A Taste of Nuclear Structure from an Experimental Point of View (in two lectures)

😳

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n_TOF Winter School 2023

Plan of Action

Keep it simple and give a flavour of WHY/WHAT/HOW of nuclear structure.

- Back to basics: what is a nucleus?
  nucleus as a quantum system, single-particle and collective structure, exotic nuclei – not comprehensive, just a flavour!
- What characterises a nucleus and how do we study them?
  nuclear properties, nuclear reactions, historical context, stable and exotic ion beams.
- Case study: some recent example measurements from ISOLDE@CERN – will push the boundaries of nuclear structure into other areas
- Perspectives.

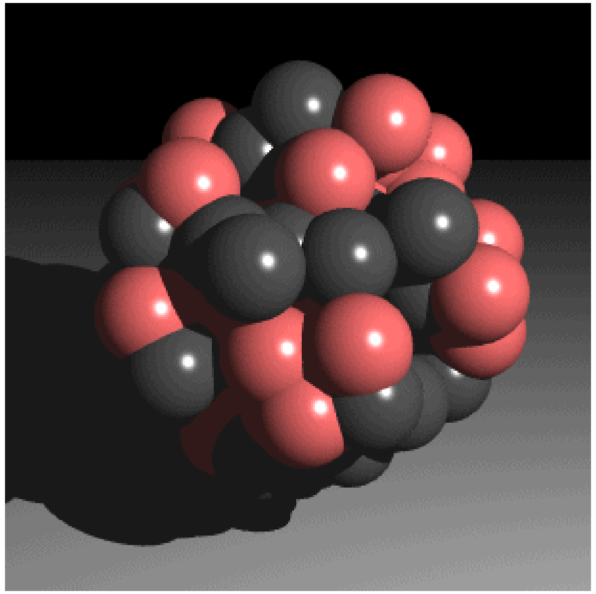
PHYSICS

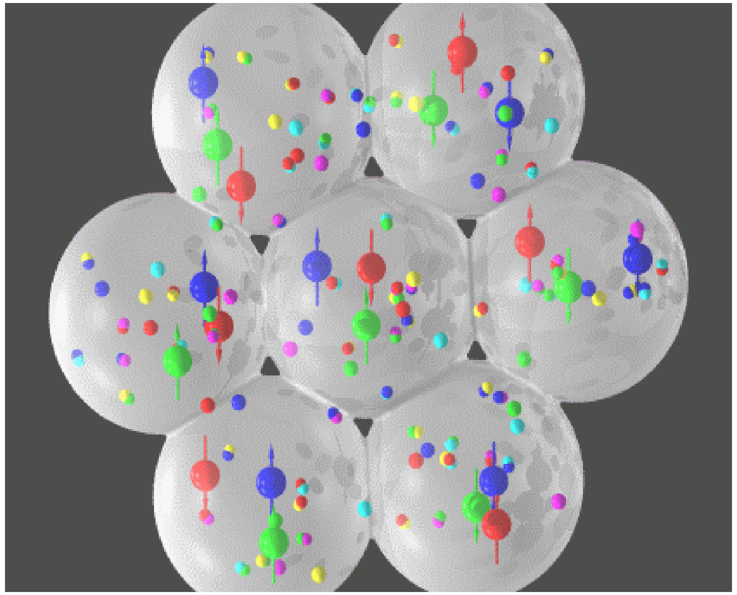
EXPERIMENTS

⚠ - taking an experimental, intuitive, pedagogical, heuristic approach – with lots of "cartoon" explanations!

What is a nucleus?

- Protons (charged) and neutrons; *nucleons*.
- Electrostatic repulsion vs strong attraction.
- Nucleon incompressibility, r=1.2A$^{1/3}$ fm.
- Looks static, dull and uninteresting.

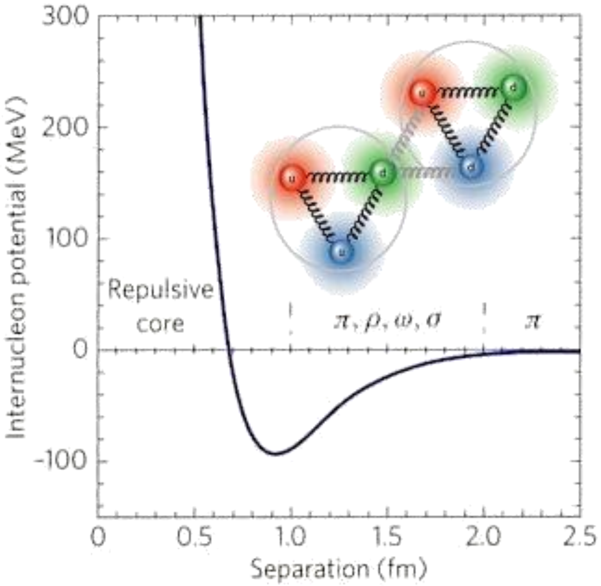


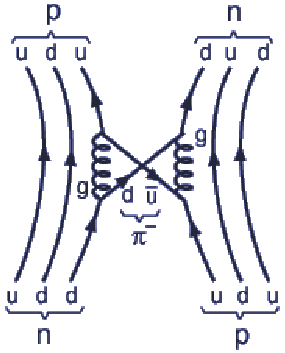


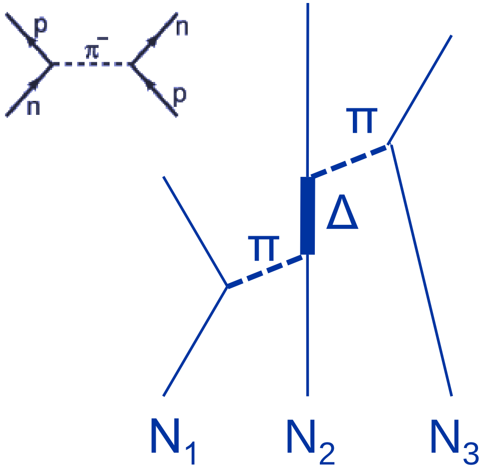
- Quantum mechanics makes it much more dynamic – see next.

- N-N binding force that depends on separation, spin orientation, and relative momentum with tensor, non-central and exchange contributions.

- In-medium effects make things even more complex with three-body forces and higher order contributions.







Challenges in nuclear structure

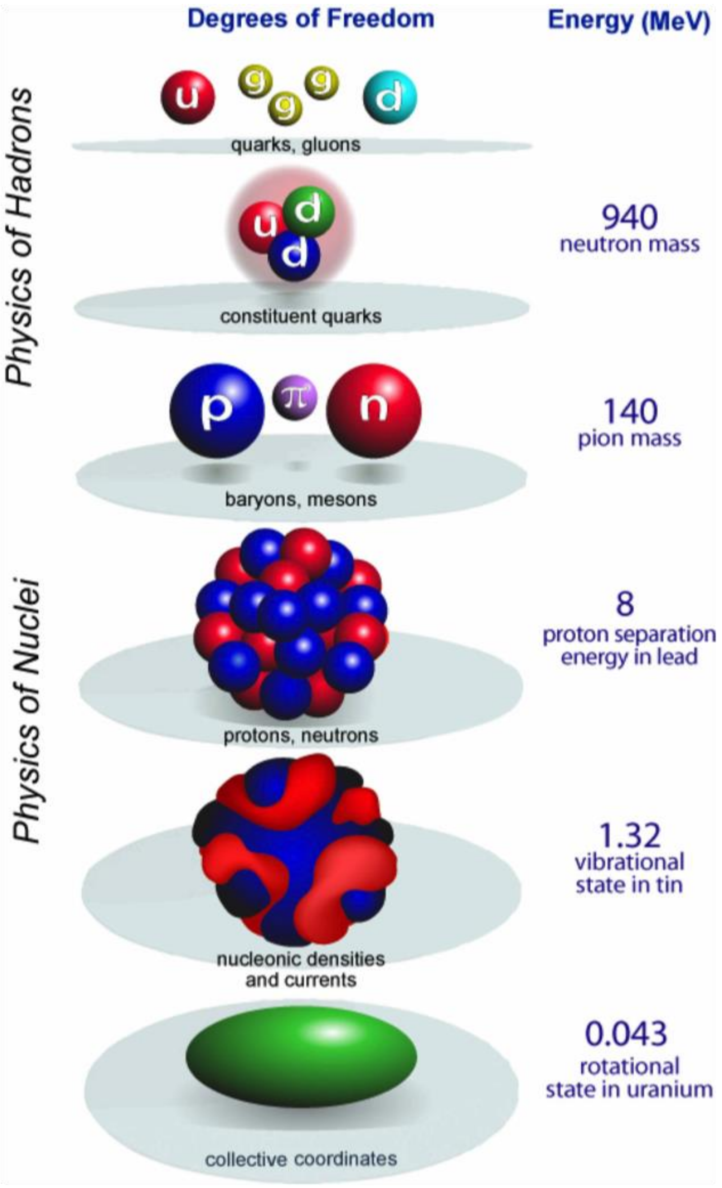
- Describe a many-body system using quantum mechanics where particles interact via a complicated force.

- In principle, could operate like solving hydrogen atom.
  Ab-initio Models: write down the Schrödinger equation for each nucleon including interactions with all other nucleons using nucleon-nucleon interaction – complex coupled equations.

- Calculations beyond A=12 become difficult; with a good form of the N-N force:
  - ^{4}He takes ~1 cpu-hour
  - ^{8}Be takes ~300 cpu-hour
  - ^{12}C takes ~70,000 cpu-hour (8 years!)

- In principle, could operate like solid-state physics and use statistical mechanics, but not enough 300 particles rather than 10^{23}!

- Some analogy with a liquid droplet, can approach macroscopically.



Mean-field approaches to single-particle structure

- *Mean-field potential*: assume that all the interactions with all the other nucleons averages out to some potential that only depends on the coordinates of the nucleon in question. Schrödinger equation separates into single nucleon equations.

- *Hartree-Foch* is one theoretical tool – but you can guess the general form!

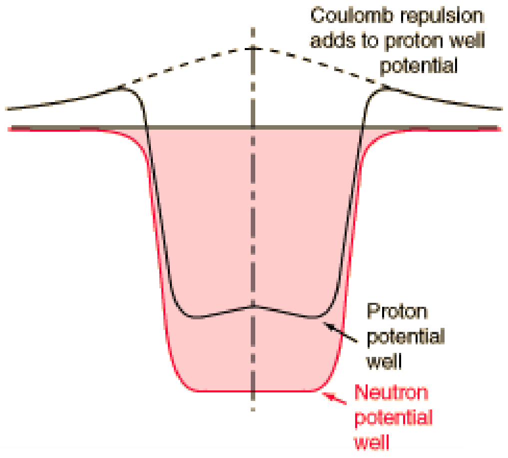
- The *nuclear shell-model* uses a simple approach with a harmonic oscillator potential with a *spin-orbit interaction* – could use anything that is a complete basis set!

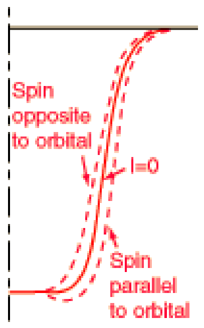
- *Spin-orbit interaction* is a famous addition from 75 years ago that "fixes" the magic numbers.

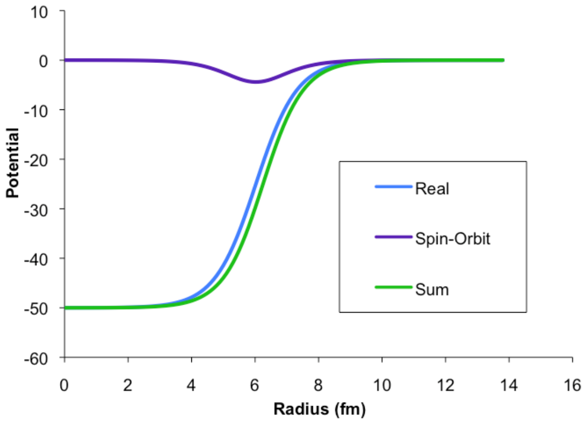
- *Run the now easy quantum mechanics and get levels in the well…*

Example of potentials for a neutron bound to a ^{112}Sn nucleus

$$\hat{H}\Psi \approx \left[-\frac{\hbar^2}{2m}\sum_i^A \nabla_i^2 + U(r_i)\right]\Psi = \sum_i^A h_i\Psi = E\Psi$$



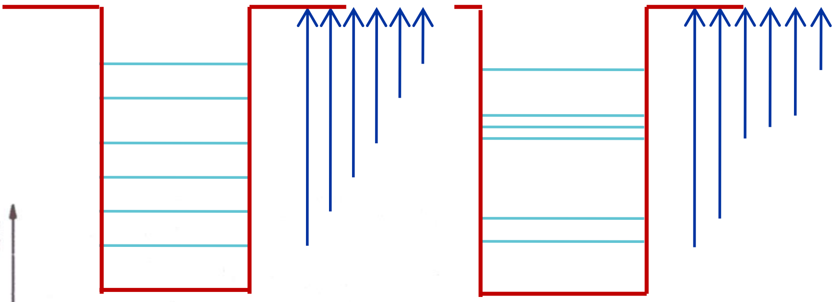


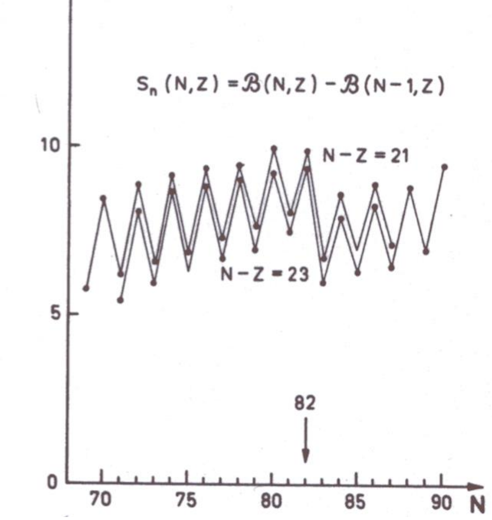


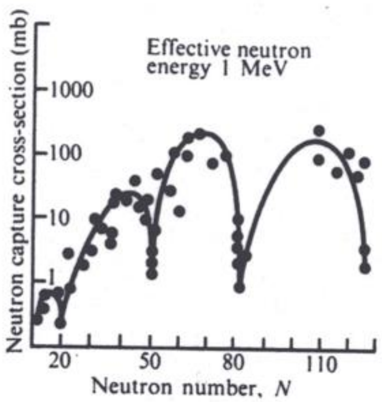
$$V_{so} = -V_0\frac{1}{r}\frac{\partial U(r)}{\partial r}\ell.\mathbf{s}$$

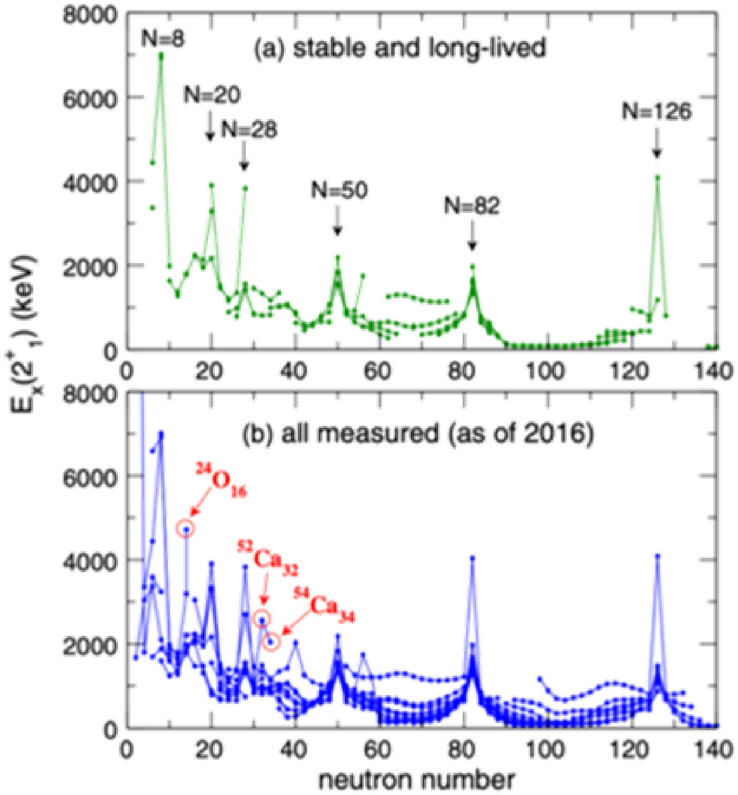
Magic numbers

Nucleons as fermions fill single-particle levels…clumping of levels causes jumps in nuclear properties.

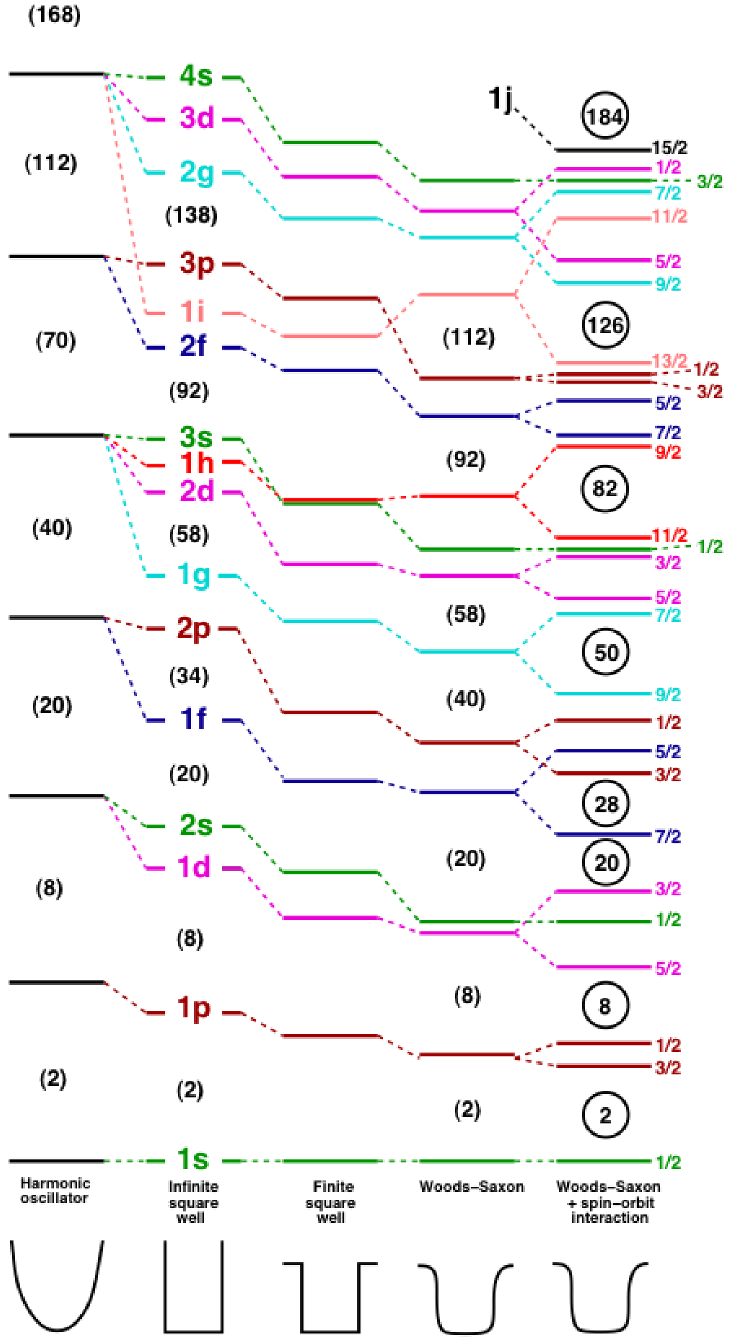








from Rev. Mod. Phys. 92, 015002 (2020)



(STABLE) Magic numbers 2, 8, 20, 28, 50, 82 and 126

But starting to these disappear and new ones appear away from stability.

Independent-particle model:

Single-nucleon wavefunctions characterised by:
n, l, and *j* quantum numbers.

Nuclear wavefunction constructed using products of single-nucleon wavefunctions coupled to give the right spin and appropriately anti-symmetrised.

BUT – extremely limited success in describing experimental data.
Essentially just spin-parities of a few nuclei around closed shells along the line of stability.

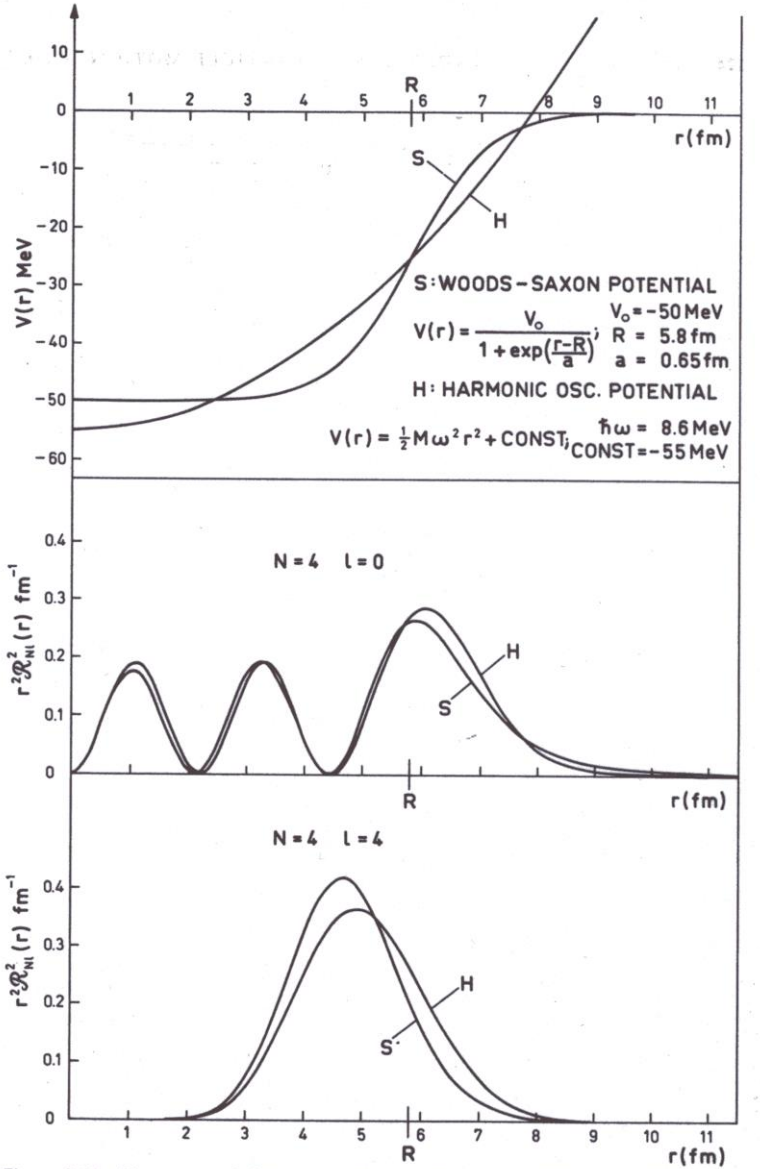


Figure 2-22 The square of the wave function times r^2 for the harmonic oscillator and the Woods-Saxon potential are plotted in units of fm^{-1}.

Beware the residual interaction:

The nucleus is made up of *A* nucleons:

$$\hat{H}\Psi = \left[-\frac{\hbar^2}{2m}\sum_{i}^{A}\nabla_i^2 + \sum_{ij}V_{ij}\right]\Psi = E\Psi$$

Depends only on
coordinates of one nucleon, i
one-body operator

Limit to
two-body interaction – ignoring 3-body forces already!

Invent an AVERAGE or MEAN-FIELD POTENTIAL:

$$\hat{H}\Psi = \left[\sum_{i}^{A}\left(-\frac{\hbar^2}{2m}\nabla_i^2 + U(r_i)\right) + \left(\sum_{ij}V_{ij} - \sum_{i}^{A}U(r_i)\right)\right]\Psi = E\Psi$$

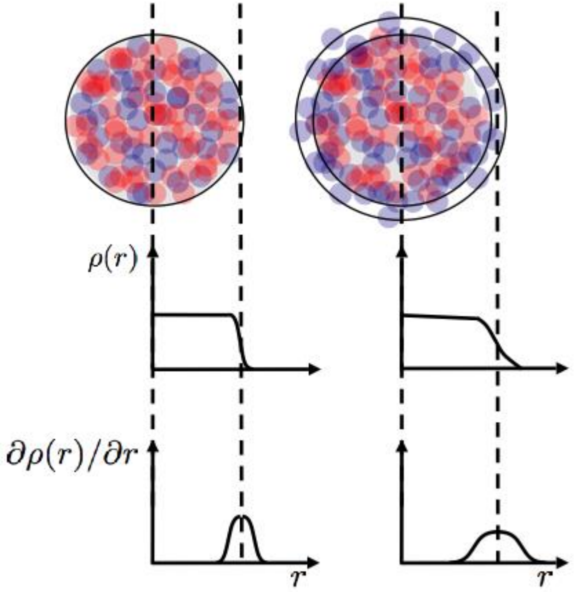
KE plus mean-field potential are
one-body operators
generates IPM configurations as a basis set

the residual interaction,
contains the two-body terms
that mixes the basis sets.

Depends on the motion of nucleons i and j, i.e. the associated single-particle quantum numbers, and builds "correlations" between nucleons. Scatters from below Fermi surface to above (later!).

You cannot ignore the residual interaction – nuclear shell model uses phenomenological residual interactions and matrix diagonalization to solve the problem – results are admixtures of independent-particle configurations.

Expectations in very exotic nuclei:

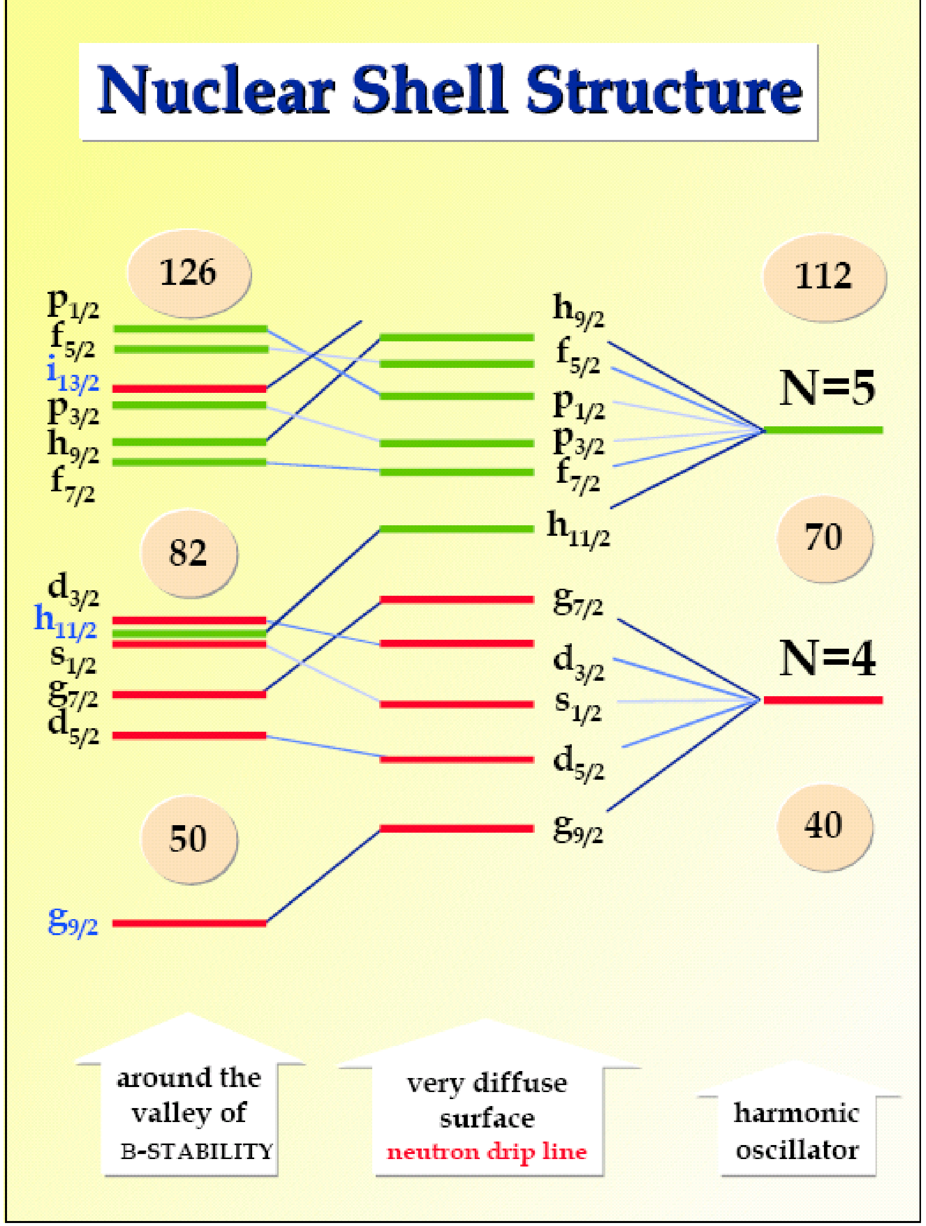


When adding nucleons can expect the system to become less well bound; final nucleons can wander more: surface becomes more diffuse.

$$V_{so} = -V_0 \frac{1}{r}\frac{\partial U(r)}{\partial r}\ell.\mathbf{s}$$

Changes in diffuseness of mean-field potential near neutron drip line may influence spin-orbit interaction:

Nuclei with neutron haloes have been observed!

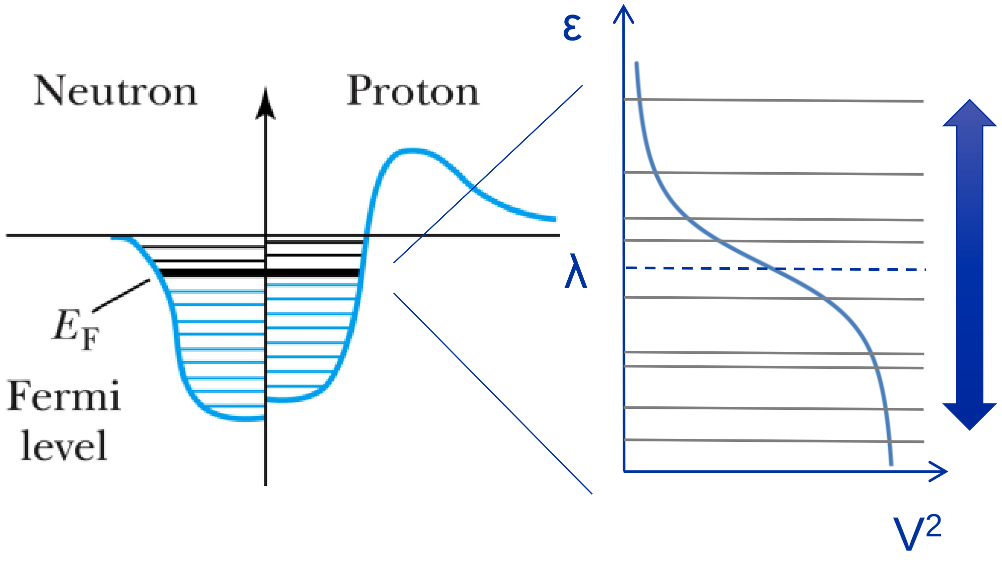


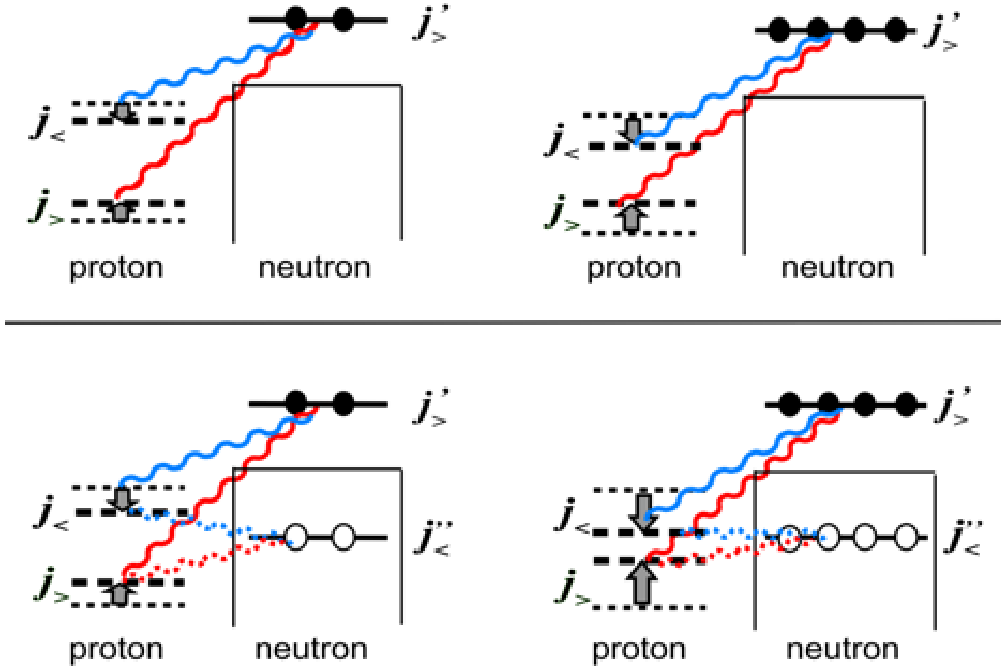
J.Dobaczewski *et al.* Prog.Part.Nucl.Phys. **59** 432 (2007)

Shell evolution

In IPM, protons and neutrons fill the levels according to Pauli, e.g. stable mid-shell nucleus with N>Z.

- Different isotopes have different N/Z
- Fermi surfaces sample different single-particle orbitals.
- Correlations between nucleons depend on their orbitals, expect to different nuclear structure in different nuclei.





from Rev. Mod. Phys. 92, 015002 (2020)

- Potentials around 50 MeV deep (nucleon scattering).
- Energy in N-N residual interactions
- << 7 MeV (binding energy per nucleon).
- Residual interactions scatter nucleons from orbitals around the Fermi level.

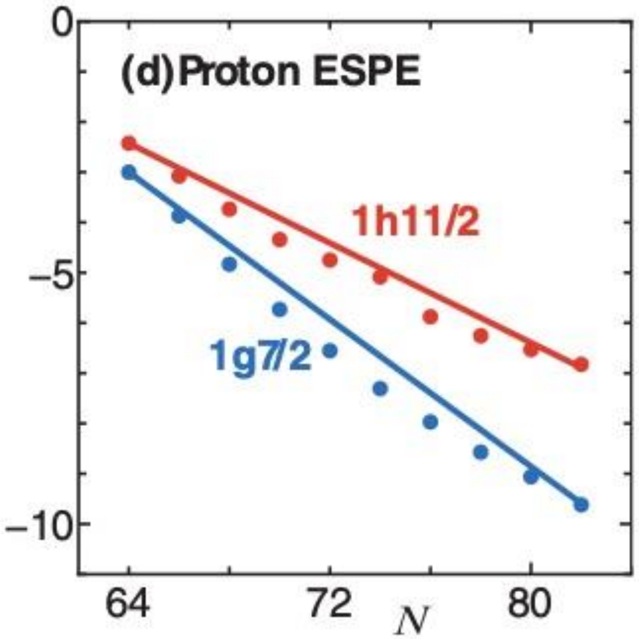
- Expect changes in shell structure of protons/neutrons as you move along a chain of isotones/isotopes – sometimes enough to create or destroy magic numbers
- Expect differences in the overall effect of residual interactions when you excite nucleons within a nucleus.

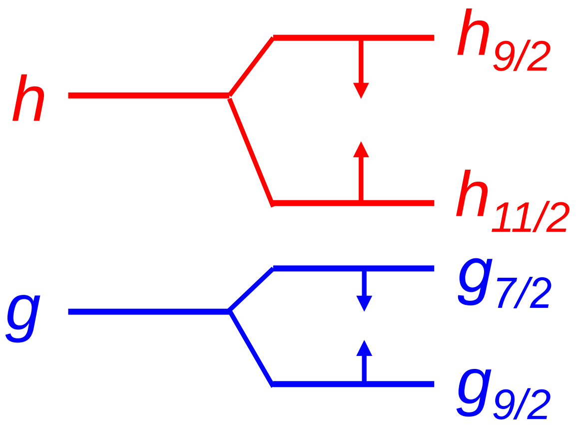
Shell evolution

^{16,18}O are stable!

As chains of isotopes and exotic nuclei are probed, beginning to see examples of phenomena.

Proton states in Sb isotopes probed by gently adding a proton to Sn targets in a *transfer reaction*.



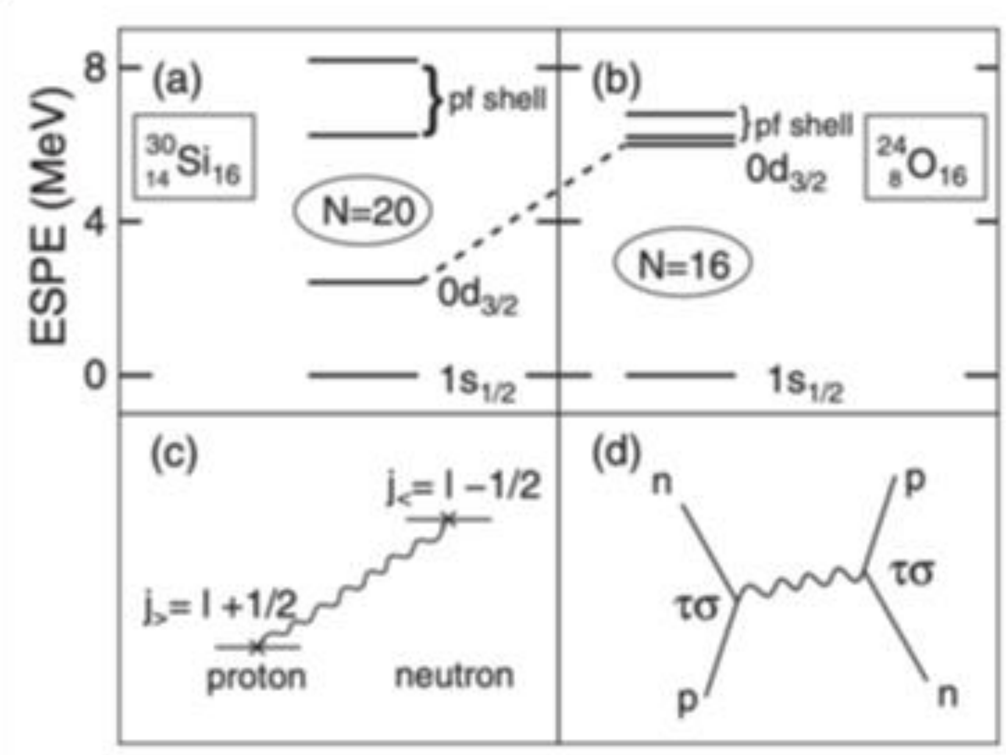


Neutrons filling $h_{11/2}$ tensor interactions with proton orbitals.

from PRL 92 (2004) 162501

Other examples of new magic numbers starting to emerge e.g. N=32 and N=34 in calcium isotopes.

^{25}O produced in single-neutron *knockout reaction* from ^{26}O. Ground-state mass reconstructed from the reaction products; difference with ^{24}O tells you the $d_{3/2}$ energy.



from Rev. Mod. Phys. 92, 015002 (2020)

Prompted discussions of what makes a magic number and what quantities characterise them?

Collectivity and nuclear shape

For a nucleus corresponding to a shell closure, large jump from Fermi level to the next empty orbital – effect of residual interactions low and IPM works (a little) better.

Going away from a closed shell, with increasing numbers of (valence) nucleons outside the shell, the correlations between them increase and can have macroscopic effects on the nuclear structure, distorting the surface.

Distortions of the nuclear surface described by a spherical harmonic expansion – good angular momentum:

$$R(\theta,\phi) = c(\alpha_{\lambda\mu})R_0\left[1+\sum_{\lambda=0}^{\infty}\sum_{\mu=-\lambda}^{\lambda}\alpha_{\lambda\mu}Y_{\lambda\mu}(\theta,\phi)\right]$$

Excitations can arise if the shape changes with time – NUCLEAR VIBRATIONS.

Permanent distortions lead to NUCLEAR SHAPE and excitations can arise from ROTATIONS of that shape.

Coherence in the admixtures of single-particle configurations can greatly increase some observables – e.g. electrostatic moments, e/m transition rates...

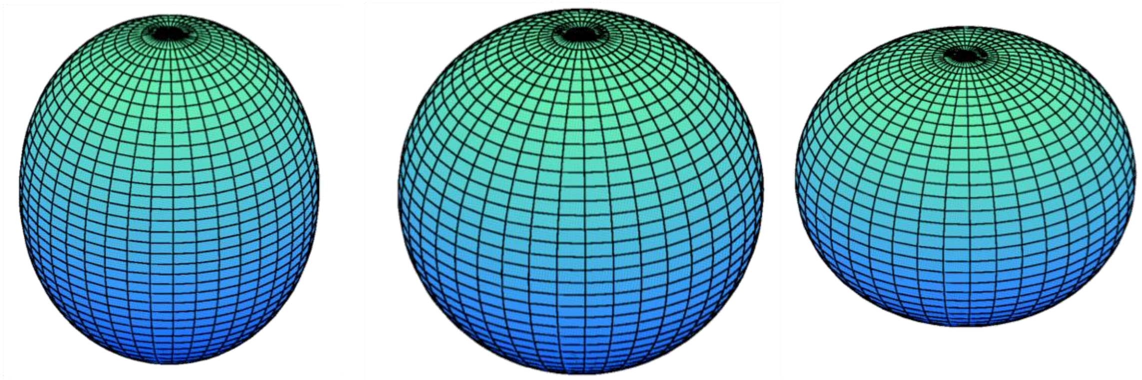
Example: quadrupole shapes

$$Q_0 = Z\left[3\langle z^2\rangle - \langle r^2\rangle\right]$$

$\langle z^2\rangle > \frac{1}{3}\langle r^2\rangle$

$3\langle z^2\rangle = \langle r^2\rangle$
$\langle x^2\rangle = \langle y^2\rangle = \langle z^2\rangle$

$\langle z^2\rangle < \frac{1}{3}\langle r^2\rangle$



$Q_0 > 0$ $Q_0 = 0$ $Q_0 < 0$

Prolate Spherical Oblate

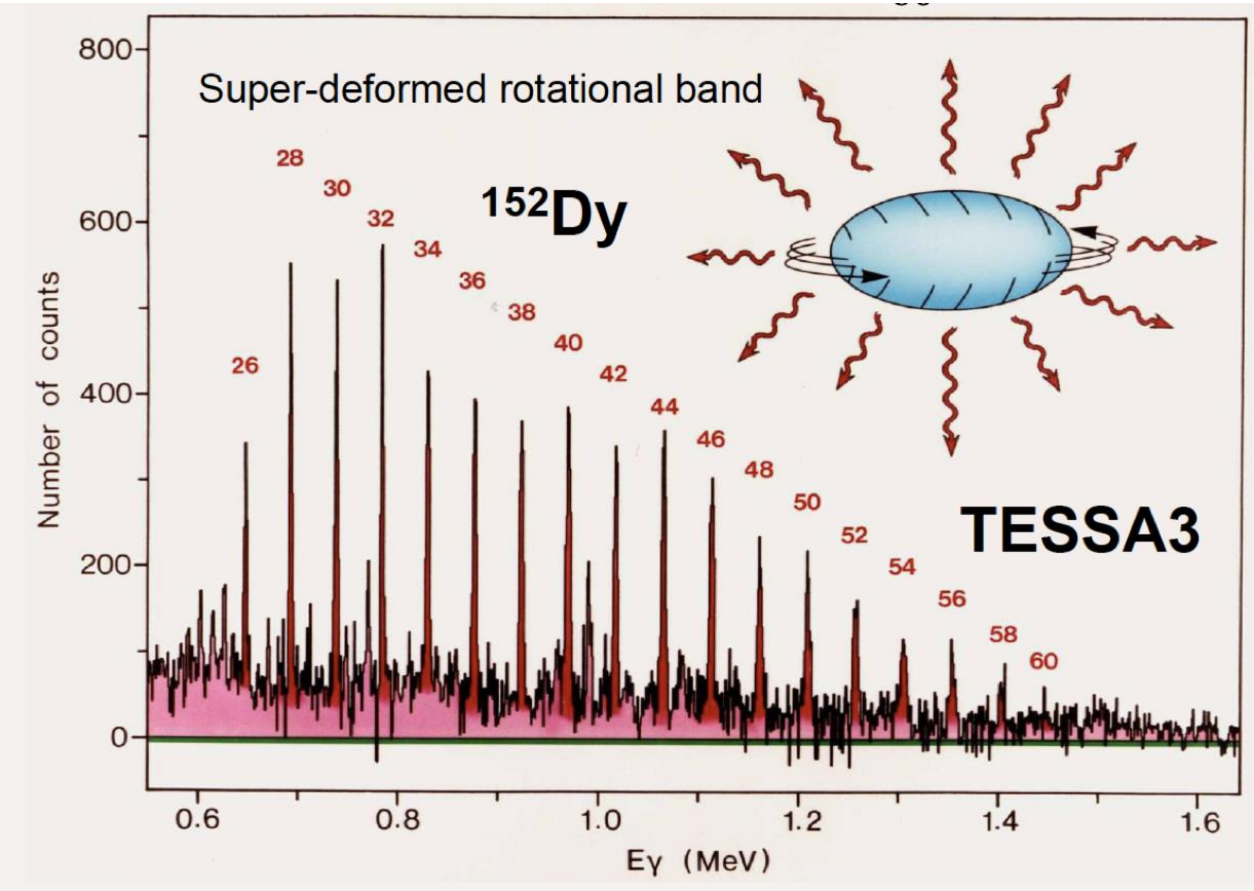
Given the nucleus has a charge – distortion results in electromagnetic moments, which can be probed experimentally in some nuclear reactions or by their effect on electron levels in the associated atom/ion (see later!).

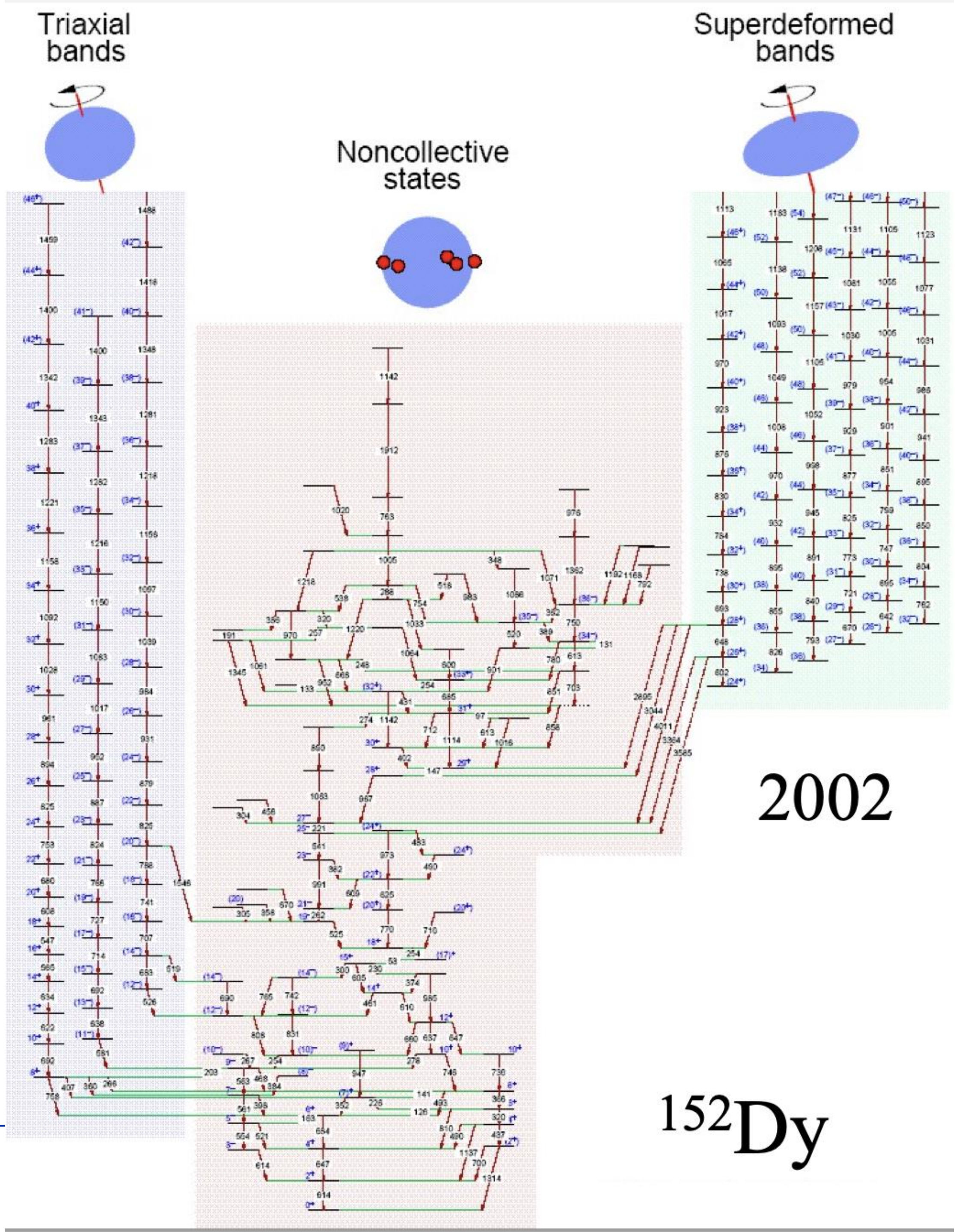
Vibrations and rotations

Harmonic vibrators give equally spaced energy levels.

Rotational levels proportional to I(I+1) – gaps between them as I.

e/m transition strengths between levels (deduced by measuring the lifetime of the excited state) are also characteristic.

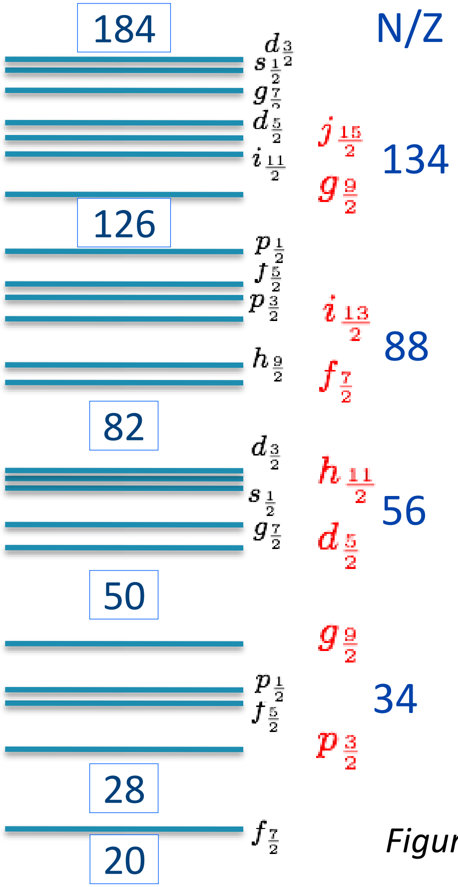


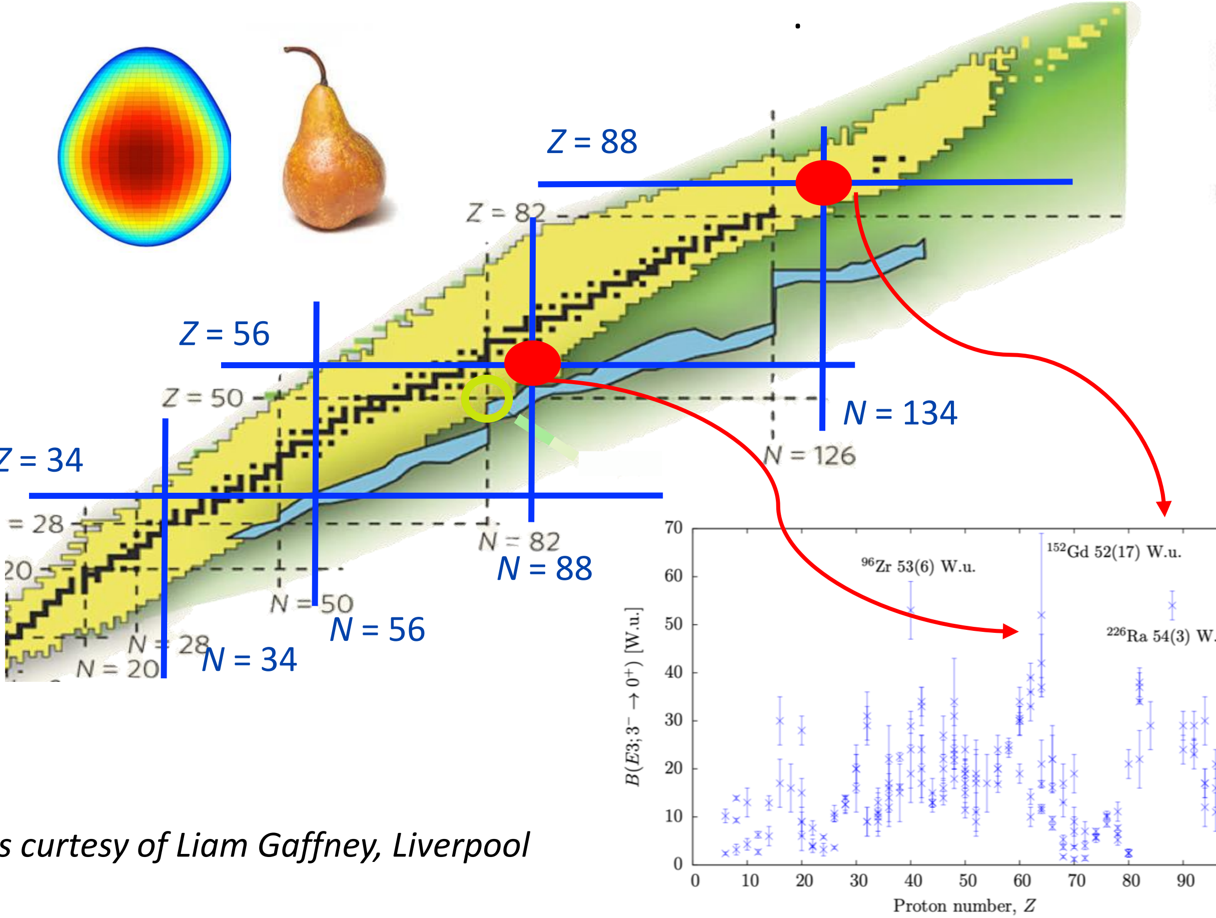


Shape evolution and coexistence

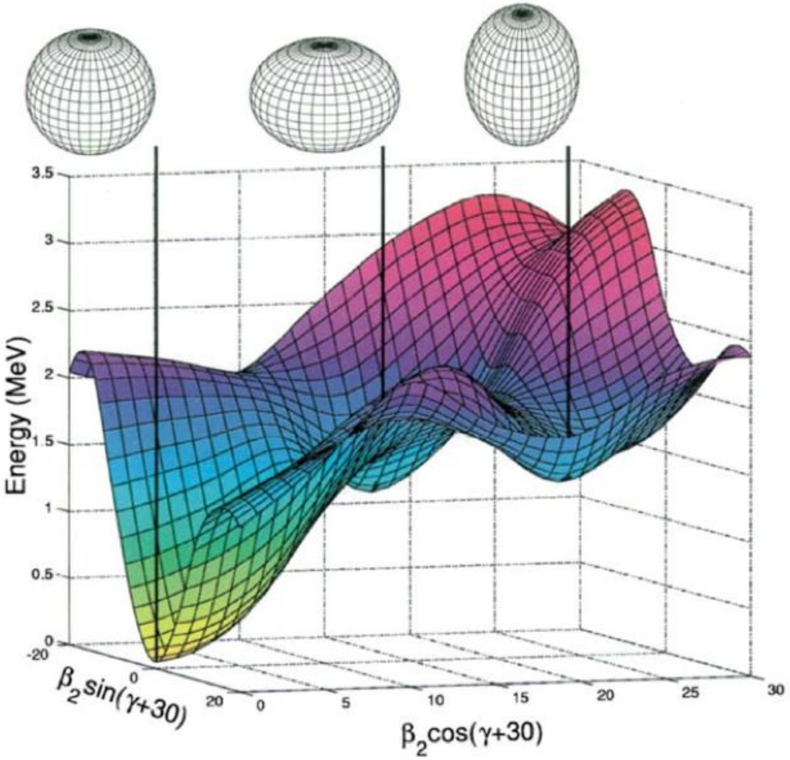
We saw that the effect of residual interactions changes along chains of isotopes/isotones and within excited states in the same nucleus – these also drive evolution in nuclear shape.
You need to access particular (N,Z) to study certain shapes.

EXAMPLE: octupole or pear-shaped deformation related to correlations induced by a Y_3 operator, strong between orbitals of opposite parity and ΔJ, ΔL = 3 close to the Fermi level.





Figures curtesy of Liam Gaffney, Liverpool



EXAMPLE: spherical, oblate and prolate shapes exist as different excited states in the same nucleus^{186}Pb.

A.Andreyev et al., Nature **405**, 430 (2000)

Pause for thought:

- nuclei = a complex, many-body problem bound with complicated strong force.
- relatively simple structures emerge from this complexity.
- correlations between nucleons are very important.
- nuclear structure has microscopic (single-particle) and macroscopic (collective) features.
- the only bound system of two different fermions – the proton/neutron Fermi surfaces sample different single-particle orbitals and the resulting correlations support different structures.
- leads to an evolution of shell structure, nuclear shape and shape coexistence.
- expectation of strange effects in the most exotic, least bound systems near the proton and neutron driplines.

- How can we understand the forces binding nuclei?
- How do these forces lead to the microscopic structure of nuclei?
- How do macroscopic structures arise in nuclei?
- What are the limiting conditions for the nuclear binding and what phenomena emerge at the limits?
- What impact does nuclear structure have on other areas such as the origin of the chemical elements and fundamental physics?

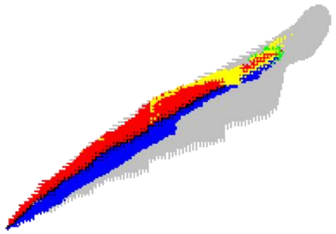
Nuclei far from the line of stability hold the keys to answering these questions.

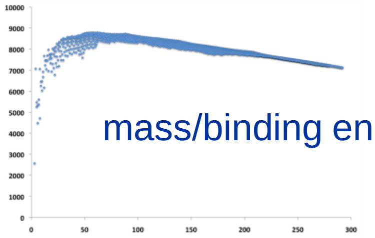
How do we access and study exotic nuclei?.

What characterizes a nucleus?

Some examples of relevant quantities….

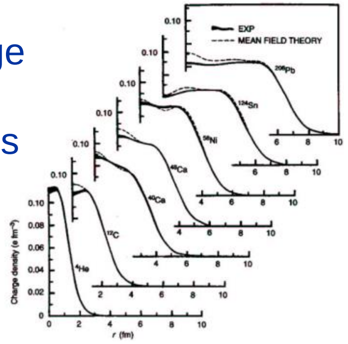
numbers of nucleons

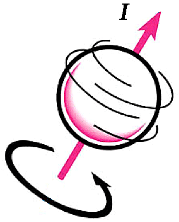




mass/binding energy

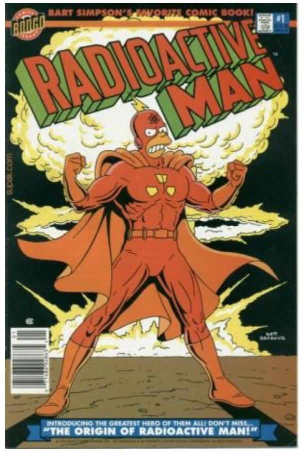
radii, charge
and matter
distributions





spin-parity
and e/m moments

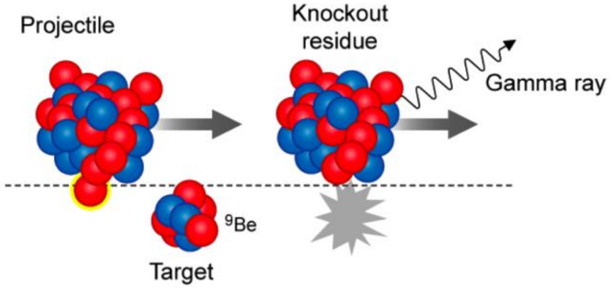
decay properties:
mode, lifetime, BR..



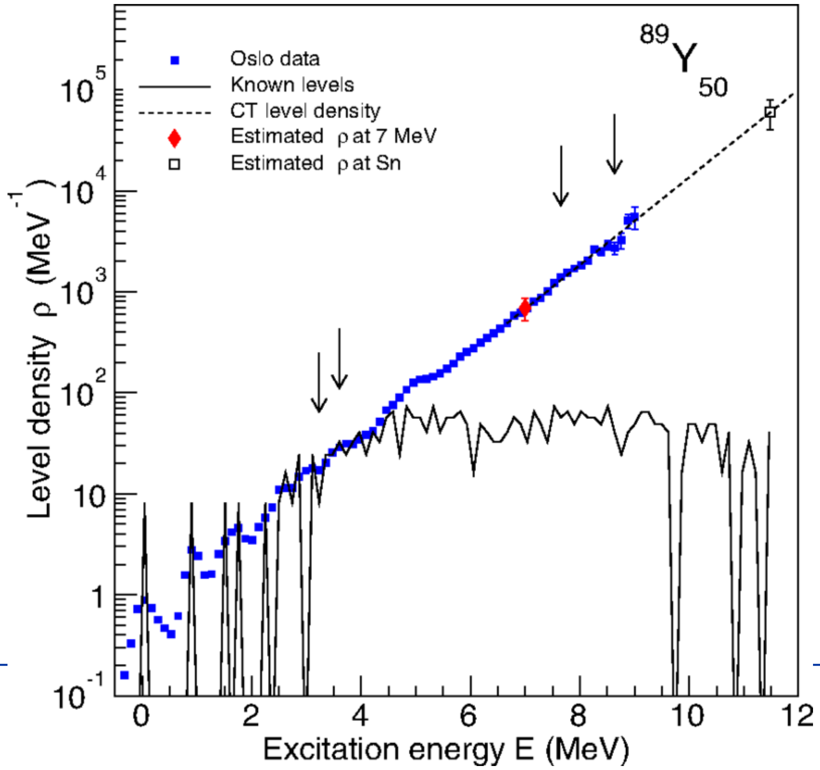
….in principle, for the ground state and excited states.

Nuclear reactions are important tools:

(i) produce nuclides.
(ii) select states.
(iii) reaction properties such as cross sections.



Deduce, mostly model-dependently:
transition rates
orbital occupancy
single-particle nature
pairing and clustering
etc.



M. Guttormsen et al., PRC 90, 044309 (2014)

Historical perspective

(i) Early Years: discoveries of radioactivity, nucleus, nuclear reactions, protons and neutrons, isotopes – using mainly decay.

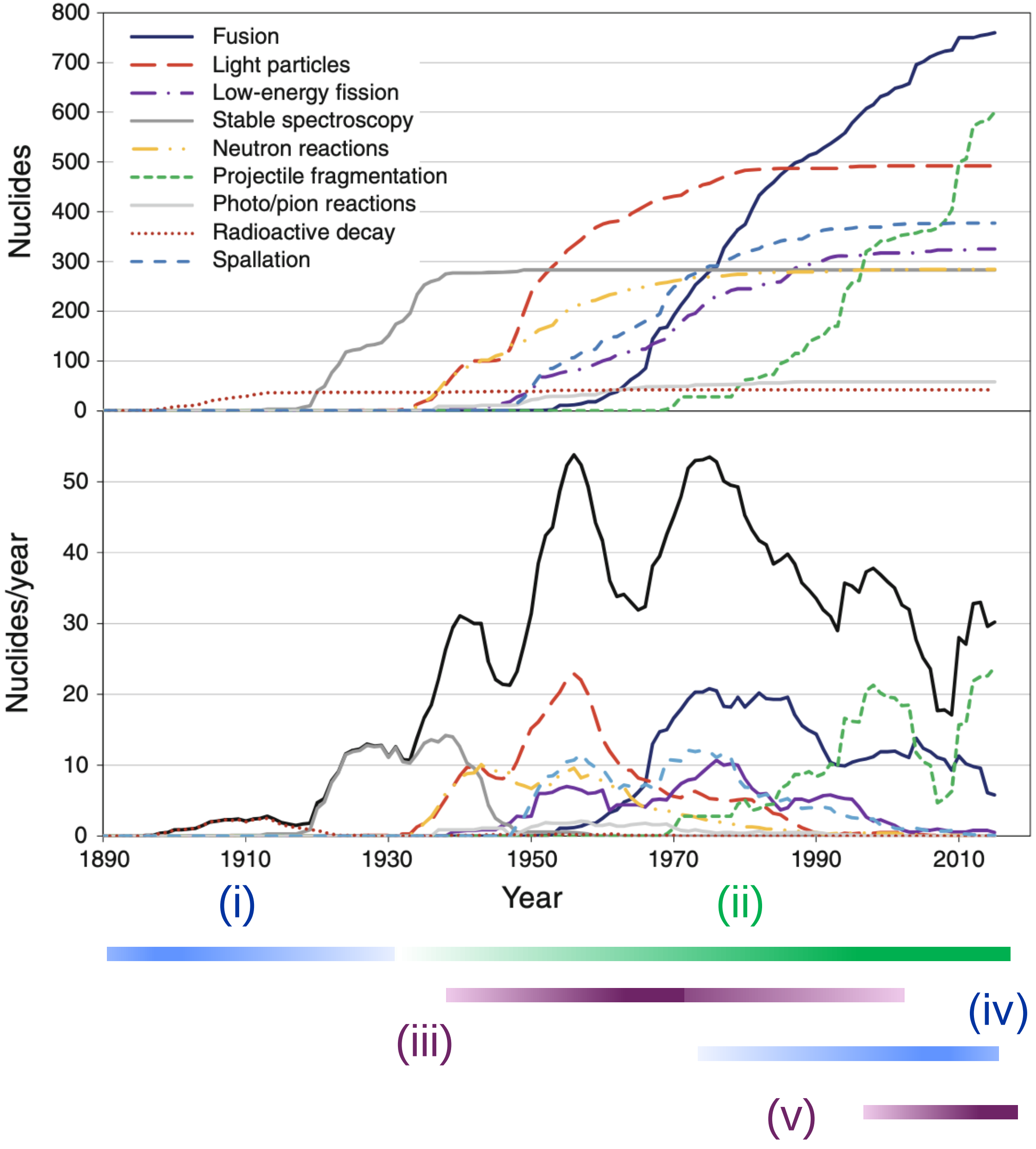
(ii) Neutrons: from reactions initiated by radioactivity, then fission, then accelerators.

(iii) Light-ion accelerators: explosion of small machines for protons, deuterons and alphas for elastic/inelastic scattering, compound nucleus, transfer, with increasing energy allows spallation etc.

(iv) Heavy-ion accelerators: Coulomb excitation, fusion evaporation, with increasing energy projectile fragmentation

(v) Radioactive ion beam facilities: early work on spallation and fragmentation harnessed for production of beams of exotic nuclei used to induce secondary nuclear reactions.

from “The Discovery of Isotopes” Michael Thoennessen



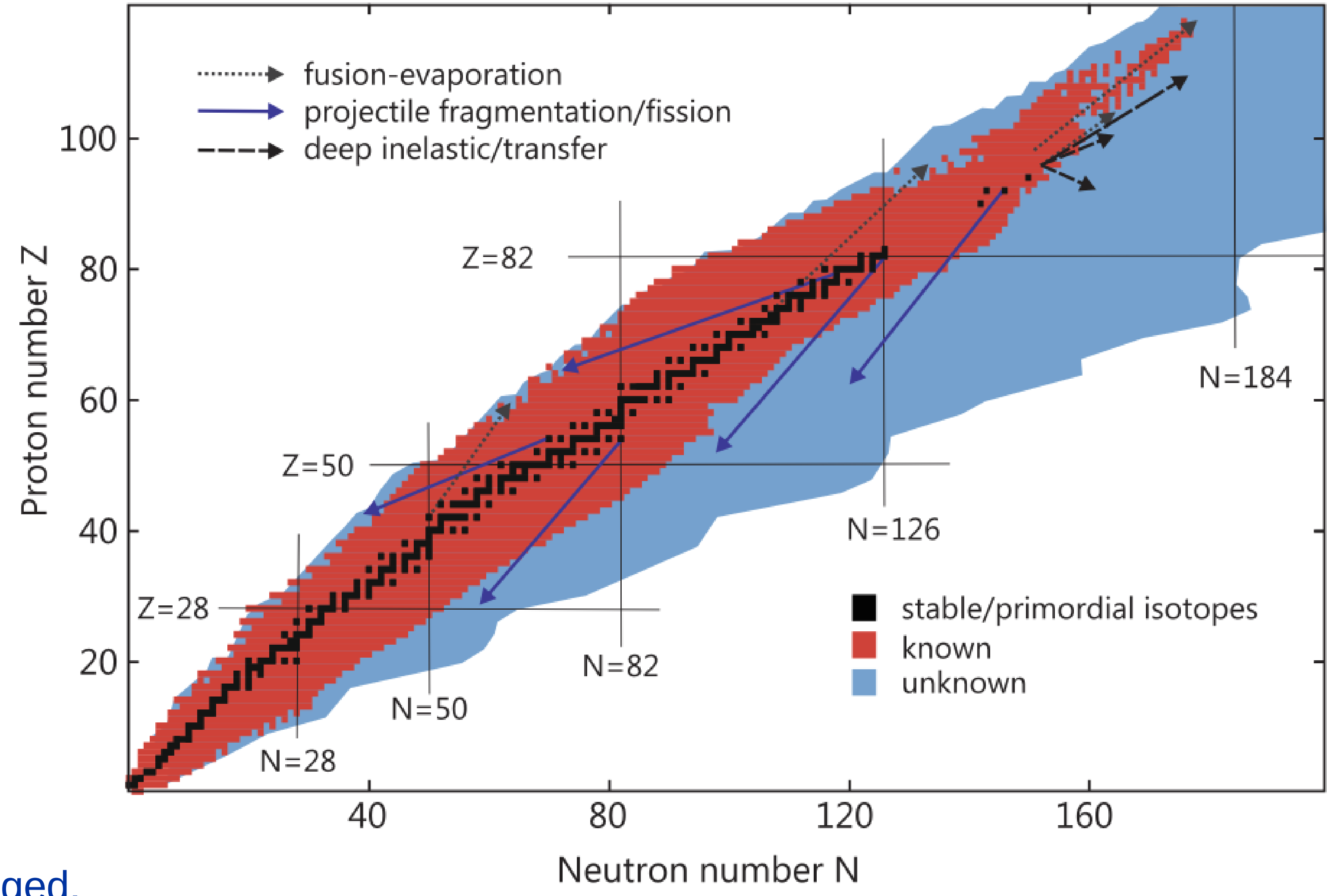
Radioactive Ion Beam Facilities

- Most isotopes predicted to exist are not known.
- Many known exotic isotopes have only rudimentary studies.
- The proton drip line has been reached in many cases; the neutron drip line is largely unknown.

Requires:

i. high-intensity exotic nuclei for direct study.

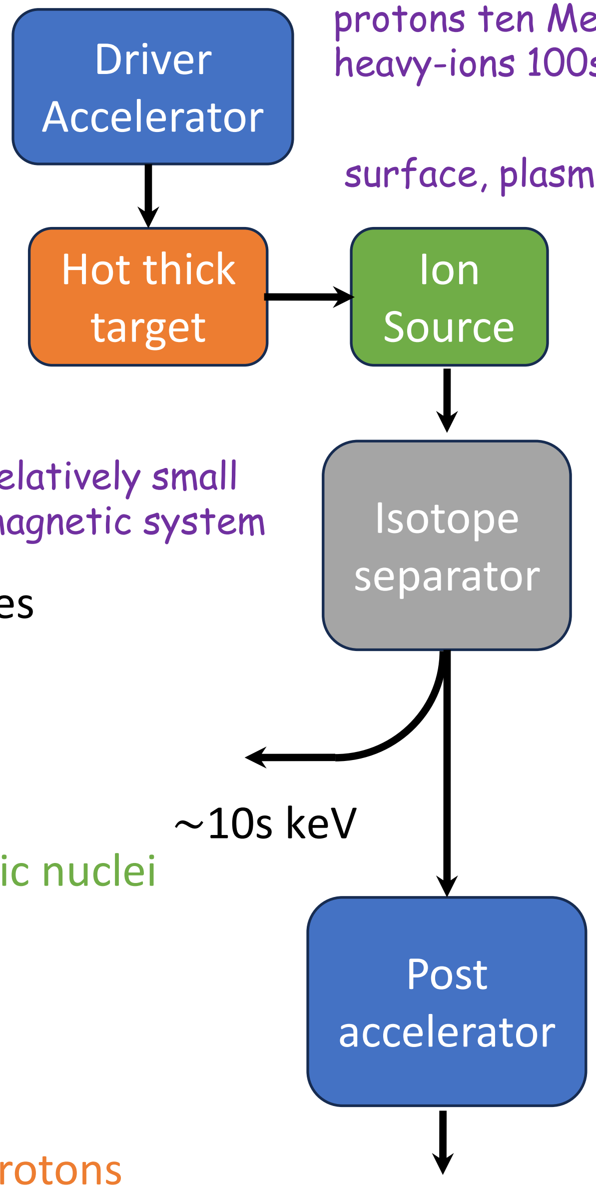
ii. high-energy exotic beams to initiate secondary reactions



from “The Discovery of Isotopes” Michael Thoennessen

Two main types of facility have emerged.

ISOL



protons ten MeV to GeV
heavy-ions 100s MeV

surface, plasma, lasers

- uranium carbide, Ta metal, molten metals and salts
- fusion, fission, spallation, fragmentation

relatively small
magnetic system

excellent beam properties
chemical sensitivity
half-lives > 1ms

~10s keV

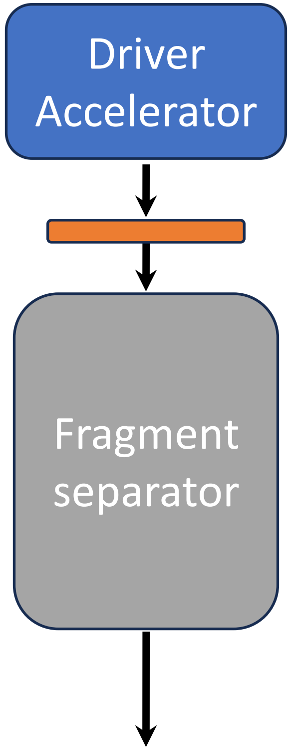
DISCOVERY POTENTIAL:
precision studies of exotic nuclei

~10 MeV/u

Examples:
ISOLDE 1.4 GeV protons
TRIUMF-ISAC 600 MeV protons
INFN-SPES and RAON-Korea
70 MeV protons
SPIRAL/DESIR–GANIL heavy-ions 25 MeV/A (fusion etc.)

IN-FLIGHT

usually heavy-ions 100s MeV/A



- thin light target: Be, Li..
- projectile fragmentation

extensive
magnetic
system

chemical insensitivity
half-lives < 1ms
beam properties fixed

DISCOVERY POTENTIAL:
loosely-bound isotopes at the very edge of stability

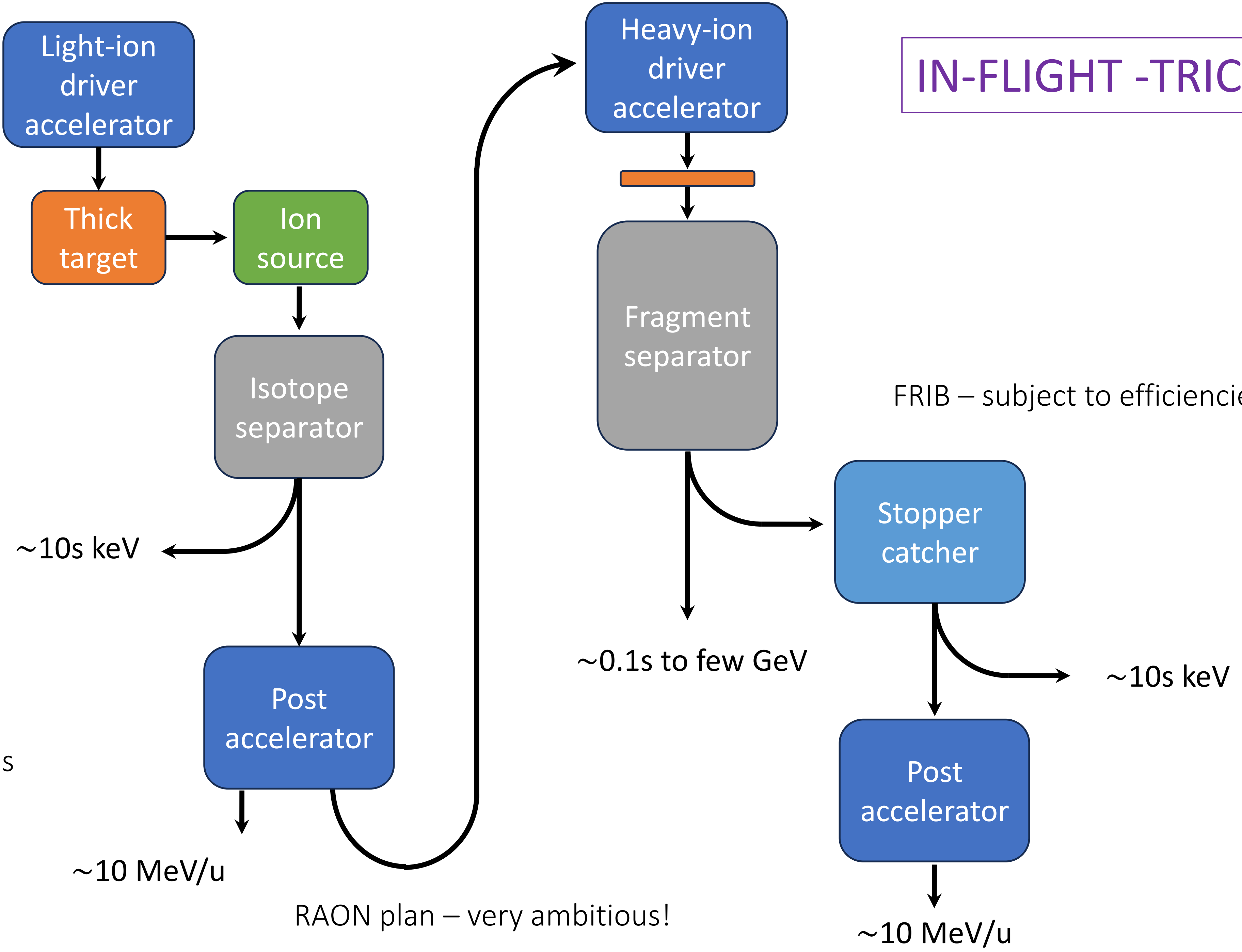
~0.1 to few GeV

Examples:
RIBF-RIKEN 350 MeV/A heavy ions
FRIB-USA 200-250 MeV/A heavy ions
FAIR-GERMANY 2 GeV/A heavy ions
GANIL 95 MeV/A

ISOL - TRICKS

play with chemistry e.g. make and extract molecules for refractory species

>1 ms is fundamental limit, but has the advantage of easy to switch between isotopes with systematics under control

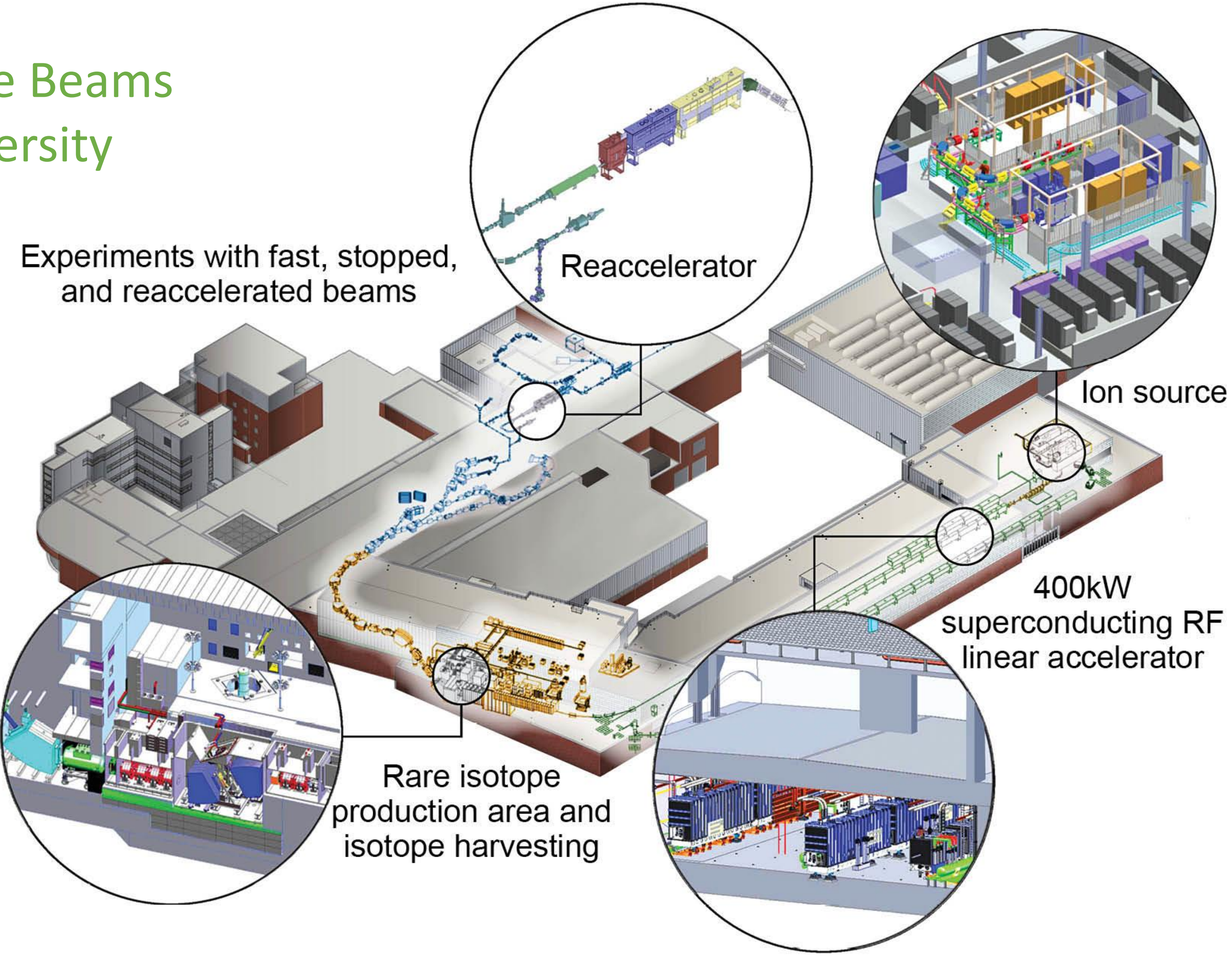


IN-FLIGHT -TRICKS

FRIB – subject to efficiencies

RAON plan – very ambitious!

Facility for Rare Isotope Beams at Michigan State University



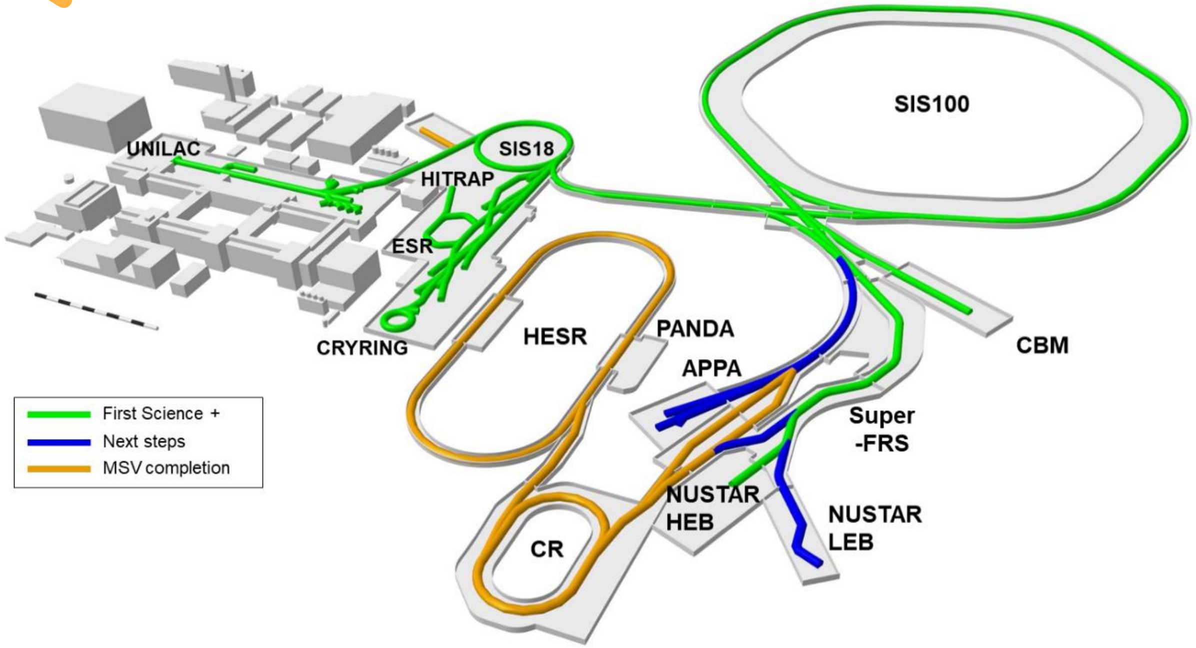
Experiments with fast, stopped, and reaccelerated beams

Reaccelerator

Ion source

400kW superconducting RF linear accelerator

Rare isotope production area and isotope harvesting

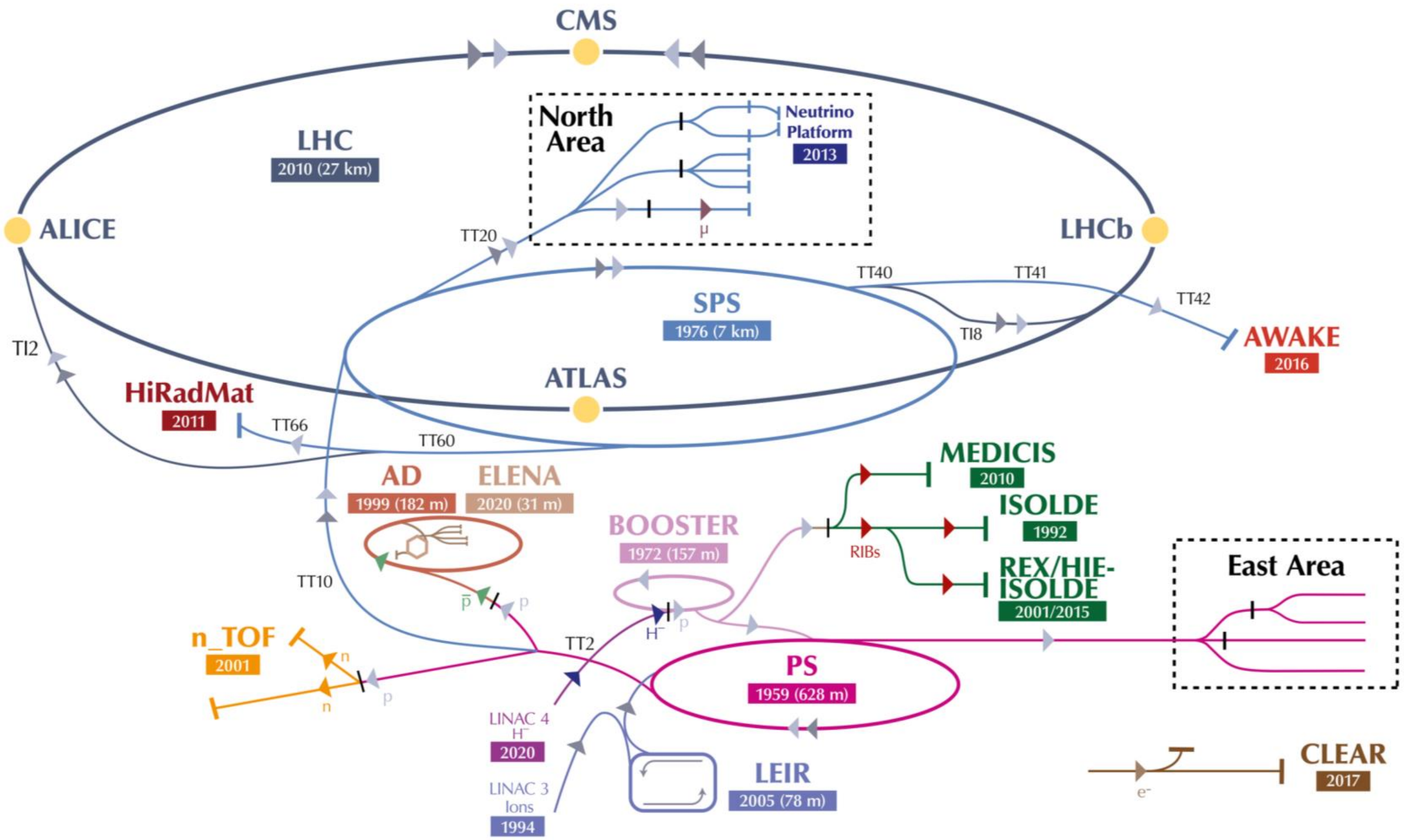

UNILAC
SIS18
HITRAP
ESR
CRYRING
HESR
PANDA
APPA
SIS100
CBM
Super -FRS
NUSTAR HEB
NUSTAR LEB
CR
First Science +
Next steps
MSV completion

As an example of an ISOL facility and a slightly deeper dive into the experiments in nuclear structure and the physics that can be addressed….will stray into other scientific areas in the process!

Still high-level view – presenting work of a vast array of scientific, engineering and technical experts.


ISOLDE

The CERN accelerator complex
Complexe des accélérateurs du CERN



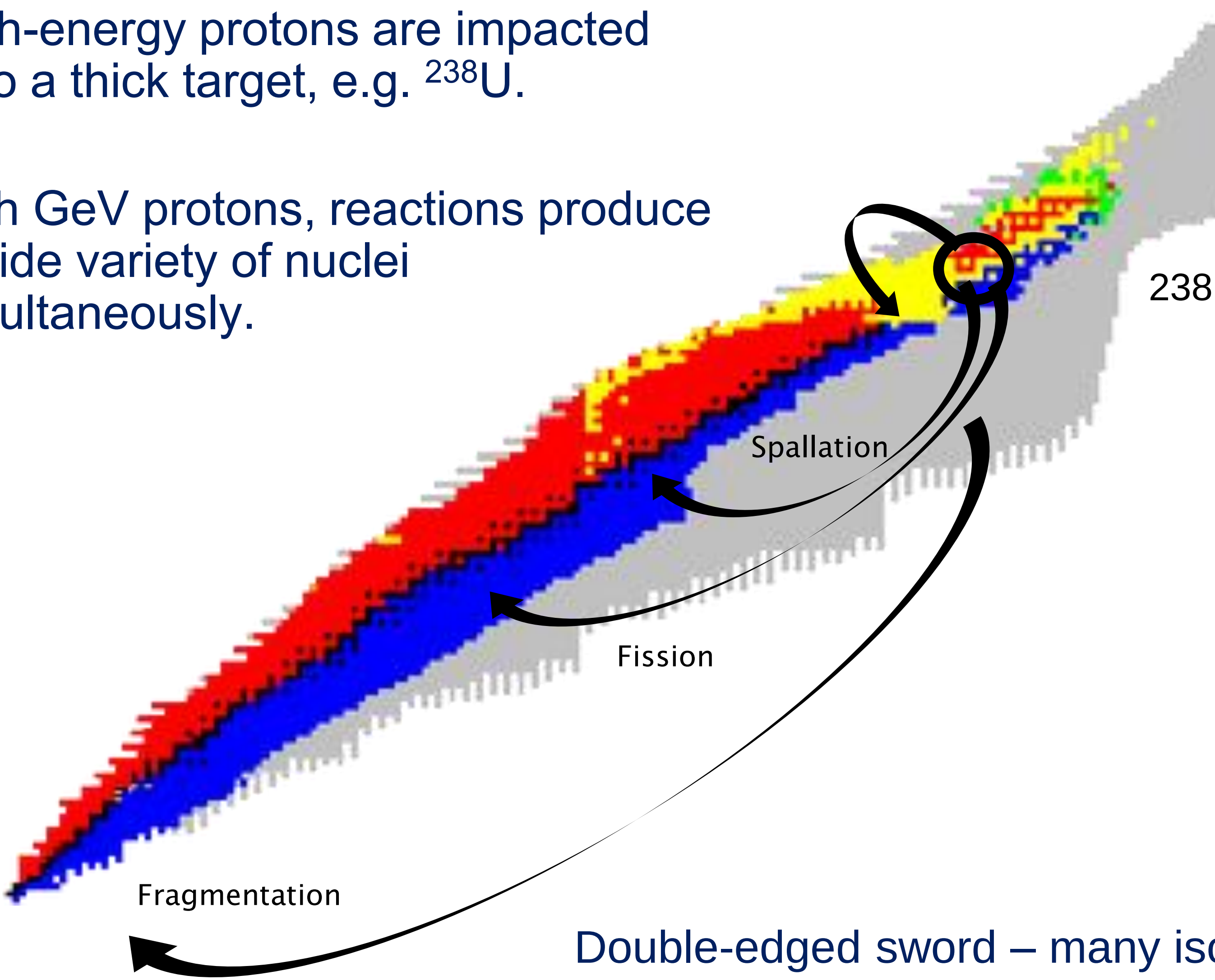
▶ H^- (hydrogen anions) ▶ p (protons) ▶ ions ▶ RIBs (Radioactive Ion Beams) ▶ n (neutrons) ▶ $\bar{p}$ (antiprotons) ▶ e^- (electrons) ▶ μ (muons)

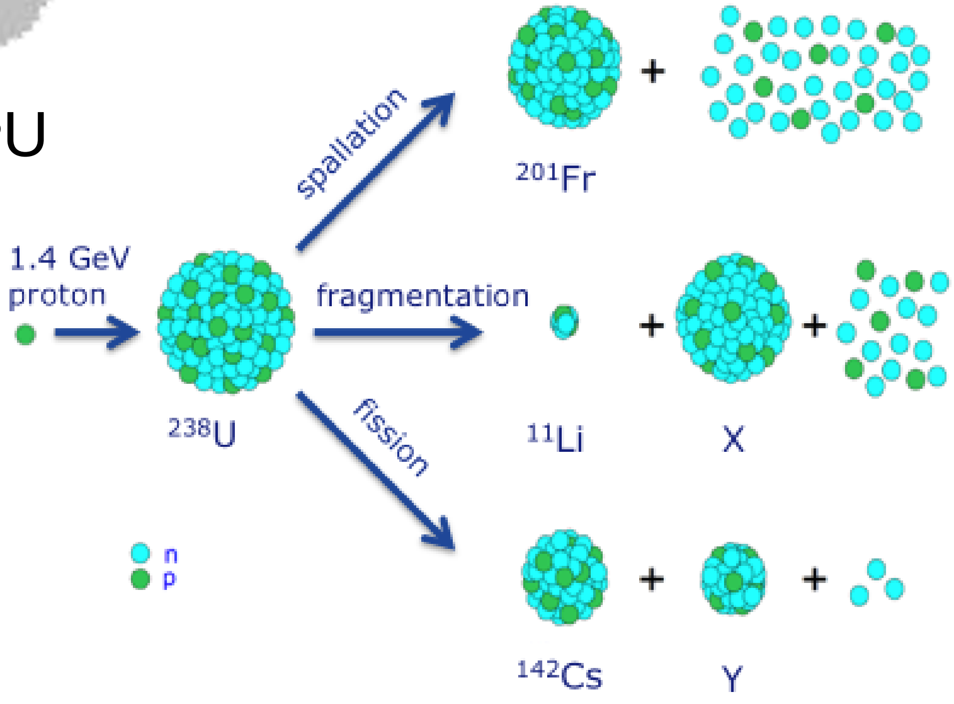
LHC - Large Hadron Collider // SPS - Super Proton Synchrotron // PS - Proton Synchrotron // AD - Antiproton Decelerator // CLEAR - CERN Linear Electron Accelerator for Research // AWAKE - Advanced WAKefield Experiment // ISOLDE - Isotope Separator OnLine // REX/HIE-ISOLDE - Radioactive EXperiment/High Intensity and Energy ISOLDE // MEDICIS // LEIR - Low Energy Ion Ring // LINAC - LINear ACcelerator // n_TOF - Neutrons Time Of Flight // HiRadMat - High-Radiation to Materials // Neutrino Platform

ISOL with GeV Protons

High-energy protons are impacted onto a thick target, e.g. ^{238}U.

With GeV protons, reactions produce a wide variety of nuclei simultaneously.



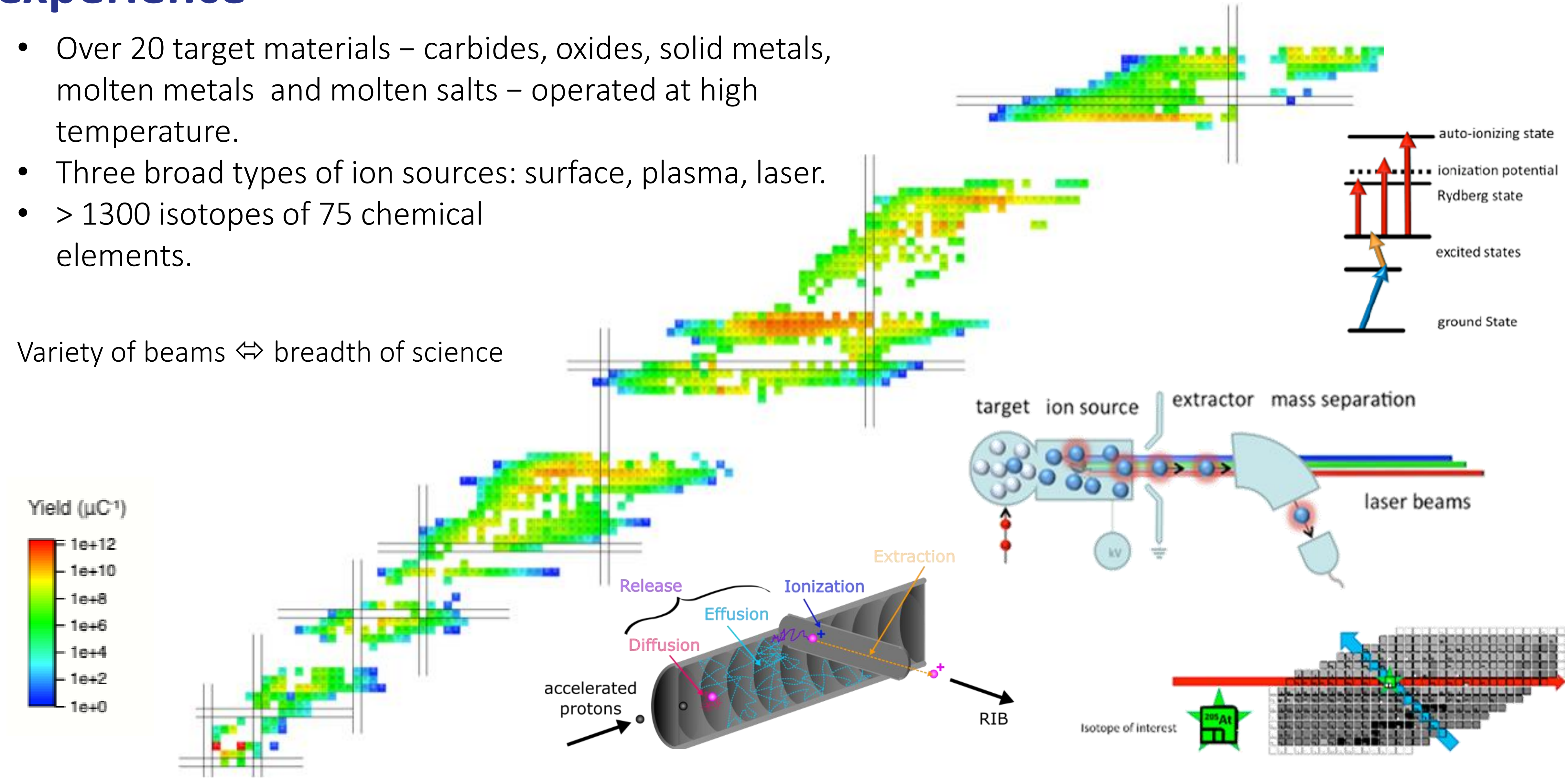


Double-edged sword – many isotopes, but an experiment will just want one!

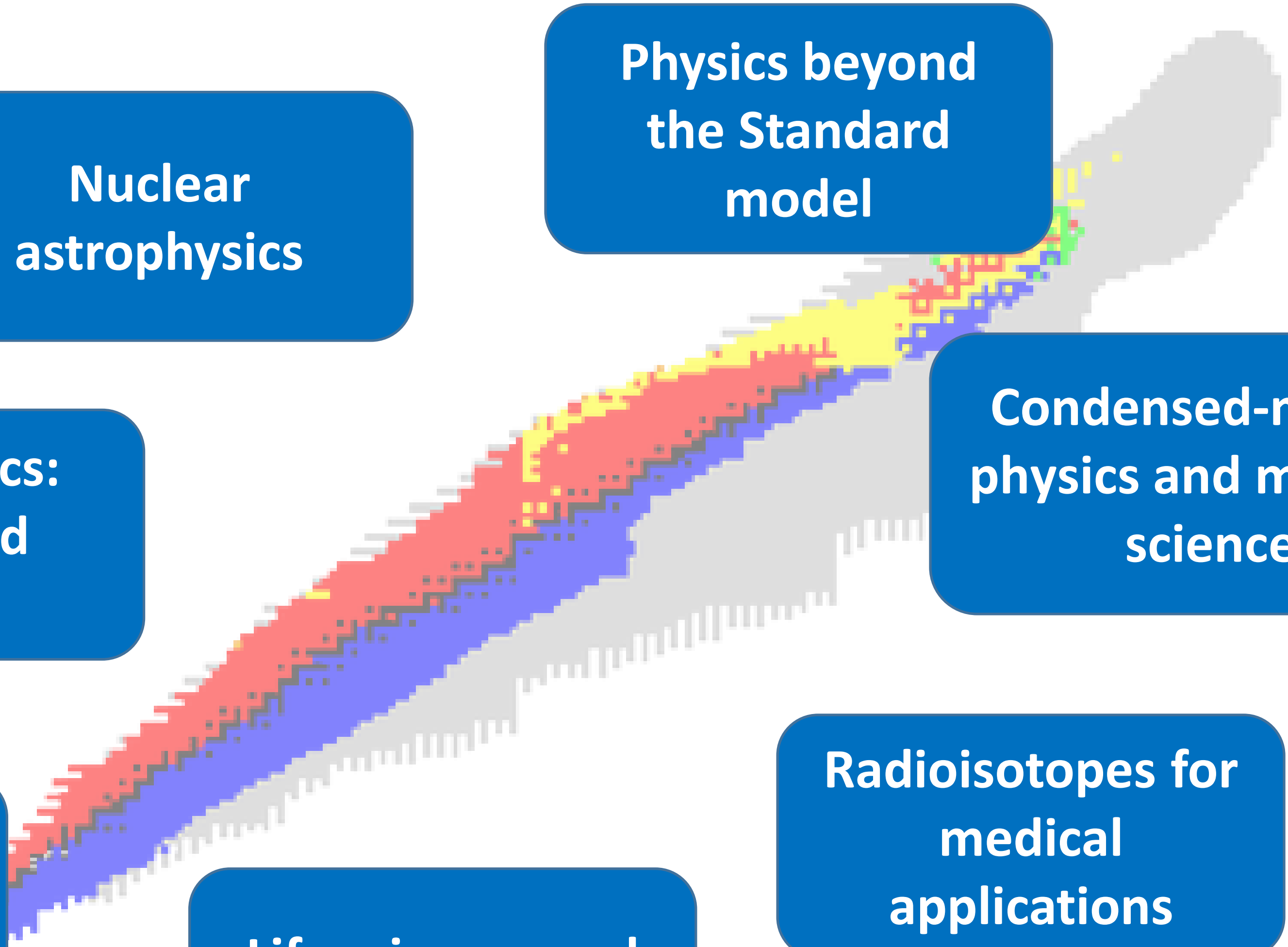
Isotope Production with GeV protons and over 50 years of experience

- Over 20 target materials – carbides, oxides, solid metals, molten metals and molten salts – operated at high temperature.
- Three broad types of ion sources: surface, plasma, laser.
- > 1300 isotopes of 75 chemical elements.

Variety of beams ⇔ breadth of science



Research with radioactive beams at ISOLDE



Physics beyond the Standard model

Nuclear astrophysics

Nuclear physics: reactions and structure

Condensed-matter physics and material science

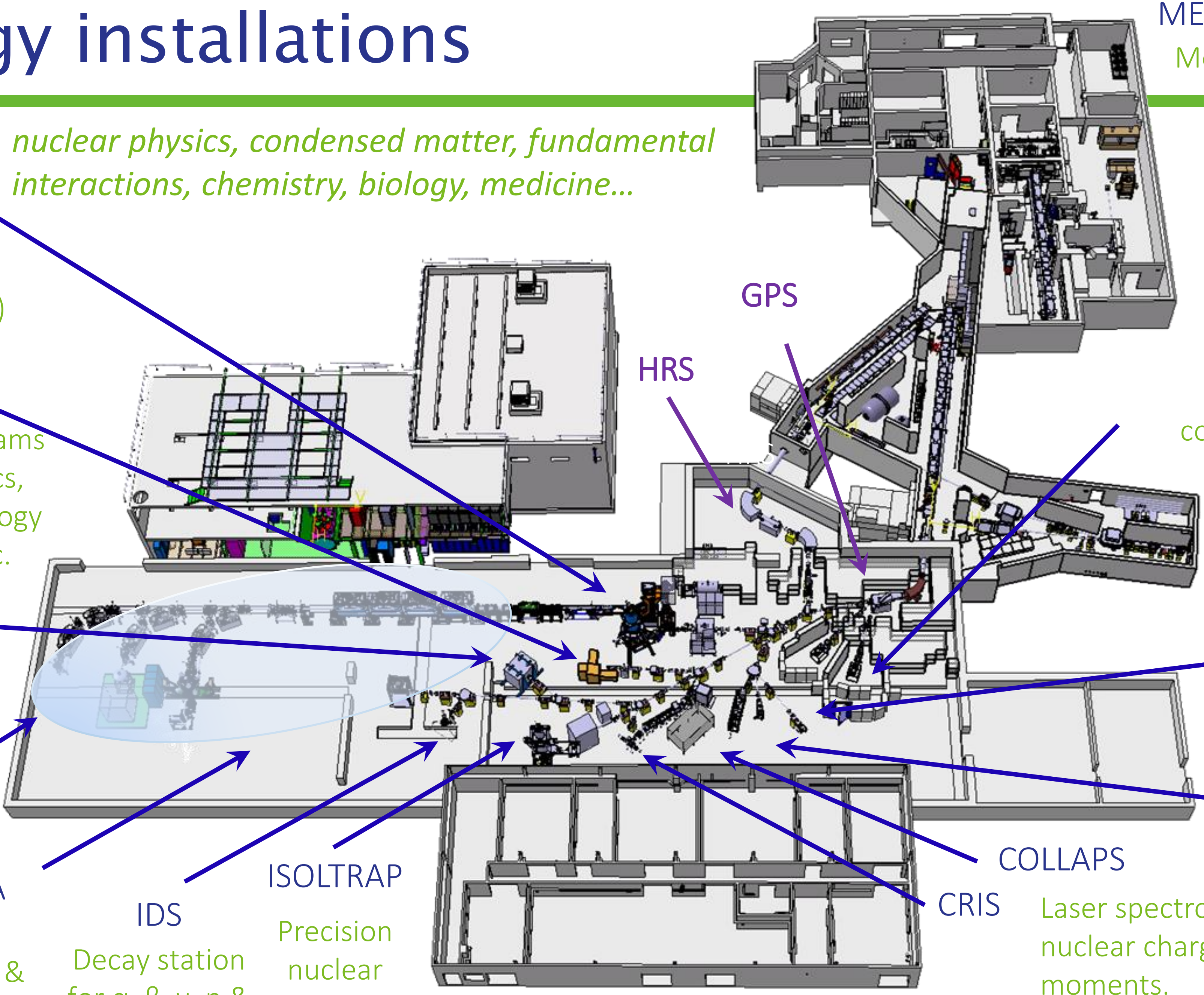
Atomic and molecular physics

Radioisotopes for medical applications

Life sciences and biophysics

Low-energy installations

nuclear physics, condensed matter, fundamental interactions, chemistry, biology, medicine…



MEDICIS

Medical isotopes research

WISArD

Scalar and tensor currents in weak interactions: βν(θ)

VITO

Laser-polarised beams for nuclear physics, chemistry and biology using β-NMR etc.

TAS

Total absorption spectrometer for β-decay feeding

High-energy area: see next slide!

PUMA

Coming soon! Interaction of RIB & antiprotons

IDS

Decay station for α, β, γ, p & n.

ISOLTRAP

Precision nuclear masses

HRS

GPS

Condensed-matter physics

Emission channeling, perturbed angular correlations, Mössbauer, isotope collections….

.

Protons

Travelling setups

MIRACLS

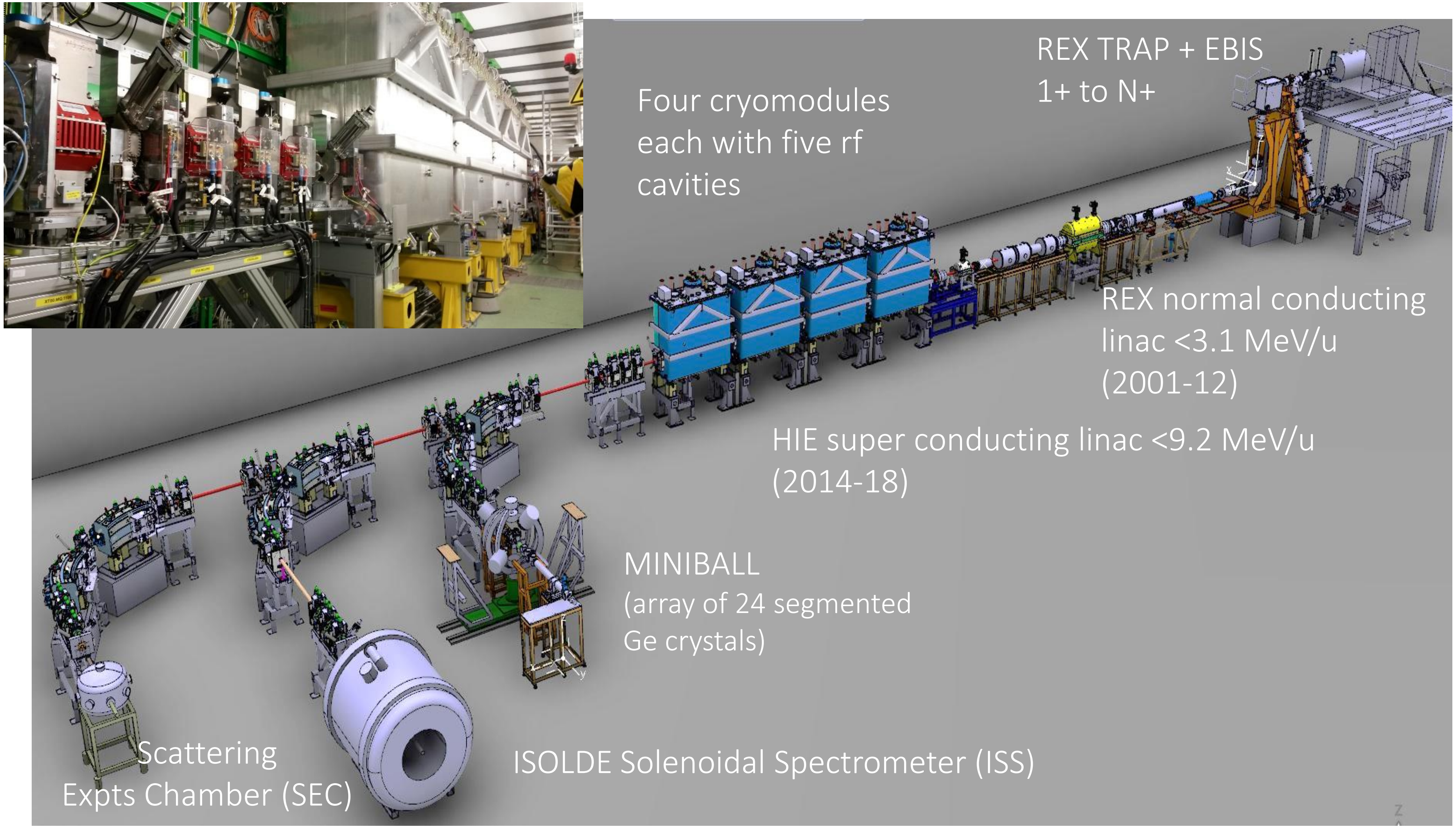
MR-TOF

COLLAPS

CRIS

Laser spectroscopy: nuclear charge radii and moments.

HIE-ISOLDE completed 2018



40-60 keV 1+ ions

REX TRAP + EBIS
1+ to N+

Four cryomodules each with five rf cavities

REX normal conducting linac <3.1 MeV/u (2001-12)

HIE super conducting linac <9.2 MeV/u (2014-18)

MINIBALL
(array of 24 segmented Ge crystals)

Scattering Expts Chamber (SEC)

ISOLDE Solenoidal Spectrometer (ISS)

nuclear structure, reactions and astrophysics

Some recent science highlights from ISOLDE: *a quick stroll through fundamental science, nuclear physics to condensed matter…*

Difficult to be representative of the overall science programme – spoilt for choice!

Electric dipole moment searches

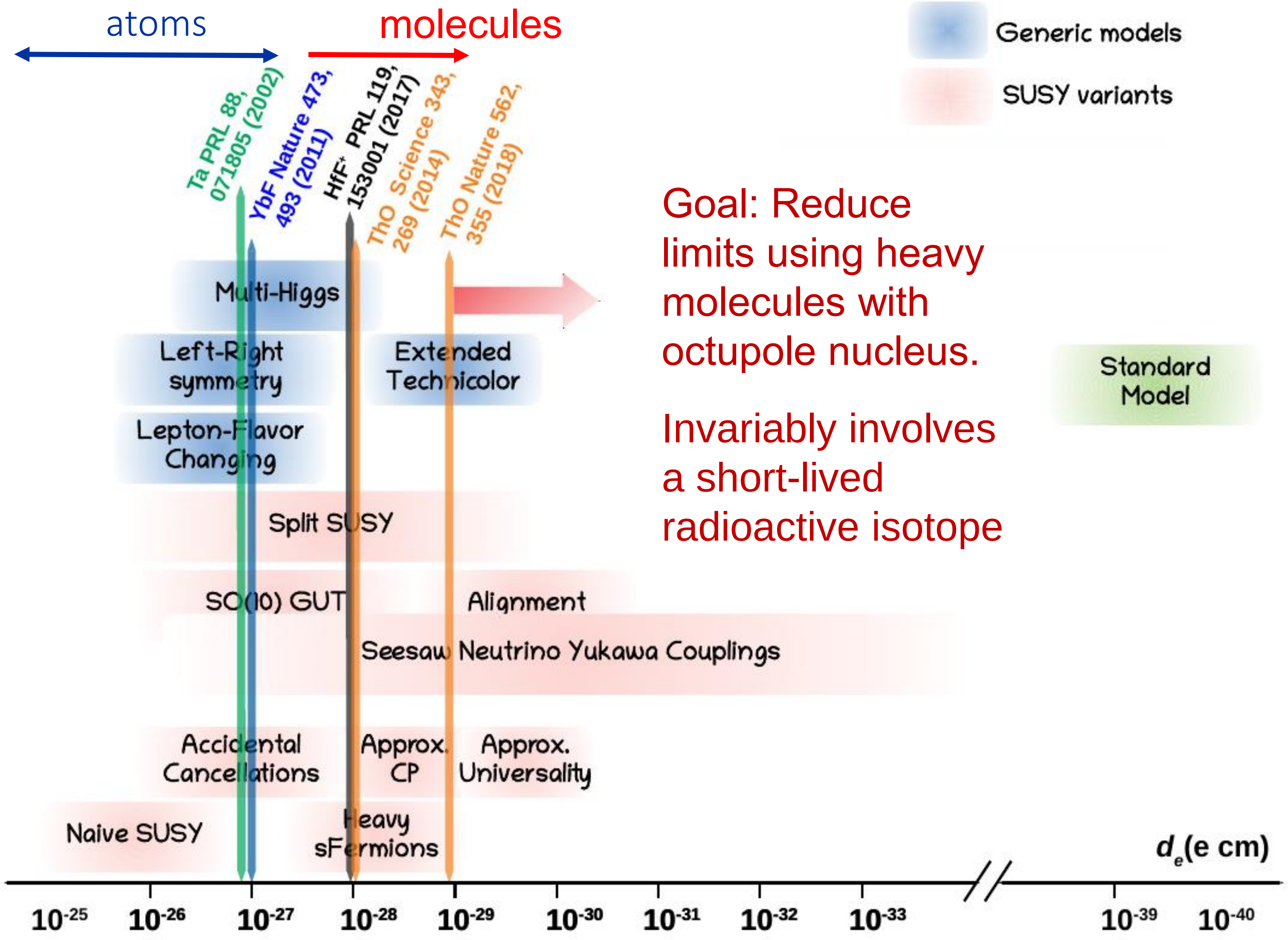
Searching for effects of EDM in atomic energy levels provides a precision method to test fundamental physics..

Polarisation of molecules of heavy elements amplifies the interaction with external electric fields by factors of up to 10^6 and are less sensitive to problematic systematic effects.

Static nuclear octupole deformation of the heavy element can add an additional enhancement via the atomic Schiff moment.

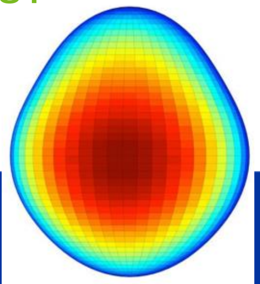
Where do octupole nuclei lie away from stability and what signatures?

Molecular spectroscopy of heavy molecules?



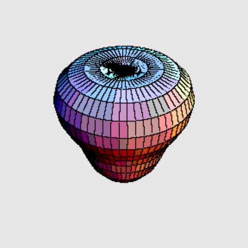
Goal: Reduce limits using heavy molecules with octupole nucleus.

Invariably involves a short-lived radioactive isotope

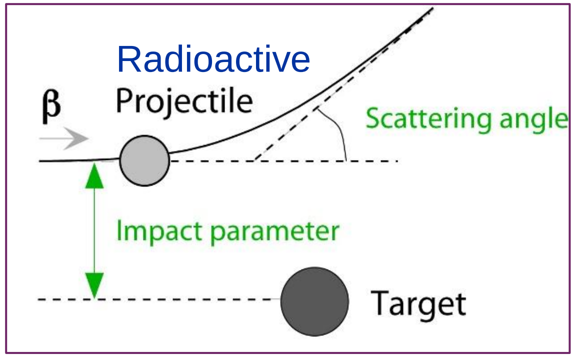


Stable octupole shape versus octupole vibration?

Circumstantial evidence existed for some time that certain nuclei show octupole distortion…but observables (interleaved parity bands in even-even; parity doublets in odd-A; enhanced E1) are indirect

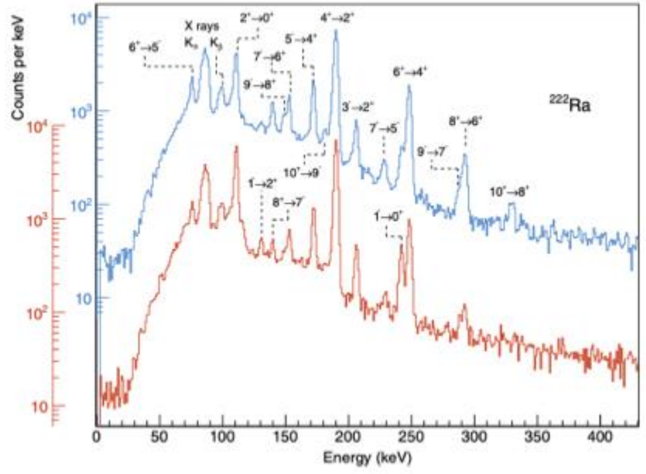


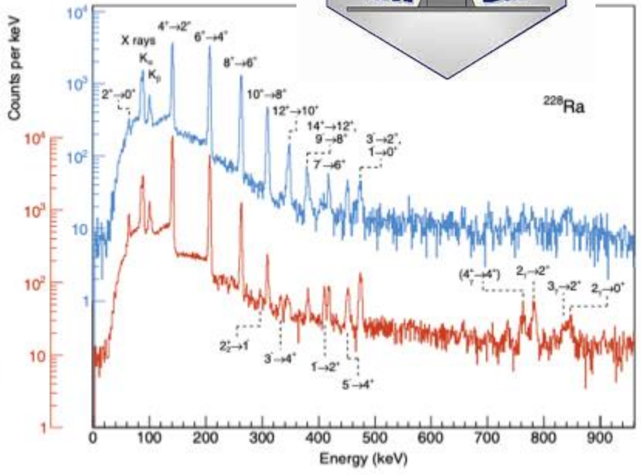
ISOLDE Coulomb excitation establish direct evidence for stable octupole deformation in ^{224}Ra via measurements of transition matrix elements – neighboring odd isotopes would have enhanced EDM’s. ^{220}Rn appears to how dynamic octupole vibration – ^{219,221}Rn unlikely to have enhancement.



Nature 497, 199 (2013)

REX-ISOLDE 2.8 MeV/u





Sparse data on stable pear shapes extended to show the boundaries of this region:

- ^{222}Ra has patterns of transitions and matrix elements consistent with stable octupole shape.
- ^{228}Ra is exhibits octupole vibration.

PRL 124, 042503 (2020)

HIE-ISOLDE 4.3 MeV/u

Spectroscopy of Radioactive RaF

Multiple laser beams stepwise excite a neutral radioactive atom/molecule to ionization continuum.
Tuning the frequency of one laser as the ion yield is monitored enables the molecular levels to be mapped out.

Nature 581, 396 (2020)

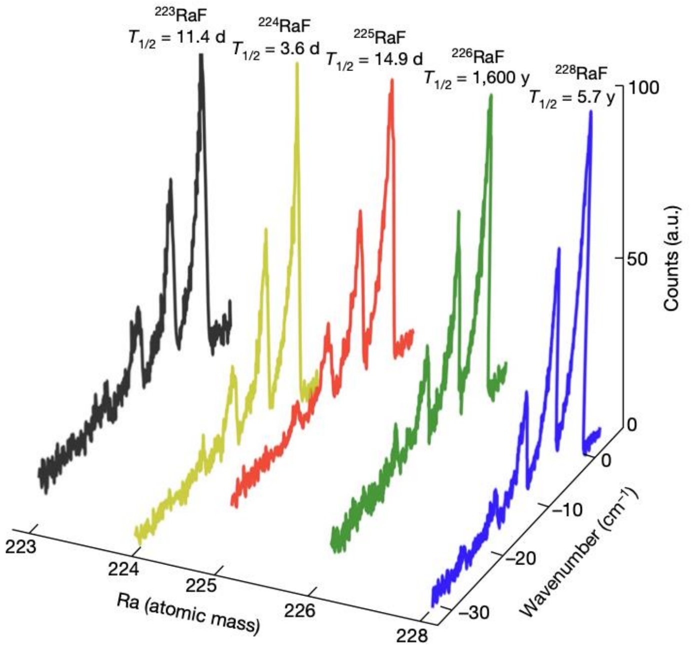
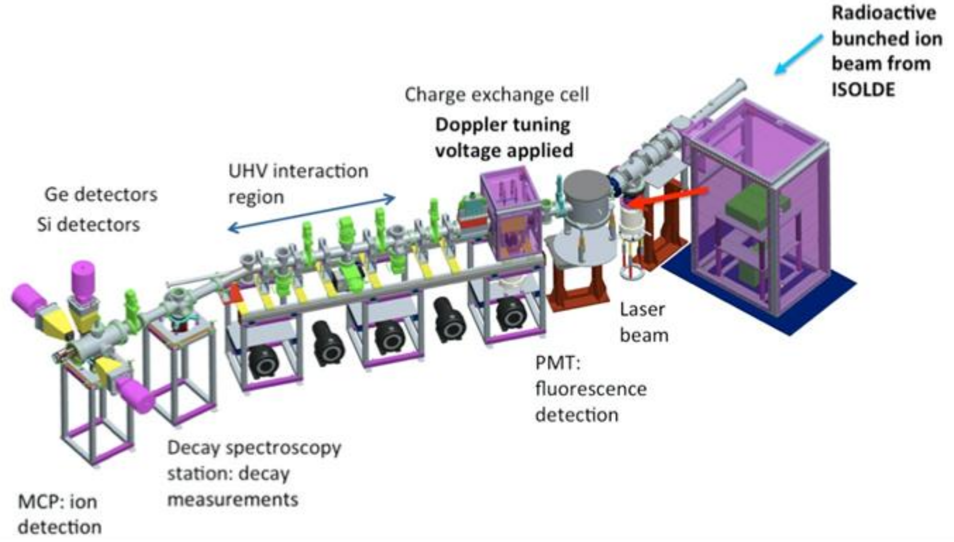


Fig. 3 | Vibronic spectra measured for different isotopologues of RaF. Measured vibronic absorption spectra for the $A^2\Pi_{1/2} \leftarrow X^2\Sigma^+$ transition are shown for the isotopologues ^{223}RaF, ^{224}RaF, ^{225}RaF, ^{226}RaF and ^{228}RaF. Wavenumber values are relative to the transition (0, 0) of ^{226}RaF.

ISOLDE experiments established low-lying electronic structures of RaF with nuclear octupole deformation giving evidence for their suitability for laser cooling, a pivotal step to precision measurements for EDM searches.

Recently followed up by AcF measurements during "winter physics" in 2022.



CHEMISTRY WORLD

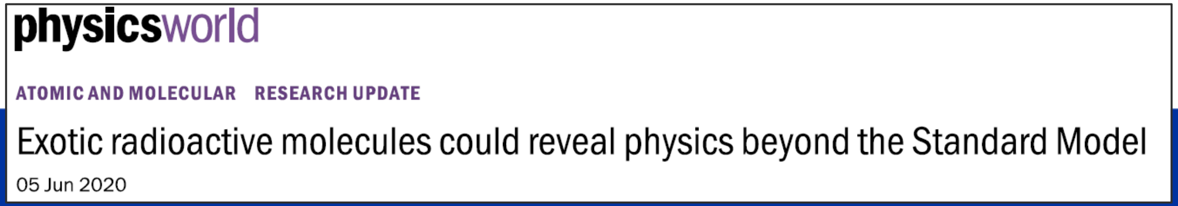
Molecular experiments hope to reveal new physics

BY ANDY EXTANCE | 5 JUNE 2020

PHYSICS TODAY

11 Jun 2020 in Research & Technology

Spectroscopy of molecules with unstable nuclei



physicsworld

ATOMIC AND MOLECULAR RESEARCH UPDATE

Exotic radioactive molecules could reveal physics beyond the Standard Model

05 Jun 2020

ISOLDE Solenoidal Spectrometer

Direct reactions: e.g. addition of neutron to a nucleus (d,p) without excitation of other degrees of freedom probe single-particle strength distributions.

Stable species: deuteron beam on target – CM with small velocity.

Unstable species: heavy beam on deuterated target - CM with large velocity, creating kinematic issues for measuring outgoing proton.

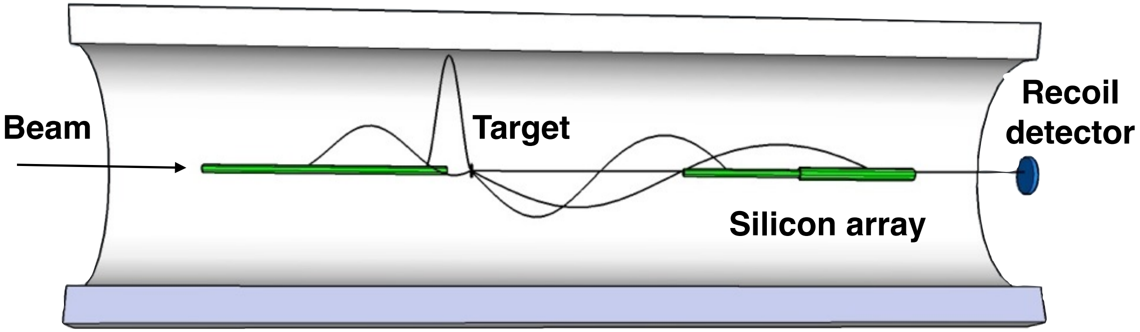
ISOLDE Solenoidal Spectrometer

4T superconducting (former MRI) solenoid from UQ hospital, Brisbane to ISOLDE in 2017

Helical orbit spectrometer principle

Target on the field axis + array of Si detectors.

MEASURE: position z, cyclotron period T_{cyc} and **energy E_p of emitted protons** from transfer reaction



Linear transformation between E_{cm} and E_{lab}

CM Energy: $$E_{\rm cm} = E_{\rm lab} + \frac{mV_{\rm cm}^2}{2} - \frac{mzV_{\rm cm}}{T_{\rm cyc}}$$

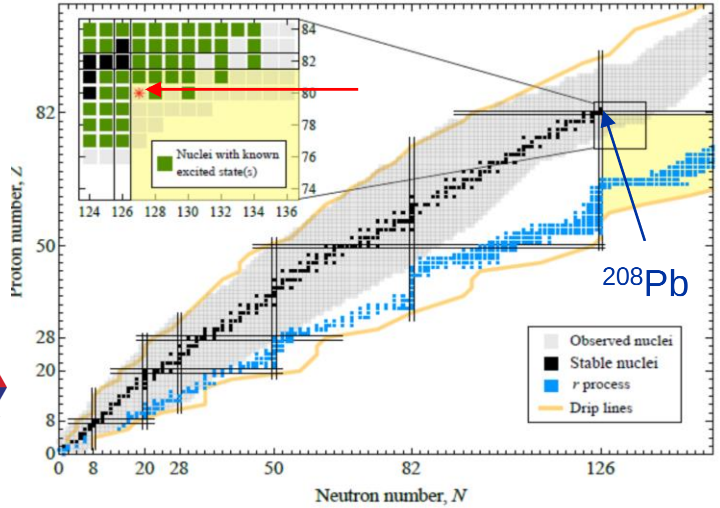
No kinematic compression of the Q-value spectrum – excellent resolution without need for γ rays.

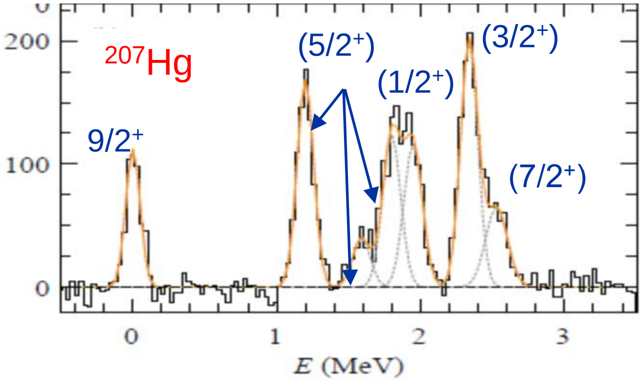
First ISS Physics (CERN Run 2) 2018 – with HELIOS Si array.

(i) Terra incognita Z<82 N>126

Study excited states in ^{207}Hg for the first time using transfer reactions, ^{206}Hg(d,p)@7.4 MeV/A, 5x10^5 pps, 165 μg/cm^2,140-keV FWHM.

on-axis singles

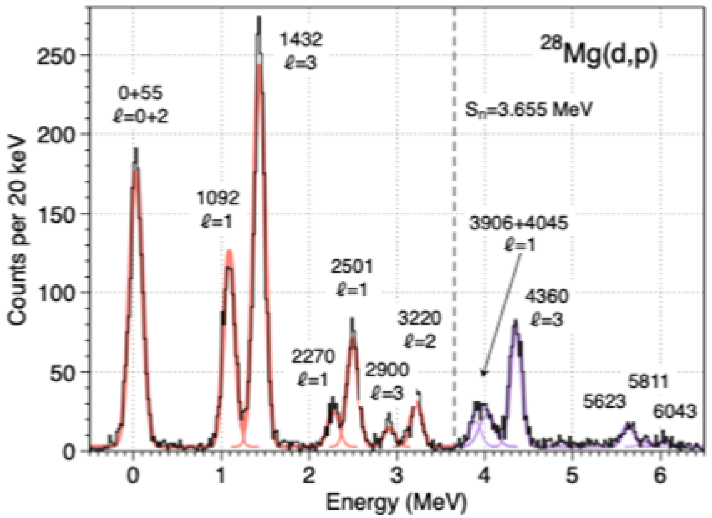




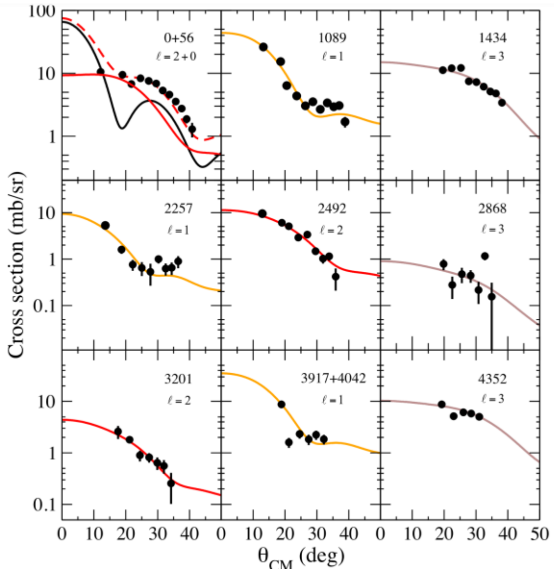
A first step in improving the understanding of sp structure of nuclei in a key part of the r process

Tang et al.
PRL 124, 062502 (2020)

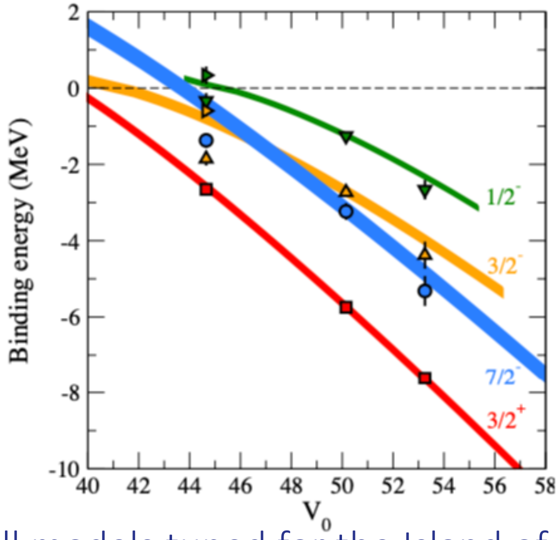
(ii) Single-particle evolution driving shape changes



Map single-particle trends close to abrupt shape change in ^{30}Mg: ^{28}Mg(d,p)@9.47 MeV/A, 10^6 pps, 80 and 120 μg/cm^2, 150-keV FHWM.



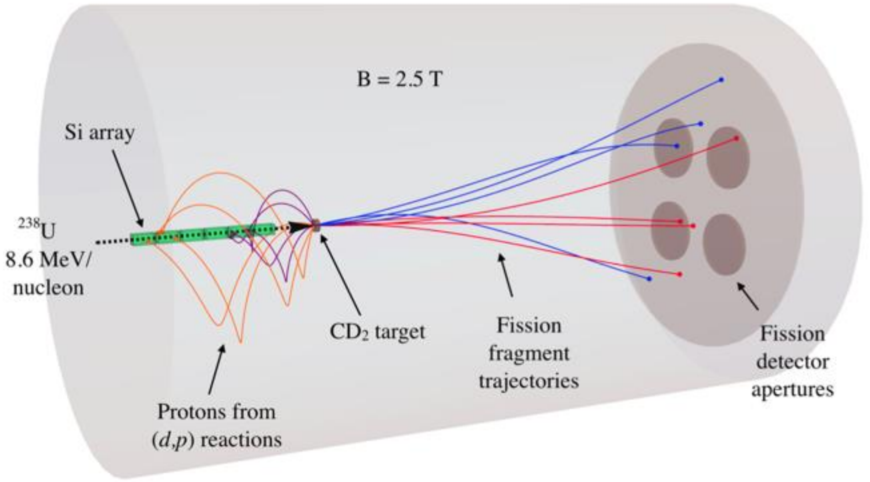
Si recoil detector



Tests of shell models tuned for the Island of Inversion and highlights the role of geometry of the binding potential on behaviour of orbitals close to threshold.

MacGregor et al.
PRC Letts 104, L051301 (2021)

Transfer-induced fission:

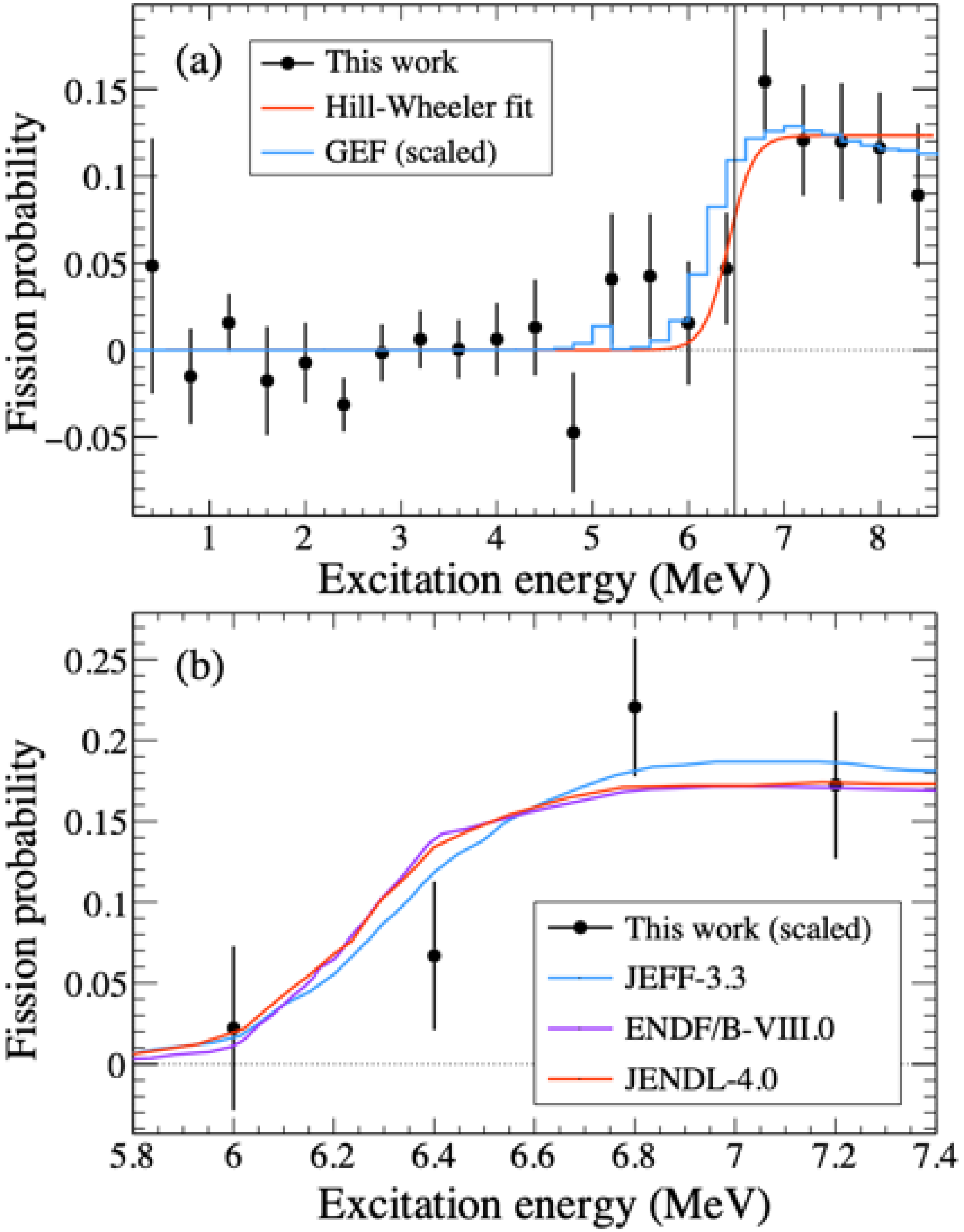


Proof of principle experiment using the HELIOS@ANL ^{238}U(d,pf) 8.6 MeV/u

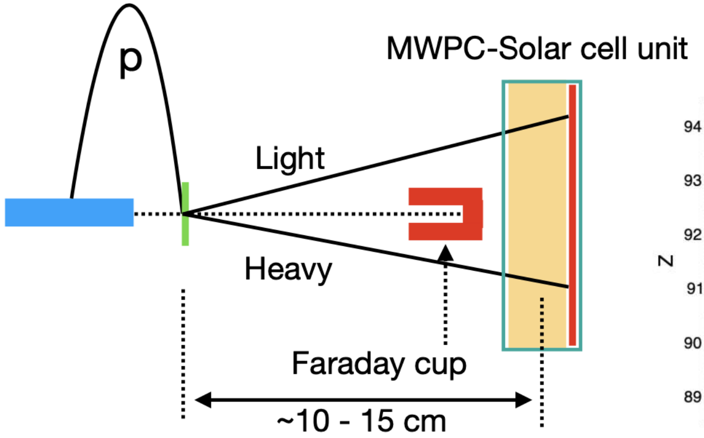
Accepted PRL 2023

MANCHESTER
1824
The University of Manchester

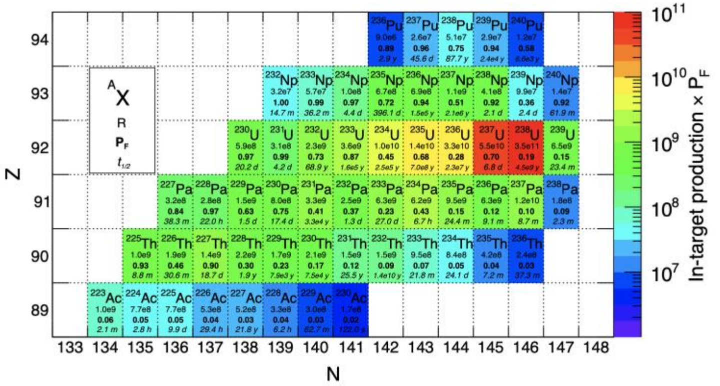
CHALMERS



ISOLDE: MWPC coupled to solar-cell array being developed to study transfer-induced fission



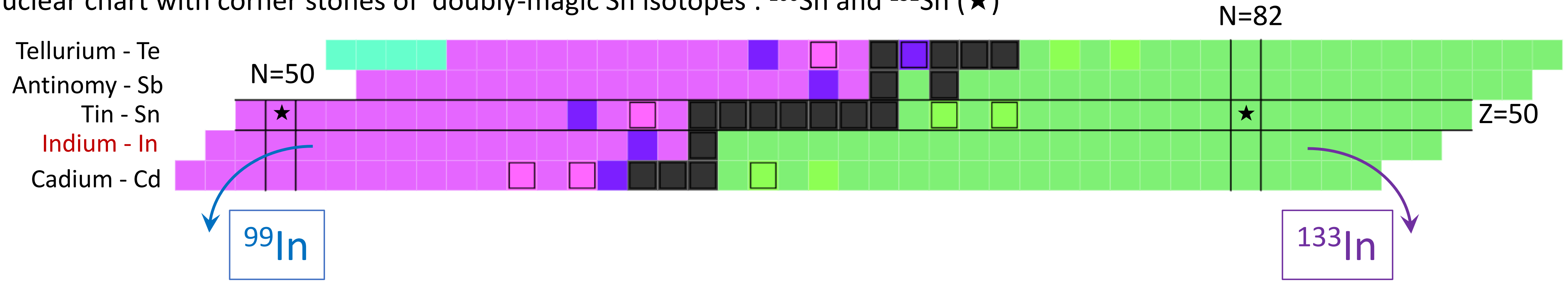
ISOLDE – LISA initiative to develop actinide beams for study



	133	134	135	136	137	138	139	140	141	142	143	144	145	146	147	148
94										^{236}Pu 9.0e6 0.89 2.9 y	^{237}Pu 2.6e7 0.96 45.6 d	^{238}Pu 5.1e7 0.75 87.7 y	^{239}Pu 2.9e7 0.94 2.4e4 y	^{240}Pu 1.2e7 0.58 6.6e3 y		
93		^{A}X R P_F $t_{1/2}$					^{232}Np 3.2e7 1.00 14.7 m	^{233}Np 5.7e7 0.99 36.2 m	^{234}Np 1.0e8 0.97 4.4 d	^{235}Np 6.7e8 0.72 396.1 d	^{236}Np 6.9e8 0.94 1.5e5 y	^{237}Np 1.1e9 0.51 2.1e6 y	^{238}Np 4.1e8 0.92 2.1 d	^{239}Np 9.9e7 0.36 2.4 d	^{240}Np 1.4e7 0.92 61.9 m	
92						^{230}U 5.9e8 0.97 20.2 d	^{231}U 3.1e8 0.99 4.2 d	^{232}U 2.3e9 0.73 68.9 y	^{233}U 3.6e9 0.87 1.6e5 y	^{234}U 1.0e10 0.45 2.5e5 y	^{235}U 1.4e10 0.68 7.0e8 y	^{236}U 3.3e10 0.28 2.3e7 y	^{237}U 5.5e10 0.70 6.8 d	^{238}U 3.5e11 0.19 4.5e9 y	^{239}U 6.5e9 0.15 23.4 m	
91				^{227}Pa 3.2e8 0.84 38.3 m	^{228}Pa 2.8e8 0.97 22.0 h	^{229}Pa 1.5e9 0.63 1.5 d	^{230}Pa 8.0e8 0.75 17.4 d	^{231}Pa 3.3e9 0.41 3.3e4 y	^{232}Pa 2.5e9 0.37 1.3 d	^{233}Pa 6.3e9 0.23 27.0 d	^{234}Pa 6.2e9 0.43 6.7 h	^{235}Pa 9.5e9 0.15 24.4 m	^{236}Pa 6.3e9 0.12 9.1 m	^{237}Pa 1.2e10 0.10 8.7 m	^{238}Pa 1.8e8 0.09 2.3 m	
90			^{225}Th 1.0e9 0.93 8.8 m	^{226}Th 1.9e9 0.46 30.6 m	^{227}Th 1.4e9 0.90 18.7 d	^{228}Th 2.2e9 0.30 1.9 y	^{229}Th 1.7e9 0.23 7.9e3 y	^{230}Th 2.1e9 0.17 7.5e4 y	^{231}Th 1.5e9 0.12 25.5 y	^{232}Th 1.5e9 0.09 1.4e10 y	^{233}Th 9.5e8 0.07 21.8 m	^{234}Th 8.4e8 0.05 24.1 d	^{235}Th 4.2e8 0.04 7.2 m	^{236}Th 2.4e8 0.03 37.3 m		
89		^{223}Ac 1.0e9 0.06 2.1 m	^{224}Ac 7.7e8 0.05 2.8 h	^{225}Ac 7.7e8 0.05 9.9 d	^{226}Ac 5.3e8 0.04 29.4 h	^{227}Ac 5.2e8 0.03 21.8 y	^{228}Ac 3.3e8 0.04 6.2 h	^{229}Ac 3.0e8 0.03 62.7 m	^{230}Ac 1.7e8 0.02 122.0 s							

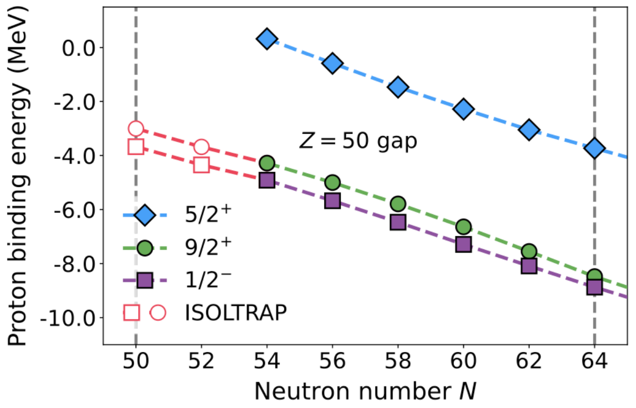
Indium – from one extreme to the other - *two back-to-back ISOLDE PRL's in July*

Part of nuclear chart with corner stones of doubly-magic Sn isotopes : ^{100}Sn and ^{132}Sn (★)



PHYSICAL REVIEW LETTERS **131,** 022502 (2023)

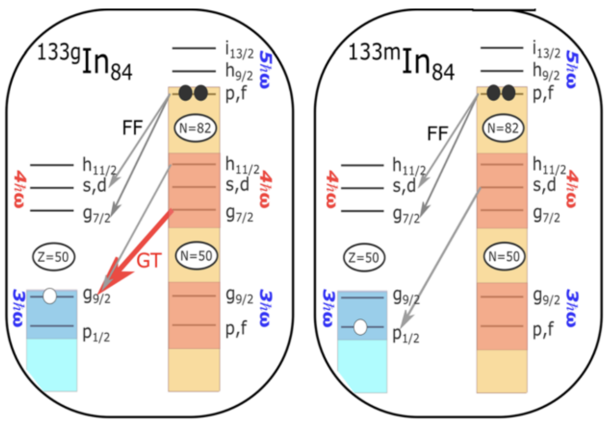
Isomeric Excitation Energy for ^{99}In^{m} from Mass Spectrometry Reveals Constant Trend Next to Doubly Magic ^{100}Sn



- Precision measurement of ground and isomeric state using ISOLTRAP.
- Excitation of isomer extremely constant across In
- In contrast to measurements of magnetic moment, which increases near N=50 - also ISOLDE experiment from 2022!
- Very difficult to reproduce with modern calculations and may point to missing physics.

PHYSICAL REVIEW LETTERS **131,** 022501 (2023)

^{133}In: A Rosetta Stone for Decays of *r*-Process Nuclei



- Measured β decays from ground and isomeric levels using ISOLDE DECAY STATION.
- Decays populate just a few unbound levels in ^{133}Sn.
- Measured resonance properties that are critical for benchmarking models of the *astrophysical r process* that manufactures many of the heavy chemical elements.

Good example of versatility of ISOLDE – precision studies of both neutron-rich and neutron-deficient exotic isotopes separated by 34 neutrons!

Towards a nuclear clock...

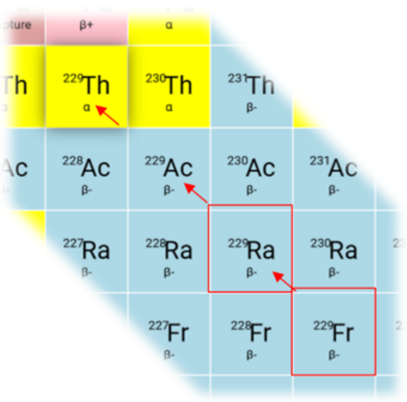
For 60 years, atomic clocks have been used with a precision of 1s in 300 million years.
Based on the frequency of a transition between two atomic levels in cold ^{133}Cs atoms.

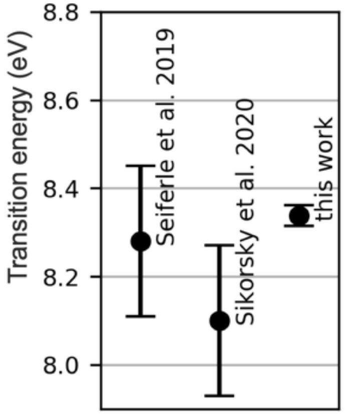
If you can find two nuclear levels with separation corresponding to optical photons, the nuclear clock would be much more precise as less sensitive to external perturbations.

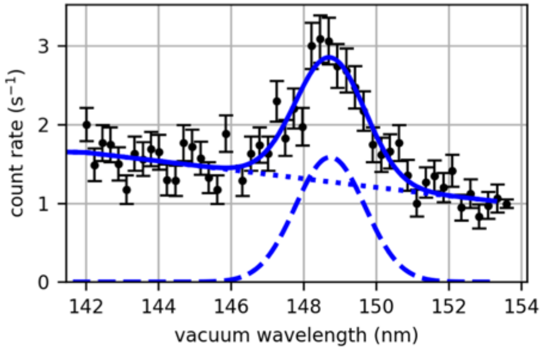
^{229}Th isomer is currently the best candidate for a nuclear clock, with a first excited state at only around 8 eV from the ground state and a long half life

Experiment at ISOLDE: ^{229m}Th ions produced using β-decay of a ^{229}Fr - ^{229}Ra beam implanted into CaF_2 and MgF_2 crystals. Radiative decays of ^{229}Th observed for the first time giving precise measurement of transition energy (essential for laser excitation of the clock) and confirmed “long” lifetime of ^{229m}Th state

KU LEUVEN





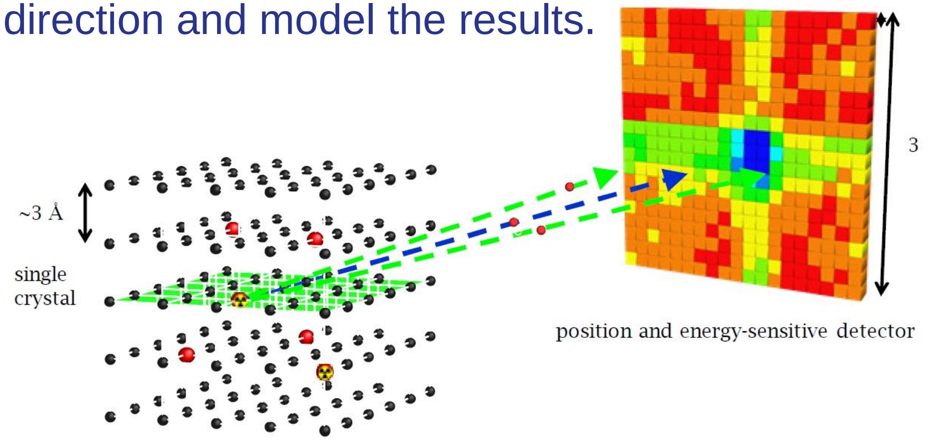


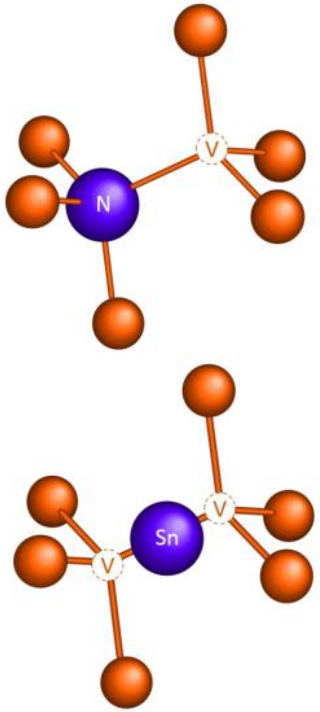
Vacancy centres in diamond as potential qubits

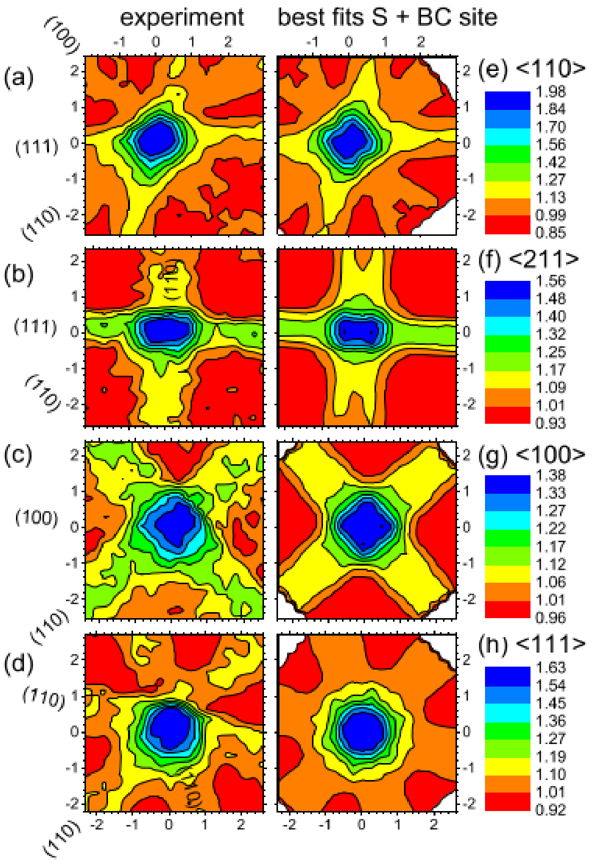
Diamond has excellent optical/mechanical properties for integrating into photonic circuits and quantum info tech – refractive index, transmission window, band gap, high Young’s modulus etc.

Optically active crystal defects “color centres” can exhibit stable single-photon fluorescence, combined with nanophotonic circuits, could act as qubits - those created by nitrogen are well studied.

Implantation of radioactive ^{121}Sn into diamond at ISOLDE allows β “emission channeling” to study the lattice site location – measure intensity of β as a function of angle to lattice direction and model the results.





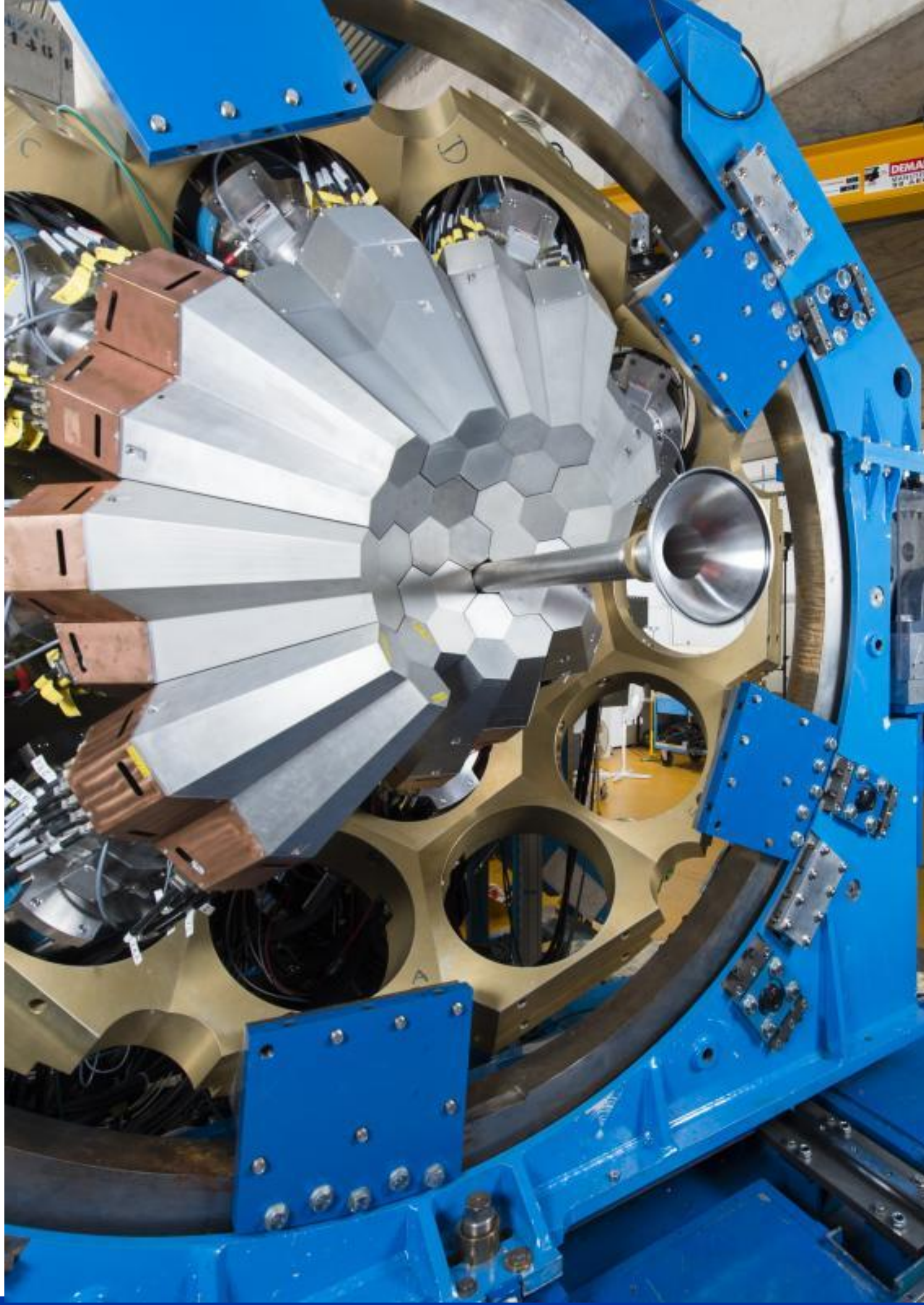


Experiments revealed that Sn vacancy centres are very promising candidates for single-photon emission due to their excellent optical properties and a very simple structural formation mechanism.

PRL 125, 045301 (2020)

Perspectives

- The study of the nuclear many-body problem, effectively “nuclear structure”, is a tricky and difficult problem.
- It is (endlessly!) fascinating how the nucleus can exhibit such different behaviour and how simplicity emerges from such a complex system.
- The study of exotic nuclei is giving new impetus to these challenges and the start of several new facilities – FRIB (USA), FAIR (Germany), RAON (Korea), SPES (Italy)… and improvements to others GANIL (France), ISOLDE (CERN), RIKEN (Japan) – make it an exciting time for nuclear structure.
- More and more nuclear structure and the techniques used to study the nucleus are becoming important for other areas of study from fundamental forces through to condensed matter physics.



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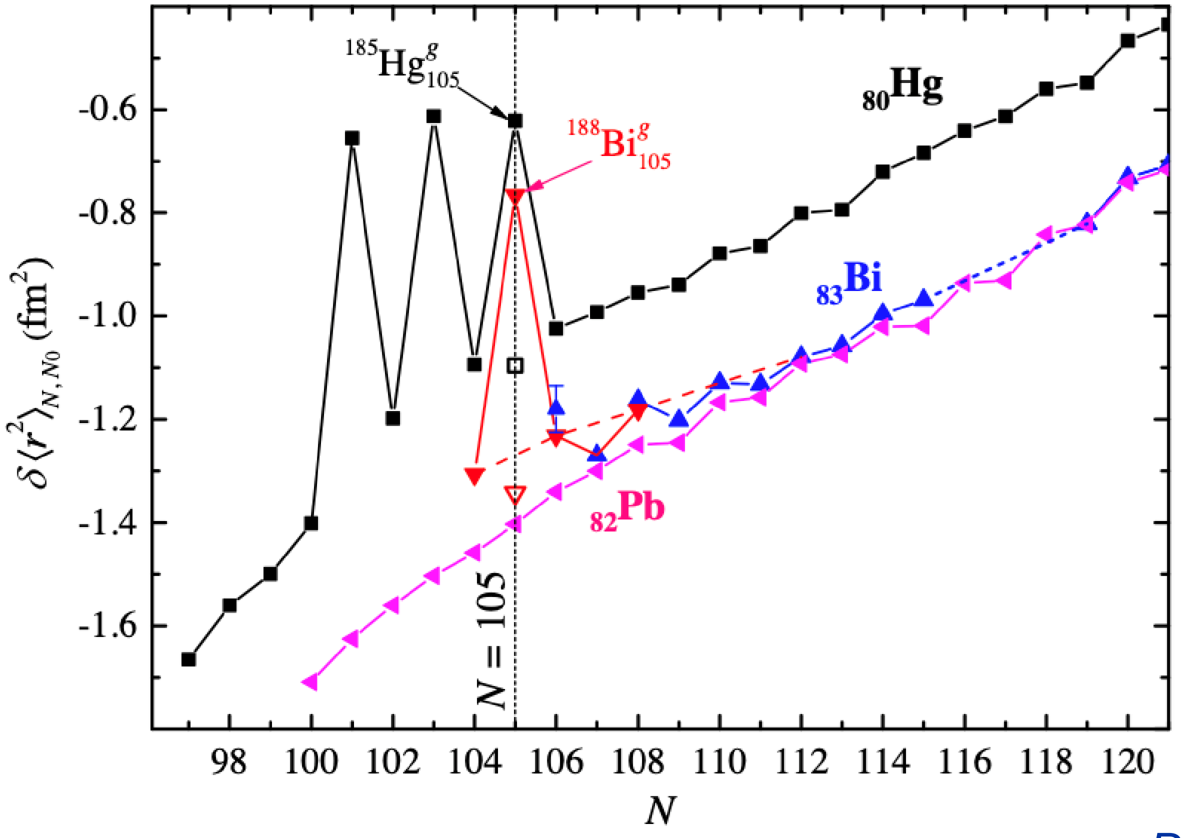
Large Shape Staggering in Neutron-Deficient Bi Isotopes



In-source laser spectroscopy – wavelengths of ionising lasers scanned as yields deduced by measurements of α decay, mapping out the atomic hyperfine structure.

Deduce changes in mean-square charge radii via the isotope shifts.

Spectacular changes in radius in Bi isotopes due to rapidly changing gs shapes.

Only second example of such dramatic changes – Hg isotopes studied at ISOLDE 50 years ago.

PRL 127, 192501 (2021)

UNIVERSITY of York

ISS Science Programme: (d,p) studies

ISOLDE Solenoidal Spectrometer

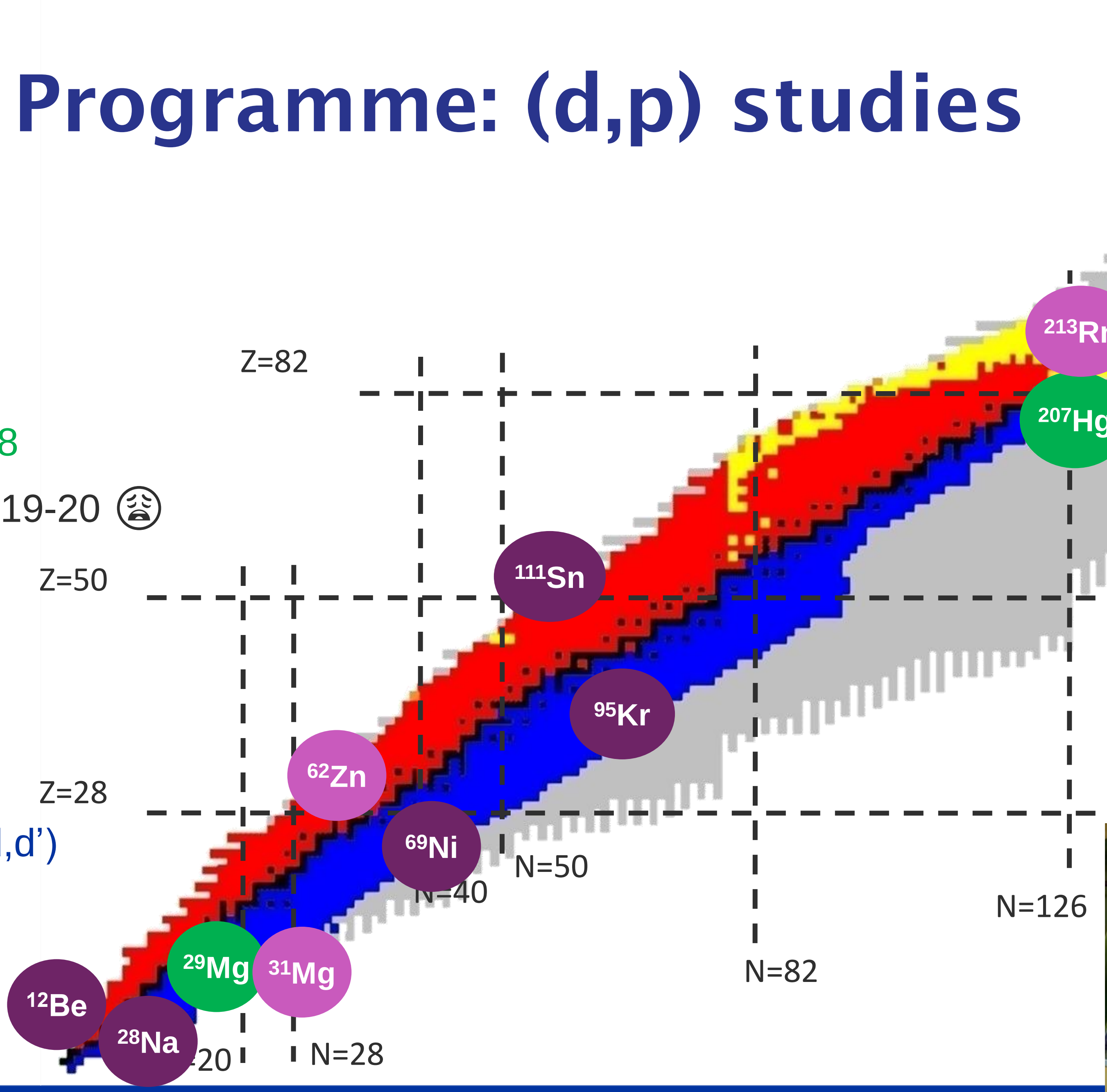
Early implementation 2018

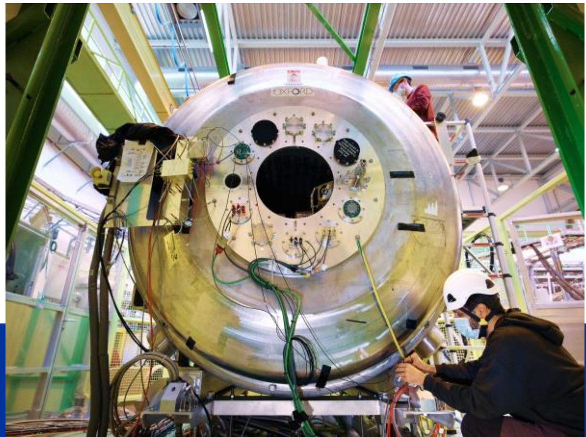
CERN Long Shutdown 2019-20 😩

Fully commissioned 2021

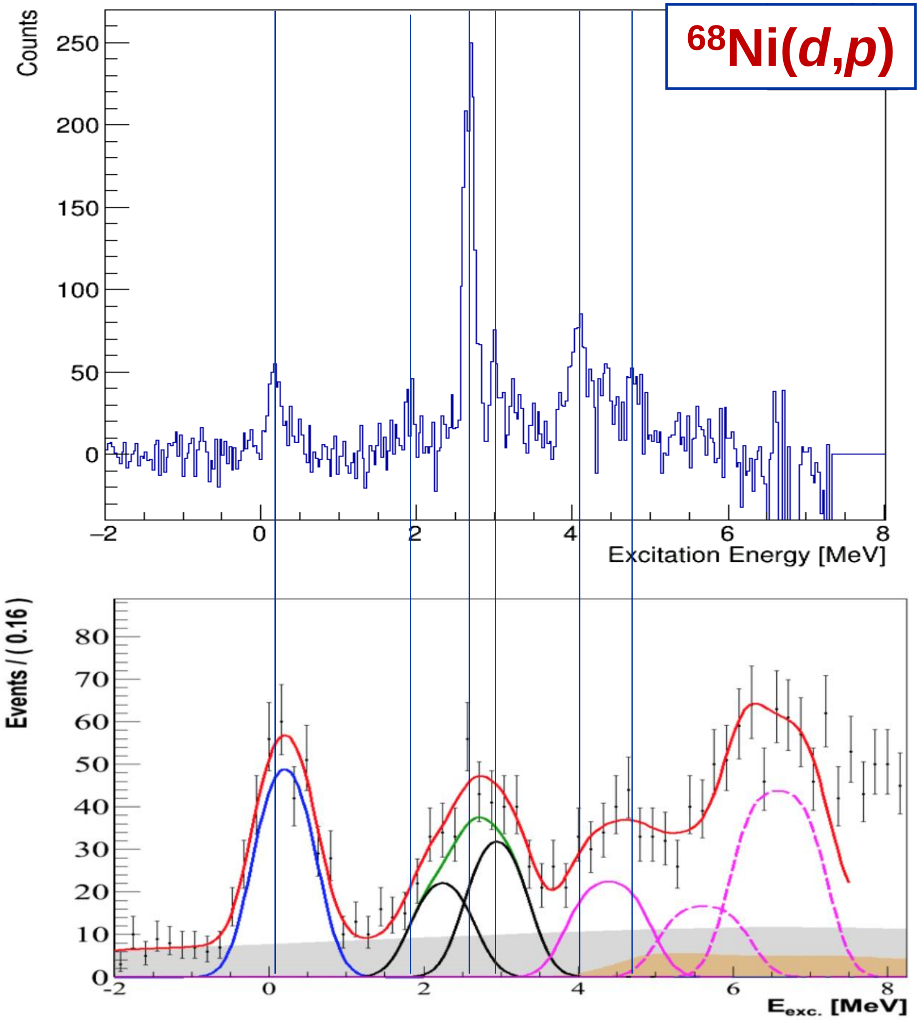
Fully commissioned 2022

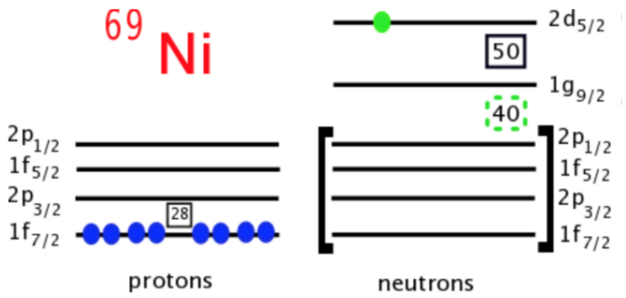
For the future:
(t,p) and (t,α)
forward-going reactions (d,d’)



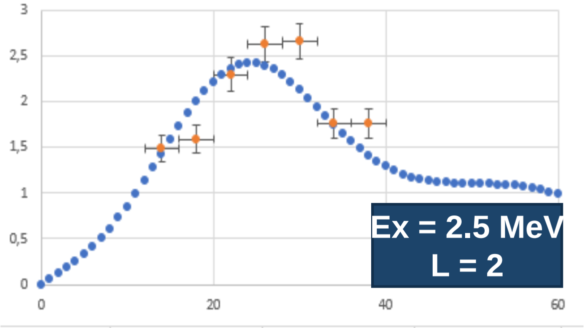


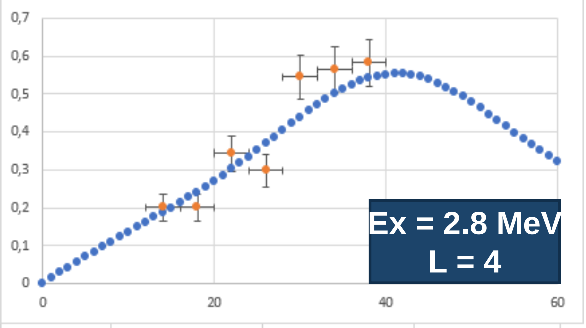
Third ISS Physics (CERN Run 2) 2022 – with ISS Si array.





- ^{68}Ni ~2 x 10^4 pps @ 6.0 MeV/*u*
- *N* = 50 shell gap approaching ^{78}Ni
- Intruder configurations leading to shape coexistence





GANIL experiment

(2010, unpublished, M. Moukkamad et al.)
E$_{beam}$ = 25.14 MeV/*u*; CD$_2$ Target : 2.6 mg/cm^2