# Fundamental Symmetries and FRIB

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# Framework

**Rough definition of "Fundamental Symmetries"**

Search for beyond-standard-model physics at low energies

Study of symmetry-violating interactions in the nucleus

**Examples**

$0\nu\beta\beta$ decay and lepton-number violation

$\beta$ decay and breaking/extension of $SU(2)_L$

EDMs and beyond-standard-model CP/T violation

P-violating nucleon-nucleon interaction

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**FRIB at day 1 and after can contribute in two distinct ways**

1. Experiments to see BSM effects online
2. Contributions to offline experiments

   Preparatory work (e.g. for EDM searches)

   Finding good isotopes

   Harvesting isotopes (Greg Severin's talk)

   Measurements to constrain theory necessary to interpret expts.

# Examples of Experiments of Different Kinds

**Experiments to see BSM effects**

$\beta$-decay electron spectrum to search for scalar and tensor currents

**Preparatory Work**

Laser spectroscopy for EDM experiments (later in this talk)

**Finding good isotopes for atomic EDM experiments**

$J = 1/2$ parity doublets for Schiff moments
Higher-spin doublets for magnetic quadrupole moment

**Producing Isotopes**

$^{225}$Ra for EDM experiments
$^{221,223}$Rn, $^{229}$Pa for possible EDM experiments
Fr isotopes for PNC experiments

**and ...**

# Measurements to Constrain Theory

- Octupole moment of $^{225}$Ra (planned at ANL)
- $^{225}$Ra on isoscalar target (or vice versa) to measure isoscalar dipole strength?
- Proxy for $V_{PT}$ (e.g. $\vec{\sigma} \cdot \vec{r}$) ?
- Magnetic quadrupole operator or proxy?
- Momentum dependence of "$g_A$ quenching" for $\beta\beta$ decay: charge-changing cross sections at non-zero $q$?

Let's look at **Schiff moments** (radially weighted EDMs that transmit T violation to atomic electrons) and focus on $^{225}$Ra…

# Uncertainties in Schiff Moments

Schiff operator:

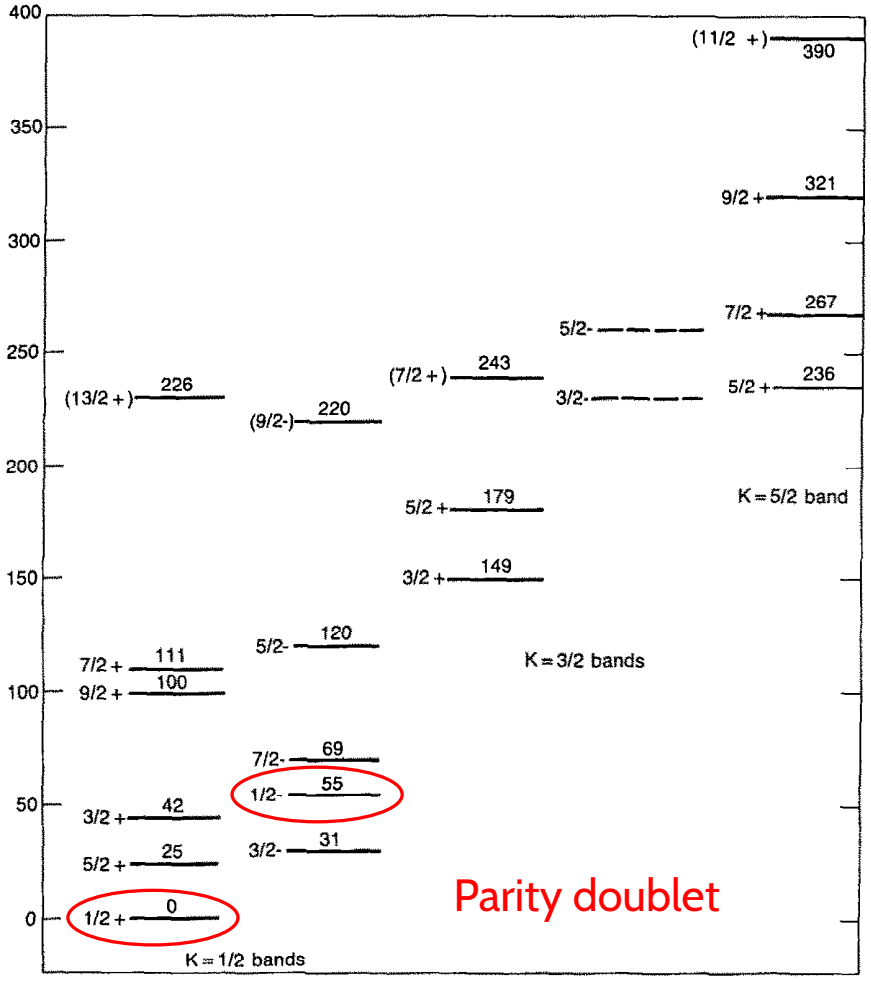
$$S_z \propto \sum_{i=1}^{A} e_i \, r_i^2 z_i + \ldots$$

Leading-order PT-violating Hamiltonian contains unknown constant in each of three isospin channels. Schiff moment reflects action of both $S_z$ and $V_{PT}$.

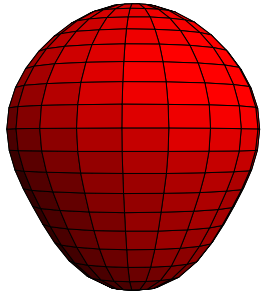
| | isoscalar | isovector | isotensor |
|---|---|---|---|
| $^{199}$Hg | 0.005 – 0.05 | -0.03 – +0.09 | 0.01 – 0.06 |
| $^{129}$Xe | -0.005 – -0.05 | -0.003 – -0.05 | -0.005 – -0.1 |
| $^{225}$Ra | -1 – -6 | 4 – 24 | -3 – -15 |

Recommended range of normalized Schiff moments corresponding to different terms in $V_{PT}$, based on spread in reasonable calculations

# Octupole Deformation and $^{225}$Ra




Unlike in Hg, these two states are the whole story.



Deformed density

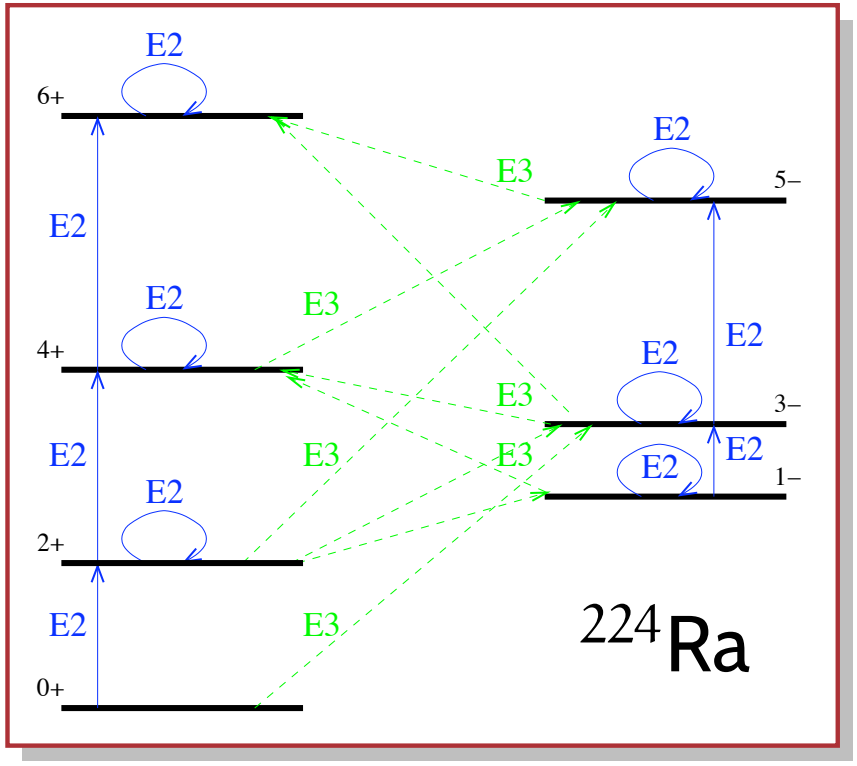
$$|\tfrac{1}{2}^{\pm}\rangle = \frac{1}{\sqrt{2}}\left( |\,\bigcirc\,\rangle \pm |\,\bigcirc\,\rangle \right)$$

$$\langle S_z \rangle \approx 2 \sum_m \frac{\langle 0|\, S_z \,|m\rangle \langle m|\, V_{PT} \,|0\rangle}{E_0 - E_m}$$

$$\longrightarrow 2 \frac{\langle \frac{1}{2}^+ |\, S_z \,| \frac{1}{2}^- \rangle \langle \frac{1}{2}^- |\, V_{PT} \,| \frac{1}{2}^+ \rangle}{E_+ - E_-}$$

# Reducing Uncertainty: Ra


$\langle 1/2^- | S_z | 1/2^+ \rangle$ correlated with octupole moment, which is extracted from E2 and E3 rates.




Rates in $^{225}$Ra to be measured at ANL.

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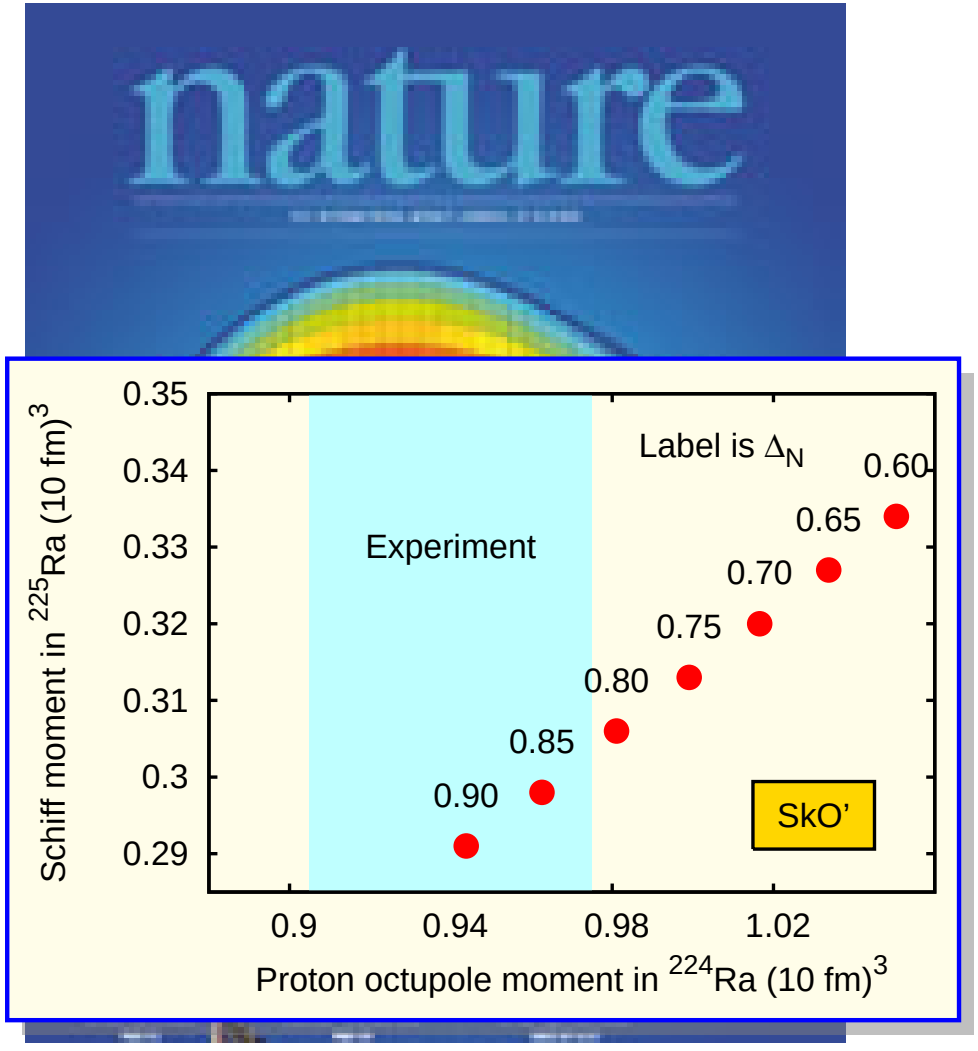
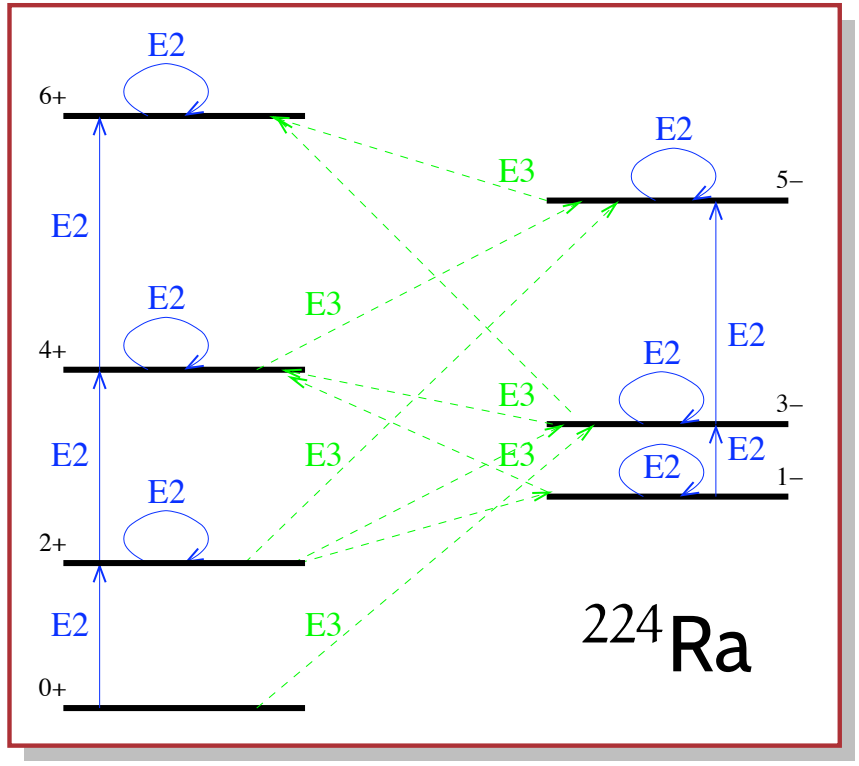



Strength of neutron pairing constrained by octupole moment

$\langle 1/2^- | S_z | 1/2^+ \rangle$ correlated with octupole moment, which is extracted from E2 and E3 rates.




Rates in $^{225}$Ra to be measured at ANL.

# The Future for Ra

- **Measurement of isoscalar dipole strength between members of parity doublet?**

  Operator is isoscalar version of Schiff operator.

  Can we measure $\langle 1/2^- | \sum_{i=1}^{A} r_i^2 z_i | 1/2^+ \rangle$?

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- **Measurements to help with matrix element of time-reversal violating potential?**

  In one-body approximation $V_{PT} \approx \vec{\sigma} \cdot \vec{\nabla} \rho$

  The closest simple one body operator is $\vec{\sigma} \cdot \vec{r}$ .

  Can we measure $\langle 1/2^- | \vec{\sigma} \cdot \vec{r} | 1/2^+ \rangle$ or something like it?

  What about charge-changing transition strength to isobar analog of $|1/2^-\rangle$ in $^{225}$Fr? Axial-charge $\beta$ decays in other nuclei?

  $V_{PT}$ is similar to two-body current operator in axial-charge channel.

# In the Meantime

## Getting Theory Ready for Day 1

- Better $0\nu\beta\beta$ matrix elements

  Topical collaboration devoted to this and part of the next item.

- Better calculations of Schiff and anapole moments

  Will require improved density functionals with well-determined statistical uncertainty.

- Ab initio calculations of interesting beta decay matrix elements, including recoil-order terms

- Improved calculations of radiative corrections in superallowed beta decay

  $W-\gamma$ box diagram particularly important.

- Linear response for understanding $g_A$ quenching

  Both ab initio and density-functional methods important.

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