Fundamental Symmetries

Lecture 3:

- **Time-reversal (=CP) Violation**
- **Properties Nuclear matter**
- **Dark matter searches**

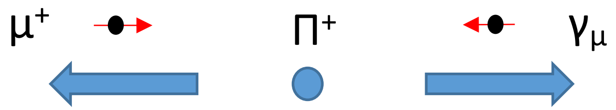
R.F. Garcia Ruiz
MIT

Charge conjugation Violation

Charge conjugation Violation

1957: Garavin, Lederman, Weinrich

-> Observation of C-violation in pion decays



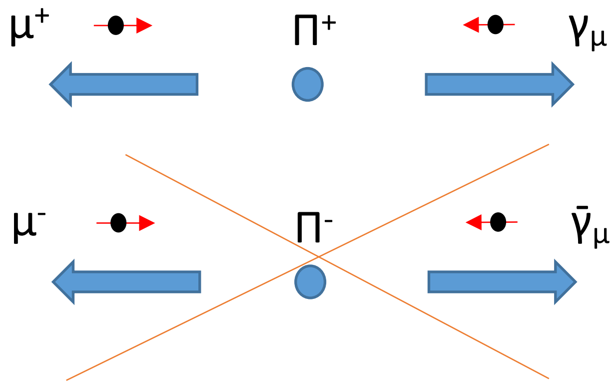
Phys. Rev. **105**, 1415 (1957)

Charge conjugation Violation

1957: Garavin, Lederman, Weinrich

-> Observation of C-violation in pion decays

Not observed:



Phys. Rev. **105**, 1415 (1957)

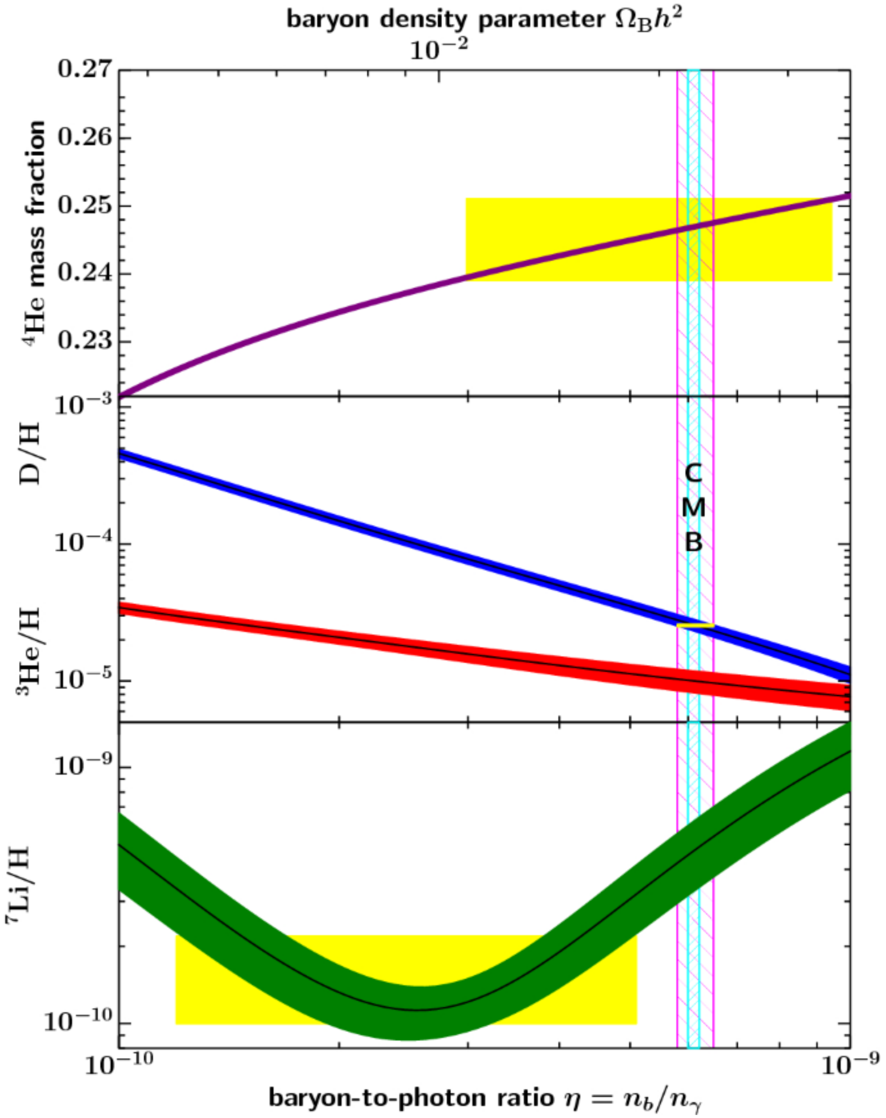
Time-reversal Violation

Baryon Asymmetry

Sakharov (1967): Conditions to achieve matter-antimatter asymmetry via baryogenesis:

- B violation
- C and CP-violation
- Deviation from thermal equilibrium

Baryon Asymmetry



Particle Data Group), PTEP 2020, 083C01 (2020)

Time-reversal Violation in the SM

- 1964: Cronin and Fitch discovered CP violation

Phys. Rev. Lett. 13, 138 (1964)

Without CP violation:

$$|K_S\rangle = |K_1\rangle \equiv \frac{1}{\sqrt{2}}(|K^0\rangle - |\overline{K}^0\rangle) \qquad K_S \to \pi\pi$$

$$|K_L\rangle = |K_2\rangle \equiv \frac{1}{\sqrt{2}}(|K^0\rangle + |\overline{K}^0\rangle) \qquad K_L \to \pi\pi\pi$$

However, $K_L \to \pi\pi$ **Observed -> CP violation**

- Kaon decays

N1 : $K^0{}_L \to \pi^+ + e^- + \underline{\nu}_e$

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Phys. Rev. Lett. 13, 138 (1964)

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$$K_S \to \pi\pi$$
$$K_L \to \pi\pi\pi$$

However, $K_L \to \pi\pi$ **Observed -> CP violation**

- Kaon decays

N1 : $K^0_L \to \pi^+ + e^- + \underline{\nu}_e$

N2: $K^0_L \to \pi^- + e^+ + \nu_e$

$N1/N2 \sim 3 \times 10^{-3}$

Time-reversal Violation in the SM

- **Cabibbo–Kobayashi–Maskawa matrix (CKM matrix)**

Probability of a transition from one flavour j quark to another flavour i quark. These transitions are proportional to $|V_{ij}|^2$.

$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

2008 Nobel Prize
Kobayashi & Maskawa

- **Pontecorvo–Maki–Nakagawa–Sakata matrix (PMNS matrix)**

  Neutrino mixing matrix between mass and flavor

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

- **Strong CP-problem**

Dipole Moments

Magnetic dipole moment:

$$\boldsymbol{\mu} = \mu \mathbf{S}$$

$$H_{md} = -\boldsymbol{\mu} \bullet \mathbf{B} \xrightarrow{P} -\boldsymbol{\mu} \bullet \mathbf{B}$$

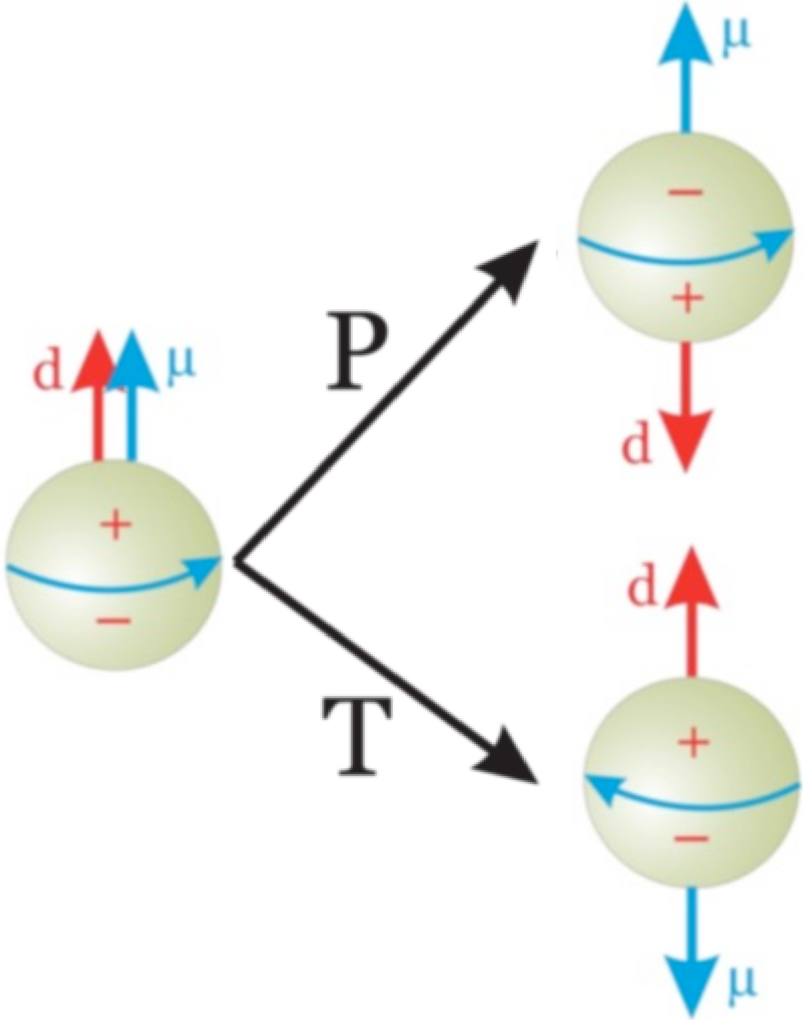
$$\xrightarrow{T} -\boldsymbol{\mu} \bullet \mathbf{B}$$

Electric dipole moment (EDM):

$$\mathbf{d} = d\mathbf{S}$$

$$H_{ed} = -\mathbf{d} \bullet \mathbf{E} \xrightarrow{P} \mathbf{d} \bullet \mathbf{E}$$

$$\xrightarrow{T} \mathbf{d} \bullet \mathbf{E}$$



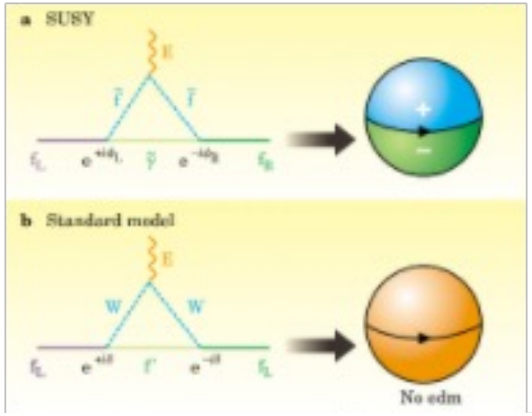
Observation of a non-zero value of an EDM requires PT violation (CP) violation!

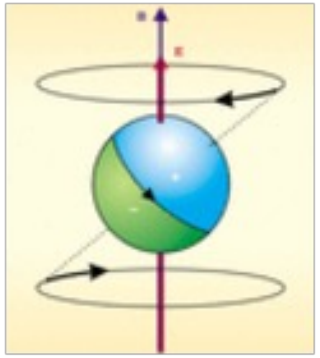
EDM experiments

	Result	95% u.l.	
	Paramagnetic systems		
Xe^m	$d_A = (\ 0.7 \pm 1.4) \times 10^{-22}$	3.1×10^{-22}	e cm
Cs	$d_A = (-1.8 \pm 6.9) \times 10^{-24}$	1.4×10^{-23}	e cm
	$d_e = (-1.5 \pm 5.7) \times 10^{-26}$	1.2×10^{-25}	e cm
	$C_S = (2.5 \pm 9.8) \times 10^{-6}$	2×10^{-5}	
	$Q_m = (3 \pm 13) \times 10^{-8}$	2.6×10^{-7}	$\mu_N R_{\mathrm{Cs}}$
Tl	$d_A = (-4.0 \pm 4.3) \times 10^{-25}$	1.1×10^{-24}	e cm
	$d_e = (\ 6.9 \pm 7.4) \times 10^{-28}$	1.9×10^{-27}	e cm
YbF	$d_e = (-2.4 \pm 5.9) \times 10^{-28}$	1.2×10^{-27}	e cm
ThO	$d_e = (-2.1 \pm 4.5) \times 10^{-29}$	9.7×10^{-29}	e cm
	$C_S = (-1.3 \pm 3.0) \times 10^{-9}$	6.4×10^{-9}	
HfF^+	$d_e = (0.9 \pm 7.9) \times 10^{-29}$	1.6×10^{-28}	e cm
	Diamagnetic systems		
^{199}Hg	$d_A = (2.2 \pm 3.1) \times 10^{-30}$	7.4×10^{-30}	e cm
^{129}Xe	$d_A = (0.7 \pm 3.3) \times 10^{-27}$	6.6×10^{-27}	e cm
^{225}Ra	$d_A = (4 \pm 6) \times 10^{-24}$	1.4×10^{-23}	e cm
TlF	$d = (-1.7 \pm 2.9) \times 10^{-23}$	6.5×10^{-23}	e cm
n	$d_n = (-0.21 \pm 1.82) \times 10^{-26}$	3.6×10^{-26}	e cm
	Particle systems		
μ	$d_\mu = (0.0 \pm 0.9) \times 10^{-19}$	1.8×10^{-19}	e cm
τ	$Re(d_\tau) = (1.15 \pm 1.70) \times 10^{-17}$	3.9×10^{-17}	e cm
Λ	$d_\Lambda = (-3.0 \pm 7.4) \times 10^{-17}$	1.6×10^{-16}	e cm

Rev. Mod. Phys. 91, 015001 (2019)

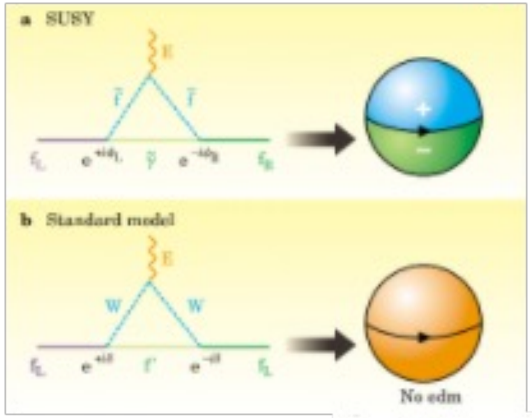
EDM measurements

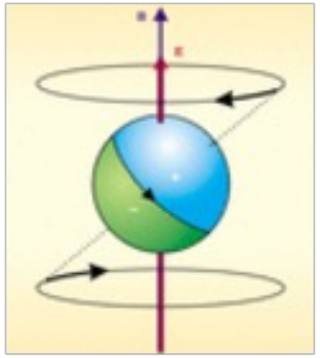




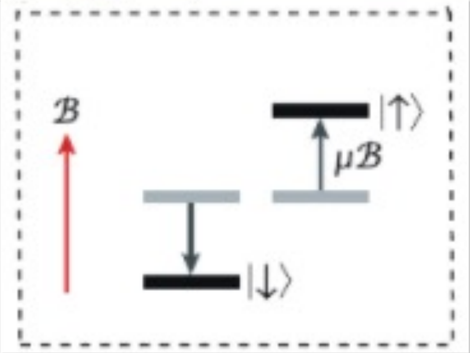
[Fortson & Sandars & Barr Phys. Today 56, 33 (2003)]

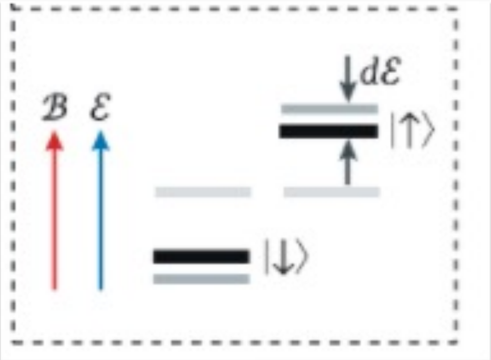
EDM measurements



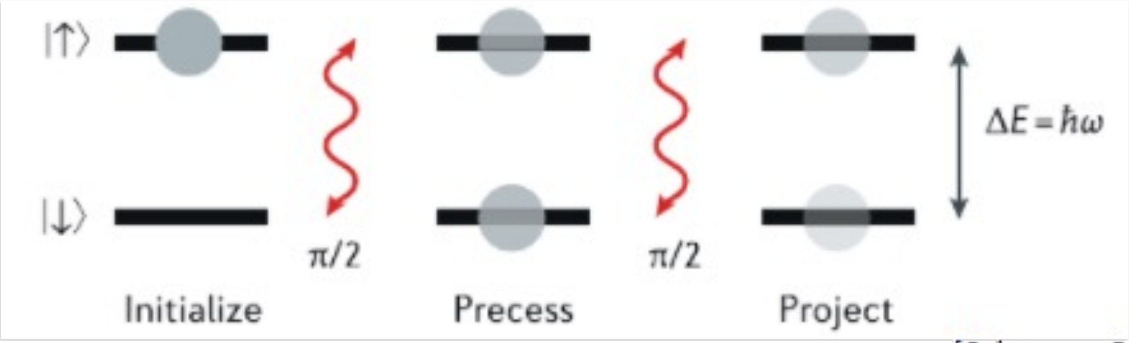


[Fortson & Sandars & Barr Phys. Today 56, 33 (2003)]





Ramsey spectroscopy sequence



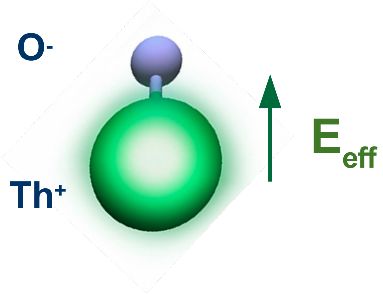
[Cairncross & Ye, Nature Rev. 1, 511 (2019)]

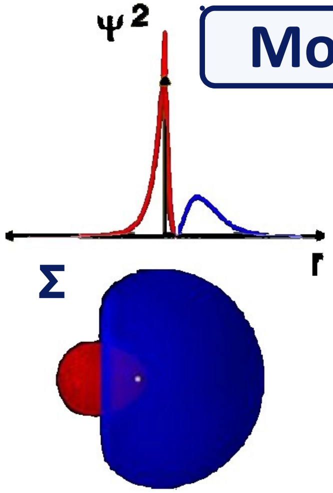
EDMs

Molecules

$$H_{\mathrm{EDM}} = -\mathbf{d} \cdot \boldsymbol{\mathcal{E}}$$

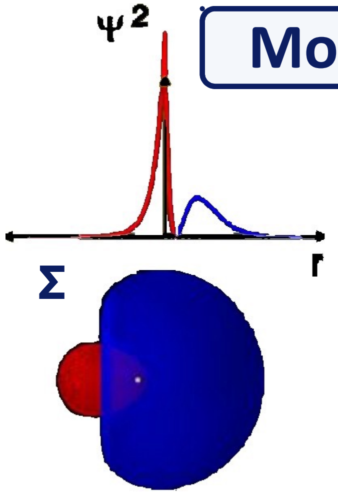
$\} \; 2\mu B + e_{\mathrm{EDM}} E_{\mathrm{eff}}$





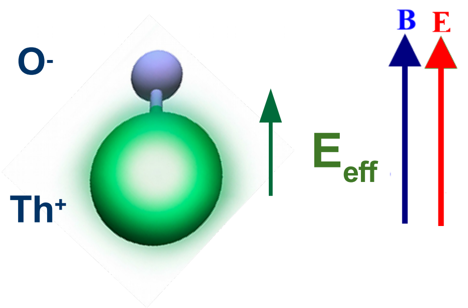
EDMs

Molecules



$$H_{\mathrm{EDM}} = -\mathrm{d} \cdot \mathcal{E}$$

} $2\mu B + e_{\mathrm{EDM}} E_{\mathrm{eff}}$



E_{ext} ~1 V/cm

E_{eff} ~80 GV/cm

Molecular enhancement > 10^3

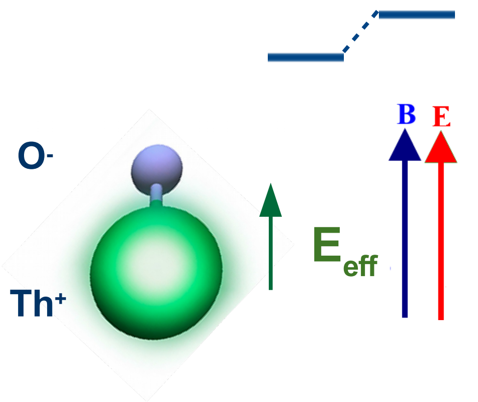
$|d_e| \leq 1.1 \times 10^{-29}$ e · cm

[ACME, Nature 562, 355 (2018)]
[Baron et al. Science 343, 269 (2014)]
[Sandars Phys. Rev. Lett. 18, 1396 (1967)]

EDMs

Molecules

$H_{\mathrm{EDM}} = -\mathbf{d} \cdot \boldsymbol{\mathcal{E}}$



} $2\mu B + e_{\mathrm{EDM}} E_{\mathrm{eff}}$

E_{ext} ~1 V/cm

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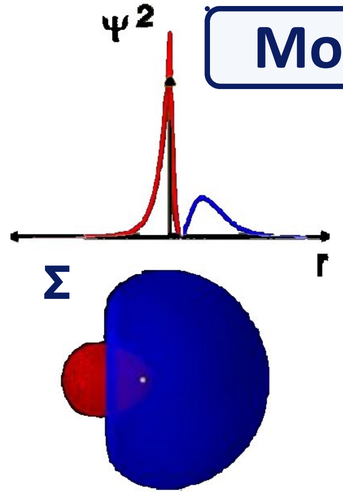
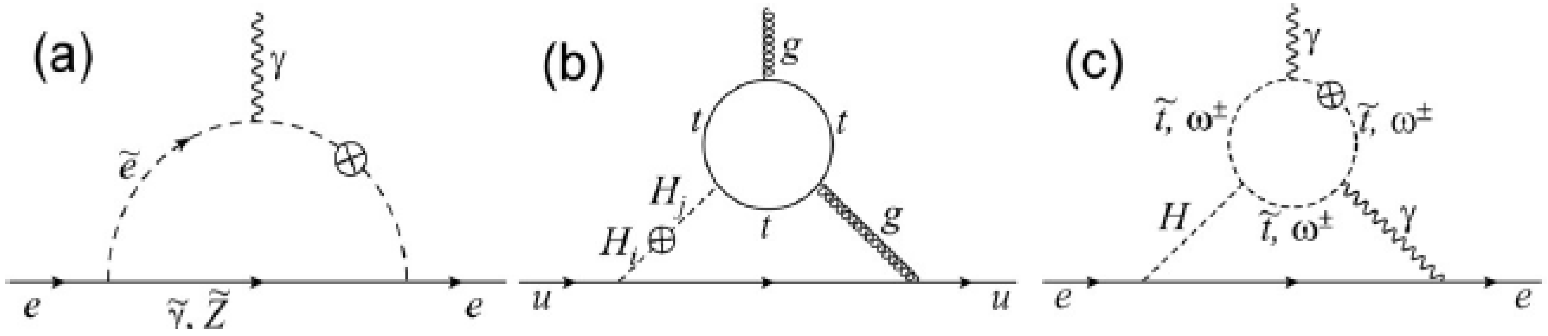
Molecular enhancement > 10^3



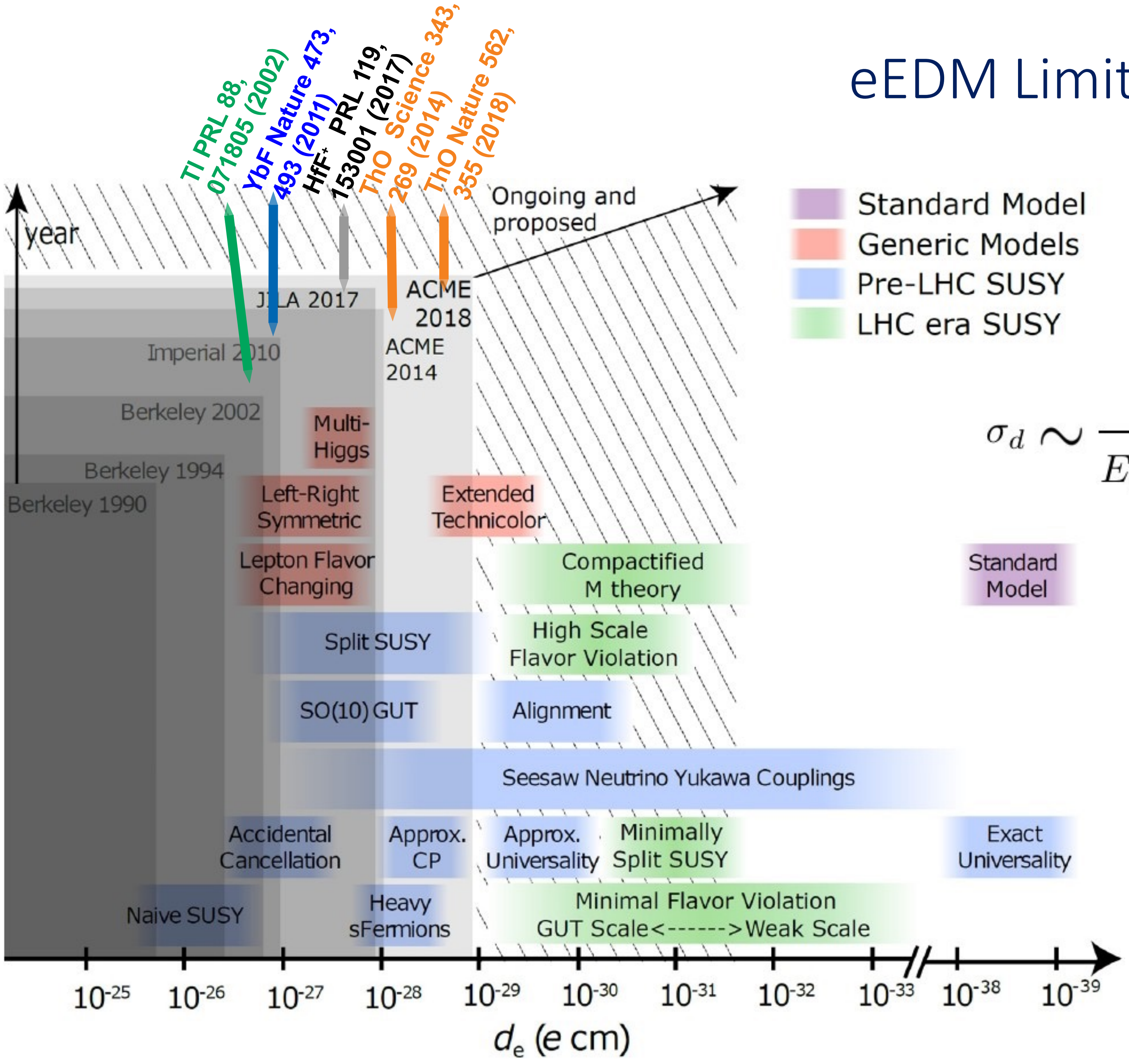
$|d_e| \leq 1.1 \times 10^{-29}$ e · cm

$$d_e \sim \mu_B \left(\frac{g^2}{2\pi}\right)^N \left(\frac{m_e}{m_\chi}\right)^2 \sin\phi$$

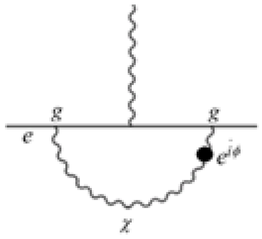
[ACME, Nature 562, 355 (2018)]
[Baron et al. Science 343, 269 (2014)]
[Sandars Phys. Rev. Lett. 18, 1396 (1967)



eEDM Limits



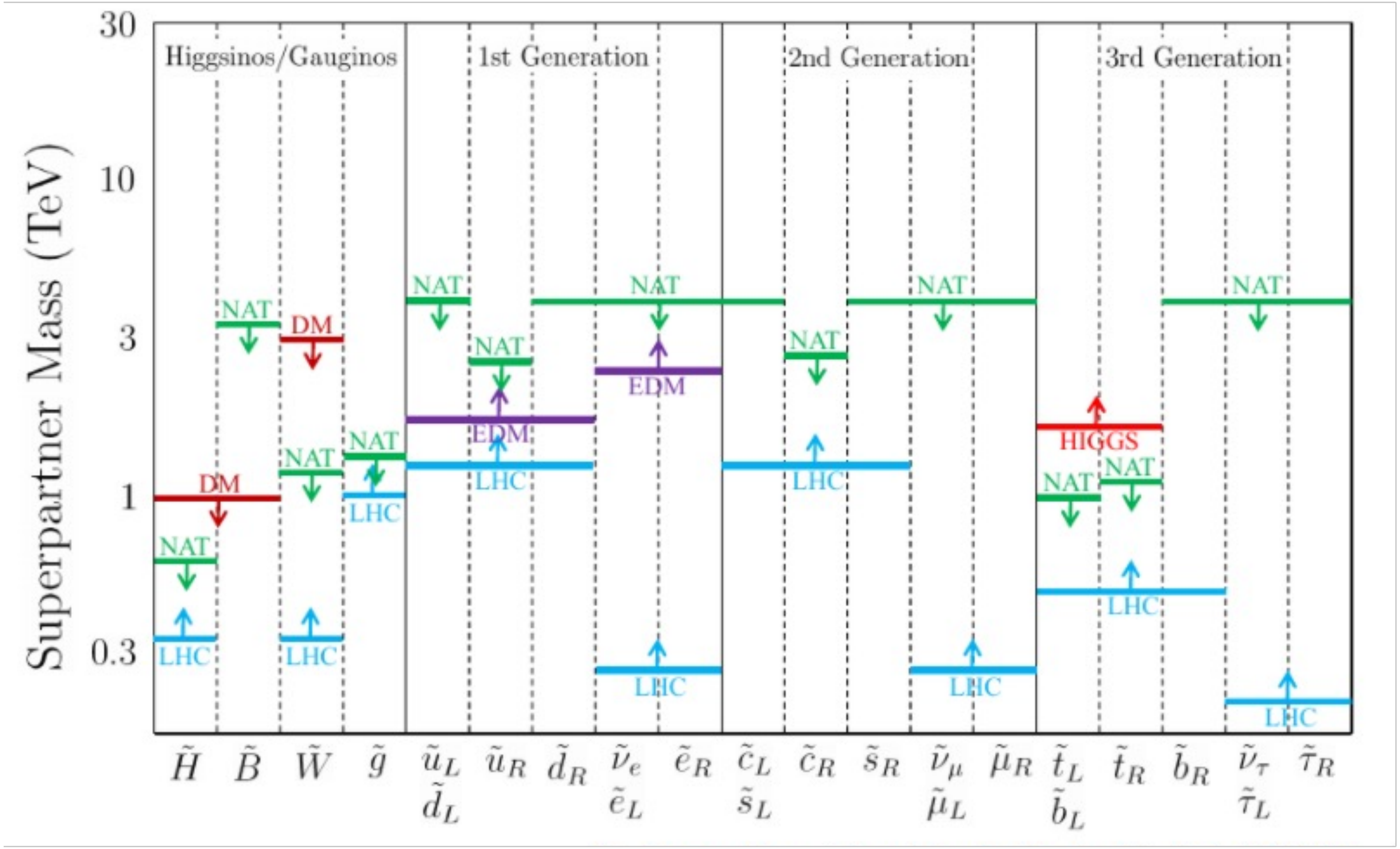
$$\sigma_d \sim \frac{1}{E_{\text{eff}}\tau\sqrt{\dot{N}T}}$$



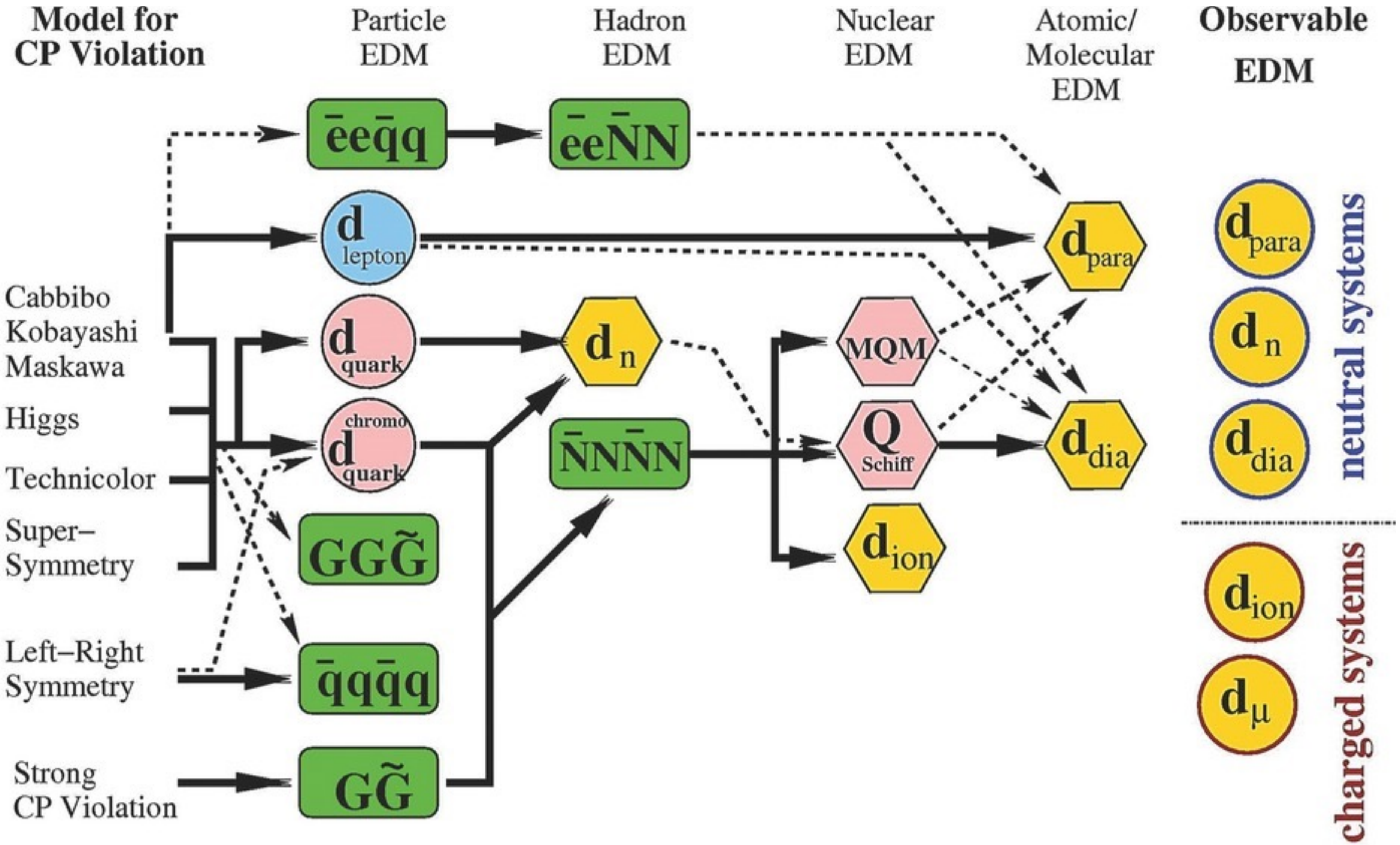
$$d_e \sim \mu_B \left(\frac{g^2}{2\pi}\right)^N \left(\frac{m_e}{m_\chi}\right)^2 \sin\phi$$

[Source: D. DeMille. Manipulating Quantum Systems: An Assessment of Atomic,Molecular, and Optical Physics in the United States (2019)]

Constraints on Supersymmetry



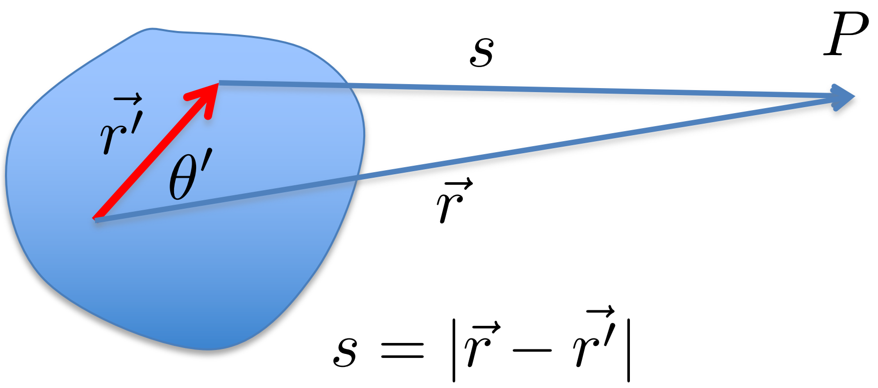
[J. Feng Ann. Rev. Nucl. Part. 63, 351 (2013)]



[Jungmann et al. Ann. Phys. 525, 550 (2013)]

Symmetry-Violating Nuclear Properties

multipole expansion
of electrostatic potential



Electric multipoles:

$$\mathbf{Q}_{lm} = \int \mathbf{r}_i^l Y_{lm}^*(\theta_i, \phi_i)\rho_e(r)dr$$

Parity = ?

Magnetic multipoles:

$$\mathbf{M}_{lm} = \frac{-1}{c(l+1)} \int \mathbf{j}(\mathbf{r}) \cdot (\mathbf{r} \times \nabla)\mathbf{r}_i^l Y_{lm}^*(\theta_i, \phi_i)dr$$

Parity = ?

Symmetry-Violating Nuclear Properties

multipole expansion
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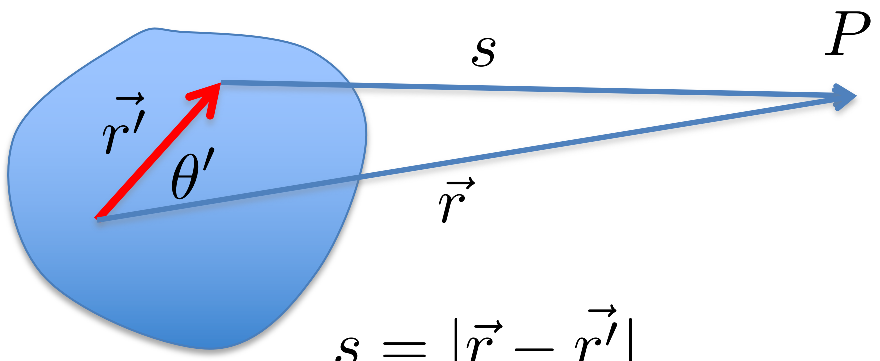

$$s = |\vec{r} - \vec{r}'|$$

Electric multipoles:

$$\mathbf{Q}_{lm} = \int \mathbf{r}_i^l Y_{lm}^*(\theta_i, \phi_i)\rho_e(r)dr$$

Parity = (-1)^l

Magnetic multipoles:

$$\mathbf{M}_{lm} = \frac{-1}{c(l+1)} \int \mathbf{j}(\mathbf{r}) \cdot (\mathbf{r} \times \nabla)\mathbf{r}_i^l Y_{lm}^*(\theta_i, \phi_i)dr$$

Parity = (-1)$^{l+1}$

Symmetry-Violating Nuclear Properties

multipole expansion
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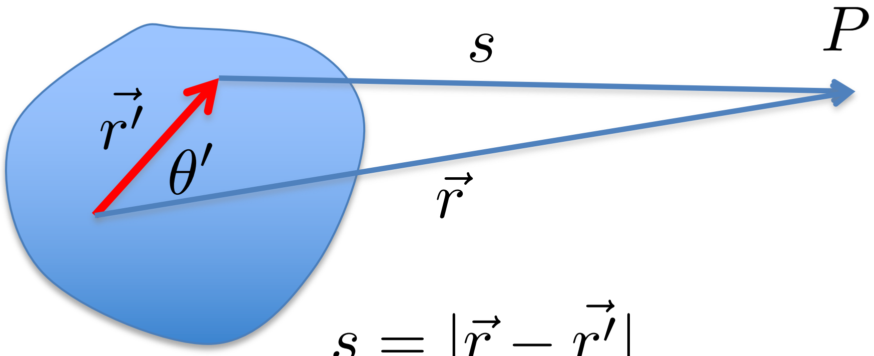

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$$\mathbf{Q}_{lm} = \int \mathbf{r}_i^l Y_{lm}^*(\theta_i, \phi_i)\rho_e(r)dr$$

Parity = (-1)^{l}

P-even:	**l=0,**	**Monopole**
	2,	**Quadrupole**
	4,	**Hexadecapole**
	....	**.....**

Magnetic multipoles:

$$\mathbf{M}_{lm} = \frac{-1}{c(l+1)} \int \mathbf{j}(\mathbf{r}) \cdot (\mathbf{r} \times \nabla)\mathbf{r}_i^l Y_{lm}^*(\theta_i, \phi_i)dr$$

Parity = (-1)$^{l+1}$

P-even:	**l=1,**	**Dipole**
	3,	**Octopole**
	5,	
	....	**.....**

Nuclear Schiff Moment

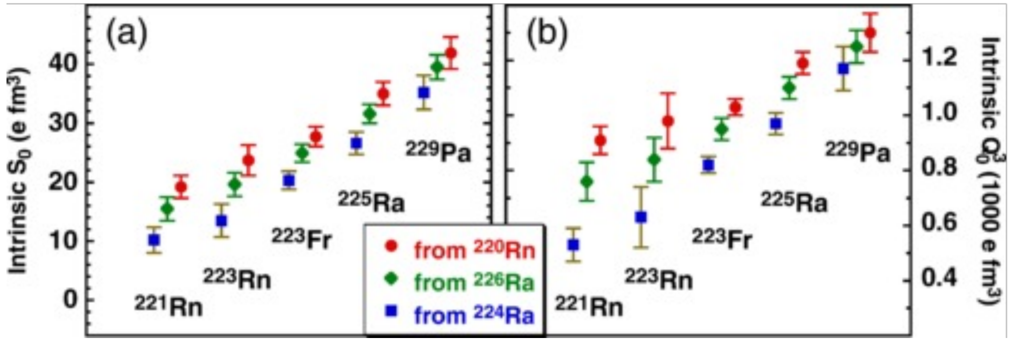
P,T-odd nucleon-nucleon interaction

$$S = \langle \Psi_0 | S_z | \Psi_0 \rangle = \frac{\langle \Psi_+ | S_z | \Psi_- \rangle \langle \Psi_+ | V_{PT} | \Psi_- \rangle}{E_+ - E_-}$$

Nuclear structure

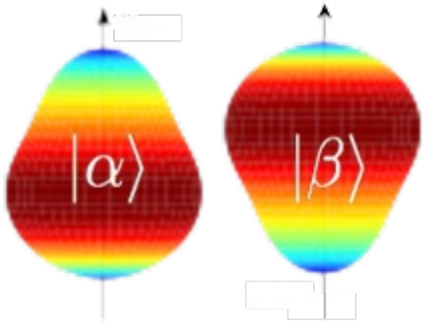
Theory + Experiment

Experiment



Phys. Rev. Lett. 121, 232501 (2018)

ΔE: Energy splitting of opposite parity states



^{225}Ra

ΔE = 55 keV

[Gaffney et al. Nature 497, 199 (2013)]

$$S \sim Z^a A^b \beta_2 \beta_3 / (E_+^N - E_-^N)$$

Slide from L. Gaffney

Radioactive Molecules

$\sim O_{Nucl}\, F_{mol}$

$$H_{mol} = H_e + H_{vib} + H_{rot} + \;\ldots\; + H_{hfs} + H_{PV} + H_{PTV}$$

eV	H_e	H_{vib}	H_{rot}	H_{hfs}	H_{PV}	H_{PTV}
eV	~ 2	10^{-2}	10^{-5}	10^{-8}	$<10^{-12}$	$<10^{-18}$

- ✓ Large Z, A
- ✓ Nuclear spin I >0
- ✓ $\beta_2\ \beta_3 > 0$

^{225}Ra

[Gaffney et al. Nature 497, 199 (2013)]

Nuclear

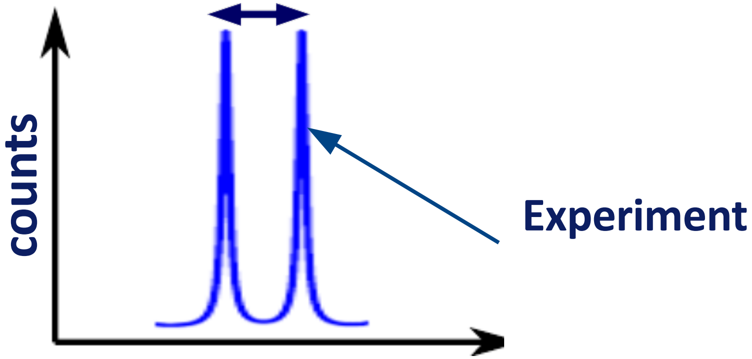
$\sim Z^a A^b \beta_2\beta_3 / (E_+^N - E_-^N)$

Atom/molecule

$\sim Z^c / (E_+^N - E_-^N)$

$E_+^N - E_-^N \sim 10^{-5}$ smaller in molecules

$$\sim O_{Nucl}\, F_{mol}$$

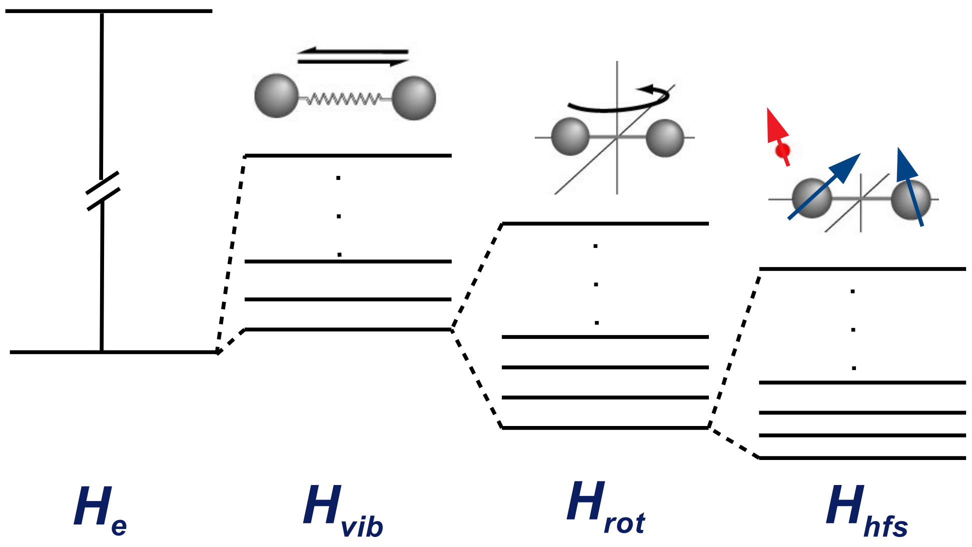


Nuclear *x* **Molecule**

Molecule	> 10^3
Nuclear amplification	> 10^3

RaF molecules=> Best of all worlds!

Recent Results (RaF)



$$H_{mol} = H_e + H_{vib} + H_{rot} + \ldots + H_{hfs} + H_{PV} + H_{PTV}$$

eV: ~ 2, 10^{-2}, 10^{-5}, 10^{-8}, $<10^{-12}$, $<10^{-15}$

S. Udrescu

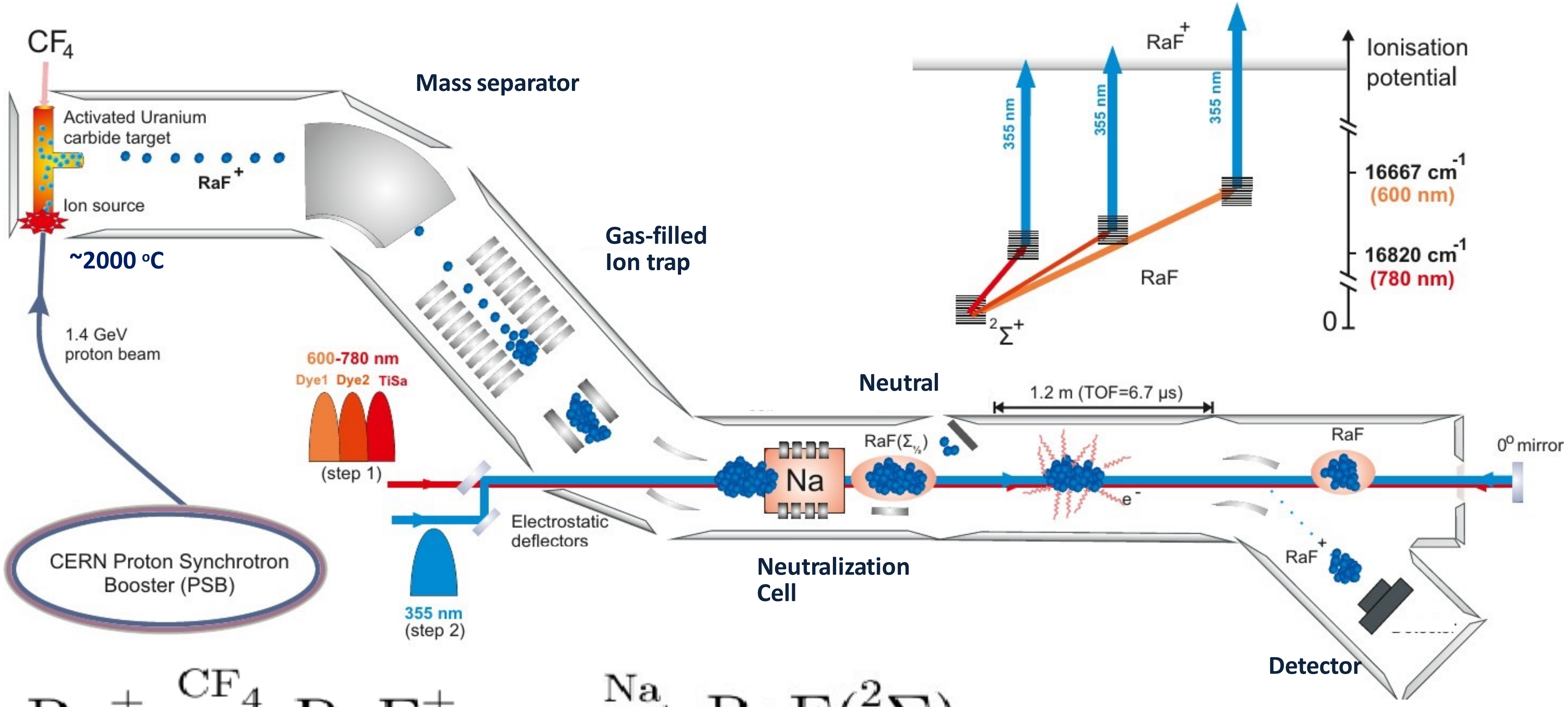
A. Brinson

S. Wilkins

Recent Results (RaF)

Collinear resonance ionization spectroscopy of RaF molecules

[Garcia Ruiz, Berger et al. Nature 581, 396 (2020)]



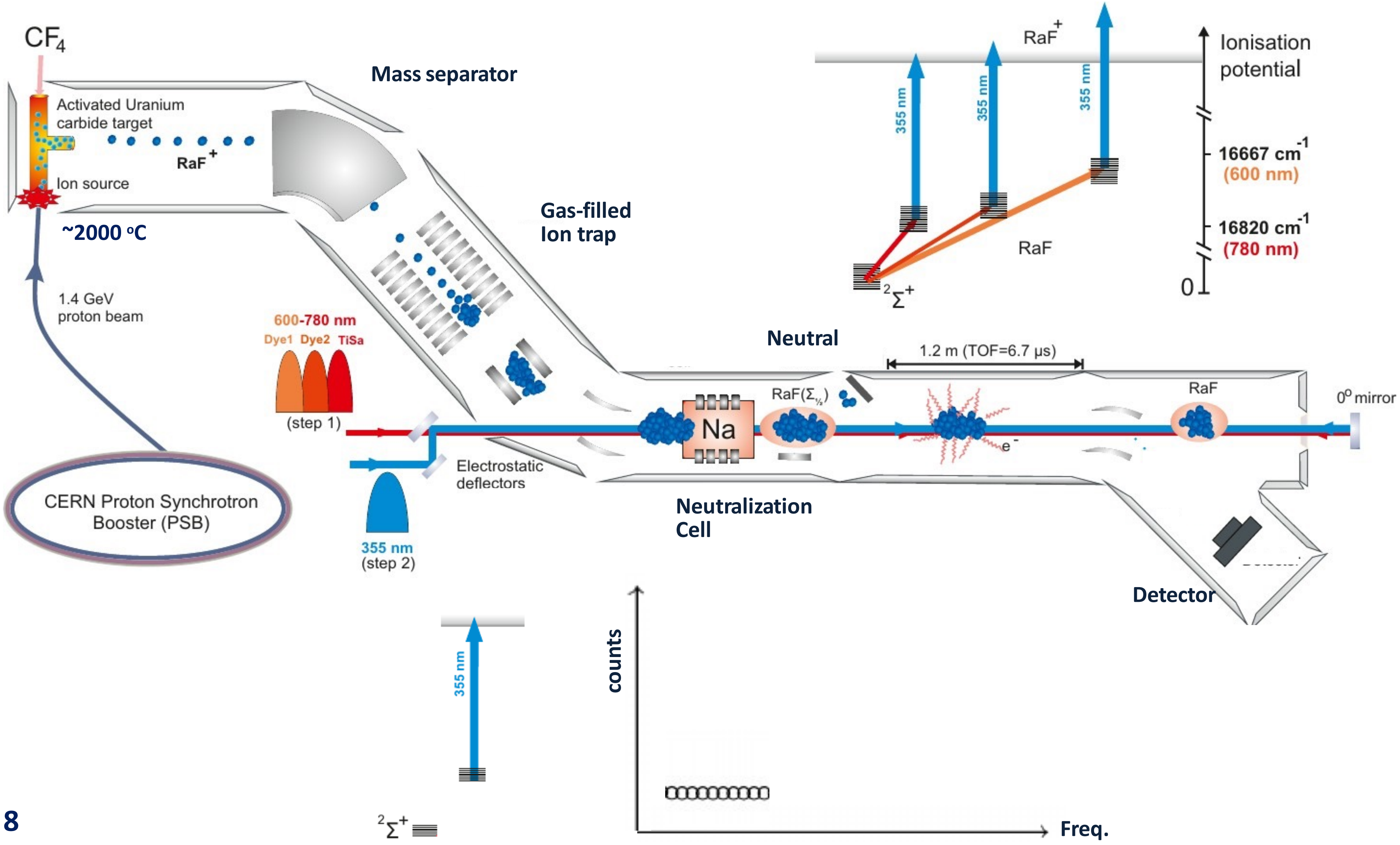
$$\mathrm{Ra}^+ \xrightarrow{\mathrm{CF}_4} \mathrm{RaF}^+ \xrightarrow{\mathrm{Na}} \mathrm{RaF}(^2\Sigma)$$

[Garcia Ruiz et al. Nature 581, 396 (2020)]

Recent Results (RaF)

Collinear resonance ionization spectroscopy of RaF molecules

[Garcia Ruiz, Berger et al. Nature 581, 396 (2020)]



Recent Results (RaF)

Collinear resonance ionization spectroscopy of RaF molecules

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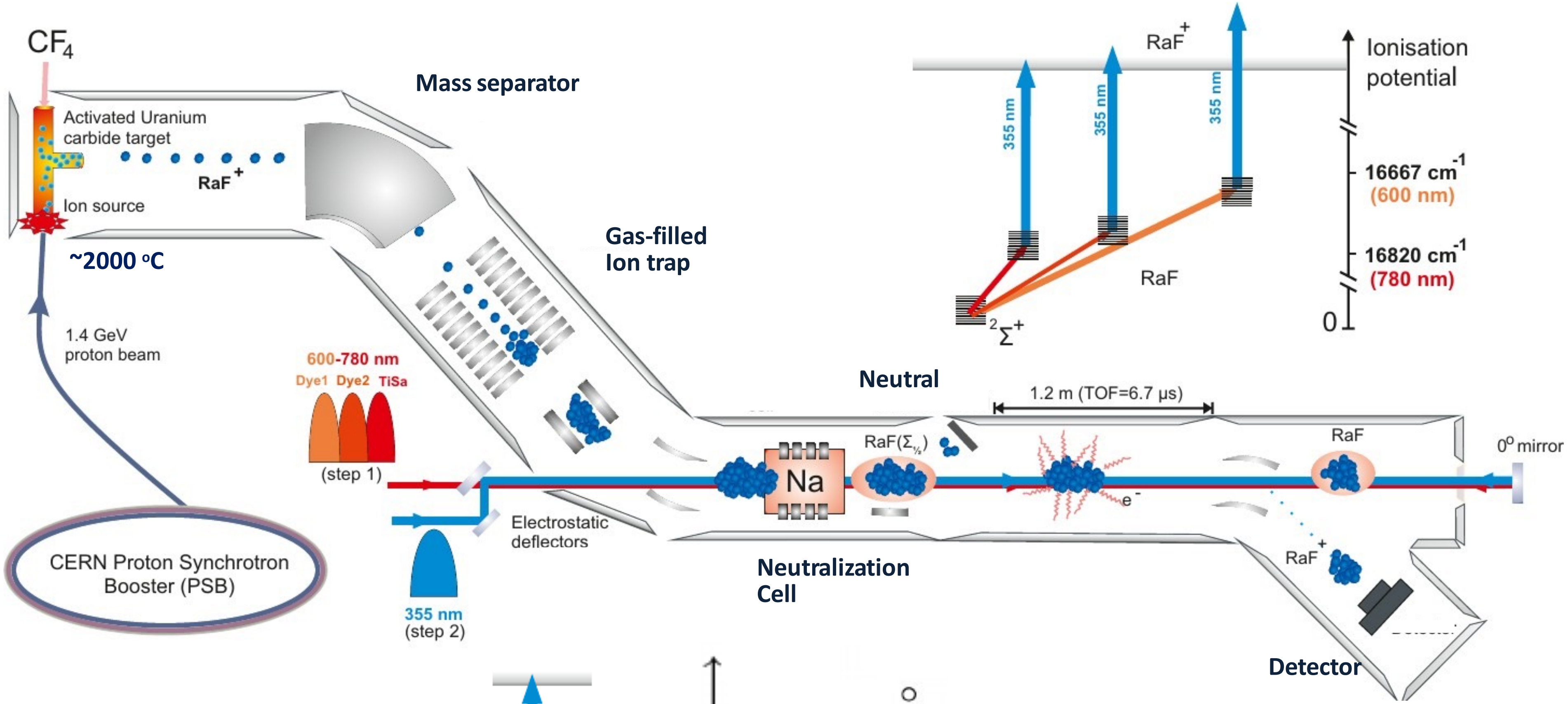
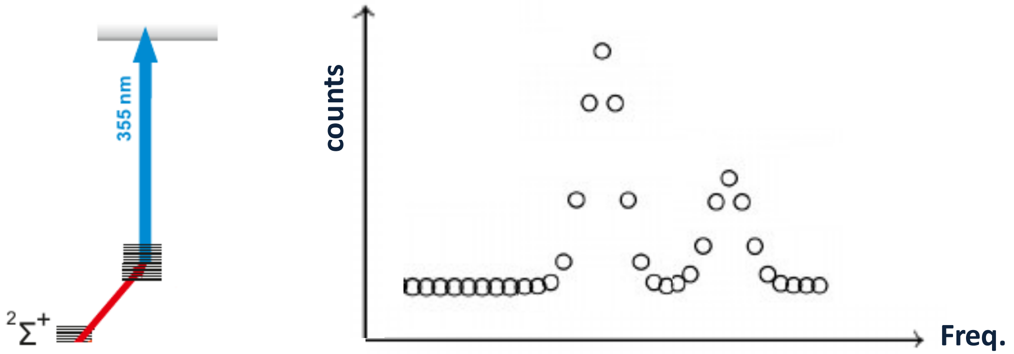
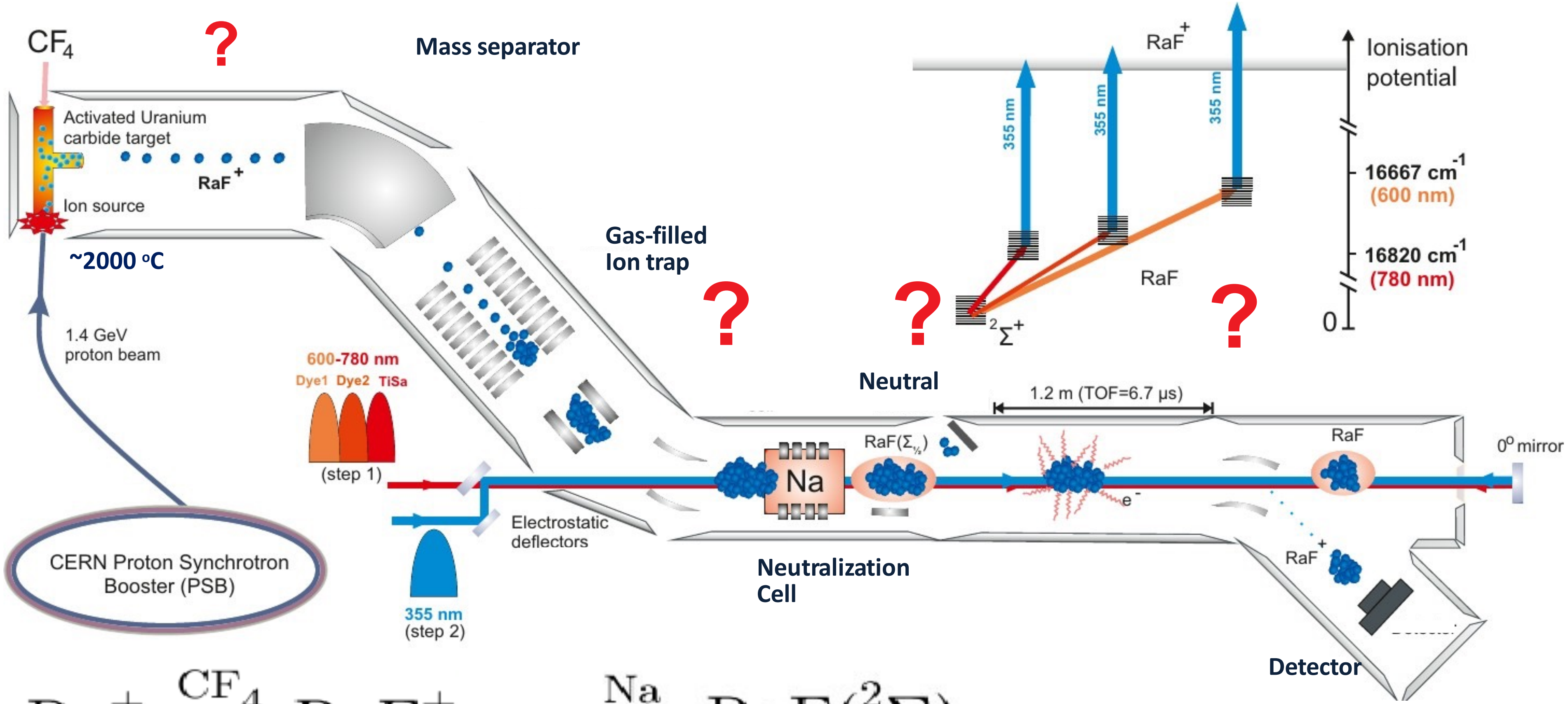




Recent Results (RaF)

Collinear resonance ionization spectroscopy of RaF molecules

[Garcia Ruiz, Berger et al. Nature 581, 396 (2020)]



$$Ra^+ \xrightarrow{CF_4} RaF^+ \xrightarrow{Na} RaF(^2\Sigma)$$

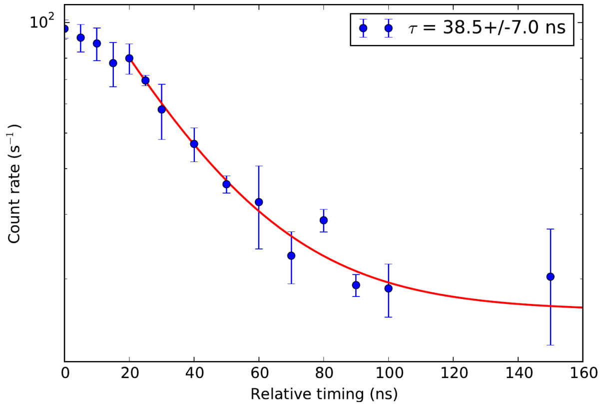
Experimental details

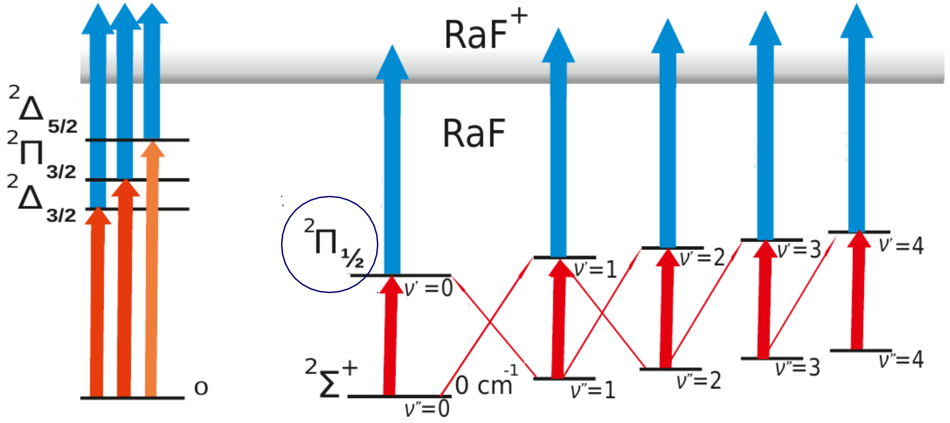
Recent Results (RaF)

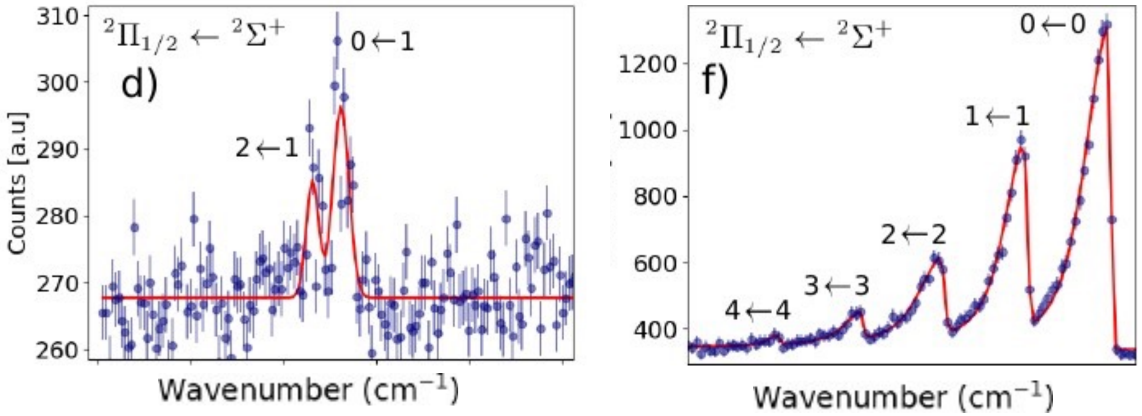
I. Low-lying structure ✓

II. Feasibility of laser cooling?

1. **Dominant f_{00}? → $f_{00}/f_{ij} > 0.97$** ✓
2. **Short-lived excited state ($T_{1/2}$)?→$T_{1/2} < 50$ ns** ✓
3. **Electronic states of lower energy (E)?**







[Garcia Ruiz, Berger et al. Nature 581, 396 (2020)]

Recent Results (RaF)

“Hot” molecules can be super cool!

nature

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Spectroscopy of short-lived radioactive molecules

R. F. Garcia Ruiz, R. Berger, […]

Nature **581**, 396–400 (2020) | Cite this article

$$H_{mol} = H_e + H_{vib} + H_{rot} + \ldots + H_{hfs} + H_{PV} + H_{PTV}$$

eV	~ 2 ✓	10^{-2} ✓	10^{-5}	10^{-8}	$<10^{-12}$	$<10^{-15}$

S. Udrescu

A. Brinson

S. Wilkins

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DOI:10.1063/PT.6.1.20200611a

11 Jun 2020 in Research & Technology

Spectroscopy of molecules with unstable nuclei

Pinning down the energy transitions of radium monofluoride, and eventually other short-lived molecules, could reveal the ways they are influenced by the properties of heavy radioactive nuclei.

Andrew Grant

physicsworld

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Exotic radioactive molecules could reveal physics beyond the Standard Model

05 Jun 2020

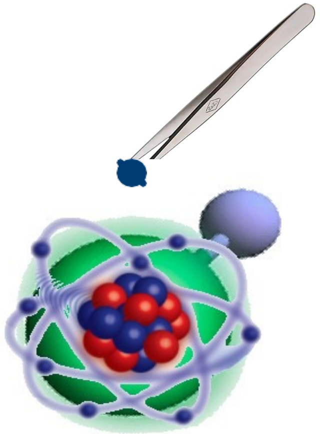
CHEMISTRY WORLD

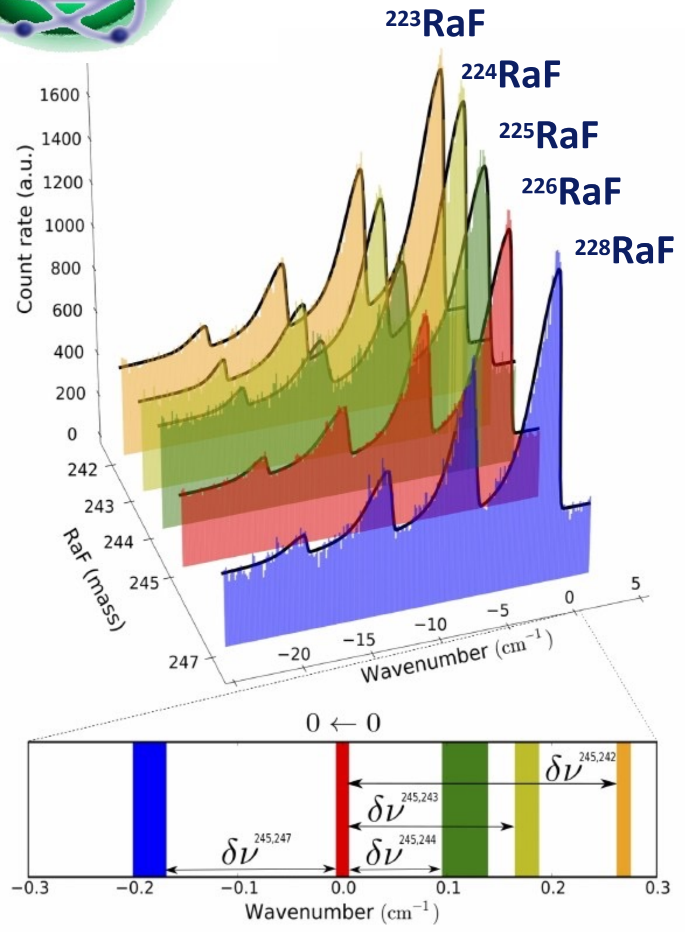
Molecular experiments hope to reveal new physics

BY ANDY EXTANCE | 5 JUNE 2020

Detecting extremely short-lived radium fluoride can explore standard model’s limits

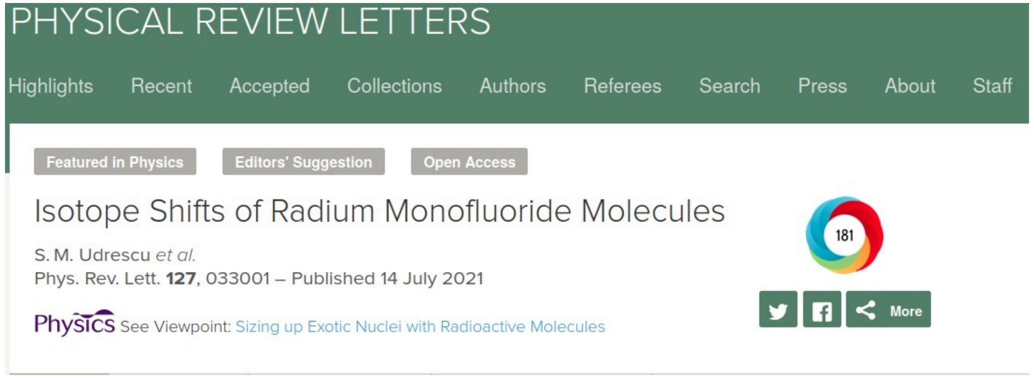
Recent Results (RaF)





New opportunities for nuclear structure studies of the heaviest elements (e.g. ThO, PaO,...)

[Udrescu et al. Phys. Rev. Lett. 127, 033001 (2021)]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Isotope Shifts of Radium Monofluoride Molecules

S. M. Udrescu *et al.*

Phys. Rev. Lett. **127**, 033001 – Published 14 July 2021

Physics See Viewpoint: Sizing up Exotic Nuclei with Radioactive Molecules

181

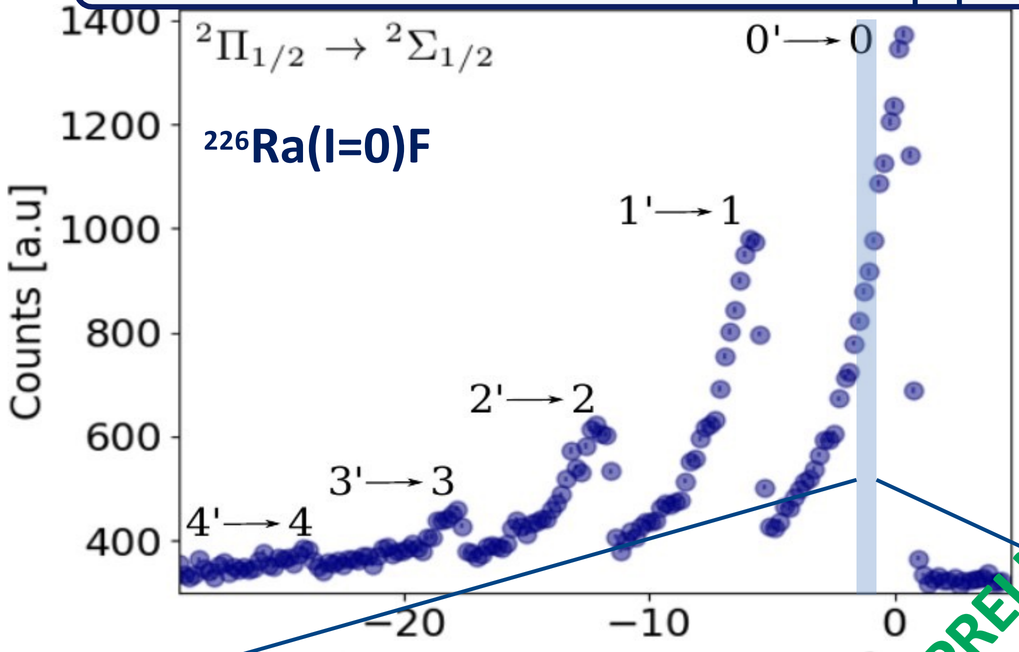
More

S. Udrescu

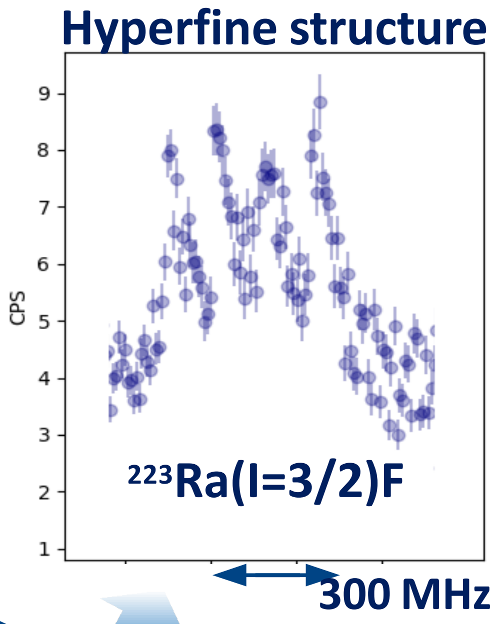
A. Brinson

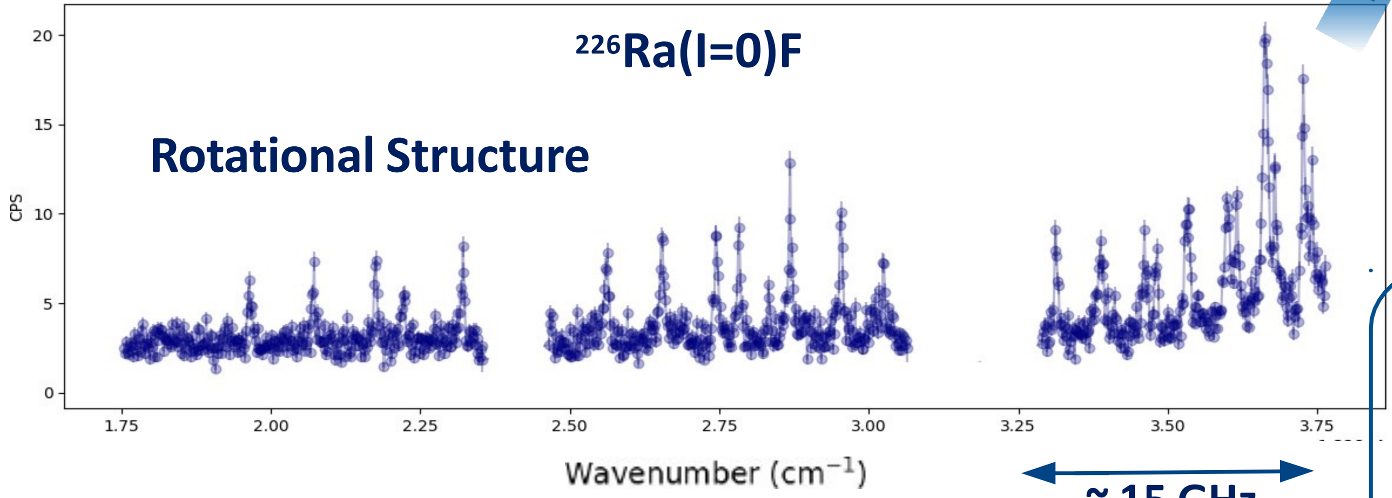
S. Wilkins

Recent results: Sub-Doppler spectroscopy (RaF)



Hyperfine structure





$$H_{mol} = H_e + H_{vib} + H_{rot} + \ldots + H_{hfs} + H_{PV} + H_{PTV}$$

Graduate students @ MIT

A. Brinson

S. Udrescu

Summary

Radii of mirror nuclei & equation of state

Can we use the properties of nuclei to constraint the properties of neutron stars?

E.g. PREX: neutron skin thickness of ^{208}Pb
[Adhikari et al. Phys. Rev. Lett. 126, 172502 (2021)]

Equation of state of nuclear matter

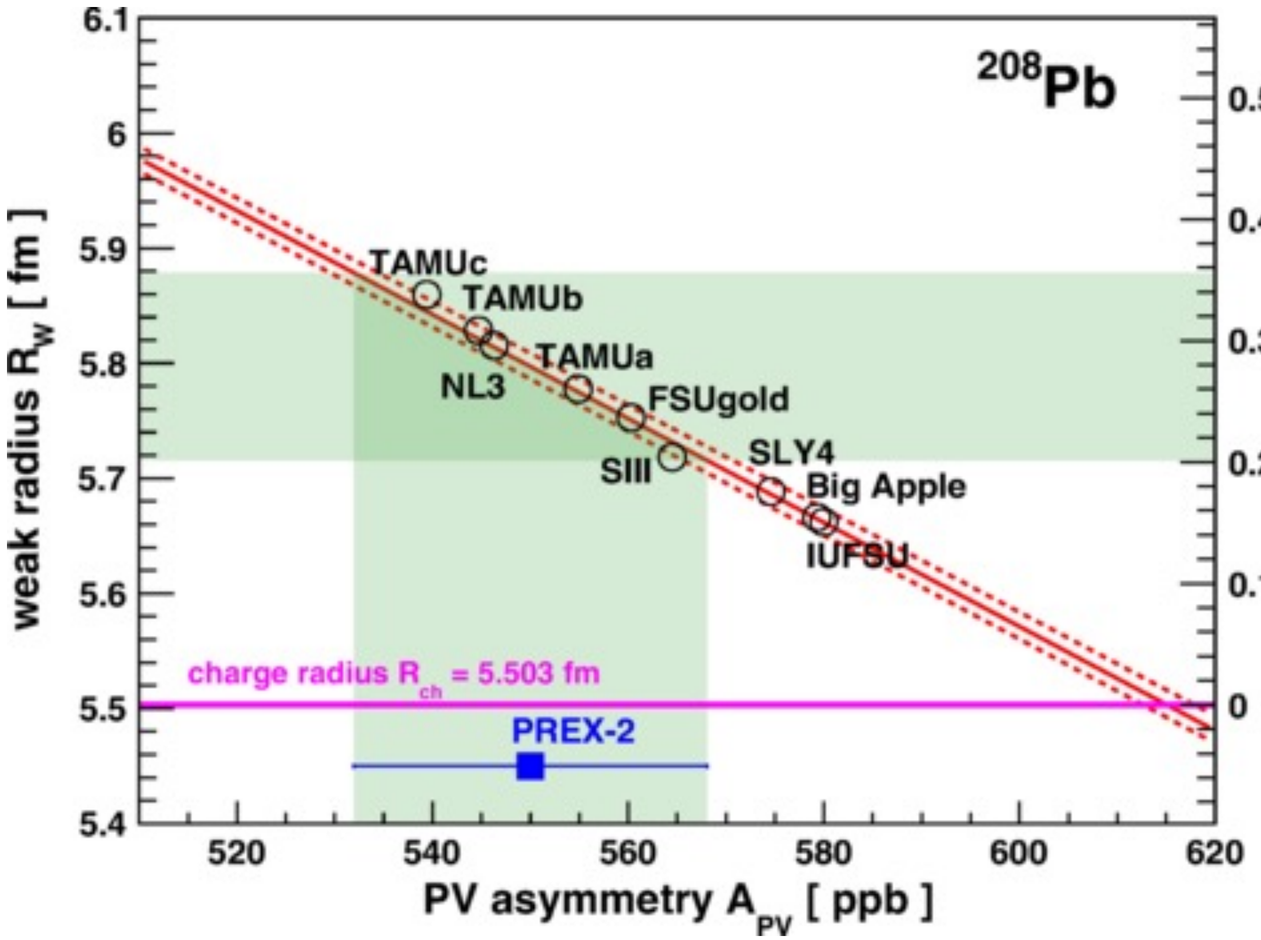
$$E(\rho,\delta) = E(\rho,0) + E_{sym}(\rho)\,\delta^2 + \mathcal{O}(\delta)^4$$

$$E_{sym}(\rho) = S_v + \frac{L}{3}\left(\frac{\rho-\rho_0}{\rho_0}\right) + \cdots$$

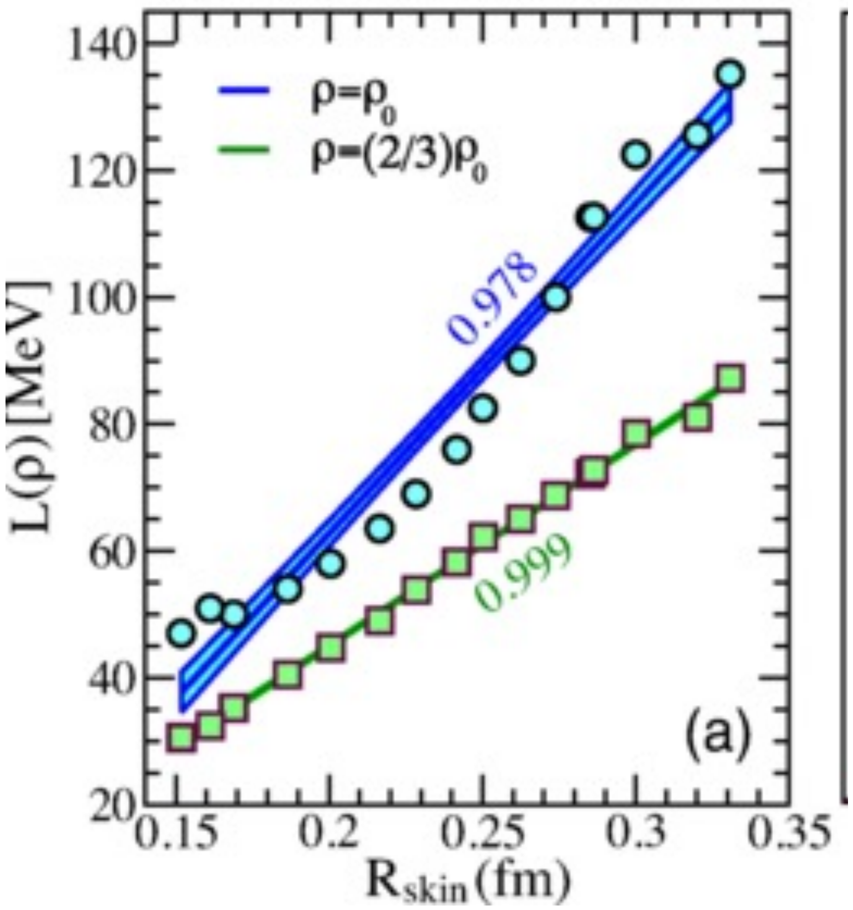
Symmetry energy

Slope ?

PV Asymmetry and Neutron Skin

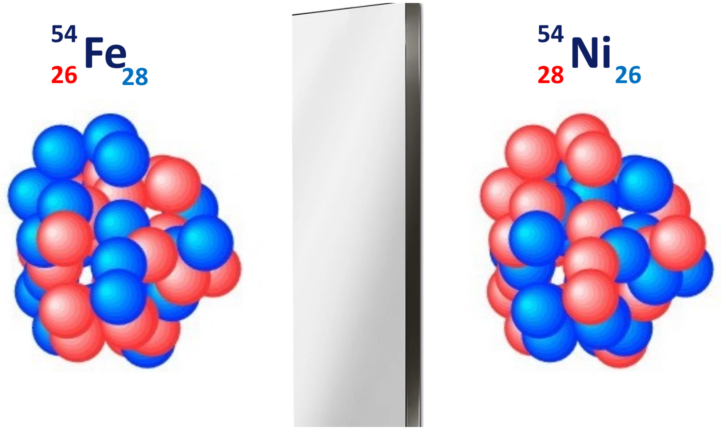


Phys. Rev. Lett. 126, 172502 (2021)



Phys. Rev. Lett. 126, 172503 (2021)

Radii of mirror nuclei & equation of state

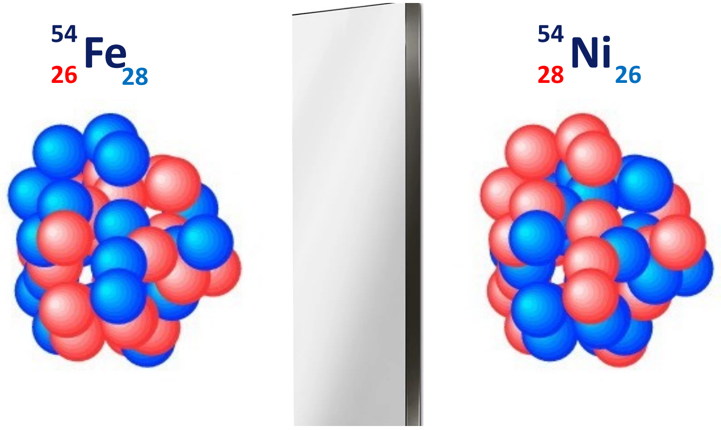


[Brown. Phys. Rev. Lett. 119, 122502 (2017)]
[Yang & Piekarewicz, PRC 97, 014314 (2018)]

$$\Delta R_{\mathrm{ch}} = R(^{54}\mathrm{Ni}) - R(^{54}\mathrm{Fe})$$

[S. Pineda Accepted in Phys. Rev. Lett (2021)]

Radii of mirror nuclei & equation of state



[Brown. Phys. Rev. Lett. 119, 122502 (2017)]
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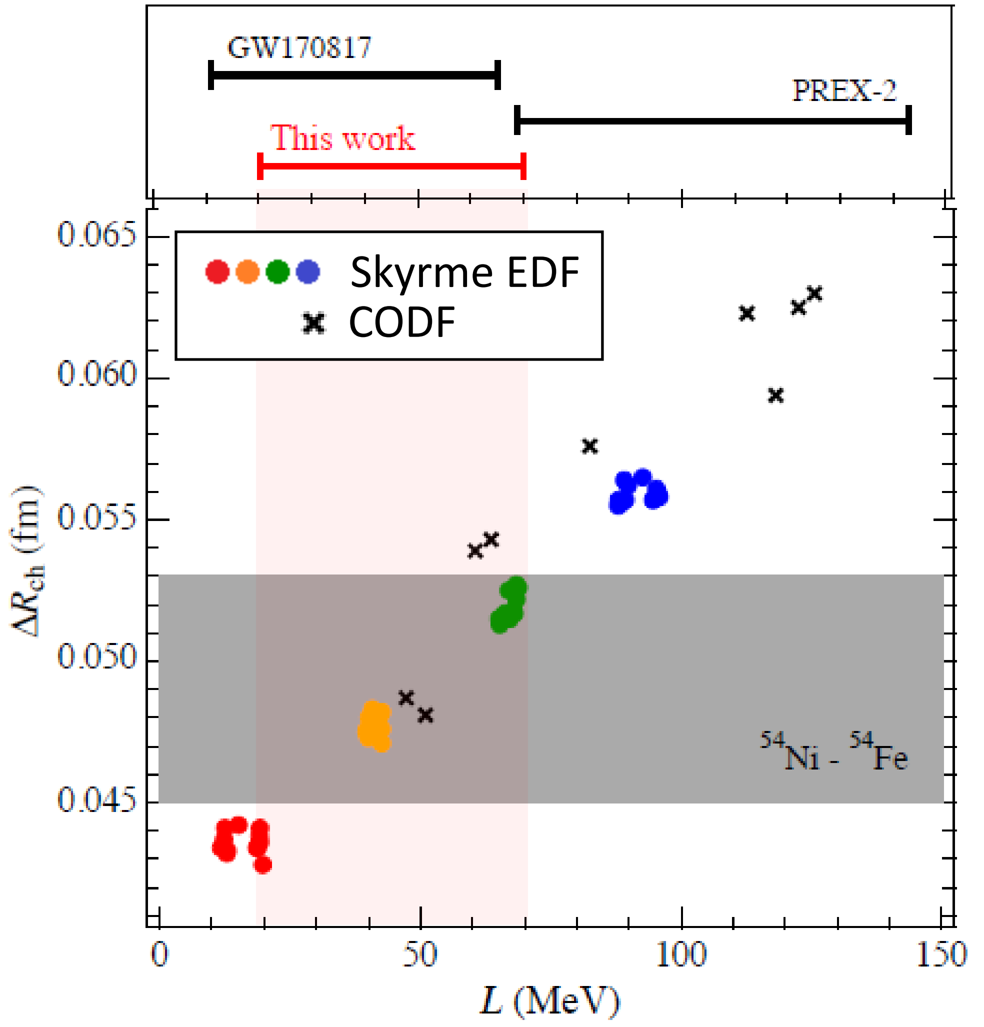
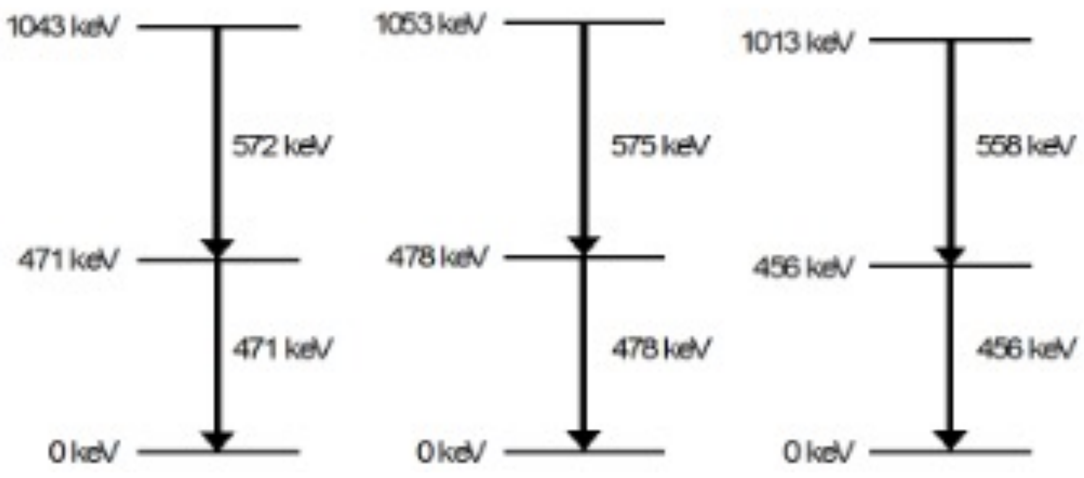


Isospin Symmetry?

Isobar: same A
Isotope: same Z
Isotone: same N



$^{74}_{38}Sr$ $^{74}_{37}Rb$ $^{74}_{36}Kr$

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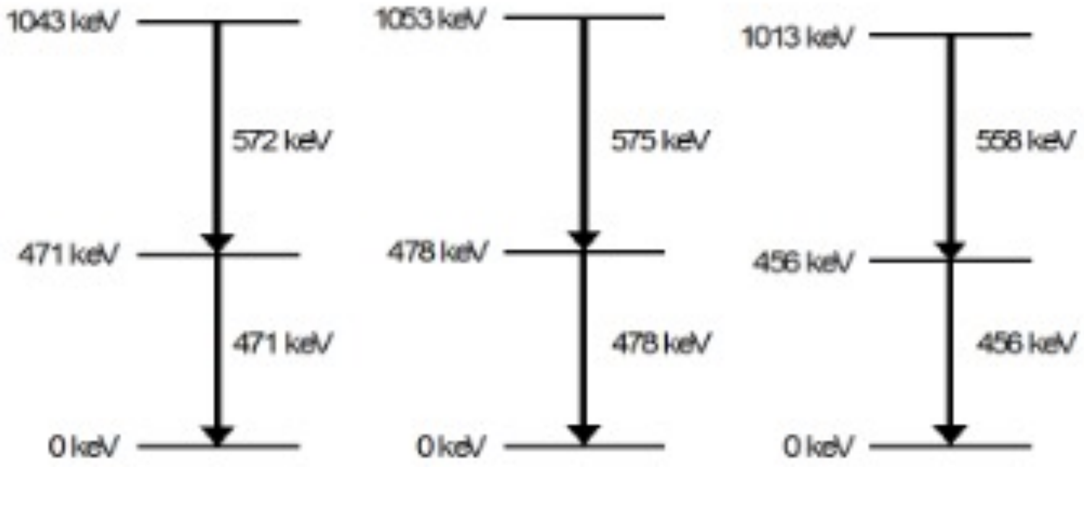
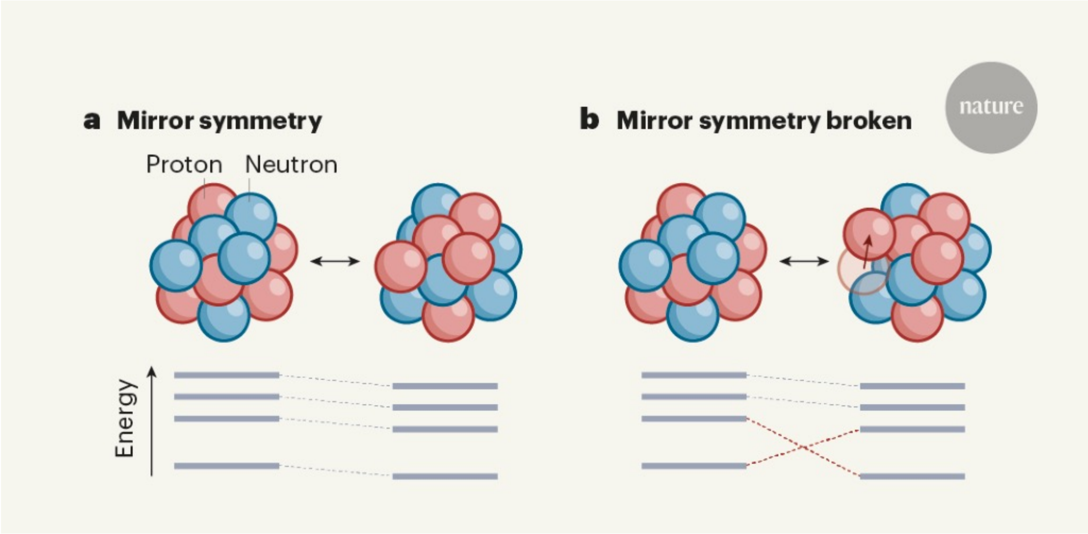
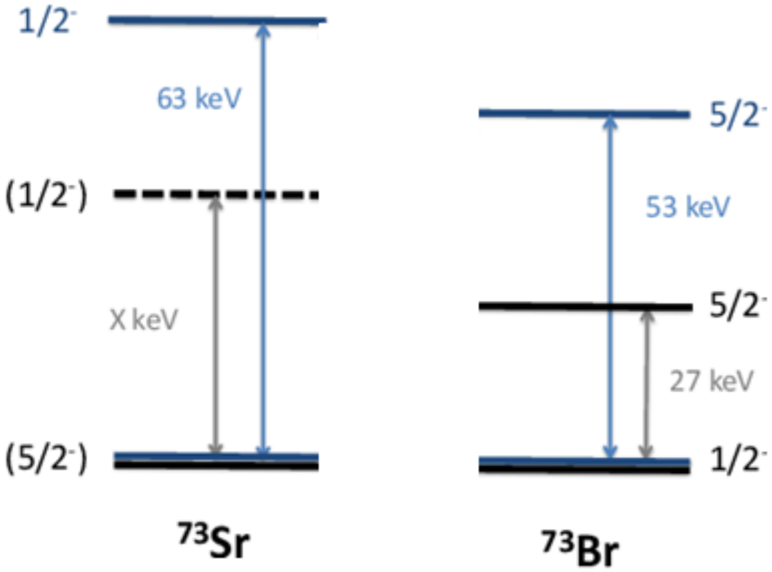


$^{74}_{38}$**Sr** $^{74}_{37}$**Rb** $^{74}_{36}$**Kr**

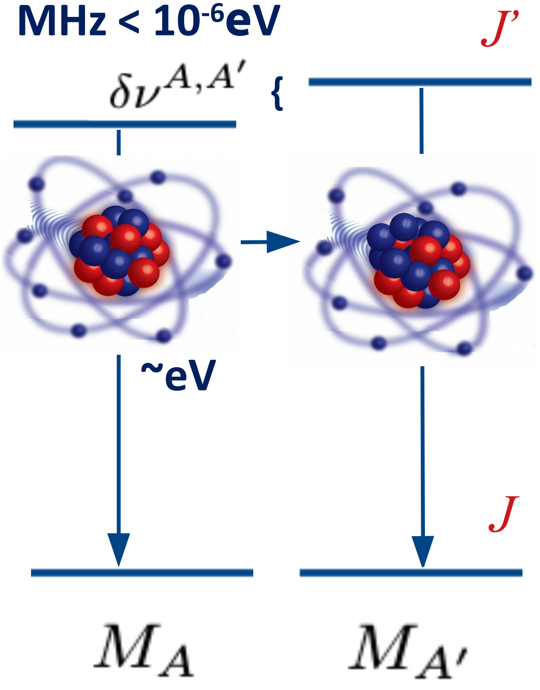




Nature 580, 2 (2020)

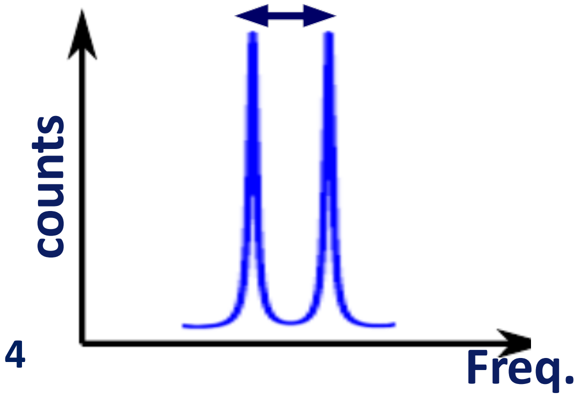
How do we do it?

Isotope shift
MHz < 10^{-6}eV



$I = 0$

$\sim F\delta\langle r^2\rangle^{A,A'}$

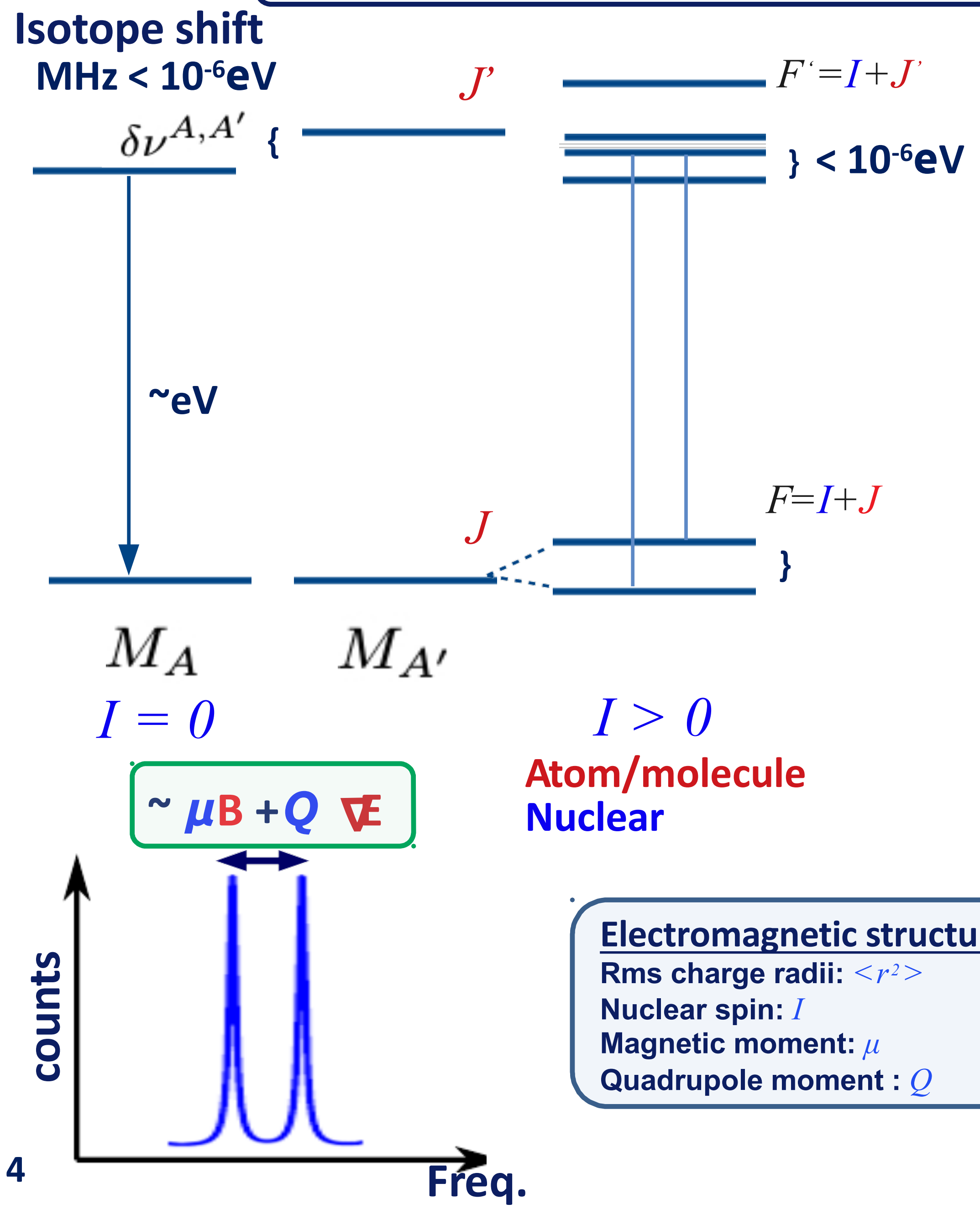


Atom/molecule
Nuclear

$$\delta\nu^{A,A'} = K_{MS}\frac{M_{A'} - M_A}{M_{A'}M_A} + F\delta\langle r^2\rangle^{A,A'}$$

Electromagnetic structure
Rms charge radii: $<r^2>$

How do we do it?



Electromagnetic structure

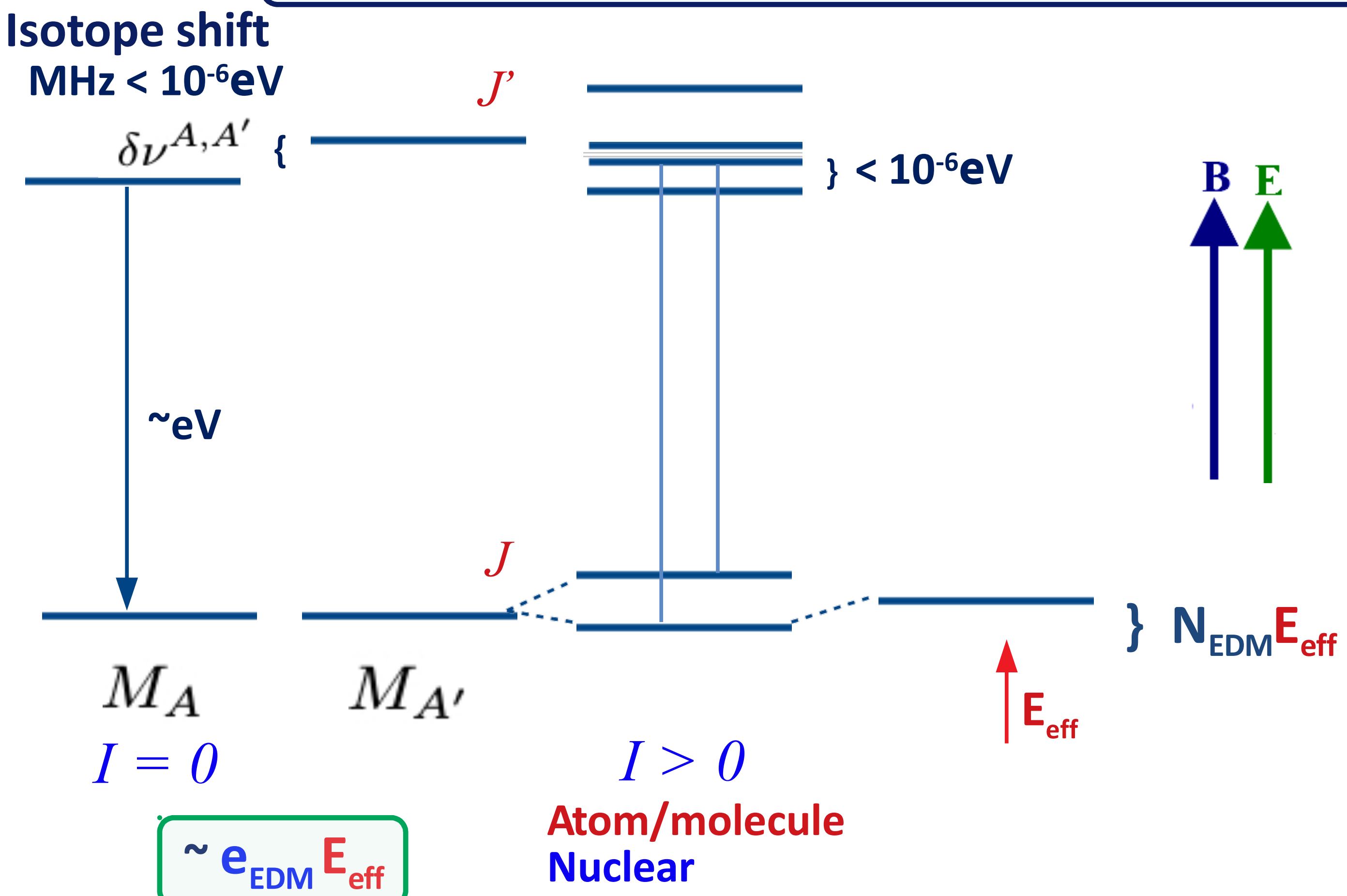
Rms charge radii: $<r^2>$

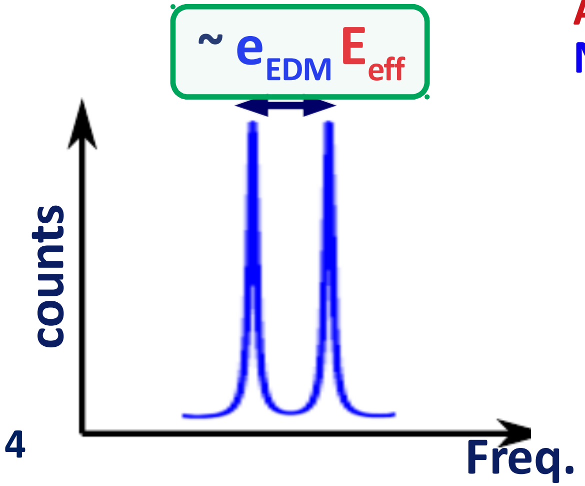
Nuclear spin: I

Magnetic moment: μ

Quadrupole moment : Q

How do we do it?





Electromagnetic structure
Rms charge radii: $<r^2>$
Nuclear spin: I
Magnetic moment: μ
Quadrupole moment : Q

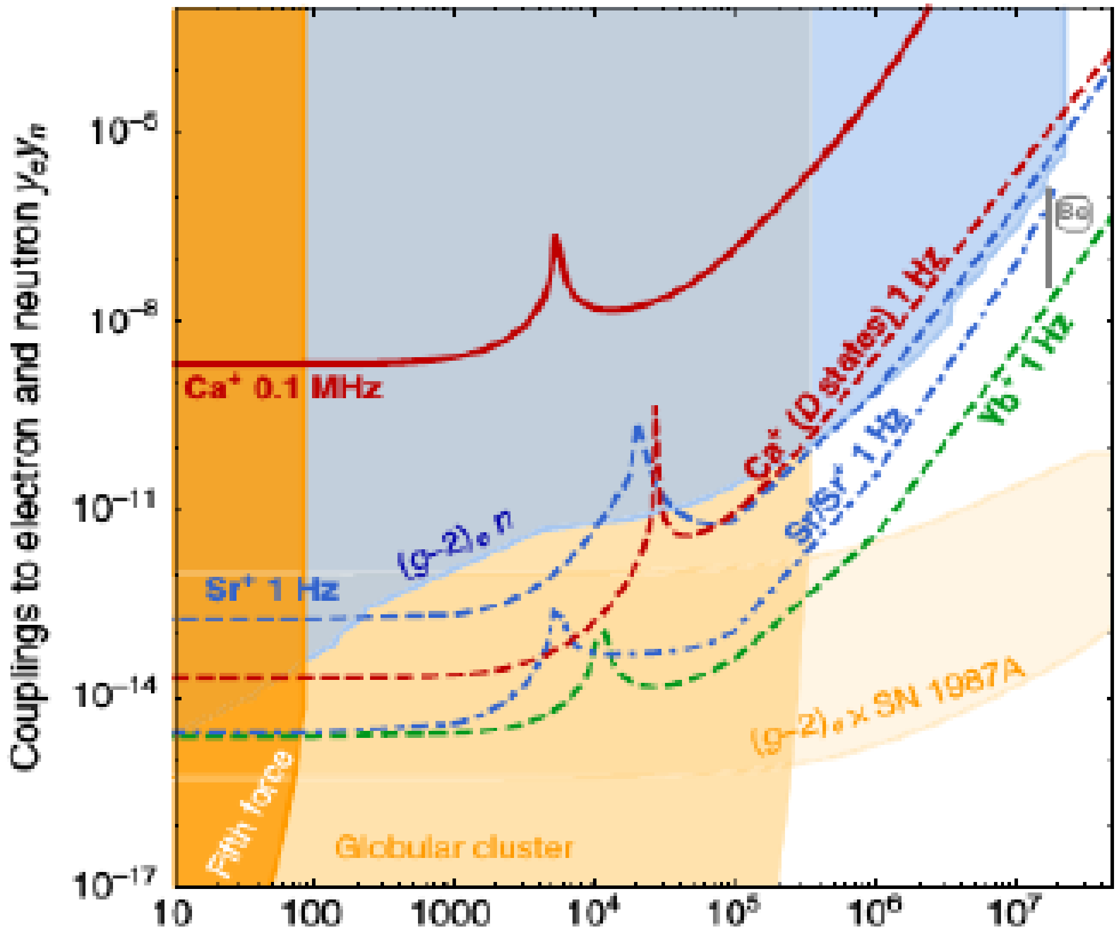
Symmetry violating moments:
Anapole (P-odd): A_{AM}
EDM (P,T-odd): $eEDM, S_{schiff}$
Magnetic quad. (P,T-odd): MQM

Dark Matter Searches

$$\nu_i^{AA'} = K_i \mu_{AA'} + F_i \delta\langle r^2 \rangle_{AA'} + \alpha_{NP} X_i \gamma_{AA'};$$

$$\alpha_{NP} = (-1)^s y_e y_n / 4\pi.$$

Phys. Rev. Lett. 128, 163201 (2022)



Limits on the electron and neutron couplings $(y_e y_n)$ of a new boson of mass m_ϕ

Phys. Rev. Lett. 120, 091801 (2018)

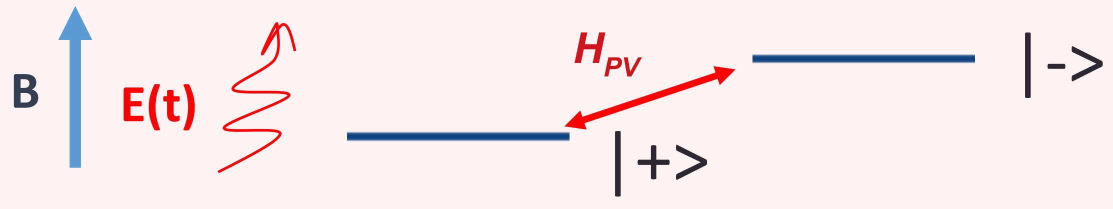
Can we achieve efficient cooling & trapping?

$$H_{mol} = H_e + H_{vib} + H_{rot} + \ldots + H_{hfs} + H_{PV} + H_{PTV}$$

?

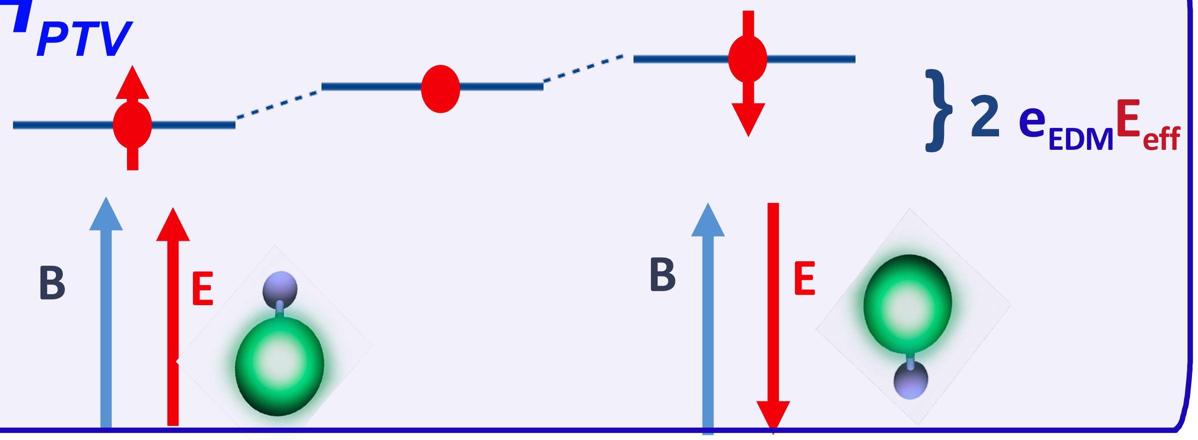
H_{PV}

[Phys Rev Lett 120, 142501 (2018)]



H_{PTV}

[ThO: Nature 562, 355 (2018)]



[HfF+: PRL 119, 153001 (2017)]

$$\frac{\Delta W}{W} \simeq \frac{1}{2\sqrt{2 N_0 t W}}$$

(Flux)(time)

Interaction time