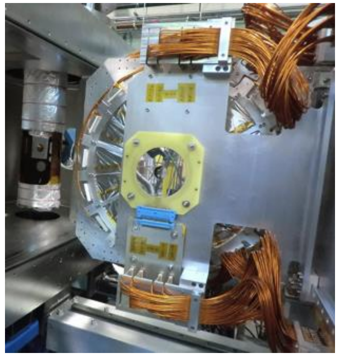
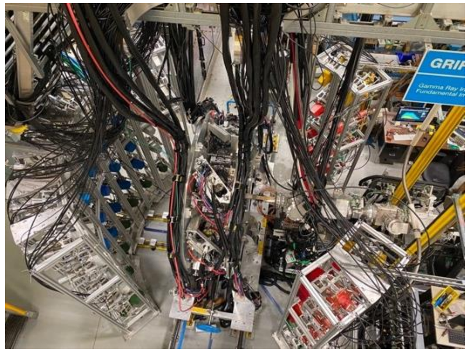
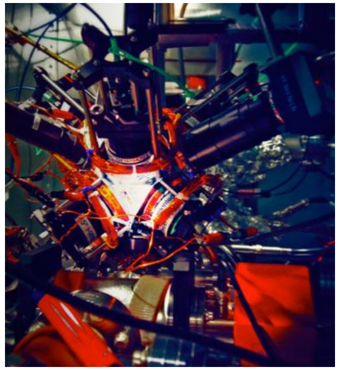
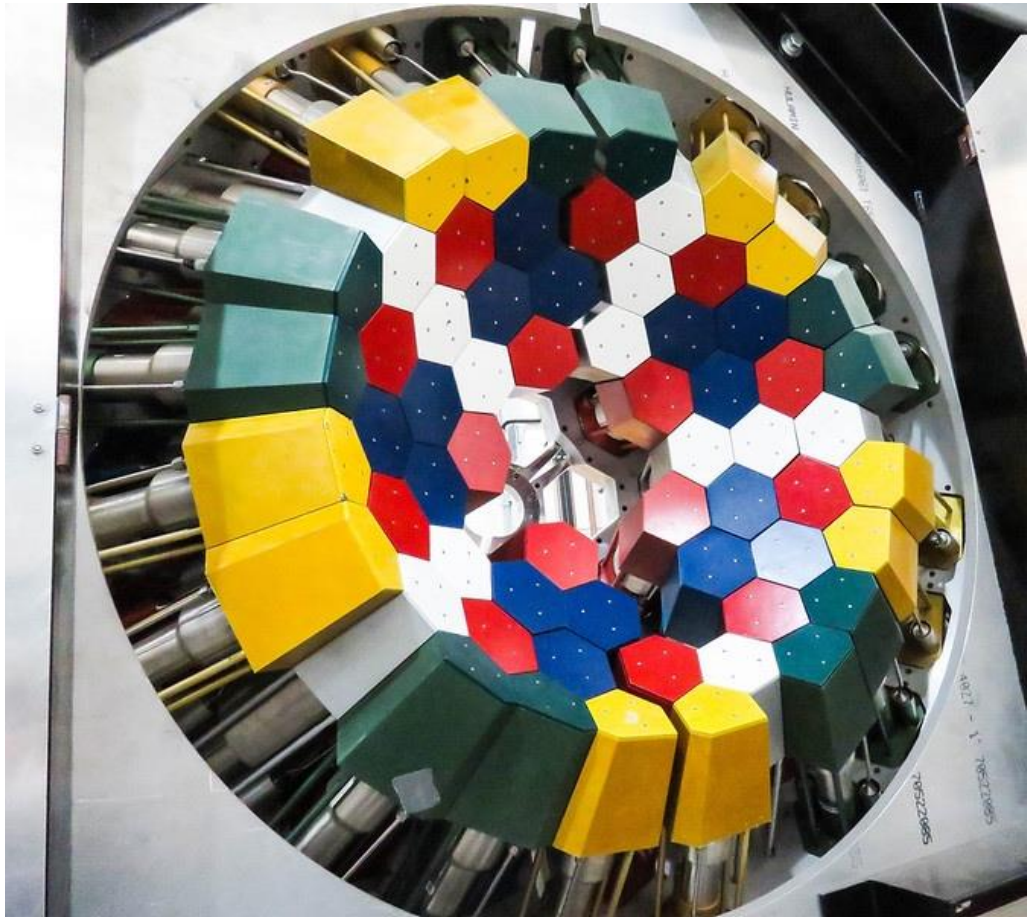
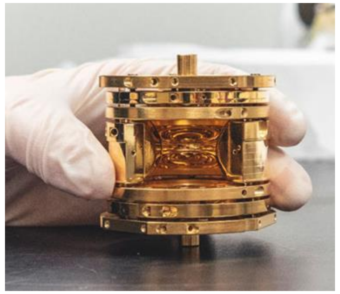
TRIUMF





Nuclear Physics Techniques

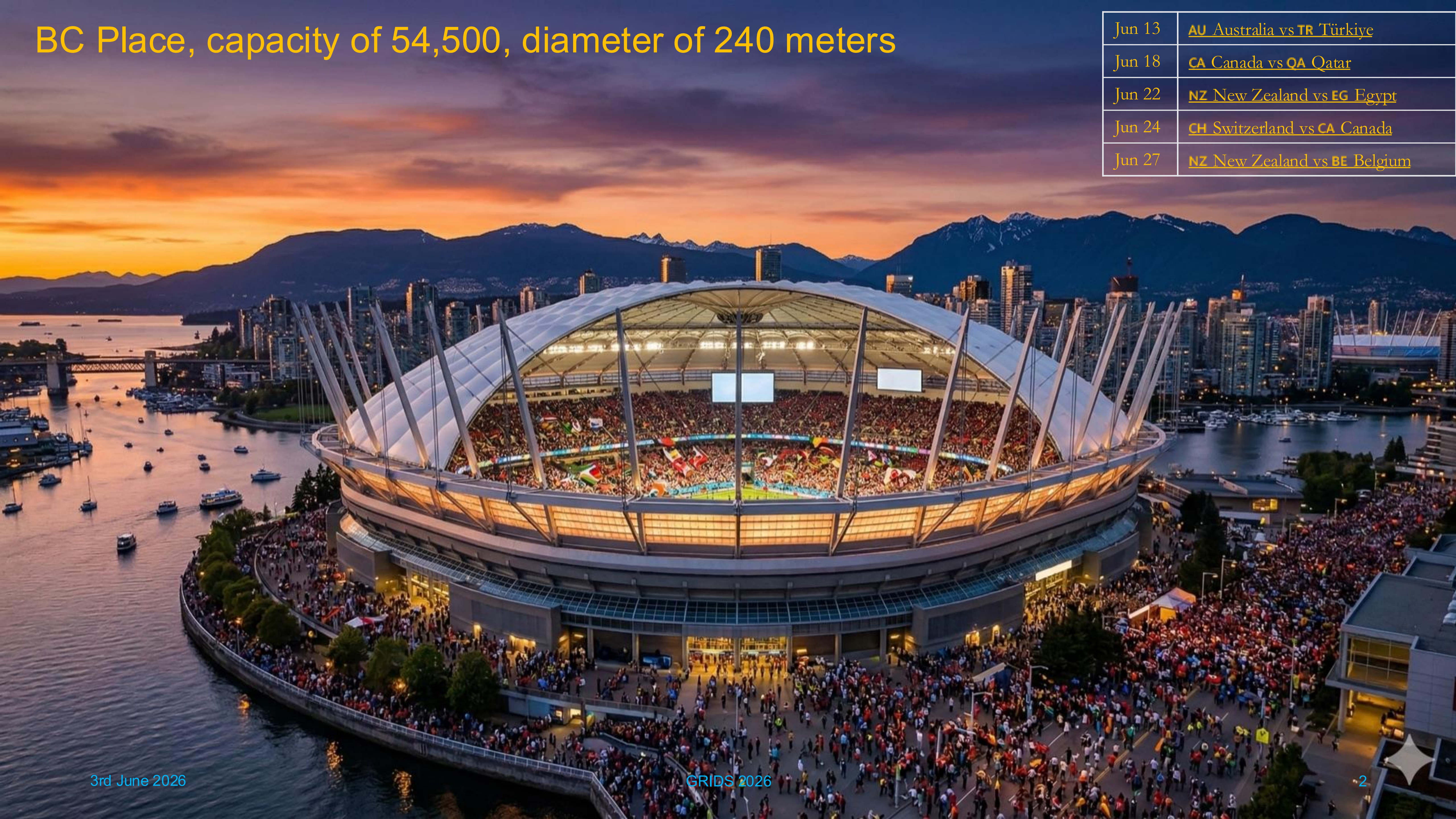

Adam Garnsworthy (he/him)
TRIUMF Senior Scientist
ARIEL Principal Scientist

GRIDS 2026

Discovery, accelerated

BC Place, capacity of 54,500, diameter of 240 meters

Jun 13	AU Australia vs TR Türkiye
Jun 18	CA Canada vs QA Qatar
Jun 22	NZ New Zealand vs EG Egypt
Jun 24	CH Switzerland vs CA Canada
Jun 27	NZ New Zealand vs BE Belgium

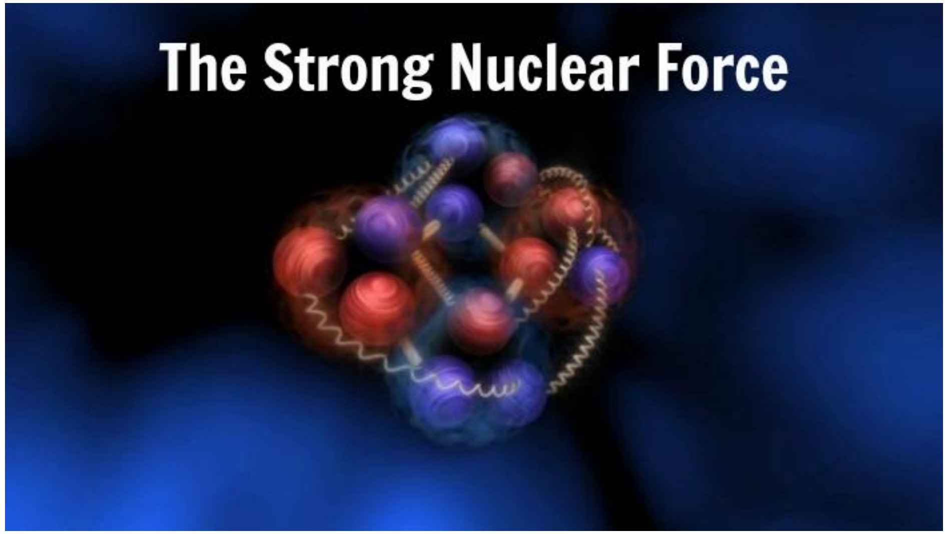


What questions can we ask about nuclei?

- How heavy is it?
  - Mass spectroscopy
- How big is it?
  - Laser spectroscopy of Hyperfine structure
- How long does it survive?
  - Decay spectroscopy
- What shape is it?
  - Coulomb excitation
- How are excitations created
  - Gamma-ray spectroscopy

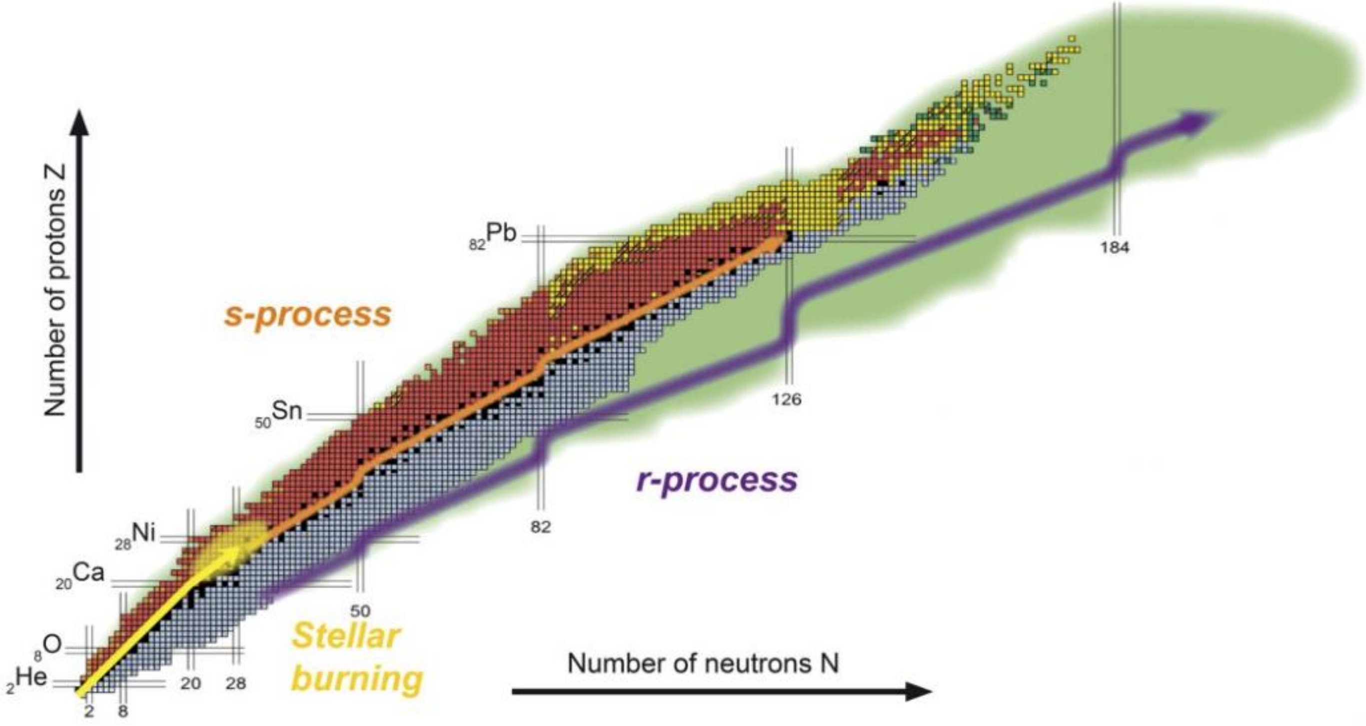
What can we learn from nuclei?

What are the details of the strong nuclear force?



credit: Futurism.com

How are the elements created in the universe?



credit: EMMI, GSI/Different Arts

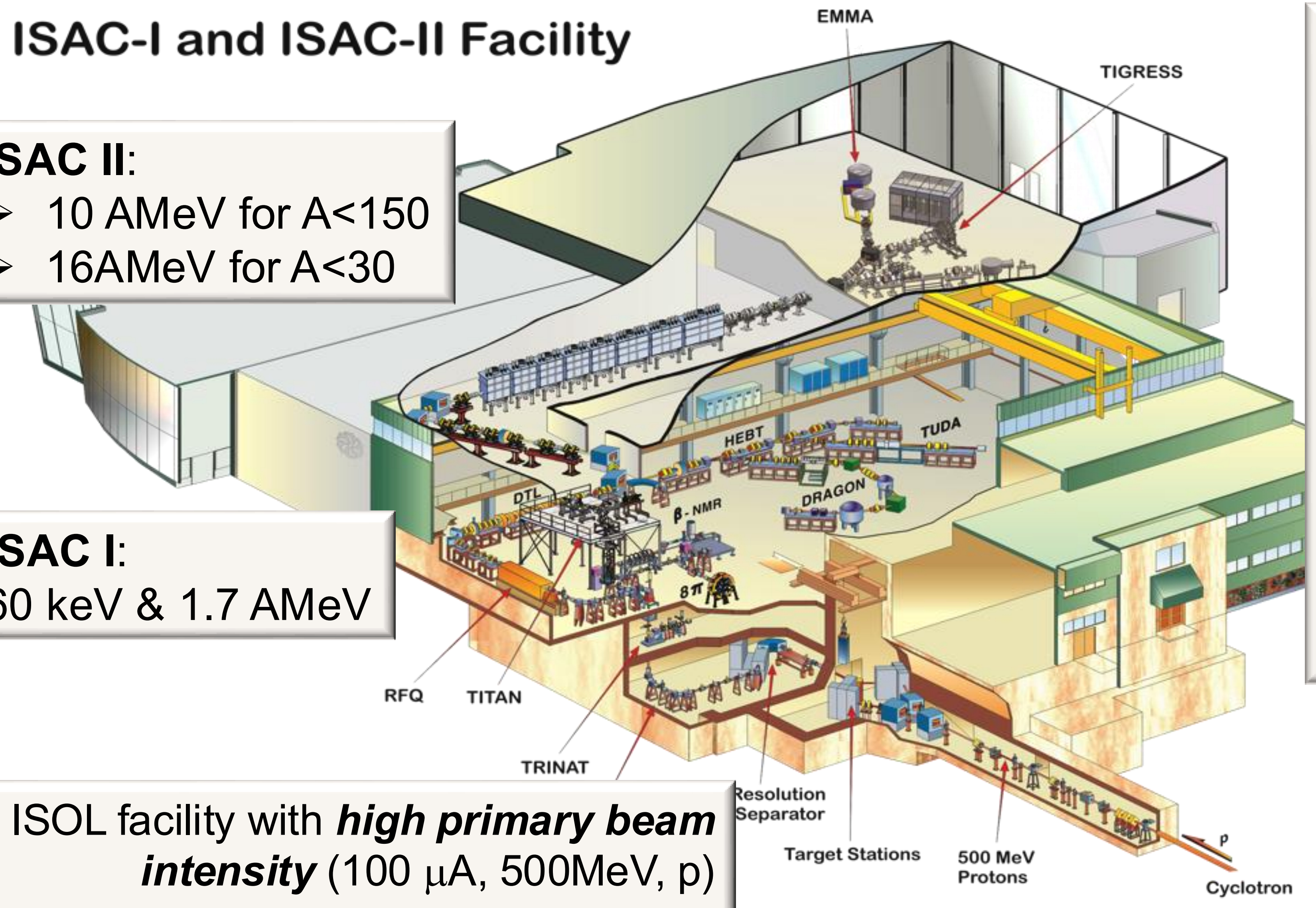
Outline

- Production of Radioactive Ion Beams (RIBs)
- Nuclear Structure Signatures
- Nuclear Masses and separation energies
- Nuclear spins and charge radii
- Decay and gamma-ray spectroscopy
- Inelastic scattering
- Direct reactions

TRIUMF Main cyclotron

18m diameter cyclotron producing 520MeV proton beams to 4 beamlines.
First beam was extracted on 15th December 1974.

ISAC-TRIUMF ISOL facility for rare isotope beams

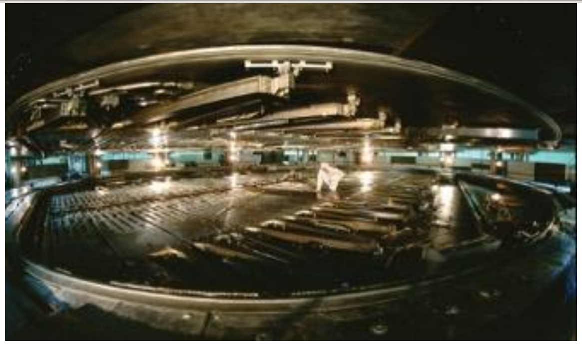


ISAC II:
- 10 AMeV for A<150
- 16AMeV for A<30

ISAC I:
60 keV & 1.7 AMeV

ISOL facility with ***high primary beam intensity*** (100 μA, 500MeV, p)
Delivering RIBs since 1999.

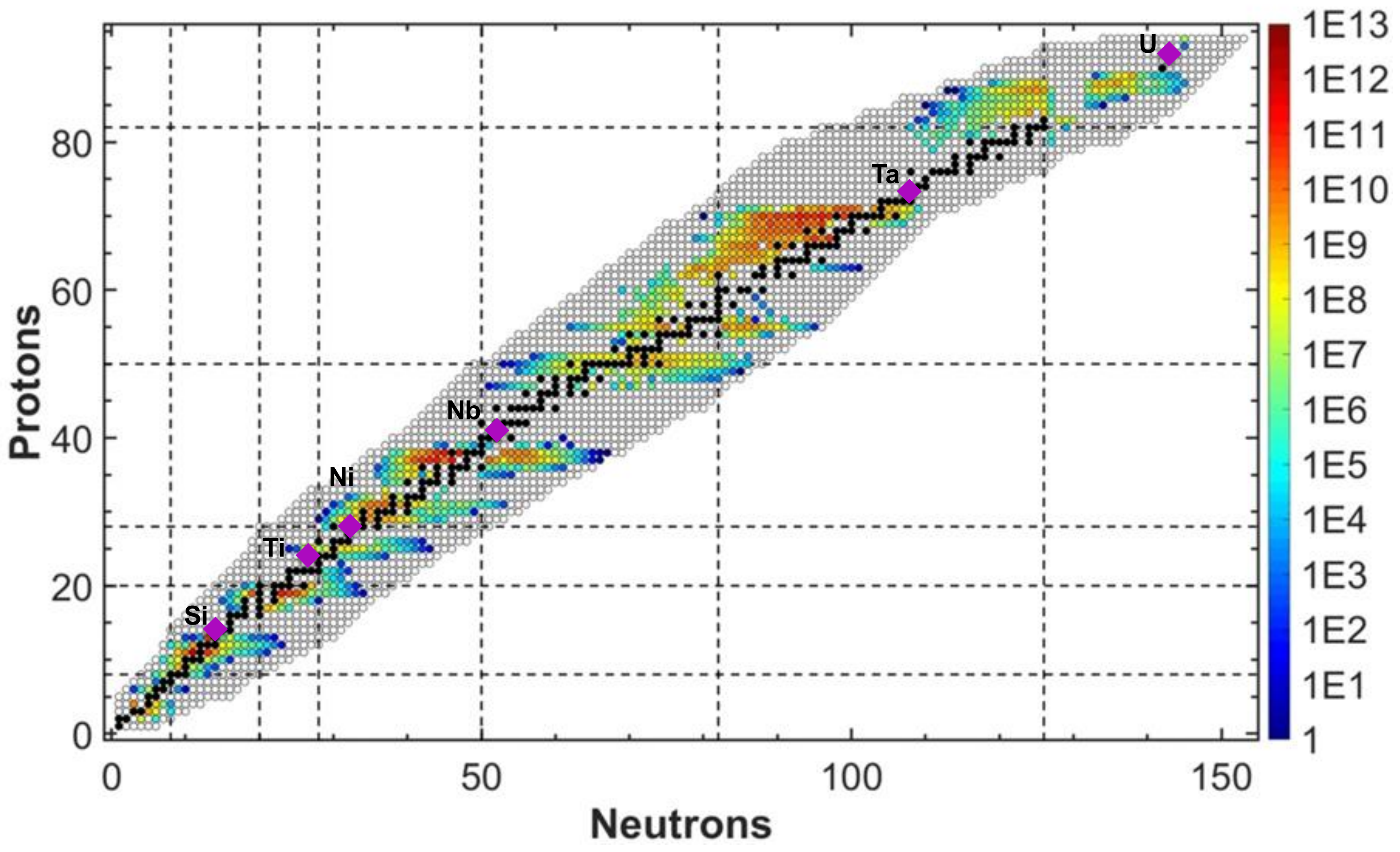
Programs in
- Nuclear Structure & Dynamics
- Nuclear Astrophysics
- Electroweak Interaction Studies
- Material Science
- 18 permanent experiments

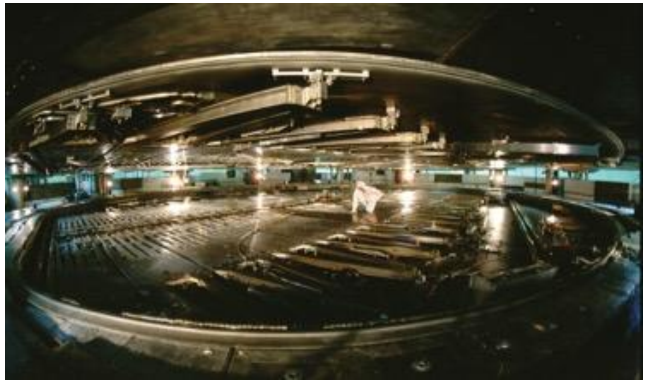


TRIUMF

ISAC-TRIUMF ISOL facility for rare isotope beams

Isotopes delivered at ISAC

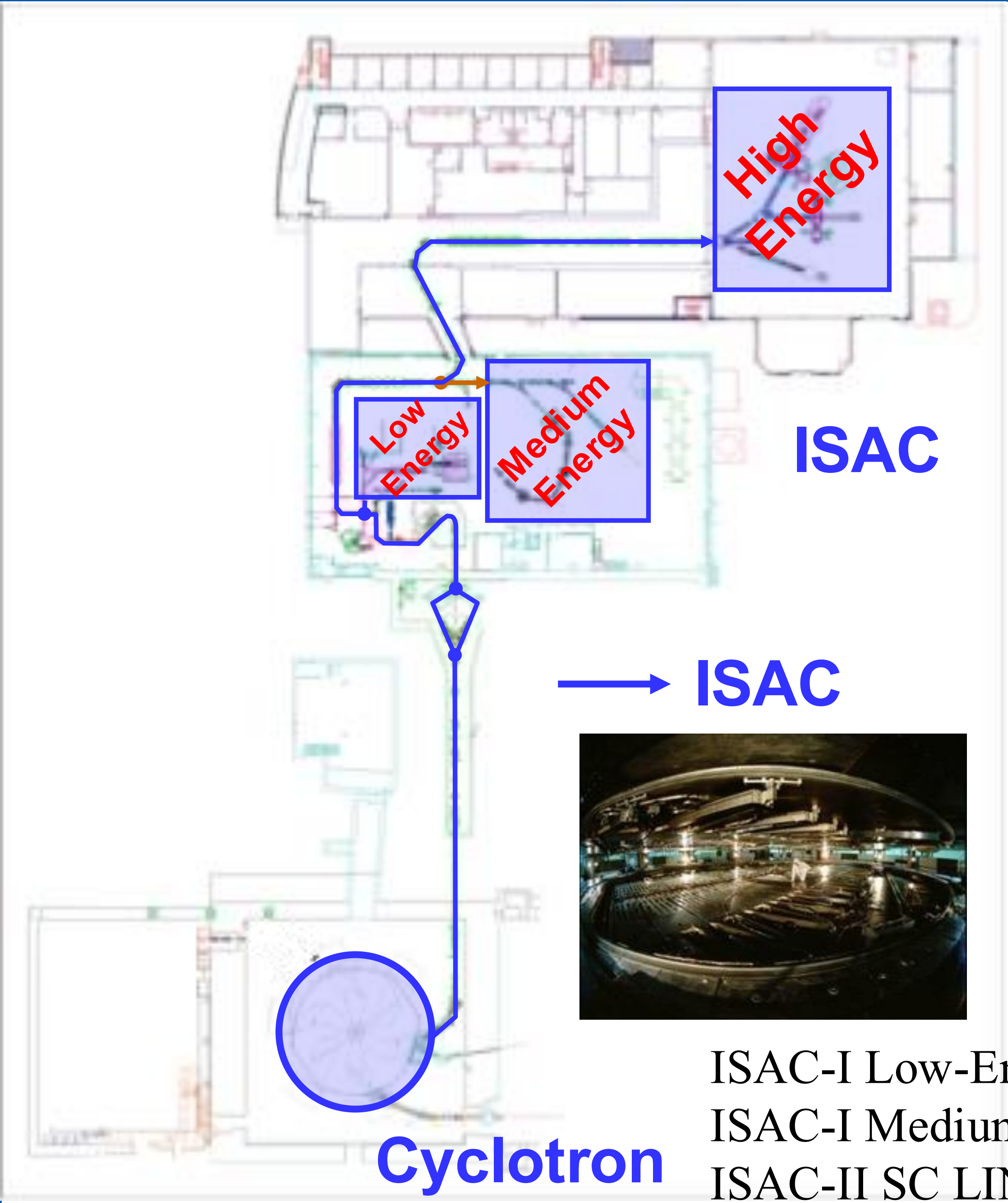




Target materials:
SiC, TiC, NiO, Nb, ZrC, Ta, TaC, ThO, UC, UO

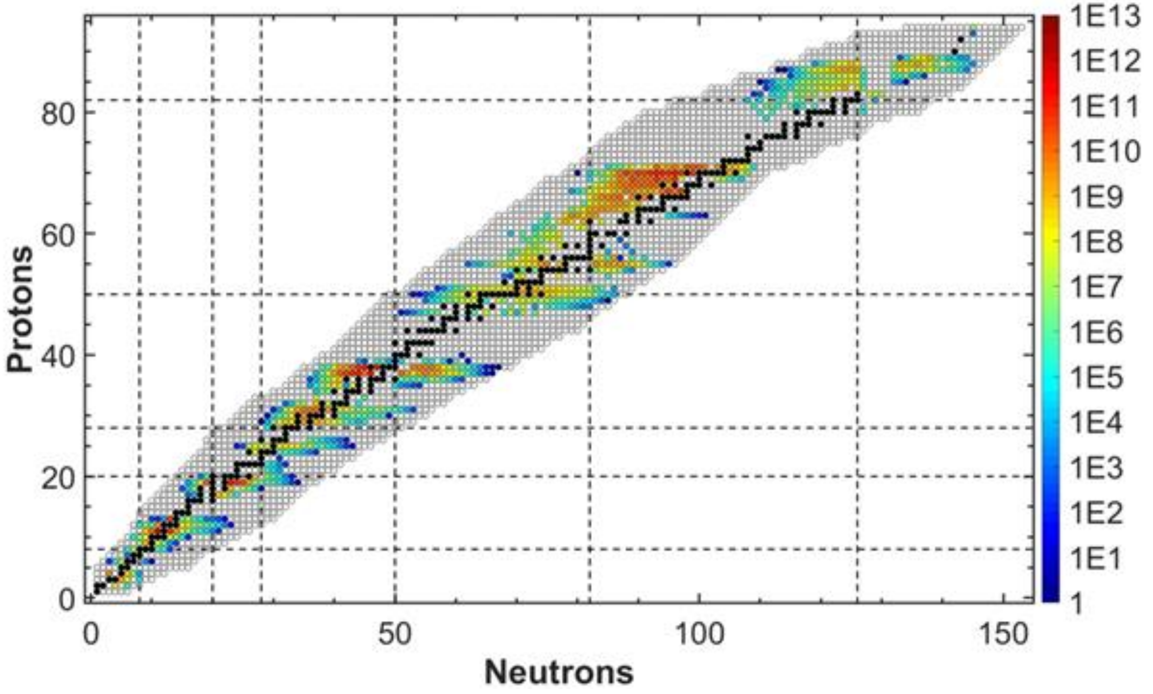
Ion sources:
Surface, TRILIS, FEBIAD, IG-LIS

ISAC-TRIUMF ISOL facility for rare isotope beams



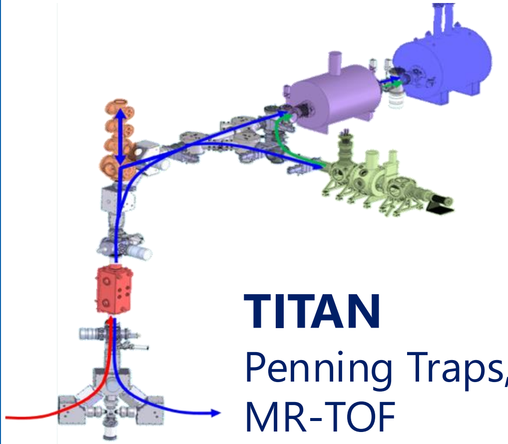
500MeV p^+ at 100μA on ISOL target

Targets: SiC, TiC, NiO, Nb, ZrC, Ta, TaC, ThO, UO, UCx
Ion sources: Surface, TRILIS, FEBIAD, IG-LIS



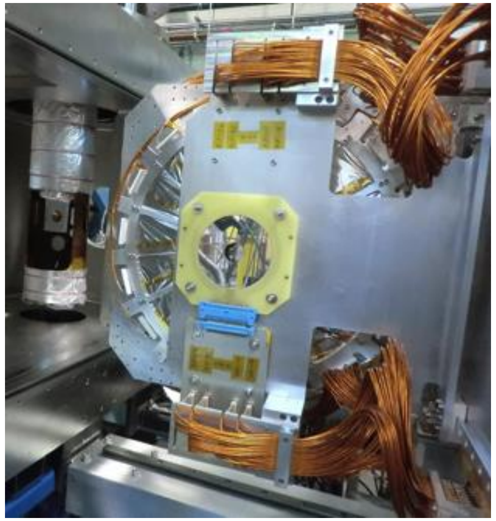
ISAC-I Low-Energy	<60keV	Ground state + decay, material science
ISAC-I Medium E	<1.5MeV/u	Astrophysics
ISAC-II SC LINAC	<10MeV/u	Nuclear reactions and structure

Nuclear Structure at TRIUMF-ISAC

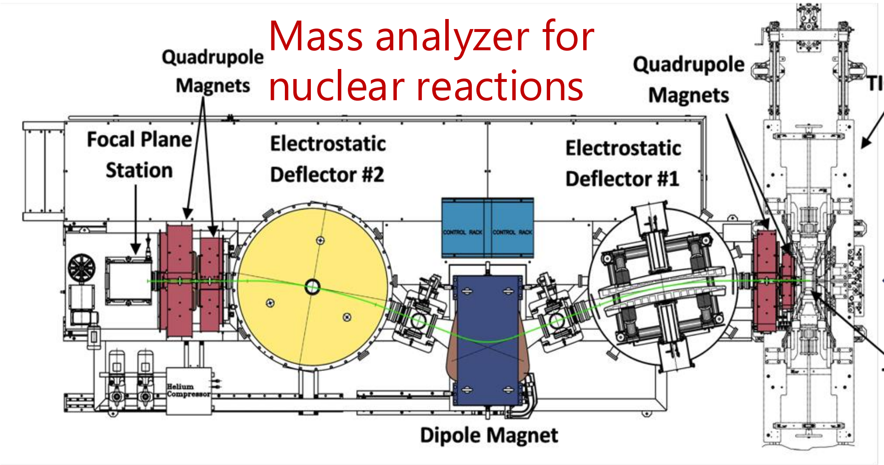


TITAN
Penning Traps,
MR-TOF
(masses,
in-trap decay)

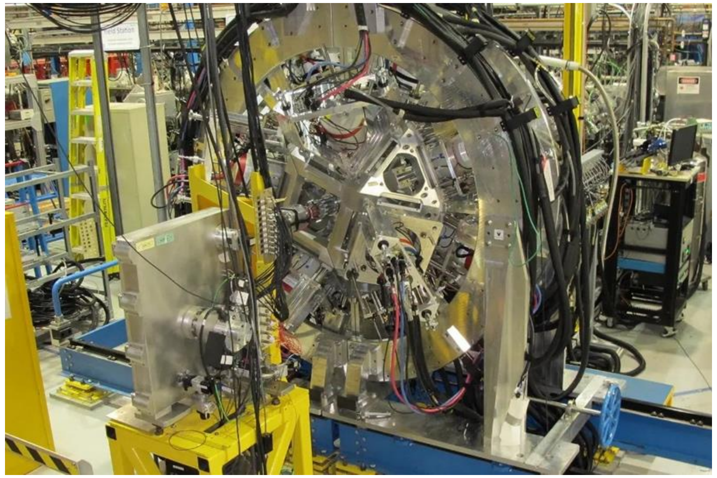
IRIS
Solid hydrogen
target for direct
reactions



EMMA+TIGRESS
Mass analyzer for
nuclear reactions

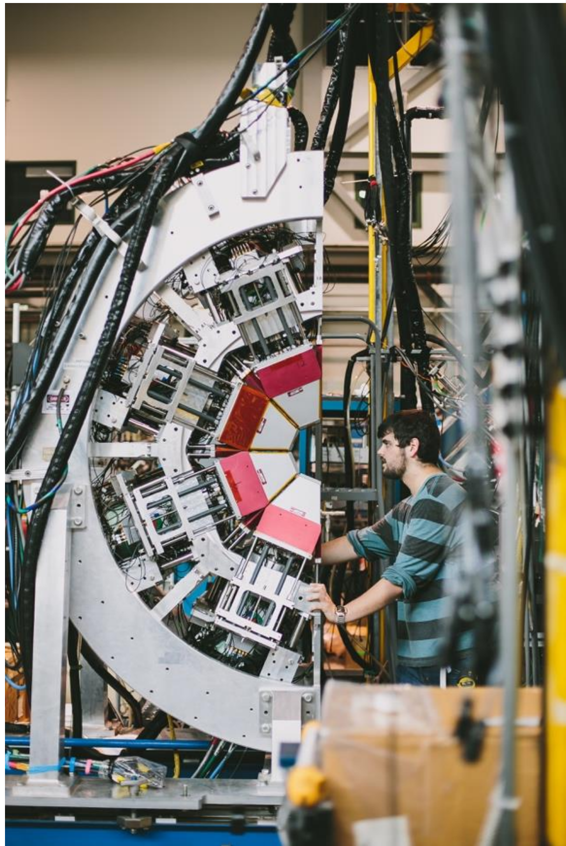


GRIFFIN
Gamma & Electron
spectrometer
(decay properties)



Polarizer beamline
Co-linear Laser spectroscopy

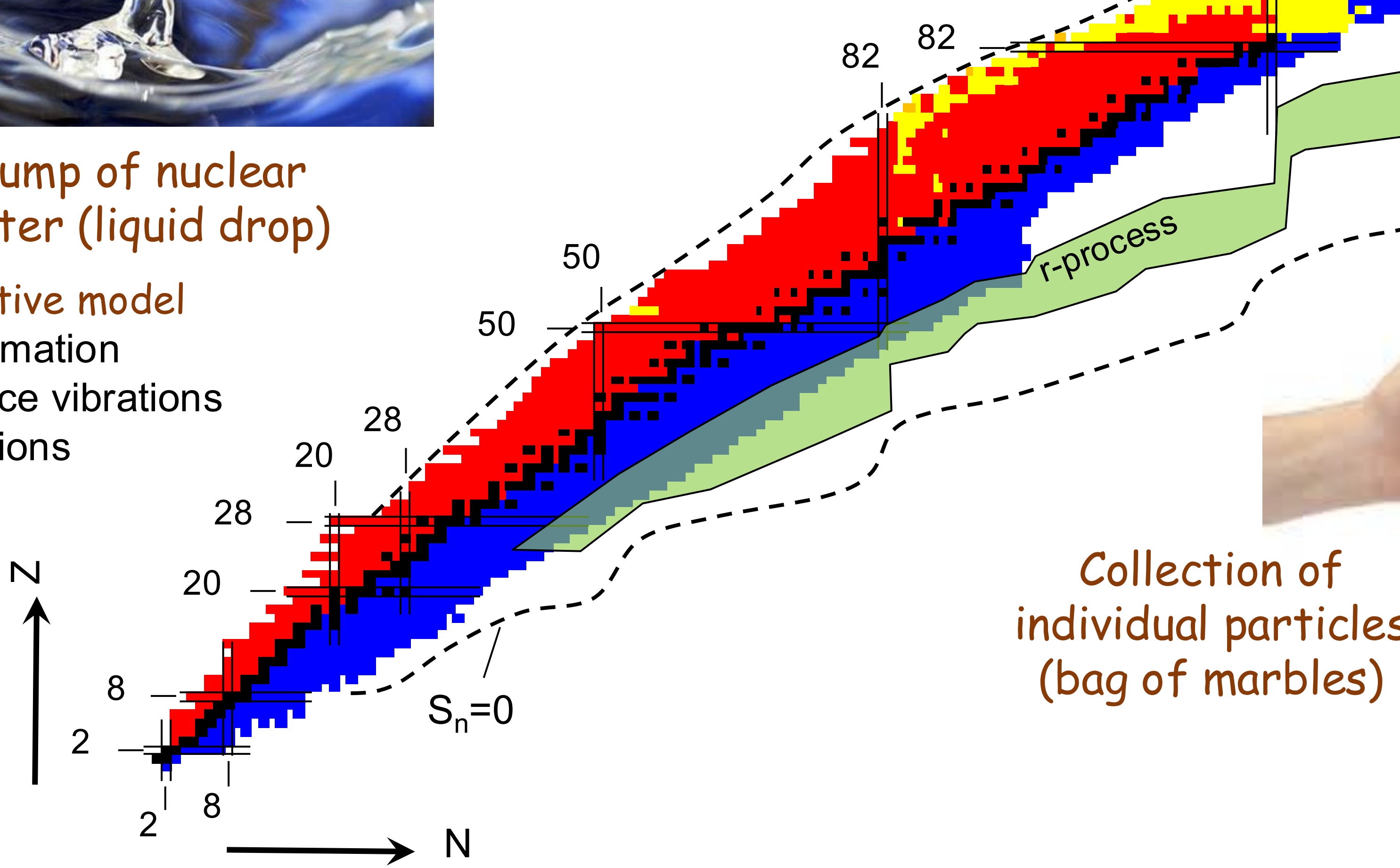
TIGRESS
In-beam γ-ray spectroscopy



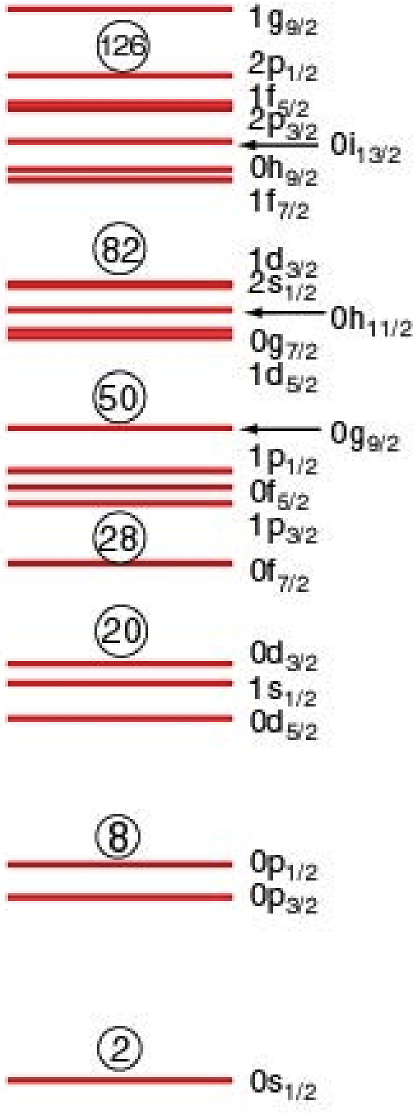
The nuclear landscape

A lump of nuclear matter (liquid drop)

Collective model
- Deformation
- Surface vibrations
- Rotations

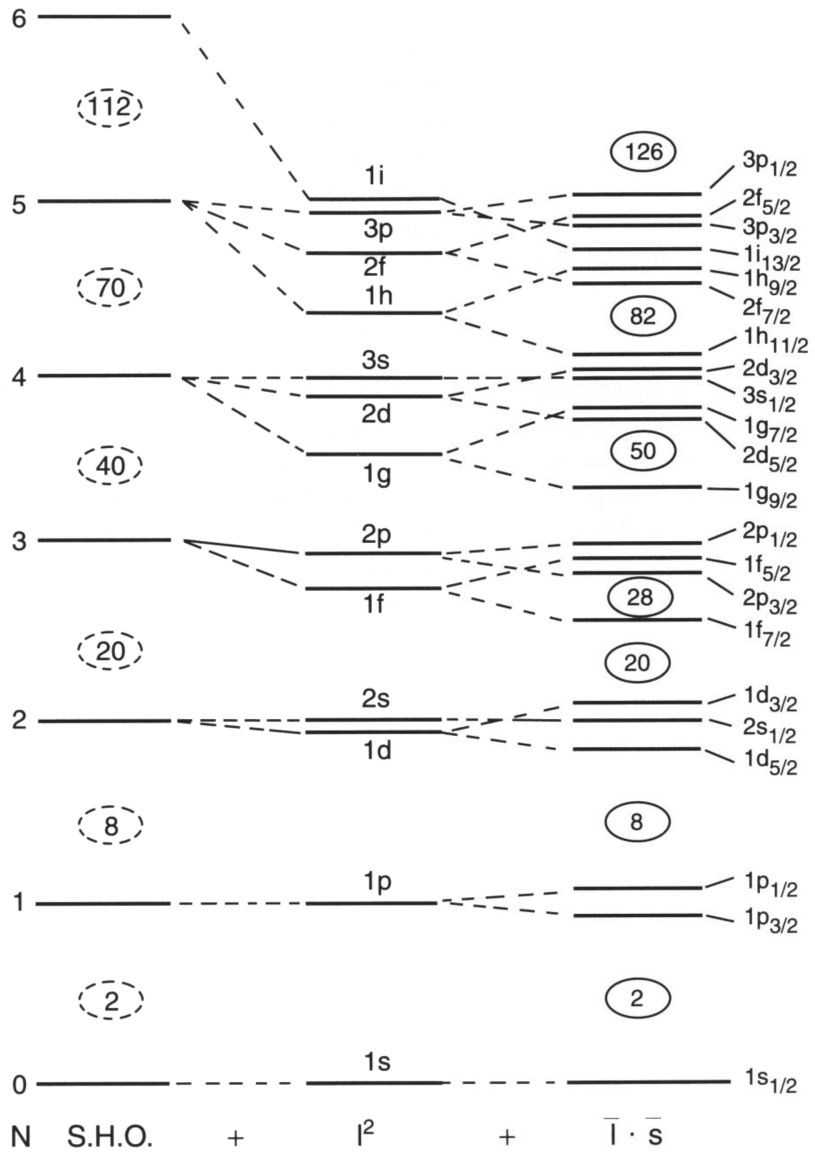


Collection of individual particles (bag of marbles)



Shell Model of Nuclei

The Nuclear Shell model



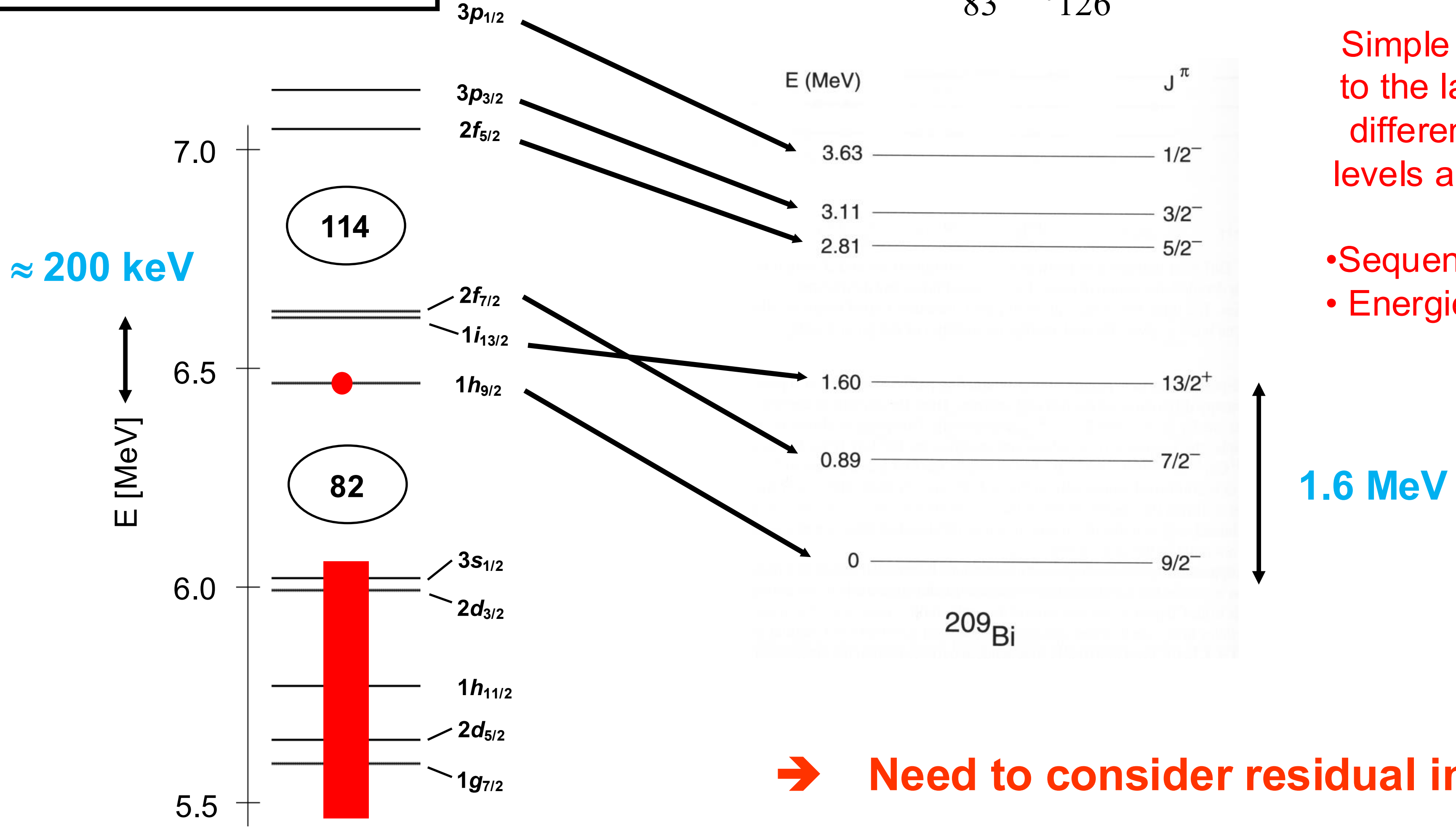
- Protons or neutrons are Fermions filling orbitals up to a Fermi surface.
- Woods Saxon (Spherical) potential
- Attractive l^2 interaction lowers energies of states with large l
- Spin-orbit effect produces additional degeneracy.

Large gaps between orbitals produce extra stability for these ‘magic’ numbers.

Shell model – simple predictions

Proton single particle orbitals (no residual interaction)

Excited states in $^{209}_{83}Bi_{126}$



Simple structure corresponding to the last proton occupying the different single-particle energy levels around the Fermi surface.

- Sequence not perfect
- Energies not perfect

➔ **Need to consider residual intractions**

Deformed nuclei – parameterization of the nuclear surface

prolate: $\beta_2 > 0,\ \gamma = 0^\circ$

oblate: $\beta_2 < 0,\ \gamma = 60^\circ$

triaxial: $|\beta_2| > 0,\ \gamma = 30^\circ$

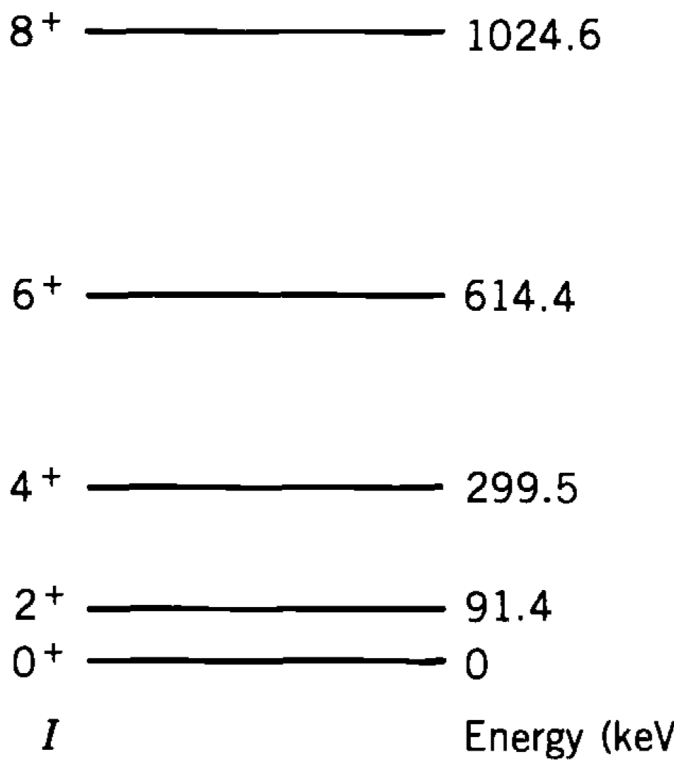
γ: “axial asymmetry” parameter

Quadrupole rotor model
Example for rotational bands

Moment of inertia

Kinetic energy of rotating object: $E_{kin} = \frac{1}{2}\Im\omega^2$

$$E_{rot} = \frac{\hbar^2}{2\Im}J(J+1)$$



Measured rotational g.s. band in ^{164}Er (from Krane)

E(8+)= $72(\frac{\hbar^2}{2\Im})$= 72*15.2 keV= 1094.4 keV

E(6+)= $42(\frac{\hbar^2}{2\Im})$= 42*15.2 keV= 638.4 keV

E(4+)= $20(\frac{\hbar^2}{2\Im})$= 20*15.2 keV= 304 keV

E(2+)= $6(\frac{\hbar^2}{2\Im})$= 91.4 keV ⇨ $\frac{\hbar^2}{2\Im}$=15.2 keV

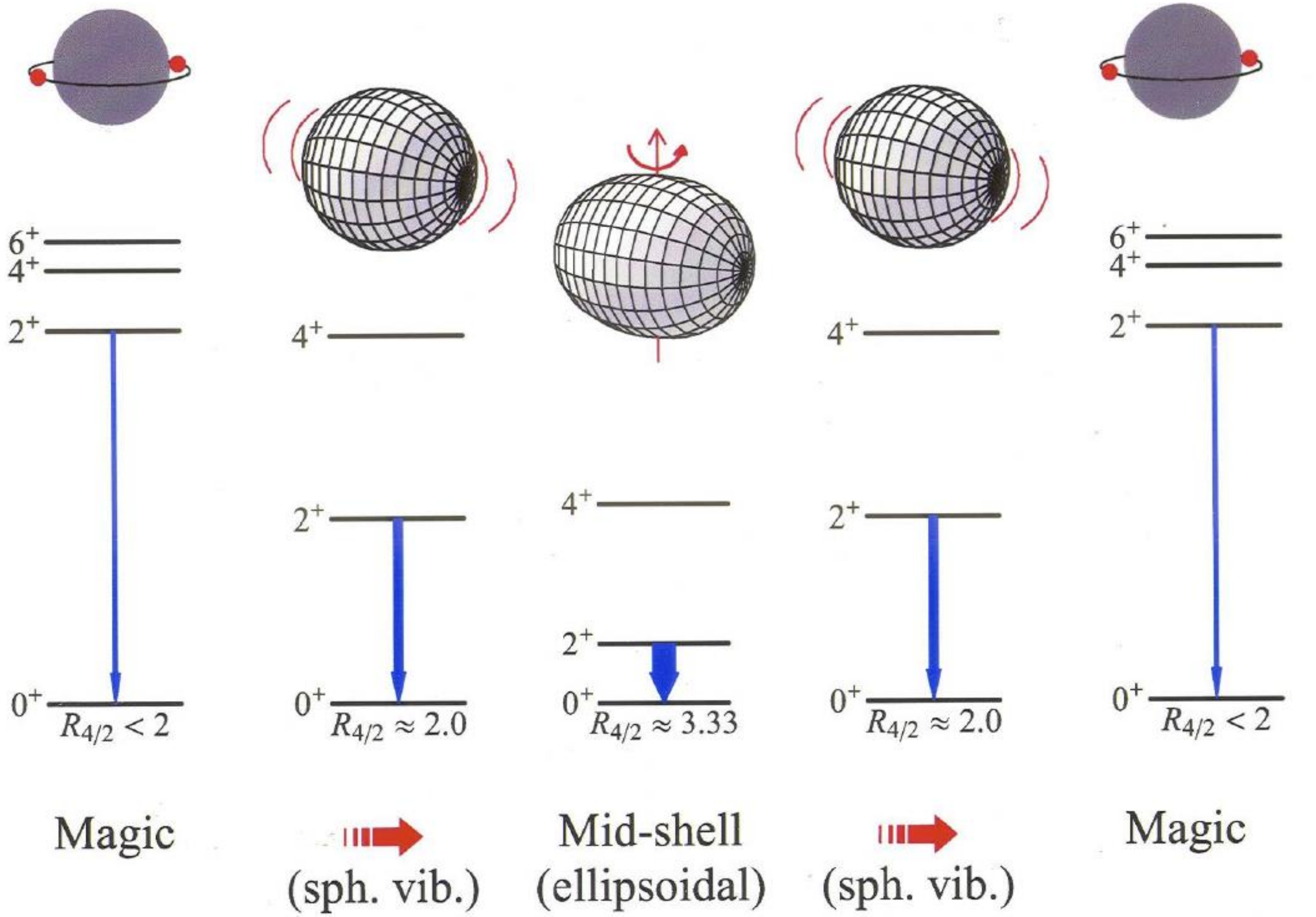
E(0+)= 0 keV

Calculated

Ratio E(4+)/E(2+) = 299.5/91.4 = **3.28**

Very close to maximum value of 3.33 for ideal rotor.

Evolution of nuclear structure

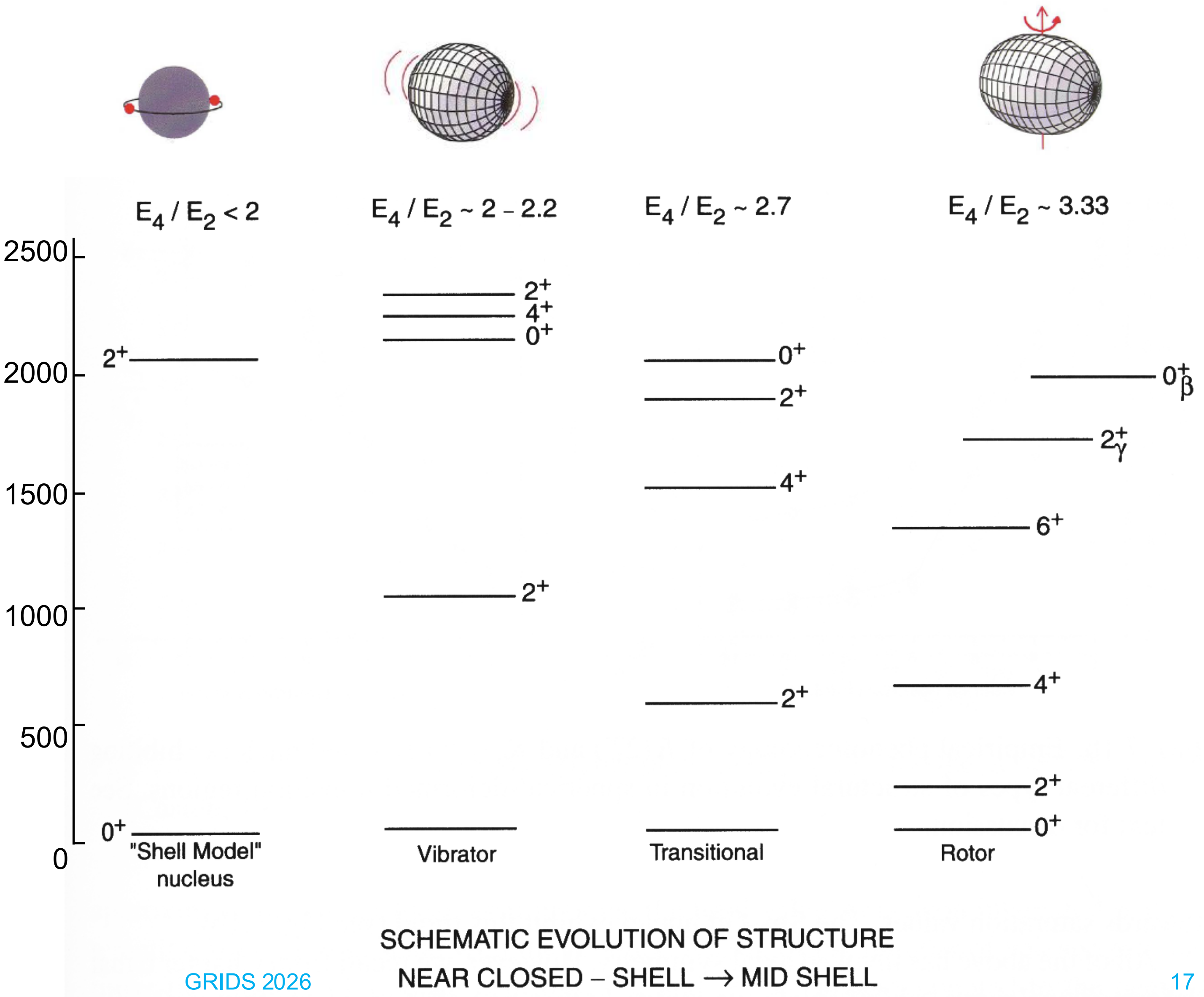


Evolution of nuclear structure

What is the structure
of these even-even nuclei?

Key signatures:

- First 2+ energy
- $B(E2, 2_1 - 0_{gs})$
- R(4/2)



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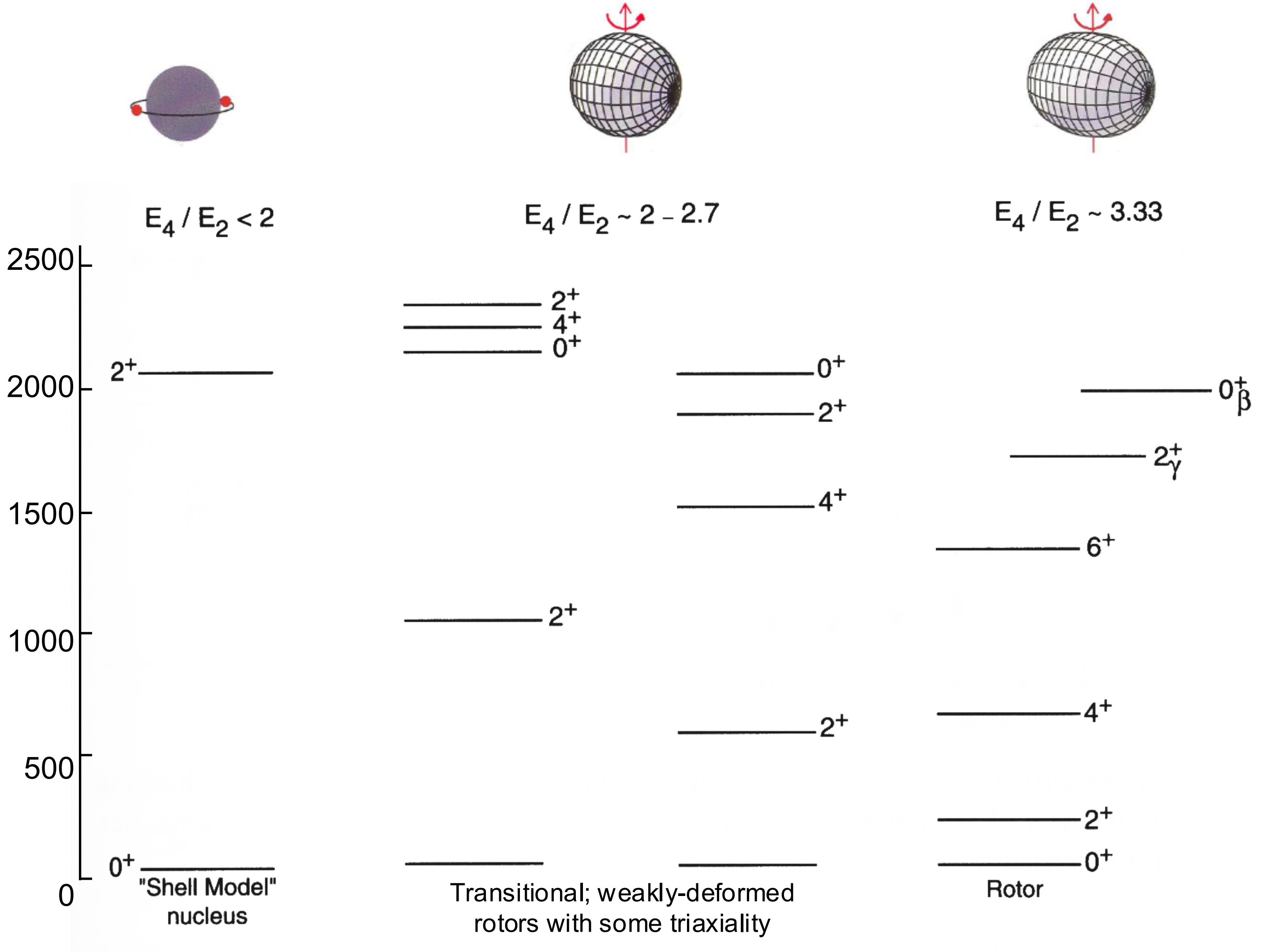


P.E. Garrett *et al.* Phys. Rev. Lett. 123, 142502 (2019).

Evolution of Structure

What mechanisms drive nuclei to transition from spherical, single-particle structures to deformed, collective excitations?

Can we develop a unified theory for all nuclear behavior?

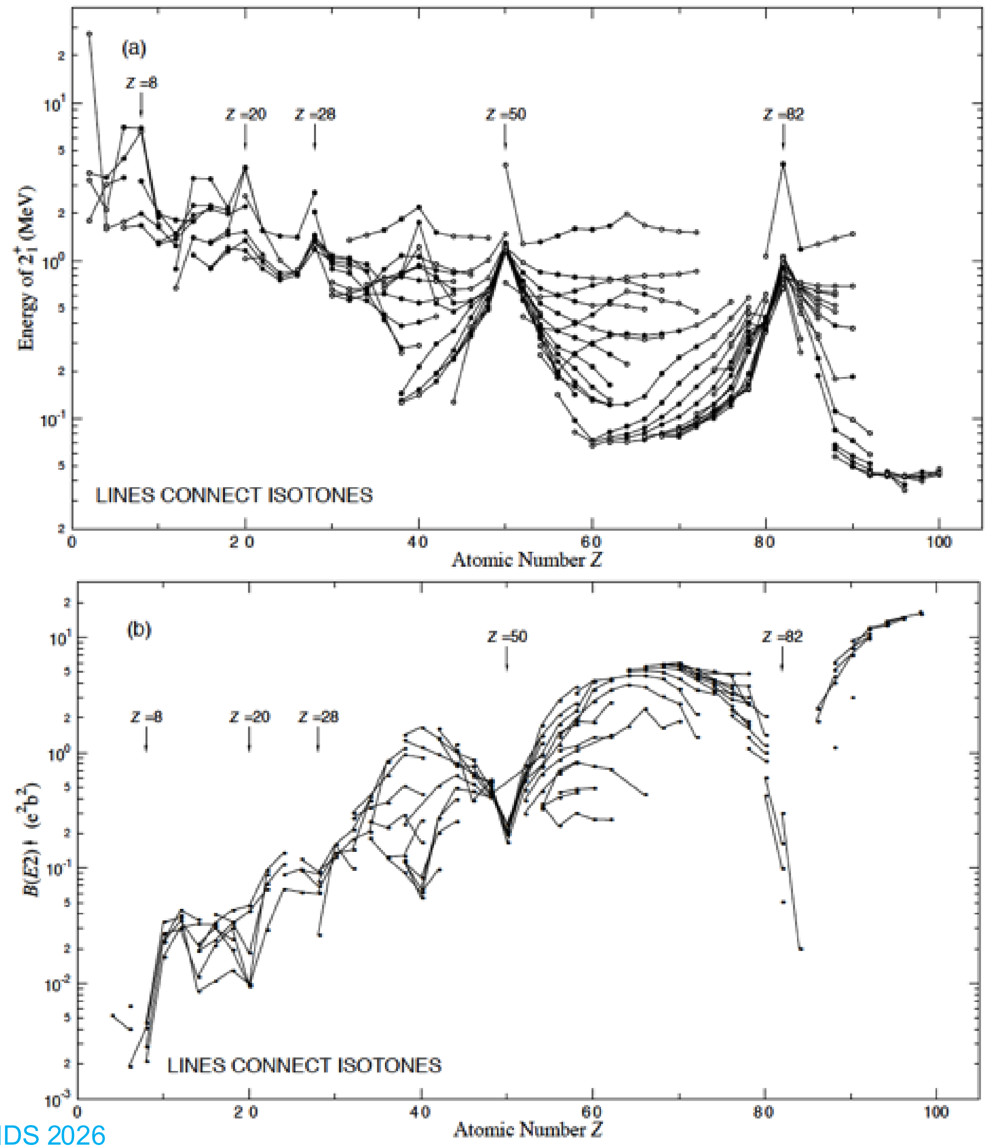
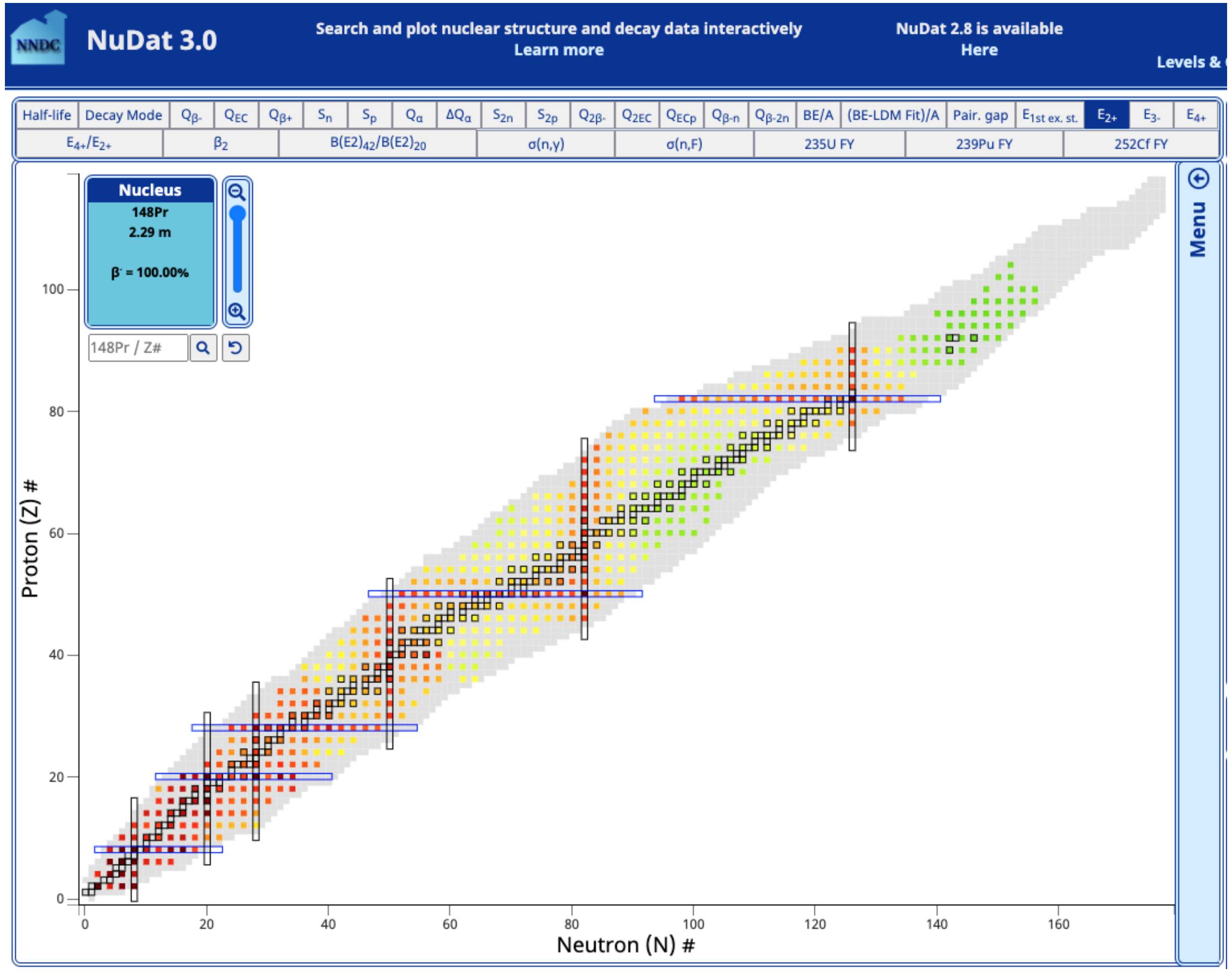


Figure from S. Raman, C.W. Nestor, JR., P. Tikkanen, Atomic Data and Nuclear Data Tables 78, 1 (2001).

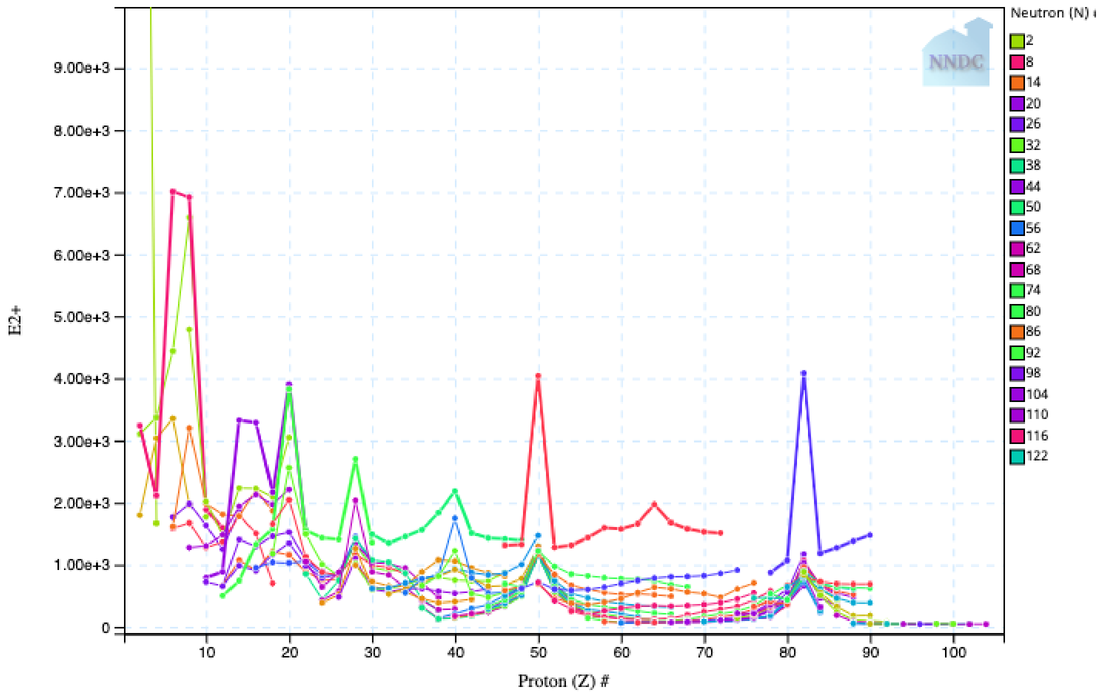
Typical features of collective behavior: E(2+)



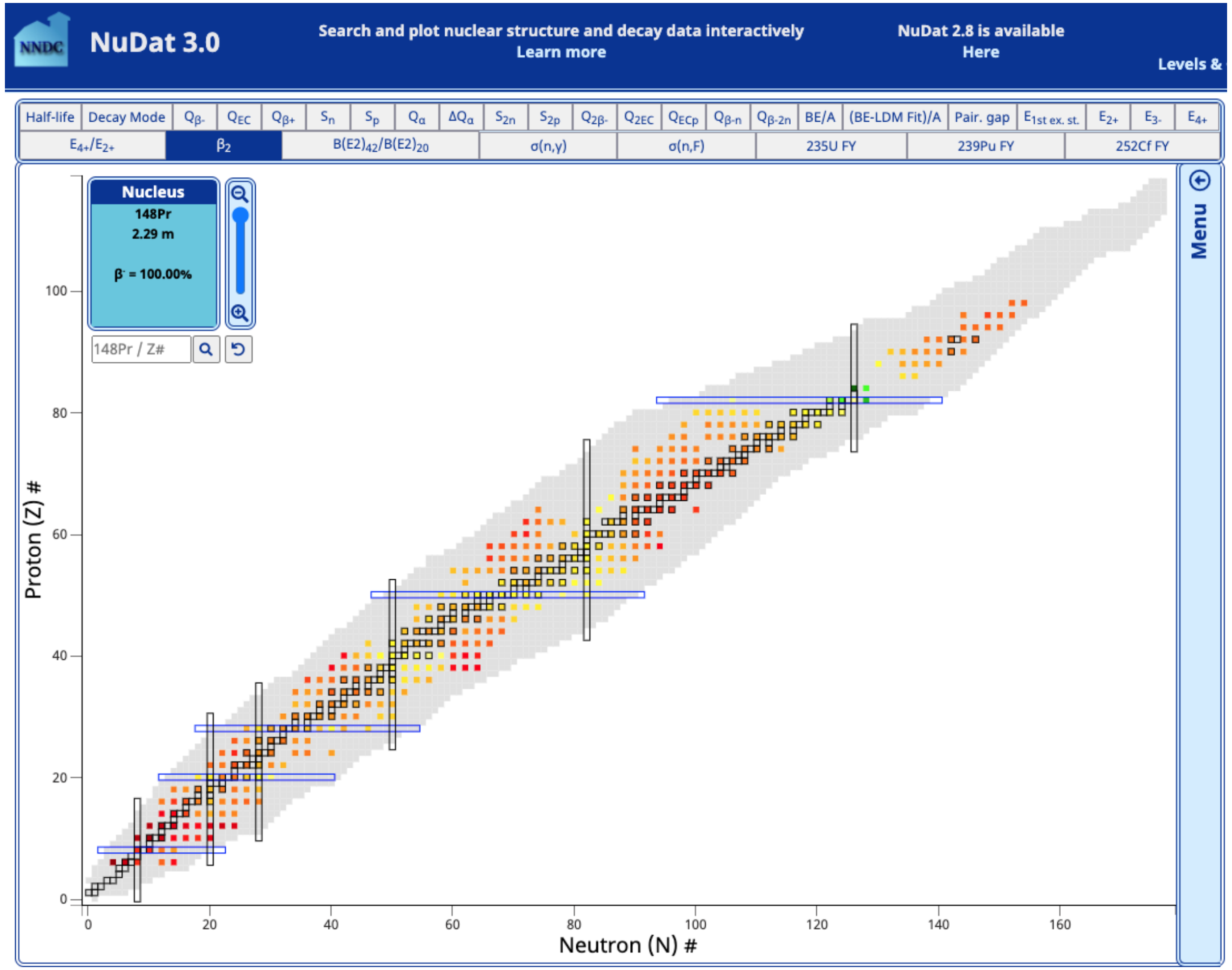
https://www.nndc.bnl.gov/nudat3/

- high E(2+) at shell closures
- low E(2+) for mid-shell nuclei
- lowest E(2+) for lanthanides (A~150-170)

and actinides (A~220-250)



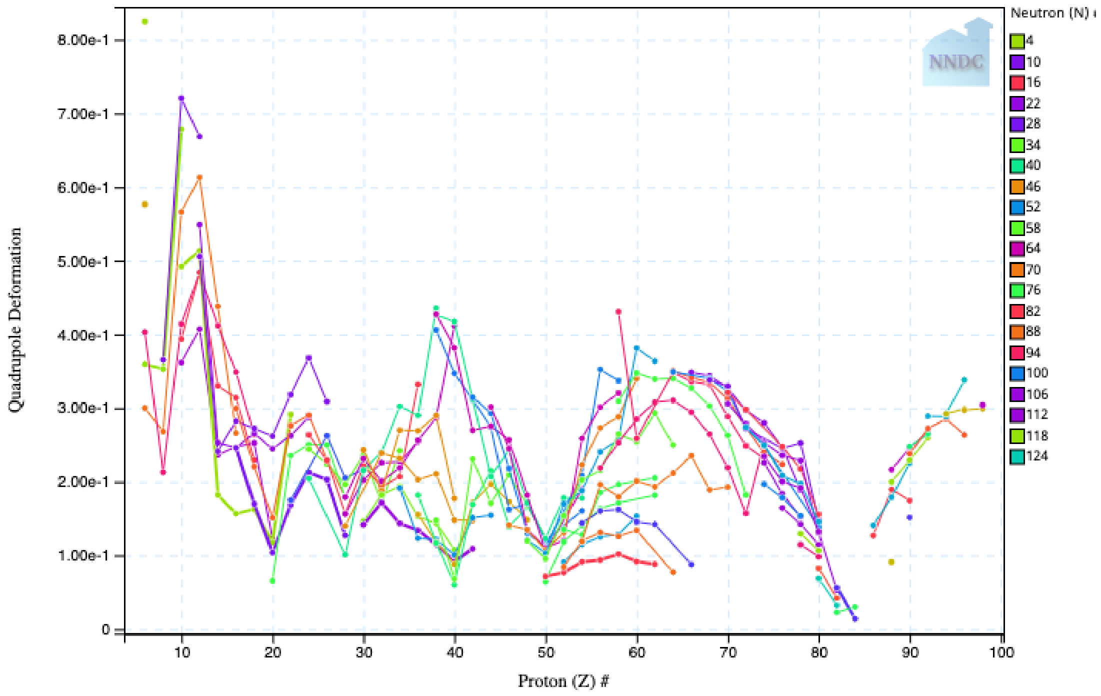
Typical features of collective behavior: β_2



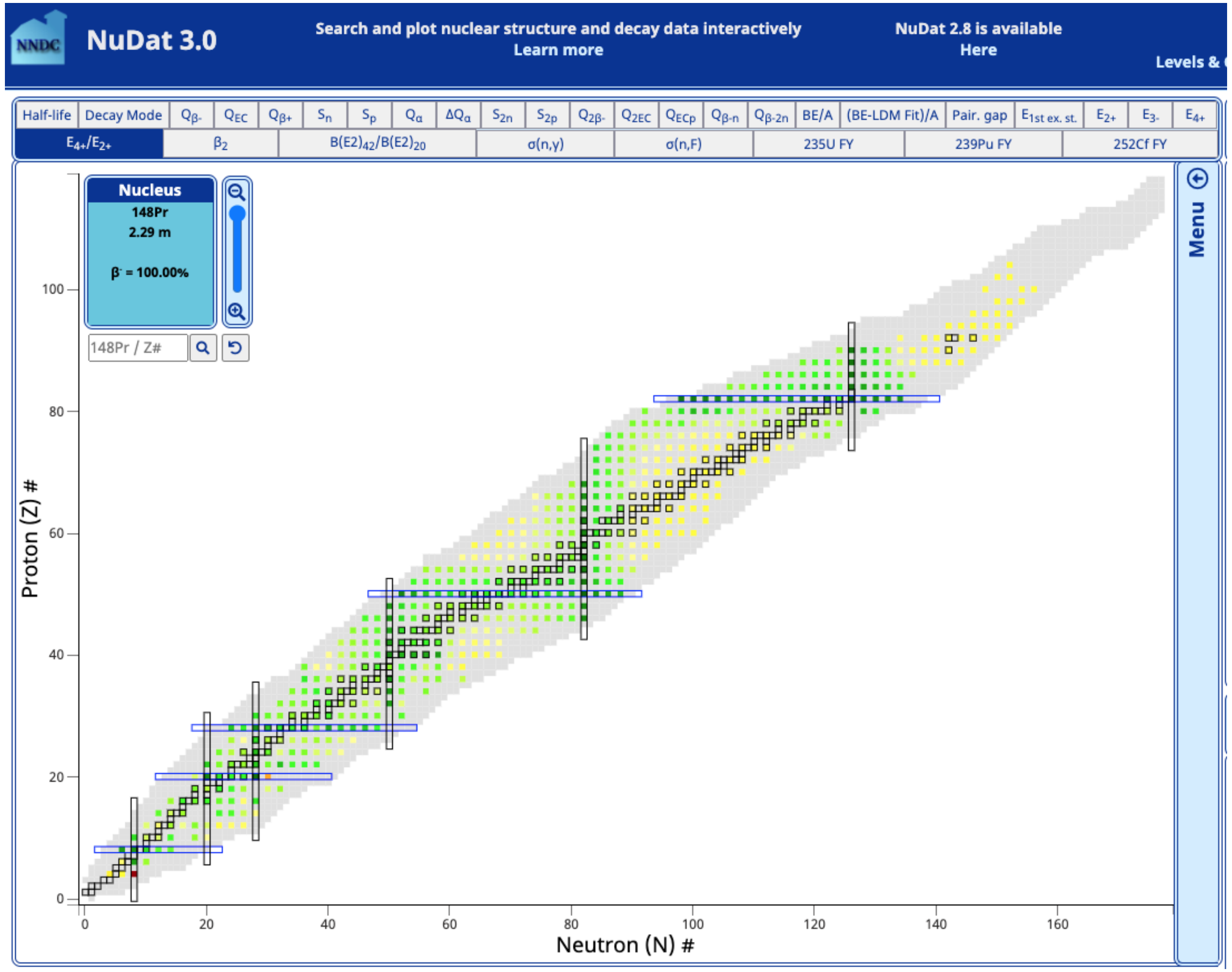
https://www.nndc.bnl.gov/nudat3/

$$\beta_2 = (4\pi / 3ZR_0^2)[B(E2)\uparrow / e^2]^{1/2}$$

- lowest B(E2) at shell closures
- larger B(E2) for mid-shell nuclei



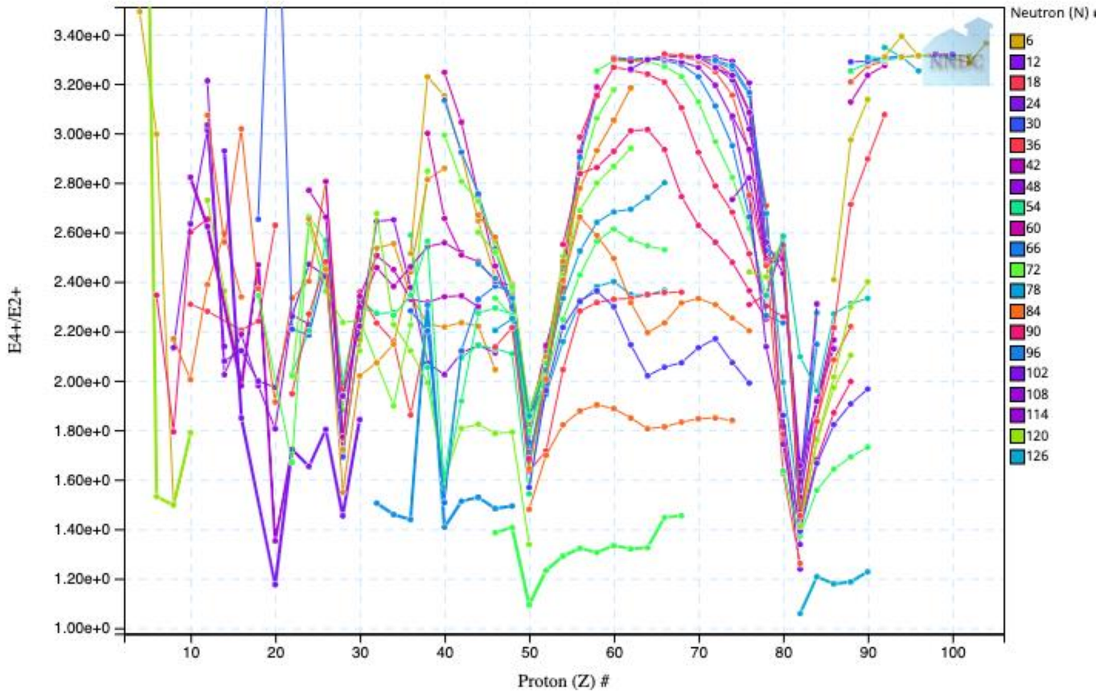
Typical features of collective behavior: E(4+)/E(2+)



https://www.nndc.bnl.gov/nudat3/

A<150: vibrations of spherical shape and/or rotations of weakly-deformed shapes

A~150-190: rotations of strongly-deformed shapes



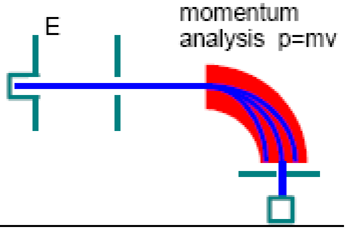
What questions can we ask about nuclei?

- How heavy is it?
  - Mass spectroscopy
- How big is it?
  - Laser spectroscopy of Hyperfine structure
- How long does it survive?
  - Decay spectroscopy
- What shape is it?
  - Coulomb excitation
- How are excitations created
  - Gamma-ray spectroscopy

Experimental approaches to Mass measurements

Conventional mass spectrometry

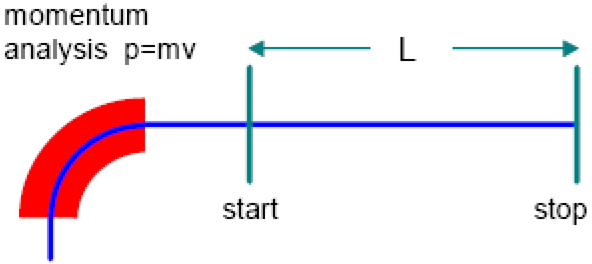
CERN-PS + ISOLDE
Chalk-River
St. Petersburg



Time-of-flight spectrometry

single turn: SPEG, TOFI

multi turn: cyclotrons CSS2, SARA,
storage ring ESR

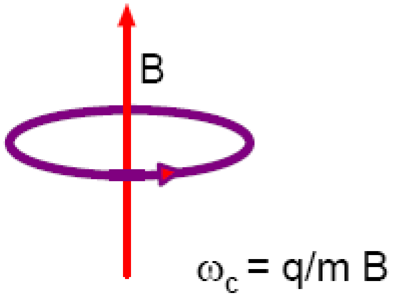


Frequency measurements

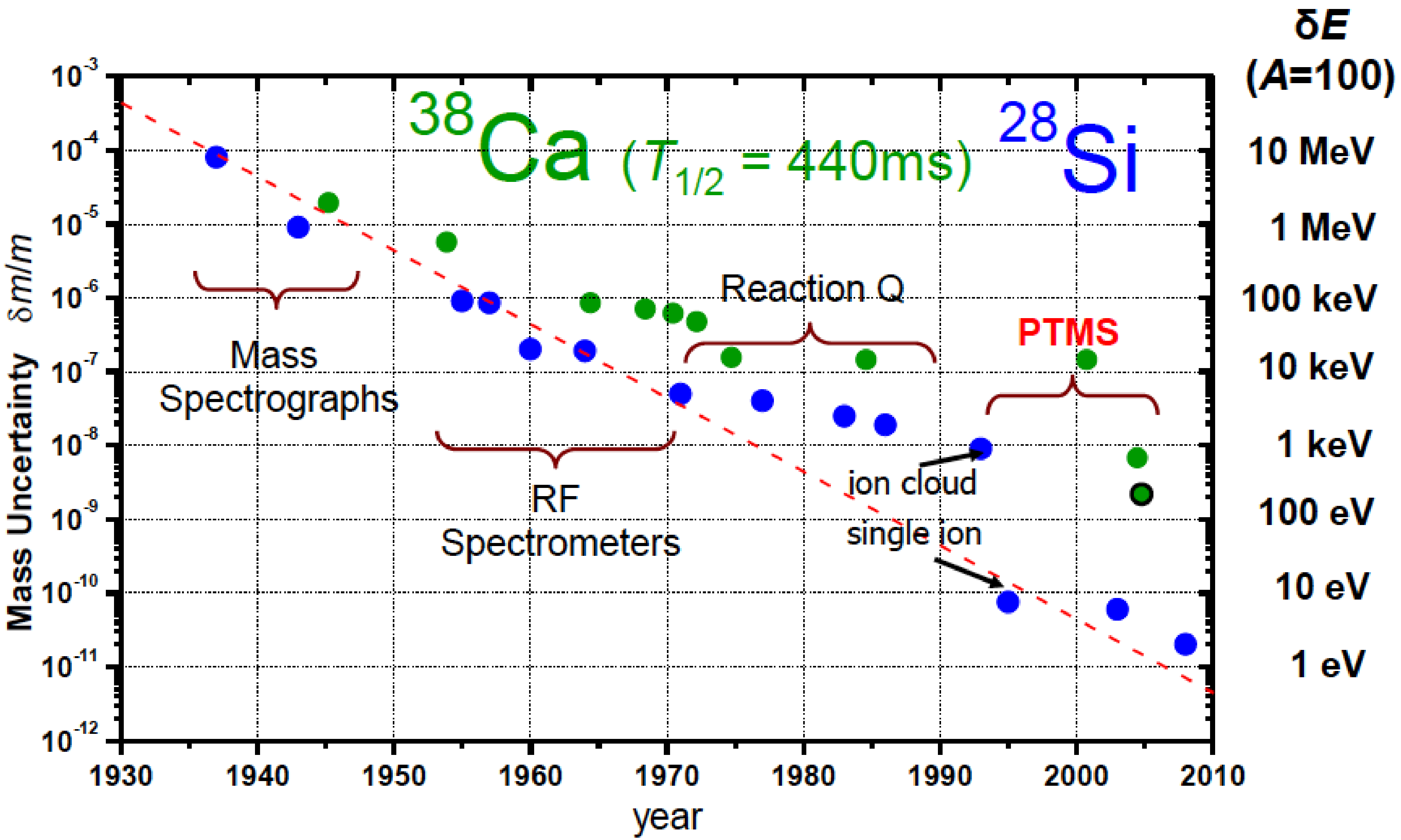
storage ring ESR/GSI,

RF transmission spectrometer MISTRAL/ISOLDE

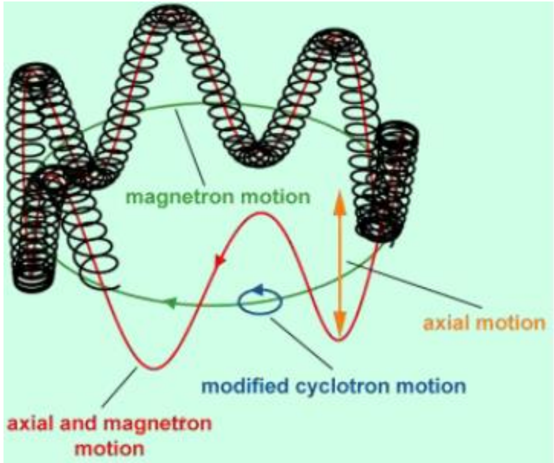
Penning traps **ISOLTRAP/ISOLDE**
CPT/ANL
SHIPTRAP/GSI
JYFLTRAP/JYFL
LEBIT/NSCL
TITAN/ISAC

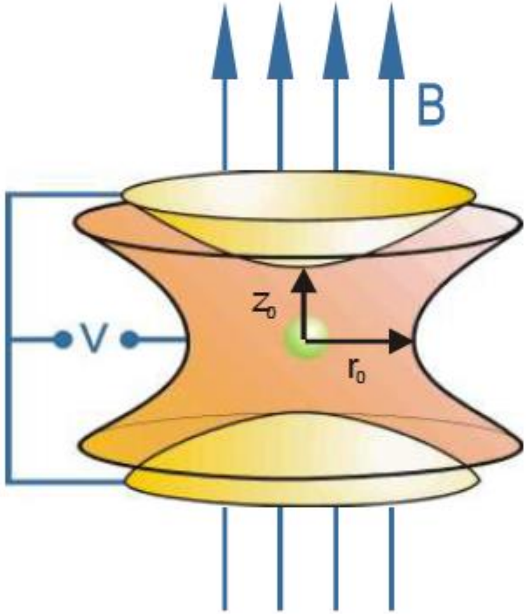


The precision of mass measurements



Penning Traps





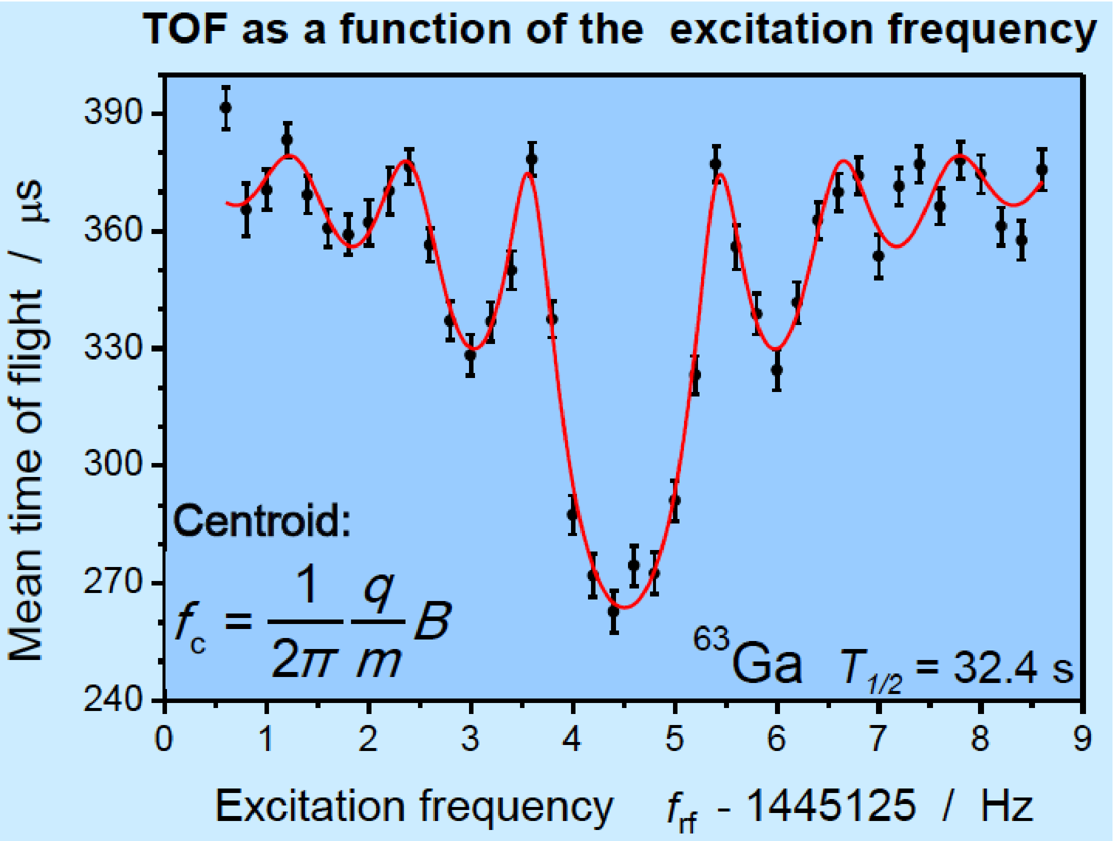
Cyclotron frequency: $\nu_c = \frac{1}{2\pi} \cdot \frac{q}{m} \cdot B$

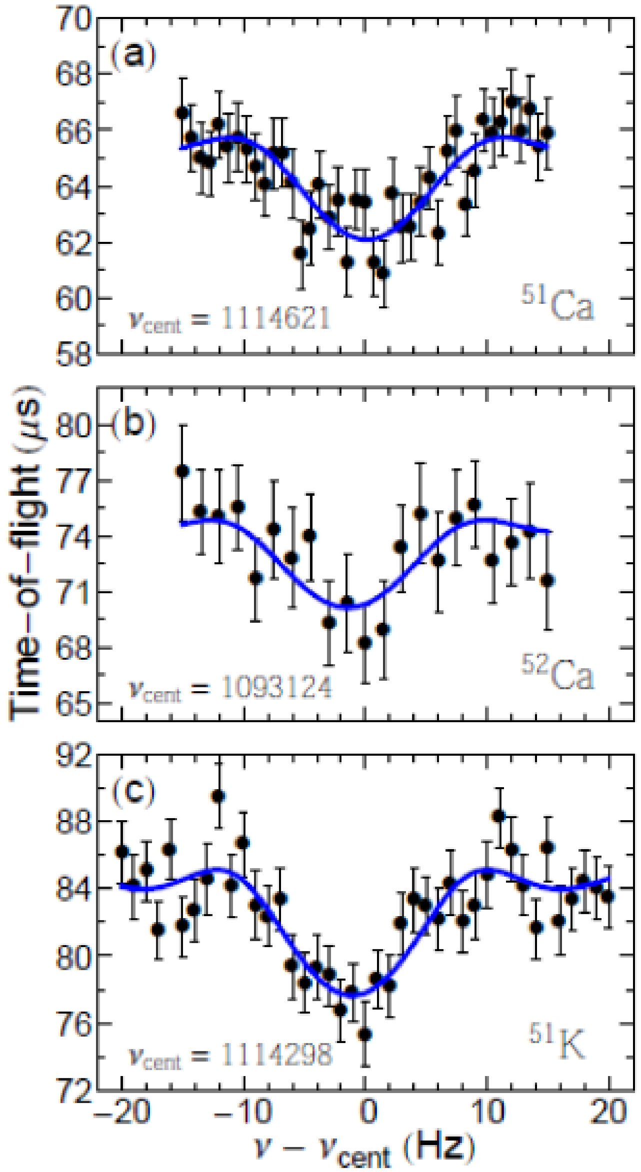
Superposition
- strong homogeneous magnetic field
- weak electrostatic quadrupole field

PENNING trap

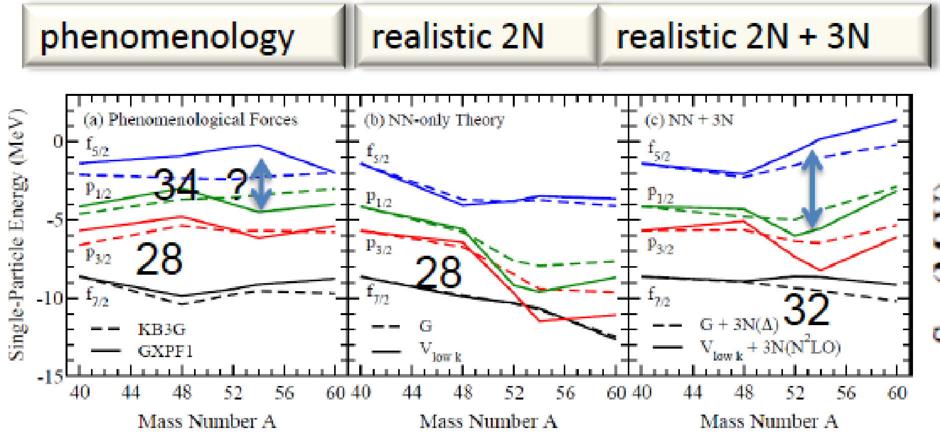
Penning Traps

RIB measurements made relative to a reference case





Penning Traps



Theory with realistic NN interaction & 3N forces:

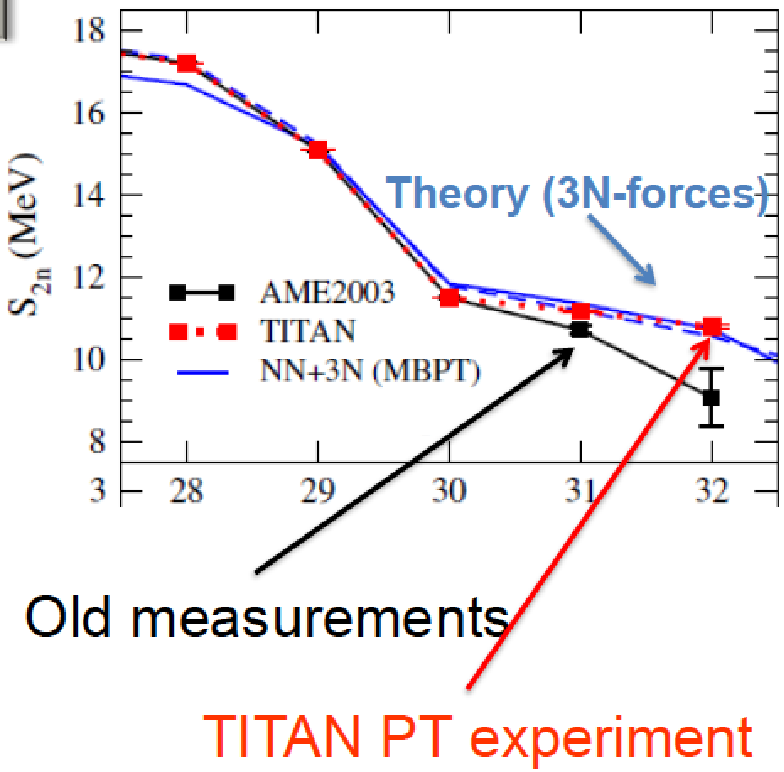
- substantially different trend for single-particle energies and separation energies
- quenching of N=28 shell gap around A=50-54
- **New magic shell closure a N=32**

Mass measurement of ^{51,52}Ca with TITAN

➔ confirms theoretical trends

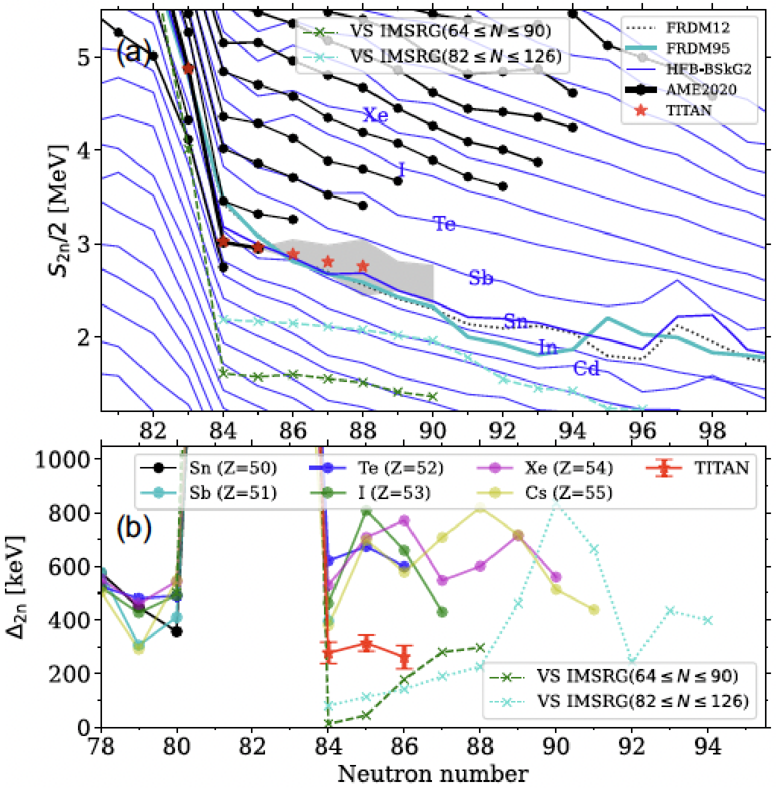
Looks like, that 3 body forces in theory required to predict the separation energy (or mass) of the neutron rich Ca isotopes.

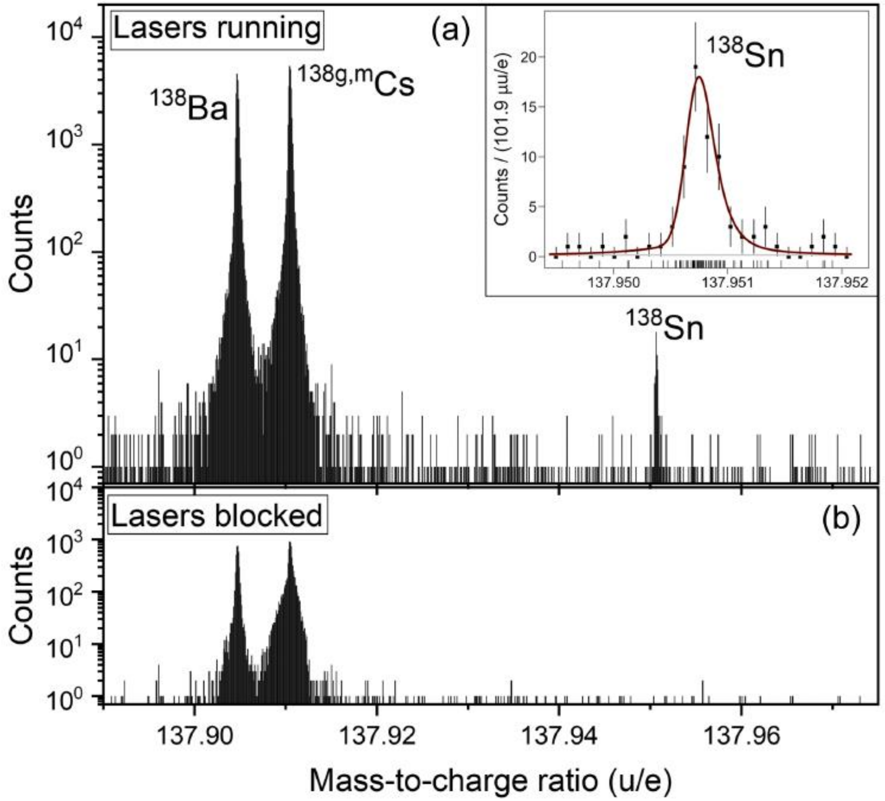
Further confirmation and extension to ^{54}Ca with ISOLTRAP

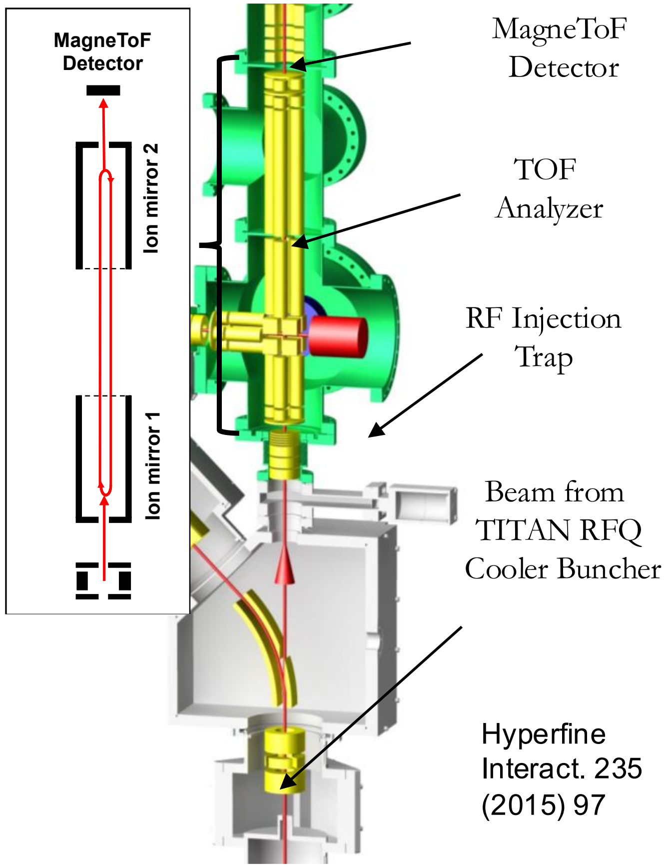


A.T. Gallant, PRL **109, 032506** (2012)

Multi-Reflection Time-Of-Flight (MR-TOF)







Hyperfine Interact. 235 (2015) 97

Technique:
Multi-reflection Time-of-Flight mass spectrometry using TITAN MR-ToF-MS with achievable precision of better than 100 ppb

- Evidence for notably decreased empirical pairing gap beyond N=82.
- S_{2n} trend is flatter than in heavier elements.
- Significantly improved uncertainty for inputs to abundance calculations

PHYSICAL REVIEW LETTERS **134,** 232701 (2025)

Nuclear Structure insight from Separation Energies

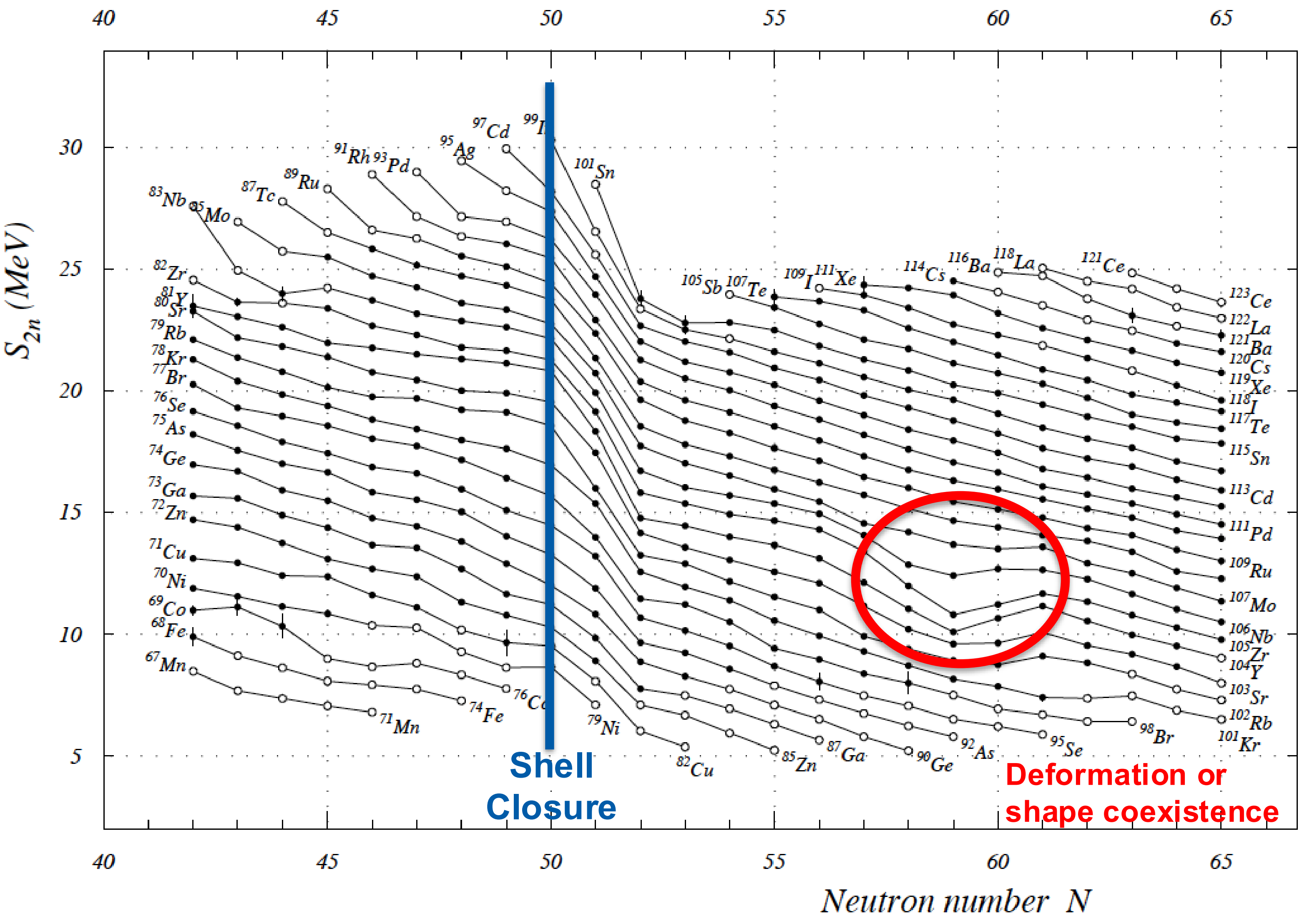
The differences between masses of different isotopes are the separation energies:

$$S(\mathrm{n}) = -M(A,Z) + M(A-1,Z) + \mathrm{n}$$
$$S(\mathrm{p}) = -M(A,Z) + M(A-1,Z-1) + {}^{1}\mathrm{H}$$

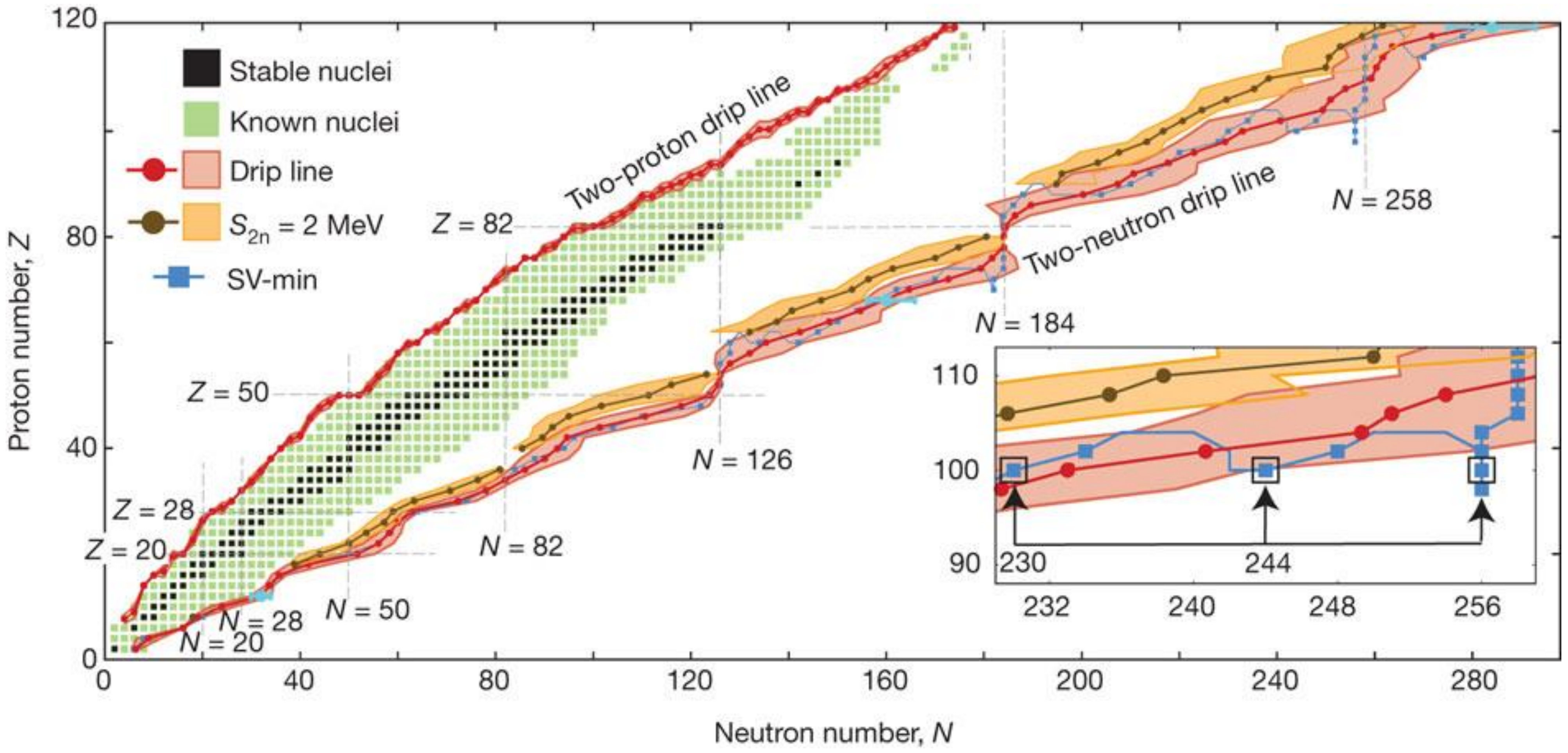
Can also look at multi-nucleon differences:

$$S(2\mathrm{n}) = -M(A,Z) + M(A-2,Z) + 2\mathrm{n}$$

$$S(2\mathrm{p}) = -M(A,Z) + M(A-2,Z-2) + 2\,{}^{1}\mathrm{H}$$



Where are the limits of nuclear existence?



J. Erler et al., Nature 486, 509 (2012)

Hyperfine structure of atoms

Electromagnetic moments of the nucleus (Q,μ) interact with the electromagnetic fields that are produced by the atomic electrons at the location of the nucleus

➔ Hyperfine splitting

$$\Delta E_{HFS} = A\frac{C}{2} + D\frac{\frac{3}{4}C(C+1) - I(I+1)J(J+1)}{2I(2I-1)J(2J-1)}$$

$$\vec{F} = \vec{I} + \vec{J}$$

$$C = F(F+1) - I(I+1) - J(J+1)$$

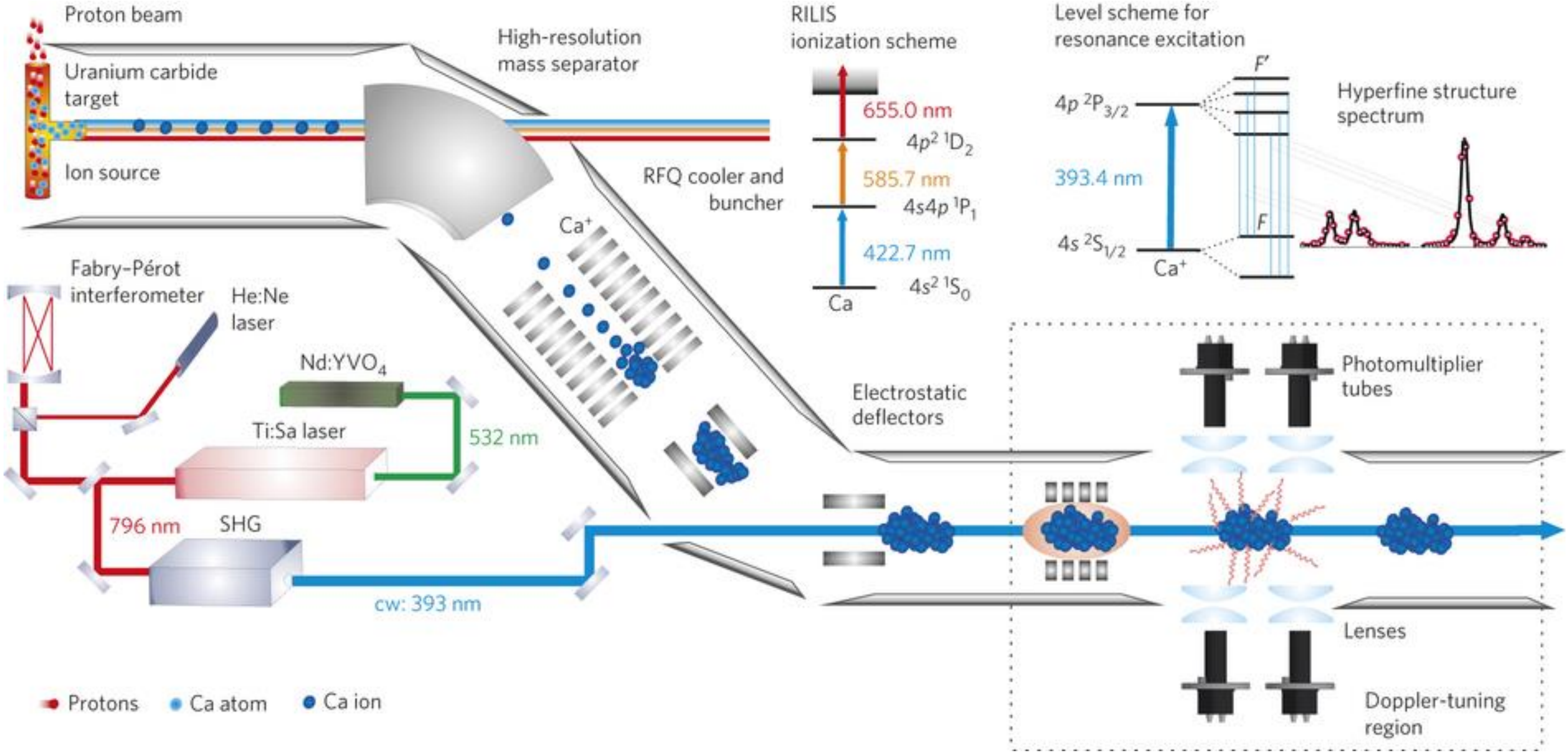
$$A = \frac{\mu_I \overline{B}_{J,0}}{IJ}$$ — Magnetic moment

$$D = eQ_S\left(\frac{\partial^2 V_J}{\partial z^2}\right)_0$$ — Quadrupole moment

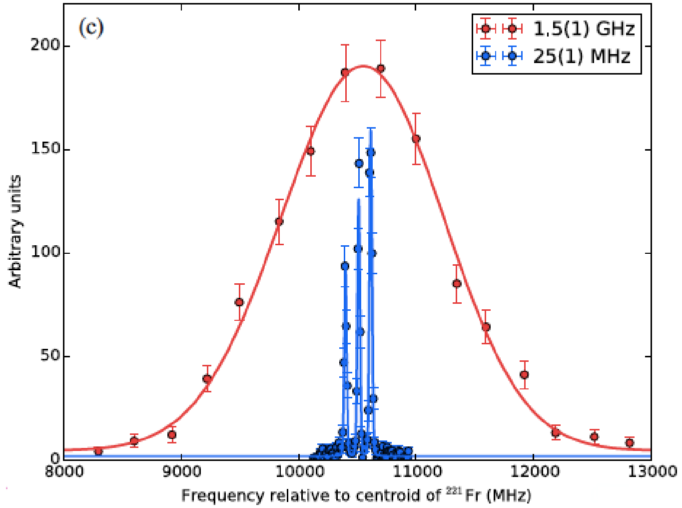
Problem:
to determine μ_I and Q_S from measured quantities A and D, one needs to know the magnetic field and electric field gradient at the location of the nucleus

Co-linear Laser spectroscopy

R.F. Garcia Ruiz et al., Nature Physics (2016)

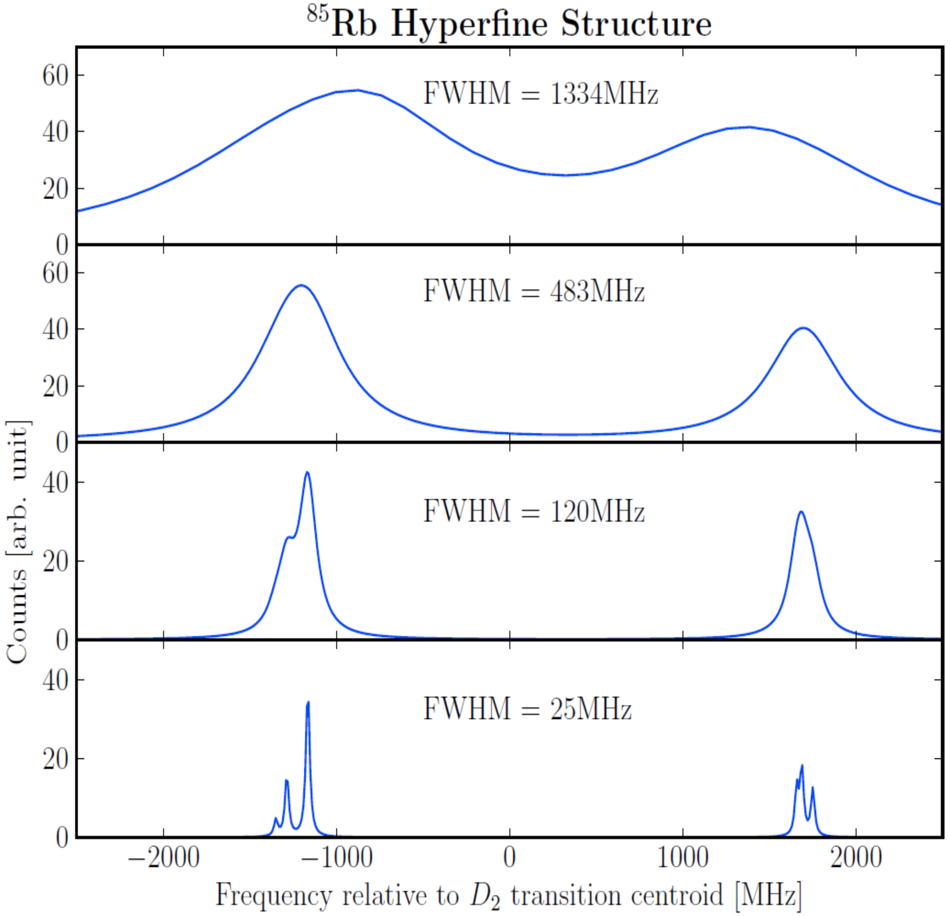


Co-linear Laser spectroscopy



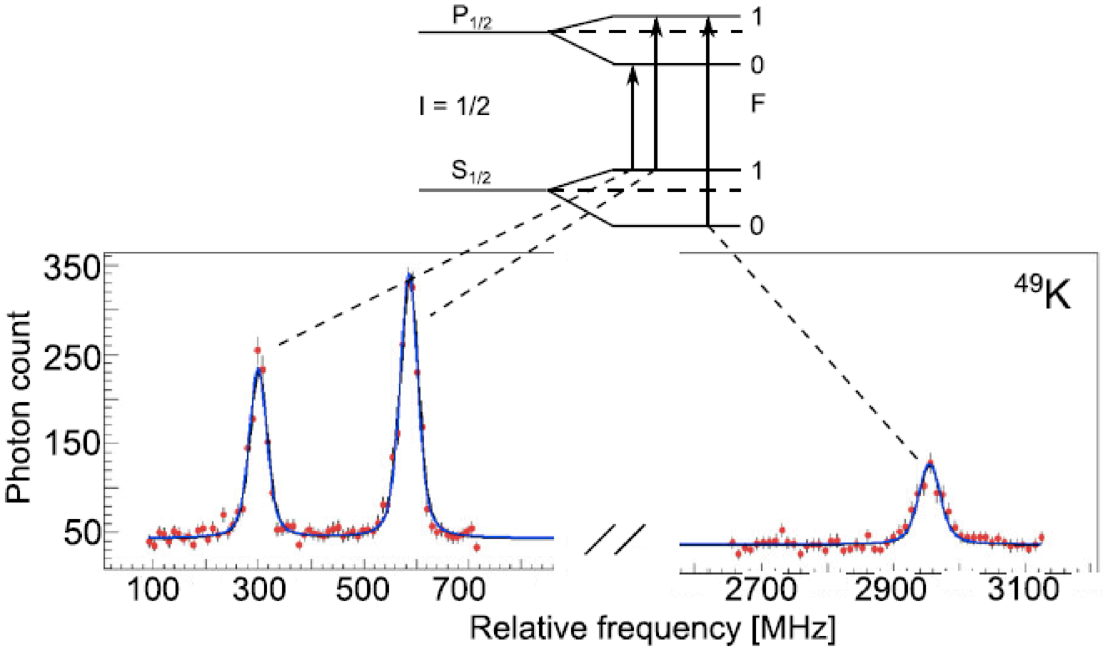
1.5GHz from hot cavity
25MHz from RFQ cooler

Dramatic improvement in resolution due to reduction in energy spread of ions
-> reduction in Doppler-broadening

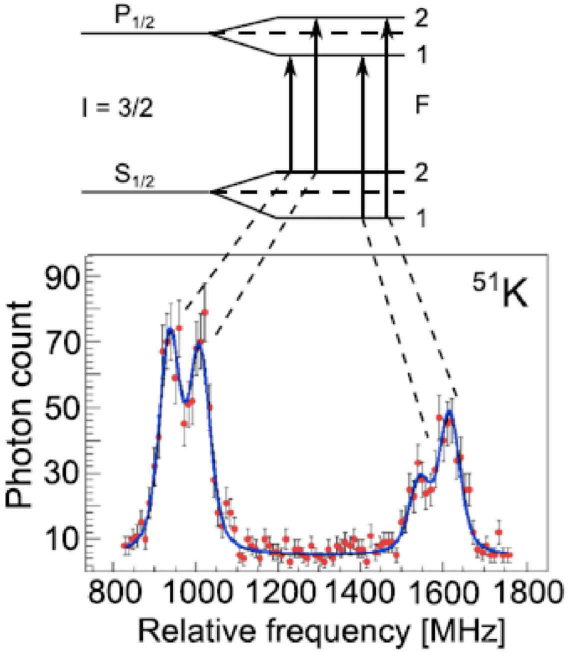


Co-linear Laser spectroscopy

- The nuclear spin can be unambiguously determined from the number of HF components (relative spacings and intensities)
- Selection rules obeyed, ΔF=0, ±1, F=0 → F=0 forbidden



Only 3 transitions allowed (no F=0 → F=0)



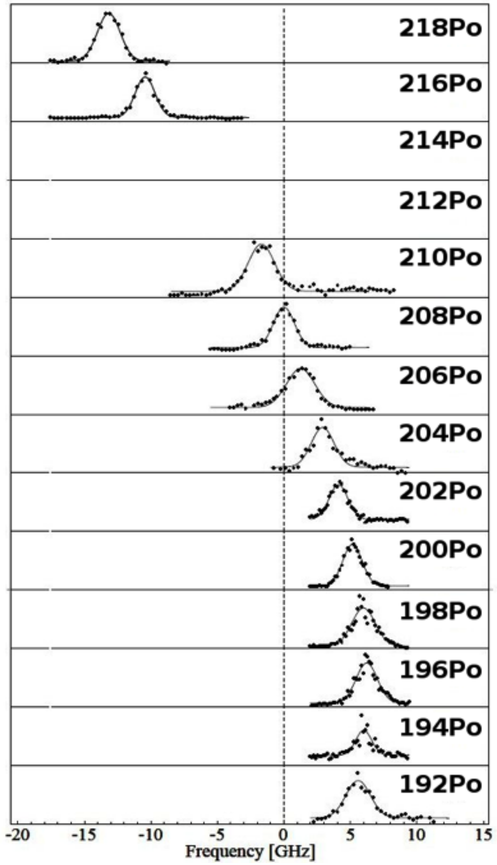
J. Papuga *et al*., PRL **110,** 172503 (2013).

Co-linear Laser spectroscopy

Isotope shift of atomic transitions between two nuclei with mass numbers A, A’

$$\delta v_{IS}^{AA'} = \delta v_{MS}^{AA'} + \delta v_{FS}^{AA'}$$

Shift of electron levels (strongest for s-electrons)



T.E. Cocolios *et al.*, PRL 106, 052503 (2011).

MS: “mass shift“ :

- Reduced masses are different for atoms with A and A’ nucleons

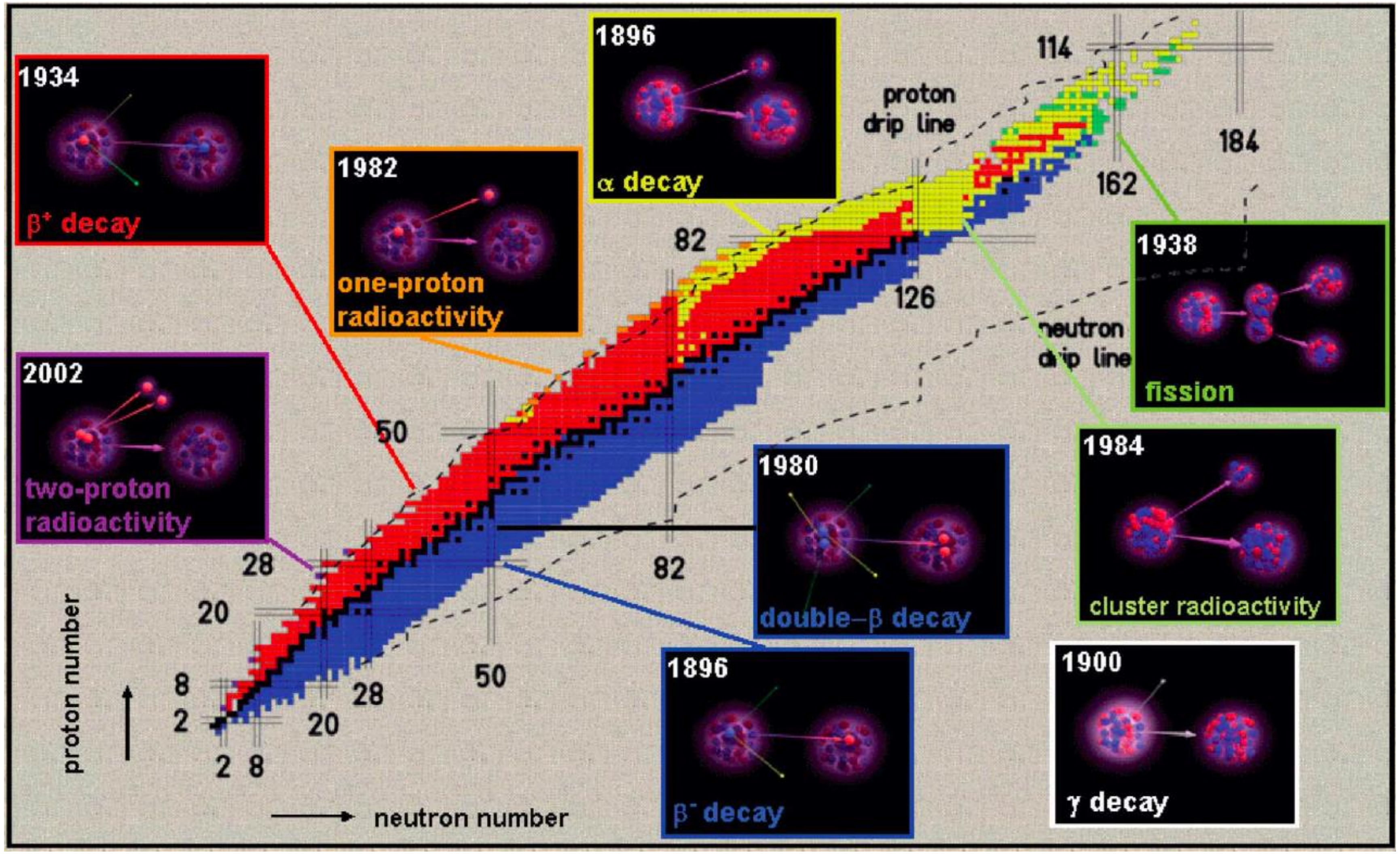
FS: “field shift“:

- Finite-sized nucleus modifies the potential and perturbs electron wavefunction

$$\delta v_{FS}^{AA'} \sim \delta\langle r^2\rangle^{AA'}$$

Decay modes

B. Blank, Nuclear Physics News 19, 14 (2009)



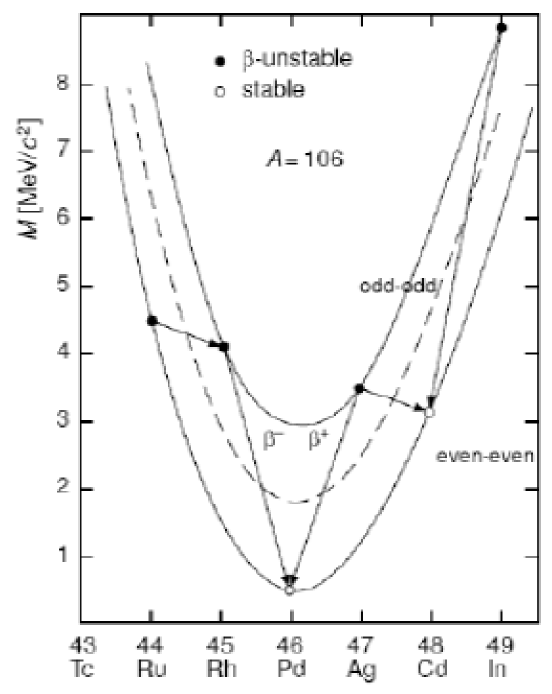
Beta transitions between nuclei

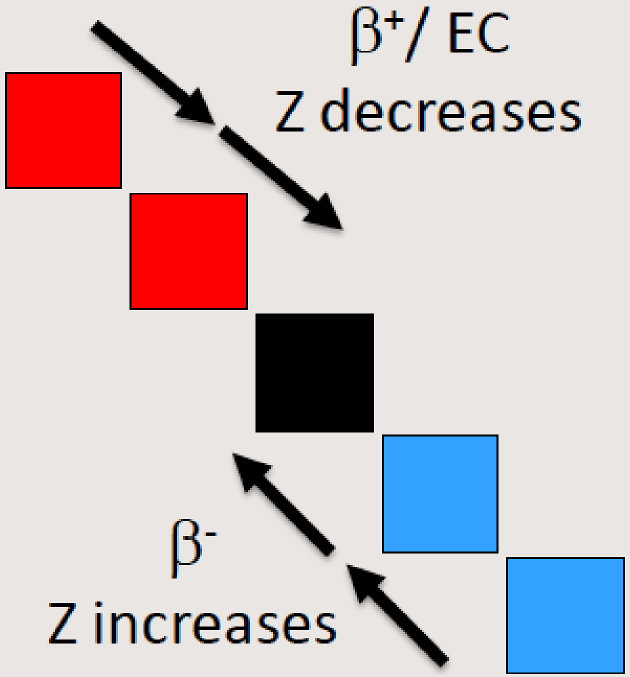
Mass parabola

$$m(Z, A) = x_1 \cdot Z + x_2 \cdot Z^2 + x_3 \cdot A \pm \delta,$$

ν needed for

- energy conservation
- (charge conservation)
- angular momentum cons.
- (mass conservation)





β⁻ - decay $\quad {}^{A}_{Z}X_N \longrightarrow {}^{A}_{Z+1}X^*_{N-1} + e^- + \bar{\nu}_e$

β⁺ - decay $\quad {}^{A}_{Z}X_N \longrightarrow {}^{A}_{Z-1}X^*_{N+1} + e^+ + \nu_e$ $\quad$ **ΔE> 1.022 MeV**

(Orbital) Electron capture $\quad {}^{A}_{Z}X_N + e^- \longrightarrow {}^{A}_{Z-1}X^*_{N+1} + \nu_e + \text{X-ray.}$ $\quad$ **ΔE< 1.022 MeV**

Half lives

Make use of the exponential decay law

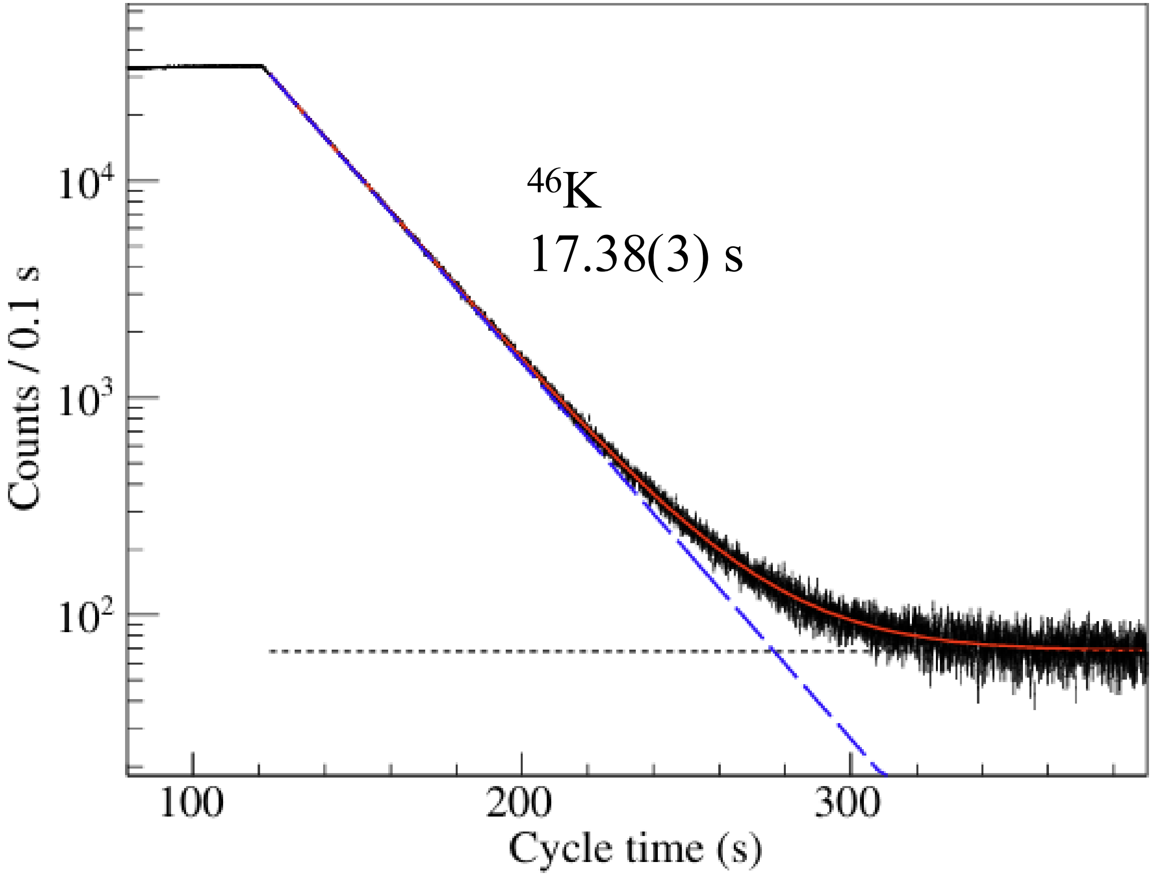
Measure the change in activity as a function of time to find the decay constant, $\boldsymbol{\lambda}$.

$$A_t = A_0 e^{-\lambda t}$$

Convert the decay constant to half life:

$$T_{1/2} = \frac{\ln(2)}{\lambda}$$

Can be measured using beta particles.
Using gamma rays can isolate a specific species.



J. Pore *et al.*, Phys. Rev. C 100, 054327 (2019)

Beta transitions between nuclei

$$T_{fi} = \frac{\ln 2}{t_{1/2}} = \frac{\ln 2 G_F^2 V_{ud}^2}{\kappa} \cdot f(Z, \varepsilon_0) \cdot |M_{fi}|^2$$

Matrix element

Fermi function

$$B = |M_{fi}|^2$$

$$B = \frac{\kappa}{G_F^2 V_{ud}^2 f t}$$

$$\kappa = 2\pi^3 \ln 2\hbar^7 / m_e^5 c^4$$

$G_F = 1.166364(5) \cdot 10^{-5} (\hbar c)^3\, GeV^{-2}$ fundamental weak interaction constant

$|V_{ud}| = 0.97367 \pm 0.00032$ coupling of up-down quarks during weak interaction

Spin for e and ν: s= 1/2
- spins parallel: S= 1 "Gamow-Teller decay"
- spins anti-parallel: S=0 "Fermi-decays"

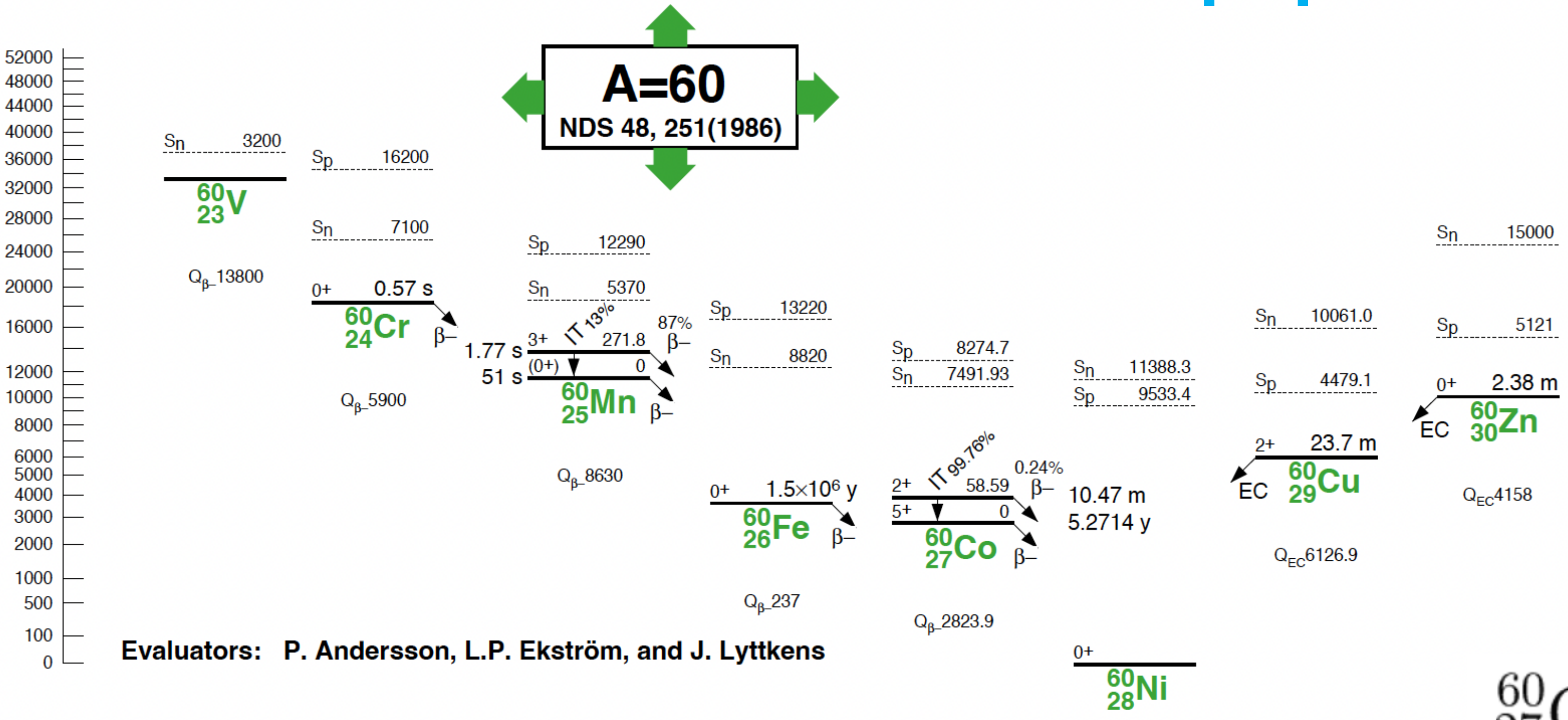
		Fermi		GT	
Type	L	ΔI	Δπ	ΔI	Δπ
Allowed	0	0	No	(0), 1	No
First Forbidden	1	(0),1	Yes	0,1,2	Yes
Second Forbidden	2	(1),2	No	2,3	No
Third Forbidden	3	(2),3	Yes	3,4	Yes
Fourth Forbidden	4	(3),4	No	4,5	No

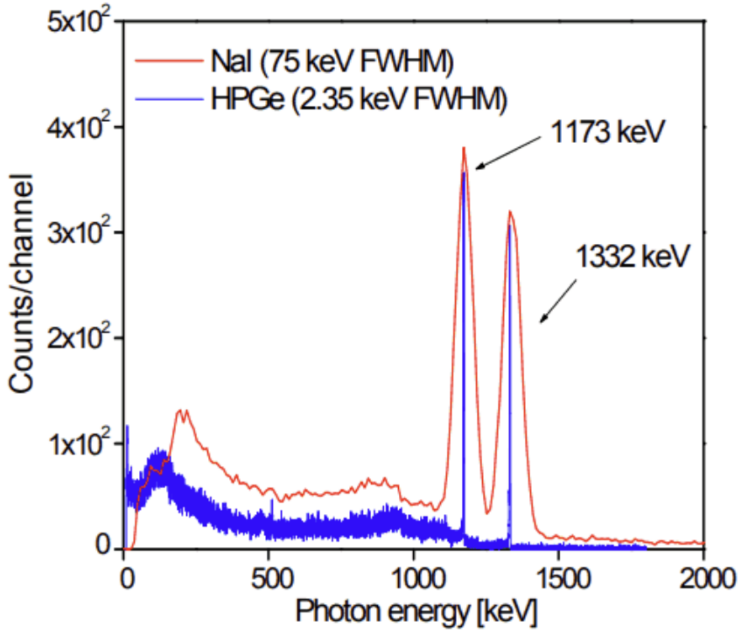
$$ft = f(Z, \varepsilon_0) \cdot t_{1/2}$$

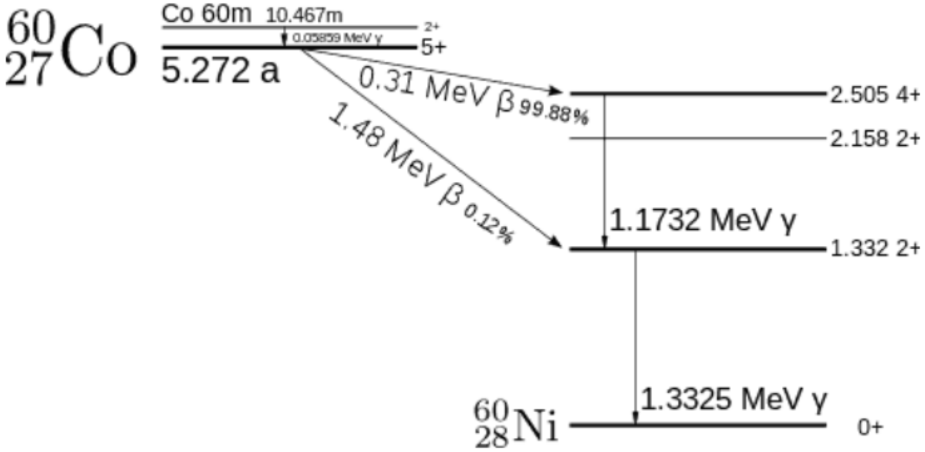
longer $t_{1/2}$

- super-allowed: log ft ≈ 3.5
- allowed: log ft ≈ 4-7
- first forbidden: log ft ≈ 6-9
- second forbidden: log ft ≈ 10-13
- third forbidden: log ft ≈ 14-20
- fourth forbidden: log ft ≈ 23

Excited states can be populated in beta decay





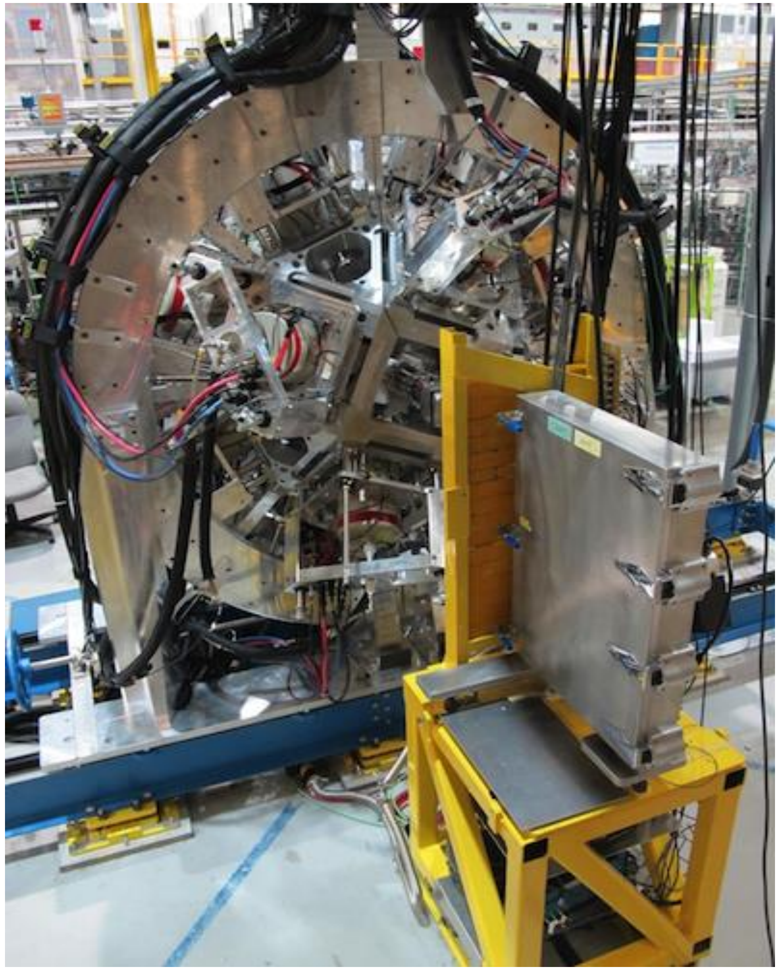


$\beta^- : \quad n \longrightarrow p + e^- + \bar{\nu}_e,$

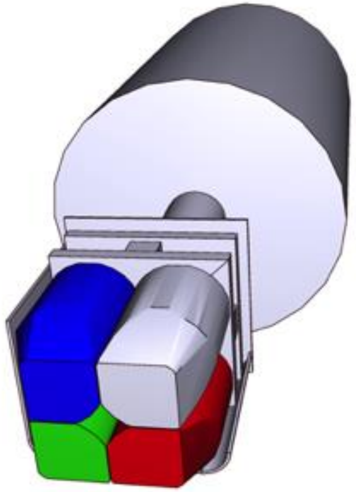
$\beta^+ : \quad p \longrightarrow n + e^+ + \nu_e$

$\mathrm{EC} : \quad p + e^- \longrightarrow n + \nu_e$

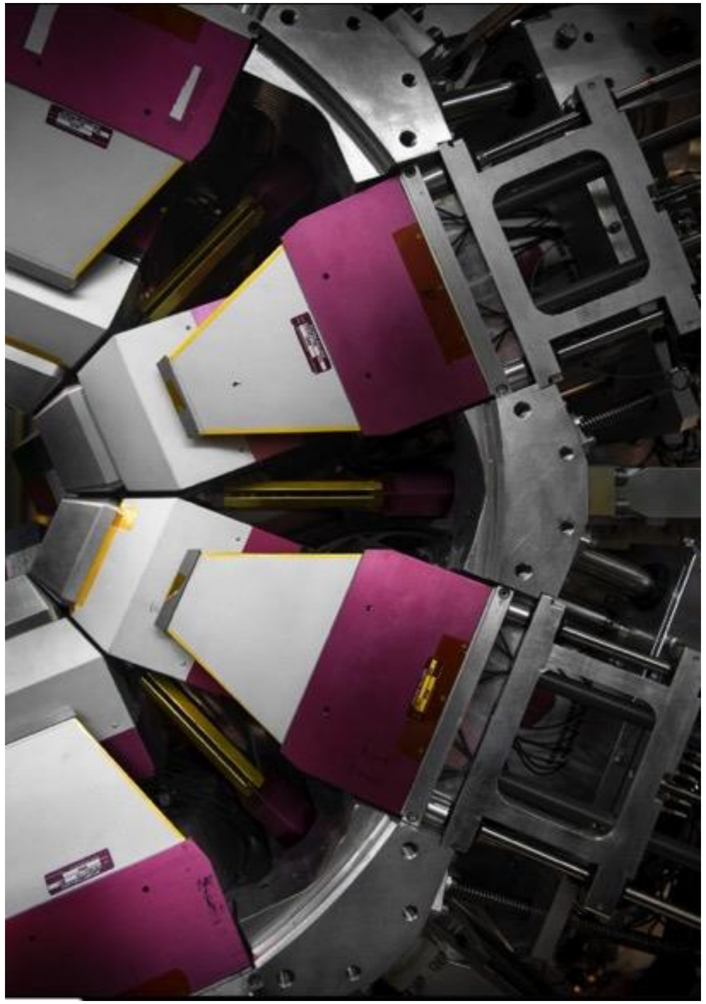
Gamma-Ray Spectrometers at ISAC



GRIFFIN used with stopped RIBs

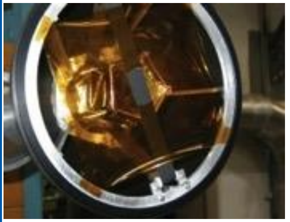


HPGe clover

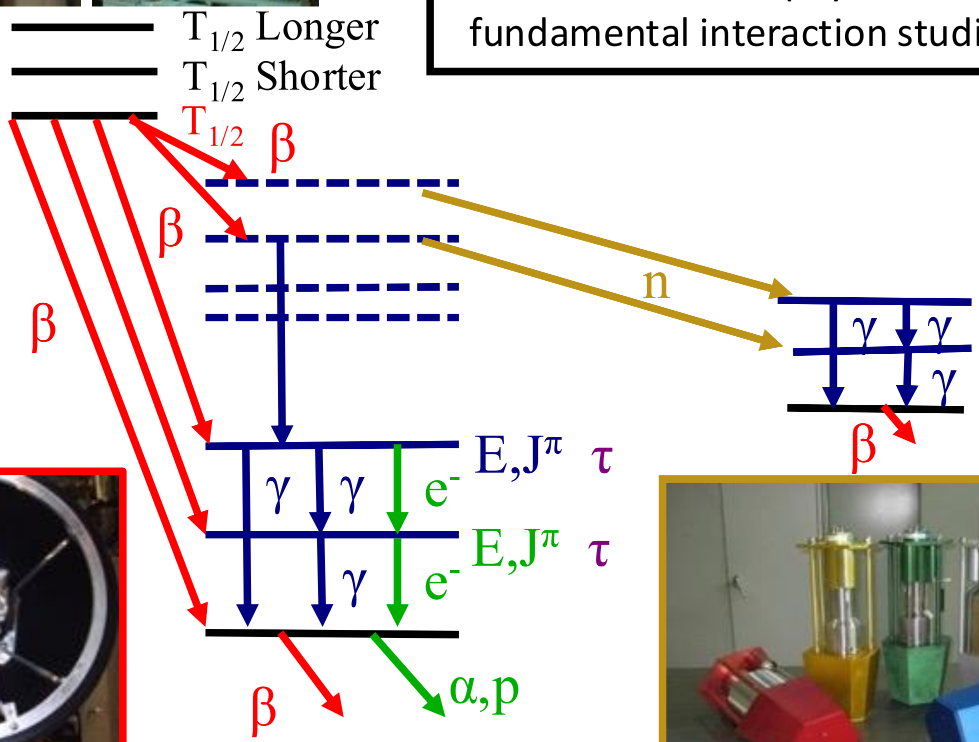


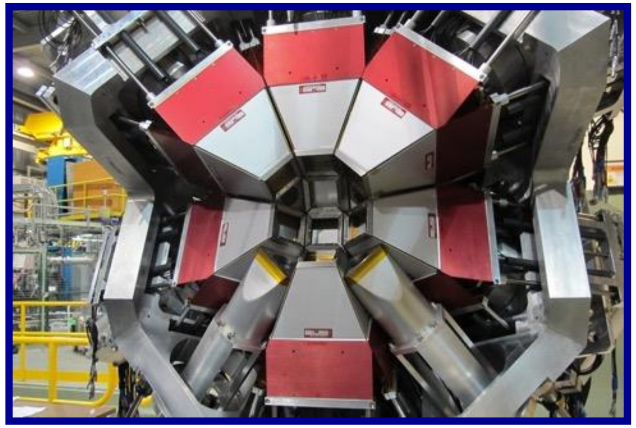
TIGRESS used with accelerated RIBs

The GRIFFIN Spectrometer for precision decay studies at ISAC



GRIFFIN is a powerful decay spectrometer for nuclear structure, astrophysics and fundamental interaction studies.





HPGe: 16 Compton-suppressed Clovers

LaBr$_3$: 8 Compton-suppressed LaBr$_3$

PACES: 5 Cooled Si(Li)s

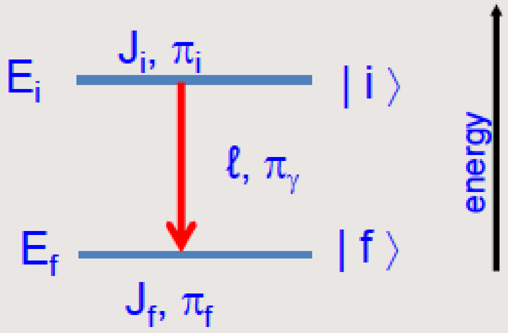
SCEPTAR: 10+10 plastic scintillators

DESCANT Neutron array

Zero-Degree Fast scintillator

Gamma transitions between excited states

- Electromagnetic transition between states $| i \rangle$, $| f \rangle$
- Conserved quantities:
  - Energy: $E_f = E_i - h\omega$
  - Angular momentum: $J_f = J_i + \ell$
  - Parity: $\pi_f = \pi_i \cdot \pi_\gamma$



- Emitted photon:
  min. intrinsic spin $\ell = | J_f - J_i |$
  max. intrinsic spin $\ell = J_f + J_i$

$$|J_f - J_i| \leq \ell \leq J_f + J_i$$

- "Multipole order": quantification of the amount of angular momentum carried by the photon ("2^ℓ –pole photon")
  - $\ell = 1$ ⇨ dipole photon
  - $\ell = 2$ ⇨ quadrupole photon
  - $\ell = 3$ ⇨ octupole photon
  - $\ell = 4$ ⇨ hexadecapole photon
- Distinguish between electric and magnetic radiation:
  Oscillating charge distribution → electric radiation (E)
  Oscillating current distribution → magnetic radiation (M)

Gamma-rays possess several observable properties which can be used to reveal properties of the nucleus.

- Energy
- Intensity
- Coincidence relations
- Spatial direction
- Degree of polarization

Gamma-rays possess several observable properties which can be used to reveal properties of the nucleus.

- Energy (level spacing)
- Intensity
- Coincidence relations
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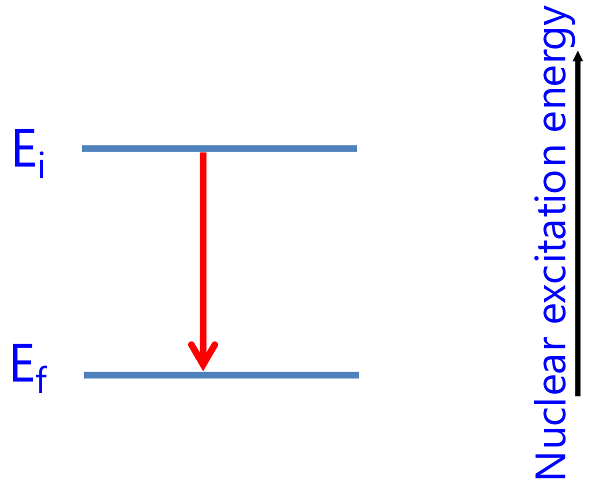
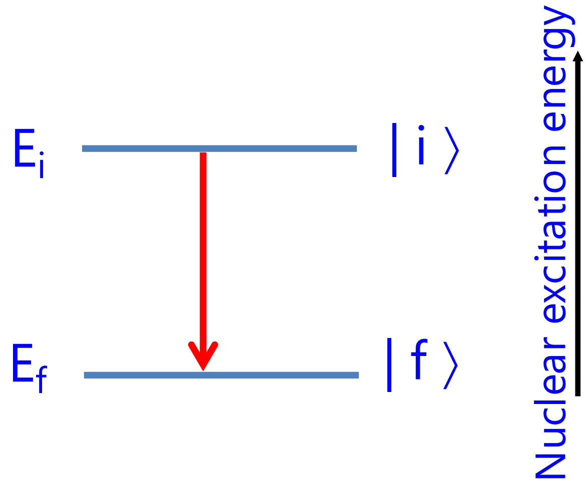


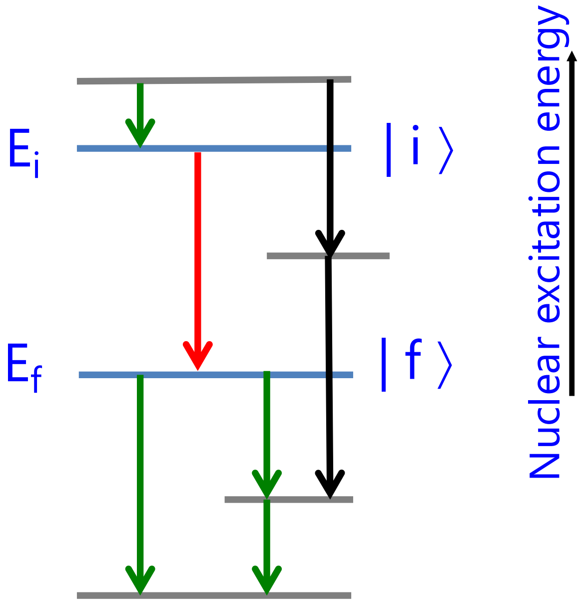
Gamma-rays possess several observable properties which can be used to reveal properties of the nucleus.

- Energy (level spacing)
- Intensity (transition strength)
- Coincidence relations
- Spatial direction
- Degree of polarization



Gamma-rays possess several observable properties which can be used to reveal properties of the nucleus.

- Energy (level spacing)
- Intensity (transition strength)
- Coincidence relations (level scheme)
- Spatial direction
- Degree of polarization



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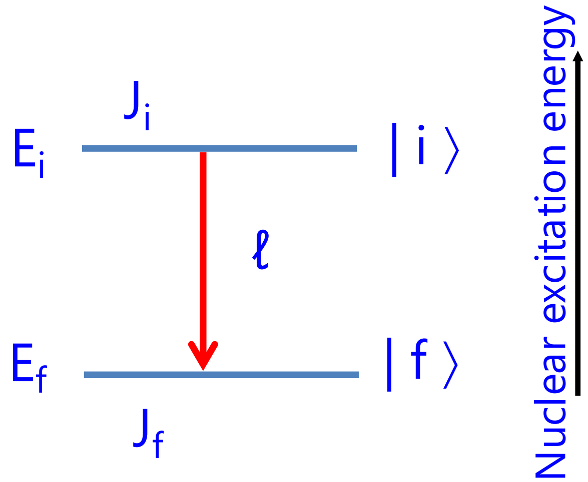
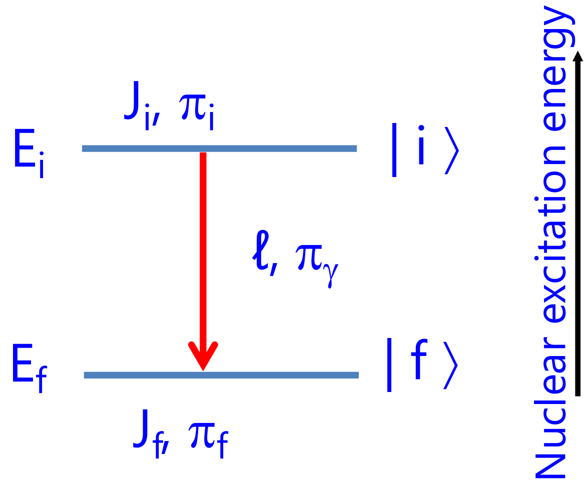
- Coincidence relations (level scheme)
- Spatial direction (angular momentum)
- Degree of polarization



Gamma-rays possess several observable properties which can be used to reveal properties of the nucleus.

- Energy (level spacing)
- Intensity (transition strength)
- Coincidence relations (level scheme)
- Spatial direction (angular momentum)
- Degree of polarization (parity)

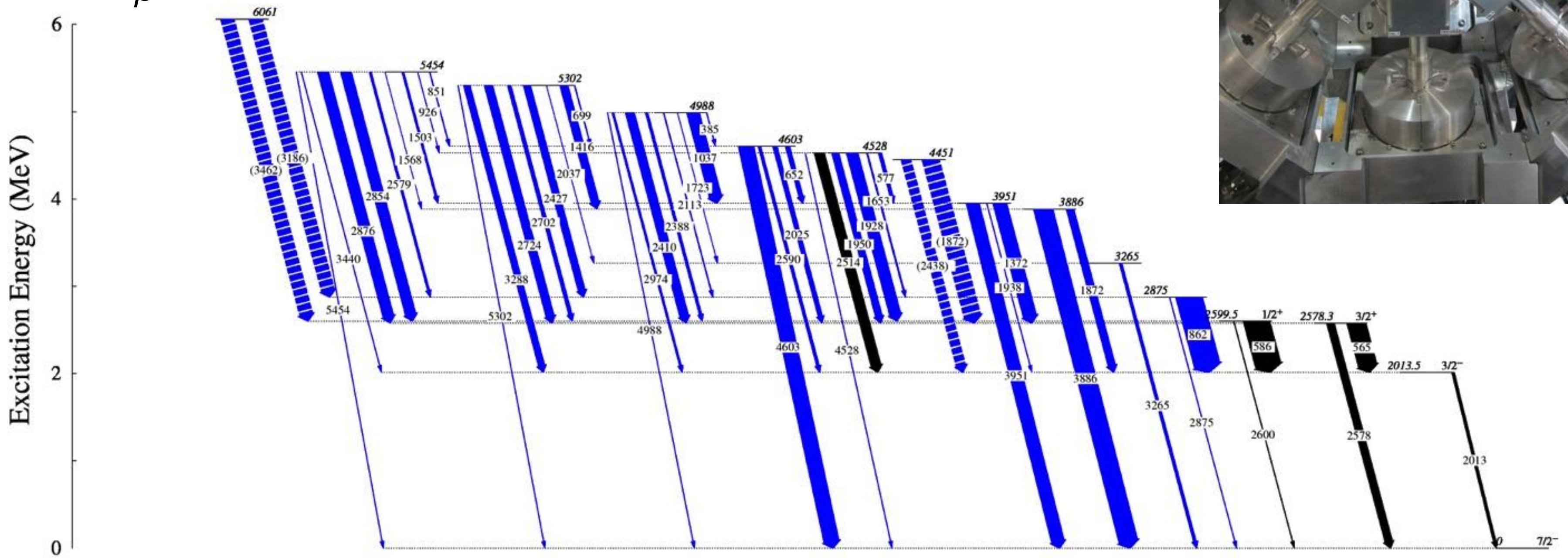


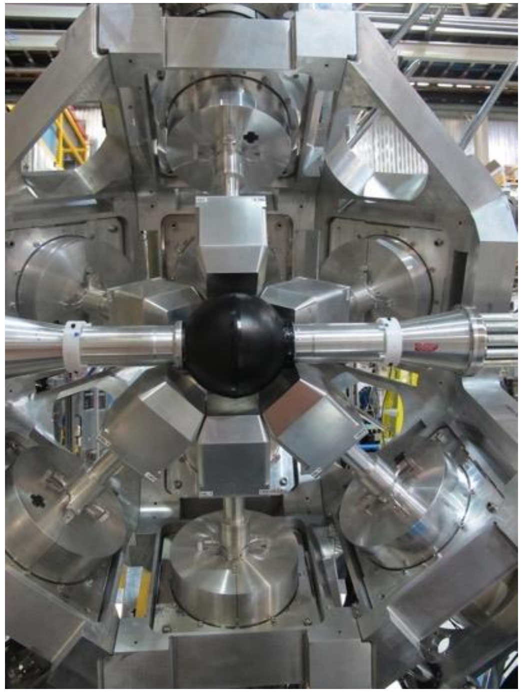
Beta decay from ^{47}K to ^{47}Ca at GRIFFIN

^{47}K GS 1/2+, ^{47}Ca GS 7/2- = 3rd Forbidden beta decay

So decays all proceed to excited states

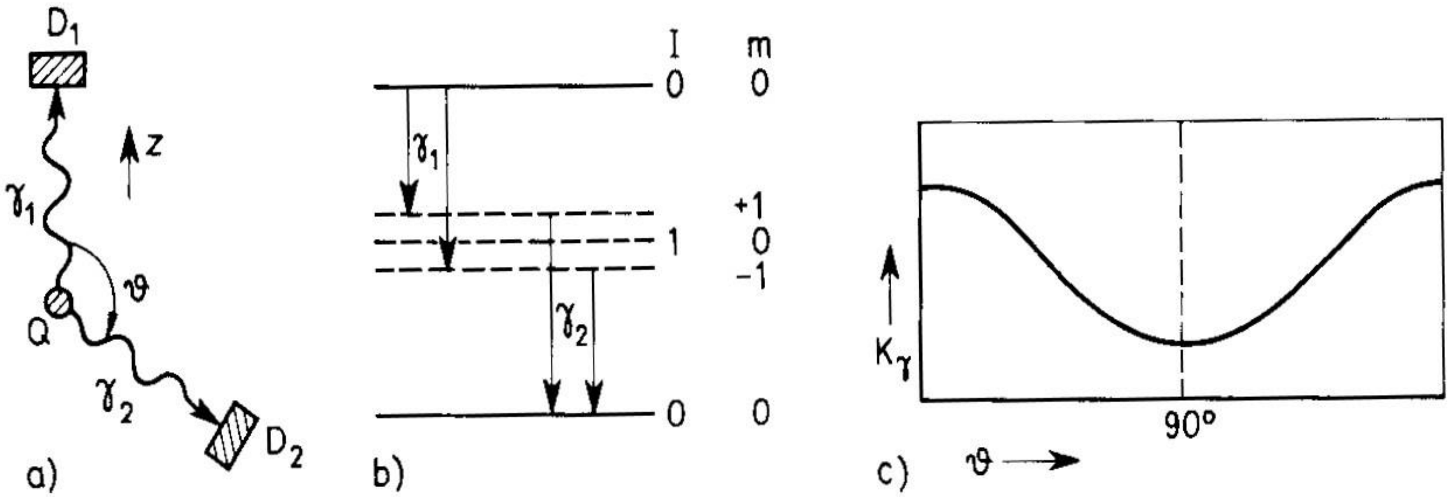
Q_β=6643keV





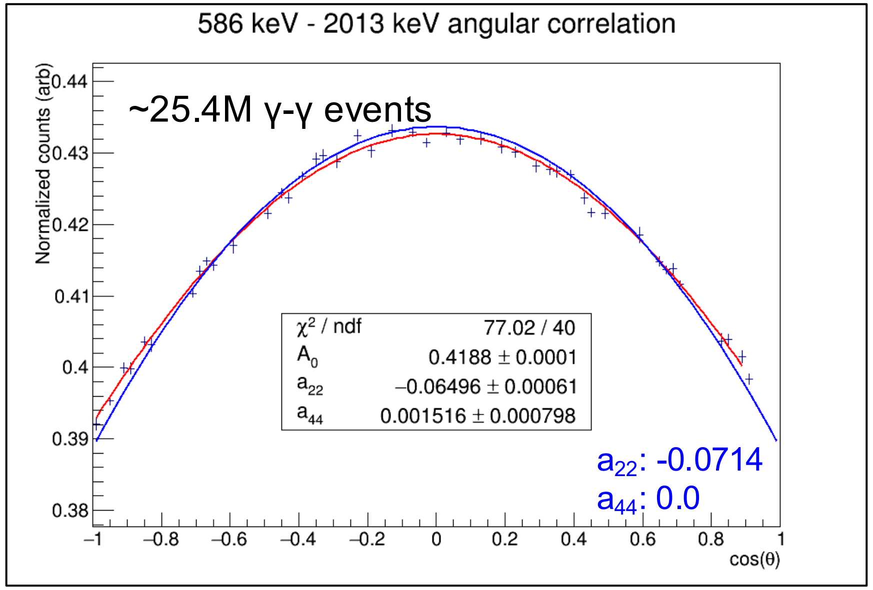
Gamma-angular correlations

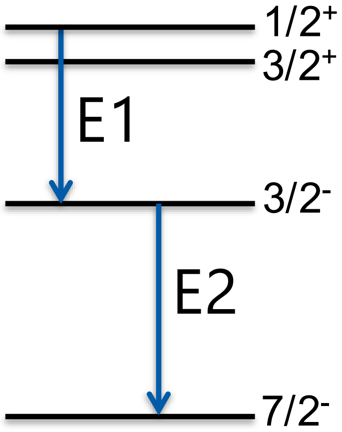
Population of a state by a gamma-transition (defines z-axis)
➔ uneven population of m-substates with respect to this axis
➔ angular distribution of decay gamma
➔ Measure both photons in coincidence
➔ Angular correlation



$$W(\theta) = 1 + A_2 P_2(\cos\theta) + A_4 P_4(\cos\theta)$$

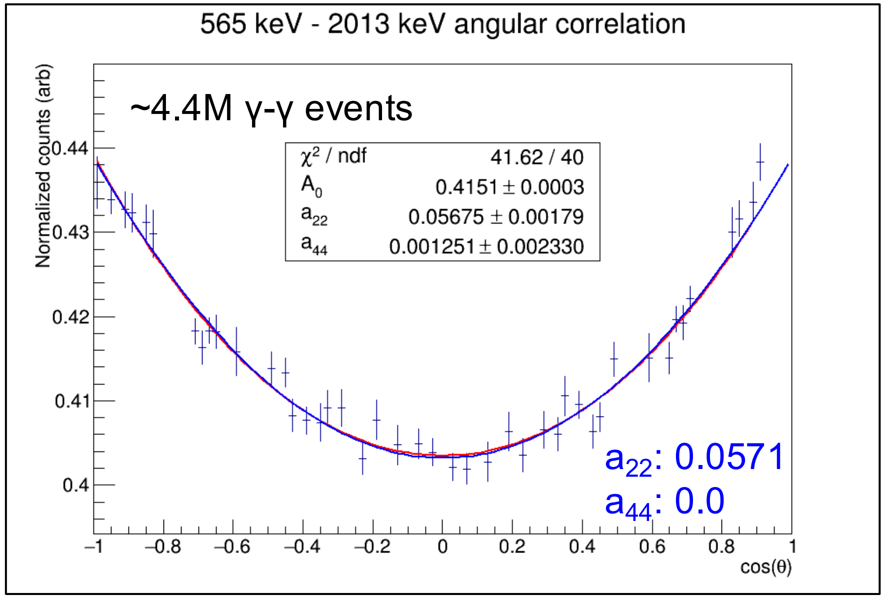
^{47}K to ^{47}Ca: angular correlations

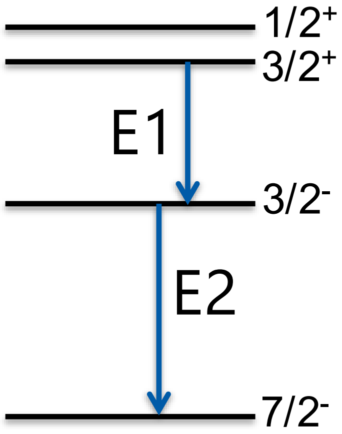




1/2+ ➔ 3/2- ➔ 7/2-

a_{22}: -0.0714, a_{44}: 0.0

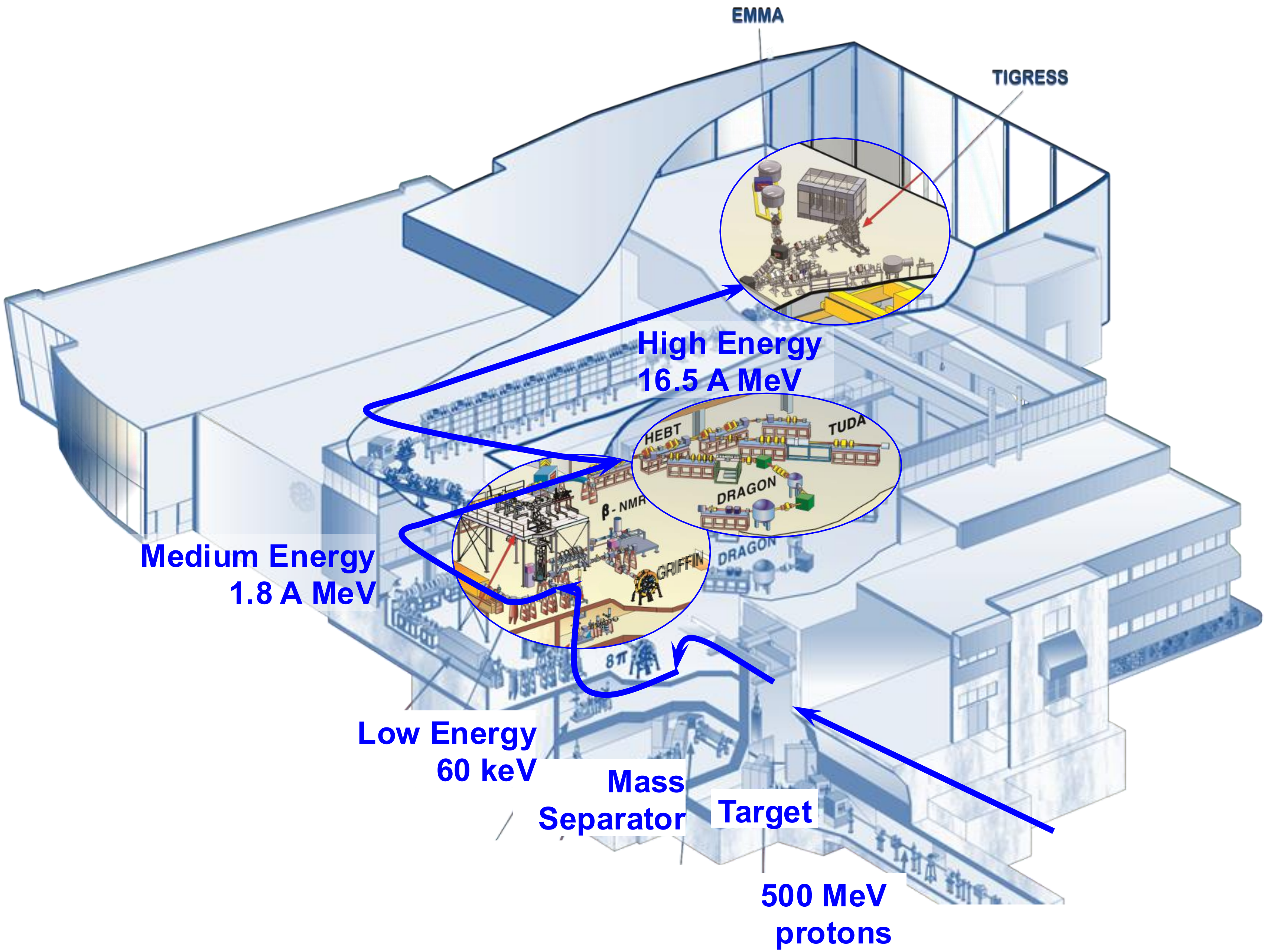




3/2+ ➔ 3/2- ➔ 7/2-

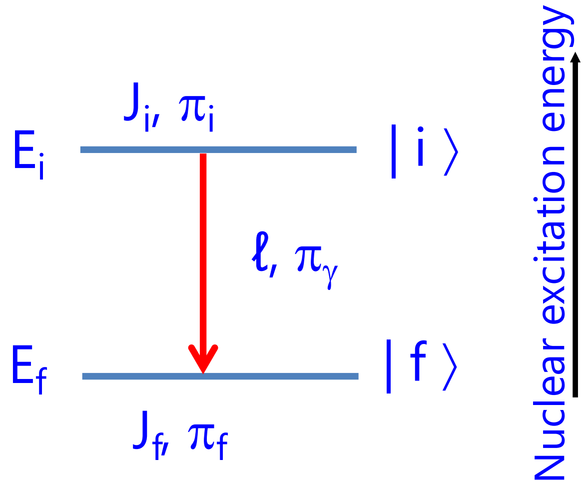
a_{22}: +0.0571, a_{44}: 0.0

ISAC-TRIUMF ISOL facility for rare isotope beams

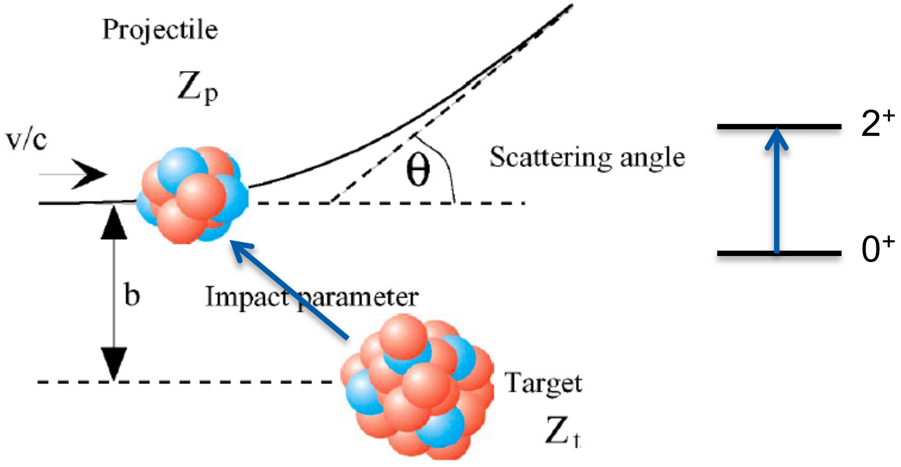


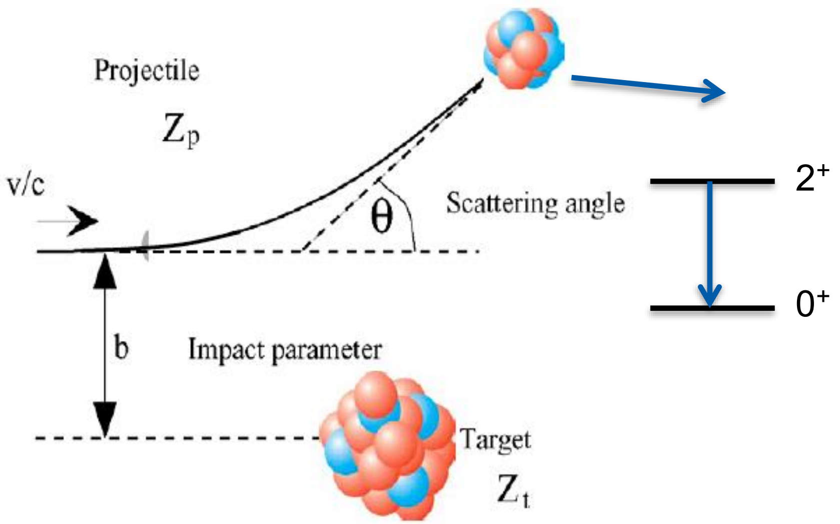
What questions can we ask about nuclei?

- How heavy is it?
  - Mass spectroscopy
- How big is it?
  - Laser spectroscopy of Hyperfine structure
- How long does it survive?
  - Decay spectroscopy
- What shape is it?
  - Coulomb excitation
- How are excitations created
  - Gamma-ray spectroscopy



Low-Energy Coulomb Excitation





Exchange of virtual photons mediates excitation

Beam energies at the Coulomb barrier (SPIRAL, ISAC-II, CARIBU, Hie-ISOLDE):
E_x, $B(\sigma\lambda)$ excitation strength, band structures ($0^+ \rightarrow 2^+ \rightarrow 4^+ \rightarrow 6^+$)

Beam energies well below the Coulomb barrier (ISOLDE, HRIBF):
Usually only the first 2^+ state accessible

Measure de-excitation γ-rays

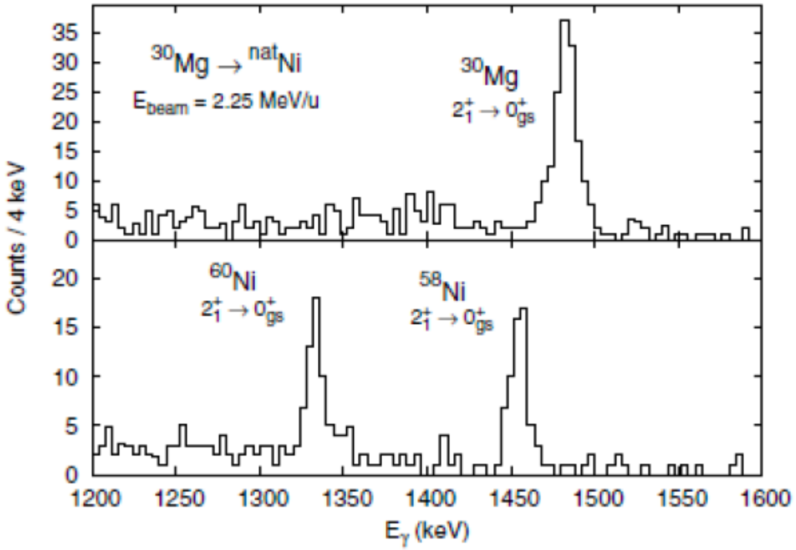
$$V_C(MeV) = \frac{1.44 \times Z_1 \times Z_2}{r(fm)}$$

$$r(fm) \sim 1.2(A_1^{1/3} + A_2^{1/3})$$

A. Goergen, J. Phys. G 37, 103101 (2010)
D. Cline, Annu. Rev. Part. Sci. 36, 683 (1986)

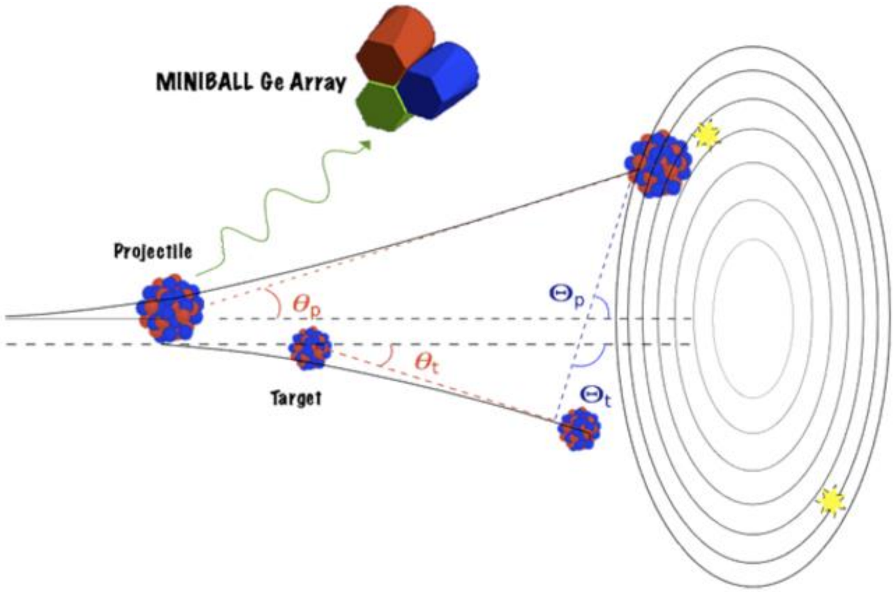
Low-Energy Coulomb Excitation

O. Niedermaier *et al.*, PRL 94, 172501 (2005)



^{30}Mg at 2.25 MeV/nucleon on natural Ni target (1.0 mg/cm^2)
From REX-ISOLDE at CERN
γ-ray detection with MINIBALL.
Particle detection with CD-shaped double-sided Si strip detector

$$\frac{\sigma_{\mathrm{CE}}(^{30}\mathrm{Mg})}{\sigma_{\mathrm{CE}}(^{58,60}\mathrm{Ni})} = \frac{\epsilon_\gamma(^{58,60}\mathrm{Ni})}{\epsilon_\gamma(^{30}\mathrm{Mg})} \frac{W_\gamma(^{58,60}\mathrm{Ni})}{W_\gamma(^{30}\mathrm{Mg})} \frac{N_\gamma(^{30}\mathrm{Mg})}{N_\gamma(^{58,60}\mathrm{Ni})},$$



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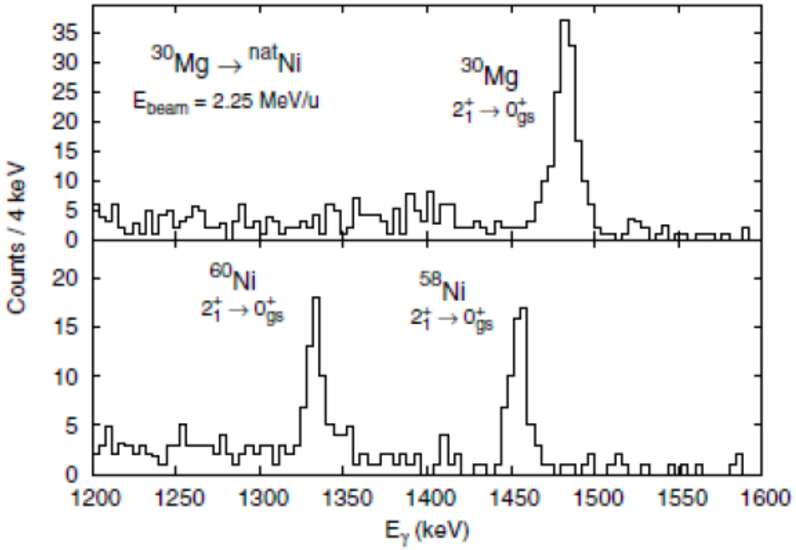
O. Niedermaier *et al.*, PRL 94, 172501 (2005)



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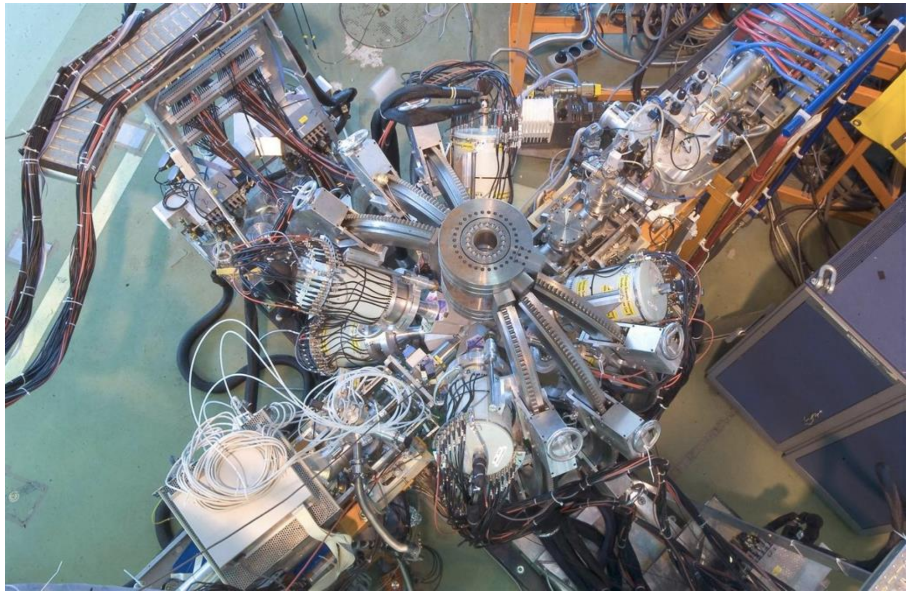
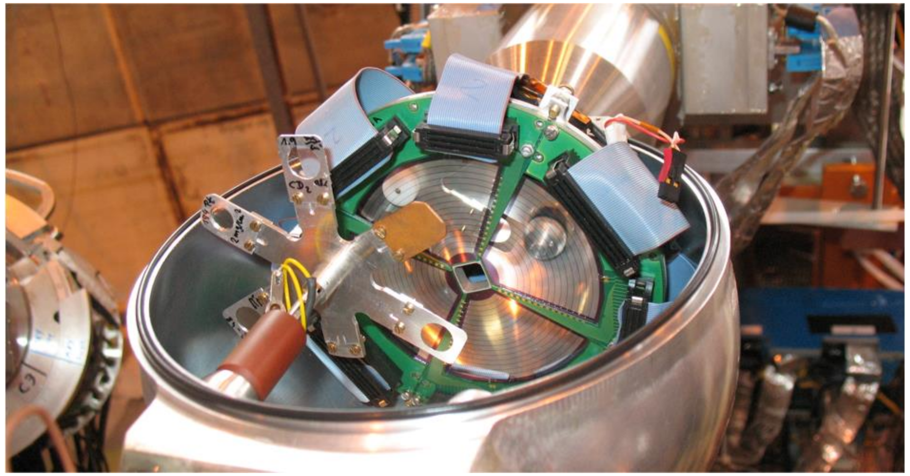
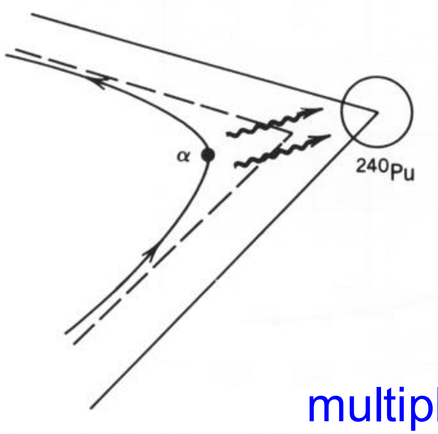
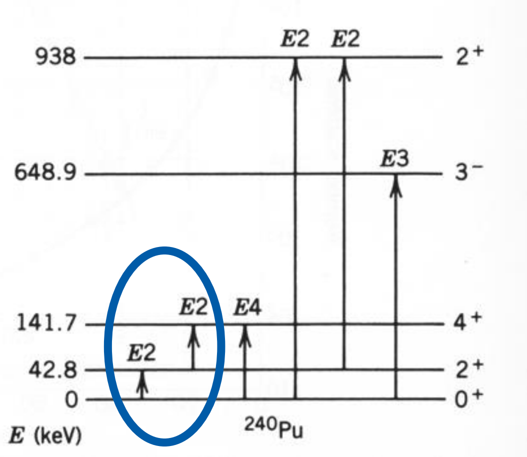




Low-Energy Coulomb Excitation





Small velocities β:
- mainly excitation via E2, E3 and E4
- magnetic excitations can be neglected

Nuclear structure

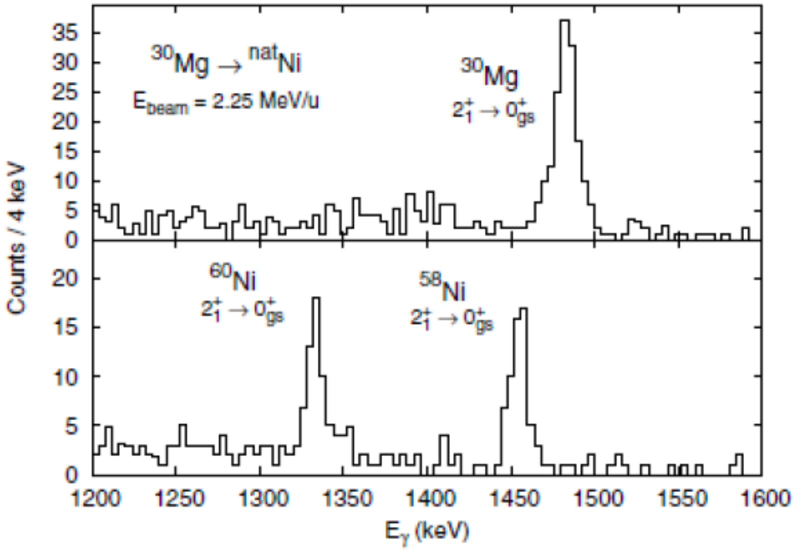
$$\left(\frac{d\sigma}{d\Omega}\right)_{CLX} = \frac{4\pi^2 Z_P^2 e^2}{\hbar^2 \sin^4(\theta_{CM}/2)} \sum_{\ell=1}^{\infty} \frac{B(E\ell)}{(2\ell+1)^3} \sum_{\mu=-\ell}^{\ell} \left|S(E\ell,\mu)\right|^2$$

Determine matrix elements from measurements of Coulomb excitation cross-section!!

- spectroscopy of scattered particles (light projectile)
- spectroscopy of gamma-rays from decay of excited states

Low-Energy Coulomb Excitation

O. Niedermaier *et al.*, PRL 94, 172501 (2005)



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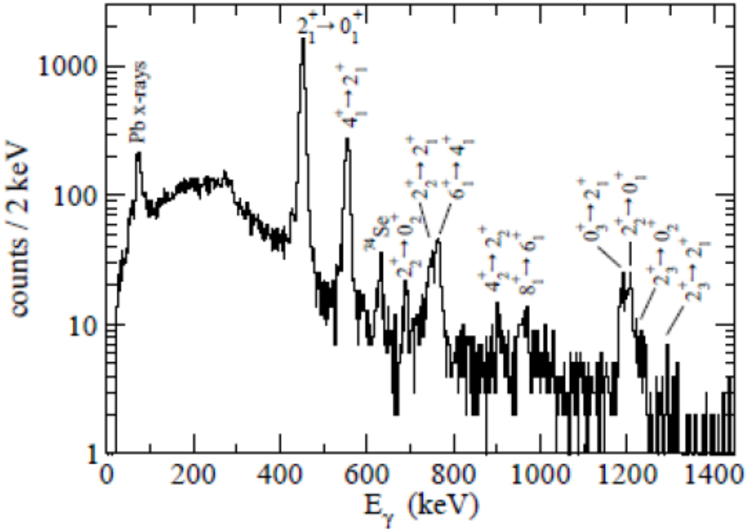
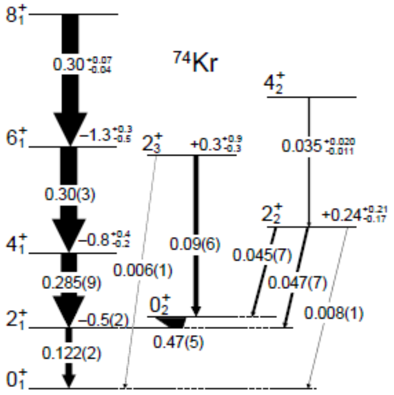
Particle detection with CD-shaped double-sided Si strip detector

$$\frac{\sigma_{CE}(^{30}\mathrm{Mg})}{\sigma_{CE}(^{58,60}\mathrm{Ni})} = \frac{\epsilon_\gamma(^{58,60}\mathrm{Ni})}{\epsilon_\gamma(^{30}\mathrm{Mg})}\,\frac{W_\gamma(^{58,60}\mathrm{Ni})}{W_\gamma(^{30}\mathrm{Mg})}\,\frac{N_\gamma(^{30}\mathrm{Mg})}{N_\gamma(^{58,60}\mathrm{Ni})},$$





^{74}Kr multistep Coulex at 4.7 MeV/u on 1mg/cm^2 ^{208}Pb target at GANIL.
Data analysis done in a χ^2 minimization with a coupled channels code (GOSIA)

E. Clement *et al.*, PRC 75, 054314 (2005)

IRIS + theory determine magnitude of 3N forces.

Selected for a Viewpoint in *Physics*
PRL **118,** 262502 (2017) PHYSICAL REVIEW LETTERS week ending 30 JUNE 2017

Nuclear Force Imprints Revealed on the Elastic Scattering of Protons with ^{10}C

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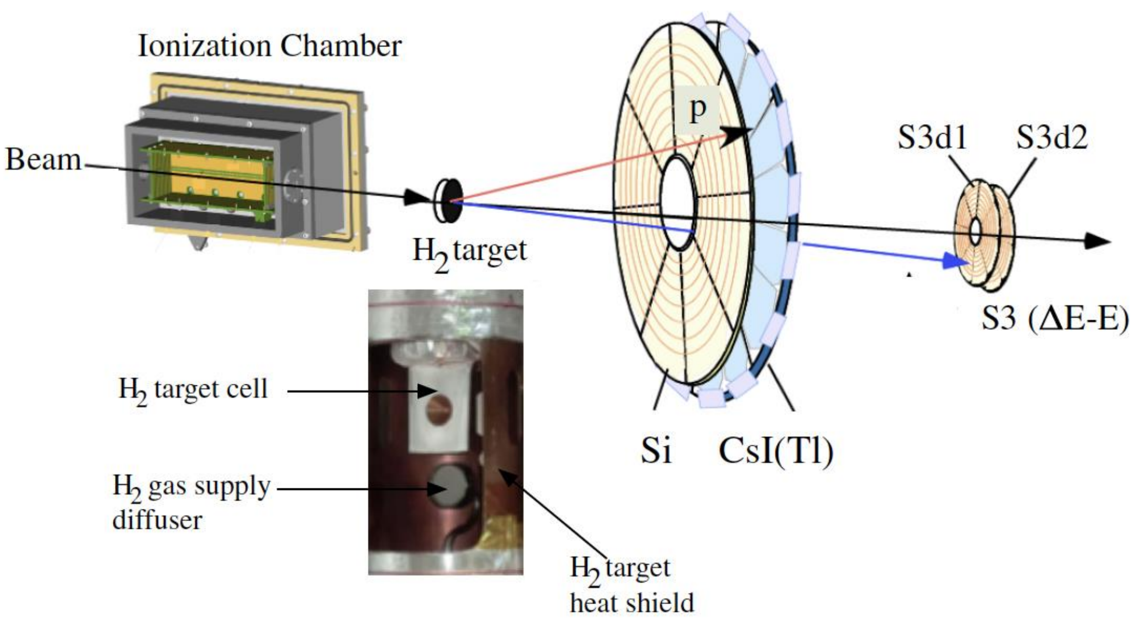

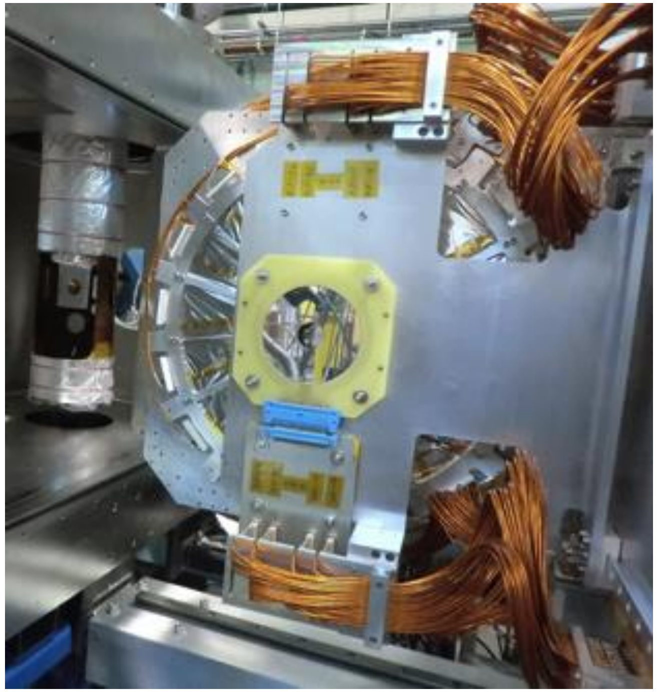

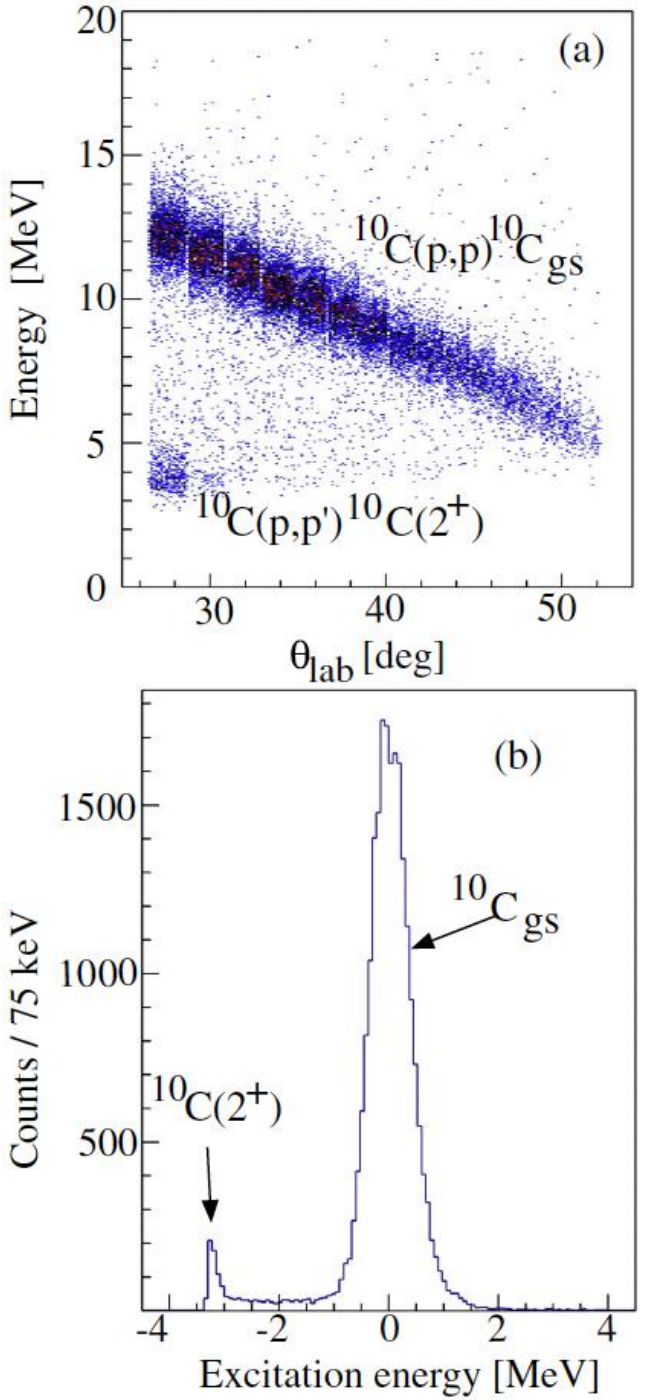

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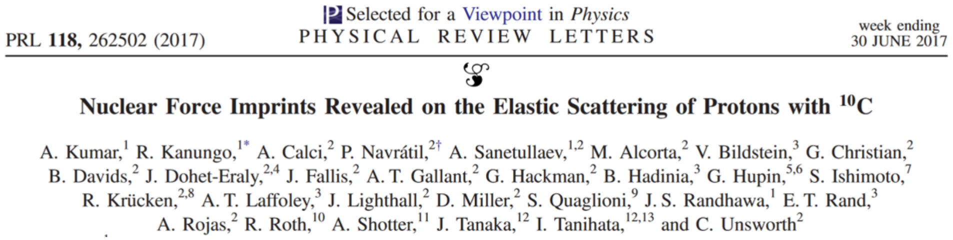
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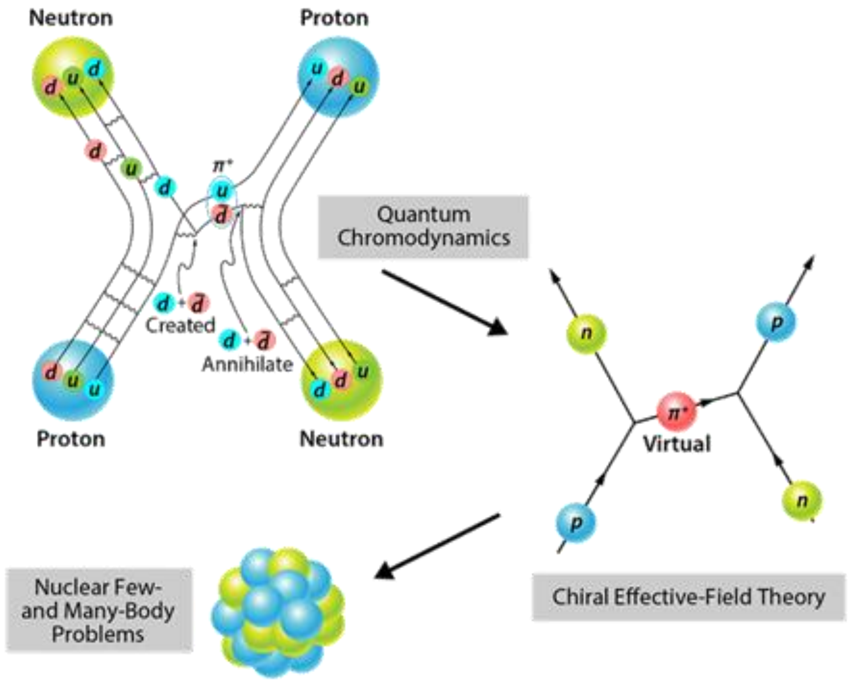
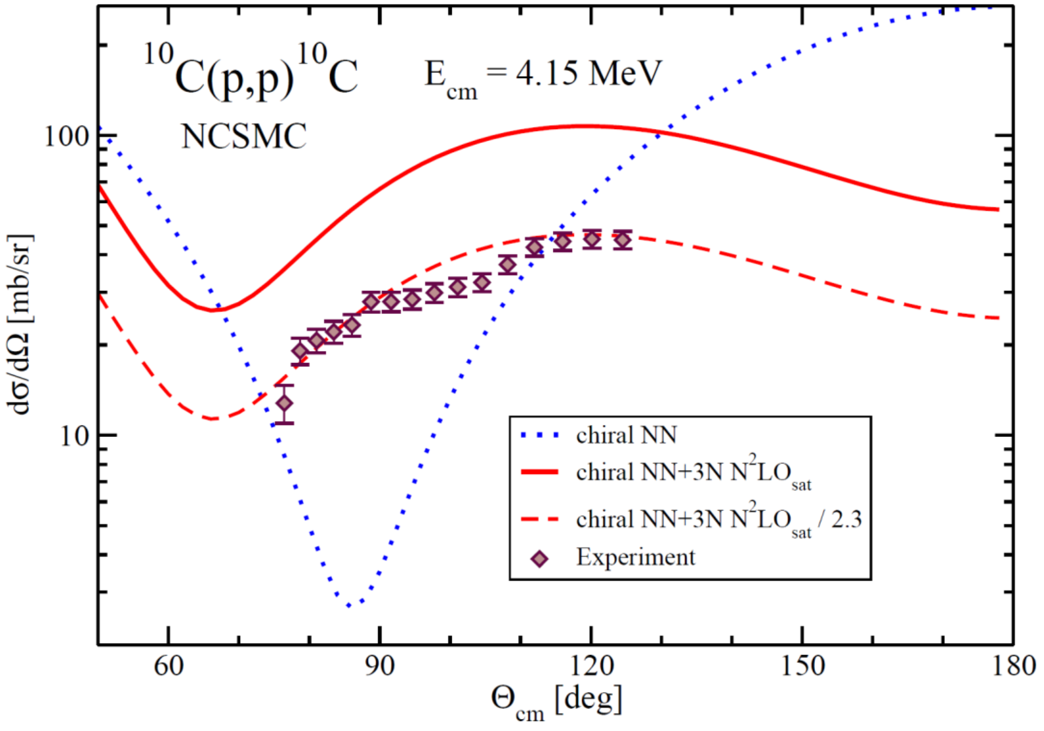


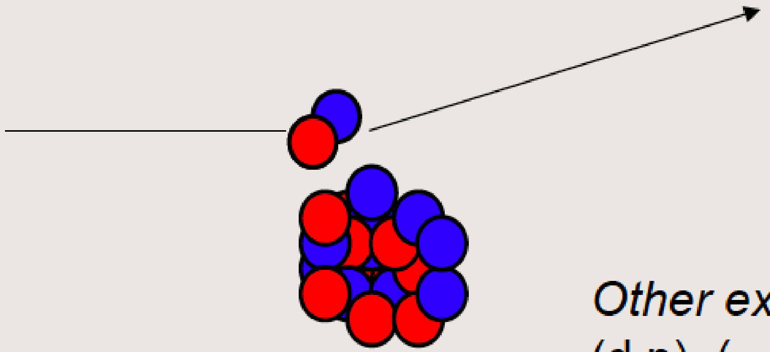


- 2000 pps ^{10}C beam scattered on solid hydrogen target at 4.54 and 4.82 A MeV.
- Scientific highlight: 3-body forces achieve qualitative agreement and correct order of magnitude.

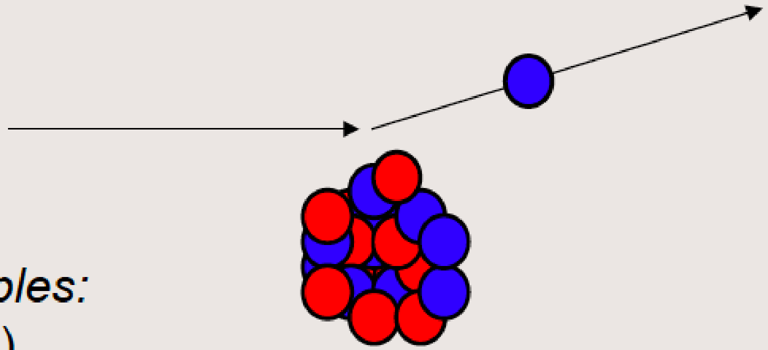
Transfer reactions

- (d,p), (^{3}He,d): Stripping of neutron or proton from light ion
- (p,d), (^{3}He,α): Pick-up of neutron/proton by light ion
- Example

$$d + {}^{90}Zr \rightarrow p + {}^{91}Zr \quad \text{or} \quad {}^{90}Zr\,(d,p)\,{}^{91}Zr$$

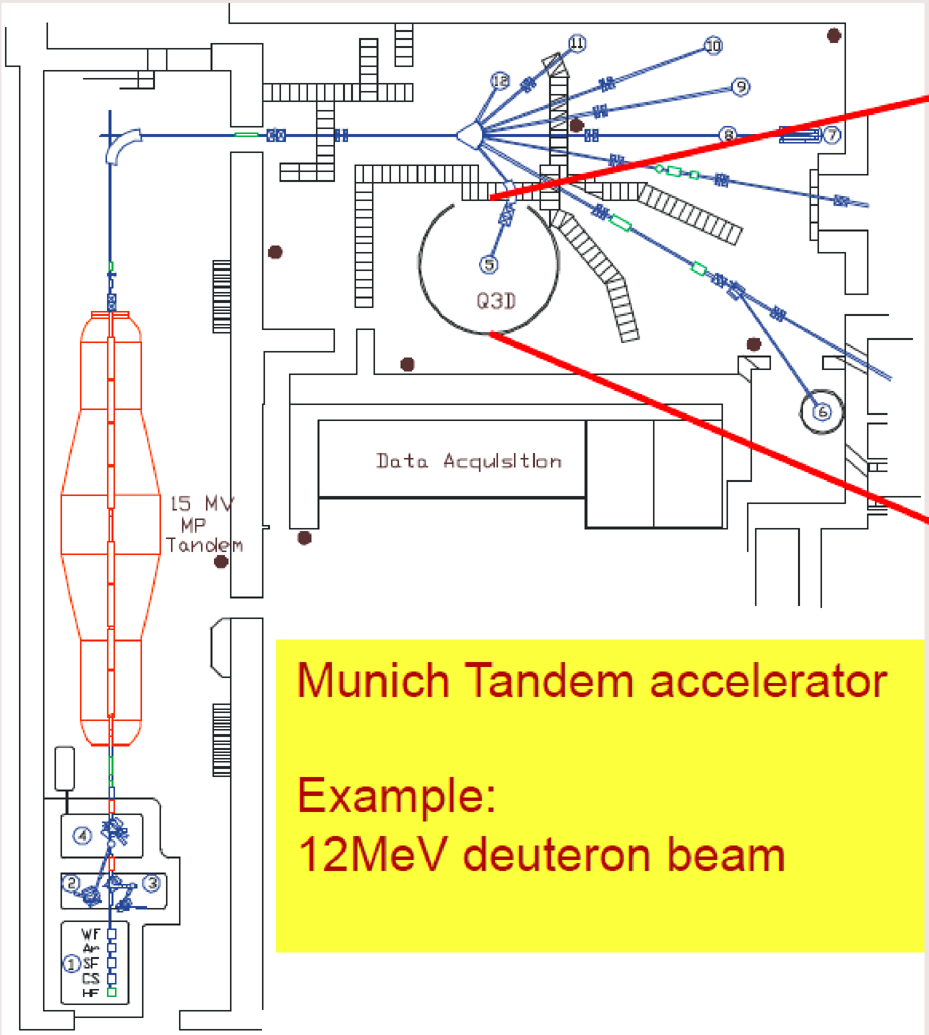


Other examples:
(d,p), (α,^{3}He)…
(p,d), (^{3}He, α)…
(^{3}He, d), (α, t)…
(d,^{3}He), (t,α)…



Measure:
- Energy of particles
- Cross section (total and diff.)
- Angular momentum

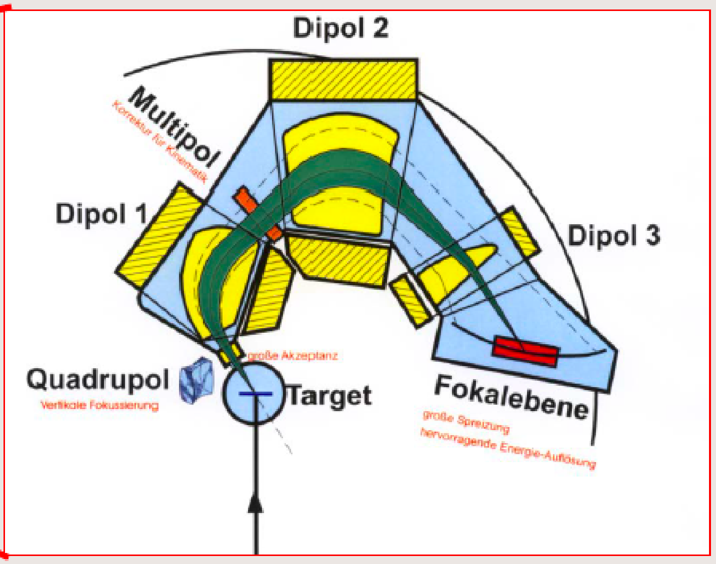
Transfer reactions



Munich Tandem accelerator

Example:
12MeV deuteron beam

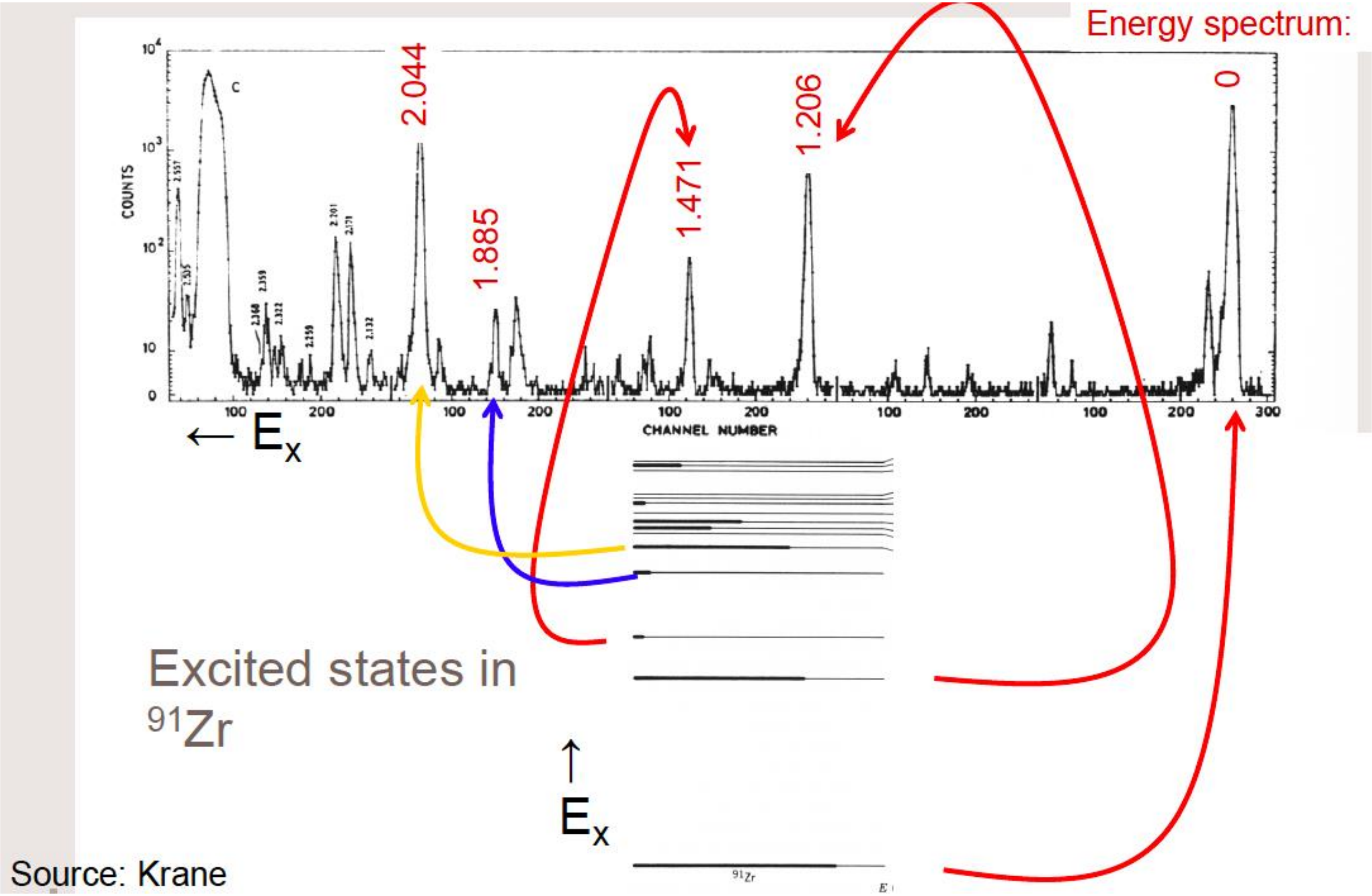
Q3D magnetic spectrograph



High resolution spectroscopy of light charged particles (e.g. protons from (d,p) reaction)

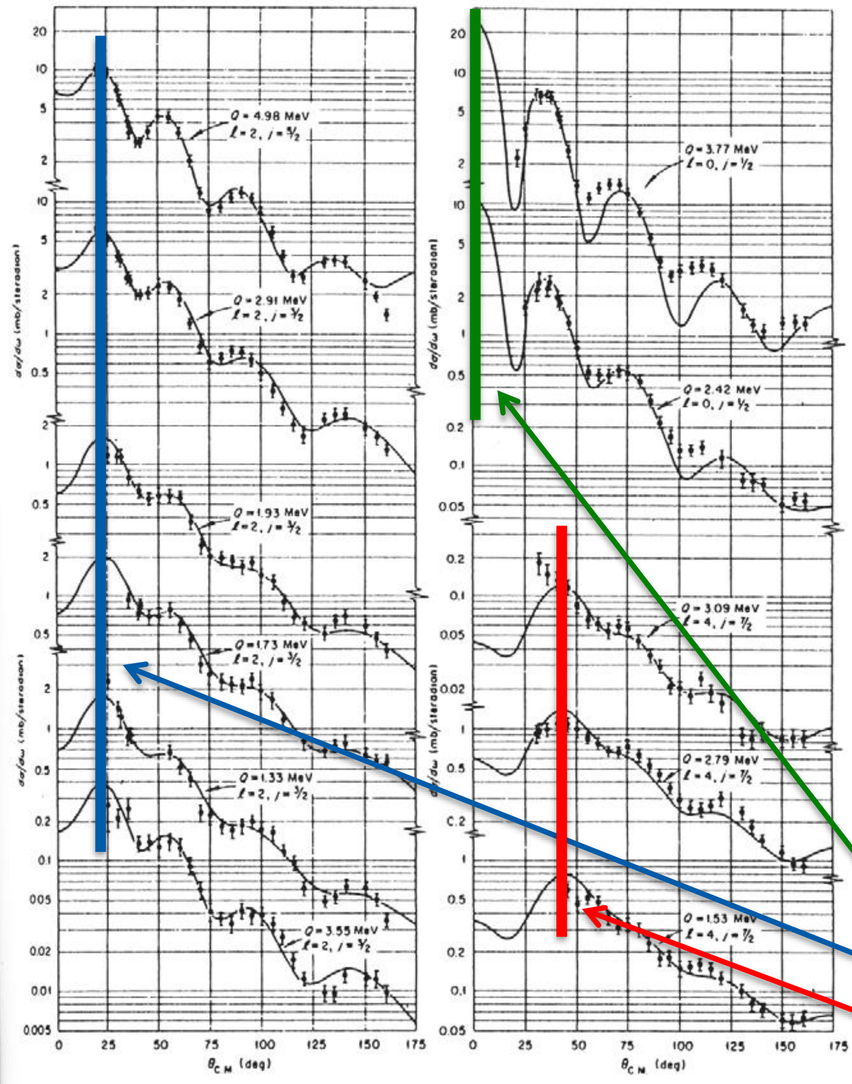
Position on focal plane related to energy of particles (via Bρ)

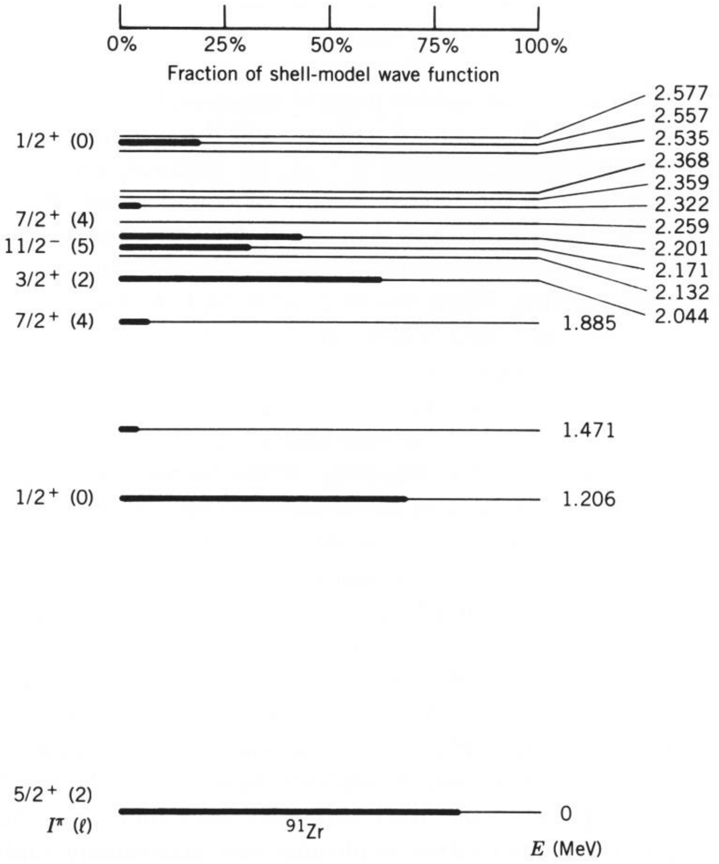
Energy spectrum of $^{90}Zr(d,p)^{91}Zr$



Source: Krane

Angular distributions of $^{90}Zr(d,p)^{91}Zr$





θ=0º → sin(0) = 0 → l=0

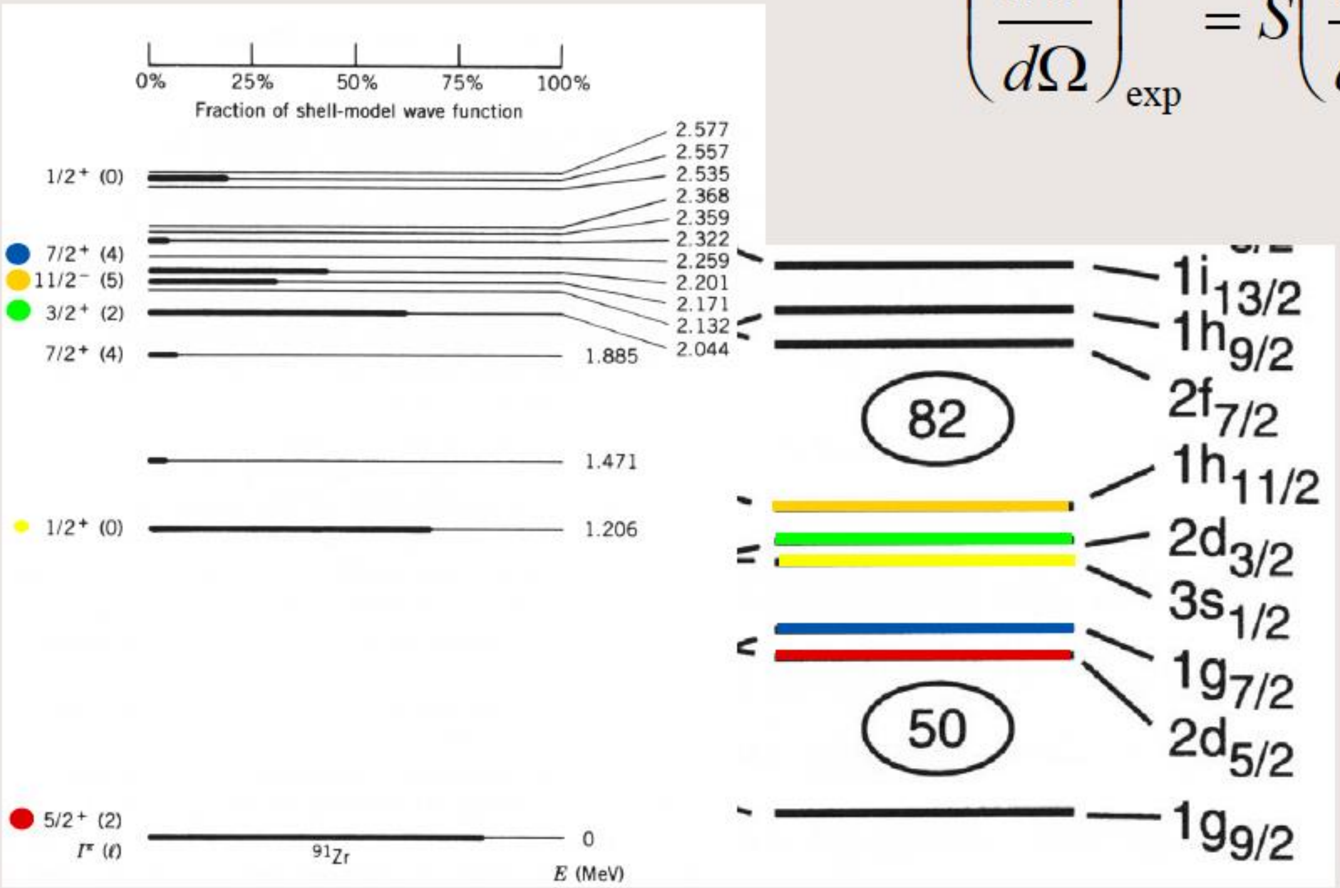
θ≈25º → sin(12.5)≈0.2 → l=2

θ≈46º → sin(23) ≈0.4 → l=4

Spectroscopic factors of $^{90}Zr(d,p)^{91}Zr$

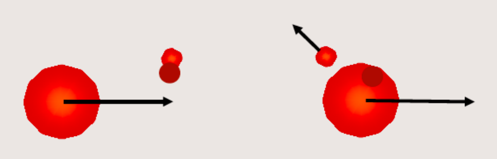
Compare measured cross-section with theoretical prediction

$$\left(\frac{d\sigma}{d\Omega}\right)_{exp} = S\left(\frac{d\sigma}{d\Omega}\right)_{theo}$$



Transfer reactions in inverse kinematics

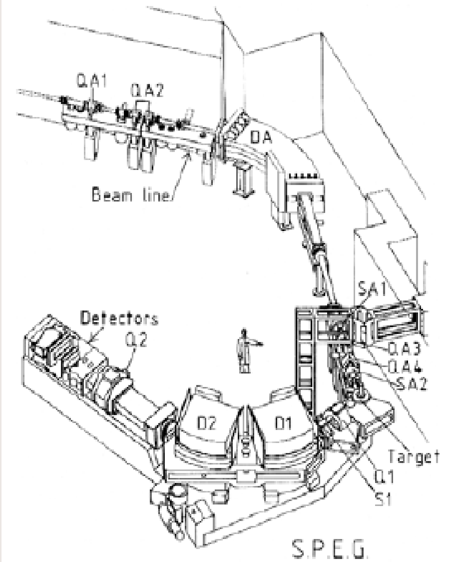
Transfer reactions with exotic nuclei

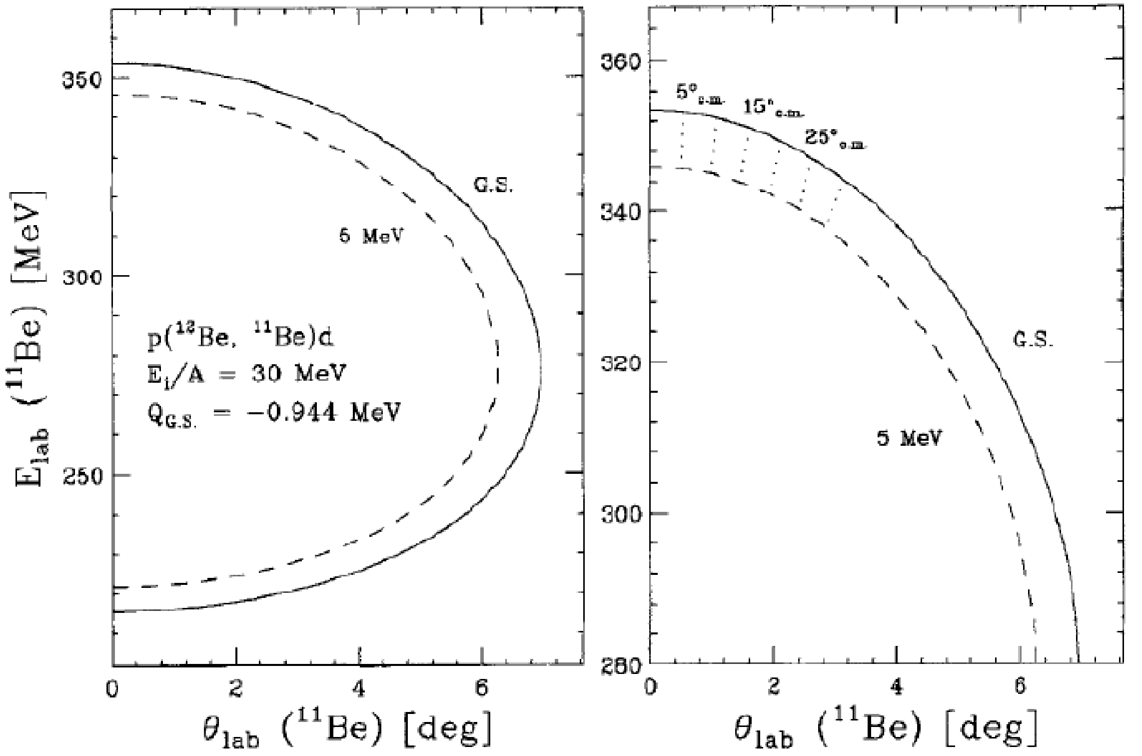


inverse kinematics experiments

- One way is to detect beam-like fragment
- Spread in beam energy (several MeV) limits resolution
- Hence, energy tagging required, or a dispersion matching spectrometer

SPEG at GANIL

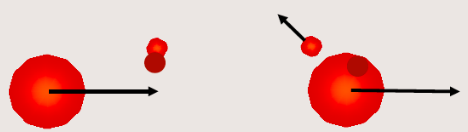




J.S. Winfield, W.N. Catford, N.A. Orr, NIM A396 (1997) 147

Transfer reactions in inverse kinematics

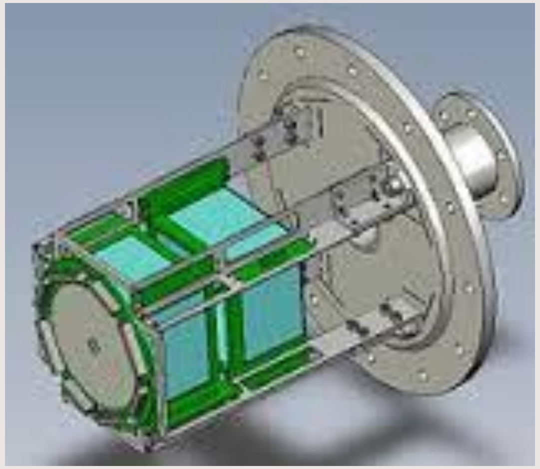
Transfer reactions with exotic nuclei

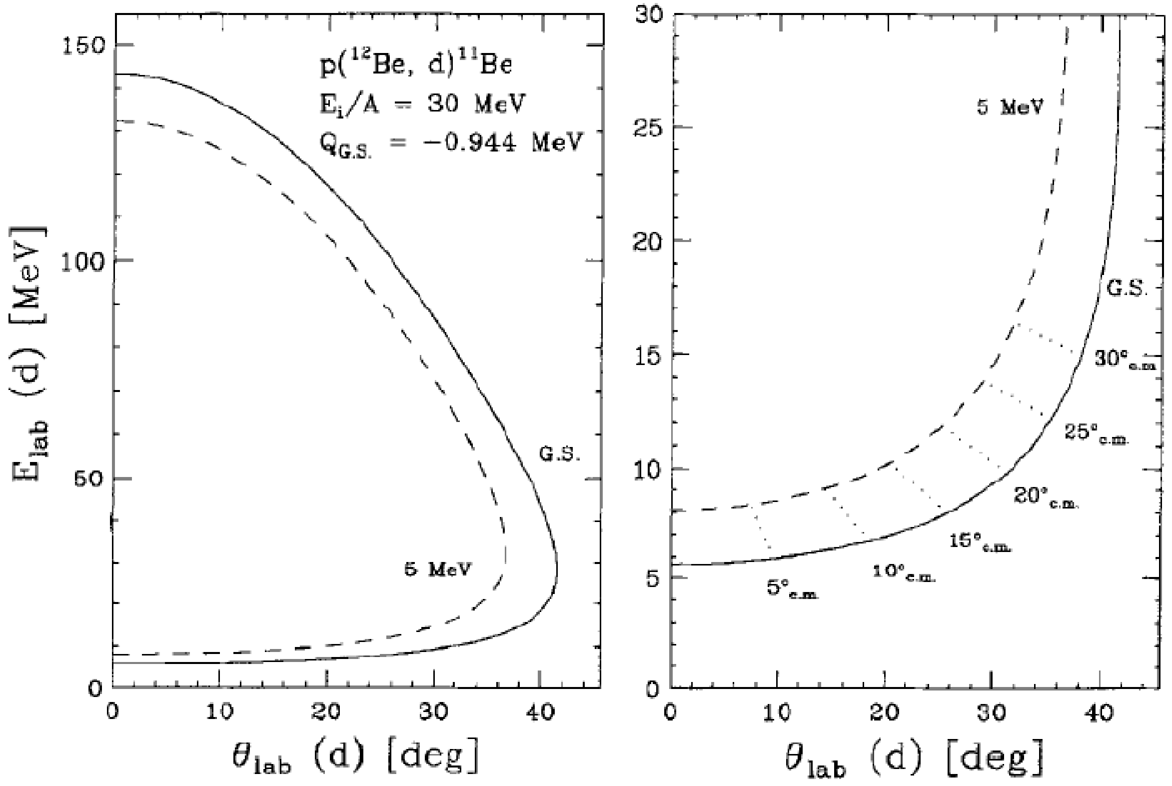


inverse kinematics experiments

- Another way is to detect target-like ejectile in Si detectors
- Resolution limited by difference: dE/dx(beam) - dE/dx(ejectile)
- Target thickness can be limiting factor

SHARC at TRIUMF





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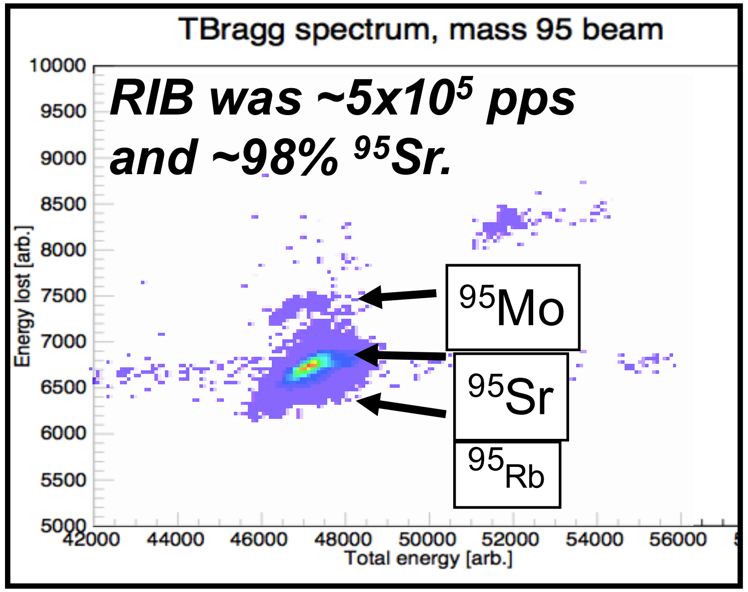
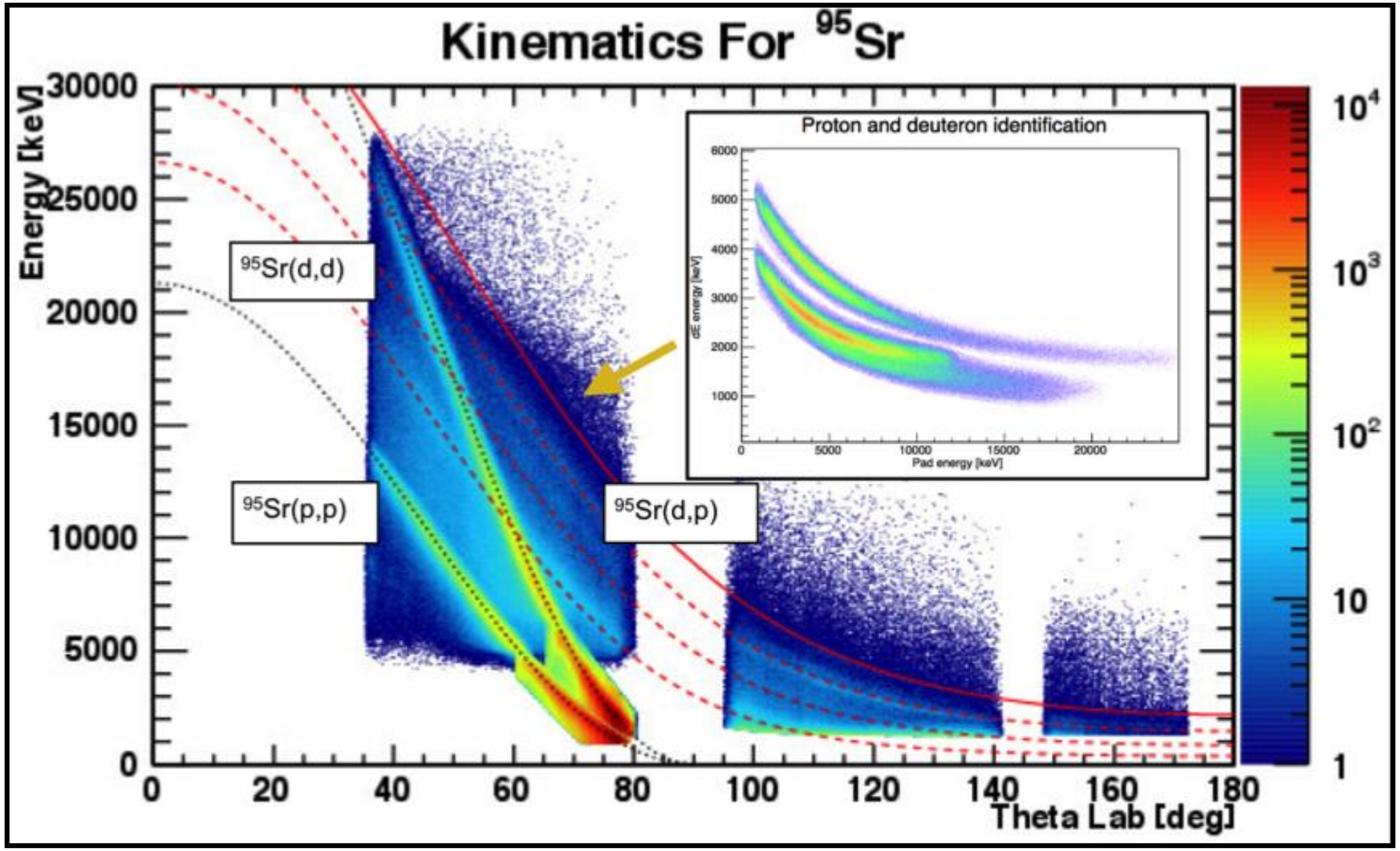
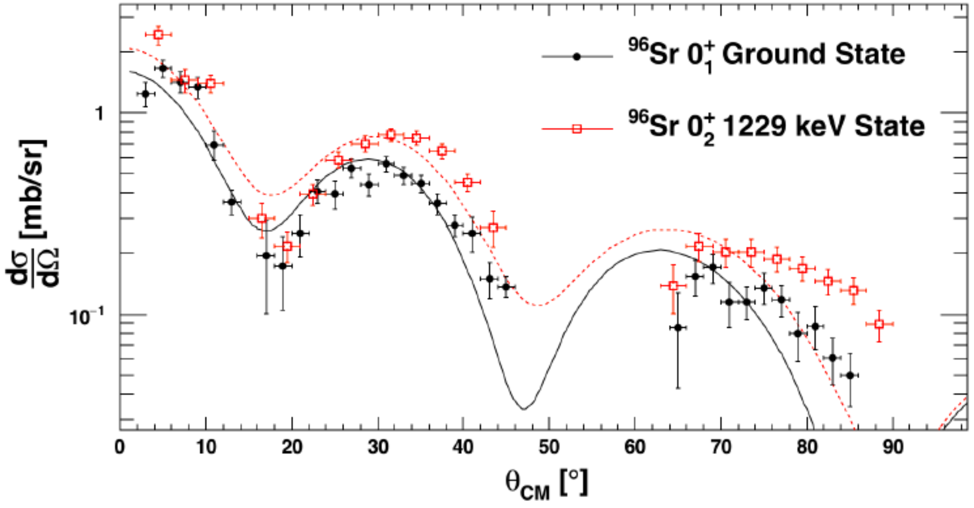
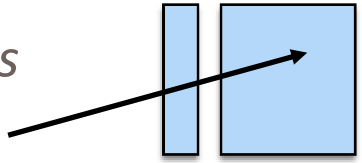
Transfer reactions with SHARC+TIGRESS





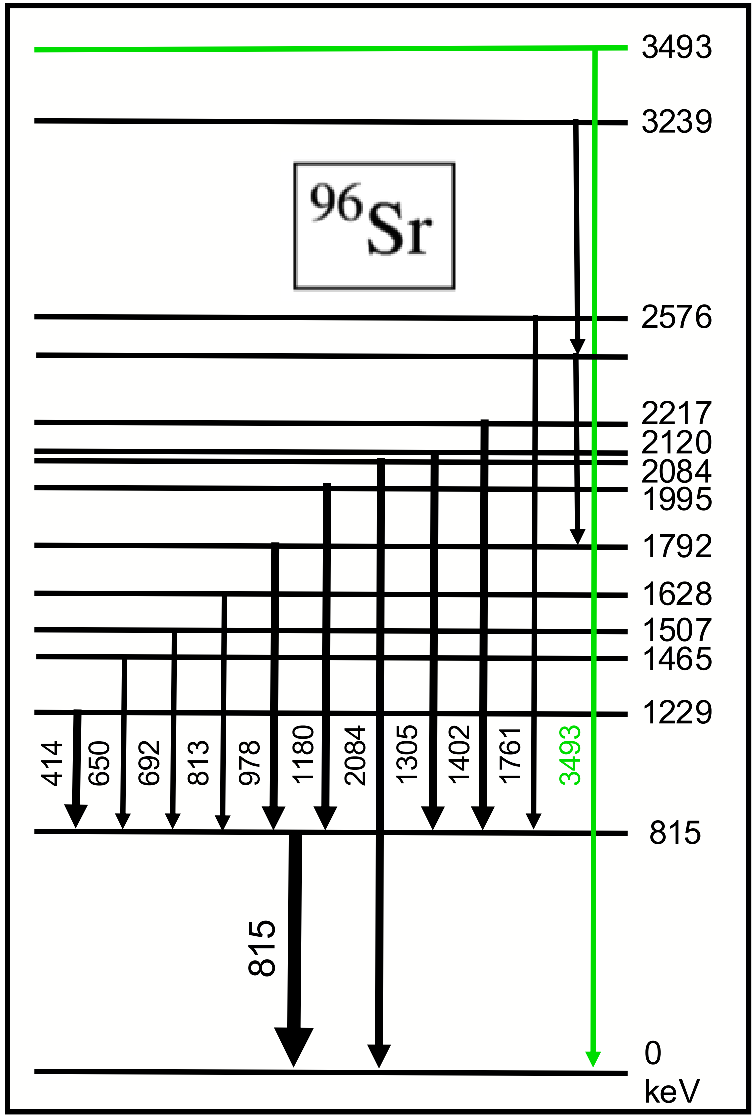


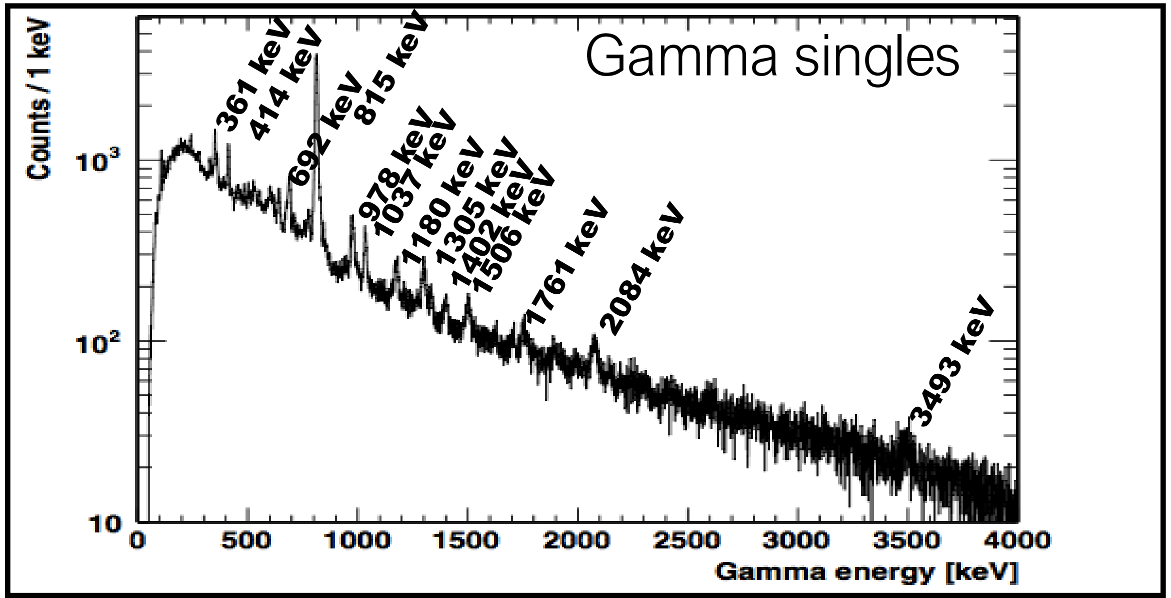
Particle ID from dE-E detectors

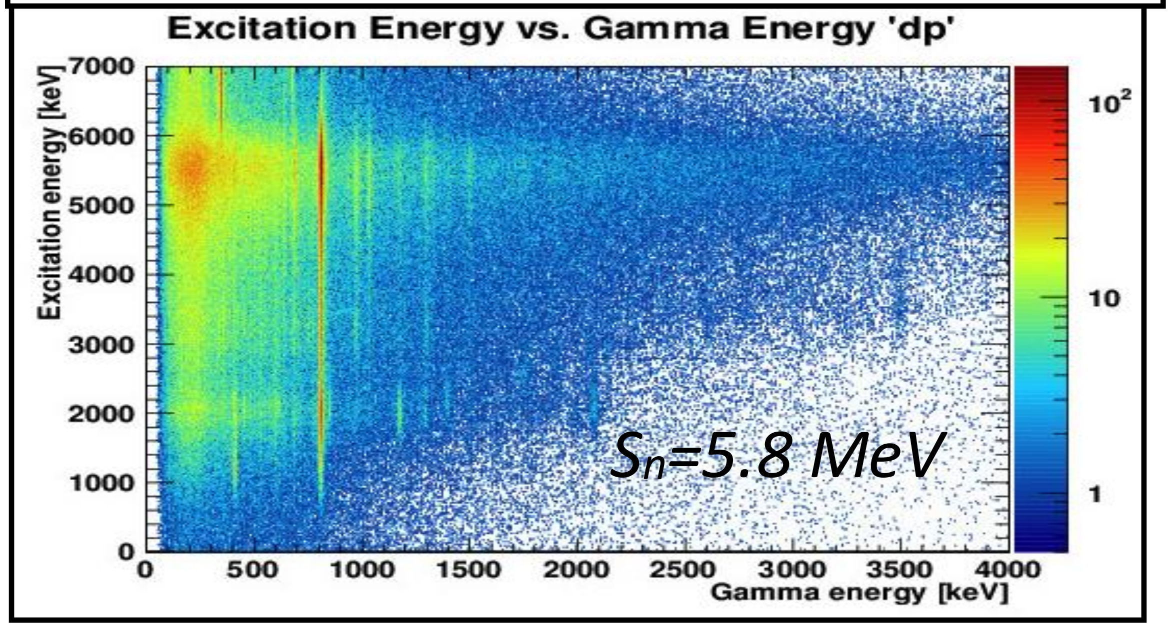


S. Cruz *et al.*, Phys. Letts. B 786, 94 (2018); Phys. Rev. C **100**, 054321 (2019)

Transfer reactions with SHARC+TIGRESS



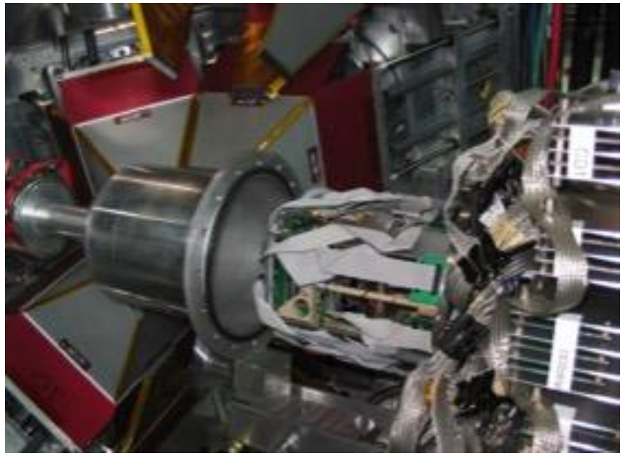


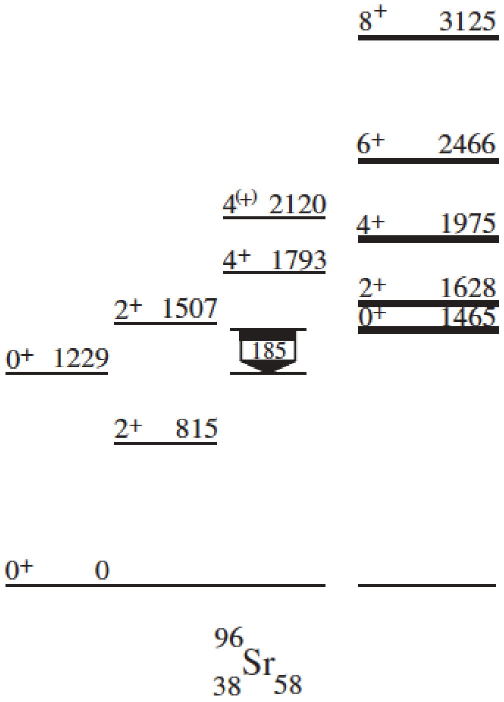


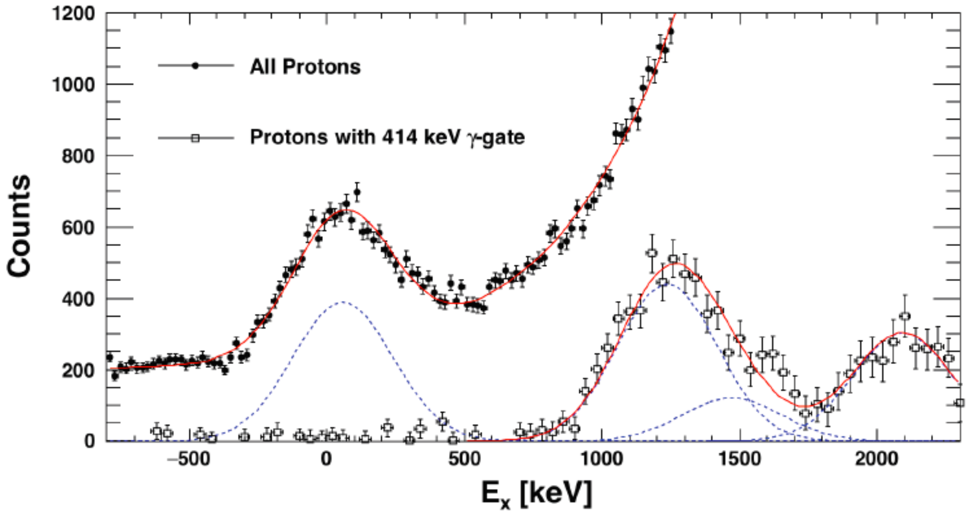
S. Cruz *et al.*, Phys. Letts. B 786, 94 (2018); Phys. Rev. C **100**, 054321 (2019)

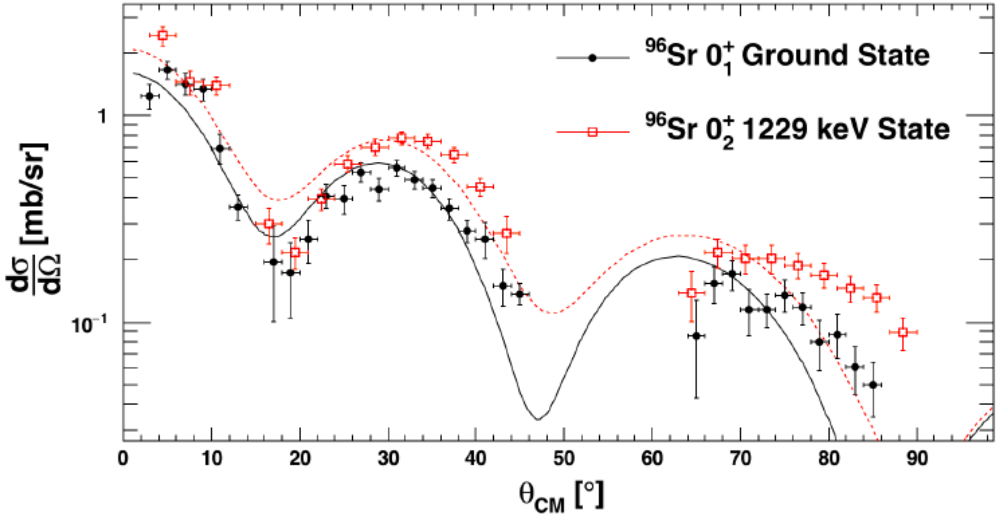
Transfer reactions with SHARC+TIGRESS

- ^{95}Sr ground state is well described as a $\nu s_{1/2}$ spherical state
- spectroscopic factors of C^2S = 0.19(3), 0.22(3), and 0.33(12) for the 0^+_1 , 0^+_2 , and 0^+_3 states
- ^{96}Sr may exhibit triple shape coexistence, with a weakly deformed ground state, and two excited 0^+ configurations – a deformed and a spherical one – which undergo strong mixing.



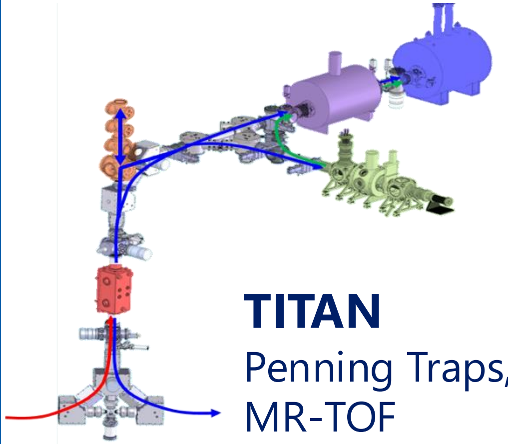






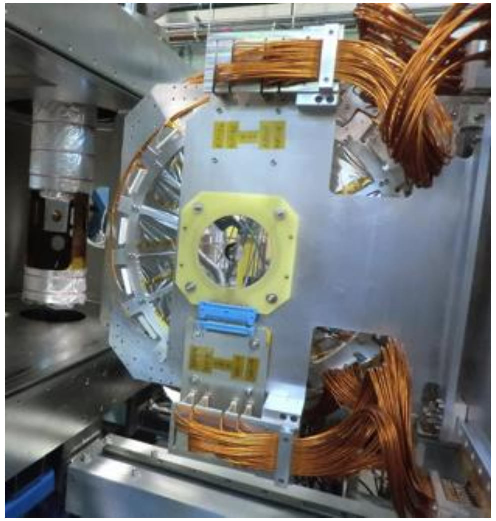
S. Cruz *et al.*, Phys. Letts. B 786, 94 (2018); Phys. Rev. C **100**, 054321 (2019)

Nuclear Structure at TRIUMF-ISAC

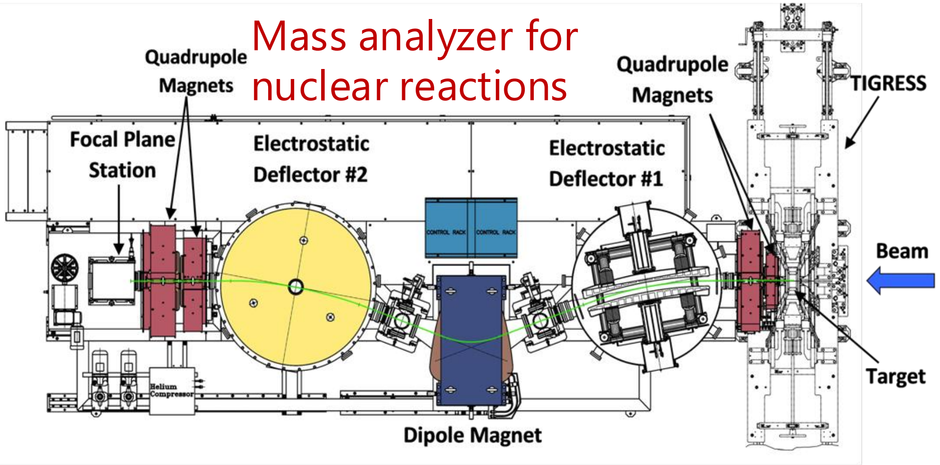


TITAN
Penning Traps, MR-TOF
(masses, in-trap decay)

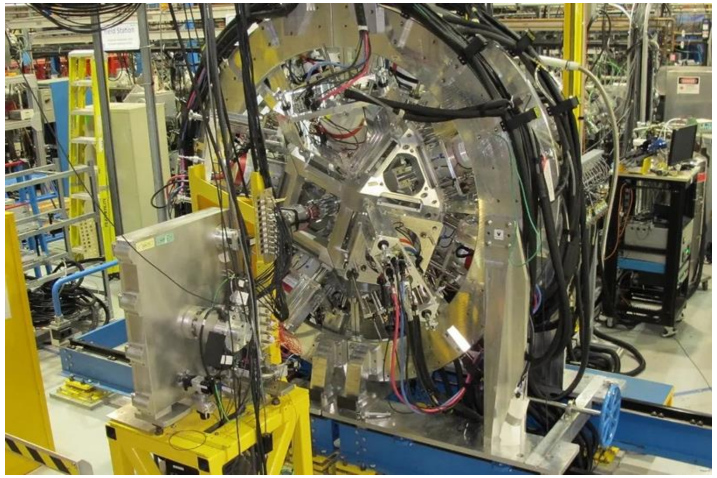
IRIS
Solid hydrogen target for direct reactions



EMMA+TIGRESS
Mass analyzer for nuclear reactions

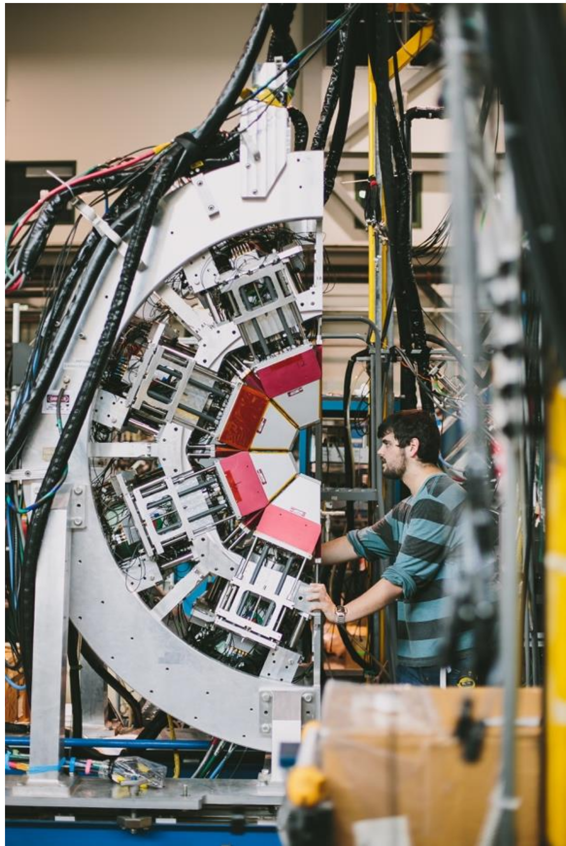


GRIFFIN
Gamma & Electron spectrometer
(decay properties)



Polarizer beamline
Co-linear Laser spectroscopy

TIGRESS
In-beam γ-ray spectroscopy



What we didn't talk about…

- Nuclear reactions – fusion evaporation, deep-inelastic collisions
- Excited state lifetimes – $LaBr_3$, plunger, DSAM
- Magnetic moments and *g* factors
- Internal conversion, internal pair formation
- Beta-delayed neutron emission, alpha decay, proton emission
- Time-projection chambers

- Isomeric long-lived nuclear states
- *N*=*Z* nuclei, isospin and neutron-proton pairing
- Octupole deformation
- Triaxiality
- Shape coexistence
- Halo nuclei, Neutron skins, equation of state, nuclear matter
- Nuclear physics tests of the standard model
- Super-heavy elements