Nuclear Electric Dipole Moments

- Nuclear Enhancements of Symmetry Violation: The Example of Parity
- Electric Dipole Moments
- Rare isotopes and octuple deformation: ^{225}Ra
- Concident atomic and nuclear scales: The strange case of ^{229}Pa

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INT Workshop: New Physics Searches

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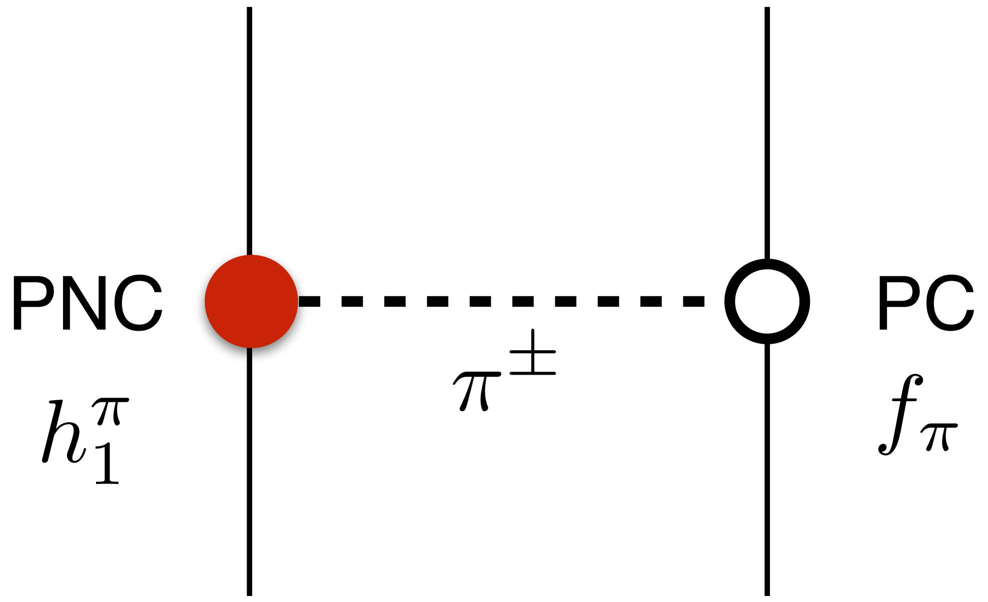
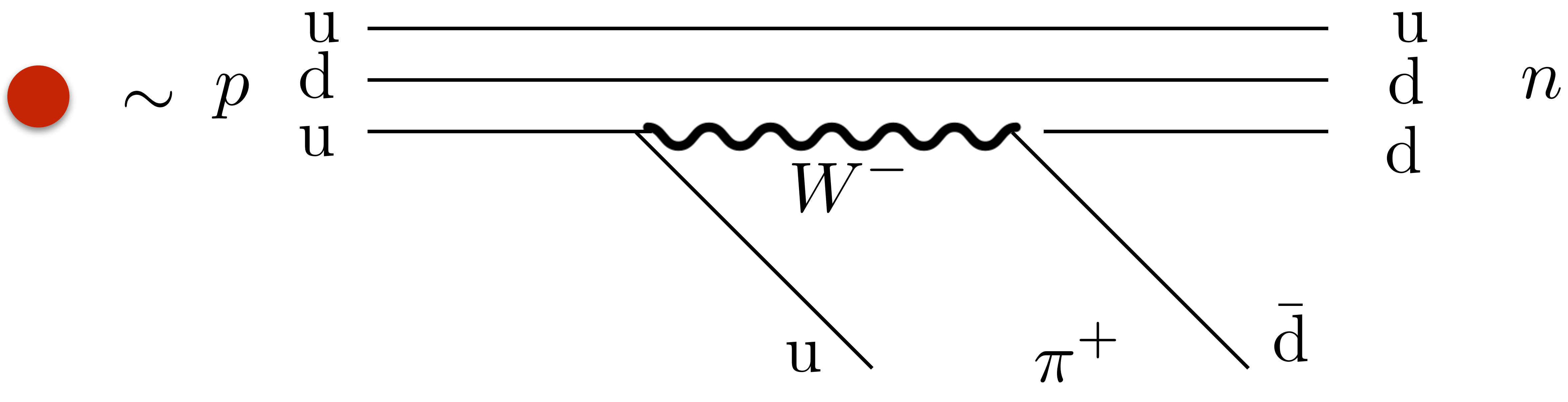
I. Introduction: Enhancements of Symmetry Violation - Parity as an Example

The example of the weak hadronic interaction: can detect its presence despite competition from the strong interaction because of the parity violation it induces.





Pseudoscalar observables — involving a weak amplitude of the form $\vec{\sigma} \cdot \vec{p}$ — arise from the interference of weak and strong observables. Unlike T-violation, many choices:

- — circular polarization of a γ -ray emitted in the decay of a state
- — an angular asymmetry in the scattering of polarized protons on a target
- — spin rotation of a polarized neutron as in travels through a nuclear medium
- — a parity-violating ground state moment (e.g., anapole moment) of a nucleon or nucleus

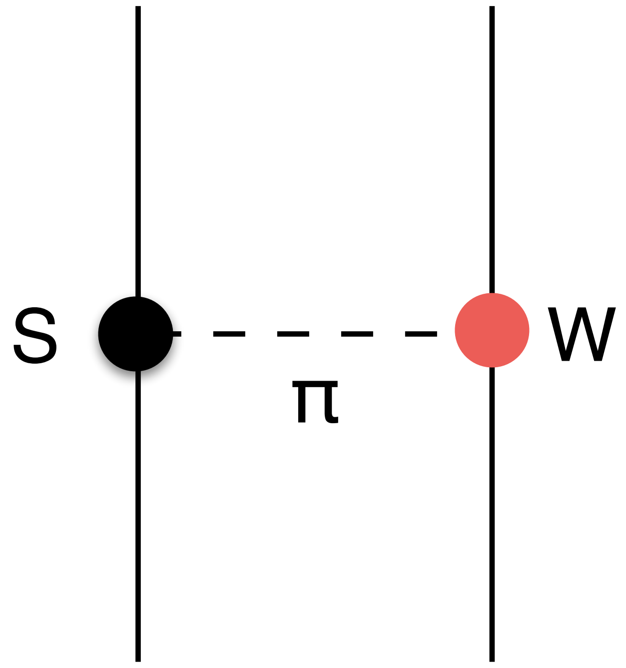
Low energies: Hadronic PNC characterized by its S-P NN partial wave amplitudes

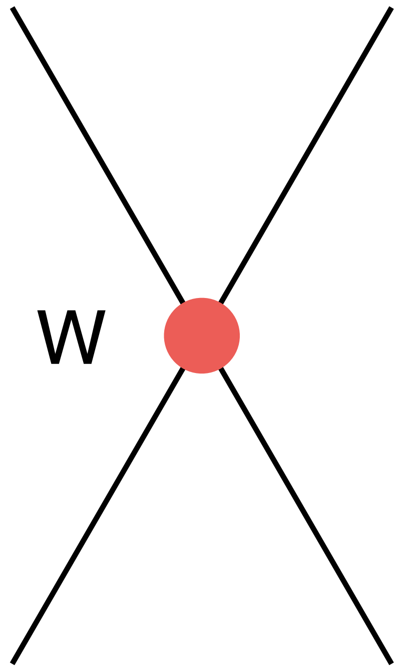
Danilov amplitudes

Transition	I ↔ I’	ΔI	n-n	n-p	p-p	NN system exchanges
$^3S_1 \leftrightarrow {}^1P_1$	0 ↔ 0	0		x		ρ ,ω
$^1S_0 \leftrightarrow {}^3P_0$	1 ↔ 1	0	x	x	x	ρ ,ω
		1	x		x	ρ ,ω
		2	x	x	x	ρ
$^3S_1 \leftrightarrow {}^3P_1$	0 ↔ 1	1		x		$\pi^{\pm}$, ρ ,ω

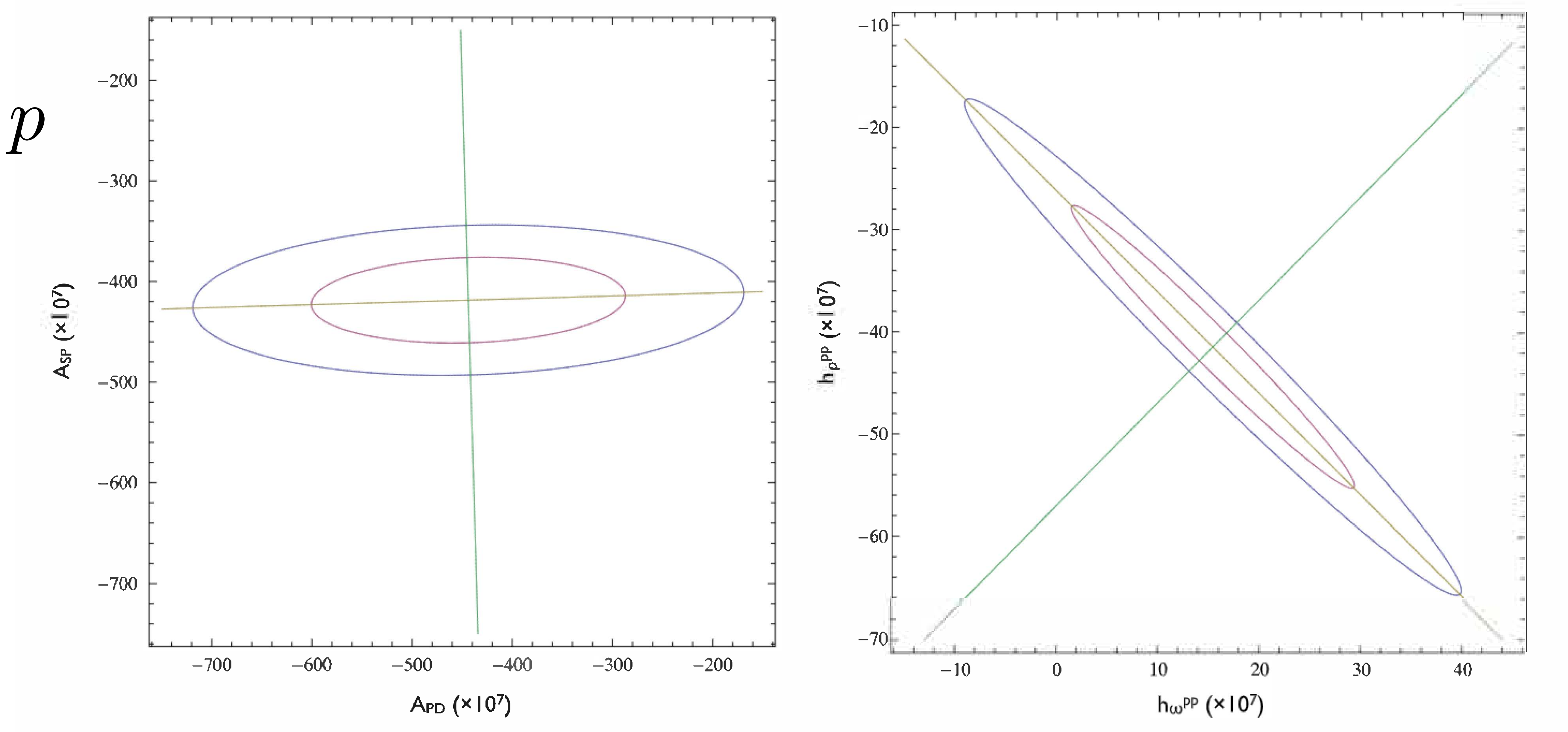
This physics can be encoded into a meson theory or EFT, with enough degrees of freedom to describe the five amplitudes and the pion’s range

e.g., $^3S_1 \leftrightarrow {}^3P_1$:





$$\vec{p} + p$$



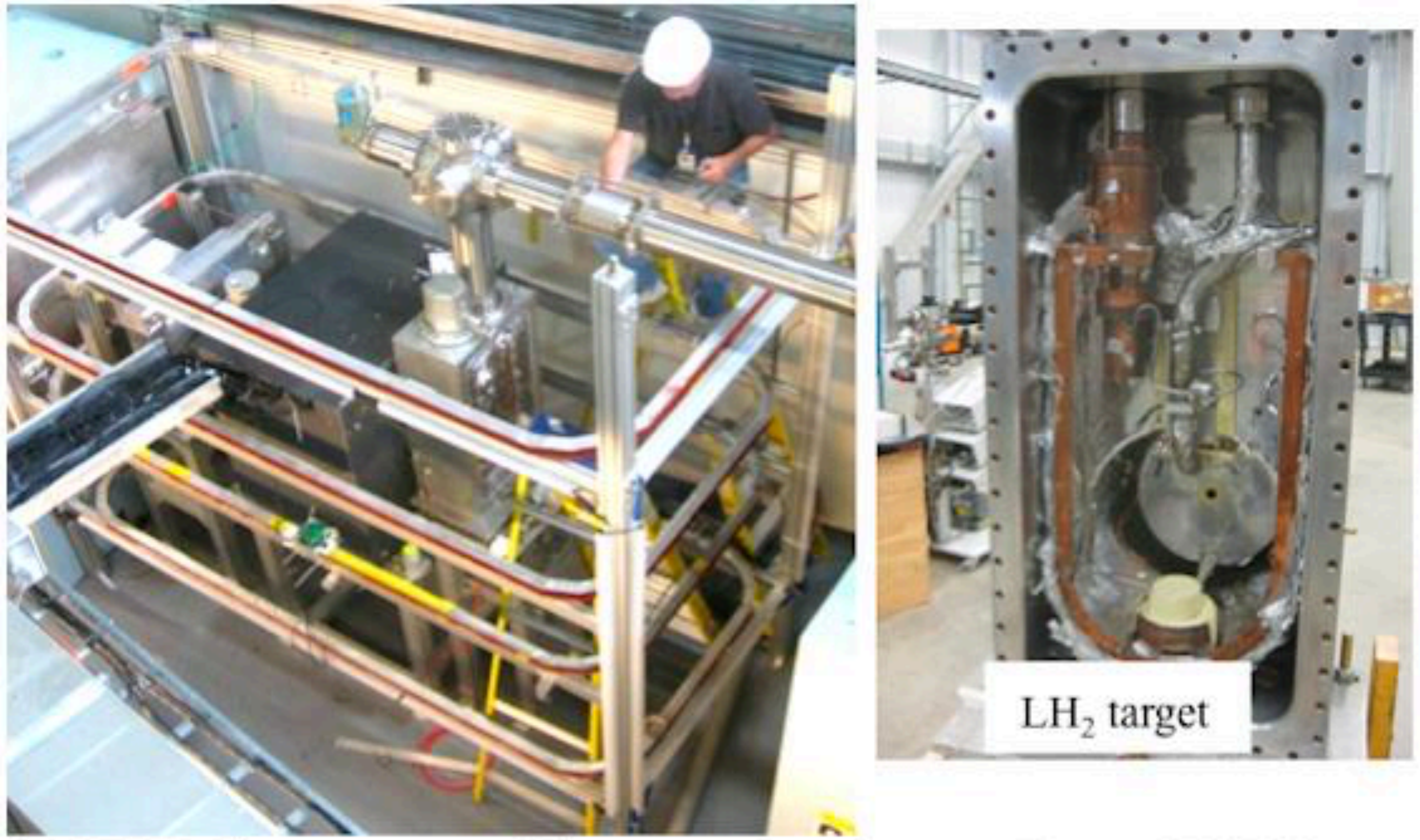
ideally one would make five independent NN measurements to determine the five Danilov amplitudes

available, interpretable constraints

$$A_L^{\vec{p}+p}(45\ \mathrm{MeV}) = (-1.57 \pm 0.23) \times 10^{-7}$$

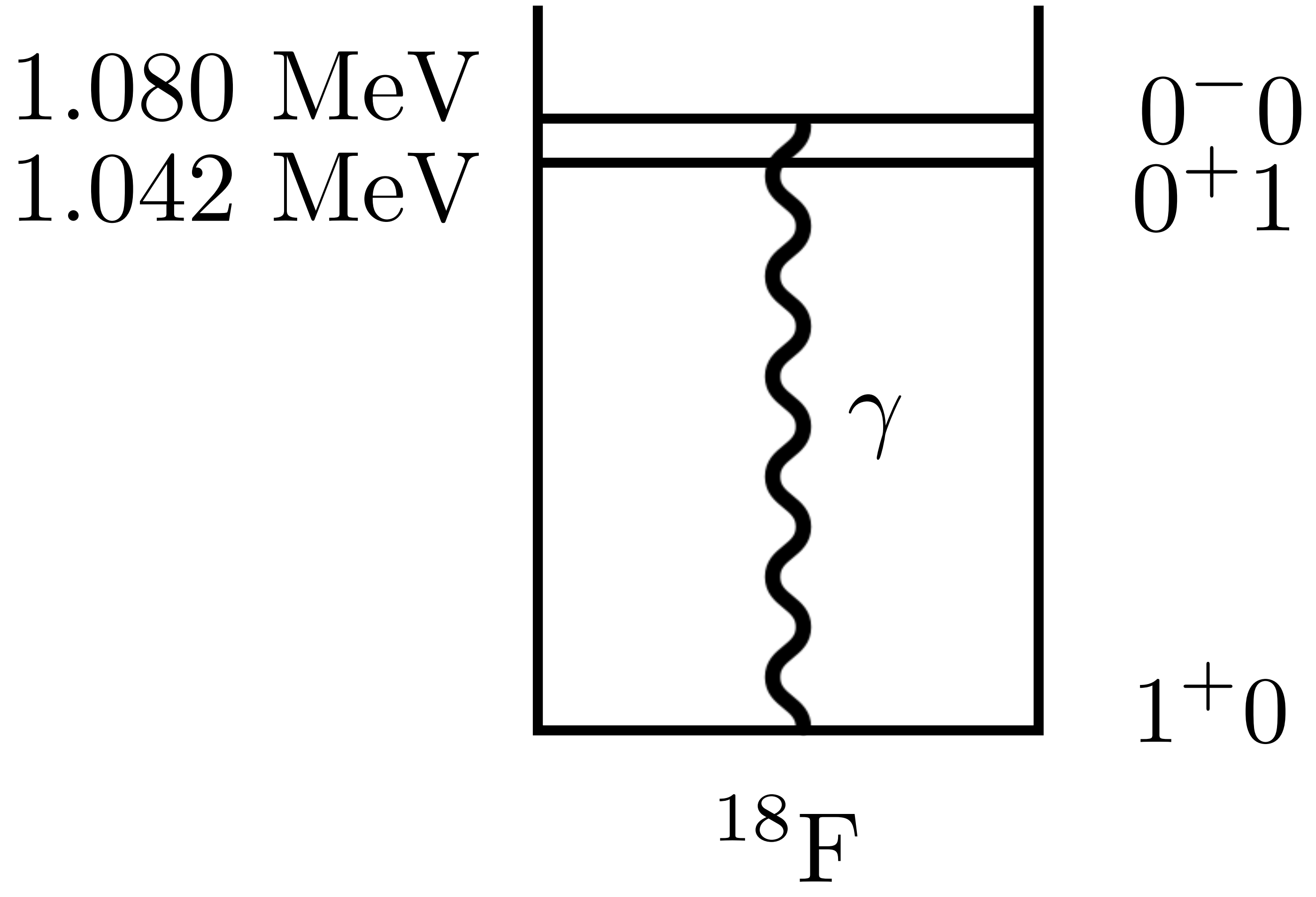
$$A_\gamma^{\vec{n}+p\to d+\gamma} = (-3.0 \pm 1.4 \pm 0.2) \times 10^{-8}$$

need more…



D. Blyth et al., PRL 121, 242002 (2018)

<u>Nuclear observables:</u> why?



circular polarization of the 1.080 MeV

$$P_\gamma \sim 10^{-3} - 10^{-4}$$

New observables: associated with the mixing of opposite parity states by the PNC NN interaction

<u>Nuclei can filter interactions:</u>

- *the quantum labels of nuclear states allow one to isolate parts of interactions of particular interest :* *isovector* $\leftrightarrow$ *expected to probe weak neutral current*

<u>They can enhance the PNC signal:</u>

- *Through nuclear degeneracies: mixing of nearby states*

- *By competing symmetry-allowed, suppressed transitions against symmetry-forbidden strong ones*

Enhancement in ^{18}F

$$P_\gamma(1081\ \mathrm{keV}) = 2Re\left[\frac{\langle+|V_{\mathrm{PNC}}|-\rangle}{39\ \mathrm{keV}}\ \frac{\langle g.s.|M1|+\rangle}{\langle g.s.|E1|-\rangle}\right]$$

1/E:
100 times typical nuclear scale ~ few MeV

⇒ ~10^{-5} vs natural scale 10^{-7}

PC E1: isoscalar E1 in a self-conjugate nucleus:
leading-order forbidden

PNC M1: unusually strong 10.3 W.u.⇒

enhancement ~ 110

- so expected effect ~10^{-3}
- would like to find T-violation observables where, similarly, both operator and degeneracy enhancements operate

II. Time Reversal Violation

- Two sources available in the standard model

$$K_L = \frac{1}{\sqrt{2}}(K_0 + \bar{K}_0) \to \pi\pi\pi + \epsilon\ \pi\pi$$

CP=-1 *CP=-1* *CP=+1*

attributed to the CP-violating phase that is allowed in the three-generation quark mass matrix

— the CP-violating theta term in QCD $L_{CPNC} = \theta \left(\frac{g^2}{32\pi^2}\right) F_a^{\mu\nu} F^*_{a\,\mu\nu}$ $exp: \quad |\theta| \lesssim 10^{-10}$

- Baryon number symmetry: Expectation that BSM sources also exist

- Somewhat tricker to identify T-odd observables

- As in parity violation, could one look at electromagnetic transitions, e.g., gamma decay of a nuclear level
  - — indeed there are observables, associated for example with a phase in the E1/M2 mixing ratio, that transform at T-odd quantities
  - — but these can't be a true test of T-violation: the time reverse of $i \rightarrow f$ is $f \rightarrow i$
  - — and detailed balance experiments in which one looks for tiny differences are extremely challenging
- These considerations lead one to focus of observables where $i = f$,

so static moments

of an electron, neutron, nucleus, ….

General classification of electromagnetic moments:

Multipole	P-even, T-even	P-odd, T-odd	P-odd, T-even	P-even, T-odd
$\langle C_J^M \rangle$	even $J \geq 0$	odd $J \geq 1$	x	x
$\langle M_J^M \rangle$	odd $J \geq 1$	even $J \geq 2$	x	x
$\langle E_J^M \rangle$	x	x	odd $J \geq 1$	even $J \geq 2$

For a spin-1/2 fermion like the electron or neutron one is limited to four interactions:

$$\langle p|J_\mu^{\rm em}|p\rangle = \bar{N}(p')\left(F_1\gamma_\mu + F_2\sigma_{\mu\nu}q^\nu + \frac{a(q^2)}{M^2}(\not{q}q_\mu - q^2\gamma_\mu)\gamma_5 + d(q^2)\sigma_{\mu\nu}q^\nu\gamma_5\right)N(p)$$

Charge	Magnetic	Anapole	Electric Dipole
C0	M1	E1	C1

In a nucleus, J is not restricted to 1/2 as it is for an isolated electron or neutron

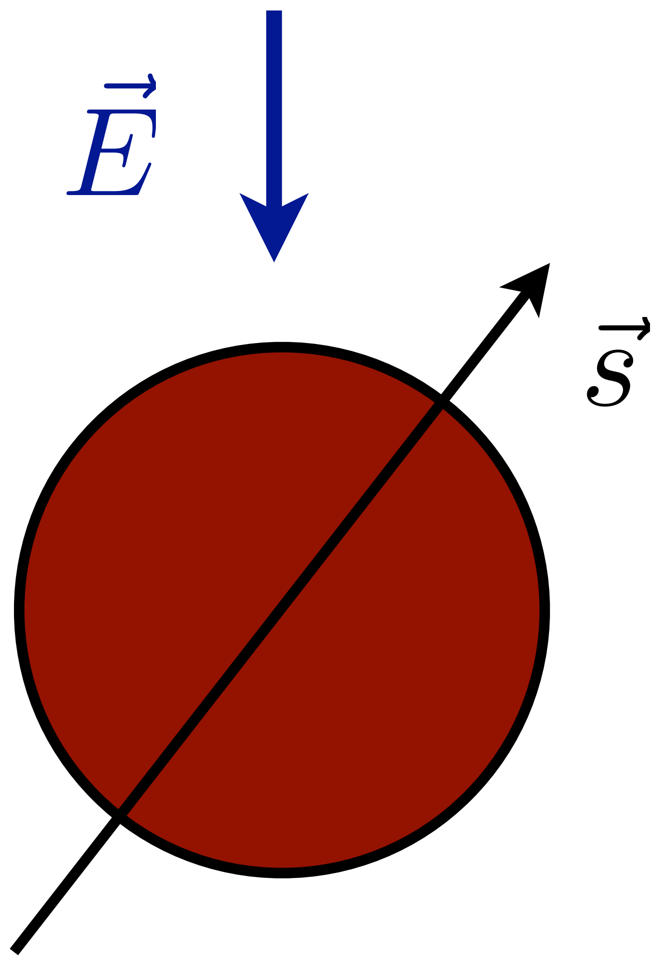
Multipole	P-even, T-even	P-odd, T-odd	P-odd, T-even	P-even, T-odd
$\langle C_J^M \rangle$	even $J \geq 0$	odd $J \geq 1$	x	x
$\langle M_J^M \rangle$	odd $J \geq 1$	even $J \geq 2$	x	x
$\langle E_J^M \rangle$	x	x	odd $J \geq 1$	even $J \geq 2$

giving rise to a larger set of P- and T-odd nuclear moments, not just the edm:

$$\langle j_N | J_\mu^{em} | j_N \rangle = \left\{ \begin{array}{ll} C_1 & j_N \geq \frac{1}{2} \\ C_1,\ M_2 & j_N \geq 1 \\ C_1,\ M_2,\ C_3 & j_N \geq \frac{3}{2} \end{array} \right. \qquad \begin{array}{l} o(R_N/R_A) \rightarrow o(R_N^3/R_A^3) \\ o(R_N^2/R_A^2)\ o(v_N/c) \\ o(R_N^3/R_A^3) \end{array}$$

III. Electric Dipole Moments

Interaction energy of a particle or composite system when placed in an electric field



$$H_{edm} = d\ \vec{E} \cdot \vec{s}$$

Under reversal of T:

$$\vec{E} \rightarrow \vec{E}$$
$$\vec{s} \rightarrow -\vec{s}$$

Under mirror reflection:

$$\vec{E} \rightarrow -\vec{E}$$
$$\vec{s} \rightarrow \vec{s}$$

$\Rightarrow H_{edm}$ is P-odd and T-odd

spin will precess around applied field
d is defined as the edm: units of e-cm

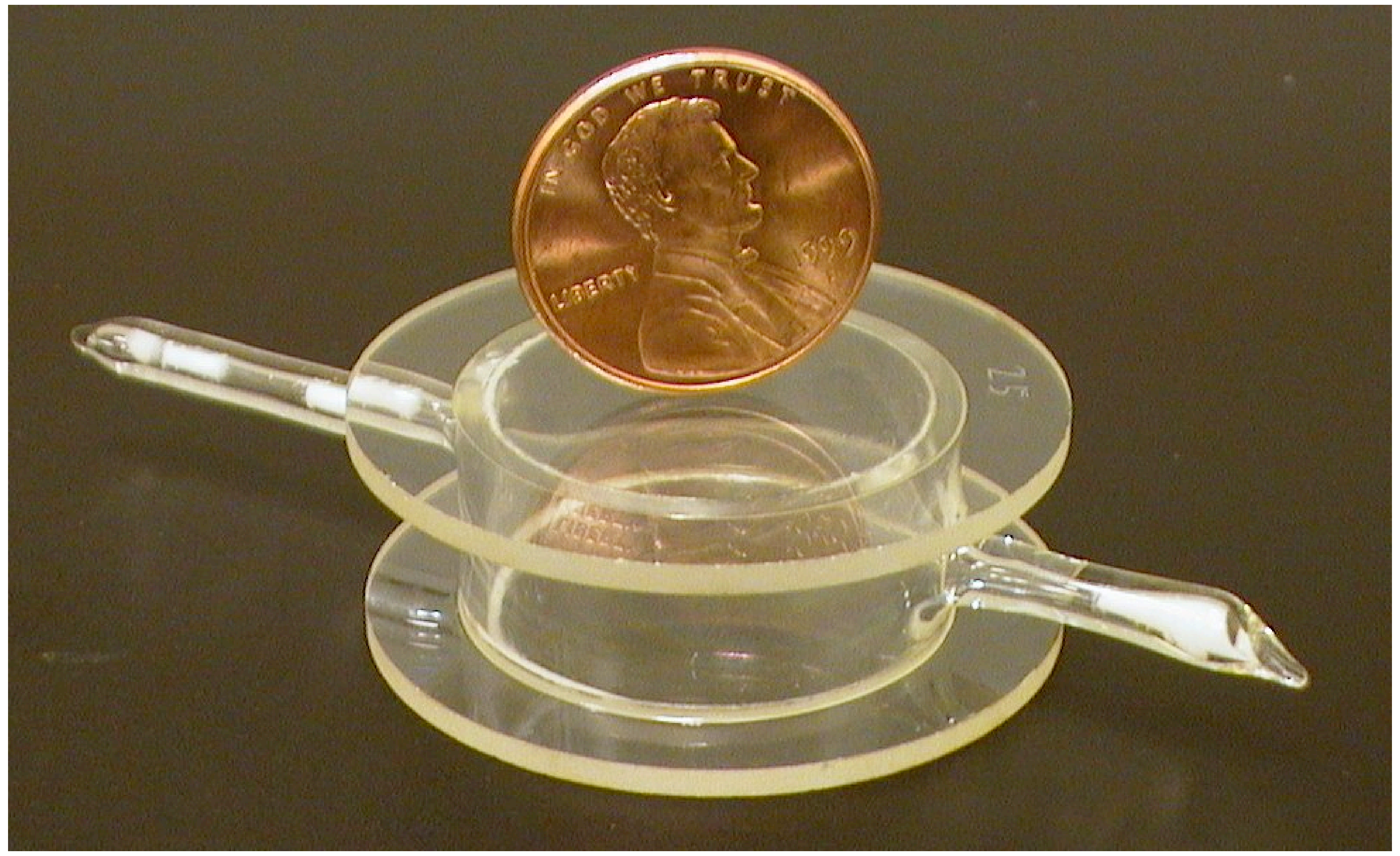
most often studied in neutral objects: neutron, neutral atoms/molecules (electrons, proton/neutron)
but also with ion traps and storage rings

Experiments:

e/p/n edm experiments break into three general categories

- —neutron or electron beam/trap/fountain edm experiments
- —paramagnetic (unpaired electrons) atoms or molecules with sensitivity to the electron edm
- —diamagnetic atoms (electrons paired, nonzero nuclear spin) with sensitivity to p and n edm and to CPNC nuclear interactions

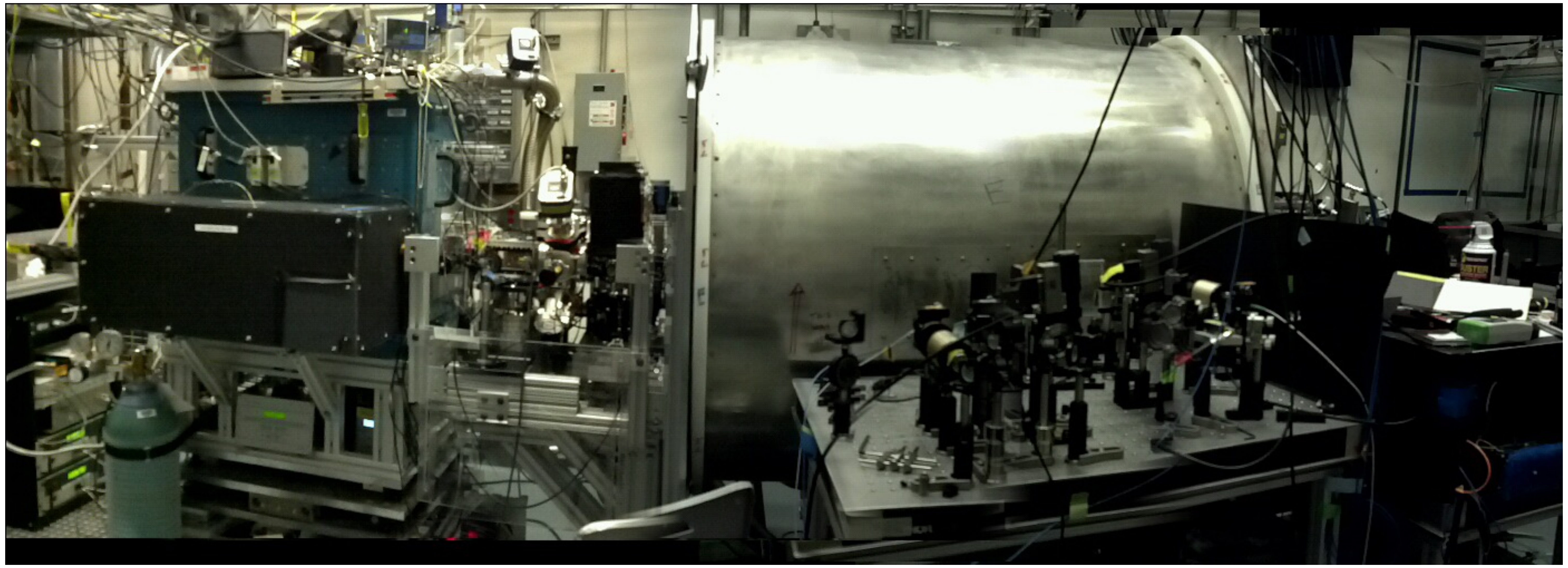
Example of the last: Seattle groups's ^{199}Hg experiment

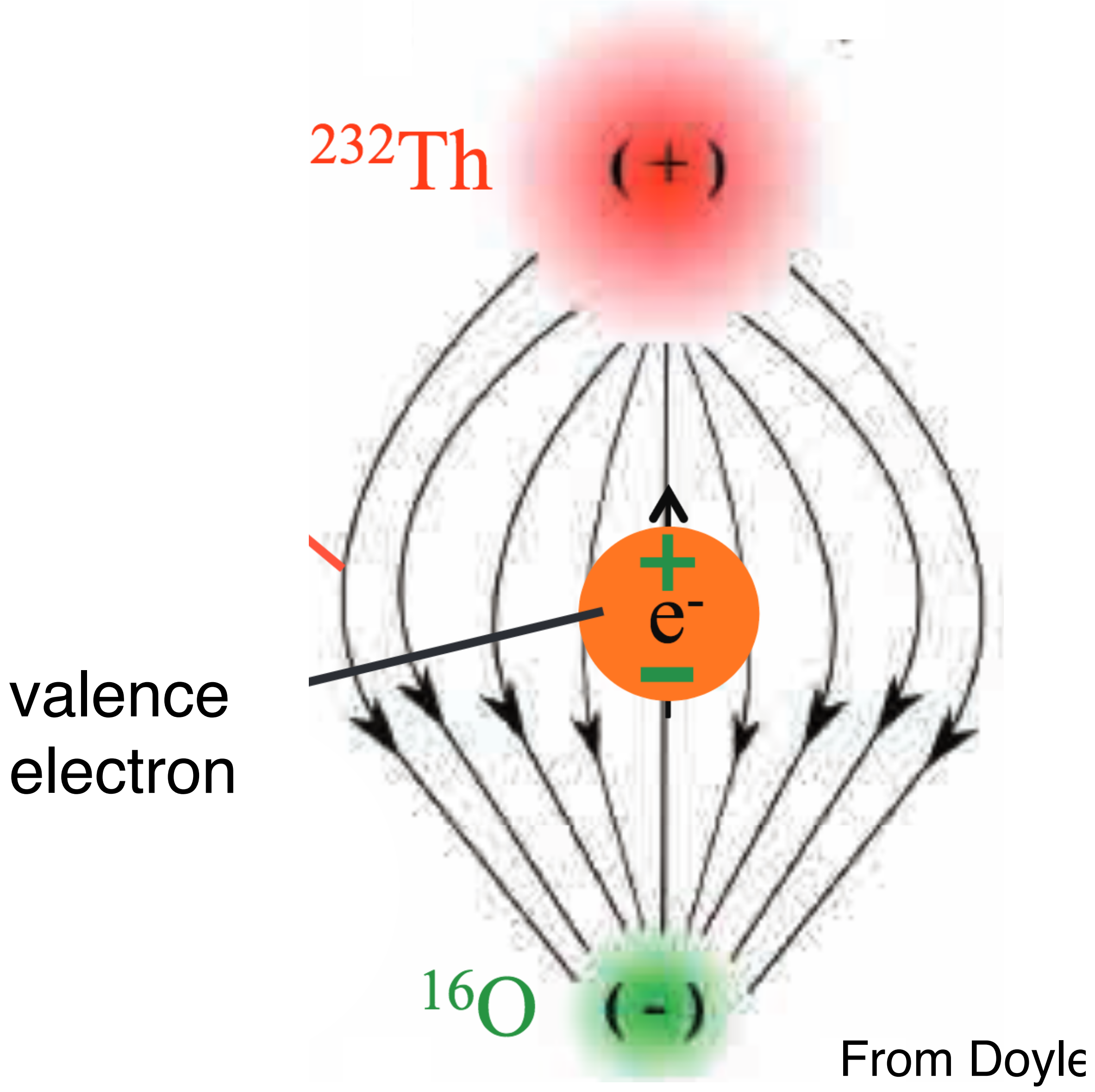


- – Number of ^{199}Hg atoms: 10^{14}
- – Leakage currents at 10 kV: 0.5 – 1 pA
- – N_2 + CO buffer gas (500 Torr)
- – Paraffin wall coating
- – Spin relaxation time: 100 – 200 sec

Sensitive to changes in atomic level differences of < 10^{-24} eV

ACME ThO electron edm experiment





From Doyle

tremendous gain is obtained from the extreme internal fields found in polar molecules

$\sim 10^3$ volts/cm in the lab vs.

$\sim 10^{11}$ volts/cm in ThO

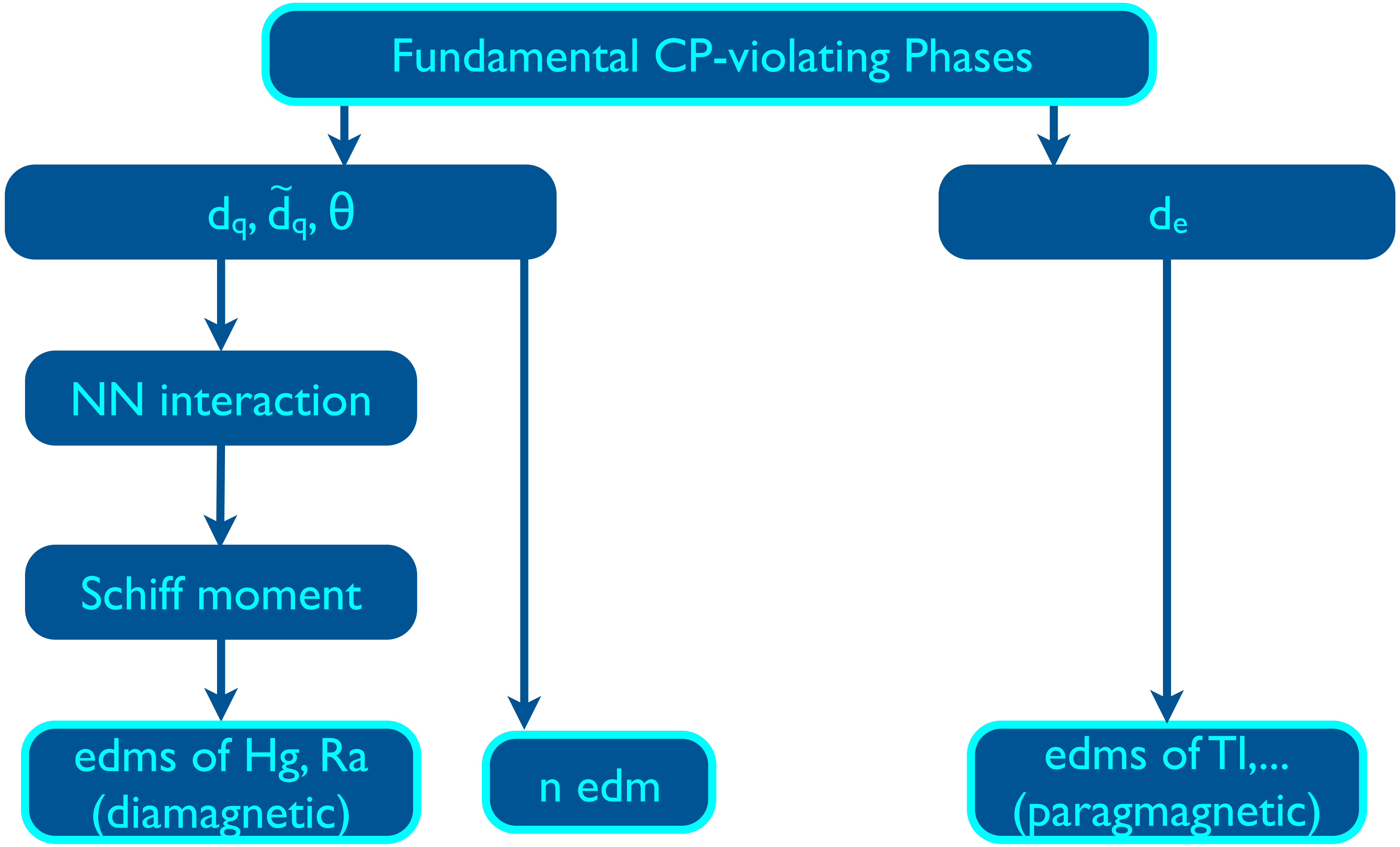
- Electron edm: measured by the ACME experiment in which the spin precession is measured in a cold beam of ThO molecules
  V. Andreev et al., Nature 562, 355 (2018)
- Neutron edm: precession of polarized cold neutrons from the PSI cold neutron source
  C. Abel et al., Phys. Rev. Lett. 124, 081803 (2020)
- Nuclear edm: ^{199}Hg vapor cell
  B. Graner, Y. Chen, E. G. Lindahl, B. R. Heckel PRL 116, 161601 (2016)

One can define a “discovery window” as the range between current bounds and the SM prediction

Particle	edm limit	discovery window	SM prediction*
e	8.7×10^{-29}	↔	10^{-38}
p	1.9×10^{-25}	↔	10^{-31}
n	1.8×10^{-26}	↔	10^{-31}
^{199}Hg	7.4×10^{-30}	↔	10^{-33}

*CKM phase

These experiments are probing the low-energy manifestation of physics that originates beyond the stadard model



Fundamental CP-violating Phases

d_q, $\tilde{d}_q$, θ

d_e

NN interaction

Schiff moment

edms of Hg, Ra
(diamagnetic)

n edm

edms of Tl,...
(paragmagnetic)

From Ramsey-Musolf

Sketch of the QCD θ parameter example

$$\bar{\theta}\frac{g^2}{32\pi^2}F_{\mu\nu}\tilde{F}^{\mu\nu}$$

Generates a low-energy CP-odd coupling to the nucleon*

$$L_{\pi N} = L_{\pi NN}^{CPNC} = \vec{\pi}\cdot\bar{N}\left(i\gamma_5 g_{\pi NN} + \bar{g}_{\pi NN}\right)N \qquad |\bar{g}_{\pi NN}| \sim 0.027\ |\bar{\theta}|$$

which happens in this case to be isoscalar - the isovector coupling arises in relative order m_π/m_N

* Crewther, Di Vecchia, Veneziano, Witten, Phys. Lett. 88B (1979) 123 and 91B (1980) 487

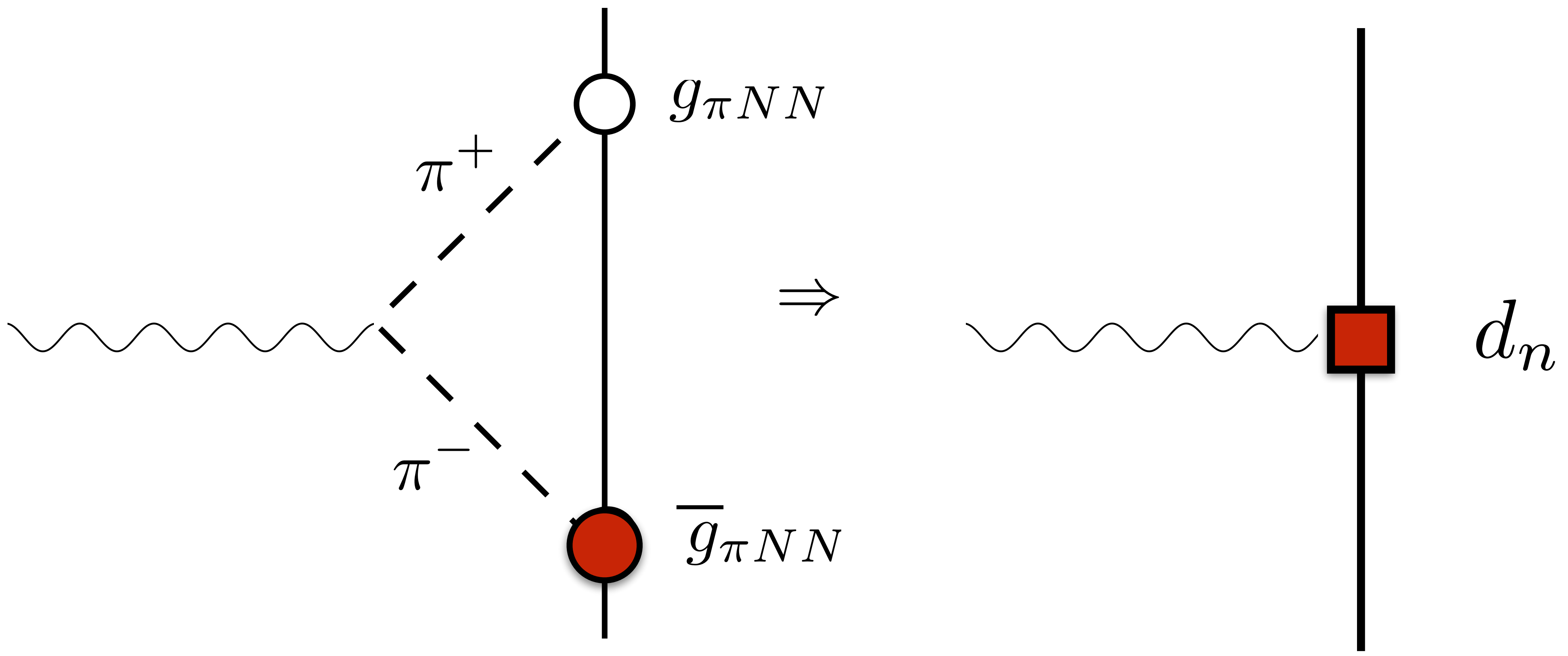
Meson-based treatments

Simonius M. Phys. Lett. B 58:147{151 (1975)
Haxton WC, Henley EM. Phys. Rev. Lett. 51:1937 (1983)
Gudkov VP, He XG, McKellar BHJ. Phys. Rev. C47:2365{2368 (1993)
Towner IS, Hayes AC. Phys. Rev. C49:2391{2397 (1994)
Liu CP, Timmermans RGE. Phys. Rev. C70:055501 (2004)

EFT

Mereghetti E, Hockings WH, van Kolck U. Annals Phys. 325:2363{2409 (2010)
Maekawa C, Mereghetti E, de Vries J, van Kolck U. Nucl.Phys. A872:117{160 (2011)
de Vries J, Mereghetti E, Timmermans RGE, van Kolck U. Annals Phys. 338:50{96 (2013)
Bsaisou J, Hanhart C, Liebig S, Meissner UG, Nogga A, Wirzba A. Eur. Phys. J. A49:31 (2013)
Bsaisou J, de Vries J, Hanhart C, Liebig S, Meissner UG, et al. JHEP 03:104 (2015), [Erratum: JHEP05,083(2015)]
Bsaisou J, Meißner UG, Nogga A, Wirzba A. Annals Phys. 359:317{370 (2015)

A nucleon edm is generated (maximizing charge separation)



$$d_n \sim \frac{e g_{\pi NN} \bar{g}_{\pi NN}}{4\pi^2 M} \, ln \left(\frac{M}{m_\pi} \right)$$

$$d_p = -d_n$$

$$\sim 3.6 \times 10^{-16} \; \bar{\theta} \text{ e cm } \; \Rightarrow \; \bar{\theta} < 10^{-11}$$

which fixes the one-body electromagnetic current operator

$$\langle p' | J_\mu^{(1)} | p \rangle = e \bar{U}(p') \Big[\qquad\qquad\qquad + d_n \sigma^{\mu\nu} q_\nu \gamma_5 \tau_3 \Big] U(p)$$

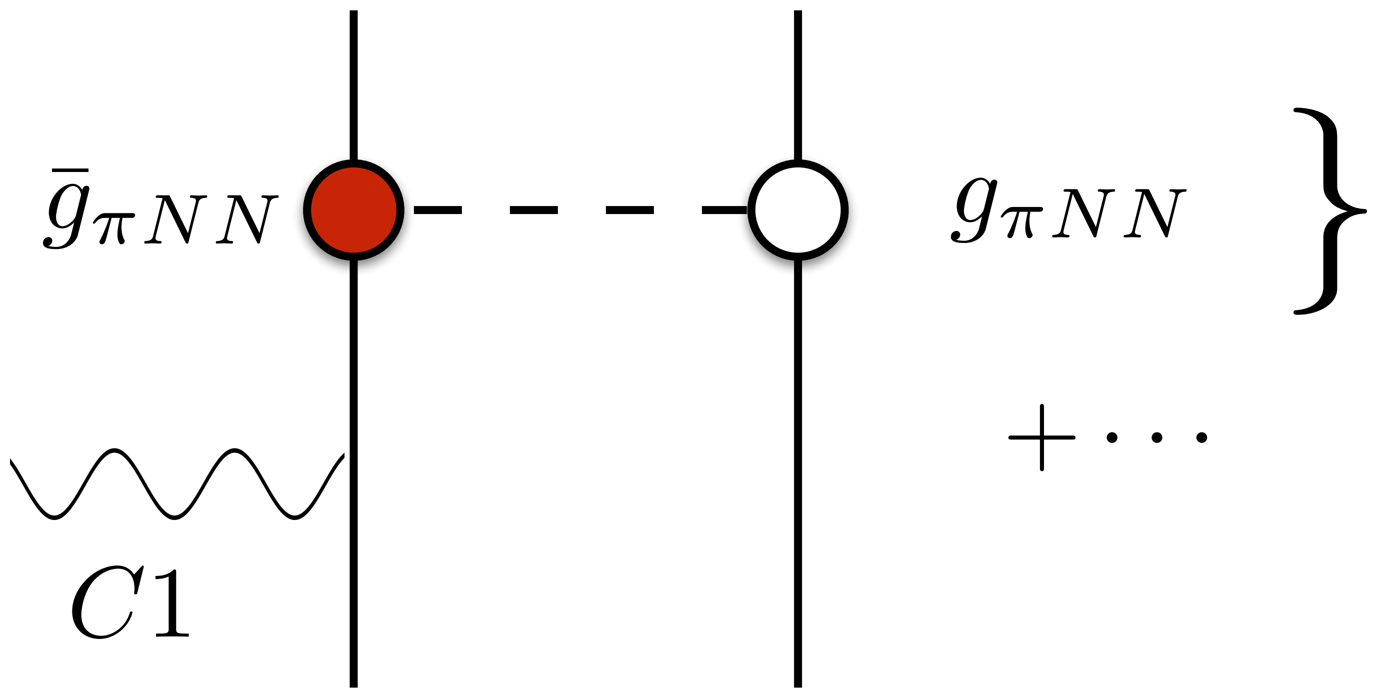
multipoles:

$\overline{\text{C1}}$, $\overline{\text{C3}}$, …
M2, M4, …

contributes:

via unperturbed wf

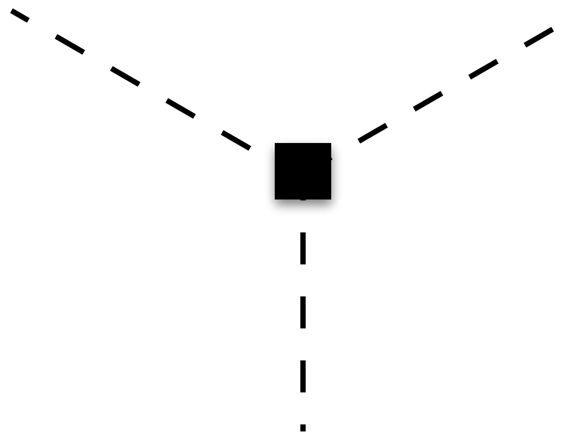
It also generates a CP- and P-violating NN interaction that generates a *nuclear* contribution to the edm



CP- and P- admixture in the nuclear wave function

$$\overline{V}_{12} = -0.9\,\frac{d_n}{e}\;m_\pi^2\;\tau(1)\cdot\tau(2)(\vec{\sigma}(1)-\vec{\sigma}(2))\cdot\hat{r}\;\frac{e^{-m_\pi r}}{m_\pi r}\left[1+\frac{1}{m_\pi r}\right]$$

Also pion-range two-body currents that prove numerically to less important numerically, but are demanded by current conservation. This includes those associated with a three-pion CP-violating vertex arising at order



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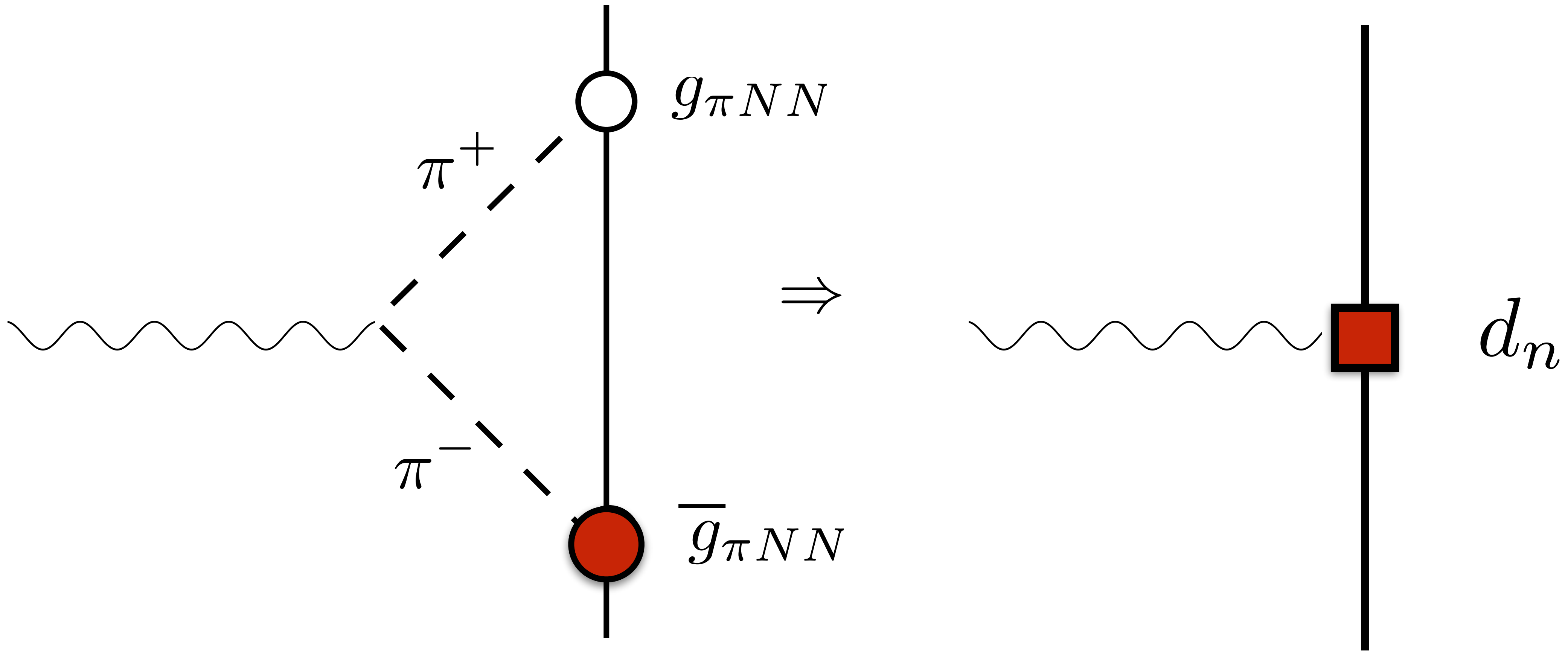

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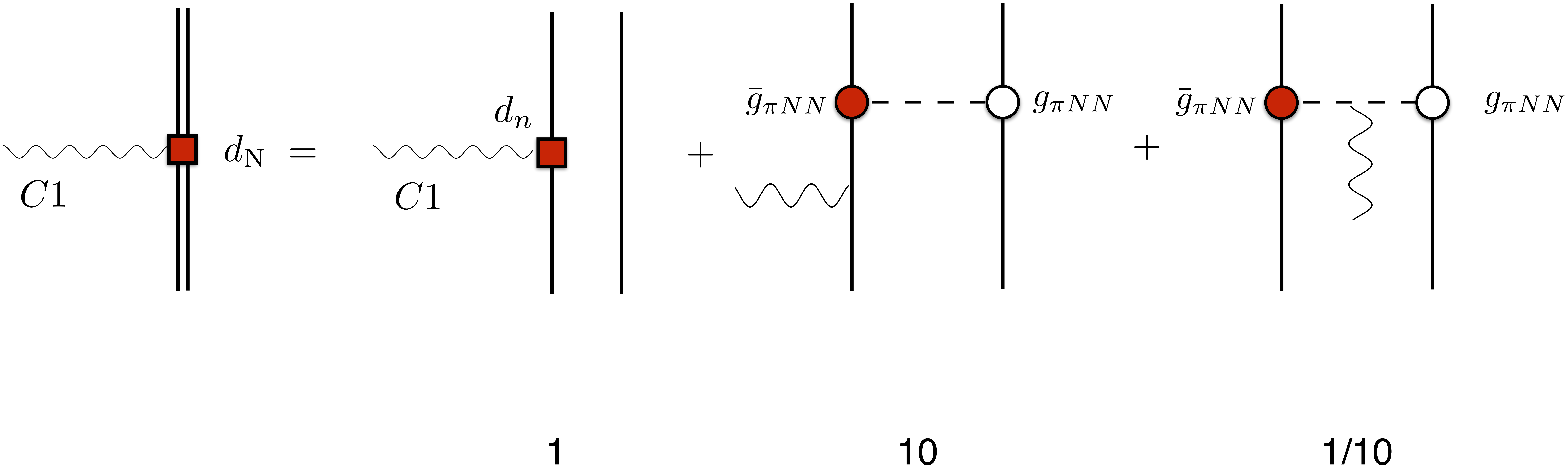
$$\langle p' | J_\mu^{(1)} | p \rangle = e \bar{U}(p') \left[F_1 \gamma^\mu + F_2 \sigma^{\mu\nu} \frac{q_\nu}{M_N} + d_n \sigma^{\mu\nu} q_\nu \gamma_5 \tau_3 \right] U(p)$$

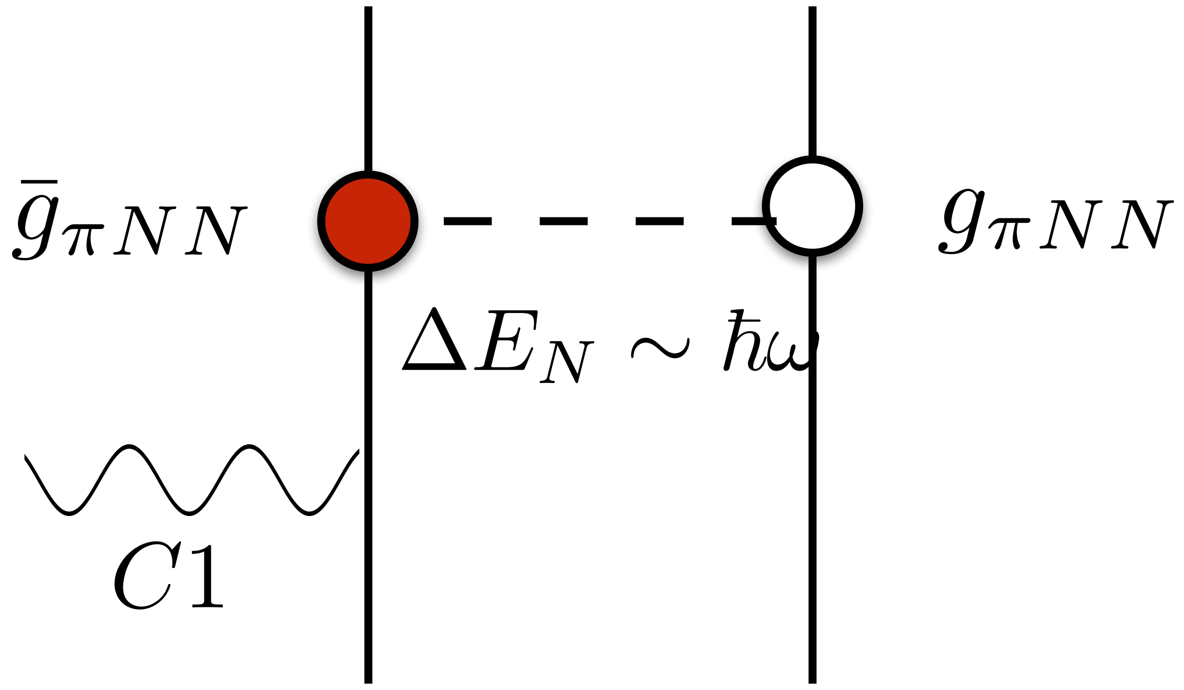
multipoles:	C1, C3, … M2, M4, …	$\overline{\text{C1}}$, $\overline{\text{C3}}$, … $\overline{\text{M2}}$, $\overline{\text{M4}}$, …
contributes:	via polarization	via unperturbed wf

These ingredients generate the various contributions to a nuclear edm



Which contribution dominates in a typical nucleus like ^{199}Hg?

The simplest argument one would make — edms are about charge separation — would argue that the nuclear polarization would dominate: the CP-odd NN interaction creates a mean field that distorts the nuclear orbital of the valence nucleon carrying the nuclear spin, producing a charge separation over the entire nucleus.



use closure: $d_{\text{Nuclear}} \sim \frac{m_\pi}{\hbar\omega} d_n \sim 10\ d_n$

So nuclear edms are typically larger than nucleon edms

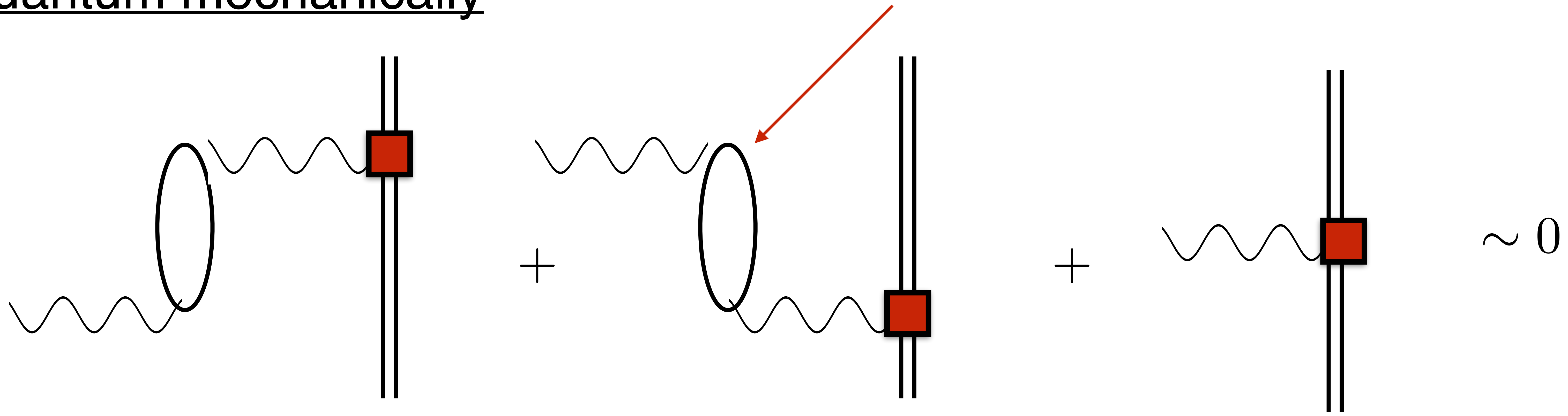
So nuclei appear to be favorably places look for edms, especially given the intrinsic precision of experiments like those don of ^{199}Hg

The familiar Schiff theorem: Classsically

- To probe an edm, one must create an electric field at the nucleus
- The ^{199}Hg atom is neutral: under an applied field, the charge center of the atom is static
- But the charged nucleus thus experiences no acceleration
- This must mean that the field at the nucleus is zero

Schiff: the interaction energy of a neutral atom with a point nucleus at its center is zero in first order in the nuclear edm

Quantum mechanically


atomic electron-hole excitation

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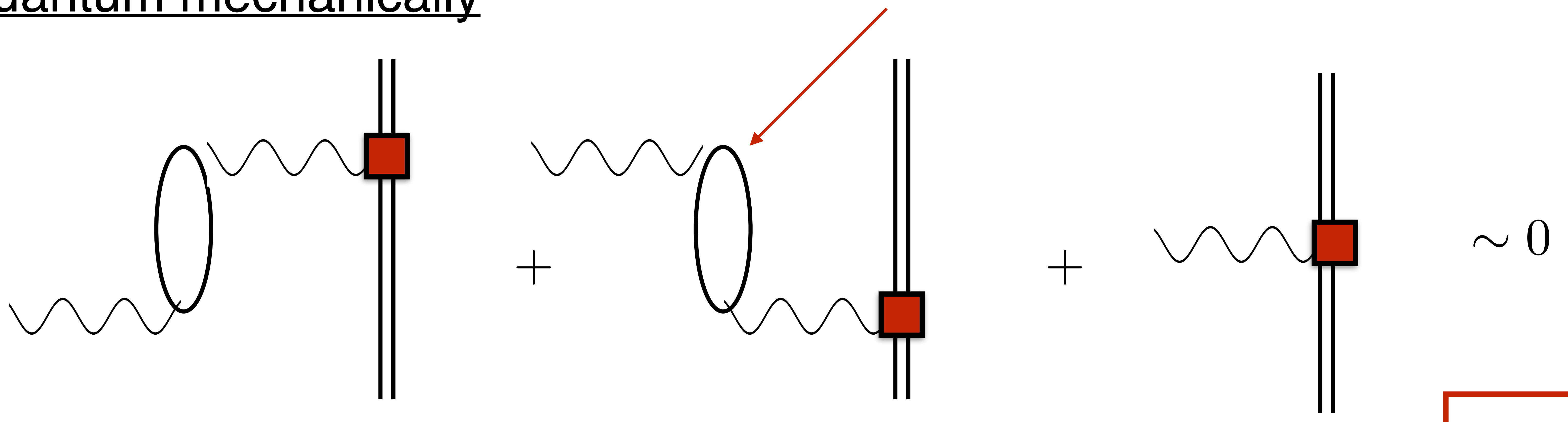
atomic electron-hole excitation

~ 0

introduce nuclear finite size:
calculate electron penetration

$$\boxed{\sim 10Z^2\ (R_N/R_A)^2 \sim 10^{-3}}$$

Back-of-the-envelope sensitivity estimates for ^{199}Hg

$$d_A(^{199}\mathrm{Hg}) \sim (0.5 \cdot 10^{-3})\,\frac{m_\pi}{\hbar\omega}\,d_n \;\sim\; 0.5 \cdot 10^{-2}\,d_n$$

Consequently the experimental bound $|d_A(^{199}\mathrm{Hg})| \lesssim 7.4 \cdot 10^{-30}$ yields

$$\boxed{\Rightarrow\;|d_n| \lesssim 1.5 \cdot 10^{-27}\mathrm{e\ cm\ 95\%\ C.L.}}$$

^{199}Hg expected

which can be compared to the free-neutron limit

$$|d_n| \lesssim 1.8 \cdot 10^{-26}\mathrm{e\ cm\ 90\%\ C.L.}$$

neutron limit

In fact, a detailed microscopic calculation of the ^{199}Hg Schiff moment (the penetration contribution) yields an anomalously small value, leading to

$$\boxed{|d_n| \lesssim 1.6 \cdot 10^{-26}\mathrm{e\ cm\ 95\%\ C.L.}}$$

^{199}Hg computed

Dmitriev and Sen'kov, Phys. Rev. Lett. 91, 212303 (2003)

IV. Need some mechanism for nuclear enhancement in order to move well beyond d_n sensitivities

- In studies of PNC, nuclear enhancements have been found of size 10^5-10^6
- There come about because of accidental energy degeneracies in combination with nuclear effects that enhance symmetry-forbidden amplitudes relative to symmetry-allowed ones

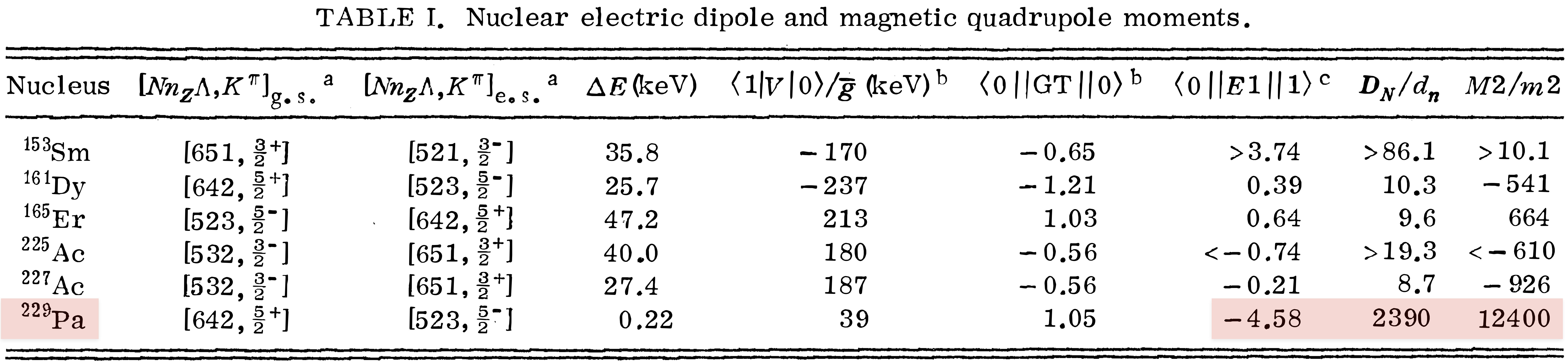

TABLE I. Nuclear electric dipole and magnetic quadrupole moments.

Nucleus	$[Nn_z\Lambda,K^\pi]_{g.s.}$ [a]	$[Nn_z\Lambda,K^\pi]_{e.s.}$ [a]	ΔE (keV)	$\langle 1\|V\|0\rangle/\bar{g}$ (keV) [b]	$\langle 0\|\|GT\|\|0\rangle$ [b]	$\langle 0\|\|E1\|\|1\rangle$ [c]	D_N/d_n	$M2/m2$
^{153}Sm	$[651, \frac{3}{2}^+]$	$[521, \frac{3}{2}^-]$	35.8	−170	−0.65	>3.74	>86.1	>10.1
^{161}Dy	$[642, \frac{5}{2}^+]$	$[523, \frac{5}{2}^-]$	25.7	−237	−1.21	0.39	10.3	−541
^{165}Er	$[523, \frac{5}{2}^-]$	$[642, \frac{5}{2}^+]$	47.2	213	1.03	0.64	9.6	664
^{225}Ac	$[532, \frac{3}{2}^-]$	$[651, \frac{3}{2}^+]$	40.0	180	−0.56	<−0.74	>19.3	<−610
^{227}Ac	$[532, \frac{3}{2}^-]$	$[651, \frac{3}{2}^+]$	27.4	187	−0.56	−0.21	8.7	−926
^{229}Pa	$[642, \frac{5}{2}^+]$	$[523, \frac{5}{2}^-]$	0.22	39	1.05	−4.58	2390	12400

Haxton WC, Henley EM. Phys. Rev. Lett. 51:1937 (1983)

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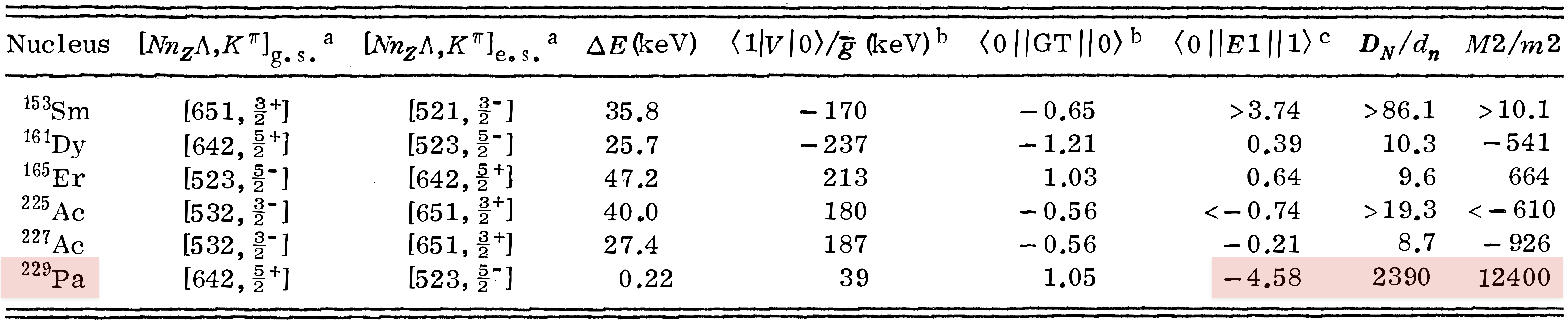

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^{227}Ac	$[532, \frac{3}{2}^-]$	$[651, \frac{3}{2}^+]$	27.4	187	−0.56	−0.21	8.7	−926
^{229}Pa	$[642, \frac{5}{2}^+]$	$[523, \frac{5}{2}^-]$	0.22	39	1.05	−4.58	2390	12400

- apart from one exception, the results are disappointing

IV. Need some mechanism for nuclear enhancement in order to move well beyond d_n sensitivities

- In studies of PNC, nuclear enhancements have been found of size 10^5-10^6
- There come about because of accidental energy degeneracies in combination with nuclear effects that enhance symmetry-forbidden amplitudes relative to symmetry-allowed ones

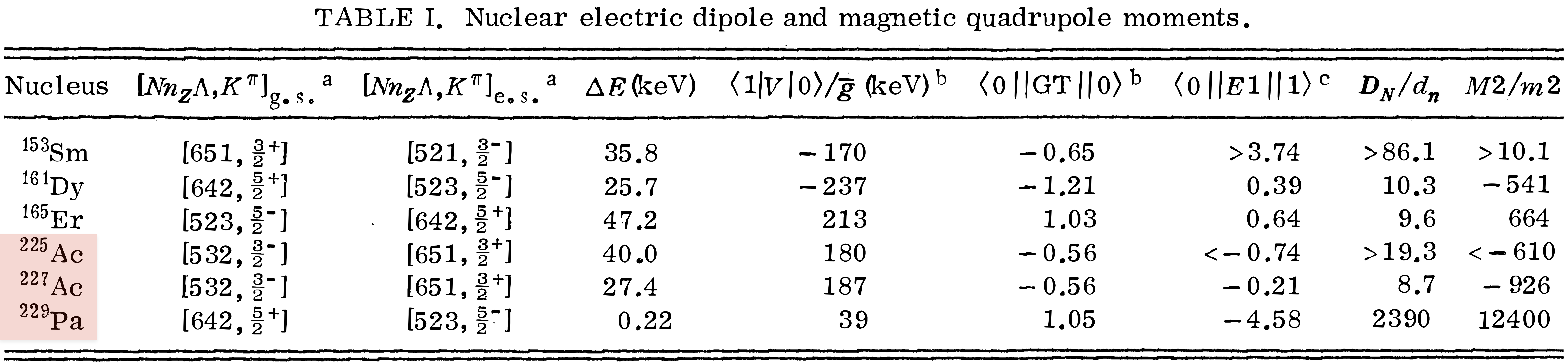

TABLE I. Nuclear electric dipole and magnetic quadrupole moments.

Nucleus	$[Nn_Z\Lambda, K^\pi]_{\mathrm{g.s.}}$ [a]	$[Nn_Z\Lambda, K^\pi]_{\mathrm{e.s.}}$ [a]	ΔE (keV)	$\langle 1 \vert V \vert 0 \rangle / \bar{g}$ (keV) [b]	$\langle 0 \Vert \mathrm{GT} \Vert 0 \rangle$ [b]	$\langle 0 \Vert E1 \Vert 1 \rangle$ [c]	D_N/d_n	$M2/m2$
^{153}Sm	$[651, \frac{3}{2}^+]$	$[521, \frac{3}{2}^-]$	35.8	−170	−0.65	>3.74	>86.1	>10.1
^{161}Dy	$[642, \frac{5}{2}^+]$	$[523, \frac{5}{2}^-]$	25.7	−237	−1.21	0.39	10.3	−541
^{165}Er	$[523, \frac{5}{2}^-]$	$[642, \frac{5}{2}^+]$	47.2	213	1.03	0.64	9.6	664
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- three of the cases involve actinides

The best case from that early search seemed exotic — ^{229}Pa — with a lifetime $\tau_{1/2} \sim 1.5\ \mathrm{d}$
No isotope source adequate to do a ^{199}Hg-style vapor-cell experiment

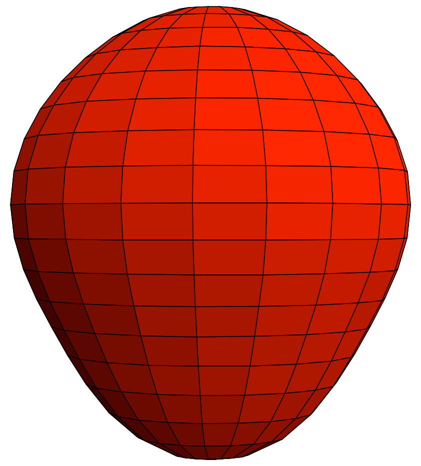
And curious: the energy degeneracy was extreme (220 eV) and simultaneously the E1 coupling of the parity doublet reasonably strong. Is this an accident, or is it physics?

familiar story of rotational symmetry-breaking and restoration in nuclei

- mid-shell nuclei have multiple angular momenta shells available to valence nucleons
- under small deformations some of these orbits gain energy due to their interactions with the quadrupole mean field generated by the core
- rotational symmetry spontaneously broken
- restored through collective rotation — low-energy modes because the entire nucleus participates

There is a similar phenomenon now identified in a set of heavy nuclei that include ^{229}Pa

octuple deformation



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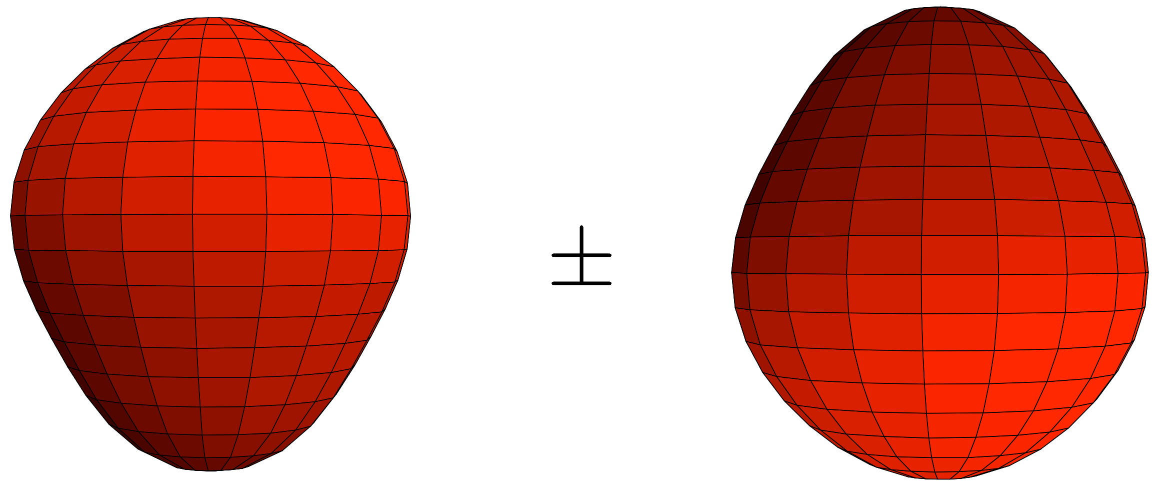
octuple deformation
parity restoration



two modes
even and odd under parity

Octupole-deformed nuclei are characterized by

- closely spaced parity doublets
- coupled by strong C1 and C3 matrix elements (correlated with large Schiff moments)

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octuple deformation
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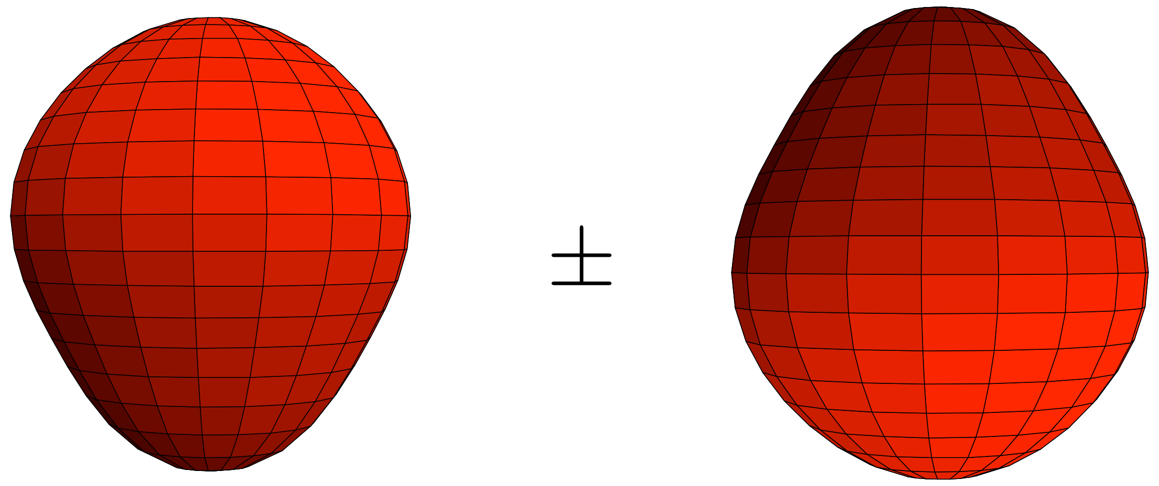

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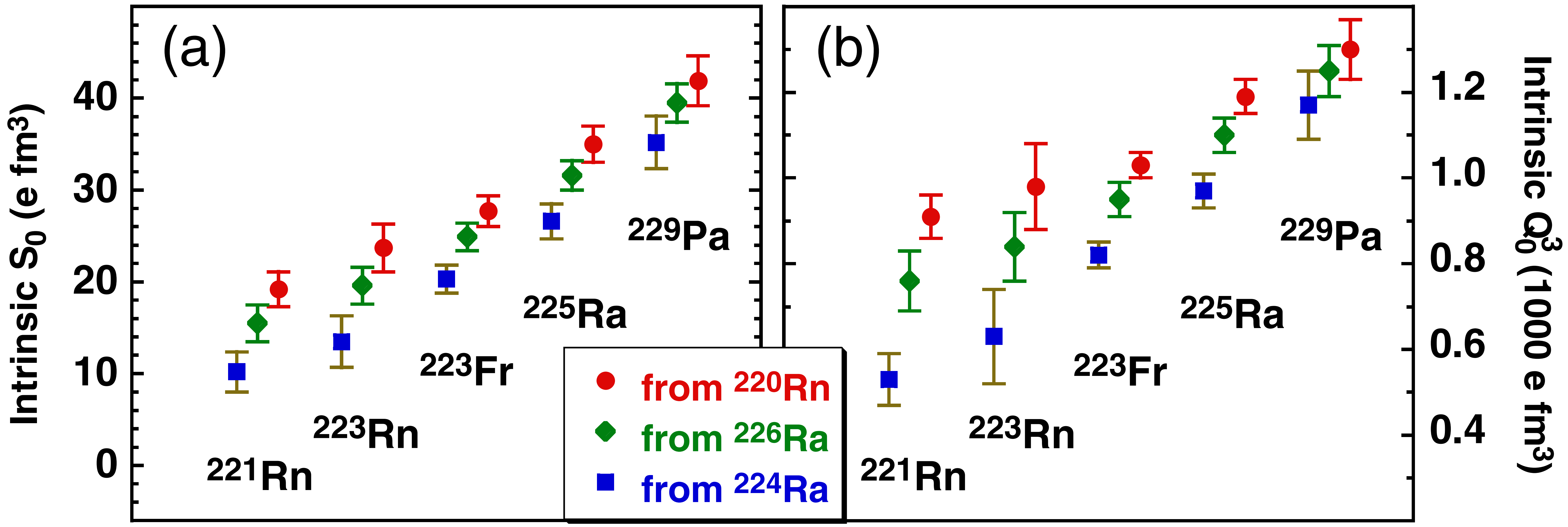


Nuclear Part of Schiff Moment

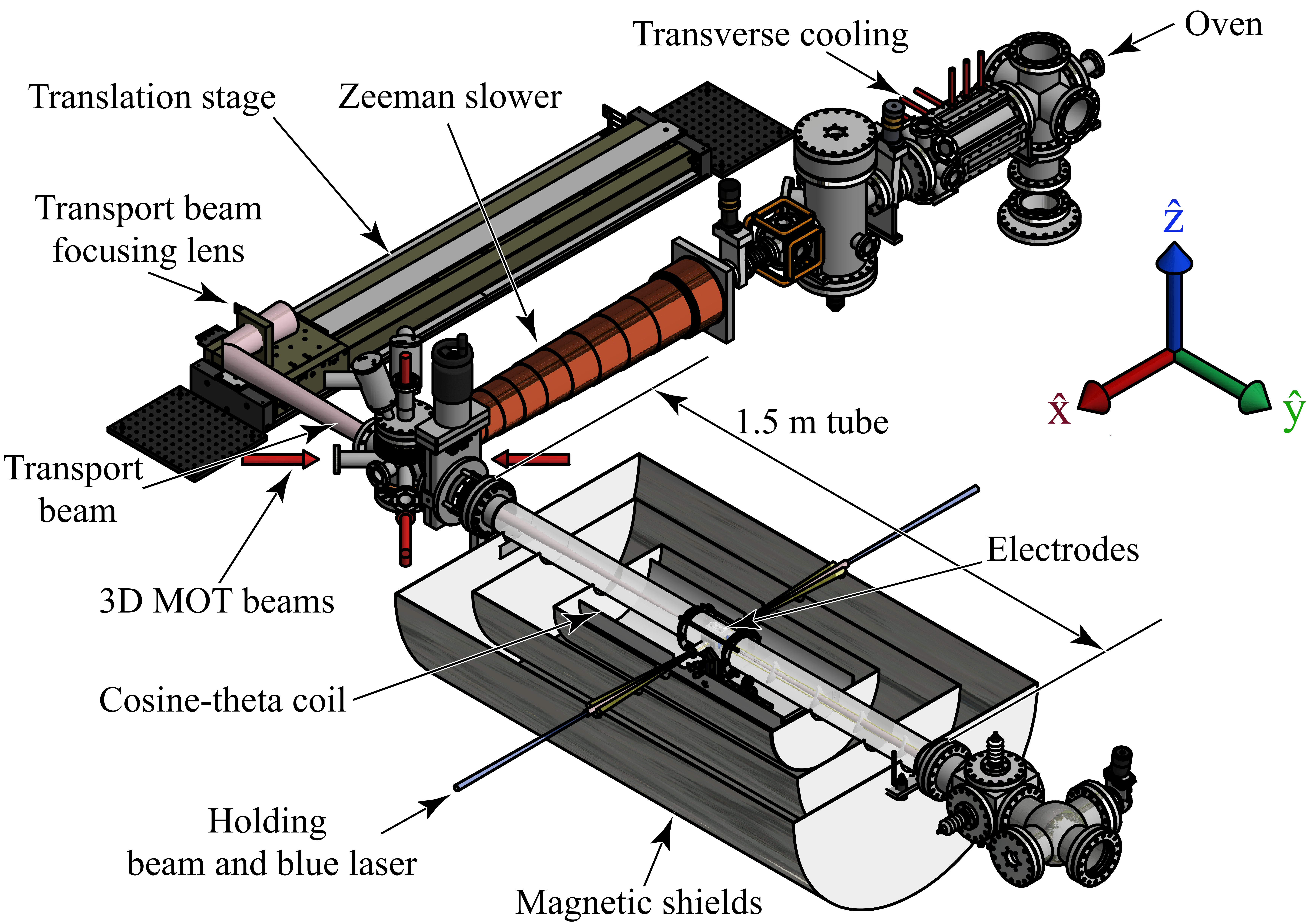
Octupole Moment

Dobaczewski, Engel, Kortelainen,
and Becker, PRL 121 (2018) 232501

(this is the nuclear amplitude -
does not include energy denominator)

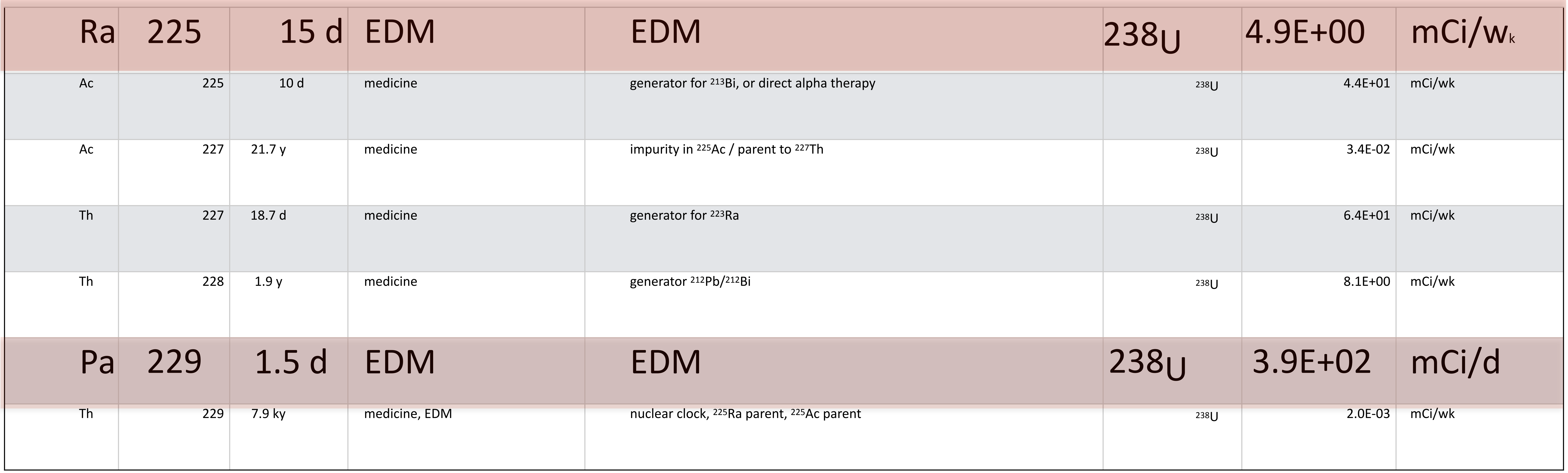
Is it feasible to do edm experiments with rare isotopes?

- A precedent was recently established: ^{225}Ra
- $\tau_{1/2} \sim 15\ \mathrm{d}$
- Doublet separation 55 keV vs 200 eV in ^{229}Pa, Schiff moment somewhat smaller than in ^{229}Pa: predicted enhancement over ^{199}Hg is $\gtrsim 100$, but falls short of ^{229}Pa by ~ 400
- Argonne experiment made use of an existing ^{225}Ra source: 3mCi and 6mCi shipments from the Isotope Development Center, ORNL
- Low vapor pressure ruled out a vapor-cell measurement (the ^{199}Hg technique)
- Instead, Ra was a laser cooled and trapped
- The limit achieved was $|d(^{225}\mathrm{Ra})| \lesssim 1.4 \cdot 10^{-23}\ \mathrm{e\,cm}$ — entirely statistically limited
- Projected sensitivity of $10^{-28}\ \mathrm{e\,cm}$ contingent on 10^4 increase in the available ^{225}Ra (surpassing ^{199}Hg in sensitivity)



M. Bishof et al., Phys. Rev. C94, 025501 (2016)

Future plan is to obtain the needed ^{225}Ra from the FRIB ^{238}U beam harvesting program



Ra	225	15 d	EDM	EDM	^{238}U	4.9E+00	mCi/wk
Ac	225	10 d	medicine	generator for ^{213}Bi, or direct alpha therapy	^{238}U	4.4E+01	mCi/wk
Ac	227	21.7 y	medicine	impurity in ^{225}Ac / parent to ^{227}Th	^{238}U	3.4E-02	mCi/wk
Th	227	18.7 d	medicine	generator for ^{223}Ra	^{238}U	6.4E+01	mCi/wk
Th	228	1.9 y	medicine	generator ^{212}Pb/^{212}Bi	^{238}U	8.1E+00	mCi/wk
Pa	229	1.5 d	EDM	EDM	^{238}U	3.9E+02	mCi/d
Th	229	7.9 ky	medicine, EDM	nuclear clock, ^{225}Ra parent, ^{225}Ac parent	^{238}U	2.0E-03	mCi/wk

But what stands out in the yields is that of ^{229}Pa — 500 times greater than that of ^{225}Ra

Harvesting under standard conditions is daily

The strange case of ^{229}Pa

Nuclear scale $\sim$ atomic scale

The CP-odd component of the ground state is entirely dominated by the parity doublet mixing

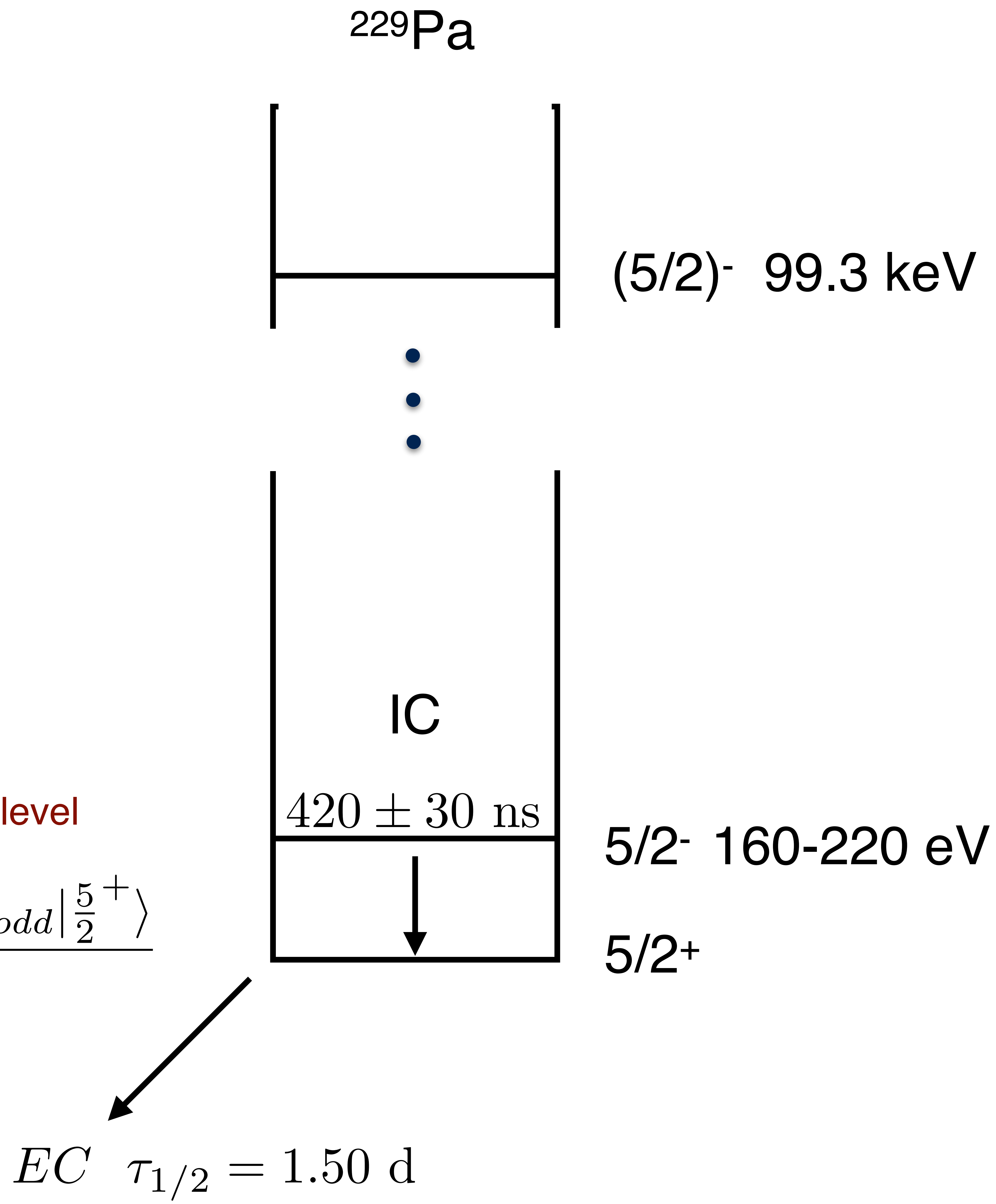
edms are proportional to the Schiff moment, the quantity obtained after treating screening

$$\hat{S}_{10} = \frac{e}{10}\sqrt{\frac{4\pi}{3}}\sum_i \left(r_i^3 - \frac{5}{3}\langle r^2_{ch}\rangle r_i\right) Y_{10}(\Omega_i)$$

Two-level

$$S = 2\sum_{i\neq g.s} \frac{\langle \frac{5}{2}^+|\hat{S}_{10}|\frac{5}{2}^-;i\rangle\langle \frac{5}{2}^-;i|\bar{V}_{CP-odd}|\frac{5}{2}^+\rangle}{E_{g.s.}-E_i} \rightarrow -2\frac{\boxed{\langle \frac{5}{2}^+|\hat{S}_{10}|\frac{5}{2}^-\rangle}\langle \frac{5}{2}^-|\bar{V}_{CP-odd}|\frac{5}{2}^+\rangle}{200\ \mathrm{eV}}$$

Difference in the center-of-mass vs. charge radius: challenging to compute reliably



^{229}Pa

(5/2)$^-$ 99.3 keV

IC

420 ± 30 ns

5/2$^-$ 160-220 eV

5/2$^+$

$EC \quad \tau_{1/2} = 1.50$ d

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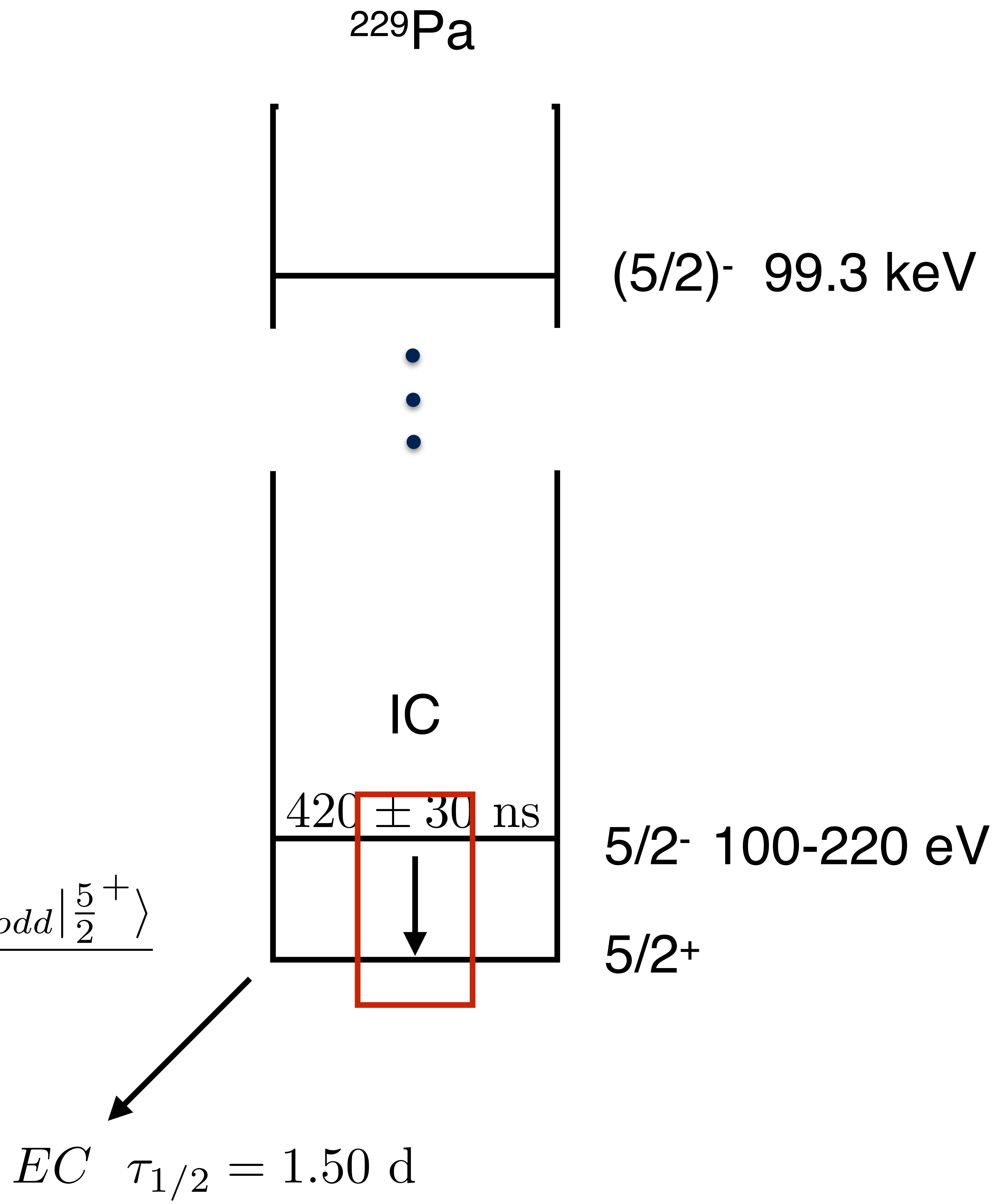
There is another electromagnetic observable involving the same two states: atomic-scale energy release



^{229}Pa

(5/2)$^-$ 99.3 keV

IC

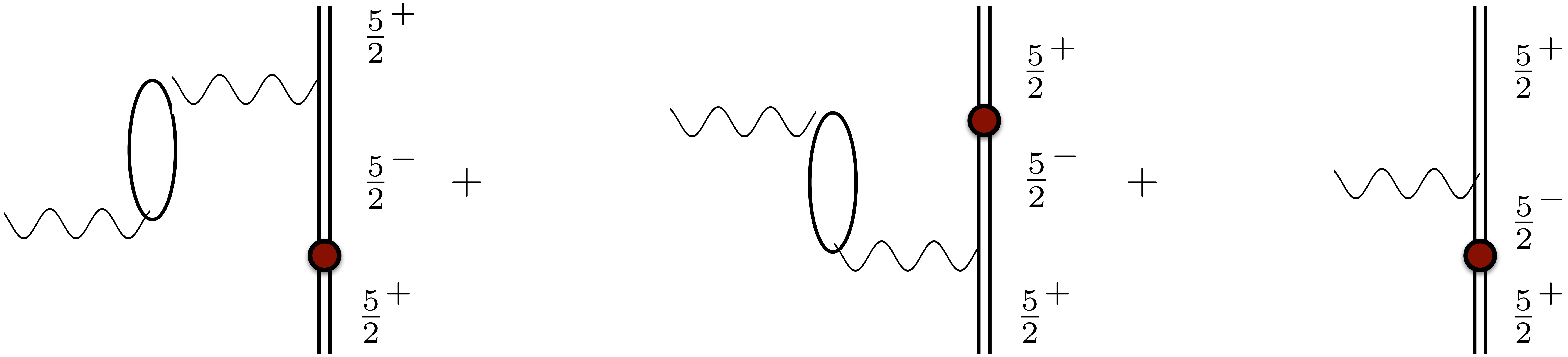
420 ± 30 ns

5/2$^-$ 100-220 eV

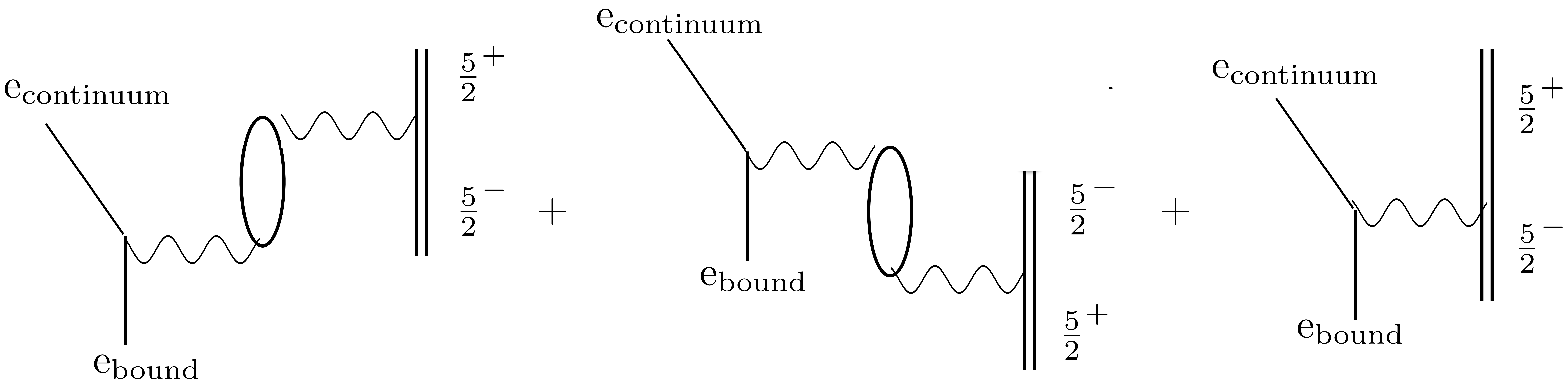
5/2$^+$

EC $\tau_{1/2} = 1.50$ d

This two-level Schiff screening of the static moment



is related to the IC conversion involving the transition



Because the energy release is small of the scale of the inverse atomic size, the IC rate should also be screened in ^{229}Pa and effectively measures the Schiff moment

Amusing: nuclear E1s are always accompanied by atomic E1s of equal but opposite “strength” — they are normally invisible at nuclear wavelengths

Leon and Seki, late 1970s

The IC rate has been calculated with a Los Alamos IC code that gives the user the options of Hartree-Fock with/without RPA corrections

The reduction in the amplitude when the RPA was turned on varied from factors of 7-14, depending on the detailed description of the valence atomic orbitals

- what was measured by Ahmad et al was not the C1, but the screened C1

This implies an exceptionally strong ground-state C1 to go with the exceptional energy denominator — thus a case where both sources of enhancement seem to operate, perhaps for the same underlying reason

Concluding comments

- The success with ^{225}Ra, the extraordinary ^{229}Pa energy denominator, FRIB isotope production, the predict C1 and M2 enhancements of 2000-12000 make ^{229}Pa intriguing as an edm target
  - LRP discussions…

- A pre-proposal was endorsed by PAC-2 at FRIB to begin a program on ^{229}Pa, focused on first verifying the doublet and re-measuring the IC rate (A. Yerby et al.)
  - will create a ^{239}U beam, EC source of ^{229}Pa for experiments

- The trapping and laser cooling then has to be demonstrated, and is a crucial hurdle
  - alternatively, optical crystals: Jaideep Singh, Hyper. Int. 240 (2019) 29

- The unique coupling of nuclear and atomic scales in this problem intriguing, and I'm not at all certain we have fully understood the associated physics