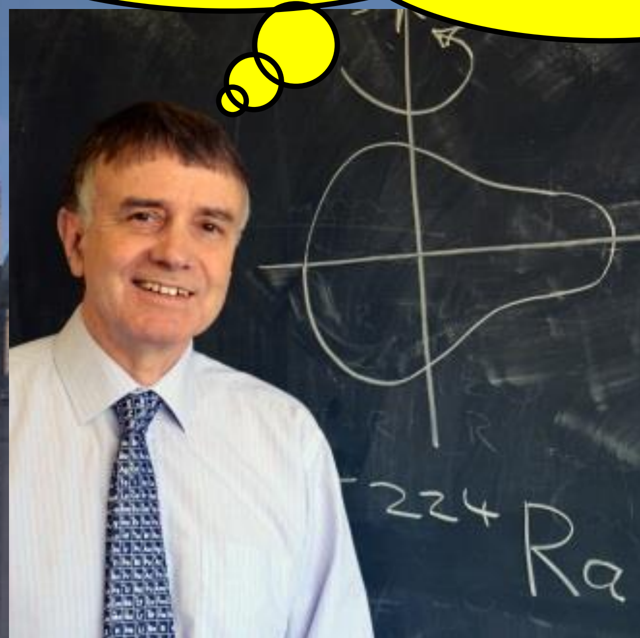
Measurement of $B(E3, 0^+ \rightarrow 3^-)$ strength in strongly octupole-correlated nuclei near ^{224}Ra

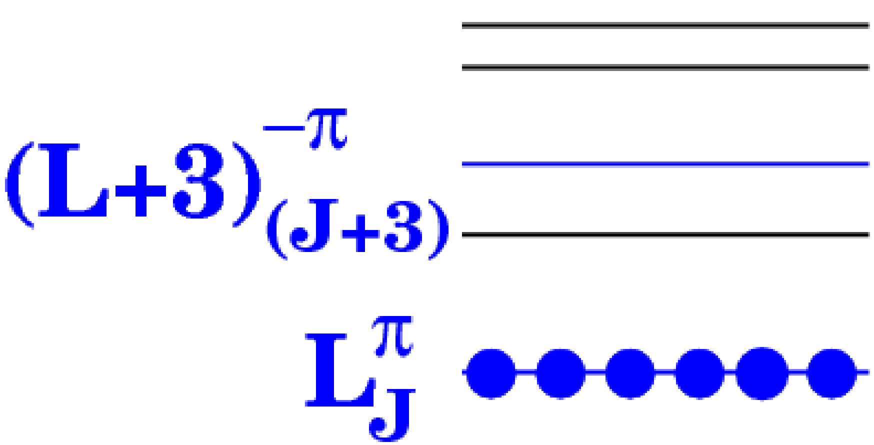


Marcus Scheck, Liam P. Gaffney
University of the West of Scotland
Peter A. Butler
Liverpool University
for the
IS475, IS552, &IS553
collaborations

Reflections on the atomic nucleus
Liverpool 2015

Octupole collectivity
- microscopic -

Nuclear shell structure



Octupole collectivity
- microscopic -

Nuclear
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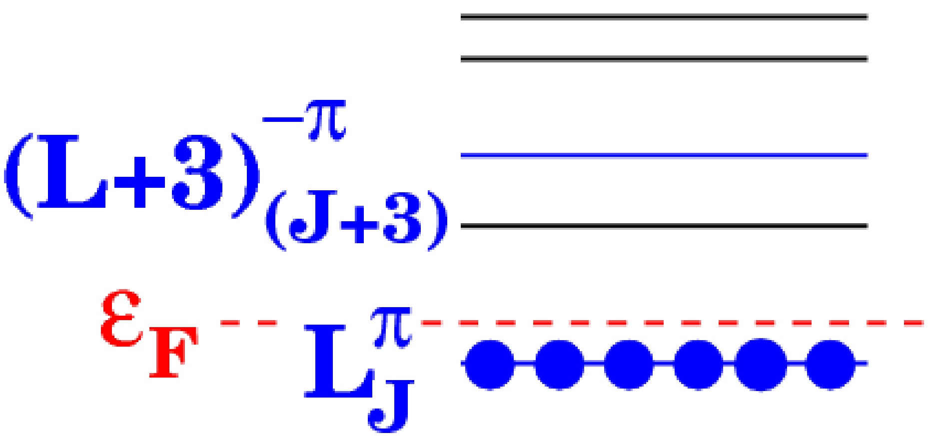
$E_L < \varepsilon_F < E_{L+3}$



Octupole collectivity
- microscopic -

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Nuclear shell structure

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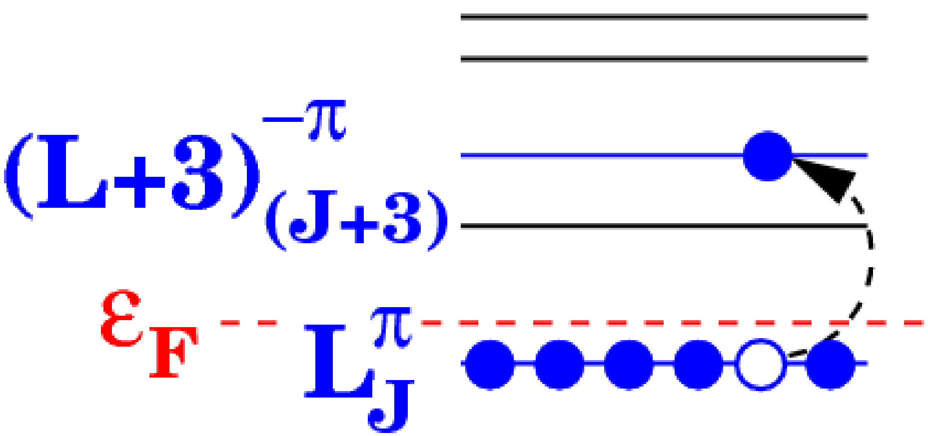
$\Delta E = E_{L+3} - E_L \ll$

⇒**enhanced octupole collectivity**



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Octupole collectivity
- microscopic -

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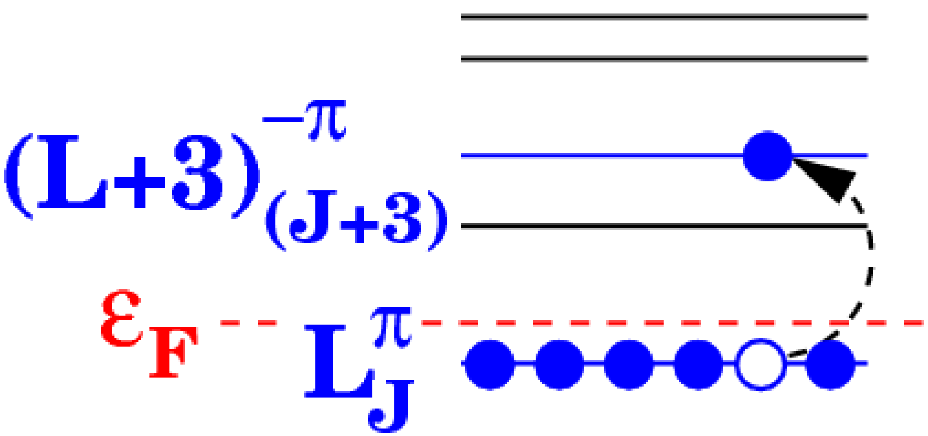

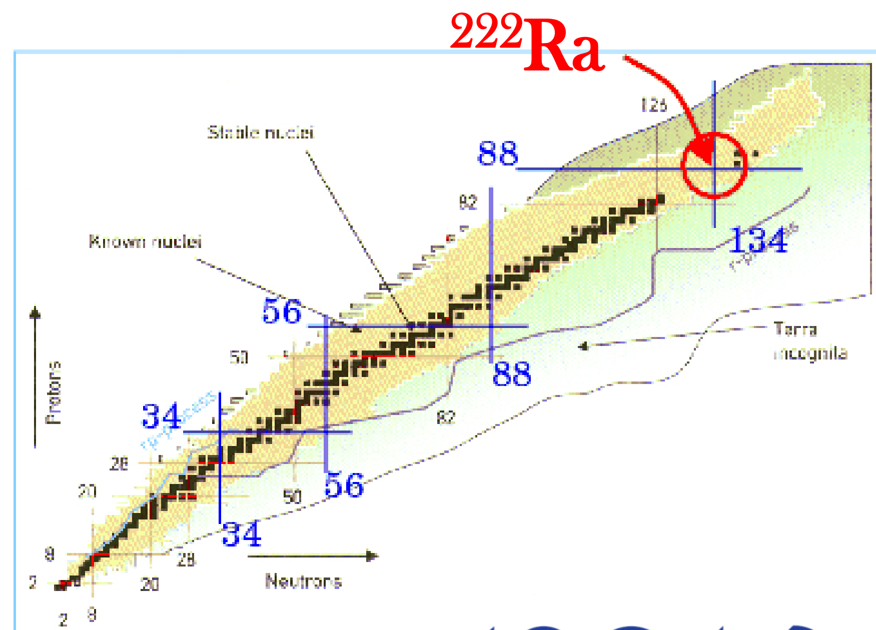

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Octupole collectivity
- macroscopic -

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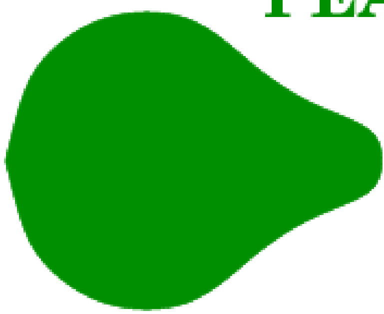
Multipole expansion of the shape:
2^L-pole and L=3 ⇒ Octupole

PEAR shape



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Octupole collectivity
- macroscopic -

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Reflection Asymmetric

Octupole collectivity - macroscopic -

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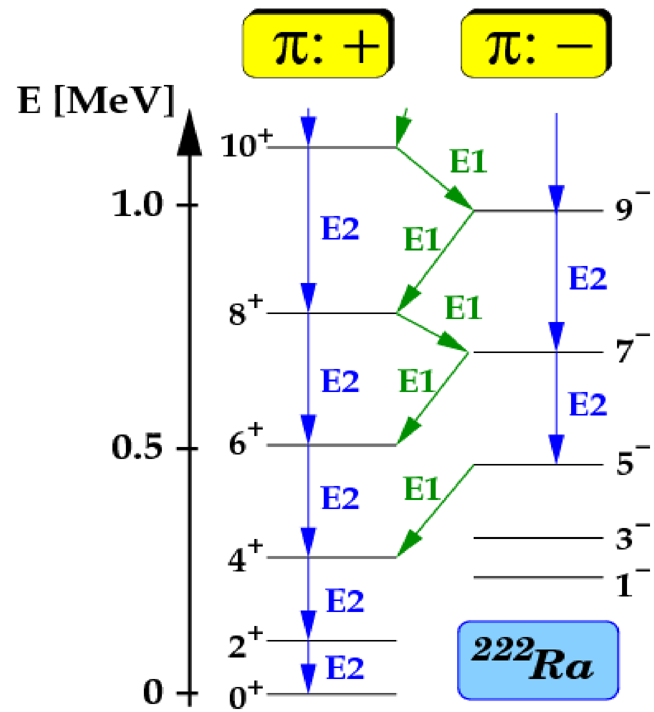
Peter's previous work:

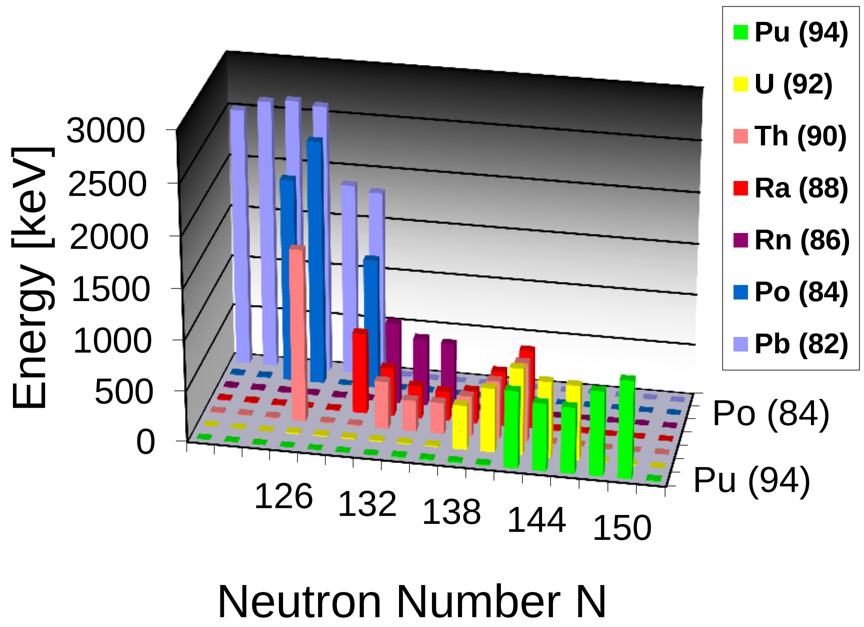


J.F.Cocks et al., PRL 78, 2920 (1997)

ISOLDE

Experimental observables E_{3^-} and $B(E3, 0^+ \mapsto 3^-)$

Excitation energy E_{3^-}



T.Kibédy & R.H.Spear, At. Data and Nucl. Data tables 80 (2002) 35

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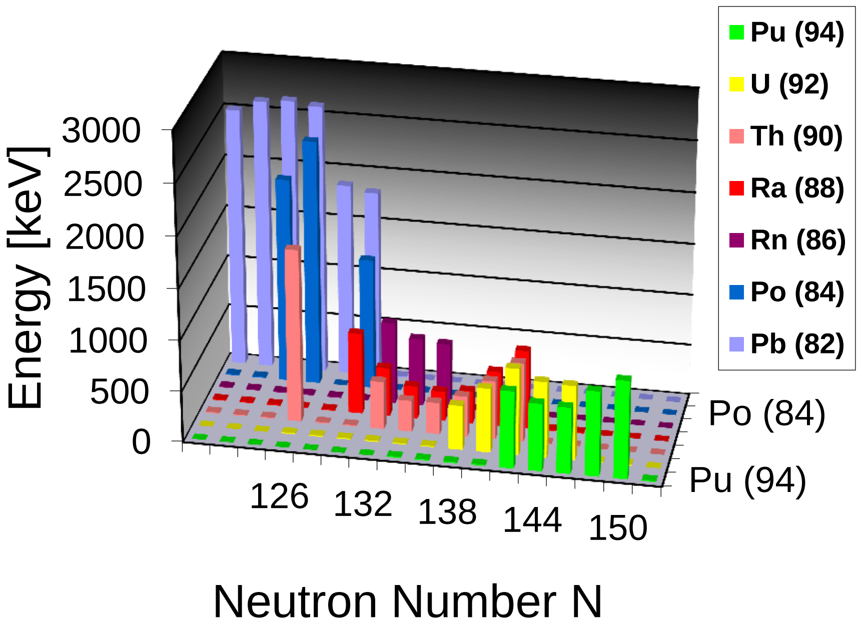
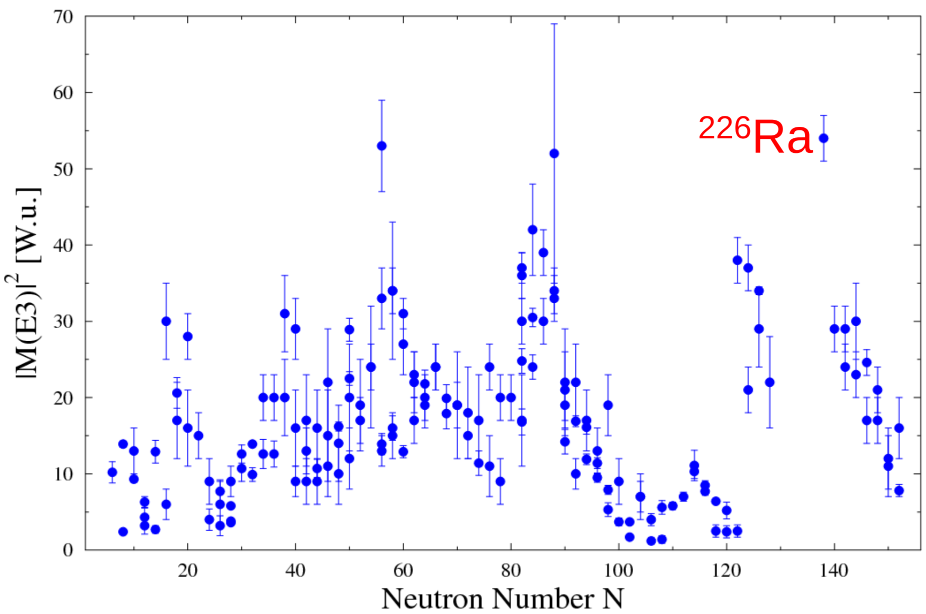


B(E3, $0^+ \mapsto 3^-$)-strength



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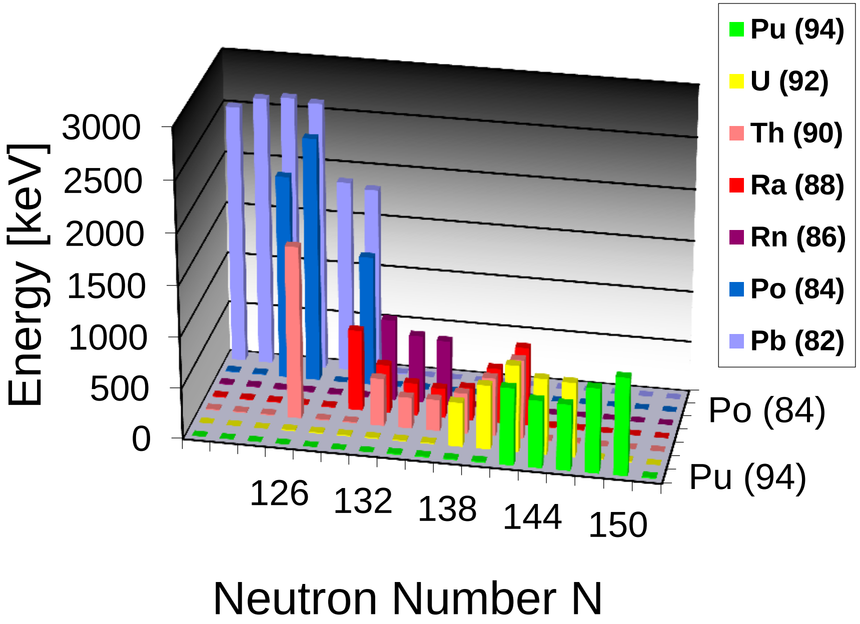
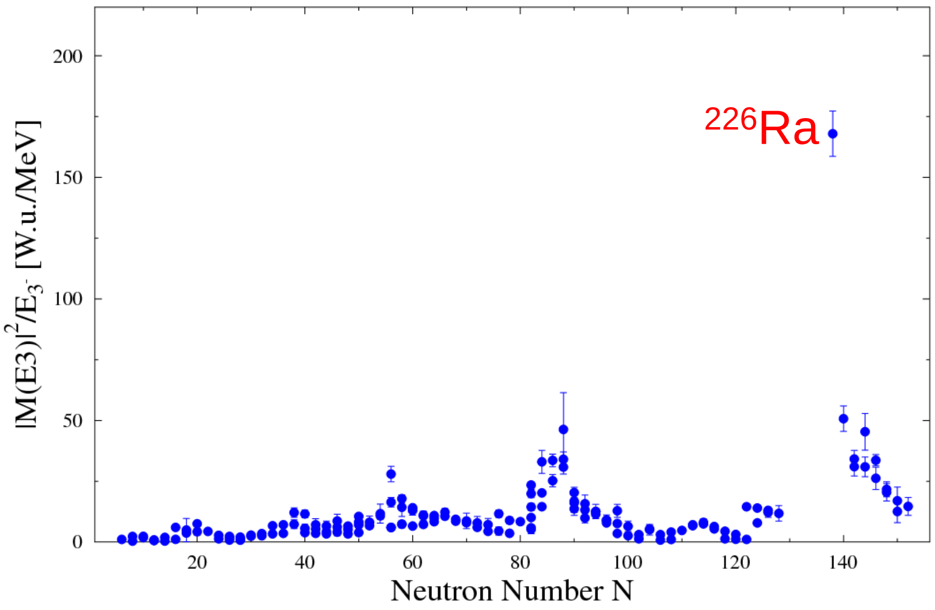


Inverse sum rule: $B(E3)/E_{3^-}$



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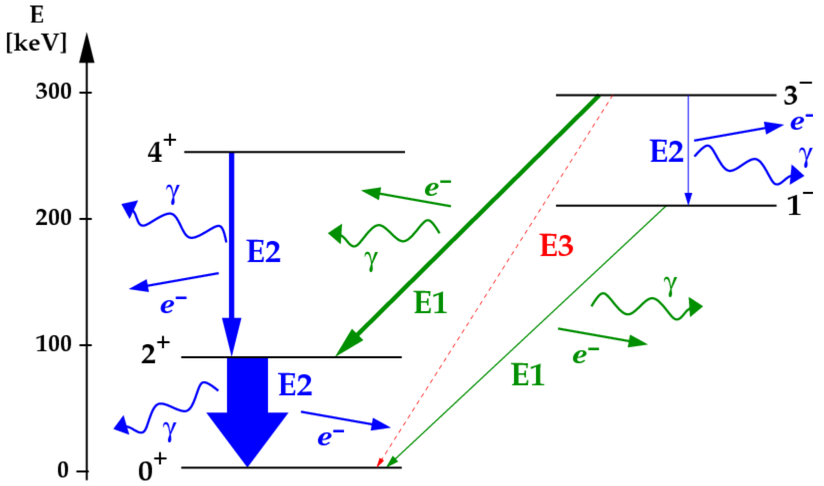
Why CoulEx?

De-excitation process



Why CoulEx?

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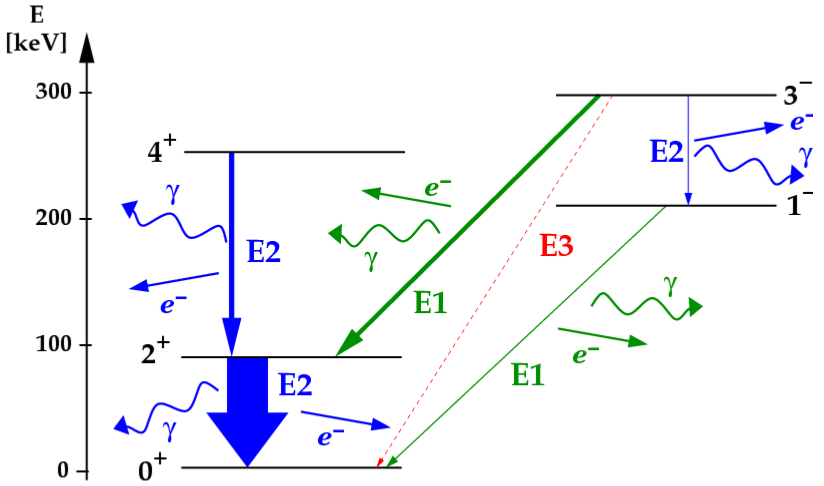

E1 10^4-10^6x more probable

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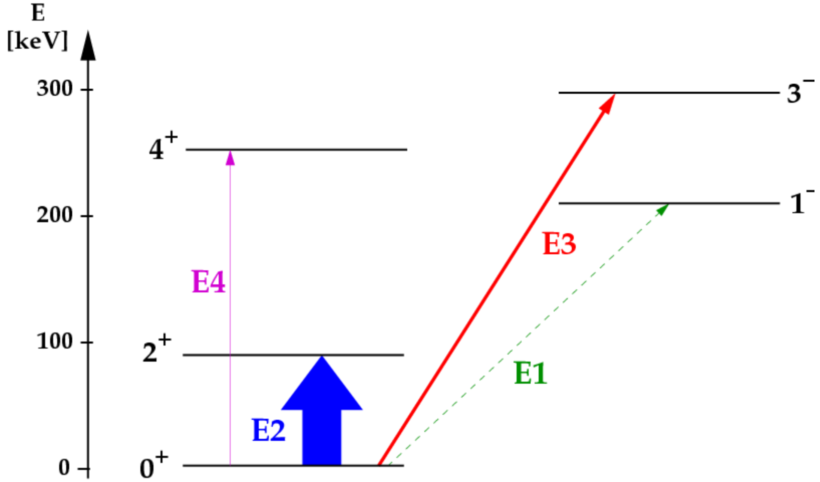
Why CoulEx?

Excitation process (first order)



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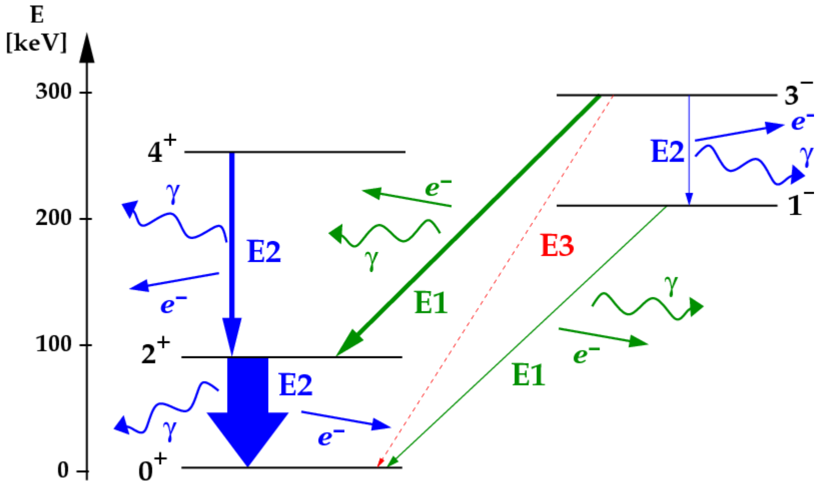

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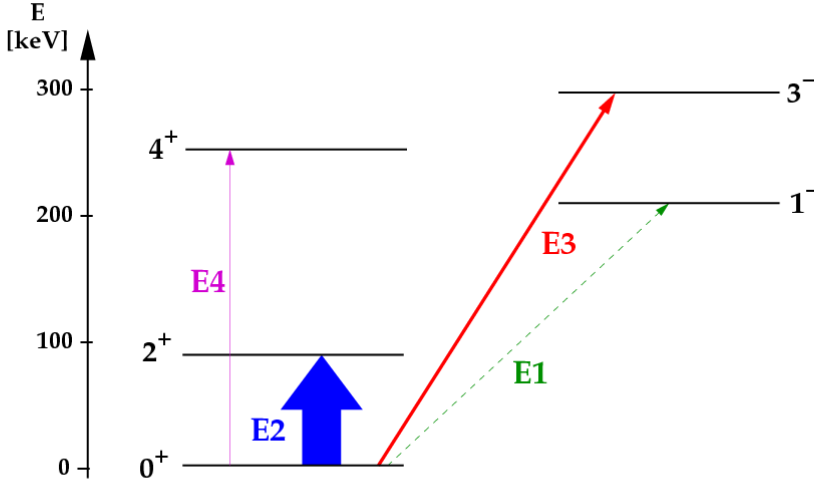

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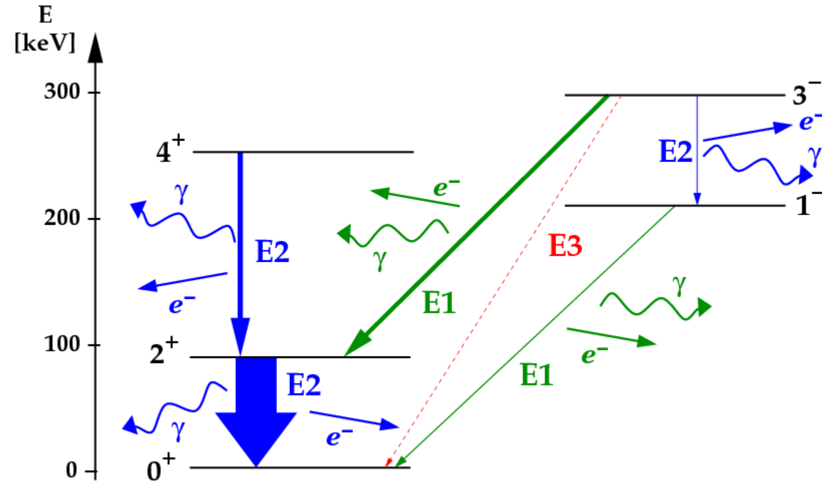


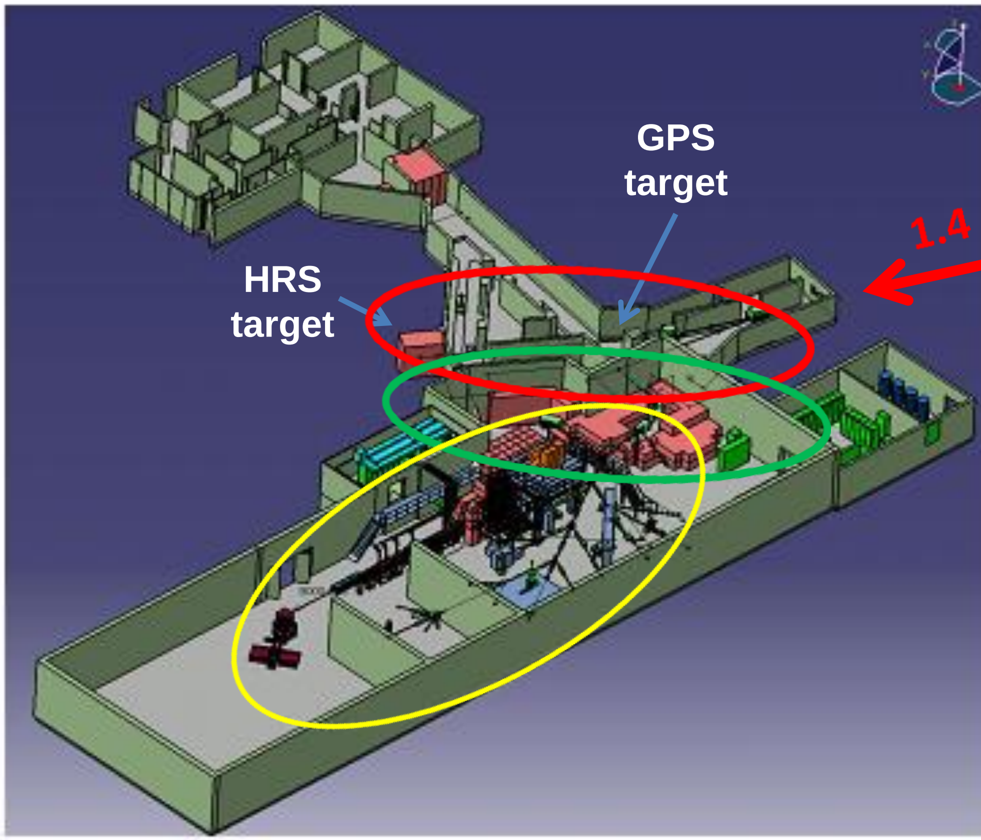
E1 10^4-10^6x more probable

Principle:

Populate 3^- level with E3 in Coulex ⇒ observe E1(and E2) decay γ ray(s)

ISOLDE @ CERN

ISOL ↦ **IS**otope **O**n**L**ine separation **DE**tector



$I_p \sim 2\ \mu A$

1.4 GeV protons

CERN accelerator complex

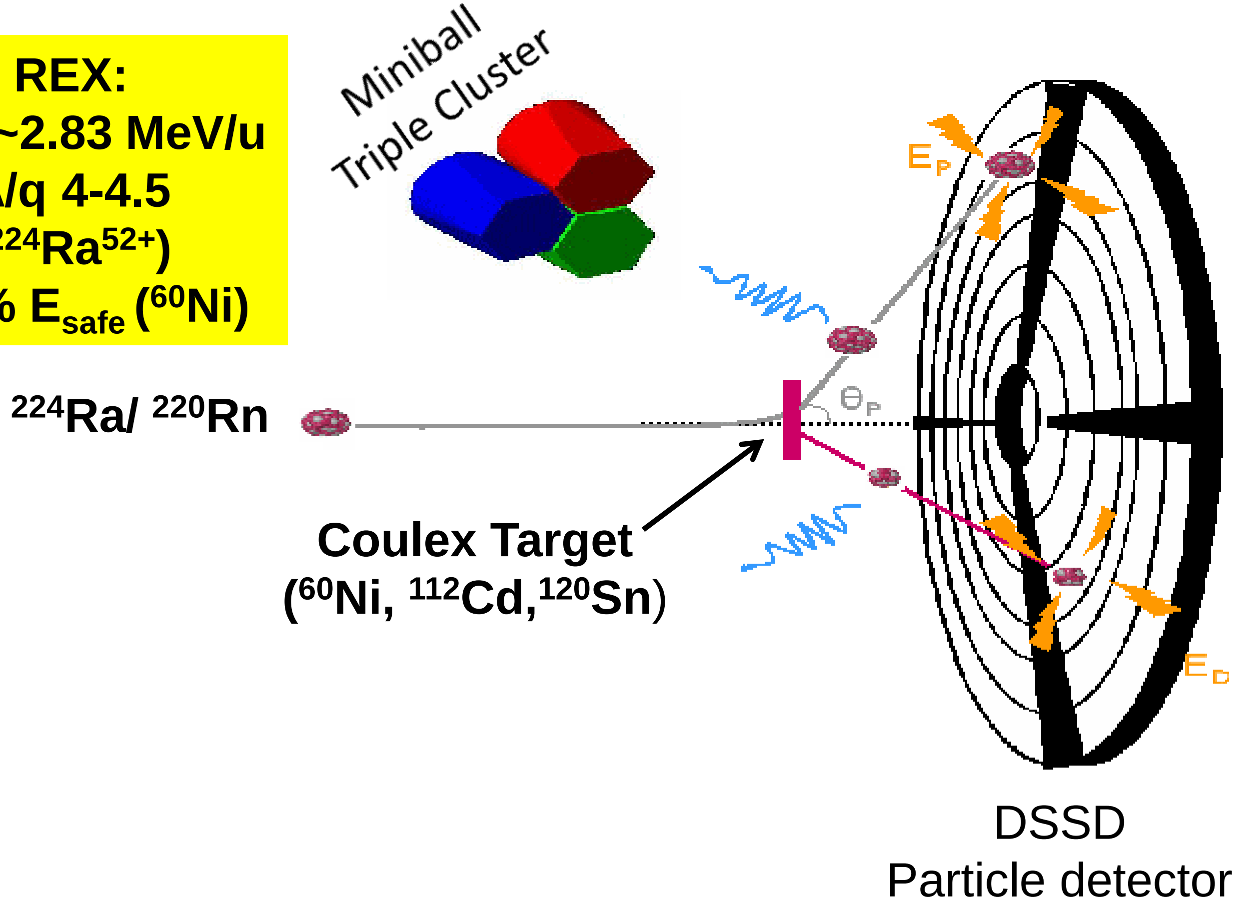
Production

Separation

Experiment

Coulomb excitation at Miniball

REX:
E_{beam}~2.83 MeV/u
A/q 4-4.5
($^{224}Ra^{52+}$)
~66% E_{safe} (^{60}Ni)



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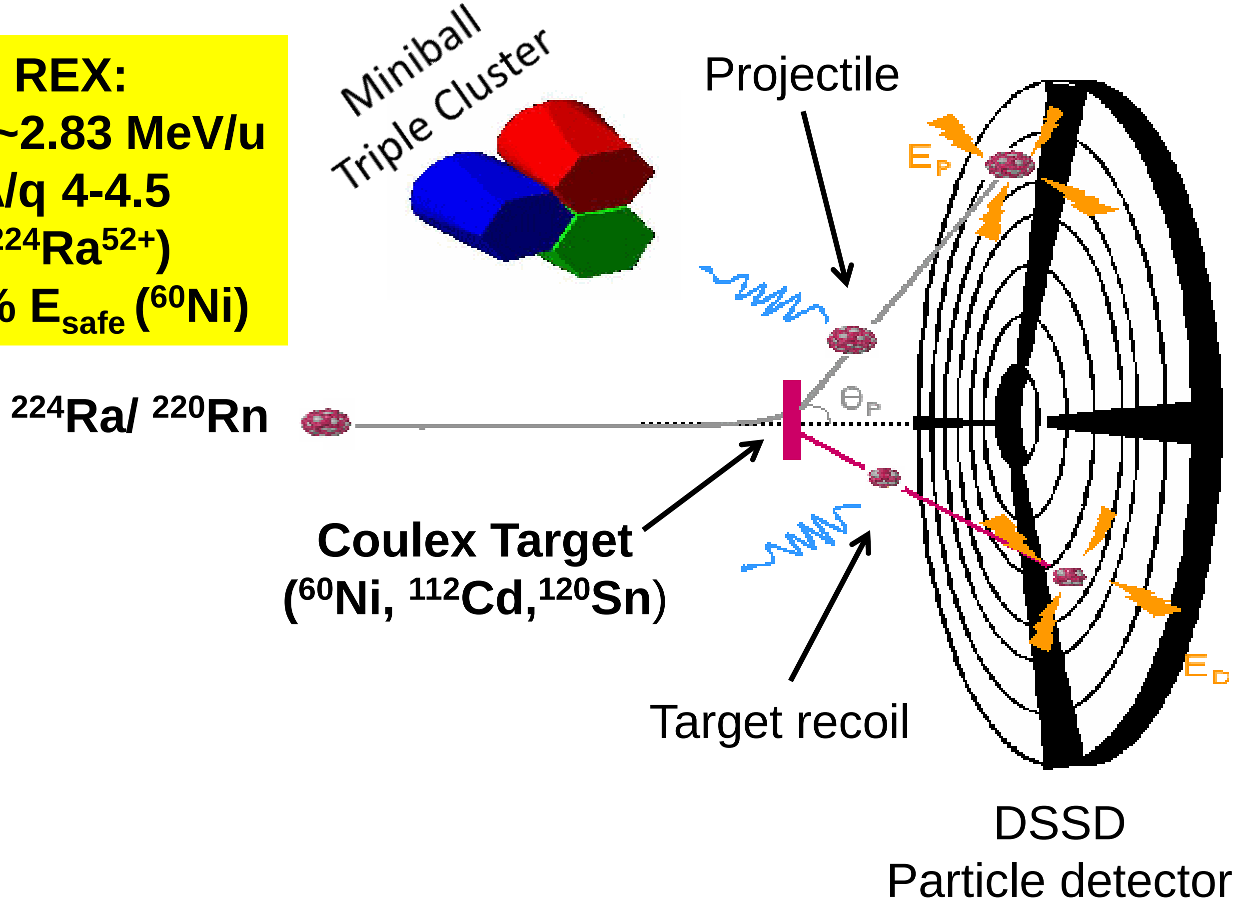

Coulomb excitation at Miniball

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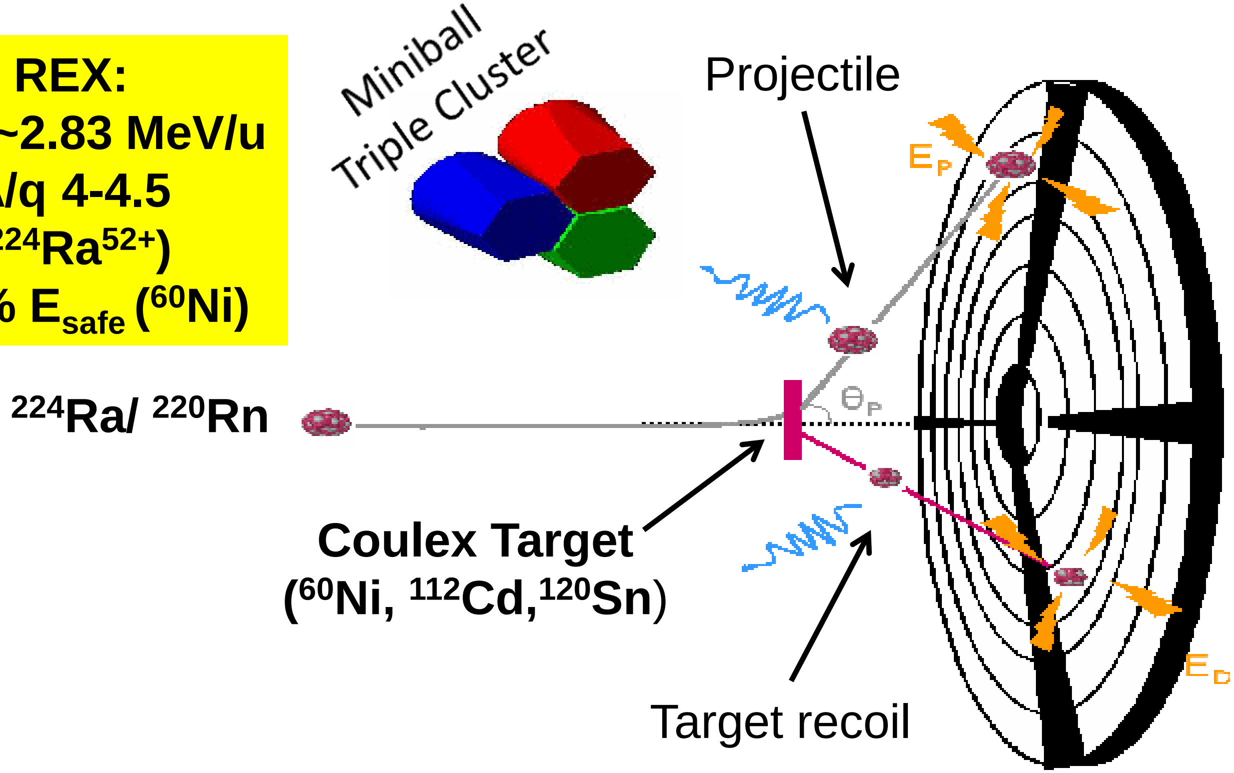

DSSD:
Angles 15º-53º
Front 16 strips
Back 24/2 strips

Miniball:
8x Triple Cluster ⇒ 24 HPGe Detectors
Solid Angle coverage: ~60% of 4π

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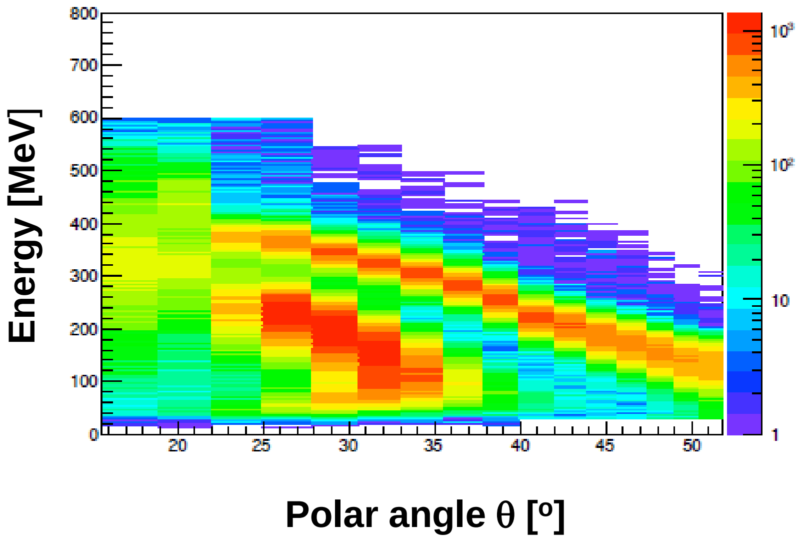
CoulEx: Experimental Info

Particle Detector:
(inverse kinematic)



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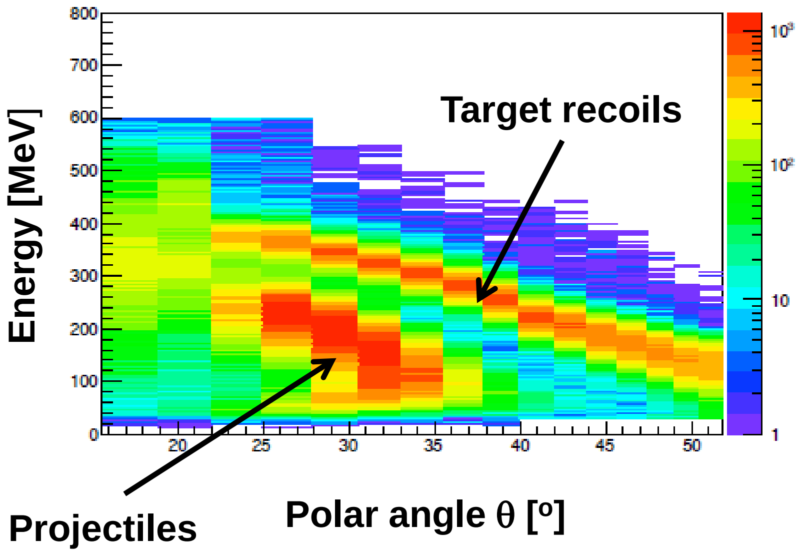

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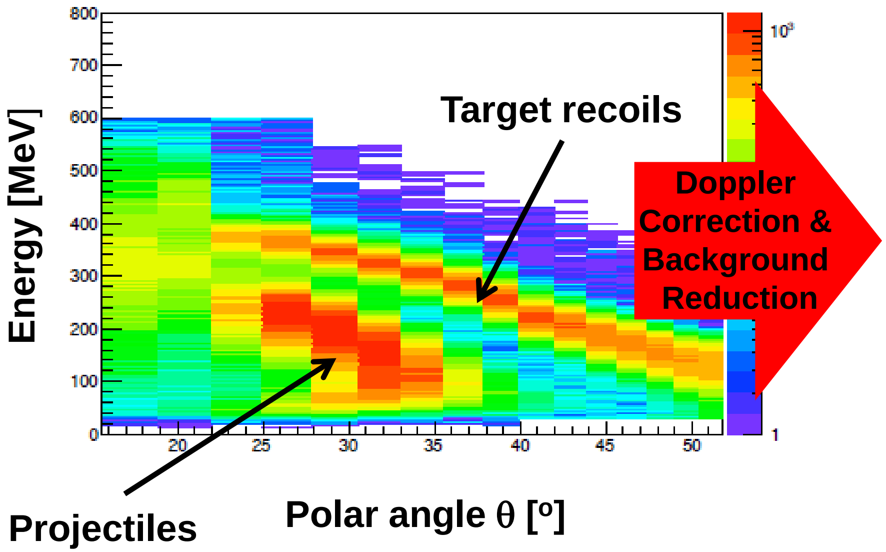
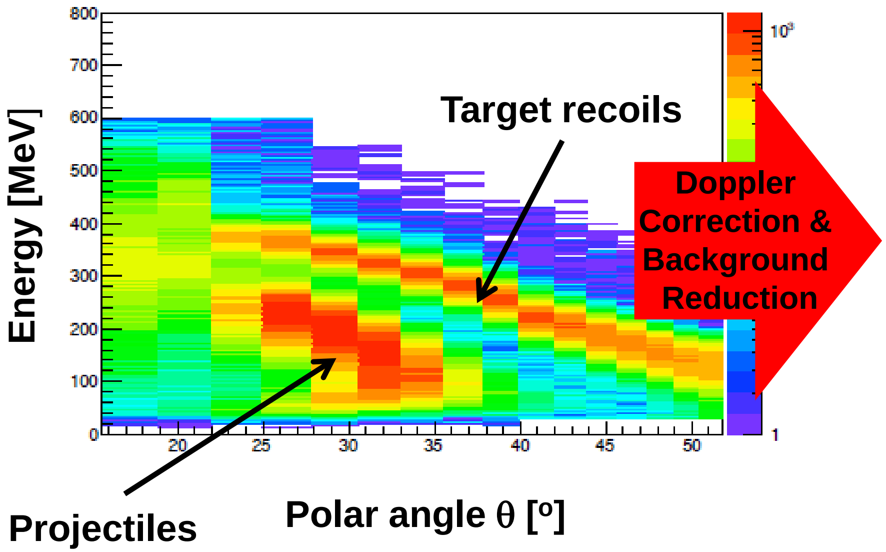
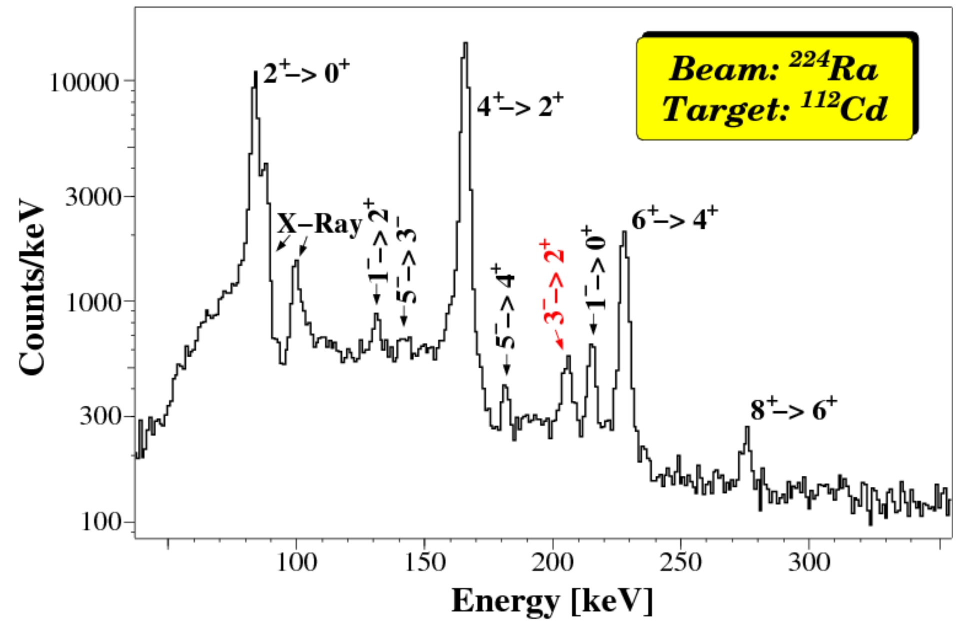


CoulEx: Experimental Info

Particle Detector: (inverse kinematic)

HPGe γ-ray Detector array





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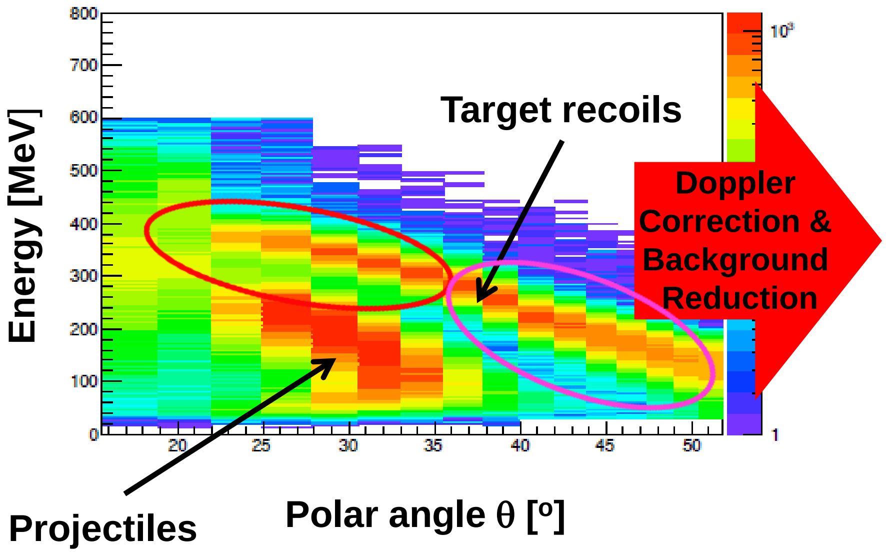
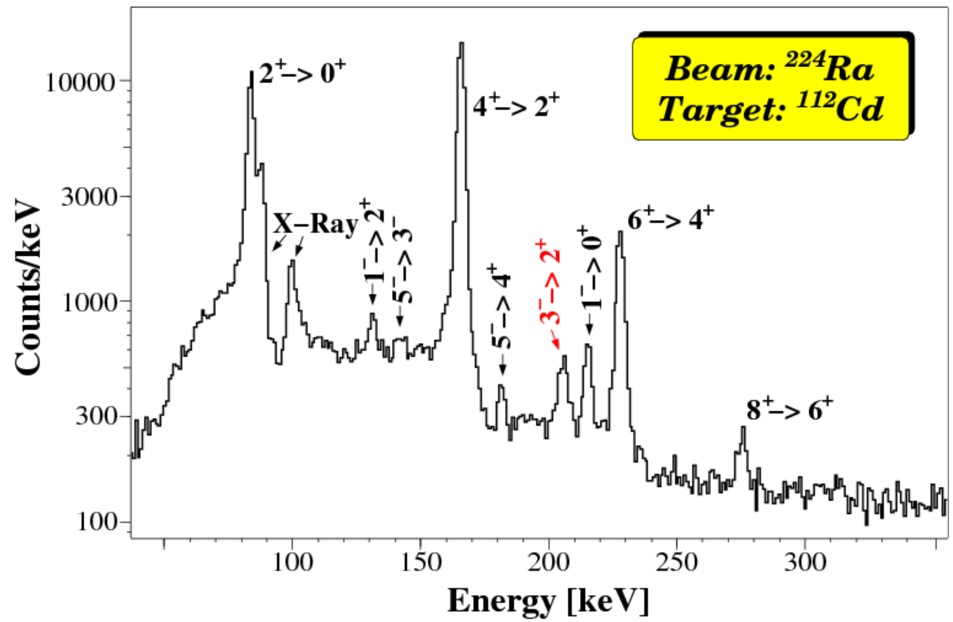


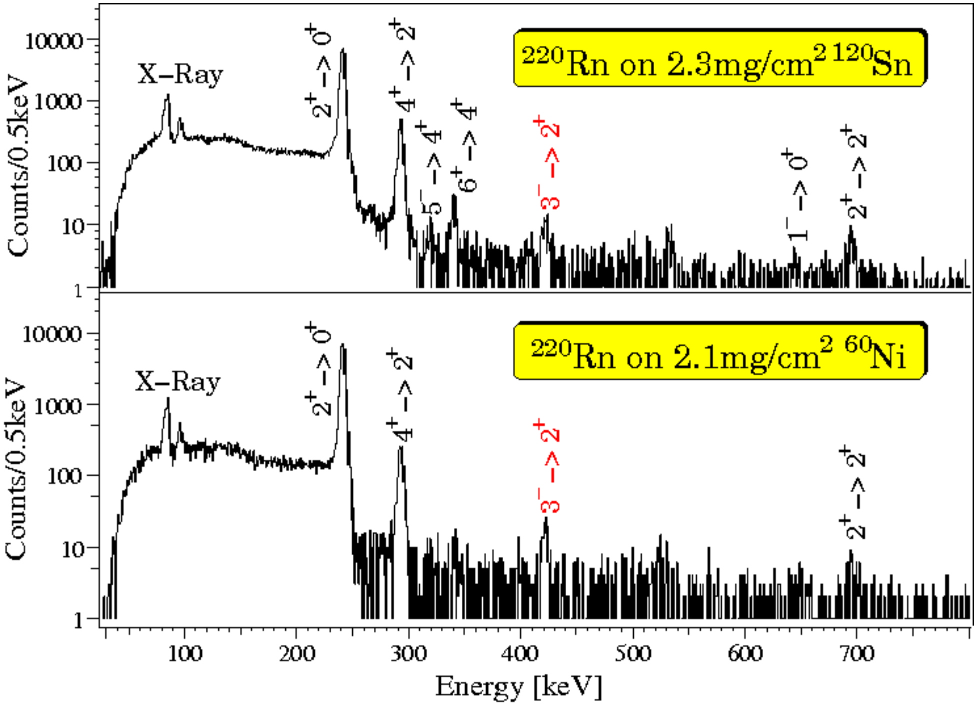


Split in 2 angular ranges

2 x 9 γ-ray yields

CoulEx: Experimental Info

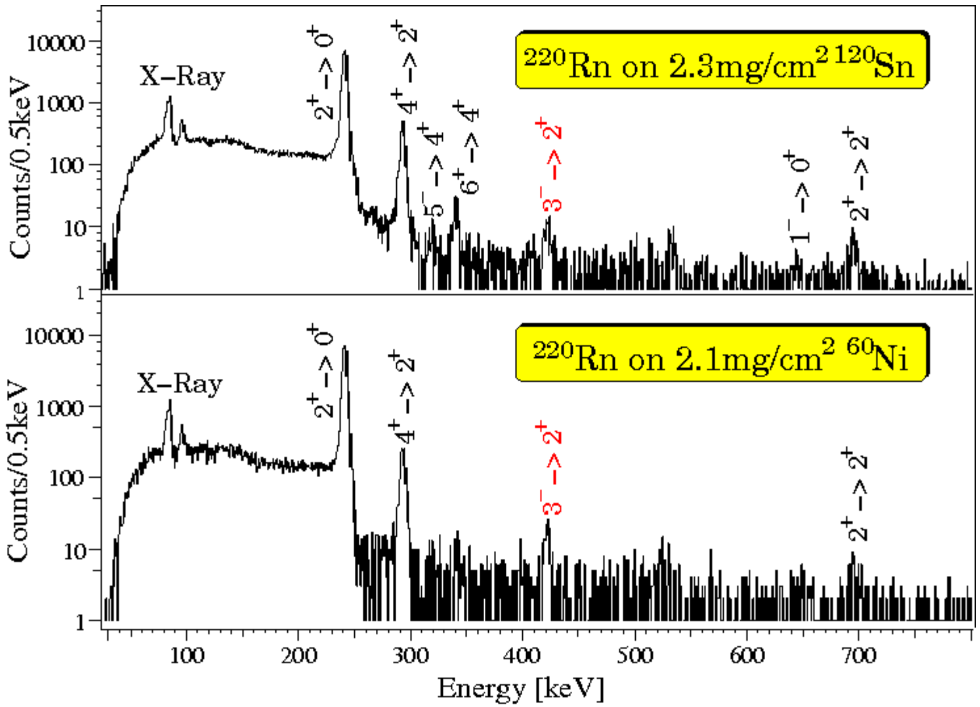
Different Targets (Z)



Disentangle one- and multi-step excitation paths

CoulEx: Experimental Info

Different Targets (Z)



Disentangle one- and multi-step excitation paths

Literature (^{224}Ra)

- Lifetimes (2x)
- Branching ratios (4x)
- Multipole mixing ratios

CoulEx: Experimental Info

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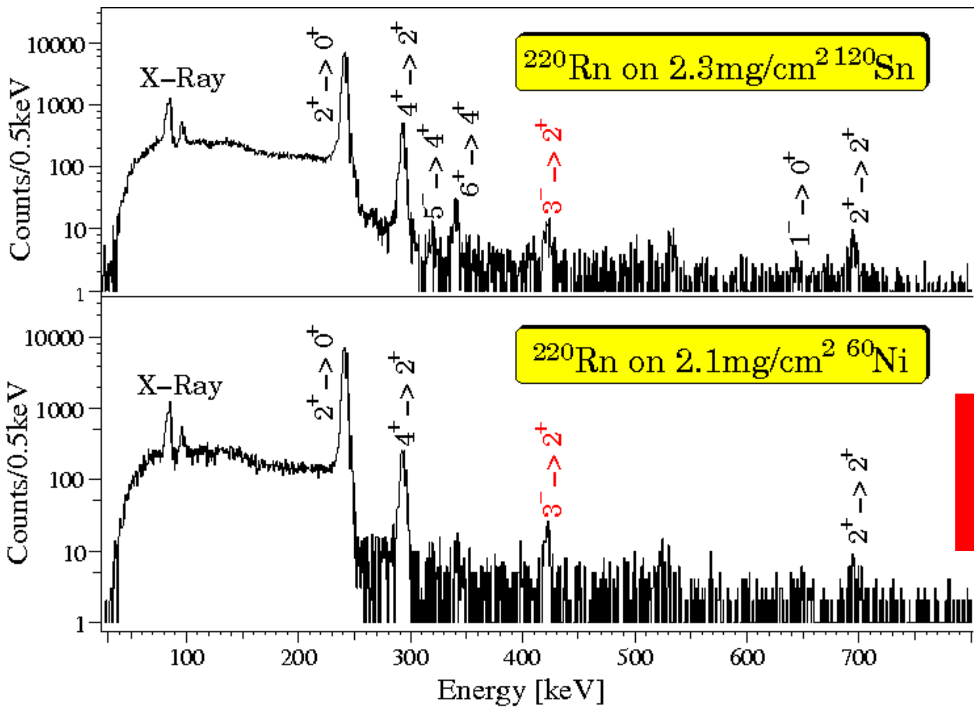

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GOSIA

ISOLDE

CoulEx: Experimental Info

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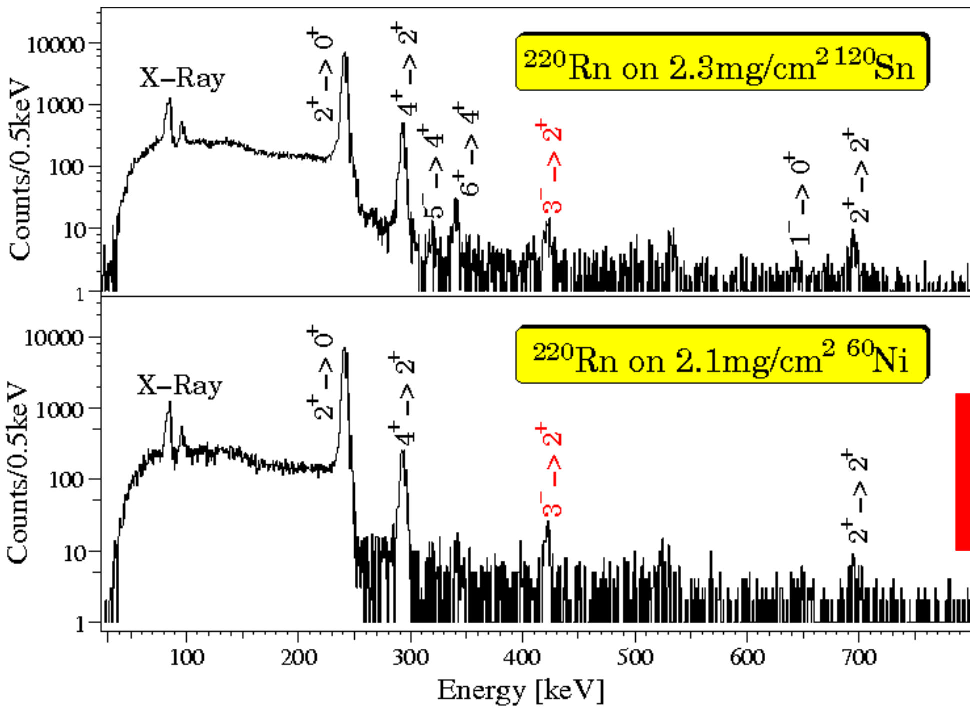

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GOSIA

Matrix elements

Decay Transitions

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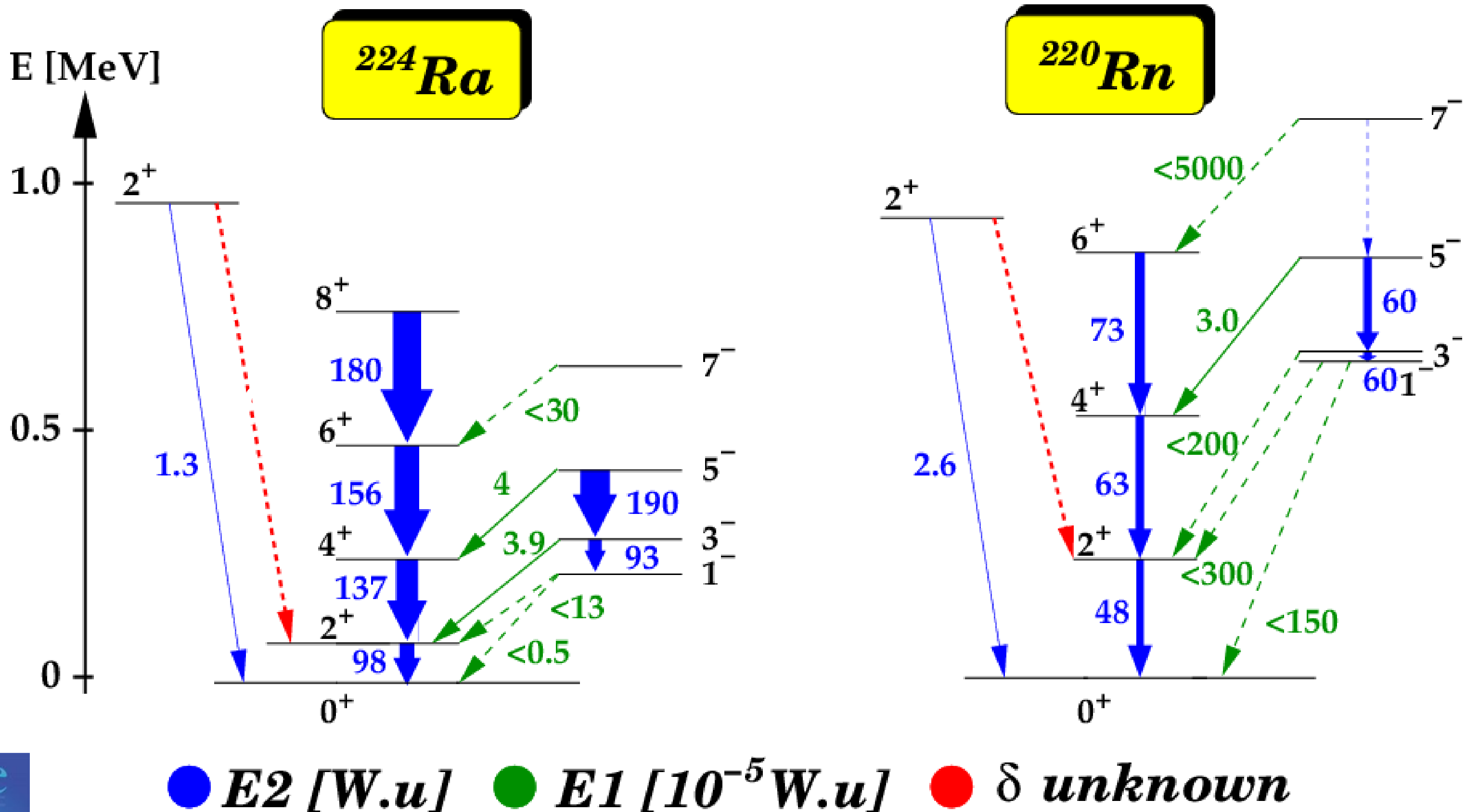

L.P. Gaffney, P.A. Butler *et al.*,
Nature **497** (2013) 199

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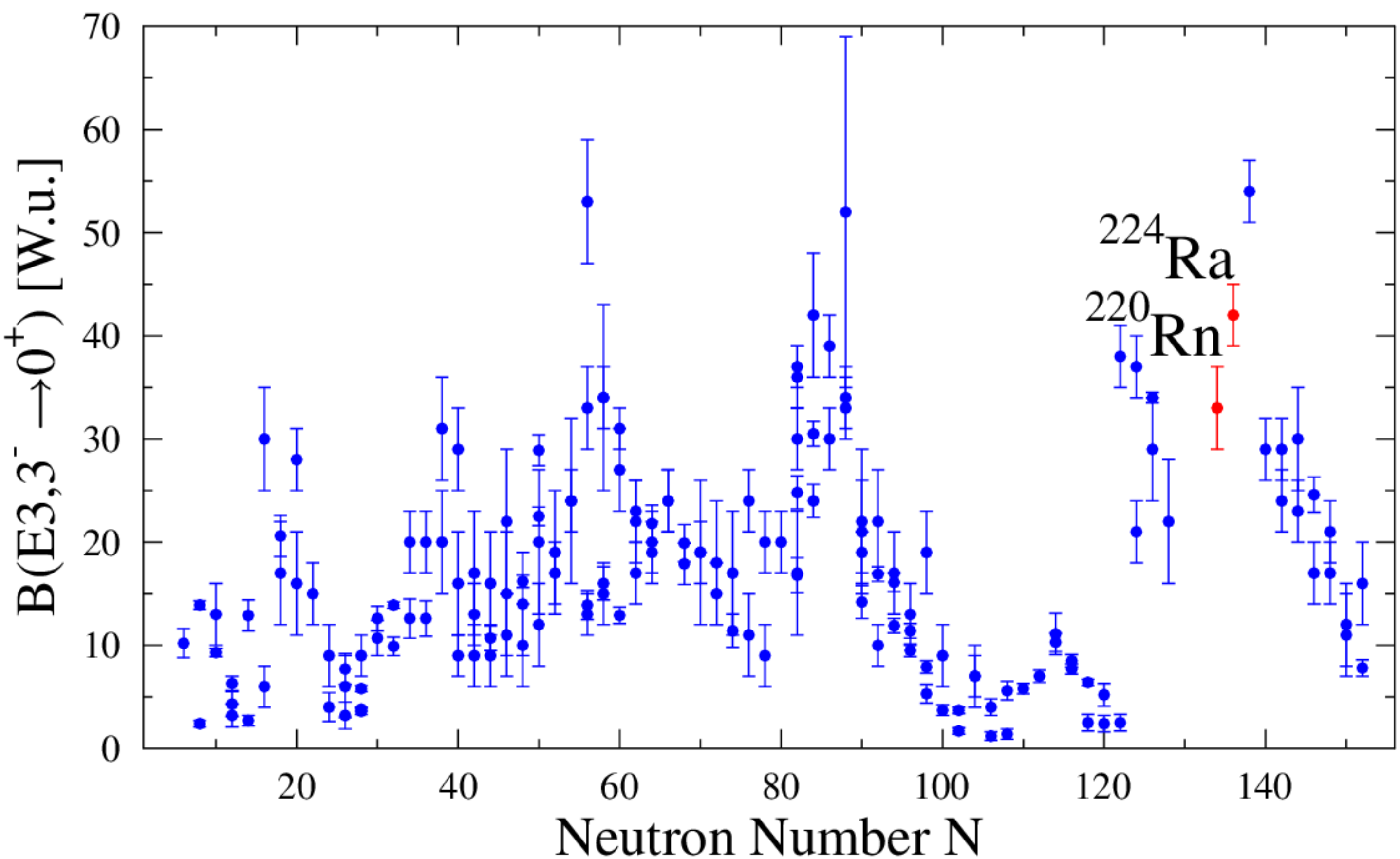
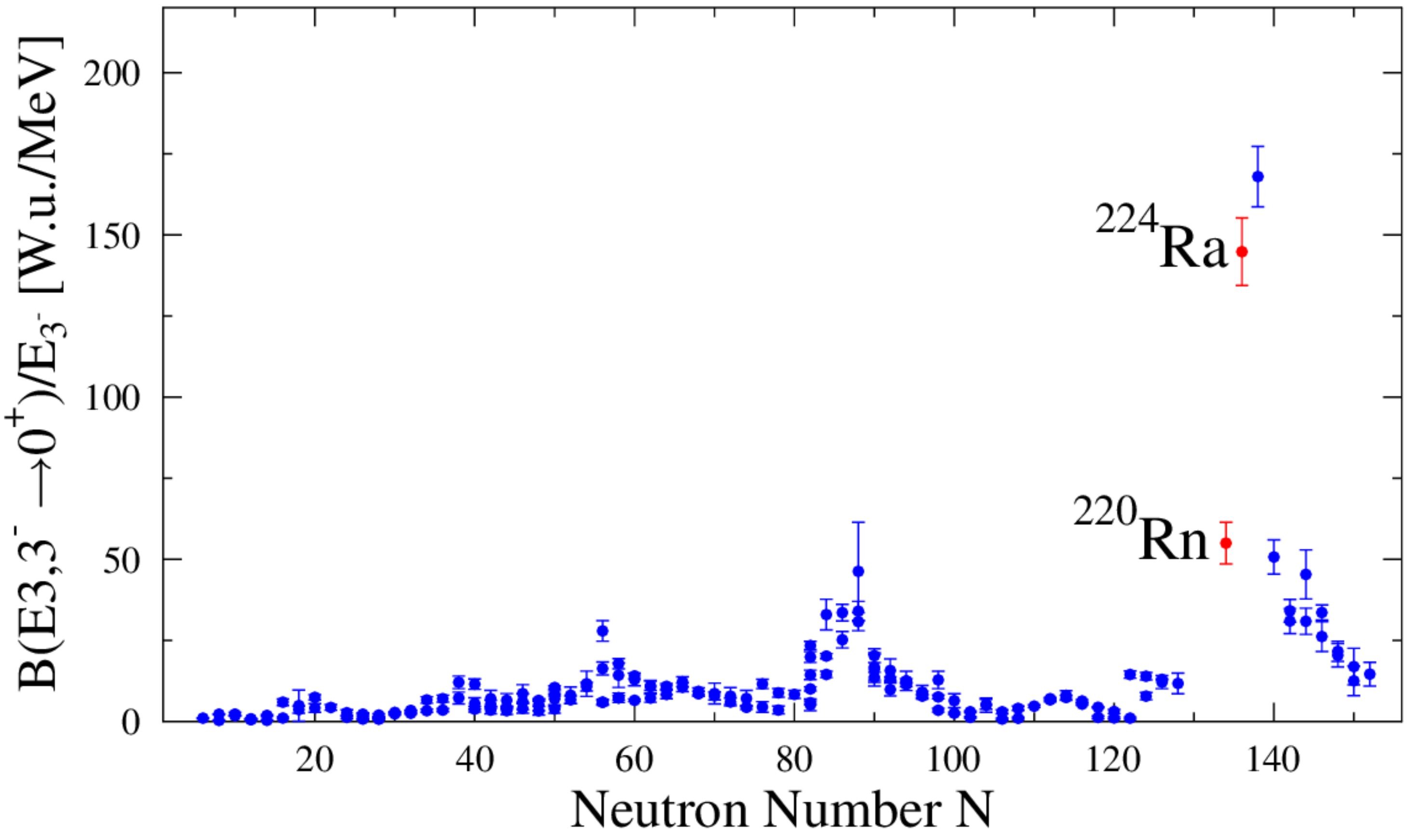
B(E3, $3^- \mapsto 0^+$) strength



L.P. Gaffney, P.A. Butler *et al.*, Nature **497** (2013) 199

Inverse sum rule



Nuclear surface

$$R(\Theta) = c(\beta_\lambda) R_0 \left[1 + \sum_{\lambda=2}^{\infty} \sqrt{\frac{2\lambda+1}{4\pi}} \beta_\lambda P_{\lambda 0}(cos\Theta) \right]$$

Our experiments: β_2,β_3 & Theory*: β_4

*W.Nazarewicz, Nucl. Phys. A**429** (1984) 269

Nuclear surface

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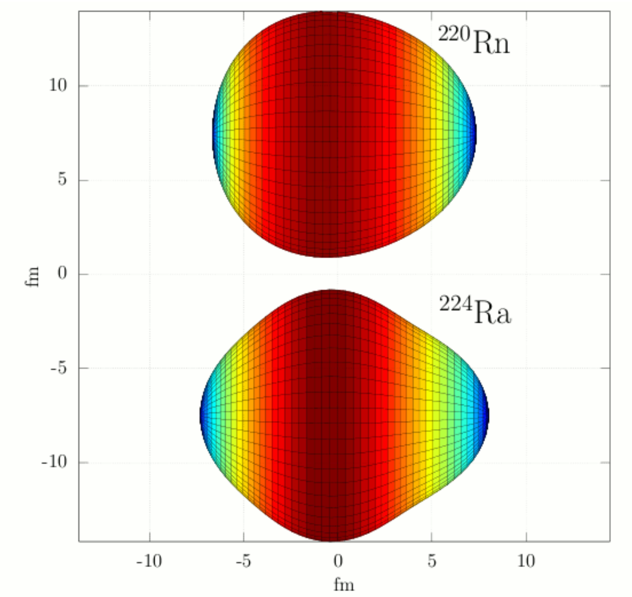

Nucleus	λ	β_λ
^{220}Rn	2	0.119
	3	0.095
	4	0.002*
^{224}Ra	2	0.154
	3	0.097
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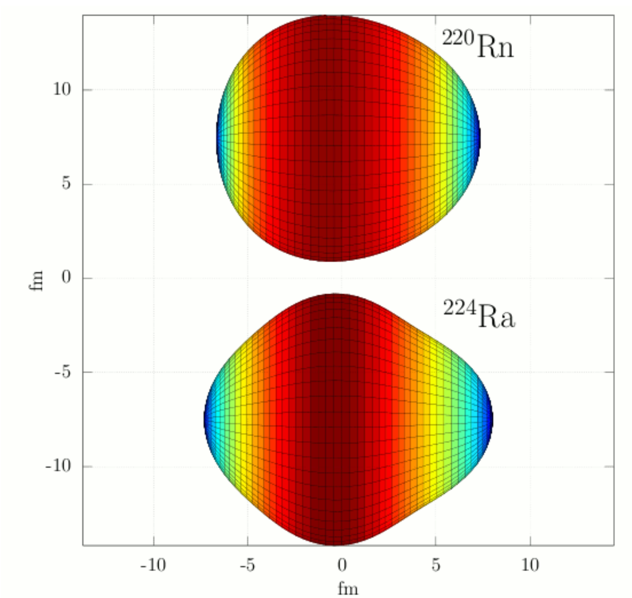

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Octupole deformation and CP violation

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Nuclear Schiff Moment

$$S = \sum \frac{\langle +_{gs}||\hat{S}_z||-\rangle\langle -||\hat{V}_{PT}||+_{gs}\rangle}{E_0 - E_i} + c.\ c.$$

N.Auerbach, V.V.Flambaum, & V. Spevak PRL 76 (1996) 4316
J.Dobaczewski & J.Engel, PRL **94** (2005) 232502

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$\sim \beta_3 \beta_2$

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Asymmetric proton distribution (Pear shape!)

N.Auerbach, V.V.Flambaum, & V. Spevak PRL 76 (1996) 4316
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$\sim\beta_3$

Asymmetric proton distribution (Pear shape!)

Lab. frame $\propto \frac{\beta_2(\beta_3)^2}{E_0 - E_i}$

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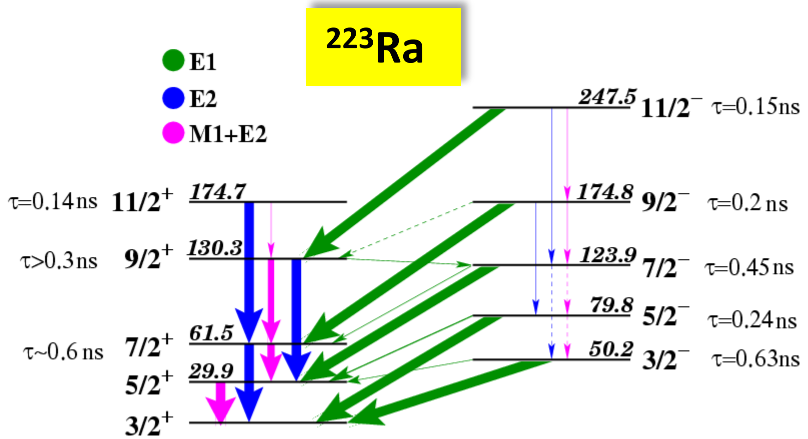

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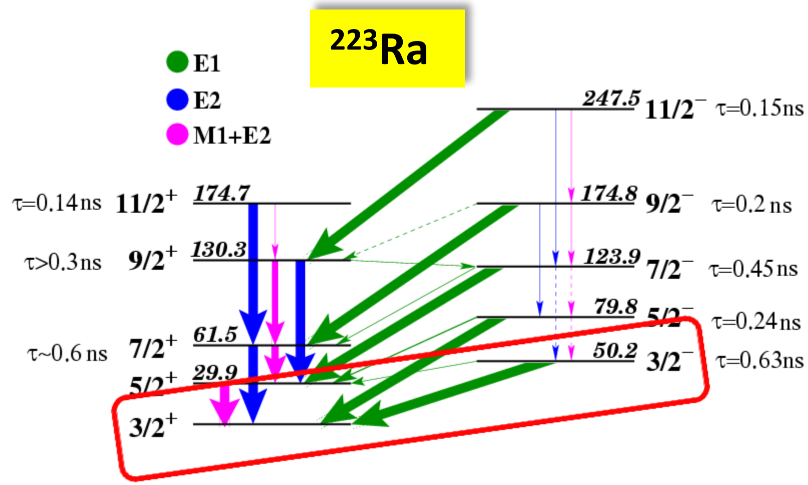

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Octupole deformation and CP violation

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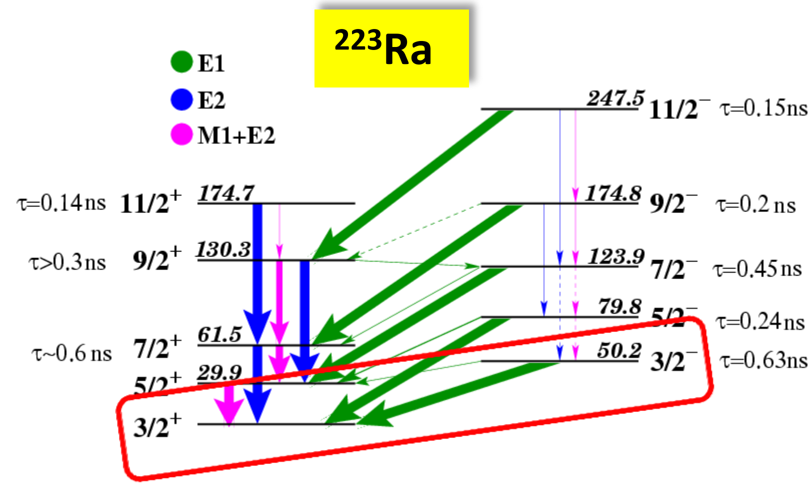

J=3/2-Parity doublet

π no longer a good QN

$\Rightarrow$ states mix

N.Auerbach, V.V.Flambaum, & V. Spevak PRL 76 (1996) 4316

J.Dobaczewski & J.Engel, PRL **94** (2005) 232502

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Octupole deformation and CP violation

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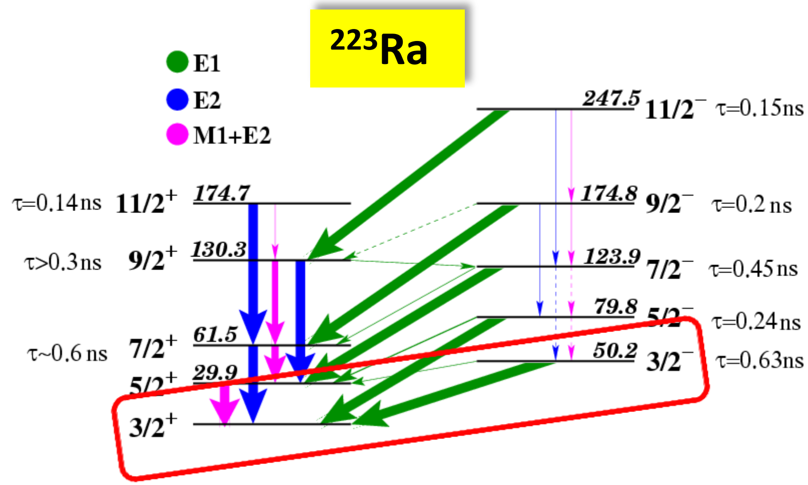
$\sim \beta_3 \beta_2$

$\sim \beta_3$

$$\hat{S}_z = \frac{e}{10} \sum_{\pi} (r_{\pi}^2 - \frac{5}{3} \bar{r}_{ch}^2) z_{\pi}$$

Asymmetric proton distribution (Pear shape!)

Lab. frame $\propto \frac{\beta_2 (\beta_3)^2}{E_0 - E_i}$



J=3/2-Parity doublet

π no longer a good QN

⇒ states mix

Atomic system: $S_{at} = Z^3 S_{nucl}$

N.Auerbach, V.V.Flambaum, & V. Spevak PRL 76 (1996) 4316

J.Dobaczewski & J.Engel, PRL **94** (2005) 232502

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Octupole deformation and CP violation

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Nuclear Schiff Moment

$$S = \sum \frac{\langle +_{gs} || \hat{S}_z || - \rangle \langle - || \hat{V}_{PT} || +_{gs} \rangle}{E_0 - E_i} + c.\,c.$$

$\sim \beta_3 \beta_2$

$\sim \beta_3$

$$\hat{S}_z = \frac{e}{10} \sum_{\pi} (r_\pi^2 - \frac{5}{3} \bar{r}_{ch}^2) z_\pi$$

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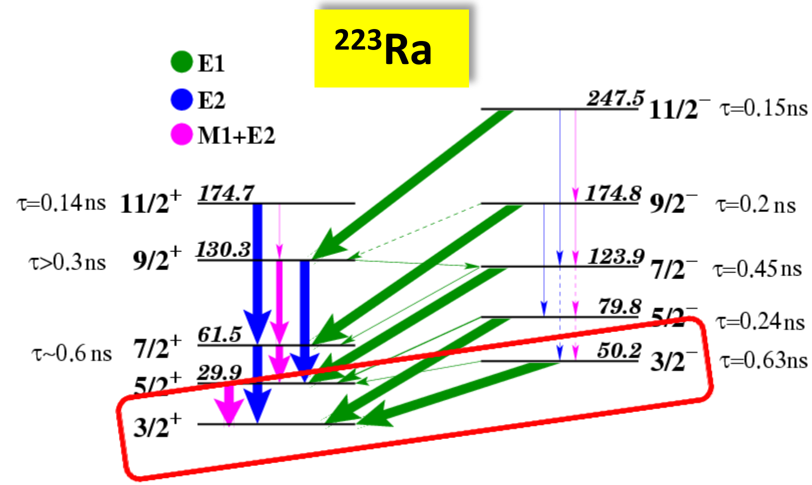

J=3/2-Parity doublet
π no longer a good QN
⇒ states mix

Atomic system: $S_{at} = Z^3 S_{nucl}$

⇒ Laser spectroscopy on ^{223,225}Ra (KVI), or ^{221,223}Rn (Tim Chupp)

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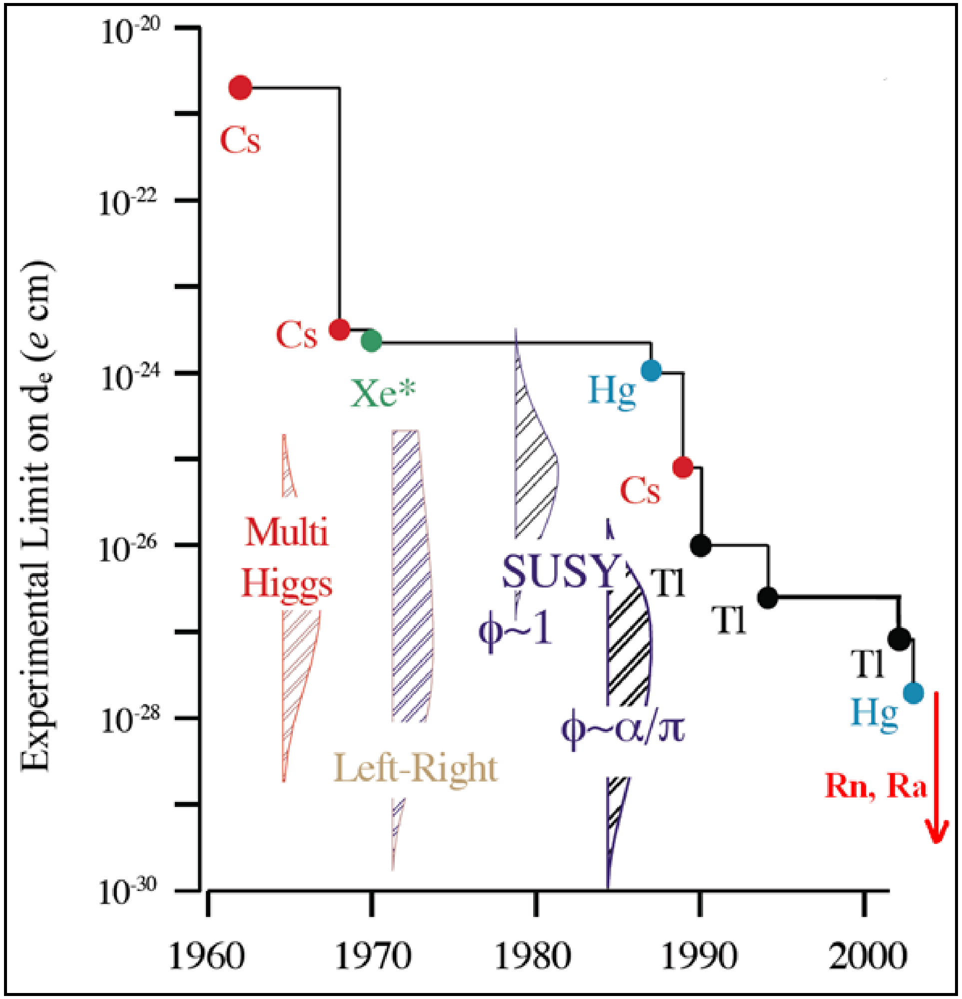
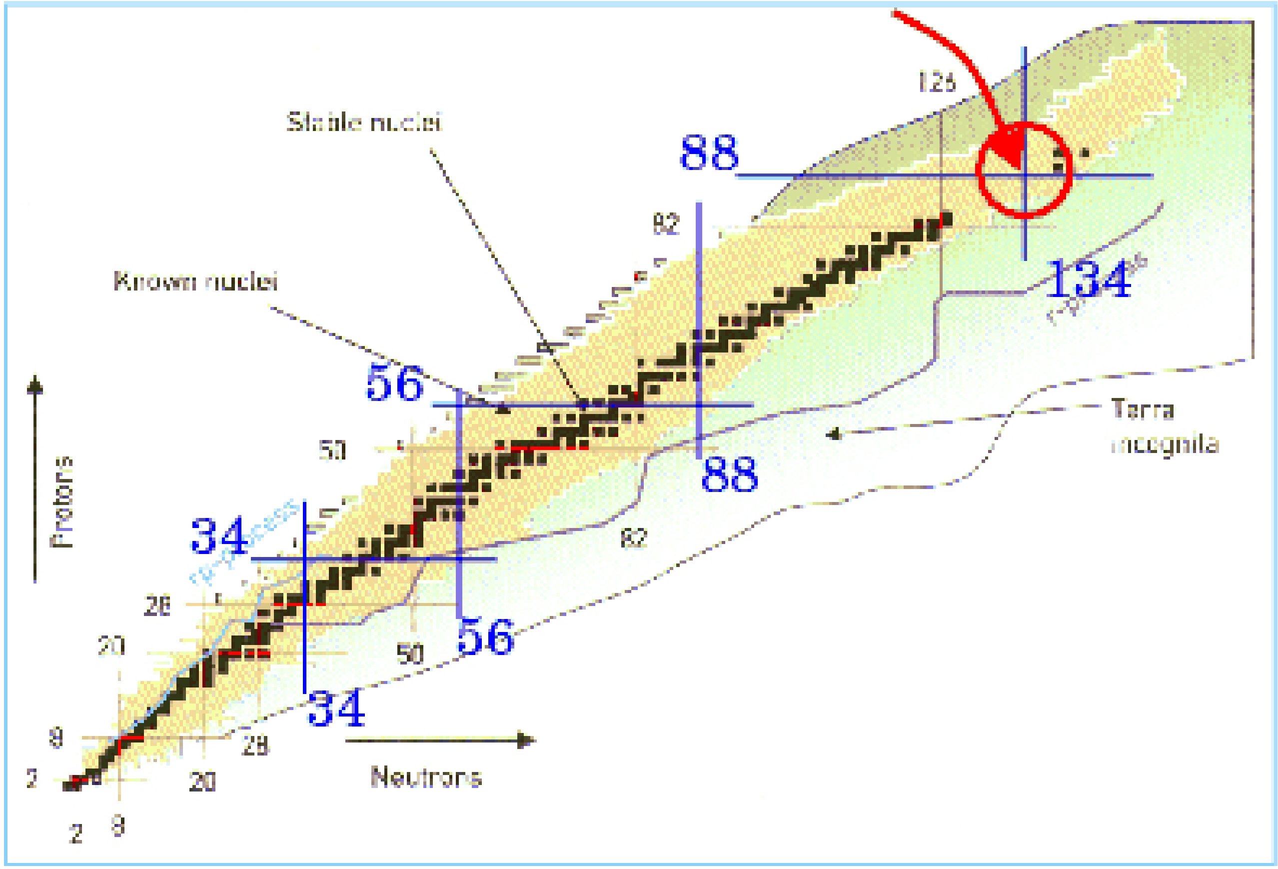
EDMs: fighting the theory Hydra…



Mid-term future?

IS552:
Coul-Ex $^{222,226,228}Ra$ & $^{221,222}Rn$



Mid-term future?

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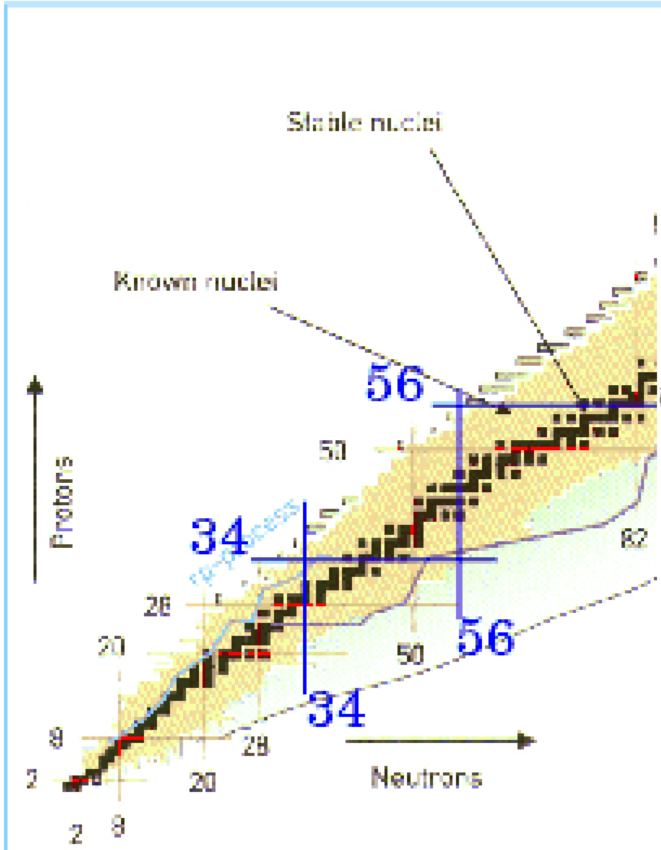

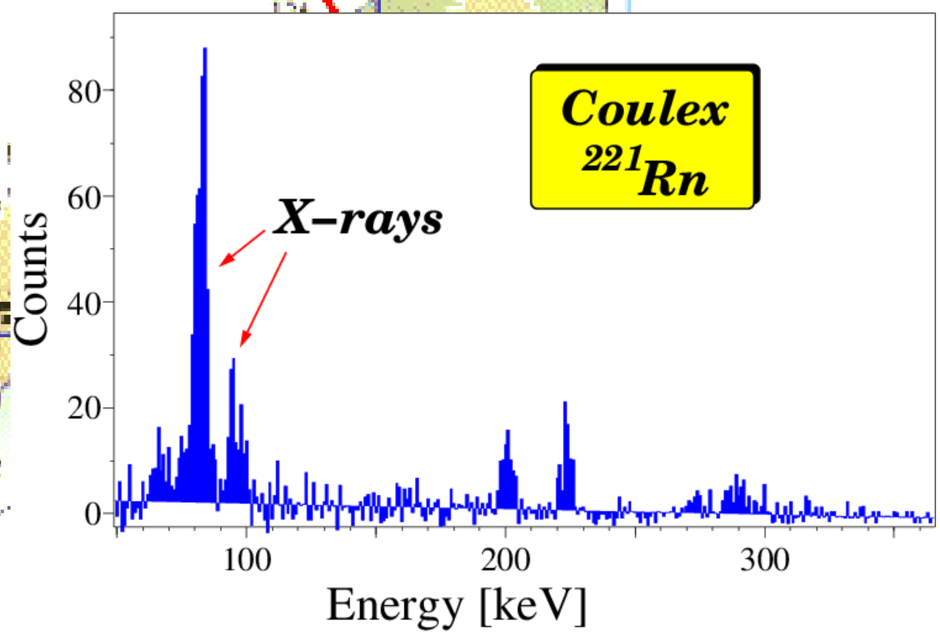

Mid-term future?

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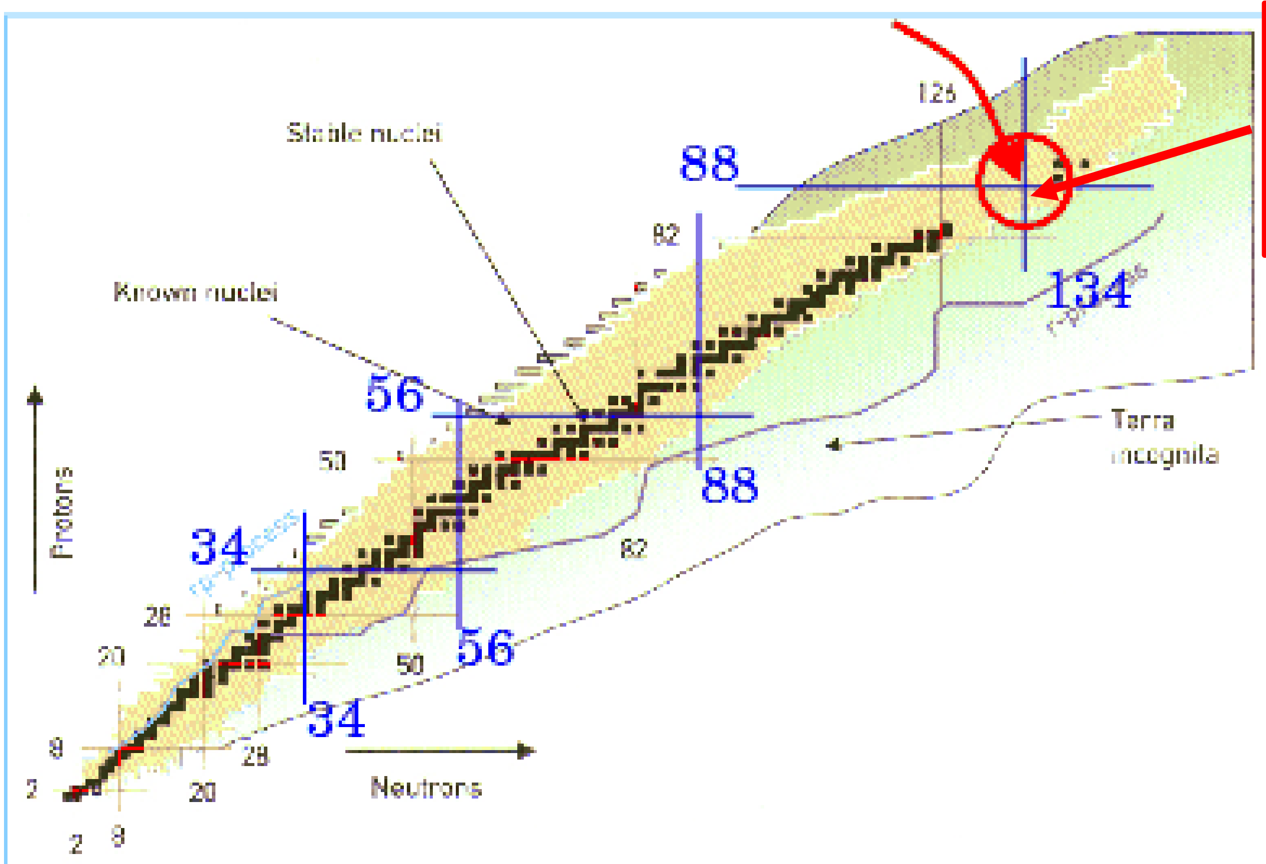
IS552:
Coul-Ex ^{222,226,228}Ra & ^{221,222}Rn

Beam development
β-decay
^{221,223}At → ^{221,223}Rn



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Mid-term future?

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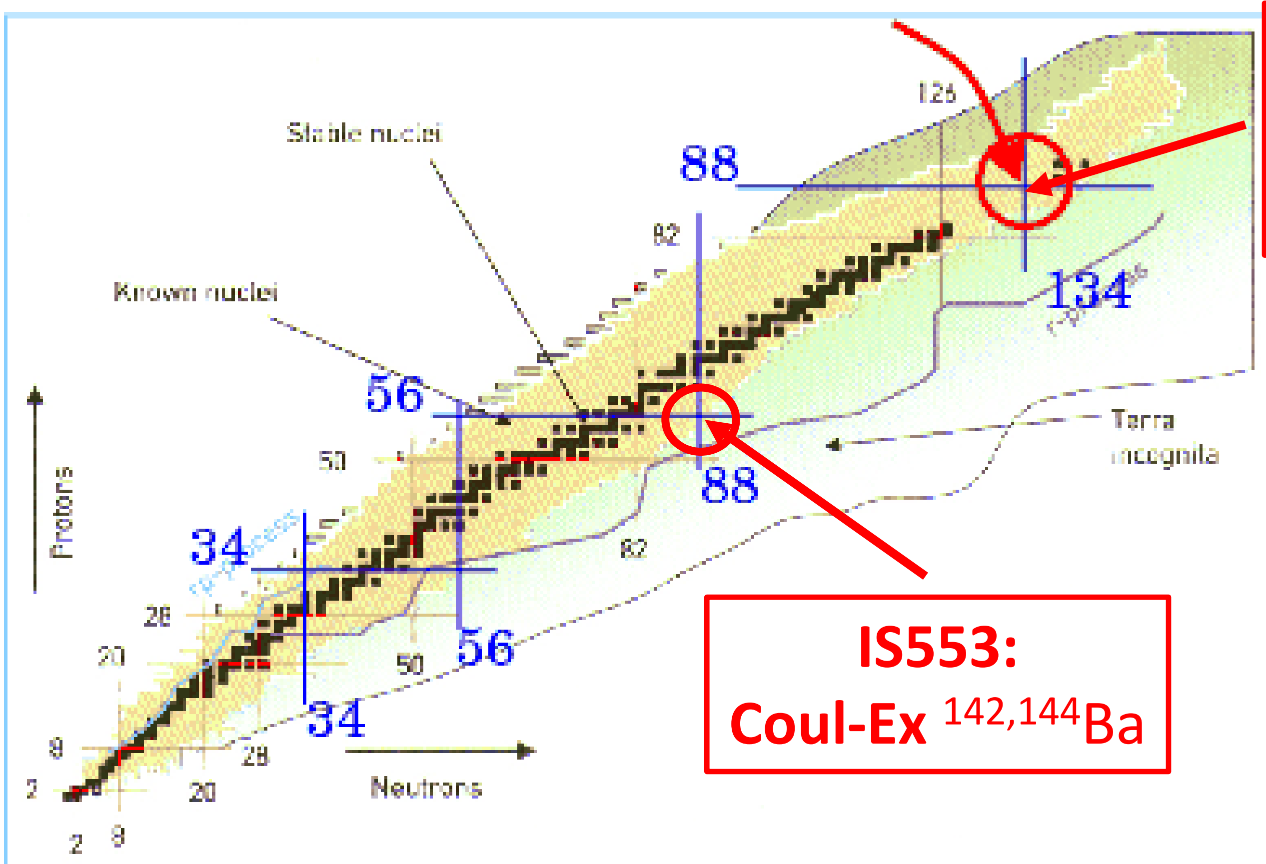

Beam development
β-decay
$^{221,223}At \rightarrow ^{221,223}Rn$

IS553:
Coul-Ex $^{142,144}Ba$

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Octupole deformation and CP violation: Question to theory

Lab. frame $\propto \frac{\beta_2(\beta_3)^2}{E_0 - E_i}$

Assume: weak coupling

$\Rightarrow$ β_2 and β_3 determined by even-even core

(Peter, Liam, …collaborators, me in the even-even mass)

Octupole deformation and CP violation: Question to theory

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(for once) nature is nice to us:
^{146}Cs, ^{148}Pr, **^{224}Fr, ^{226}Fr**, ^{222}Ac: $J_0^\pi = 1^-$
Possibly: ^{144}Cs, ^{148}Pr, ^{226}Ac

Octupole deformation and CP violation: Question to theory

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Lab. frame $\propto \dfrac{\beta_2(\beta_3)^2}{E_0 - E_i}$

Assume: weak coupling
$\Rightarrow$ β_2 and β_3 determined by even-even core
(Peter, Liam, …collaborators, me in the even-even mass)

Is it worth to write a proposal to explore ^{224,226}Fr?

^{146}Cs, ^{148}Pr, **^{224}Fr, ^{226}Fr**, ^{222}Ac: $J_0^\pi = 1^-$
Possibly: ^{144}Cs, ^{148}Pr, ^{226}Ac

We are indebted to...

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...the IS475 collaboration:

P.A.Butler, **L.P.Gaffney**, A.B.Hayes, F.Wenander, M.Albers, B.Bastin, C.Bauer, A.Blazhev, S.Boenig, N.Bree, J.Cederkall, T.Chupp, D.Cline, T. E.Cocolios, T.Davinson, H.DeWitte, J.Diriken, T.Grahn, A.Herzan, M.Huyse,D.G.Jenkins,D.T.Joss, N.Kesteloot, J.Konki, M.Kowalczyk, Th.Kroell, E.Kwan, R.Lutter, K. Moschner, P.Napiorkowski, J.Pakarinen, M.Pfeiffer, D.Radeck, P.Reiter, K.Reynders, S.V.Rigby, L.M.Robledo, M.Rudigier, S.Sambi, M.Seidlitz, B. Siebeck, T.Stora, P.Thoele, P.Van Duppen, M.J.Vermeulen, M. von Schmid, D.Voulot, N.Warr, K.Wimmer, K. Wrzosek-Lipska, C. Y. Wu & M. Zielinska

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…the ISOLDE beam operator crew

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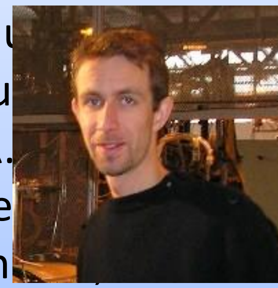

…the ISOLDE beam operator crew

…the funding organizations! Especially:

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European Nuclear Science and Applications Research ENSAR

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