Nuclear physics: the ISOLDE facility

Magdalena Kowalska
CERN, PH-Dept

on behalf of the CERN ISOLDE team
www.cern.ch/isolde

Outline

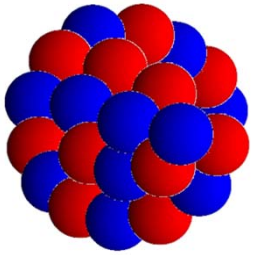
- Forces inside atomic nuclei
- Nuclei and QCD, nuclear models
- Nuclear landscape
- Open questions in nuclear physics

- ISOLDE facility
- Radio-isotope production
- Physics of ISOLDE
- Examples of experimental setups
- Physics case: “island of inversion”

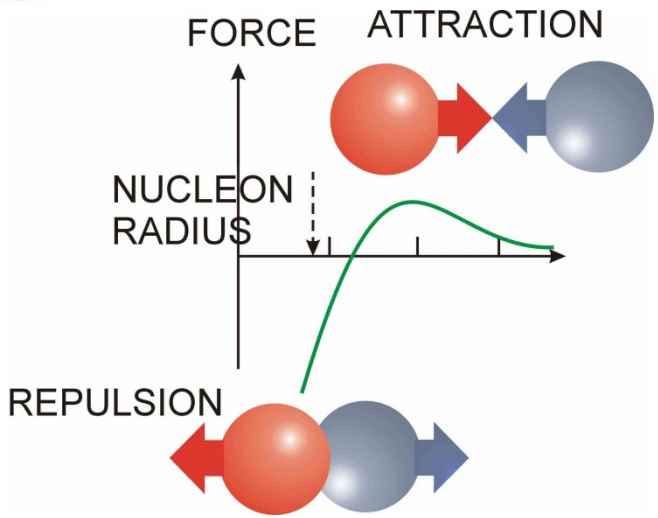
Nuclear physics today

Forces acting in nuclei

- **Coulomb force** repels protons

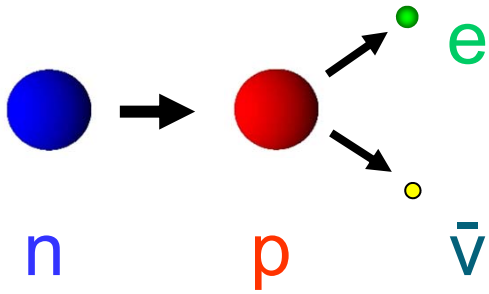


- **Strong interaction** ("nuclear force") causes binding which is stronger for pn-systems than nn-systems



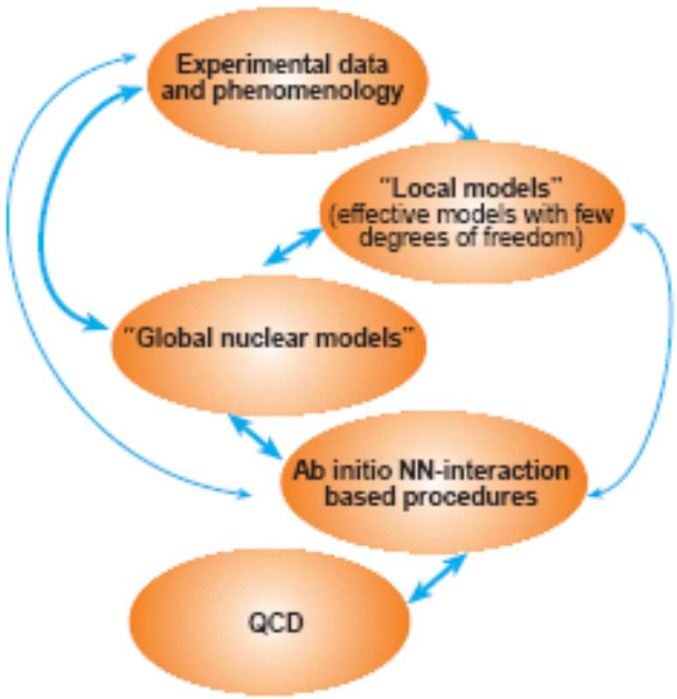
- Neutrons alone form no bound states (exception: neutron stars (**gravitation**!)

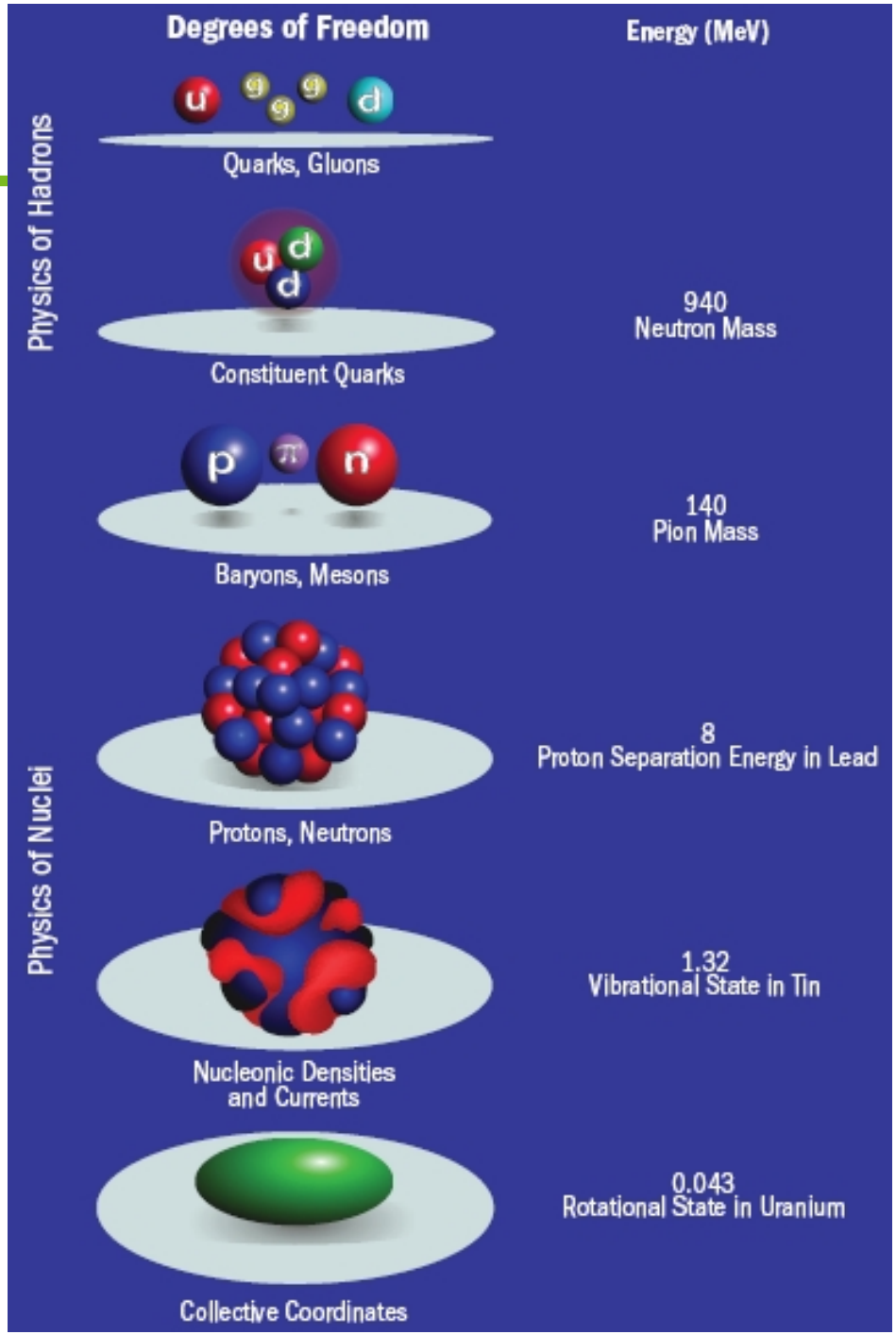
- **Weak interaction** causes β-decay



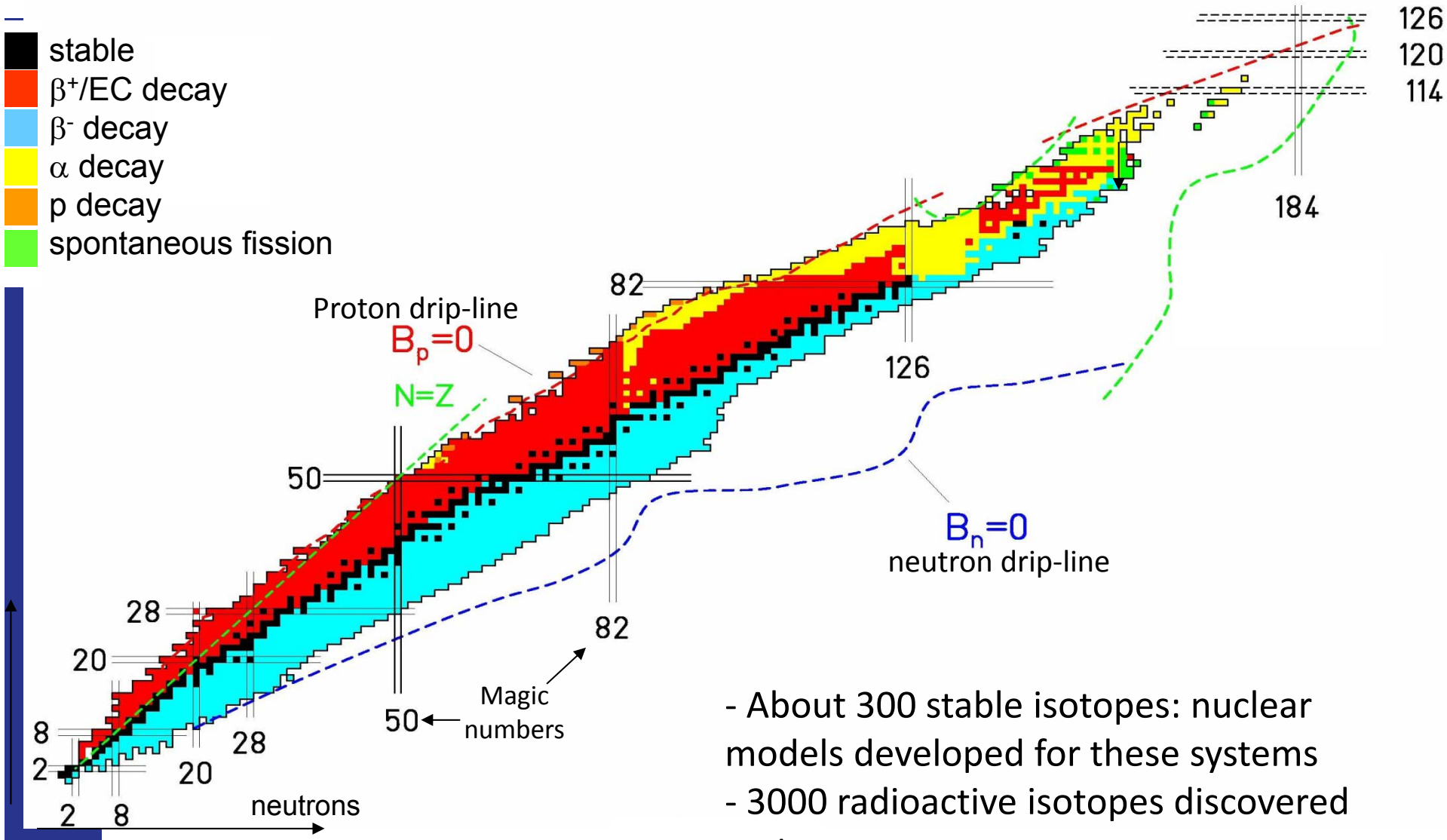
Nuclei and QCD

- Different energy scales
- In nuclei: non-perturbative QCD, so no easy way of calculating
- Have to rely on nuclear models (shell model, mean-field approaches)
- Recent progress: lattice QCD





Nuclear landscape



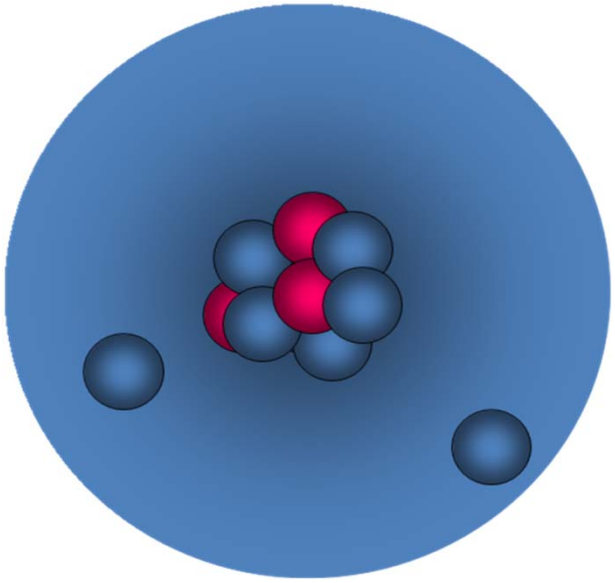
- About 300 stable isotopes: nuclear models developed for these systems
- 3000 radioactive isotopes discovered up to now

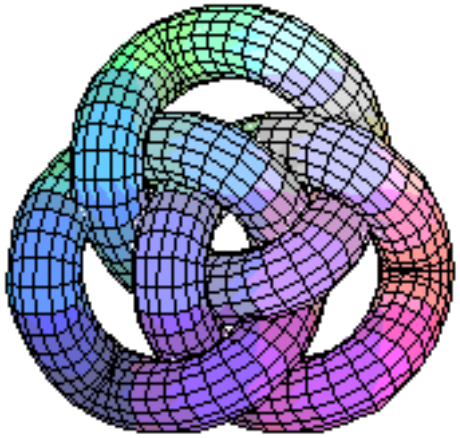
Properties of radio-nuclides

- Different neutron-to-proton ratio than stable nuclei leads to:
  - New structure properties
  - New decay modes

=> Nuclear models have problems predicting and even explaining the observations

- Example - halo nucleus 11Li:
  - Extended neutron wave functions make ^{11}Li the size of ^{208}Pb
  - When taking away 1 neutron, the other is not bound any more (10Li is not bound)

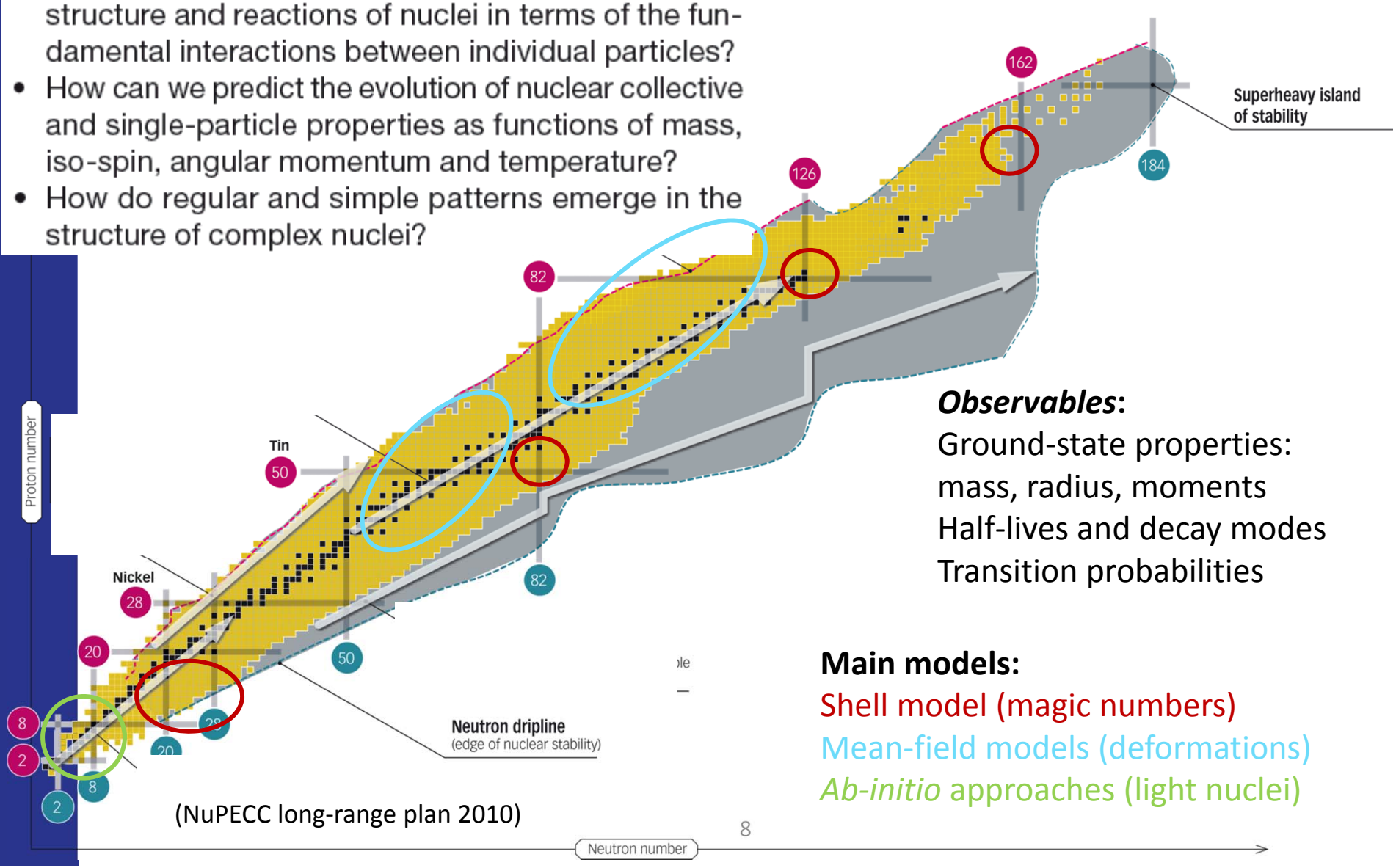




Open questions in nuclear physics

- How can we describe the rich variety of low-energy structure and reactions of nuclei in terms of the fundamental interactions between individual particles?
- How can we predict the evolution of nuclear collective and single-particle properties as functions of mass, iso-spin, angular momentum and temperature?
- How do regular and simple patterns emerge in the structure of complex nuclei?

2 kinds of interacting fermions



(NuPECC long-range plan 2010)

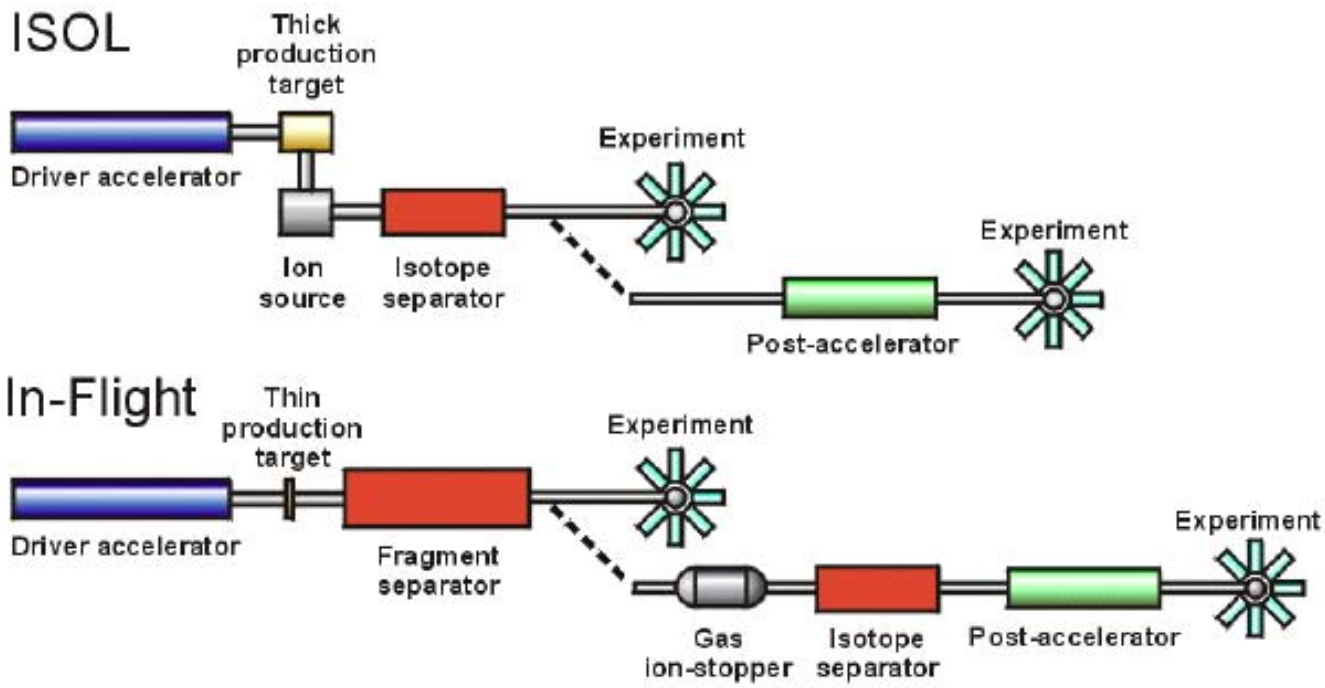
Observables:
Ground-state properties: mass, radius, moments
Half-lives and decay modes
Transition probabilities

Main models:
Shell model (magic numbers)
Mean-field models (deformations)
Ab-initio approaches (light nuclei)

ISOLDE: CERN radio-nuclide factory

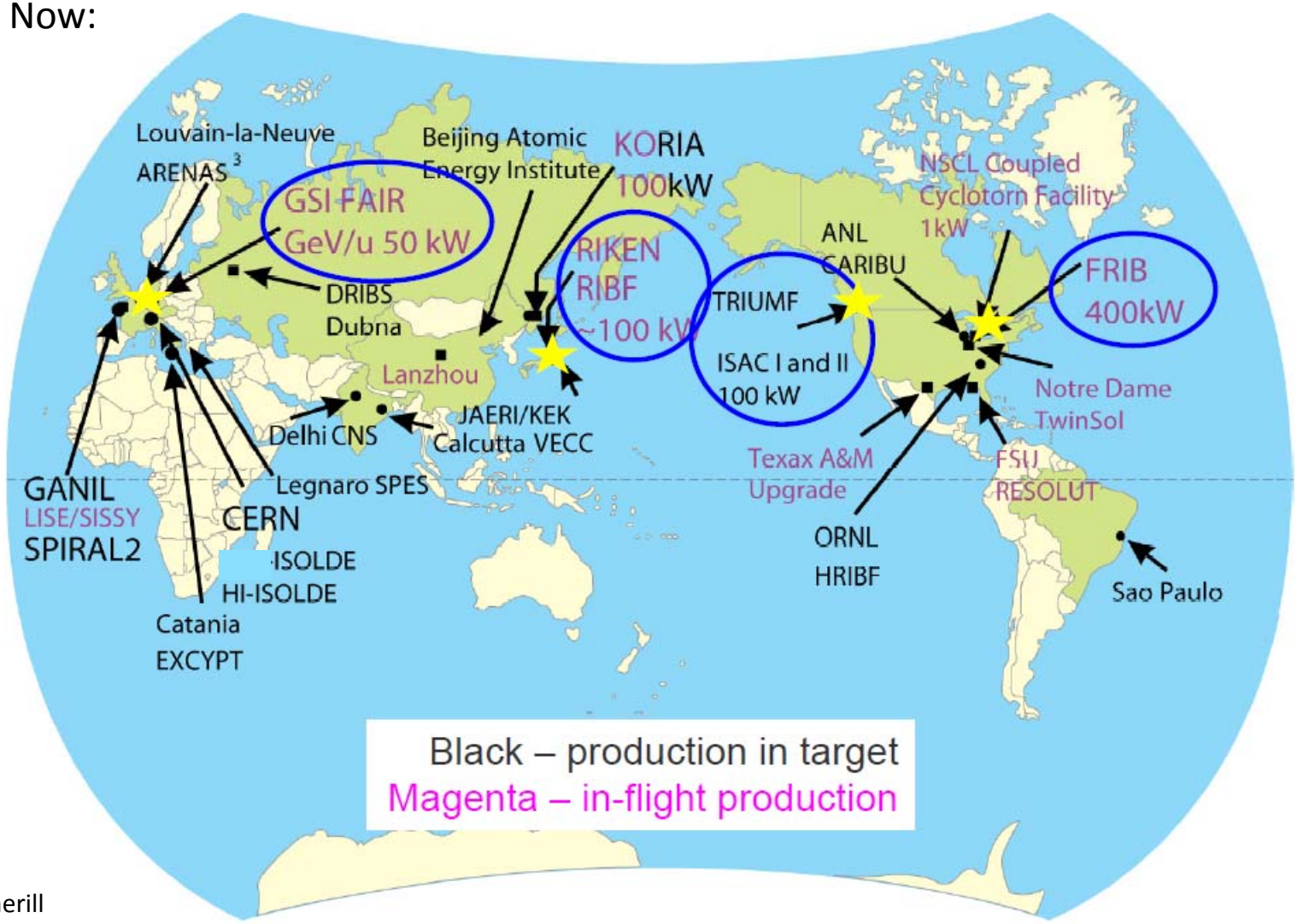
Radioactive-ion beam facilities

- Renaissance of nuclear physics:
  - access to nuclei with new proton-to-neutron ratios
  - testing ground for nuclear models
  - allows many applications



Radioactive-ion beam facilities

- 1967: ISOLDE-CERN: first ISOL-type facility
- Now:



B. Sherill

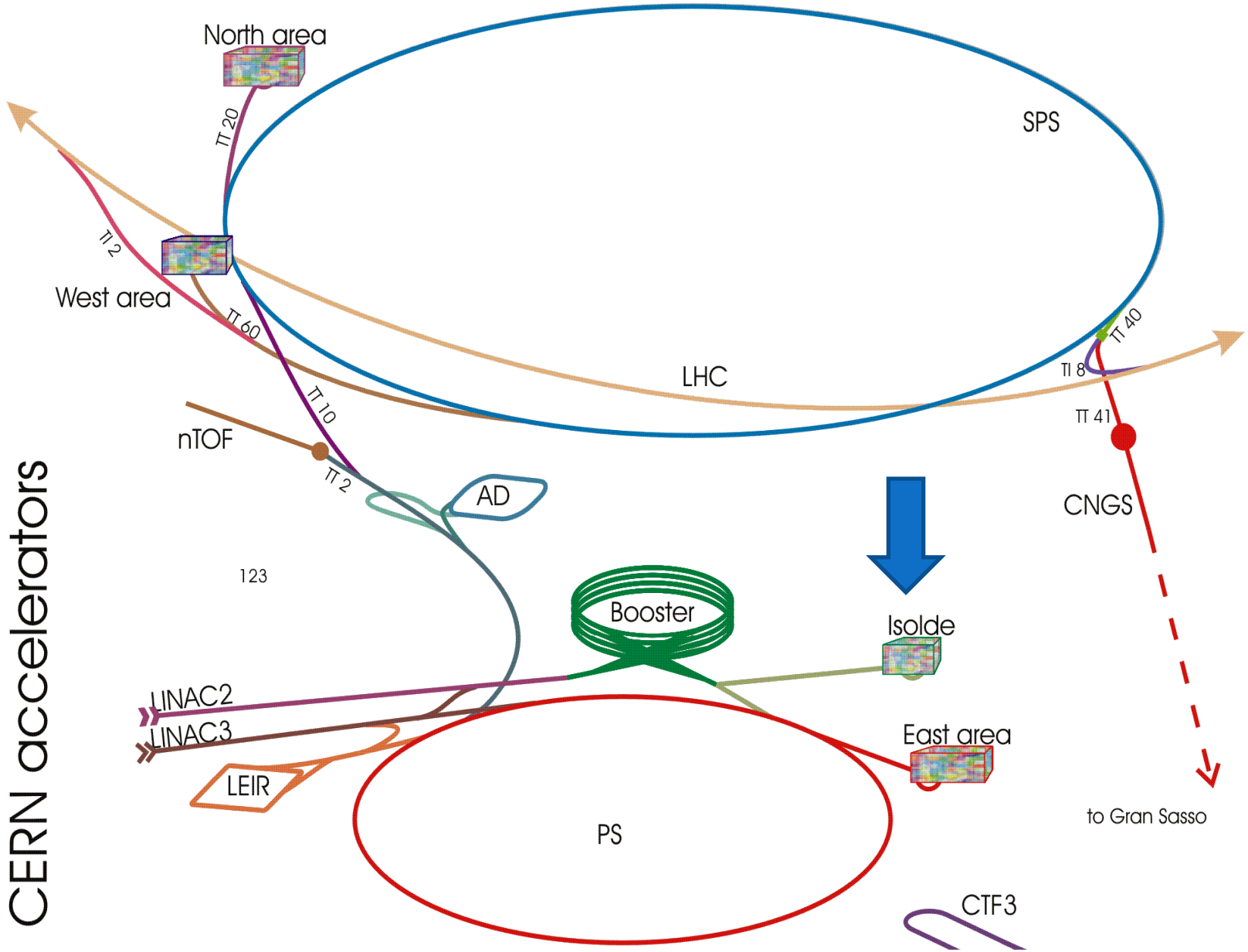
ISOLDE – short history

First beam October 1967

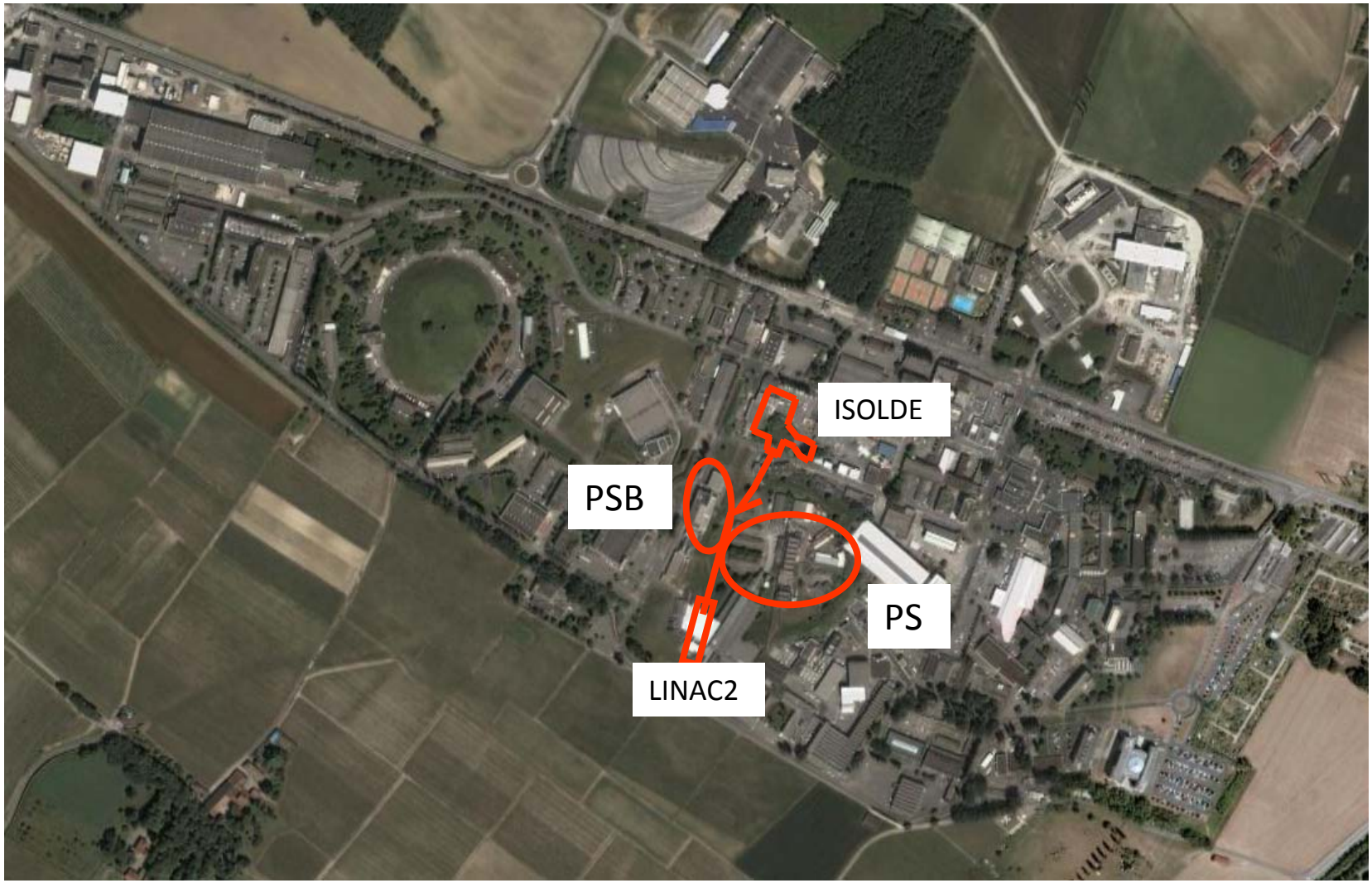
Upgrades 1974 and 1988

New facility June 1992

ISOLDE at CERN

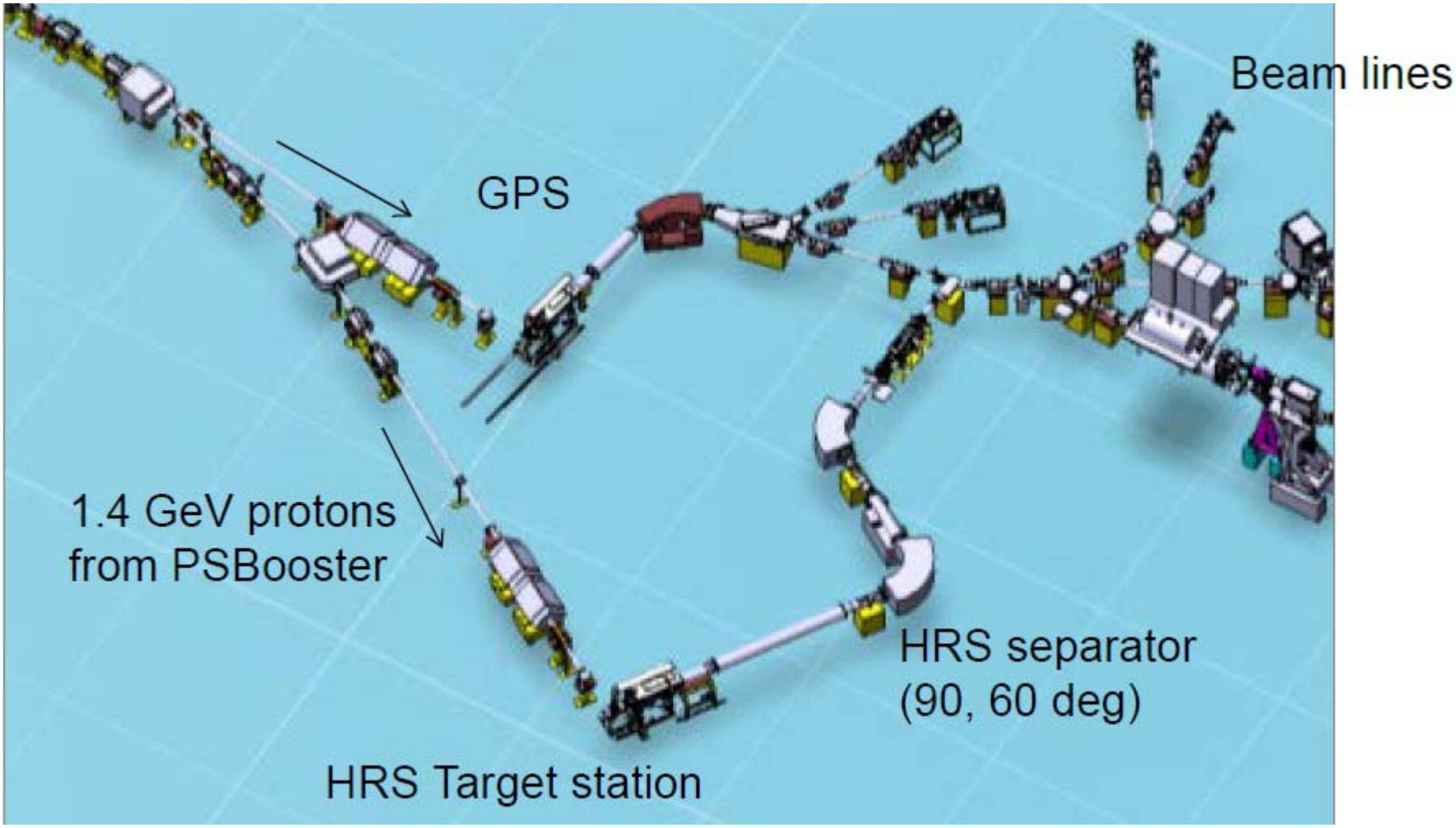


ISOLDE within CERN accelerators



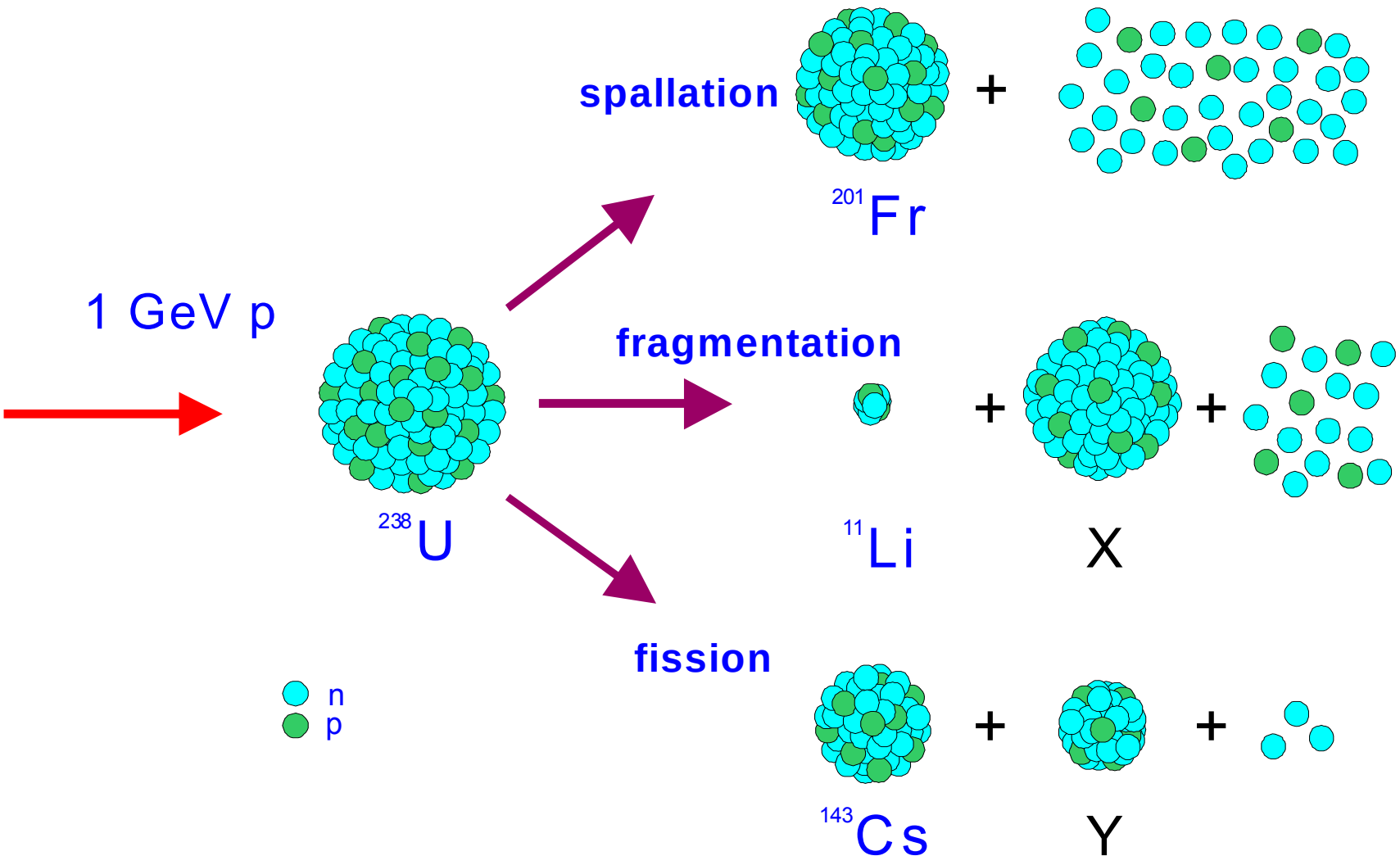
ISOLDE elements

Isotope production via reactions of light beam with thick and heavy target



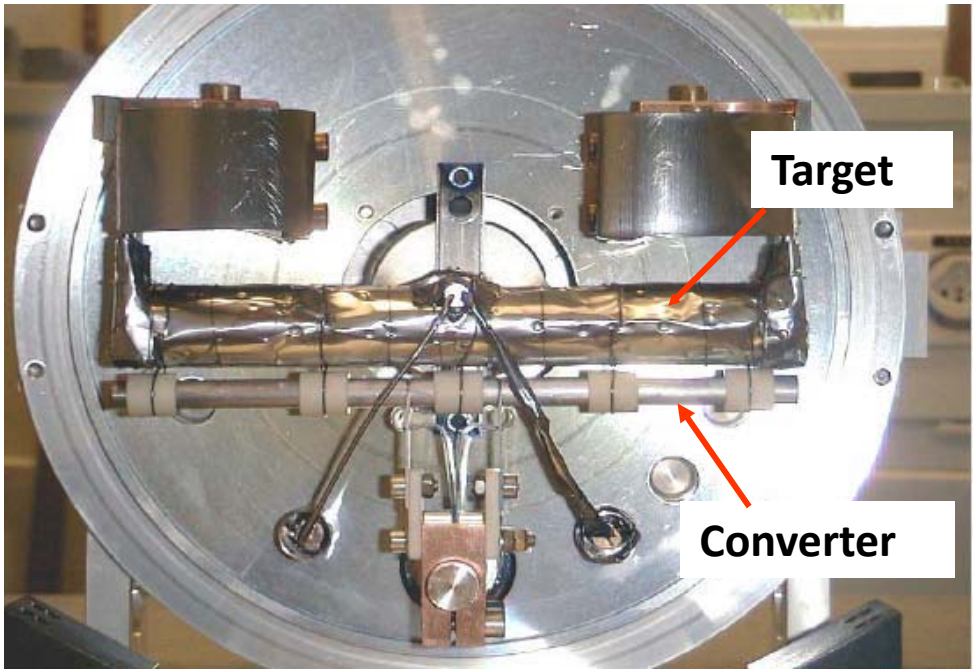
Production – ionization – separation

ISOTOPE production



Targets

- Over 20 target materials and ionizers, depending on beam of interest
- U, Ta, Zr, Y, Ti, Si, …
- Target material and transfer tube heated to 1500 – 2000 degrees
- Operated by robots due to radiation

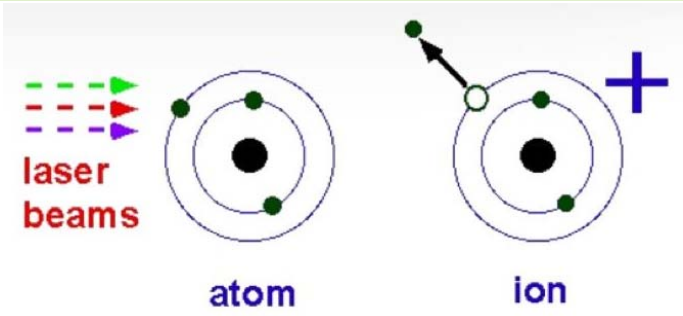


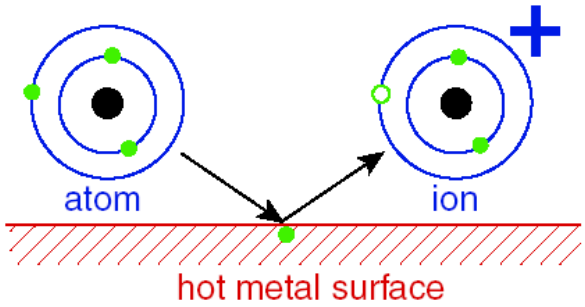
Converter Target

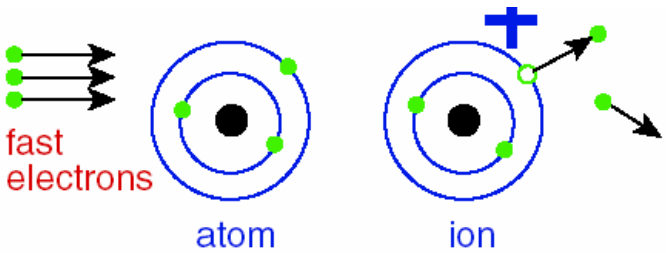
Standard

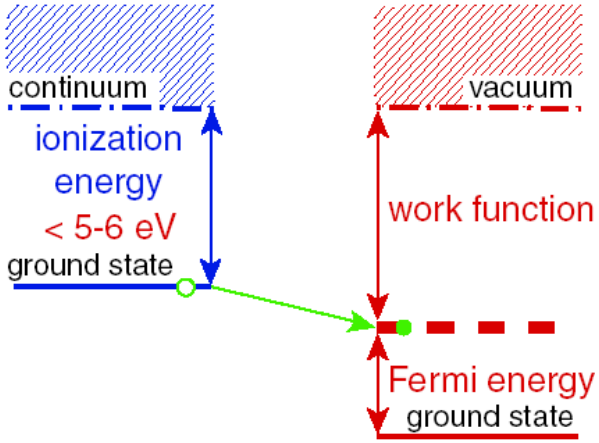
Ionization

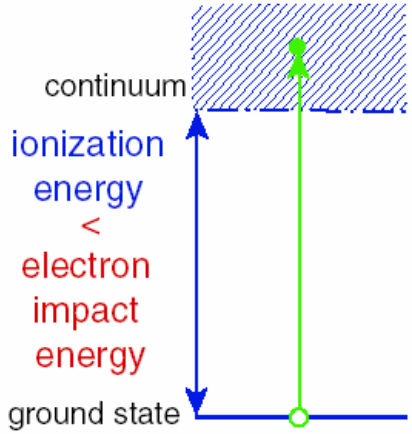
- Surface
- Plasma
- Lasers







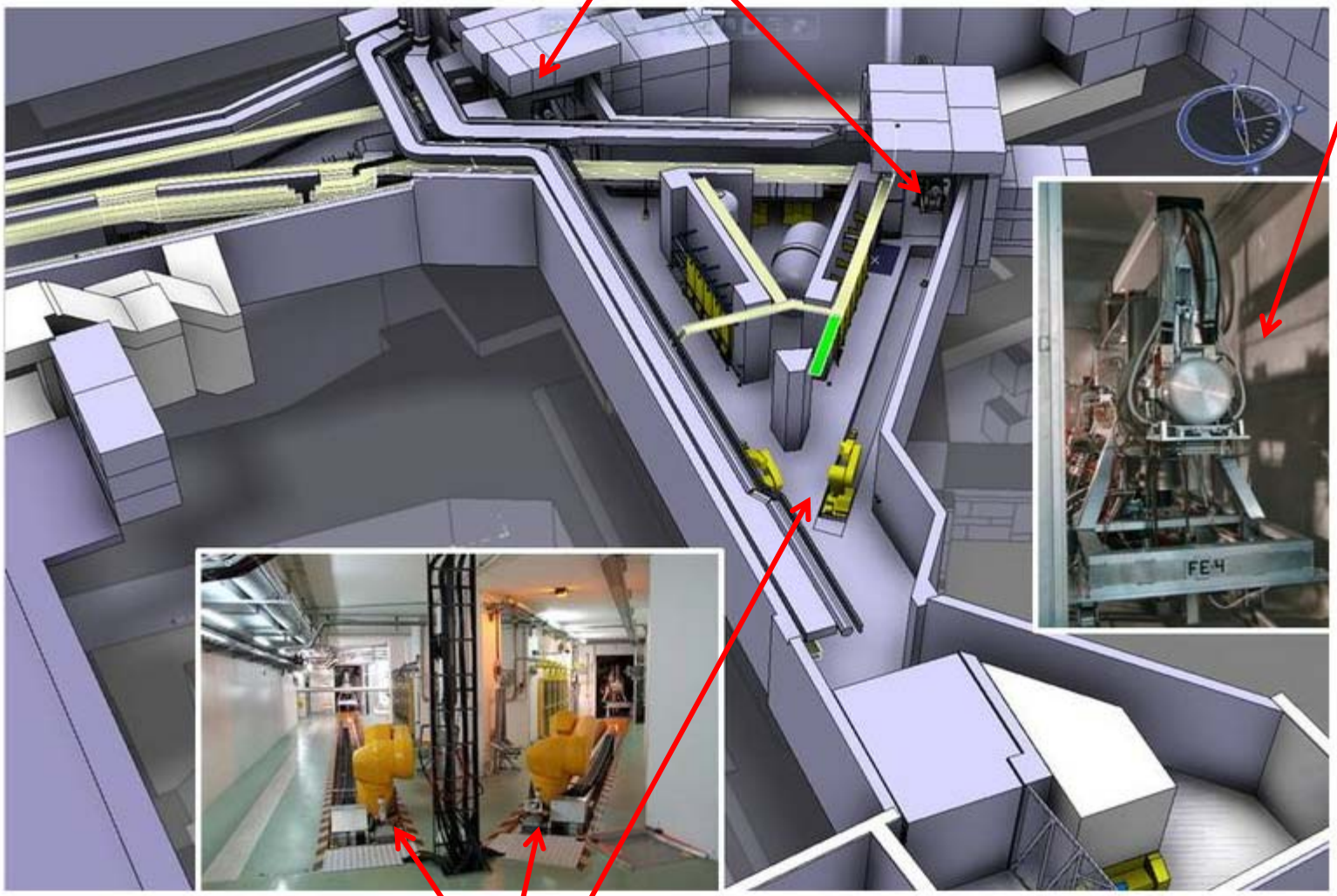




Production, ionization, extraction

target

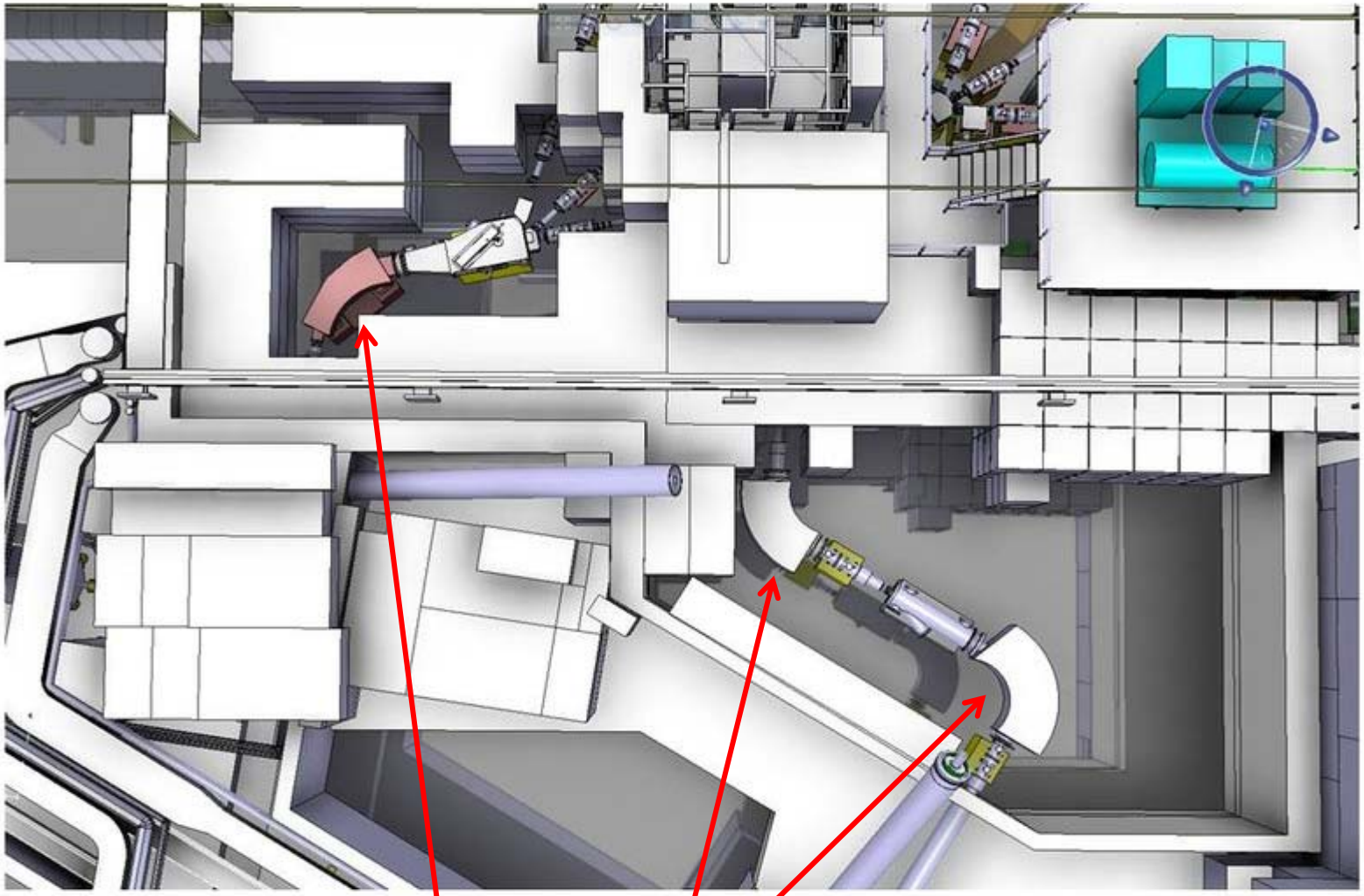
Target+ vacuum+ extraction



robots

Ion energy: 30-60keV

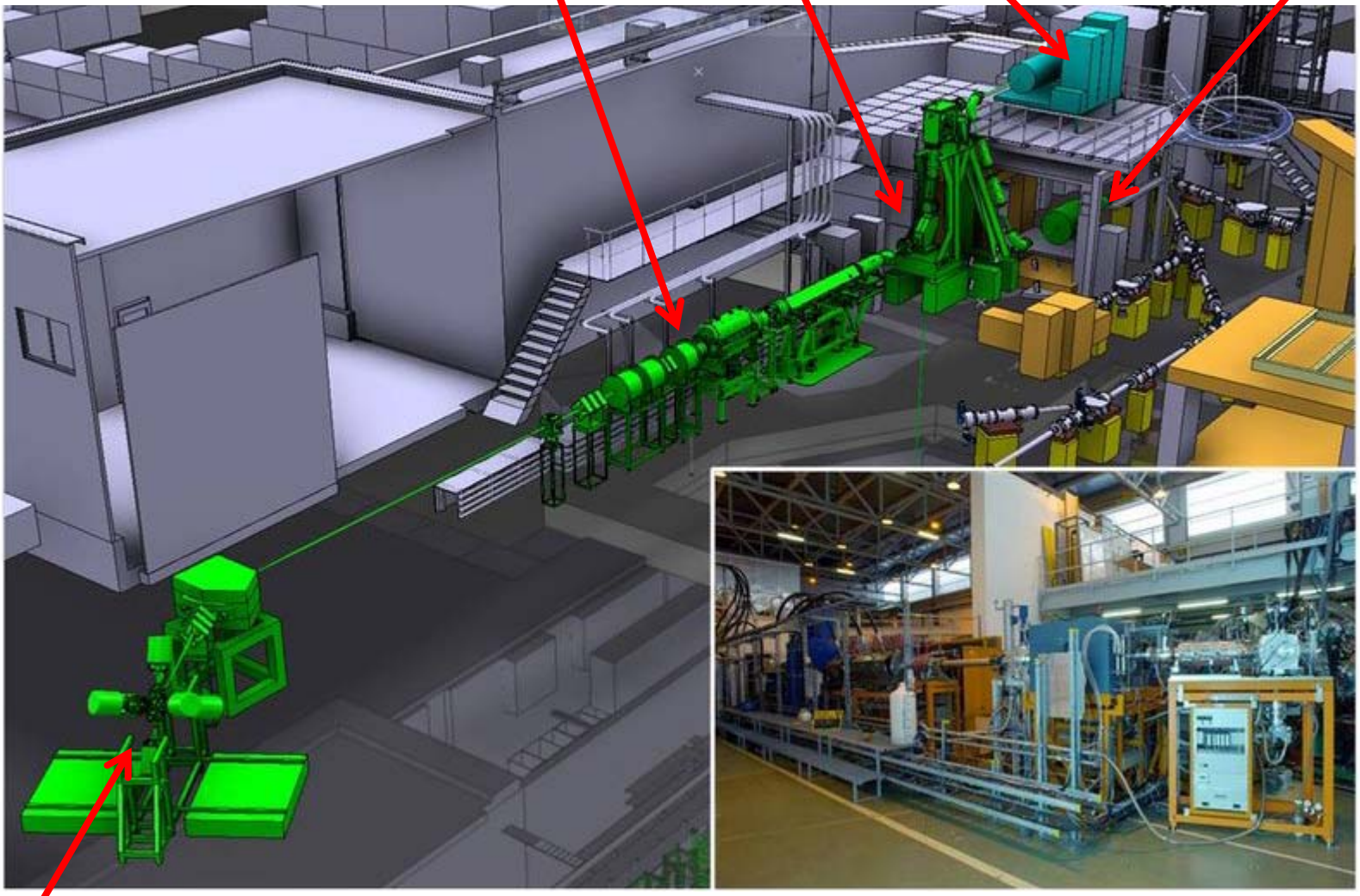
Separation



Magnet separators (General Purpose and High Resolution)

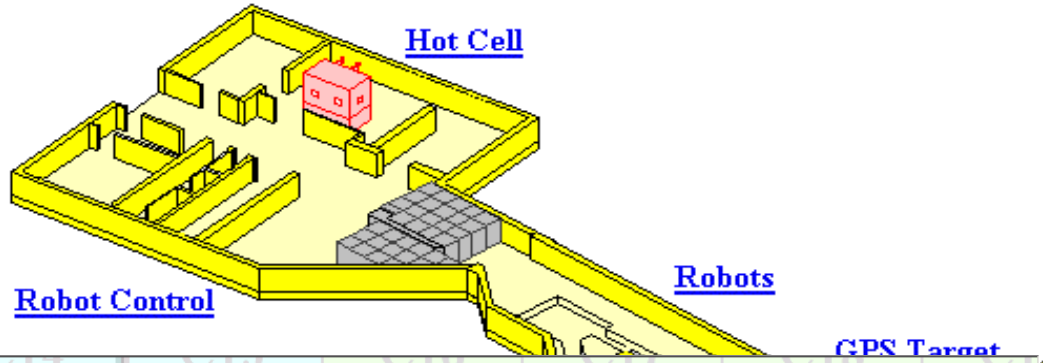
Post-acceleration

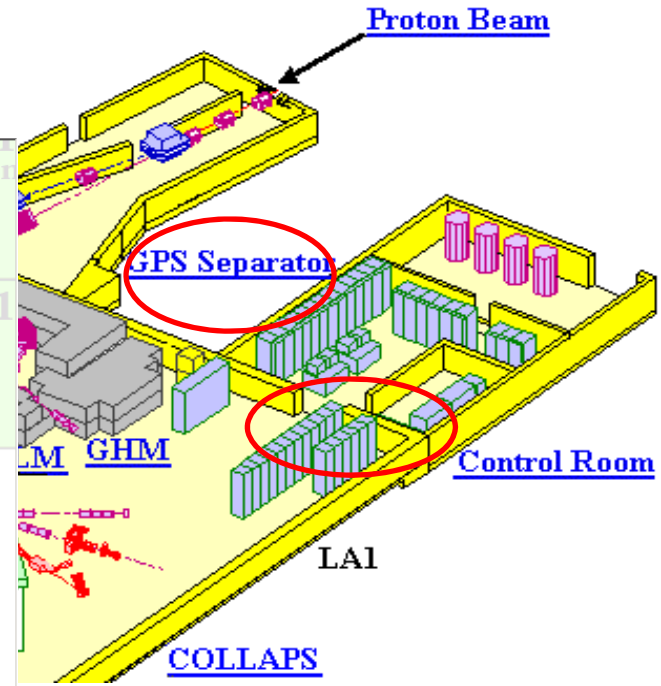
REX accelerator



Production and selection -exaple

Facility

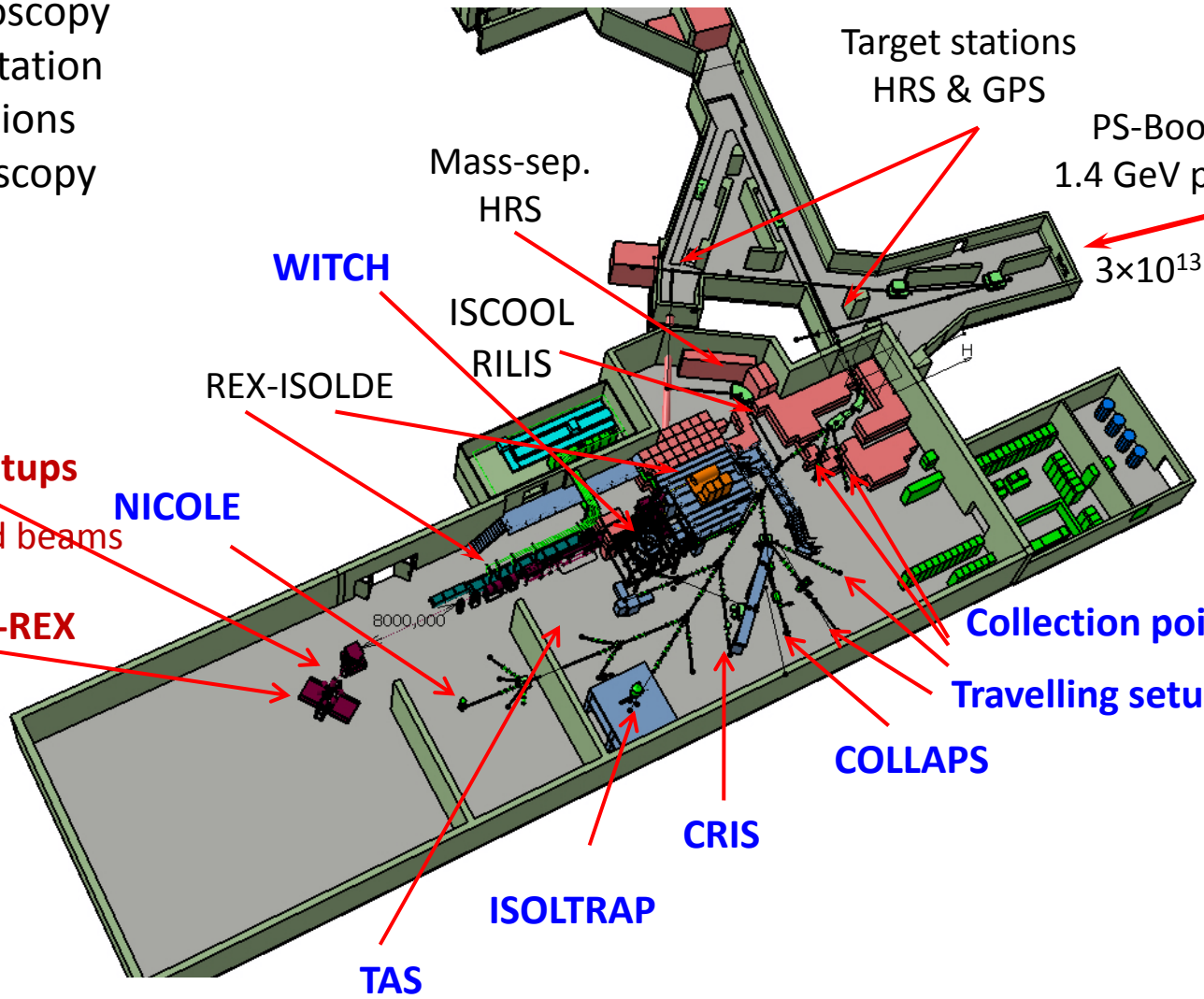




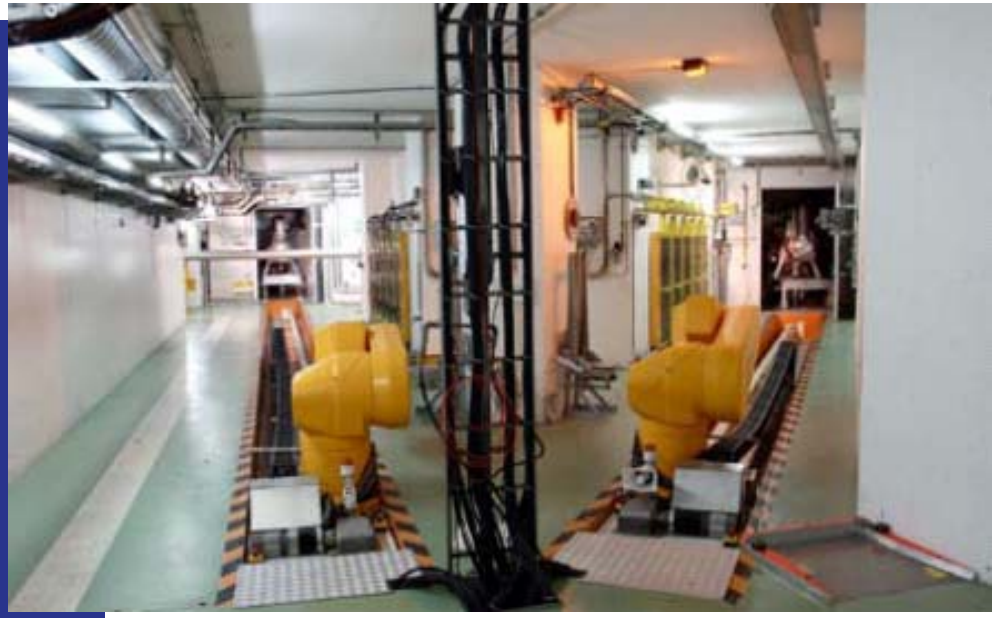
	5730 y 0+ b-	2.449 s 1/2+ b-	0.747 s 0+ b-n	193 ms b-n	95 ms 0+ b-n	46 m b-n
0 ms	B13 17.36 ms 3/2- b-n	B14 13.8 ms 2- b-	B15 10.5 ms b-	B16 200 Ps (0-) n	B17 5.08 ms (3/2-) b-n	B1
	Be12 23.6 ms 0+ b-	Be13 0.9 MeV (1/2,5/2)+ n	**Be14** **4.35 ms** **0+** **b-n,b-2n,...**		12	
MeV	Li11 8.5 ms 3/2- b-n,b-2n,...	Li12	10			
MeV	He10 0.3 MeV 0+ n					

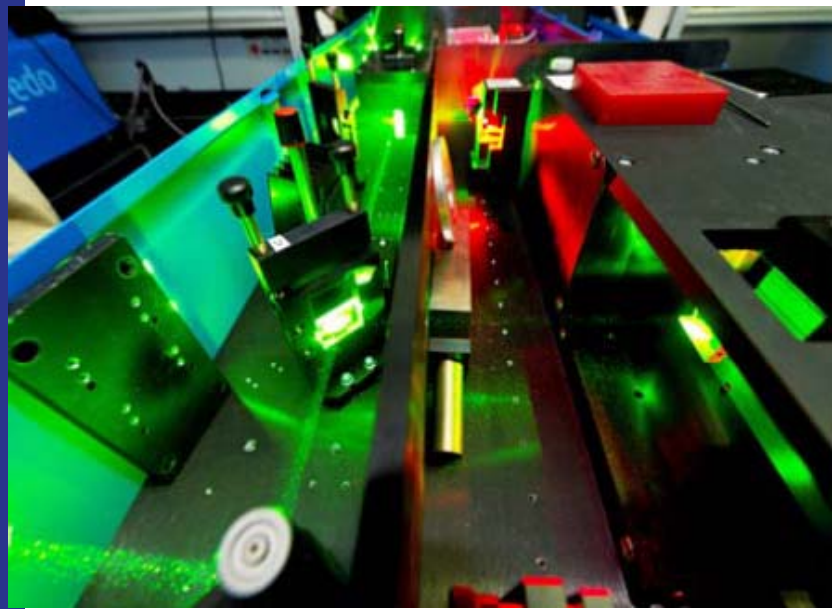
Experimental hall

Decay spectroscopy
Coulomb excitation
Transfer reactions
Laser spectroscopy
Beta-NMR
Penning traps

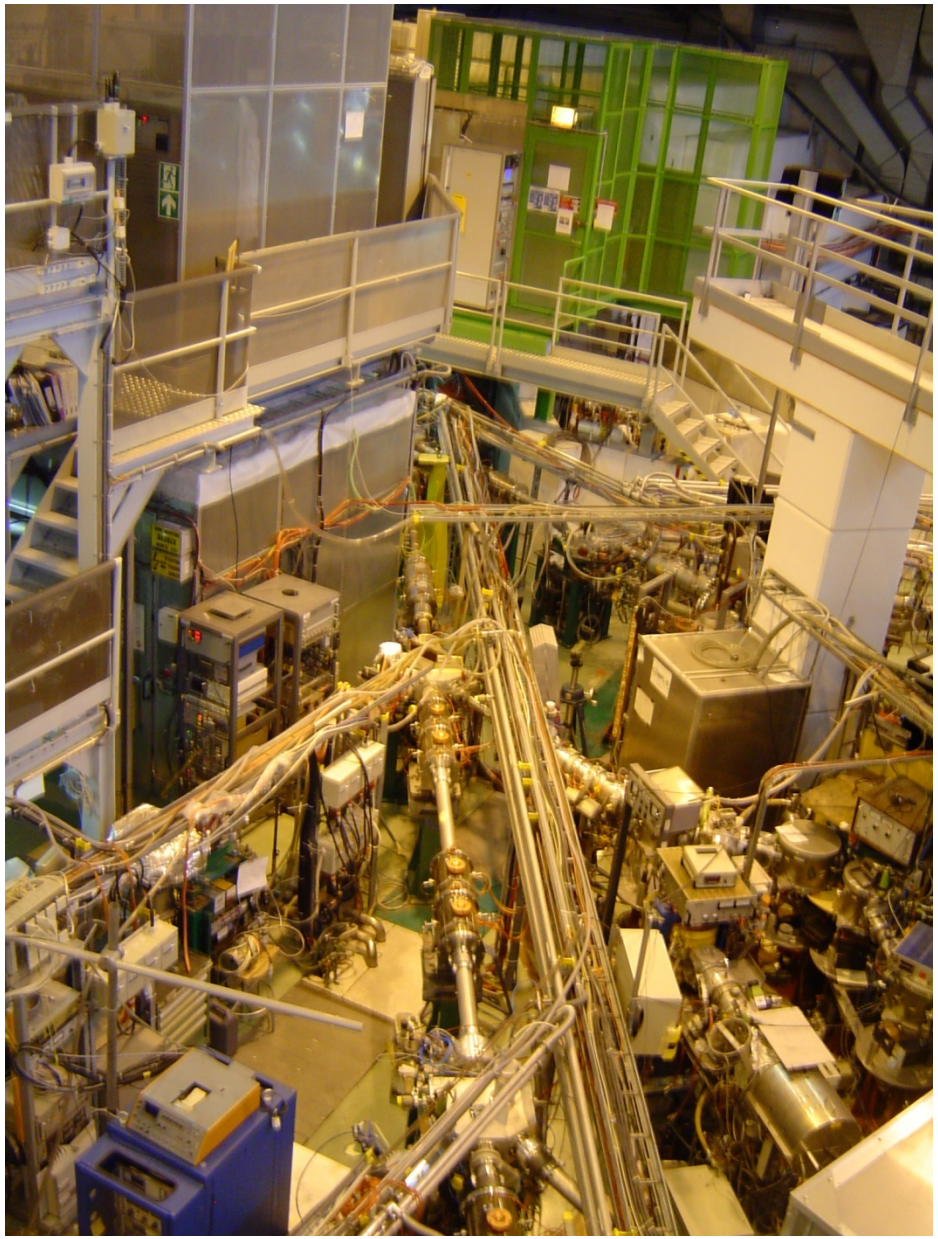


Facility photos



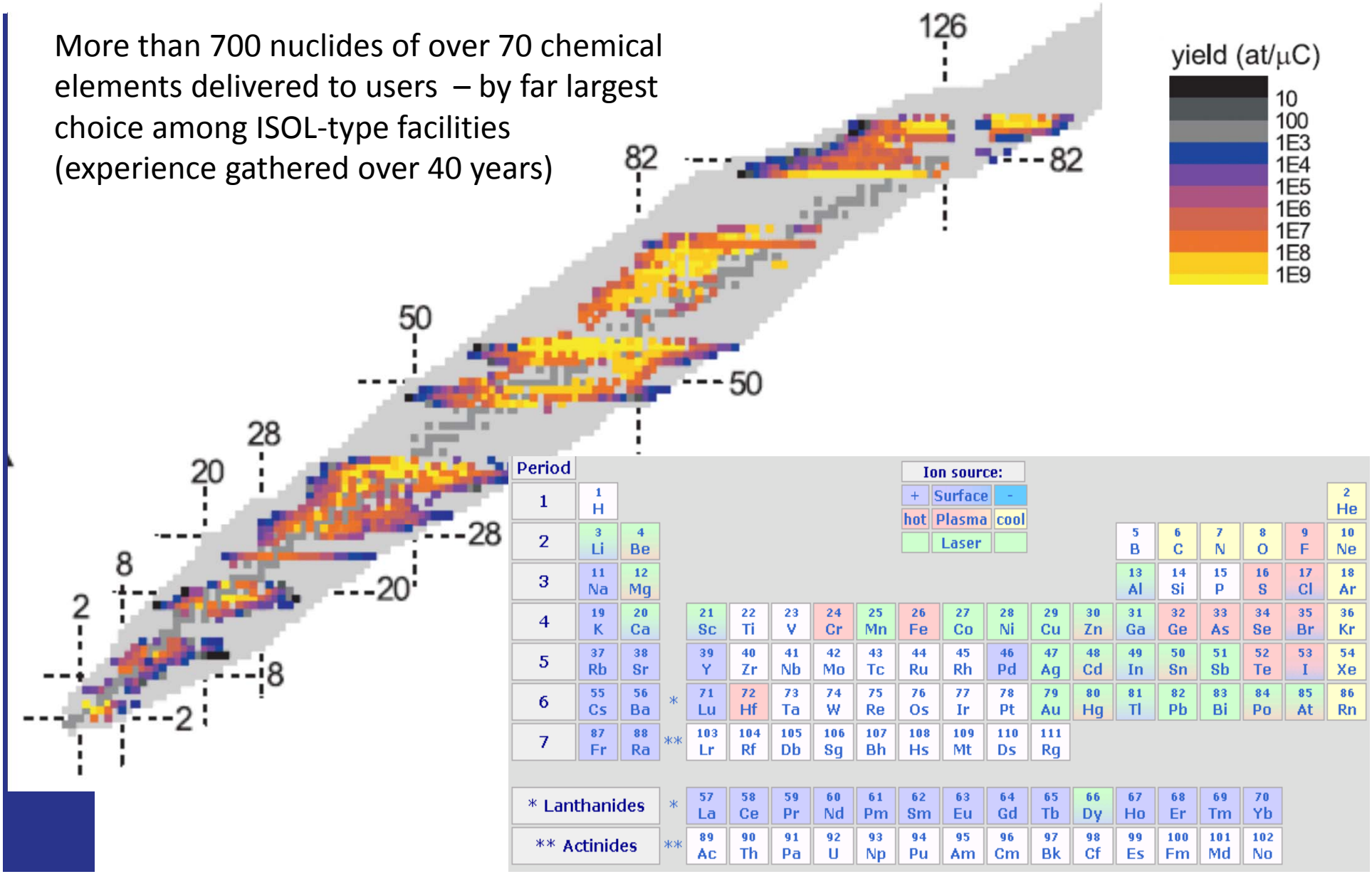


Experimental beamlines



Produced nuclides

More than 700 nuclides of over 70 chemical elements delivered to users – by far largest choice among ISOL-type facilities (experience gathered over 40 years)



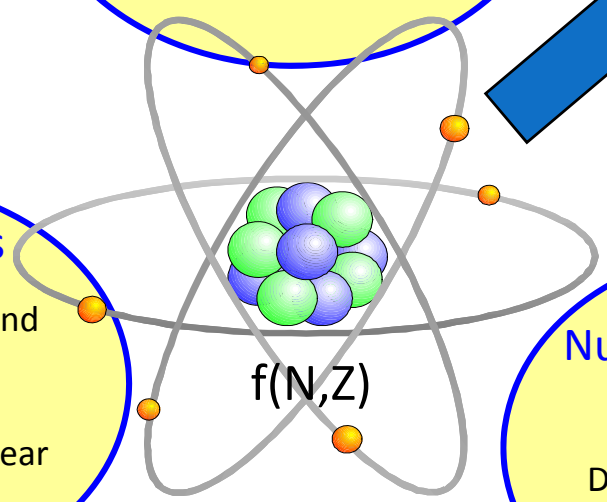
Physics topics

Applied Physics

Implanted Radioactive Probes,
Tailored Isotopes for Diagnosis and Therapy
Condensed matter physics and Life sciences

Nuclear Physics

Nuclear Decay Spectroscopy and Reactions
Structure of Nuclei
Exotic Decay Modes



Fundamental Physics

Direct Mass Measurements,
Dedicated Decay Studies - WI
CKM unitarity tests, search for b-n correlations, right-handed currents

Atomic Physics

Laser Spectroscopy and Direct Mass Measurements
Radii, Moments, Nuclear Binding Energies

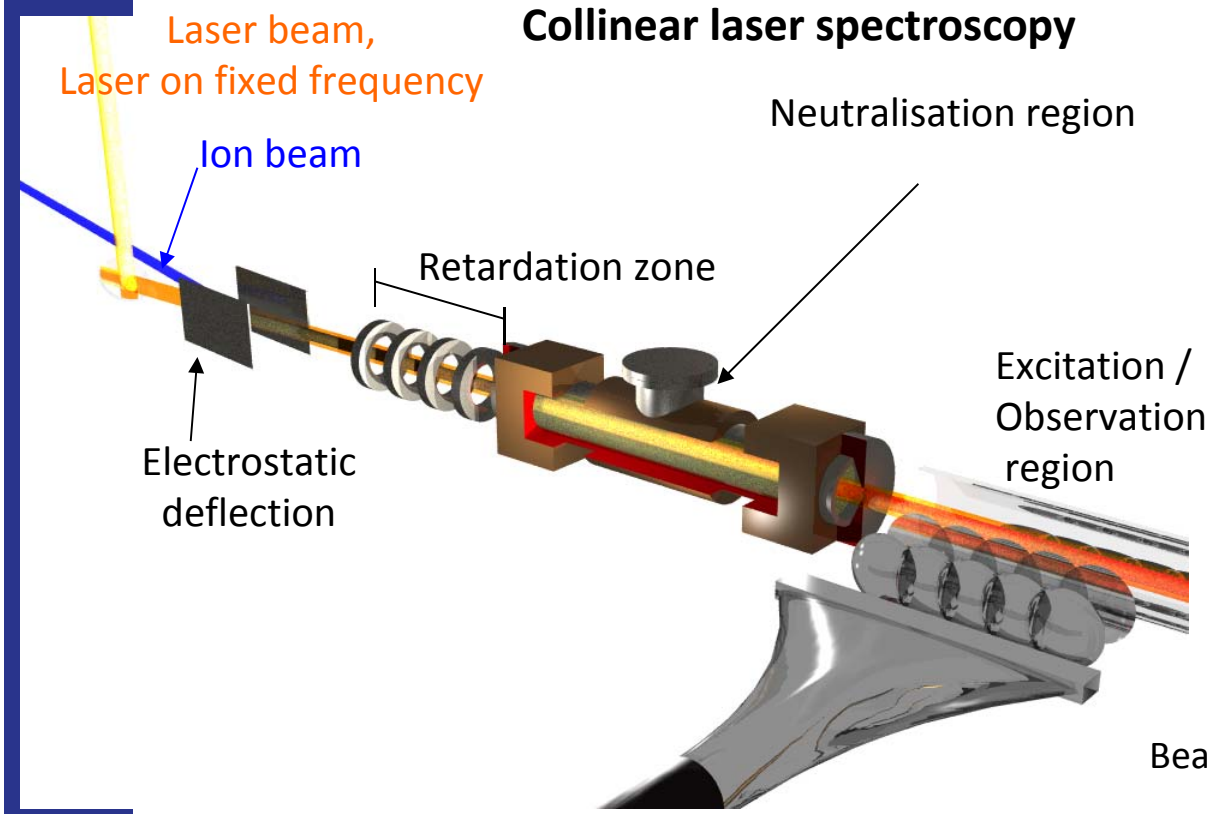
Nuclear Astrophysics

Dedicated Nuclear Decay/Reaction Studies
Element Synthesis,
Solar Processes

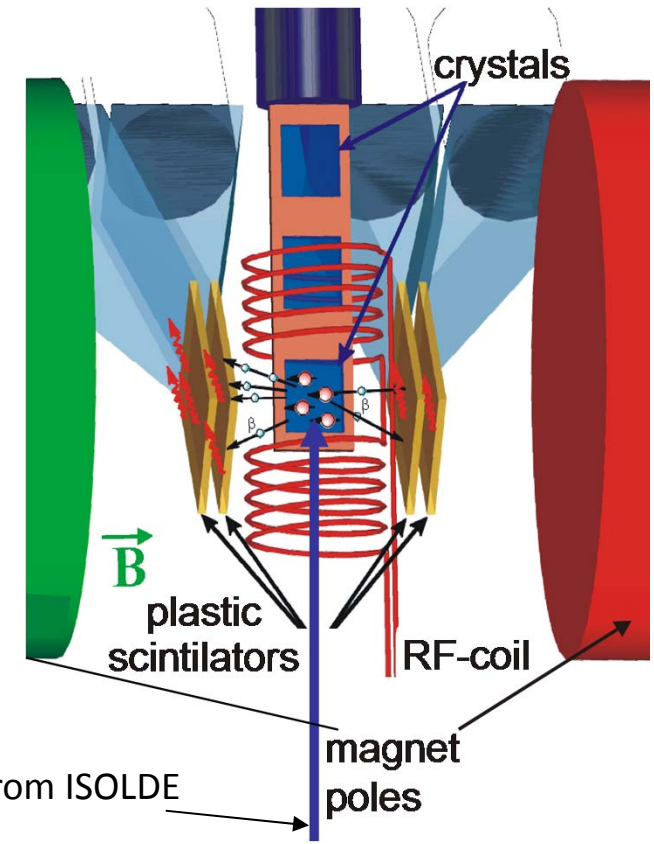
Laser and beta-NMR spectroscopy

COLLAPS setup

Collinear laser spectroscopy



Beta-NMR



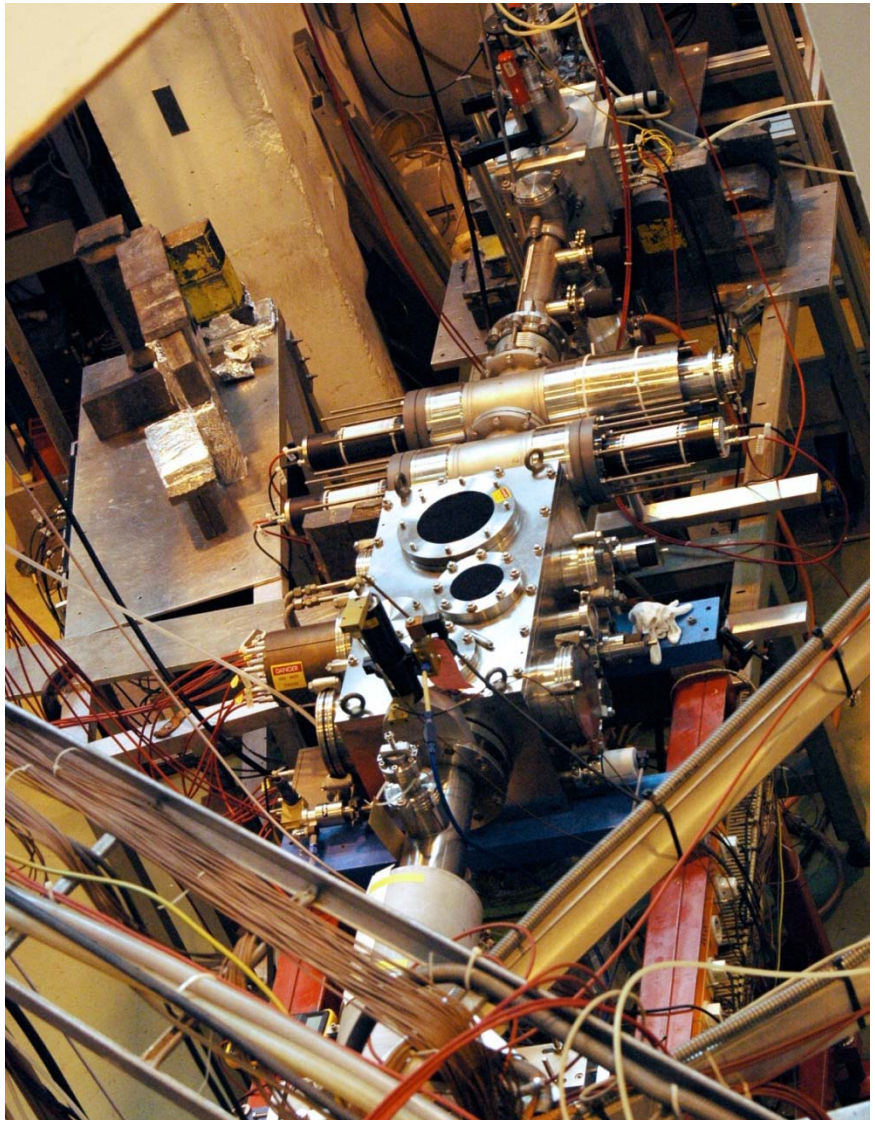
Detection method depends on the case => optimised for best S/N ratio

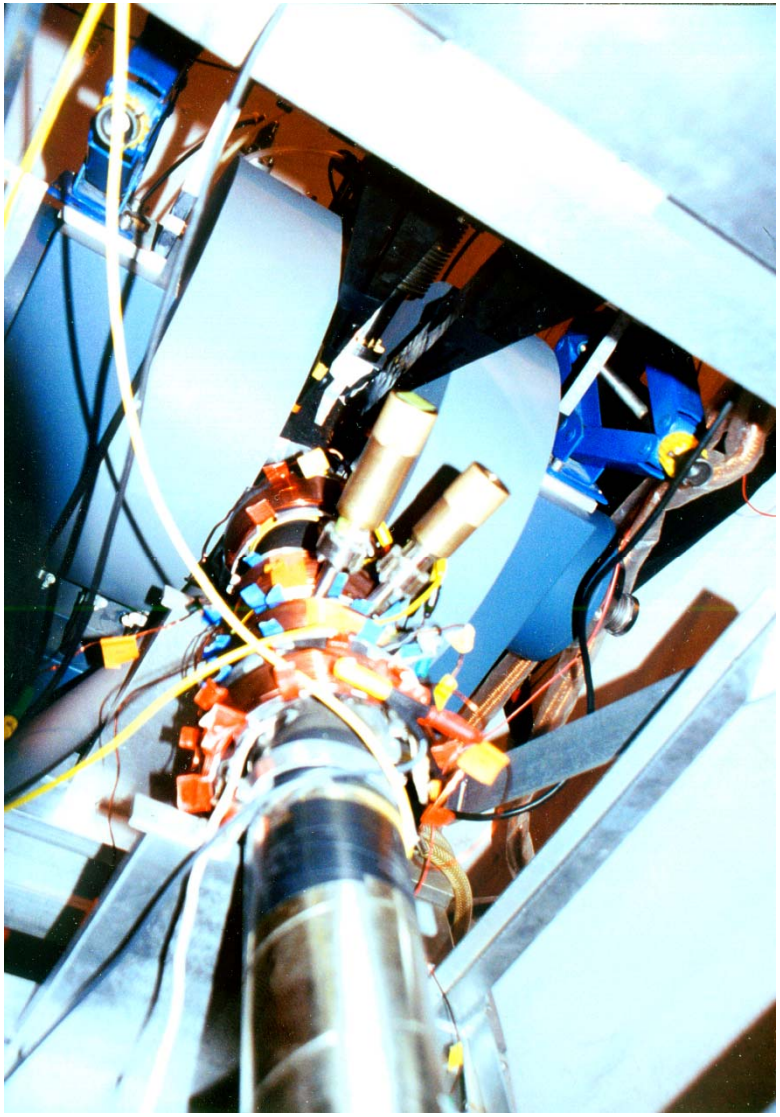
Observables: Hyperfine structure, isotope shifts, Nuclear Magnetic Resonance

Information: ground-state spin (+parity assignment), charge radius, moments

=> Probing single-particle and collective properties

Laser and beta-NMR spectroscopy



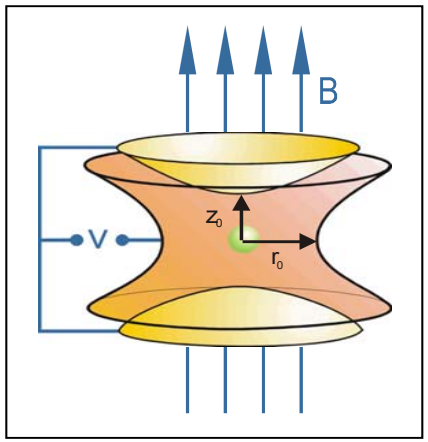


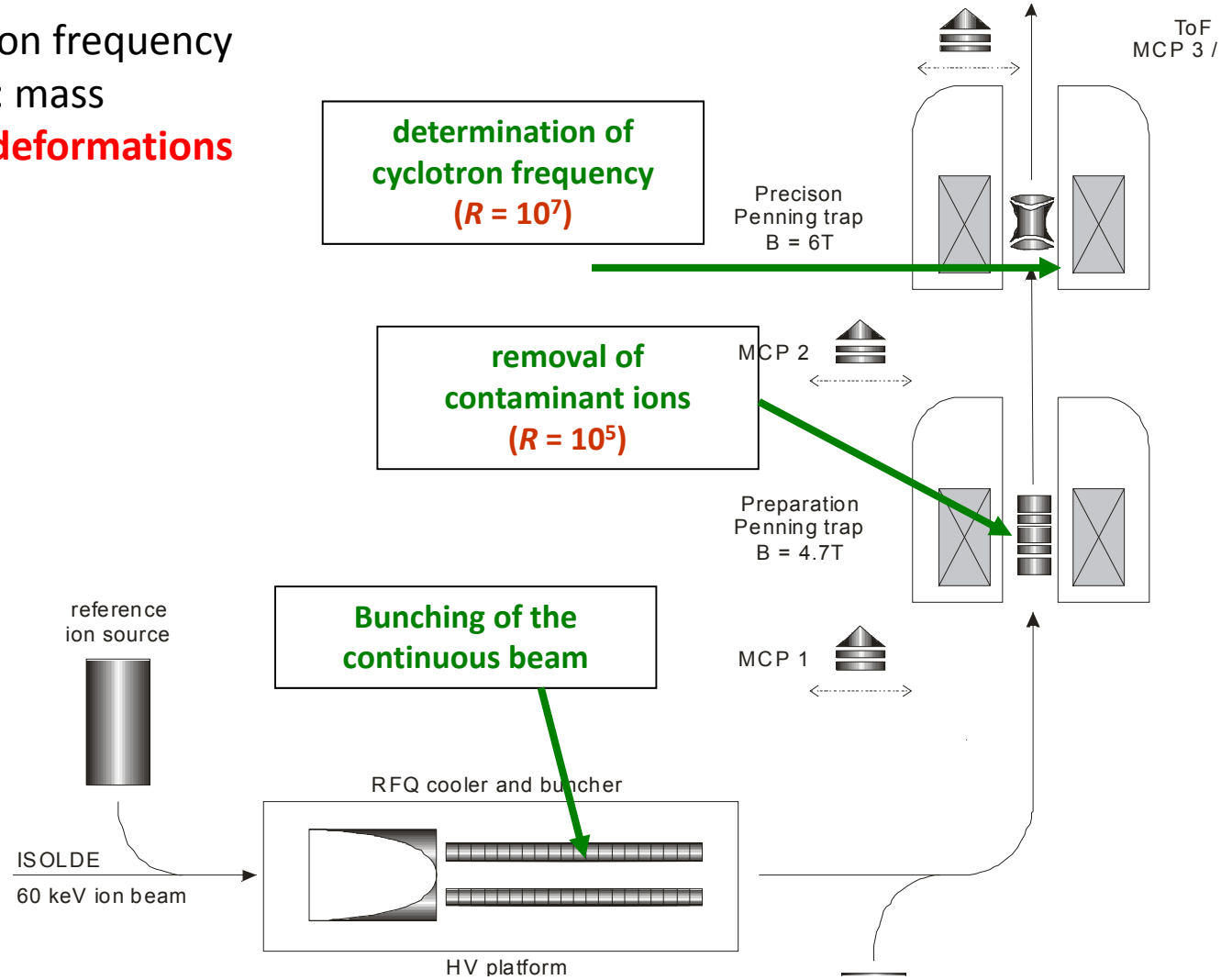
Penning-trap mass spectrometry

ISOLTRAP setup

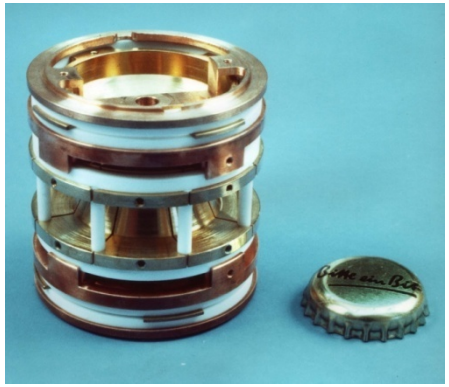
Observable: cyclotron frequency
Information: mass
=> shell structure, deformations

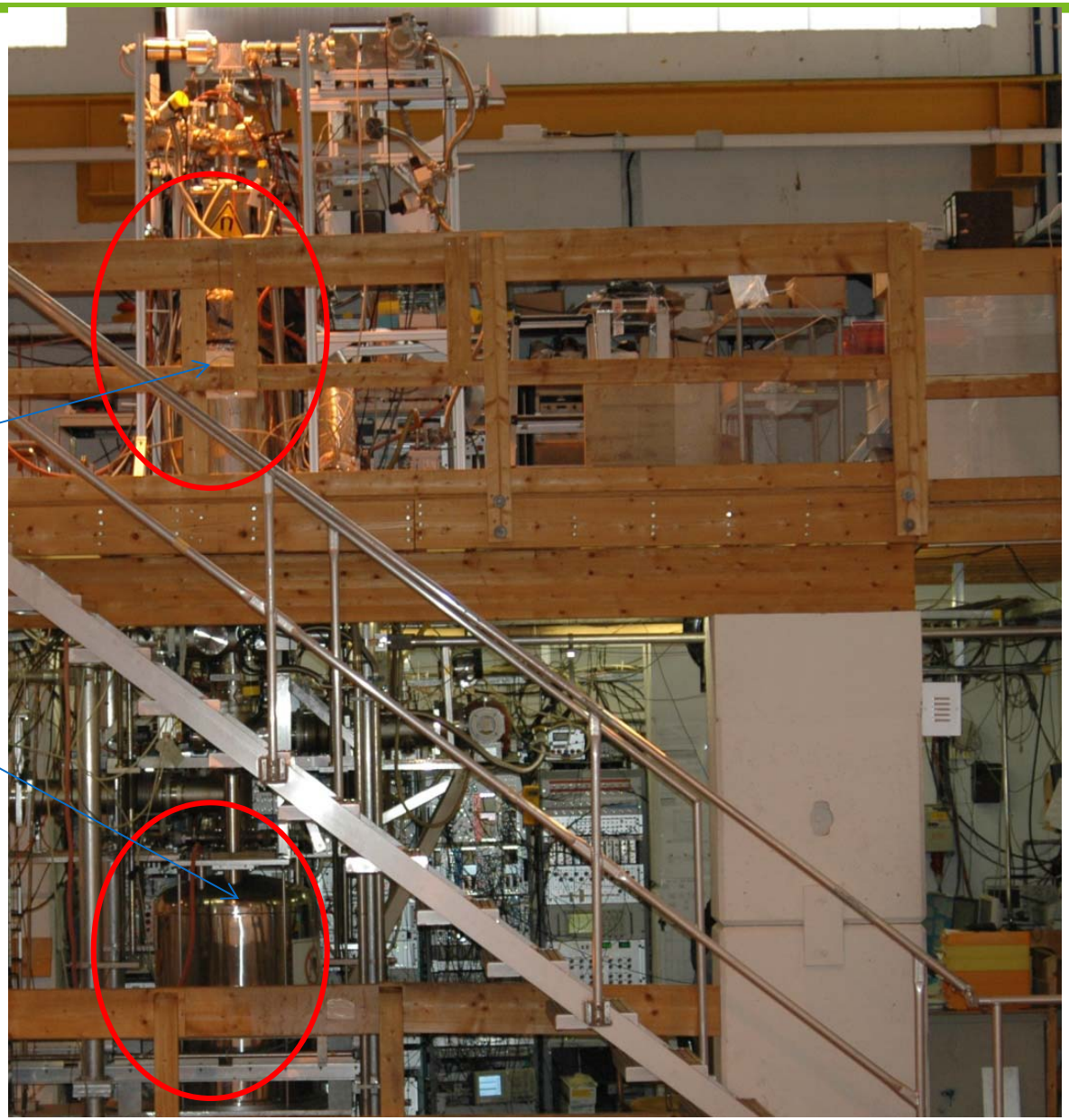
$$\nu_c = \frac{1}{2\pi}\frac{q}{m}B$$





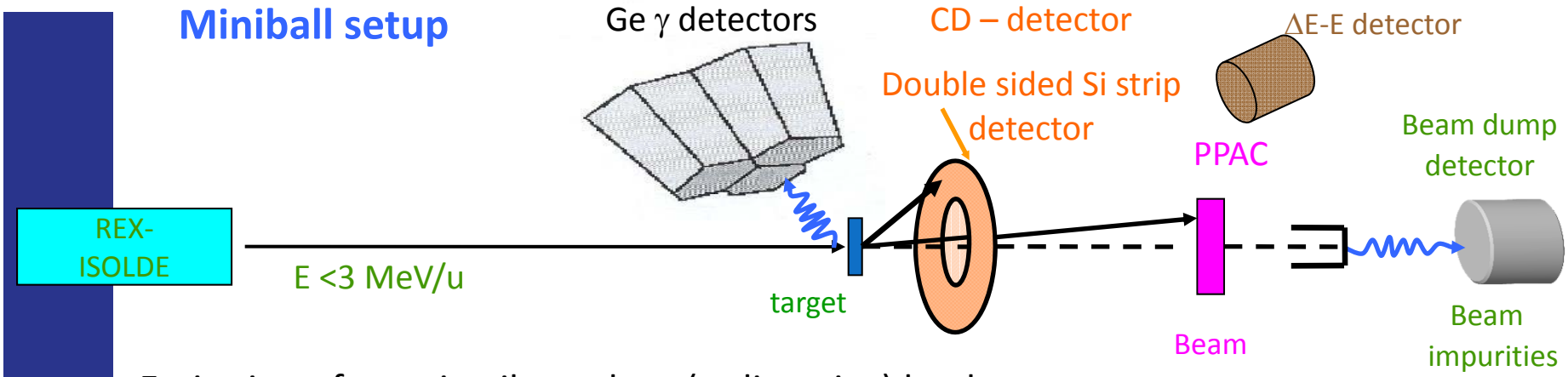
Penning-trap mass spectrometry



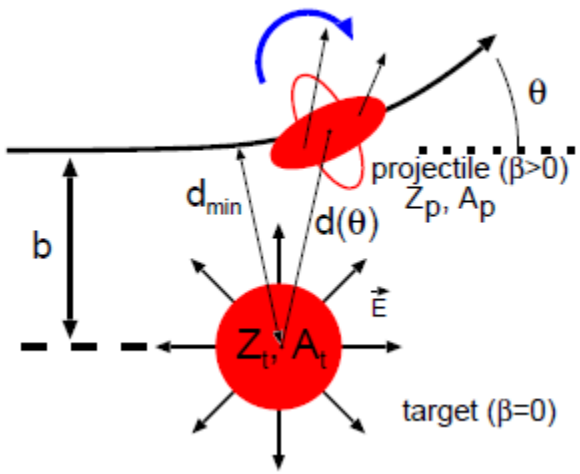


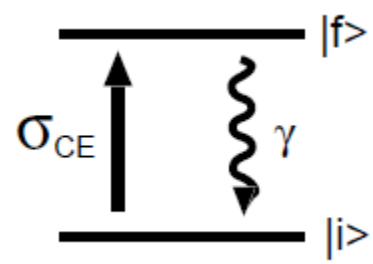
Coulomb excitation

Miniball setup



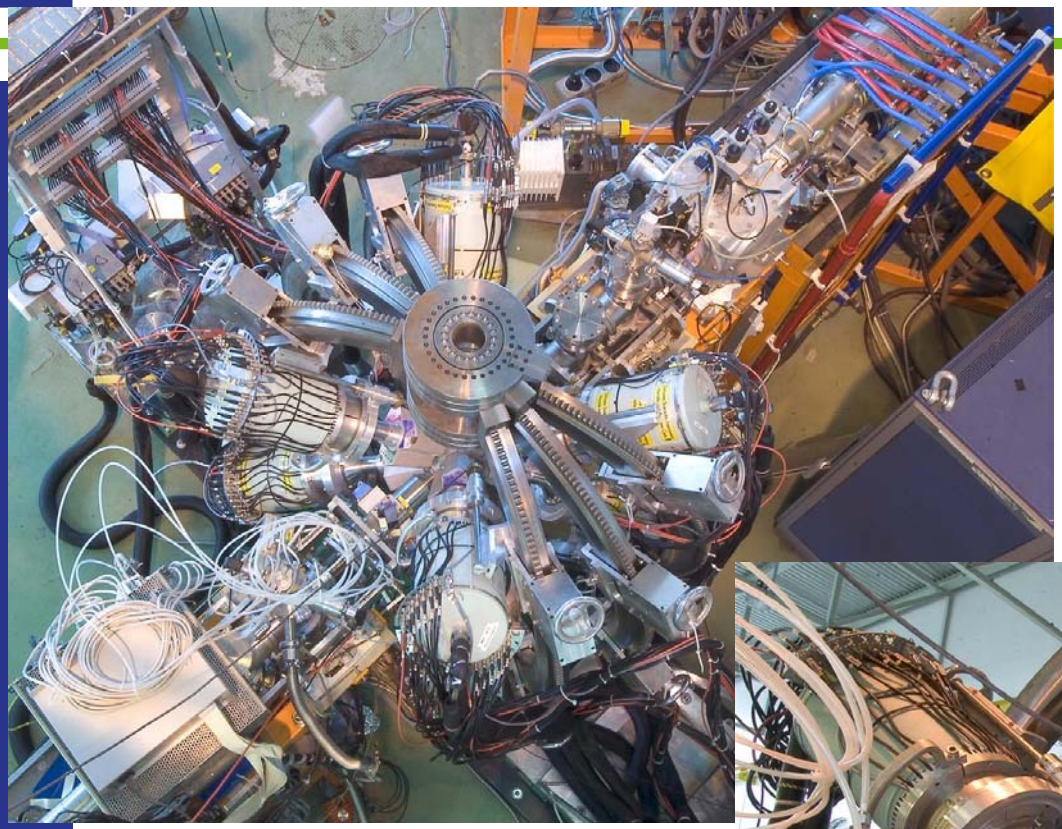
Excitation of a projectile nucleus (radioactive) by the electromagnetic field of the target (made of stable nuclei)

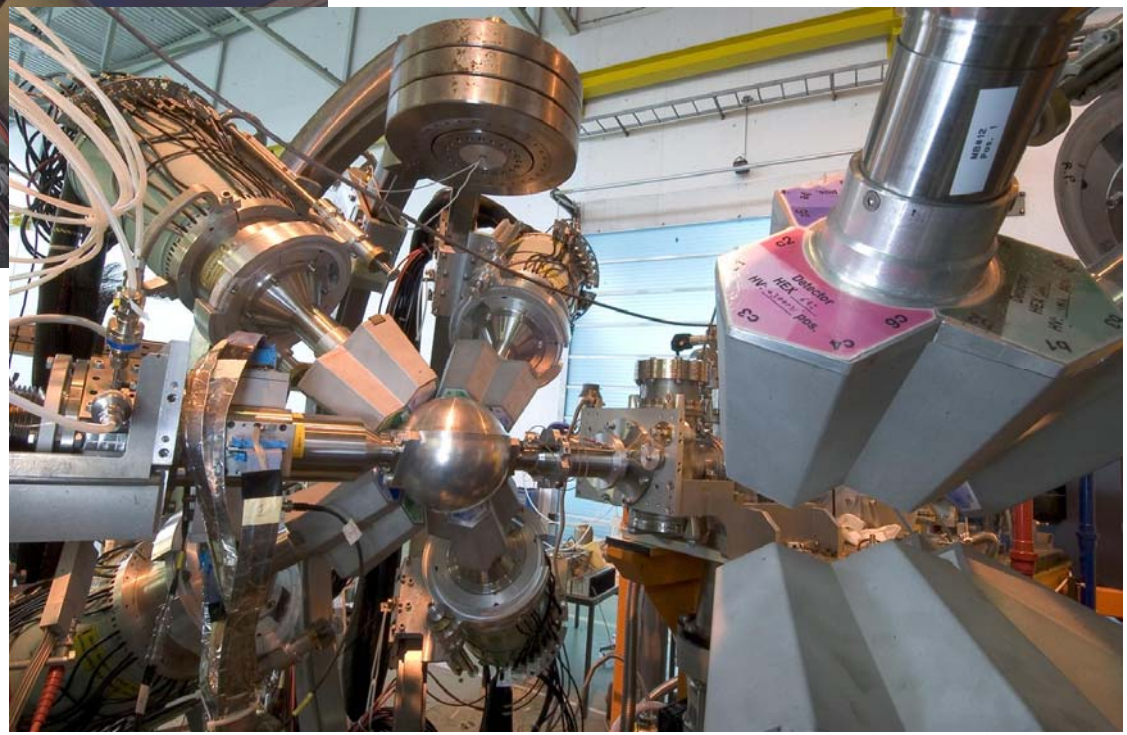




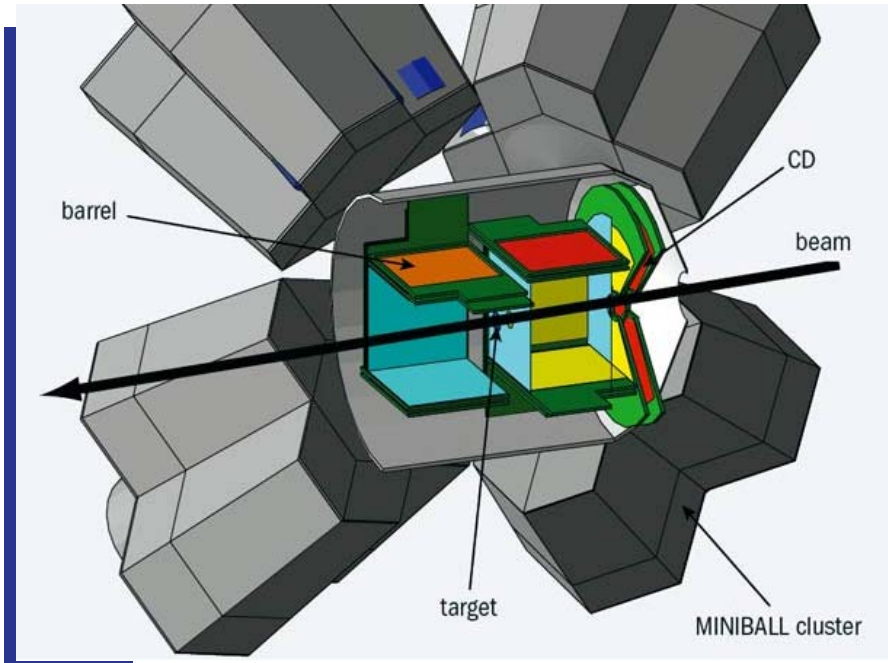
Observables: Transition energies and intensities
Information: reduced transition matrix elements
=> Study collectivity and deformations

Coulomb excitation

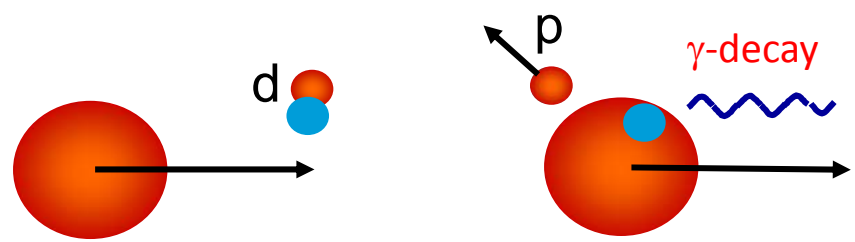




Transfer reations



Miniball + T-REX setup (Si detector barrel): gamma detectors and particle identification



Typical reactions: one or two-nucleon transfer (d,p), (t,p)

Information:

Observables

- energies of protons (+ E_g) — (single-particle) level energies
- angular distributions of protons (+ γ-rays) — spin/parity assignments
- (relative) spectroscopic factors — particle configurations

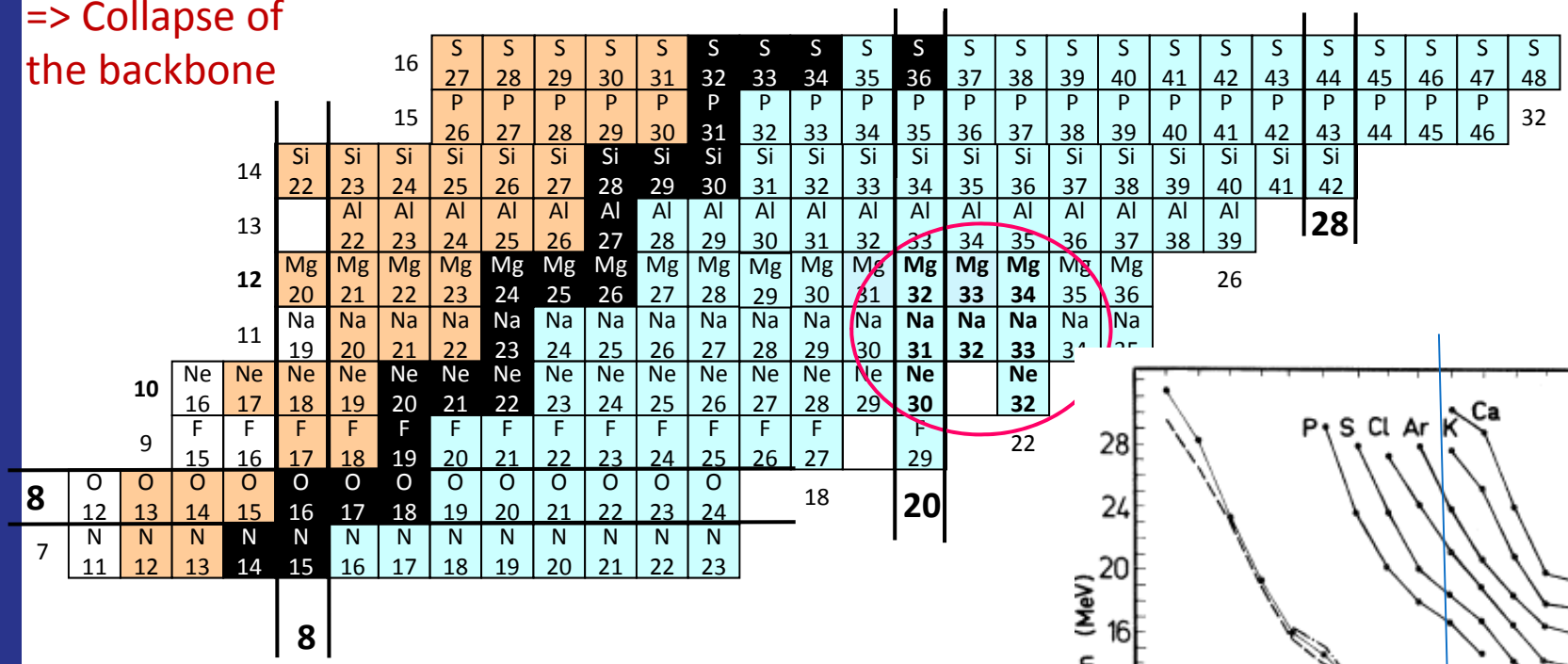
study single-particle properties of nuclei

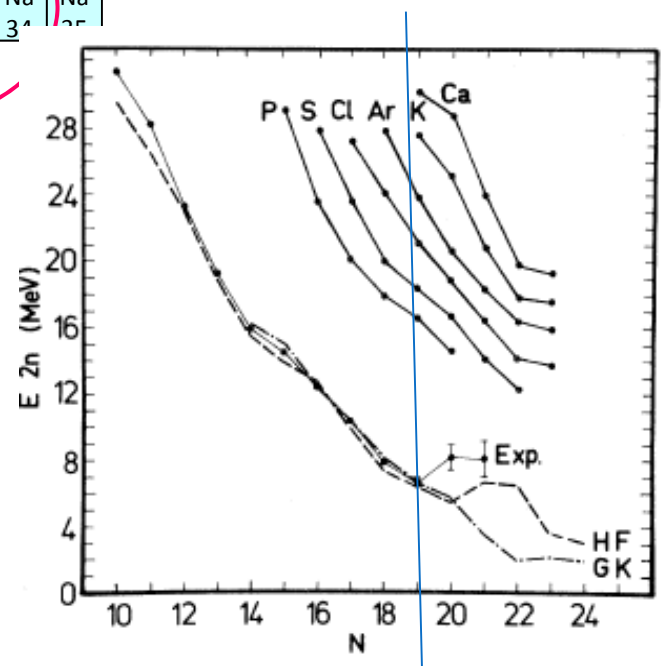
= > Similar configurations = large overlap of wave functions = Large probability of transfer reaction

“Island of inversion”: discovery

Nuclear shell model developed on stable nuclei works very well until 1975: mass measurements of neutron-rich Ne, Na, Mg isotopes => trend in binding energies can be only explained by large deformation and thus **no shell closure at N=20**

=> Collapse of the backbone

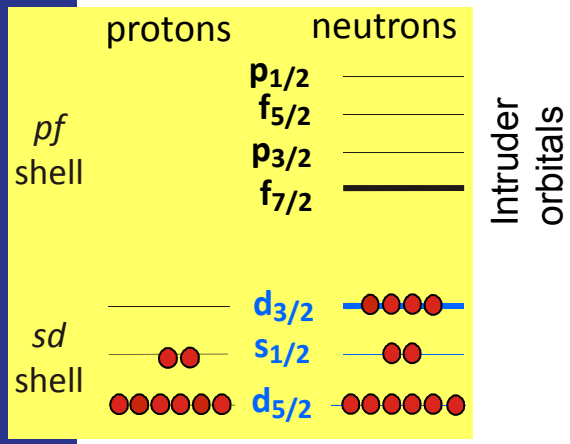




Mass measurements at PS-CERN
C. Thibault et al., Phys. Rev. C 12, 644 (1975)

Island of inversion: explanation

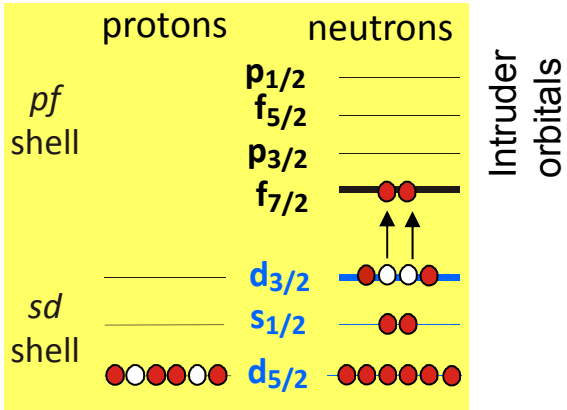
^{36}**S**: 16p and 20n



"normal"

Decreased N=20 shell gap (or even dissapeared)
Increased correlations

^{32}**Mg:** 12p and 20n



inversion of the level filling

In low-lying excited states and even in the ground state
neutrons occupy higher (intruder) orbitals before the usual shell is closed

Inversion of the usual level filling
But for nuclei with more protons N = 20 is again a magic number

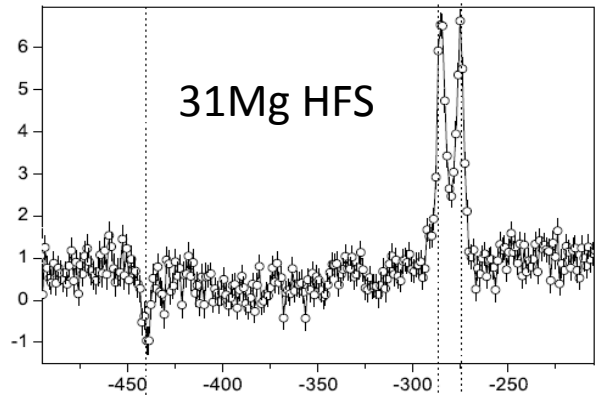
Name: island of inversion

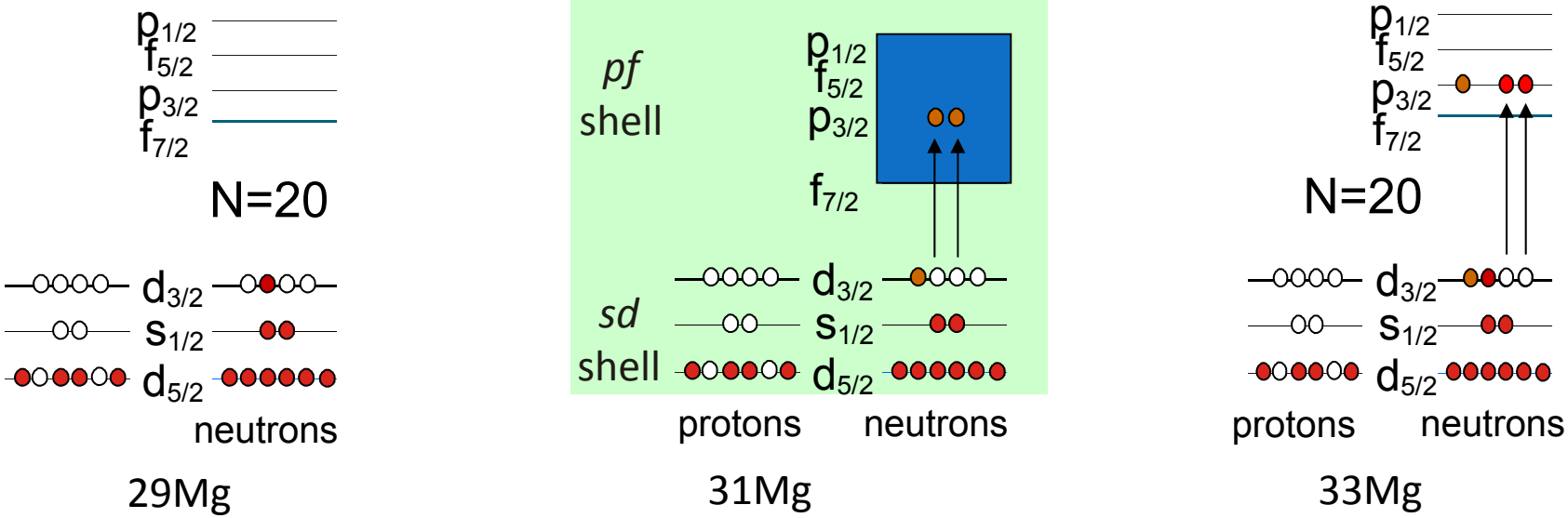
This hypothesis has to be tested/confirmed experimentally

Mg spins and moments

Spins, parities and magnetic moments => single-particle nature

Laser and beta-NMR spectroscopy on 29-33Mg
With COLLAPS setup





29Mg outside the "island"
31,33Mg inside; with 2 nucleons across N=20

G. Neyens , M. Kowalska et al, Phys. Rev. Lett. 94, 022501 (2005)
D. Yordanov, M. Kowalska et al, Phys. Rev. Lett. 99 (2007) 212501
M. Kowalska , D. Yordanov et al Phys. Rev. C77 (2008) 034307

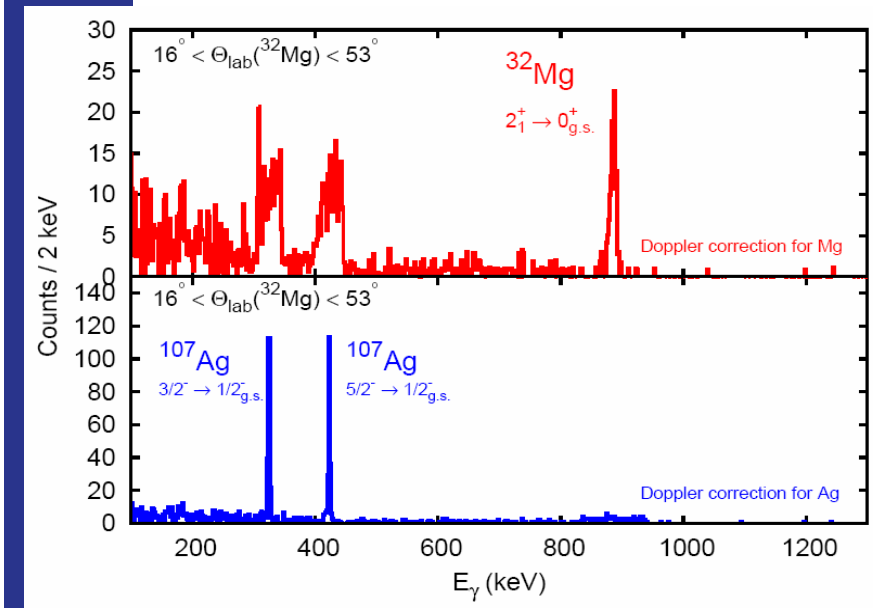
Mg Coulomb excitation

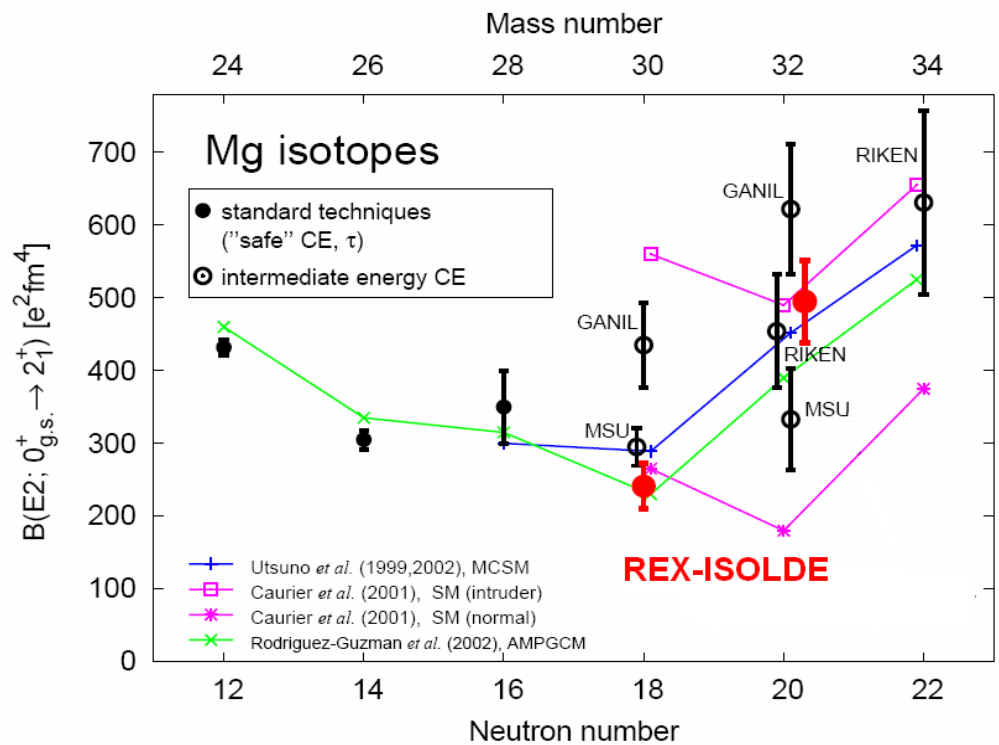
Coulomb excitation on 30,32Mg with MINIBALL setup

Excitations across N=20 will increase collectivity, due to more active nucleons and thus more correlations

World results for Mg Coulomb excitation:

only ISOLDE can provide pure e.m. excitation ("safe Coulex")





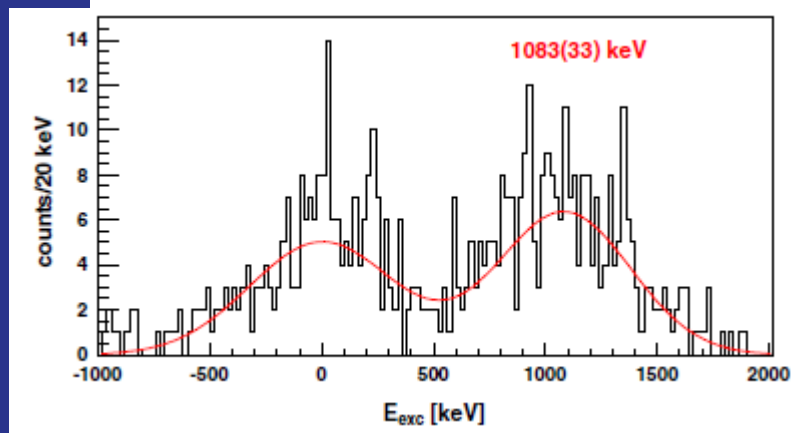
Increase in collectivity from 30Mg to 32Mg (N=20)

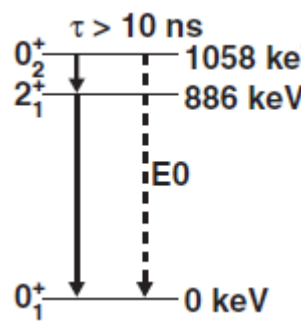
O. Niedermaier et al, Phys. Rev. Lett. 94 (2005) 172501
M. Seidlitz et al , Phys.Lett. B 700 (2011) 181

32Mg, transfer reaction

Two-neutron (t,p) transfer reactions on 30,32Mg

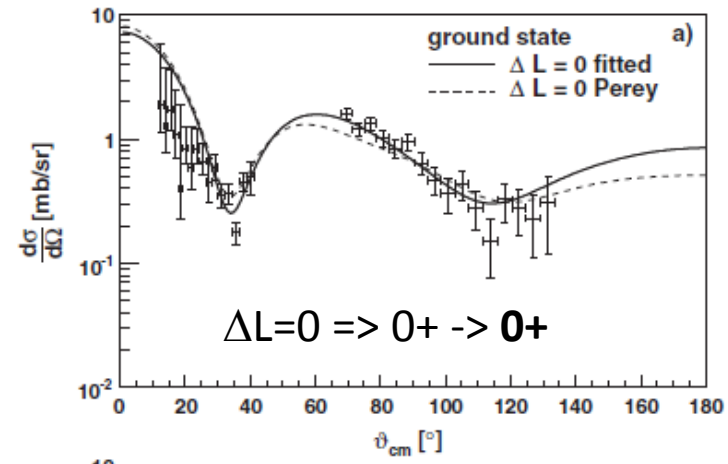
Allow finding 1st excited 0+ state and probing its nature: "normal" spherical structure or deformed structure based on 2 neutrons excited across N=20

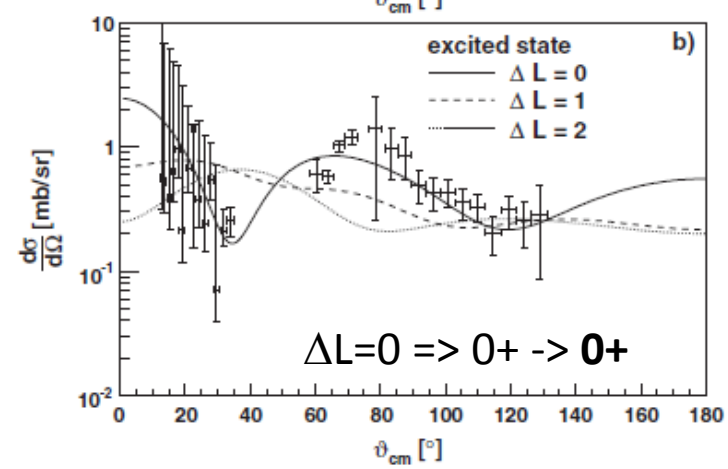




existence of excited 0+ state in 32Mg at 1058 keV

proton angular distributions



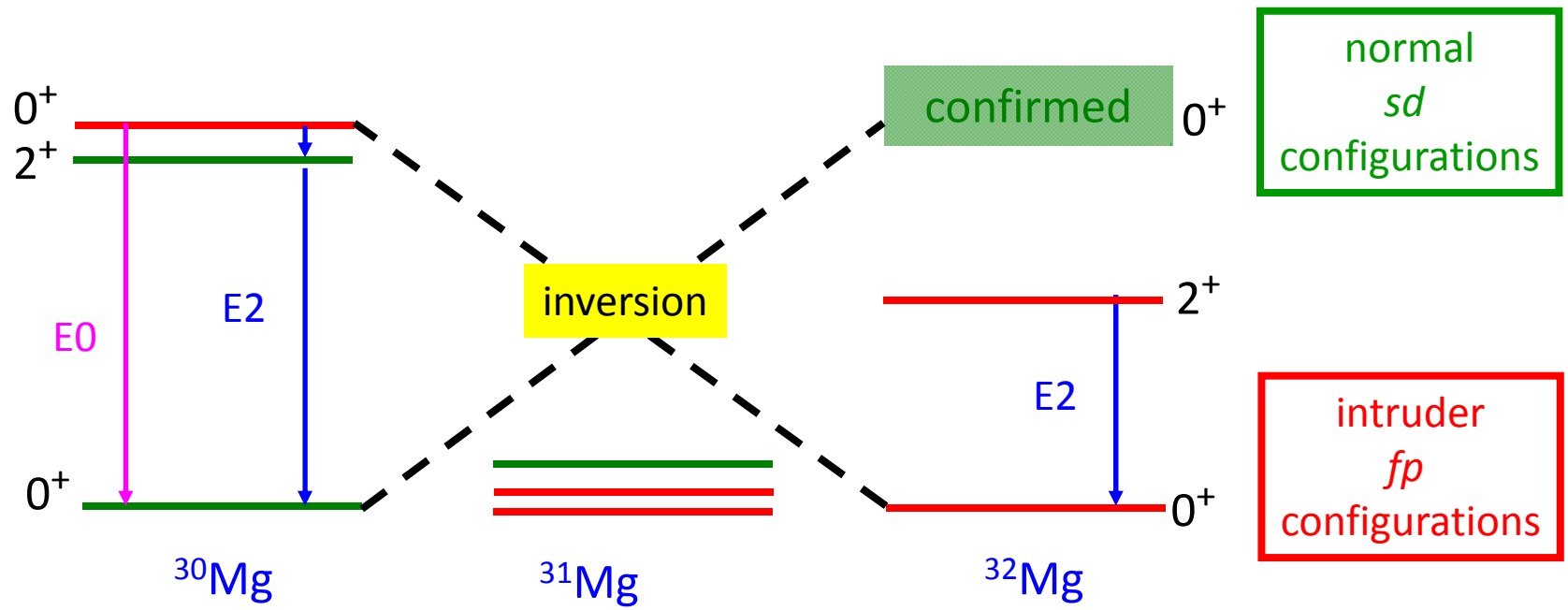


cross section to populate 32Mg excited 0+ state points to its similarity to 30Mg ground-state, i.e. **spherical structure made of orbitals below N=20**

K. Wimmer et al, Phys. Rev. Lett. 105 (2010) 252501

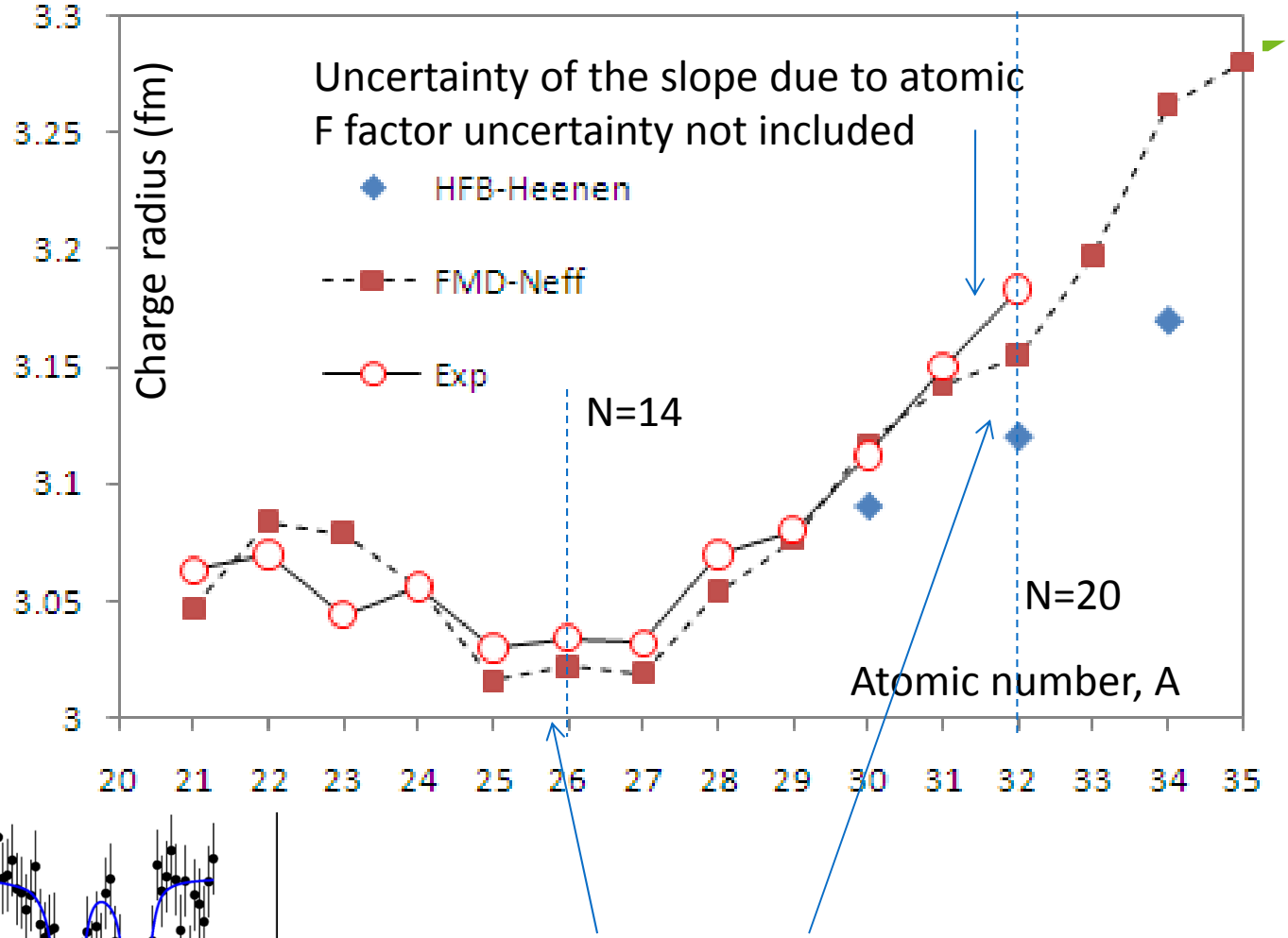
32Mg, transfer reaction

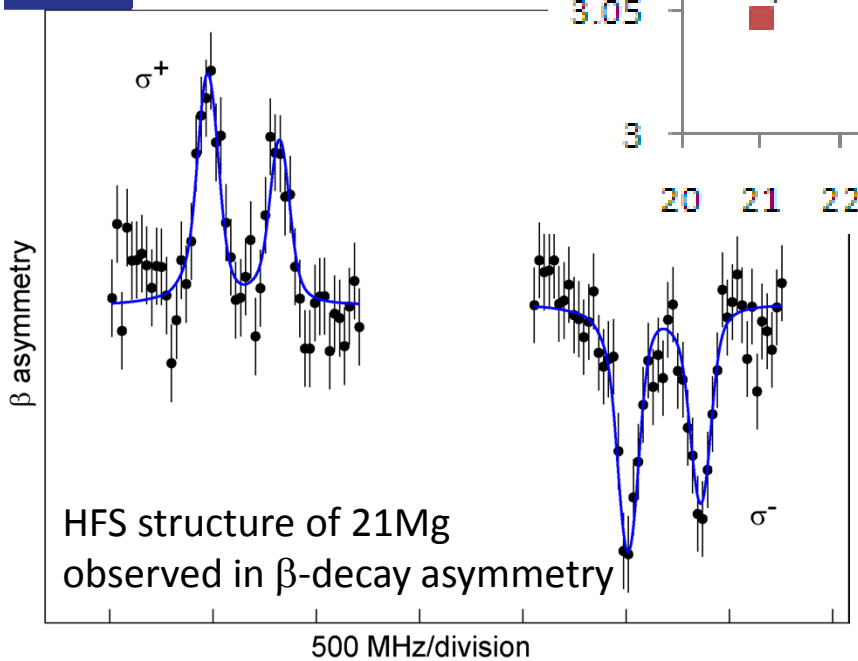
Coexistence of spherical and deformed states



Mg: laser spectroscopy

Laser spectroscopy with COLLAPS



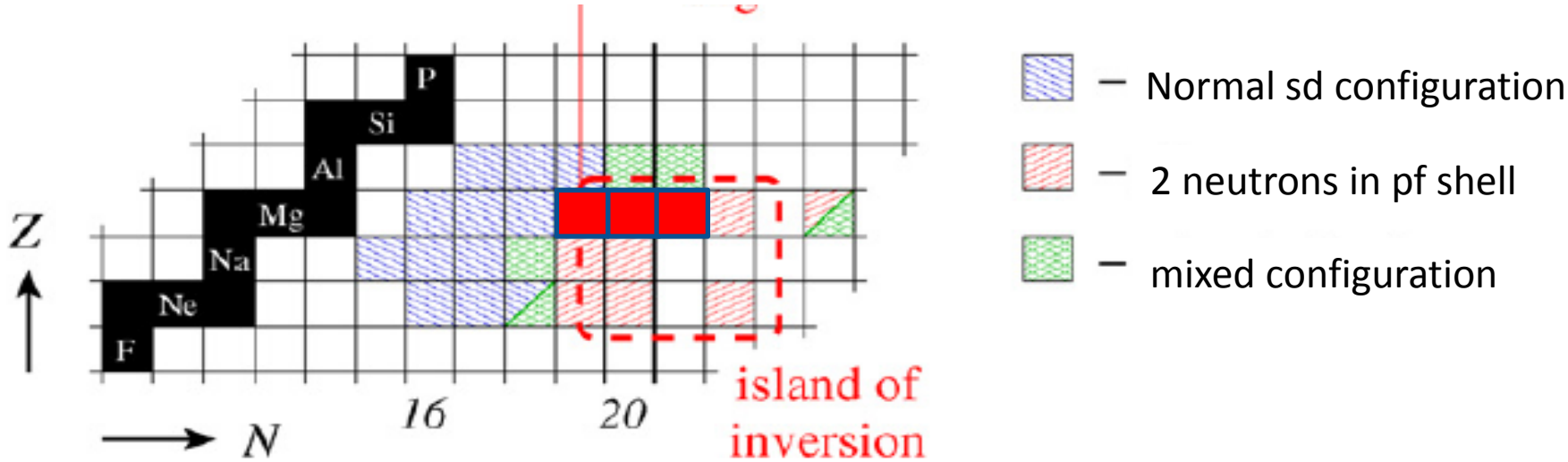


HFS structure of 21Mg observed in β-decay asymmetry

Smallest radius at N=14, not N=20: Migration of the shell closure

D. Yordanov et al, in preparation

What did we learn?



- Already at N=19 neutrons occupy higher orbits
- Transition to island of inversion is sudden
- Spherical and deformed shapes coexist at low energies
- Deformed ground states show mainly 2 neutrons across N=20 (in pf shell)
- New magic number (N=14 or N=16) appears
- Theories start agreeing with experiment

=> Mechanism driving the island connected to tensor part of nuclear interaction
=> There can be other islands like this one
(but interaction details need to be worked out based on more experiments)

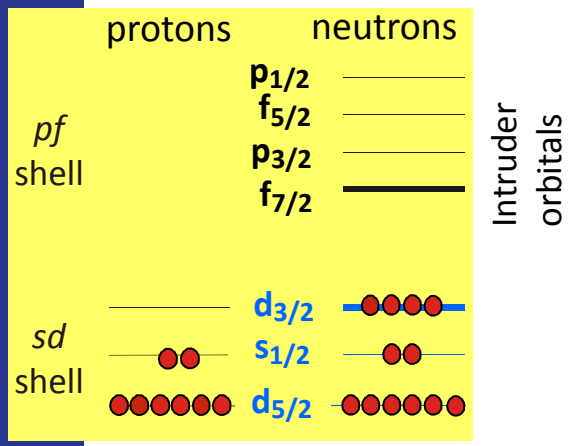
Summary and outlook

- Nuclear physics describes the atomic nucleus
- Since several decades radioactive-beam facilities have given access to many short-lived nuclei
- These nuclei have different properties than stable nuclei on which nuclear models were based
- Open questions include the description and prediction all observed properties and theoretical connection to QCD
- ISOLDE facility at CERN provides many raio-nuclides
- Various setups look at the nuclear physics, fundamental studies and applications
- Complementarily of methods is well seen in the famouv "island of inversion" region
- One answer brings new questions …

Thank you for your attention

Example – island of inversion

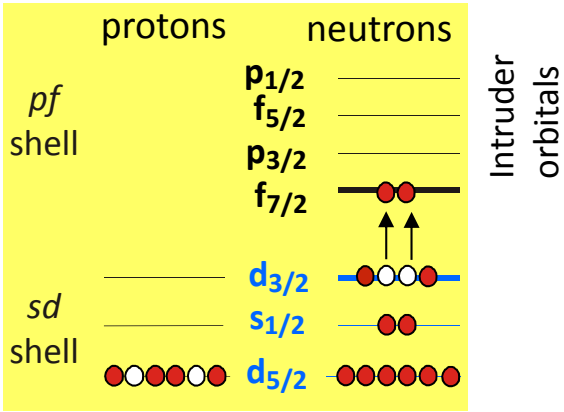
^{36}**S**: 16p and 20n



"normal"

Decreased N=20 shell gap (or even dissapeared)
Increased correlations

^{32}**Mg:** 12p and 20n



inversion of the level filling

In low-lying excited states and even in the ground state
neutrons occupy higher (intruder) orbitals before the usual shell is closed

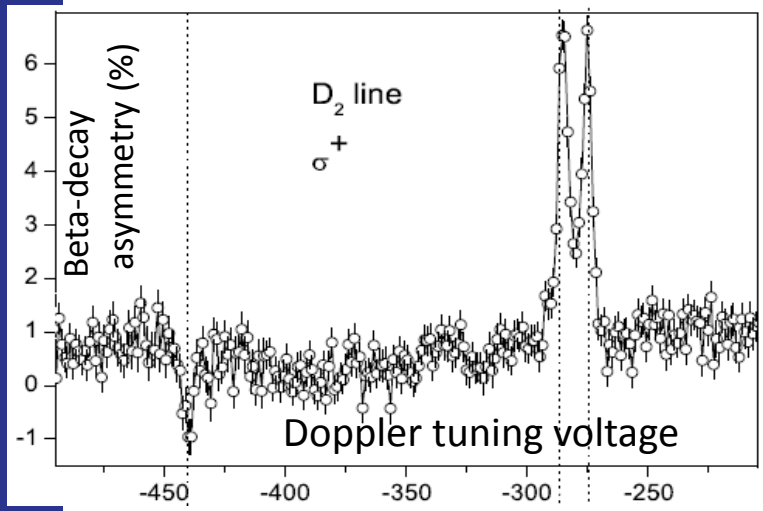
Inversion of the usual level filling
But for nuclei with more protons N = 20 is again a closed shell

Name: island of inversion

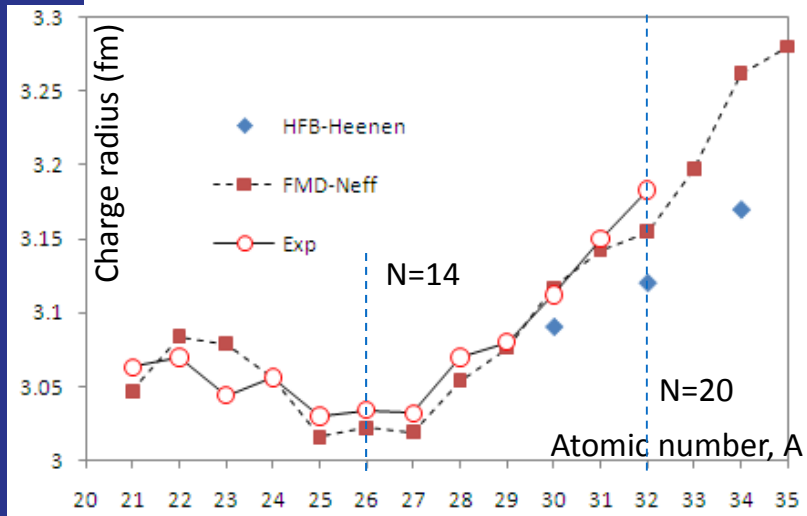
This hypothesis has to be investigated experimentally

Results – island of inversion

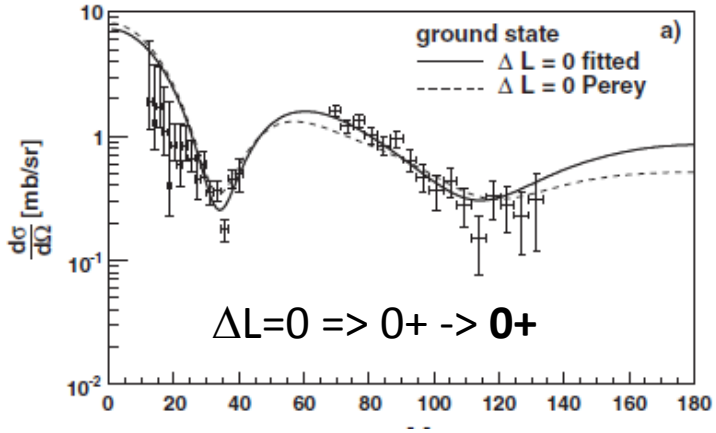
- Laser and NMR spectroscopy

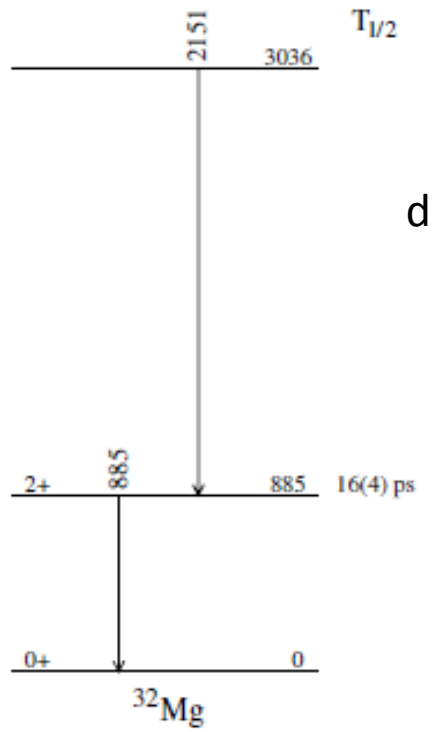


- Laser spectroscopy



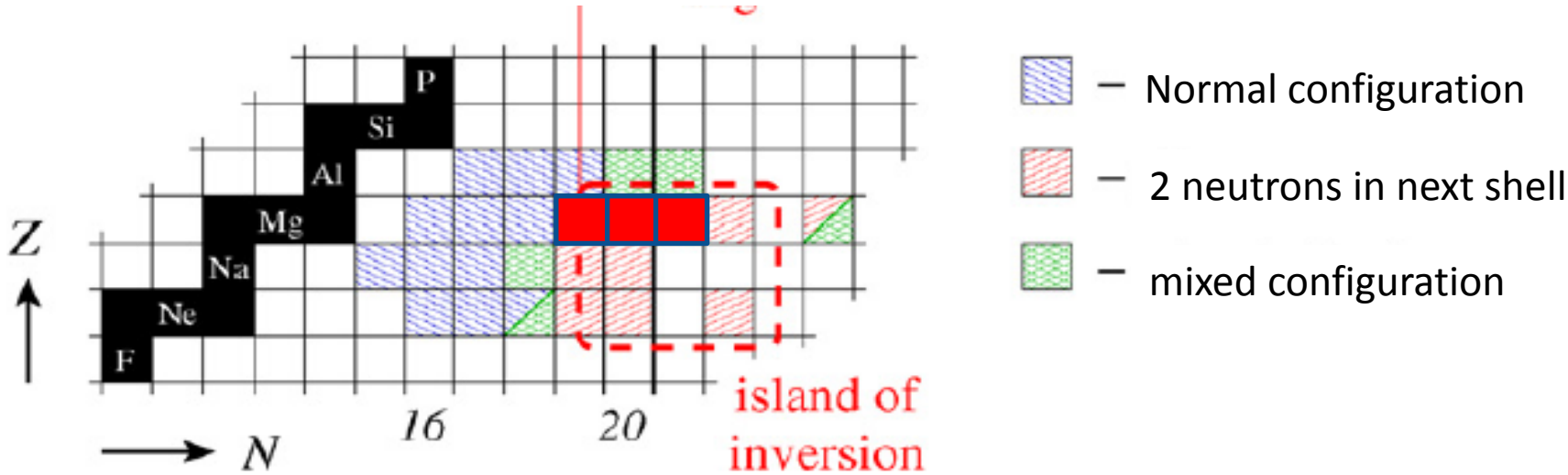
- Transfer reactions





decay

Results - island of inversion



=> Theories can now reproduce most results

=> Mechanism driving the island connected to tensor part of nuclear interaction

=> There can be other islands like this one

(but interaction details need to be worked out based on more experiments)

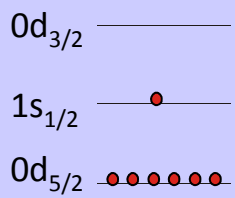
- **Spin** (orbital+intrinsic angular momentum), **parity** (I^{π})
- Nuclear ***g*-factor** and **magnetic** dipole **moment** (g_I and μ_I)
- Electric quadrupole moment (Q)
- **Charge radius** ($\langle r^2 \rangle$)

Give information on:

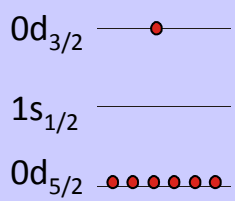
- Configuration of neutrons and protons in the nucleus
- Size and form of the nucleus

I^{π}

1/2⁺



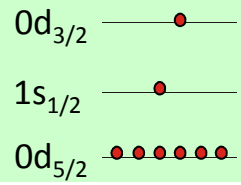
3/2⁺



g_I and μ_I

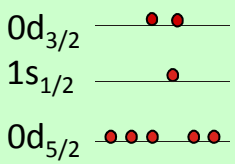
$I^p=2^+$

μ = +0.54

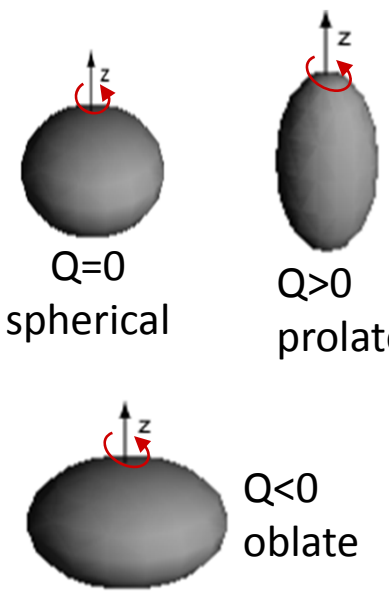


$I^p=2^+$

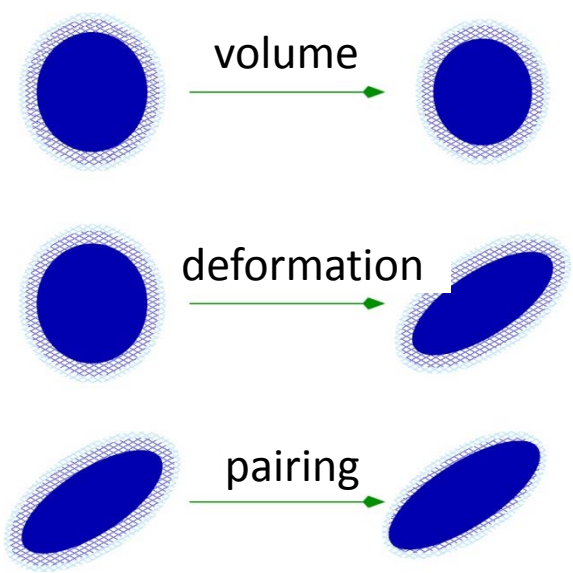
μ = +1.83



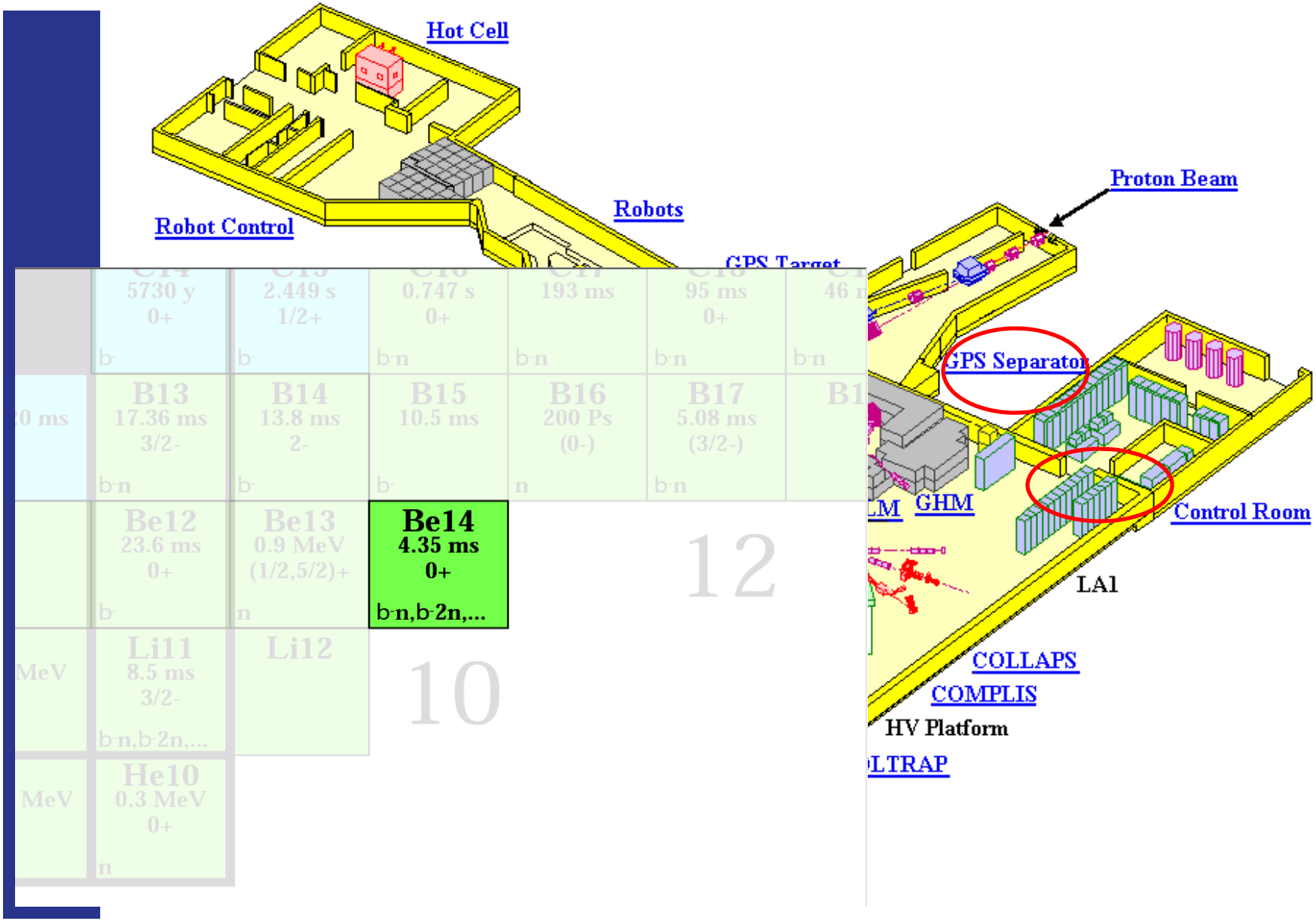
Q



$\langle r^2 \rangle$



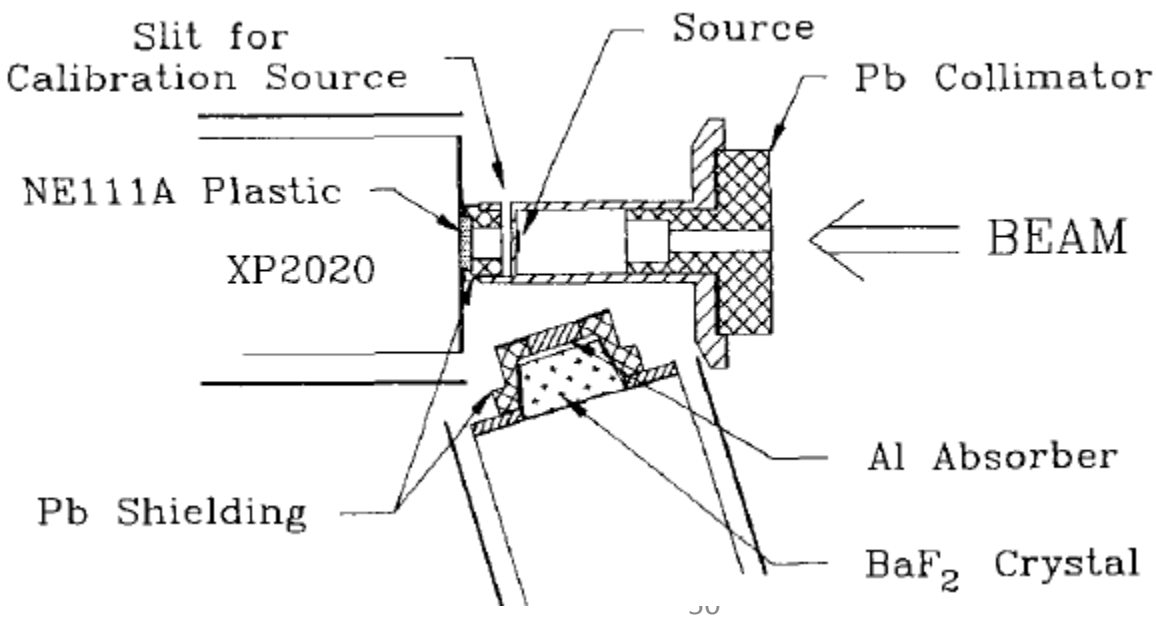
Production process



Fast-timing gamma spectroscopy

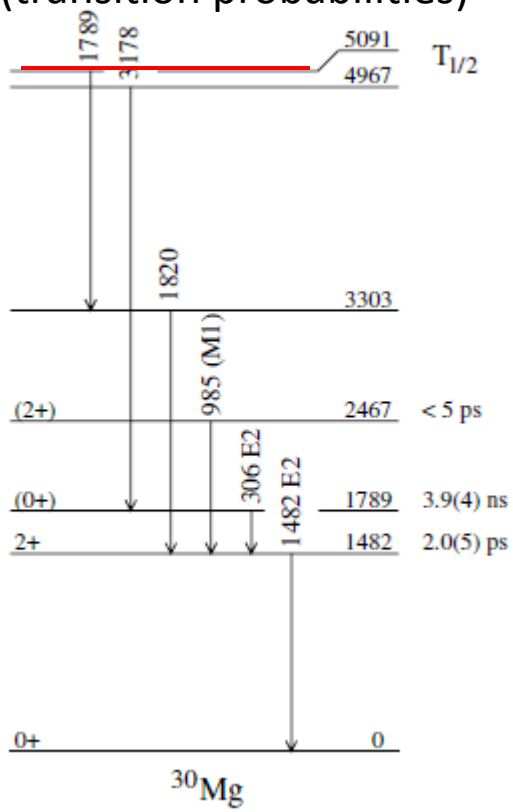
Gamma spectroscopy with BaF2 crystals
(very fast response, <ps lifetime studies)

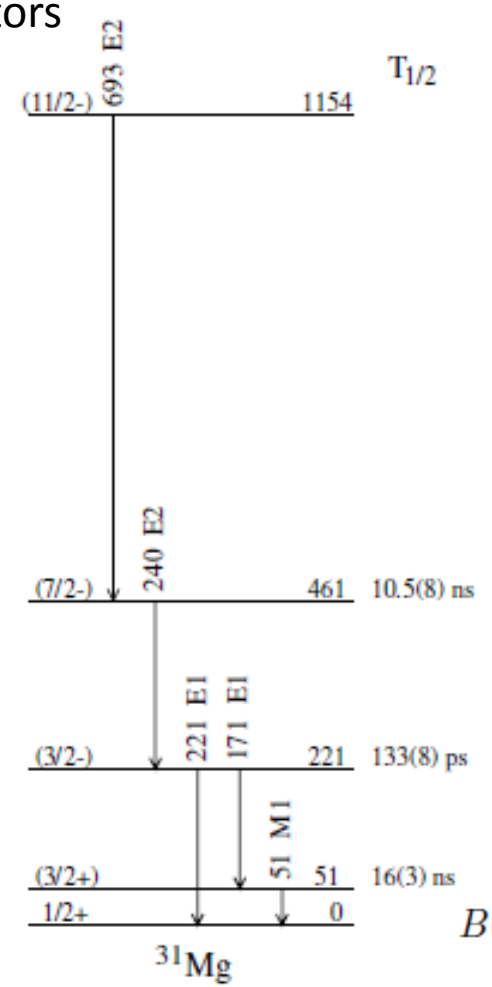
=> Transition energies and probabilities, deformations

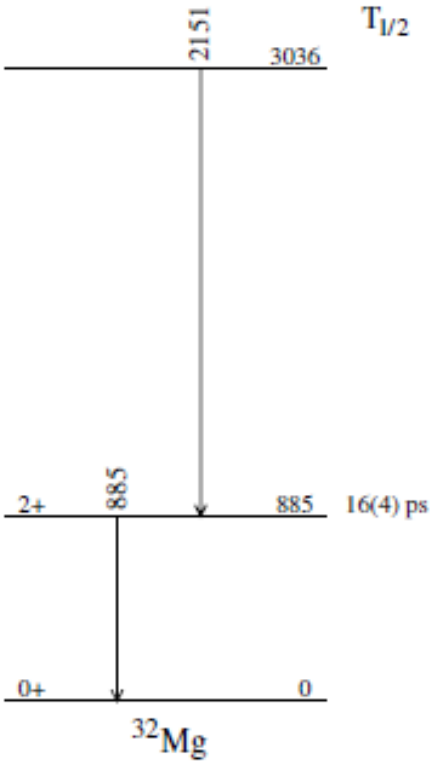


Mg: fast-timing

fast timing $\beta\gamma\gamma(t)$ using BaF_2 detectors
=>level lifetimes in 30,31,32Mg
(transition probabilities)







2+ state lifetime:

$$B(E2; 0^+ \rightarrow 2^+) = 327(87)\ e^2\mathrm{fm}^4,$$

Spherical ground state

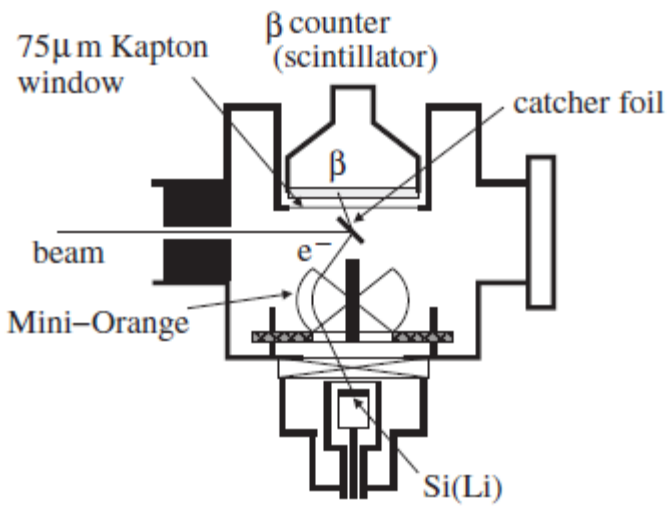
Deformed ground state

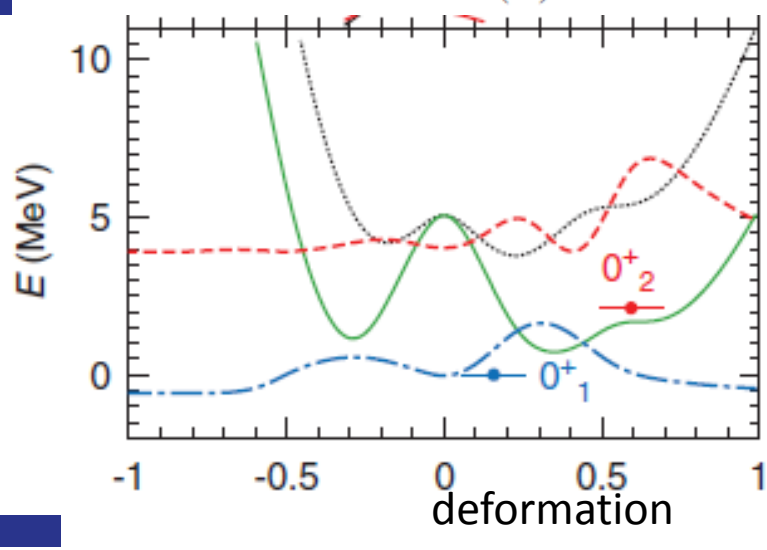
1789 keV level established : candidate for deformed 0+ configuration in 30Mg

[51] H. Mach et al., Eur. Phys. J. A 25, s01, 105 (2005)

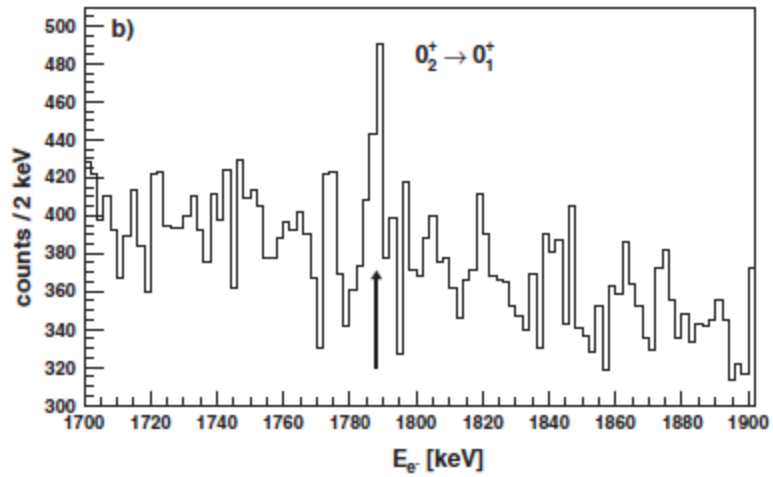
30Mg: E0 transition

E0 decay of 30Mg
electron spectrometer





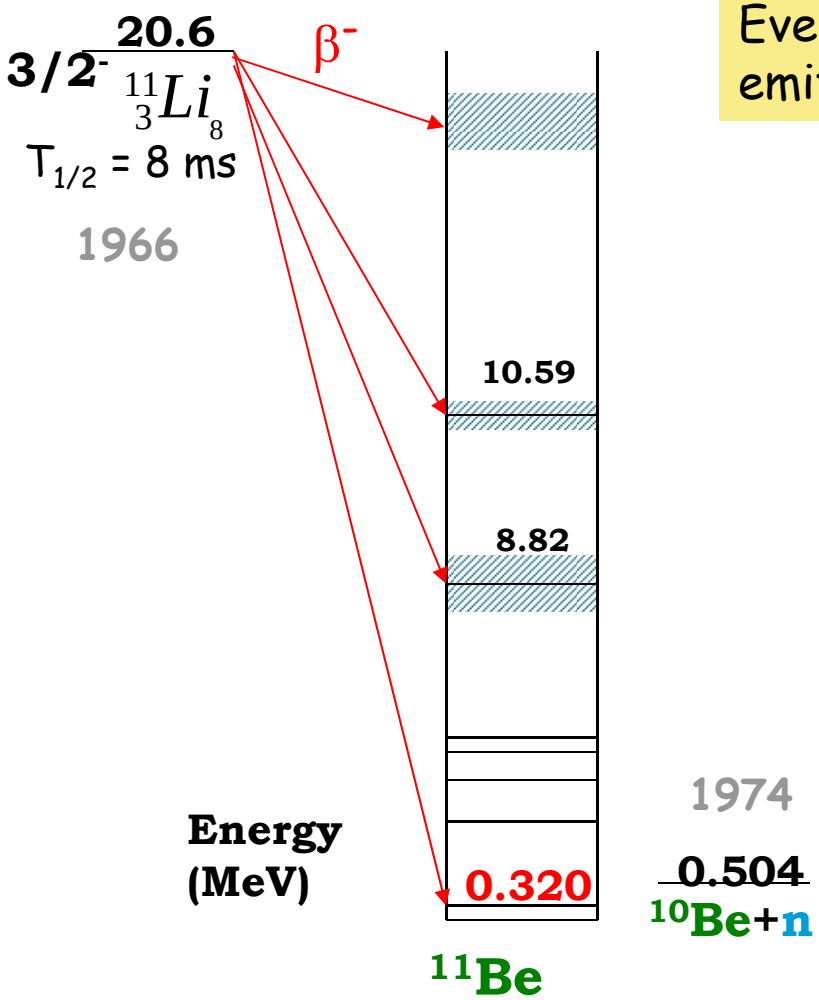
Identification of 0+ state at 1789 keV ; small mixing amplitude with spherical ground state => deformed state



30Mg: spherical 0+ground-state, deformed 1st 0+ state (2 neutrons across N=20) => **shape coexistence**

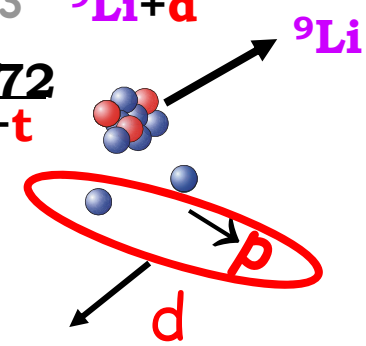
W. Schwerdtfeger et al., Phys. Rev. Lett. 103, 012501 (2009)

Results – decay of light nuclei



Even a neutron rich-nucleus emits charged particles

1996
17.91
1983
^{9}Li+d
15.72
^{8}Li+t

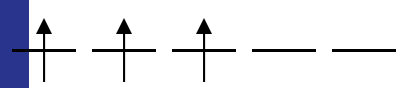
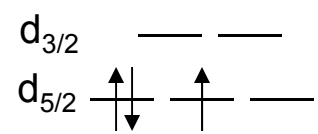


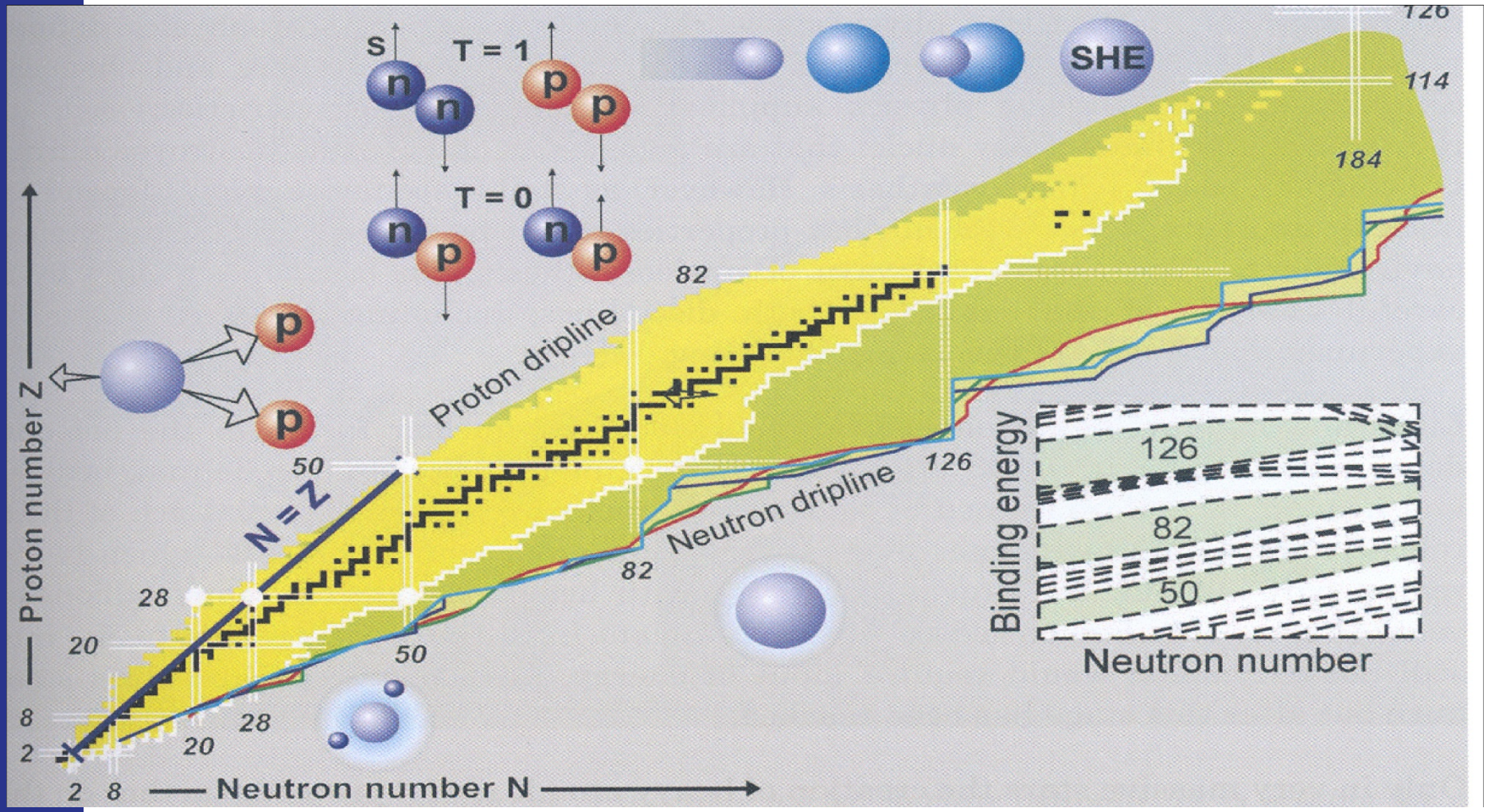
1980
8.982
2α+3n

1979
7.315
^{9}Be+2n

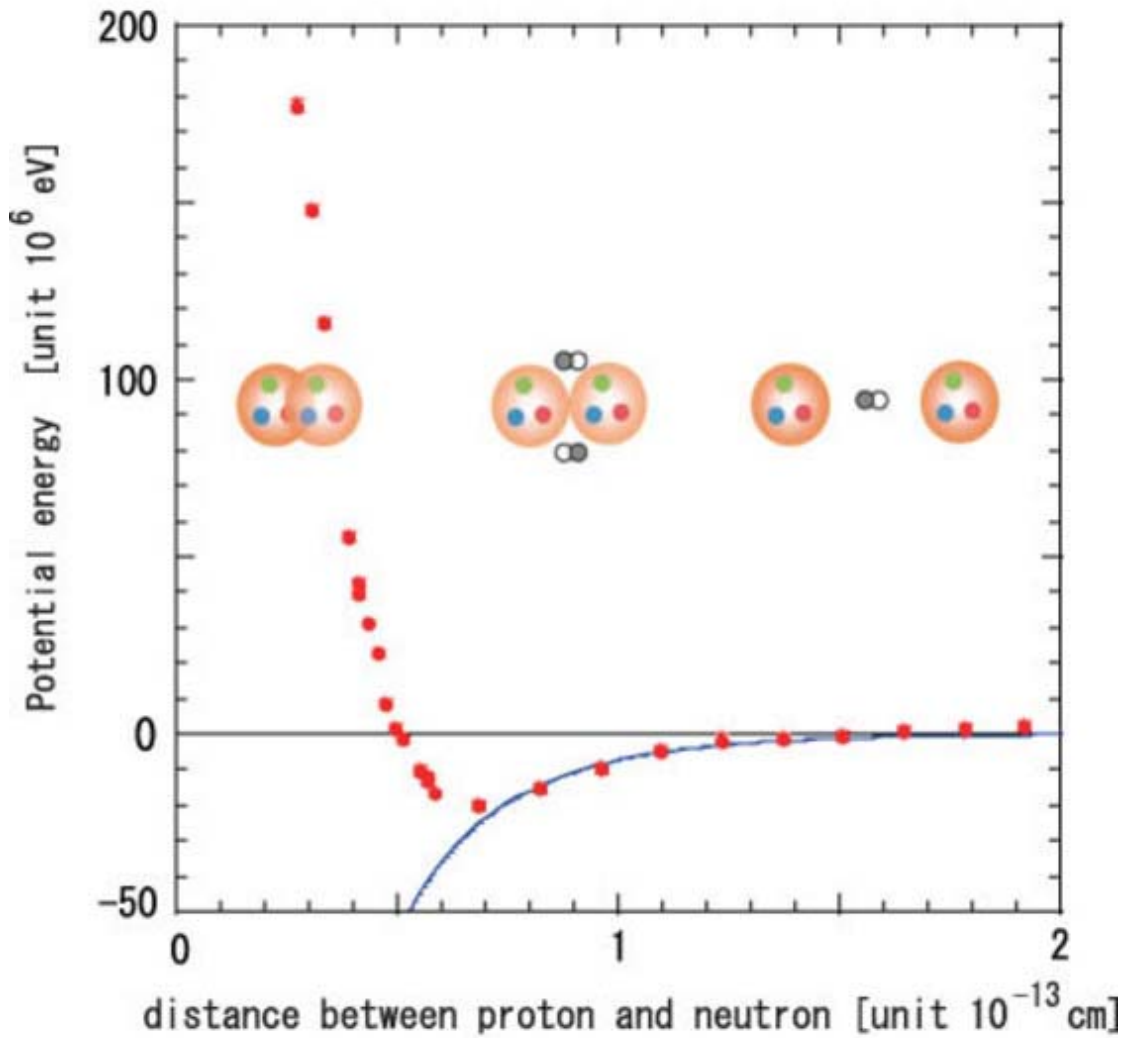
1974
0.504
^{10}Be+n

Atomic vs nuclear structure

Atoms		Nuclei
shell model: e^- fill quantized energy levels	**Description**	shell model (but not only): p and n separately fill quantized energy levels
n, l, m_ℓ, s, parity $(-1)^\ell$	**Quantum numbers**	n, l, m_ℓ, s, parity $(-1)^\ell$
max. S possible (due to Coulomb force): $J = L + S = \Sigma l_i + \Sigma s_i$ or $J = \Sigma j_i = \Sigma(l_i + s_i)$	**Lowest en. levels**	min. S possible (due to strong force pairing): $J = \Sigma j_i = \Sigma(l_i + s_i)$
weak	**Spin-orbit coupling**	strong
for 3 electrons in a *d* orbital 		for 3 nucleons in a *d* orbital 
calculated by solving Schrödinger equation with central potential dominated by nuclear Coulomb field	**Energy levels**	not easily calculated; nucleons move and interact within a self-created potential

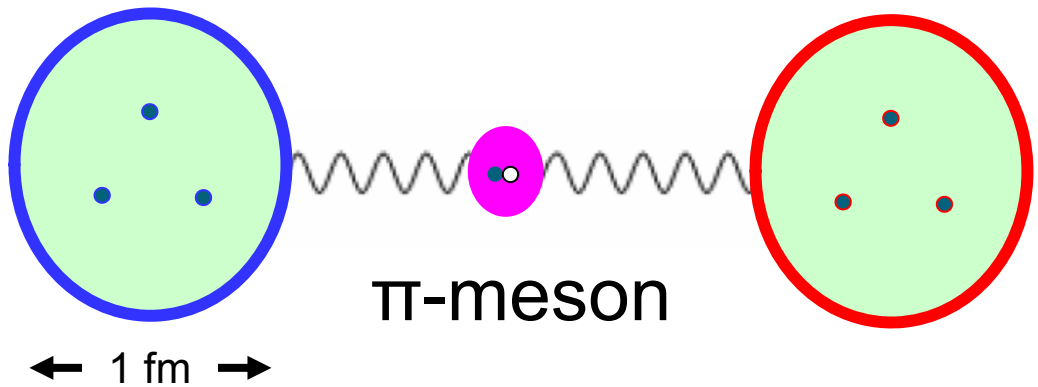

S
T = 1
n
n
p
p
T = 0
n
p
n
p
SHE
126
114
184
82
Proton dripline
p
p
50
N = Z
28
20
8
2
2
8
20
28
50
82
126
Neutron dripline
Proton number Z
Neutron number N
Binding energy
126
82
50
Neutron number

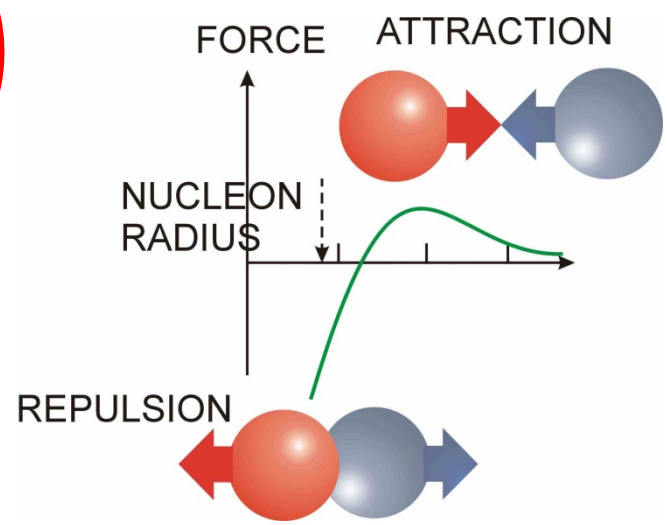
Nuclear potential



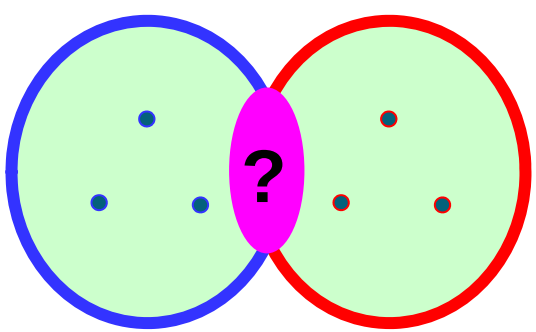
Nucleon-nucleon interaction

distance > 1 fm



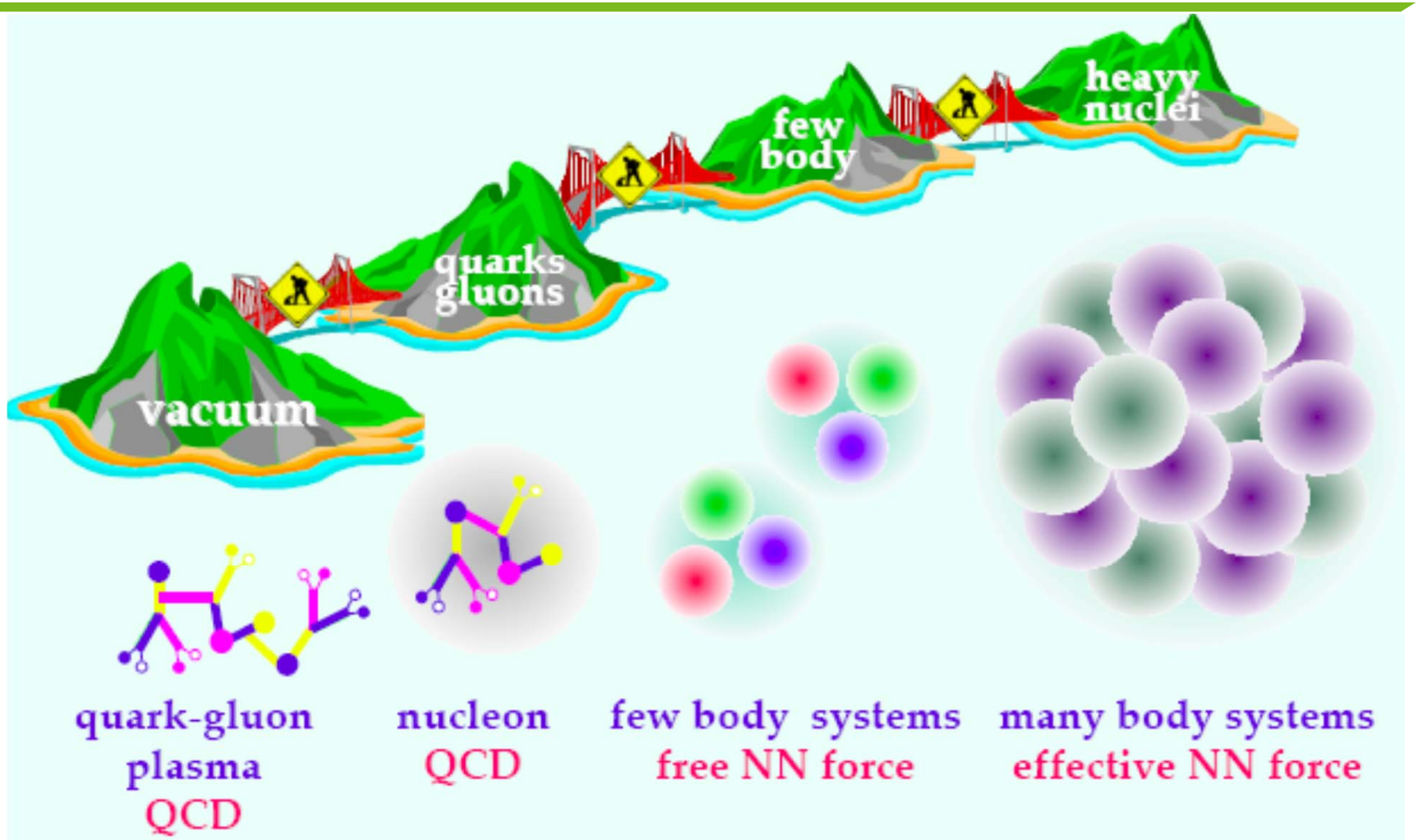


distance < 0.5 fm



three-body forces ?

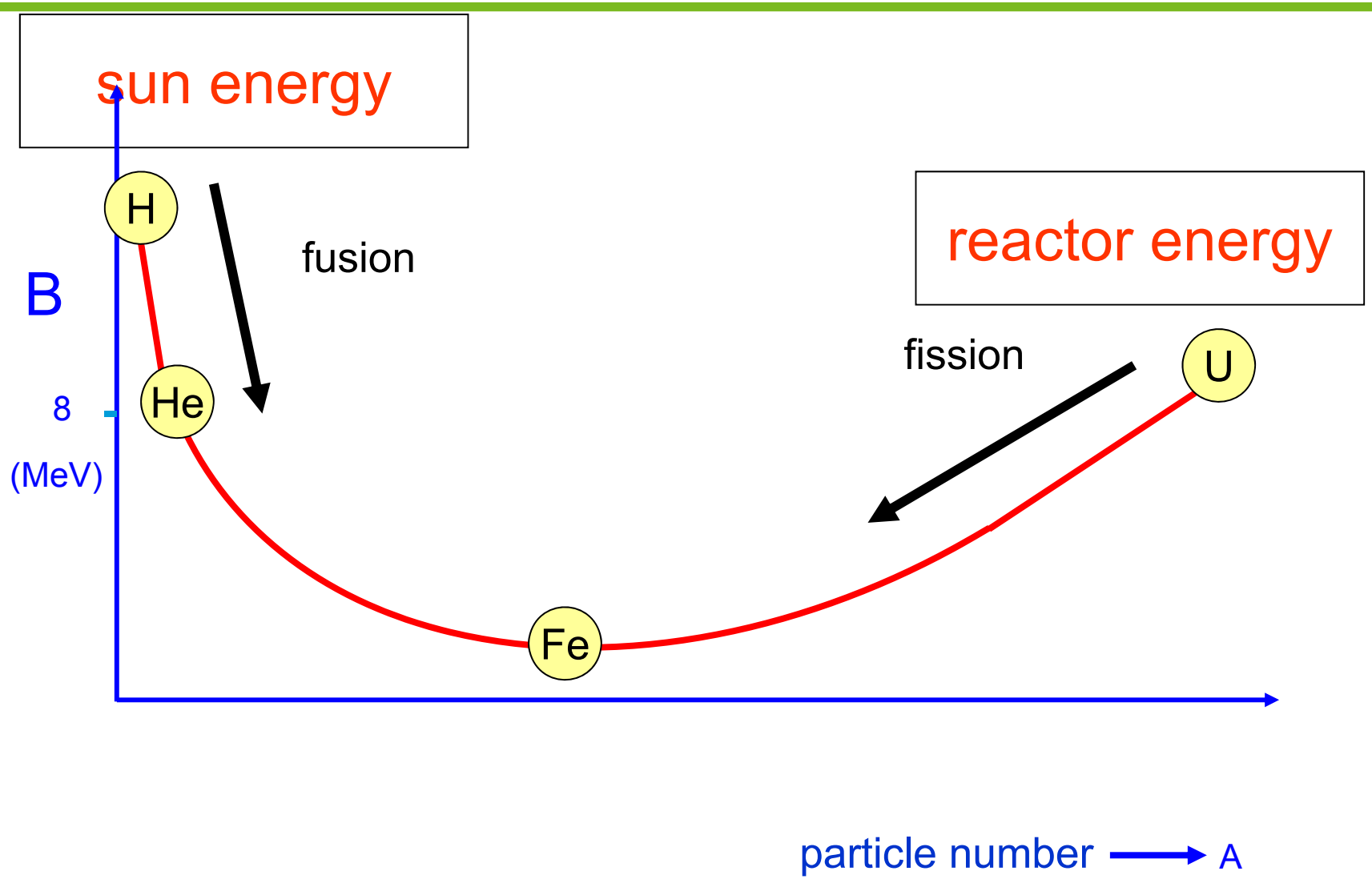
Nuclei and QCD



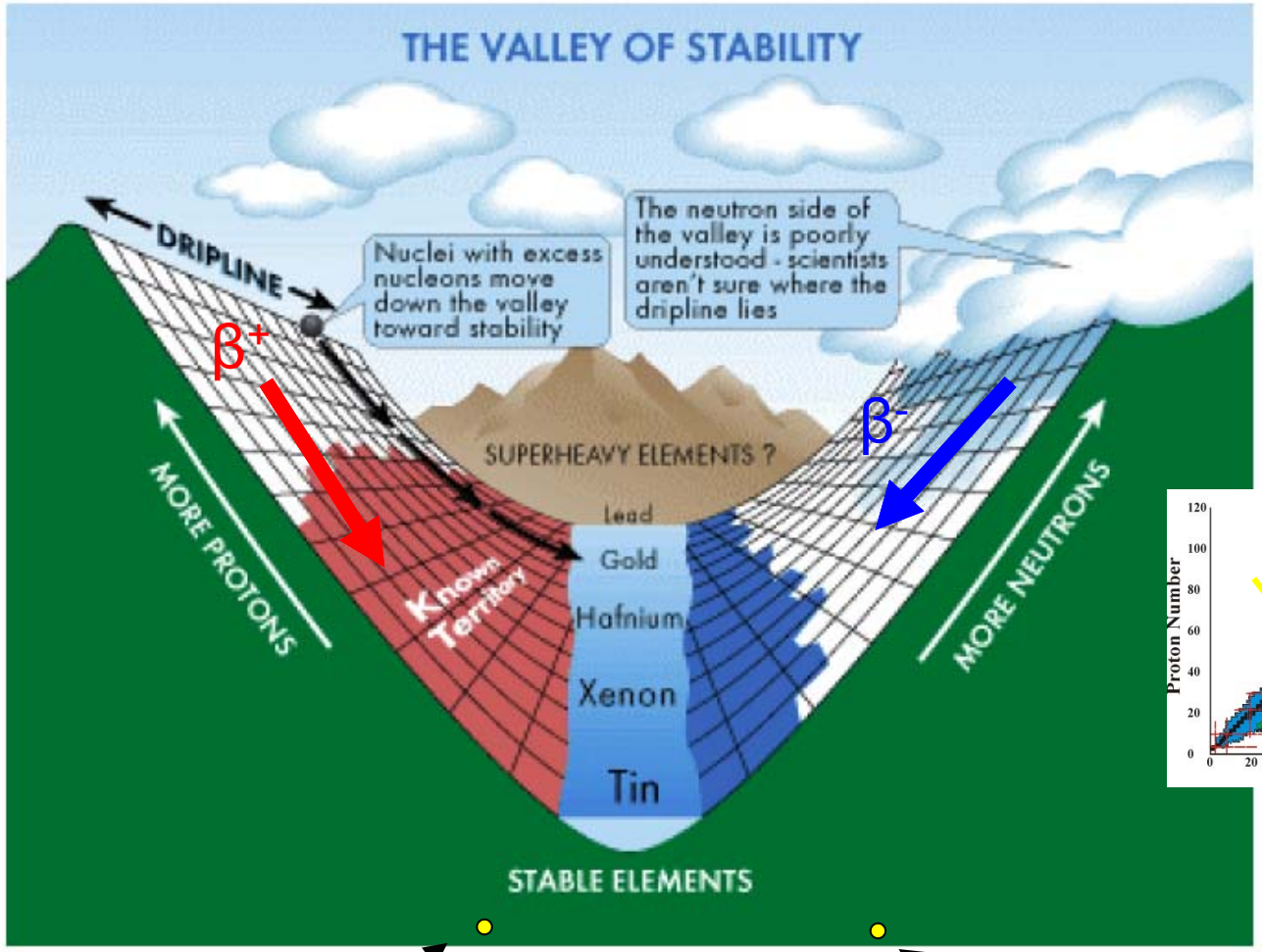
Scales: 1 GeV 100 keV

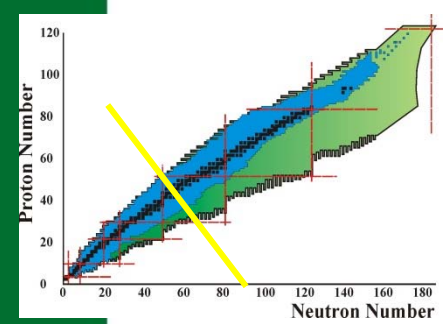
In nuclei: non-perturbative QCD, so no easy way of calculating

Binding energy per nucleon



Valey of stability





β+ decay

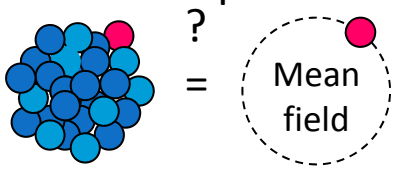
β- decay

Physics with radioactive-ion beams

Nuclear physics

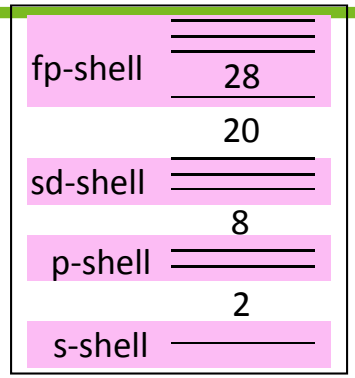
Strong interaction in many-nucleon systems

Nuclear driplines



34Ne:
10 protons + 24 neutrons

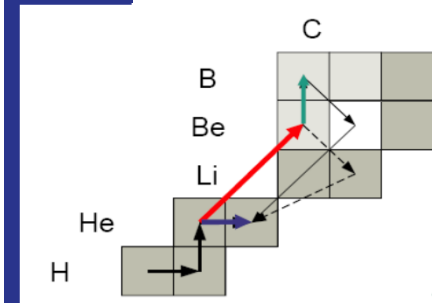
Does it exist?

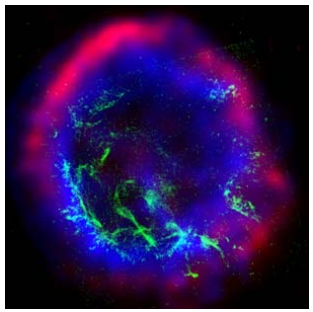


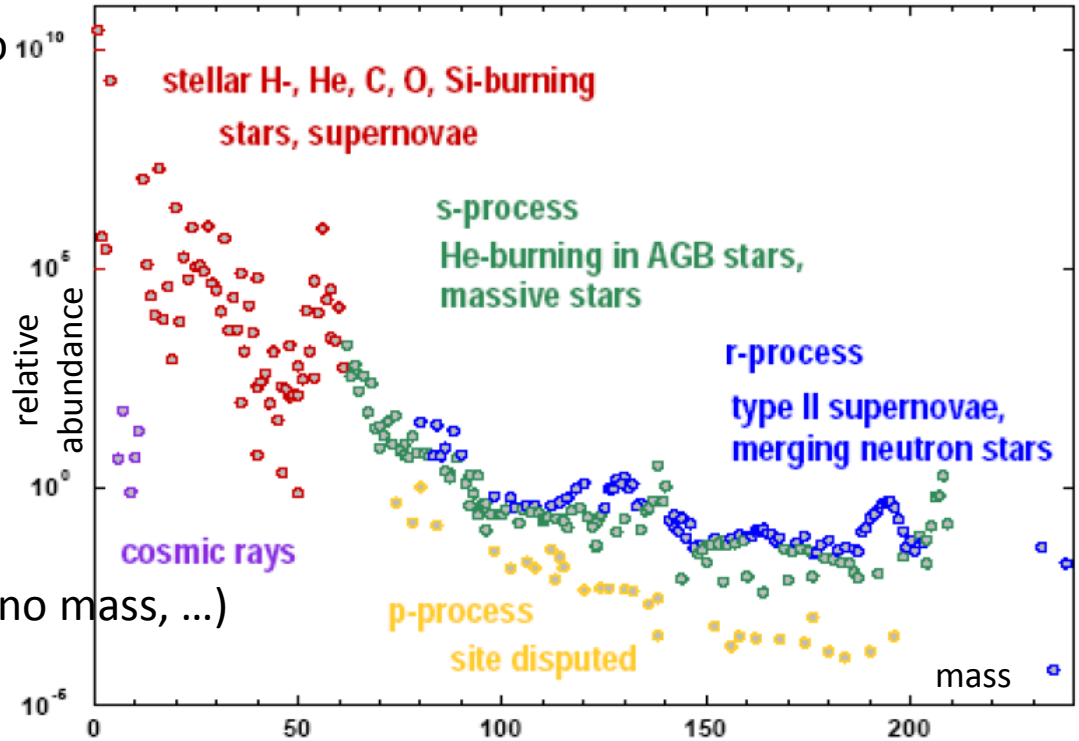
Astrophysics

Nucleo-synthesis, star evolutio

Abundances of elements







Fundamental studies

Beyond standard model (neutrino mass, ...)

Applications, *e.g.*

Solid state physics, life sciences

Modelling nuclear interaction

1. Meson-exchange theory of Yukawa (1935)
2. Fujita-Miyazawa three-nucleon potential (1955)
3. First phase-shift analysis of *NN* scattering data (1957)
4. Gammel-Thaler, Hamada-Johnston and Reid phenomenological potentials (1957–1968)
5. Bonn, Nijmegen and Paris field-theoretic models (1970s)
6. Tuscon-Melbourne and Urbana *NNN* potential models (late 70's–early 80's)
7. Nijmegen partial wave analysis (PWA93) with $\chi^2/\text{dof} \sim 1$ (1993)
8. Nijm I, Nijm II, Reid93, Argonne v_{18} and CD-Bonn (1990s)
9. Effective field theory (EFT) at N^3LO (2004–)
10. Can we constrain parameters in EFT from lattice QCD? In the mesonic sector, constraining EFT parameters from LQCD has been definitely demonstrated. With petascale and soon exascale, this will happen in the baryonic sector as well!

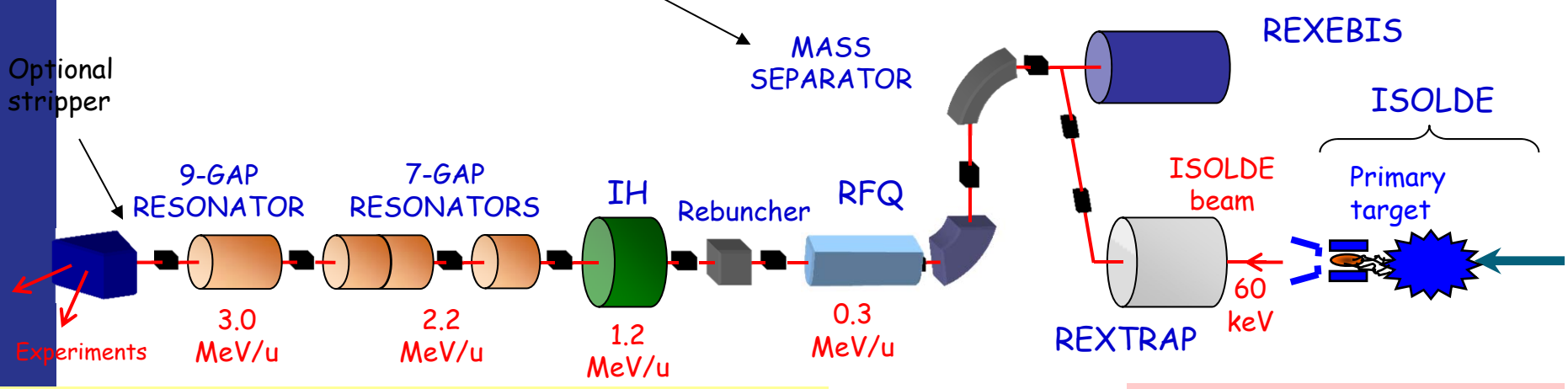
REX post-accelerator

EBIS

- Super conducting solenoid, 2 T
- Electron beam < 0.4A 3-6 keV
- Breeding time 3 to >200 ms
- Total capacity $6 \cdot 10^{10}$ charges
- A/q < 4.5

Nier-spectrometer

- Select the correct A/q and separate the radioactive ions from the residual gases.
- A/q resolution ~150



Linac

Length	11 m
Freq.	101MHz (202MHz for the 9GP)
Duty cycle	1ms 100Hz (10%)
Energy	300keV/u, 1.2-3MeV/u
A/q max.	4.5 (2.2MeV/u), 3.5 (3MeV/u)

REX-trap

- Cooling (10-20 ms)
  Buffer gas + RF
- (He), Li,...,U
- 10^8 ions/pulse

(Space charge effects >10^5)

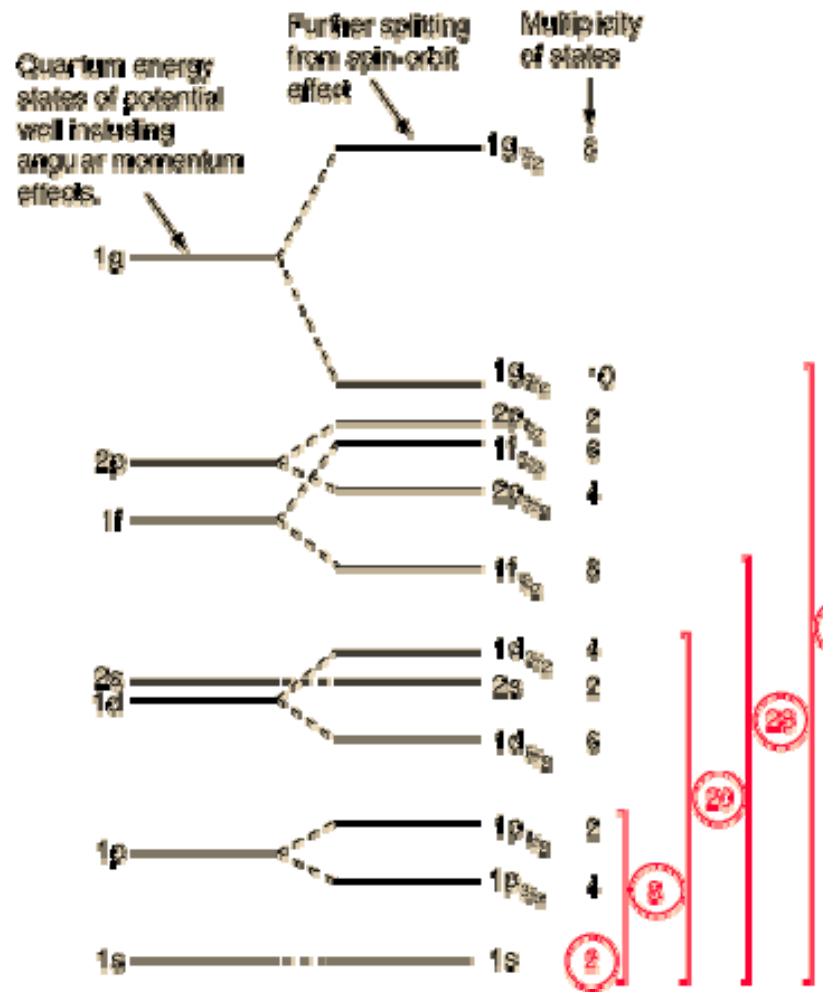
Total efficiency : 1 -10 %

Nuclear shell model

Developped about 50 years ago for stable nuclei:
Some nuclides more stable and more difficult to excite than others

Backbone of nuclear physics: with closed-shell assumption

Based on analogies to atomic shells, but differences:
- No central potential but a self-created potential
- Nucleon-nucleon interaction has tensor (non-central) components
- Two kinds of nucleons
- In ground state: all odd number of protons or neutrons couple to spin 0
- Strong spin-orbit coupling changes magic numbers: 8,20,28,50,…
- No analitic form of nucleon-nucleon interaction in nuclear medium



Describes "single-particle" properties

Challenges: dissapearing and migrating magic numbers => The backbone is not as well understood as we thought