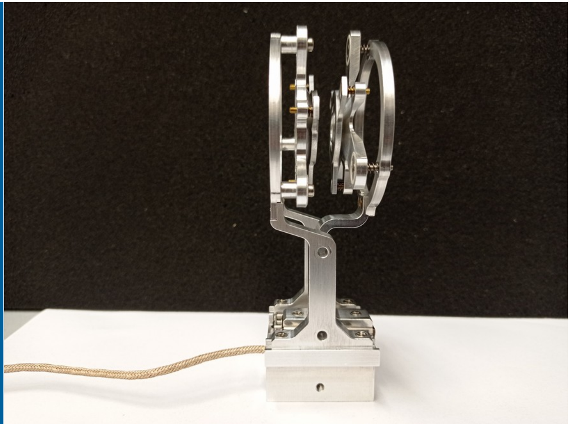
EXOTIC BEAM SUMMER SCHOOL 2023

Nuclear Structure (Experiment)



Claus Müller-Gatermann

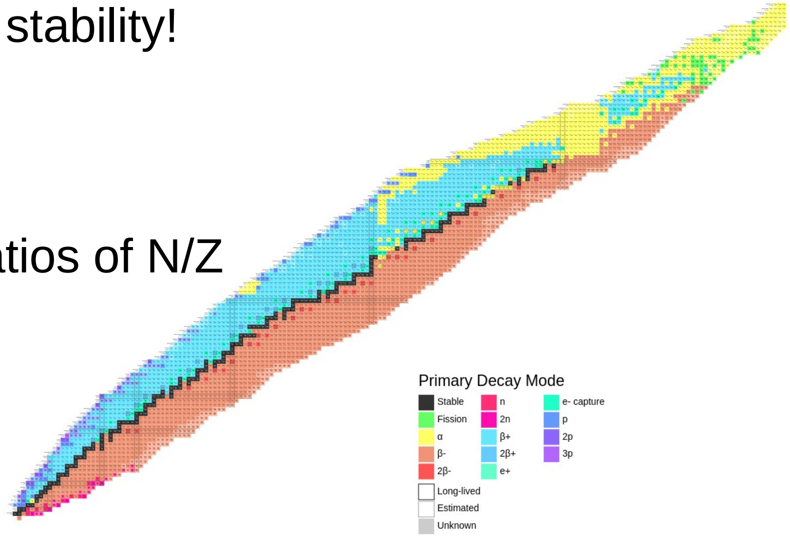
U.S. DEPARTMENT OF ENERGY
Argonne National Laboratory is a U.S. Department of Energy laboratory managed by UChicago Argonne, LLC.

MOTIVATION

Why study nuclear structure using exotic beams?
Necessary to understand nuclei far from stability!

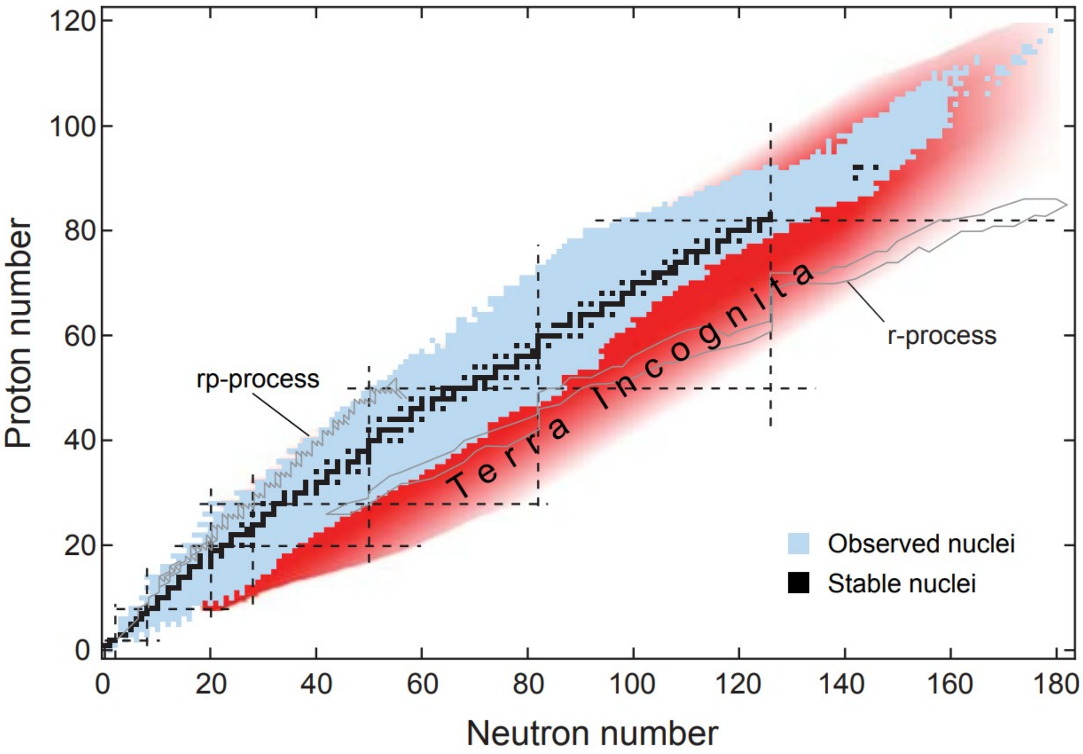
Changes in nuclear shell structure
Evolution of collectivity
Phenomena which happen at extreme ratios of N/Z

- single or multiple nucleon decay
- nucleon skins, halos
- isospin symmetry breaking
- nuclear astrophysics

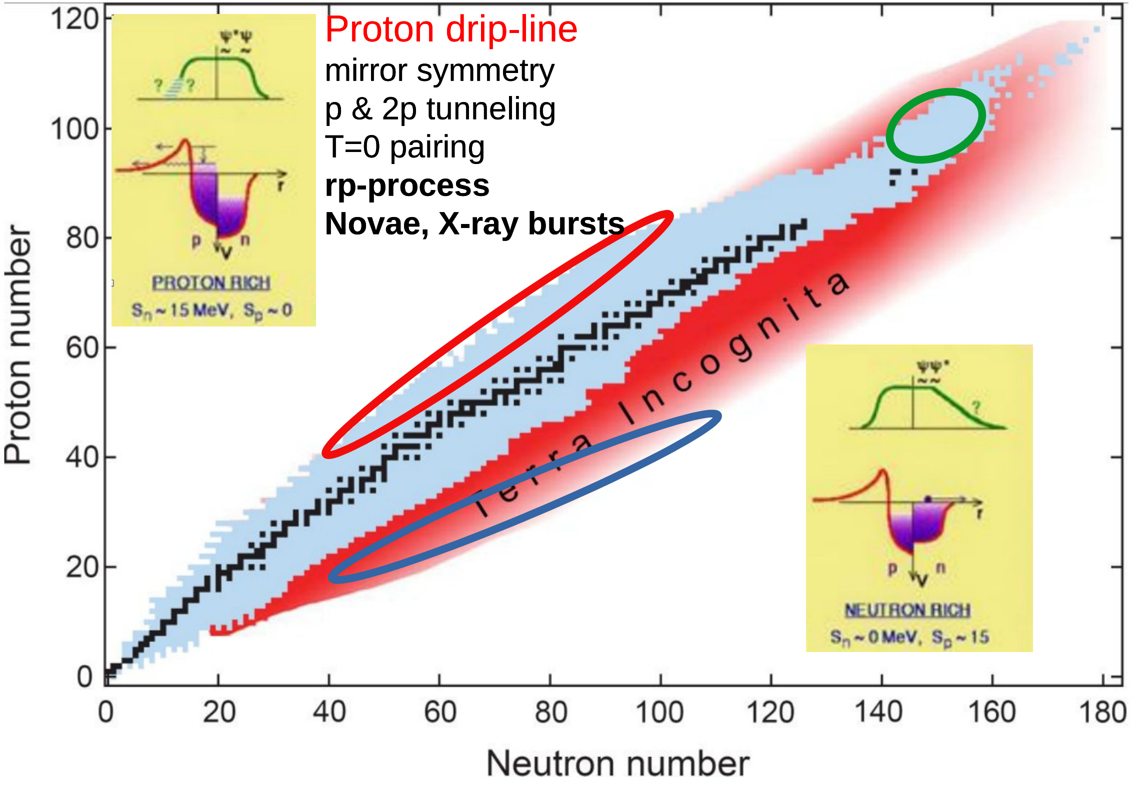


NUCLEAR LANDSCAPE

255 stable isotopes
3100 observed isotopes
6000-8000 maybe particle stable



NUCLEAR LANDSCAPE



Heavy Elements
shell stability
island of SHE

Neutron drip-line
Halos, skins
pairing at low density
new shell structure
new collective modes
r-process
Stars, Supernovae

INGREDIENTS OF AN EXPERIMENT

Accelerator facility to provide beam

- stable/radioactive, pure/cocktail, intensity
- energies from keV to 100s MeV/A

A target

- solid/liquid/gaseous, density/thickness
- active targets

Instruments

- HPGe detectors
- Double-sided strip detectors (Si,Ge)
- scintillators
- magnetic spectrometers
- gaseous detectors
- ion traps
- ...

Theory

- interpretation of the data
- motivate experiments to validate theories

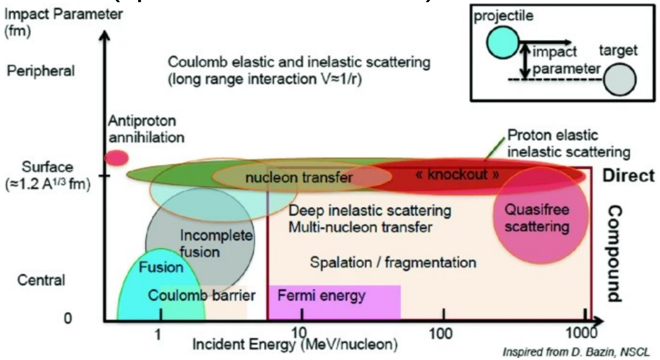
PRODUCTION OF BEAM/EXCITED STATES

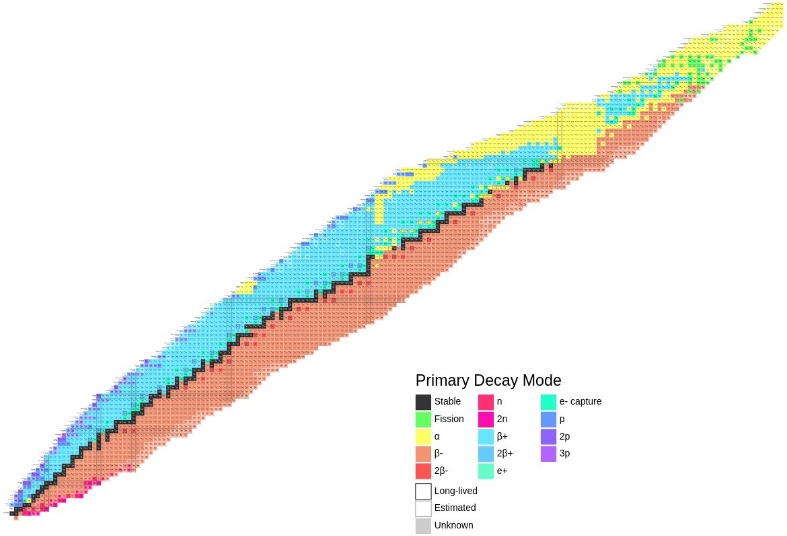
Reactions

- Coulomb excitation (low and high energy)
- (deep-)inelastic scattering, (multi-nucleon) transfer reactions, incomplete fusion
- fusion-evaporation
- target/beam fragmentation
- nucleon knockout

Decay

- alpha-decay
- beta-decay
- fission (spontaneous/induced)

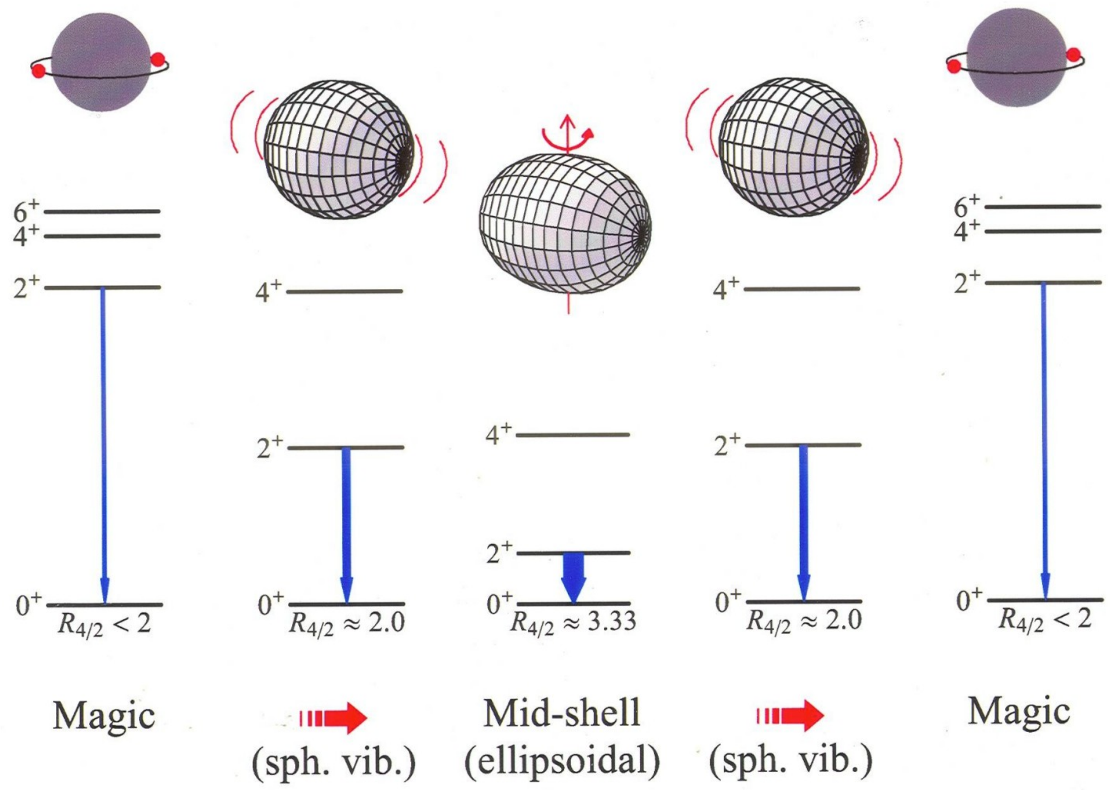




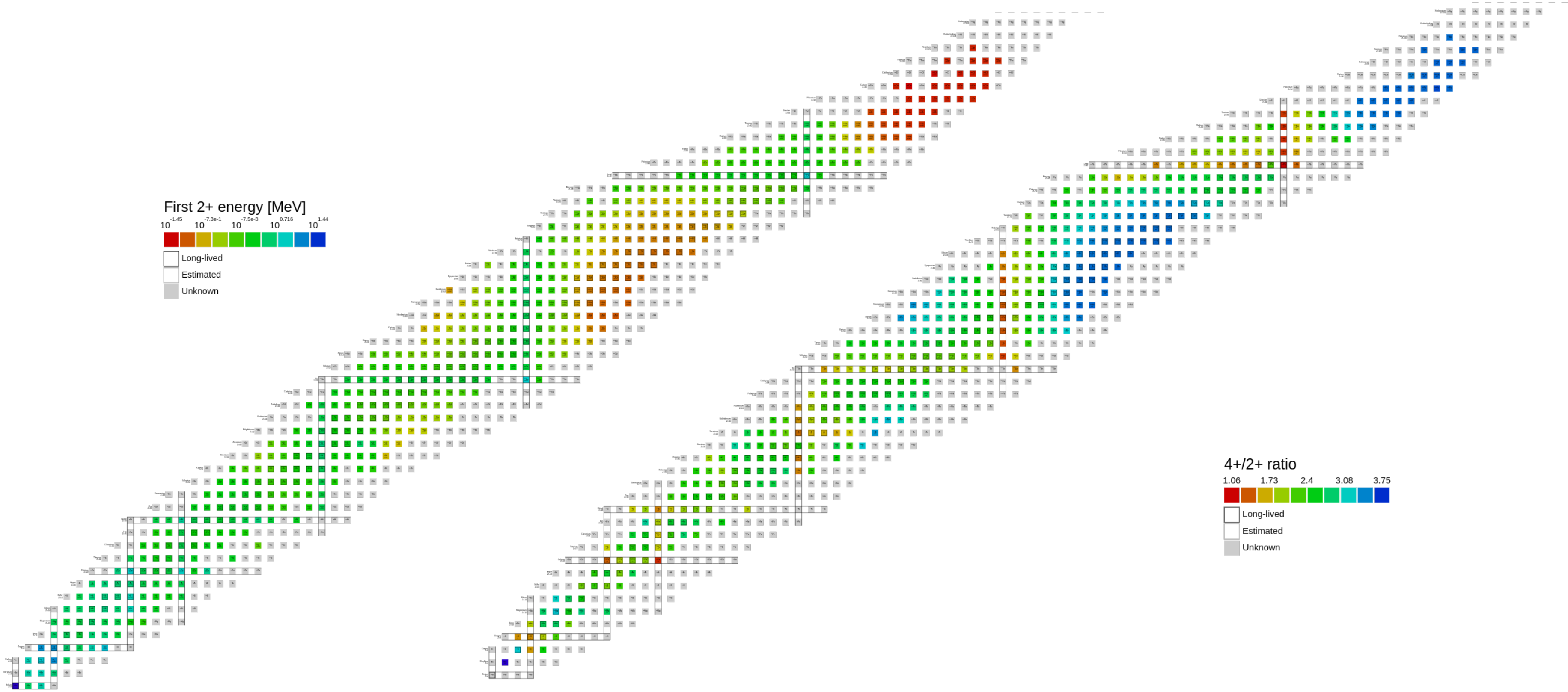
NUCLEAR PROPERTIES

- Mass, half-life – nuclear binding energy
- Level energy
- Electromagnetic matrix elements
  B(E2), B(M1), Q, lifetime, g-factor
- Reaction cross sections
  transfer, knockout (need reaction model)

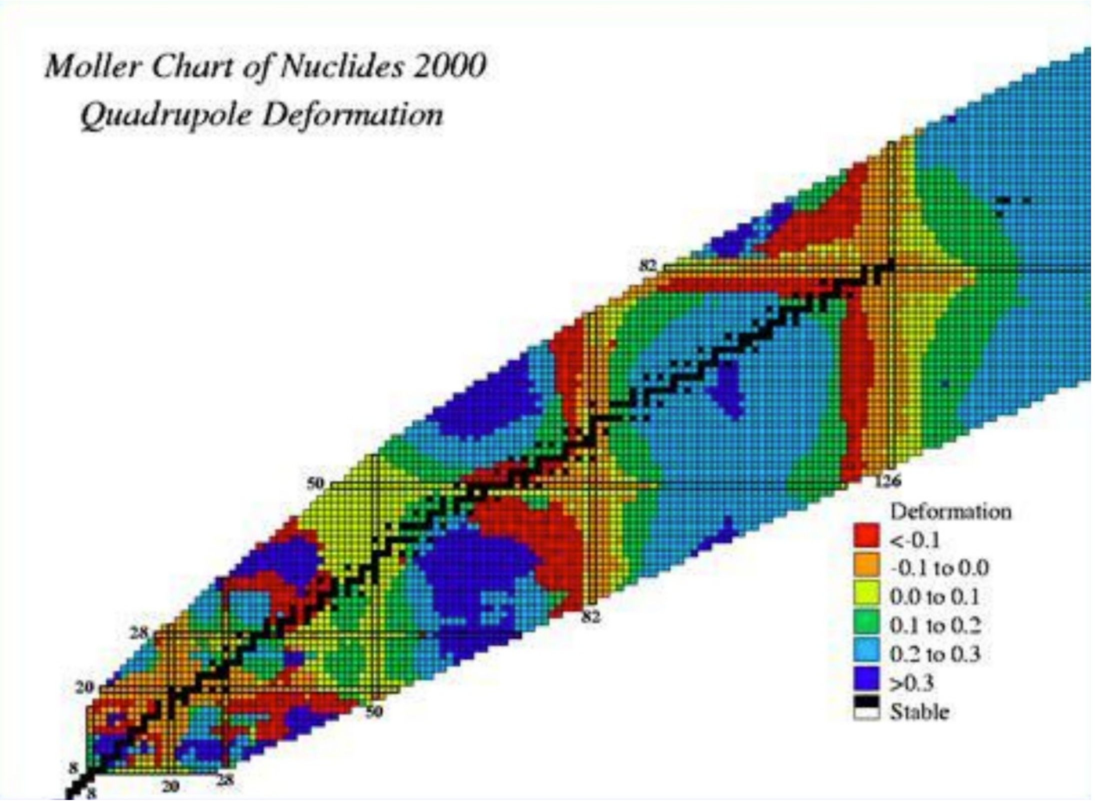
EVOLUTION OF LEVEL ENERGIES



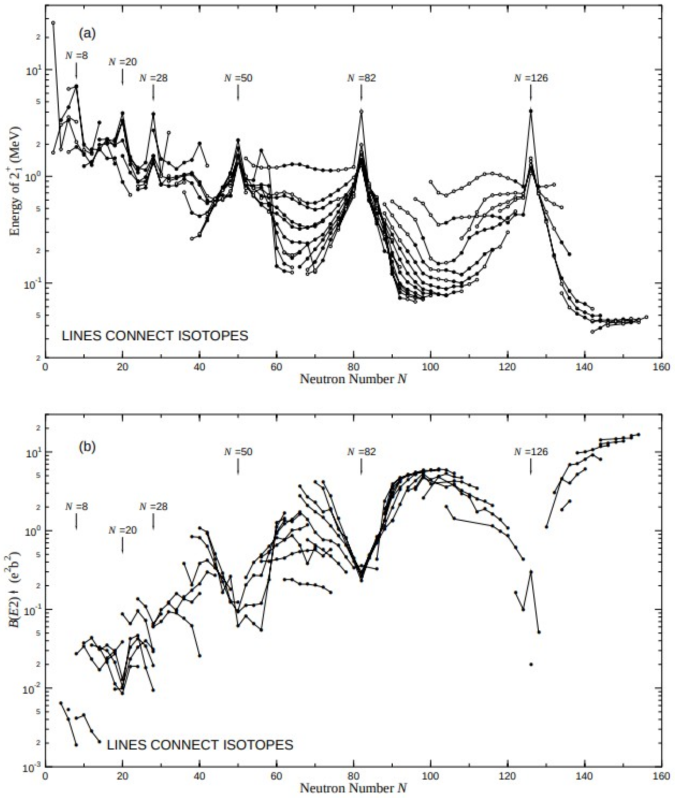
EVOLUTION OF LEVEL ENERGIES



EVOLUTION OF DEFORMATION



SHELL STRUCTURE AND MAGIC NUMBERS



On Closed Shells in Nuclei. II

MARIA GOEPPERT MAYER
Argonne National Laboratory and Department of Physics, University of Chicago, Chicago, Illinois

February 4, 1949

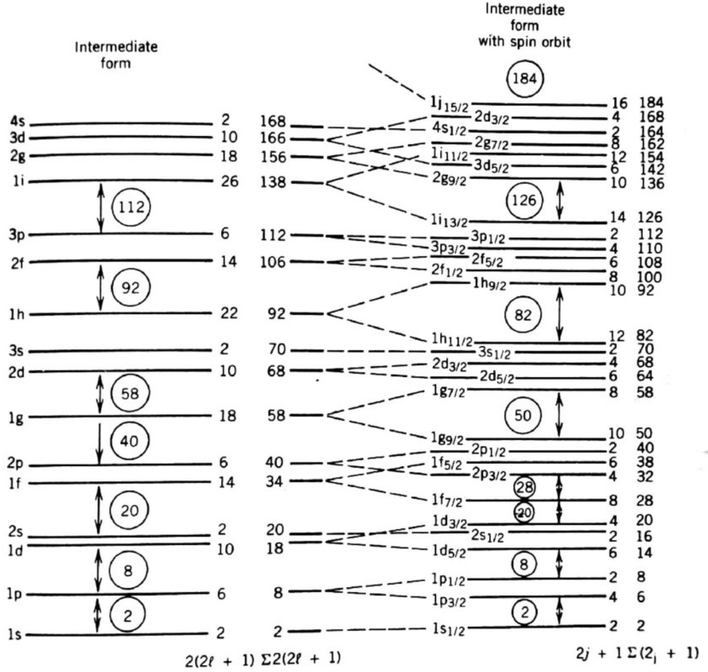
THE spins and magnetic moments of the even-odd nuclei have been used by Feenberg[1,2] and Nordheim[3] to determine the angular momentum of the eigenfunction of the odd particle. The tabulations given by them indicate that spin orbit coupling favors the state of higher total angular momentum. If strong spin-orbit coupling, increasing with angular momentum, is assumed, a level assignment different from either Feenberg or Nordheim is obtained. This assignment encounters a very few contradictions with experimental facts and requires no major crossing of the levels from those of a square well potential. The magic numbers 50, 82, and 126 occur at the place of the spin-orbit splitting of levels of high angular momentum.

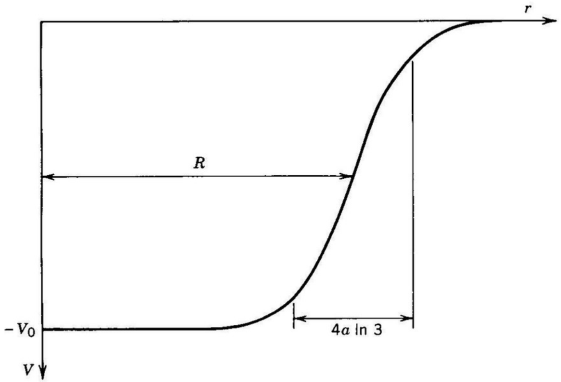
• • • • • • • • • •

Thanks are due to Enrico Fermi for the remark, "Is there any indication of spin-orbit coupling?" which was the origin of this paper.

Physical Review 75 (1949)

SHELL STRUCTURE AND MAGIC NUMBERS

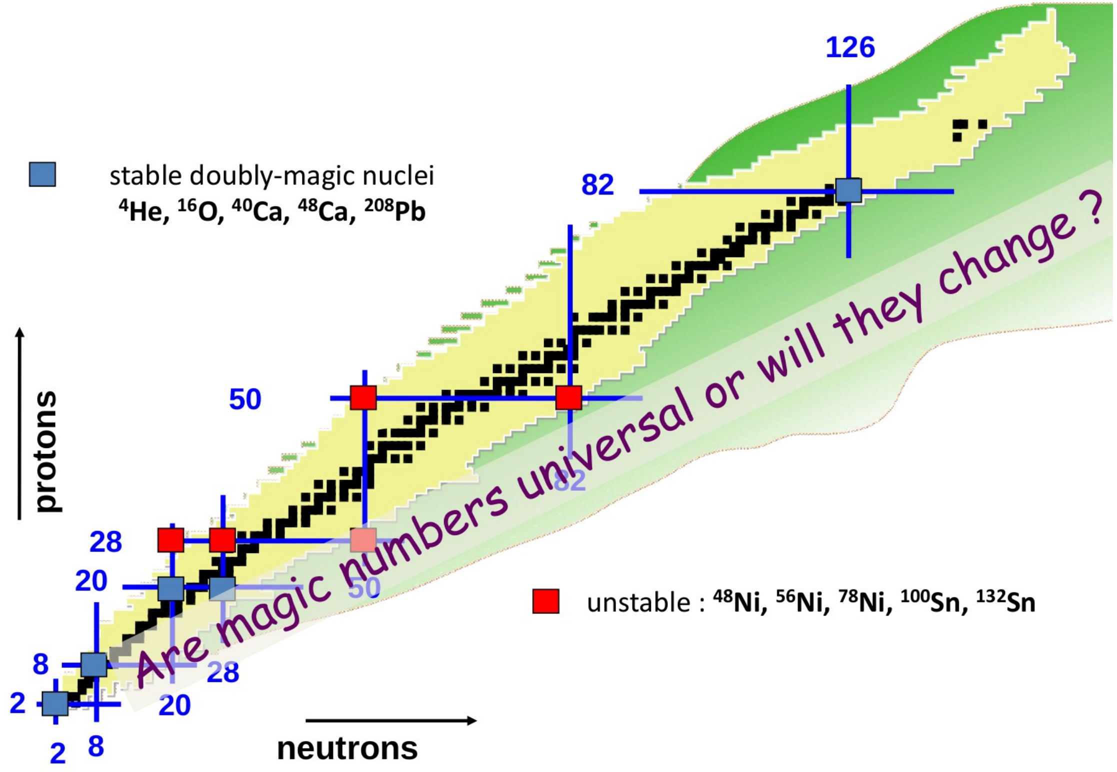




$$V(r) = \frac{-V_0}{1 + \exp\left(\frac{r-R}{a}\right)}$$

- j=l+1/2 orbitals from higher shells intrude into lower shell (f7/2, g9/2, h11/2,…)
- Increased stability for N,Z=2, 8, 20, 28, 50, 82… as energy difference to next shell is large
- intruder states remain pure as strong interaction does not mix with opposite parity

SHELL STRUCTURE AND MAGIC NUMBERS

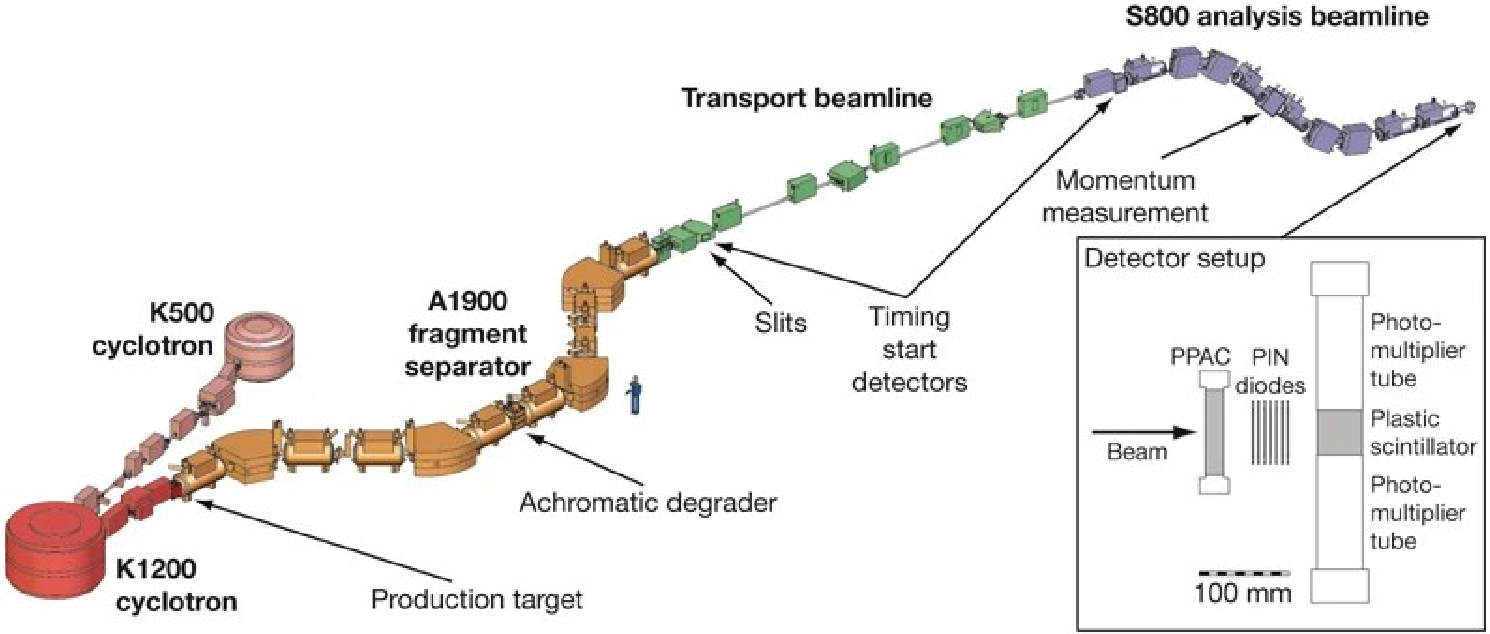


- limits of existence:
  neutron drip-line, island of SHE
- drip-lines are a benchmark for every nuclear model
- nuclear structure is different (Halo nuclei, skins, …)
- sensitive to nuclear force

How about ^{28}O and ^{40}Mg?

NSCL @ MSU

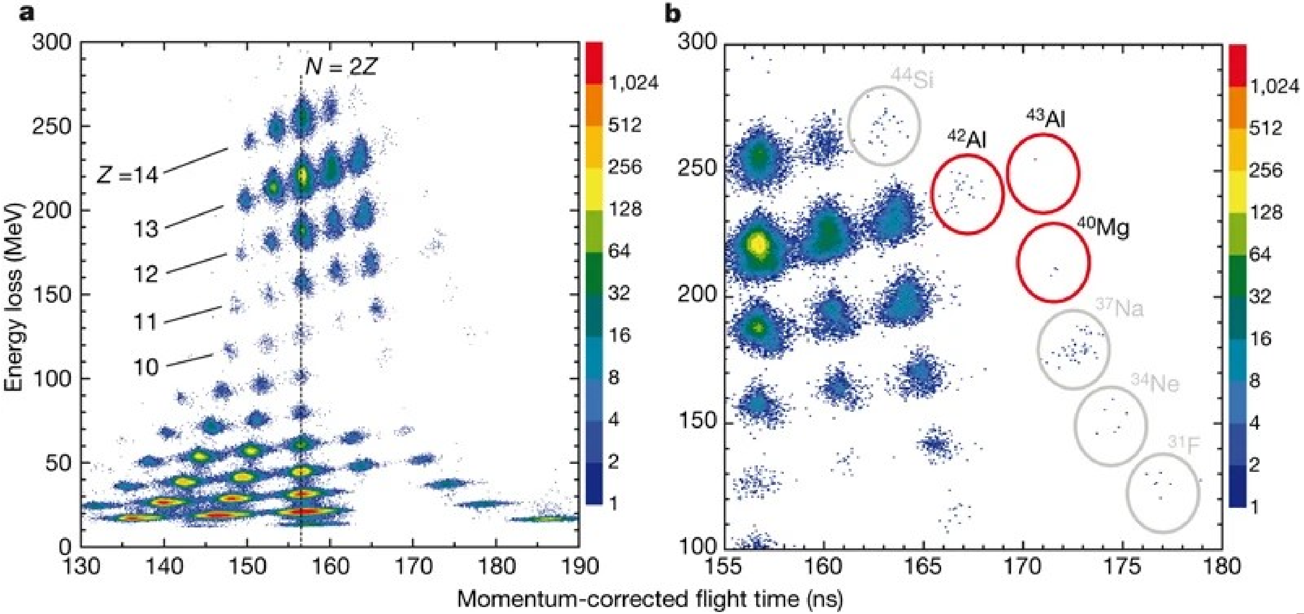
^{48}Ca @140MeV/A on ^{nat}W
7.6d @ 5x10^{11}pps



SEARCH FOR ^{40}MG

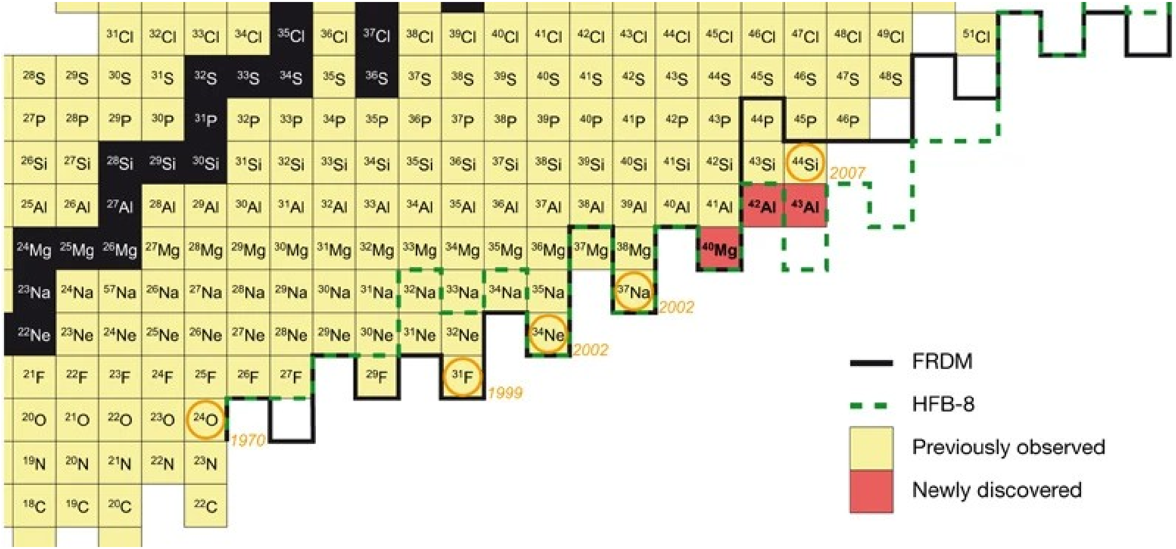
dE proportional to Z^2 (diagonal lines for same Z)
Time of flight proportional to
A/Z x flight path/magnetic rigidity (vertical line for N=2Z)

3 events ^{40}Mg
1 event ^{43}Al
23 events ^{42}Al



SEARCH FOR ^{40}MG

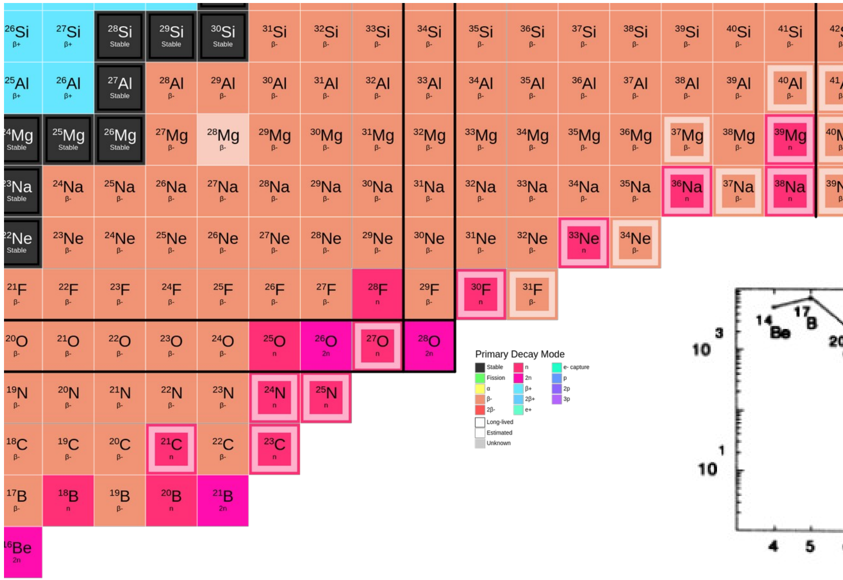
- Existence of ^{40}Mg consistent with best global models
- The existence of odd-odd ^{42}Al contradicts the predictions to be unbound of both models
- Adding 1 proton to Mg has stabilizing effect
- Same for O to F?

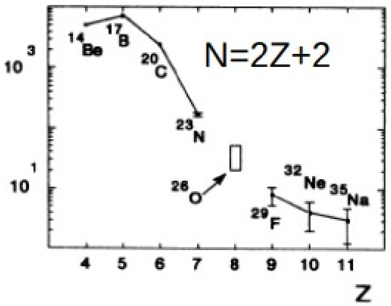


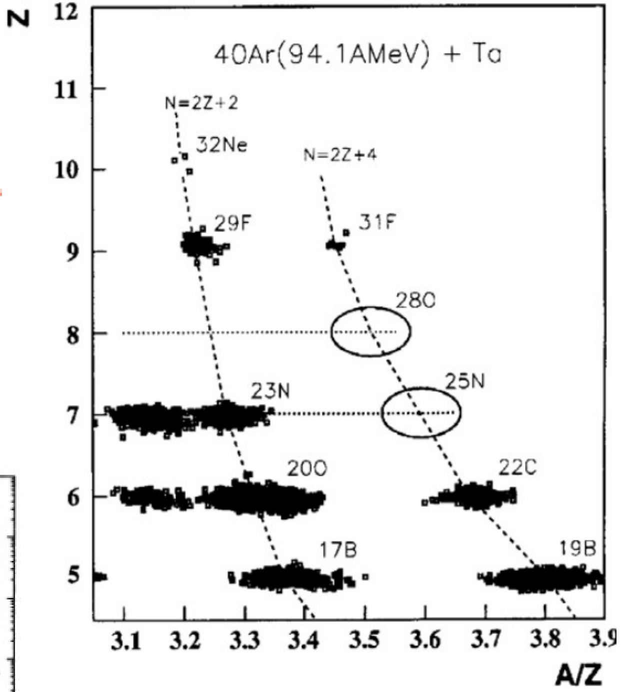
SEARCH FOR ^{28}O

- Absence of ^{28}O in N=2Z+4 systematic
- Absence of ^{26}O in N=2Z+2 systematic

=> Particle unbound, no strong shell effect







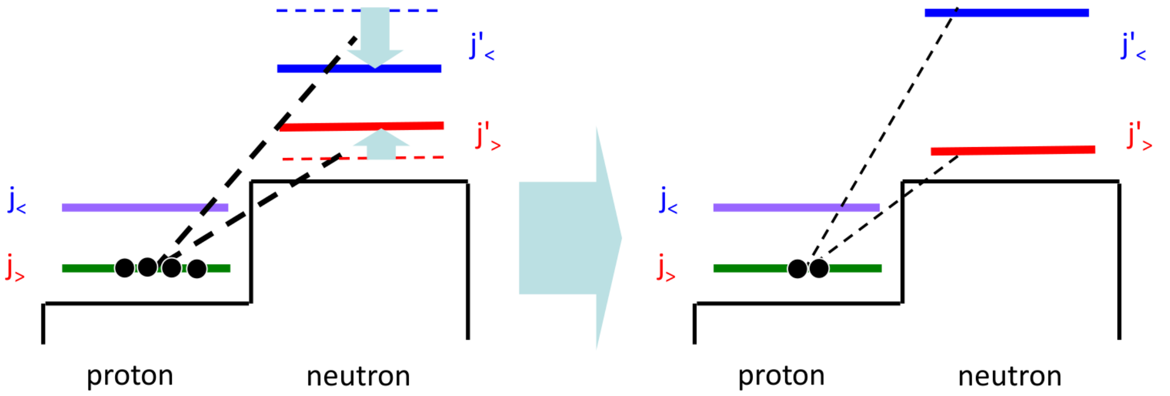
MAY THE STRONG FORCE BE WITH YOU

Proton-neutron monopole interaction changes position of single particle orbits as a function of proton-neutron ratio

Attractive p-n force between $J_<$ and $J_>$ orbitals

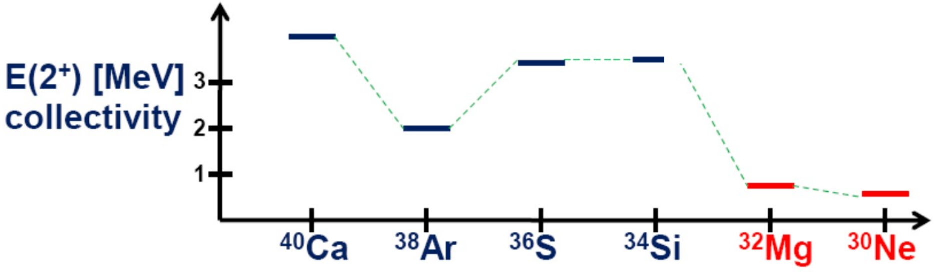
>: l+1/2

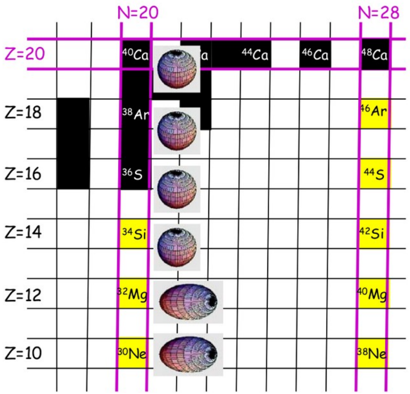
<: l-1/2

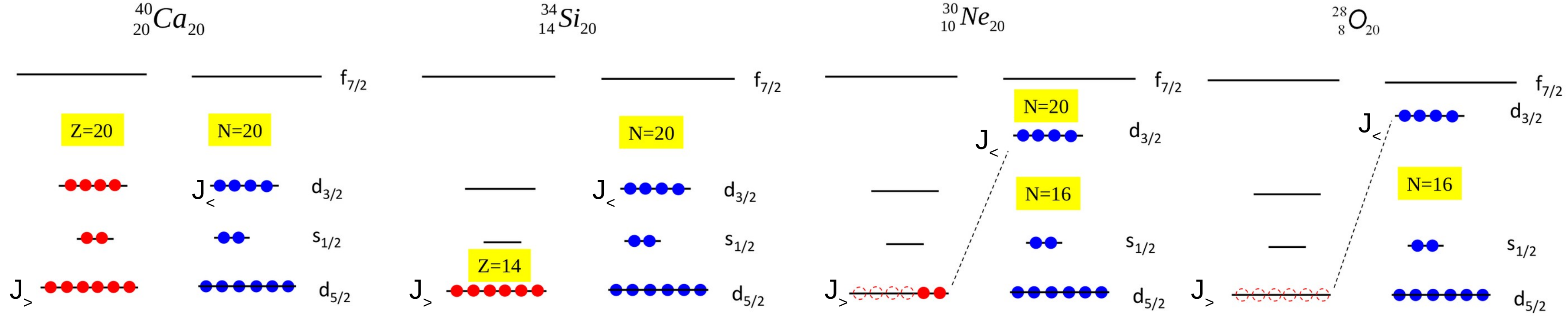


VANISHING OF THE N=20 SHELL GAP

Evolution of the N=20 shell closure







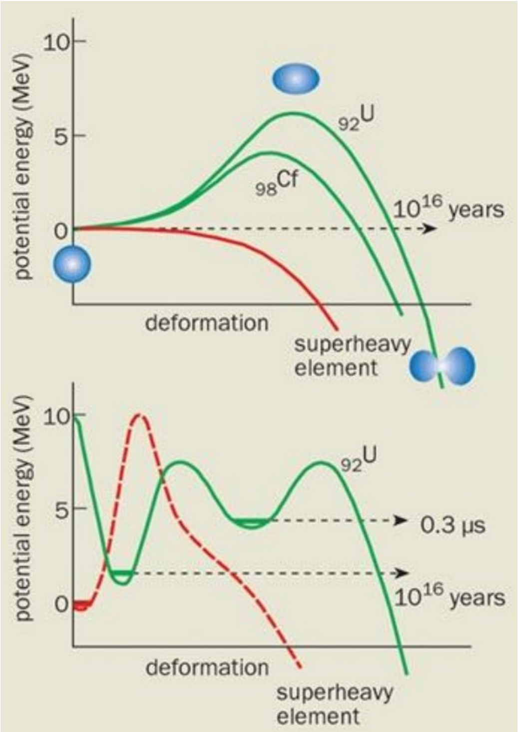
SHELL STABILIZATION OF SHE

Existence of SHE owed to shell correction to the liquid drop model

e.g. fission barrier ^{254}No:

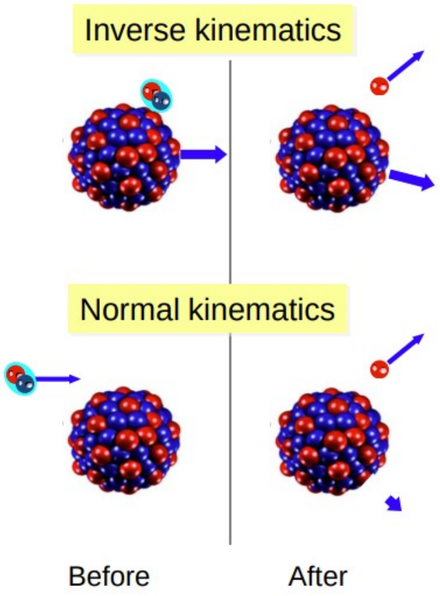
LDM: 0.9MeV
LDM + Shell: >5MeV

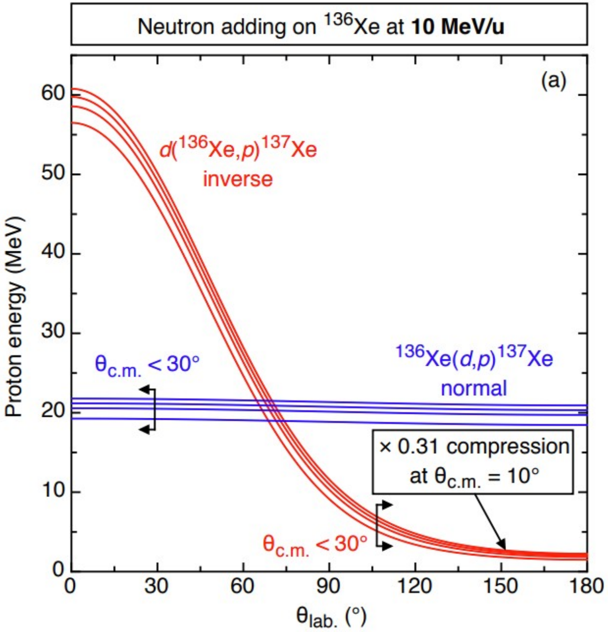
13 order of magnitude difference in $T_{1/2}$



FISSION BARRIER WITH HELIOS

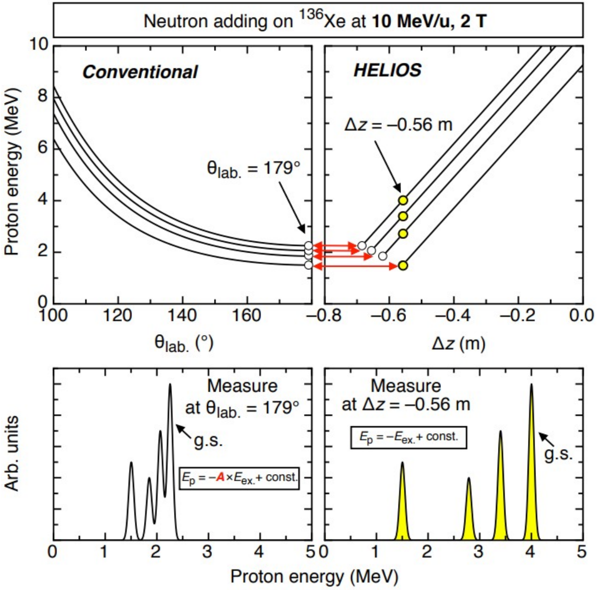
Kinematic compression in inverse kinematics - resolution
Strong angle dependence - broadening





FISSION BARRIER WITH HELIOS

Helios approach

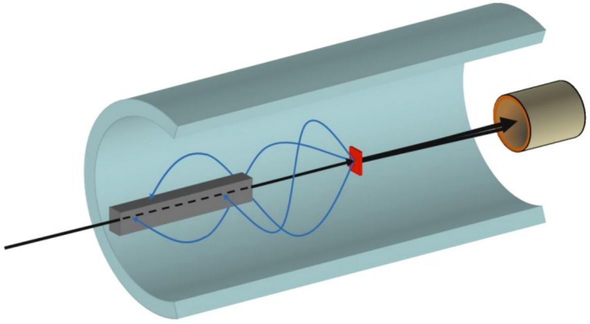


<u>Measured quantities</u>
Flight time: $T_{flight}=T_{cyc}$
Position: z
Energy: E_{lab}

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

B=2T

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



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

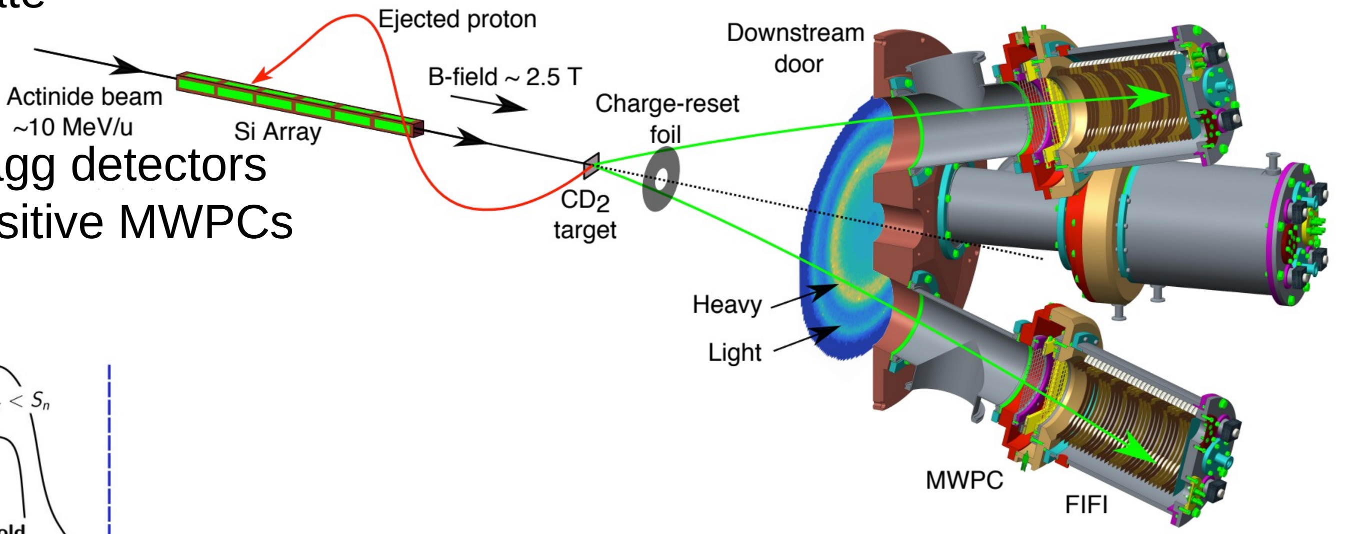
$$E_{cm} = E_{lab} + \tfrac{1}{2} m V_{cm}^2 - \frac{V_{cm} qeB}{2\pi} z$$

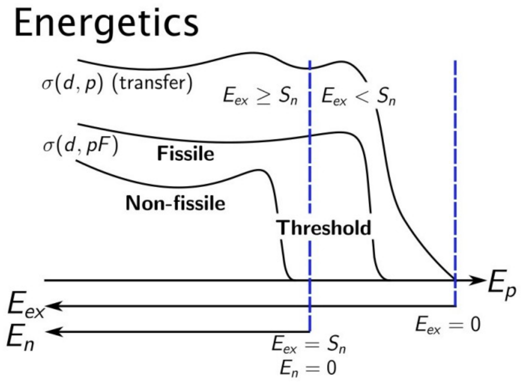
$$\theta_{cm} = \arccos\left(\frac{1}{2\pi} \frac{qeBz - 2\pi m V_{cm}}{\sqrt{2mE_{lab} + m^2 V_{cm}^2 - mV_{cm} qeBz/\pi}} \right)$$

FISSION BARRIER WITH HELIOS

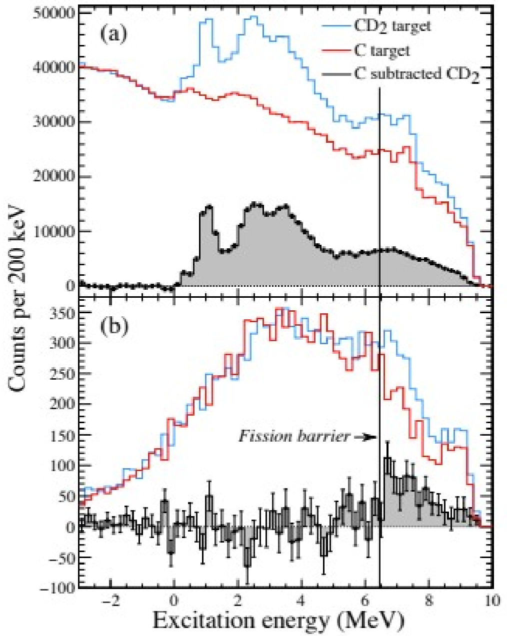
(d,pF) as surrogate
for (n,F) reaction

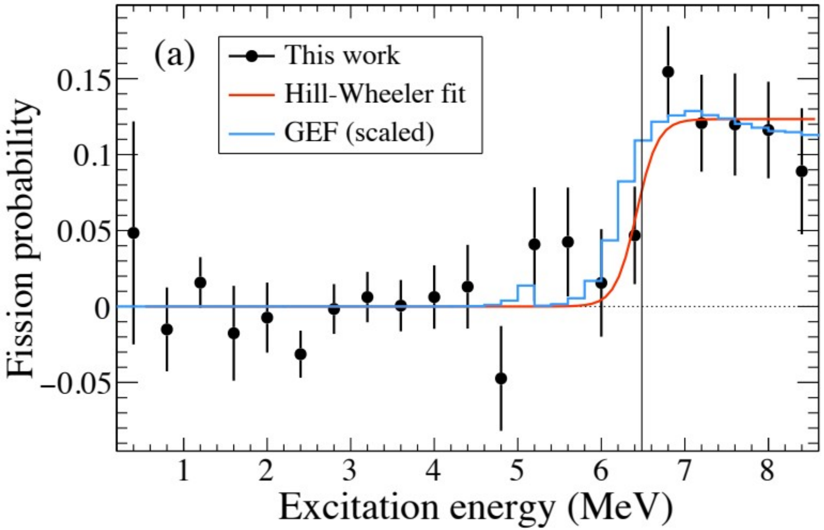
4 segmented Bragg detectors
plus position sensitive MWPCs





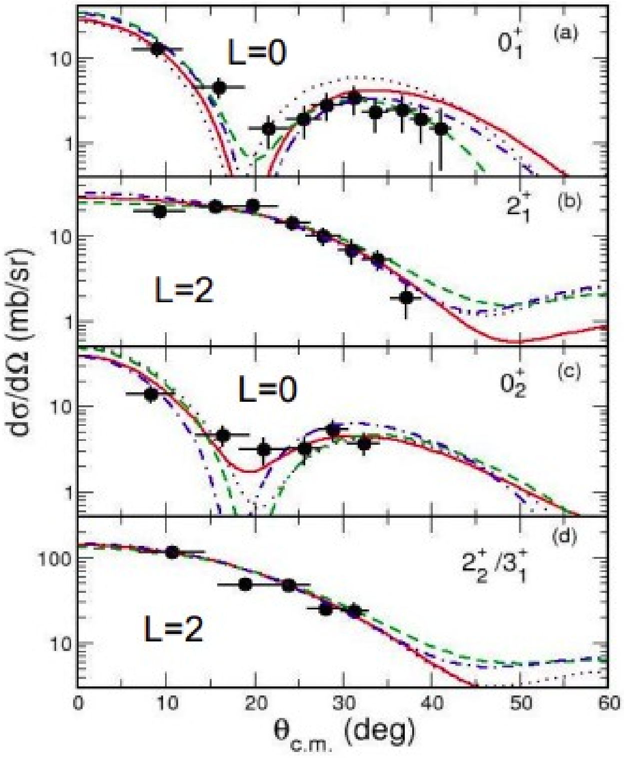
FISSION BARRIER WITH HELIOS



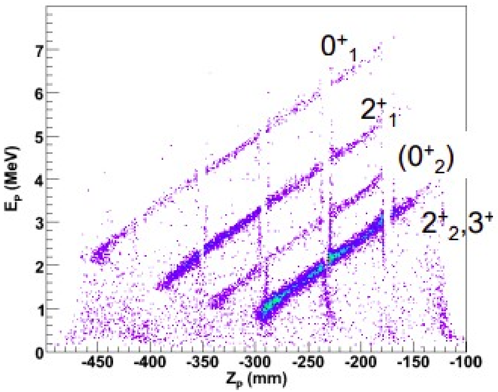


Thank you for your attention!

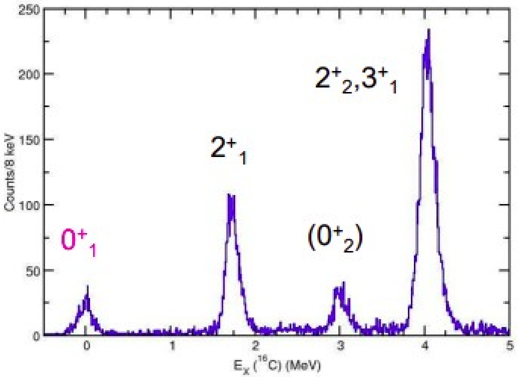
HELIOS



L=0
0^+_1
(a)
(b)
2^+_1
L=2
(c)
L=0
0^+_2
(d)
$2^+_2/3^+_1$
L=2
dσ/dΩ (mb/sr)
θc.m. (deg)



0^+_1
2^+_1
(0^+_2)
$2^+_2,3^+$
Ep (MeV)
Zp (mm)



$2^+_2,3^+_1$
2^+_1
0^+_1
(0^+_2)
Counts/8 keV
E_X (^{16}C) (MeV)

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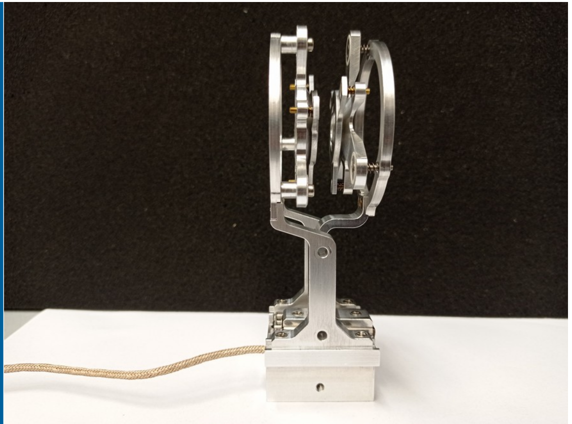
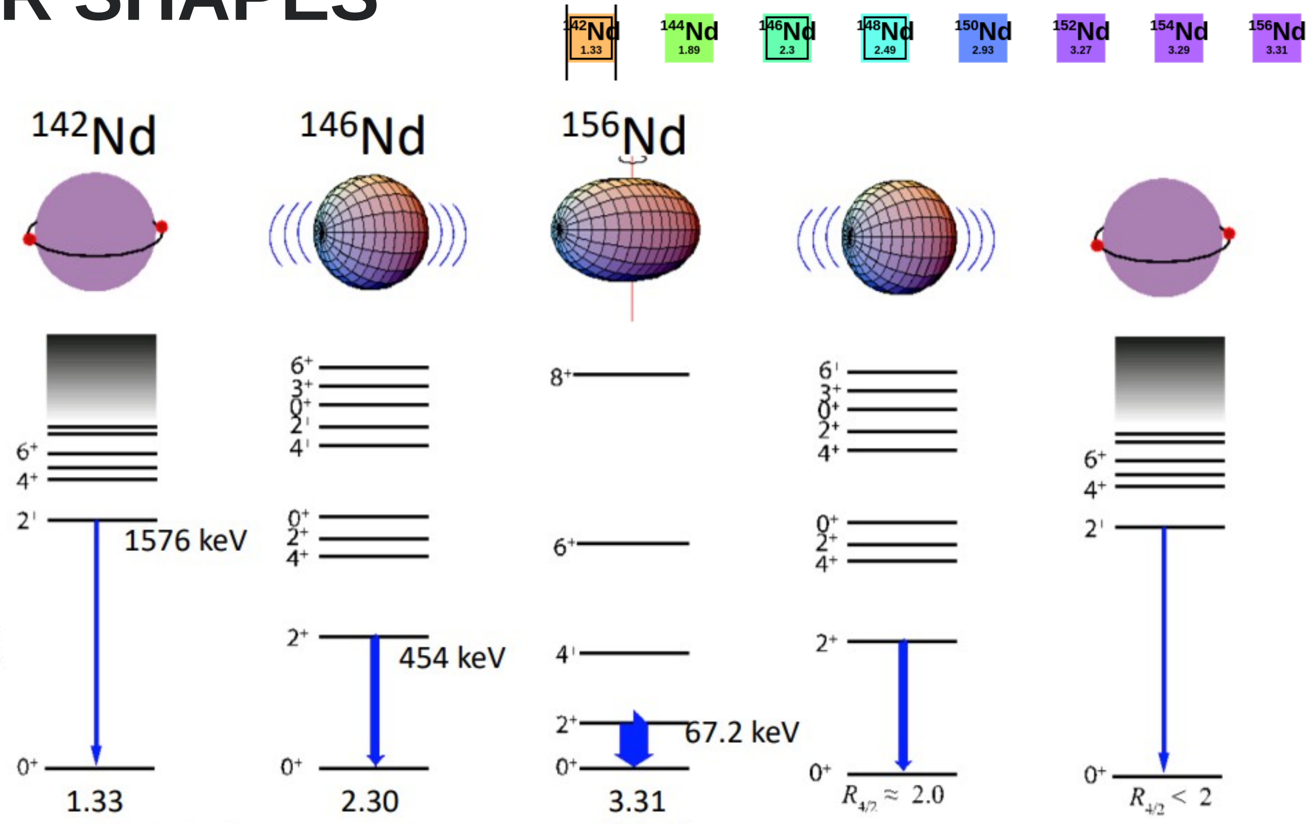


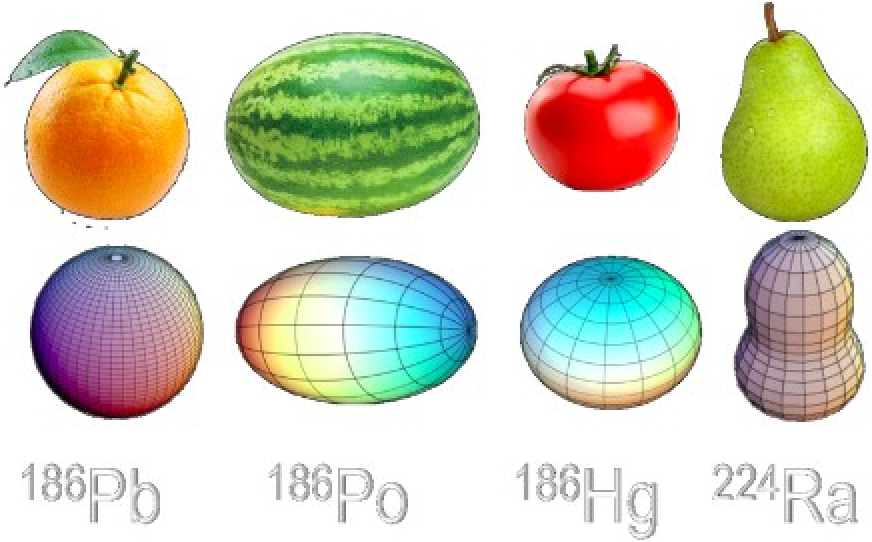
Claus Müller-Gatermann

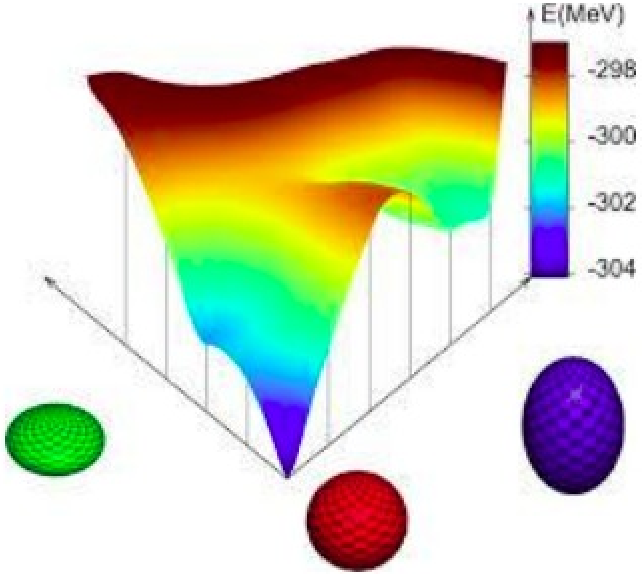
NUCLEAR SHAPES

$$E_{rot} = \frac{\hbar^2(I(I+1))}{2\mathfrak{I}}$$

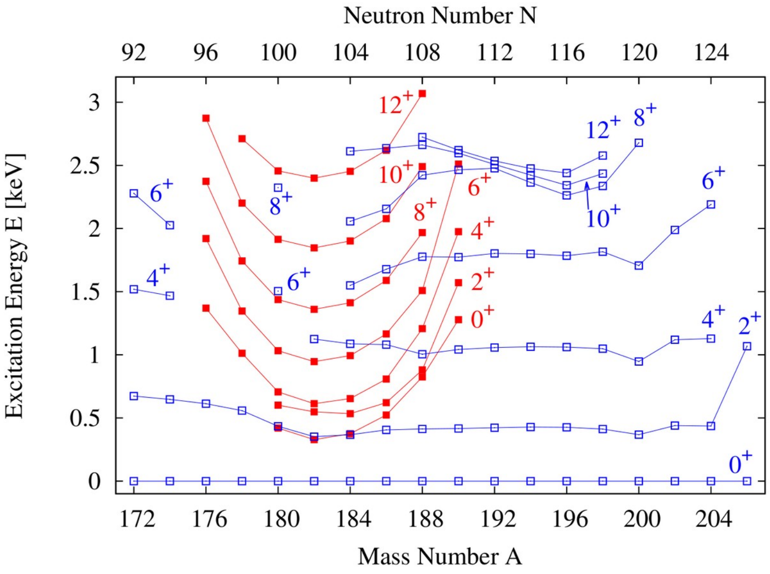


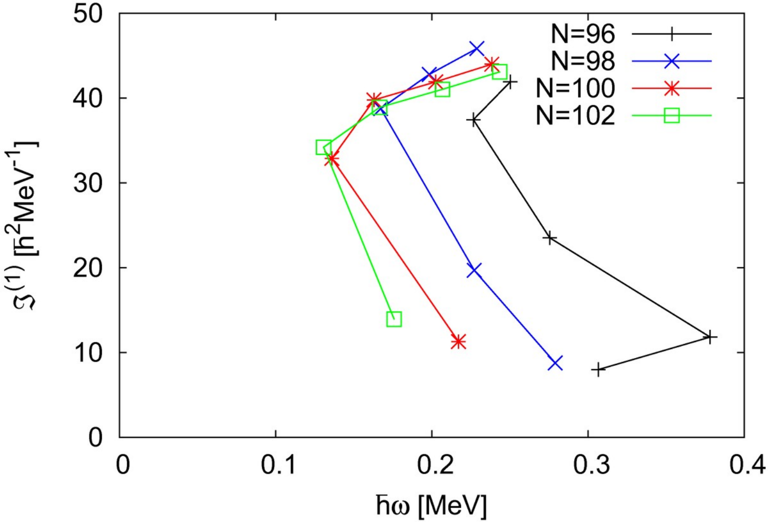
NUCLEAR SHAPES & COEXISTENCE



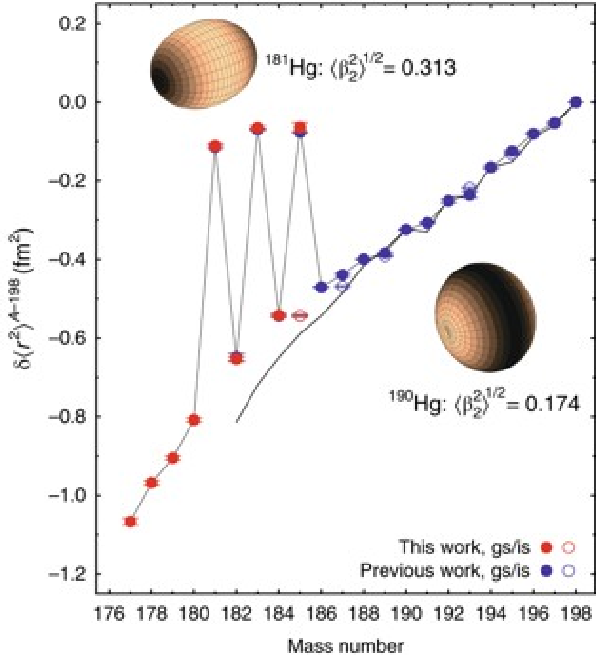


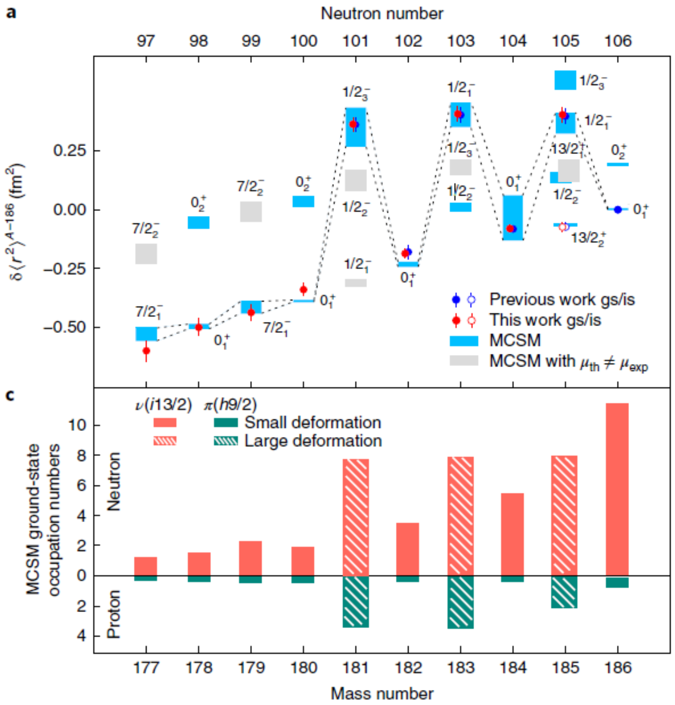
SHAPE COEXISTENCE IN HG ISOTOPES





SHAPE COEXISTENCE IN HG ISOTOPES





DEFORMATION FROM LIFETIME

$$B(E2; J_i \to J_f) = 8.197 \cdot 10^{-2} \frac{b_{ij}}{1+\alpha_{ic}(E_\gamma)} E_\gamma^{-5} \tau^{-1}$$

$$Q_t = \sqrt{\frac{16\pi}{5} \frac{B(E2; J \to J-2) 2(2J-1)(2J+1)}{3J(J-1)}}$$

$$\beta = 0.625(-5a + \frac{\sqrt{25a^2 + 16aQ_t}}{a})$$

$$a = \frac{3}{\sqrt{5\pi} Z R_0^2}$$

Transition strength can be calculated model independent from lifetime

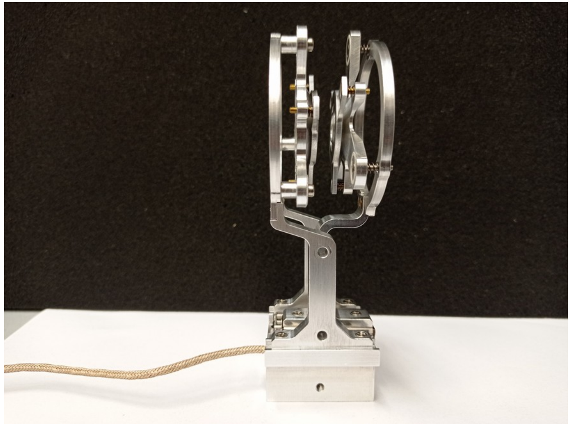
Quadratic dependence of the wavefunction (linear for energies)

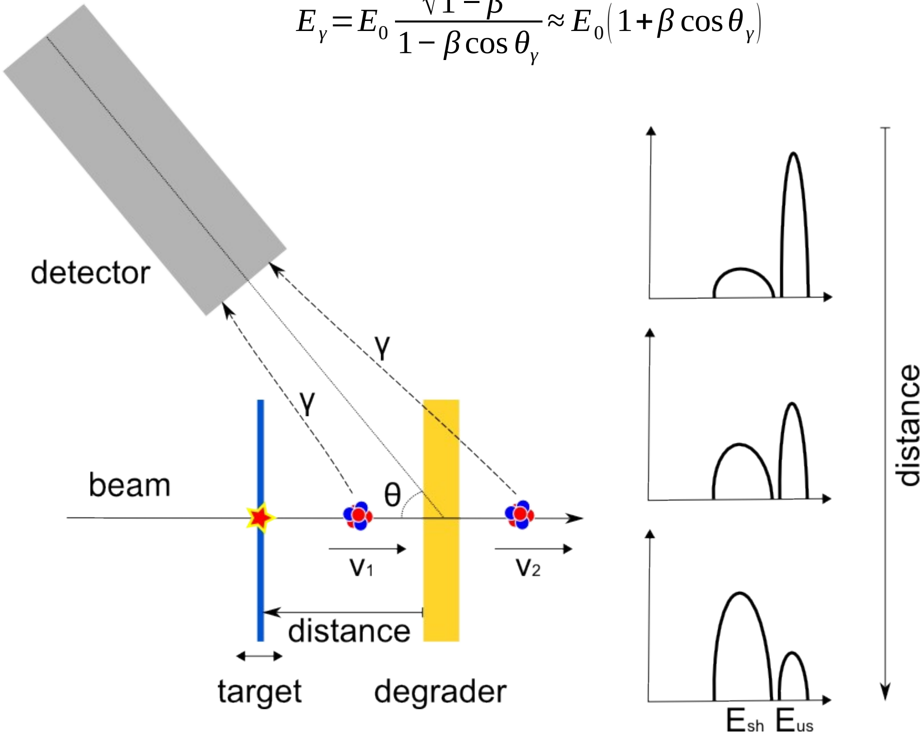
Initial and final states are considered (Selection rules)

Absolute values of quadrupole moments, deformation… (model dependent)

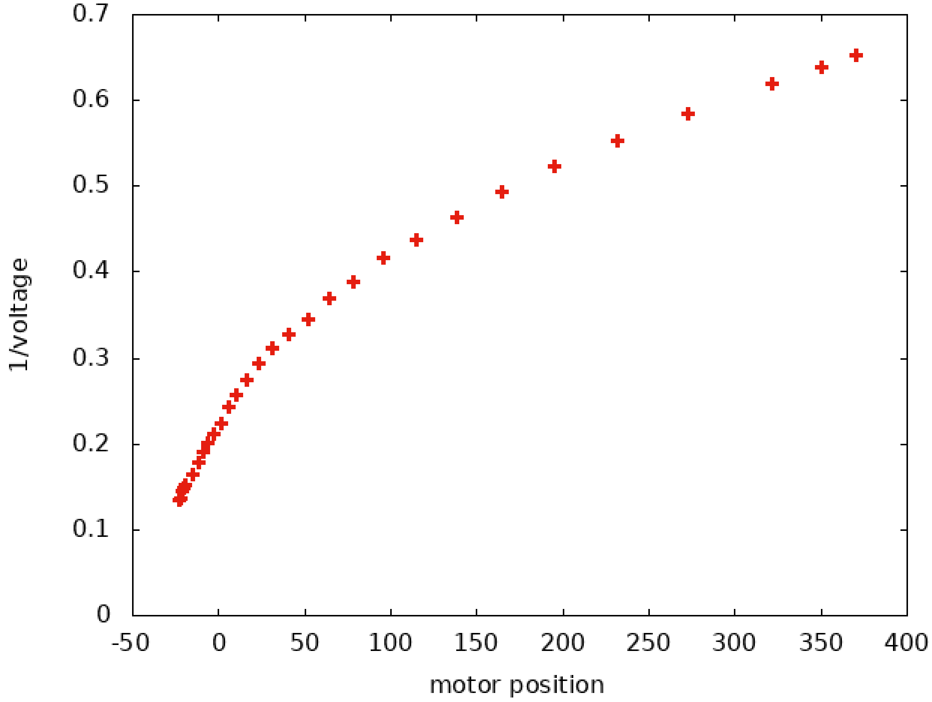
THE RDDS METHOD

$$E_\gamma = E_0 \frac{\sqrt{1-\beta^2}}{1-\beta\cos\theta_\gamma} \approx E_0\left(1+\beta\cos\theta_\gamma\right)$$





FEEDBACK SYSTEM



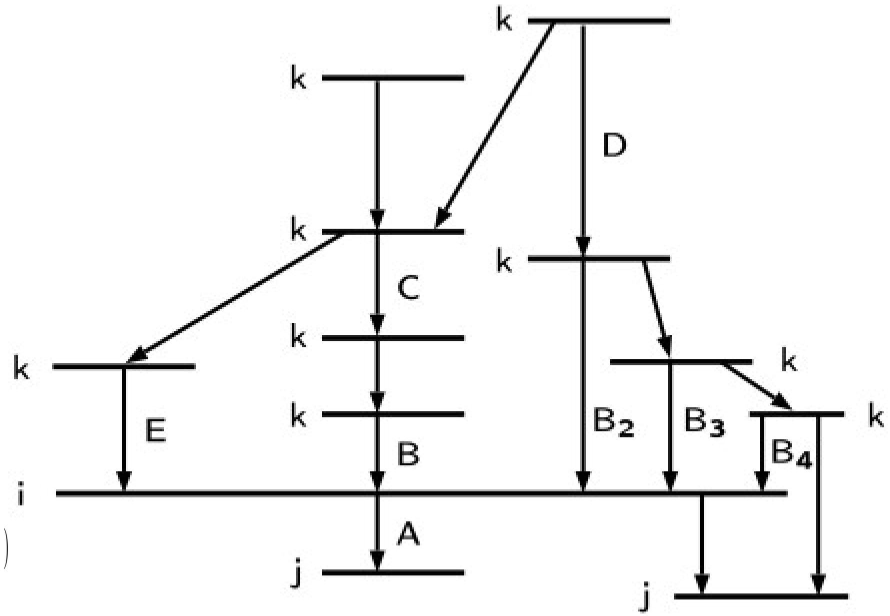
BATEMAN EQUATIONS

$$\frac{d}{dt} n_i(t) = -\lambda_i \cdot n_i(t) + \sum_{k=i+1}^{N} \lambda_k \cdot n_k(t) \cdot b_{ki}$$

$$R(t) = \frac{I_u(t)}{I_u(t) + I_s(t)}$$

$$R(t) = P_i e^{-t\lambda_i} + \sum_{k=i+1}^{N} M_{ki} \left[\left(\lambda_i / \lambda_k \right) e^{-t\lambda_k} - e^{-t\lambda_i} \right]$$

$$M_{ki} \left(\lambda_i / \lambda_k - 1 \right) = b_{ki} P_k - b_{ki} \sum_{m=k+1}^{N} M_{mk} + \sum_{m=i+1}^{k-1} M_{km} b_{mi} \left(\lambda_m / \lambda_k \right)$$



DIFFERENTIAL DECAY CURVE METHOD

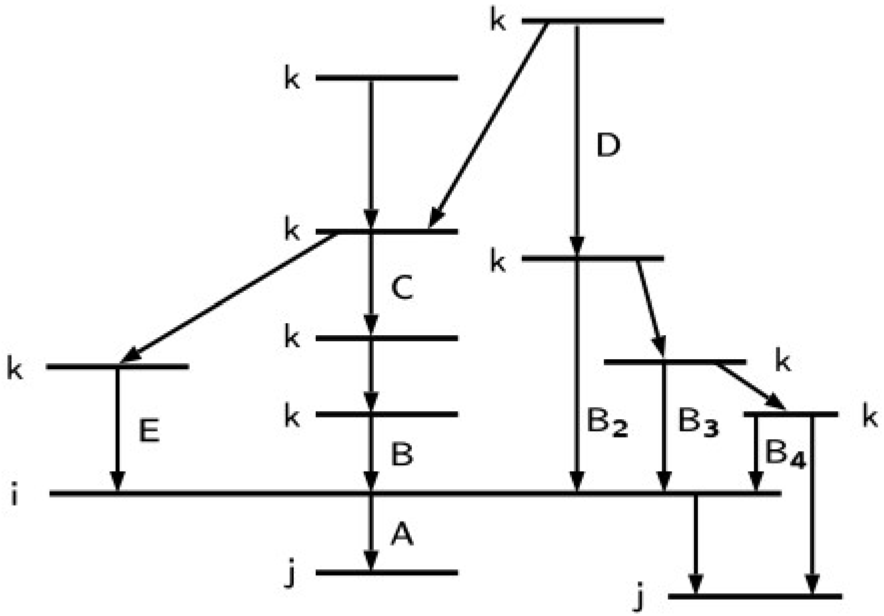
Gamma singles

$$\frac{d}{dt} n_i(t) = -\lambda_i \cdot n_i(t) + \sum_{k=i+1}^{N} \lambda_k \cdot n_k(t) \cdot b_{ki}$$

$$R(t) = \frac{I_u(t)}{I_u(t) + I_s(t)}$$

$$\tau_i(t) = \frac{-R_i(t) + \sum_k R_k(t) b_{ki} \alpha_{ki}}{\frac{d}{dt} R_i(t)}$$

$$\alpha_{ki} = \frac{\omega_k(\theta) \cdot \epsilon_k(E_{\gamma,k})}{\omega_i(\theta) \cdot \epsilon_i(E_{\gamma,i})}$$



DIFFERENTIAL DECAY CURVE METHOD

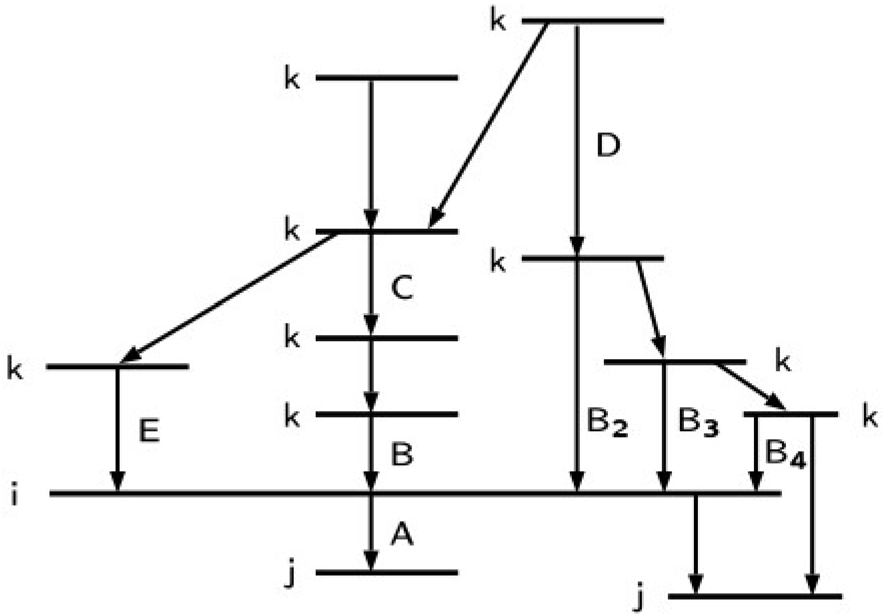
Gamma-Gamma coincidences

$$\frac{d}{dt} n_i(t) = -\lambda_i \cdot n_i(t) + \sum_{k=i+1}^{N} \lambda_k \cdot n_k(t) \cdot b_{ki}$$

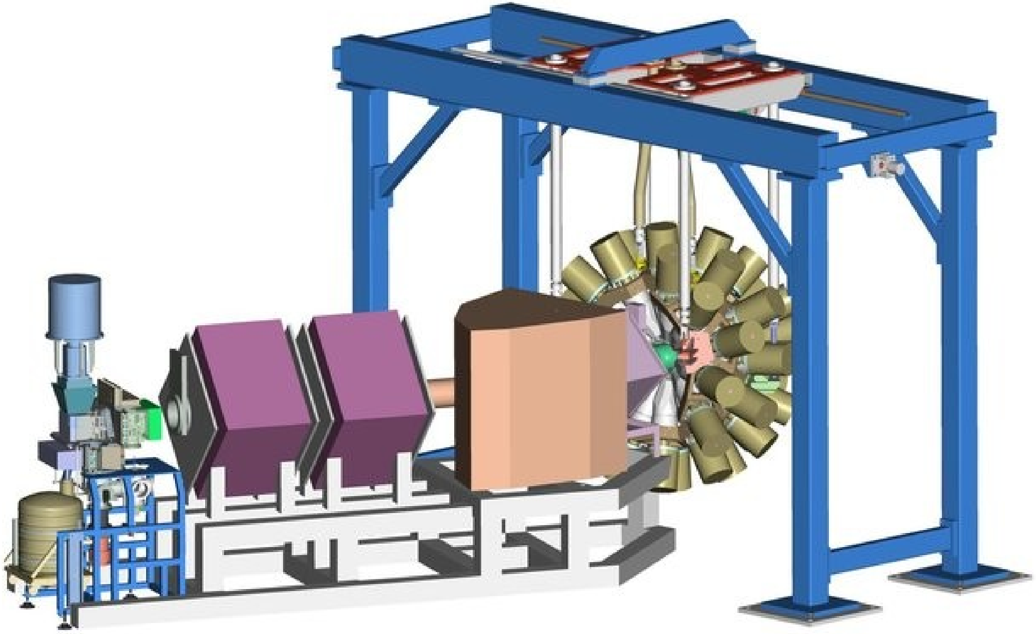
$$R(t) = \frac{I_u(t)}{I_u(t) + I_s(t)}$$

$$\tau_i(x) = \frac{I_u^A(x) - \alpha(x) I_u^B(x)}{\frac{d}{dx} I_s^A(x) \cdot v}$$

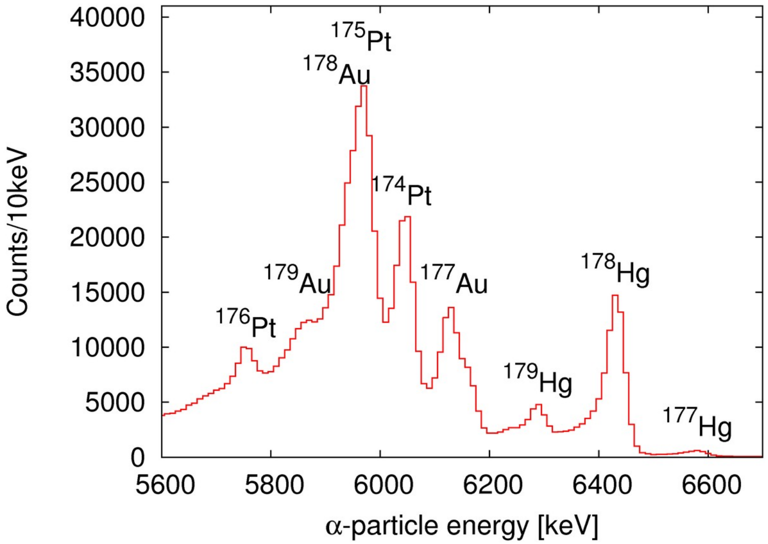
$$\alpha_x = \frac{I_u^A(x) + I_s^A(x)}{I_u^B(x) + I_s^B(x)}$$

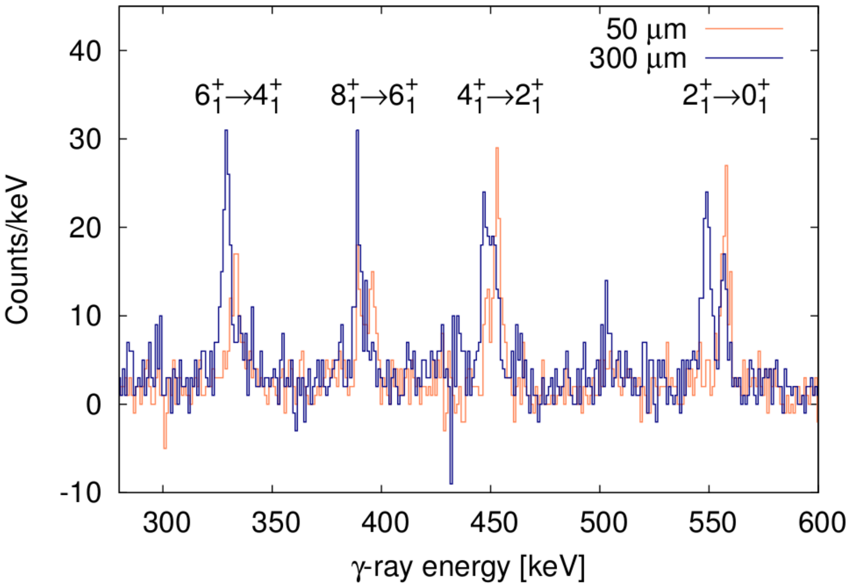


JUROGAM@RITU

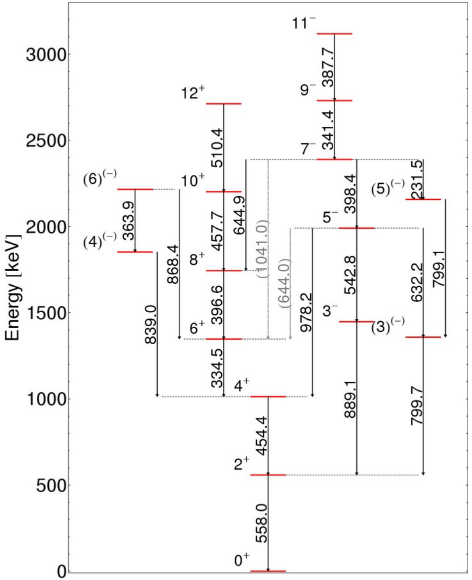


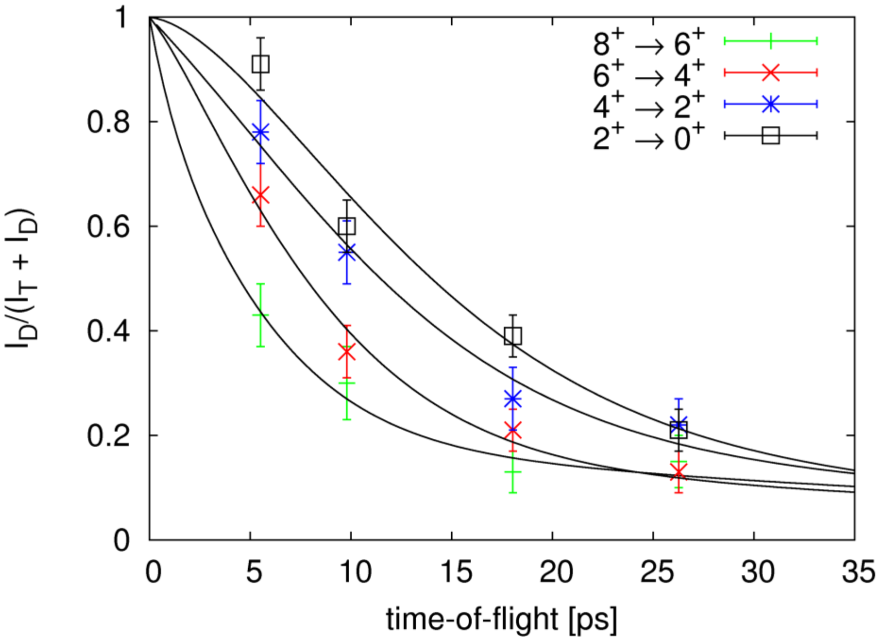
GAMMA-RAY SINGLES EXPERIMENT





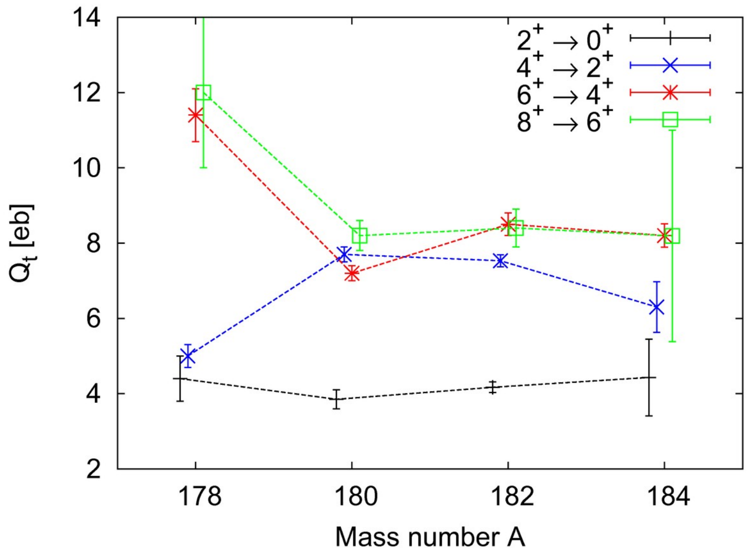
ANALYSIS OF ^{178}HG





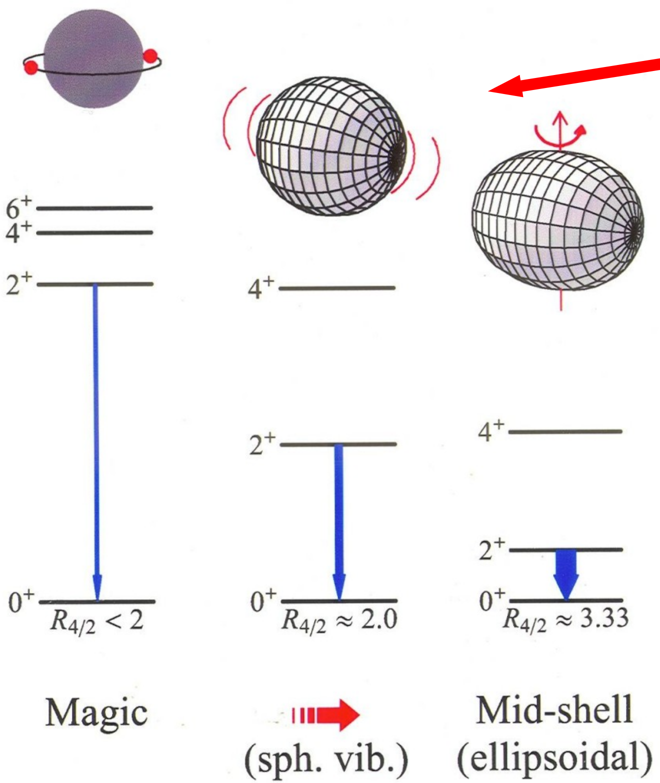
SHAPE COEXISTENCE IN HG ISOTOPES

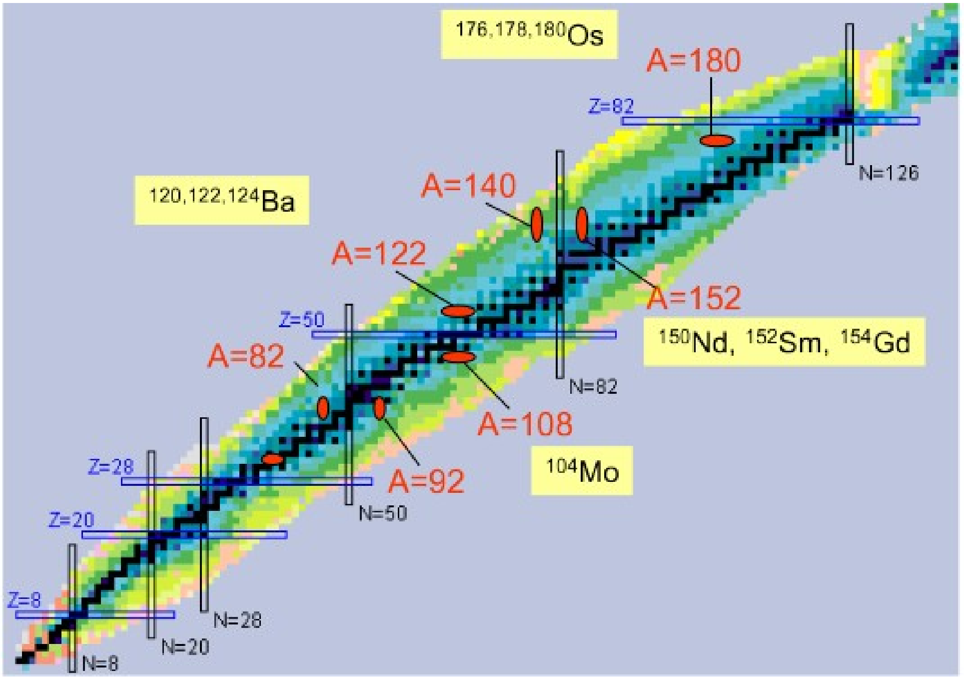
I^{π}	E_{γ}[keV]	τ[ps]	B(E2) [Wu]	β_2
2^+	558.0	3.8(9)	70(20)	0.16
4^+	454.4	5.7(6)	120(14)	0.18
6^+	334.5	4.4(5)	690(90)	0.41
8^+	396.6	1.7(5)	800(300)	0.43



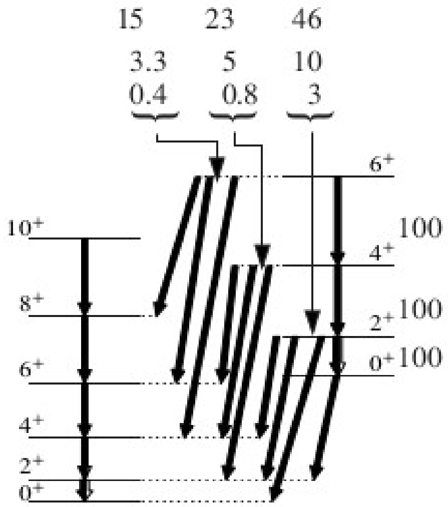
CRITICAL POINT SYMMETRIES

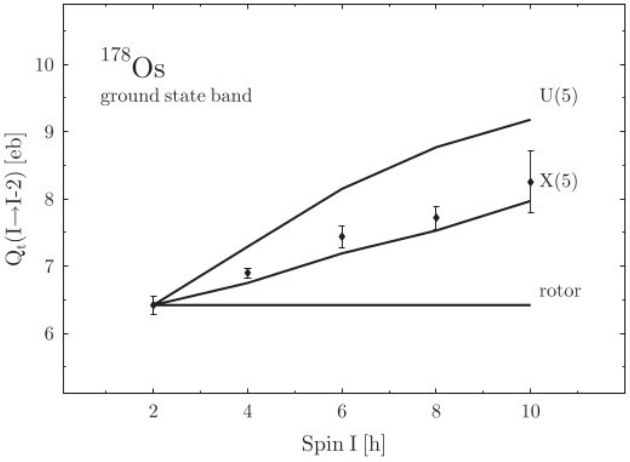
X(5) critical point symmetry

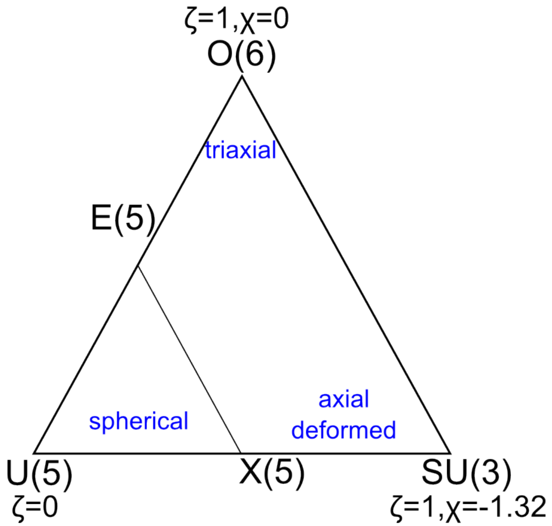




CRITICAL POINT SYMMETRIES





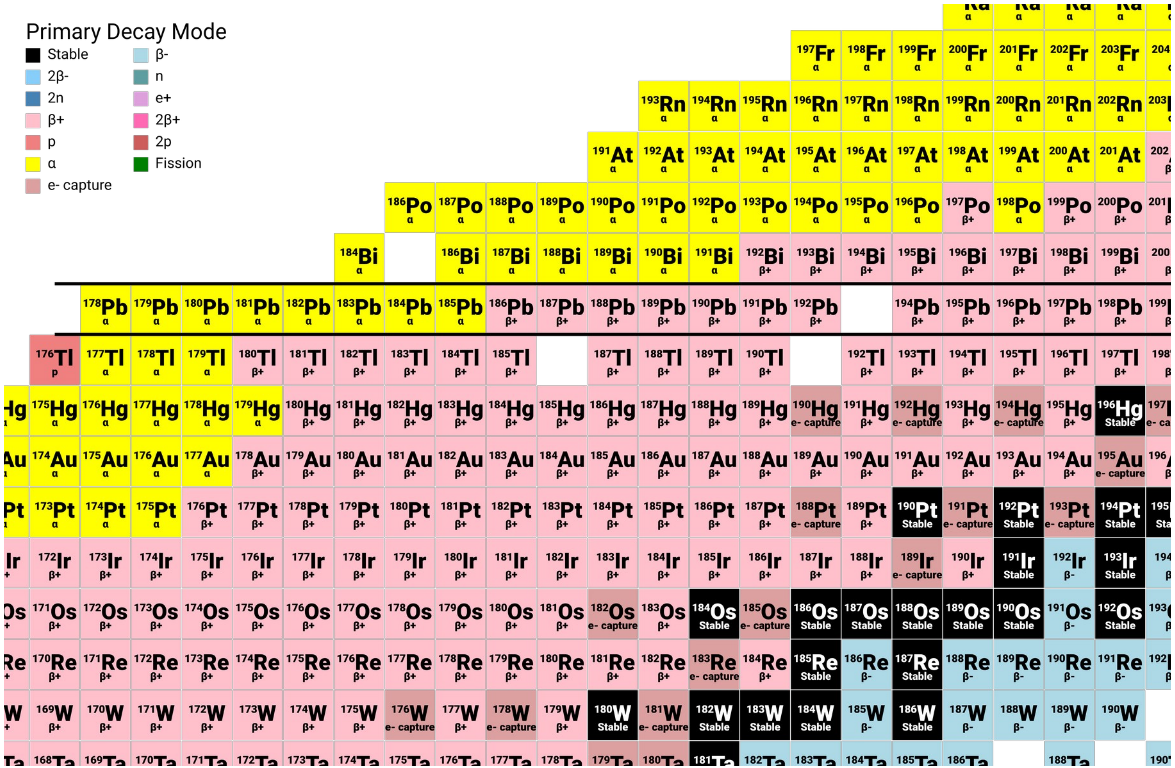


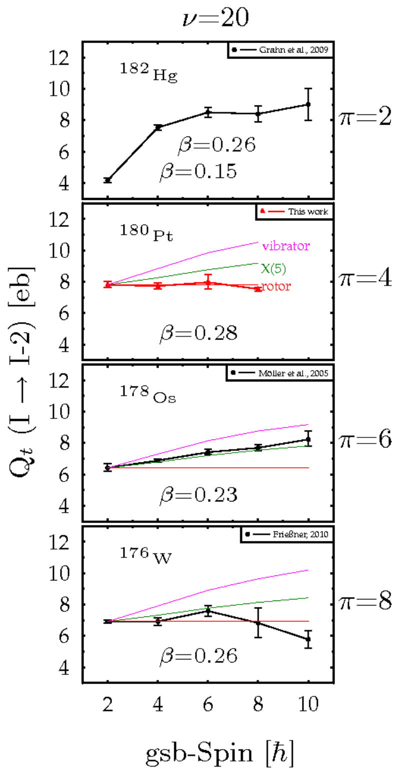
$$H(\zeta,\chi) = c\left[(1-\zeta)\hat{n}_d - \frac{\zeta}{4N_B}\hat{Q}^\chi \hat{Q}^\chi\right],$$

$$\hat{n}_d = d^\dagger\tilde{d}, \quad \hat{Q}^\chi = [s^\dagger\tilde{d} + d^\dagger s]^{(2)} + \chi[d^\dagger\tilde{d}]^{(2)},$$

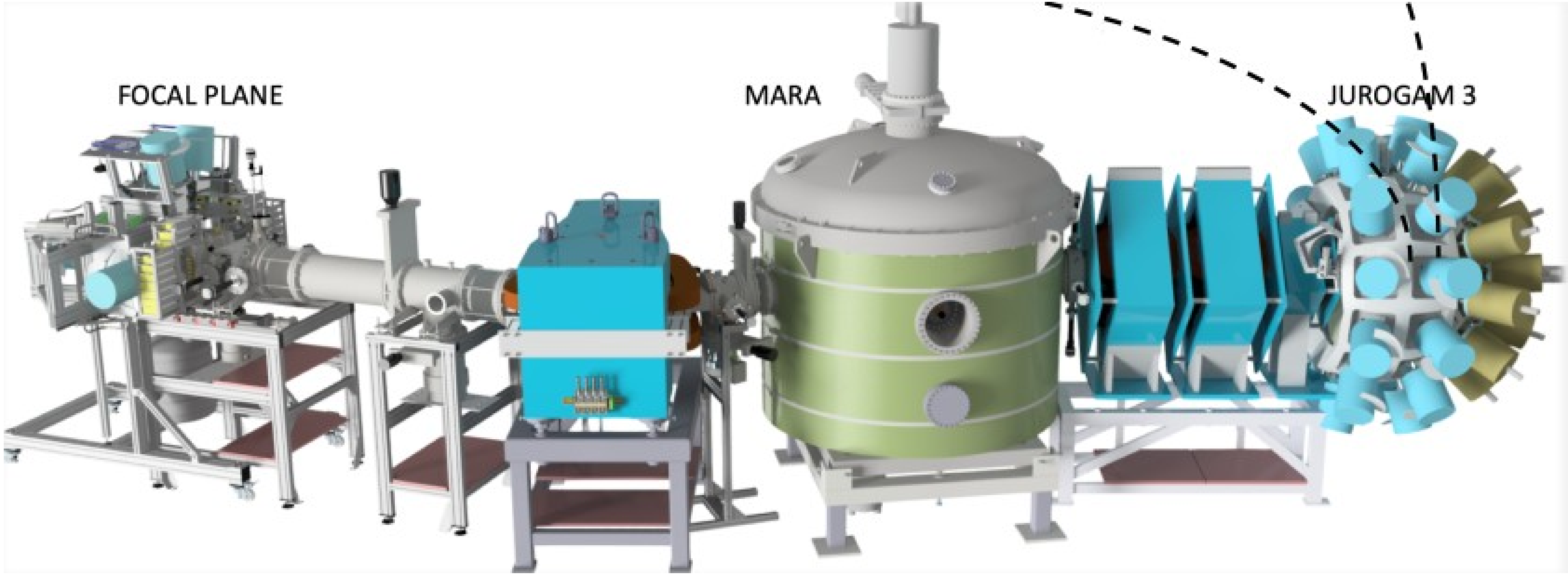
$$\hat{T}(E2) = e_B\hat{Q}^\chi,$$

EVOLUTION OF COLLECTIVITY





A CHARGED PLUNGER



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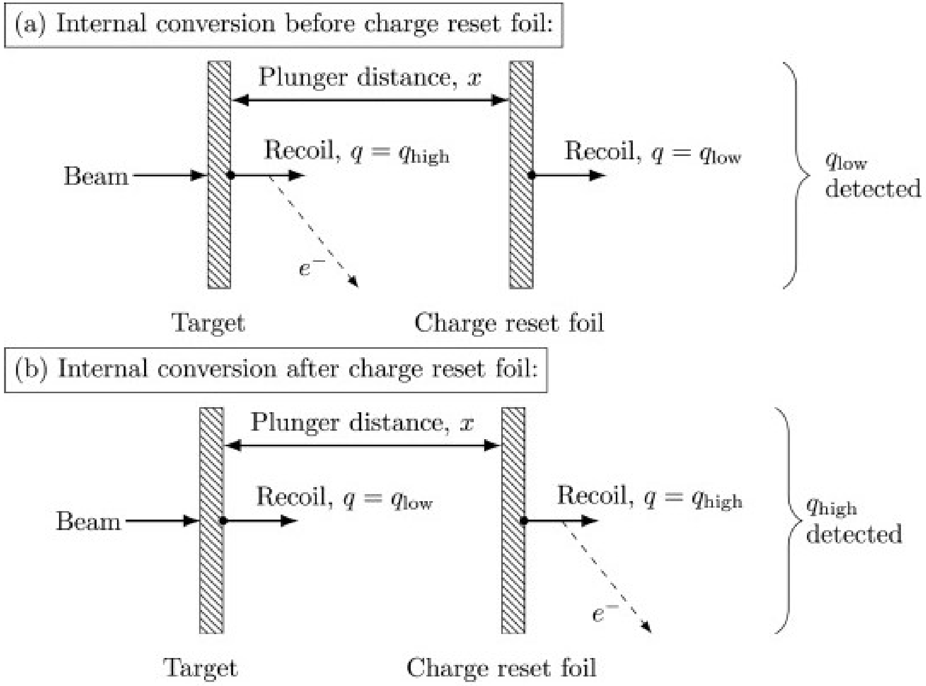
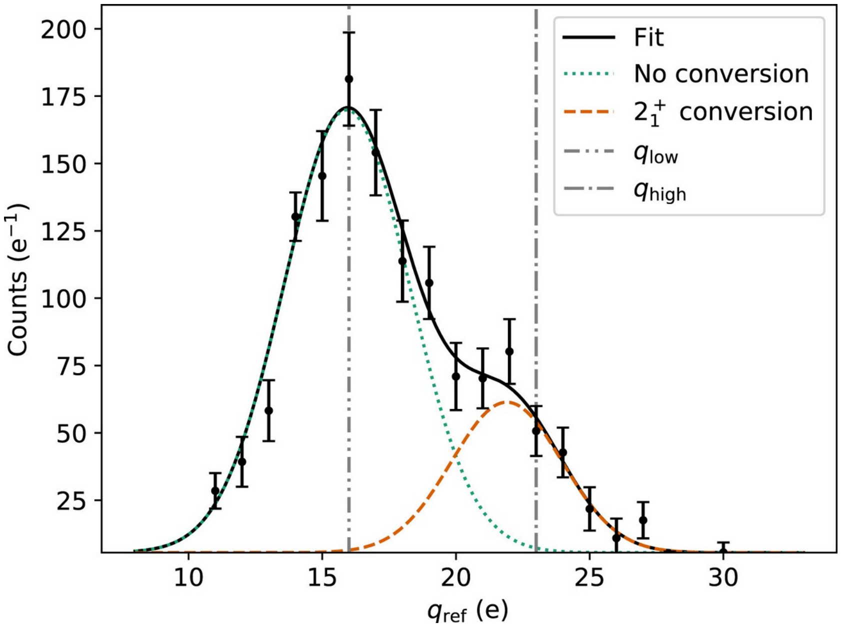
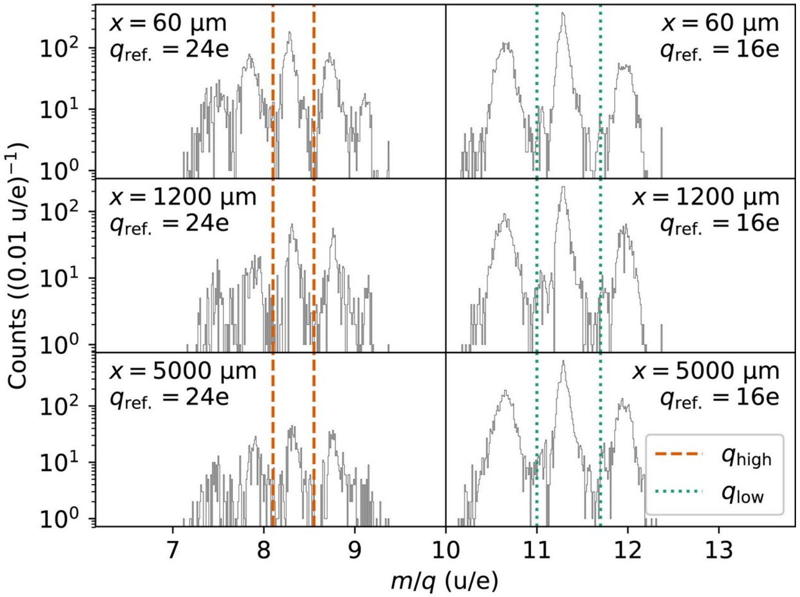
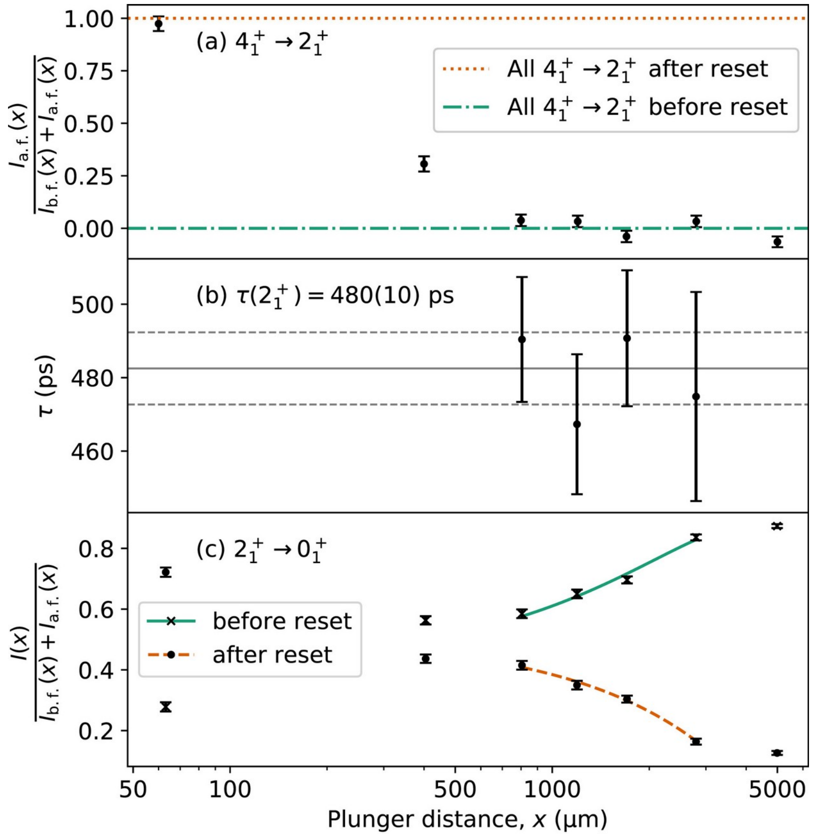


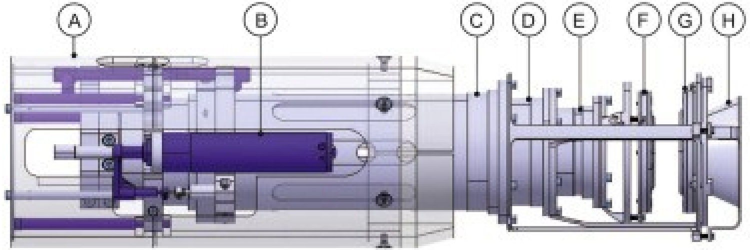


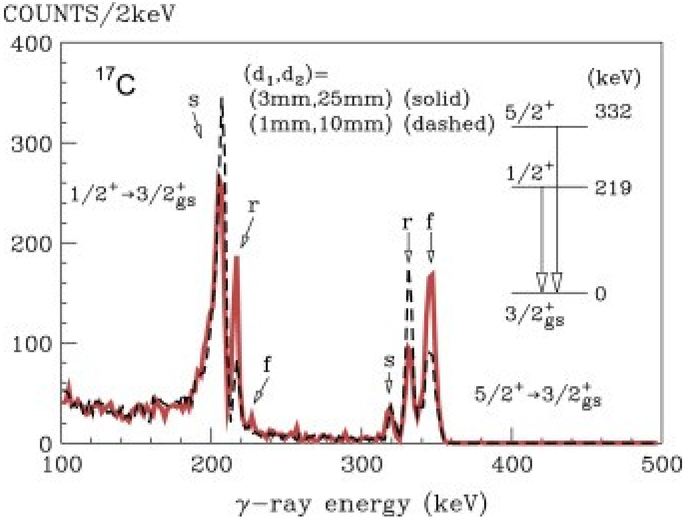
A CHARGED PLUNGER



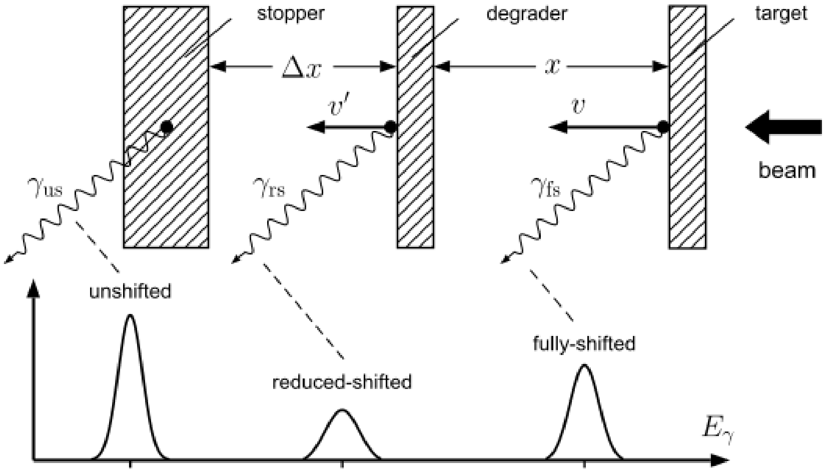


PLUNGER WITH 3 FOILS



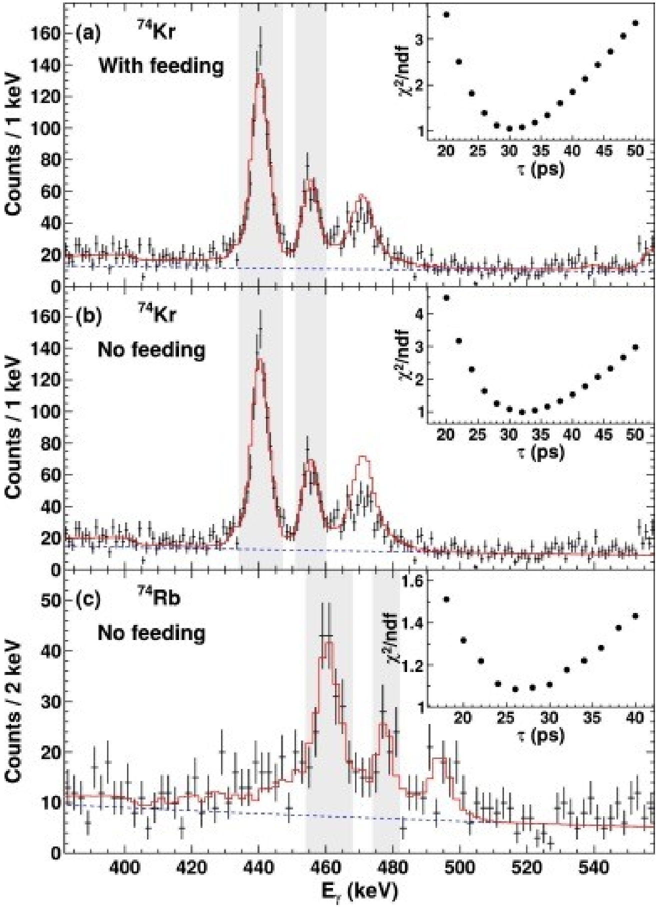


PLUNGER WITH 3 FOILS

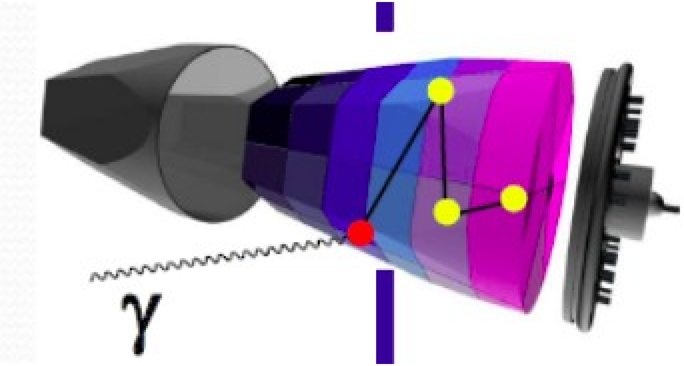


$$\tau_i(t) = \frac{-R_i(t) + \sum_k R_k(t)\, b_{ki}\, \alpha_{ki}}{\frac{d}{dt} R_i(t)}$$

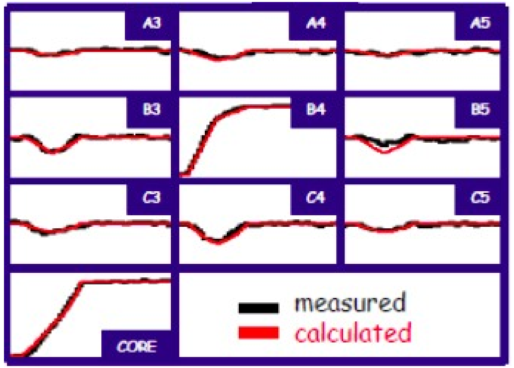
$$\frac{dR(t')}{dt} = \alpha \cdot v' \cdot I_{rs}(x)/\Delta x$$

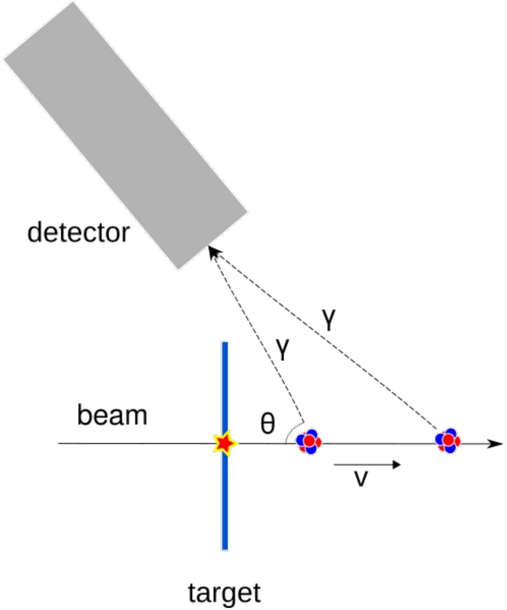


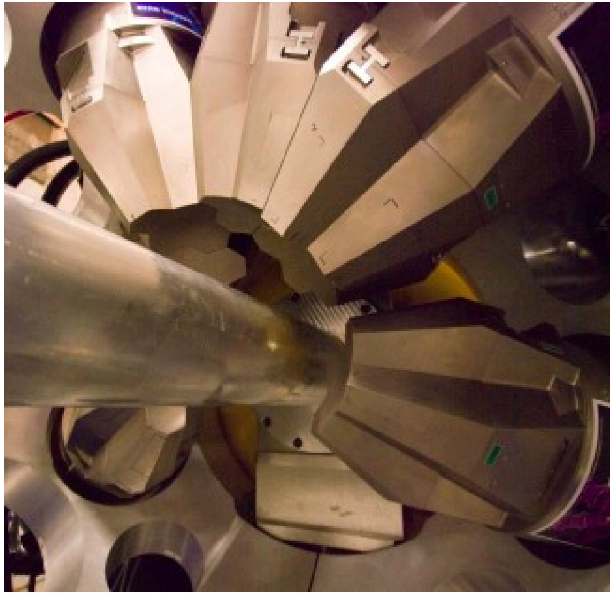
PLUNGER WITH 1 FOIL?



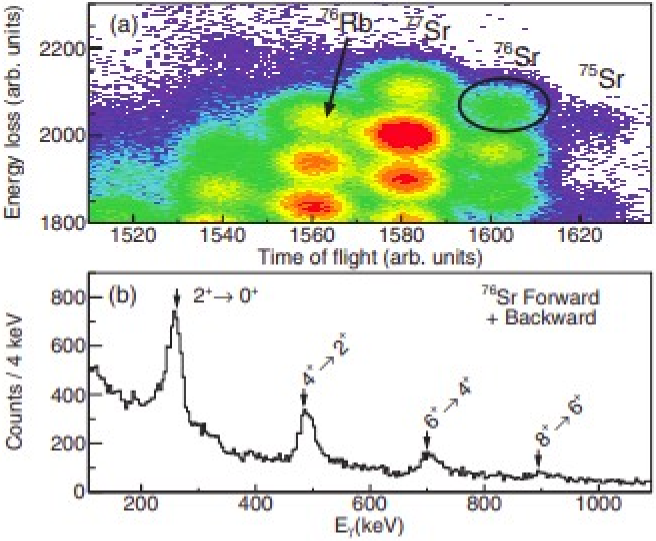
$$_\gamma = E_0 \frac{\sqrt{1-\beta^2}}{1-\beta\cos\theta_\gamma} \approx E_0\left(1+\beta\cos\theta_\gamma\right)$$

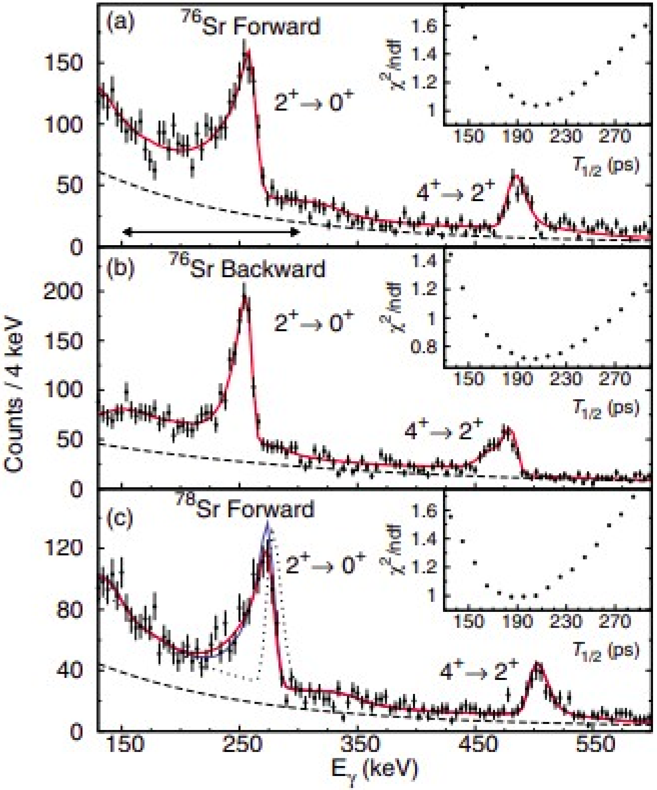






PLUNGER WITH 1 FOIL?





Thank you for your attention!