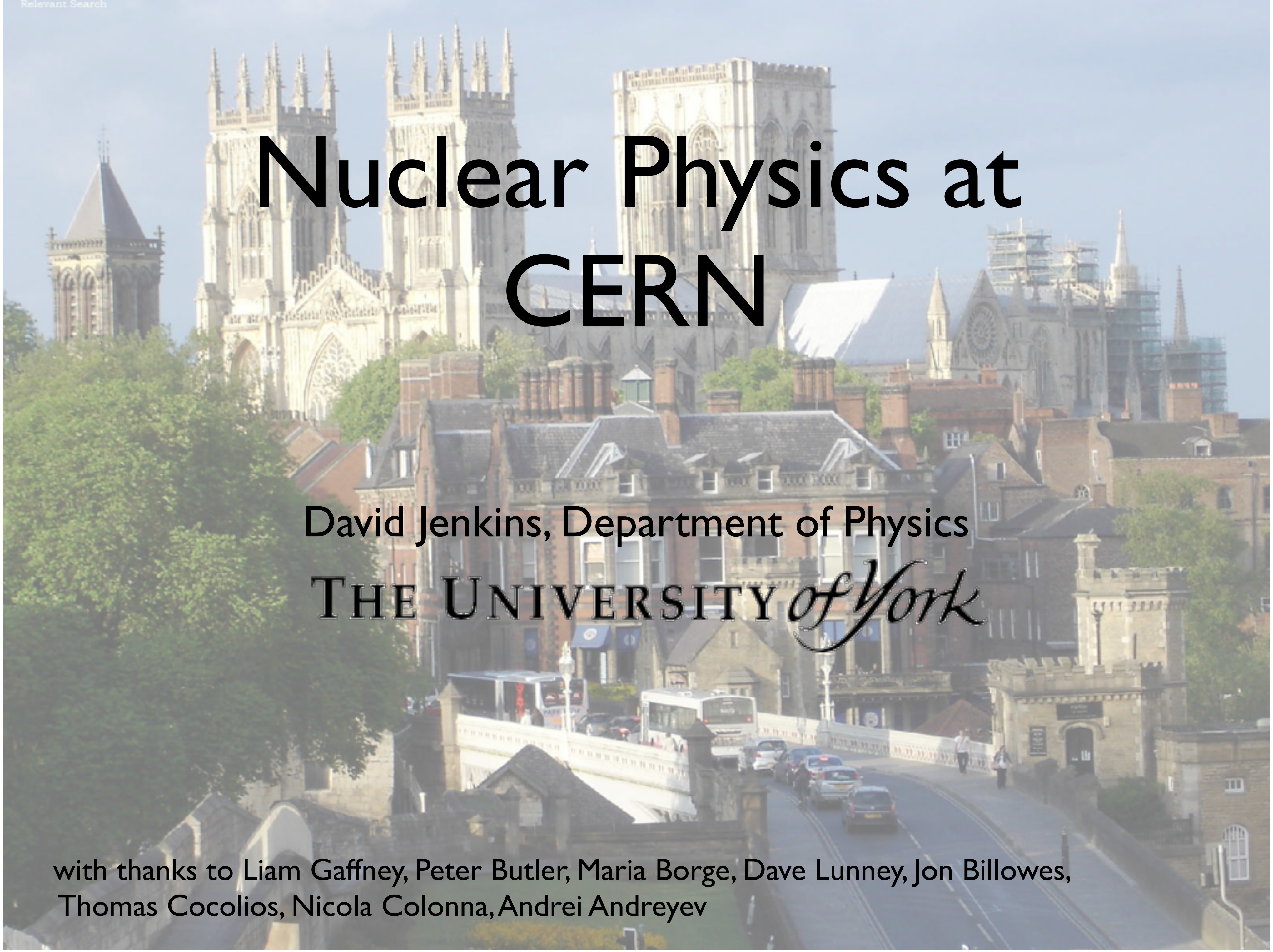


Nuclear Physics at CERN

David Jenkins, Department of Physics

THE UNIVERSITY of York

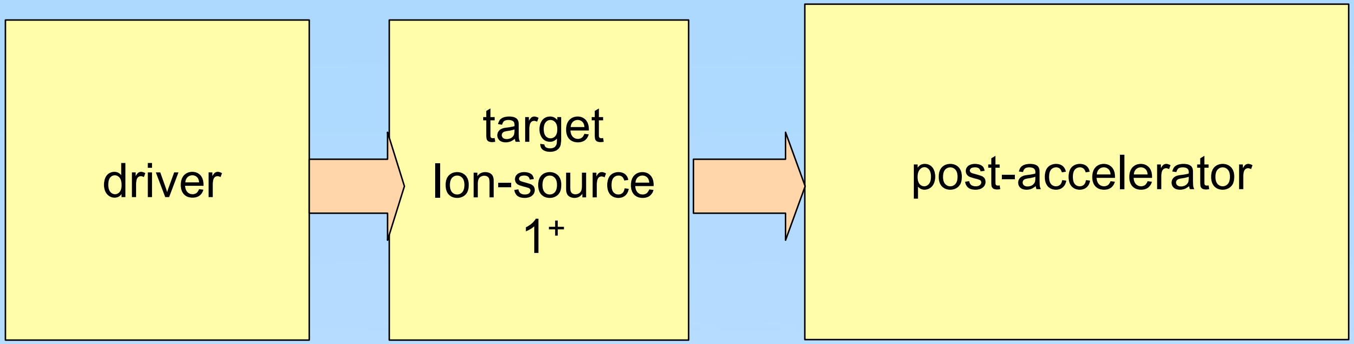
with thanks to Liam Gaffney, Peter Butler, Maria Borge, Dave Lunney, Jon Billowes, Thomas Cocolios, Nicola Colonna, Andrei Andreyev

Lecture 2: Accelerated radioactive ion beams

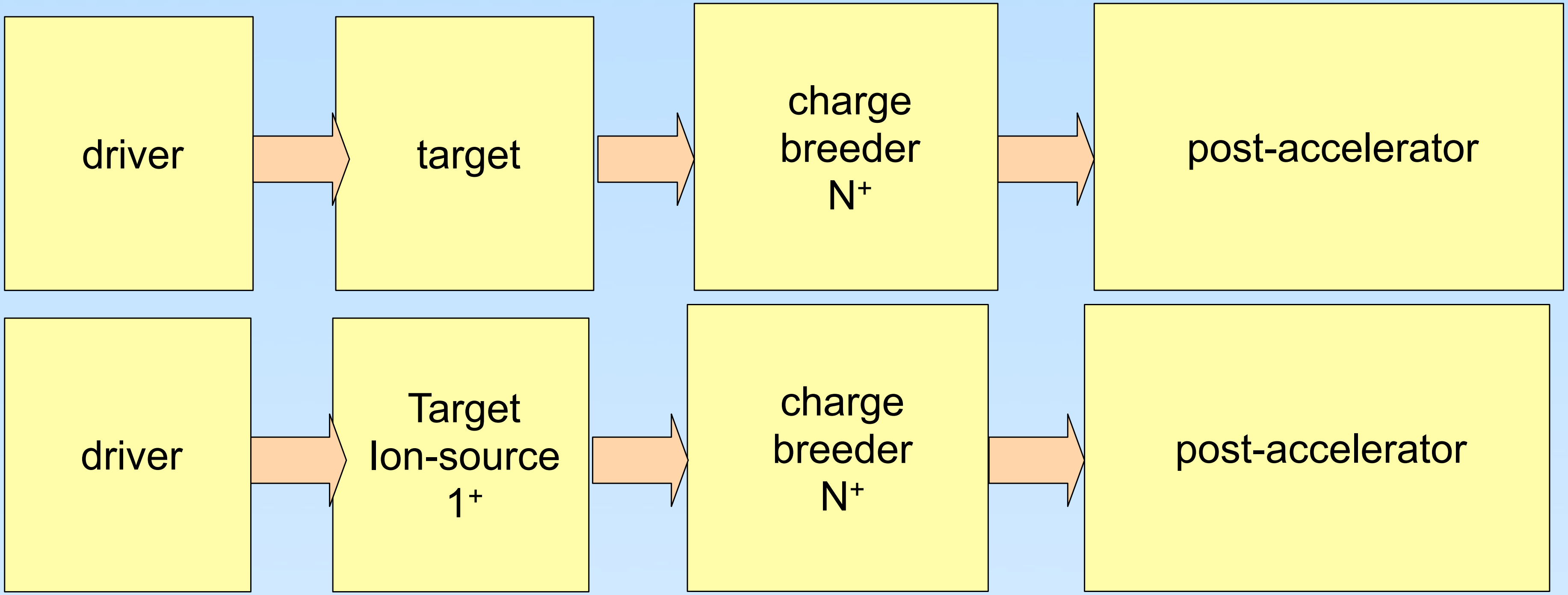
- -Accelerated radioactive beams
- -The REX-ISOLDE facility
- -The HIE-ISOLDE project

Accelerated beams

Production of charged ions for accelerator

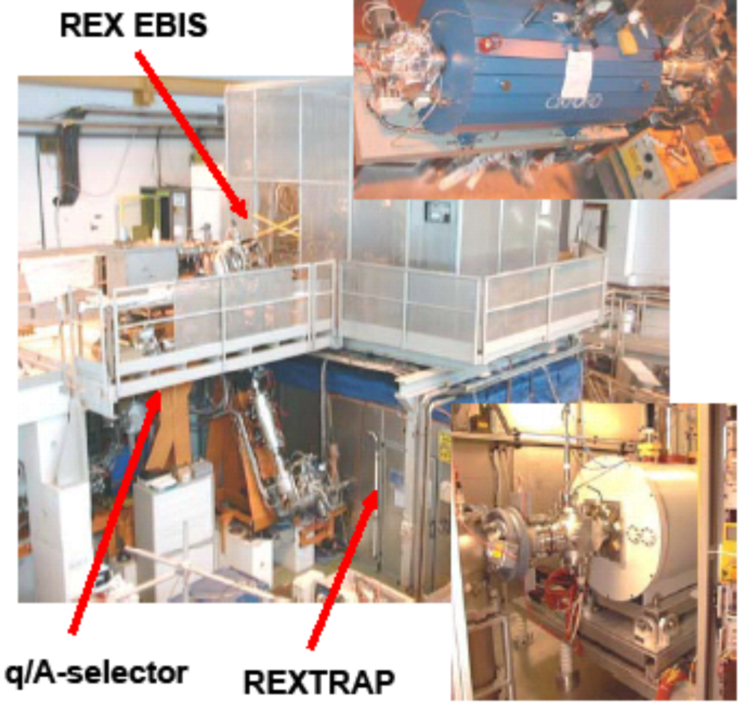


ECR or EBIS	ECR	EBIS
Mode:	CW	pulsed
background:	100pA	0.1pA
Max current	10μA	1nA
A/q	4-9	2.5-4.5

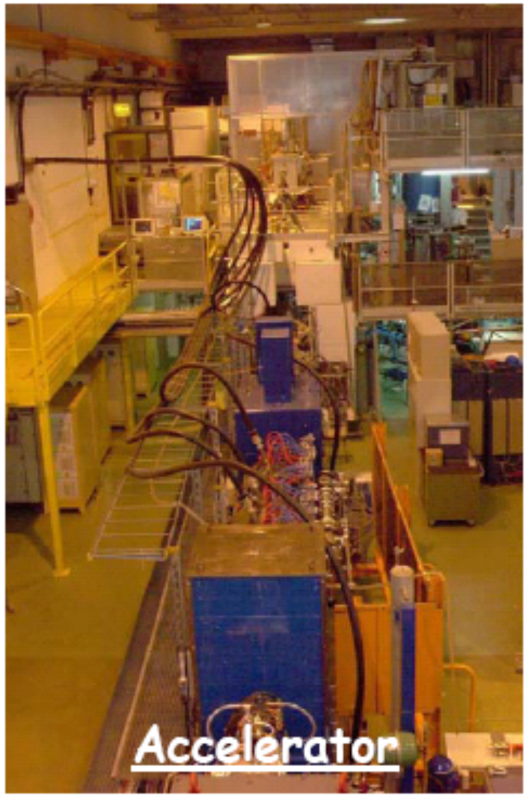


Peter Butler http://ns.ph.liv.ac.uk/pab/EFermi.pdf

REX-ISOLDE

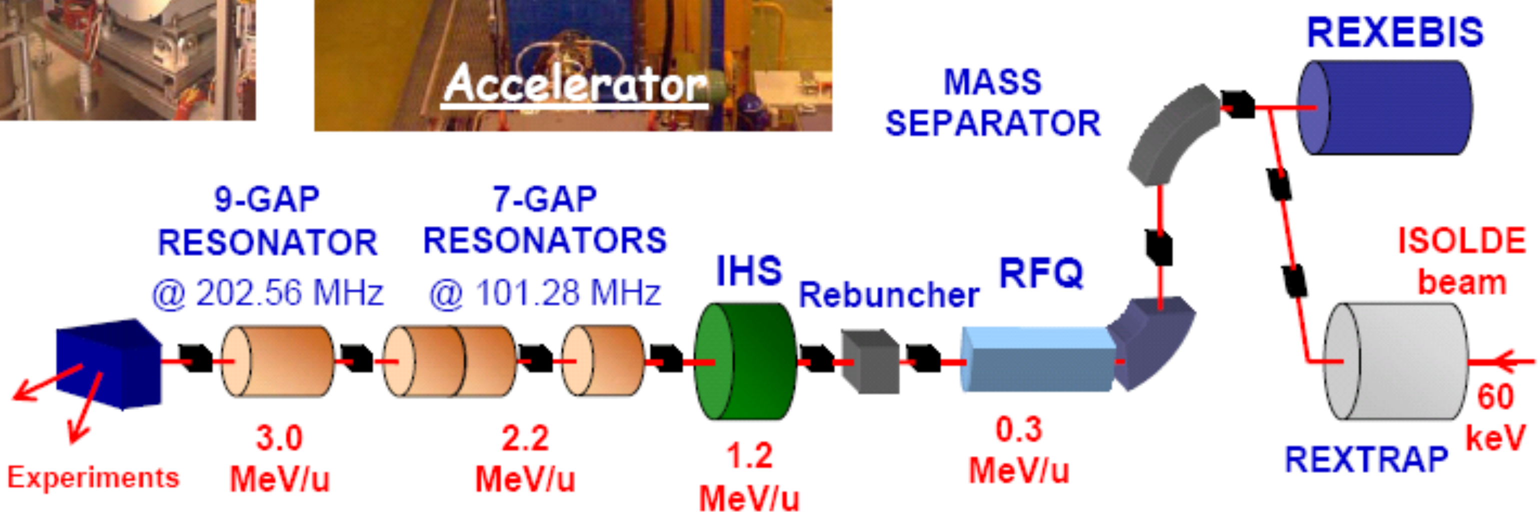


Charge Breeder

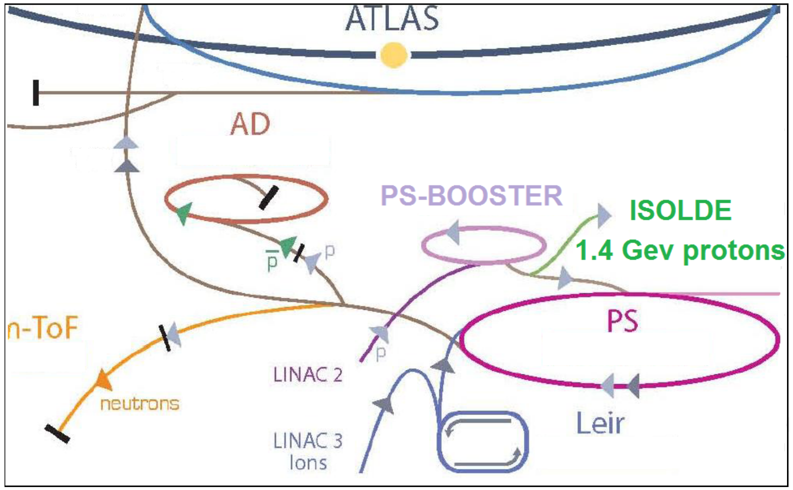


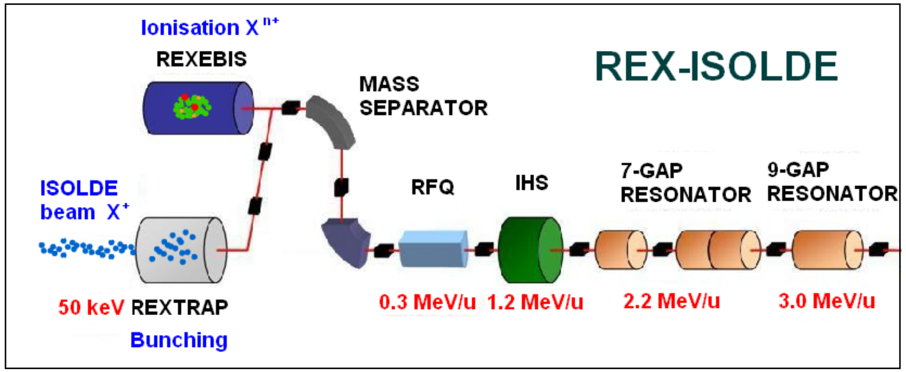
Efficiencies
(design values):

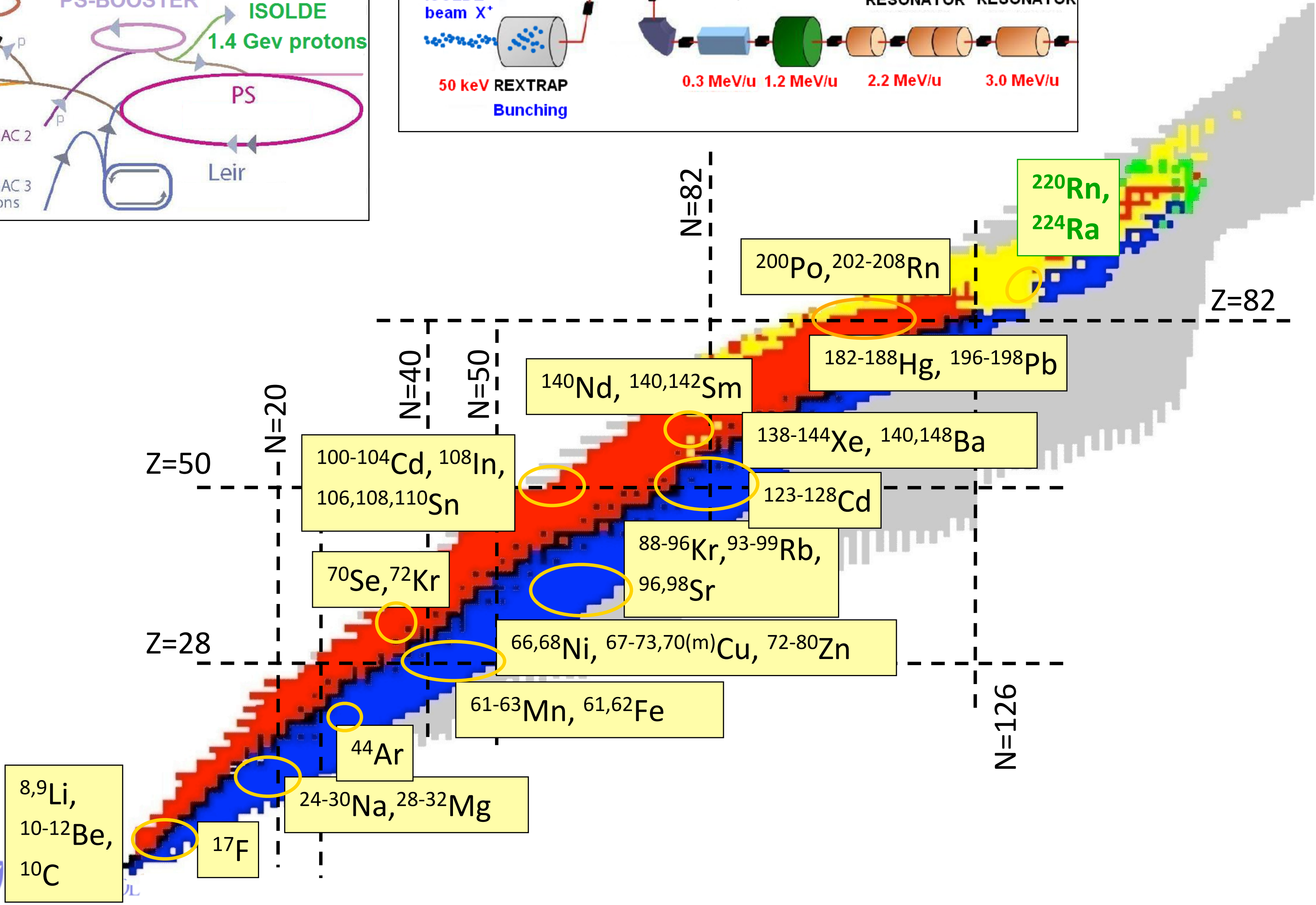
Trap Bunching:	90%
Beam Transport:	>85%
EBIS Injection:	>50%
EBIS Qi/ΣQi:	30%
Linac:	90%



Radioactive beams at REX-ISOLDE (CERN)





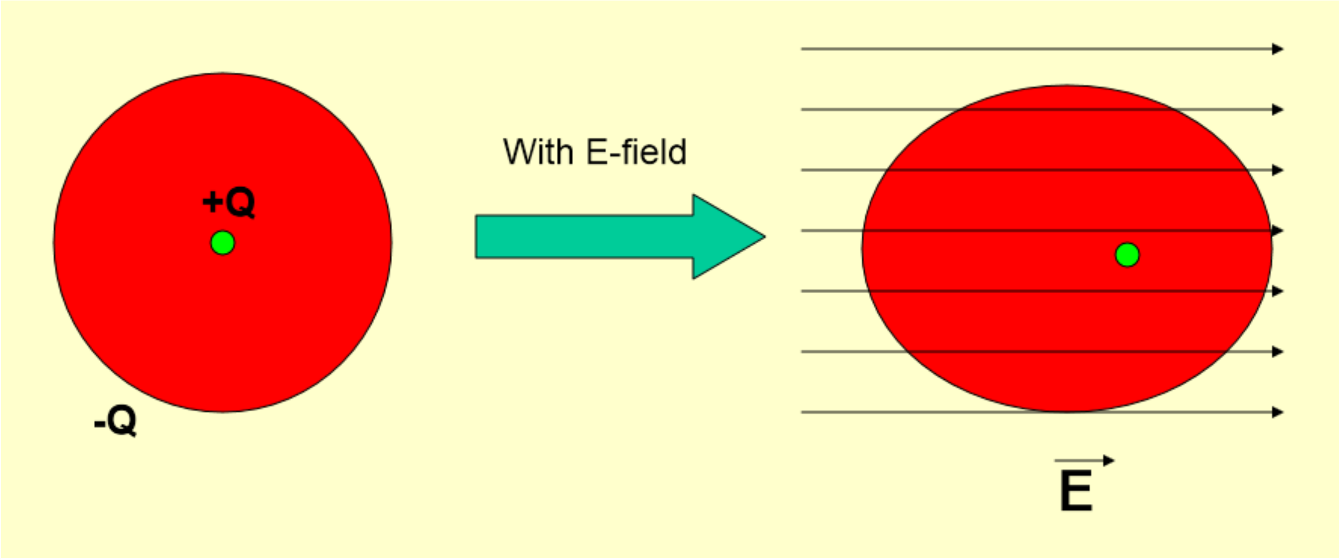


World ISOL accelerated beams

FACILITY	DRIVER	POWER	USER BEAMS ACCELERATED	ENERGY
LOUVAINE-LA-NEUVE (BELGIUM) 1989-2008	30 MeV protons	6 kW	^{6}He, ^{7}Be, ^{10,11}C, ^{13}N, ^{15}O, ^{18}F, ^{18,19}Ne, ^{35}Ar	10 MeV/u cyclotron
HRIBF Oak Ridge (USA) 1997	100 MeV p, d, α (-ve ion source)	1 kW	^{7}Be, ^{17,18}F, ^{69}As, $^{76\text{-}79}$Cu, $^{67,83\text{-}85}$Ga, $^{78,82\text{-}86}$Ge, ^{69}As, ^{83,84}Se, ^{92}Sr, ^{117,118}Ag, $^{126,128,132\text{-}136}$Sn, ^{129}Sb, ^{129,132,134,136}Te	2 - 10 MeV/u tandem
ISAC TRIUMF (CANADA) 2000	500 MeV protons	50 kW	^{8,9,11}Li, ^{11}Be, ^{18}F, $^{20\text{-}22,\ 24\text{-}29}$Na, ^{23}Mg, ^{26}Al	1.5 - 6 MeV/u linac
SPIRAL GANIL (FRANCE) 2001	100 MeV/u heavy ions	6 kW	^{6,8}He, $^{14,15,19\text{-}21}$O, ^{18}F, $^{17\text{-}19,23\text{-}26}$Ne, $^{33\text{-}35,\ 44,46}$Ar, $^{74\text{-}77}$Kr	2 - 25 MeV/u cyclotron
REX ISOLDE (CERN) 2001	1.4 GeV protons	3 kW	^{8,9,11}Li, $^{10\text{-}12}$Be, ^{10}C, ^{17}F, $^{24\text{-}29}$Na, $^{28\text{-}32}$Mg, ^{61,62}Mn, ^{61}Fe, ^{68}Ni, $^{67\text{-}71,73}$Cu, ^{74,76,78,80}Zn, ^{70}Se, ^{88,92}Kr, ^{96}Sr, ^{108}In, ^{106,108,110}Sn, ^{122,124,126}Cd, ^{138,140,142,144}Xe, ^{140,142,148}Ba, ^{148}Pm, ^{153}Sm, ^{156}Eu, ^{182,184,186,188}Hg, ^{202,204}Rn	0.3 - 3 MeV/u linac

Example 1: Octupole collectivity

Atomic EDM moment



Static Electric Dipole Moment implies CP-violation

Schiff Theorem: neutral atomic system of point particles in electric field readjusts itself to give zero E field at all charges.

BUT: finite size of nucleus can break the symmetry

$|d(^{199}Hg)| < 3.1\times10^{-29}$ e cm ***(Griffith et al PRL 102 (2009) 101601)***
In many cases provides best test extensions of the Standard Model that violate CP symmetry.

Nuclear pear-shapes can also enhance the "Schiff moment" by ~ 3 orders of magnitude
Search candidates are odd-*A* Rn [TRIUMF] and Ra [ANL, ISOLDE]

Octupole enhanced atomic EDM moment

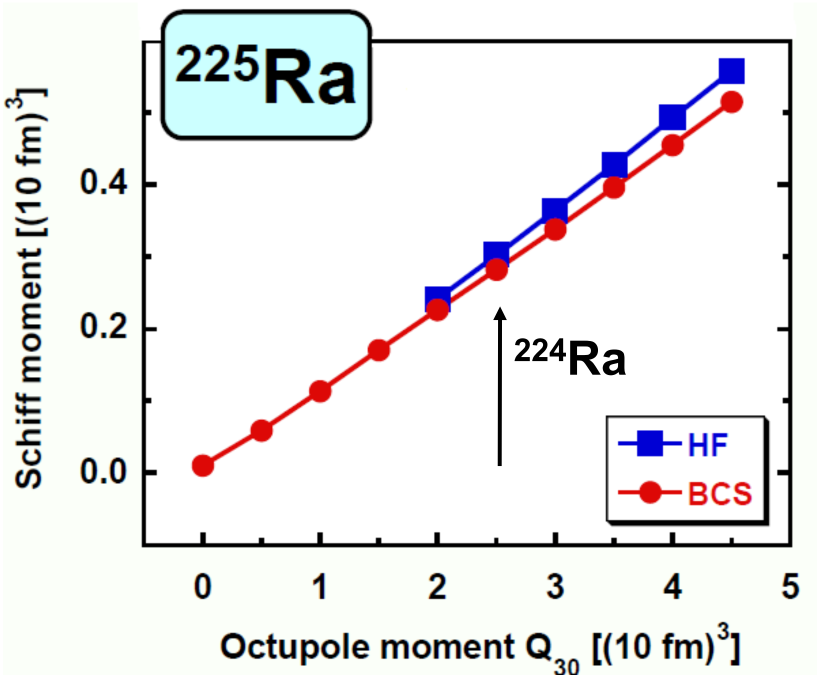
related to Q_3

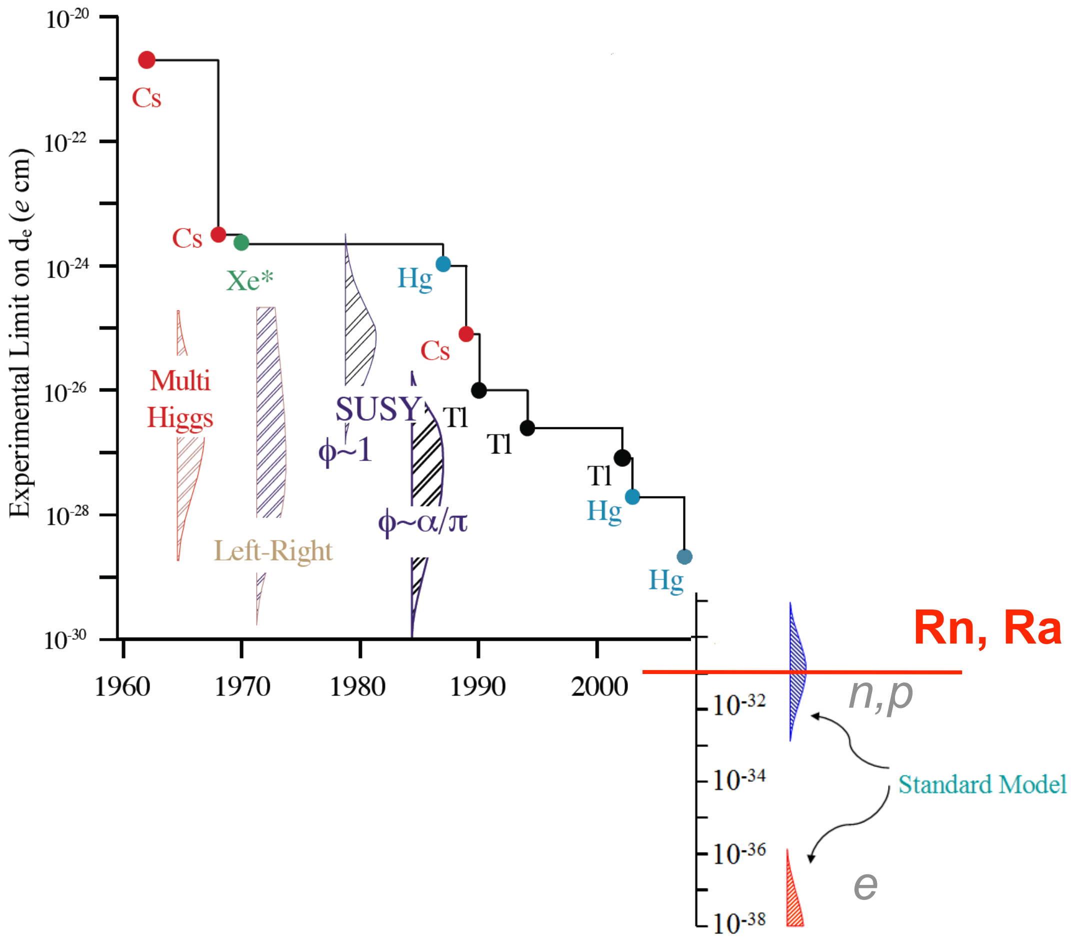
T-violating n-n interaction

Schiff moment:

$$S = -2\frac{J}{J+1}\frac{<\hat{S}_z><\hat{V}_{PT}>}{\Delta E}$$

energy splitting of parity doublet



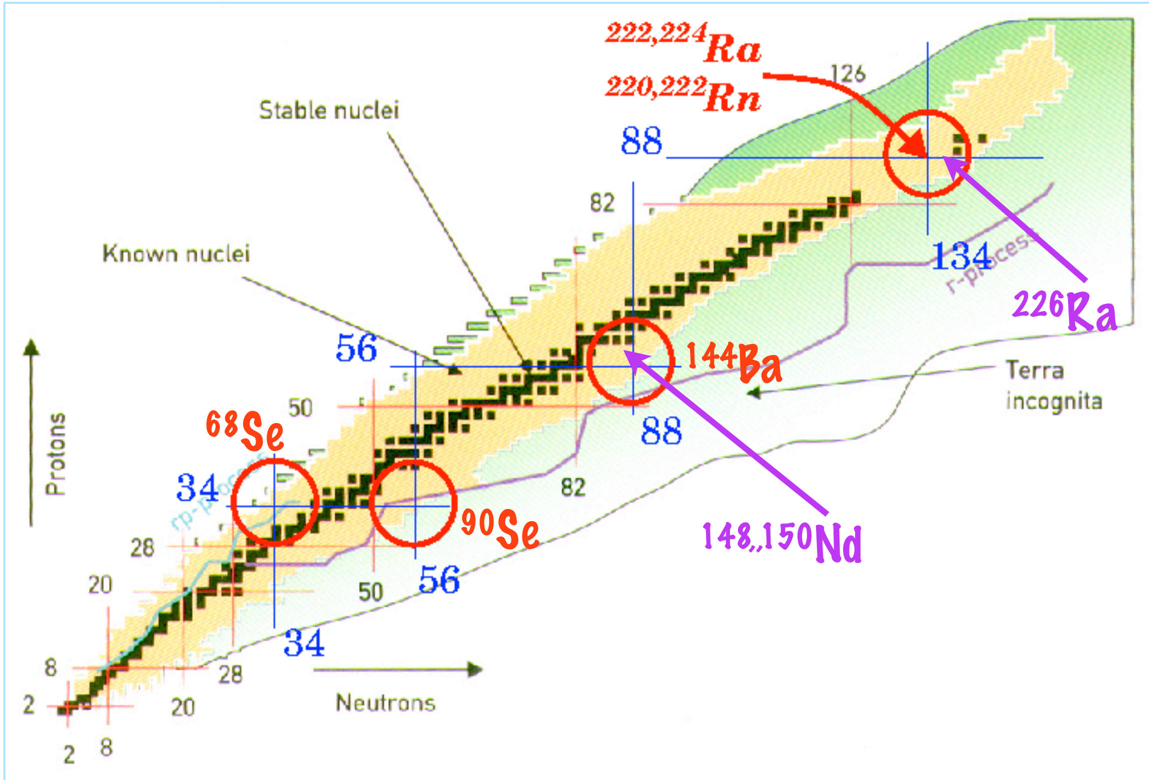


Peter Butler

UNIVERSITY OF LIVERPOOL

Octupole Collectivity

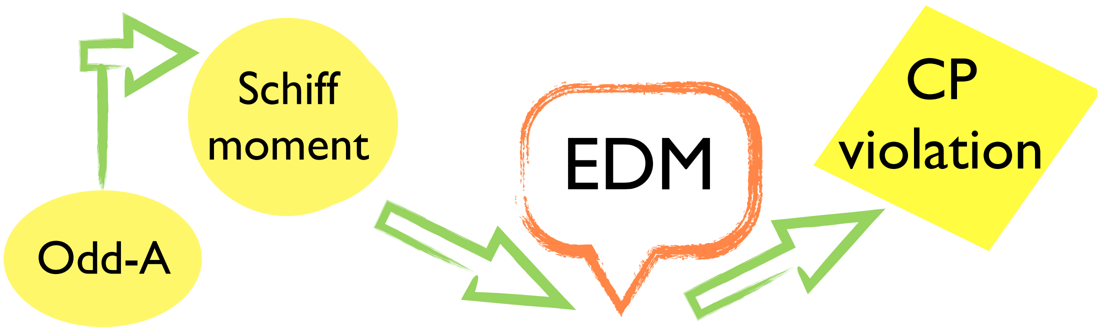
2^{λ} $\lambda = 2$ ... *Quadrupole*
$\lambda = 3$ ... *Octupole*



Octupole correlations enhanced at magic numbers: **34, 56, 88, 134**

Exotic regions of the Segré chart, so far inaccessible.

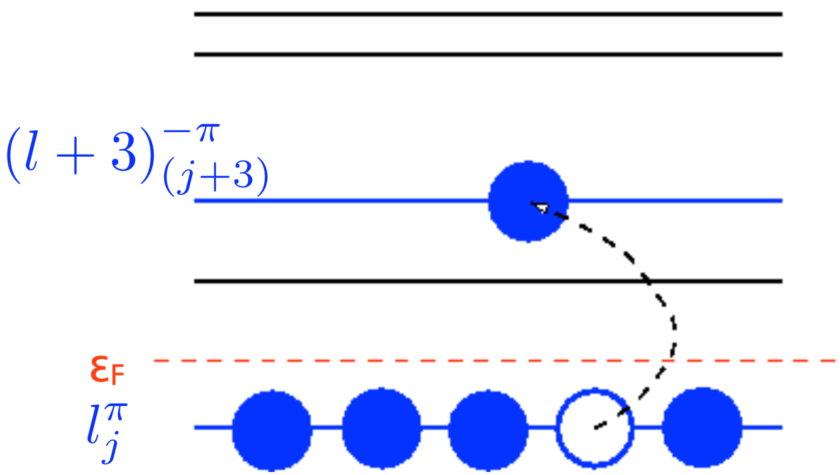
Radioactive Ion Beams are the key



Octupole Collectivity

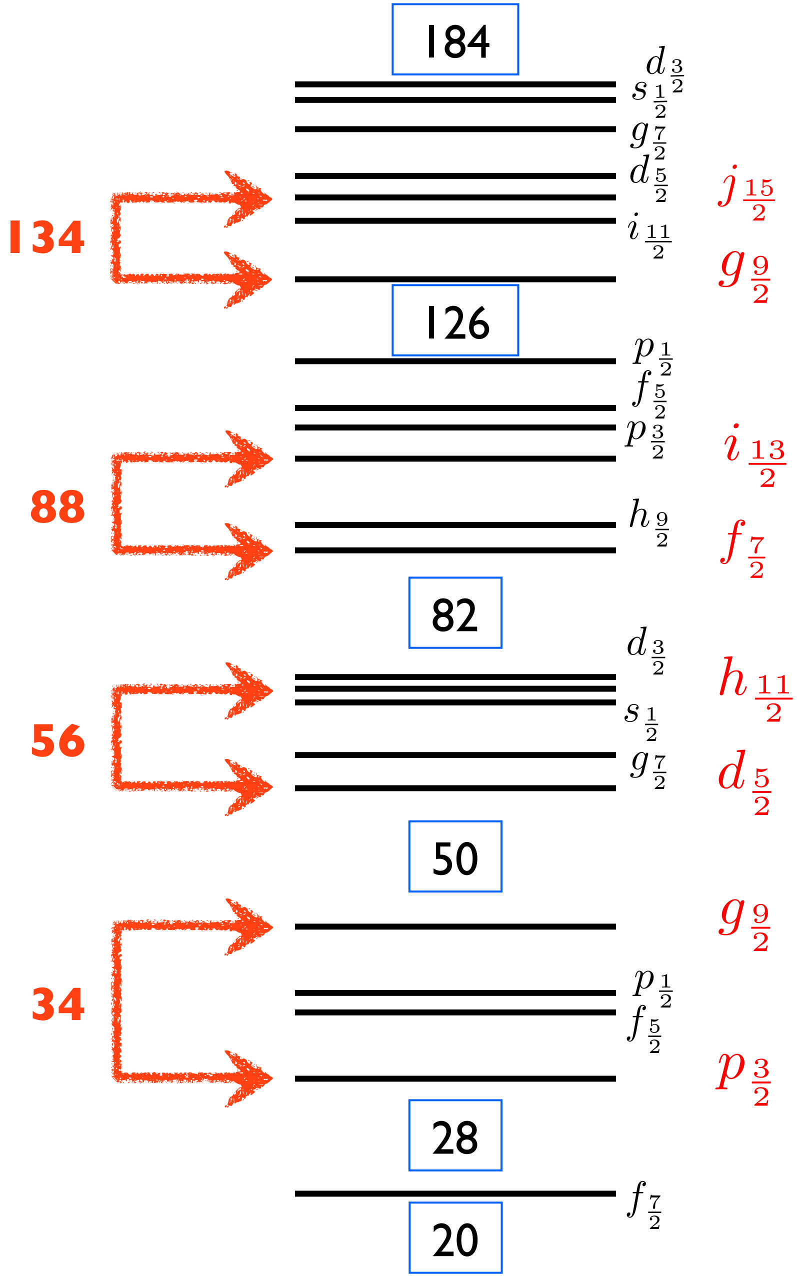
Microscopically...

Intruder orbitals of opposite parity and
ΔJ, ΔL = 3 close to the Fermi level

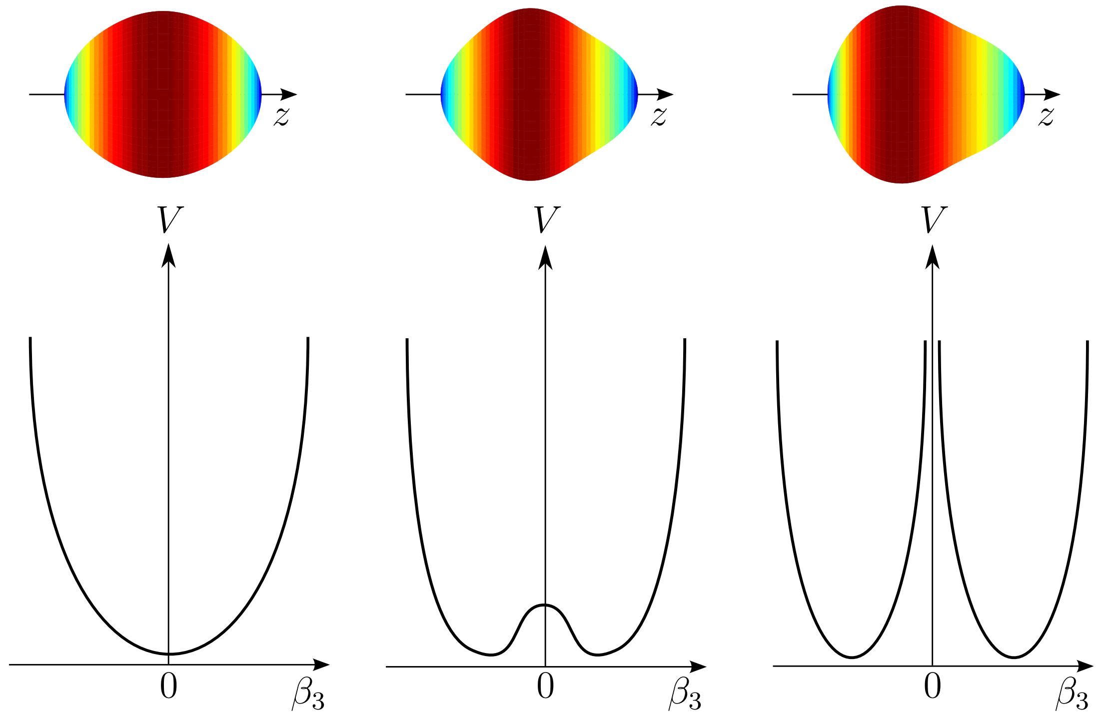


^{220}Rn and ^{224}Ra lie near *Z*=88, *N*=134

$$\pi\left(f_{7/2} \rightarrow i_{13/2}\right) \quad \nu\left(g_{9/2} \rightarrow j_{15/2}\right)$$



Octupole Collectivity



Macroscopically...

Nuclei take on a "pear" shape

Reflection asymmetric

- β_3-vibration
- Static β_3-deformation
- Rigid β_3-deformation...

Signatures...

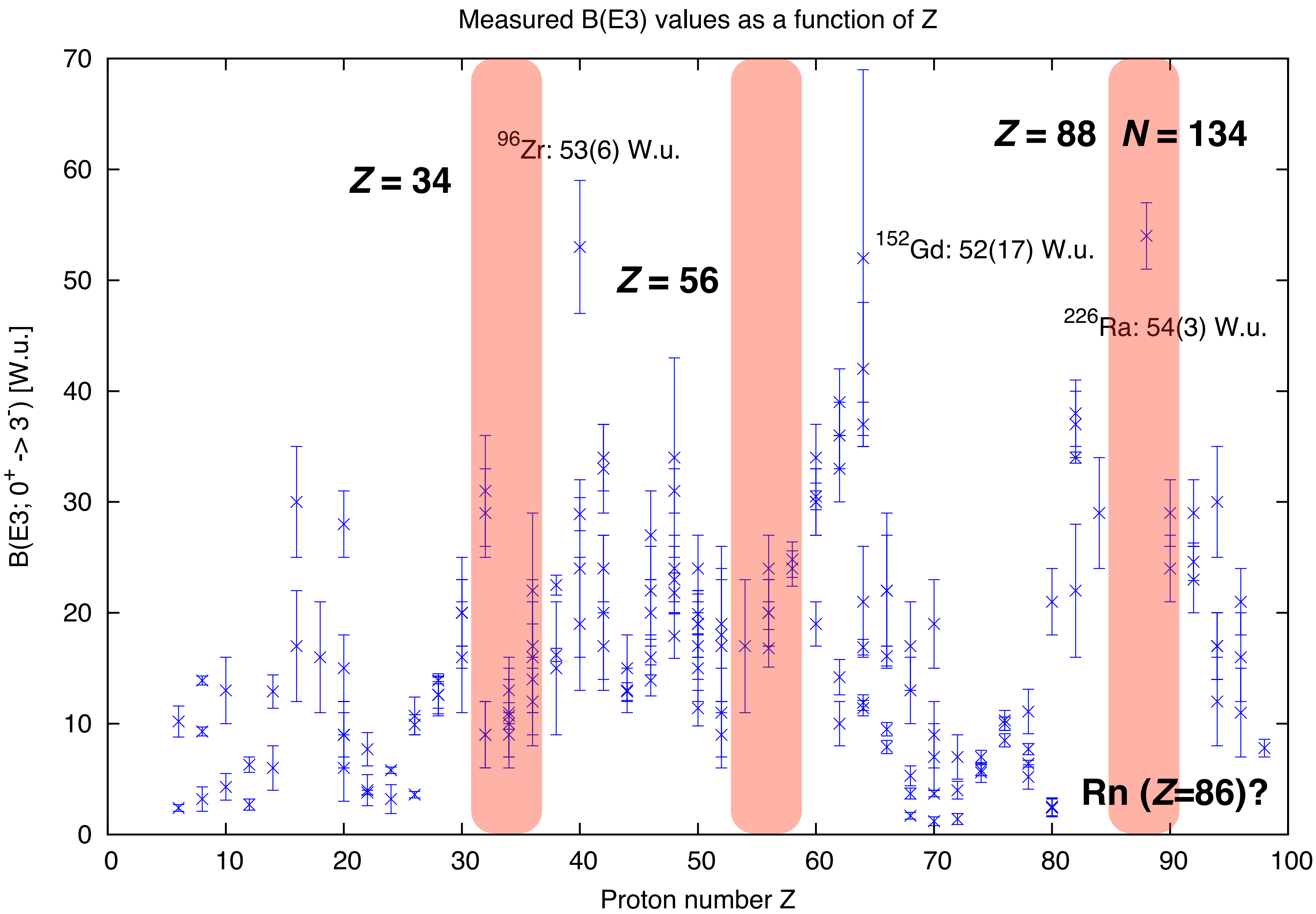
Odd-even staggering, negative parity

Parity doublets in odd-A nuclei

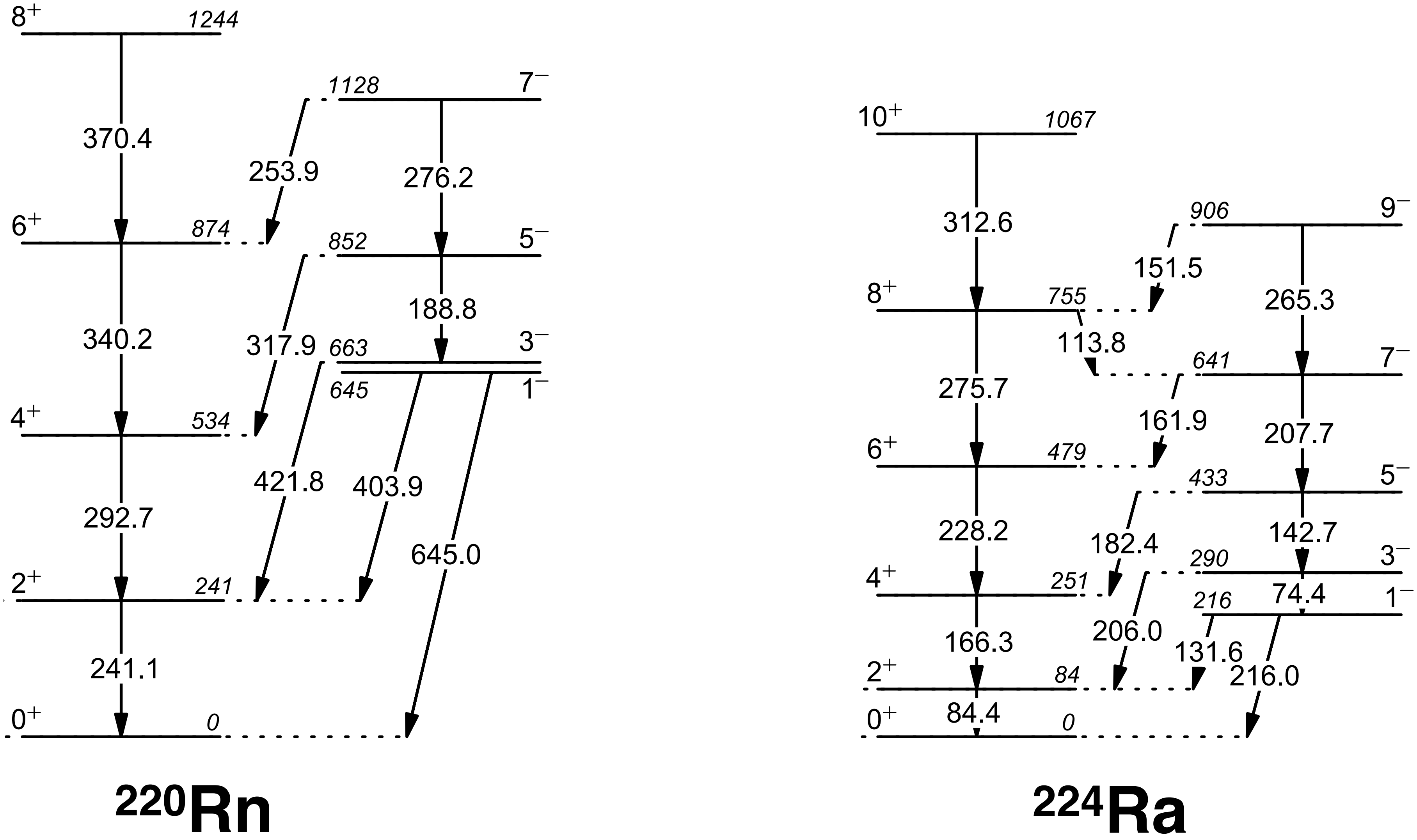
Enhanced E1 transitions

Large E3 strength → $B(E3; 3^- \rightarrow 0^+)$ = $< 0^+||E3||3^- >^2$

Octupole Collectivity

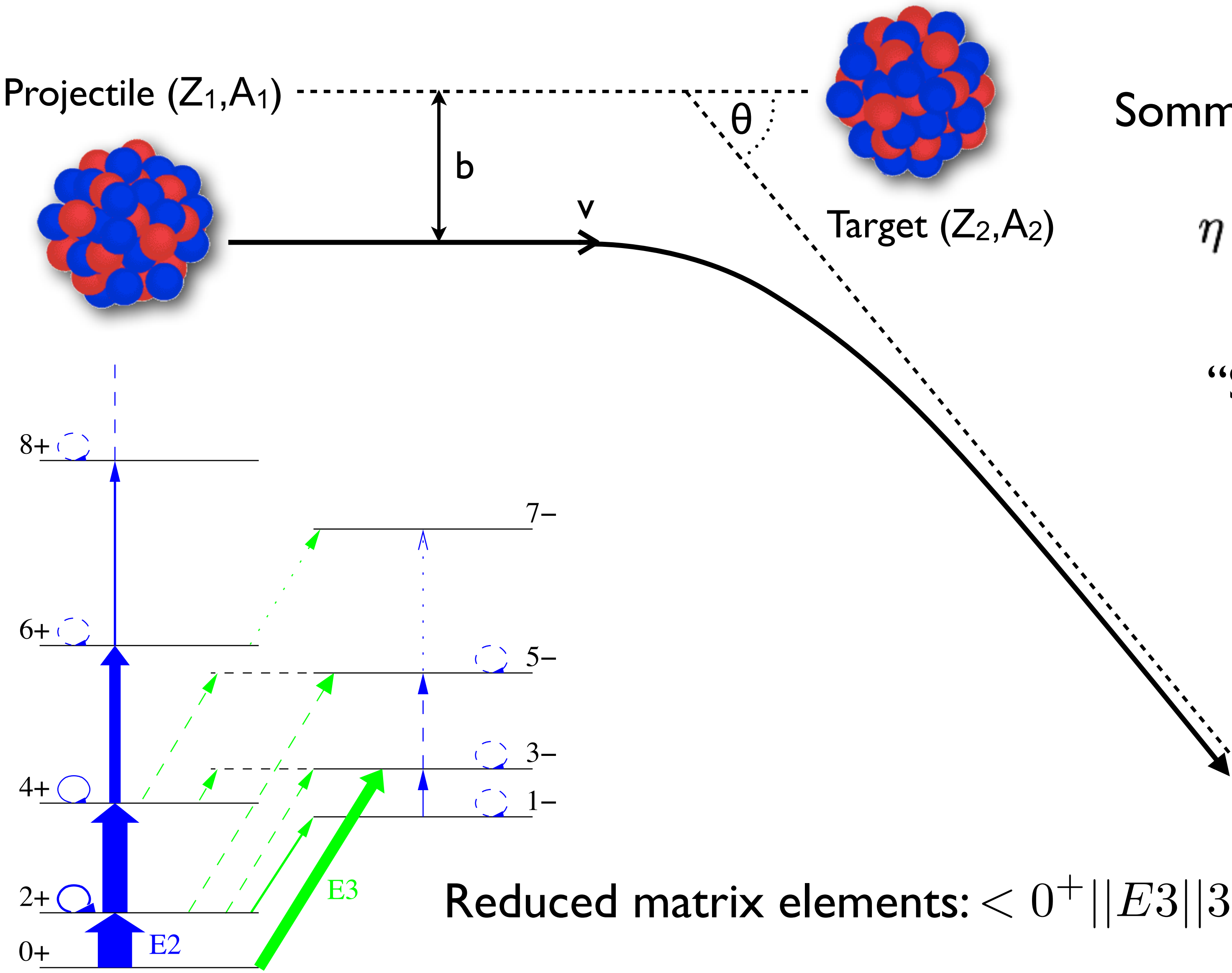


Radon-220 and Radium-224



[ref] J.F.C. Cocks *et al.* Phys. Rev. Lett. **78** (1997) and Nucl. Phys. A **645** (1999)

Coulomb Excitation



Sommerfeld parameter:

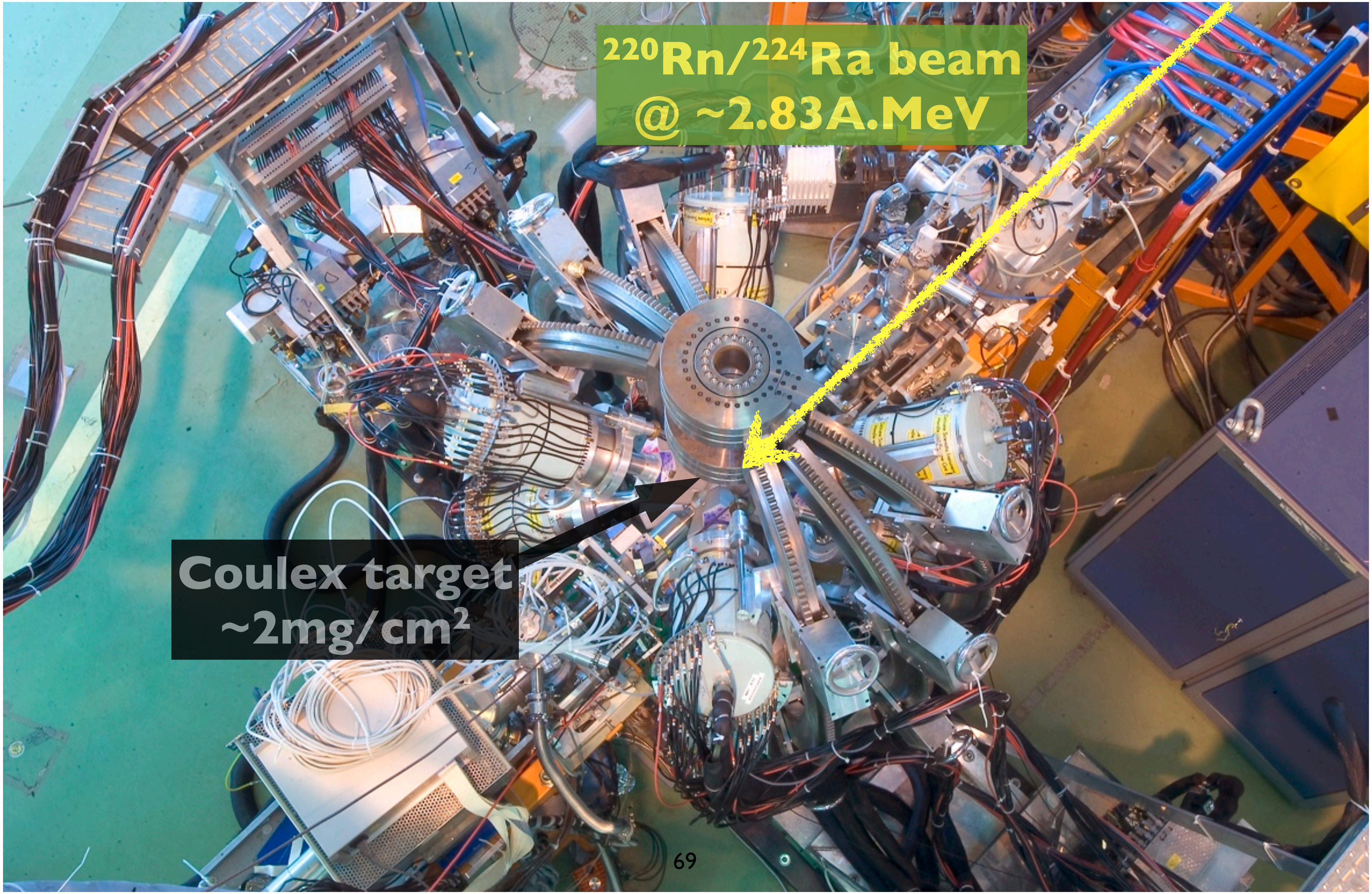
$$\eta = \frac{Z_1 Z_2 e^2}{\hbar v}$$

"Safe" Coulex:

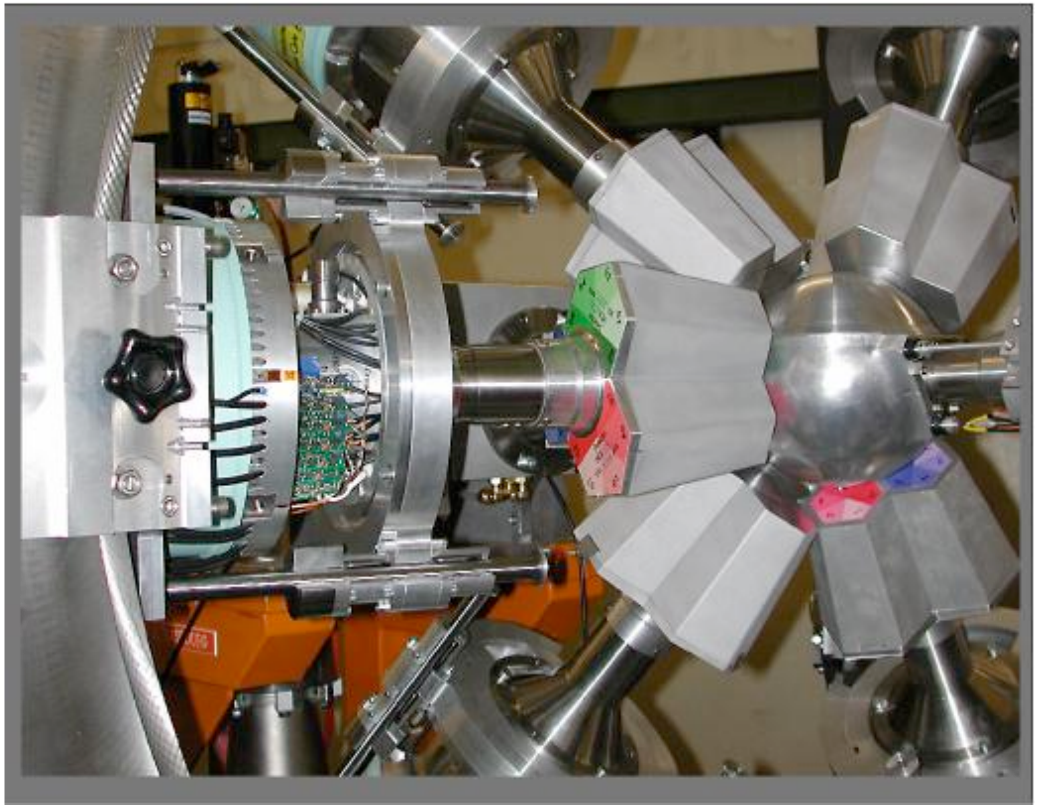
$$\eta \gg 1$$

Reduced matrix elements: $< 0^+||E3||3^- >$

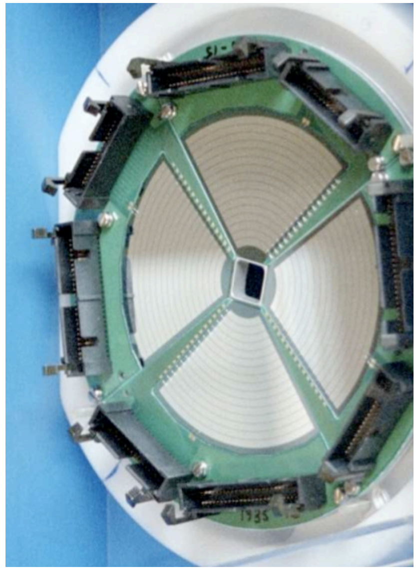
MINIBALL @ REX-ISOLDE

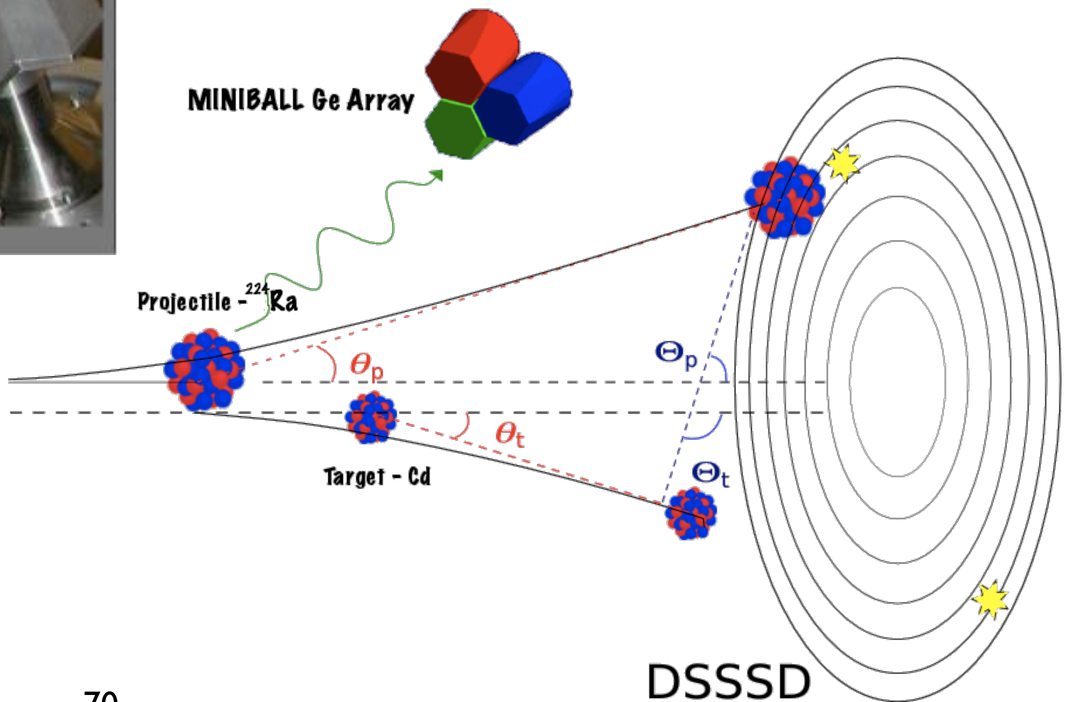


MINIBALL



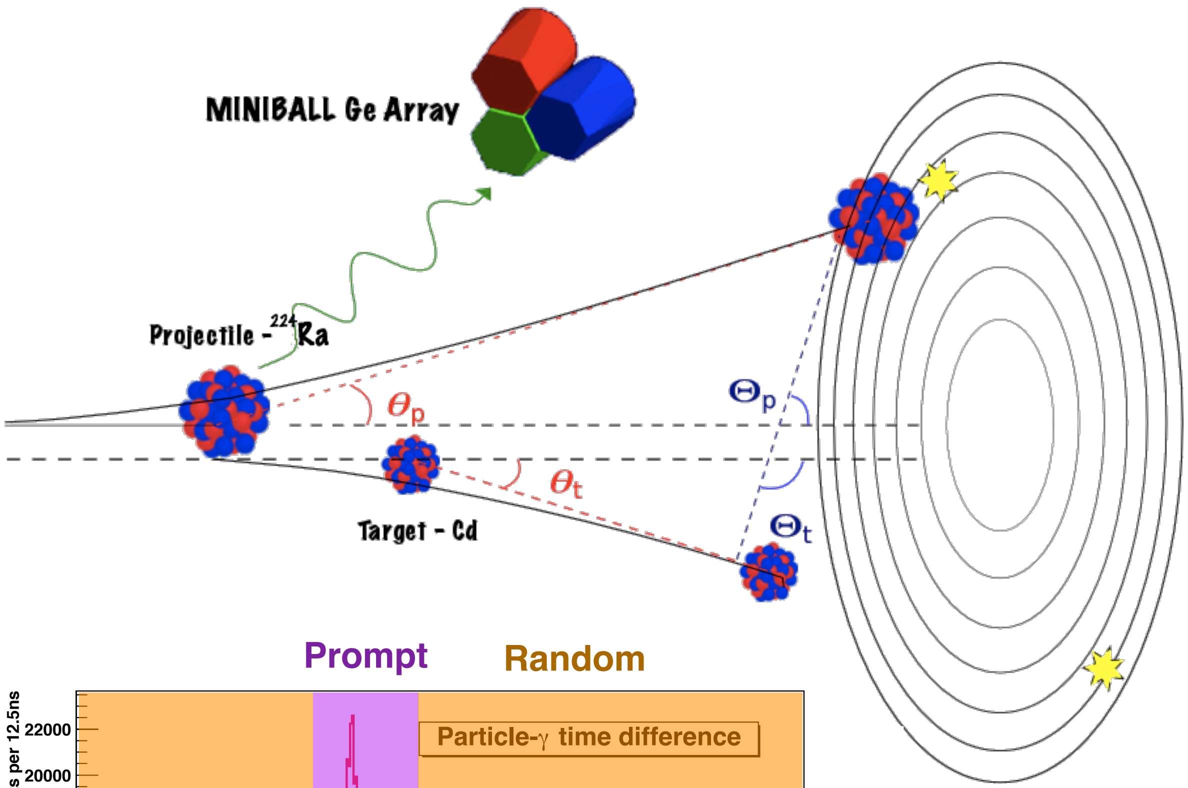
- Particle ID in a Double-Sided Si Strip Detector.
- Event by event Doppler correction.
- $17^\circ < \theta_{lab} < 54^\circ$

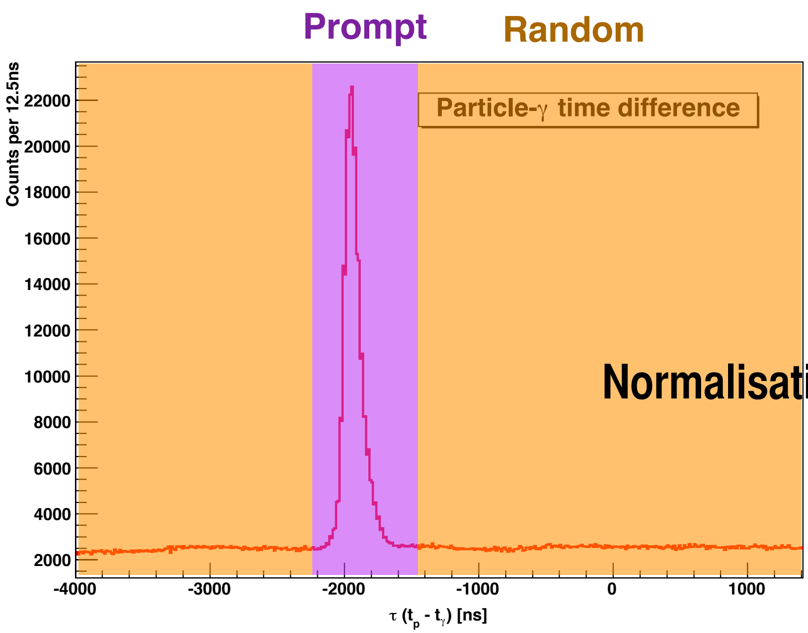




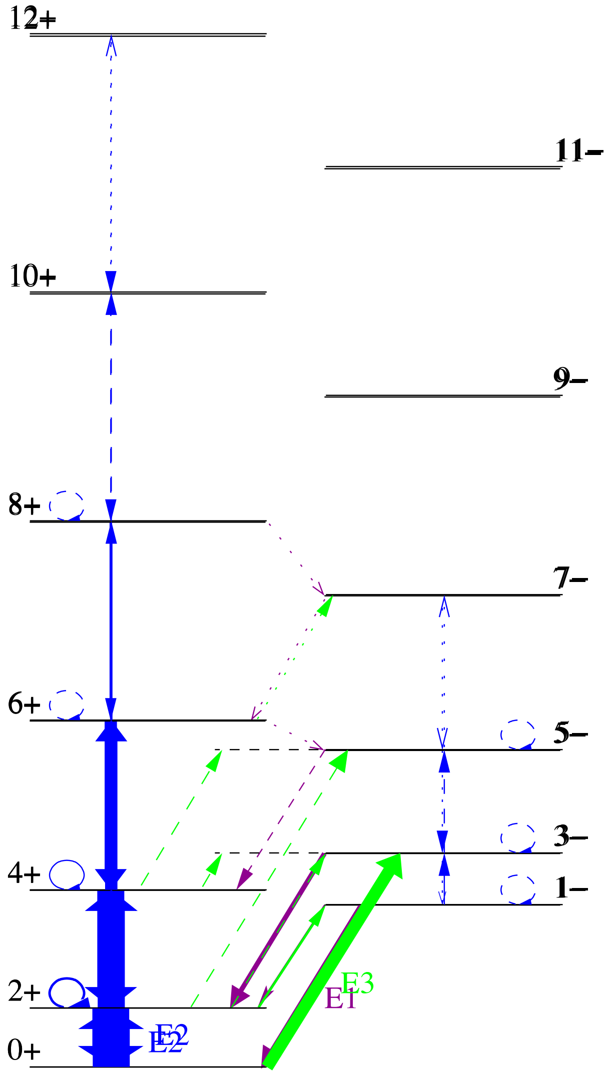
- Array of HPGe of 8 triple clusters
- 6-fold segmentation for positioning
- $\varepsilon > 7\%$ for 1.3MeV γ-rays

Particle-gamma coincidences

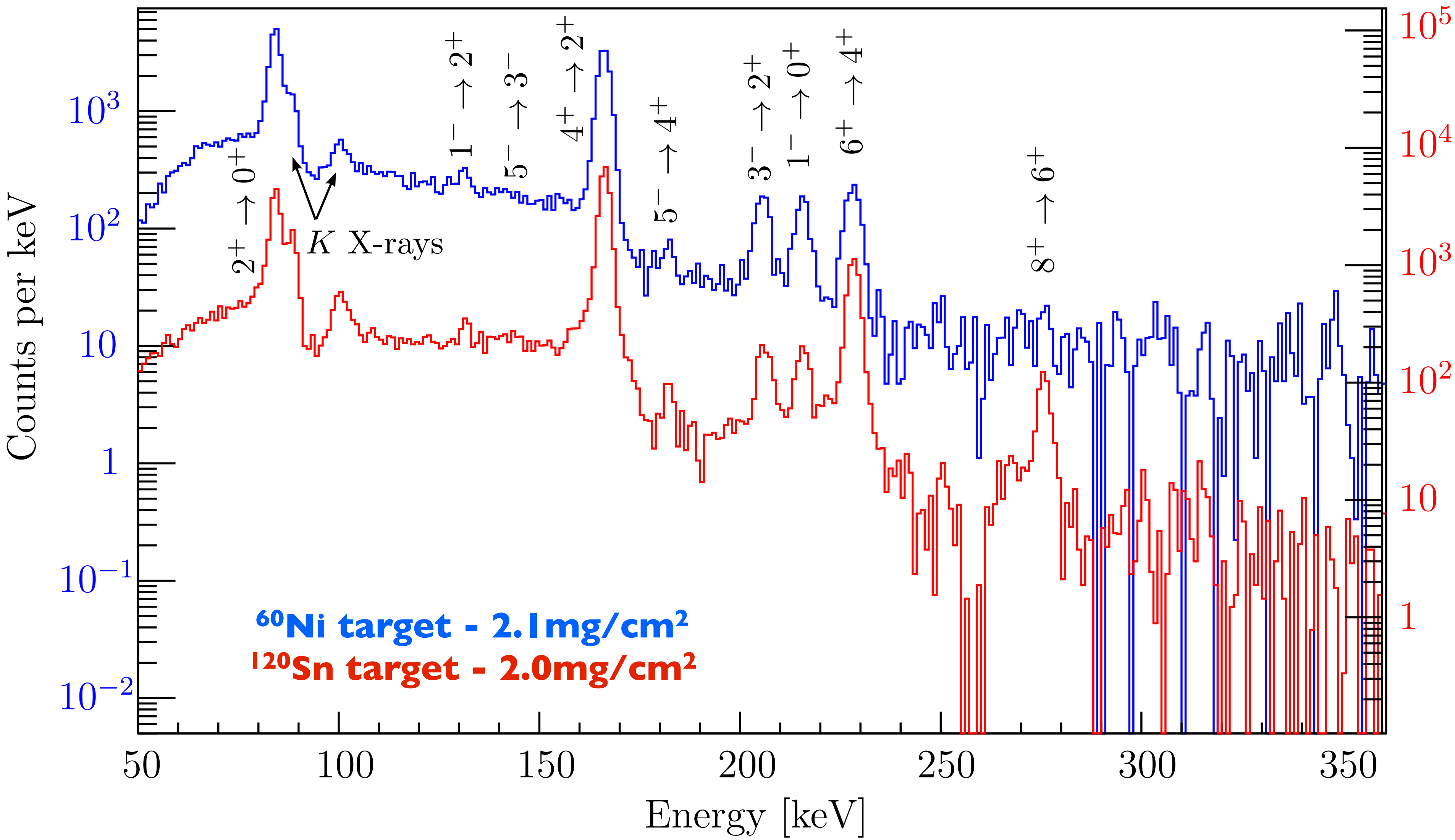




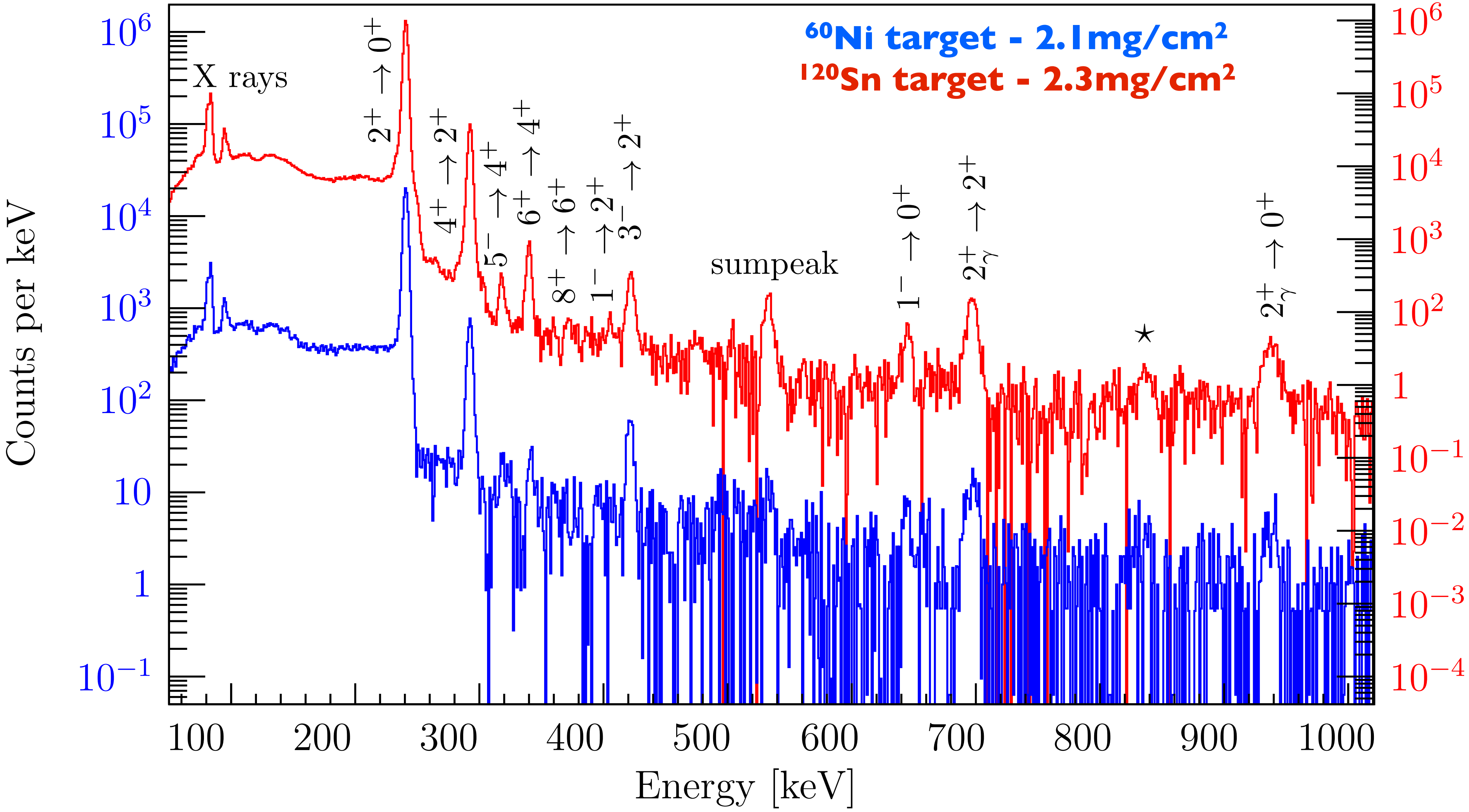
Normalisation = $\frac{t_{prompt}}{t_{random}}$



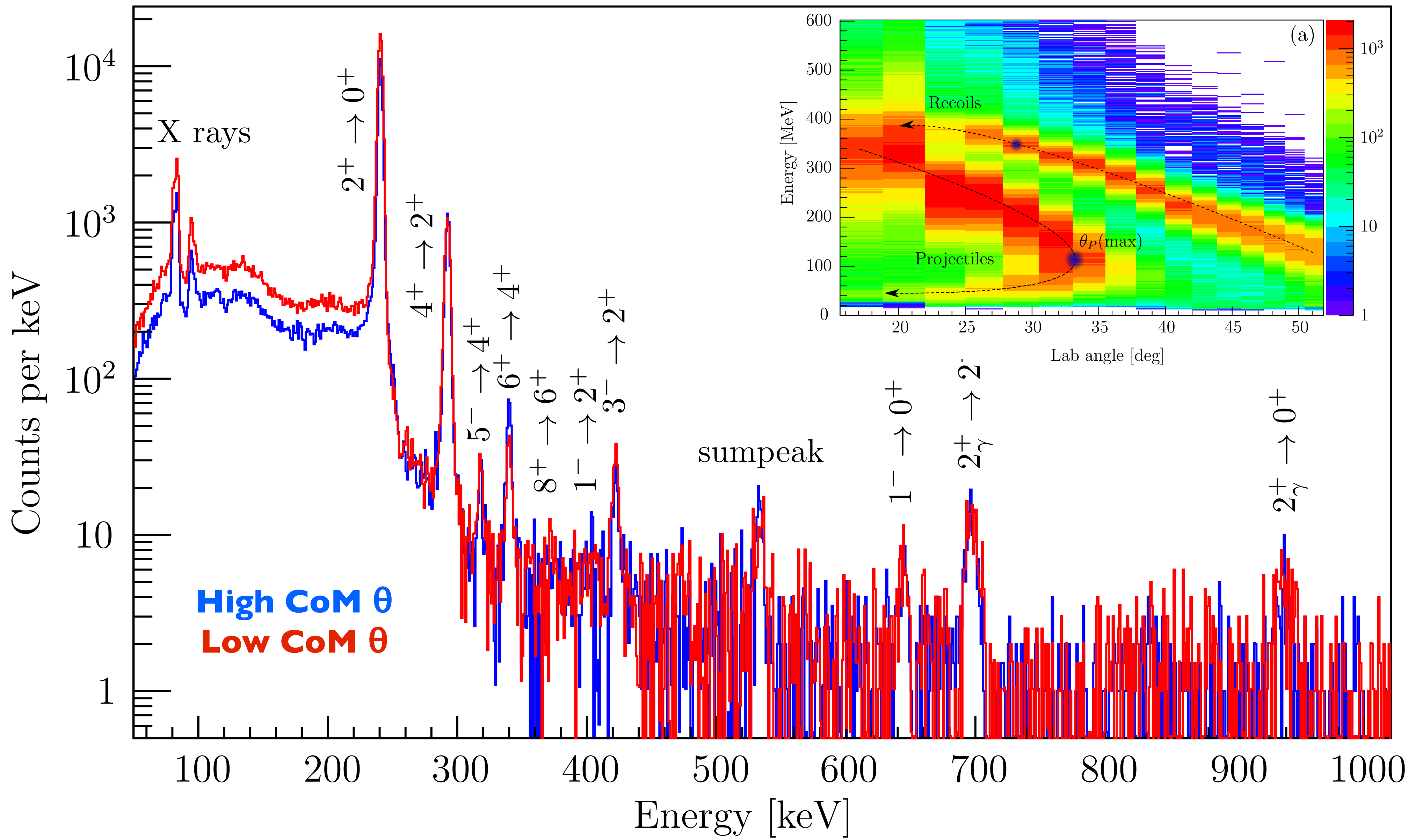
Analysis - ^{224}Ra: Ni/Sn



Analysis - ^{220}Rn: Ni/Sn



Analysis - ^{220}Rn: High/Low θ

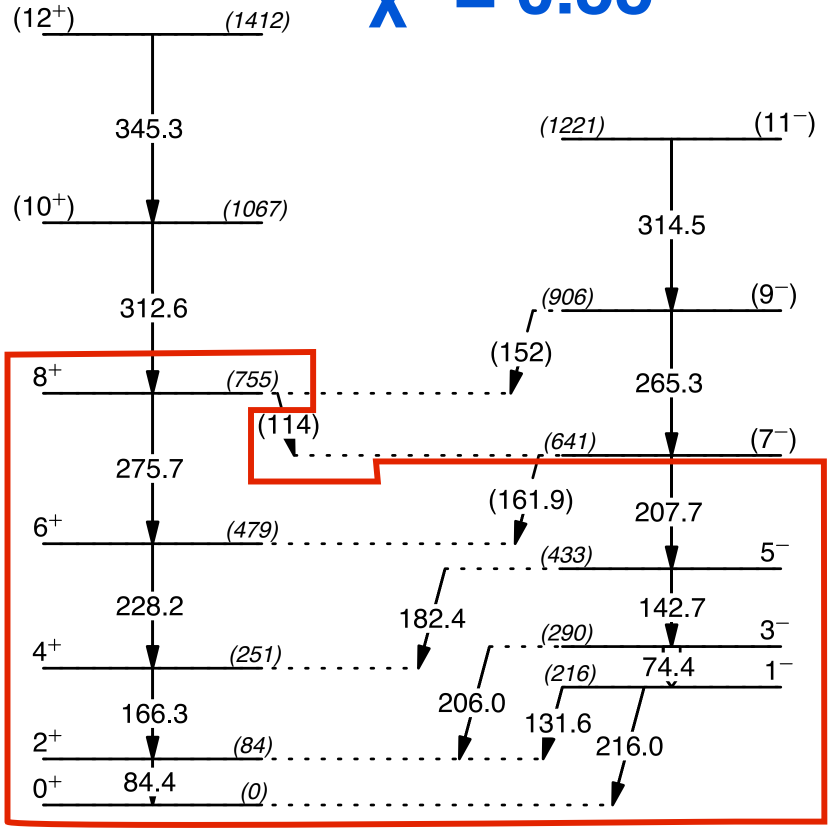


Analysis - ^{224}Ra GOSIA

16 *free* matrix elements + 6 normalisation factors

"Experiment"	Number and type of data
Multi-nucleon transfer[1,2] ^{226}Ra(^{58}Ni,^{60}Ni)^{224}Ra ^{232}Th(^{136}Xe,^{128}Te)^{224}Ra Alpha, alpha-prime[3] ^{226}Ra(α,α'2n)^{224}Ra Alpha(beta)-decay[4] ^{228}Th(^{224}Fr) → α(β)	Branching ratios (1^-, 3^-, 5^-, 7^-, 2^+_γ) **-- 5**
Delayed-coincidence[5,6]	Lifetimes (2^+, 4^+) **-- 2**
Cd/Sn high CoM range $23.9^\circ < \theta_{lab} < 40.3^\circ$	γ-ray yield **-- 8 + 7**
Ni high CoM range $23.1^\circ < \theta_{lab} < 39.9^\circ$	γ-ray yield **-- 10**
Cd/Sn low CoM range $40.3^\circ < \theta_{lab} < 54.3^\circ$	γ-ray yield **-- 8 + 8**
Ni low CoM range $39.3^\circ < \theta_{lab} < 53.2^\circ$	γ-ray yield **-- 7**
Total	**55 data points**

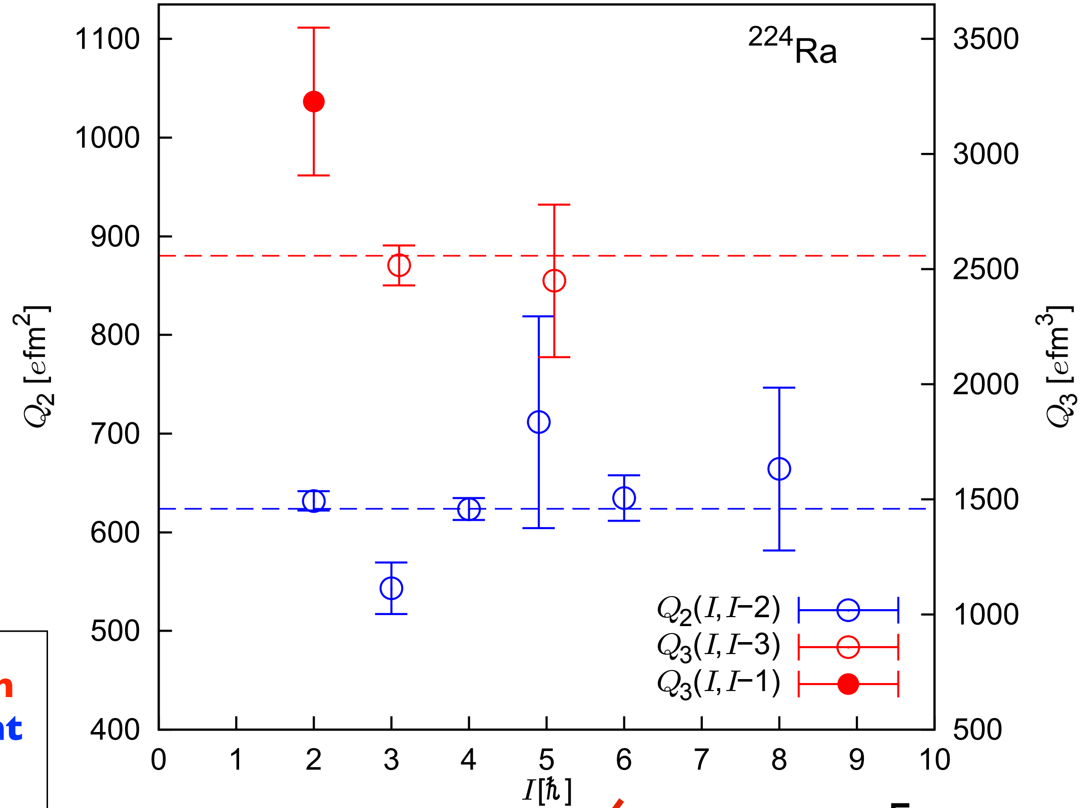
$\chi^2 = 0.55$

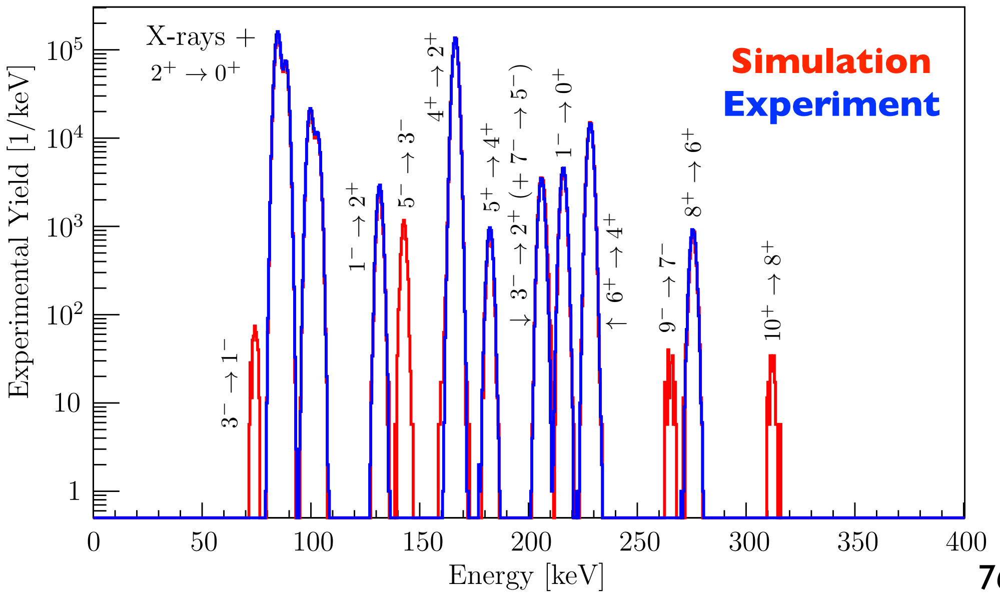


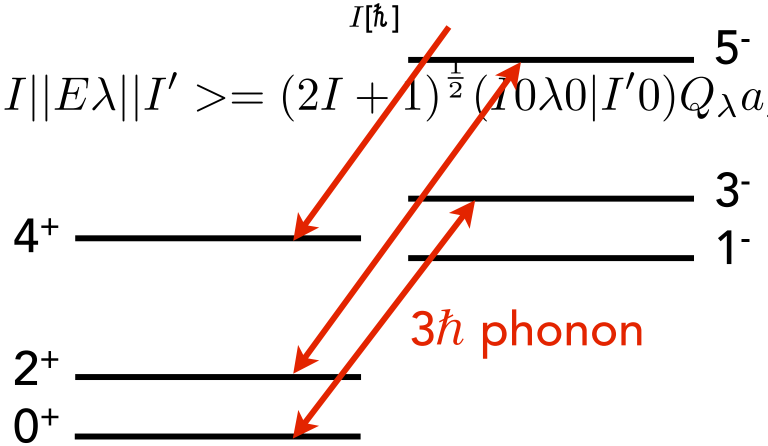
[1] Poynter *et al.*, Phys. Lett. B **232**, 447 (1989)
[2] J.F.C. Cocks *et al.*, Nucl. Phys. A **645**, 61 (1999)
[3] Marten-Tölle *et al.*, Z. Phys. A **336**, 27 (1990)
[4] W. Kurcewicz, *et al.*, Nucl. Phys. A **289** (1977)
[5] W.R. Neal and H.W. Kraner, Phys. Rev. **137**, **B**1164 (1965)
[6] H. Ton *et al.*, Nucl. Phys. A **155**, 235 (1970)

Results - ^{224}Ra

- Consistent with rotational model
- Unstretched E3 matrix elements are non-zero. Rot-vib model predicts these vanish
- Coupled with level energy data, we observe a static octupole deformation in ^{224}Ra







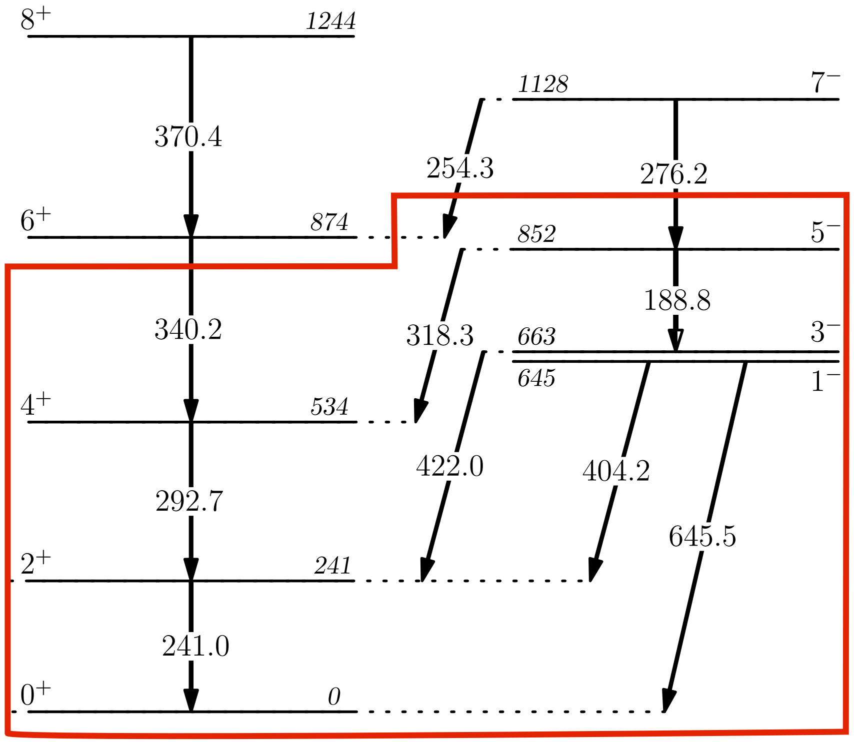
$$< I||E\lambda||I' >= (2I+1)^{\frac{1}{2}}(I0\lambda0|I'0)Q_\lambda a_\lambda$$

Analysis - ^{220}Rn GOSIA

15 *free* matrix elements + 6 normalisation factors

"Experiment"	Number and type of data
Multi-nucleon transfer[1,2] ^{226}Ra(^{58}Ni,^{60}Ni)^{224}Ra ^{232}Th(^{136}Xe,^{128}Te)^{224}Ra Alpha, alpha-prime[3] ^{226}Ra(α,α'2n)^{224}Ra Alpha(beta)-decay[4] ^{228}Th(^{224}Fr) → α(β)	Branching ratios (1^-, 5^-, 7^-) **-- 3**
Delayed-coincidence[5,6]	Lifetimes (2^+) **-- 1**
Cd/Sn/Ni high CoM range $22.1^\circ < \theta_{lab} < 37.8^\circ$	γ-ray yield **-- 2 + 8 + 5**
Cd/Sn/Ni low CoM range $37.9^\circ < \theta_{lab} < 51.8^\circ$	γ-ray yield **-- 2 + 8 + 5**
Total	**34 data points**

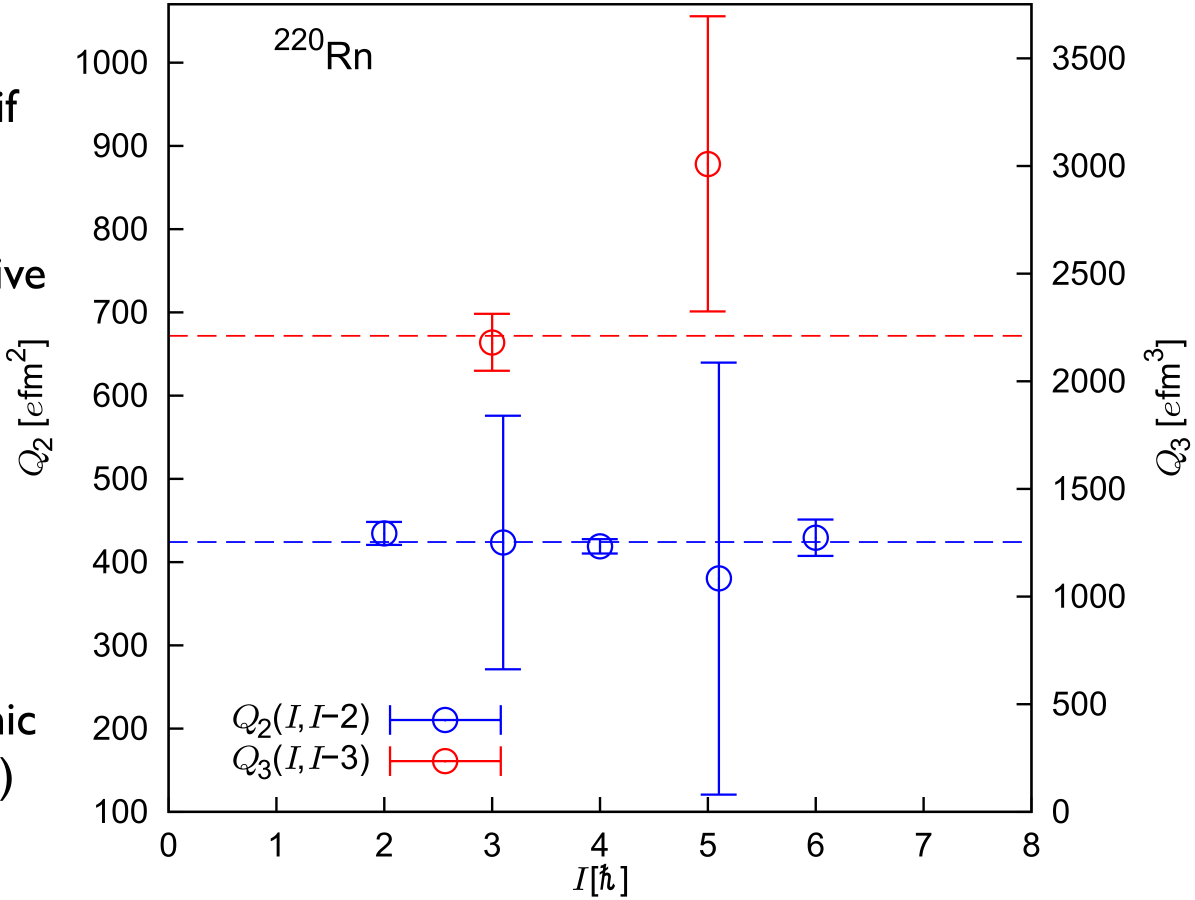
χ^2 = 0.86



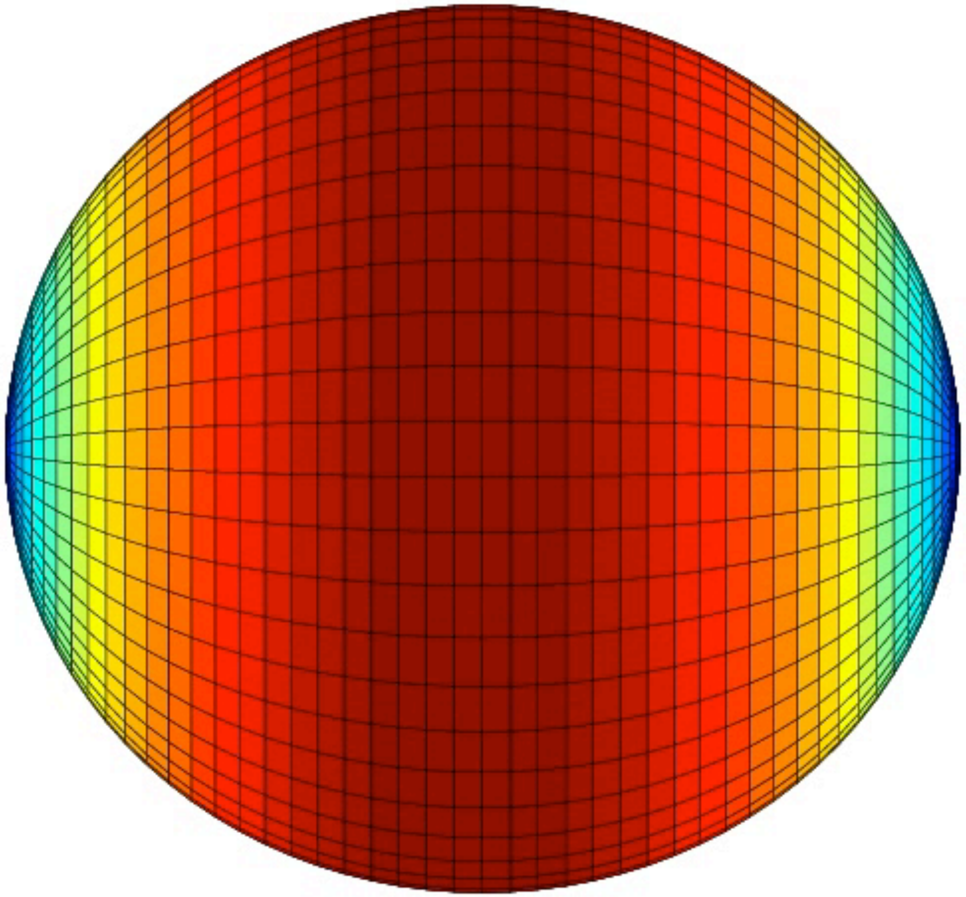
[1] Poynter *et al.*, Phys. Lett. B **232**, 447 (1989)
[2] J.F.C. Cocks *et al.*, Nucl. Phys. A **645**, 61 (1999)
[3] Marten-Tölle *et al.*, Z. Phys. A **336**, 27 (1990)
[4] W. Kurcewicz, *et al.*, Nucl. Phys. A **289** (1977)
[5] W.R. Neal and H.W. Kraner, Phys. Rev. **137**, **B**1164 (1965)
[6] H. Ton *et al.*, Nucl. Phys. A **155**, 235 (1970)

Results - ^{220}Rn

- Consistent with rotational model.
- No information on unstretched E3.
- Larger data set required to determine if <1^-||E3||2^+> or <1^-||E3||4^+> vanish.
- Not definitive determination of collective mode, dynamic (vibrational) or static (rotational) from Q_3 alone.
- δE and Δi_x implies a coupling of an octupole phonon to the even-spin rotational band.
- Magnitude of Q_3 consistent with dynamic picture, similar to $Q_3(^{208}Pb)$ and $Q_3(^{232}Th)$
- Dynamic collectivity in ^{220}Rn

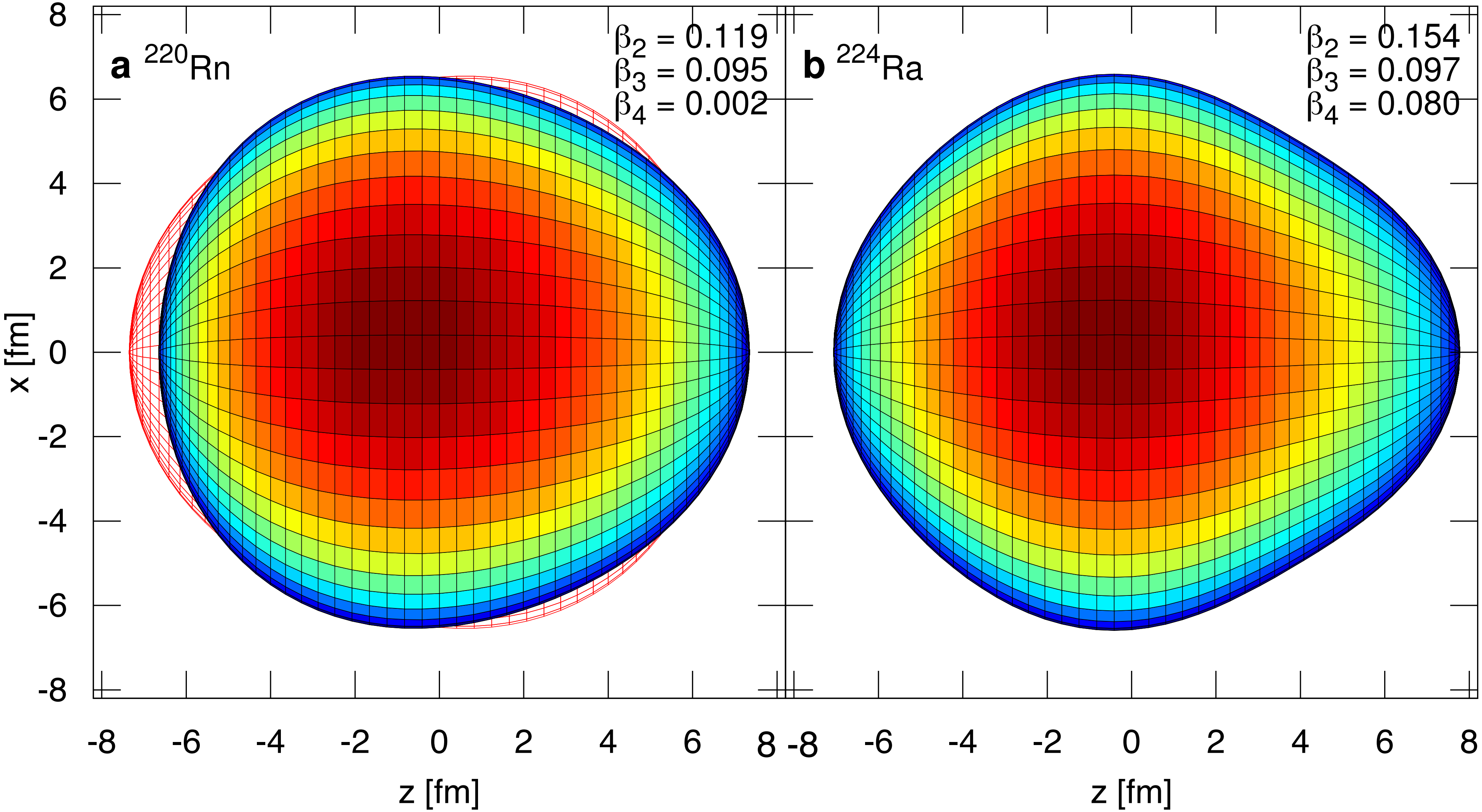


^{220}Rn - Vibrational?

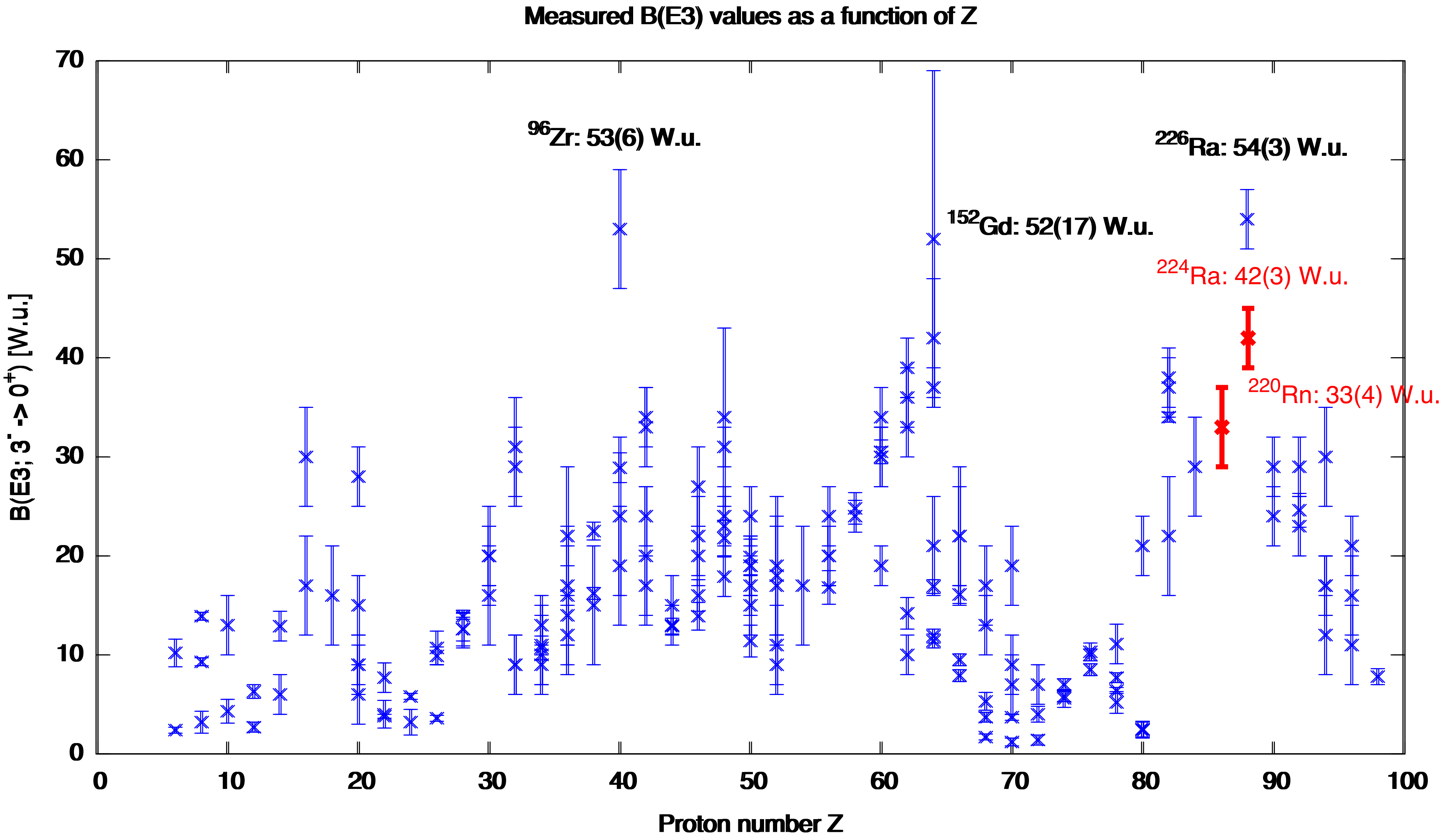


L.P. Gaffney et al., Nature 497, 199 (2013)

Discussion and Interpretation

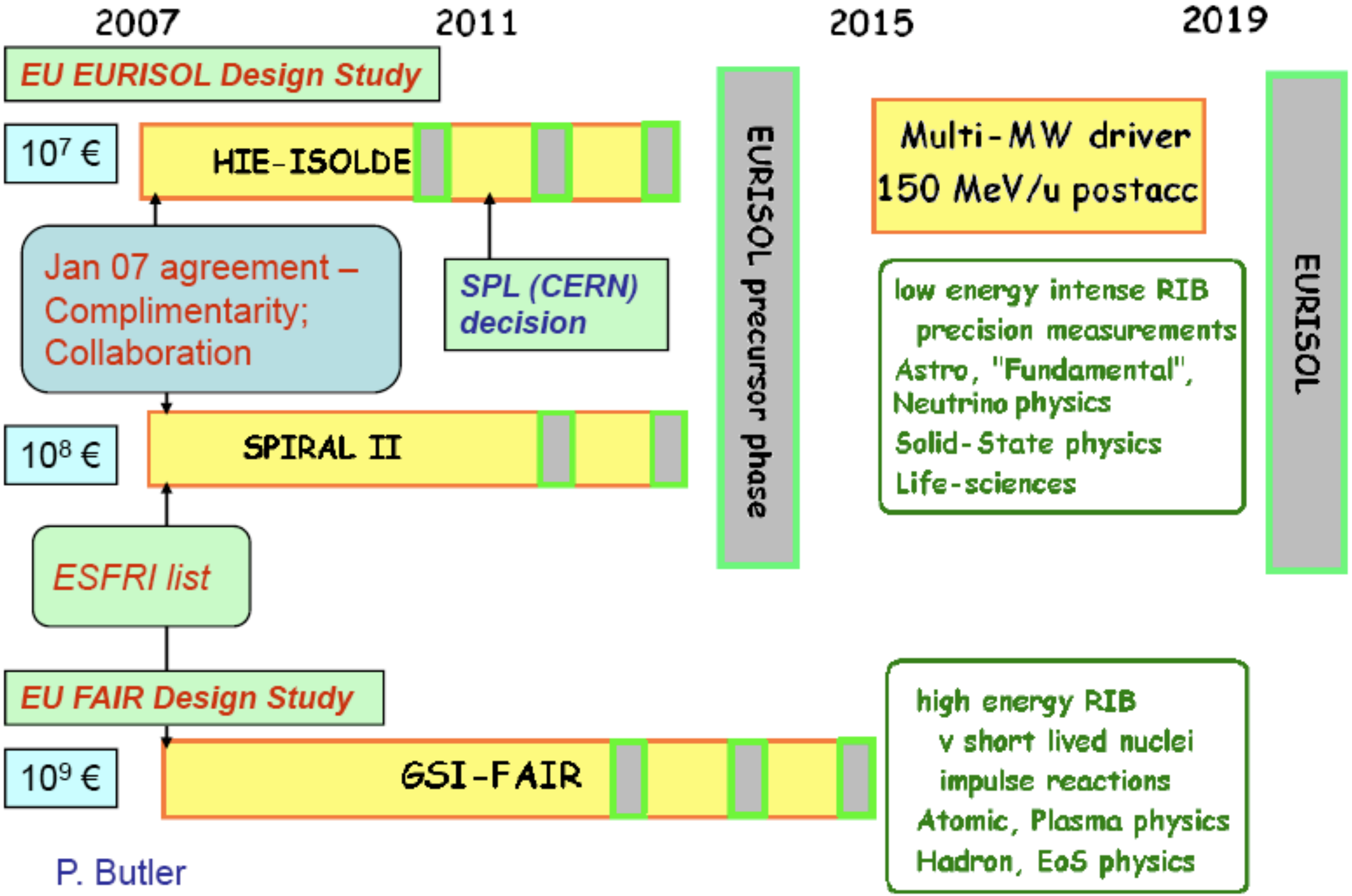


Discussion and Interpretation



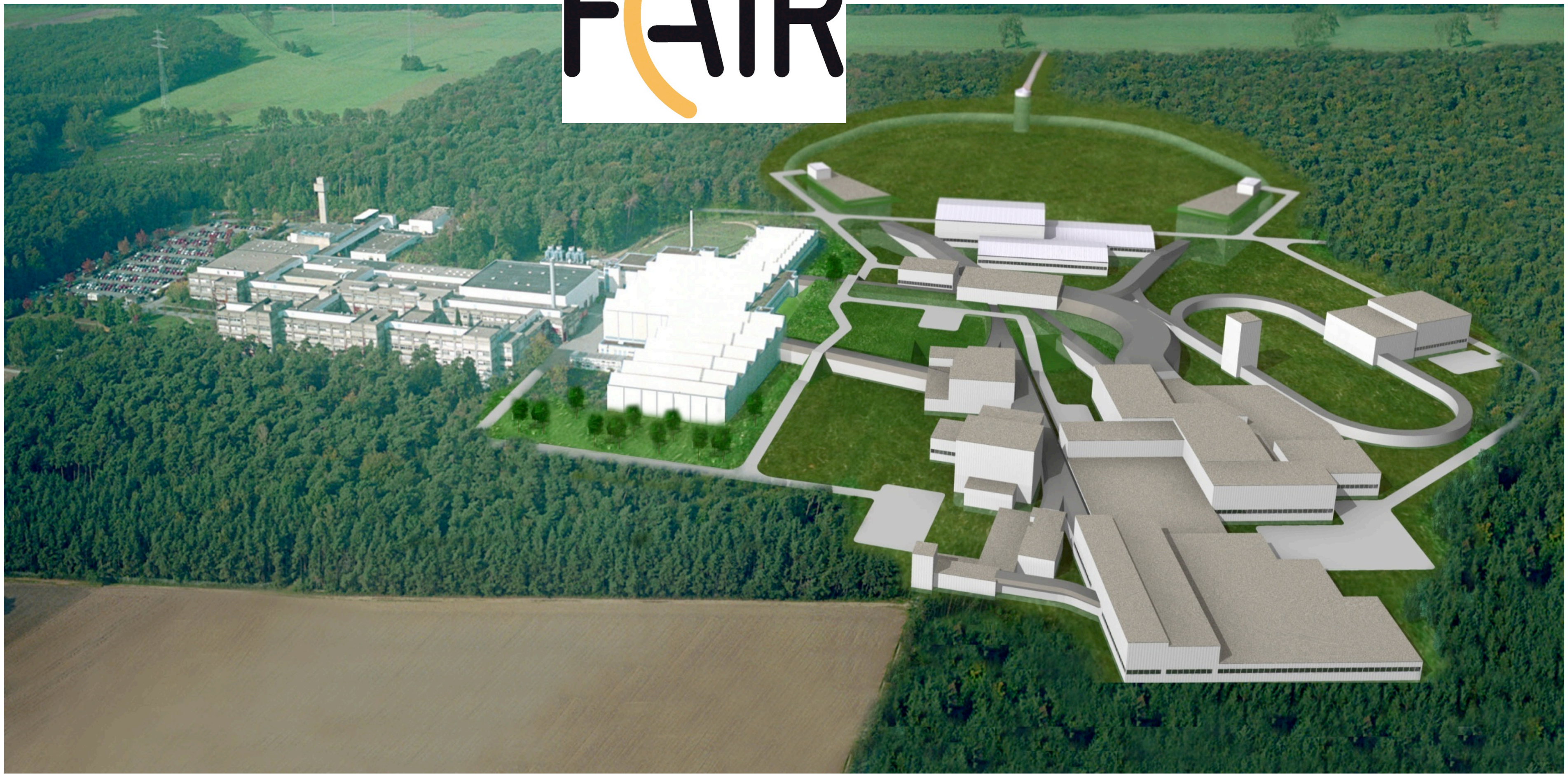
HIE-ISOLDE

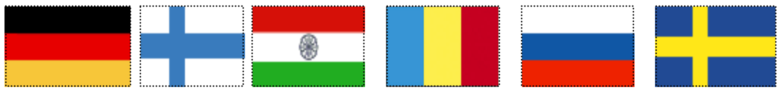
European Roadmap for RIB facilities



P. Butler

The Facility for Antiprotons and Ion Research

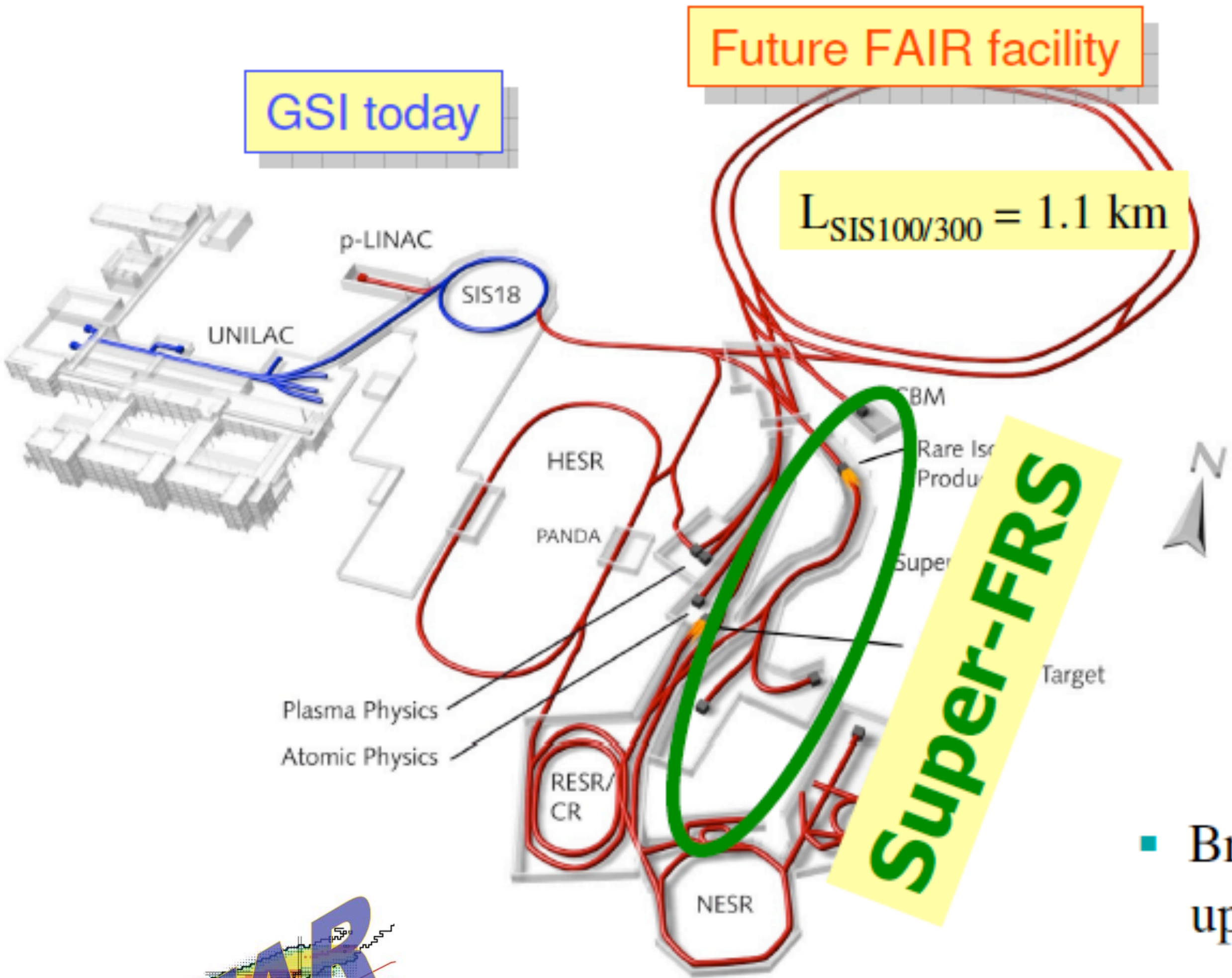




Share-holders

In the process…

Thinking on becoming shareholde



Primary Beams

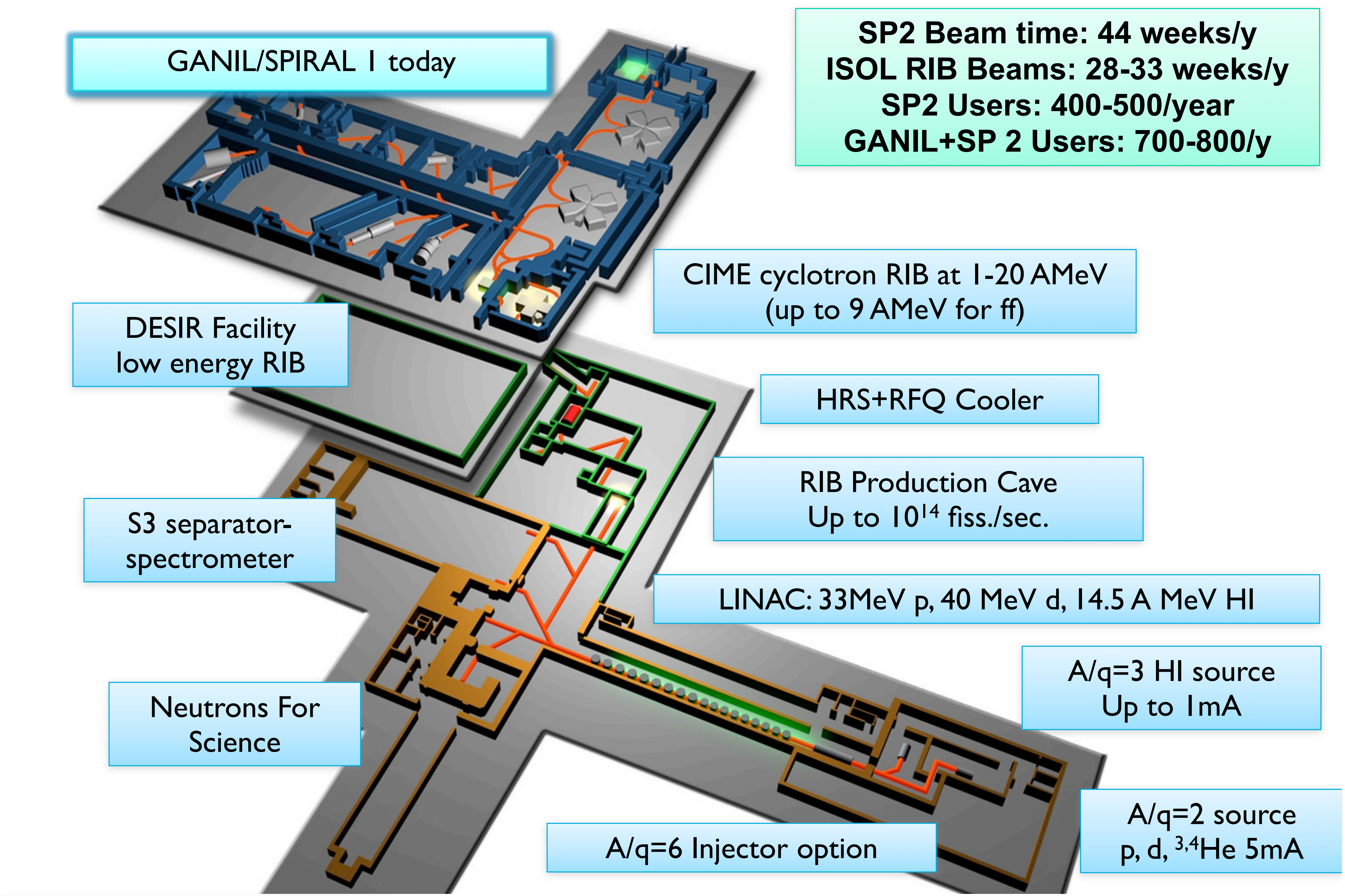
- **3.5·10^11^ $^{238}U^{28+}$/s (DC)**
  @ 1.5 GeV/u
- **5·10^11^ $^{238}U^{28+}$ (pulsed)**
  @ 1 GeV/u
- factor **100-1000** in intensity over present

Secondary Beams

- Broad range of radioactive beams up to **1.5 GeV/u**
- up to **factor 10 000 in intensity** over present

The SPIRAL2 Project

SP2 Beam time: 44 weeks/y
ISOL RIB Beams: 28-33 weeks/y
SP2 Users: 400-500/year
GANIL+SP 2 Users: 700-800/y

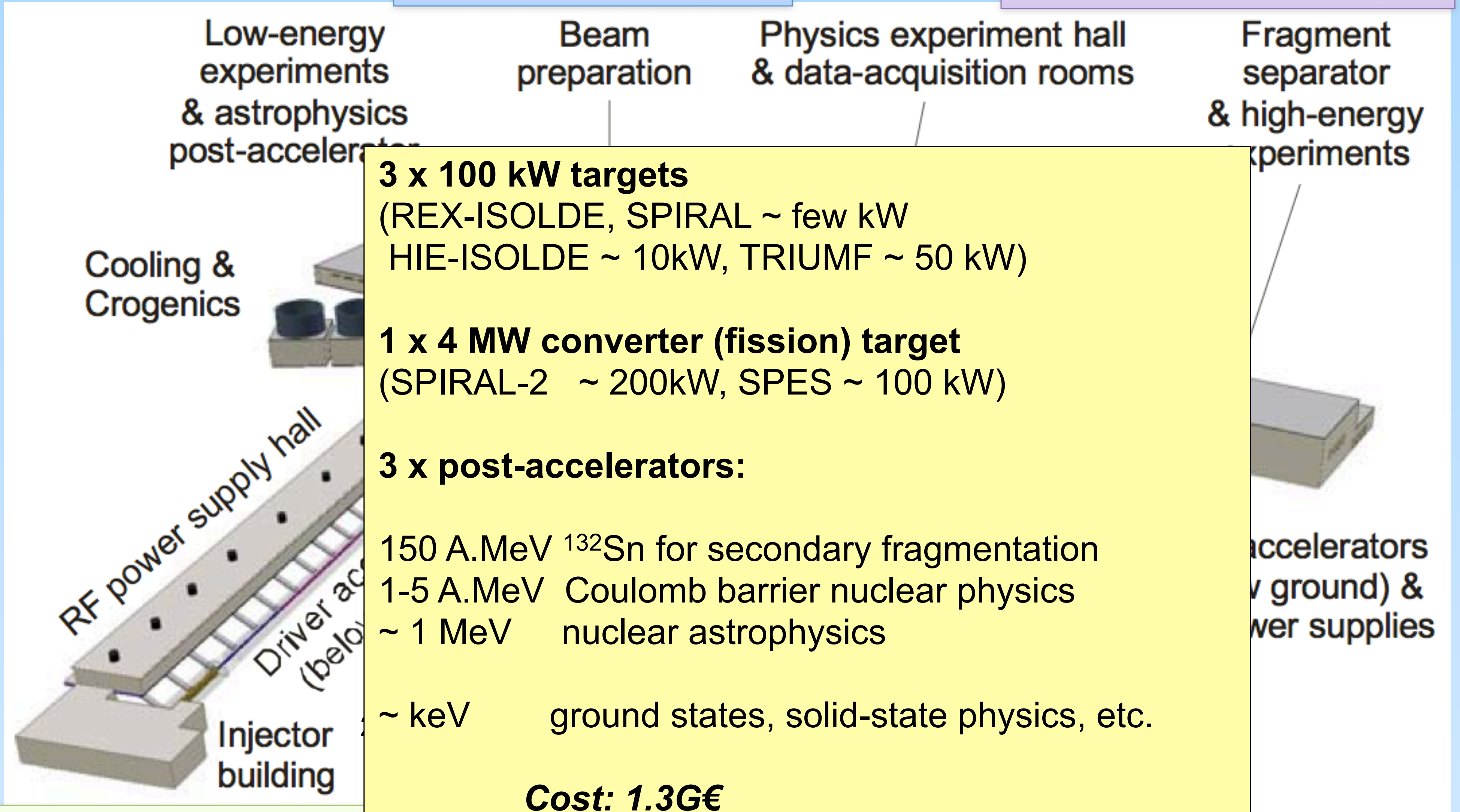


Investment Cost: 136M€

EURISOL

Multi-user capabilities

Up to 150 AMeV for ^{132}Sn



3 x 100 kW targets
(REX-ISOLDE, SPIRAL ~ few kW
HIE-ISOLDE ~ 10kW, TRIUMF ~ 50 kW)

1 x 4 MW converter (fission) target
(SPIRAL-2 ~ 200kW, SPES ~ 100 kW)

3 x post-accelerators:

150 A.MeV ^{132}Sn for secondary fragmentation
1-5 A.MeV Coulomb barrier nuclear physics
~ 1 MeV nuclear astrophysics

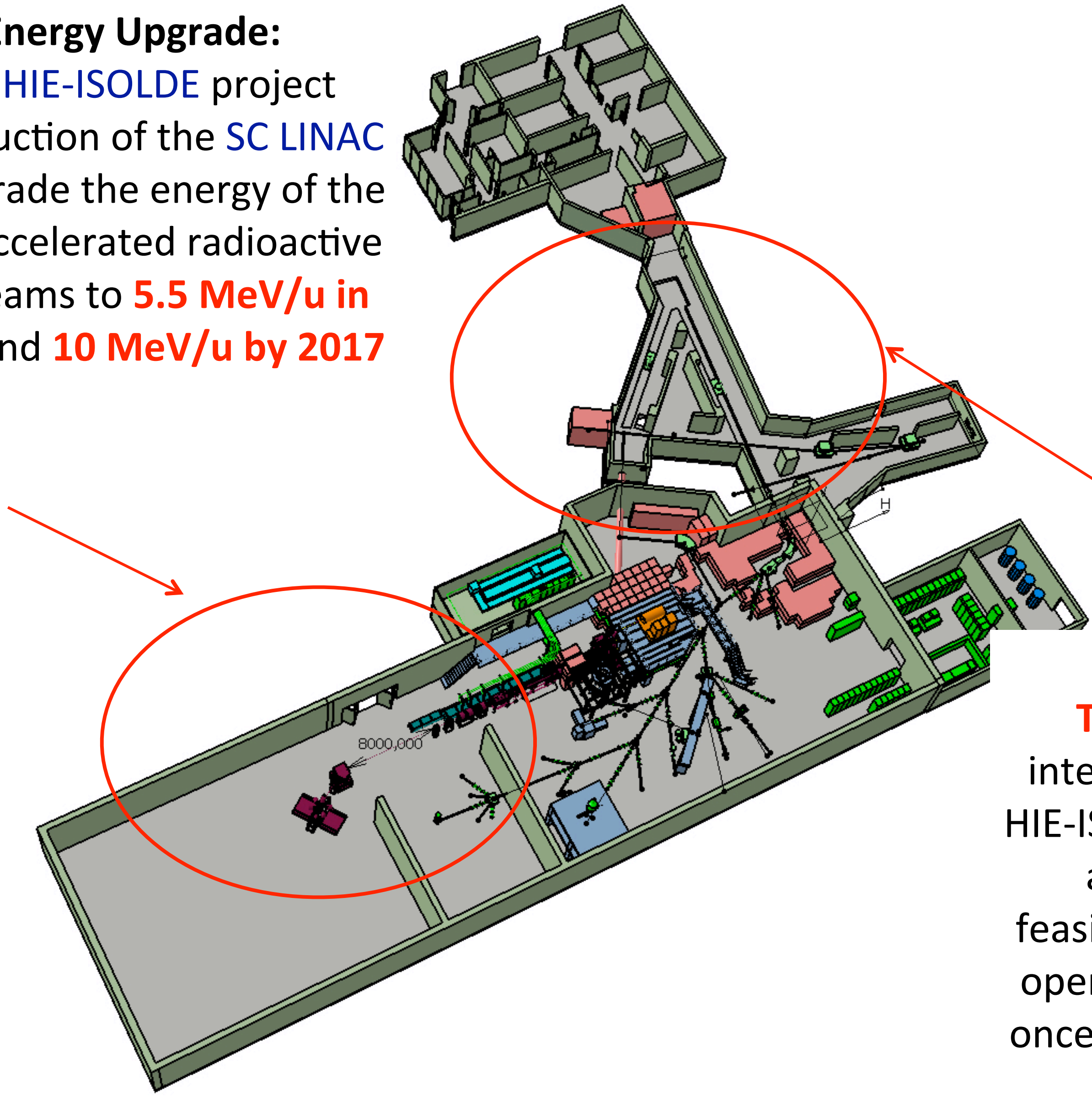
~ keV ground states, solid-state physics, etc.

Cost: 1.3G€

LINAC: H, D, He and A/q=2 ions up to 1 A GeV

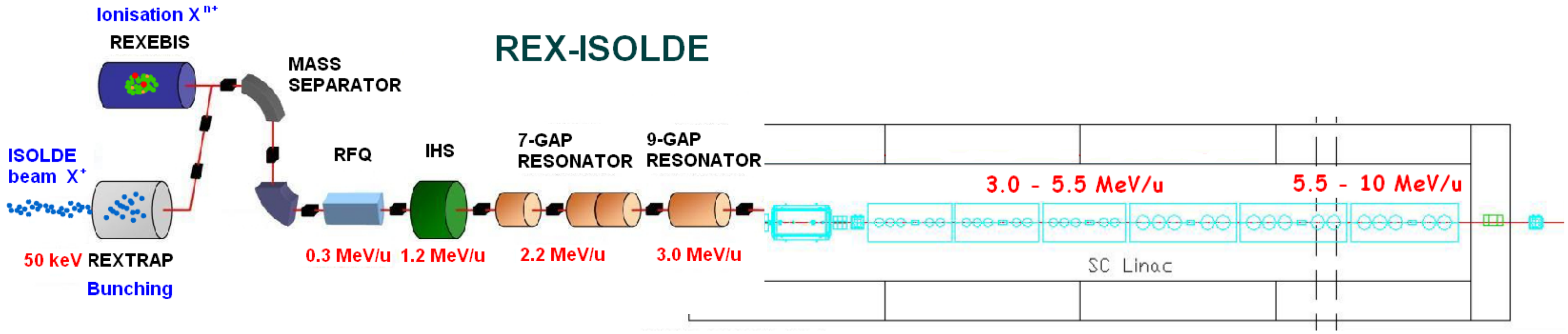
Peter Butler http://ns.ph.liv.ac.uk/pab/EFermi.pdf

Energy Upgrade:
The HIE-ISOLDE project construction of the SC LINAC to upgrade the energy of the post-accelerated radioactive ion beams to **5.5 MeV/u in 2015** and **10 MeV/u by 2017**

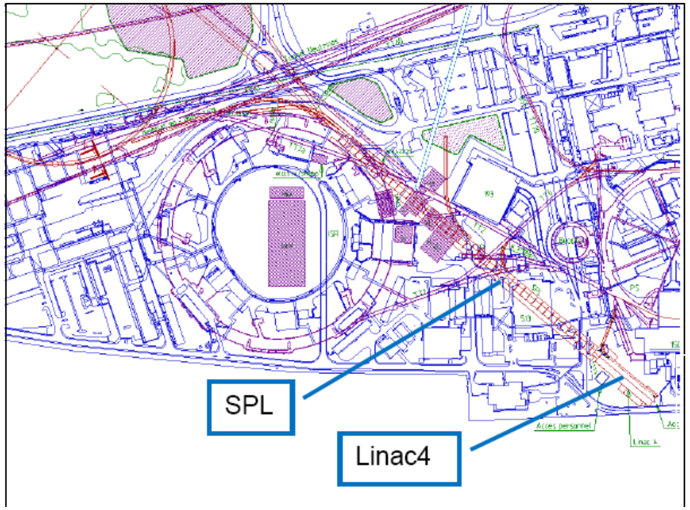


Intensity Upgrade:
The design study for the intensity upgrade, also part of HIE-ISOLDE, **started in 2011**, and addresses the technical feasibility and cost estimate for operating the facility at **10 kW** once LINAC4 and PS Booster are online.

Increase in REX energy from 3 to 10 MeV/u (first step in increase to 5.5 MeV/u) ~2013



Increase proton intensity 2 → 10 kW (LINAC4, PS Booster upgrade) – primary target upgrade ~2014



Replace PS Booster by (Low Power) SPL

10 → 70 kW ~2016

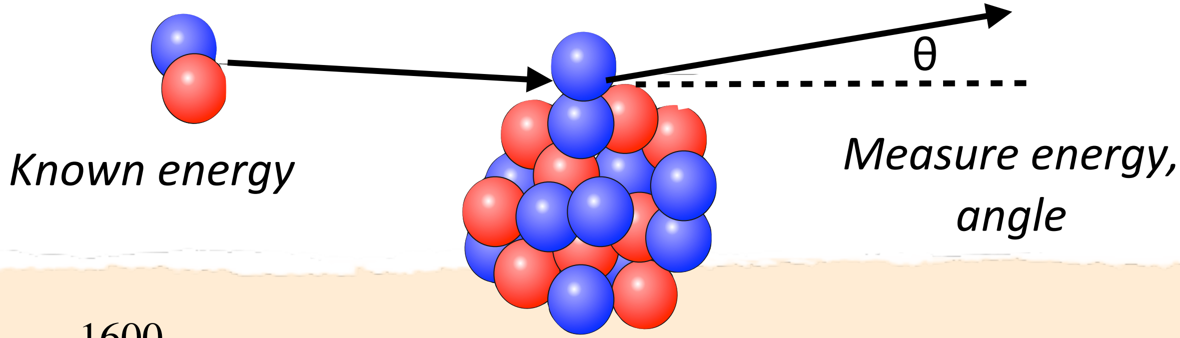
SPL-ISOLDE→ EURISOL

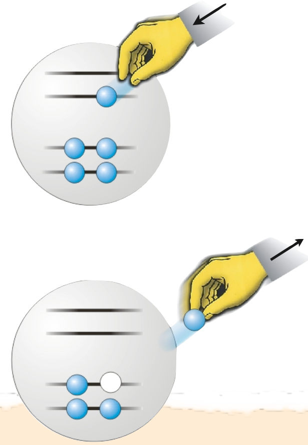
HIE-ISOLDE construction

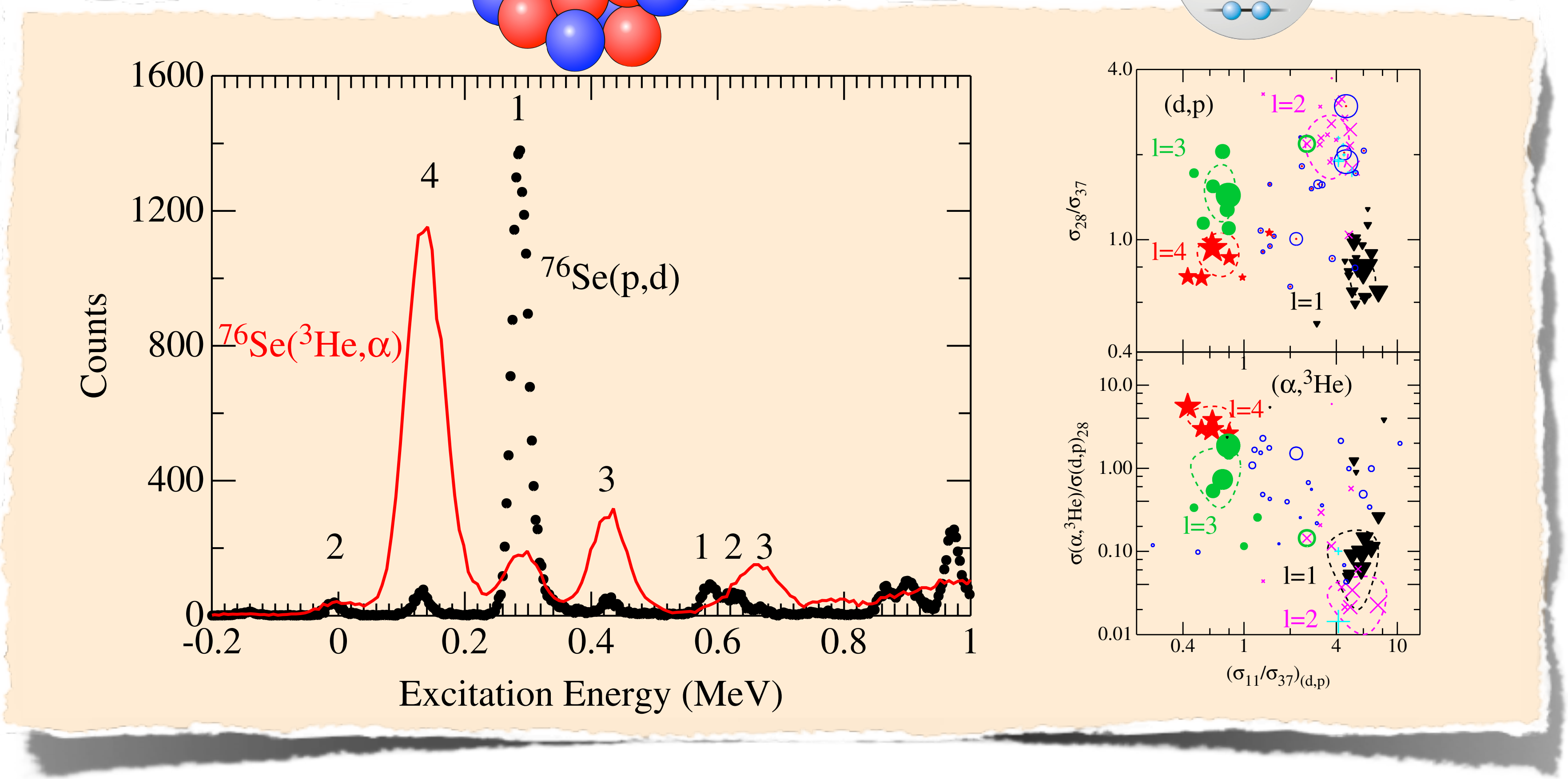
Future physics

Transfer reactions

Energy ... amount ... angle

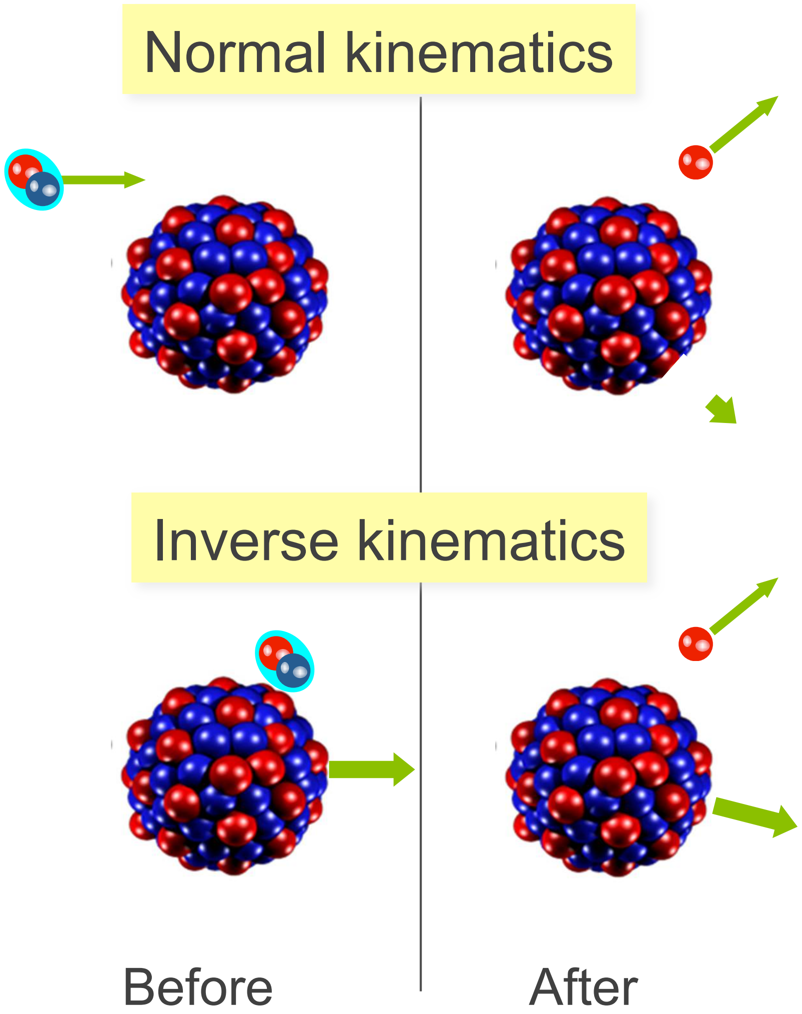


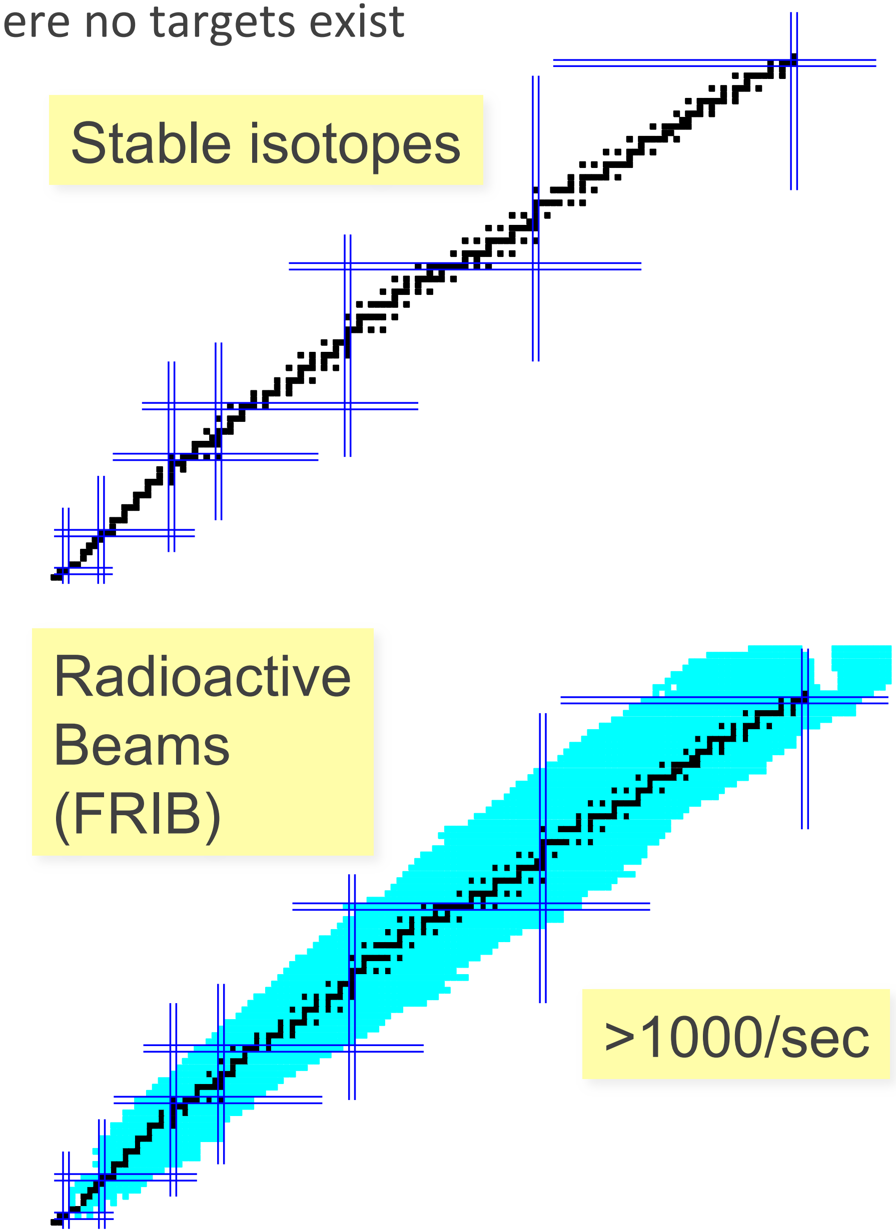




Inverse kinematics - wide applications

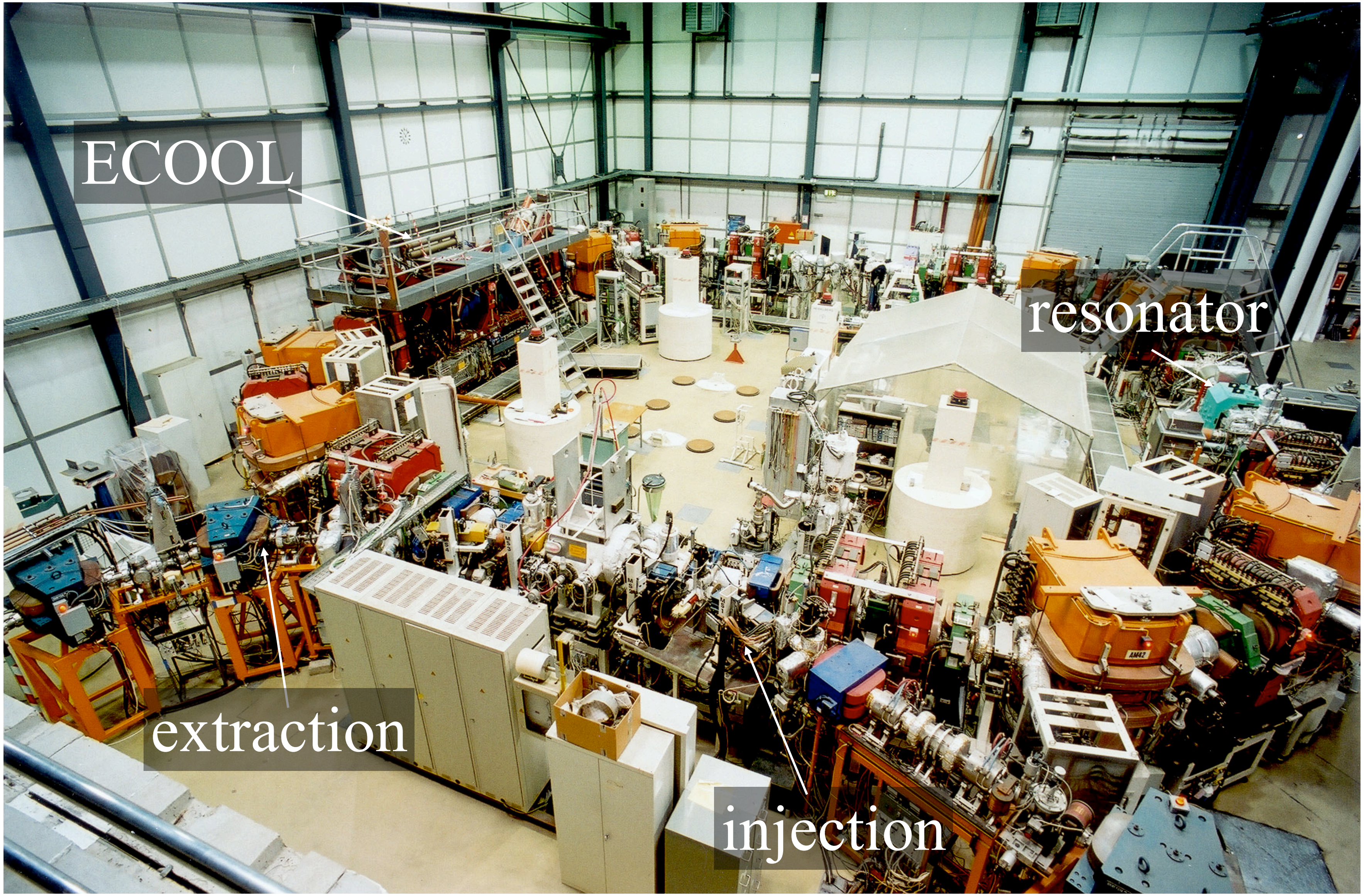
- Precision studies of nuclei in regions where no targets exist



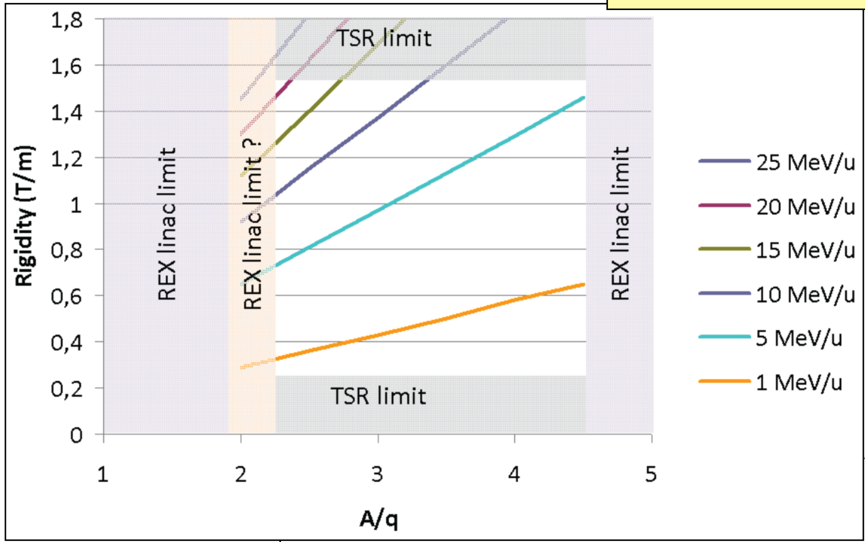


The heavy ion storage ring TSR
MPIK Heidelberg

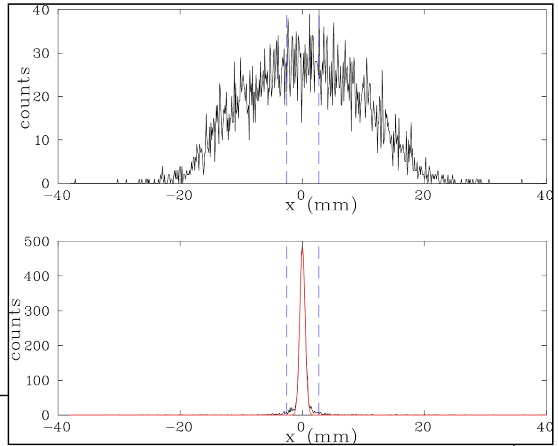
Circumference: 55m

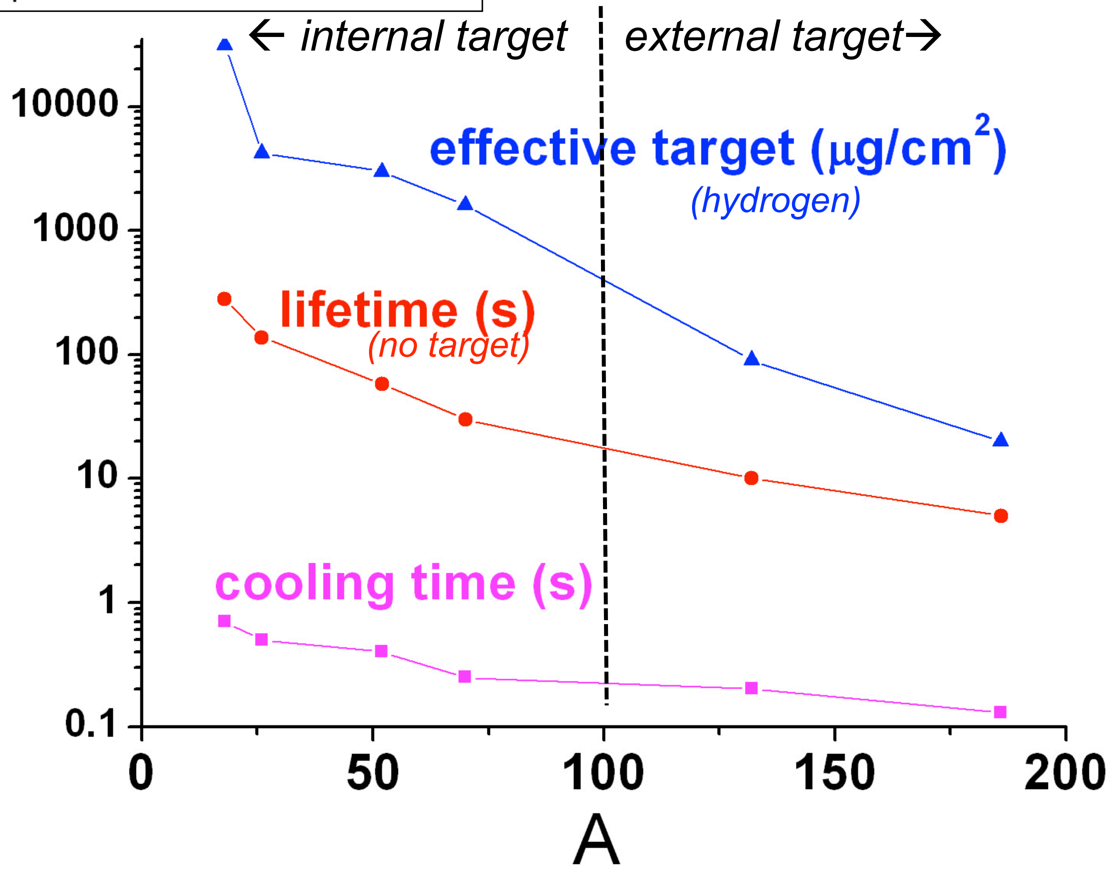


TSR properties



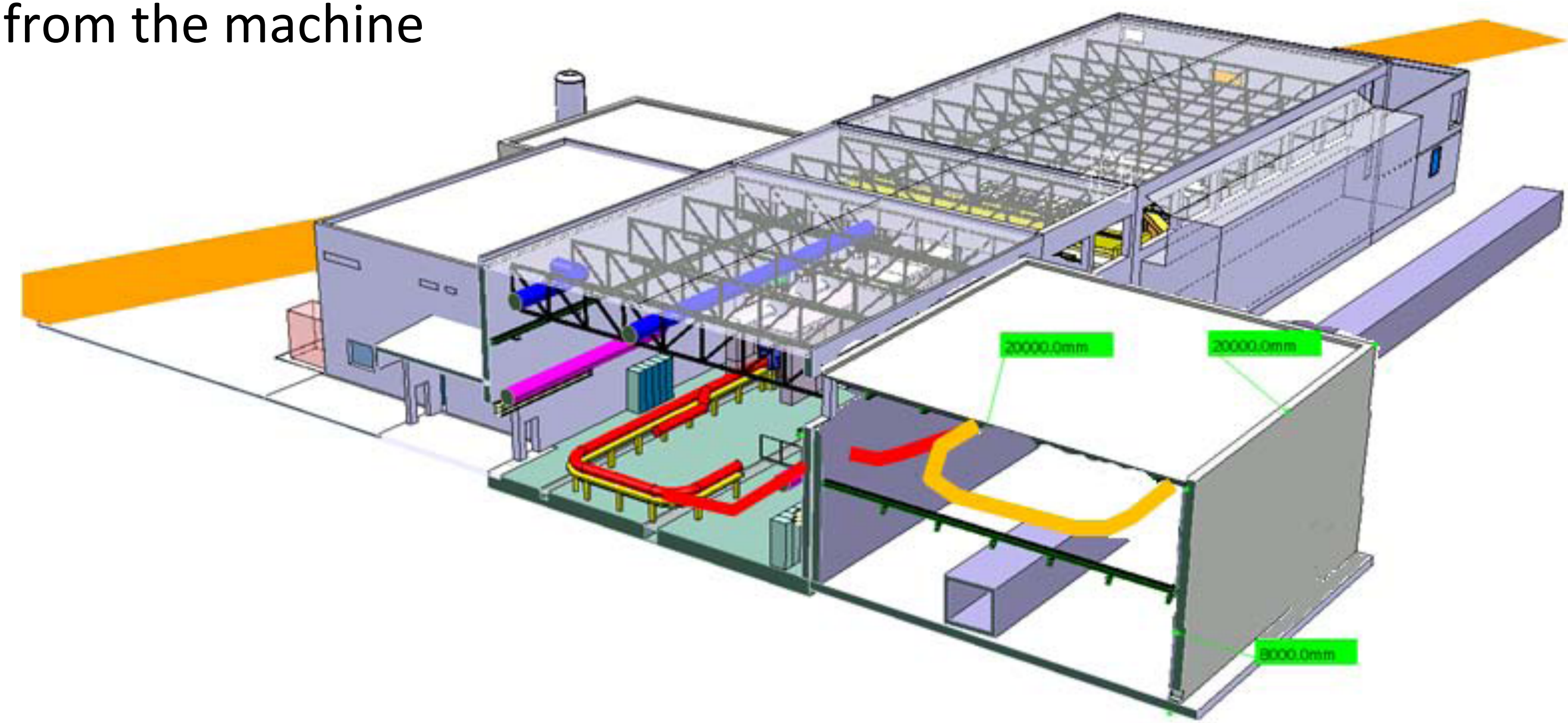
electron cooling





TSR installation

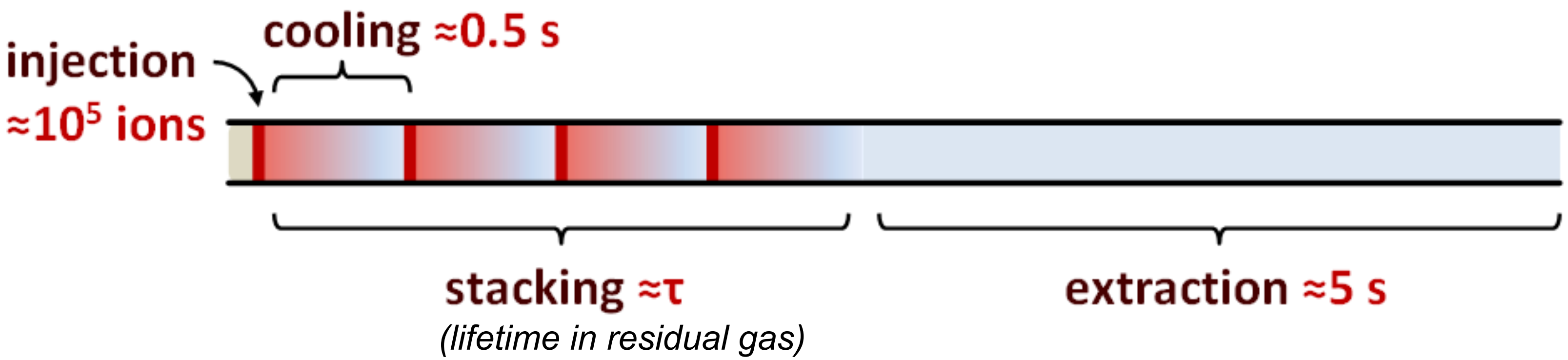
- TSR installation above a cable duct
- Tilted beam line coming up from the machine



TSR applications

M. Grieser et al. Eur. Phys. J. Special Topics 207, 1–117 (2012)

In-Ring - high luminosity achieved thru multiple beam passes (~1 MHz), important for reaction experiments, and laser measurements of static properties of exotic nuclei.

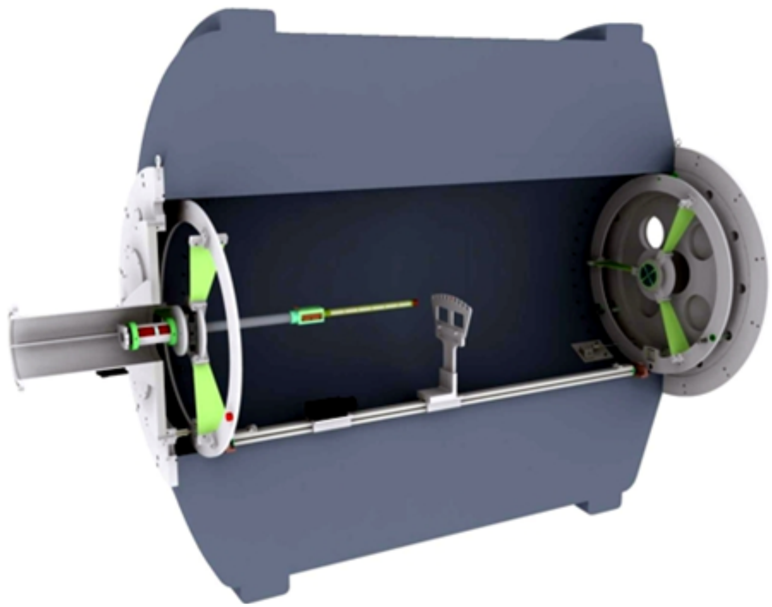


Cooled beams in HELIOS-type spectrometer:

20-30 keV resolution for (d,p)

50-70 keV resolution for (C,C')

direct scatter detection possible

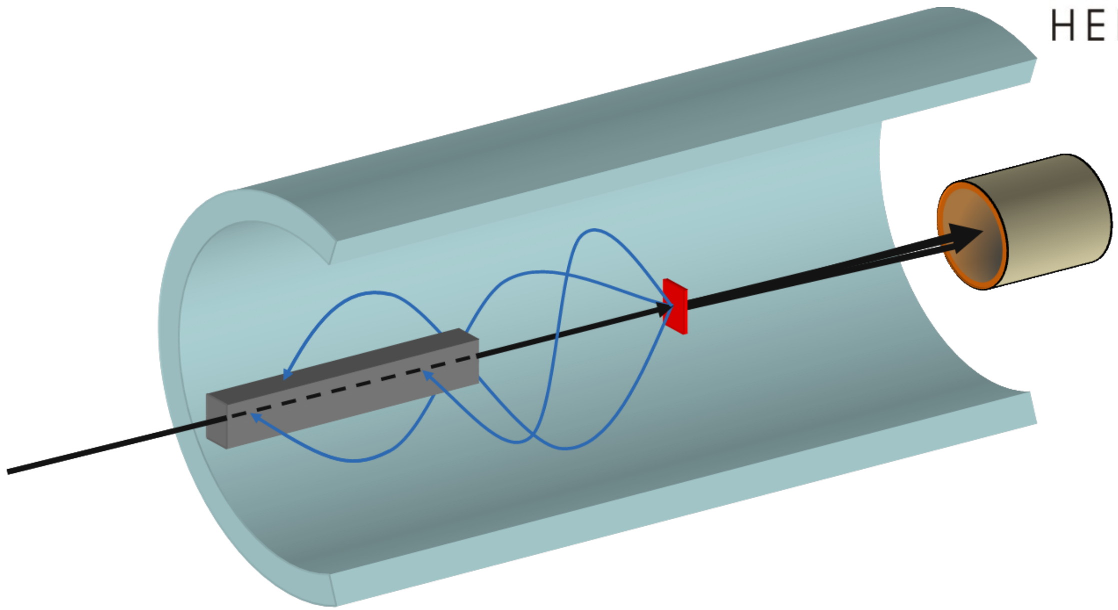


Principle of operation

HELIOS

Measured quantities
Flight time: $T_{flight}=T_{cyc}$
Position: z
Energy: E_{lab}

Derived quantities
Part. ID: m/q
Energy: E_{cm}
Angle: θ_{cm}



B=2T

Particle	T_{cyc} (ns)
p	34.2
$^{3}He^{2+}$	51.4
d, α	68.5
t	102.7

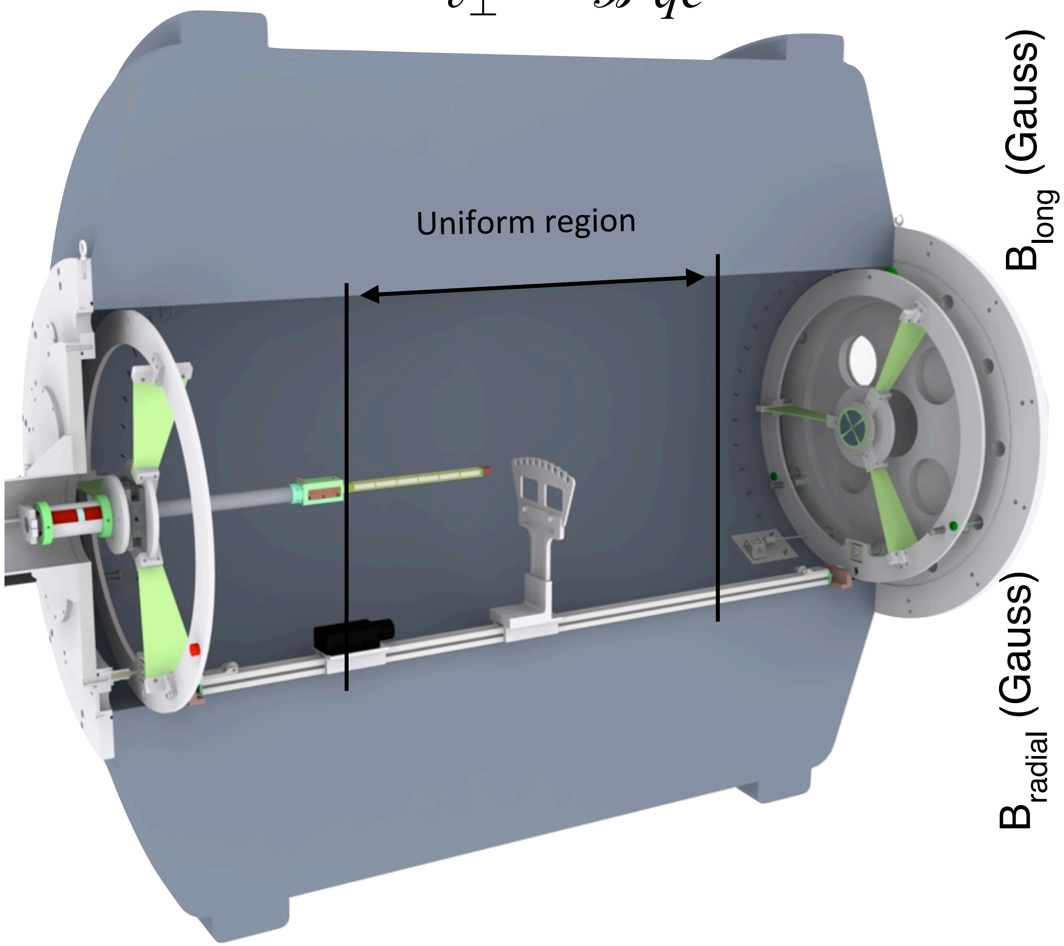
$$\frac{m}{q} = \frac{eB}{2\pi} \times T_{flight}$$

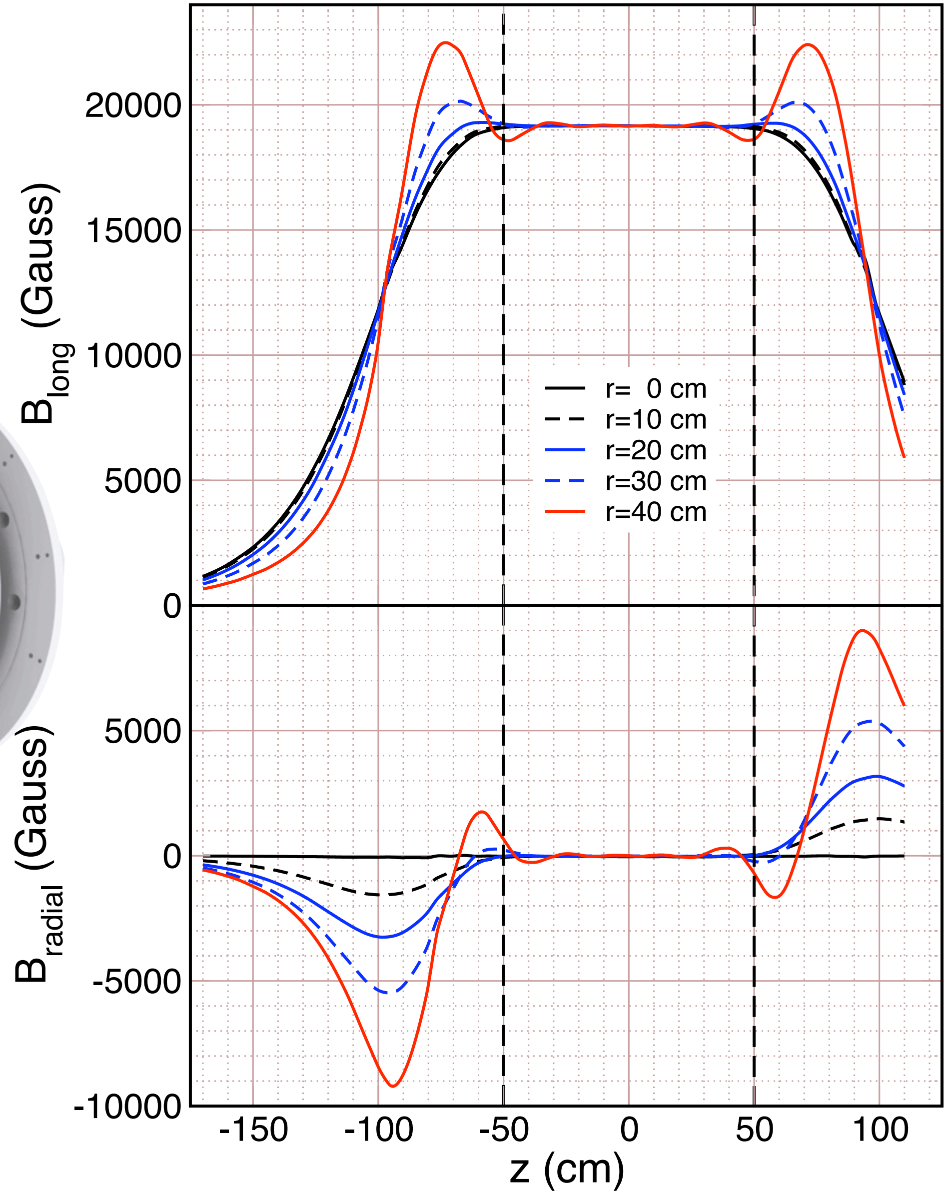
$$E_{cm} = E_{lab} + \tfrac{1}{2} m V_{cm}^2 - \frac{V_{cm} q e B}{2\pi} z$$

$$\theta_{cm} = \arccos\left(\frac{1}{2\pi} \frac{qeBz - 2\pi m V_{cm}}{\sqrt{2mE_{lab} + m^2 V_{cm}^2 - mV_{cm} qeBz/\pi}} \right)$$

The field – uniformity is key

$$T_{\rm cyc} = \frac{2\pi r}{v_\perp} = \frac{2\pi}{\mathscr{B}}\frac{m}{qe}$$





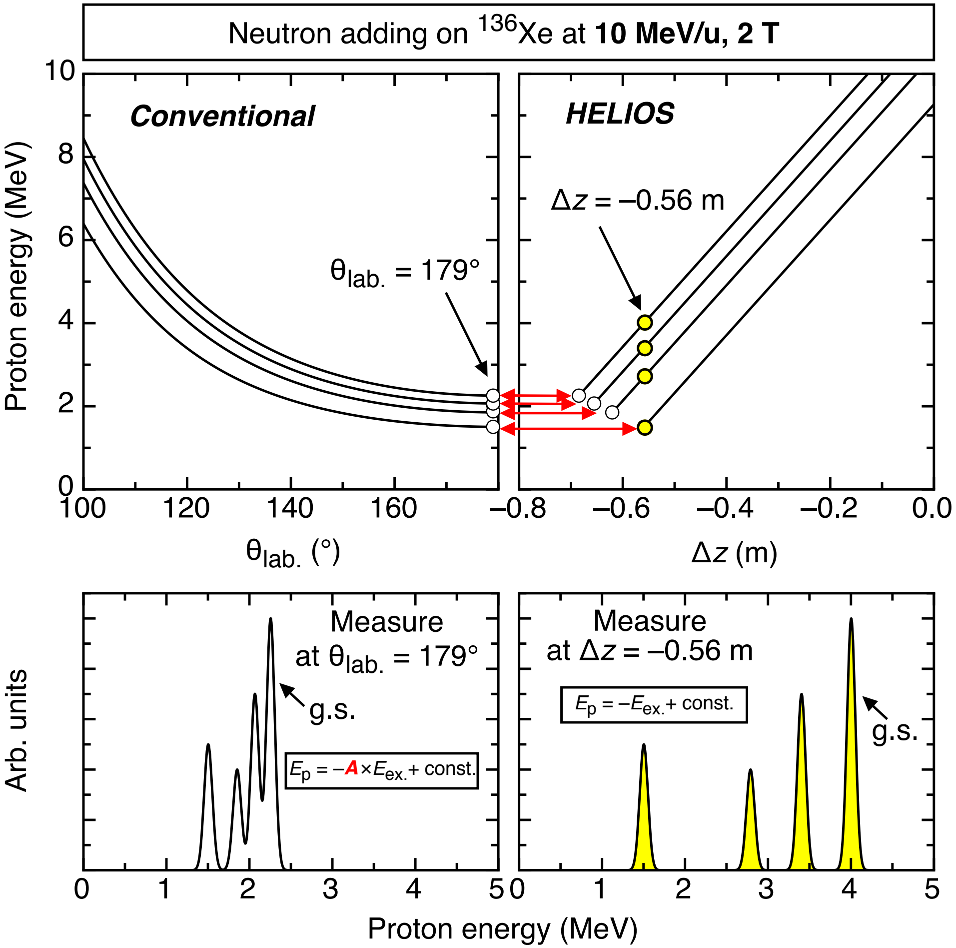
$$E_{\rm cm} = E_{\rm lab} + \frac{m}{2}V_{\rm cm}^2 - \frac{mV_{\rm cm}z}{\boxed{T_{\rm cyc}}}$$

Medical imaging (MRI): 1-5 parts in 10^7 (<µT)

Nuclear physics: 1 part in 10^3 (mT)

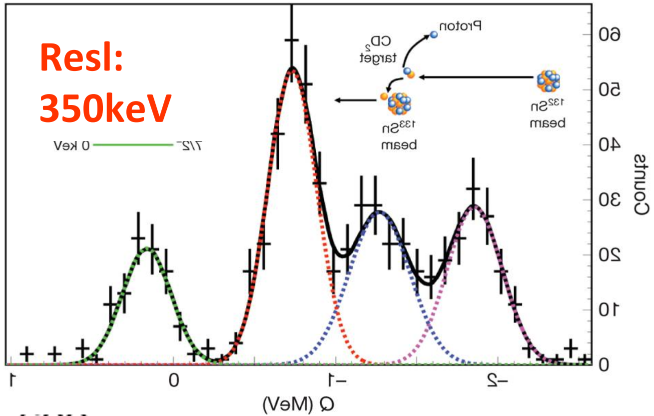
The HELIOS approach, backward hemisphere

Negative-Q-value reaction, target at Δz = 0 m



- There is ***no kinematic compression for a fixed distance Δz***. The excitation energy in the lab. and c.m. are related by only an additive constant
- The ***kinematic shift in Δz is linear*** and modest [<15 keV/mm for (*d*,*p*) at 2 T, Δ*z* resolution in HELIOS <1 mm]
- PID through cyclotron period, energy independent, readily identify ions with energies as low as ~200 keV

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



HELIOS vs. Si-detector arrays

Tiara, T-REX, Sharc, ORRUBA

K. L. Jones *et al.*,
Nature **465** 454–457 (2010).