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

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

EDMs and beyond-standard-model CP/T violation

P-violating nucleon-nucleon interaction

⋮

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

β-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:

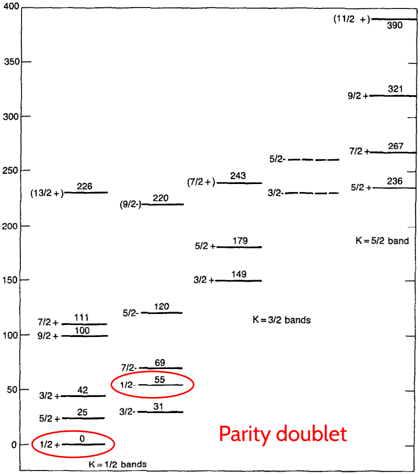
$$S_z \propto \sum_{i=1}^{A} e_i\, r_i^2 z_i + \ldots$$

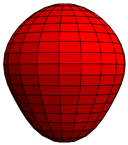
Leading-order PT-violating Hamiltonian contains unknown constant in each of three isospin channels. Schiff moment reflects action of both S_z and V_{PT}.

	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





Deformed density

$|\tfrac{1}{2}^{\pm}\rangle = \frac{1}{\sqrt{2}}\Big(|$  $\rangle \pm |$  $\rangle \Big)$

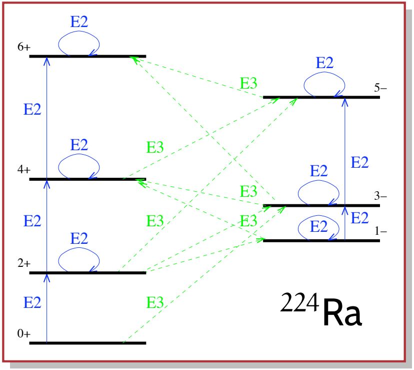
$$\langle S_z \rangle \approx 2 \sum_m \frac{\langle 0| S_z |m\rangle \langle m| V_{PT} |0\rangle}{E_0 - E_m}$$

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

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

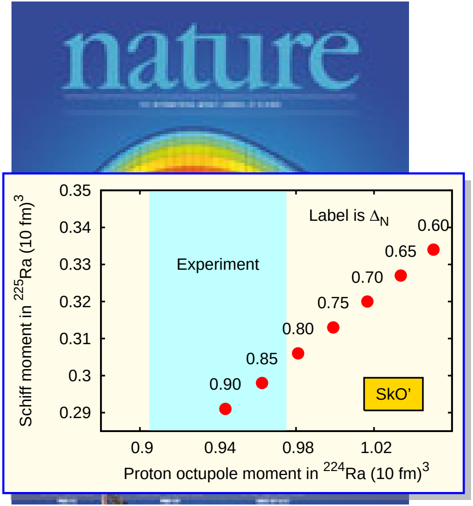
Reducing Uncertainty: Ra

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



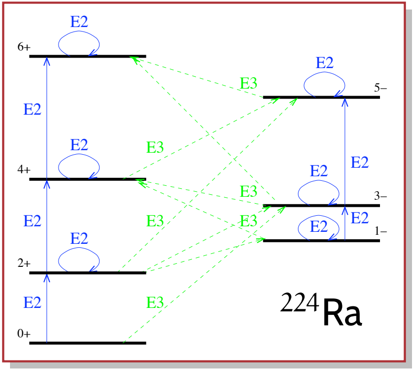
Rates in ^{225}Ra to be measured at ANL.

Reducing Uncertainty: Ra



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

  Would provide an even better constraint than the octupole moment.

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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 β 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.

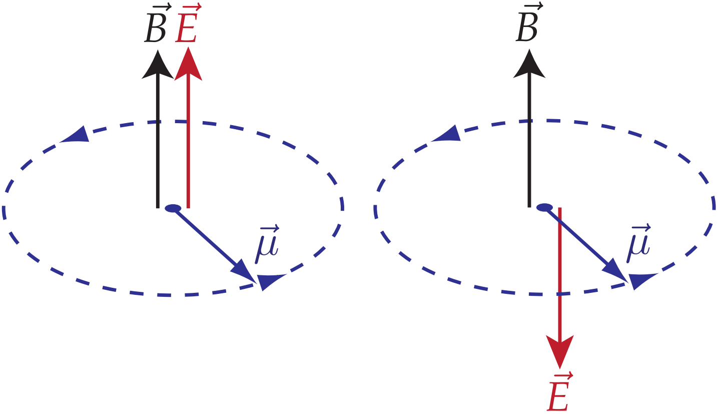
- Linear response for understanding g_A quenching

  Both ab initio and density-functional methods important.

- $\vdots$

Some Thoughts On EDM Experiments

Always Measure Frequency: Spin Precession



$$h\nu_{\uparrow} = 2(\mu B_{\uparrow} + dE) \qquad h\nu_{\downarrow} = 2(\mu B_{\downarrow} - dE)$$

Ultimate Statistical Sensitivity

$$\Delta\nu = \nu_{\uparrow} - \nu_{\downarrow} = \frac{4dE}{h}$$

statistical sensitivity:

$$\sigma_d = \frac{\hbar}{2E\sqrt{\epsilon N_a T \tau}}$$

Electric field

particle number

integration time

measurement time

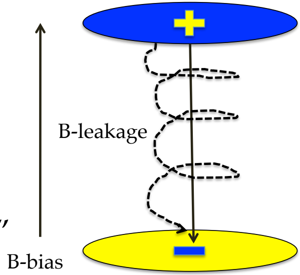
Magnetic Field Instabilities & False Effects!

$$\Delta\nu = \nu_{\uparrow} - \nu_{\downarrow} = \frac{4dE}{h} + \boxed{\frac{2\mu(B_{\uparrow} - B_{\downarrow})}{h}}$$

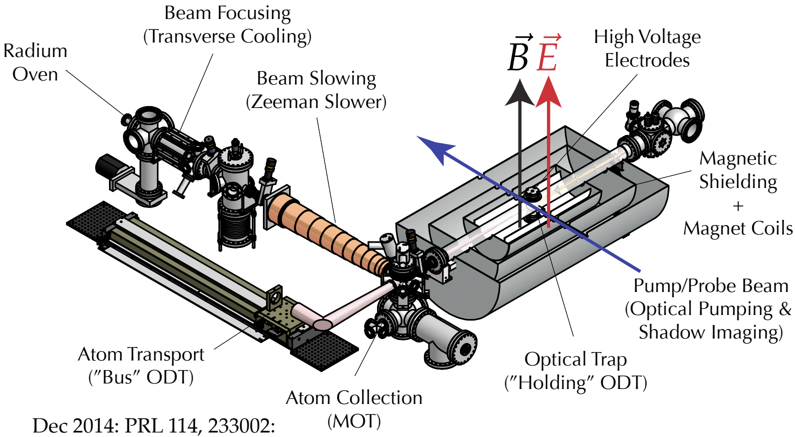
challenge!

Instabilities adds noise & limits the statistical precision.

False effects, things which change sign with the electric field, are nasty: "leakage current"



State of the Art: ^{225}Ra EDM Laser Trap Experiment



Dec 2014: PRL 114, 233002:
|d(Ra-225)| < 50x10^{-23} *e* cm (95%)
June 2015: PRC 94, 025501:
|d(Ra-225)| < 1.4x10^{-23} *e* cm (95%)

adapted from Matt Dietrich ANL

What Would A "Dream" Experiment Look Like?

- Large intrinsic sensitivity to BSM physics
  - high Z (^{199}Hg, ^{205}Tl, ^{225}Ra, ^{221,223}Rn, ^{229}Pa)
  - octupole deformed nucleus (^{225}Ra, ^{221,223}Rn, ^{229}Pa)
- Large *E*-field or *B*-field gradient to amplify observable
  - internal molecular fields (diatomic & triatomic molecules)
  - local crystal fields (solids)
  - unshielded nucleus (ions in an ion trap or storage ring)
- Repeat the measurement as many times as possible
  - large number of nuclei (stable)
  - long integration time (stable, long $\tau_{1/2}$, or steady supply for short $\tau_{1/2}$)
  - long measurement time (long coherence and/or trapping times)
- High efficiency extraction of experimental signal
  - convert a large fraction of "source" nuclei into "signal" nuclei
  - make a high SNR detection of each "signal" nucleus (many photons)

One Possibility: Actinide Ions (^{229}Pa) in Optical Crystals

- Large intrinsic sensitivity to BSM physics
  - **high Z** (^{199}Hg, ^{205}Tl, ^{225}Ra, ^{221,223}Rn, **^{229}Pa**)
  - **octupole deformed nucleus** (^{225}Ra, ^{221,223}Rn, **^{229}Pa**)
- Large *E*-field or *B*-field gradient to amplify observable
  - **local crystal fields with large spin-orbit couplings (solids)**
- Repeat the measurement as many times as possible
  - ~~large number of nuclei (stable)~~
  - **long integration time (FRIB: steady supply for short $\tau_{1/2}$)**
  - **long trapping time: nuclei "stored" in the solid**
  - **long coherence time (for suitably chosen energy levels…>1 s for lanthanide ions in optical crystals used for quantum information)**
- High efficiency extraction of experimental signal
  - **near unity capture and trapping efficiency in solid**
  - **optical detection via laser probing**
  - **major areas for development pre-FRIB: optically-detected NMR and overcoming inhomogenous broadening**

Imaginary FRIB Experimental Fun. Sym. Timeline

1. Before FRIB
    - nuclear structure measurements & calculations (^{225}Ra, ^{221,223}Rn, ^{229}Pa)
    - development of experimental techniques (CRES, implantation beta spectroscopy, beta decay polarimetry, Ra EDM laser trap experiment, spectroscopy of atoms & molecules in solids, two-photon spectroscopy of noble gases)
    - harvesting studies at NSCL (Severin Talk)
2. FRIB Day 1
    - nuclear structure measurements (what is still needed – ^{229}Pa?)
    - development of experimental techniques with FRIB isotopes (CRES, implantation beta spectroscopy, beta decay polarimetry, spectroscopy of actinide ions & RaO molecules in solids, two-photon spectroscopy of Radon)
    - harvesting studies at FRIB (Severin talk)
3. FRIB Long Term
    - beta decay spectroscopy & polarimetry with isotopes online at FRIB
    - harvesting of ^{225}Ra for laser trap experiment (statistics+systematics)
    - actinide ion (^{229}Pa) in solid based "EDM"-type search at MSU?
    - molecule based ^{225}Ra EDM experiment somewhere?

Backup Slides

Existence Proof: Royce-Bloembergen Experiment

Cr^{3+} in Al_2O_3: Royce & Bloembergen Phys. Rev. 131 1912 (1963)

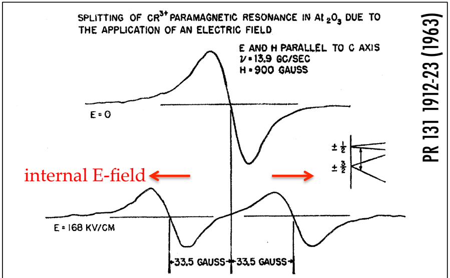
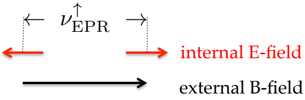
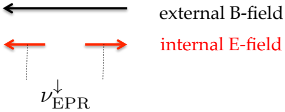


FIG. 1. Experimental absorption derivative curves showing the electric-field-induced splitting of the $\frac{1}{2} \rightarrow \frac{3}{2}$ resonance line of Cr^{3+} in ruby.



$$\Delta\nu_{\mathrm{EPR}} = \frac{4\Delta m d E}{J}$$



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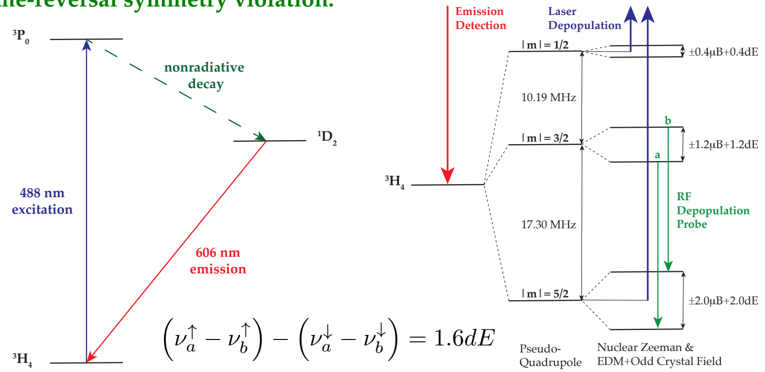
One Example of a "Modern RB Experiment"

Key Concept: The non-degeneracy of a Kramers Doublet is an indication of time-reversal symmetry violation.



$$\left(\nu_a^{\uparrow} - \nu_b^{\uparrow}\right) - \left(\nu_a^{\downarrow} - \nu_b^{\downarrow}\right) = 1.6dE$$

Pr^{3+} (I=5/2) in Y_2SiO_5 [stable Surrogate for ^{229}Pa ($\tau_{1/2}$=1.5 d , I= 5/2)]

Optically-detected NMR: Shift in NMR frequency upon B-field reversal

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