Towards a new search for hadronic CP-violation using ultracold assembled ^{223}FrAg molecules

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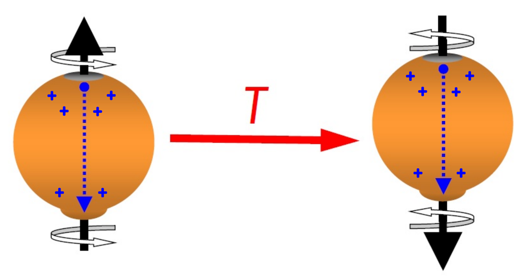
Motivation

- Universe has more matter than antimatter → baryon asymmetry
- Need new time-reversal (equivalently CP) violating interactions to explain baryon asymmetry
- T-violating new physics can cause Nuclear Schiff moment (NSM), an aspherical charge distribution along the spin axis
- Sensitive to new T-violating physics in hadronic sector such as chromo-EDMs ($\tilde{d}$), CP-violating QCD term ($\bar{\theta}$), pion-nucleon couplings



$$\mathcal{H}_{\text{eff}} = S\vec{I}\cdot\hat{E}_{\text{ext}}\mathcal{P}$$

$$\Delta E = \Lambda W_S \vec{I}\cdot\hat{E}_{\text{ext}}\mathcal{P}$$

degree of electrical polarization

Nuclei $\tilde{d}$ enhancement factor

Λ ~ 1000 times larger [1] for pear-shaped nuclei

→ want octupole-deformed nucleus

Molecule internal field enhancement factor

$W_S \propto A^{2/3}, Z^2$

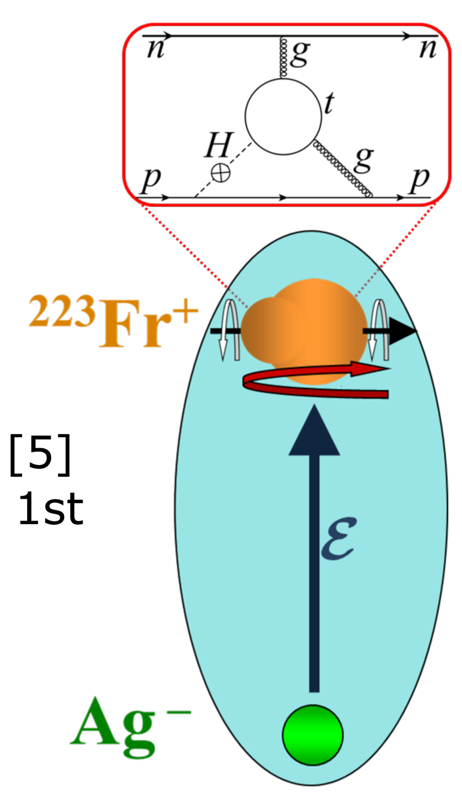
→ want heavy nucleus

Deformed Nuclei in Polar Molecules

$$\delta\tilde{d} \sim \frac{1}{2\tau\Lambda W_S \mathcal{P}\sqrt{N}}$$

τ: coherence time
N: Total number of molecules measured

- ^{223}Fr has known octupole deformation [2]
- Calculations show alkali-silver molecules are ionic-like [3,4]
→ Large W_s for ^{223}Fr in FrAg + small field ~1 kV/cm sufficient for $\mathcal{P} \sim 1$
- Fr and Ag have alkali-like structure
→ amenable to standard laser cooling
- Ultracold-assembled molecules already demonstrated ~10 s nuclear spin coherence time [5]
- Project **3000x** improvement in chromo EDM for 1st generation experiment with already demonstrated parameters
- Probing energy scales up to 200 TeV



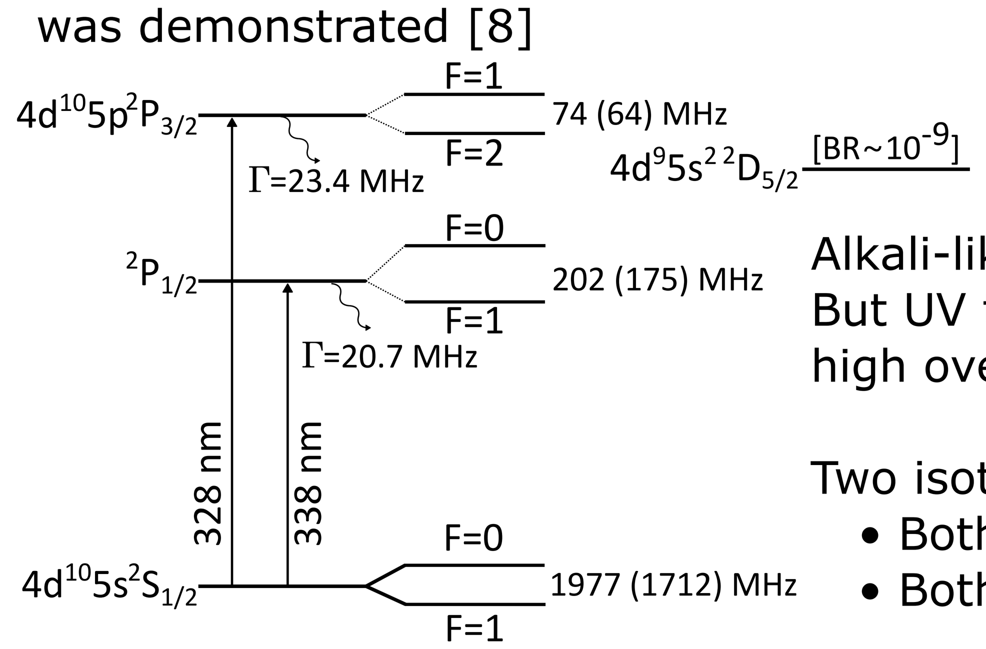
Quantity	Value
Coherence Time, τ	10 s
Time per single measurement, T_{meas}	30 s
Measured molecules per single measurement, $\dot{N}$	10^4
Averaging Time, T	70 days
Number of molecules measured ($=\dot{N}\frac{T}{T_{\text{meas}}}$), N	2×10^9
Frequency Sensitivity ($=\frac{1}{\tau\sqrt{N}}$), ν_0	$2\pi \times 355$ nHz
W_S(FrAg) [1]	41755 a.u.
Statistical limit on ^{223}Fr Schiff Moment ($=\frac{\nu_0}{2W_S}$), S	8.8×10^{-14} e fm^3
^{223}Fr chromo-EDM conversion, Λ	1.6×10^4 e fm^2 [6]
$\delta\tilde{d}$ ($=S/\Lambda$)	6×10^{-31} cm
Statistical limit on ^{199}Hg Schiff moment, S	1.1×10^{-13} e fm^3 [7]
^{199}Hg chromo-EDM conversion, Λ	5 e fm^2 [6]
$\delta\tilde{d}$ ($=S/\Lambda$)	2×10^{-27} cm

3000x improvement!

Silver Laser Cooling

Immediate goal: Measure Ag scattering properties to make Ag condensate, needed to assemble FrAg

- Use 2γ photoassociation spectroscopy to find s-wave scattering length and estimate locations of Feshbach resonances
- Silver MOT made once 20 years ago but no trapping was demonstrated [8]



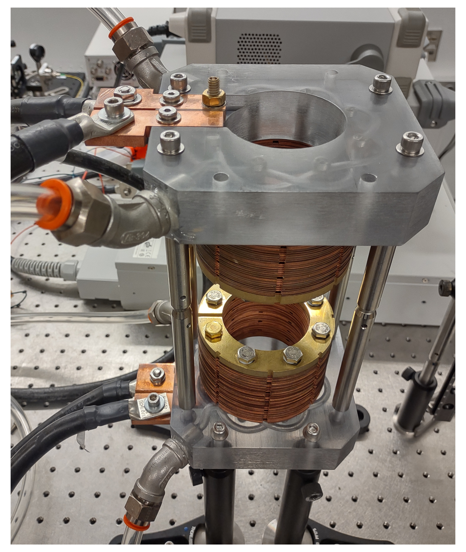
Alkali-like!
But UV transitions + high oven temperature (950°C)

Two isotopes: ^{107}Ag and ^{109}Ag
- Both I=1/2
- Both ~50% isotopic abundance

- I_{sat} ~ 90 mW/cm^2 → need high laser power at 328 nm
- Expect >1 W at 328 nm   1114 nm + 1596 nm →(SFG) 656 nm →(SHG) 328 nm
- Repump with ~1.9 (1.7) GHz EOM
- Use Λ-enhanced D1 (338 nm) cooling for dipole trap loading [9]

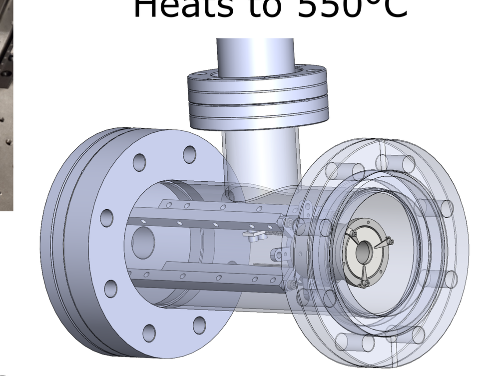
Progress Towards a Silver MOT

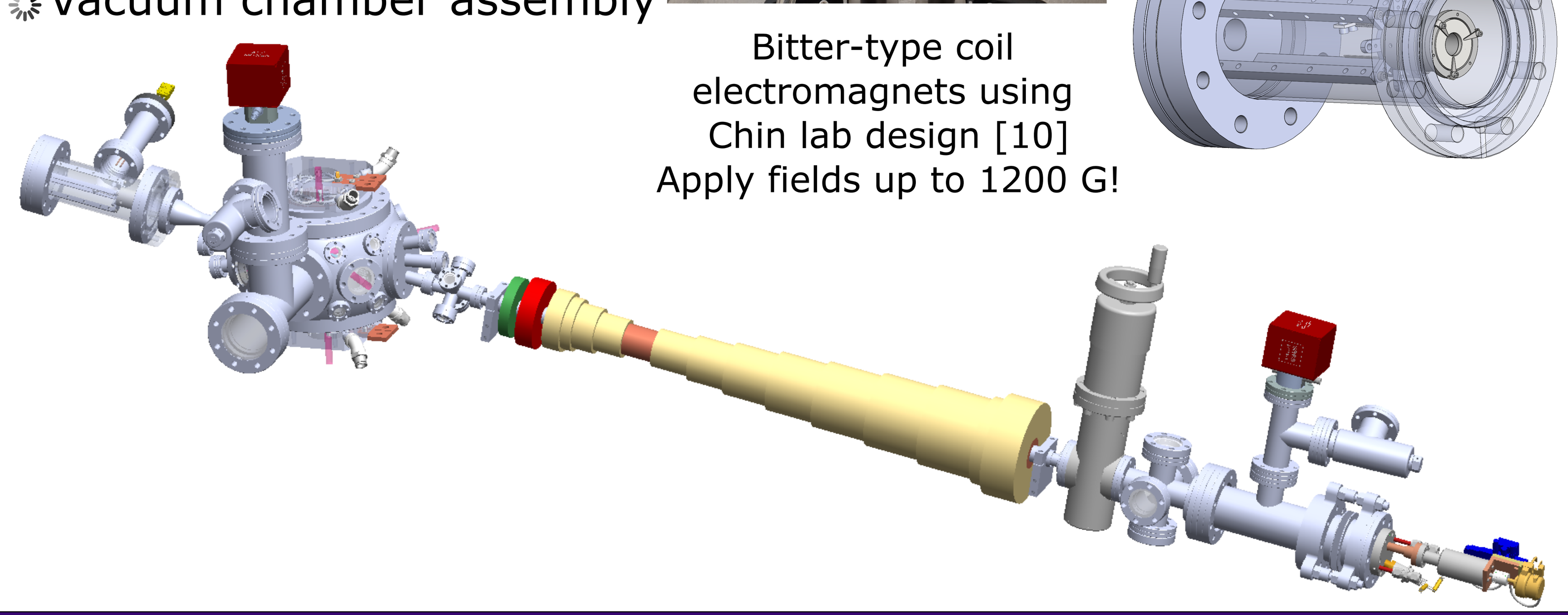
- ✓ Silver oven source
- ✓ Zeeman slower
- ✓ Anti-Helmholtz coils
- ✓ 5W 656 nm laser
- ⚙ In-vacuum heated Zeeman slower window
- ⚙ Laser locking to scanning interferometer
- ⚙ >1W 328 nm light
- ⚙ Vacuum chamber assembly



Bitter-type coil electromagnets using Chin lab design [10]
Apply fields up to 1200 G!

Silver plasma frequency = D2 frequency
→ silver-coated optics strongly absorb Zeeman slower light
Solution: In-vacuum sapphire window. Heats to 550°C





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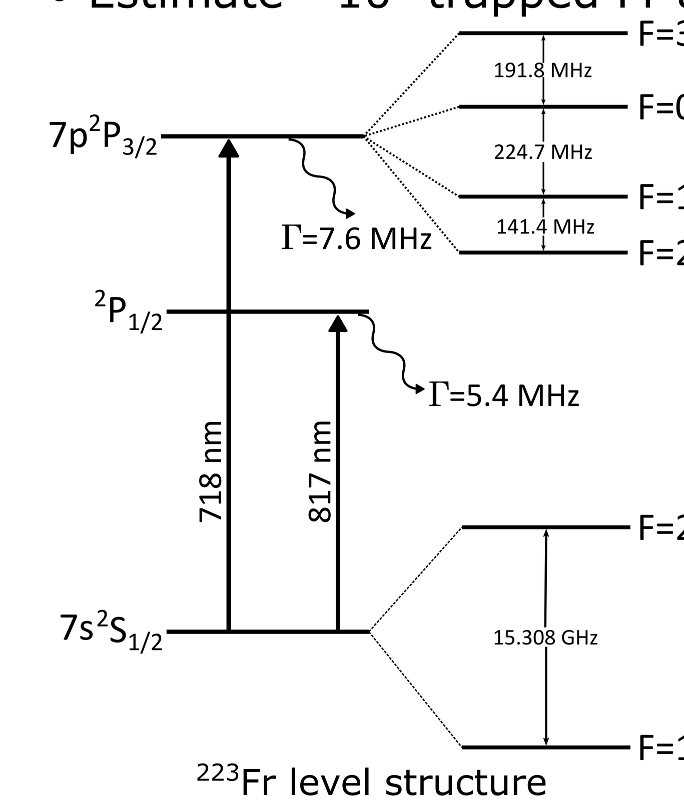
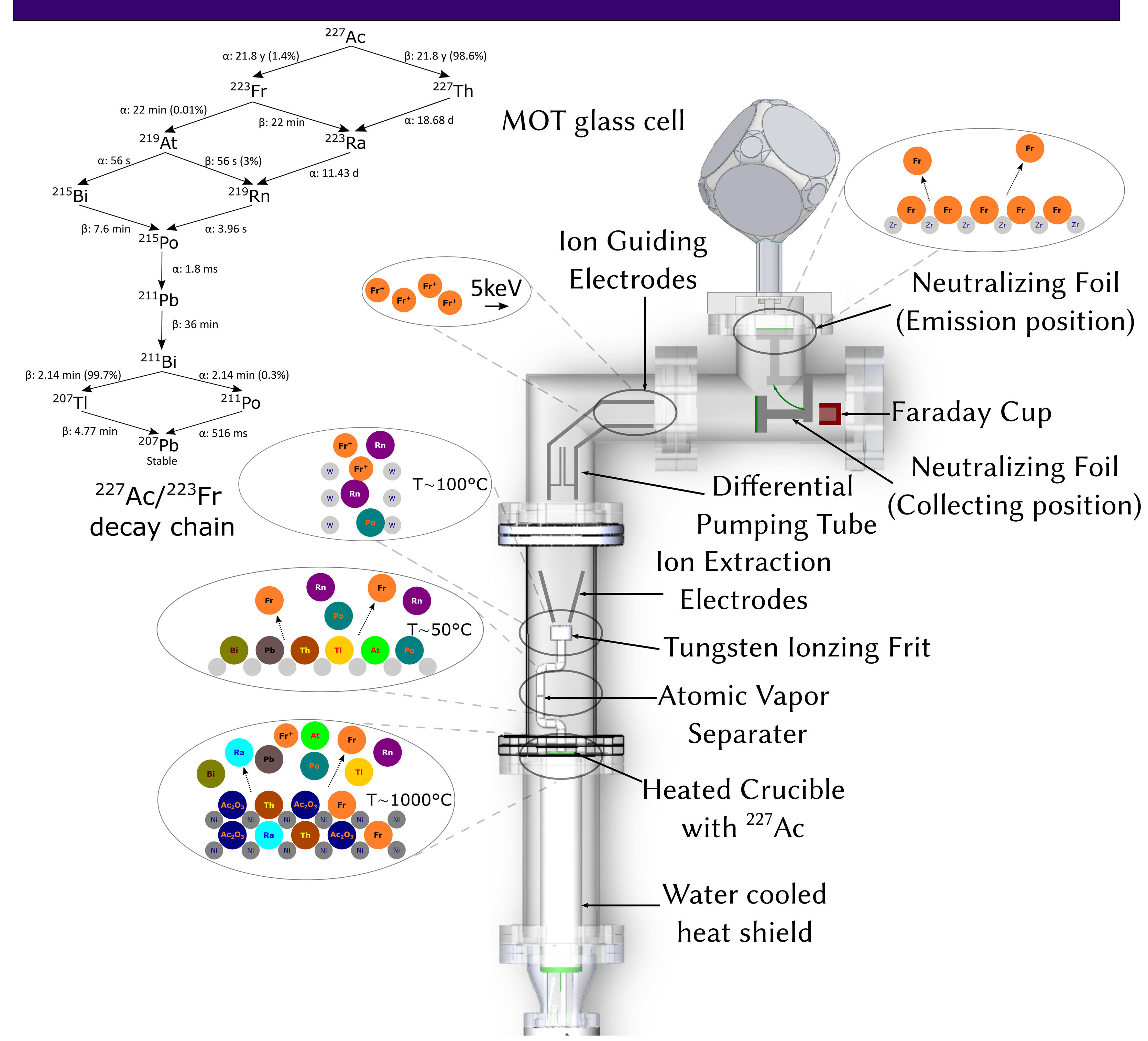
Francium Laser Cooling

- Goal: Measure scattering properties of ^{223}Fr to make ^{223}Fr condensate and ^{223}FrAg
- Plan: Vapor cell MOT using continous offline source of ^{223}Fr generated from ^{227}Ac
- Estimate ~10^6 trapped Fr atoms with 10 mCi ^{227}Ac source



Quantity	Value
^{227}Ac Activity, A	10 mCi
^{227}Ac Decays rate, Γ_{Ac}	4×10^8 s^{-1}
^{223}Fr Branching Ratio, BR_{Fr}	1.4%
^{223}Fr production rate, $\Gamma_{\text{Fr}}(=\Gamma_{\text{Ac}}\text{BR}_{\text{Fr}})$	5×10^6 s^{-1}
^{223}Fr$^+$ Extraction and Transport Efficiency, η_{trans}	1% [11]
^{223}Fr$^+$ Batch loading time, T_{load}	60 s
Number ^{223}Fr delivered to MOT, $\text{N}_{\text{Fr}}(=\Gamma_{\text{Fr}}\eta_{\text{trans}}\text{T}_{\text{load}})$,	3×10^6
Trapping Efficiency, η_{trap}	50% [12,13]
MOT atom number ($=\text{N}_{\text{Fr}}\eta_{\text{trap}}$)	1.5×10^6

Plan for Offline Francium Production



Proposed design extracts ^{223}Fr while keeping all undesired elements outside the MOT region

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