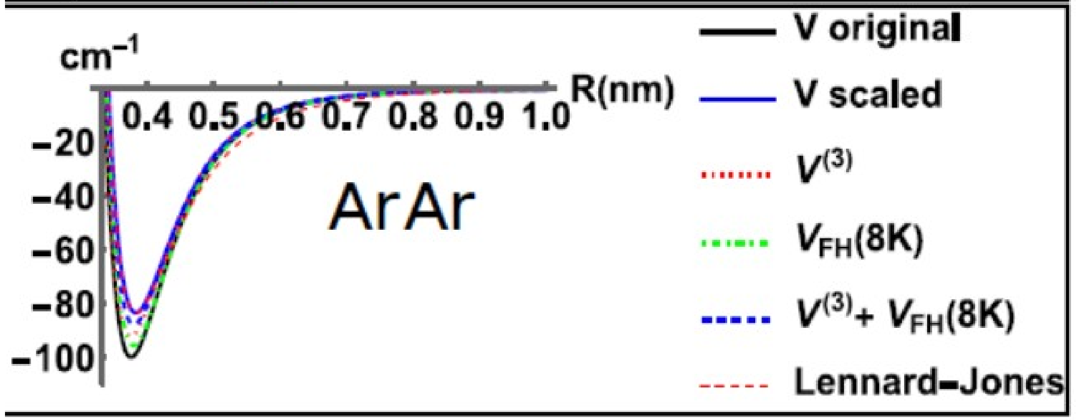


$$V = \sum_{i=1}^{N-n} V_{\mathrm{Ar-Cs}}(r_{Cs-Ari}) + \sum_{1 \le i < j \le N-n} V_{\mathrm{Ar}}(r_{ij})$$

N ~ 1000 atoms

n vacancies

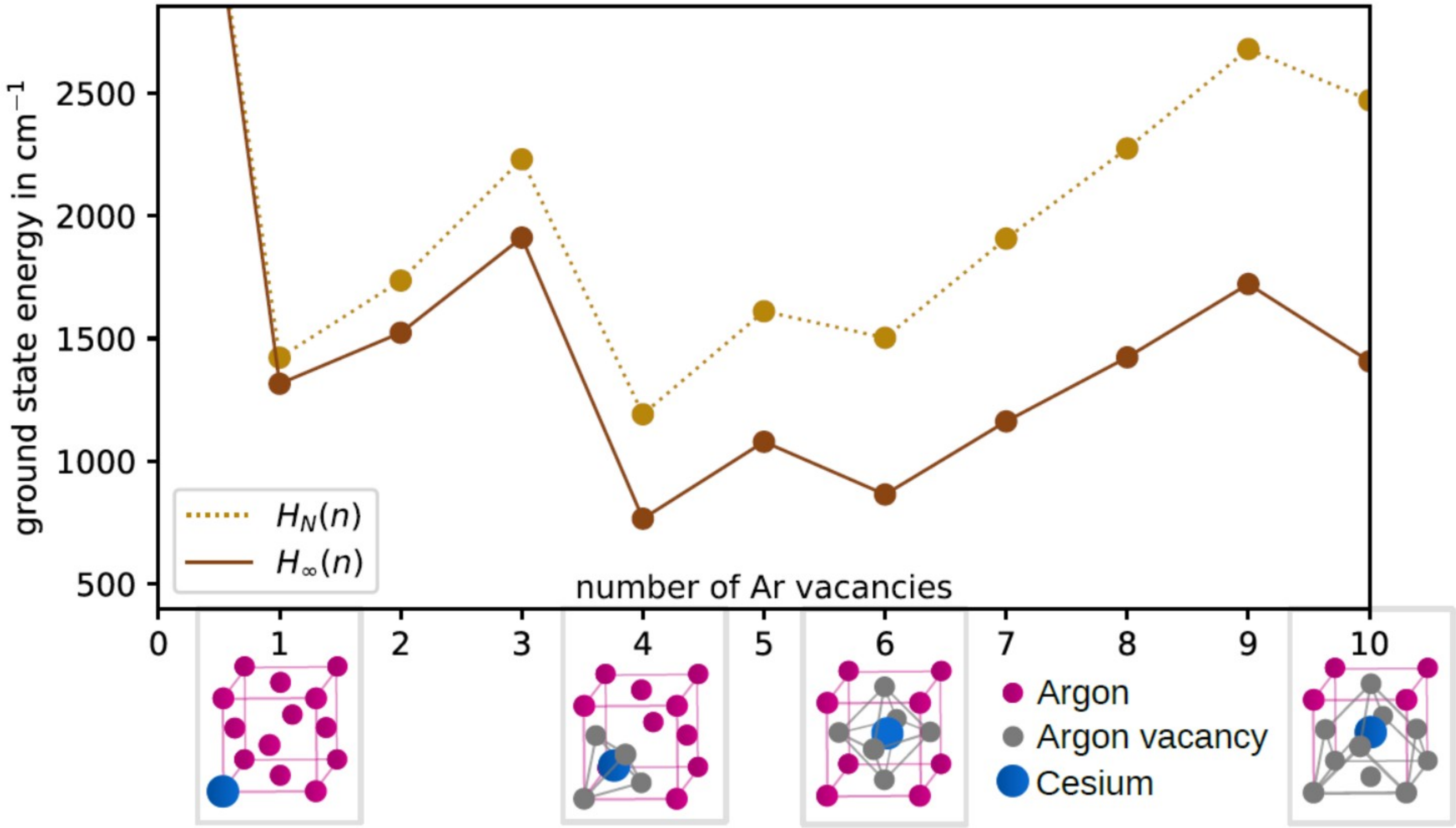




Stability diagram

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

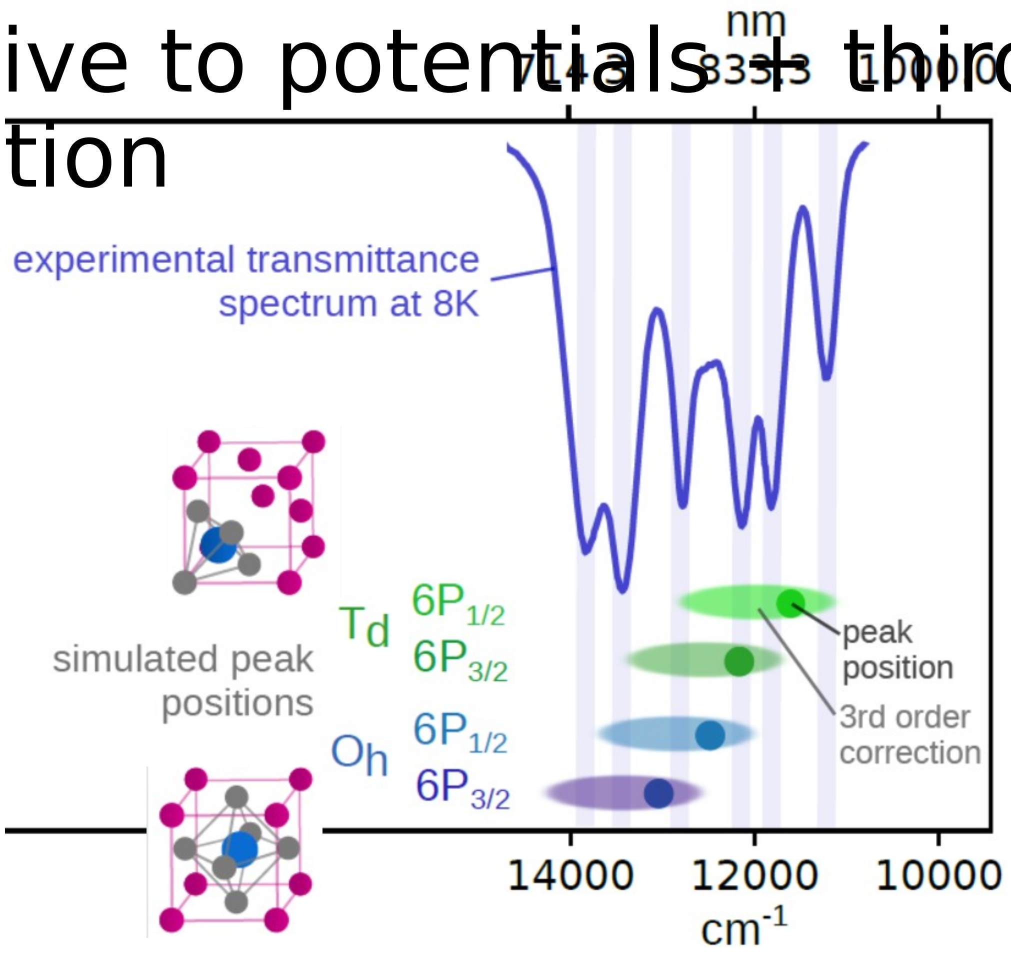
$$\Delta E_N(n) = E_{\mathrm{Cs}}(n, N) - E_{\mathrm{Ar}}(N)(N-n)/N$$



4(T_d) 6 (O_h)

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

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

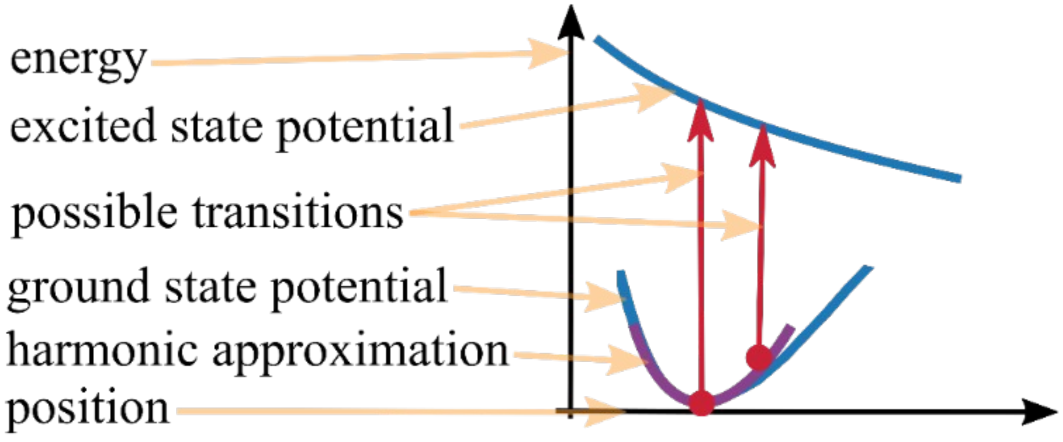


Oh(6) blue shift

Td(4)~0 shift

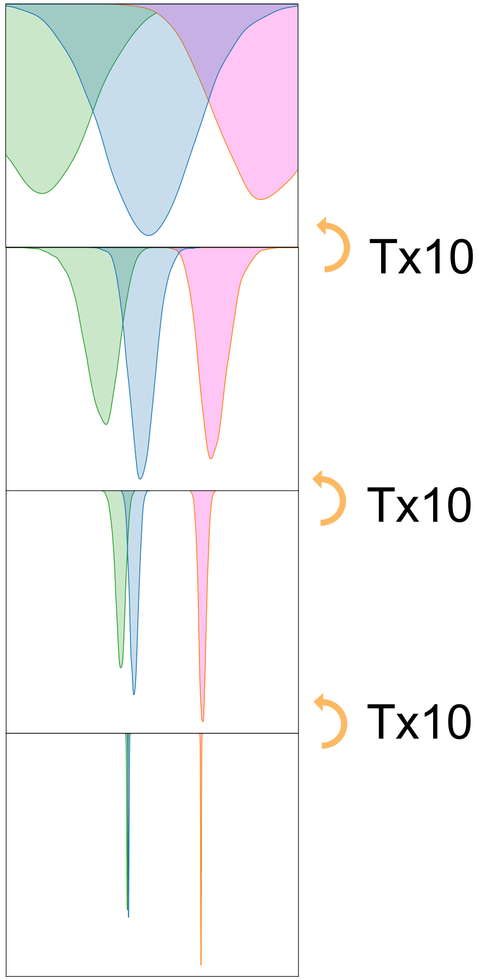
Jahn-Teller Dynamical (thermal) effect

- Broadening and splitting



Semi-classical Franck-Condon approximation

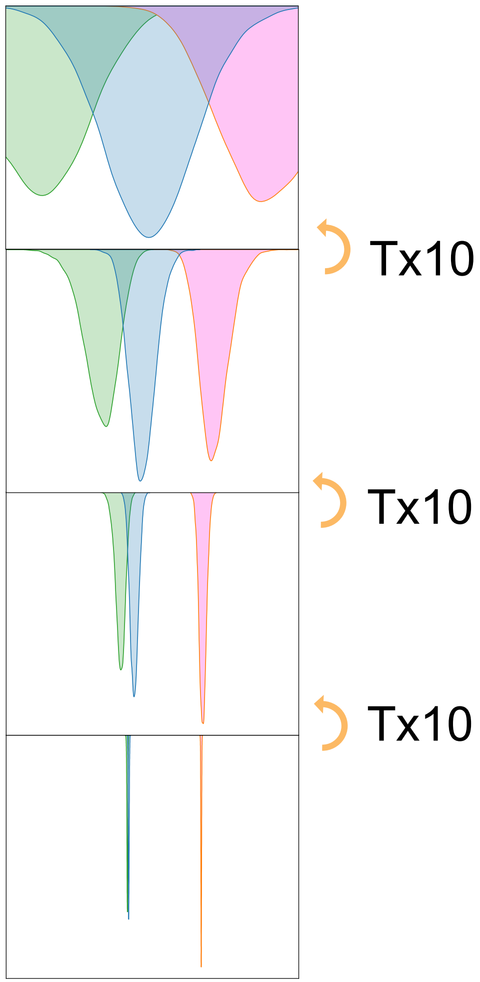
Crystal field
1st order in excited state

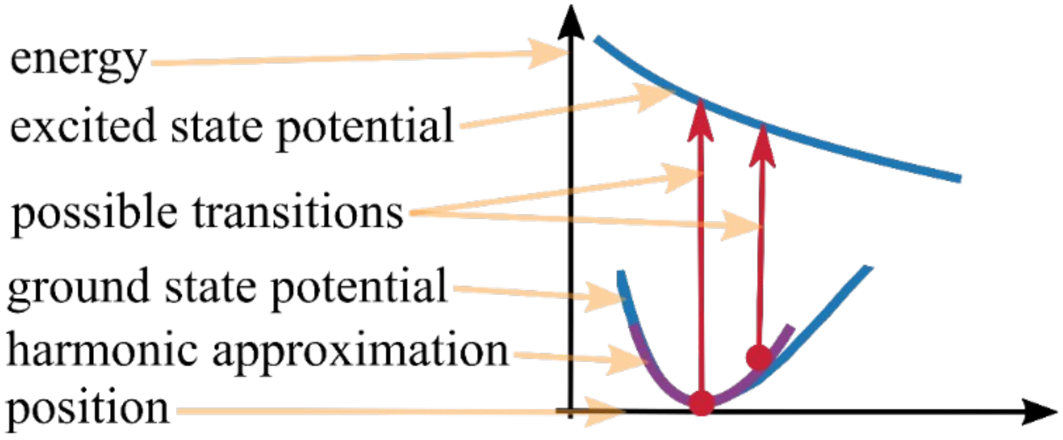


Jahn-Teller Dynamical (thermal) effect

- Broadening and splitting

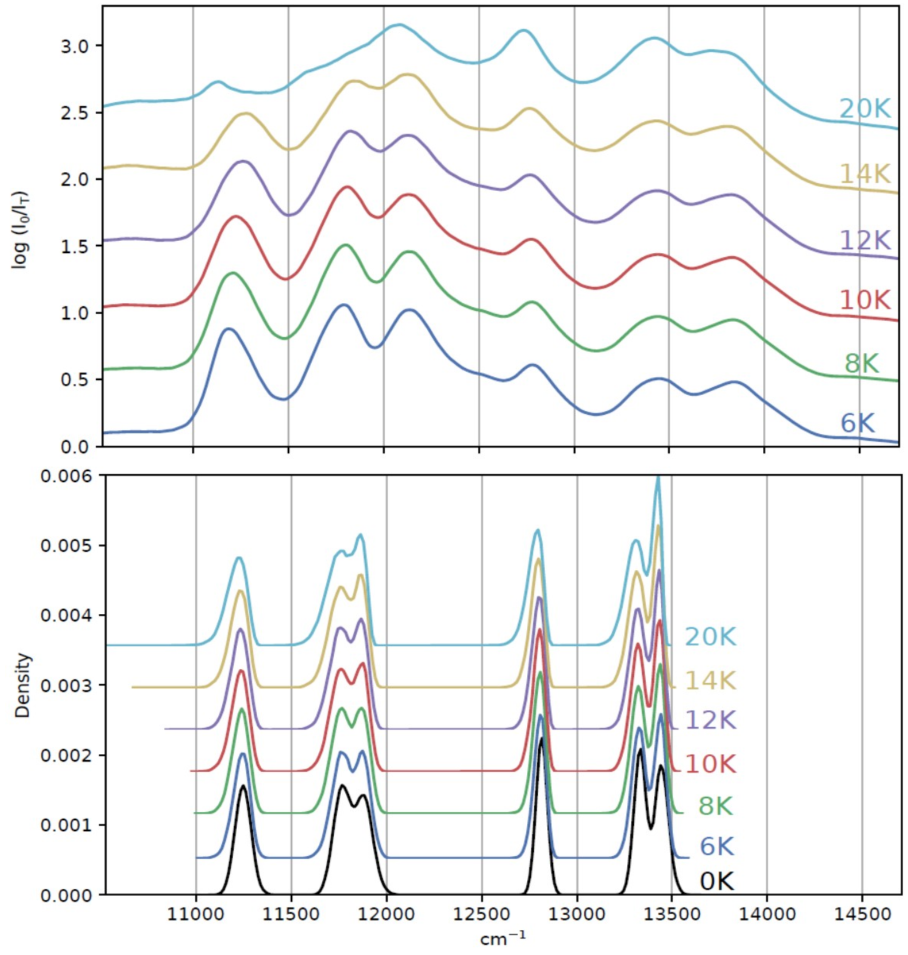
Crystal field
1st order in excited state





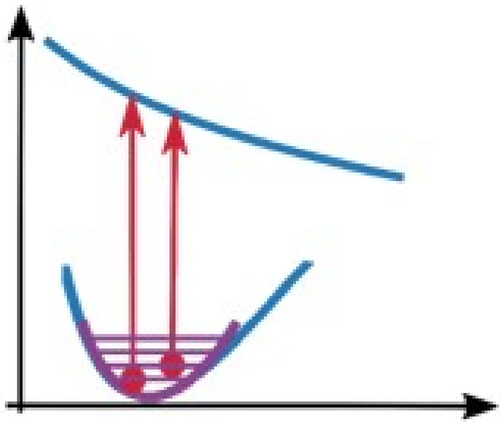
Semi-classical Franck-Condon approximation

But incorrect shape (Reflexion approximation + Crystal Field theory)



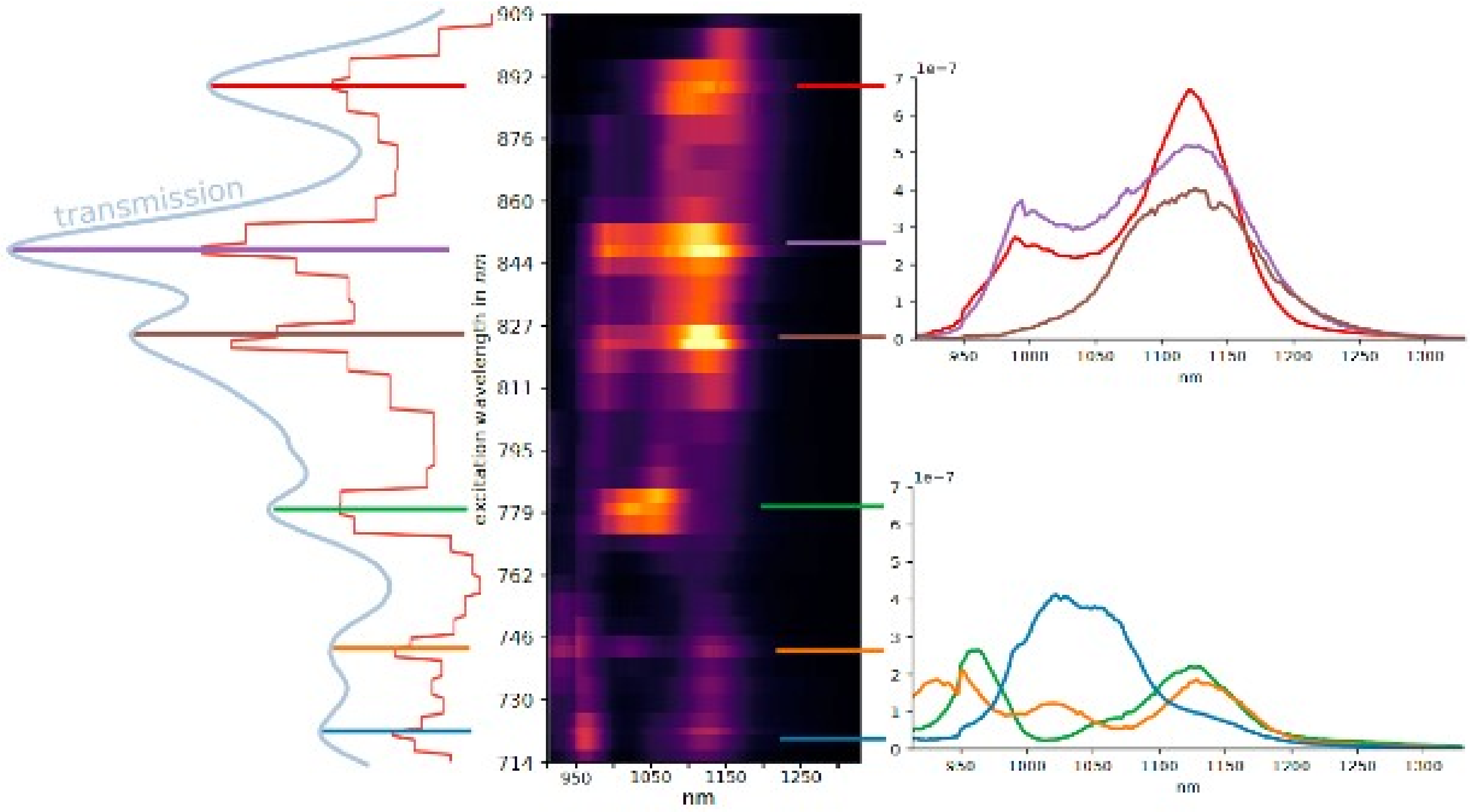
Experiment

Theory



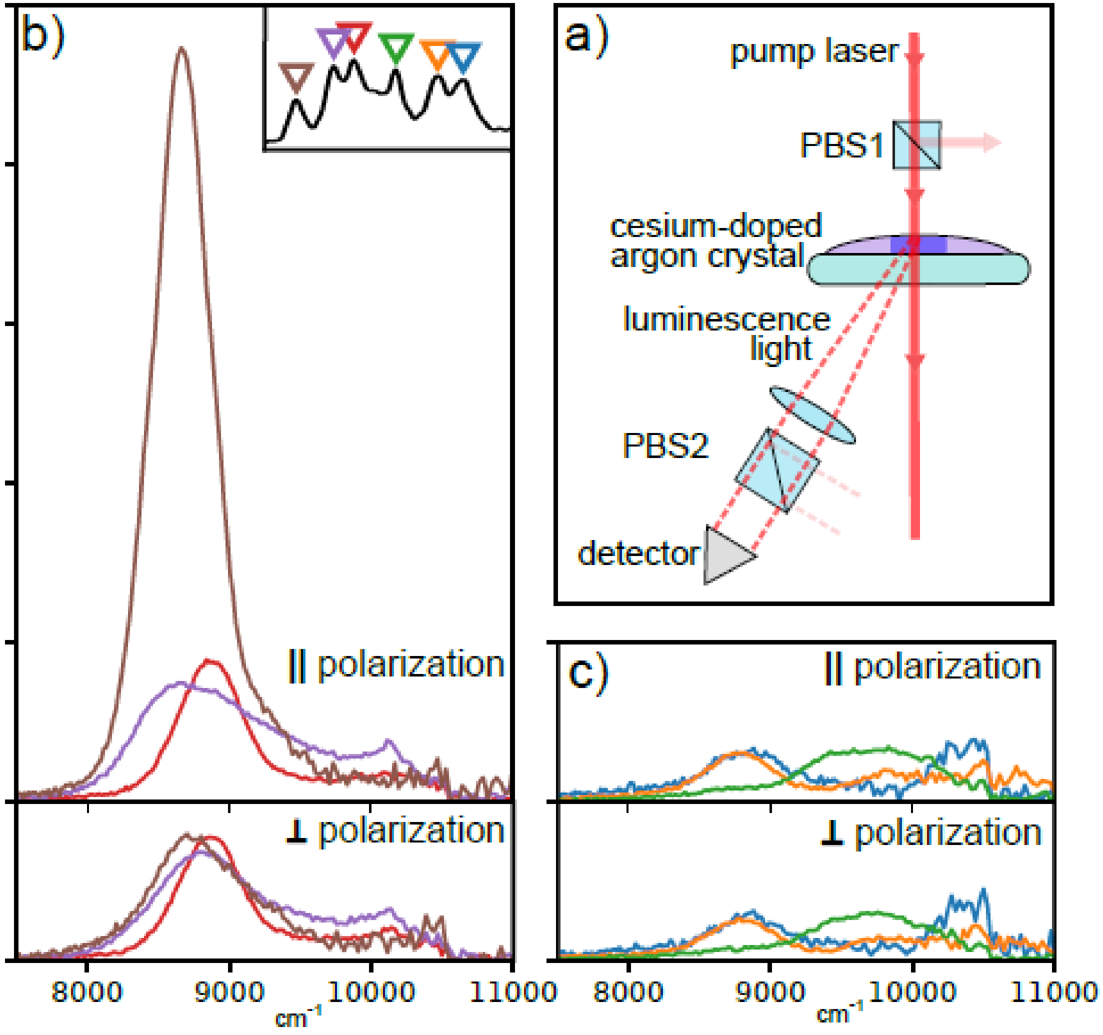
$$A(E) \propto \sum_i P_i \int |\Psi_i(\boldsymbol{Q})|^2 \, \delta[E - (V_\mathrm{e}(\boldsymbol{Q}) - E_i)] \mathrm{d}\boldsymbol{Q}$$

Next steps: Preliminary results on Fluorescence

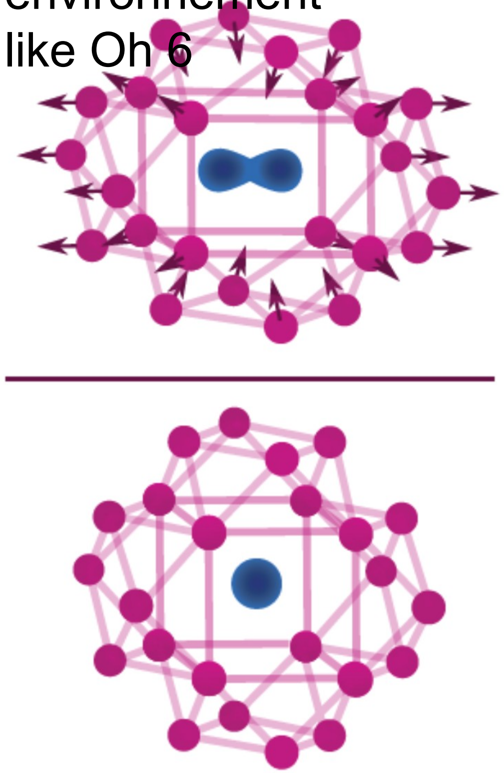


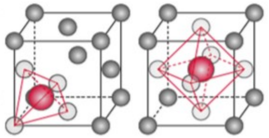
Unexpected (non) relaxation p3/2 p1/2

Preliminary results with polarized light



The redest line might be
6s—>6p1/2
excitation in a very
symmmetric
environnement
like Oh 6



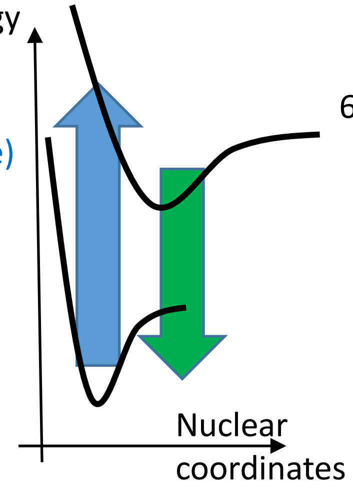
Conclusion 

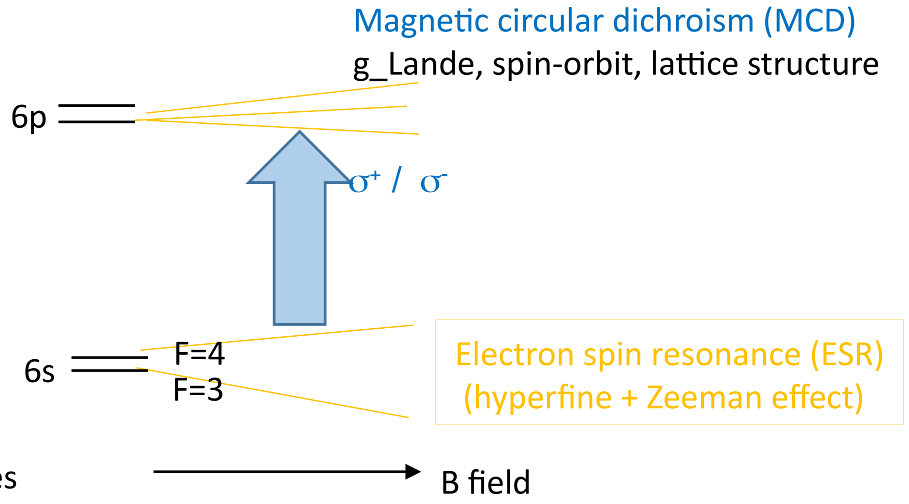
- Cs in Ar seems promising for EDM measurment below 10^{-30} e.cm ☾ new physics
- In solid state systems, there can be dangerous mixing terms.
- Absorption spectra shows that multiple trapping sites are present at the same time. Is it Td (4 vacancies) + Oh (6 vacancies) ? What about hcp phase ?

Next steps

More absorption (temperature dependence)
Fluorescence measurment
Temperature dependence
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)





P and T violating moments of Cs in cryogenic matrices.

- https://cnrs.zoom.us/j/96208775835?pwd=GfpE5GcMiTpYfyACZKb2yB1vNXadon.1 *Nov 3rd 3pm*

- **Polarizabilities as probes for P, T, and PT violation :** S. Lahs and D. Comparat 2024 *New J. Phys.* **26** 125001
- **Atomic Observables Induced by Cosmic Fields :** S. Lahs, D. Comparat, F. Kirk, B. Roberts arXiv:2510.08007

New observables in cristal vs gaz phase

Sébastian Lahs

$$V^{EM} = -\boldsymbol{d}\cdot\boldsymbol{\mathcal{E}} - \boldsymbol{\mu}\cdot\boldsymbol{\mathcal{H}} - Q_{ij}\partial_i\mathcal{E}_j$$

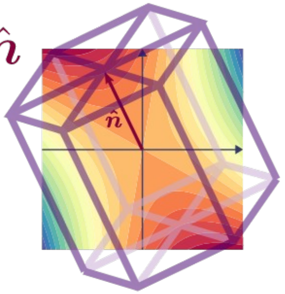
electric dipole — magnetic dipole — electric quadrupole

$$ {}^{d\mu}_{PT}\alpha^{\ell}_{ij} = \sum_{k,l} \frac{\langle n| V^{PT} |l\rangle \langle l| d_i |k\rangle \langle k| \mu_j |n\rangle}{(\omega_{kn}^2 - (\omega^\ell)^2)\omega_{ln}}\omega_{kn} + \text{permutations}$$

P odd $\Delta E \propto {}^{dQ}_{P}\alpha_{t_m} (\boldsymbol{\mathcal{H}}\cdot\hat{\boldsymbol{n}})(\boldsymbol{\mathcal{E}}\times\boldsymbol{\mathcal{H}})\cdot\hat{\boldsymbol{n}}$

T odd $\Delta E \propto {}^{\mu Q}_{T}\alpha_{t_m} (\boldsymbol{\mathcal{E}}\cdot\hat{\boldsymbol{n}})(\boldsymbol{\mathcal{H}}\times\boldsymbol{\mathcal{E}})\cdot\hat{\boldsymbol{n}}$

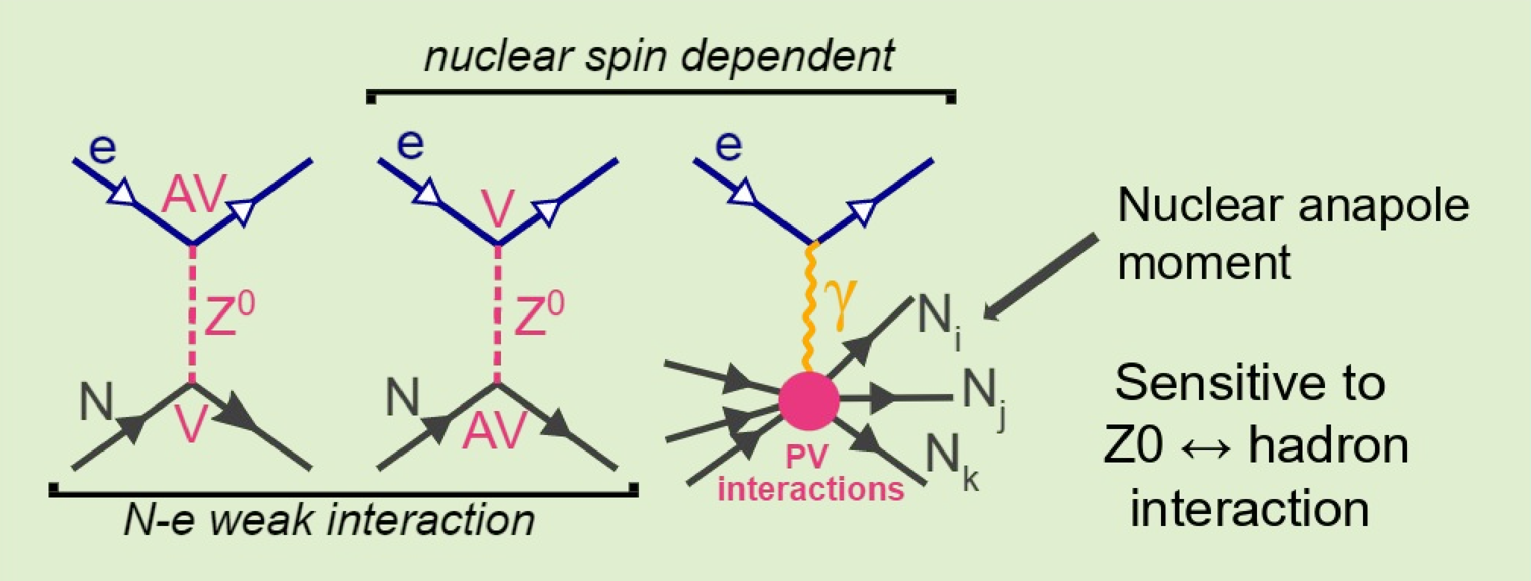
P&T odd $\Delta E \propto {}^{dQ}_{PT}\alpha_{v_m} (\boldsymbol{\mathcal{E}}\cdot\boldsymbol{\mathcal{H}}) - (\boldsymbol{\mathcal{E}}\cdot\hat{\boldsymbol{n}})(\boldsymbol{\mathcal{H}}\cdot\hat{\boldsymbol{n}})$



.Bouchiat, M & Bouchiat C. Eur. Phy. J. D, 15.1 (2001): 5-18.

Nuclear Anapole Moment

1997 only successful measurement in Cs beam [2]



Bouchiat & Bouchiat:
Observable as a linear stark shift in cryogenic matrix [3]

$$\Delta E_{stark} \propto \frac{(\hat{n} \cdot \vec{B})\, \hat{n} \cdot (\vec{E} \times \vec{B})}{B^2}$$

with symmetry breaking crystal axis