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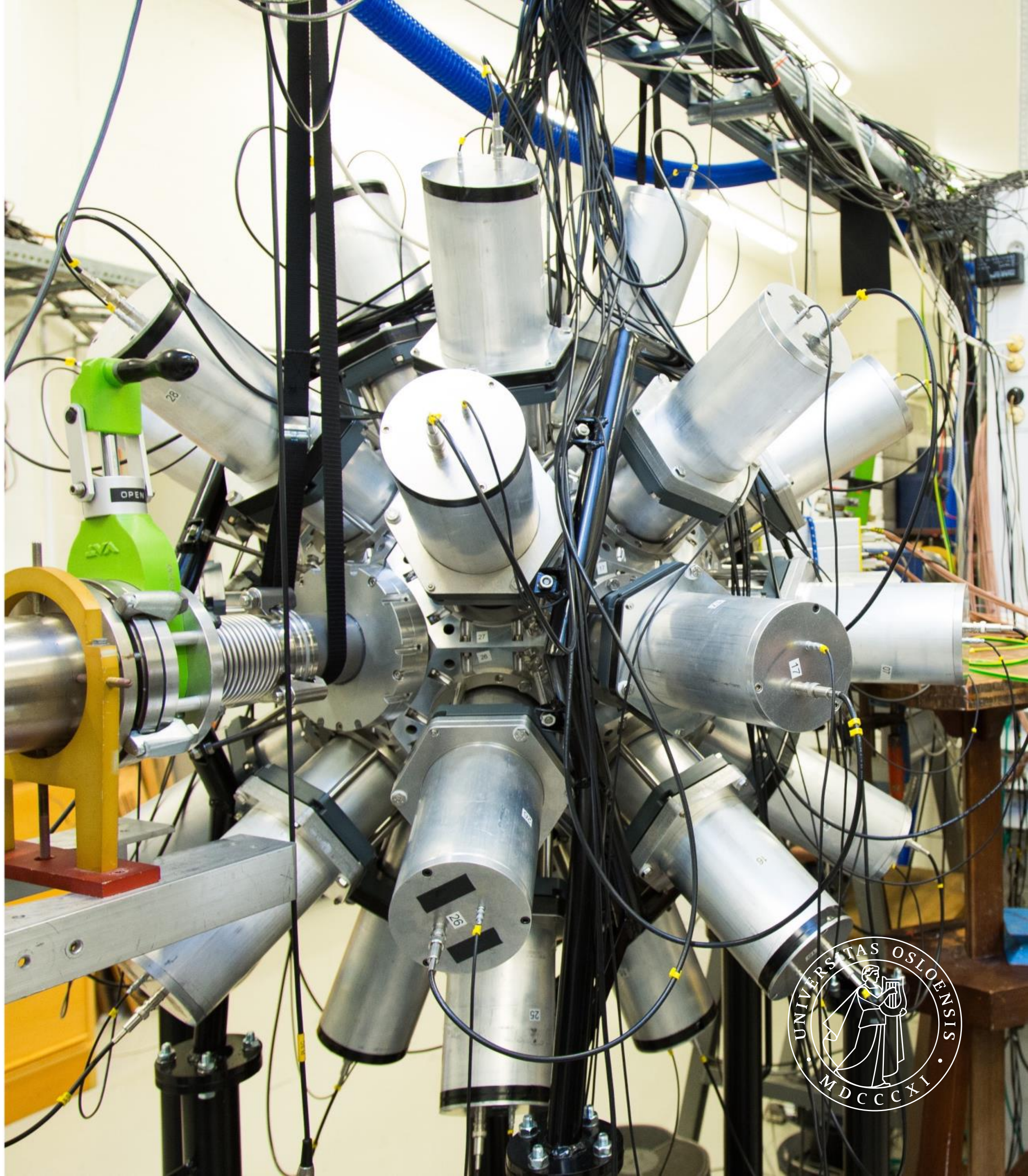
Low energy nuclear physics at CERN

NorCC Workshop 2024

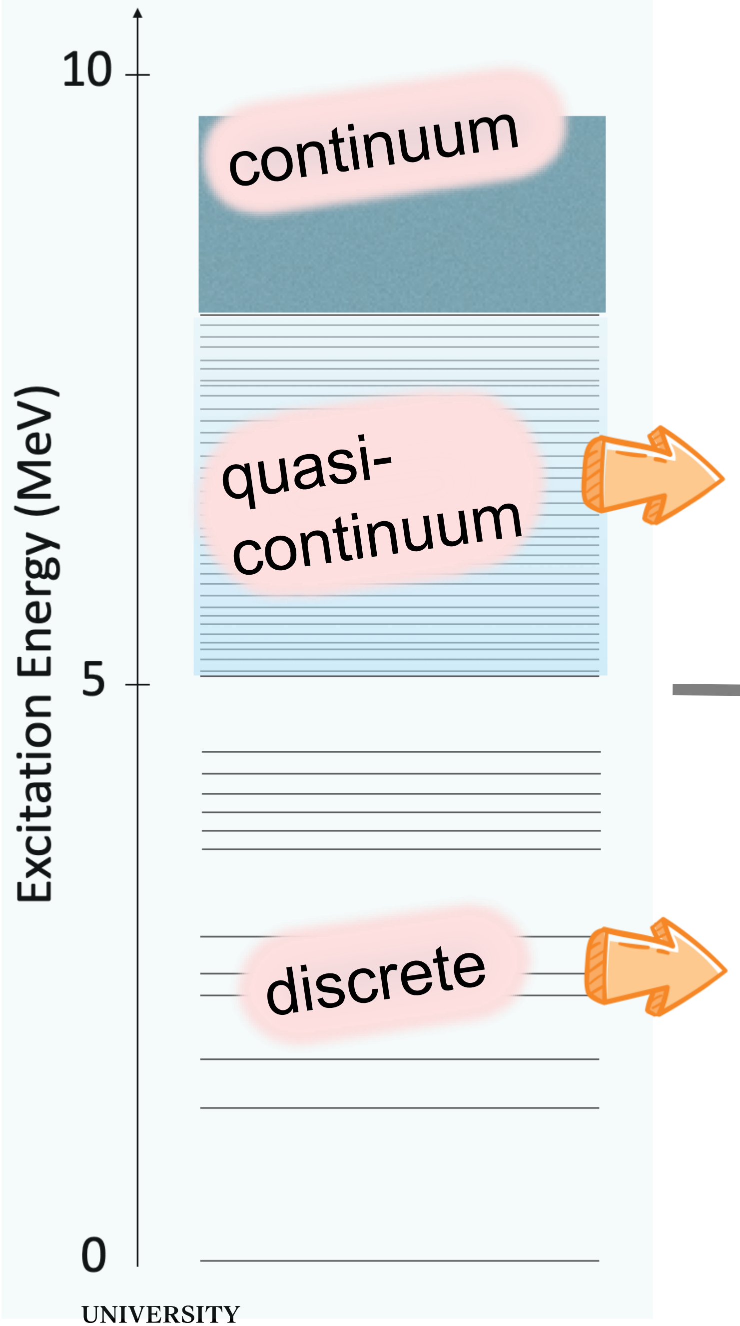
Vetle Wegner Ingeberg
Postdoc
Nuclear and energy physics group

Trondheim, 04.09.2024



Outline

- Physics interests of the low energy nuclear physics community
  - Basic nuclear properties
  - Statistical properties of nuclei
  - Nuclear astrophysics
- Facilities at CERN relevant for low energy nuclear physics
  - ISOLDE
  - MEDICIS
  - n_TOF
- Plans for the next decade
- Long range plans
- How to reach the goals



Nuclear properties at
Quasi-continuum states-
higher lying states

Statistical Properties

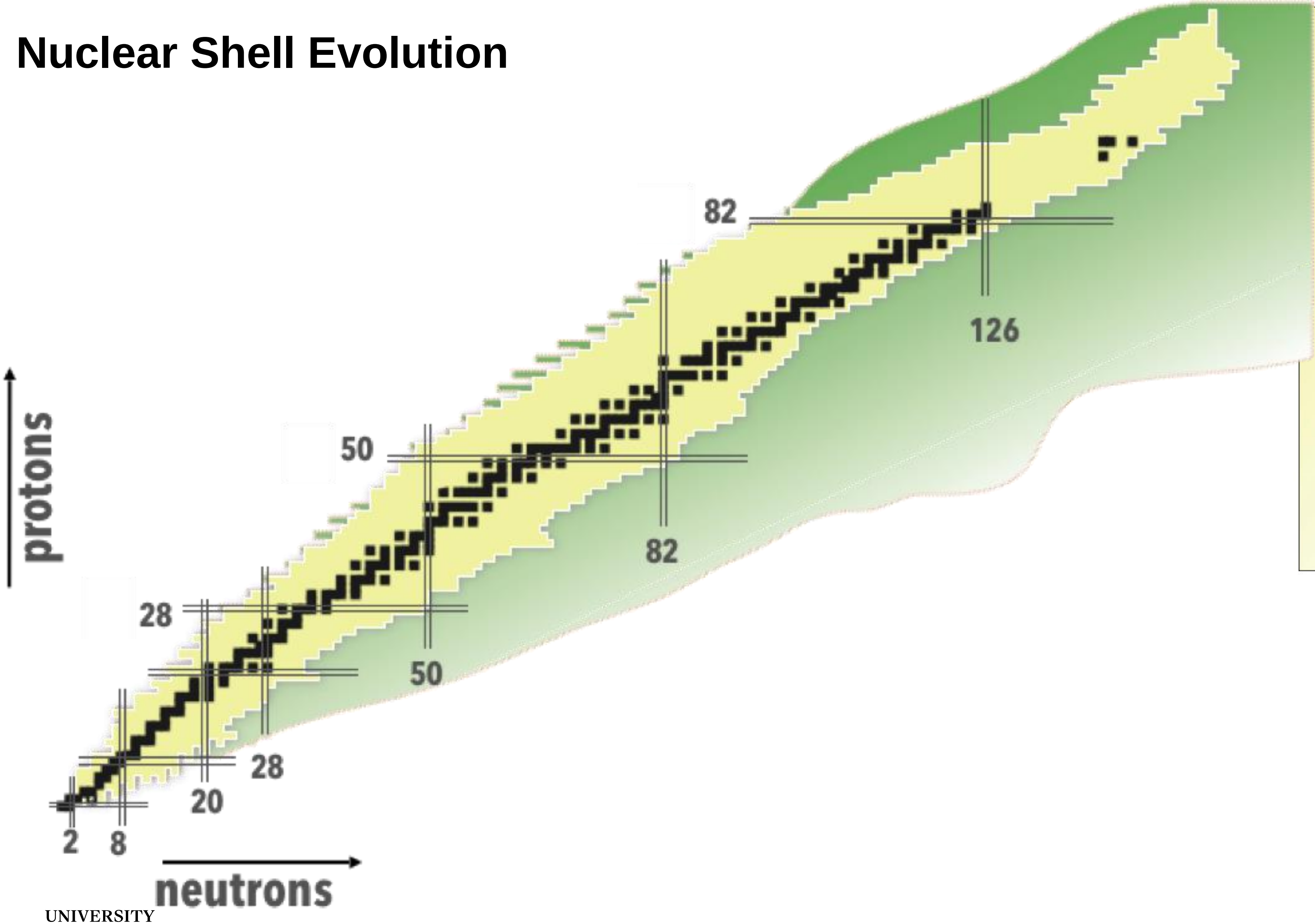
- Nuclear level density
- Gamma strength function
- Astrophysical application

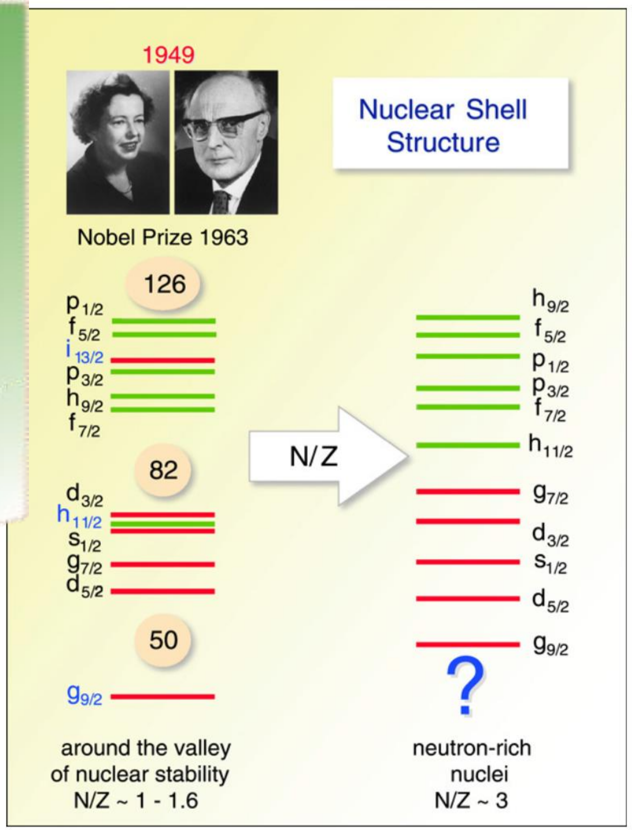
Nuclear properties at
discrete states –
low lying states

Physics of exotic nuclei

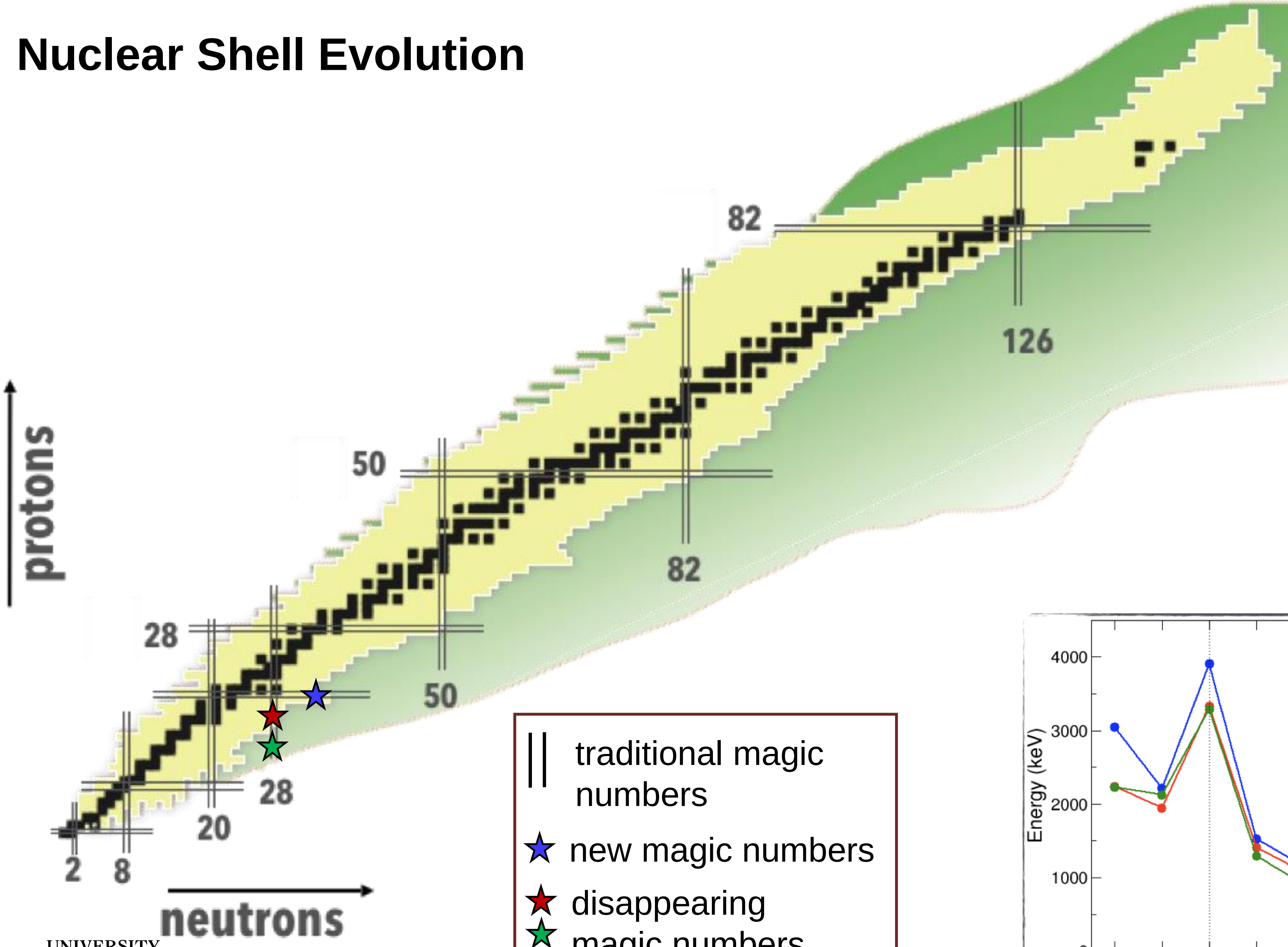
- Nuclear shell evolution
- Nuclear shapes
- Deformation

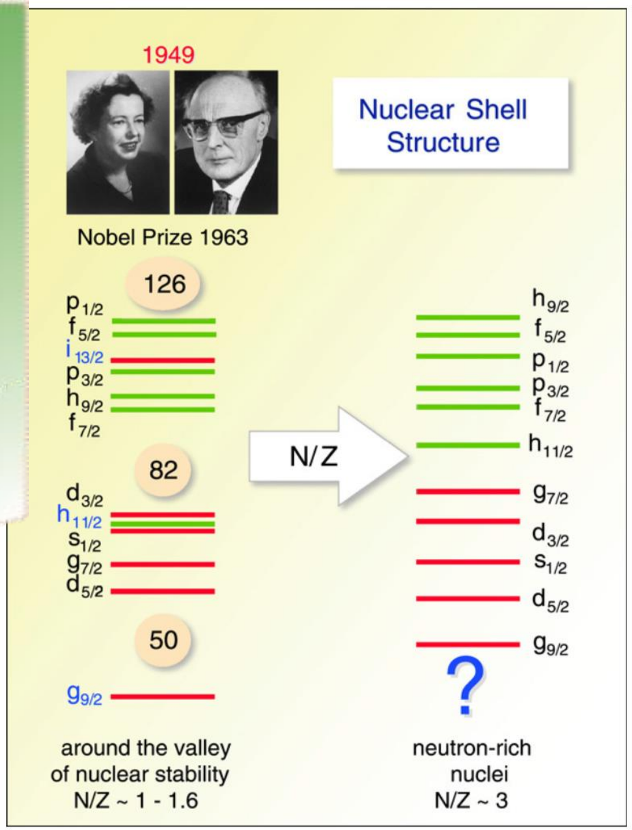
Nuclear Shell Evolution





Nuclear Shell Evolution

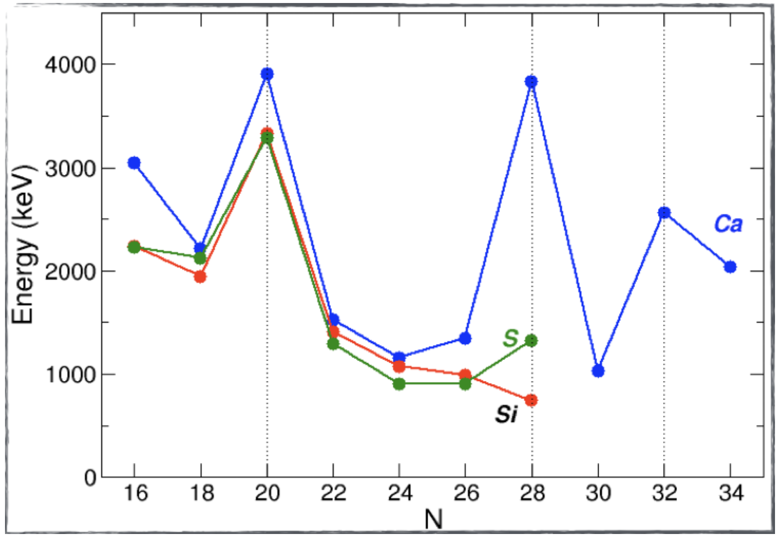




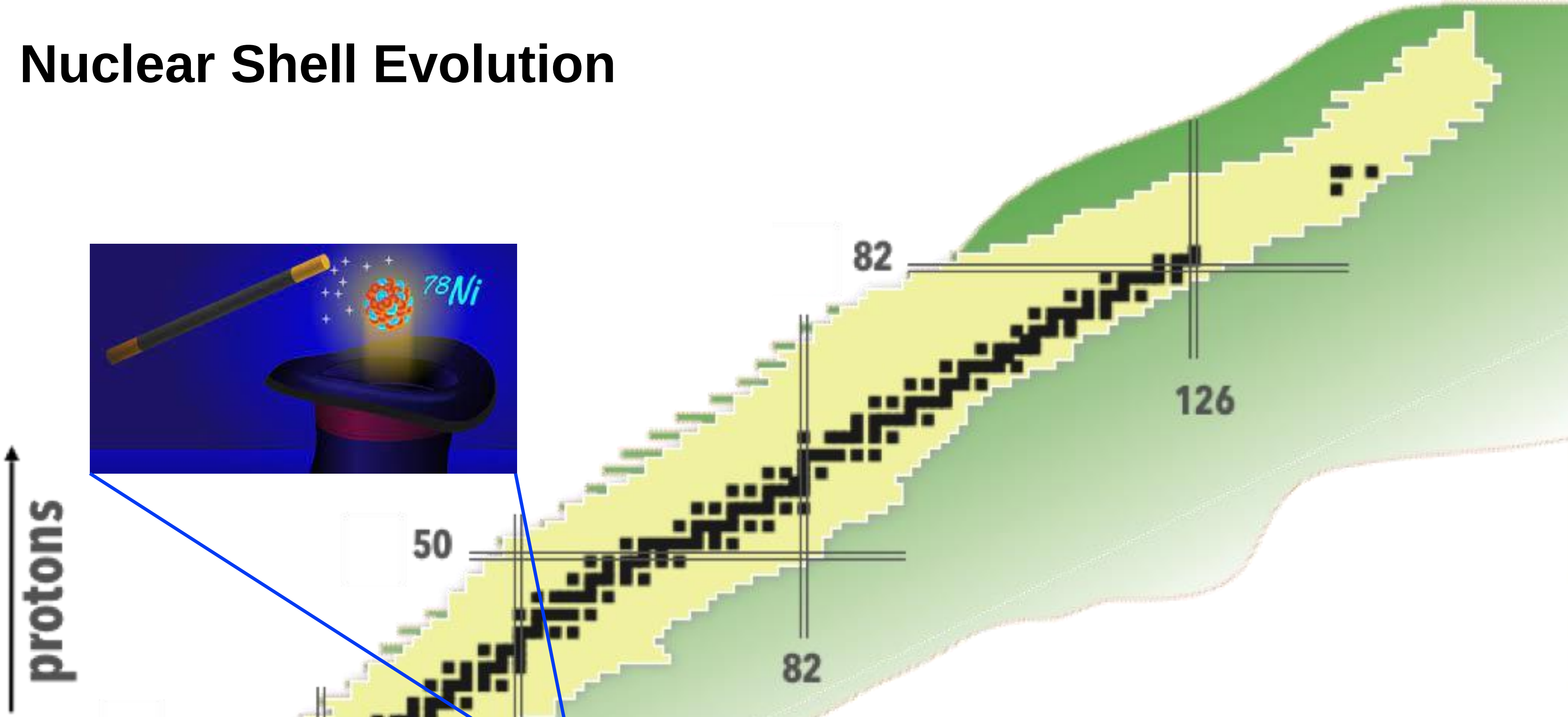
|| traditional magic numbers

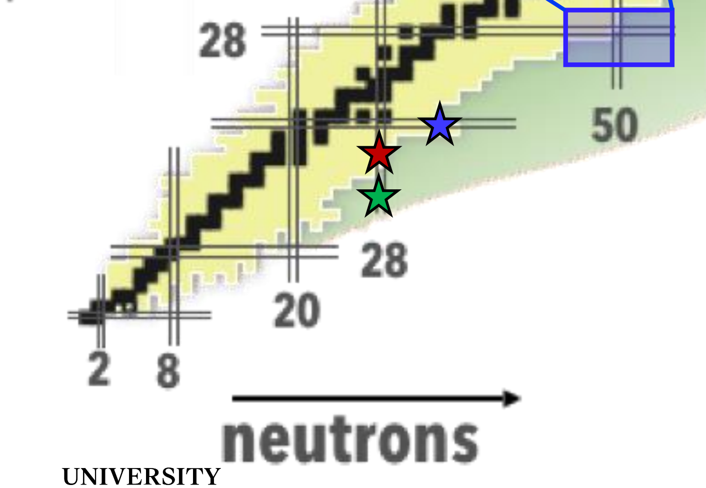
★ new magic numbers

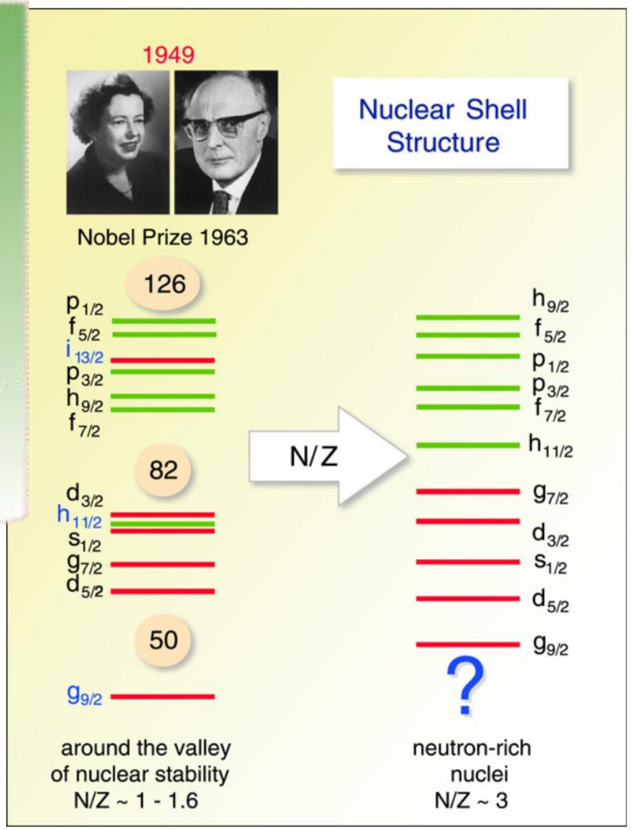
★ disappearing
★ magic numbers



Nuclear Shell Evolution







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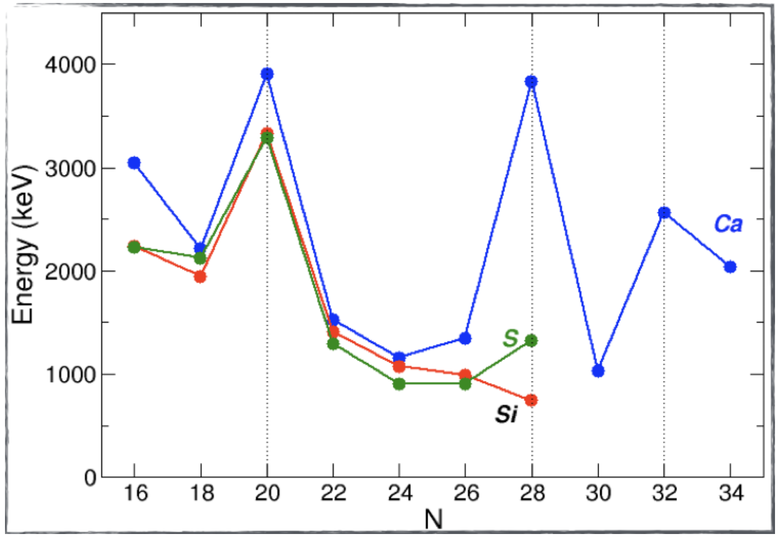
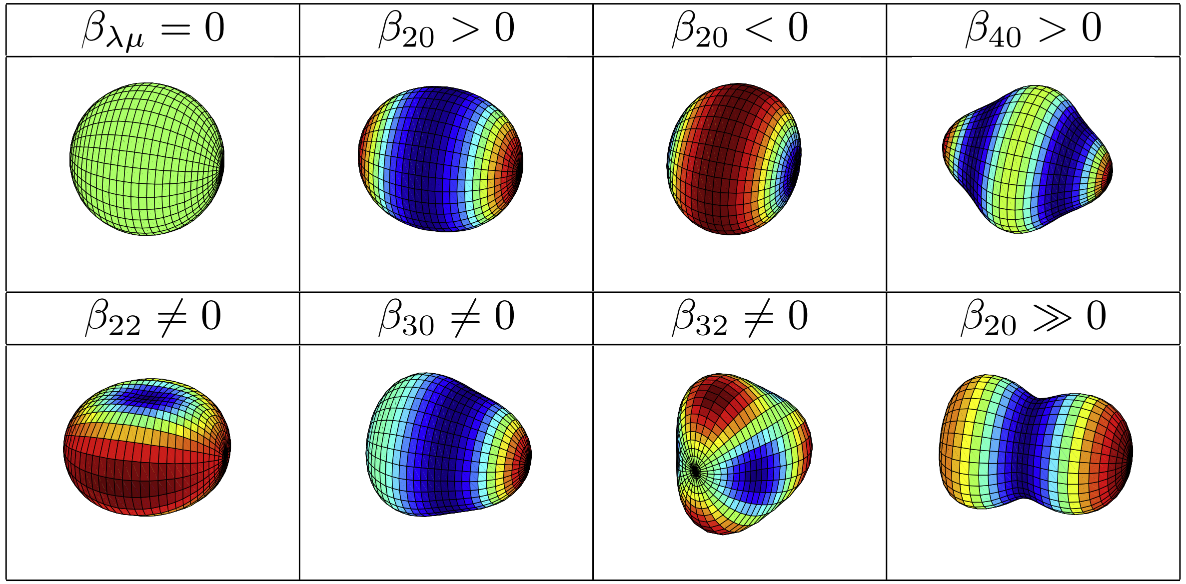
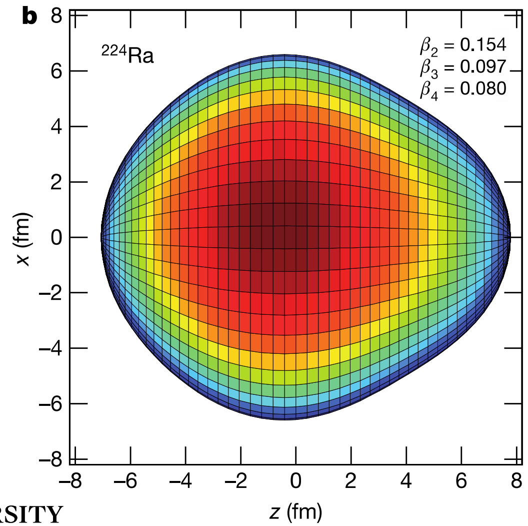


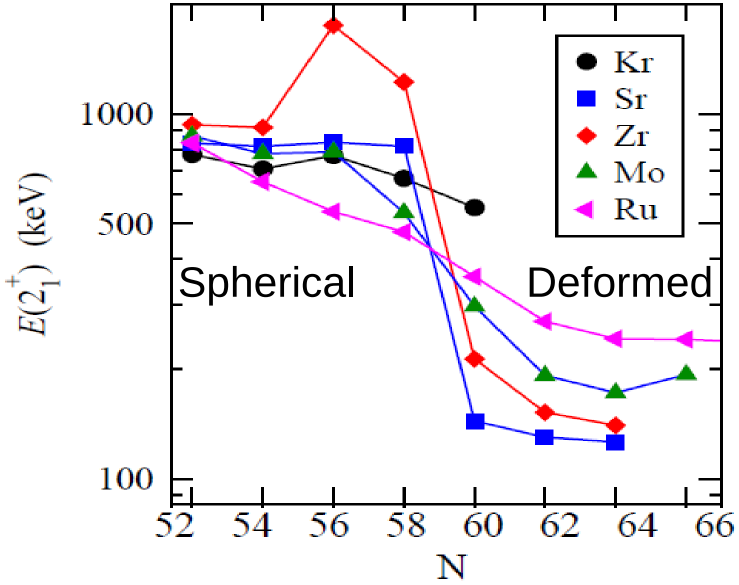
Nuclear Deformation



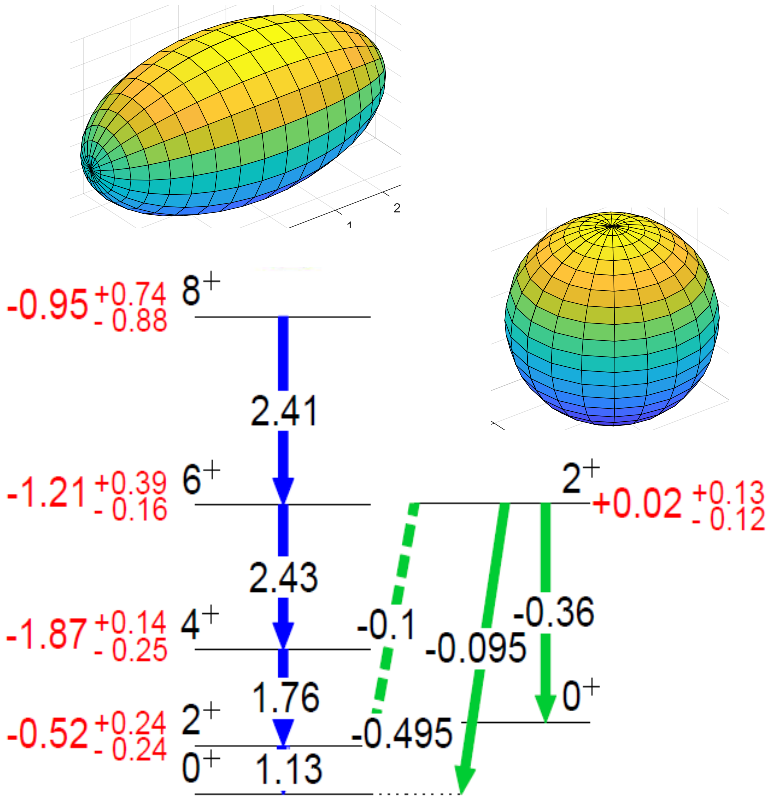
Shan-Gui Zhou, Phys. Scr. **91**, 063008 (2016)

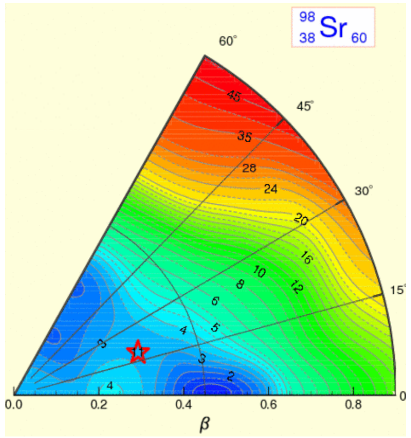


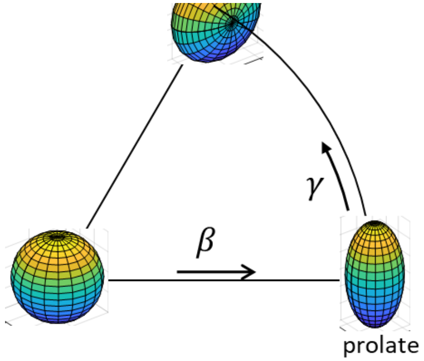
L. Gaffney *et al.*, Nature **497**, 199 (2013)



A. Görgen, W. Korten, J. Phys. G **43**, 024002 (2016)







E. Clément, M. Zielinska, A. Görgen *et al.*, Phys. Rev. Lett. **116**, 022701 (2016)

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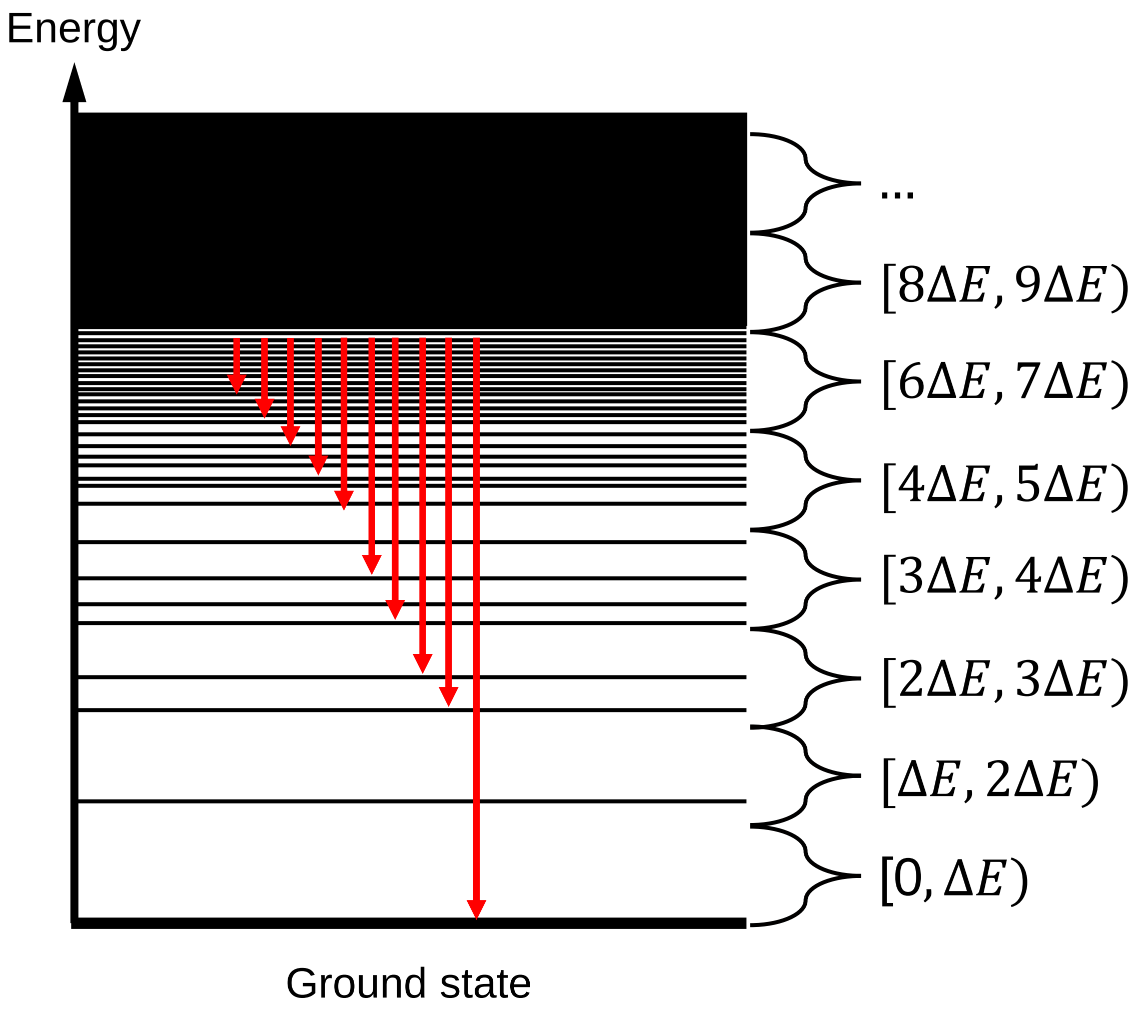
Statistical Properties of nuclei



Nuclear level density

Average number of levels with a given spin and parity per unit energy

$$\rho(E,J,\pi) = \frac{\Delta N(E,J,\pi)}{\Delta E}$$

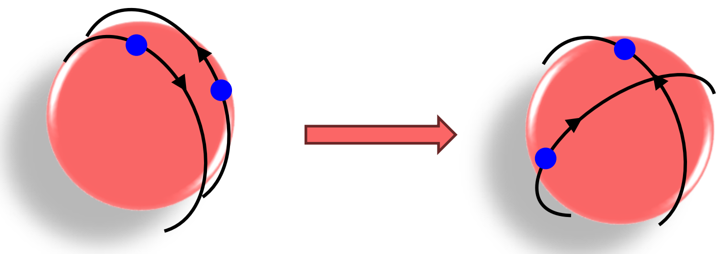
Gamma strength function

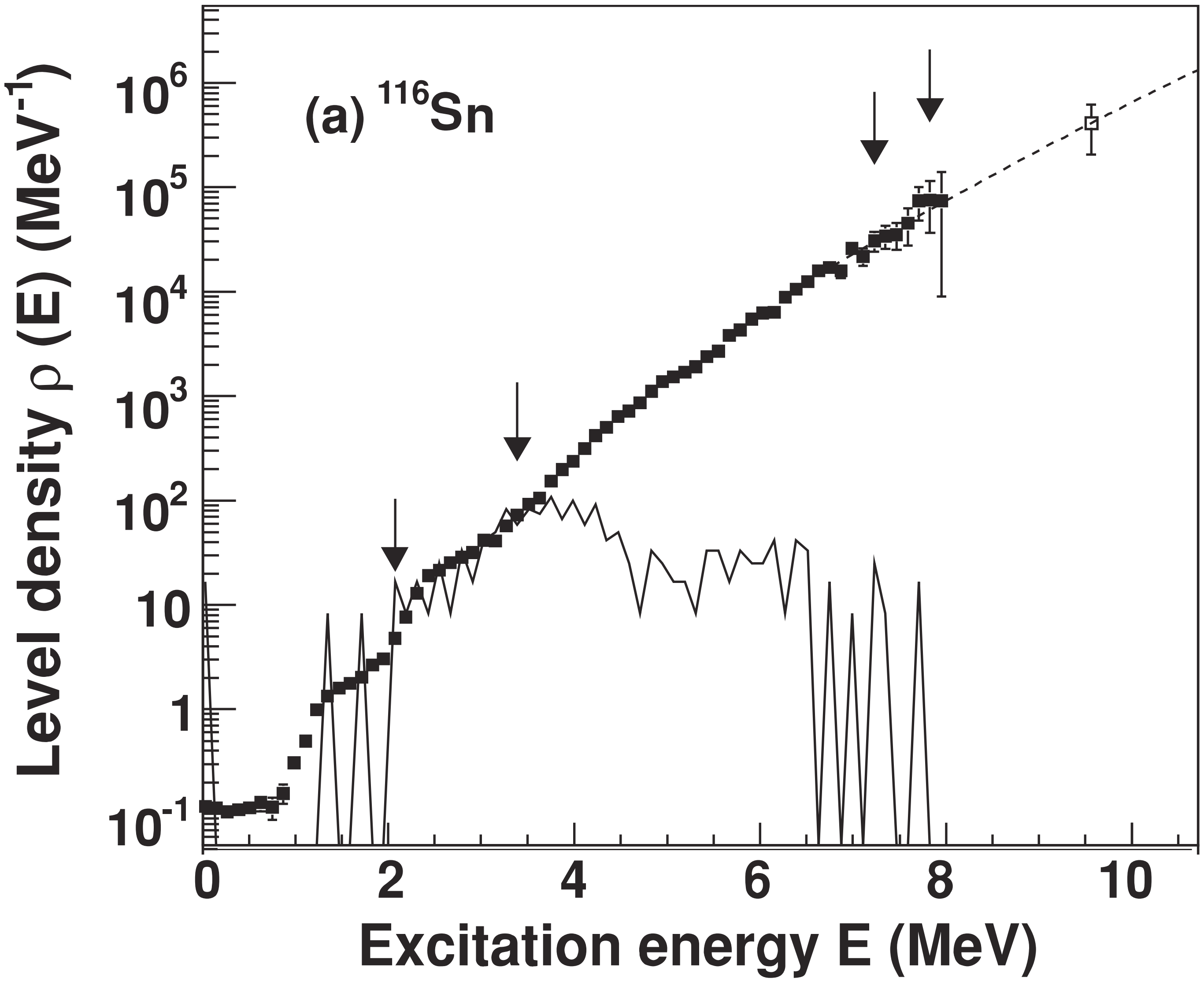
Average decay strength for gamma decay with emission of a photon with a given character and multipolarity

$$f_{XL}(E,E_i,J_i,\pi_i) = \frac{\langle\Gamma_\gamma^{XL}\rangle(E,E_i,J_i\pi_i)}{E^{2L+1}}\rho(E_i,J_i,\pi_i)$$

Nuclear level density

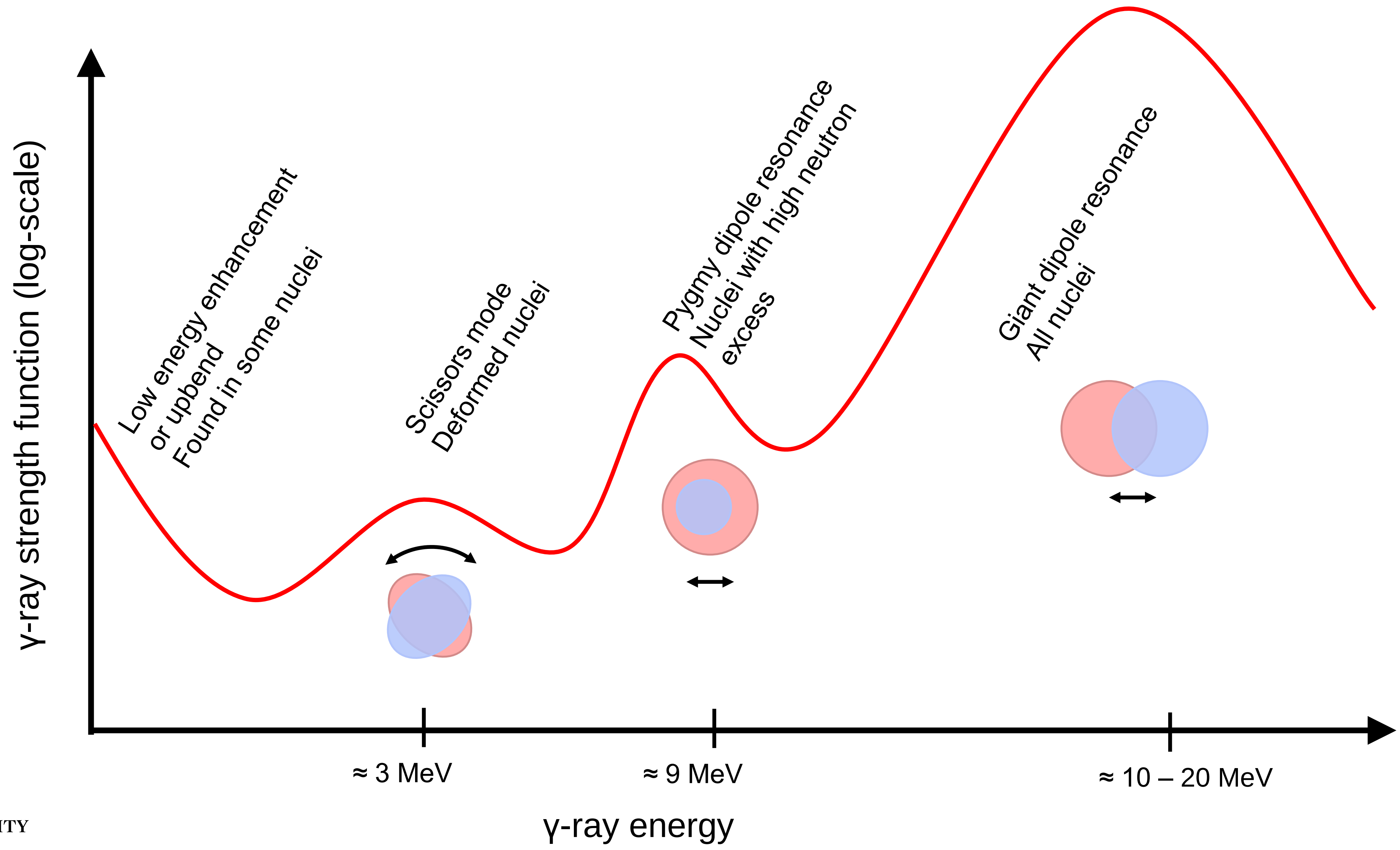
- Pair breaking
- Phase transition



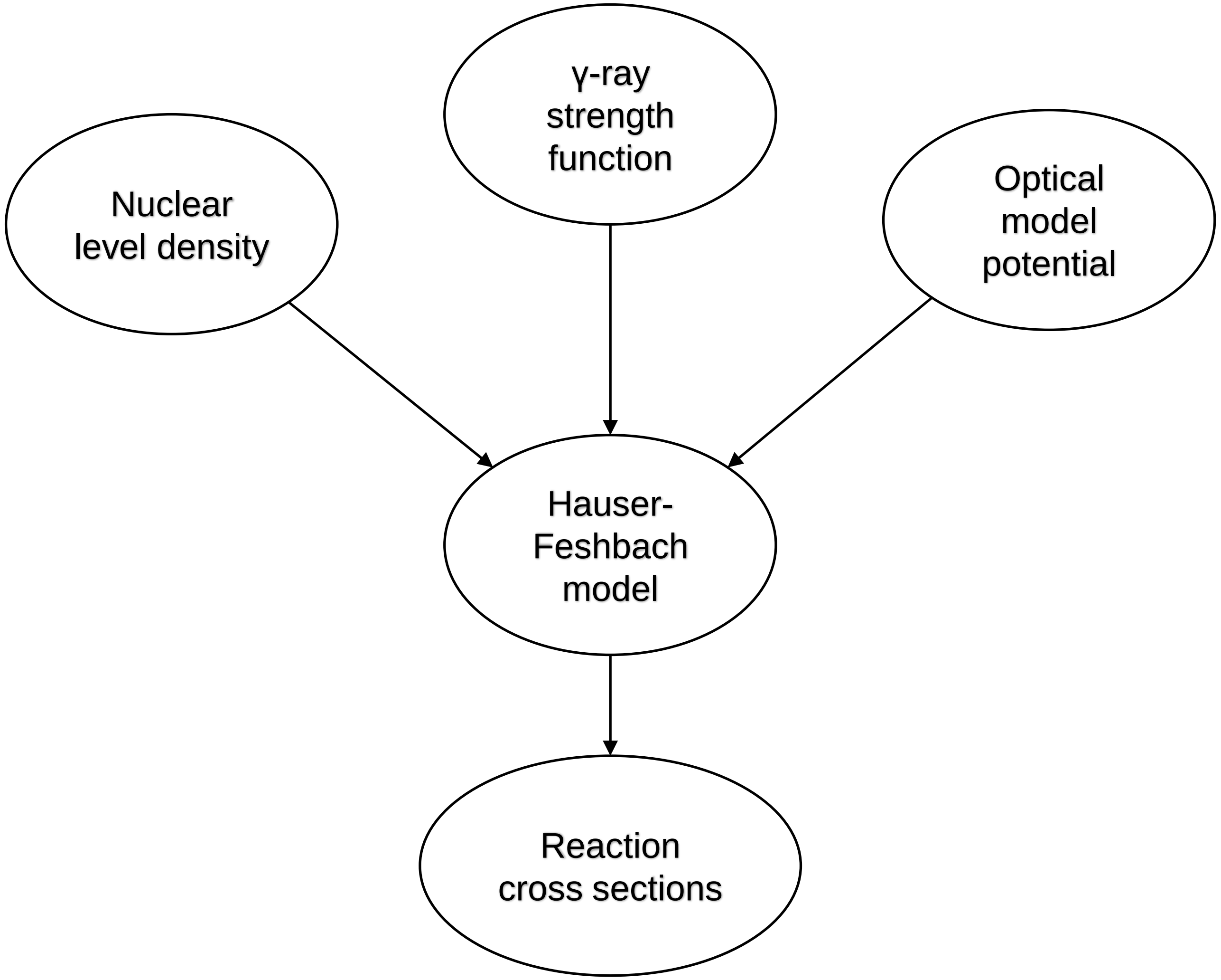


U. Agvaanluvsan *et al.*, Phys. Rev. C **79**, 014320 (2009)

Gamma strength function



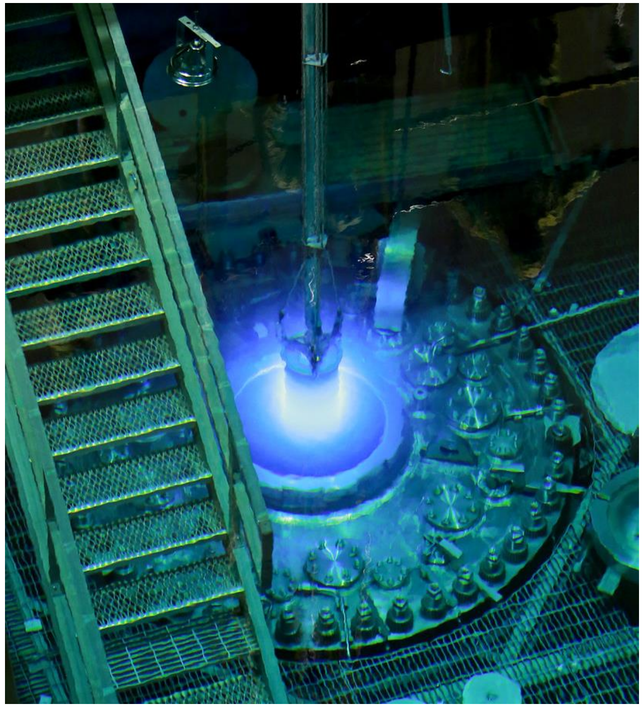
Statistical properties – applications



Statistical properties - applications

Reactor physics
Energy

Figure: Jason Richards/ORNL (CC)



Isotope production
Nuclear medicine

Nuclear astrophysics
How are elements made?

Figure: ESO/L. Calçada/M. Kornmesser (CC)

Nuclear Astrophysics

Nucleosynthesis

Consecutive neutron capture

- Slow process (s-process)
- Rapid process (r-process)
- Intermediate process (i-process)

Neutron star merger

First observed r-process

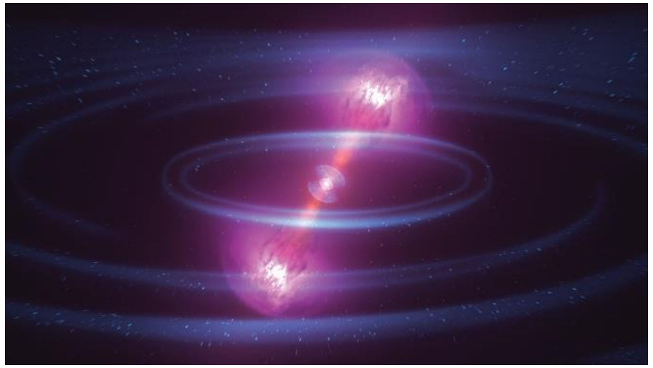


Image: NASA Goddard Space Flight Center/CI Lab

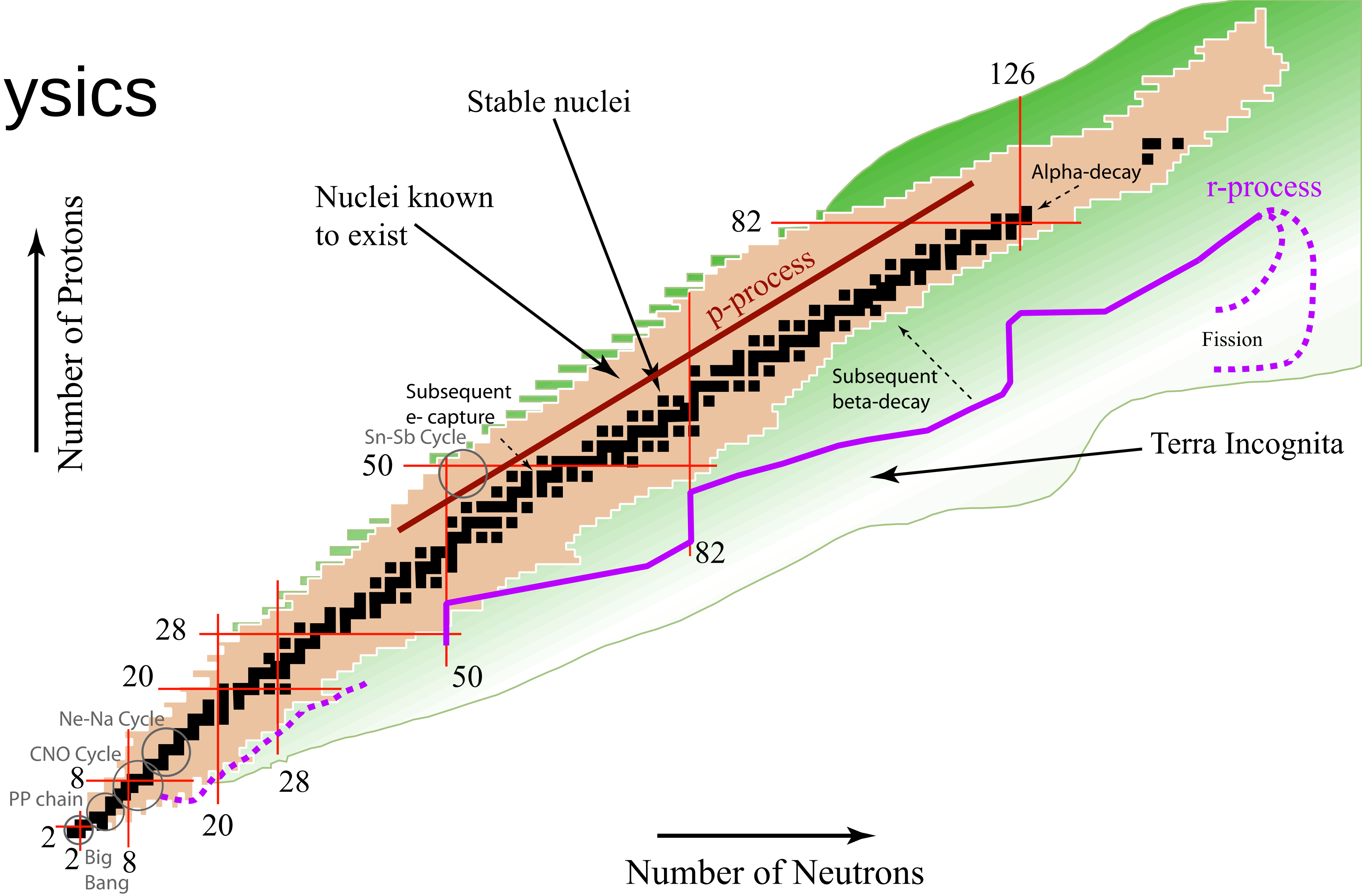
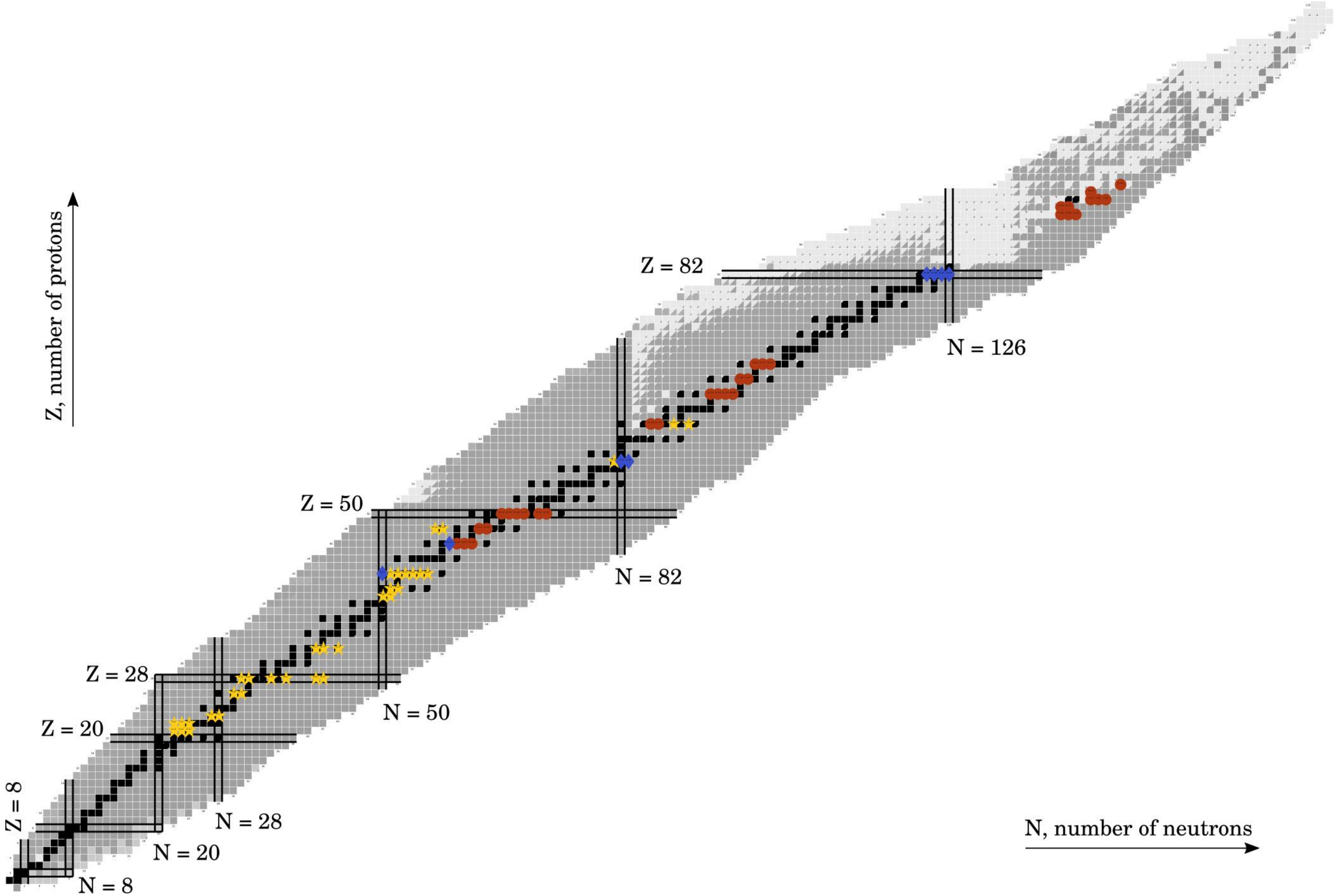


Figure credit: F. Timmes, http://cococubed.asu.edu/images/nuclide_chart/table_nuclei04.pdf

The Oslo Method

- Developed by the nuclear physics group in Oslo
- Method to extract nuclear level density and gamma strength function
- Excitation energy tagged gamma spectra
- Only method able to simultaneously extract nuclear level densities and gamma strength function
- Used by researchers in USA, Japan, China, France, etc.

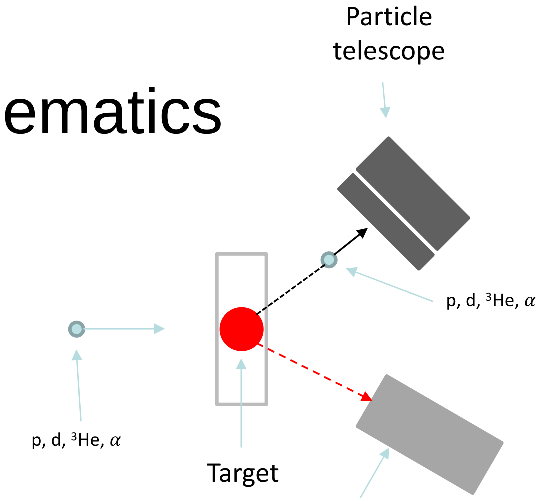


J. Midtbø *et al.*, Phys. Rev. C **98**, 064321 (2018)

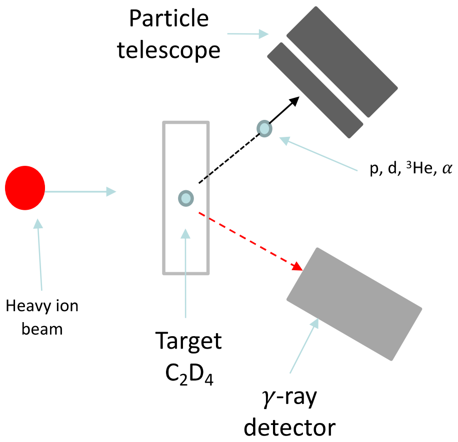
The Oslo Method – experiments

Reactions

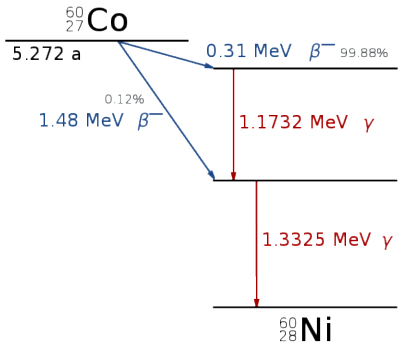
- Direct kinematics

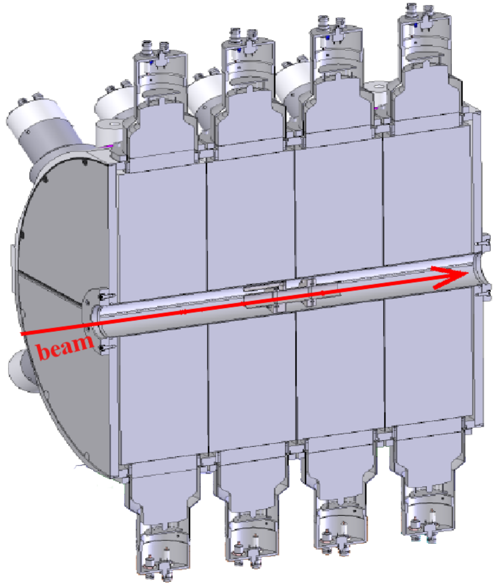


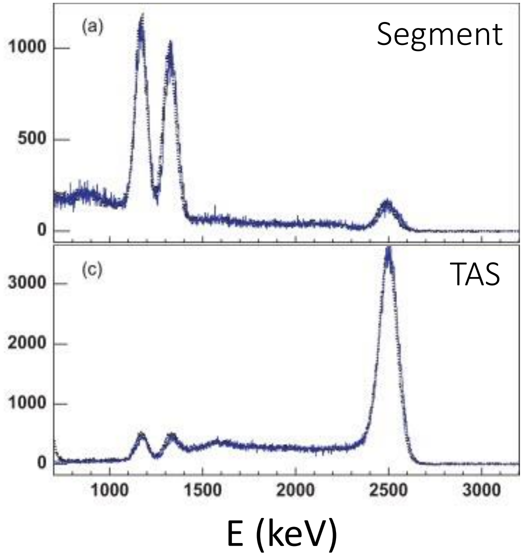
- Inverse kinematics



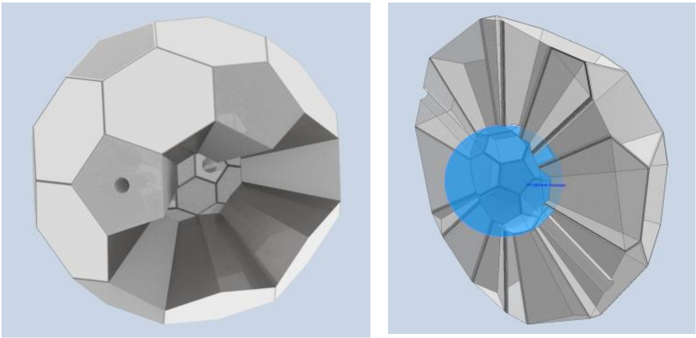
Beta-decay







A. Simon *et al.*, NIM A **703**, 16 (2013)



Design drawings by Maren Lithun, UiO; “StarLight”, of NaI(Tl+Li)

ISOLDE

- Oldest collaboration at CERN
- First beam in 1967
- Provides secondary beams of radioactive nuclei to a variety of experimental setups
- Re-accelerated beams HIE-ISOLDE
- Currently 12 fixed experimental setups
- Roughly half of all protons accelerated at CERN goes to ISOLDE

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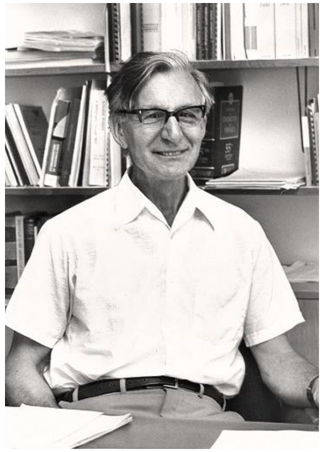
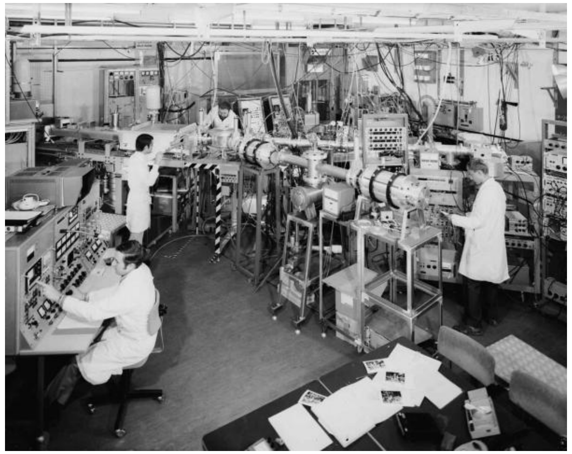
ISOLDE

1992: move from SC to PSB

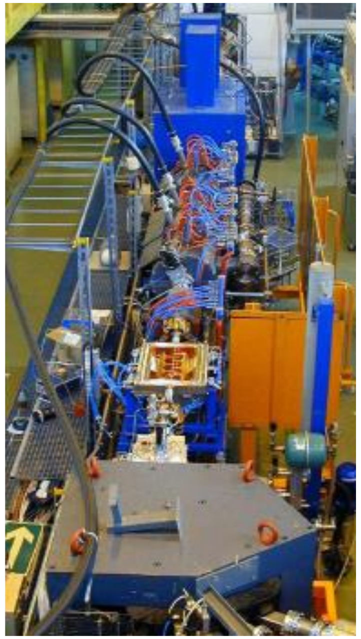


1957: Wolfgang Gentner asks Alexis Pappas (UiO) to assemble a nuclear chemistry group at CERN

1967: First proton beams at ISOLDE



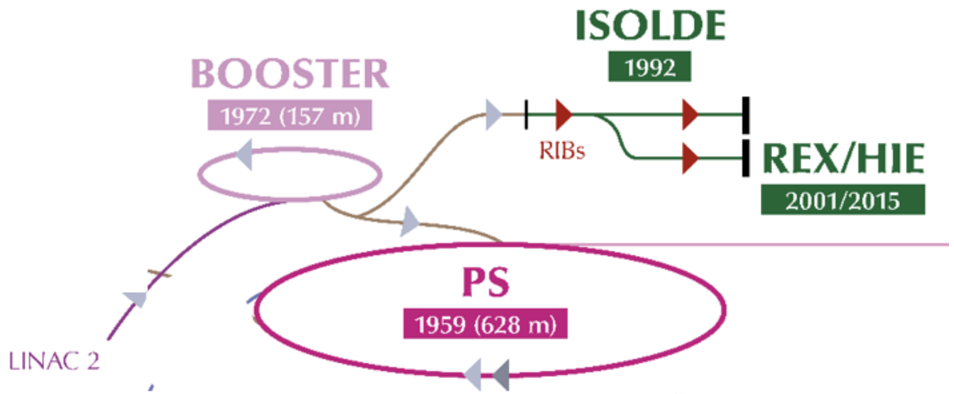
2014-2018: HIE-ISOLDE
High-intensity and high-energy upgrade
new superconducting linac



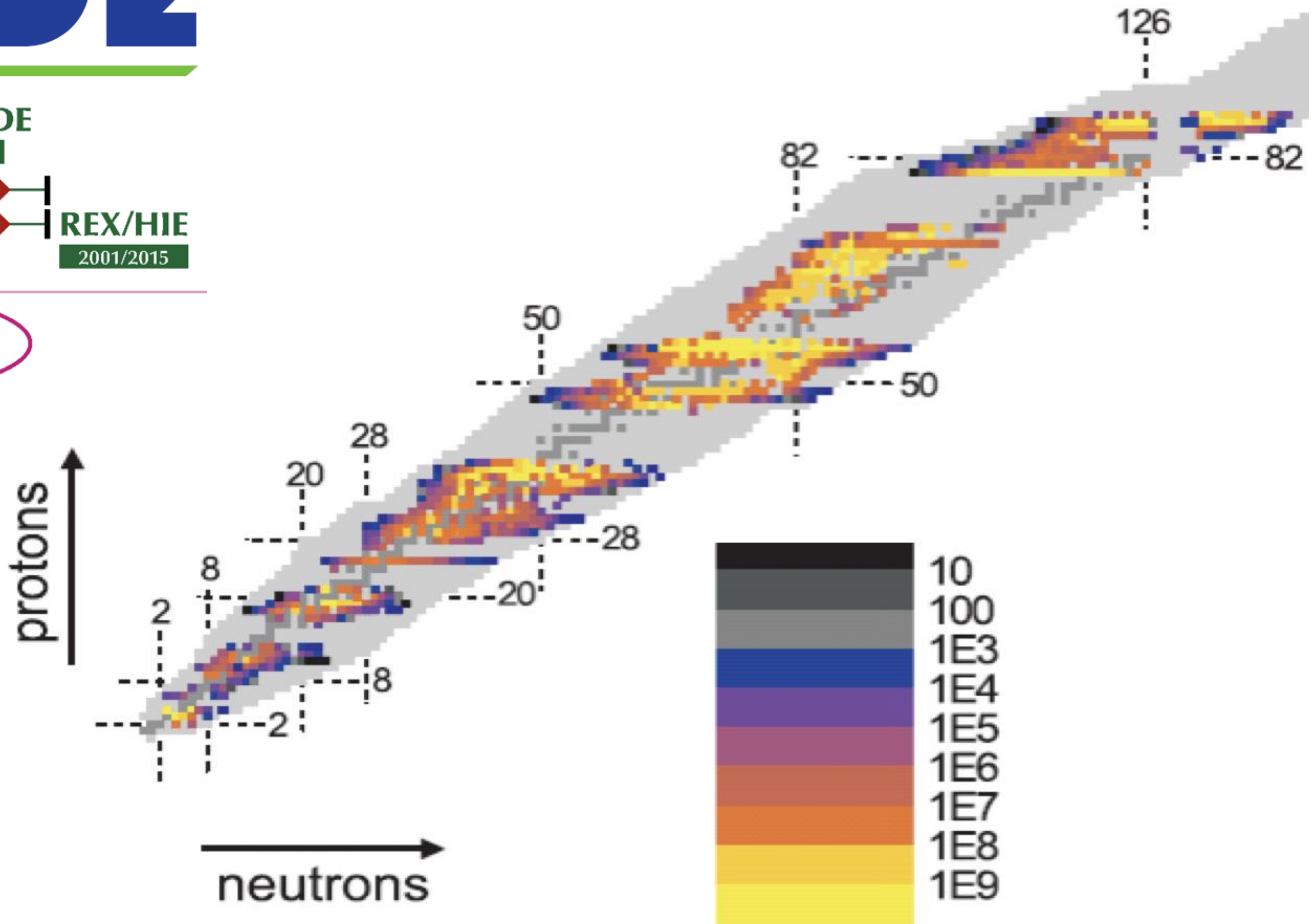
2001: first postaccelerator for radioactive ion beams
REX - ISOLDE

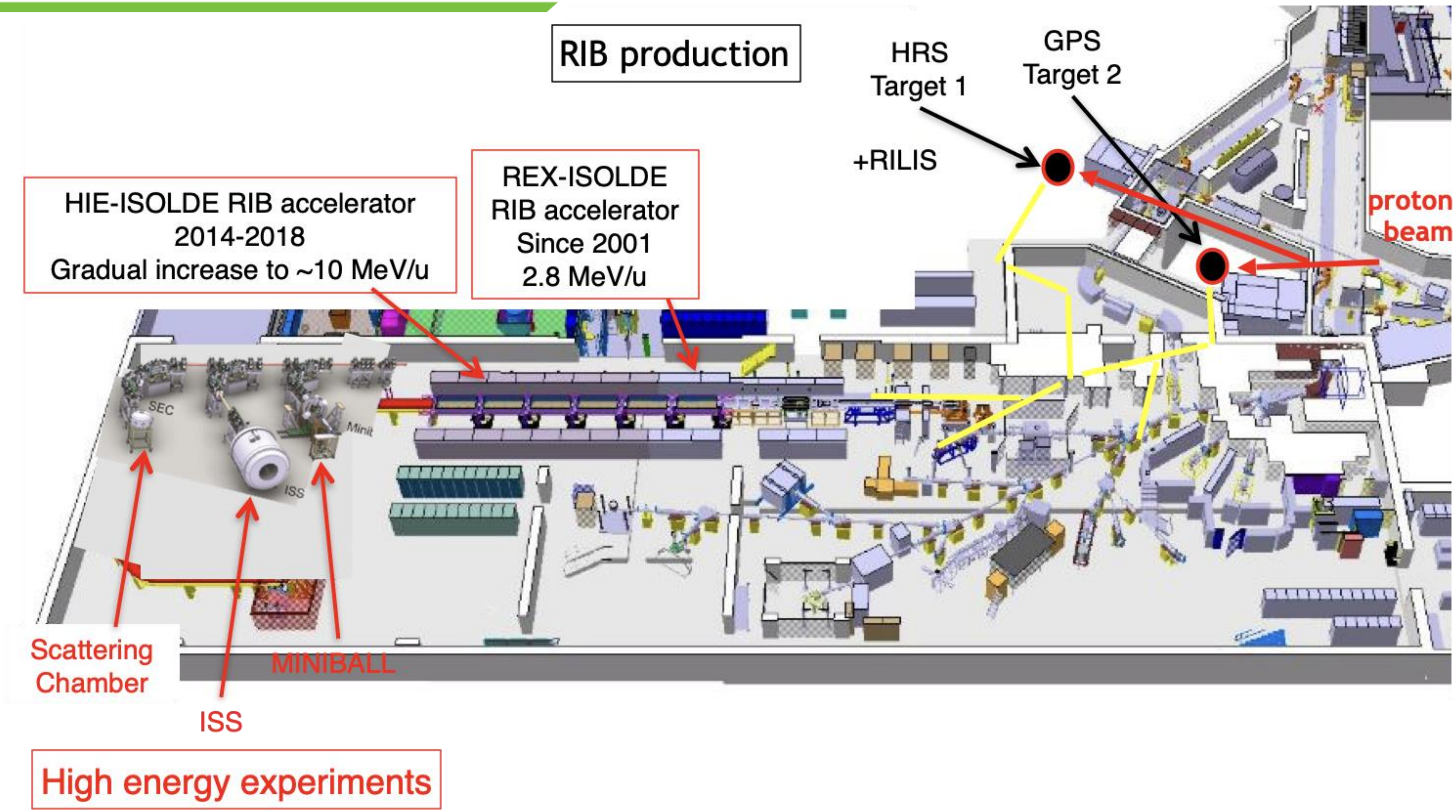
Shift in focus:
nuclear chemistry → nuclear physics

Also in Norway:
UiO nuclear physics group takes over ISOLDE activity from nuclear chemistry in 2006



Capable of delivering more than 1300 radioactive nuclei





RIB production
HRS
Target 1
GPS
Target 2
+RILIS
proton
beam
HIE-ISOLDE RIB accelerator
2014-2018
Gradual increase to ~10 MeV/u
REX-ISOLDE
RIB accelerator
Since 2001
2.8 MeV/u
SEC
ISS
Scattering
Chamber
MINIBALL
ISS
High energy experiments

Miniball

- Large segmented HPGe detector array for gamma tracking
- T-REX & C-REX Si particle detector array
- Can be coupled with other devices such as plungers, etc.

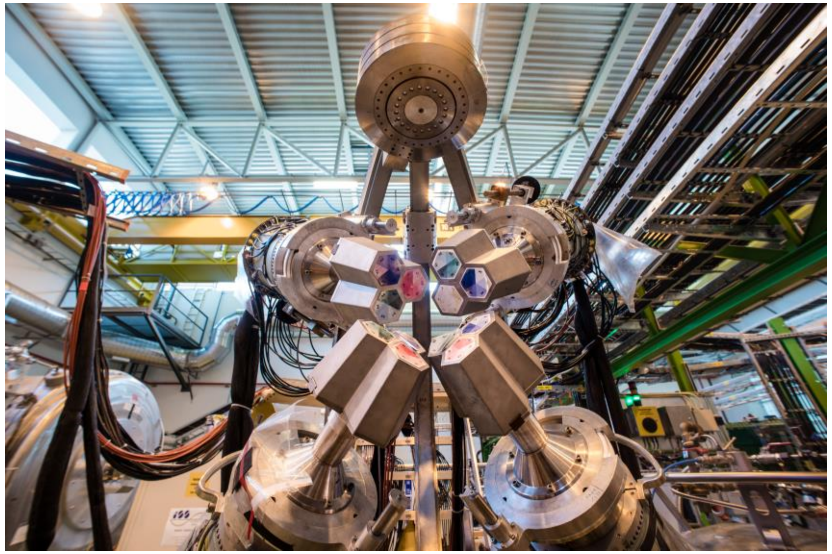
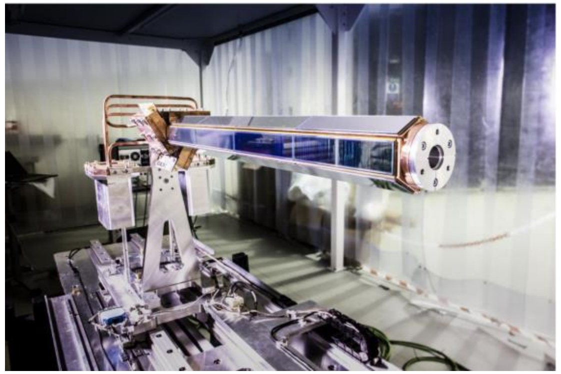
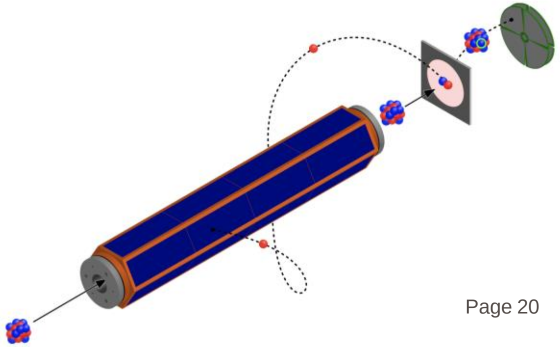


Photo: Julius Marius Ordan/CERN

ISS

- Large MR machine re-purposed as scattering chamber
- Ideal tool for inverse kinematics
- Si array & SpecMAT



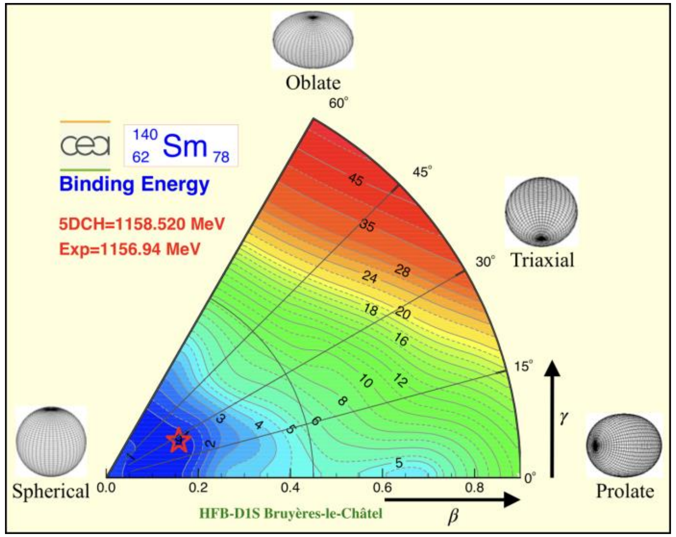


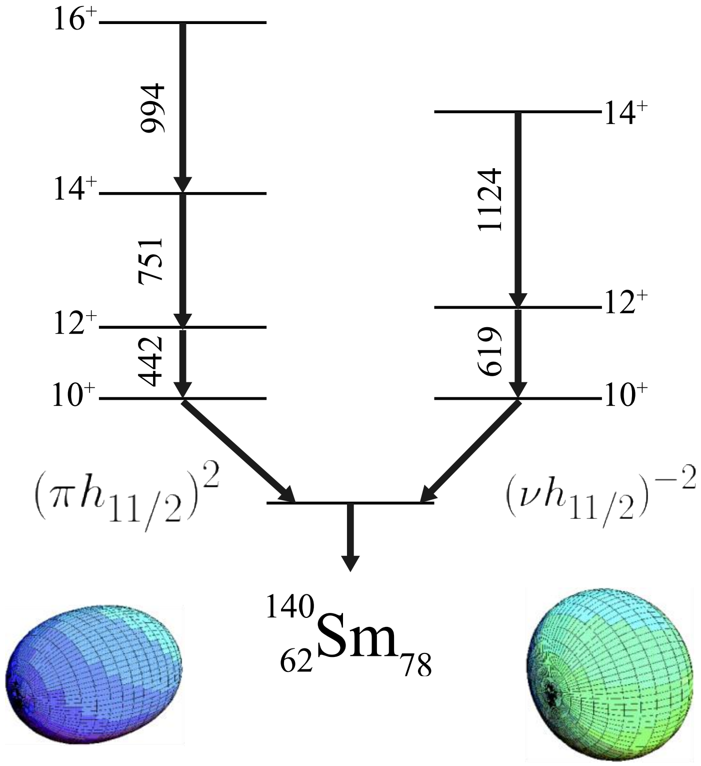
Photos/figures: ISS collaboration

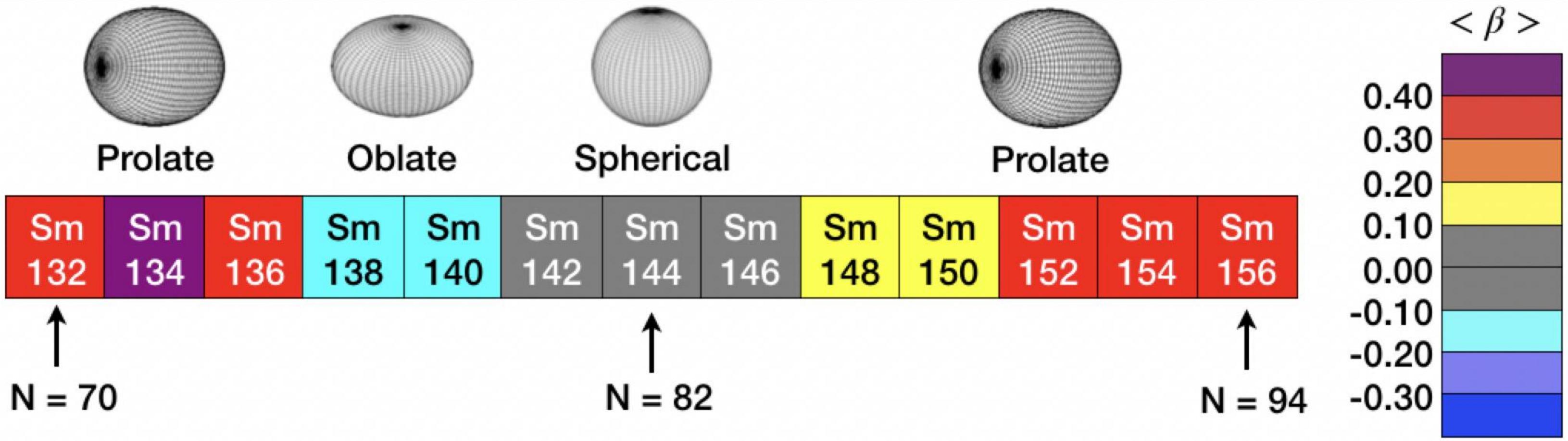
Past experiments lead by UiO at ISOLDE

Shape coexistence - ^{140}Sm Coulomb excitation

- UiO lead experiment
- MINIBALL + C-REX array
- ^{140}Sm beam @ 4.1 MeV/u on ^{208}Pb



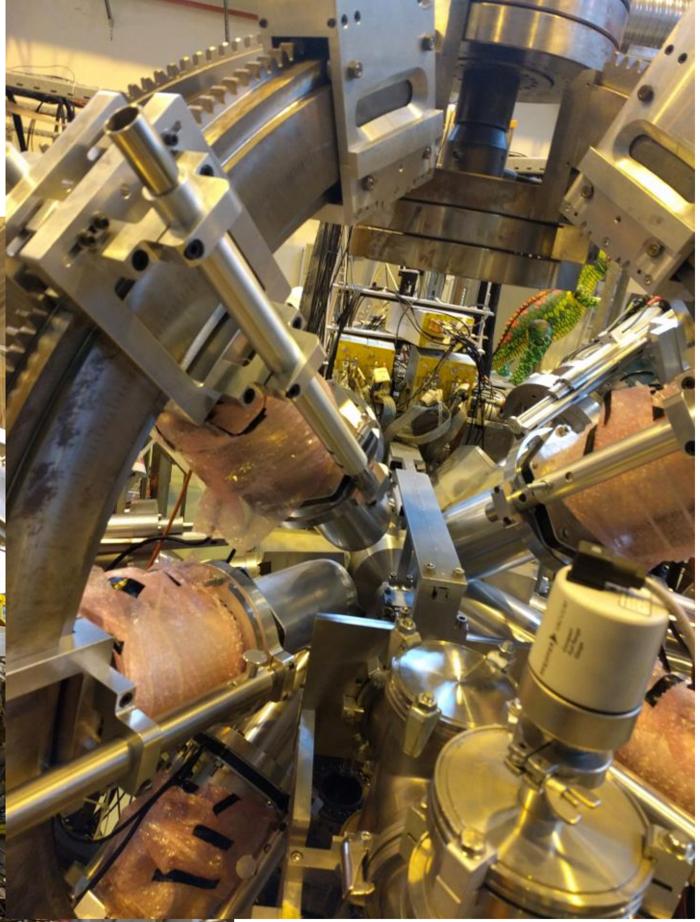




Past experiments lead by UiO at ISOLDE

The Oslo Method with inverse kinematics –
first ever with radioactive beam

- Investigate the ^{66}Ni(n,g) bottleneck the weak i-process
- ^{66}Ni beam impinging on deuteron enriched polyethylene target
- Beam energy: 4.47 MeV/u
- Miniball + C-Rex
- Supplemented with $LaBr_3$:Ce detectors from OSCAR
- Paper in review



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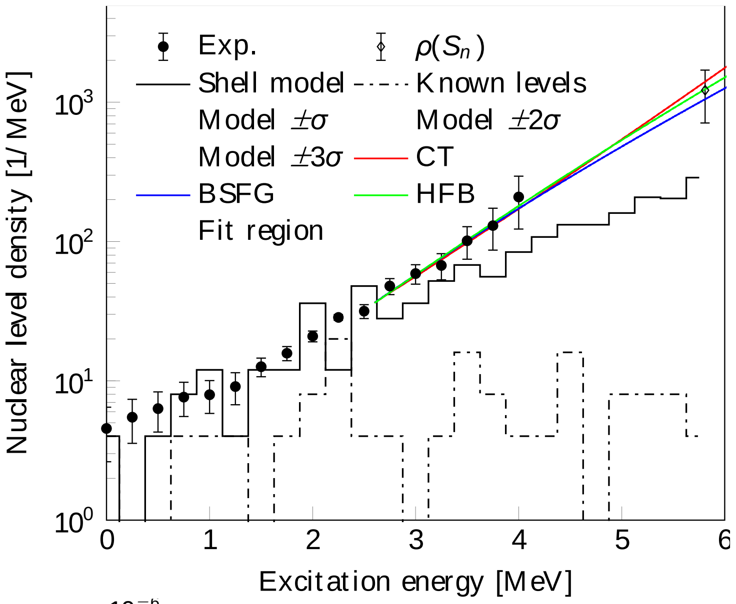
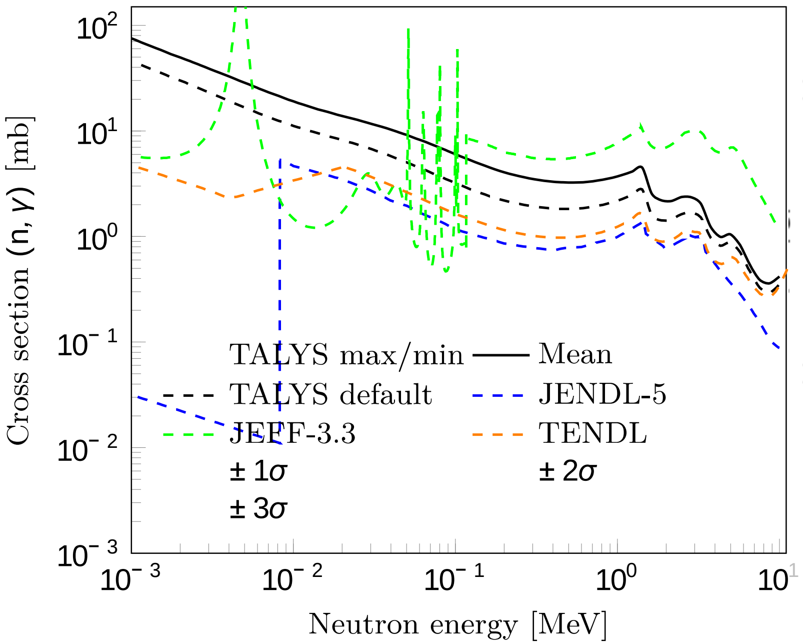
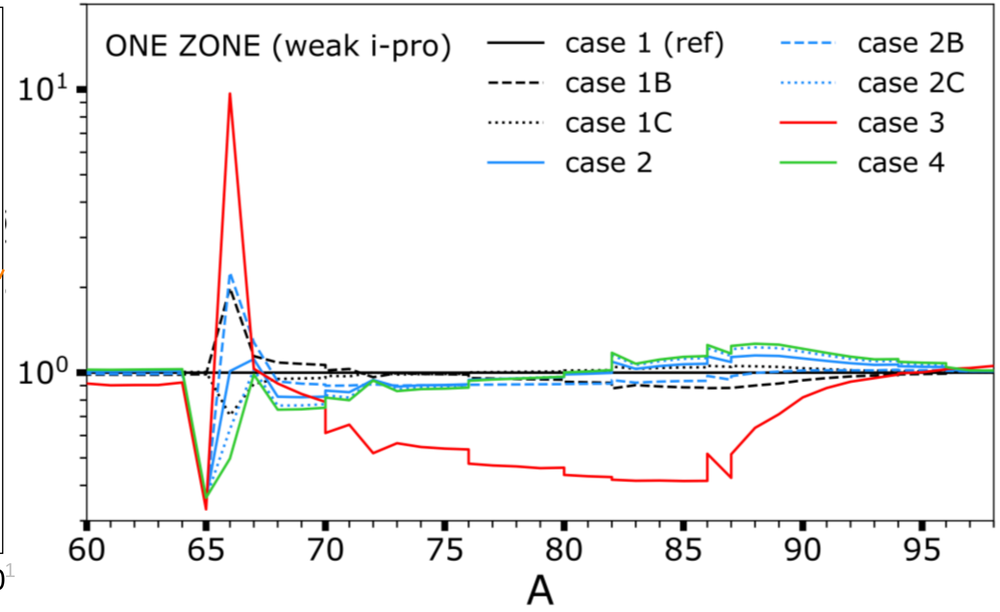
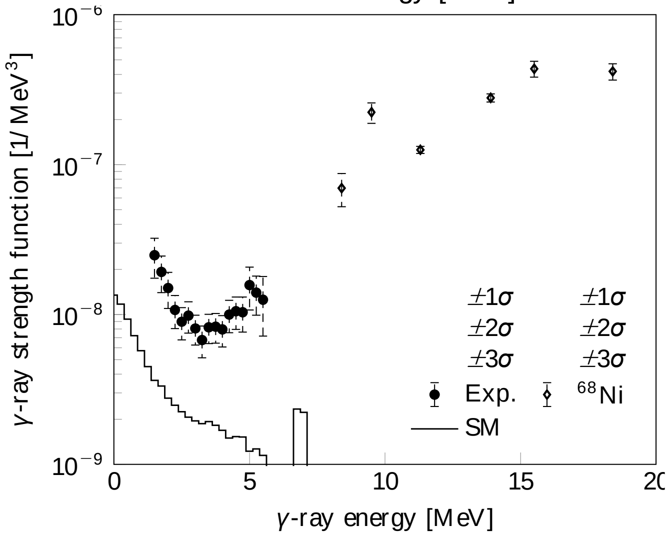
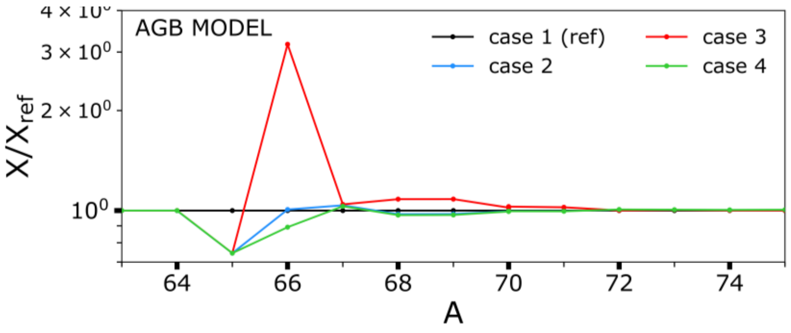
Oslo Method at HIE-ISOLDE

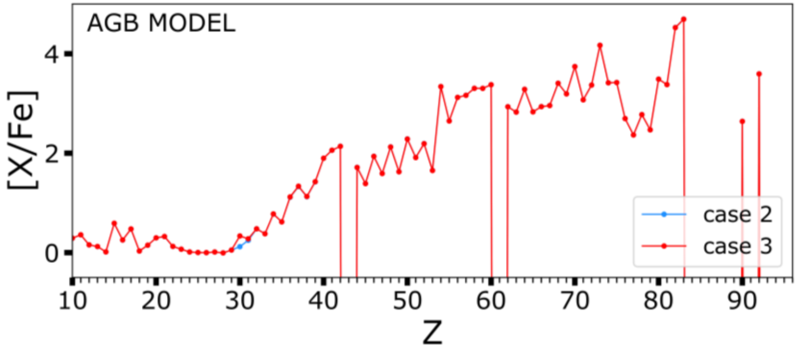








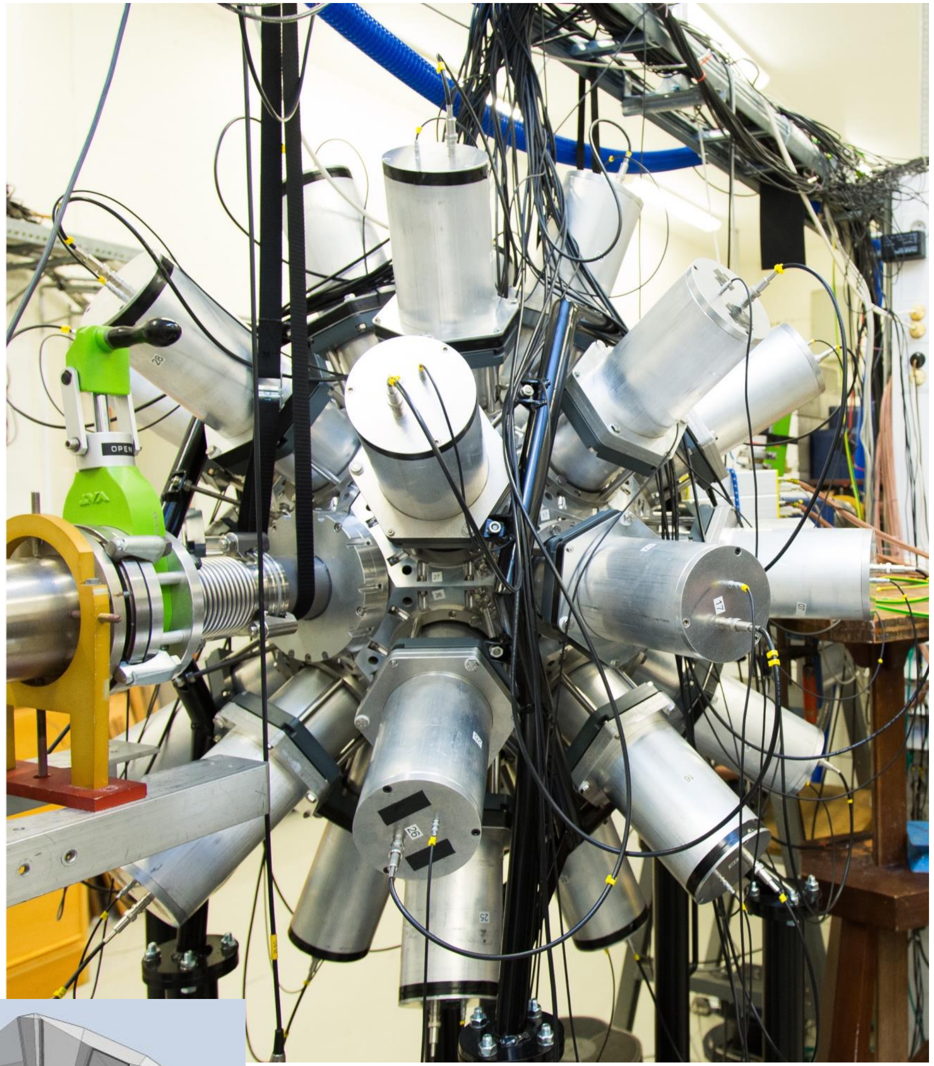


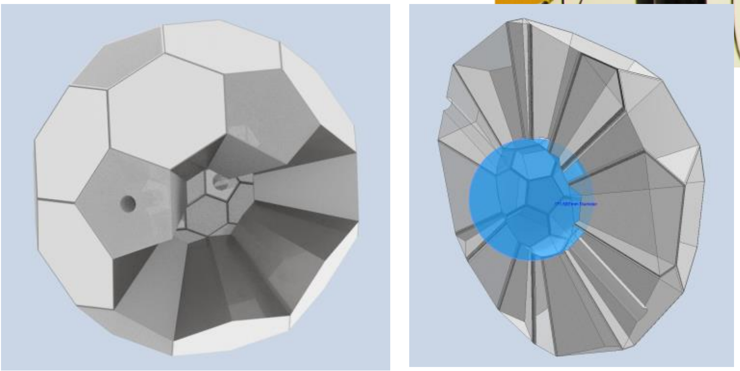


V. W. Ingeberg *et al.*, Phys. Rev. C (in review)

Activity at ISOLDE during Run 4: OSCAR goes to Genève

- Apply the Oslo Method to neutron rich/exotic nuclei relevant for nucleosynthesis
- Oslo SCintillator ARay (OSCAR)
- Largest $LaBr_3$:Ce detector array in the world
- 30 3.5x8-inch LaBr3:Ce detectors
- Superior efficiency
- Excellent energy and time resolution
- Experimental campaign (1/2-1 year)
- StarLight

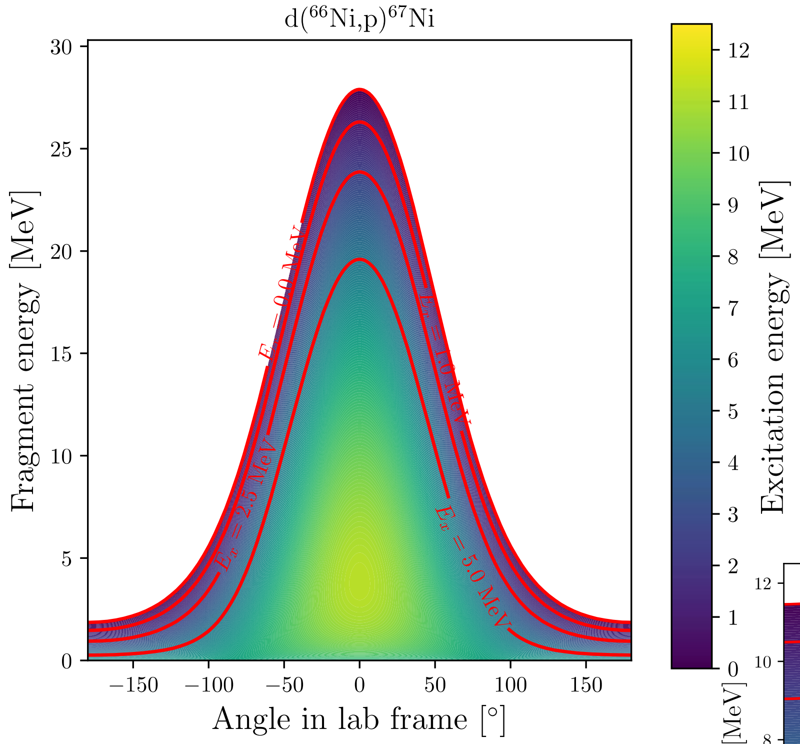


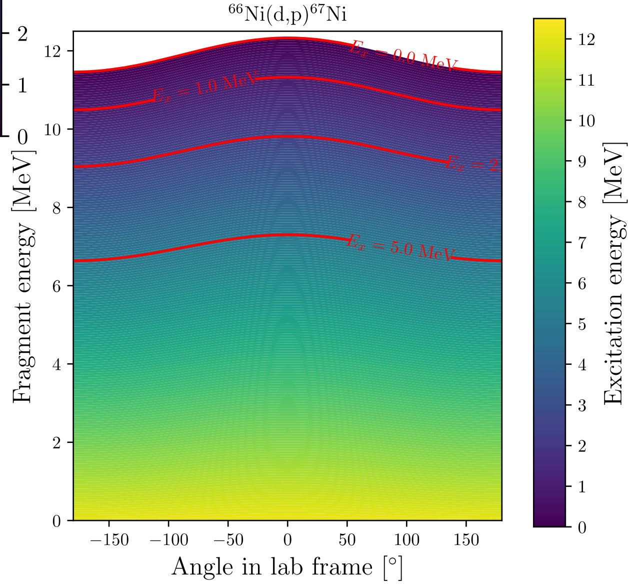


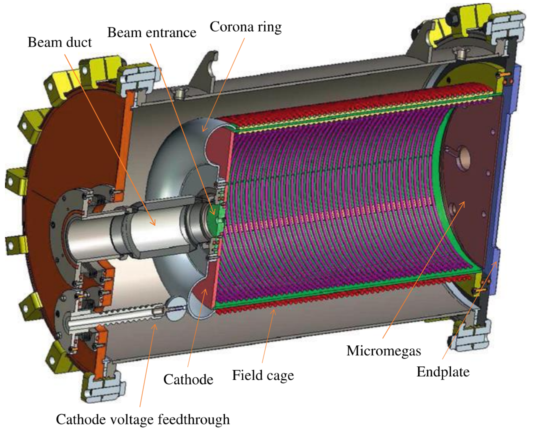
Design drawings by Maren Lithun, UiO; “StarLight”, of NaI(Tl+Li)

OSCAR goes to Genève – Challenges

- Excitation resolution
  - Significant kinematics compression
- Target thickness
- Possible solution
  - Active target
  - TPC + Si detectors/scintillator detectors
  - Develop SiPM readout for OSCAR
- Analysis challenges: Event-by-event unfolding
- Possible synergy with detector development in ATLAS/ALICE?







D. Suzuki *et al.*, NIM A **691**, 39 (2012)

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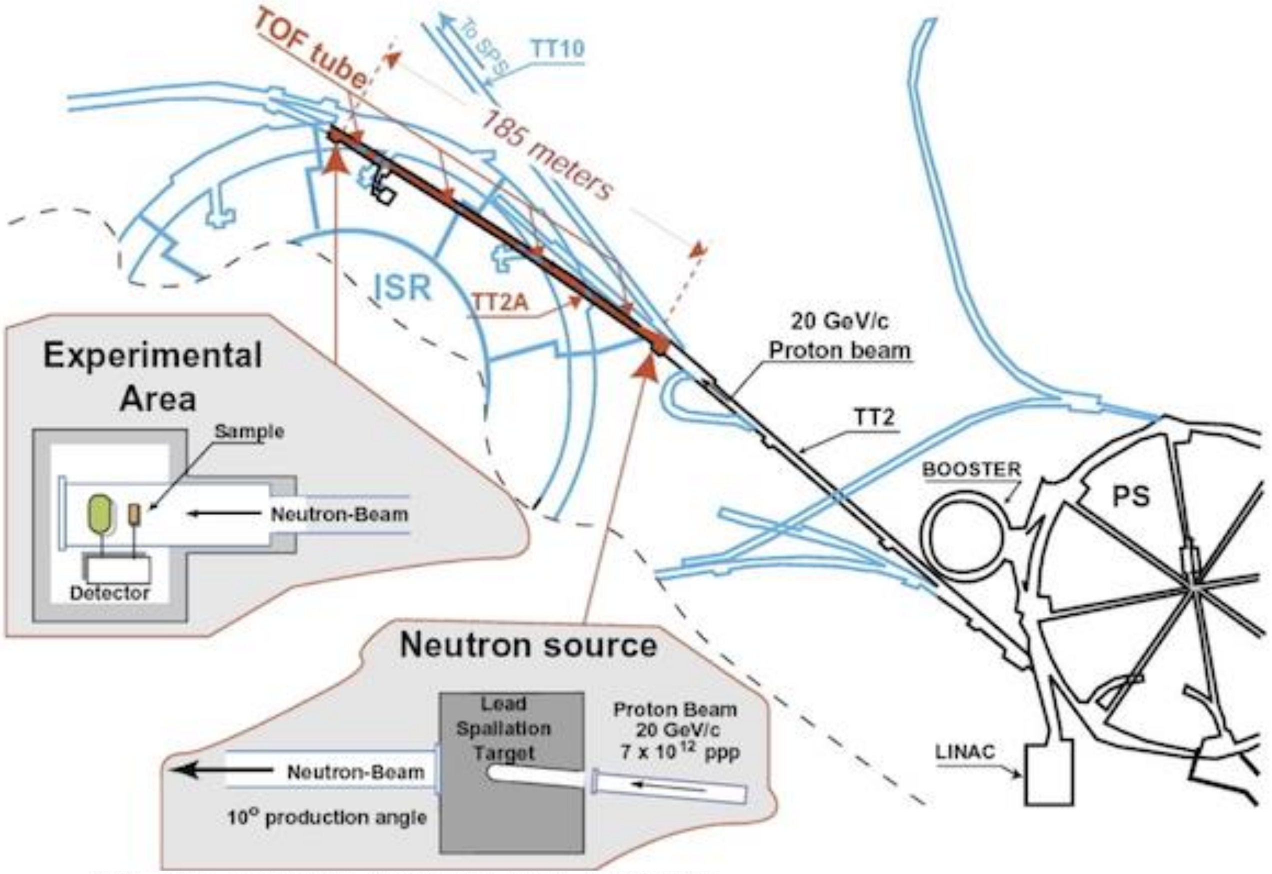
n_TOF

- Neutron time-of-flight facility at CERN
- Neutrons produced through spallation due to 20 GeV/c protons on lead target
- Long 185-metre TOF beam line
- Provides neutrons with energies ranging from meV to GeV
- Complements data from ISOLDE and Oslo Cyclotron Laboratory



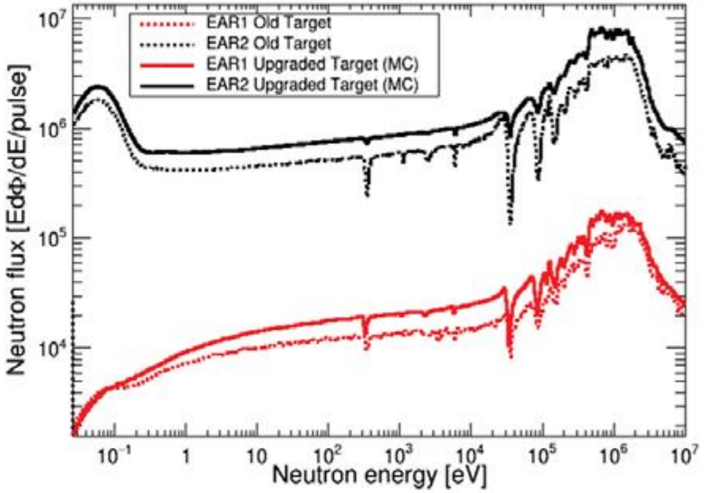
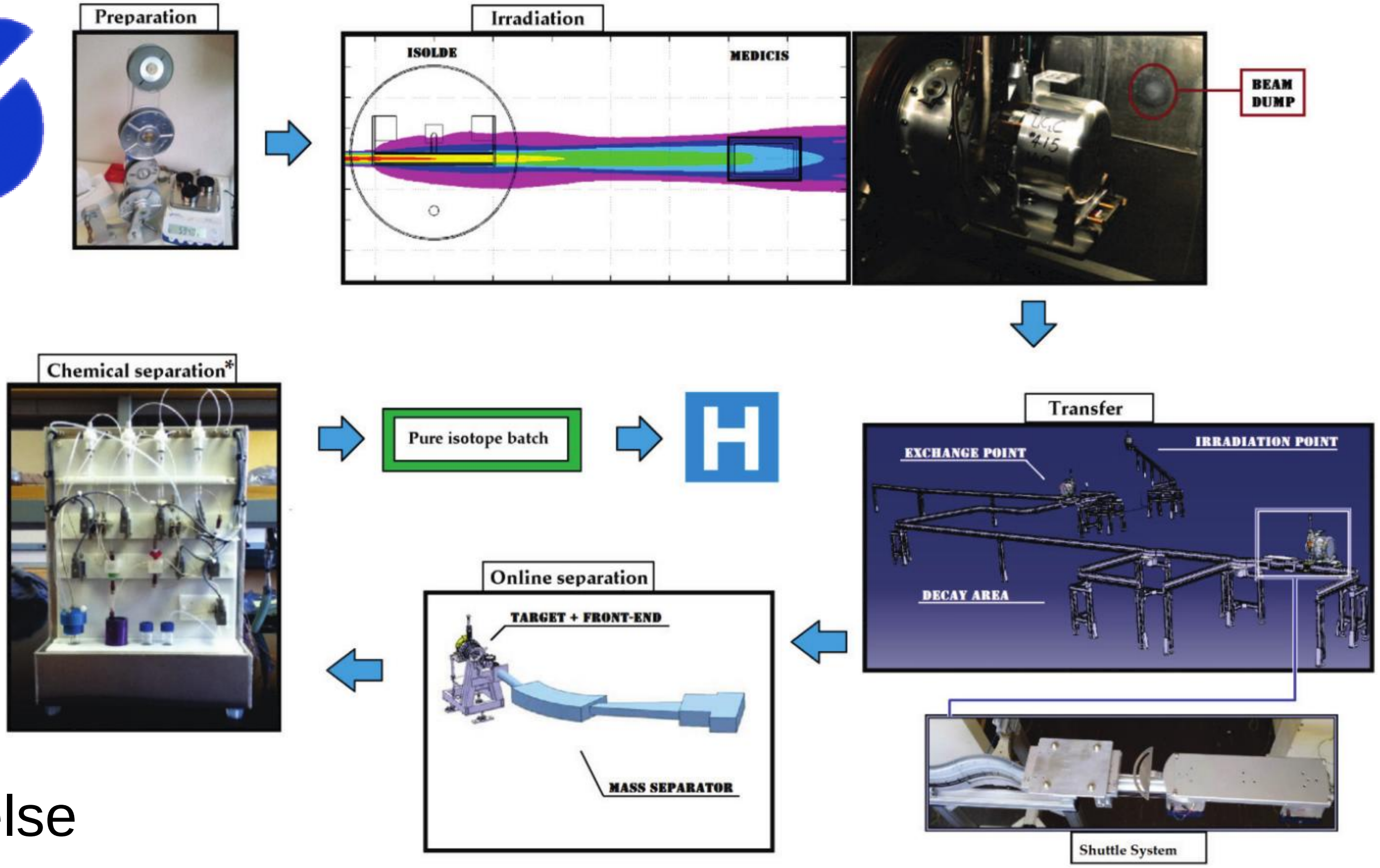


Fig. credits: C. Domingo-Pardo *et al.*, J. Phys. Conf. Ser. **2586**, 012150

MEDICIS

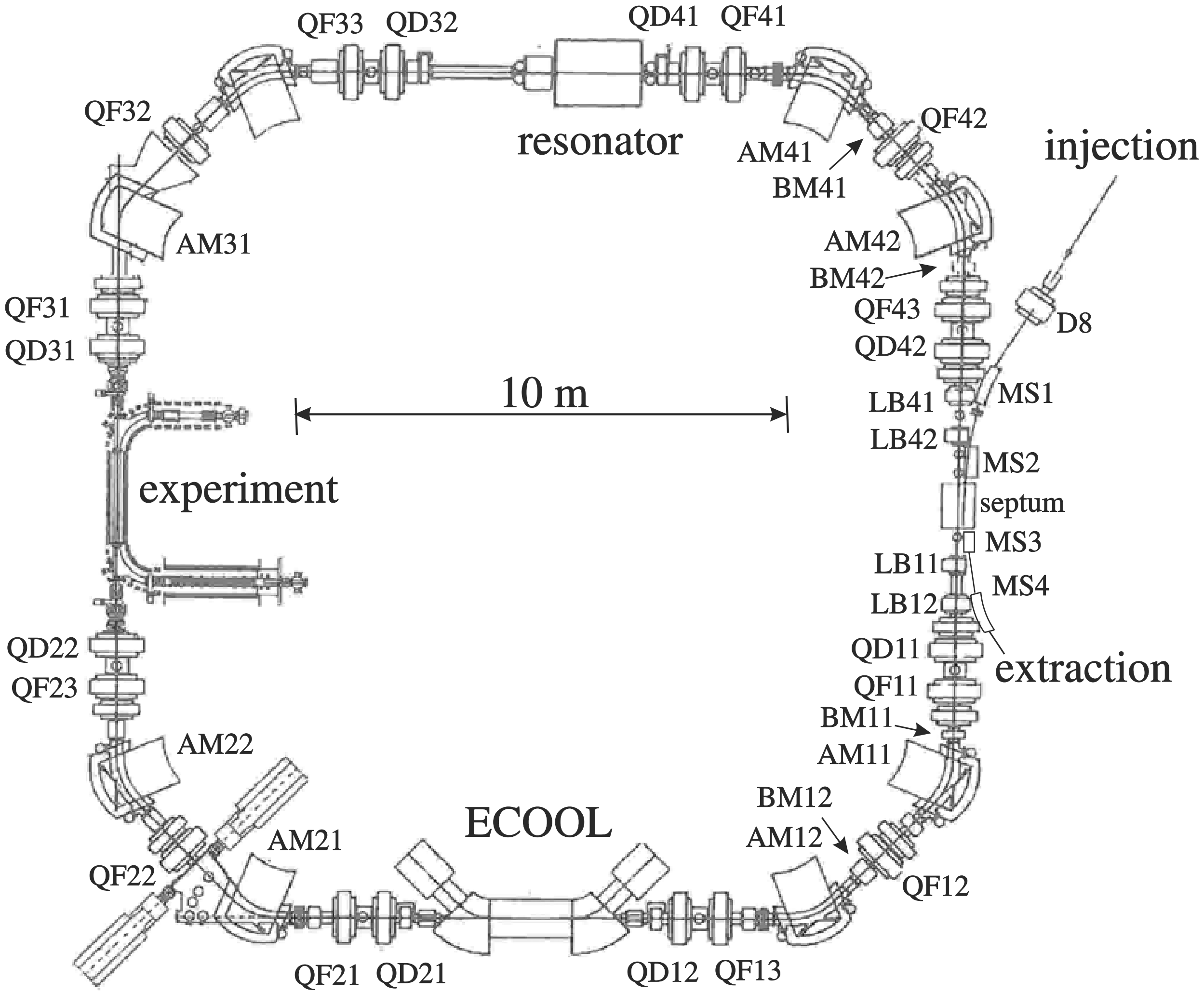


R. M. Dos Santos Augusto *et al.*, Appl. Sci. **2014**, *4*, 265

- Initiated in 2010
- Commissioned in 2017
- Spin-off from ISOLDE
- Using un-reacted protons from the ISOLDE primary targets
- Unique facility able to provide radioisotopes not available anywhere else
- Membership would help secure access to radioisotopes for Norwegian medical research

Long term future for ISOLDE

- Storage ring at HIE-ISOLDE
- Cooled radioactive nuclei
- Allows for measurements currently not possible
- More precise measurements
- We can contribute with dedicated in-ring setup for neutron transfer reactions with gamma spectroscopy



M. Grieser *et al.*, Eur. Phys. J. Spec. Top. **207**, 1 (2012)