Do nuclei go pear-shaped?

Coulomb excitation of ^{220}Rn and ^{224}Ra at REX-ISOLDE(CERN)

Marcus Scheck
University of the West of Scotland
Peter A. Butler, Liam P. Gaffney
University of Liverpool
for the IS475 collaboration

CGS XV - Dresden 2014

Octupole collectivity
- microscopic -

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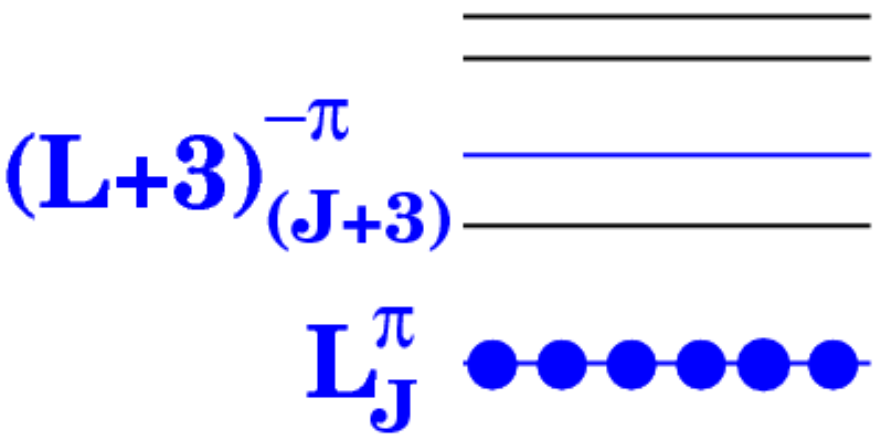
Nuclear shell structure



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Octupole collectivity
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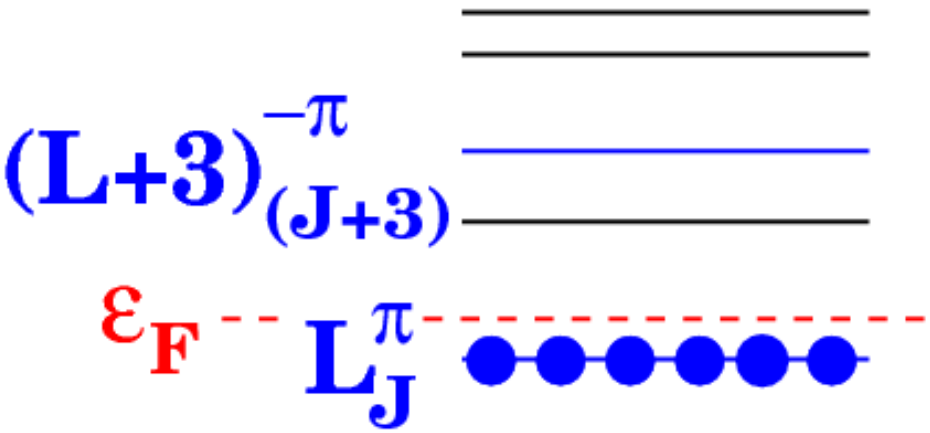
Nuclear shell structure

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



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Octupole collectivity
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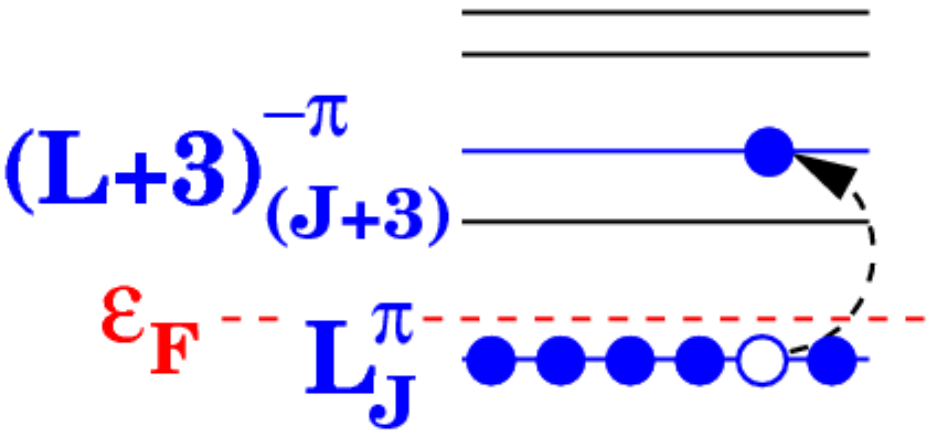
Nuclear shell structure

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

⇒**enhanced octupole collectivity**



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Octupole collectivity
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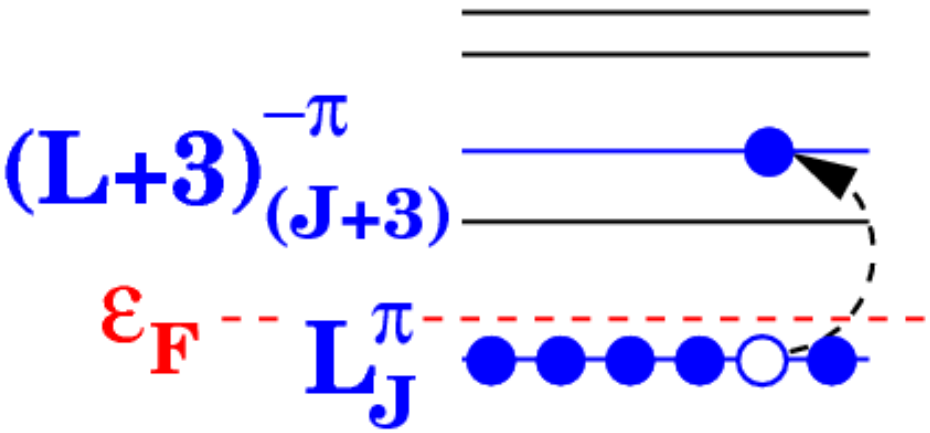

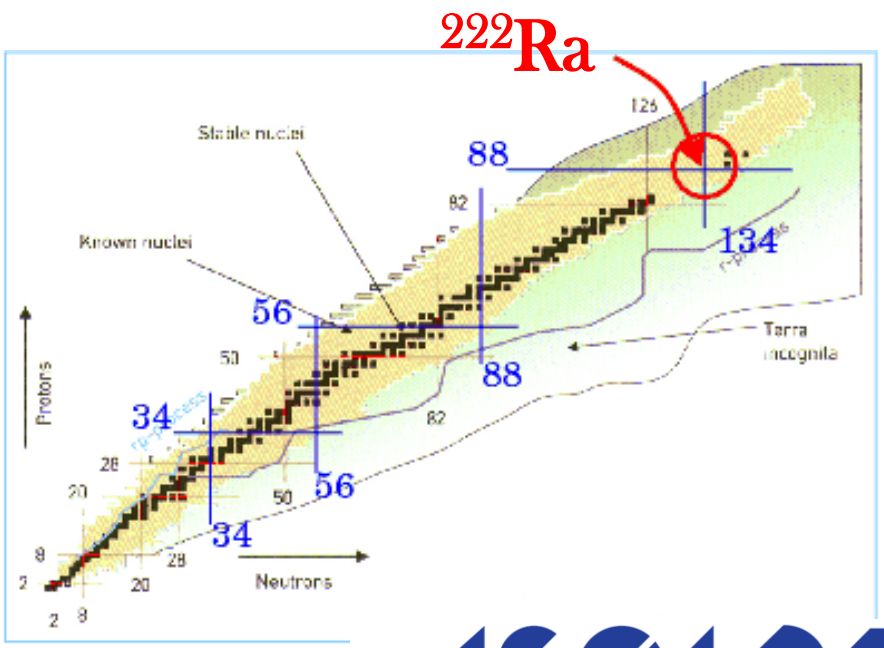

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Octupole collectivity
- macroscopic -

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

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Octupole collectivity
- macroscopic -

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Multipole expansion of the shape:
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Reflection Asymmetric

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Octupole collectivity
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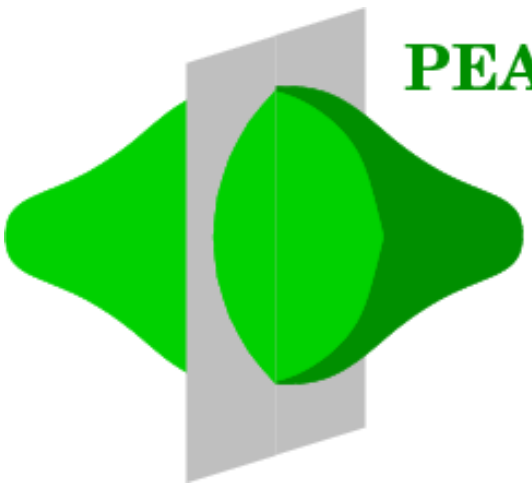
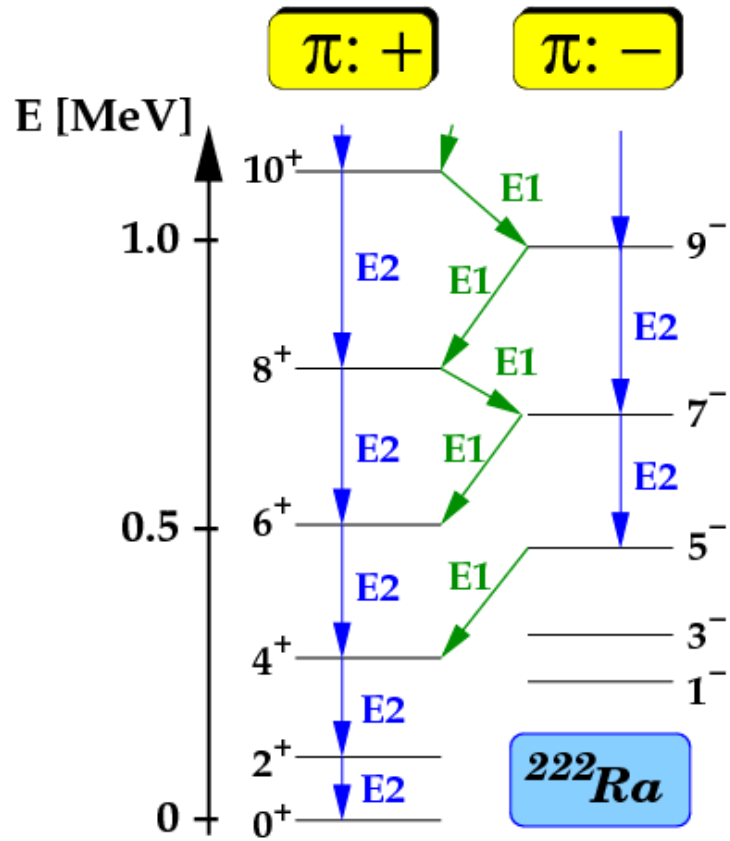


PEAR shape

Reflection Asymmetric



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

ISOLDE

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

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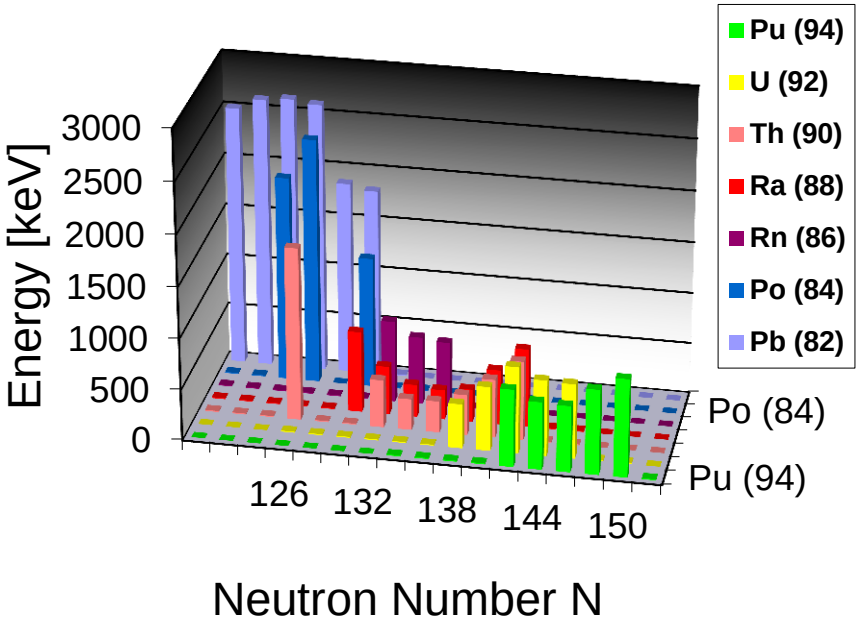
Excitation energy E_{3^-}



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

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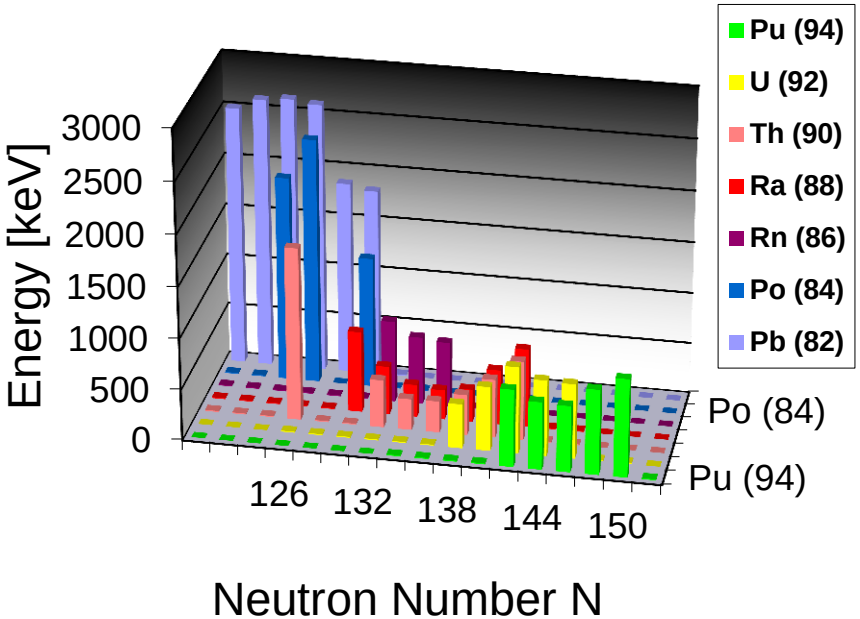
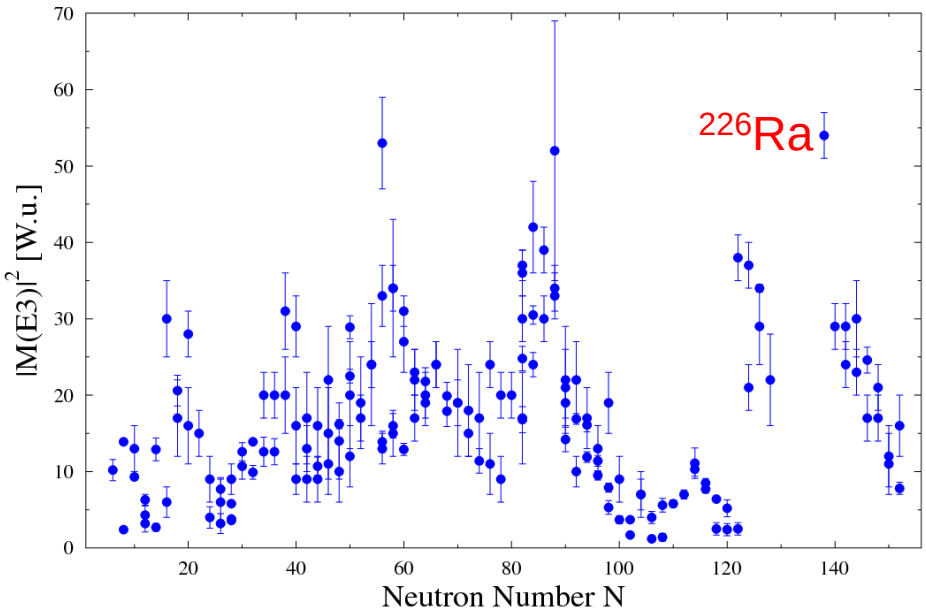


$B(E3, 0^+ \mapsto 3^-)$-strength



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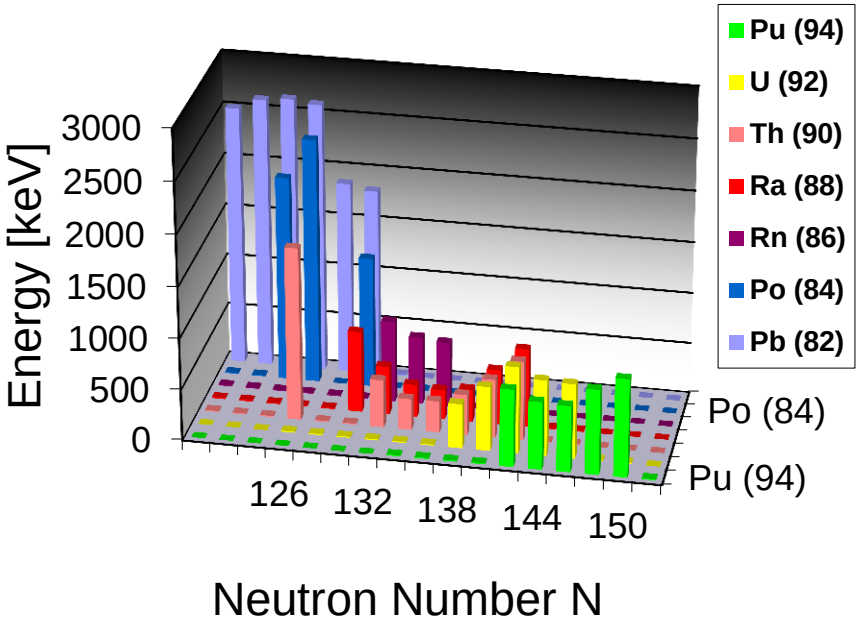
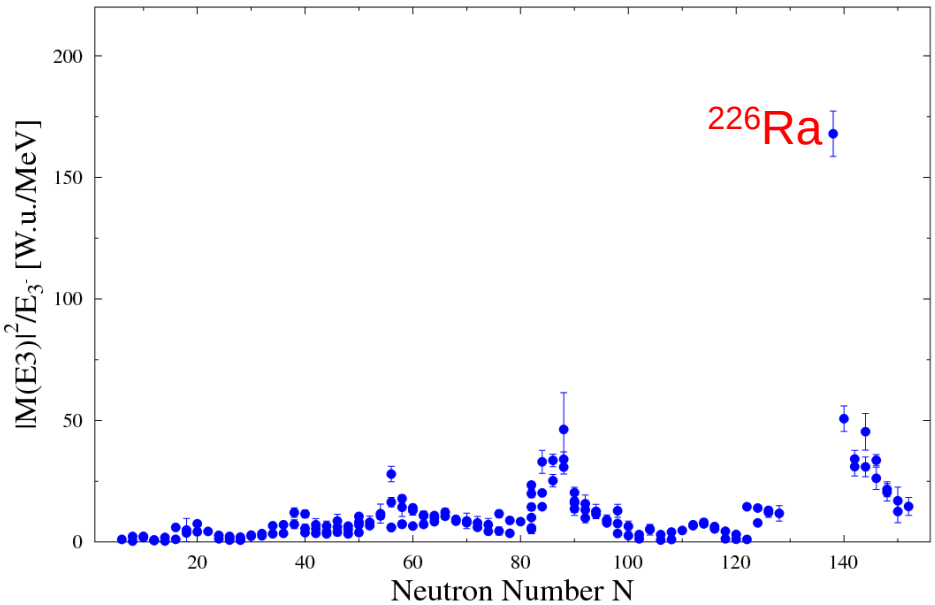


Inverse sum rule



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

ISOLDE

ISOLDE @ CERN

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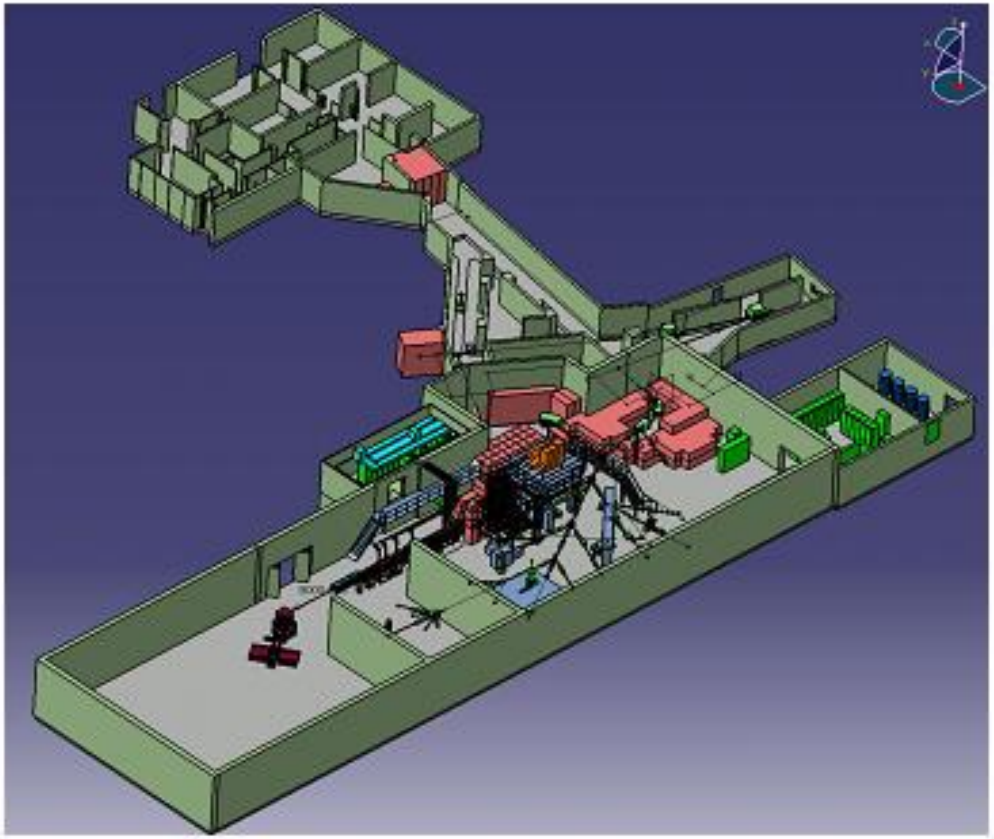
ISOL $\mapsto$ **IS**otope **O**n**L**ine separation **DE**tector



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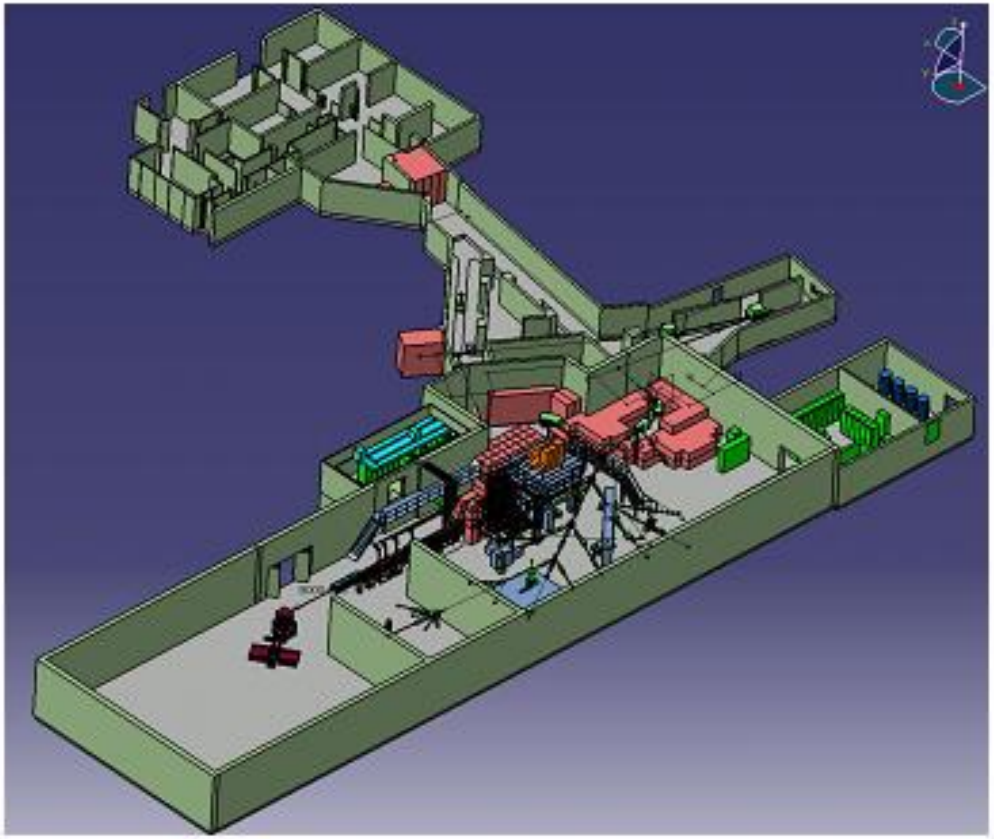

CERN accelerator complex

ISOLDE

ISOLDE @ CERN

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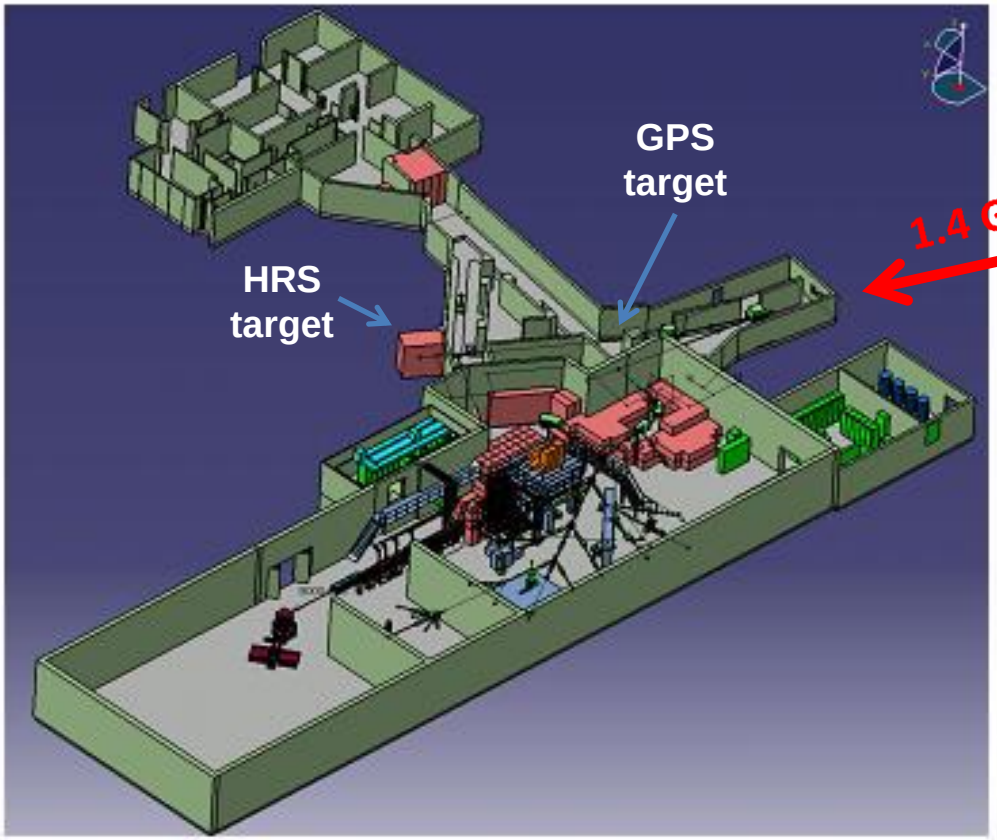

$I_p \sim 2\ \mu A$

1.4 GeV protons

CERN accelerator complex

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ISOLDE @ CERN

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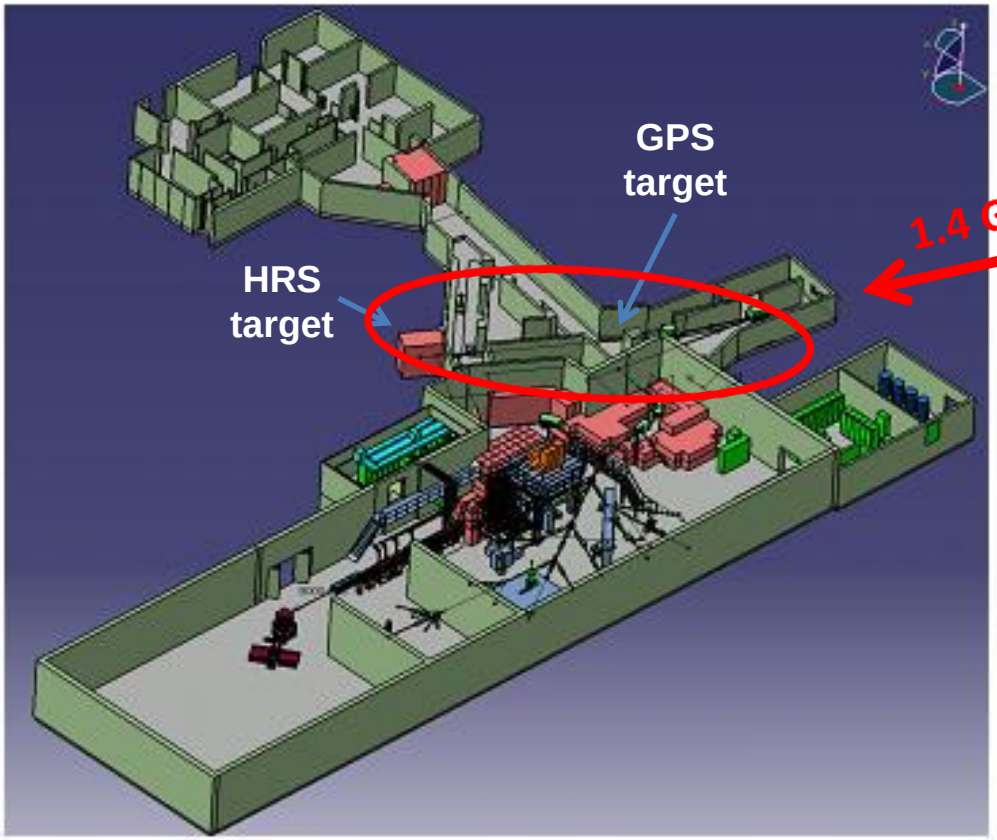

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CERN accelerator complex

Production

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Production of ISOL-Radioactive Ion Beams

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Physical processes

^{238}U binding energy: 1.8 GeV

Target nucleus

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Production of ISOL-Radioactive Ion Beams

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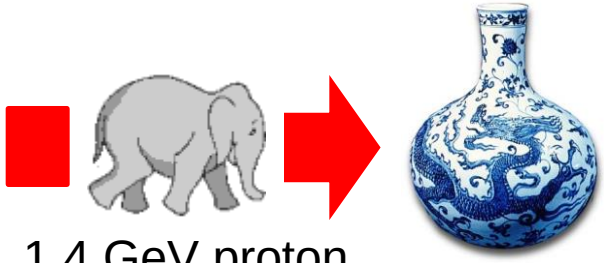

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Production of ISOL-Radioactive Ion Beams

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1. Spallation ⇒ heavy nucleus
2. Fission ⇒ medium mass nucleus
3. Fragmentation ⇒ light nucleus

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Production of ISOL-Radioactive Ion Beams

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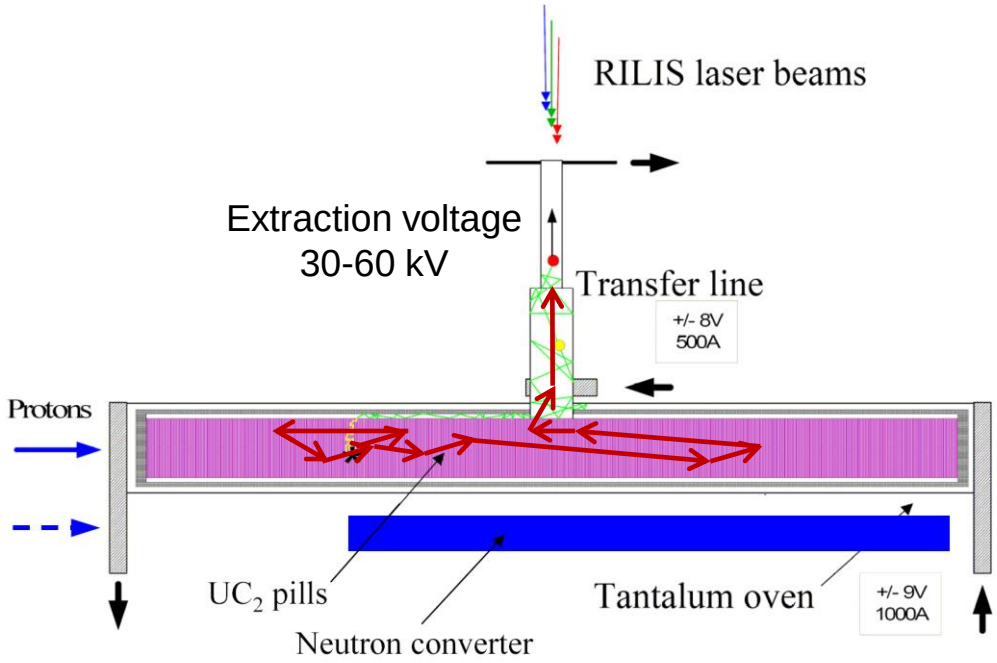
Target Outline



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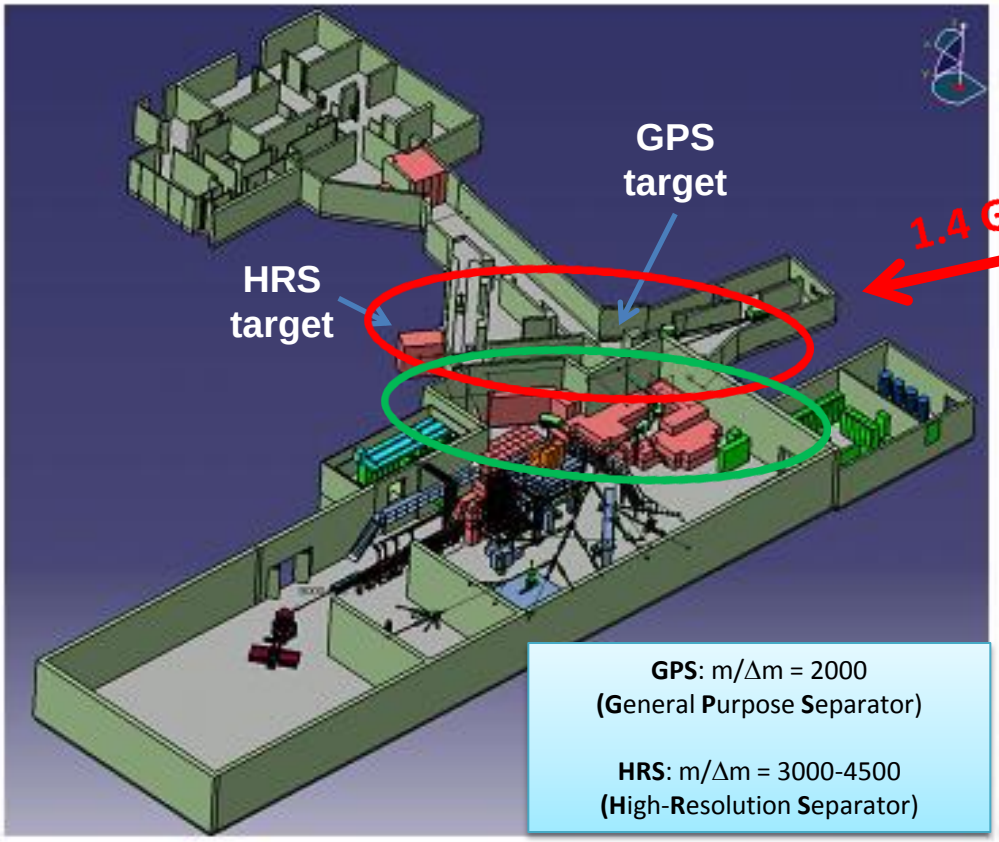
ISOL ↦ **IS**otope **O**n**L**ine separation **DE**tector



GPS: m/Δm = 2000
(**G**eneral **P**urpose **S**eparator)

HRS: m/Δm = 3000-4500
(**H**igh-**R**esolution **S**eparator)

I_p ~ 2 μA

1.4 GeV protons

CERN accelerator complex

Production

↓

Separation

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ISOLDE @ CERN

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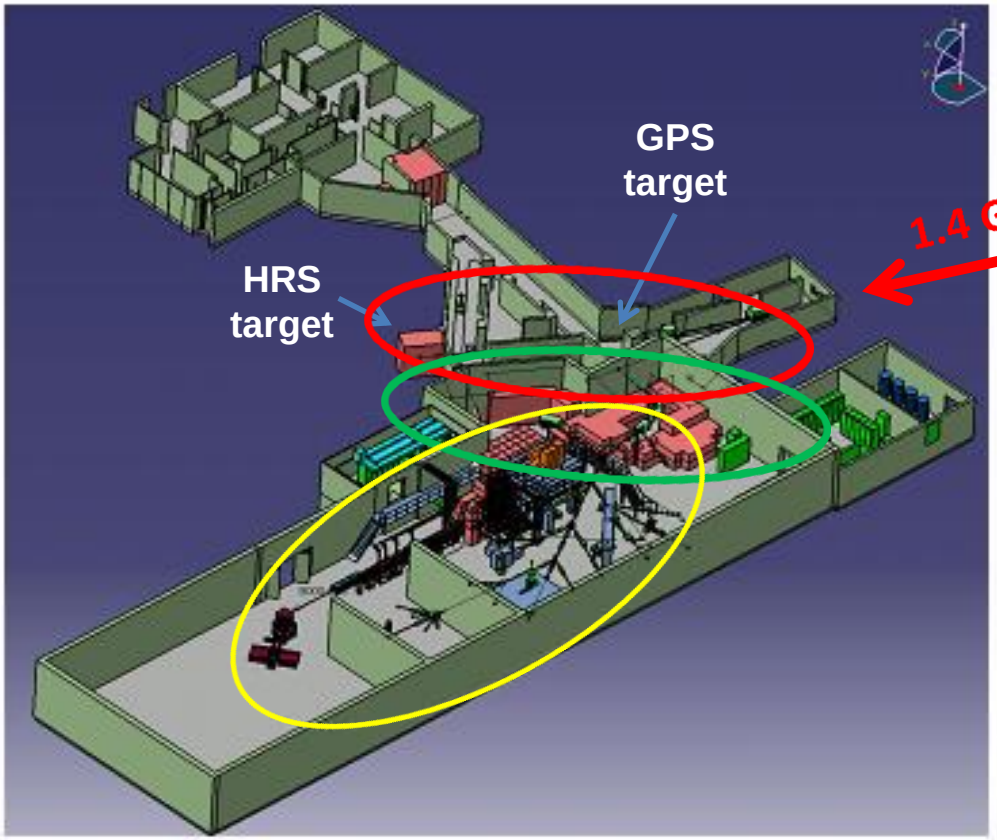

$I_p \sim 2\ \mu A$

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CERN accelerator complex

Production

↓

Separation

↓

Experiment

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Radioactive ion beam EXperiment - REX

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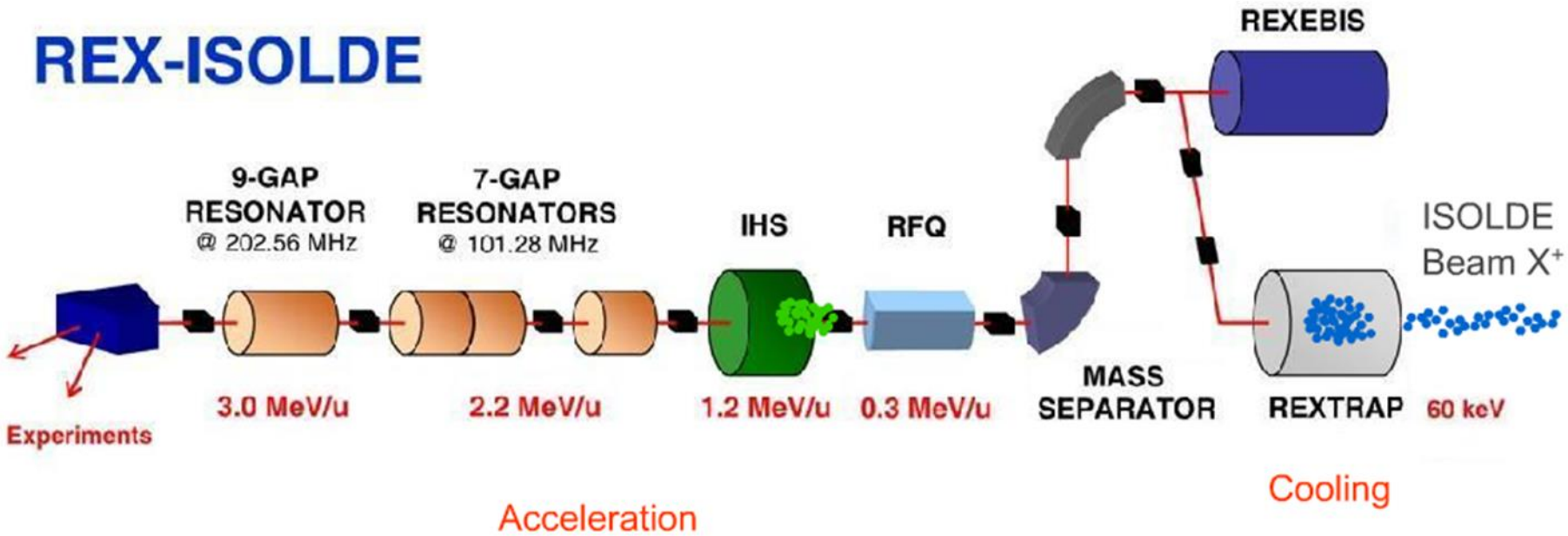

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Coulomb excitation at Miniball

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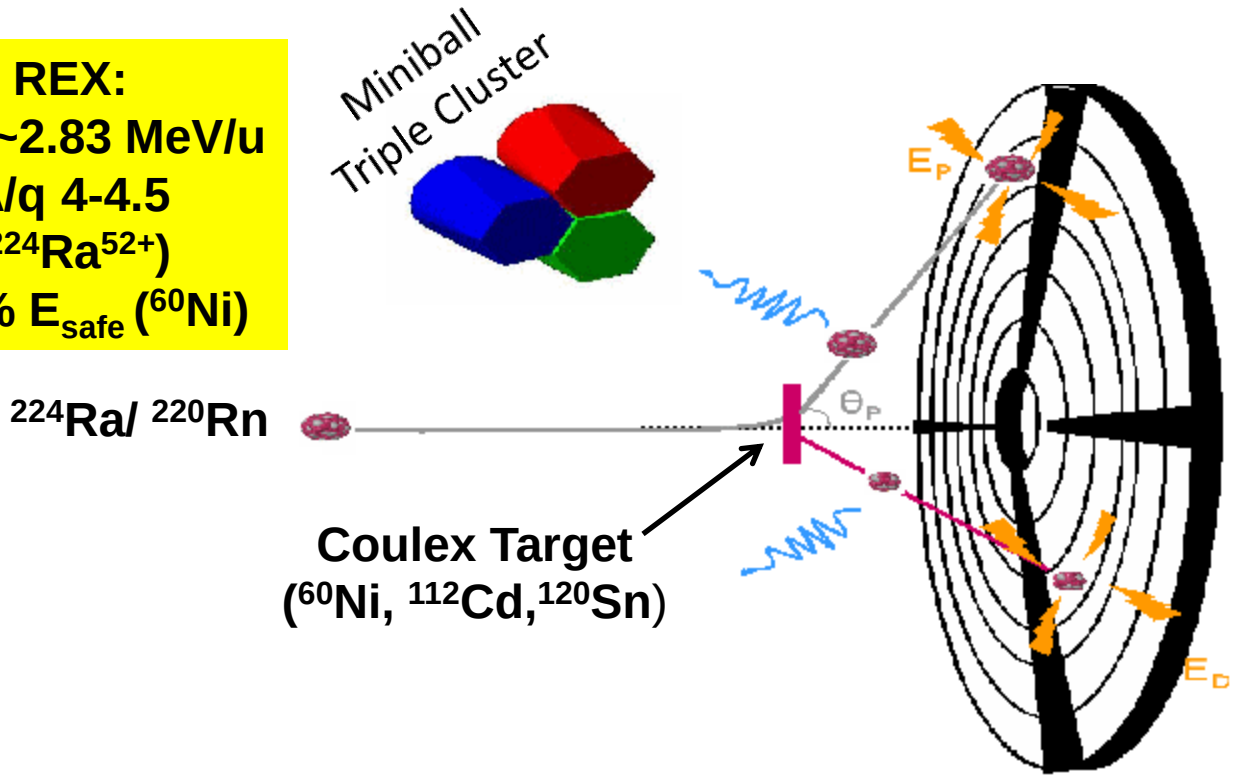
REX:
E_{beam}~2.83 MeV/u
A/q 4-4.5
($^{224}Ra^{52+}$)
~66% E_{safe} (^{60}Ni)



DSSD
Particle detector

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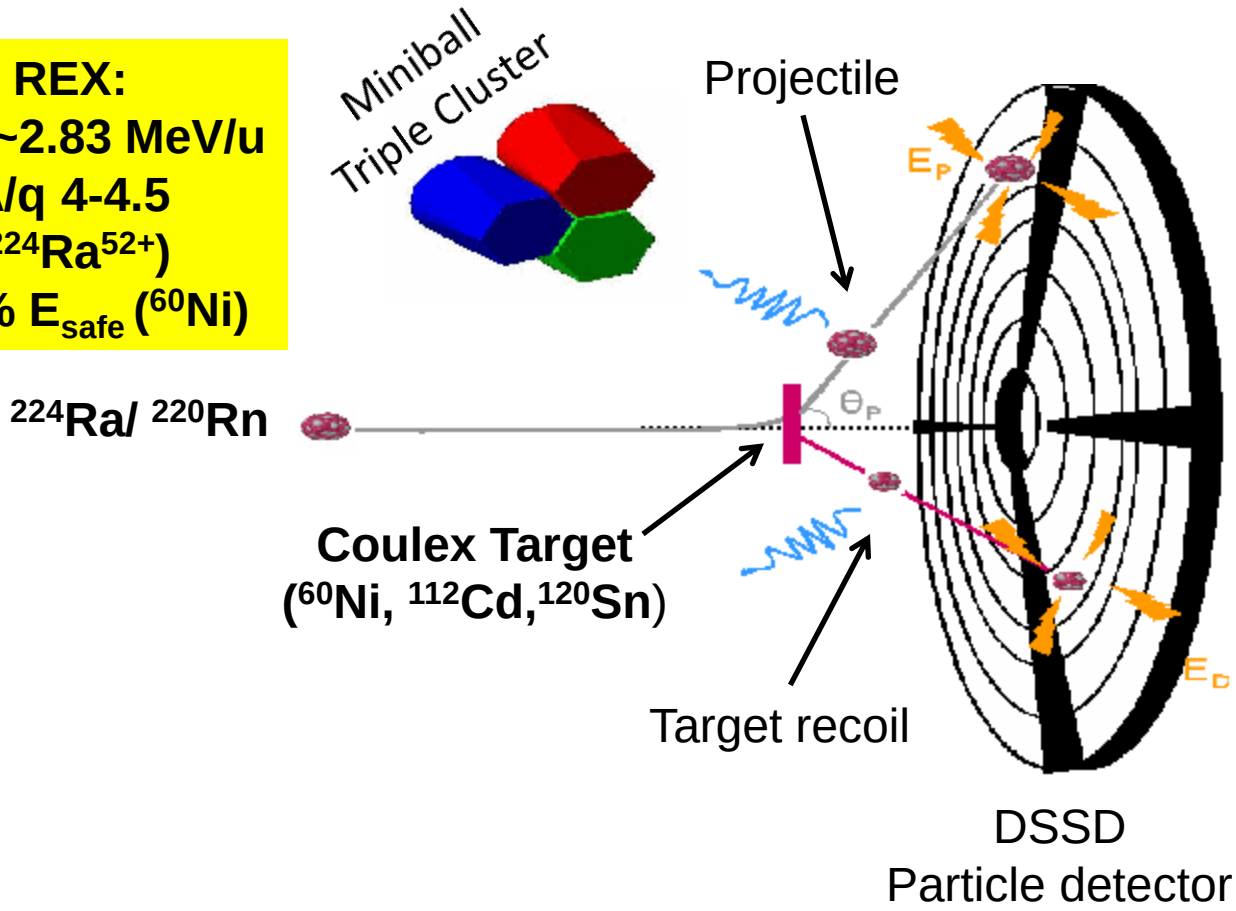

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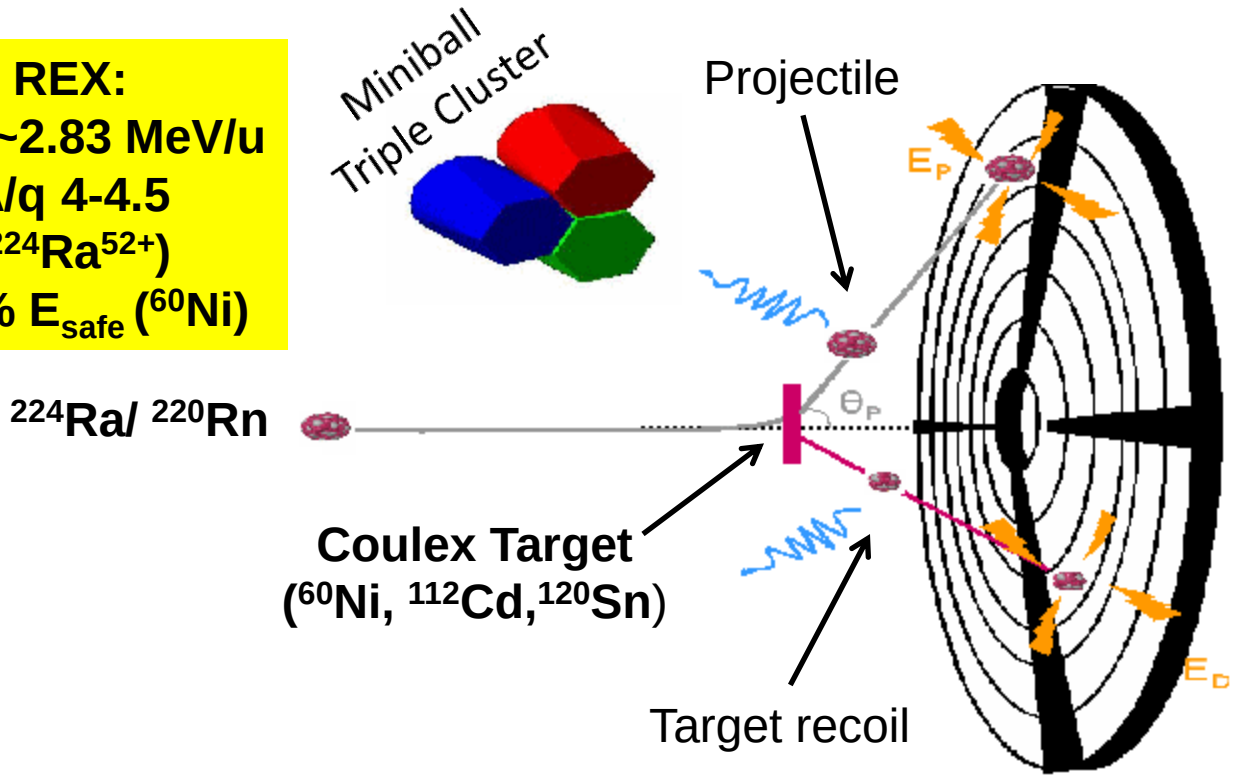

DSSD:
Angles 15°-53°
Front 16 strips
Back 24/2 strips

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

DSSD
Particle detector

ISOLDE

Why CoulEx?

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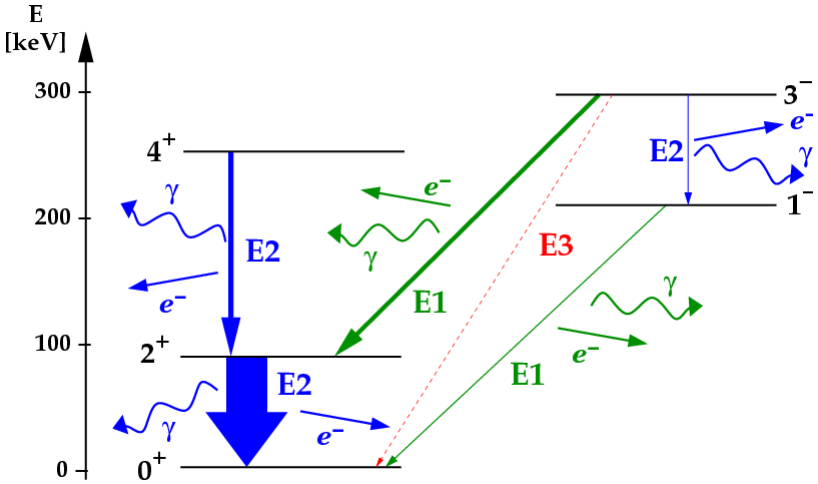
De-excitation process



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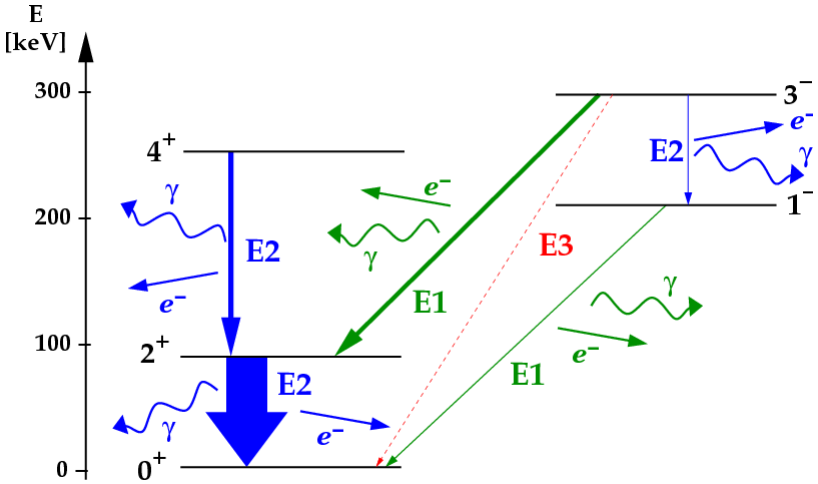

E1 10^4-10^6x more probable

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Why CoulEx?

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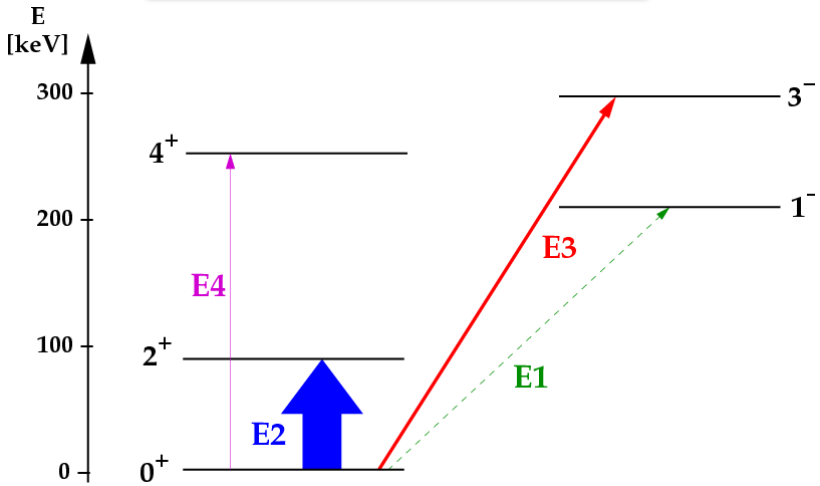
Excitation process (first order)



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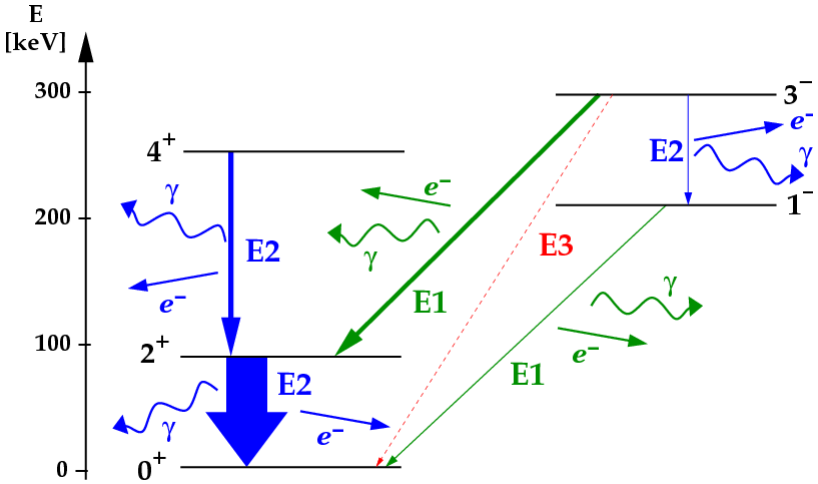

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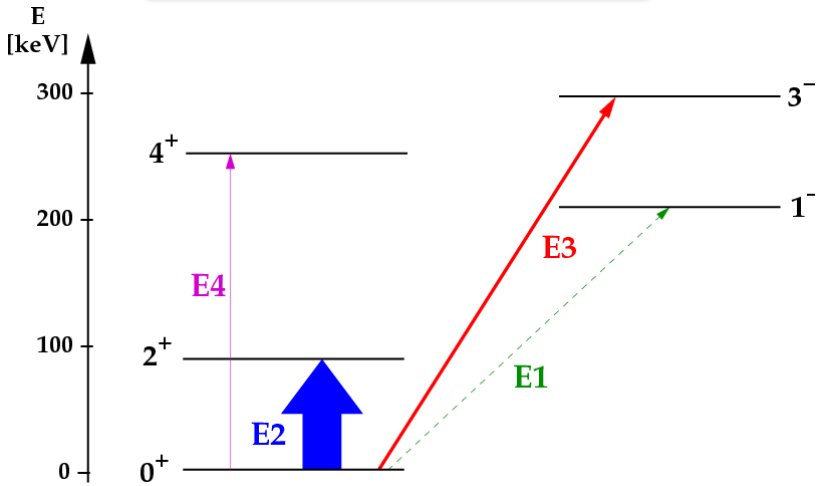

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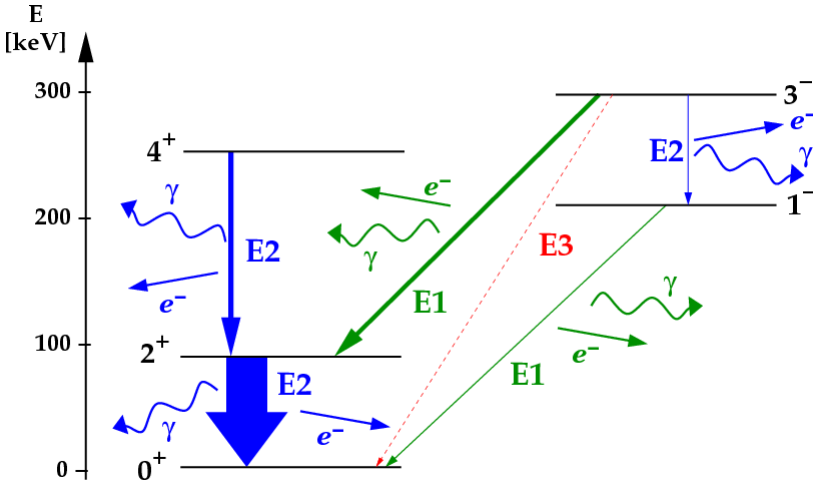

E1 10^4-10^6x more probable

Principle:

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

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CoulEx: Experimental Info

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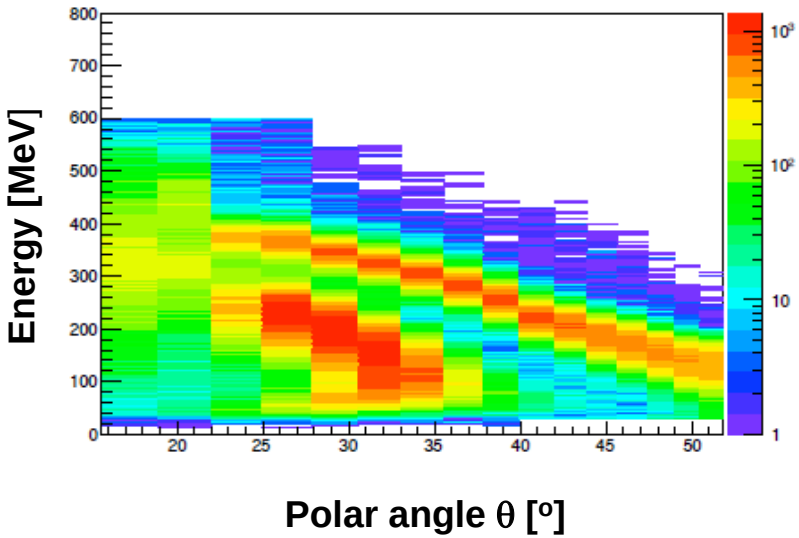
Particle Detector:
(inverse kinematic)



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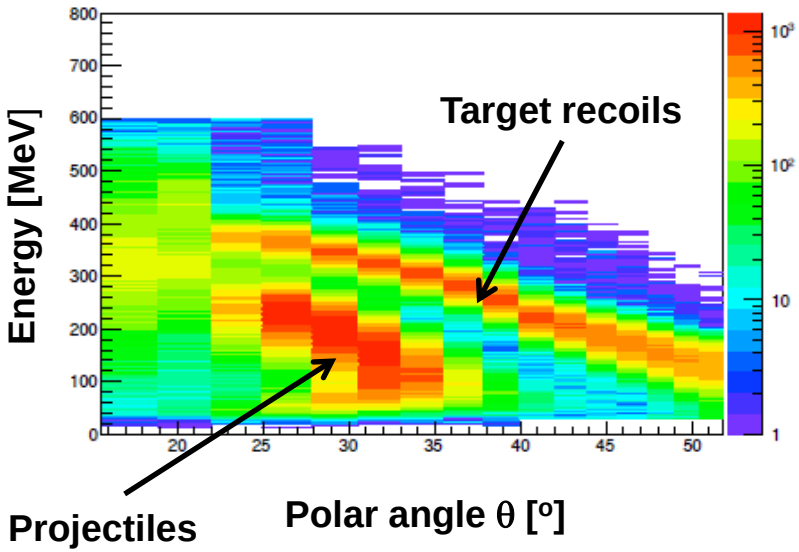

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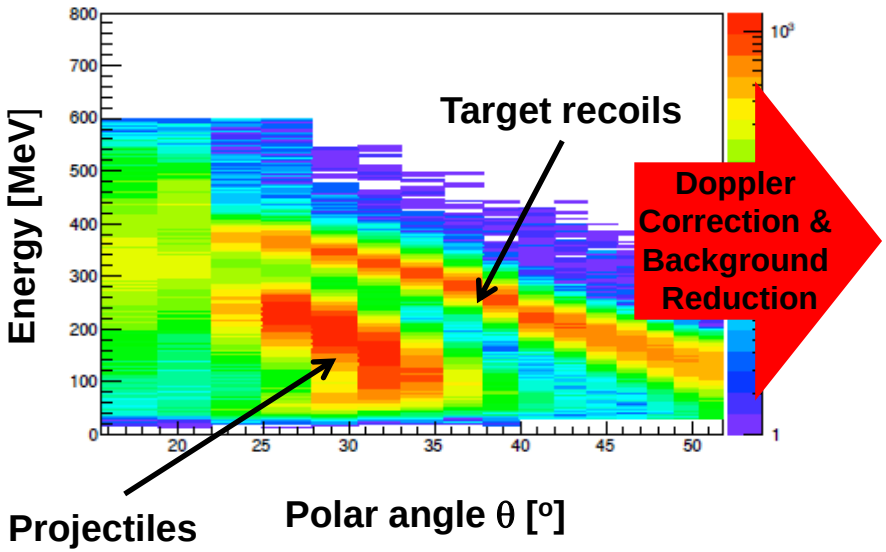

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CoulEx: Experimental Info

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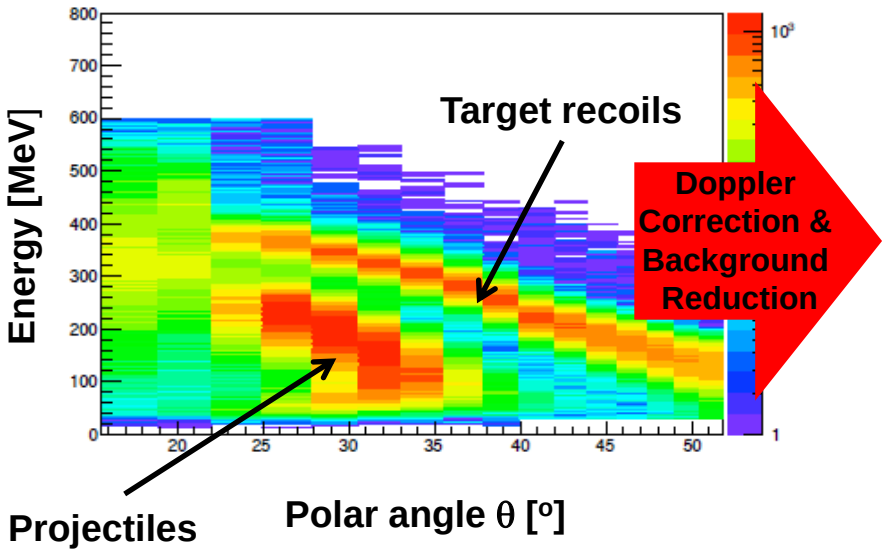
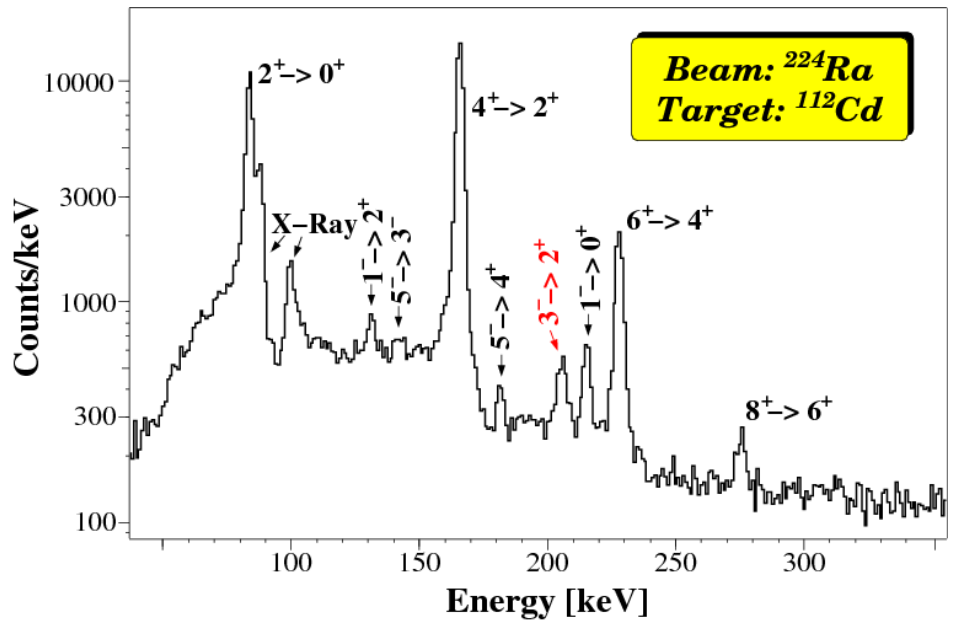
Particle Detector: (inverse kinematic)

HPGe γ-ray Detector array





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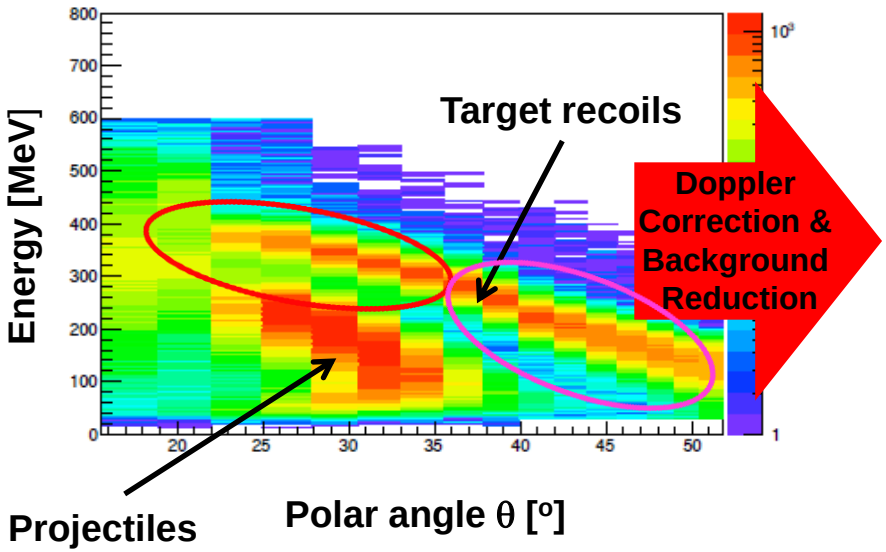

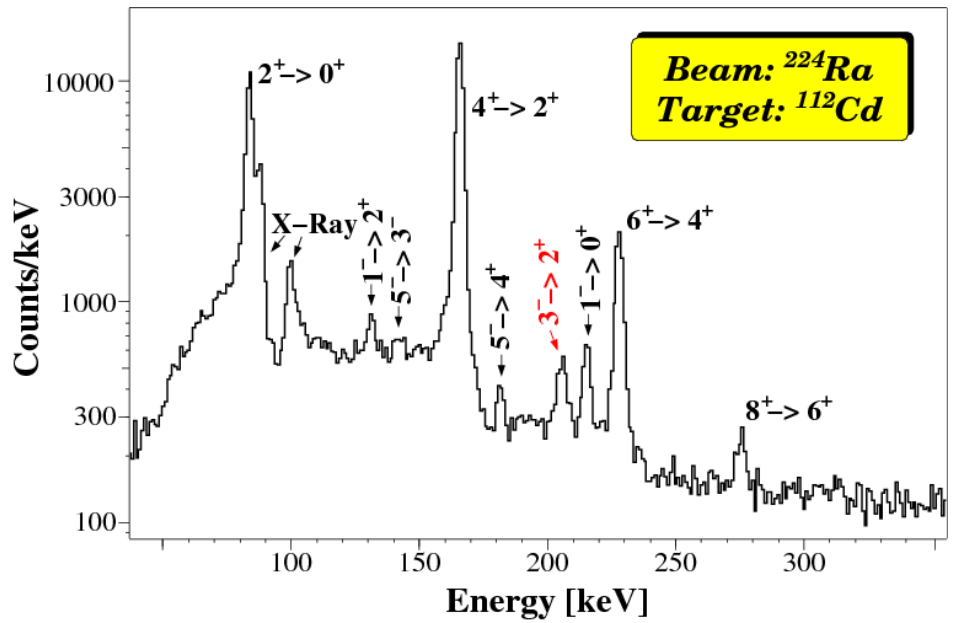

Split in 2 angular ranges

2 x 9 γ-ray yields

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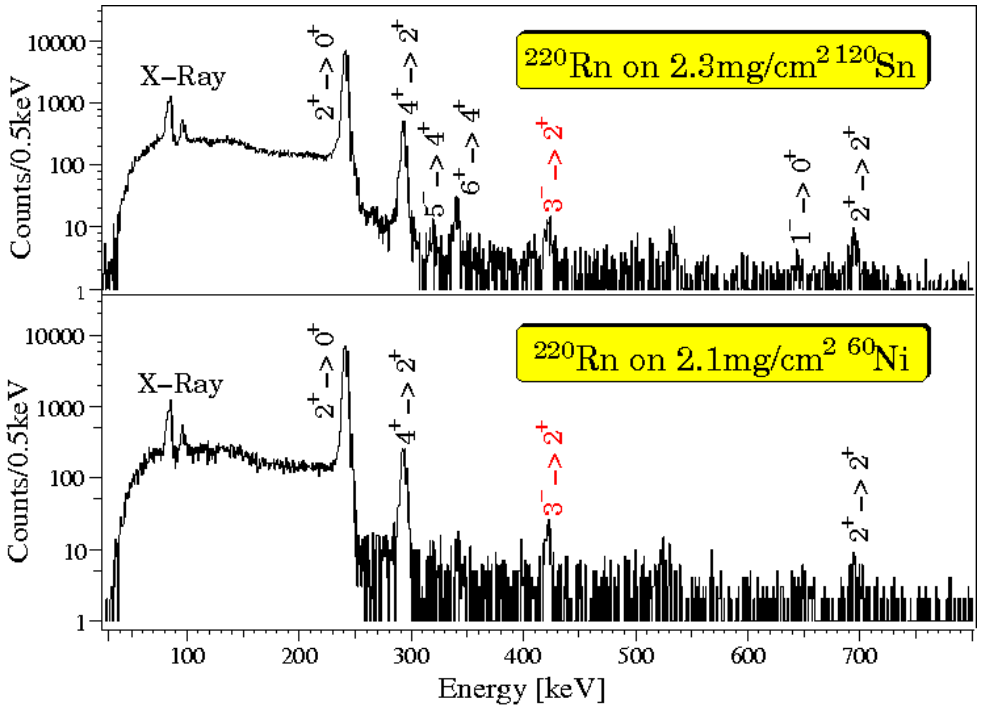
Different Targets (Z)



Disentangle one- and multi-step excitation paths

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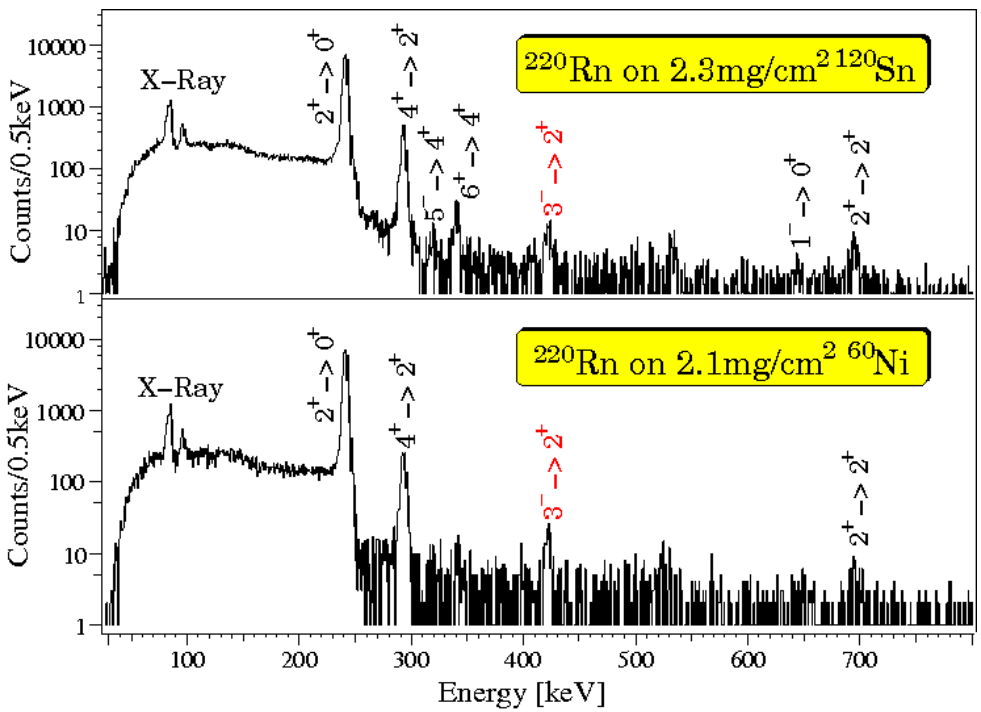
Different Targets (Z)



Disentangle one- and multi-step excitation paths

Literature (^{224}Ra)

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

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CoulEx: Experimental Info

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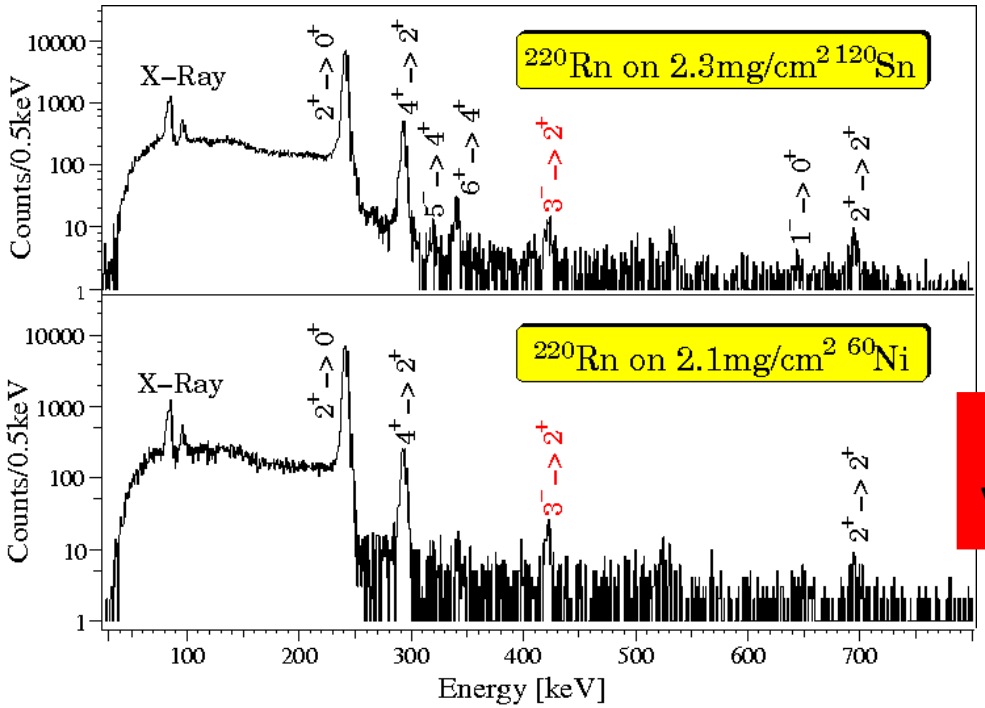

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γ-ray yields

GOSIA

Disentangle one- and multi-step excitation paths

ISOLDE

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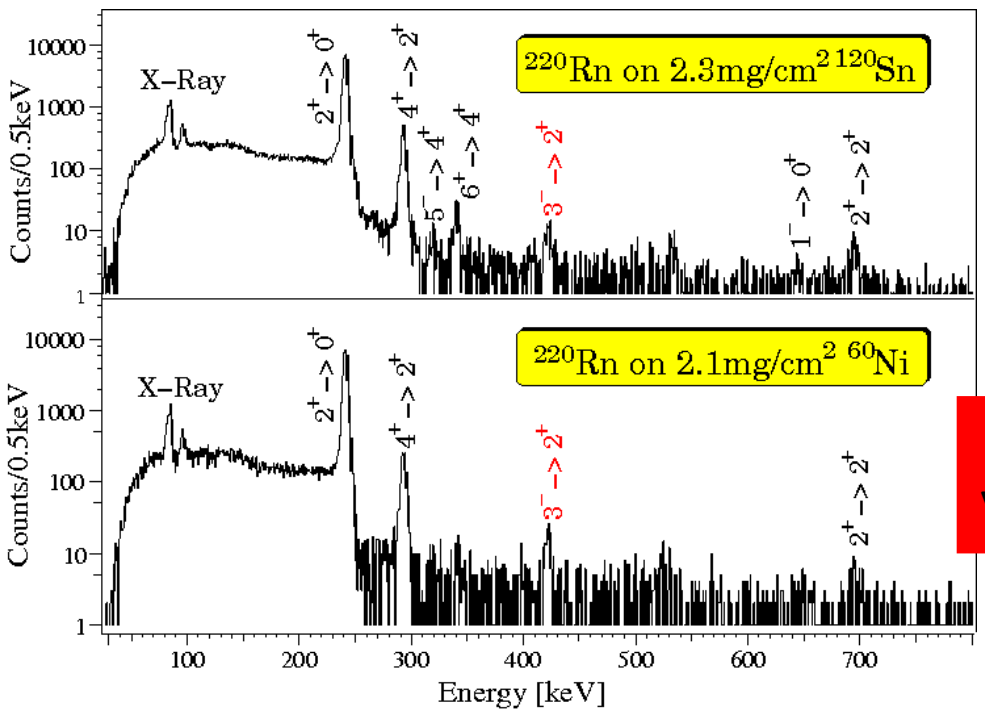

Disentangle one- and multi-step excitation paths

γ-ray yields

Literature (^{224}Ra)

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

GOSIA

Matrix elements

ISOLDE

Decay Transitions

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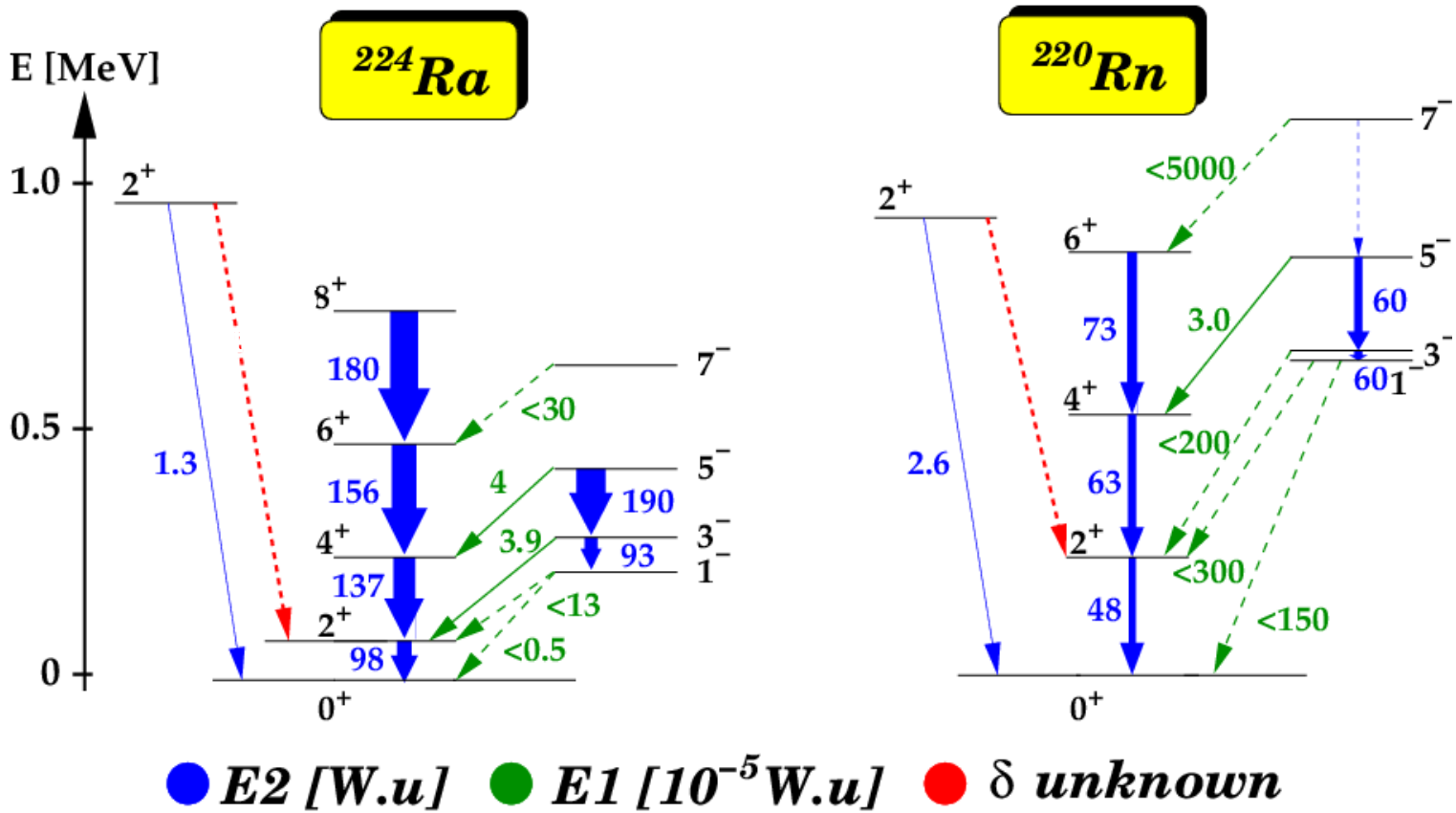

L.P. Gaffney *et al.*, Nature **497** (2013) 199

ISOLDE

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

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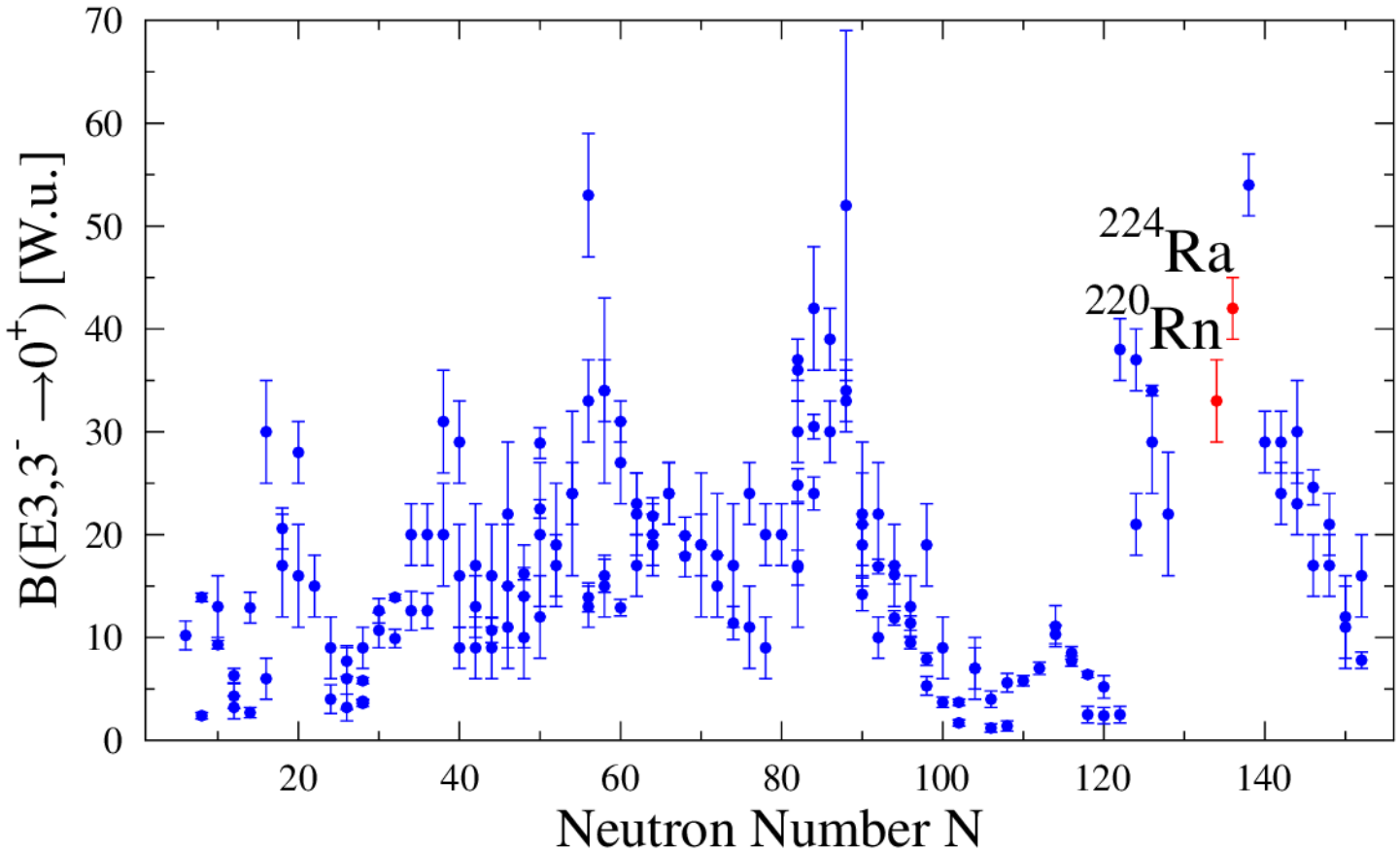
UWS



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

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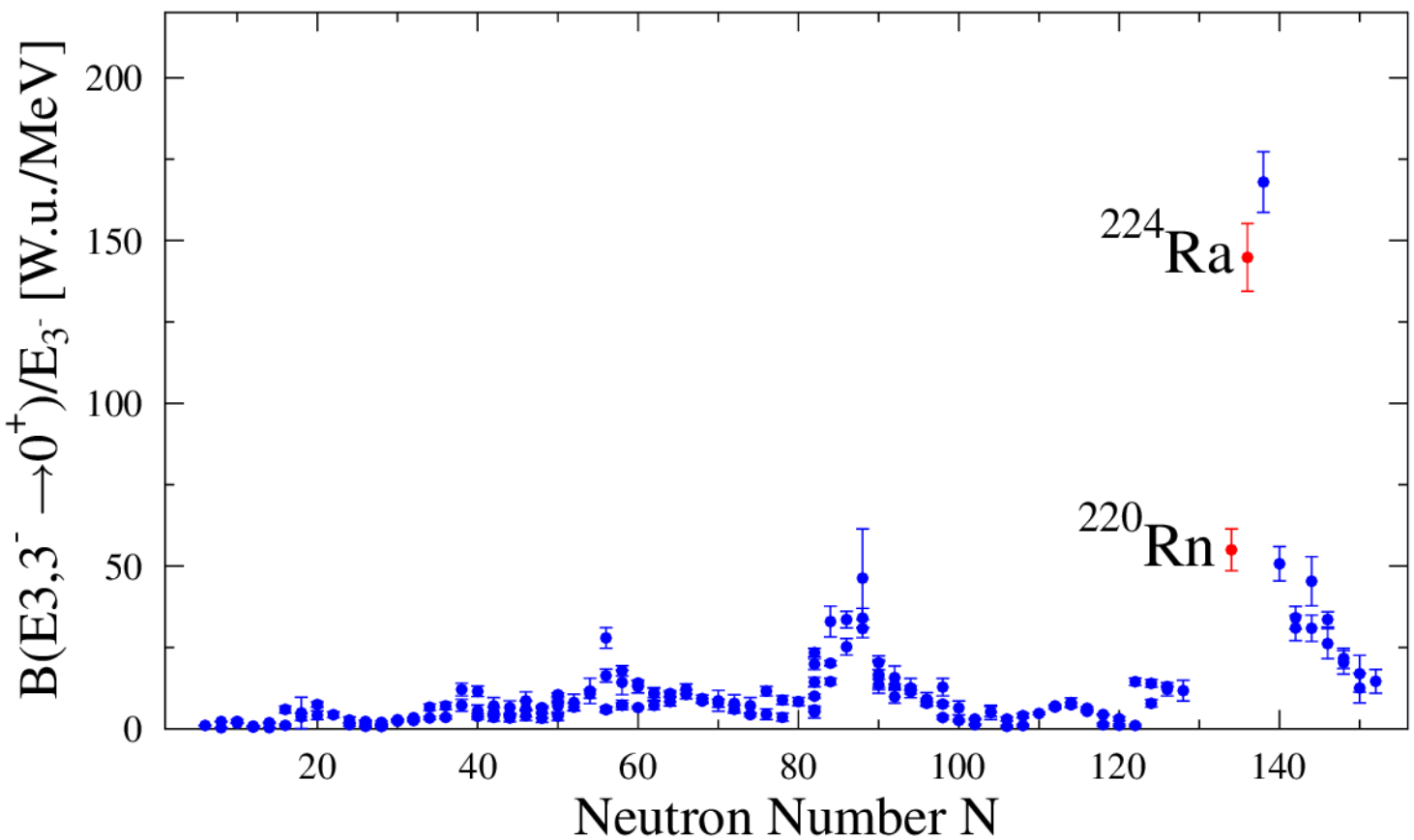
Inverse sum rule



Nuclear surface

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

Our experiments: β_2,β_3 & Theory*: β_4

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

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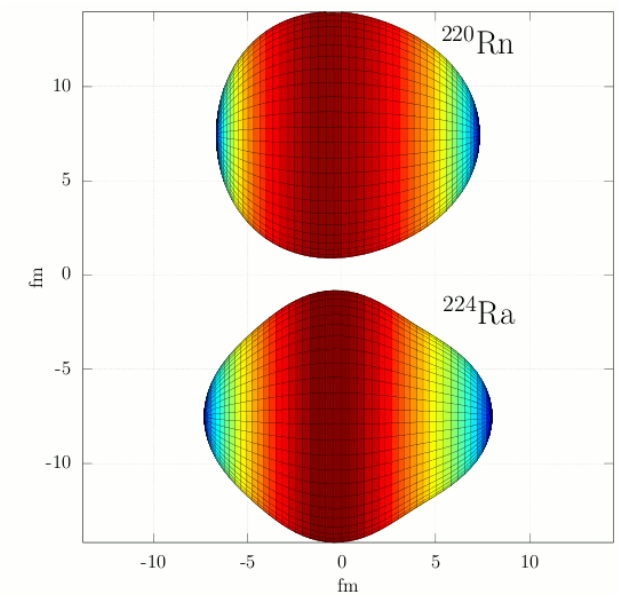

Nucleus	λ	β_λ
^{220}Rn	2	0.119
	3	0.095
	4	0.002*
^{224}Ra	2	0.154
	3	0.097
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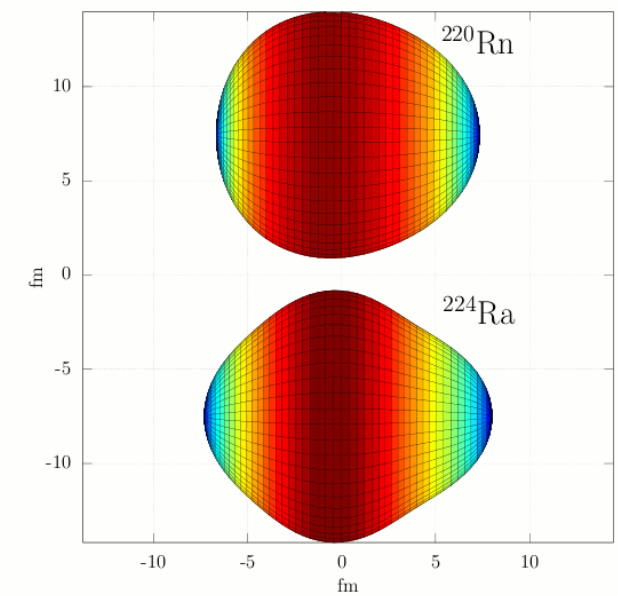

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ISOLDE

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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$\sim \beta_3 \beta_2$

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

Asymmetric proton distribution (Pear shape!)

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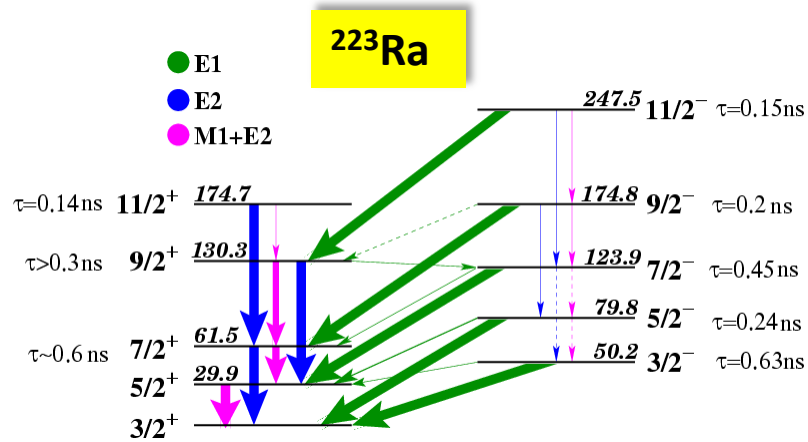

N.Auerbach, V.V.Flambaum, & V. Spevak PRL 76 (1996) 4316
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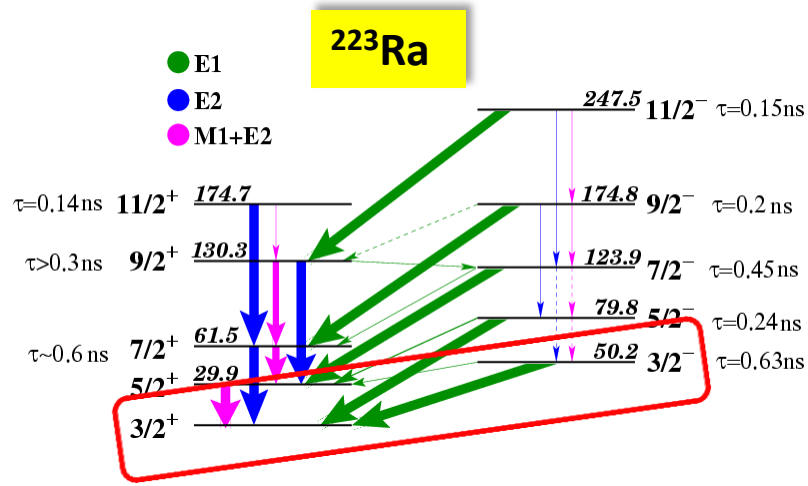

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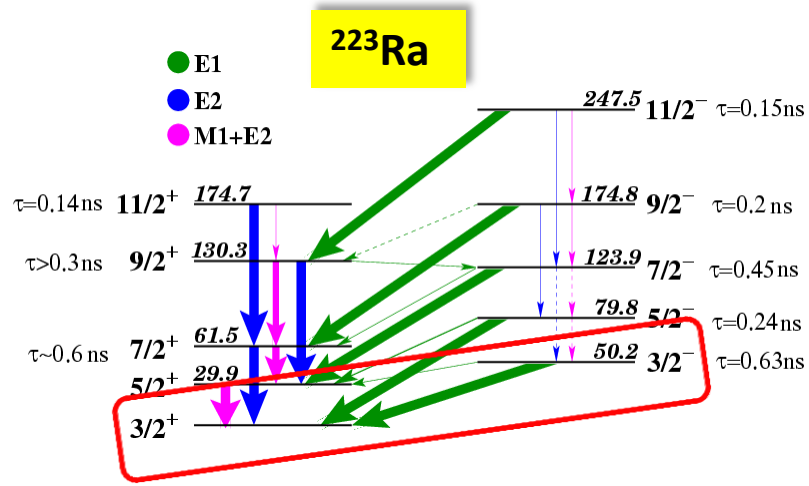

J=3/2-Parity doublet
π no longer a good QN
⇒ states mix

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Octupole deformation and CP violation

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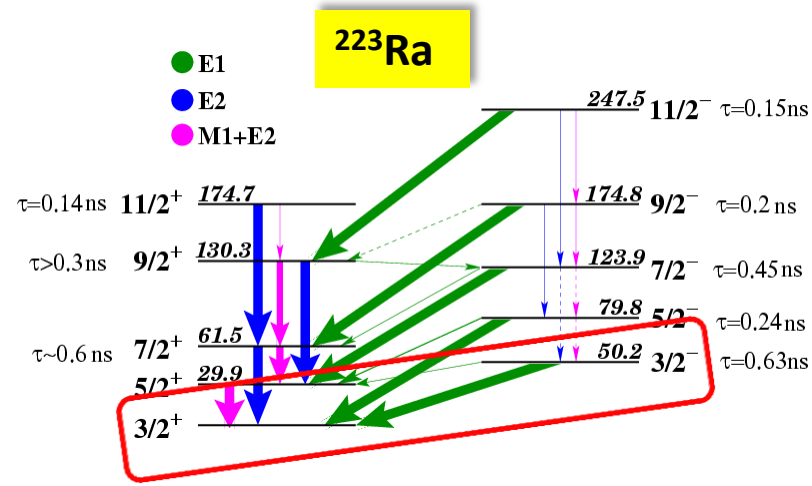

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Atomic system: $S_{at} = Z^3 S_{nucl}$

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Octupole deformation and CP violation

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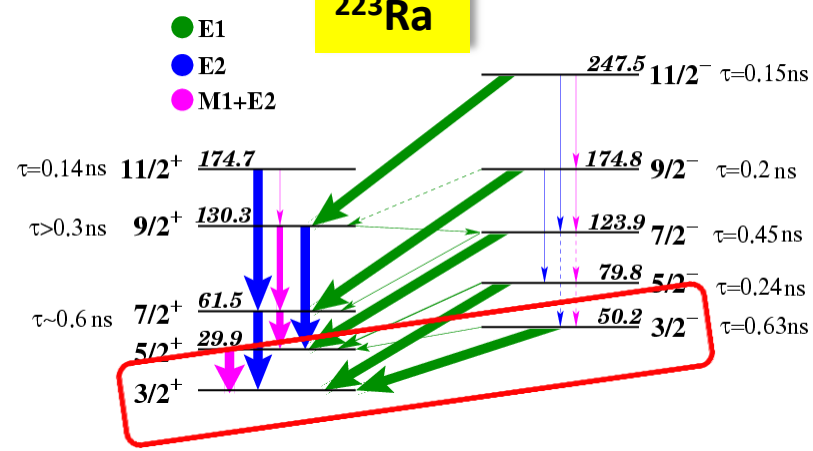
N.Auerbach, V.V.Flambaum, & V. Spevak PRL 76 (1996) 4316
J.Dobaczewski & J.Engel, PRL **94** (2005) 232502

^{223}Ra



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

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

K.Jungmann & L. Willmann (KVI) et al.,
⇒ Laser spectroscopy on ^{223,225}Ra

ISOLDE

Mid-term future?

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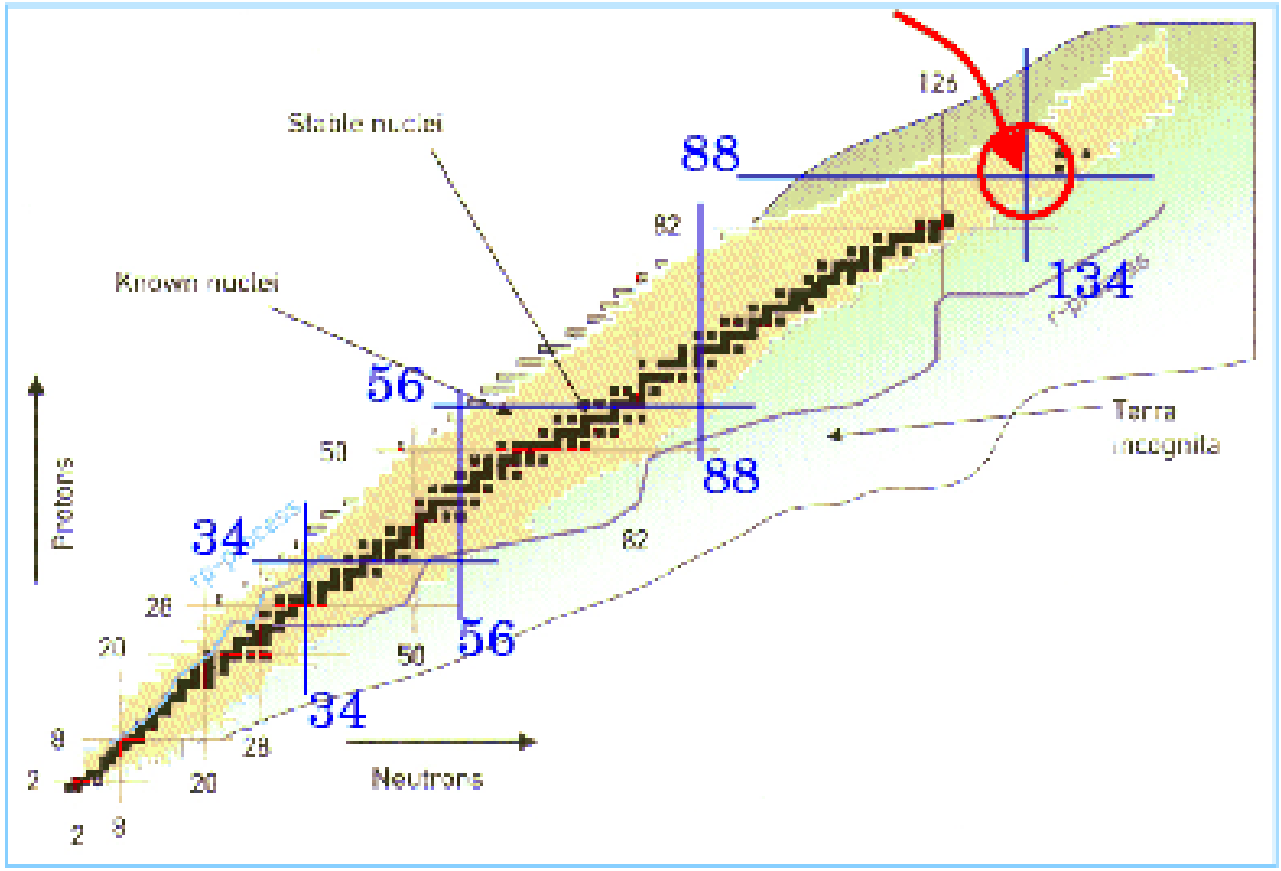
UWS

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



ISOLDE

Mid-term future?

UNIVERSITY OF THE WEST of SCOTLAND
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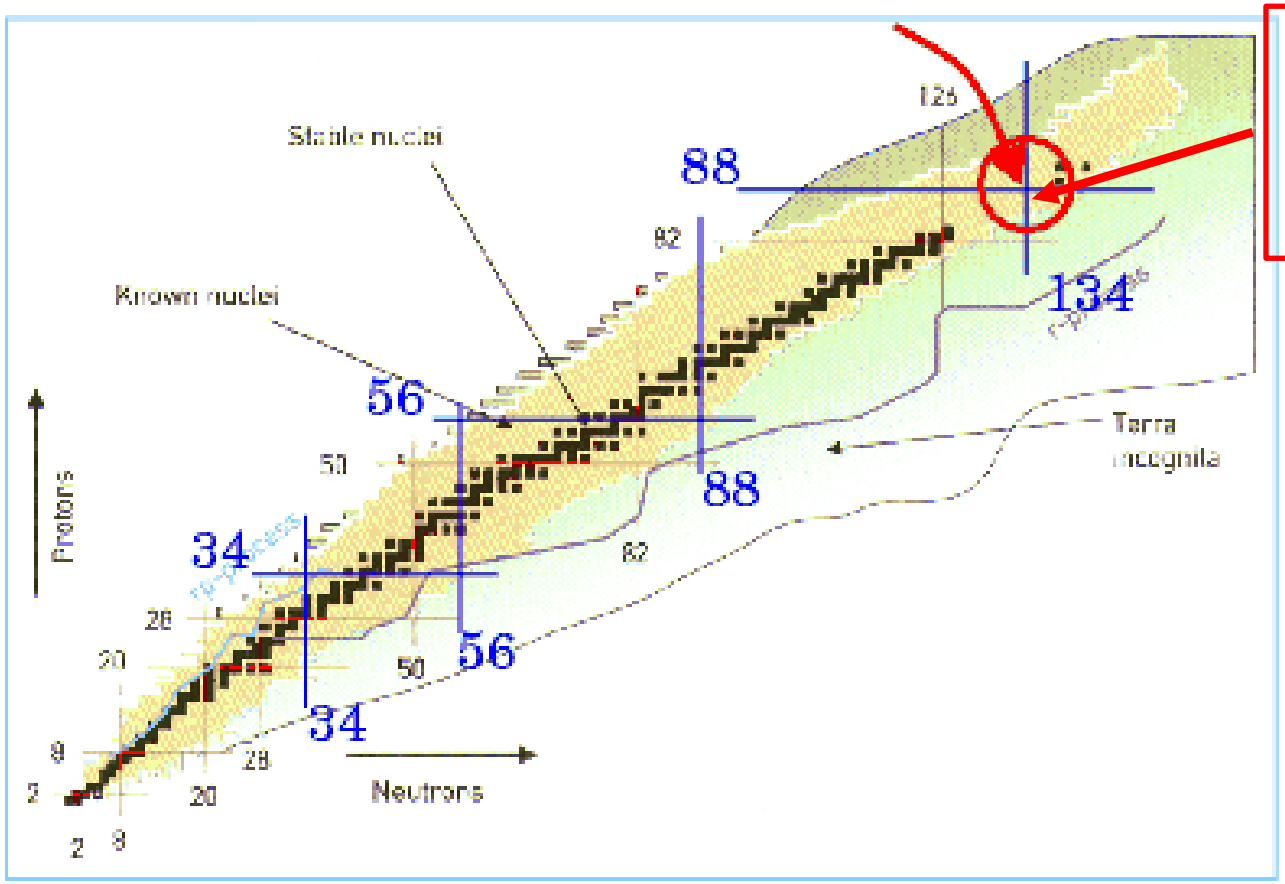

Beam development
β-decay
^{221,223}At → ^{221,223}Rn

ISOLDE

Mid-term future?

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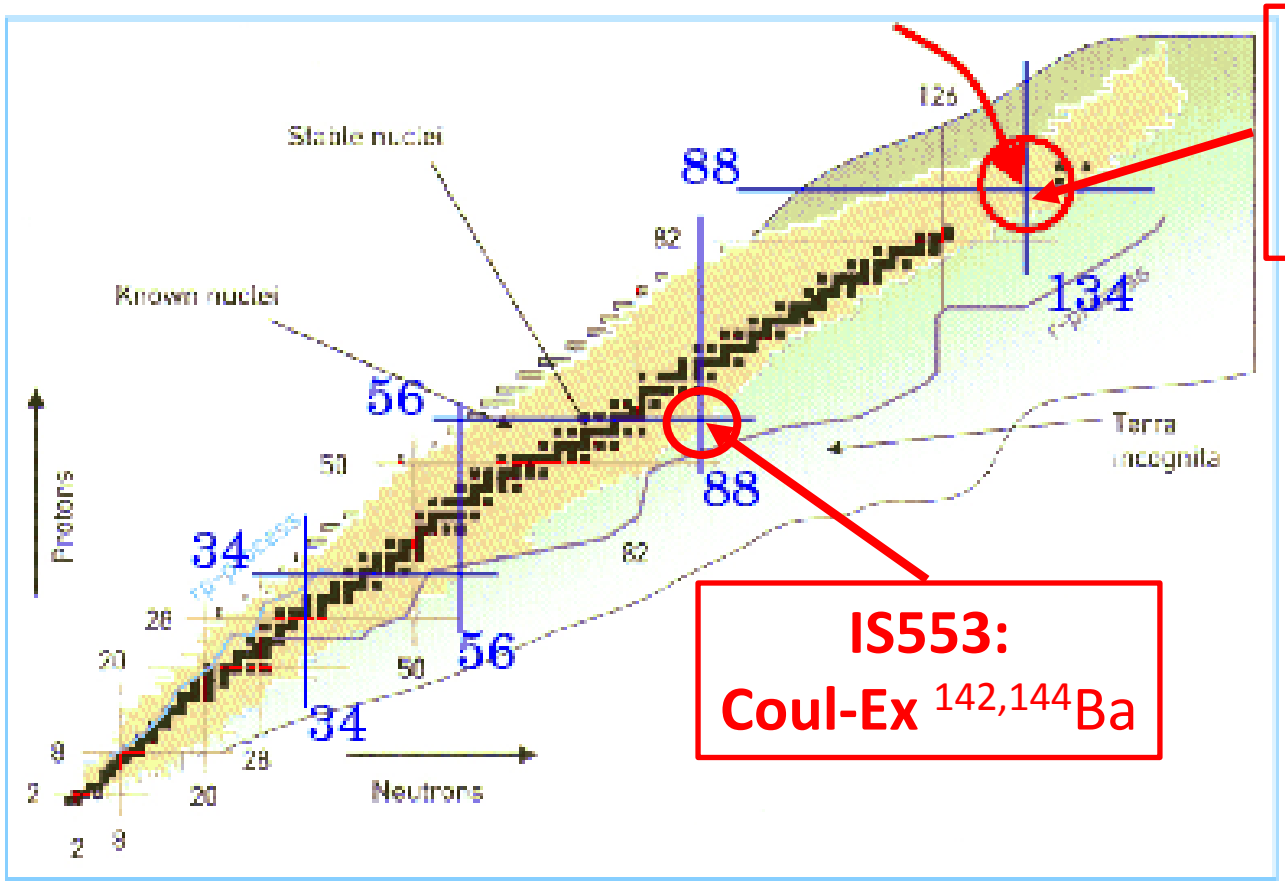
IS552:
Coul-Ex ^{222,226,228}Ra & ^{221,222}Rn



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

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

ISOLDE

I am 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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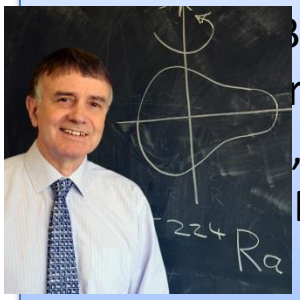

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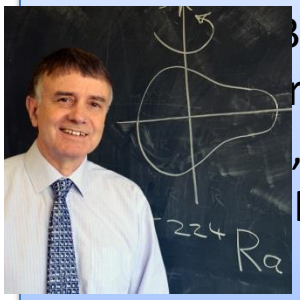

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…the ISOLDE beam operator crew

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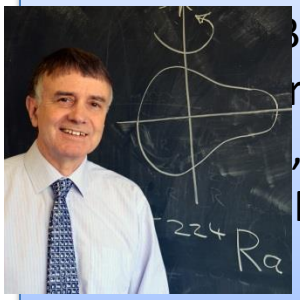


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…the ISOLDE beam operator crew

…the funding organizations! Especially:

Science & Technology Facilities Council

European Nuclear Science and Applications Research ENSAR

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Why odd-mass?

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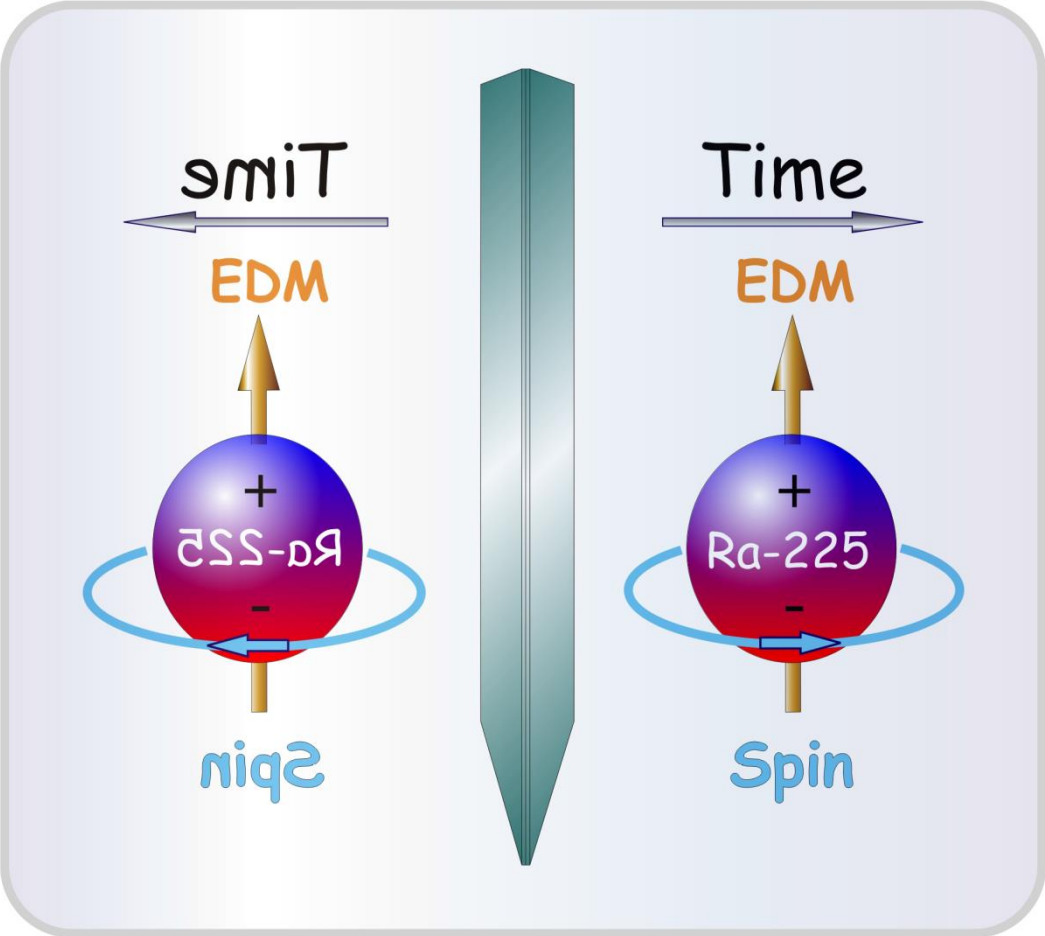
UWS



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^{224}Ra: Comparison to Theory

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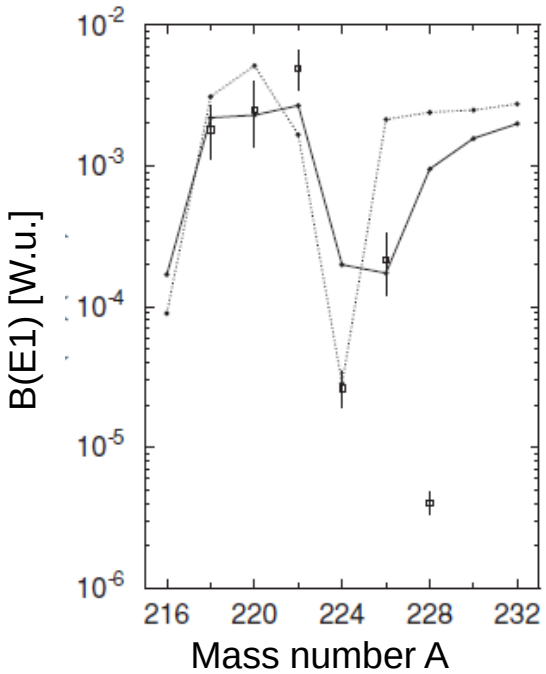
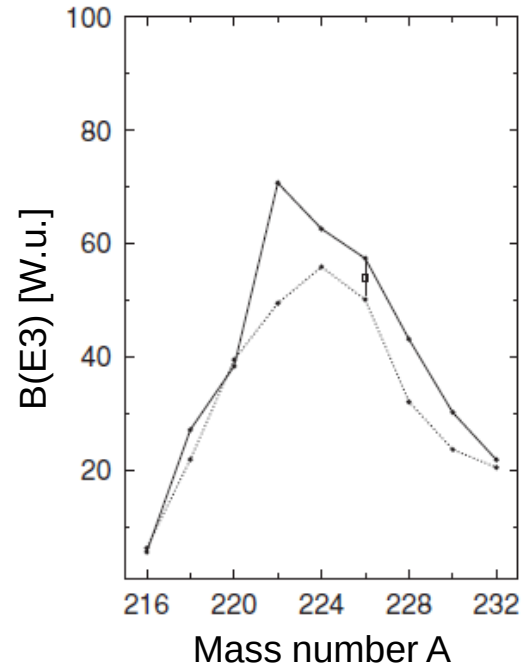
B(E1, $1^- \mapsto 0^+$)



BCP:
Barcelona-Catania Paris
Energy Density Functional

D1S:
HFB Mean-Field
(D1S Gogny Force)

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



L.M.Robledo et al., PRC 81 (2010) 034315

ISOLDE

^{224}Ra: Comparison to Theory

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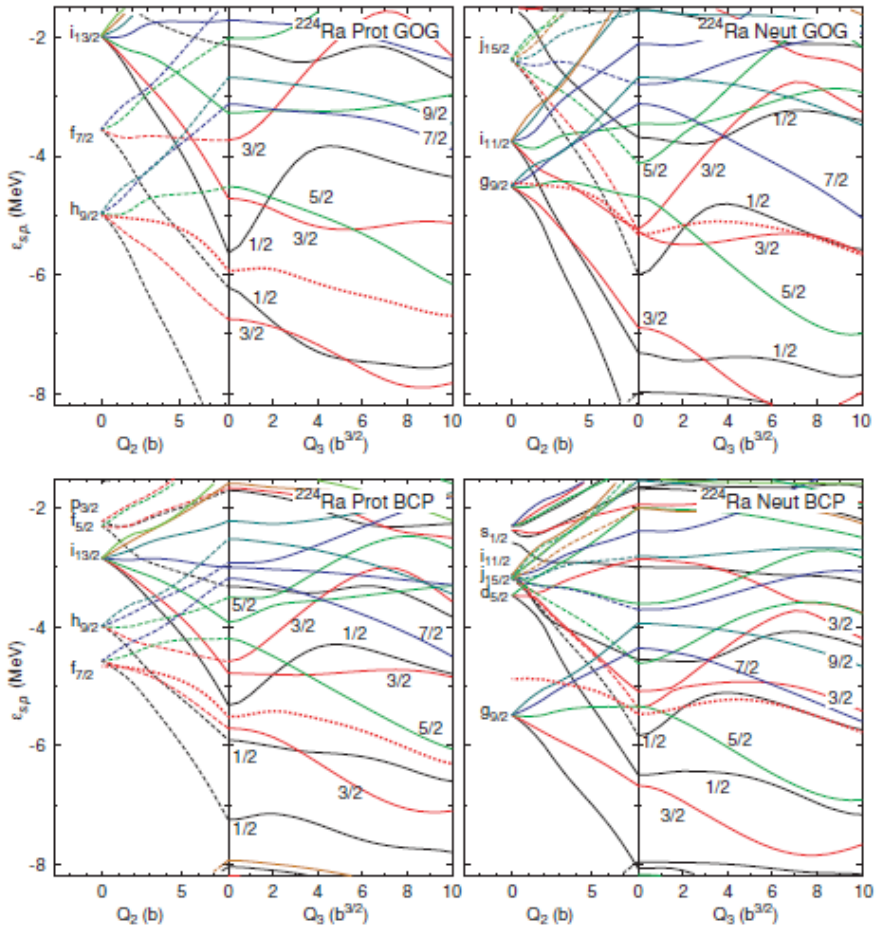

GOC/D1S:
Hartree-Fock Bogoliubov
(Gogny D1S Force)

BCP:
Barcelona Catania Paris
Energy Density Functional

L.M.Robledo et al., Phys.Rev.C 81 (2010) 034315

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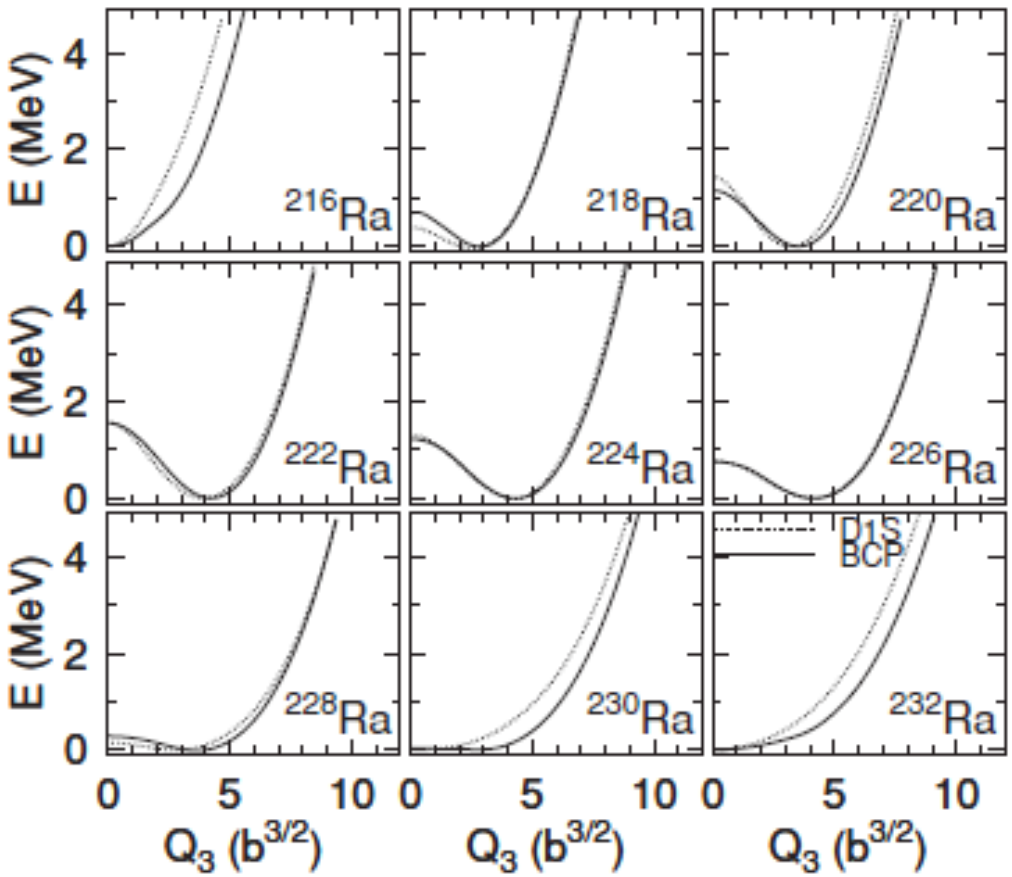

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L.M.Robledo et al., Phys.Rev.C 81 (2010) 034315

ISOLDE

E1 moments in nuclei

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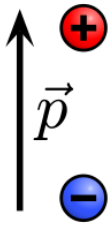
Electric dipole

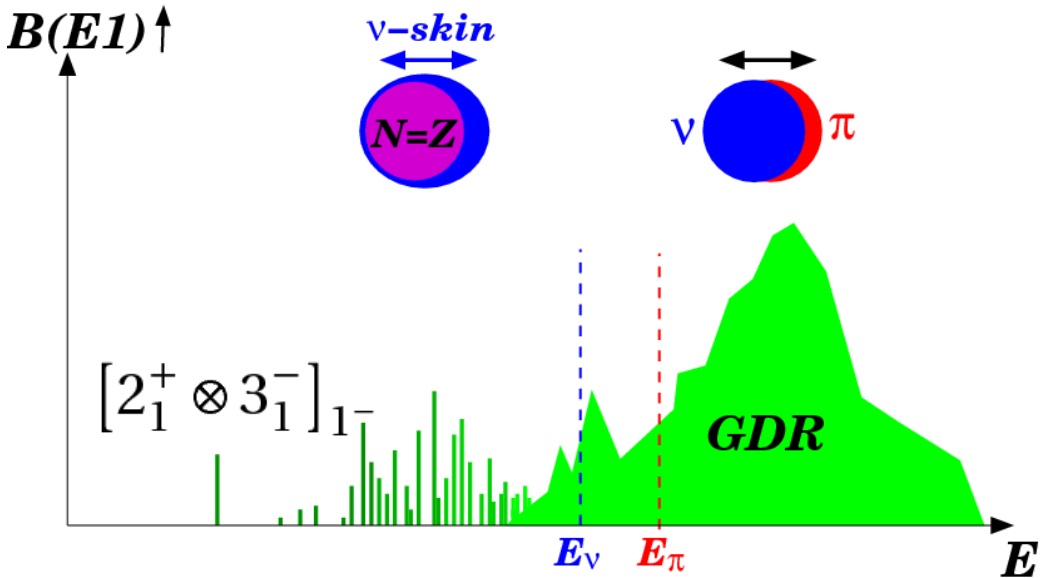


Not possible!!!
Only protons are charged

Mechanism

Divide center of charge and center of mass

E1 strength in spherical nuclei?



ISOLDE

Coupling quadrupole and octupole degrees-of-freedom

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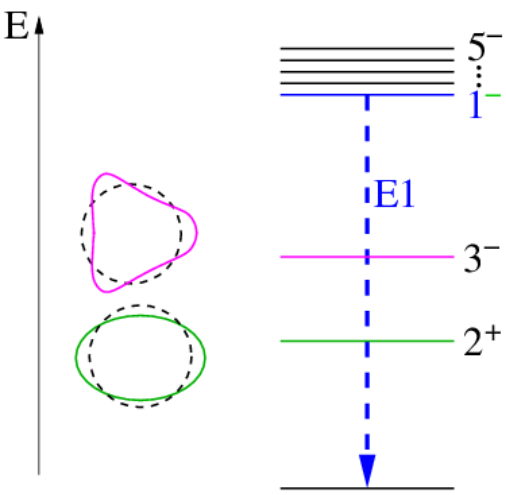
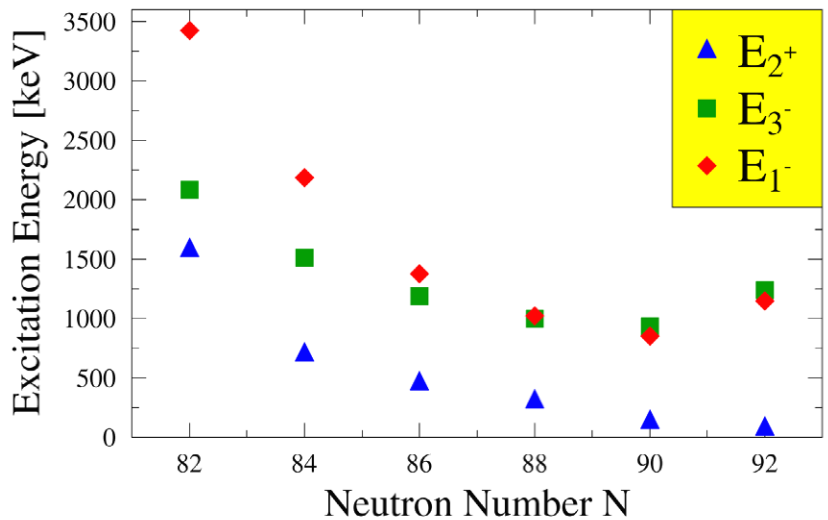
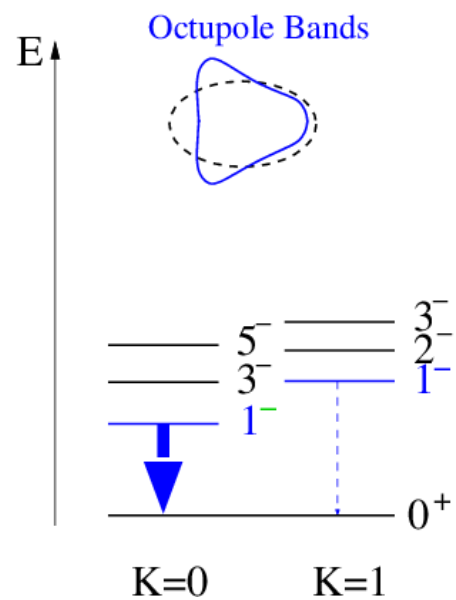
Spherical nucleus

Quadrupole deformed nucleus



Example: Nd-isotopic chain

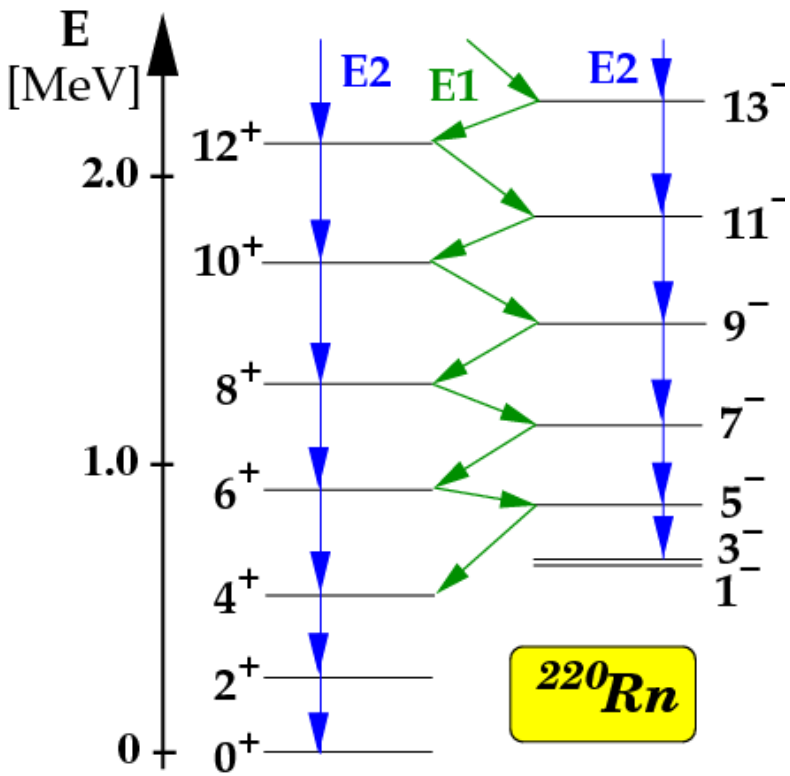




Question: Are there nuclei that have a static octupole deformation?
Nuclear Schiff moment?

ISOLDE

Odd-even parity levels: energy differences



J.F.Cocks, P.A.Butler et al., PRL **78**, 2920 (1997)

Odd-even parity levels: energy differences

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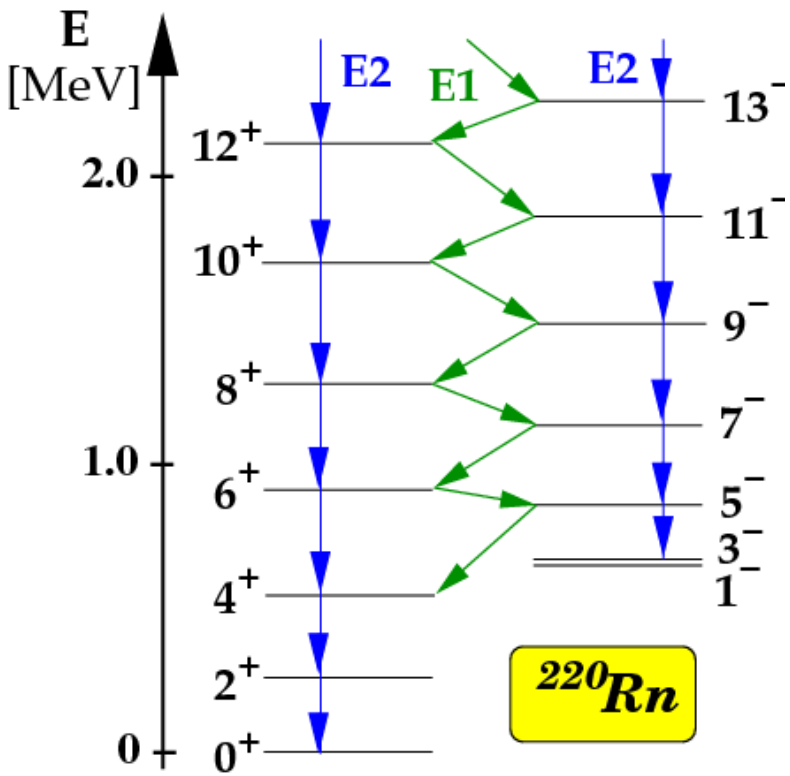

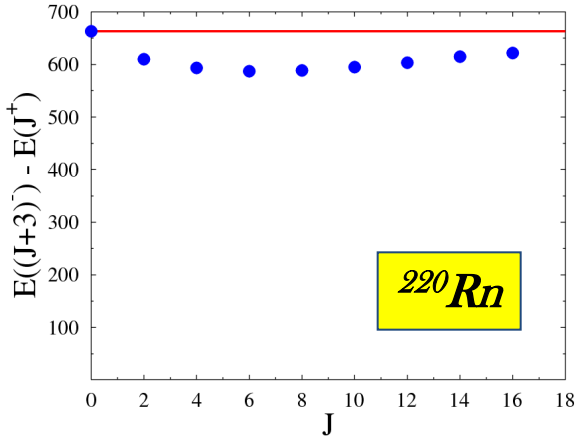

J.F.Cocks, P.A.Butler et al., PRL **78**, 2920 (1997)

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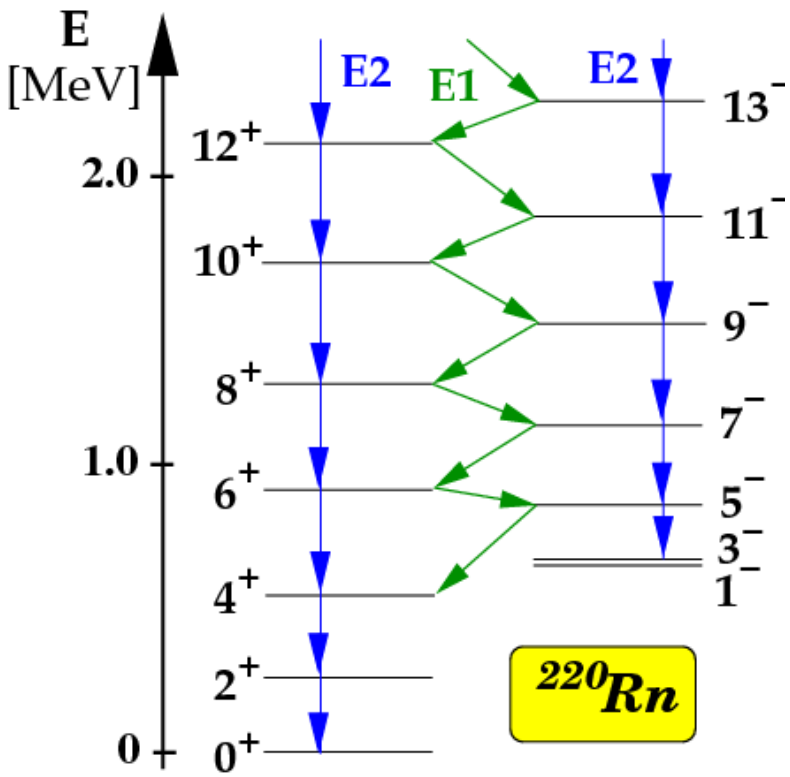

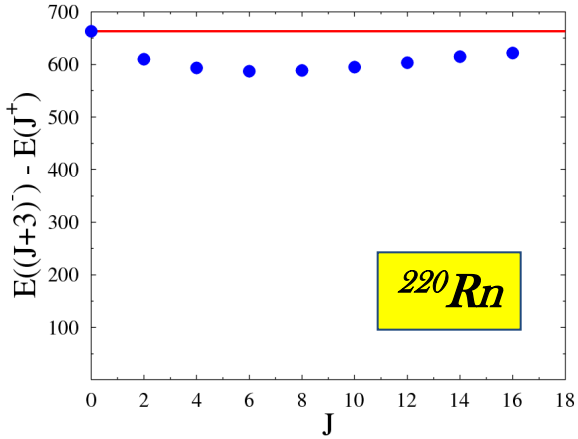

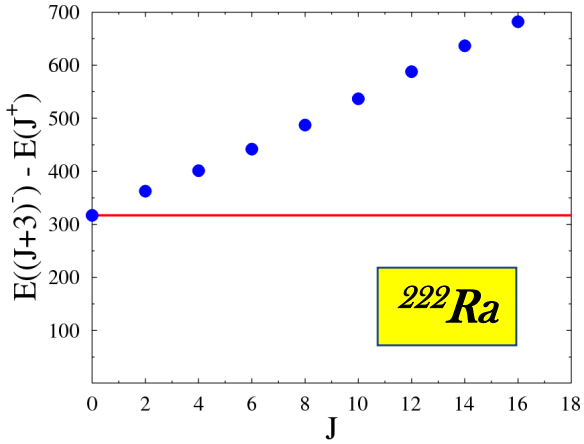

J.F.Cocks, P.A.Butler et al., PRL **78**, 2920 (1997)

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Production of ISOL-Radioactive Ion Beams

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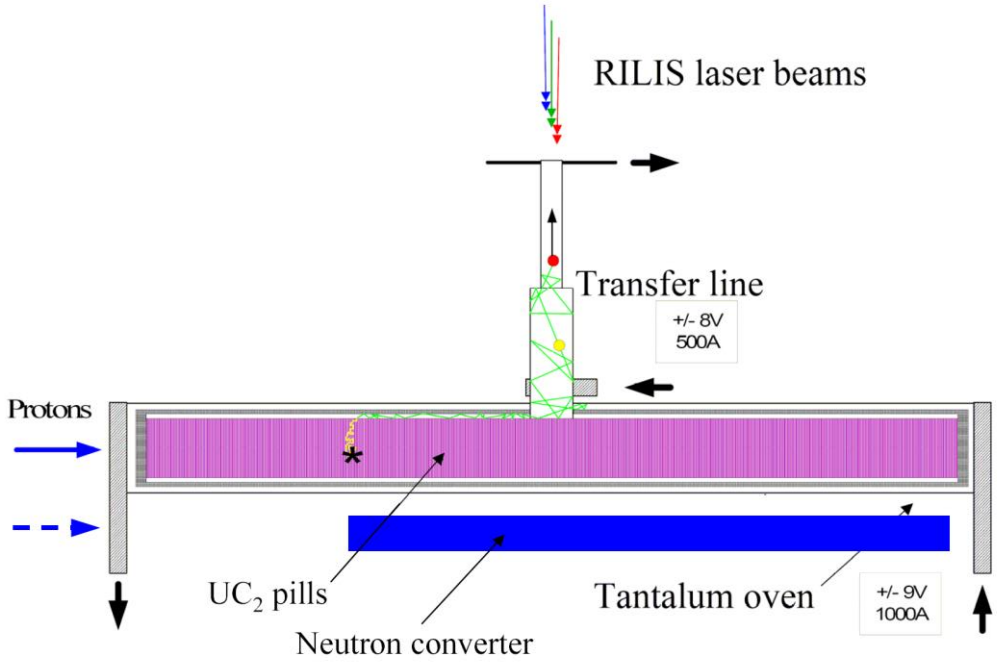
Physical processes

^{238}U binding energy: 1.8 GeV

1. Spallation ⇒ heavy nucleus
2. Fission ⇒ medium mass nucleus
3. Fragmentation ⇒ light nucleus

Target Outline



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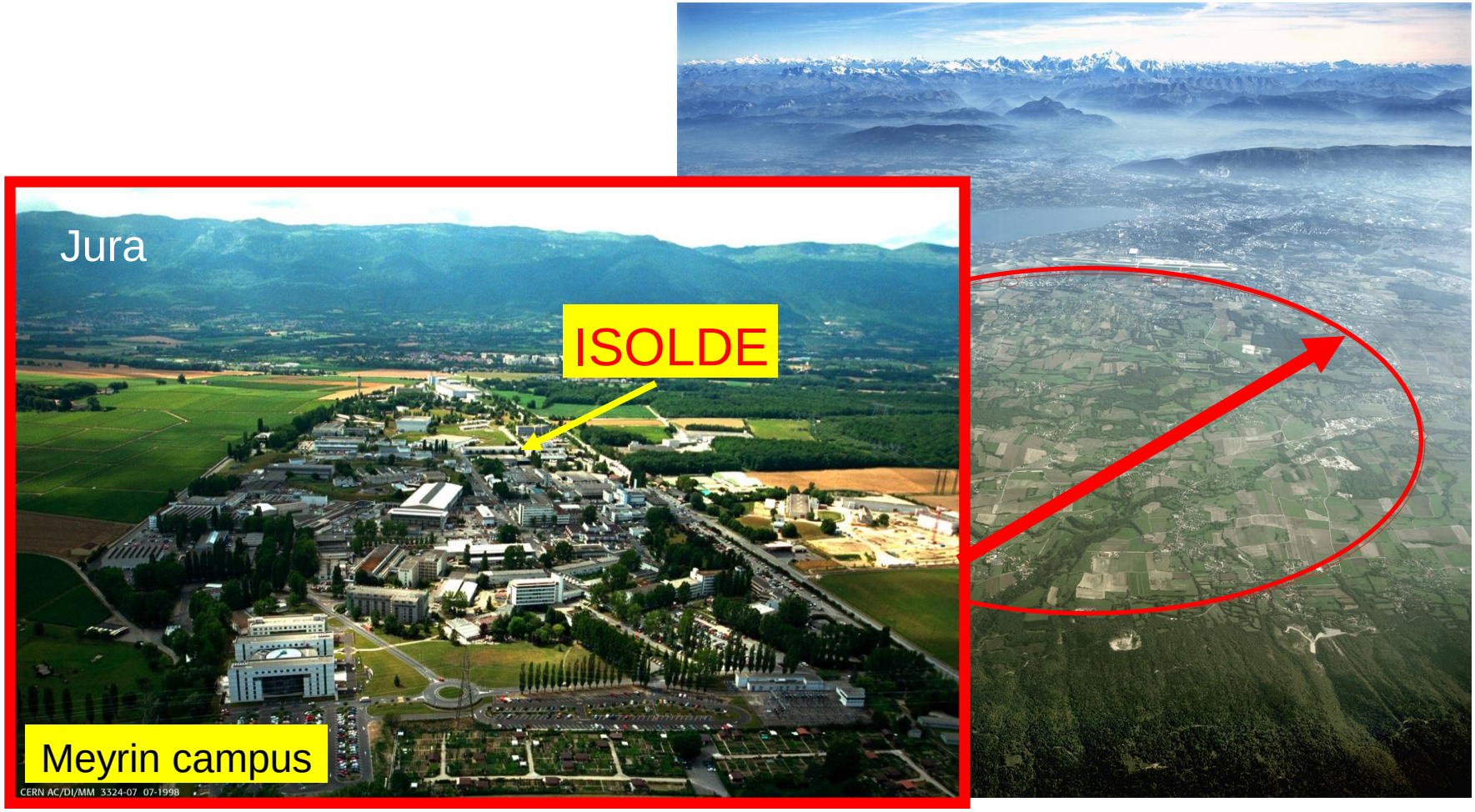

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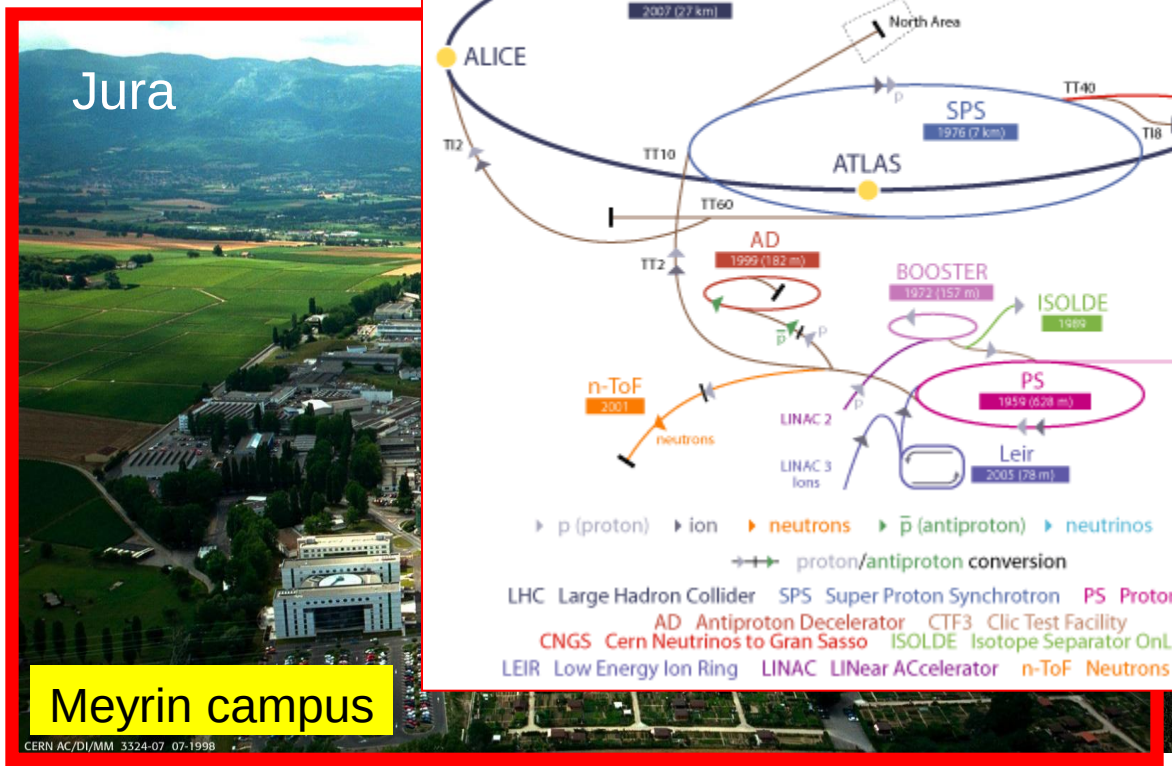

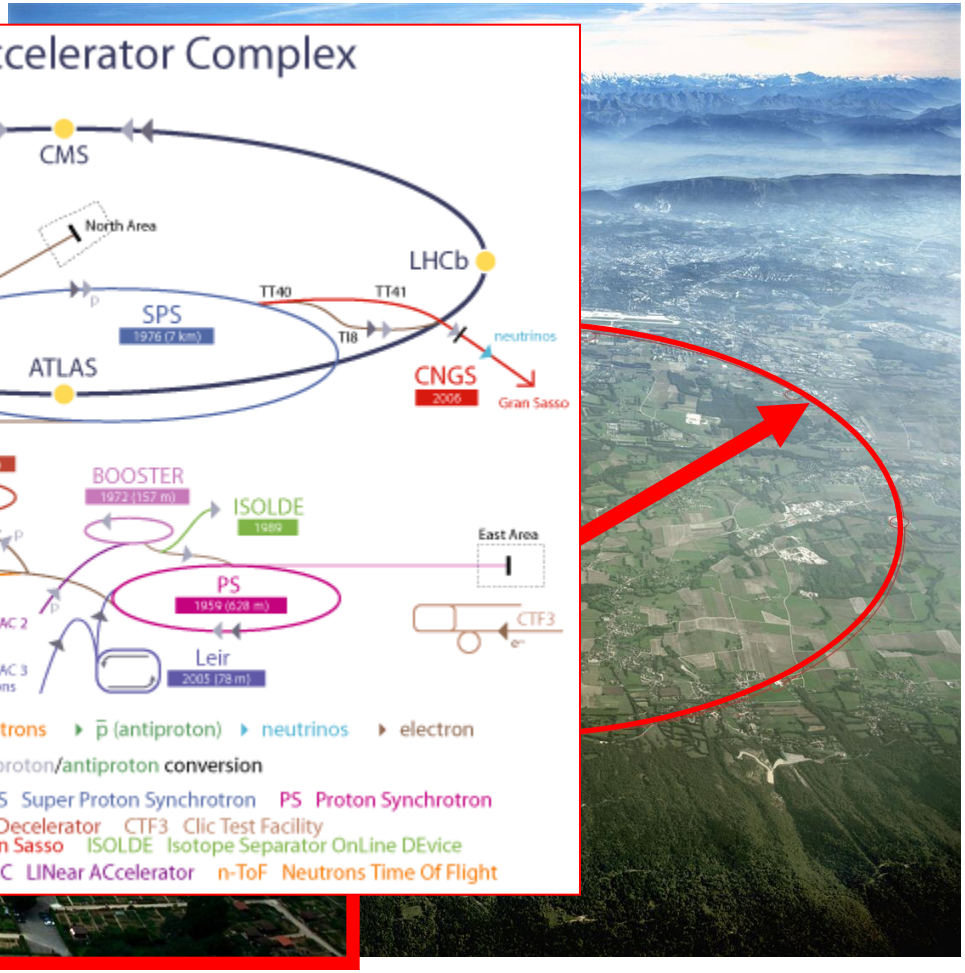

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