Probing Fundamental Symmetries and Interactions by low energy excitations with RIBs

EDM and deformed nuclei at SPES

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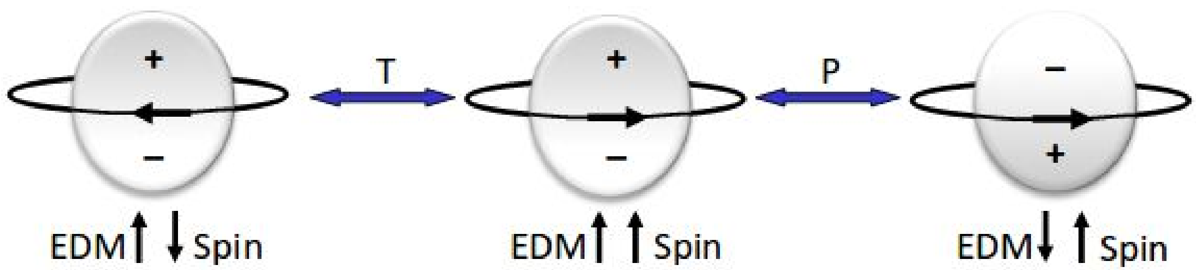


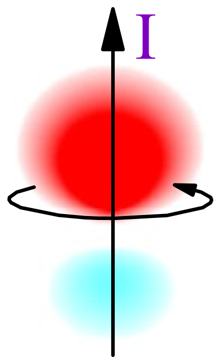
SPES-Nusprasen Workshop – Fundamental Symmetries – Pisa 1-2 February 2018

EDM and deformed nuclei at SPES

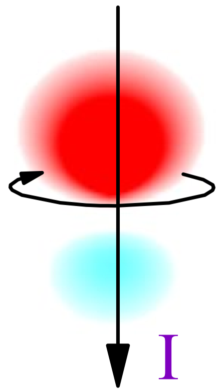
- The SM is insufficient to account for the observed barion asymmetry of the universe.
- CP violation observed in K and B decays is not sufficient to explain the observed **asymmetry of matter**.
- Many theoretical models with CP violation.
- One of the most stringent test for models is the predicted EDM for neutron, electron and atoms.
- RIB facilities allow to select special nuclei where such moments are greatly enhanced

T and CP violation by a permanent EDM

- Time Reversal:



$$t \to -t$$
$$\vec{I} \to -\vec{I}$$
$$\vec{d} \to \vec{d}$$



- Vector: $\vec{d} = d\frac{\vec{I}}{I}$ $\quad d \to -d \to 0$

$d \neq 0 \to$ *violation of time reversal symmetry*

- CPT theorem also implies violation of CP symmetry

EDM $\to$ T violation $\leftrightarrow$ CP violation

Courtesy of M. Romalis

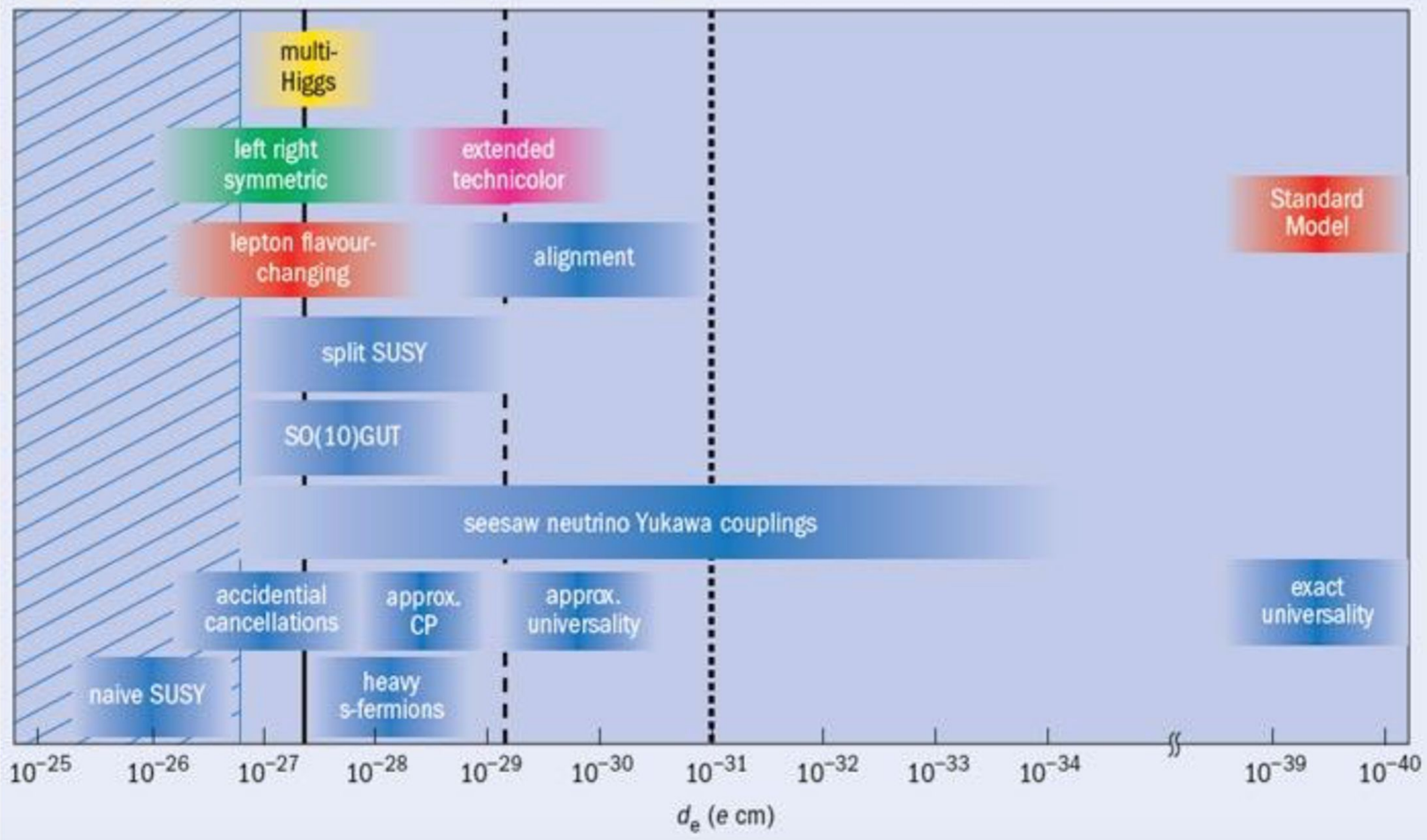
Strong CP

- Matter – antimatter asymmetry
  - 1967, Andrei Sakharov: CP violation
  - CP violation observed so far is not sufficient
  - Can be explained with more CP violating mechanisms

$$\frac{n_B}{n_\gamma} = (6.1^{+0.3}_{-0.2}) \times 10^{-10}$$

- Baryogenesis → asymmetry between baryons and antibaryons in the Universe
  - Distant galaxies made of matter of antimatter?
  - No evidence of annihilations
  - No void in CMB
- Supersymmetry
  - More particles → more CP-violating phases
- Strong CP problem
  - CP not violated in quantum chromodynamics, fine tuning

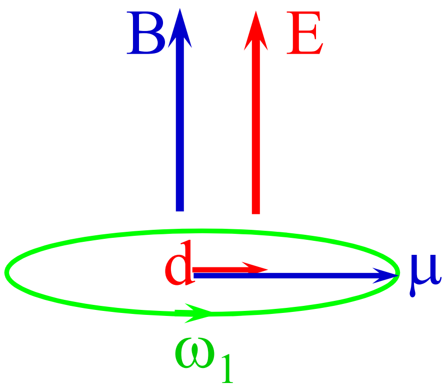
Strong CP

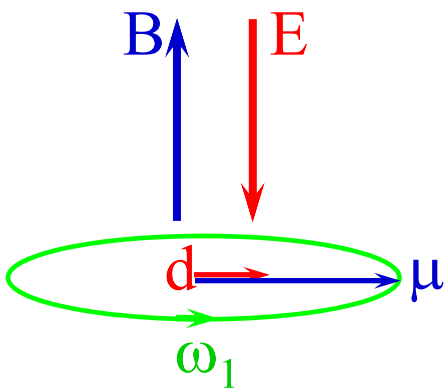


multi-Higgs
left right symmetric
extended technicolor
Standard Model
lepton flavour-changing
alignment
split SUSY
SO(10)GUT
seesaw neutrino Yukawa couplings
accidential cancellations
approx. CP
approx. universality
exact universality
naive SUSY
heavy s-fermions
10^{-25} 10^{-26} 10^{-27} 10^{-28} 10^{-29} 10^{-30} 10^{-31} 10^{-32} 10^{-33} 10^{-34} 10^{-39} 10^{-40}
d_e (e cm)

Experimental Detection of an EDM

- Measure spin-precession frequencies





$$H = -\vec{\mu}\cdot\vec{B} - \vec{d}\cdot\vec{E}$$

$$\omega_1 = \frac{2\mu B + 2dE}{\hbar} \qquad \omega_2 = \frac{2\mu B - 2dE}{\hbar} \qquad \omega_1 - \omega_2 = \frac{4dE}{\hbar}$$

- Statistical Sensitivity:

Single atom with coherence time τ: $\delta\omega = \frac{1}{\tau}$

N uncorrelated atoms measured for time T >> τ: $\delta d = \frac{\hbar}{2E}\frac{1}{\sqrt{2\tau T N}}$

Courtesy of M. Romalis

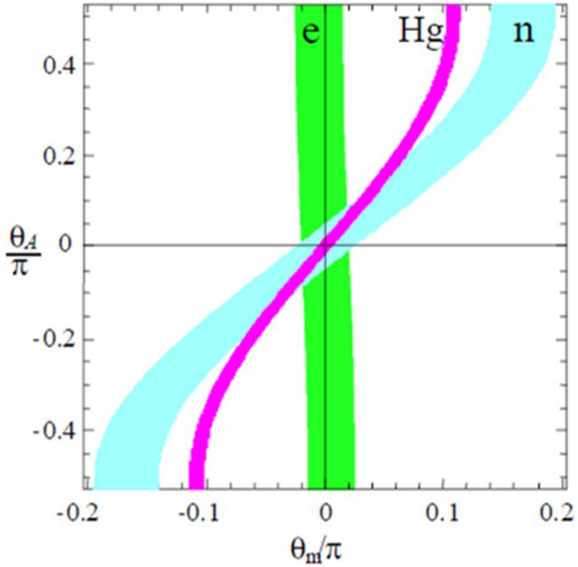
Present limits

Sector	Exp Limit (e-cm)	Location	Method	Standard Model
Electron	9×10^{-29}	Harvard (ACME)	ThO molecules in a beam	10^{-38}
Neutron	3×10^{-26}	ILL	UCN in a bottle	10^{-31}
Nuclear	7×10^{-30}	U. Washington	^{199}Hg atoms in a cell	10^{-33}

Nuclear Physics B 560 (1999) 3–22

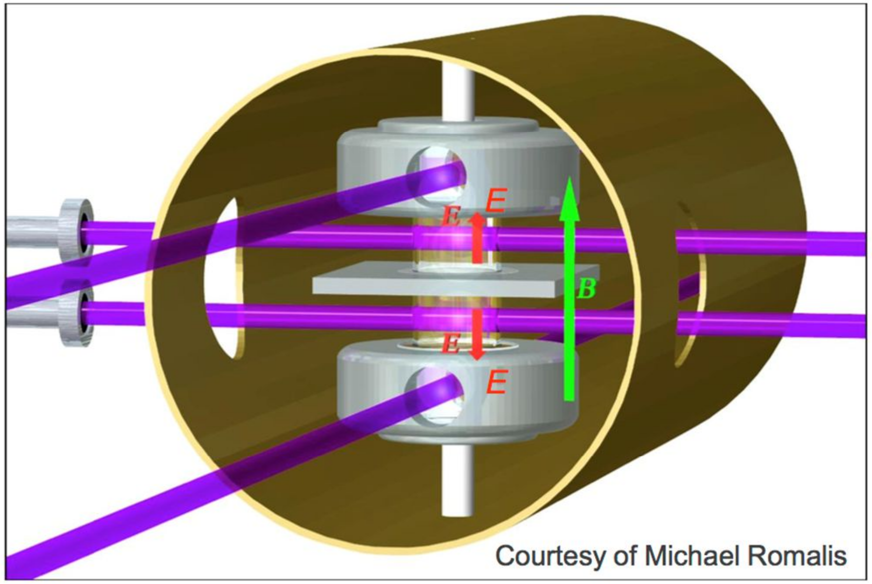
MSSM predictions for the electric dipole moment of the ^{199}Hg atom

Toby Falk[a,1], Keith A. Olive[b,2], Maxim Pospelov[b,3], Radu Roiban[c,4]

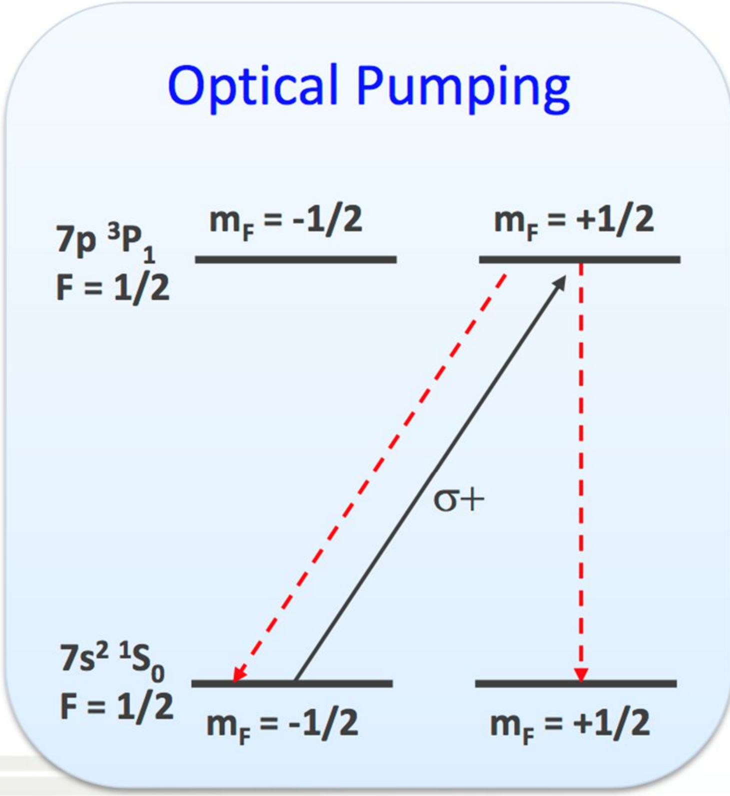


Experimental technique

^{199}Hg stable, high Z, groundstate $^1S_0$, I = ½, high vapor pressure



Courtesy of Michael Romalis



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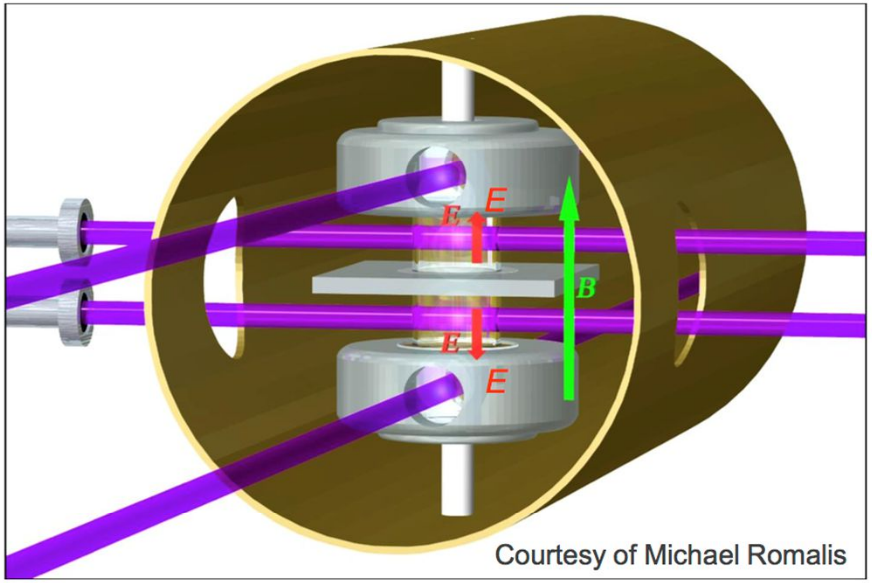


Courtesy of Michael Romalis

$$f_+ = \frac{2\mu B + 2dE}{h} \approx 15\ \text{Hz}$$

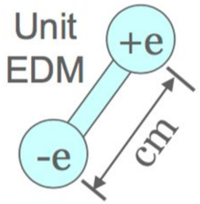
$$f_- = \frac{2\mu B - 2dE}{h} \approx 15\ \text{Hz}$$

$$|f_+ - f_-| < 0.2\ \text{nHz}$$

The best limit on atomic EDM

EDM (^{199}Hg) < 7.4 x 10^{-30} e-cm

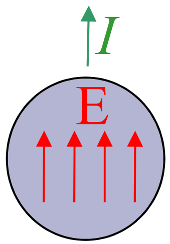
Graner *et al.*, Phys Rev Lett (2016)



Atomic EDM proportional to Shiff moment

- No atomic EDM due to EDM of the nucleus - Schiff' s Theorem
  - Electrons screen applied electric field
- *d*(Hg) is due to finite nuclear size
  - nuclear Schiff moment S - Difference between mean square radius of the charge distribution and electric dipole moment distribution

$$\vec{S} = \frac{2\pi}{5}\int dx^3 \rho(x)\left(x^2\vec{x} - \frac{5}{3}\langle r^2 \rangle_{ch}\vec{x} \right)$$



Recent work by Haxton, Flambaum on form of Schiff moment operator

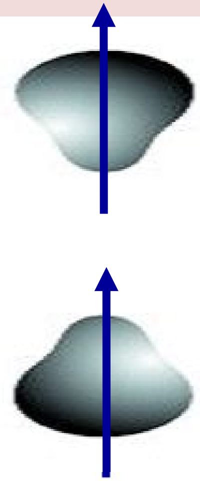
- Schiff moment induces parity mixing of atomic states, giving an atomic EDM:

$$d_a = k \cdot S$$

V. Dzuba *et al. Phys.Rev. A66 (2002) 012111*

Courtesy of M. Romalis

Octupole Enhancement



$|+\rangle$

$|-\rangle$

$$\Psi^+ = (|+\rangle + |-\rangle)/\sqrt{2}$$

ΔE

$$\Psi^- = (|+\rangle - |-\rangle)/\sqrt{2}$$

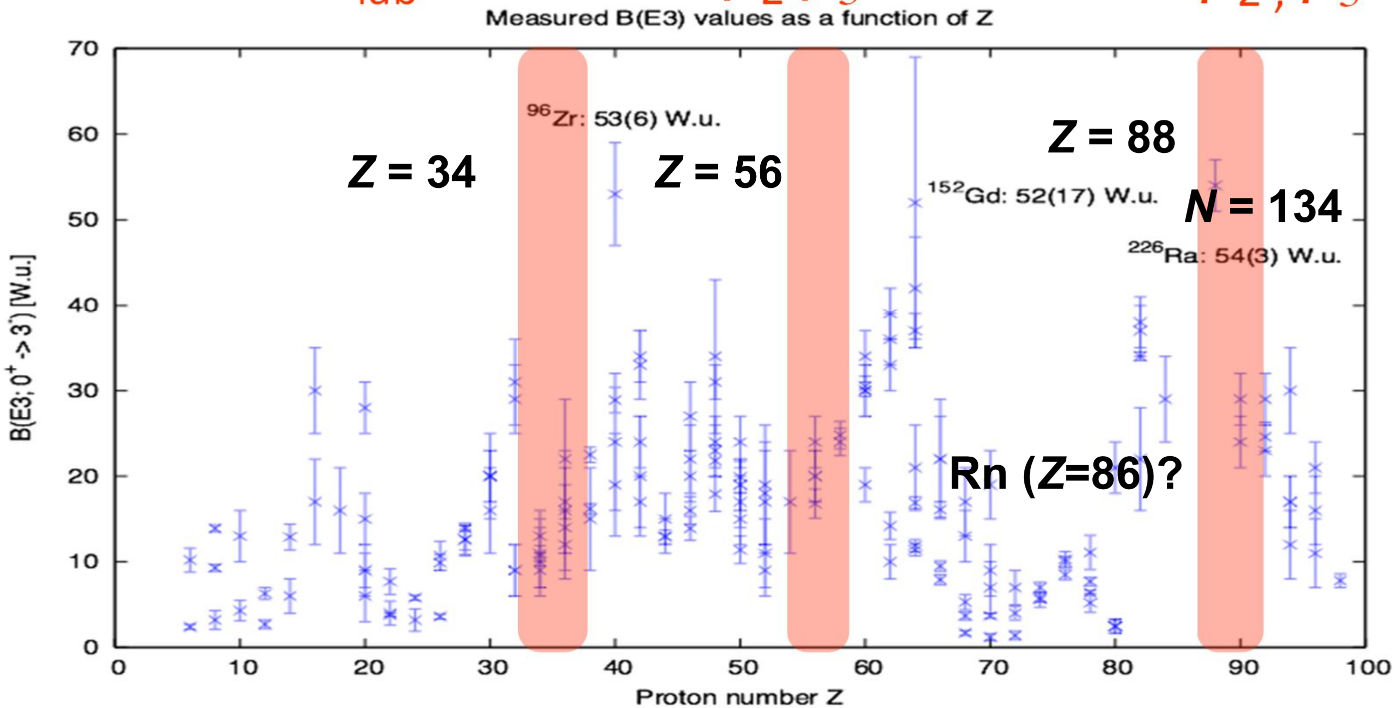
$\cancel{P}, \cancel{T}$ $\Rightarrow$

$$\Psi^+ = ((1+\alpha)|+\rangle + (1-\alpha)|-\rangle)/\sqrt{2}$$

$$\Psi^- = ((1-\alpha)|+\rangle + (1+\alpha)|-\rangle)/\sqrt{2}$$

$$\alpha = \frac{\left\langle \Psi^- \middle| V^{PT} \middle| \Psi^+ \right\rangle}{\Delta E} \sim \frac{\beta_3 A^{-1/3}}{\Delta E}$$

$S_{intr} \sim eZA\beta_2\beta_3$ $\quad$ $S_{lab} \sim e\,Z\,A^{2/3}\,\beta_2\,\beta_3^{\,2}/\Delta E$ $\quad$ $\beta_2, \beta_3 \sim 0.1$



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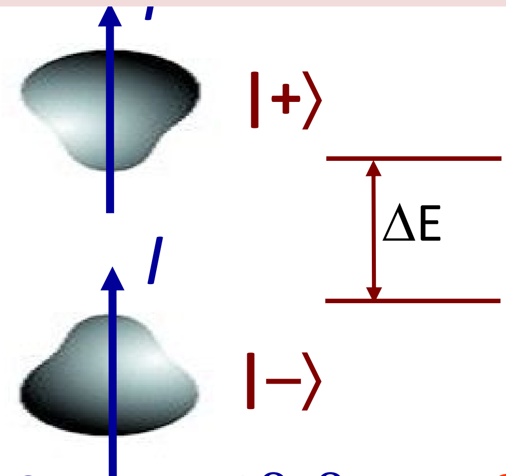

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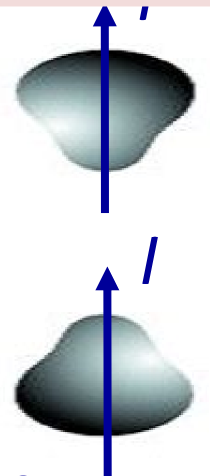
Haxton & Henley; Auerbach, Flambaum & Spevak; Hayes, Friar & Engel; Dobaczewski & Engel

	^{223}Rn	^{223}Ra	^{225}Ra	^{223}Fr	^{225}Ac	^{229}Pa	^{199}Hg	^{129}Xe
$t_{1/2}$	23.2 m	11.4 d	14.9 d	22 m	10.0 d	1.5 d		
I	7/2	3/2	1/2	3/2	3/2	5/2	1/2	1/2
Δe_{th} (keV)	37	170	47	75	49	5		
ΔE_{exp} (keV)	--	50.2	55.2	160.5	40.1	0.22		
10^5 S ($e$fm^3)	1000	400	300	500	900	12000	-1.4	1.75
10^{28} d_A (e cm)	**2000**	**2700**	**2100**	**2800**			-5.6	0.8

Octupole Enhancement



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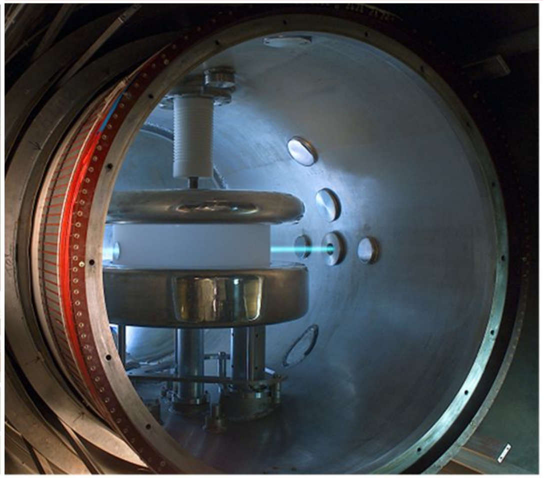
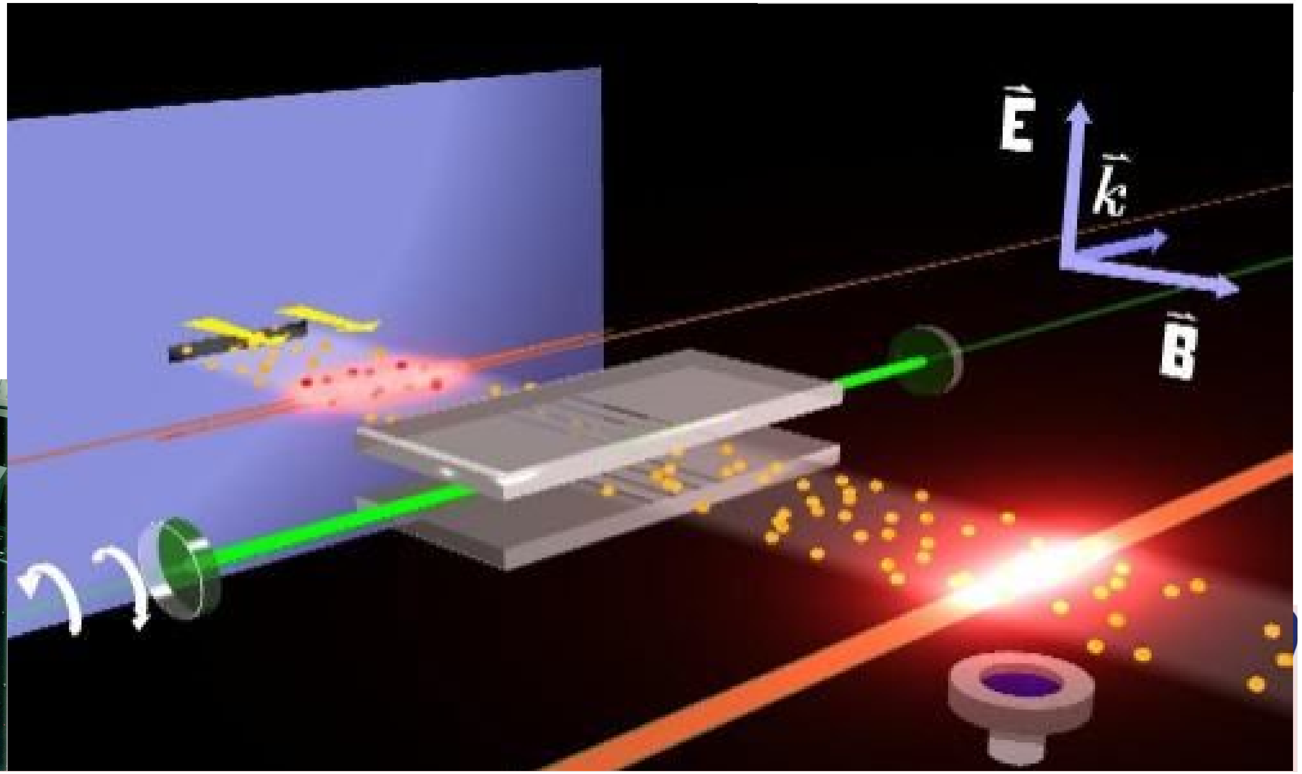
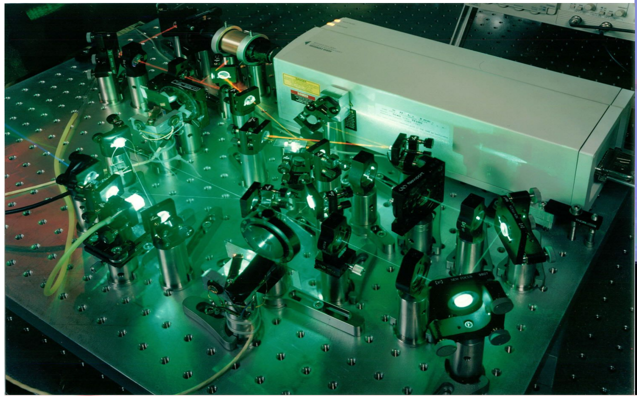
EDM measurement

- Production
- Separation
- Trapping
- Orientation
- Precession
- Detection

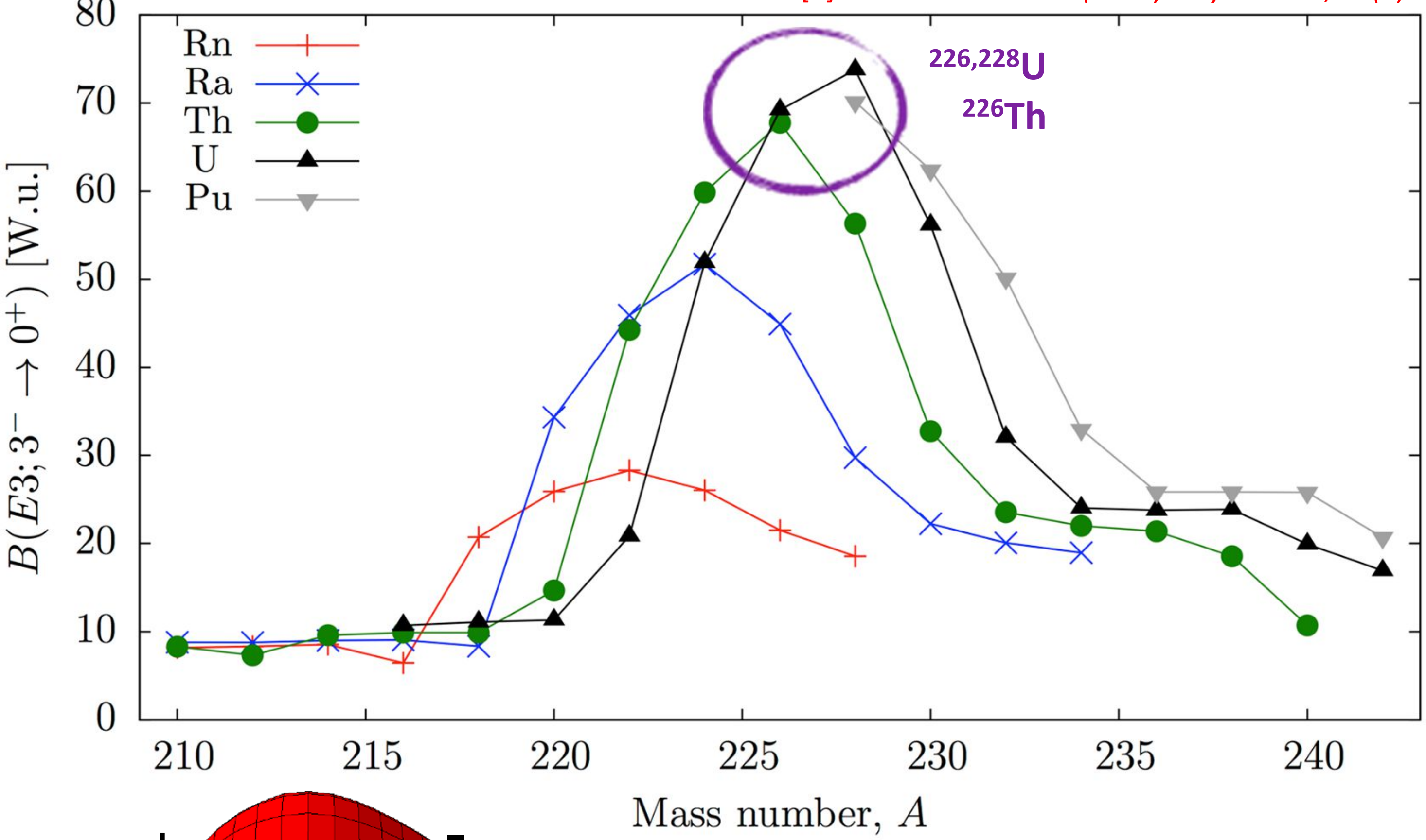


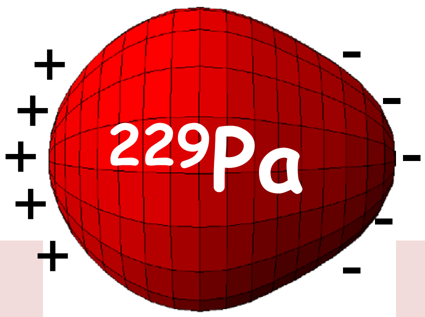




Most of these nuclei need to be characterized

[1] Robledo & Bertsch (2011). Phys. Rev. C, ***84****(5) 54302.*





30000 more sensitive than ^{199}Hg

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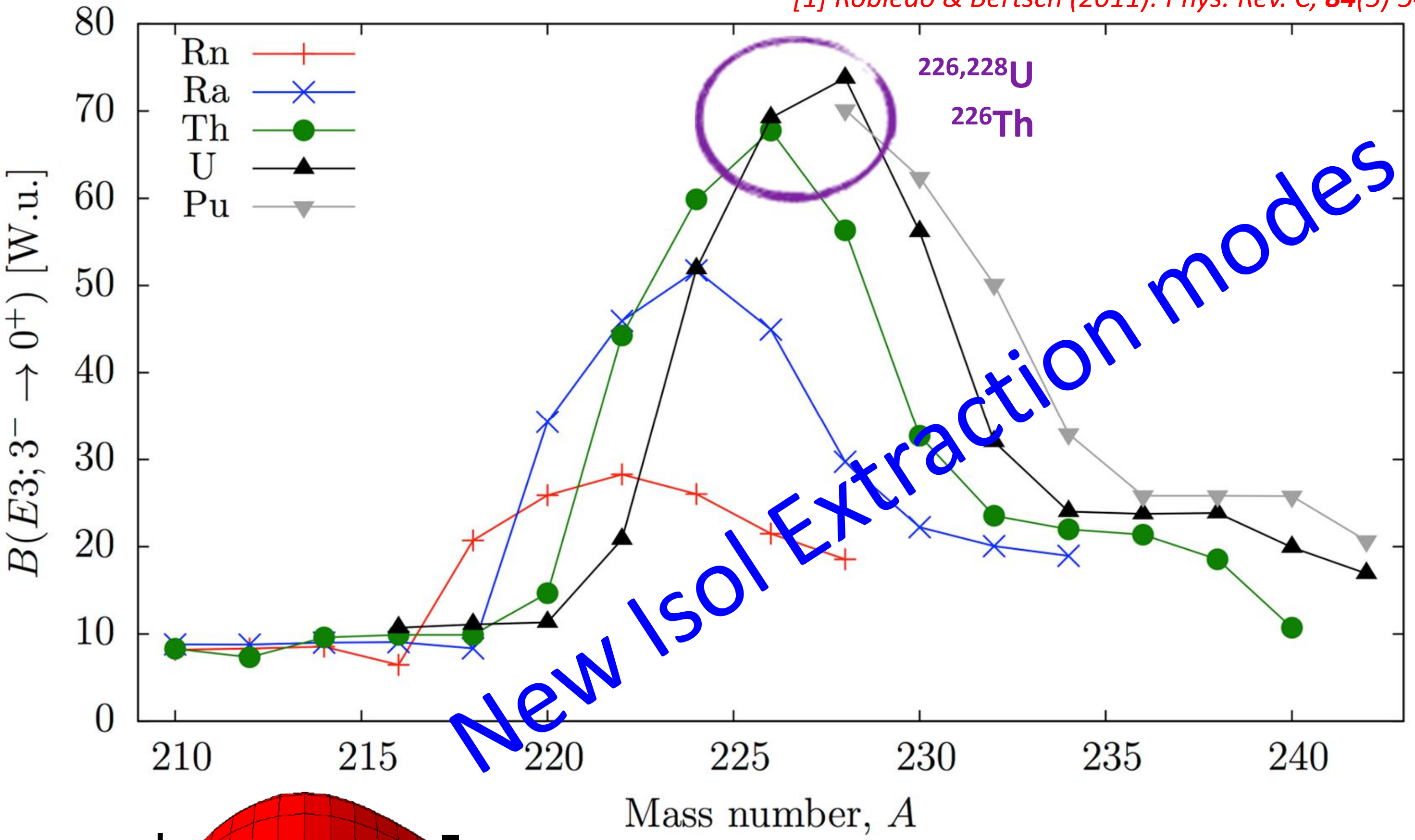
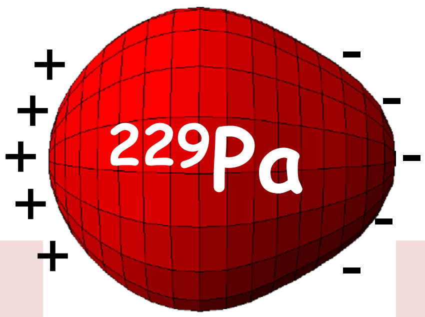
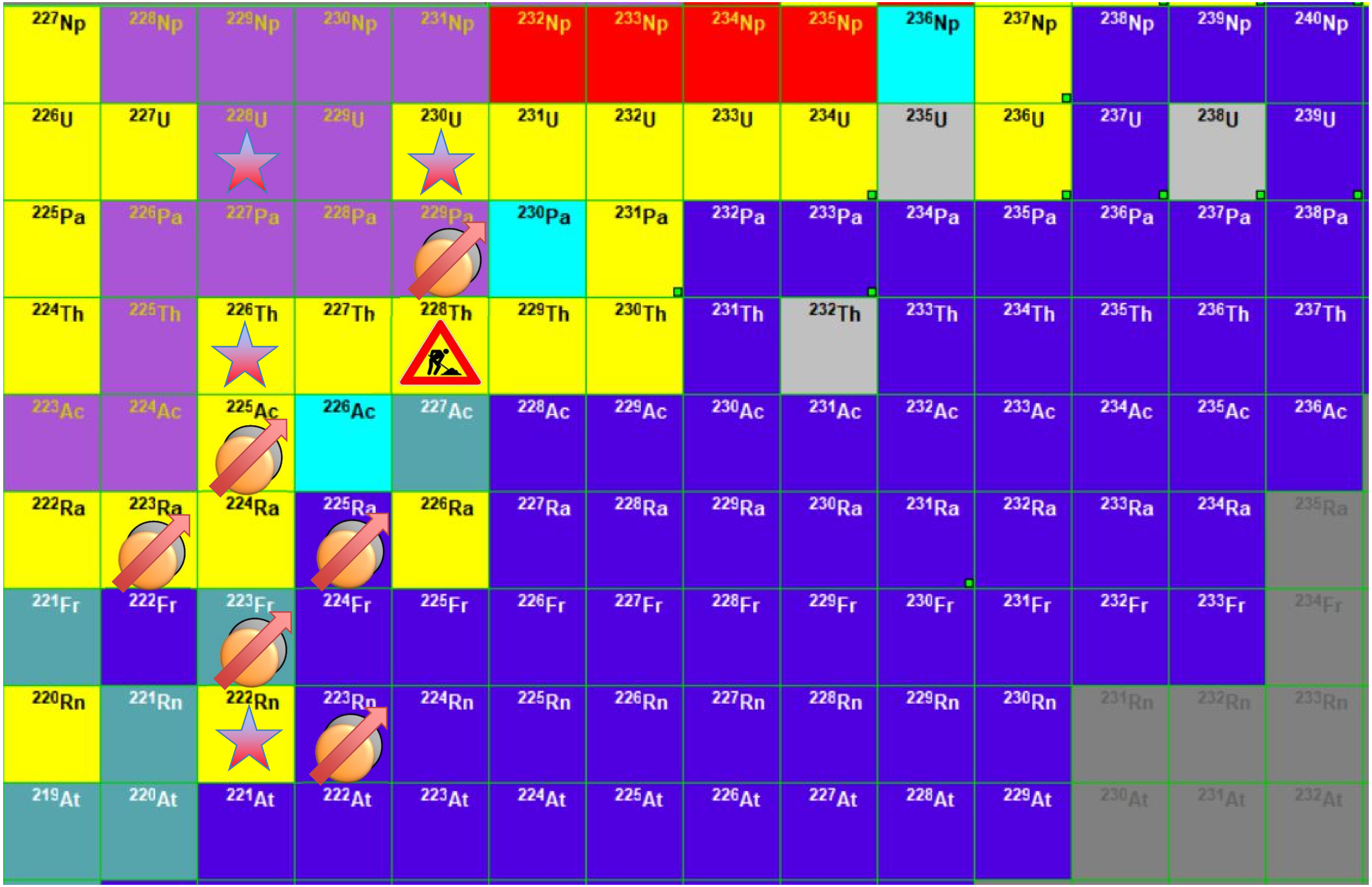




30000 more sensitive than ^{199}Hg

Spectroscopy of “EDM” isotopes
+ Coulex or (p,p’) of even-even



Level density in Protactinium

^{229}Pa: Previously studied w/ ^{231}Pa(p,t)
→ (p,p')?

→ Internal conversion coefficients for J^{π} assignment

A.I. Levon et al./Nuclear Physics A 576 (1994) 267–307

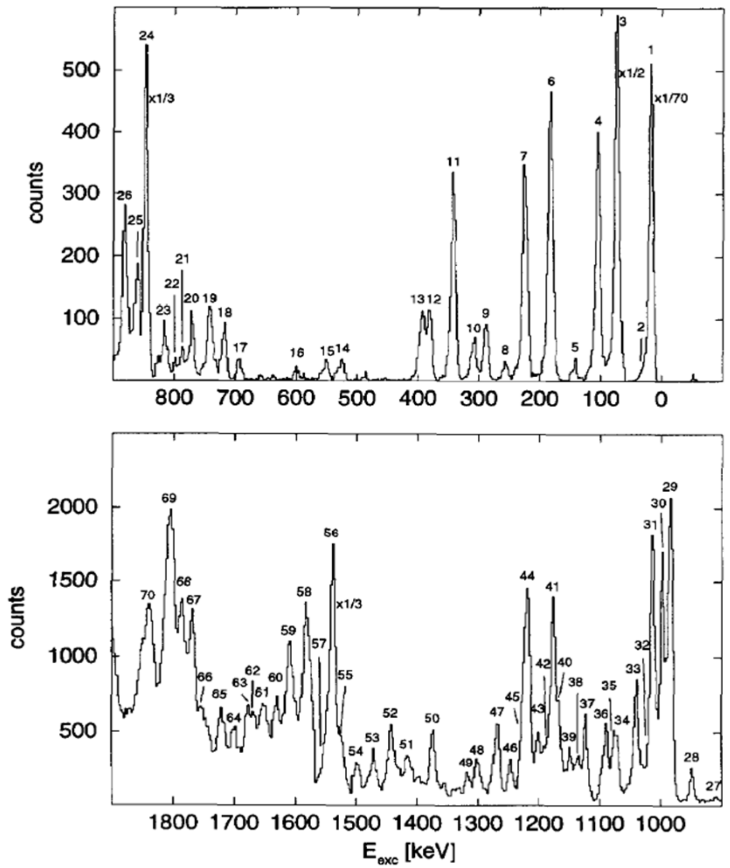
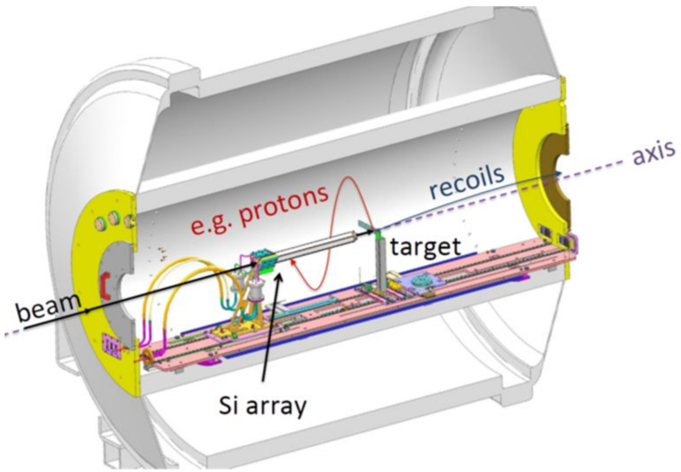
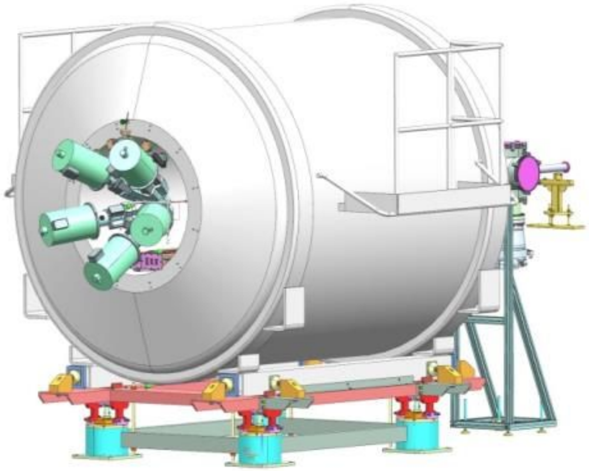
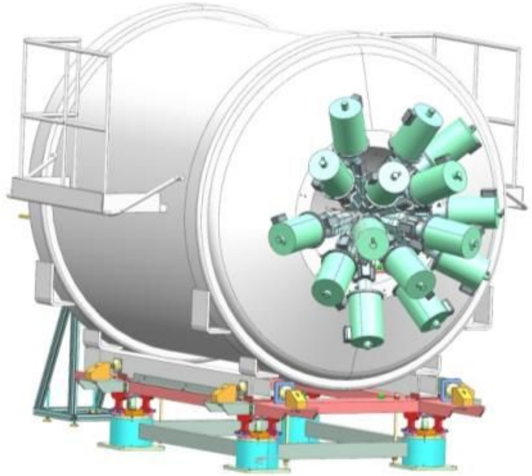


Fig. 1. Triton spectrum from the ^{231}Pa(p,t)^{229}Pa reaction at E_p = 22 MeV and θ = 45°. The peaks are numbered according to Table 1.

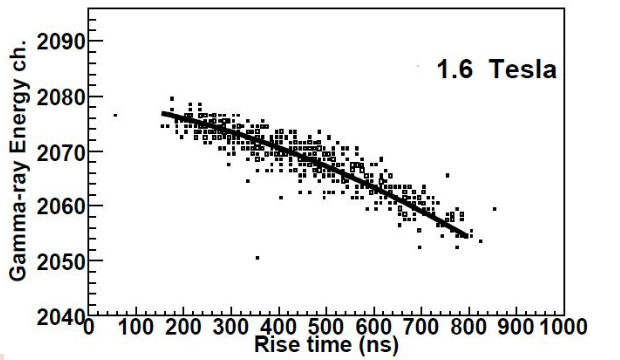
Superconducting Solenoid + Germaniums



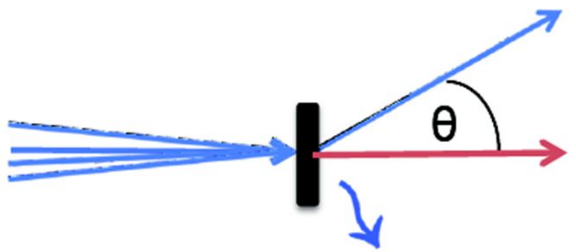




- Helios-like superconducting solenoid
- Add germanium detectors
  - Proper signal treatment is needed



Superconducting Solenoid



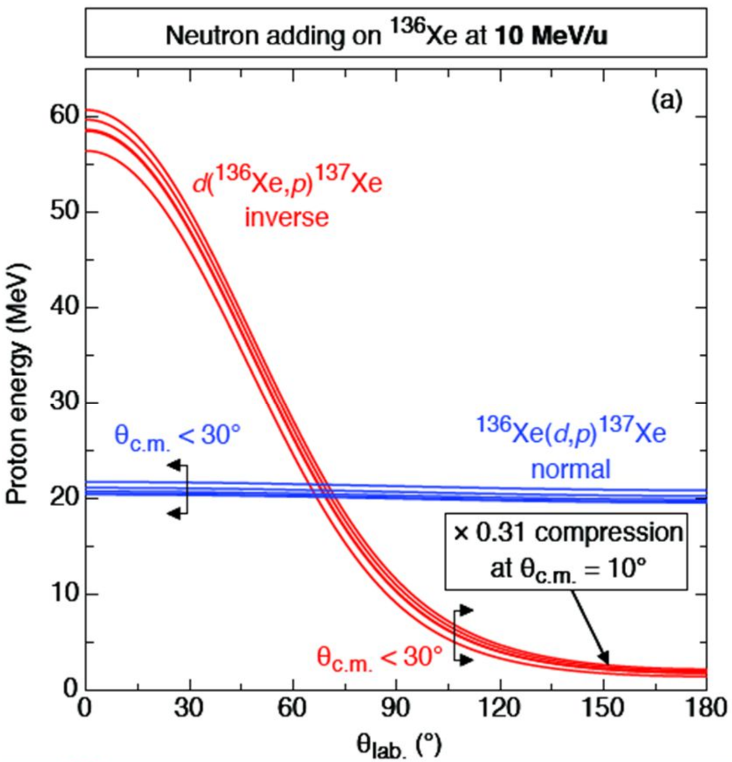
$$m_1 + m_2 = m_3 + m_4$$

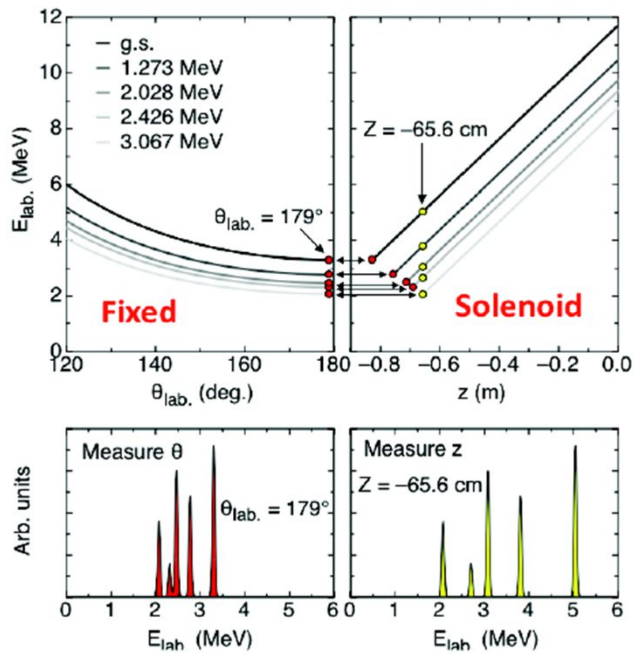
$$Q = \left(1 + \frac{m_3}{m_4}\right) E_{obs} - \left(1 - \frac{m_1}{m_4}\right) E_{lab} - \frac{2}{m_4} (m_1 m_3 E_{obs} E_{lab})^{1/2} \cos \psi_3 . \qquad (59)$$

D. K. Sharp
The University of Manchester, UK

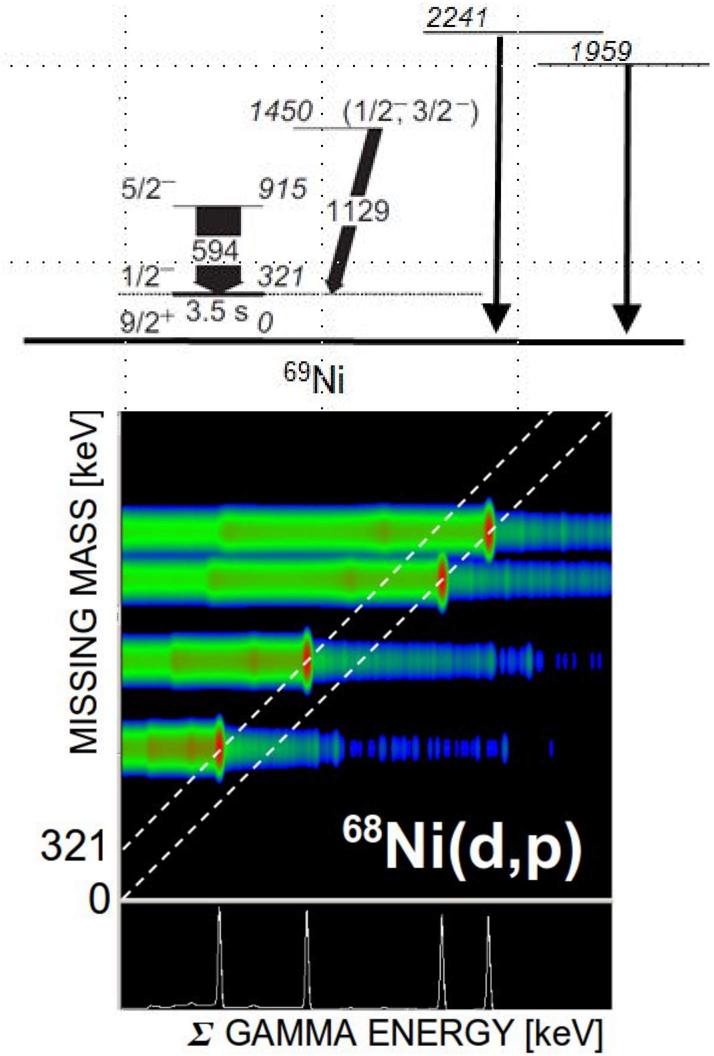
ISOLDE Workshop
7th-9th December 2016

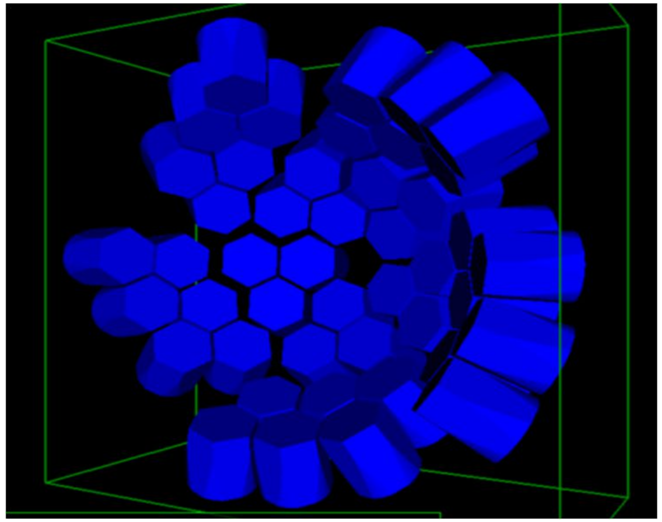
$$E_{\rm cm} = E_{\rm lab} + \frac{mV_{\rm cm}^2}{2} - \frac{mzV_{\rm cm}}{T_{\rm cyc}}$$

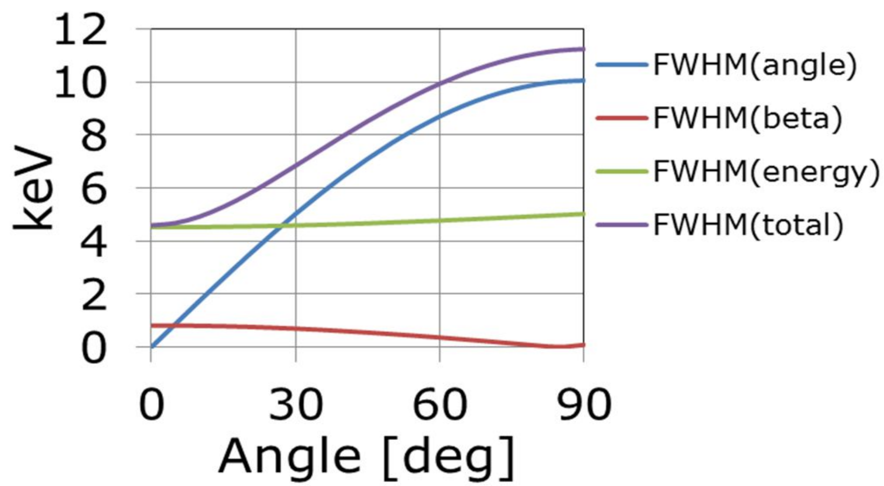




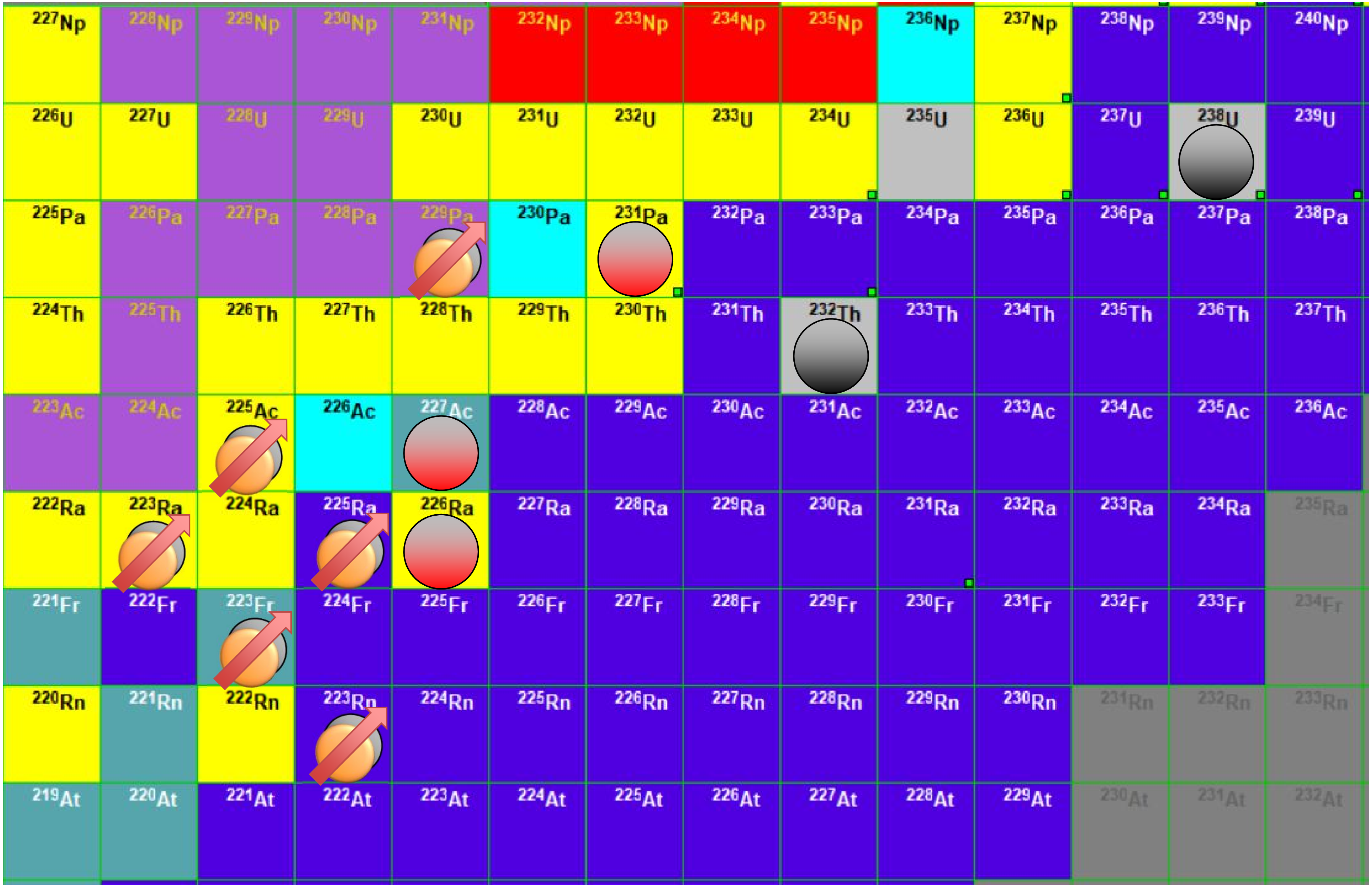
Superconducting Solenoid + Germaniums







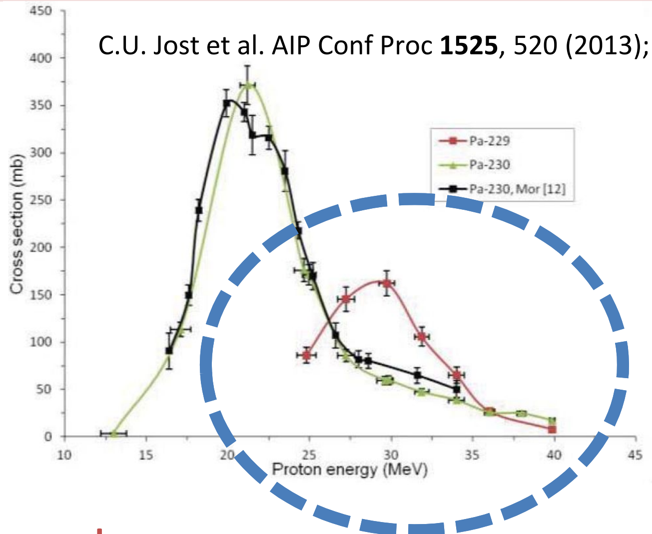
Production of nuclei for EDM studies at SPES



Production at SPES

- $^{232}ThO_2$ target
  - p(40 MeV)+^{232}Th→ **^{229}Pa 150 mbarn**
  - p(70MeV)+^{232}Th→ ^{225}Ac 10 mbarn
  - p(70MeV)+^{232}Th→ ^{223}Rn 15 µbarn

C.U. Jost et al. AIP Conf Proc **1525**, 520 (2013);



RIB Facilities:
Estimated intensity at
- FRIB ^{225}Ra: 6x10^{9} s^{-1}
- HIE-ISOLDE ^{223}Fr: 2x10^{9} s^{-1}
- SPES ^{229}Pa by ^{232}Th(p,4n): 10^{9} s^{-1}
if extraction efficiency 0.05

- ^{226}Ra target
  - p(15 MeV)+^{226}Ra→ **^{225}Ac 700 mbarn**
    - Batch mode: τ = 10 days
  - p(70MeV)+^{226}Ra→ ^{223}Fr 3 mbarn
  - p(70MeV)+^{226}Ra→ ^{223}Rn 100 µbarn

WARNING:
Cross sections to be measured

Conclusions

- Radioactive/Stable Ions
- Nuclear structure (Ex, β_2, β_3…)
- New extraction modes (ex. for Th target)
- Trap and orientation developments
- New instrumentation