LECTURE 3: THE NUCLEAR SHELL STRUCTURE

NUCLEAR STRUCTURE
STUDIED WITH
SPECTROSCOPY AND REACTIONS

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TU Darmstadt, IKP, February 2017

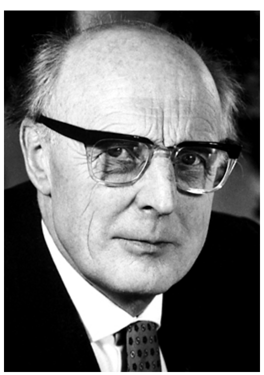
Outline

- The shell model and shell closures
- Origins of shell evolution
  - diffusiveness of the nuclear surface
  - spin-isospin and tensor terms of the NN interaction
  - reduction of spin-orbit
  - 3N forces
- RI beam production and future facilities
- The N=16 “new magic number”, collapse of N=20, 28 shell closures
- Mirror region: the N=40 island of inversion and the ^{78}Ni region
- Are N=32 and 34 “new” magic numbers?
- Heavier doubly-magic nuclei: ^{100}Sn and ^{132}Sn

The shell model: history

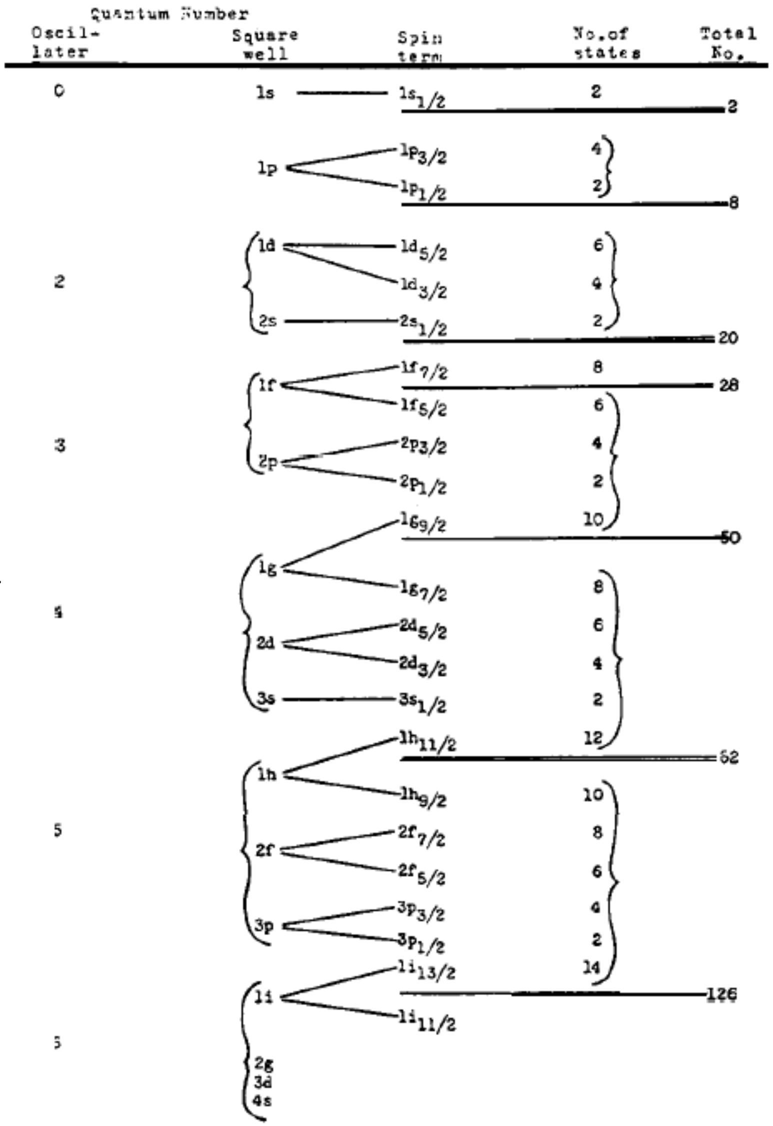
- **1932**: Chadwick discovers the neutron (Nobel 35')
- W.M. Elsasser, J. Phys. Radium 4, 549 (**1933**)
  Magic numbers from binding energies, abundancies
- M. Goeppert-Mayer, Phys. Rev. 74, 235 (**1948**)
  « On closed shells in nuclei »
- H.E. Suess, J.H.D Jensen, Arkiv. Fys. 3, 577 (1951)
- **1963**: Nobel prize in Physics to Mayer and Jensen for « their discoveries concerning nuclear shell structure »

M. Goeppert-Mayer



J.H.D. Jensen

E. Wigner*



M. Goeppert-Mayer, december 1963
From Nobel lecture

- E. Wigner won ½ of the 1963 Nobel Prize for his contribution to the theory of the atomic nucleus and fundamental symetries

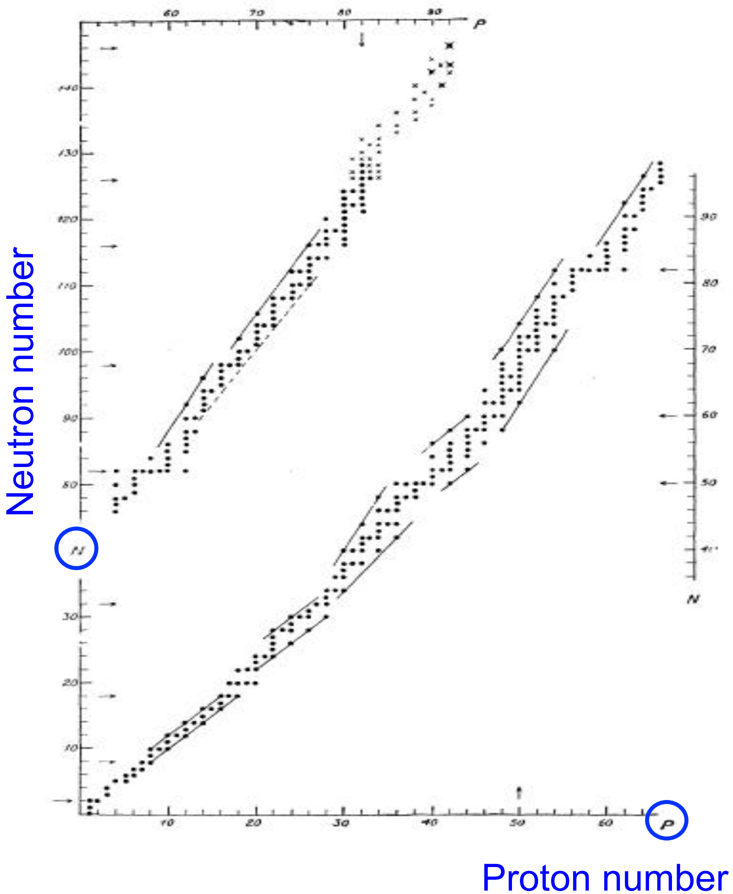
Evidence for shells

- Several observables show a pattern consistent with the simple shell model picture
- Abundances, separation energy, first excitation energy, moments, spins,…
- Huge efforts over the past decades in experimental nuclear physics

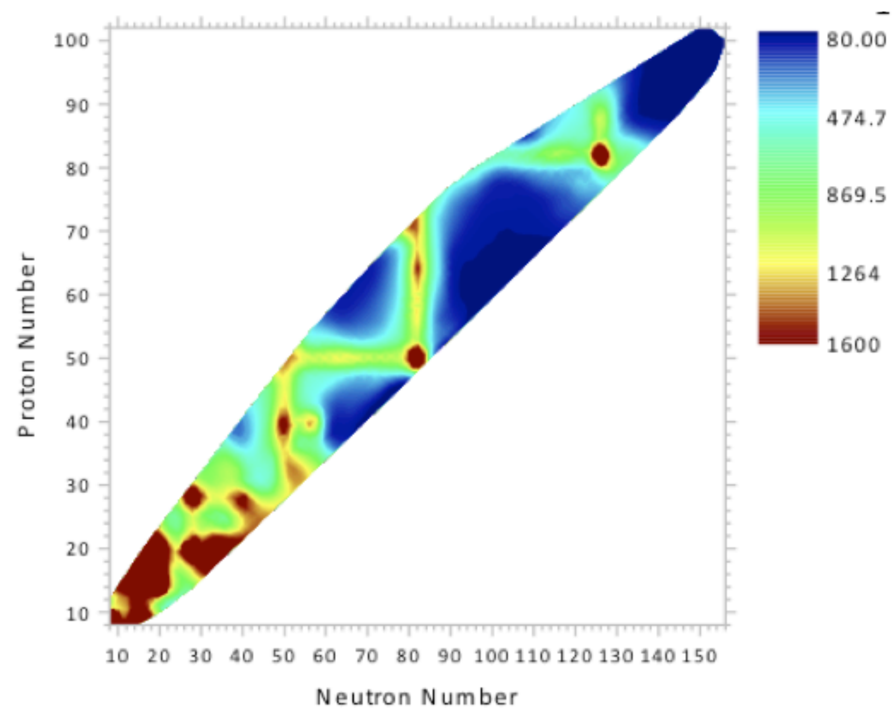
W.M. ELSASSER

La structure des noyaux atomiques complexes

Annales de l'I. H. P., tome 5, n° 3 (1935), p. 223-262.



First 2^+ excitation energies (even-even nuclei in 2016)



Shell evolution

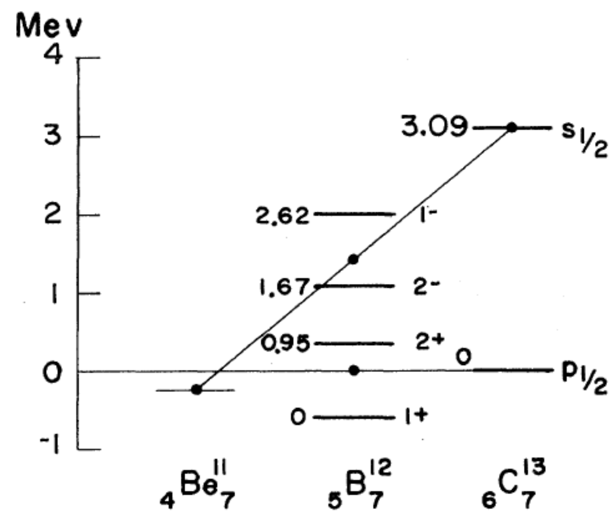
VOLUME 4, NUMBER 9 PHYSICAL REVIEW LETTERS MAY 1, 1960

ORDER OF LEVELS IN THE SHELL MODEL AND SPIN OF Be^{11*}

I. Talmi and I. Unna
Department of Physics, The Weizmann Institute of Science, Rehovoth, Israel
(Received April 4, 1960)

- **1960**: first interpretation of **shell evolution** as a monopole drift of single-particle orbits due to **neutron-proton interactions**
- Explanation of the ½+ « abnormal » ground-state spin of ^{11}Be
- **2000**: experimental proof of a ½+, l=0 gs and ½-, l=1 first excited state

  A. Navin et al., PRL **85**, 266 (2000)
- **2016**: ab-initio prediction of the ^{11}Be level scheme



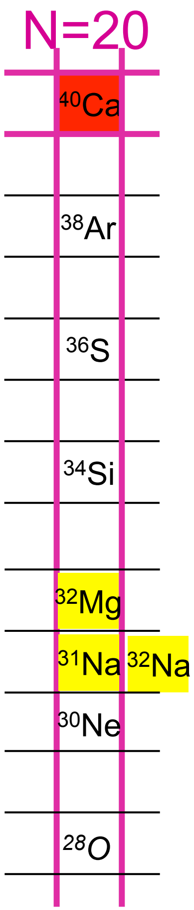
$$\langle j^2(J=0)j' | V_{1n} + V_{2n} | j^2(J=0)j'\rangle = 2 \sum_{J=|j-j'|}^{J=j+j'} (2J+1)\langle jj'J | V | jj'J\rangle \Big/ \sum_{J=|j-j'|}^{J=j+j'} (2J+1). \quad (1)$$

First evidence for non universality of magic numbers

- Mass measurement of $^{26-32}Na$ leads to an unexpected region of deformation at N=20

  C. Thibault et al., Phys. Rev. C **12** (1975)

> Then the behavior of the experimental data for the sodium isotopes at $N=20$ is inconsistent with the classic shell closure effect, and more reminiscent of the behavior one observes when entering a region of sudden deformation.



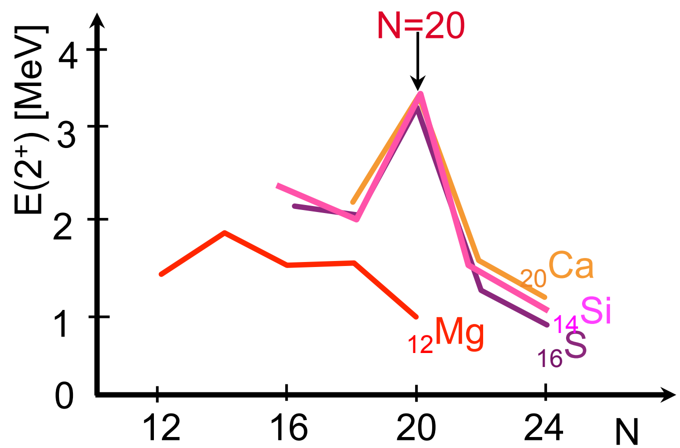
- Low 2^+ excitation energy (885 keV) of ^{32}Mg

  C. Détraz *et al.*, Phys. Rev. C 19, 164 (1979)

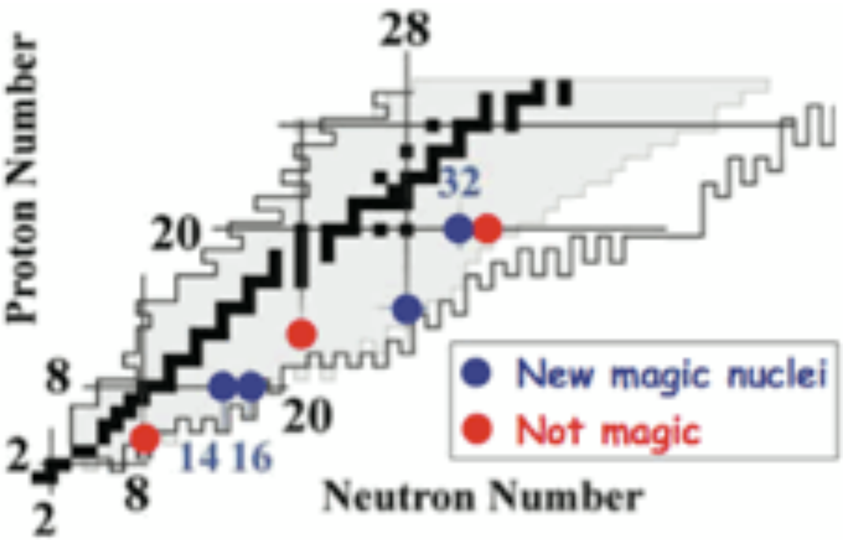
> (ii) The confirmation of the onset of the new region of deformation at $Z \simeq 11$ and $N = 20$ definitively observed with spectroscopic tools. The location of the first 2^+ state of ^{32}Mg at an energy of only 885 keV (fig. 24) is associated with a large deformation at $N = 20$.

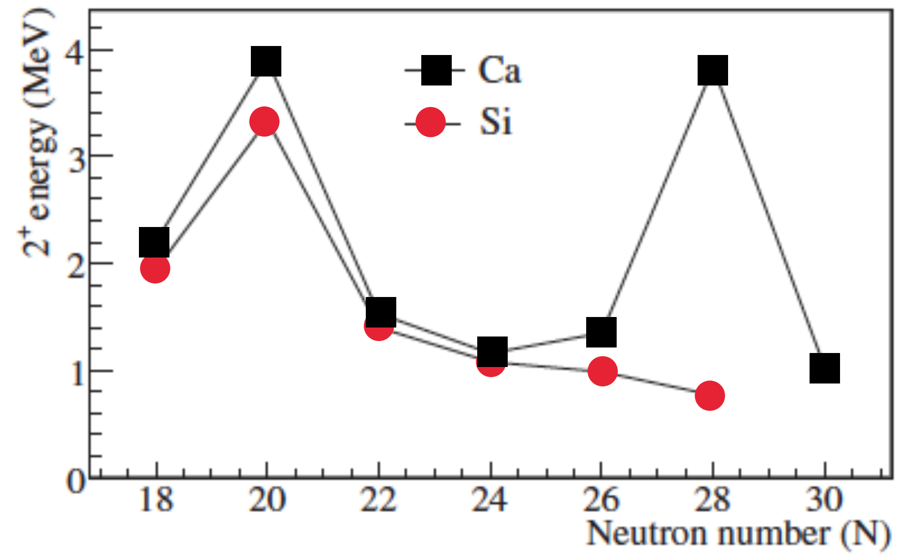
- High BE2 value for 0+->2+ in ^{32}Mg

  T. Motobayashi et al., PLB 346, 9 (**1995**)



Shell evolution with isospin





B. Bastin et al., PRL **99** (2007)

- shell structure is **not yet known experimentally nor fully understood theoretically**
- main reason to investigate **radioactive nuclei**

stable=specific **radioactive=general**

- **experimental difficulty : low production rates** for most exotic nuclei
- new methods and priviledged observables suited for low rates

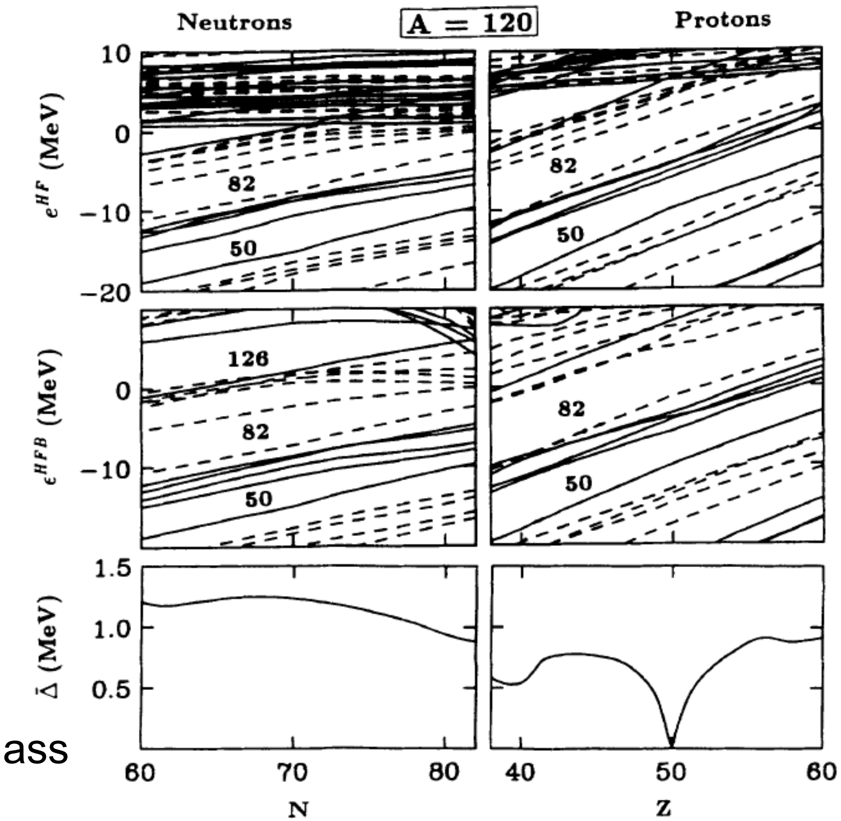
Shell evolution at the drip line

VOLUME 72, NUMBER 7 PHYSICAL REVIEW LETTERS 14 FEBRUARY 1994

Nuclear Shell Structure at Particle Drip Lines

J. Dobaczewski,* I. Hamamoto,† W. Nazarewicz,* and J. A. Sheikh‡

- ❑ Shell evolution investigated at the HF level
- ❑ shell structure of neutron dripline nuclei strongly affected by **interaction with continuum**
- ❑ Significant difference between HF and RMF predictions for **isospin dependence for the neutron spin-orbit splitting**
- ❑ Large diffusiveness of neutron density and central potential lead to a single-particle spectrum close to that of the **harmonic oscillator with spin-orbit term**
- ❑ conclusion do not apply to most studied medium-mass nuclei still quite far from the neutron dripline



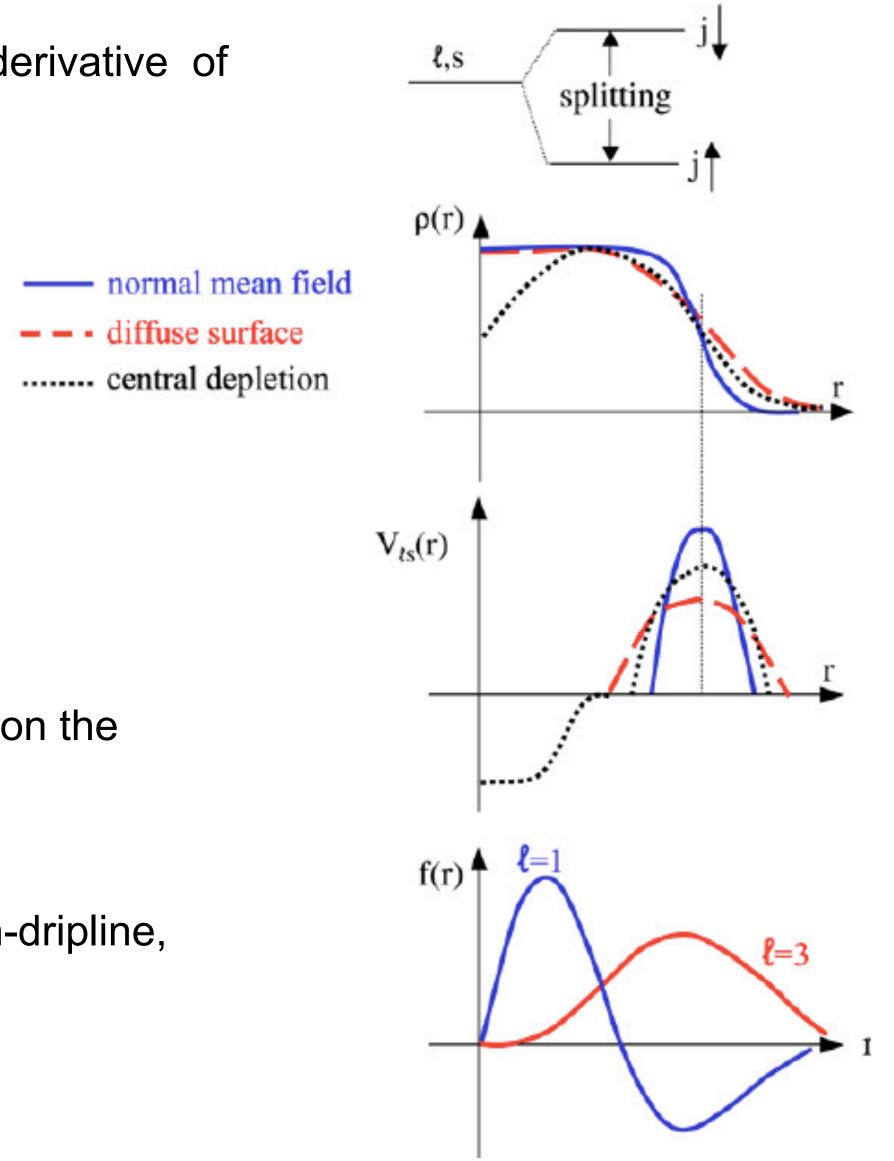
Spin-orbit one-body potential

- One-body spin-orbit interaction depends on the derivative of the nuclear density

$$V_{\ell s}^{n}(r) \propto \frac{1}{r}\frac{\partial}{\partial r}\left[2\rho_n(r)+\rho_p(r)\right]\vec{\ell}.\vec{s}$$

$$V_{\ell s}^{p}(r) \propto \frac{1}{r}\frac{\partial}{\partial r}\left[\rho_n(r)+2\rho_p(r)\right]\vec{\ell}.\vec{s}$$

D. Vautherin, D.M. Brink, Phys. Rev. C5 (1972) 626.



- weighting factors in front of p,n densities depend on the formalism

- Diffuse-surface nuclei, for example at the neutron-dripline, may experience a smaller spin-orbit splitting

Origin of shell evolution: monopole drift

- Hamiltonian can be decomposed in a monopole and a multipole part

$$\mathcal{H} = \mathcal{H}_m(\text{monopole}) + \mathcal{H}_M(\text{multipole}).$$

- **monopole**: effective single-particle energies

$$\langle SC \pm 1 | H | SC \pm 1 \rangle = \langle SC \pm 1 | H_m | SC \pm 1 \rangle$$

SC: Shell Closure (core or filled valence space)

- **multipole**: correlations (Qpole, pairing,…)

- Gaps evolve linearly with the number of nucleons when an orbital is filled
- Changes depend on the 2B matrix elements

Example: neutron gap between orbitals n_1,n_2 with proton number varying from 0 to $(2j_{p1}+1)$

$$\Delta\varepsilon_{n1} = x V^{pn}_{j_{p1}j_{n1}}$$

$$\Delta(gap) = (2j_{p1}+1)(V^{pn}_{j_{p1}j_{n1}} - V^{pn}_{j_{p1}j_{n2}})$$

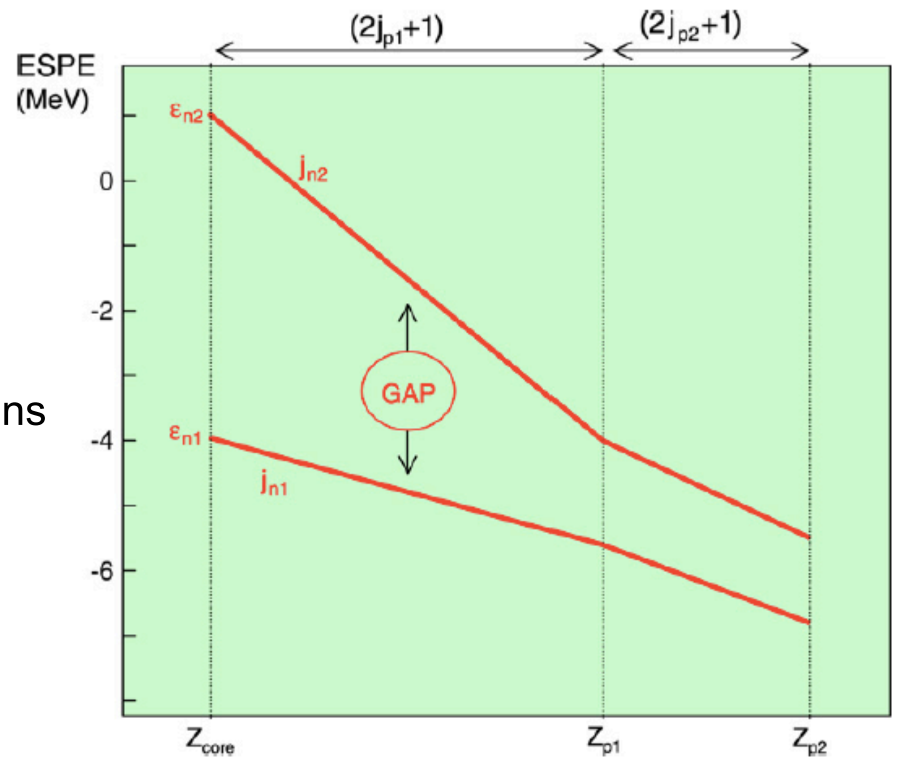
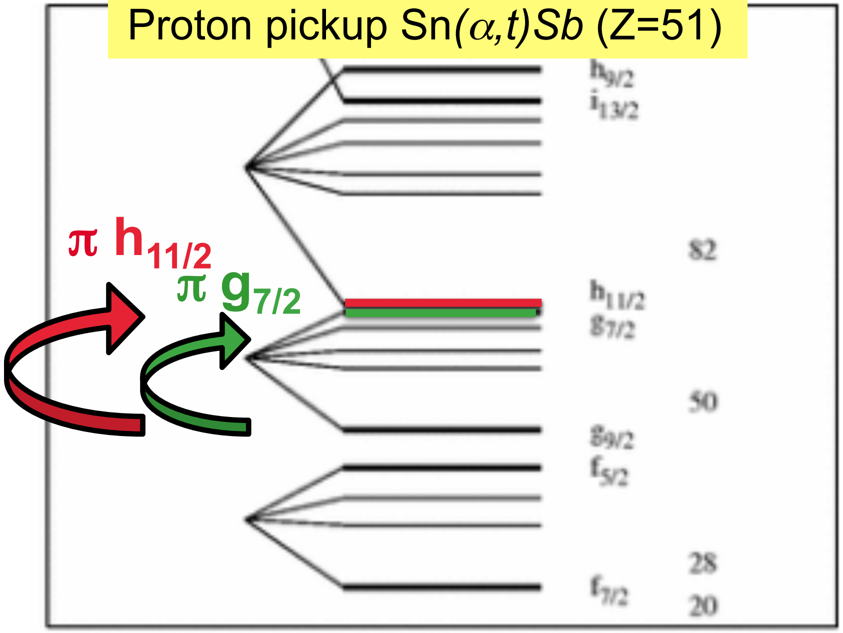
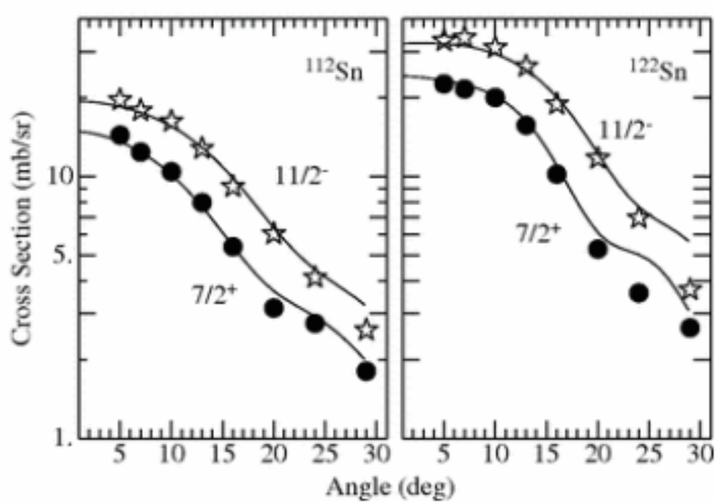


Figure from
O. Sorlin, M.-G. Porquet, Prog. In Part. Nucl. Phys. 61, 602 (2008)

The example of proton "ESPE" in Sb isotopes

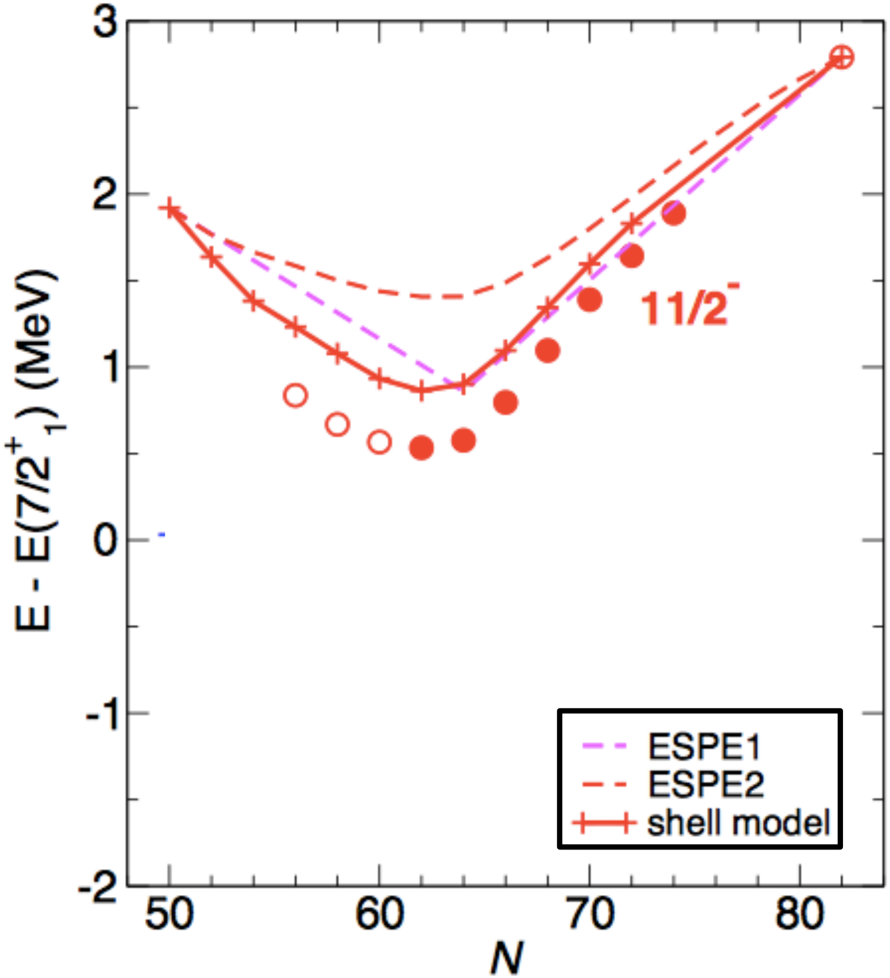
Proton pickup Sn(α,t)Sb (Z=51)





J.P. Schiffer et al., PRL **92** (2004)

Shell model calculations versus data

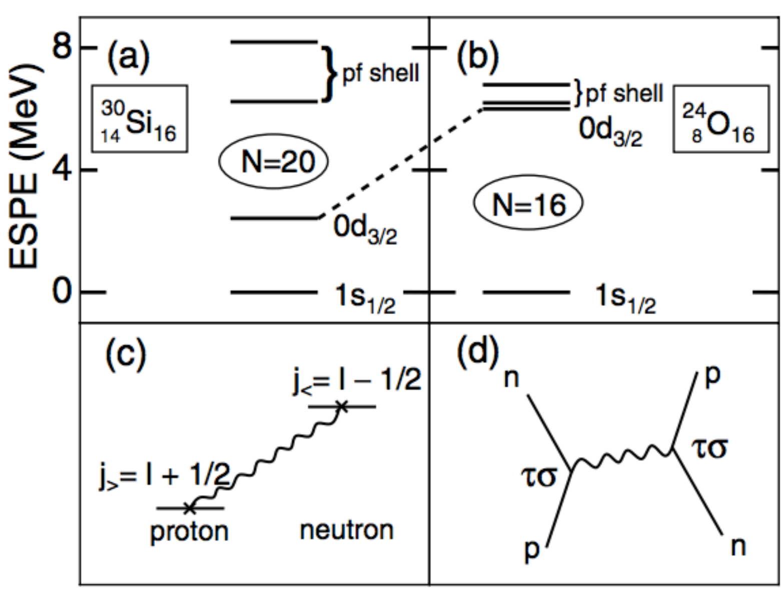


Spin-isospin central term

- Central part of NN force depends on the relative distance with spin and isospin dependences
- The **spin-isospin term** belongs to the central part of the effective interaction:

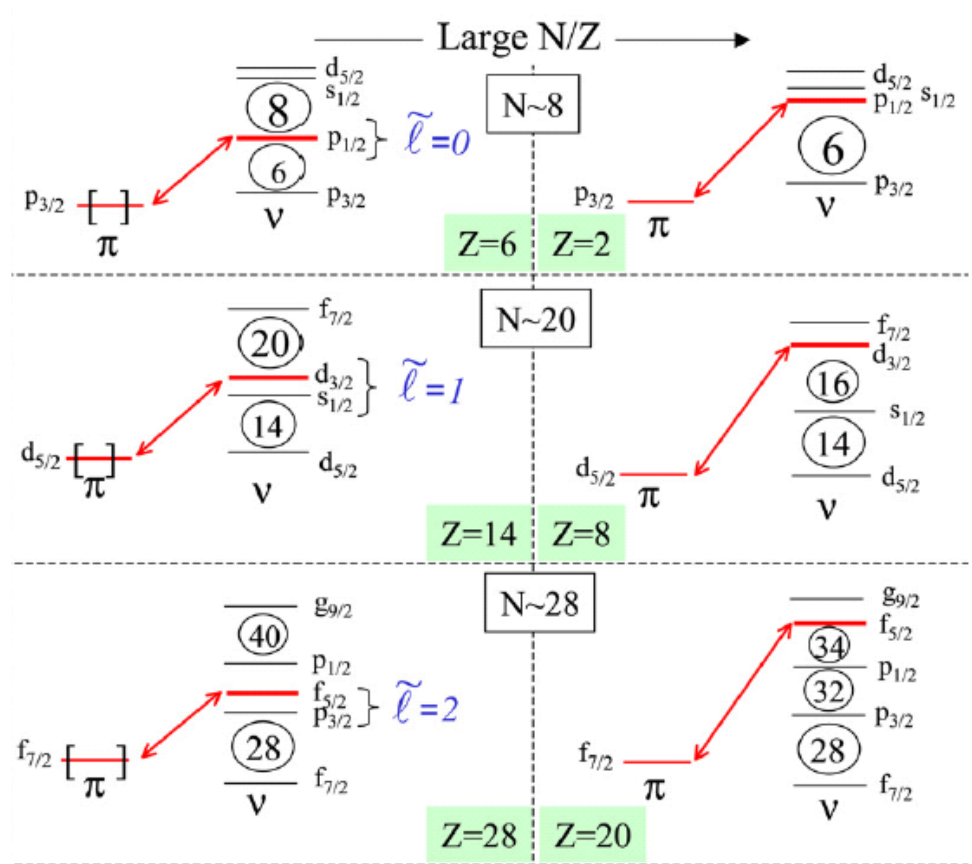
$$V_{\tau\sigma} = \tau.\tau\,\sigma.\sigma\; f_{\sigma\tau}(r)$$

- Couples more strongly p-n pairs with j> and j<



T. Otsuka *et al.*, PRL **87**, 082502 (2001)

O. Sorlin, M.-G. Porquet / Progress in Particle and Nuclear Physics 61 (2008) 602–673

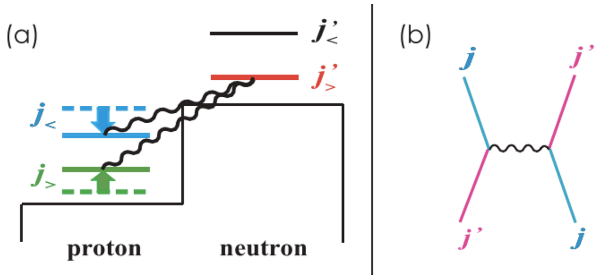


Tensor term

- The tensor force contains an angular momentum, spin and isospin component:

$$V = (\vec{\tau}_1.\vec{\tau}_2)(\left[\vec{\sigma}_1.\vec{\sigma}_2\right]^{(2)}.Y^{(2)})f(r)$$

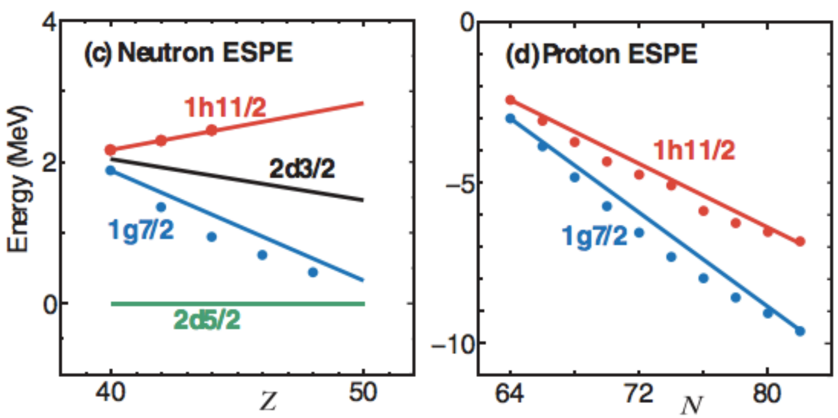
- proton-neutron interaction with opposite spin is attractive and claimed to play a major role in shell evolution
T. Otsuka *et al.*, PRL **95**, 232502 (2005)



- Extension of the spin-isospin mechanism for proton and neutron in different shells

- EDF approaches with Skyrme or Gogny forces **do not include explicite tensor term**

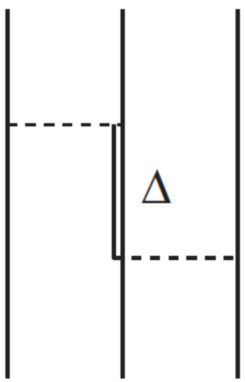
- Explicit introduction of tensor term in effective Skyrme functionals does not give obvious improvement of spectroscopy
T. Lesinski *et al.*, PRC **76**, 014312 (2007)



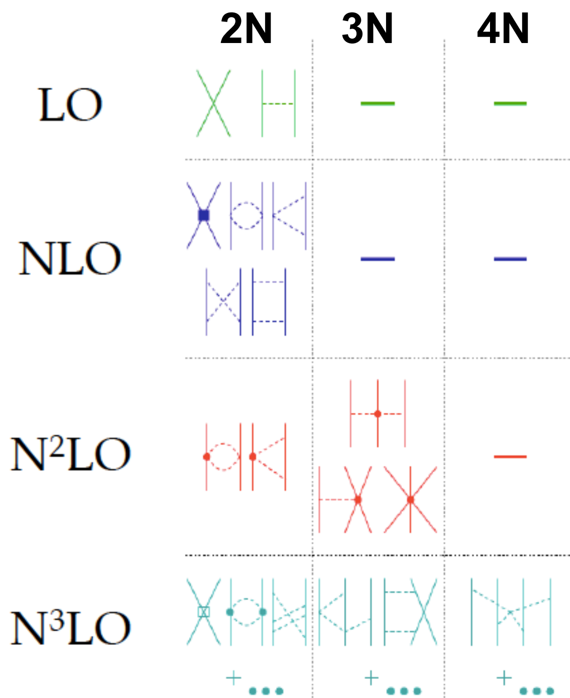
Three-body forces

- Nucleons are not point like particles
- Some **internal degrees of freedom are neglected**

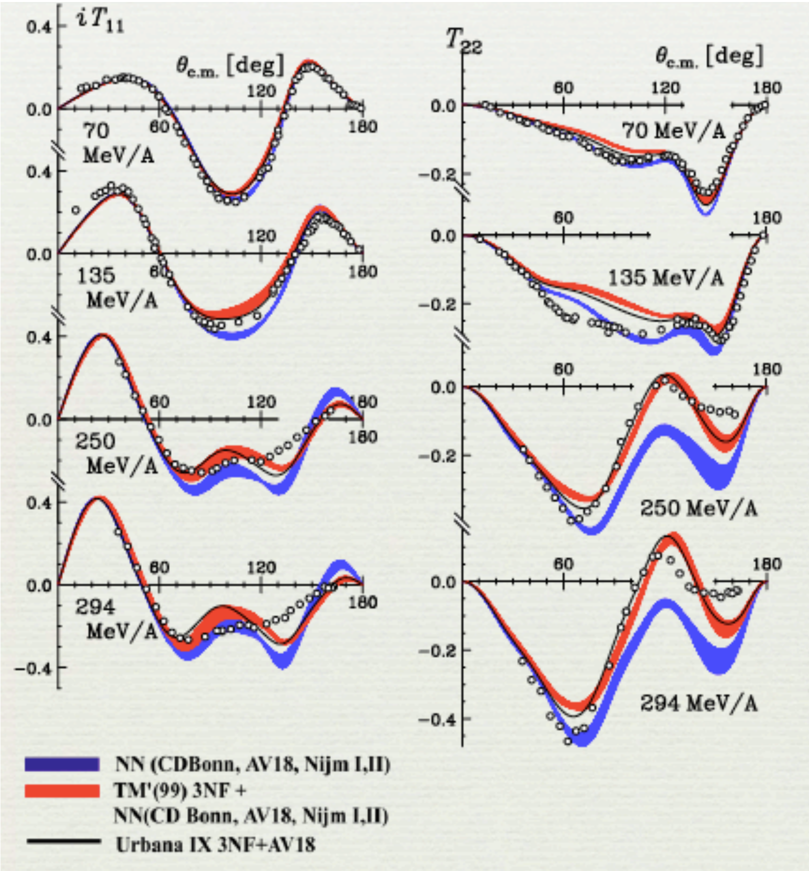
  Example: Nucleons may excite into a Δ resonnance



Fujita-Miyazawa representation



pol(p)-d elastic scattering analysing power



K. Sekiguchi *et al.*, PRC 83, 061001 (2011)

- **Chiral Effective Field Theory** (EFT):
  - pion is the only explicit degree of freedom
  - expansion in powers of momenta
  - **many-body forces emerge naturally**

Shell evolution: 3N forces

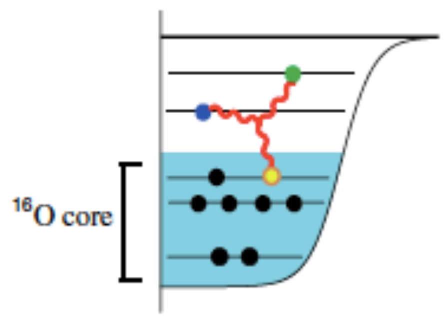
PRL **105,** 032501 (2010) PHYSICAL REVIEW LETTERS week ending 16 JULY 2010

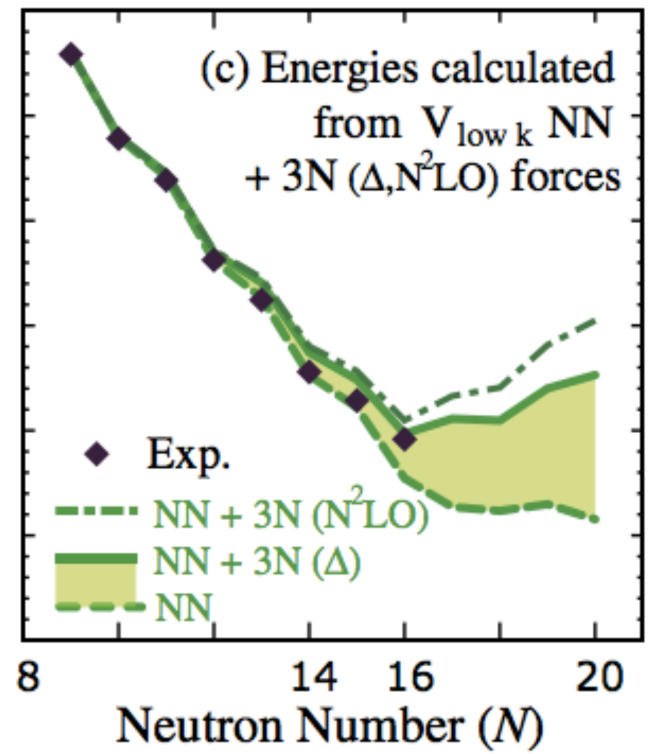
Three-Body Forces and the Limit of Oxygen Isotopes

Takaharu Otsuka,[1,2,3] Toshio Suzuki,[4] Jason D. Holt,[5] Achim Schwenk,[5] and Yoshinori Akaishi[6]

- 3N forces explain the dripline location for oxygens
- 3N forces between 2 valence neutrons and one core neutron induce repulsion among excess neutrons (linked to Pauli exclusion principle)

(d) Schematic picture of two-valence-neutron interaction induced from 3N force



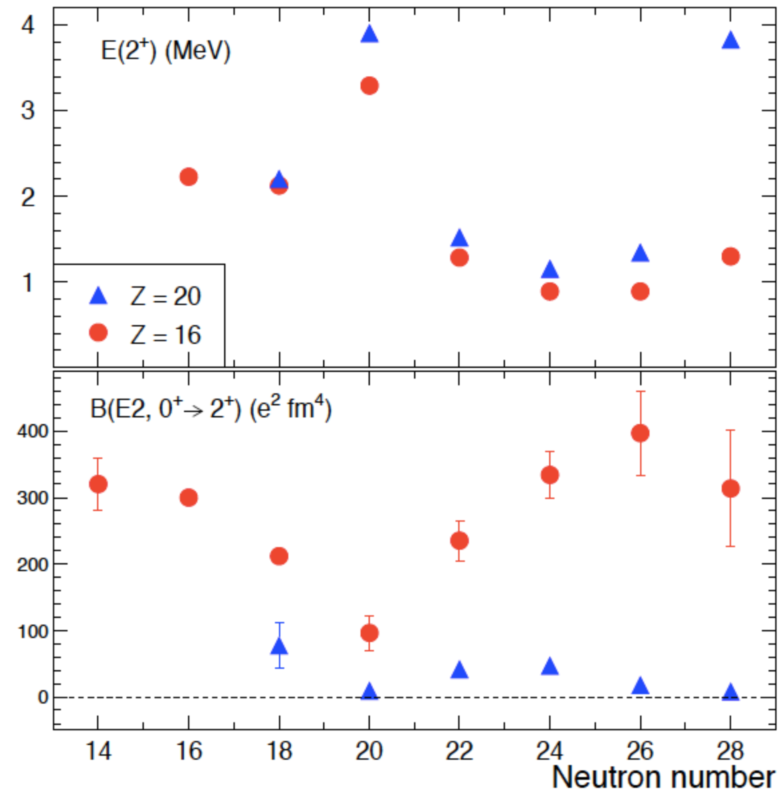


- Modify the ESPE (monopole) of valence orbitals
- Key to explain the magic character of ^{48}Ca

J. Holt et al., J. Phys. G 39, 085111 (2012)

Spectroscopic observables and shell closures

- ❑ Masses
- ❑ beta-decay lifetime
- ❑ Excitation energy of the first excited state (most of the time 2^+ in even-even nuclei)
- ❑ Transition probabilities $B(E2;0^+\text{->}2^+)$



Spectroscopy:

- ❑ spectroscopy is often the first information
- ❑ in-beam γ and spectroscopy following β decay are both competitive
- ❑ in-beam γ wins for most neutron-rich species (high P_n in β decay)

Spectroscopic factors extracted from direct reaction cross sections

- ❑ Still uncomplete/inconsistent theory for quantitative interpretation (see Lecture 4, tomorrow)

- **The shell model and shell closures**

- **Origins of shell evolution**
  - diffusiveness of the nuclear surface
  - spin-isospin and tensor terms of the NN interaction
  - reduction of spin-orbit
  - 3N forces

- **RI beam production and future facilities**

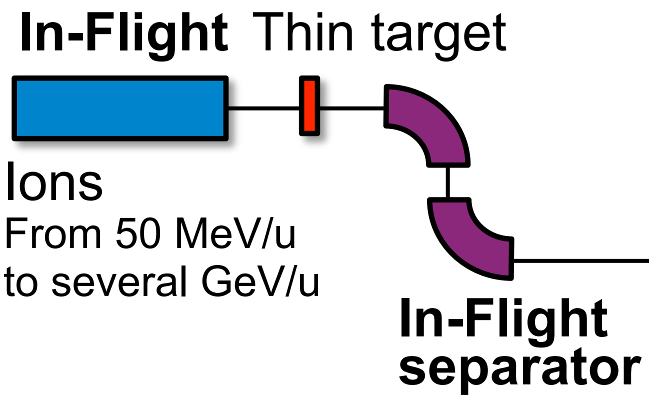
- **The N=16 “new magic number”, collapse of N=20, 28 shell closures**

- **Mirror region: the N=40 island of inversion and the ^{78}Ni region**

- **Are N=32 and 34 “new” magic numbers?**

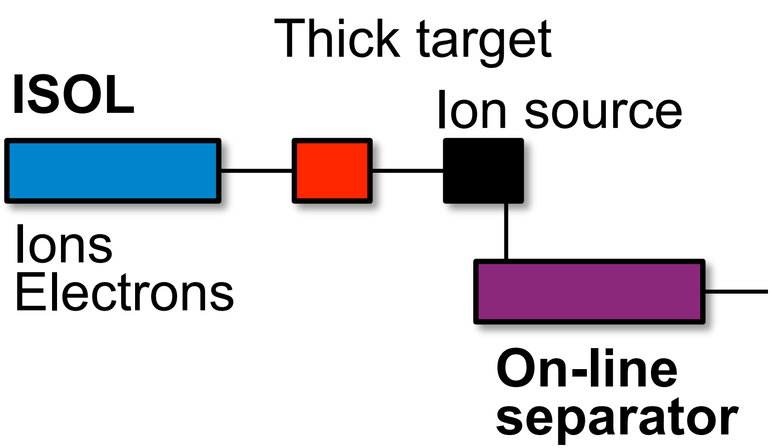
- **Heavier doubly-magic nuclei: ^{100}Sn and ^{132}Sn**

Overview of Radioactive Ion beam production



Chacteristics:

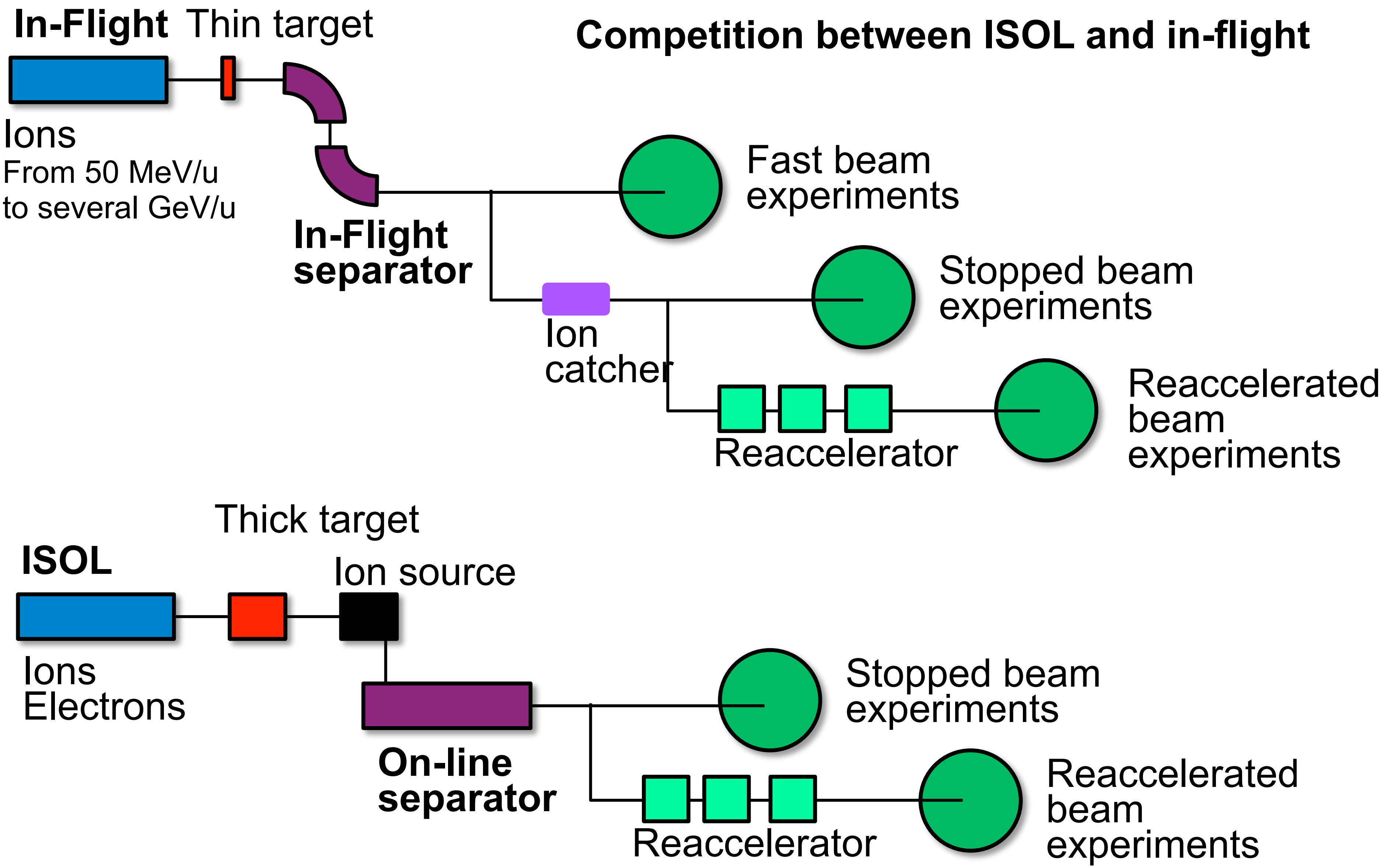
- ❑ > 50 MeV/nucleon
- ❑ no chemical selection
- ❑ fast production (short lives < ms)
- ❑ limited beam « quality »



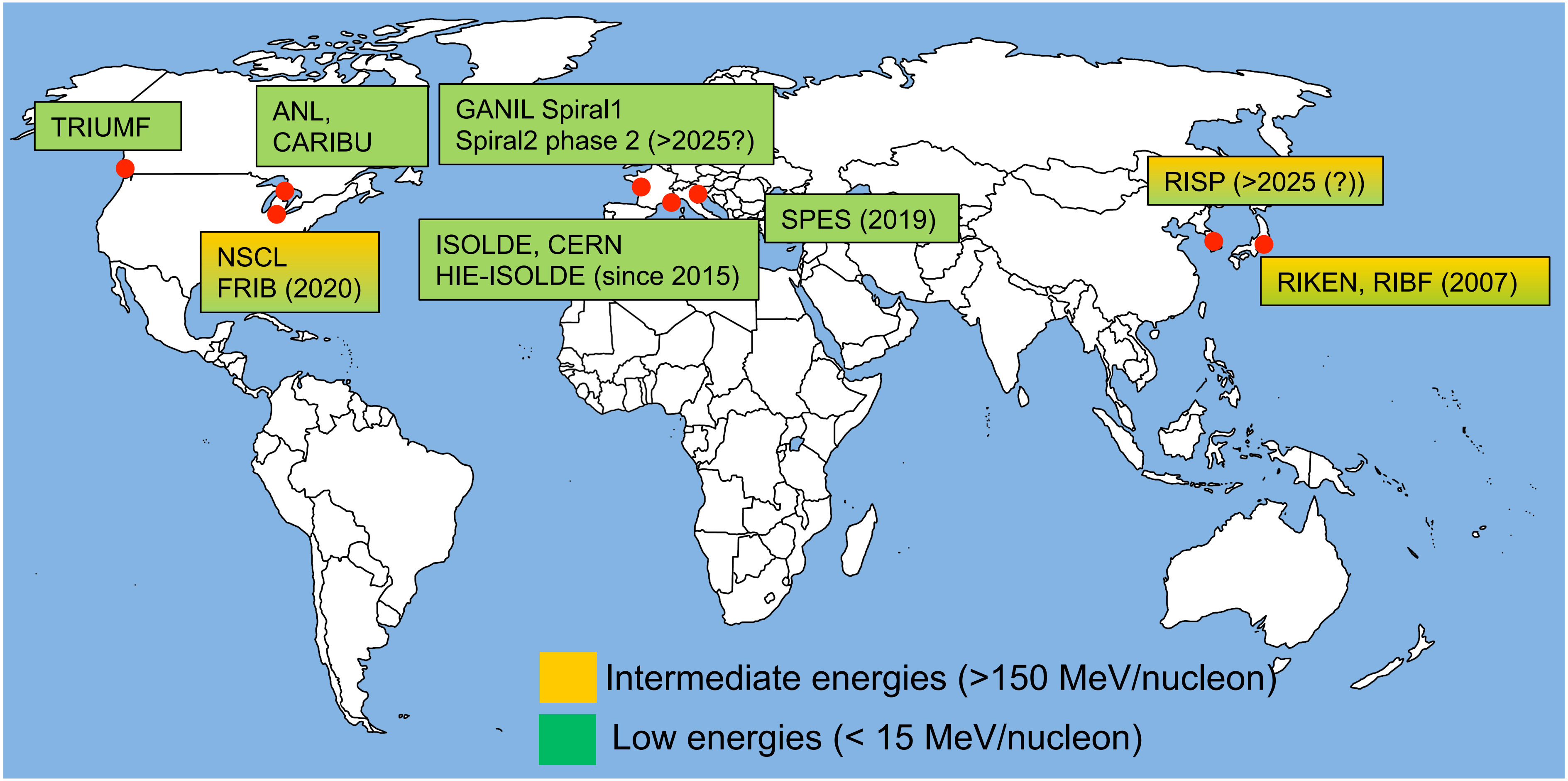
Characteristics:

- ❑ Low energy (from kV)
- ❑ Need for re-acceleration for reactions
- ❑ high-quality emittance
- ❑ Chemical selectivity
- ❑ diffusion / charge breeding time (> 1ms)

Overview of Radioactive Ion beam production



New ISOL / re-accelerated RI beam facilities worldwide



CERN / HIE-ISOLDE

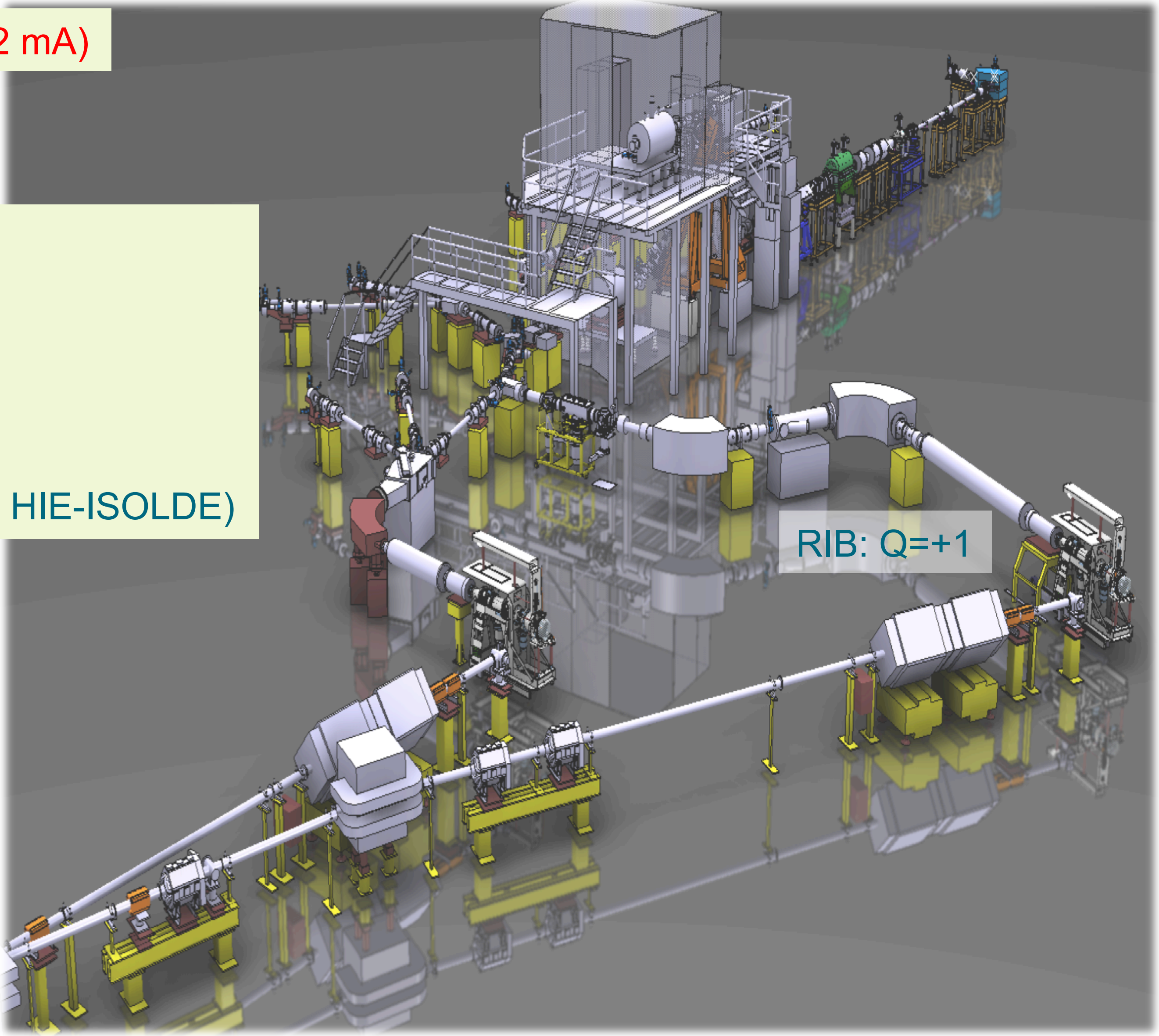
Proton beam (1.4 GeV, ~2 mA)

Target UC_x (~ 50 g/cm^2)

Ionization Laser
Selectivity in Z

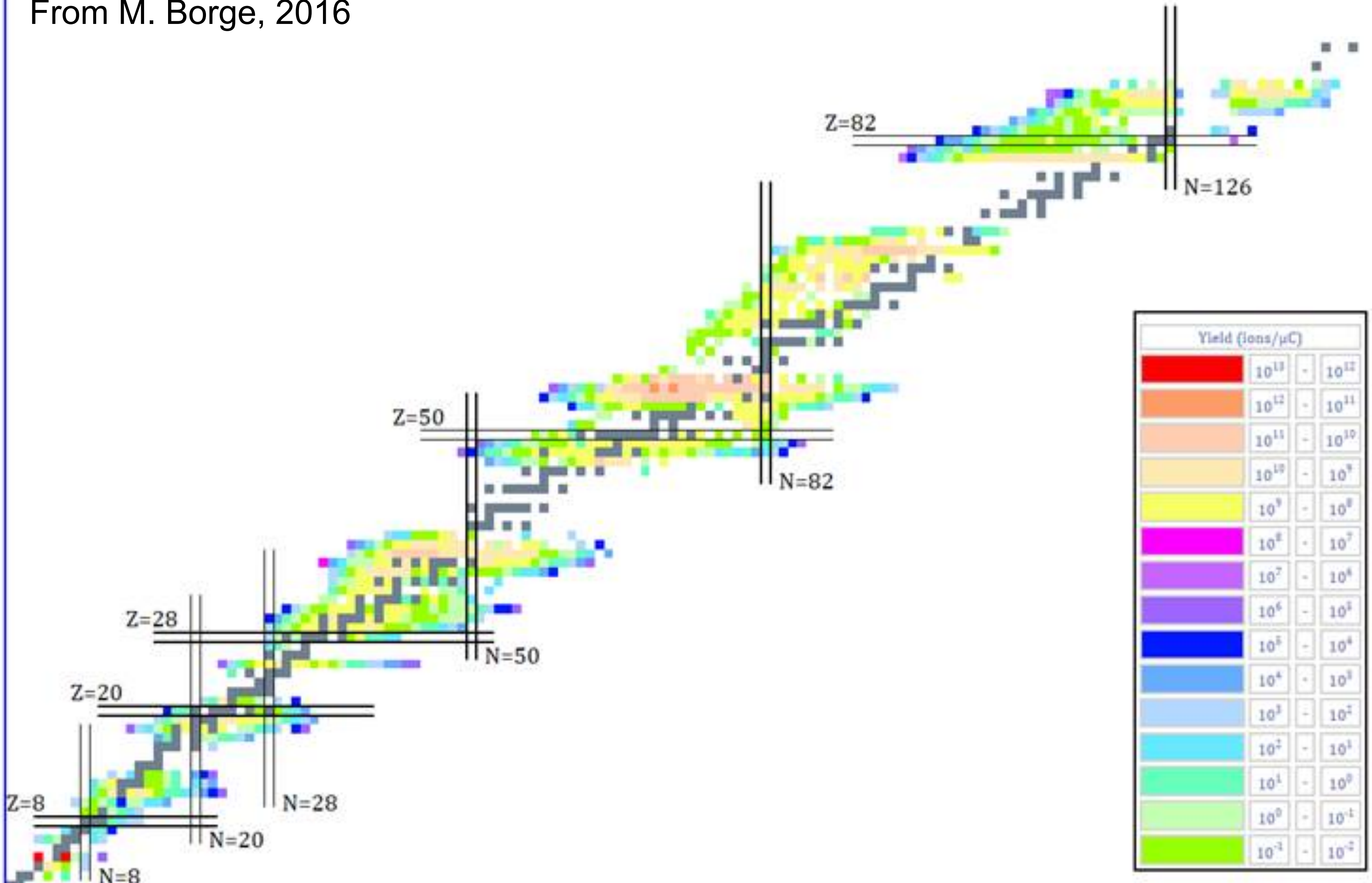
Magnetic spectrometer
Selectivity in A/Q

Post-acceleration (REX & HIE-ISOLDE)



CERN / ISOLDE

From M. Borge, 2016

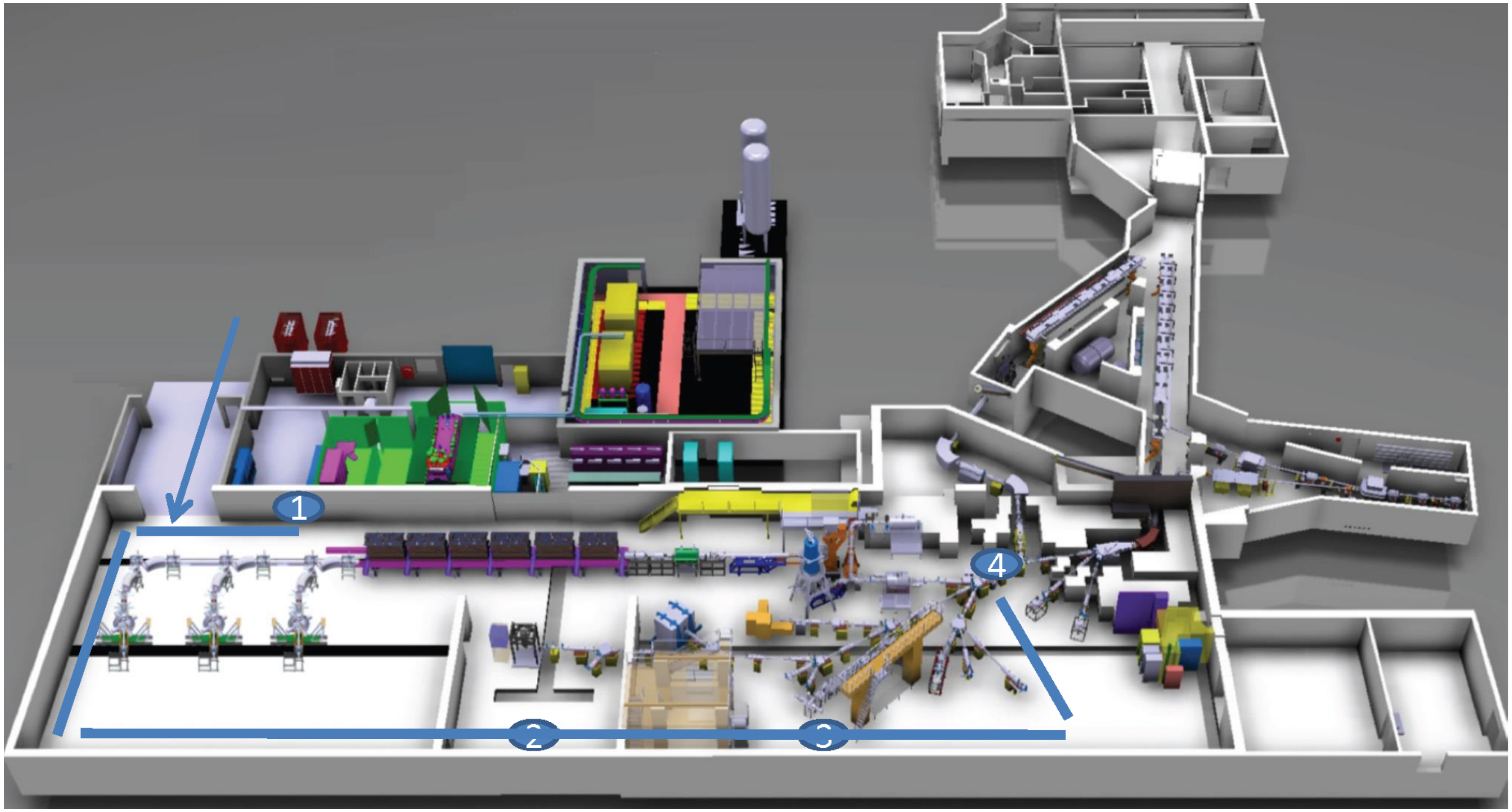


CERN / HIE - ISOLDE

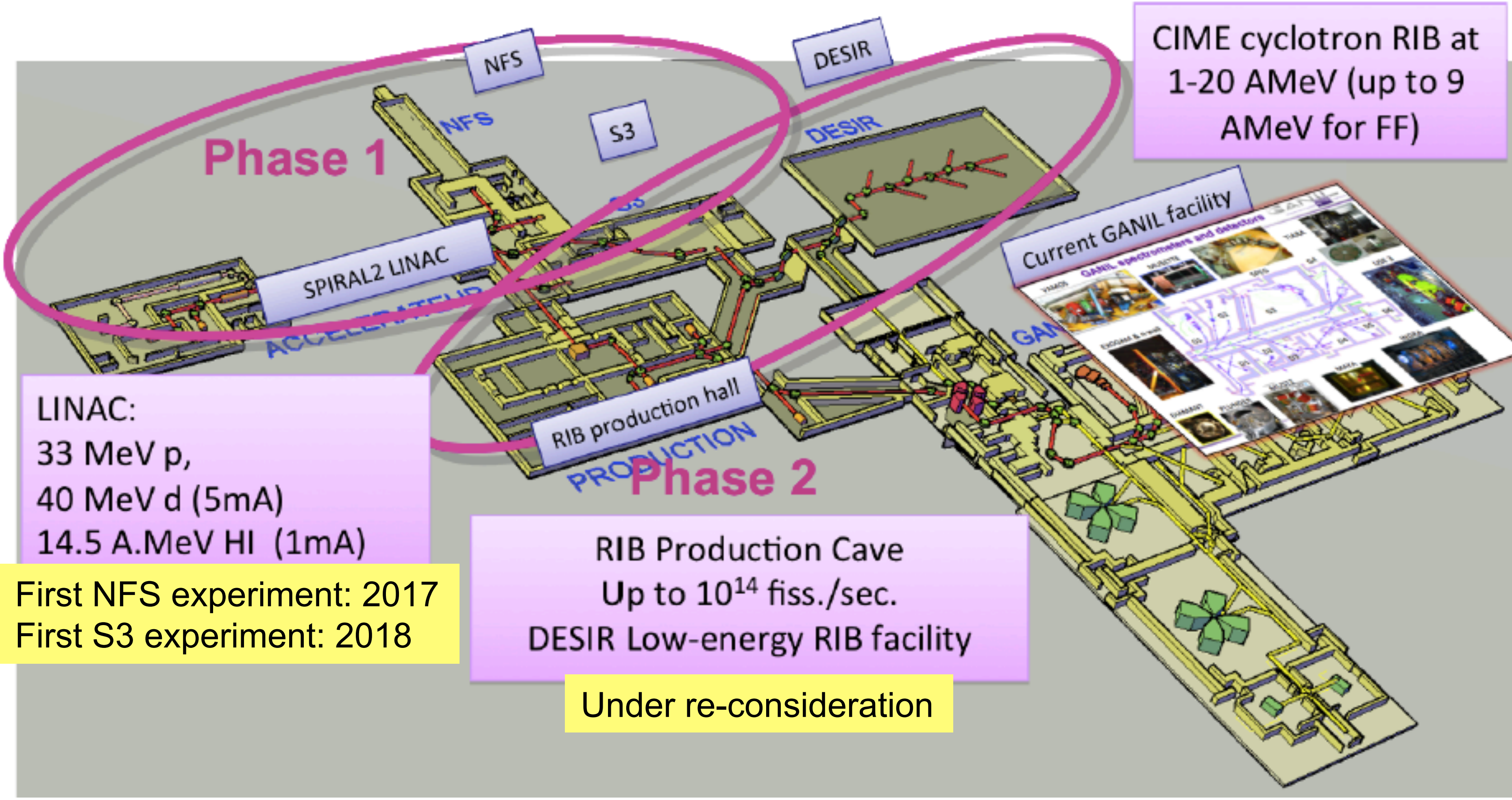
- LINAC cavities: 6MV/m

- September 10th, 2016: Miniball started taking data with $^{110}Sn^{26+}$ at 4.5 MeV/u with 2 CMs for the first time. (stage 1) Up to 5.5 MeV/u for A/Q=4.5 in Spring 2017.

- 2017: extension to 10 MeV/nucleon (stage 2)



GANIL-SPIRAL2



CIME cyclotron RIB at 1-20 AMeV (up to 9 AMeV for FF)

LINAC:
33 MeV p,
40 MeV d (5mA)
14.5 A.MeV HI (1mA)

First NFS experiment: 2017
First S3 experiment: 2018

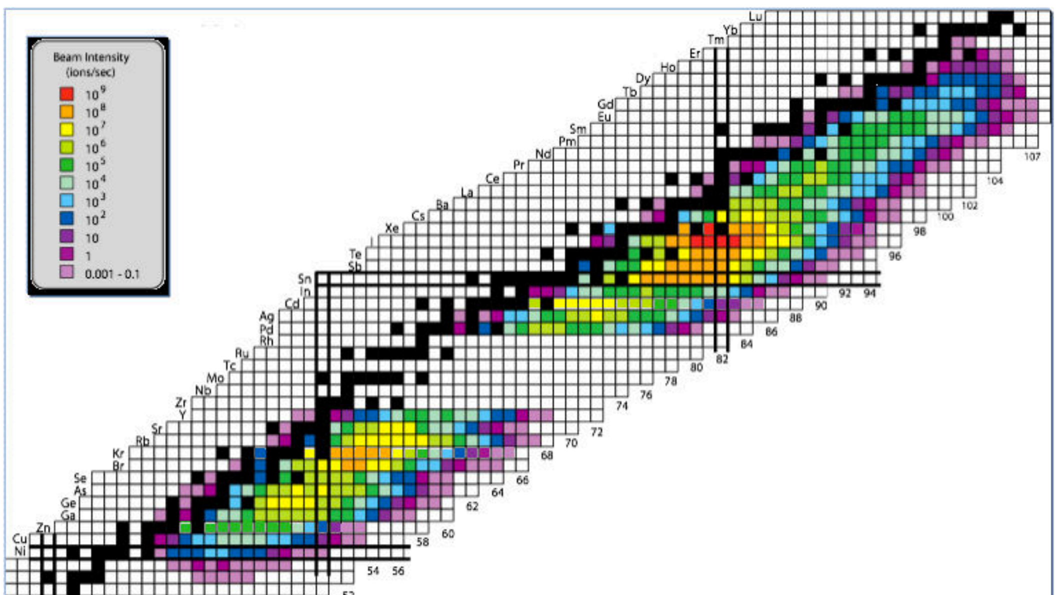
RIB Production Cave
Up to 10^{14} fiss./sec.
DESIR Low-energy RIB facility

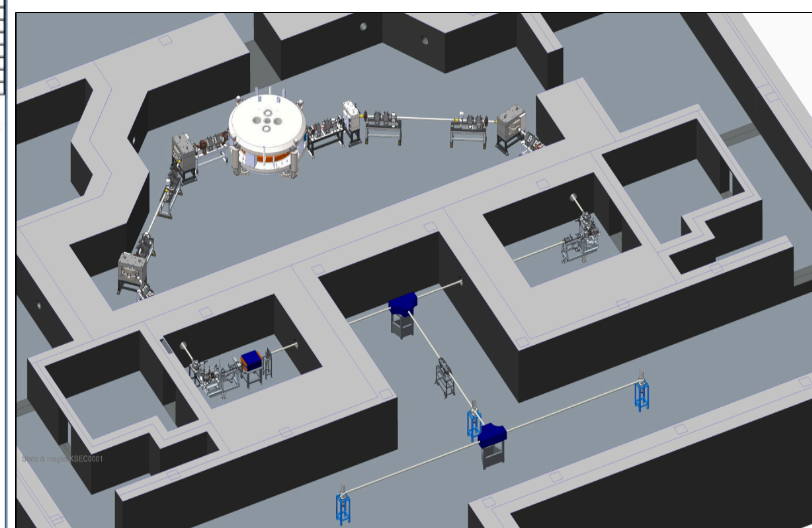
Under re-consideration

SPES

- ❑ RIB production via p-induced fission on UCx target, 10^{13} fissions/s
- ❑ Proton driver: 35-70 MeV cyclotron, 750 μA
- ❑ RIB delivered to the existing experimental areas
- ❑ Status: cyclotron installed, ISOL facility under test

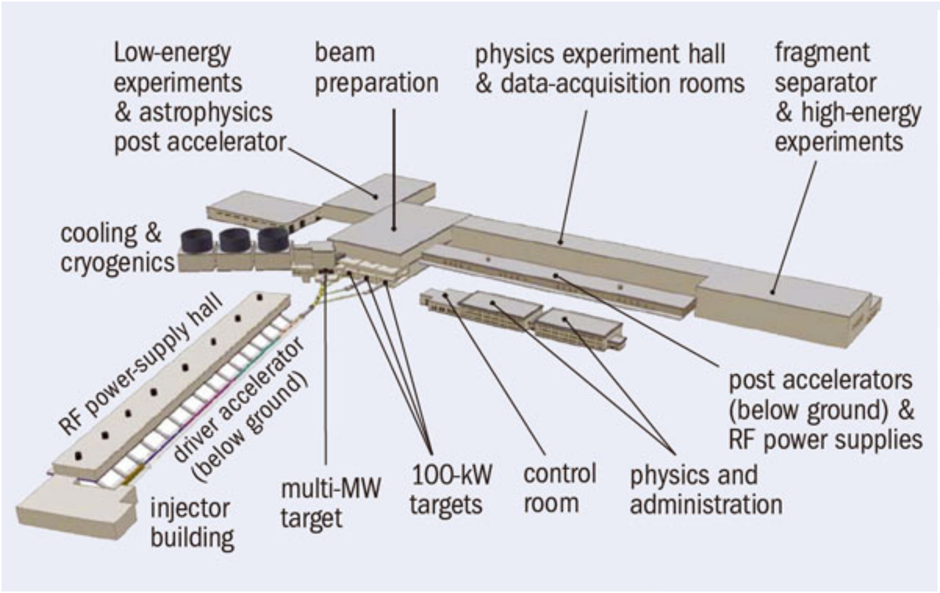
EXPECTED RIB PRODUCTION RATE



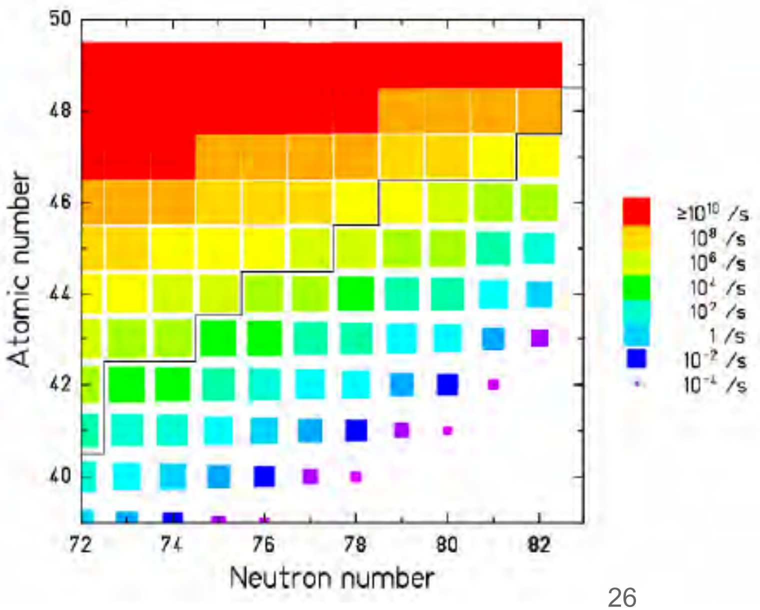


EURISOL

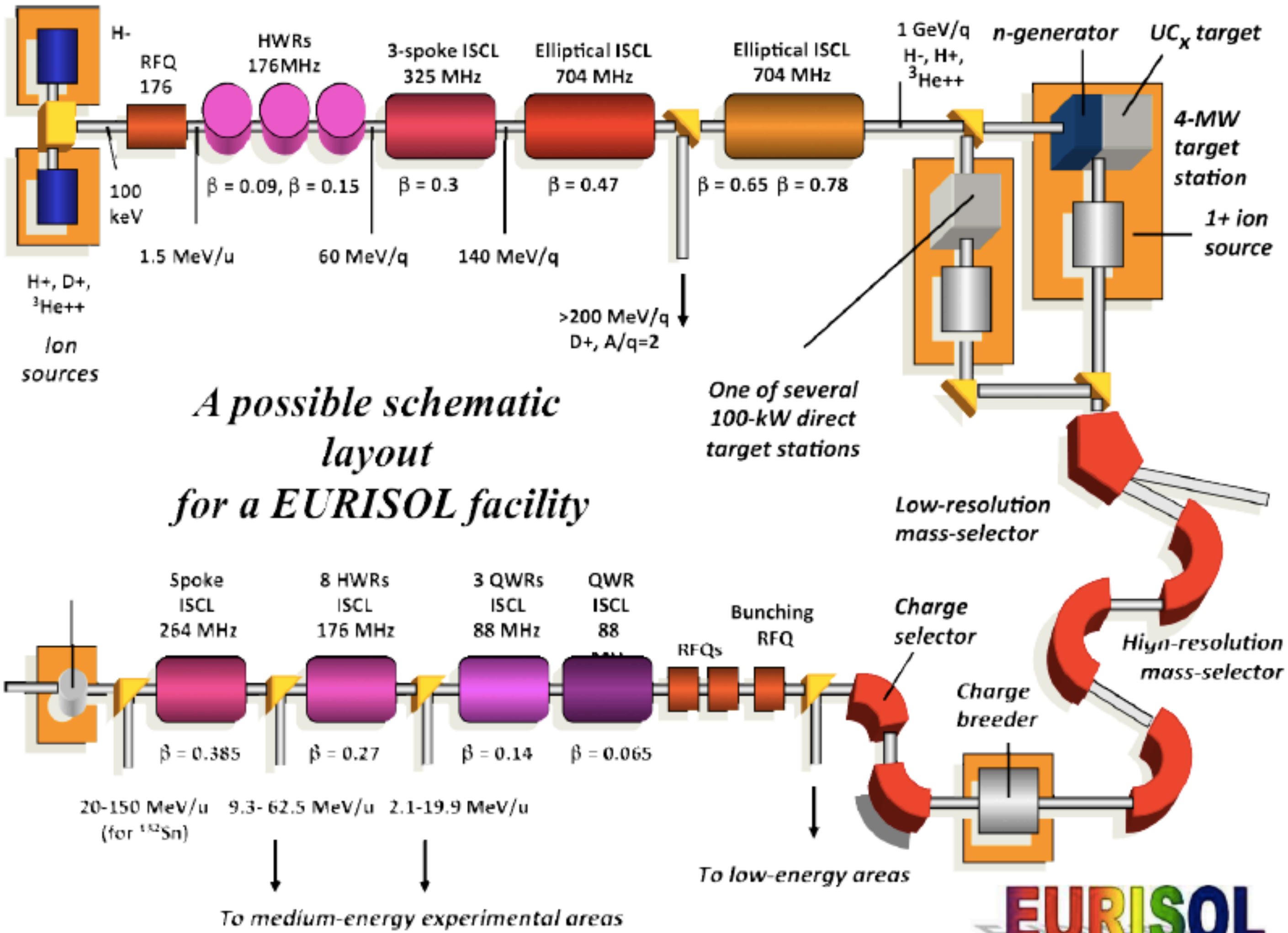
- Next generation **European ISOL facility** (at the concept stage)
- Superconducting linear accelerator, protons at 1 GeV and 5 MW (and ions up to A=40)
- RIB production mechanism: proton induced AND conversion+neutron induced fission
- Low energy lines AND **reacceleration up to 150 MeV/u**, fragmentation of ISOL beams
- EURISOL DF charged of preparing physics cases and coordinate existing European ISOL facilities



YIELD AFTER ^{132}Sn FRAGMENTATION

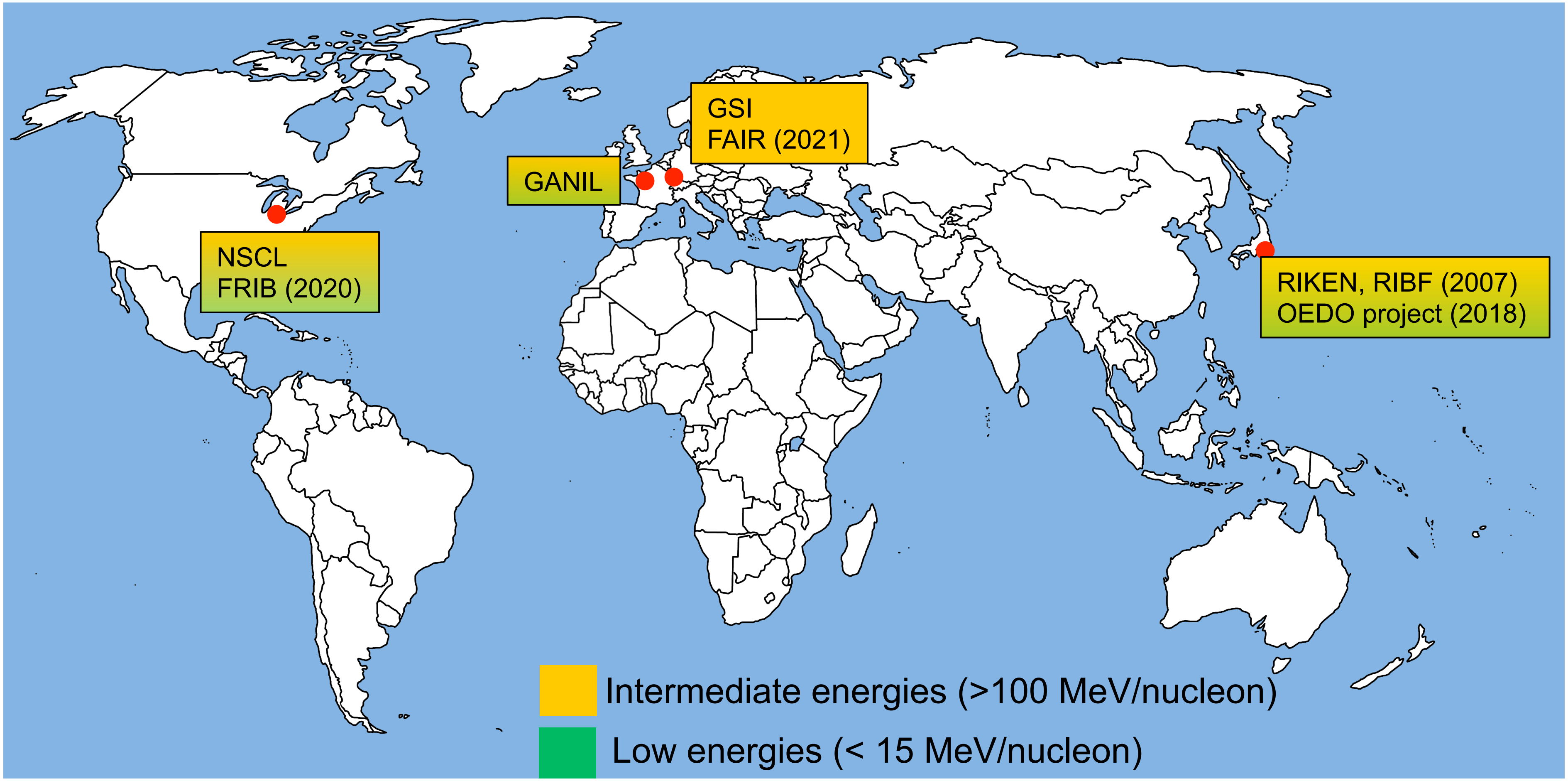


EURISOL

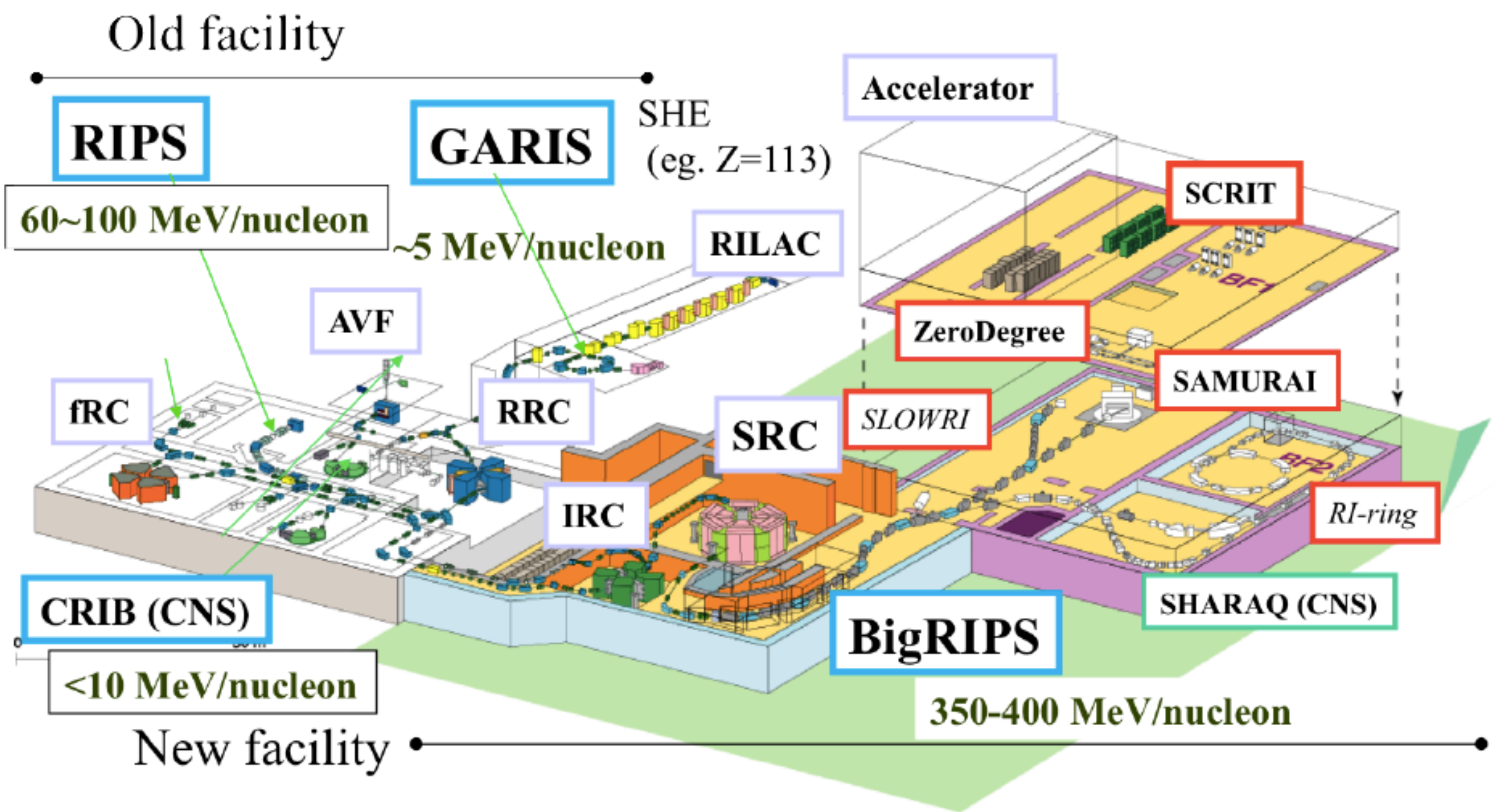


H-
RFQ 176
HWRs 176MHz
3-spoke ISCL 325 MHz
Elliptical ISCL 704 MHz
Elliptical ISCL 704 MHz
1 GeV/q H-, H+, ^{3}He++
n-generator
UC_x target
4-MW target station
1+ ion source
100 keV
β = 0.09, β = 0.15
β = 0.3
β = 0.47
β = 0.65 β = 0.78
1.5 MeV/u
60 MeV/q
140 MeV/q
H+, D+, ^{3}He++
Ion sources
>200 MeV/q D+, A/q=2
One of several 100-kW direct target stations
A possible schematic layout for a EURISOL facility
Low-resolution mass-selector
Spoke ISCL 264 MHz
8 HWRs ISCL 176 MHz
3 QWRs ISCL 88 MHz
QWR ISCL 88
RFQs
Bunching RFQ
Charge selector
High-resolution mass-selector
Charge breeder
β = 0.385
β = 0.27
β = 0.14
β = 0.065
20-150 MeV/u (for ^{132}Sn)
9.3- 62.5 MeV/u
2.1-19.9 MeV/u
To low-energy areas
To medium-energy experimental areas
EURISOL

Leading fragmentation RIB facilities in the world

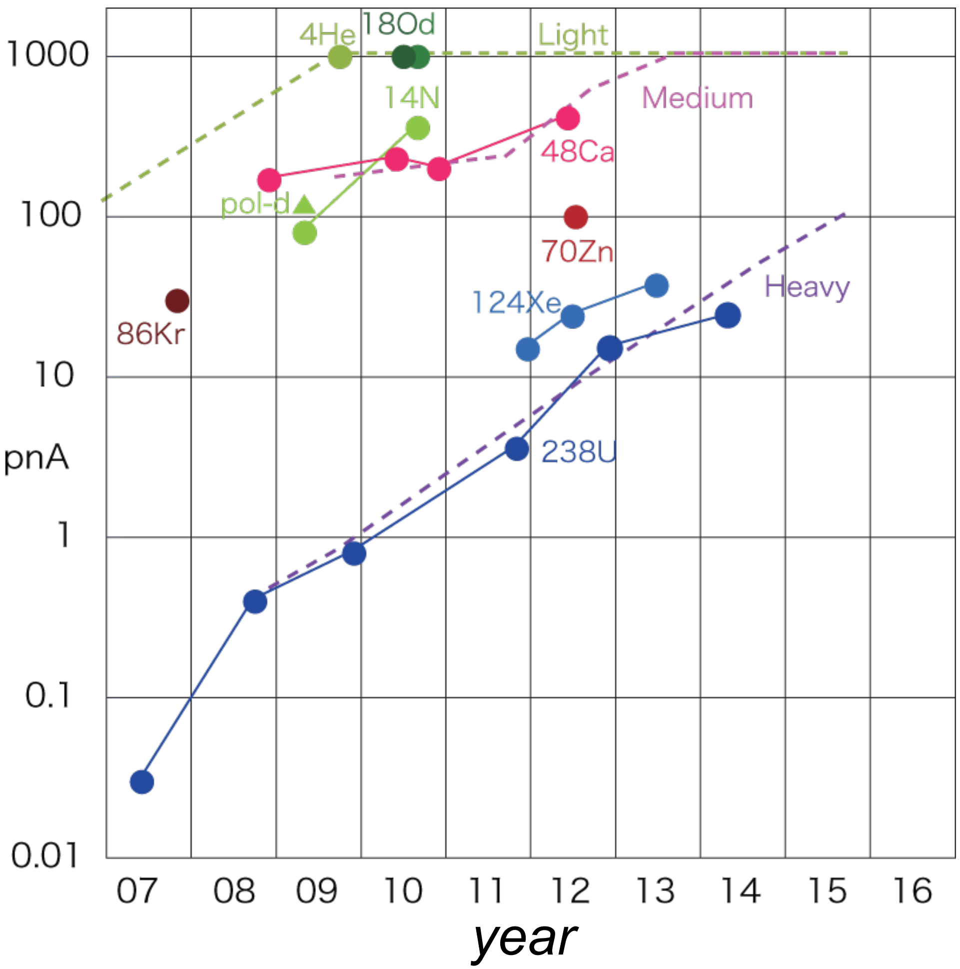


Radioactive Isotope Beam Factory (RIBF)

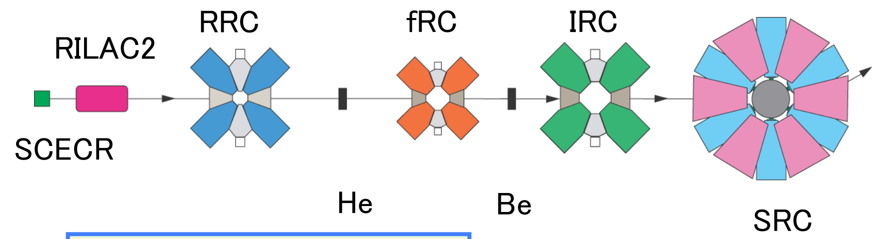


Radioactive Isotope Beam Factory (RIBF)

RIBF started operation in **2007**
Worldwide unique intensities
Continuous progression



345 MeV/u



Typical configuration

Maximum primary beam intensities

- ^{48}Ca beam : 415 pnA in 2012
- ^{70}Zn beam : 125 pnA in 2012
- ^{78}Kr beam : 275 pnA in 2015
- ^{124}Xe beam: 40 pnA in 2013
- ^{238}U beam: 40 pnA in 2015

- *2016-17 upgrade to achieve 100pnA U-beam*

Ex. ^{11}Li at 10^5 pps, ^{24}O at 3000 pps
^{104}Sn at >1000 pps

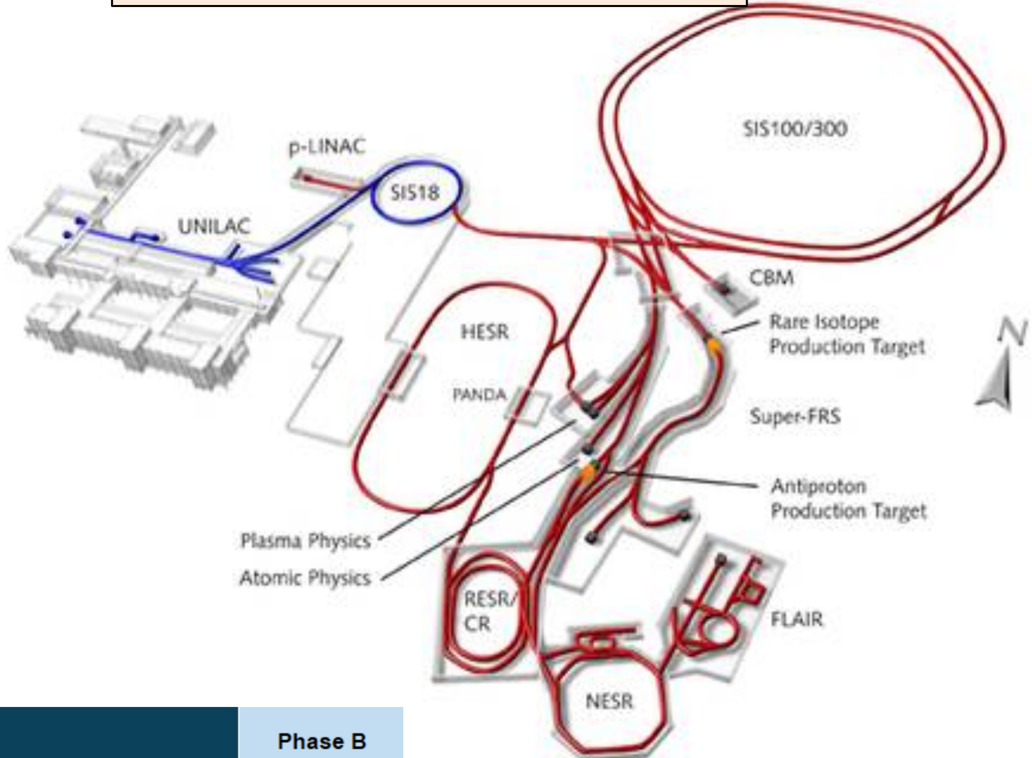
- Upgrade for **1 pmA of ^{238}U in ≈2020**

FAIR

- Super- conducting double-synchrotron SIS100/300 with magnetic rigidities of 100 and 300 Tm
- Unprecedented variety of accelerated particles from antiprotons to Uranium
- Injection from UNILAC and SIS18
- Operation expected from >2023
- Different physics communities:

APPA: Atomic Physics, Plasma Physics, Appl.
CBM: Compressed Baryonic Matter
NuSTAR: Nuclear Structure & Astrophysics
PANDA: Hadron Structure & Dynamics

Gain in intensity of 1000-10000 compared to GSI



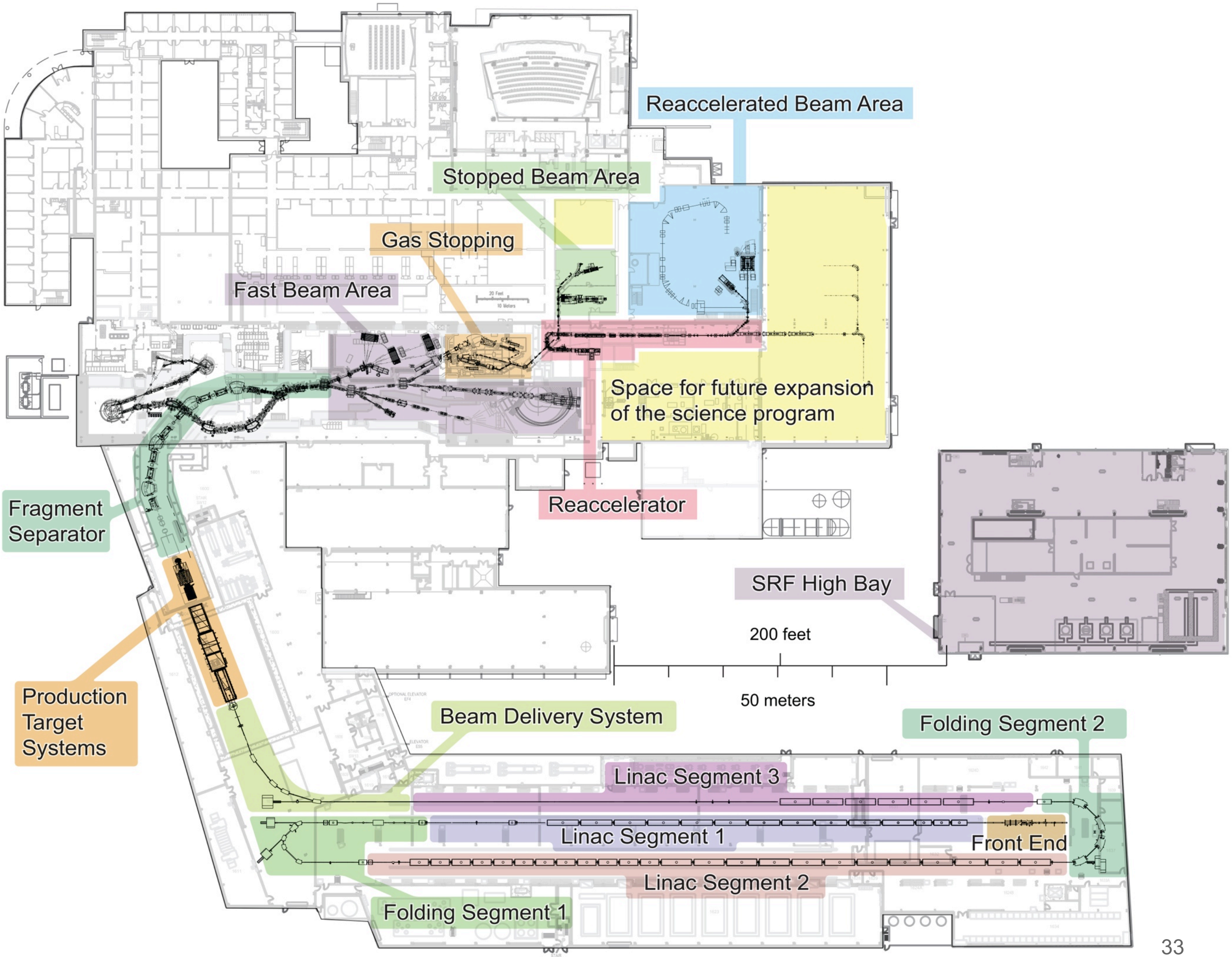
Start Version Phase A (SIS100)						Phase B (SIS300)
Modularised Start Version						
Module 0	Module 1	Module 2	Module 3	Module 4	Module 5	
SIS100	Exp. halls *CBM & APPA*	Super-FRS *NuSTAR*	Antiproton Facility *PANDA & options NuSTAR*	LEB, NESR, FLAIR *NuSTAR & APPA*	RESR *PANDA, NuSTAR & APPA*	

financed

FRIB

- next generation RIB facility in the US, first beams expected in 2021
- 200 MeV/u linac primary beams (future extension to 400 MeV/u possible)
- Primary beam intensities of 400 kW (^{238}U@200 MeV/u = 8 pmA)
- Intermediate and low energy:
  - in-flight fission and fragmentation: secondary beams at about 150 MeV/u
  - stopped and reaccelerated beam (up to 12 MeV/u)

FRIB



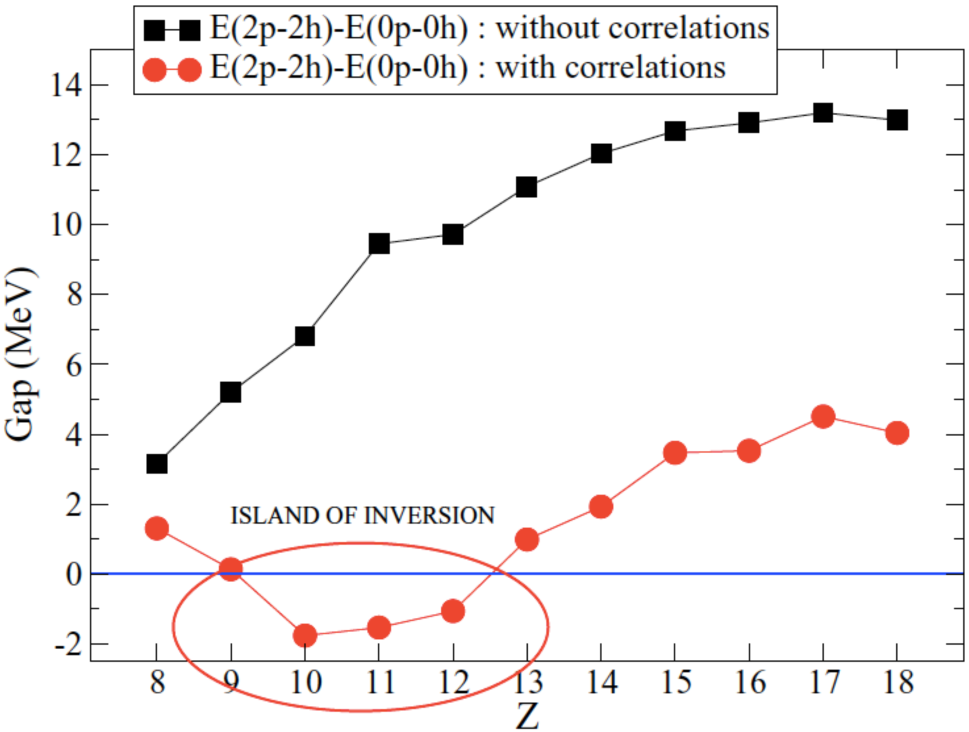
Reaccelerated Beam Area
Stopped Beam Area
Gas Stopping
Fast Beam Area
Space for future expansion of the science program
Reaccelerator
Fragment Separator
SRF High Bay
200 feet
50 meters
Production Target Systems
Beam Delivery System
Folding Segment 2
Linac Segment 3
Linac Segment 1
Front End
Linac Segment 2
Folding Segment 1

- The shell model and shell closures
- Origins of shell evolution
  - diffusiveness of the nuclear surface
  - spin-isospin and tensor terms of the NN interaction
  - reduction of spin-orbit
  - 3N forces
- RI beam production and future facilities
- **The N=16 "new magic number", collapse of N=20, 28 shell closures**
- **Mirror region: the N=40 island of inversion and the ^{78}Ni region**
- Are N=32 and 34 "new" magic numbers?
- Heavier doubly-magic nuclei: ^{100}Sn and ^{132}Sn

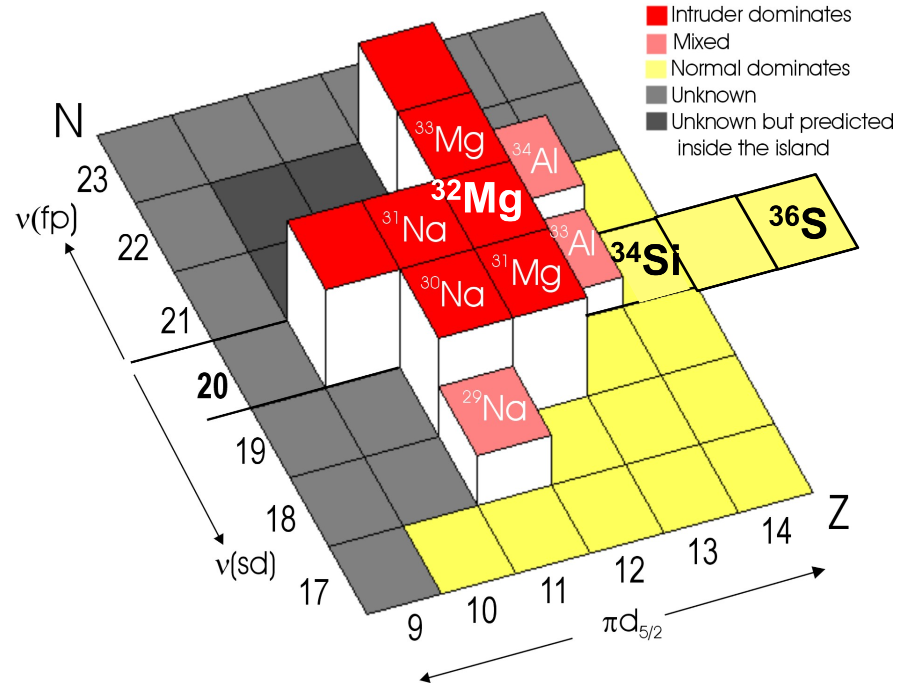
The N=20 island of inversion (IoI)

- **Island of Inversion**: Due to quadrupole deformation, the « intruder » configuration (np-nh) is energetically favored relative to the « normal » configuration.

- Mechanism proposed by
  - X. Campi et al., Nucl. Phys. A 251, 193 (1975)
  - A. Poves, J. Retamosa, Phys. Lett. B 184, 311 (1987)
  - W. Warburton, J.A. Becker, B.A. Brown, Phys. Rev. C 41, 1147 (1990).



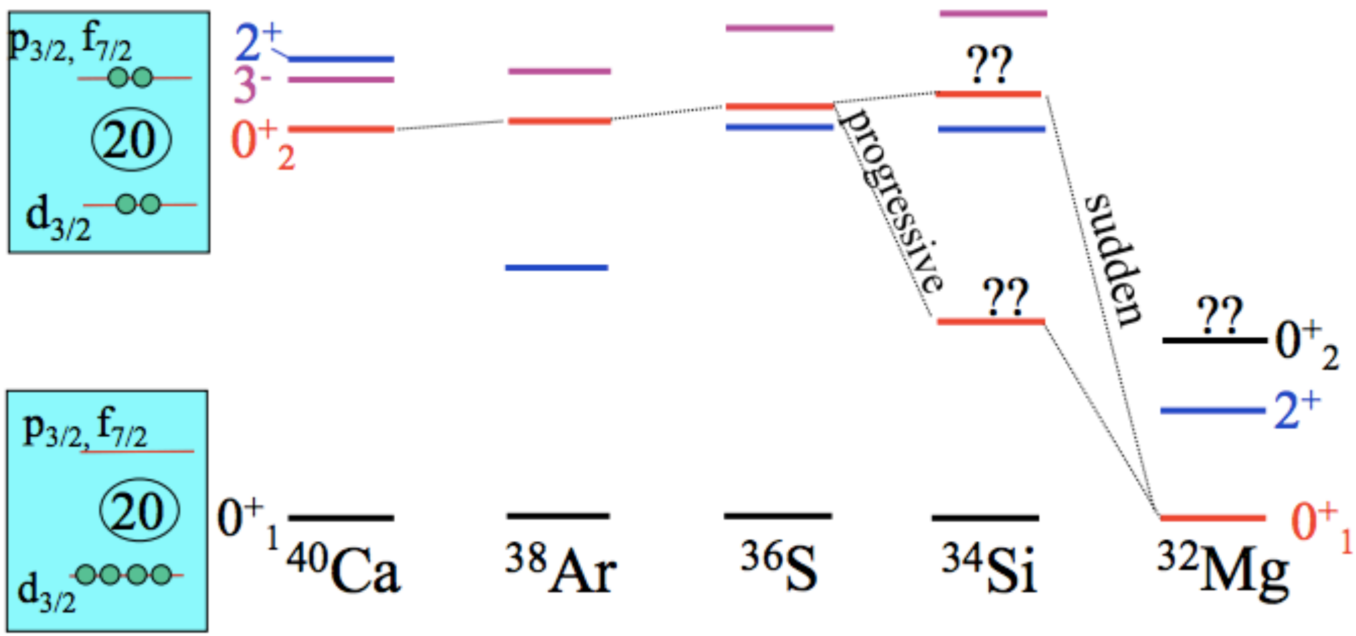
F. Nowacki, A. Poves, Phys. Rev. C **90**, 014302 (2014)



Search for 0p-0h 0⁺ states at N=20

- Competition of « normal » and « intruder » configurations at low excitation energy
- How does the inversion occurs: sharp or progressive?
- Need to know the relative energy of the 0p-0h and 2p-2h configurations

- Before 2010: the second 0^+ state in ^{34}Si and ^{32}Mg were not know.

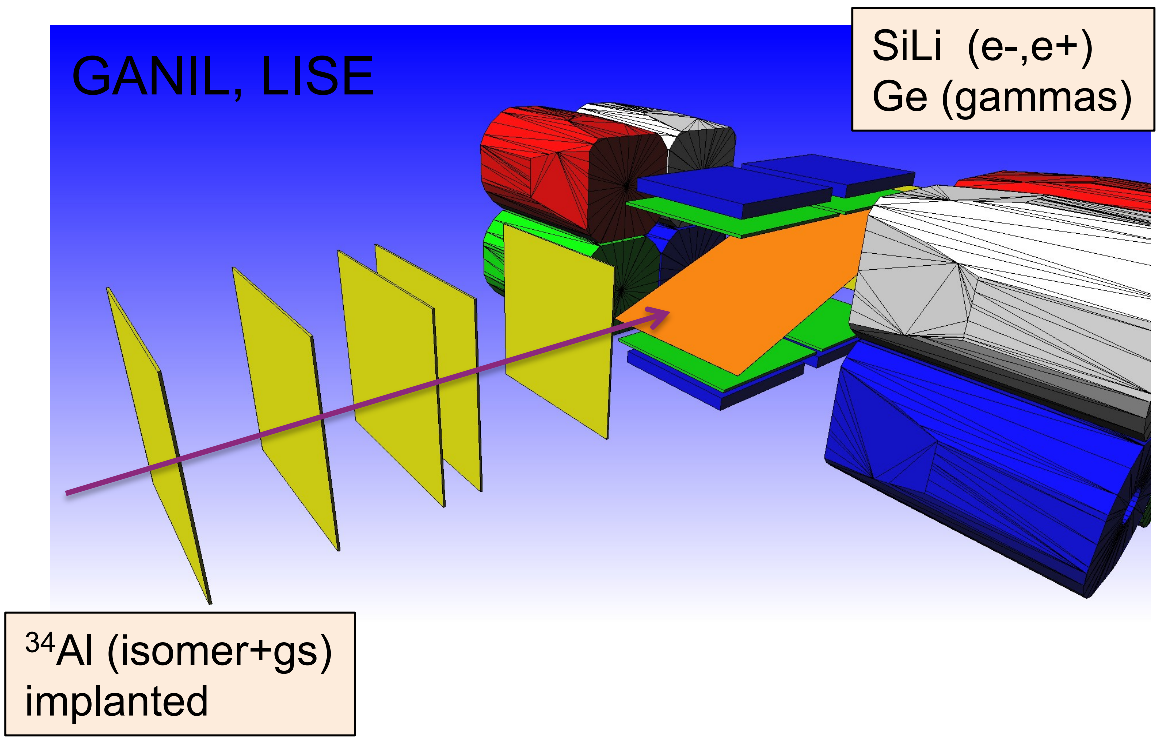


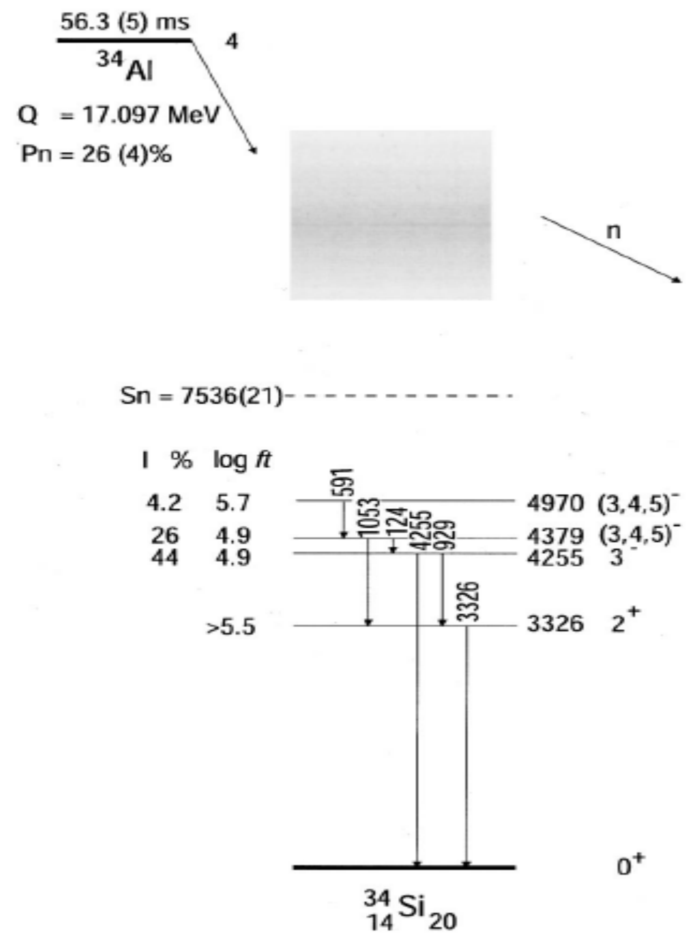
Stable **Island of inversion**

Discovery of the 0^+_2 state in ^{34}Si at GANIL

- All previous experiments (inelastic scattering, beta decay) failed in finding this 0^+_2 state
- 0^+_2 expected to be located below the 2_1^+ state and therefore forbidden to decay via gamma
- Should then decay via electron conversion (E<1022 keV) or e^+e^- pair creation

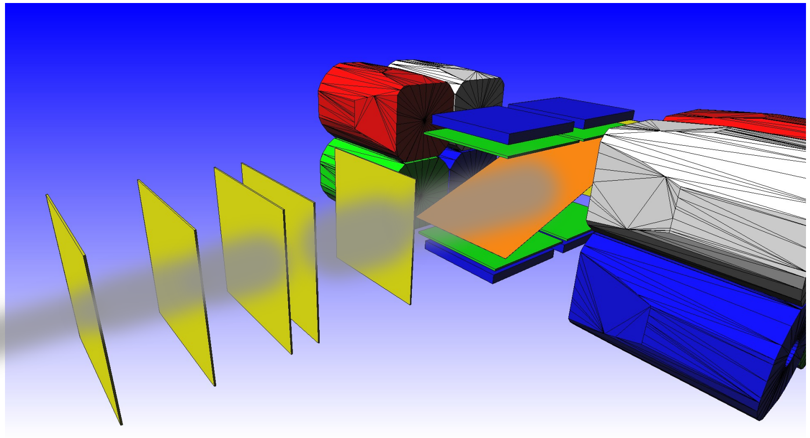
- 1^+ isomeric state was predicted in ^{34}Al
- 1^+ isomer expected to decay to 0^+_2 in ^{34}Si



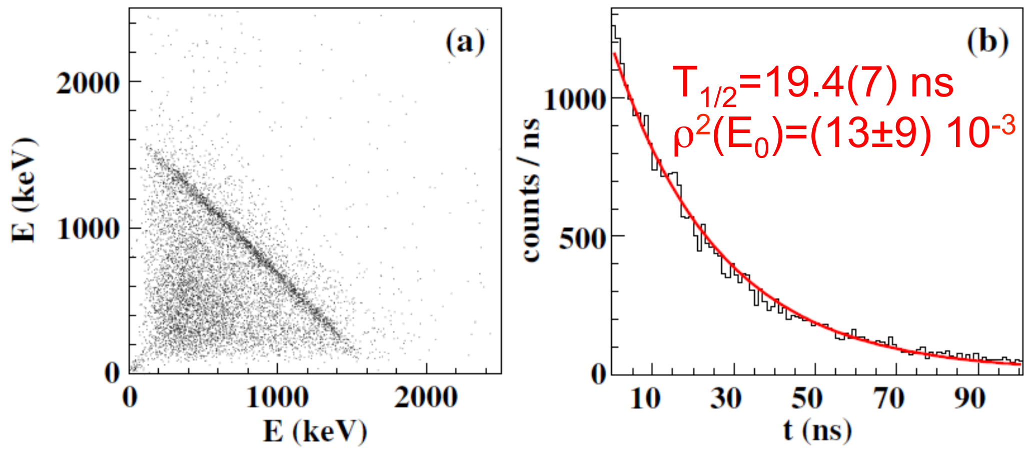


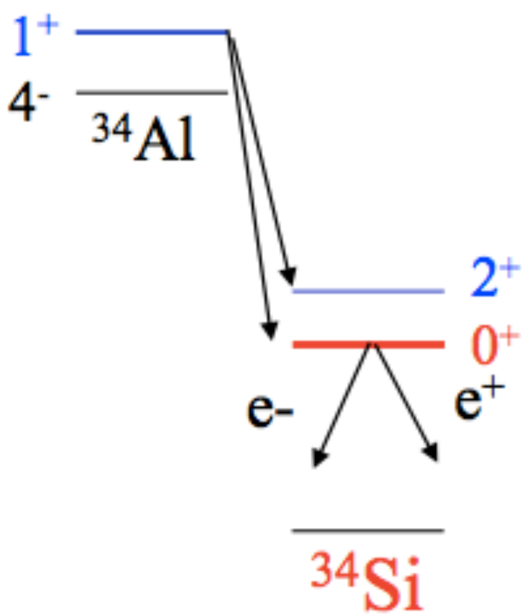
Courtesy S. Grévy, CENBG

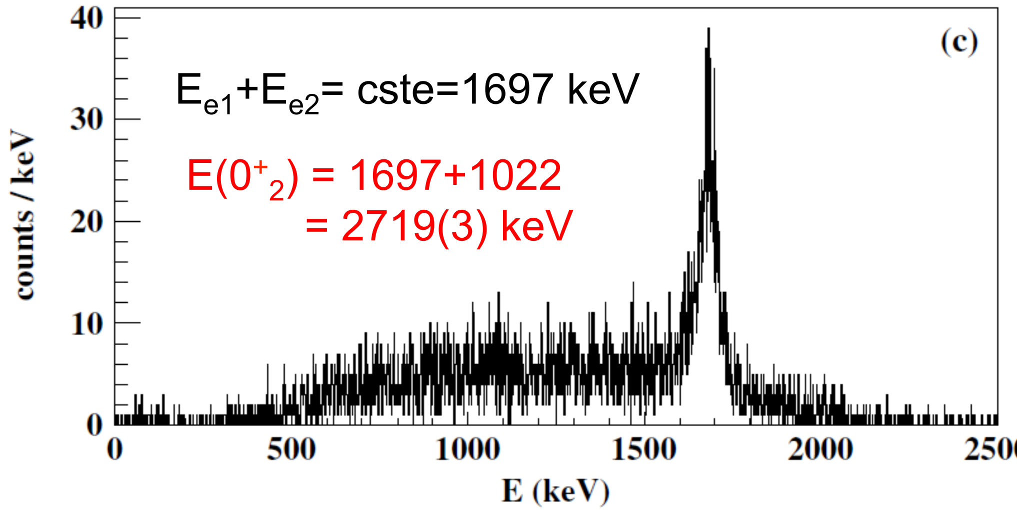
Discovery of the 0^+_2 state in ^{34}Si at GANIL



F. Rotaru *et al.*, Phys. Rev. Lett. **109**, 092503 (2012)



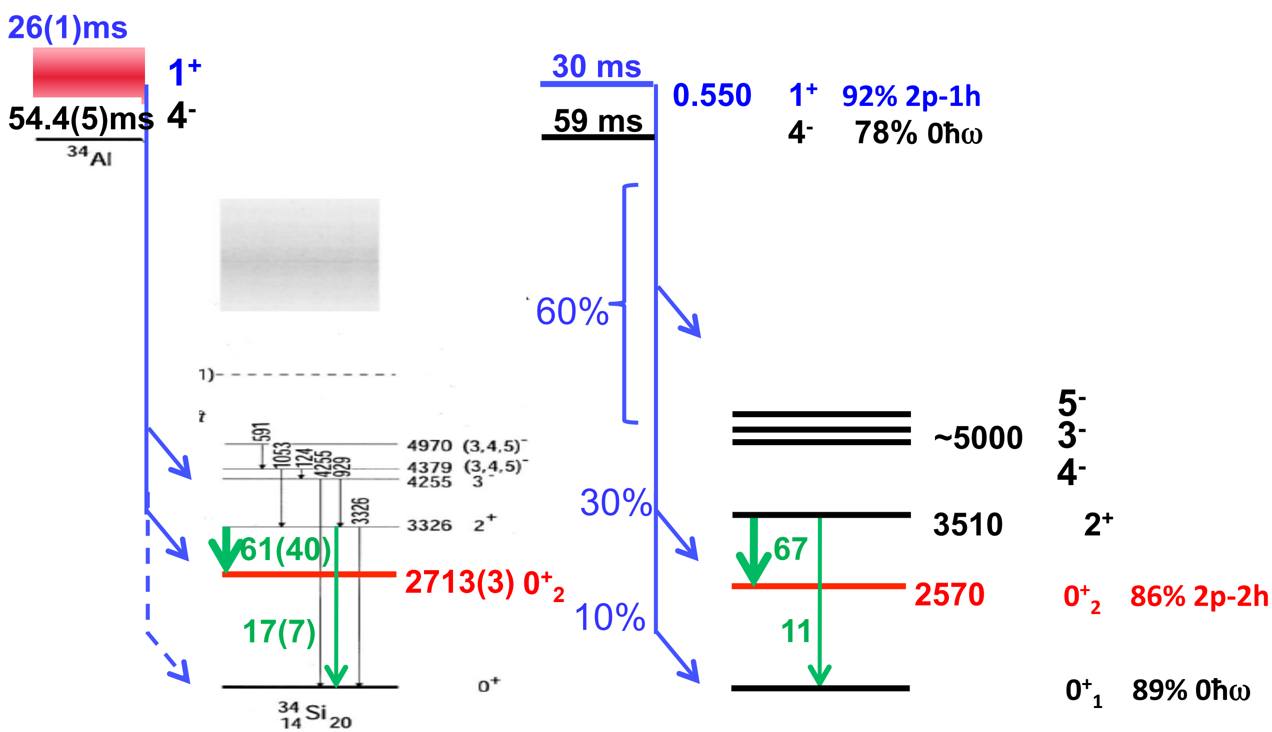




Courtesy S. Grévy, CENBG

Discovery of the 0^+_2 state in ^{34}Si at GANIL

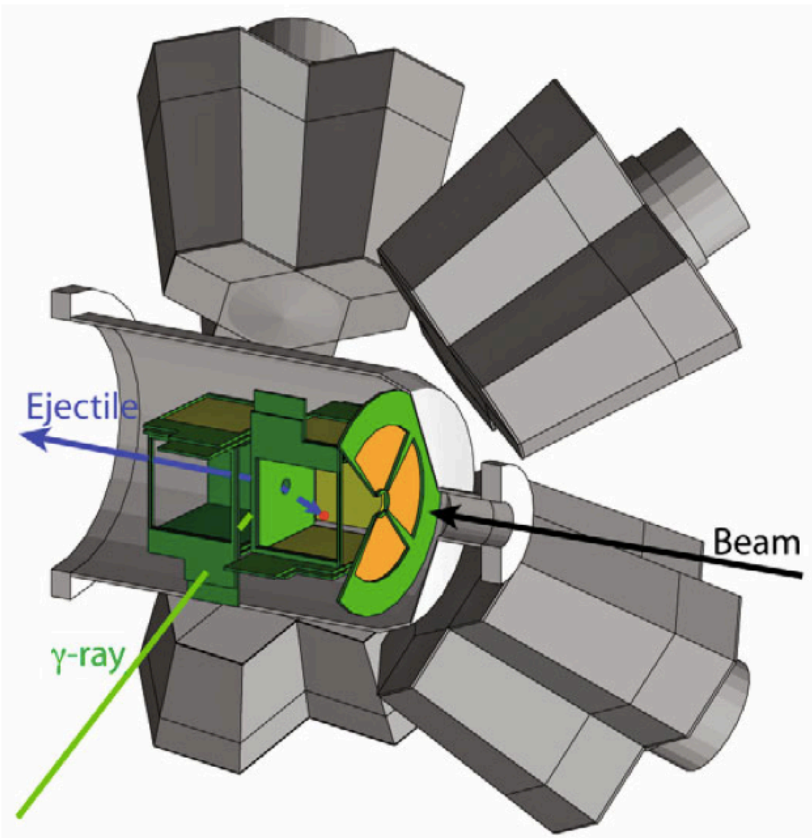
- Shell model (SDP-U-mix interaction) and experiment in very good agreement
- Second 0^+ state in ^{34}Si is calculated to be 86% 2p-2h
- 2713 keV is still a rather high value of excitation energy (sign for a sharp transition to IoI)

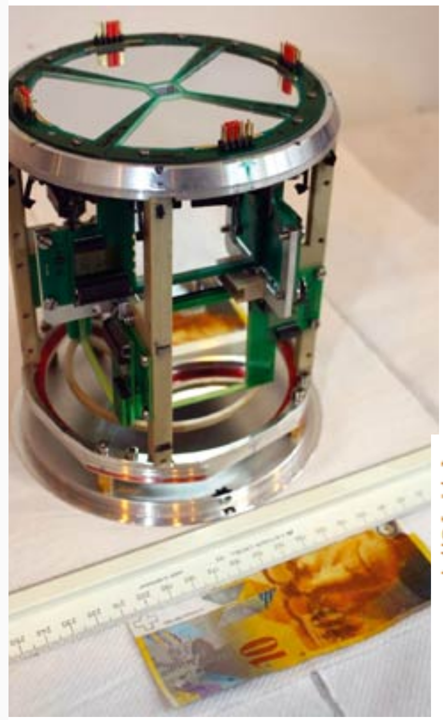


Courtesy S. Grévy, CENBG

Second 0^+ of ^{32}Mg from two-neutron transfer

- **T-REX+MINIBALL** setup at **ISOLDE, CERN**: particle-γ detection for direct reactions





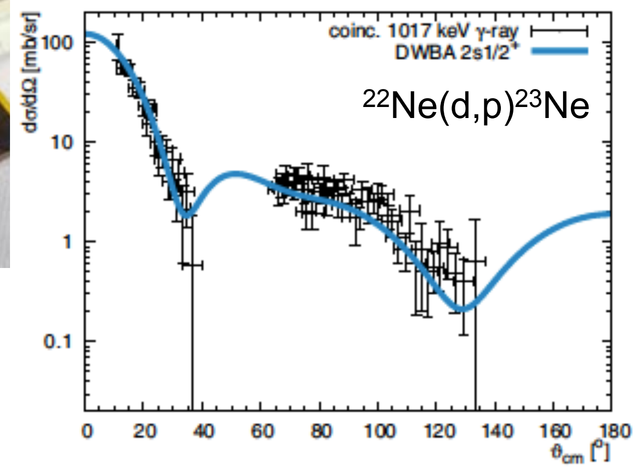
- **Particle resolution**
  - 150 keV FWHM

  For a 100 μg.cm^{-2} target
  - 600 keV FWHM

  For a 1 mg.cm^{-2} target

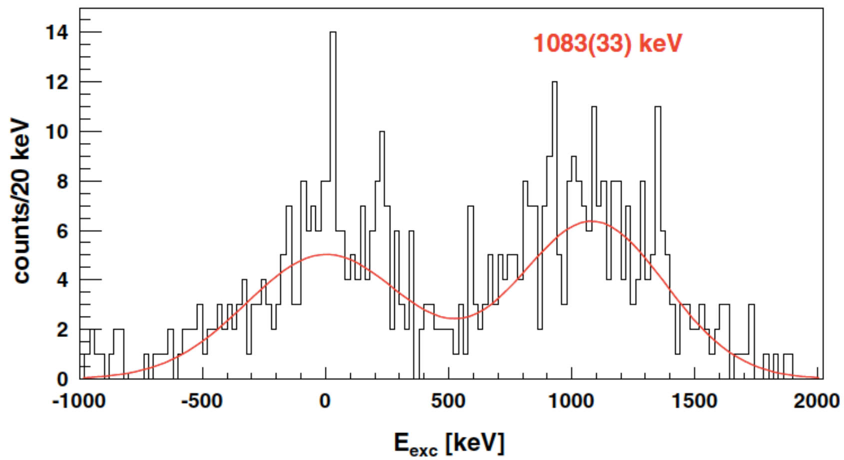
- **Photopeak γ efficiency**

  5% at 1.3 MeV

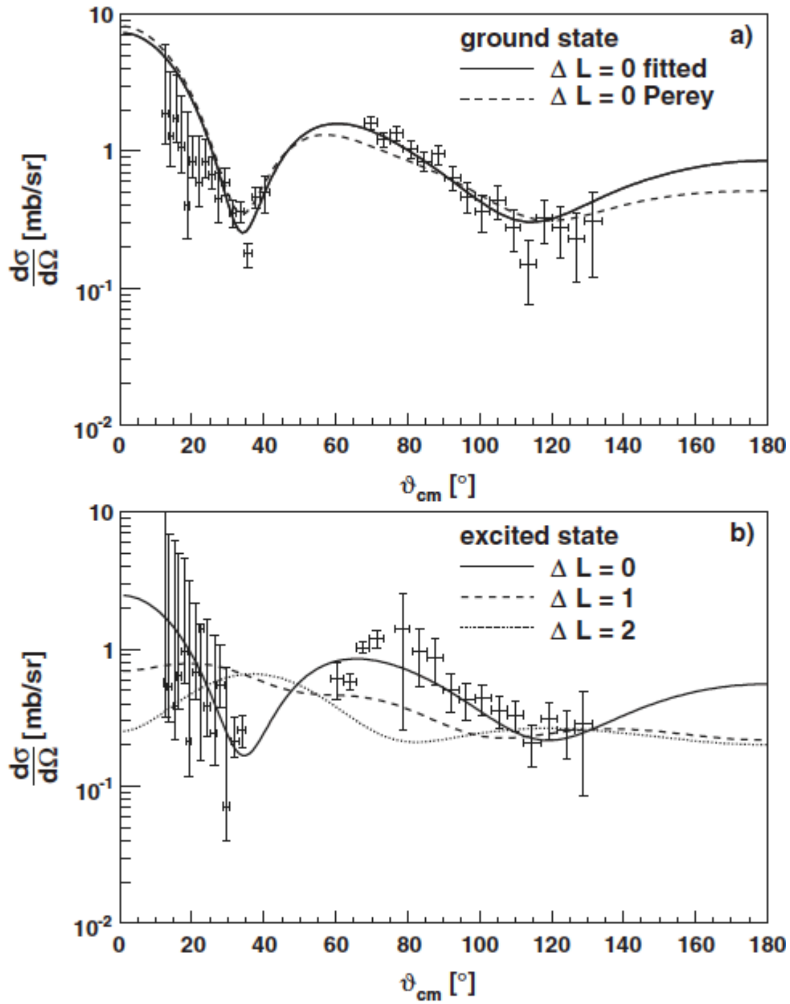


Remark: Other « similar » setups worldwide.
SHARC+Tigress at TRIUMF,TIARA+MUST2+EXOGAM at GANIL
… other ongoing developments (TRACE - GASPARD for SPES/GANIL in Europe)

Second 0^+ of ^{32}Mg from two-neutron transfer



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

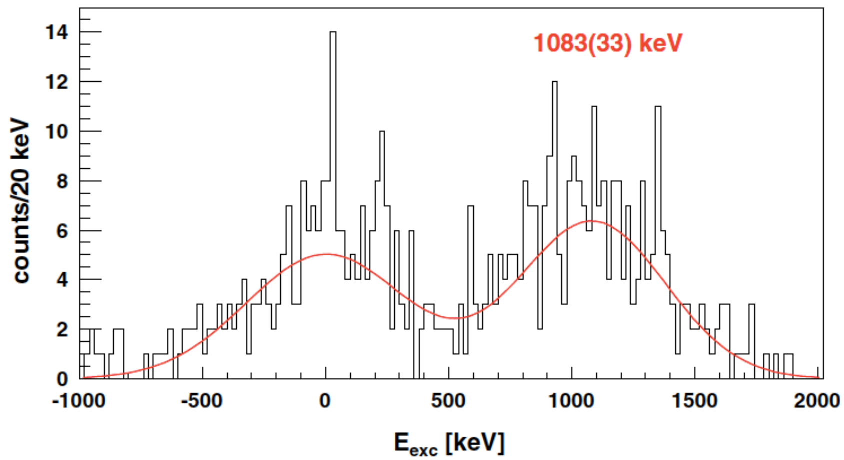


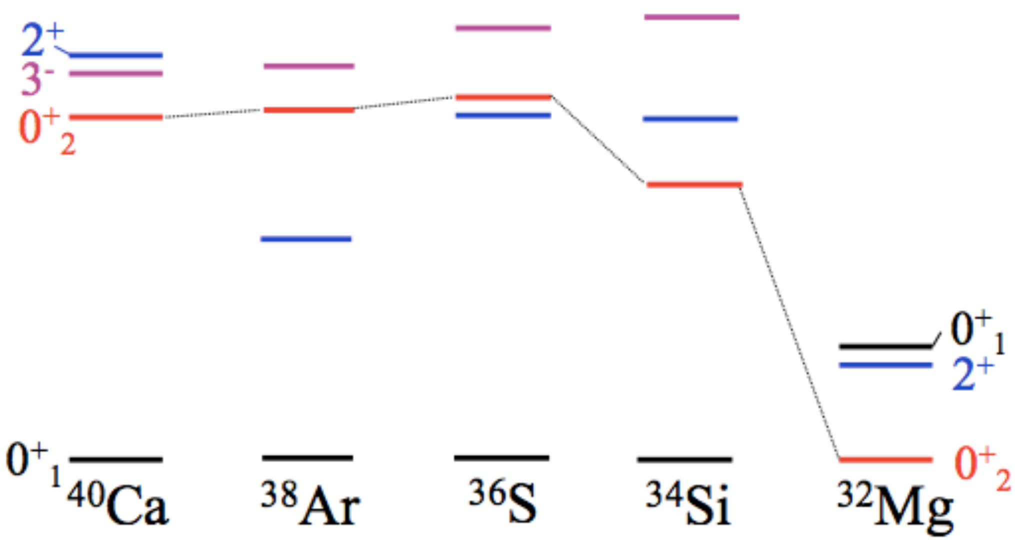
- Ti foil loaded with tritium $^3H/Ti$ ratio of 1.5
- Equivalent to 40 μg.cm-2 of ^3H
- Activity of the target is 10 GBq

- missing mass (t,p): absolute excitation energy
- modest energy resolution (about 800 keV FWHM)

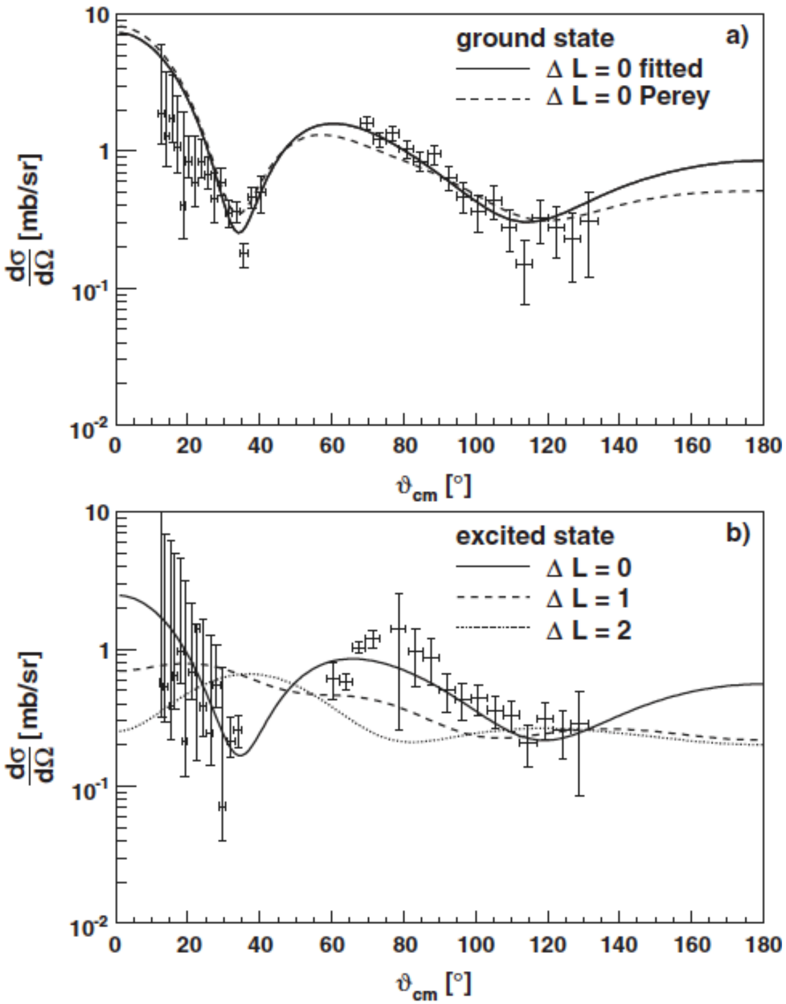
- 0^+_2 state assigned from angular distribution
- E_x=1083(33) keV

Second 0$^+$ of ^{32}Mg from two-neutron transfer





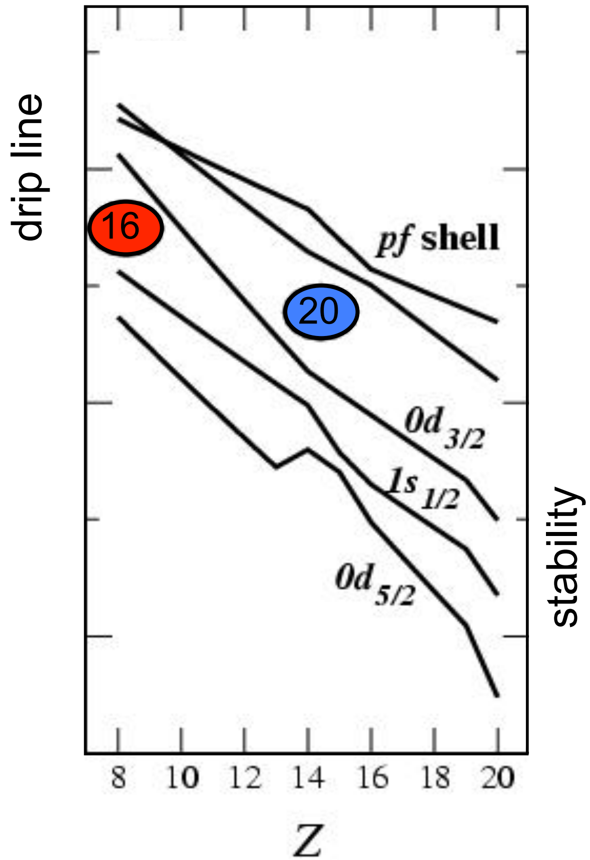
K. Wimmer *et al.*, Phys. Rev. Lett. **105**, 252501 (2010)

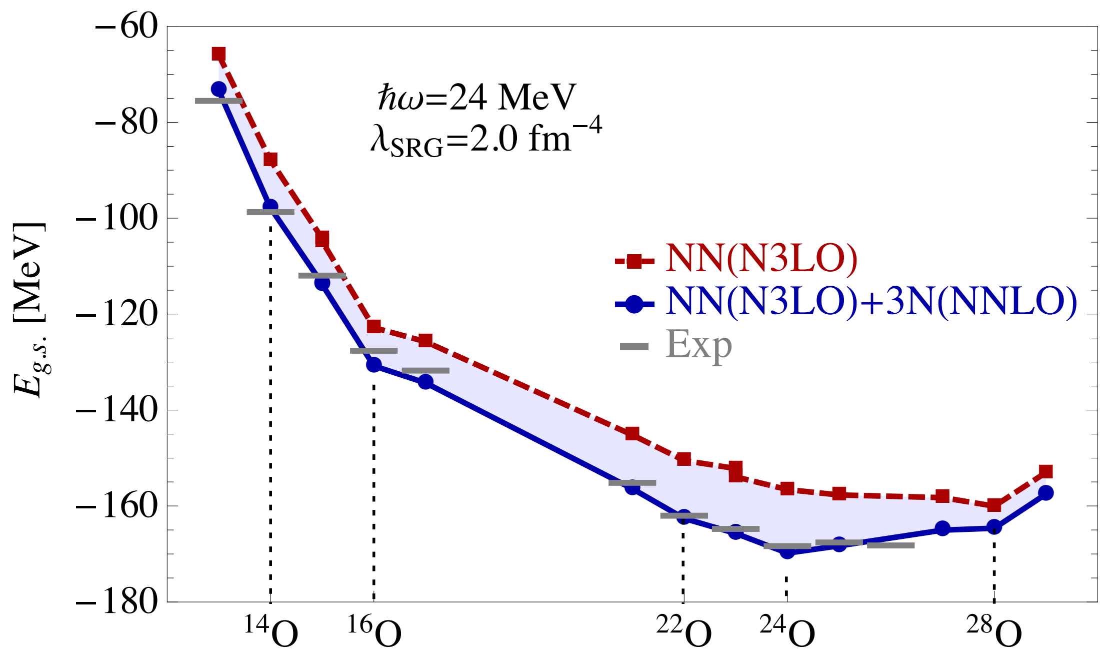


N=16, a new magic number

- Disapearance of the N=20 shell closure and emergence of N=16 connected
- Spin-isospin mechanism between the $\pi d_{5/2}$ and $\nu d_{3/2}$
- The dripline nucleus ^{24}O would then be doubly magic
- No bound excited state seen in ^{24}O in in-beam γ spectroscopy: unbound 2^+ ($E>S_n$=4.09 MeV)

M. Stanoiu *et al.*, Phys. Rev. C **69**, 0234312 (2004).



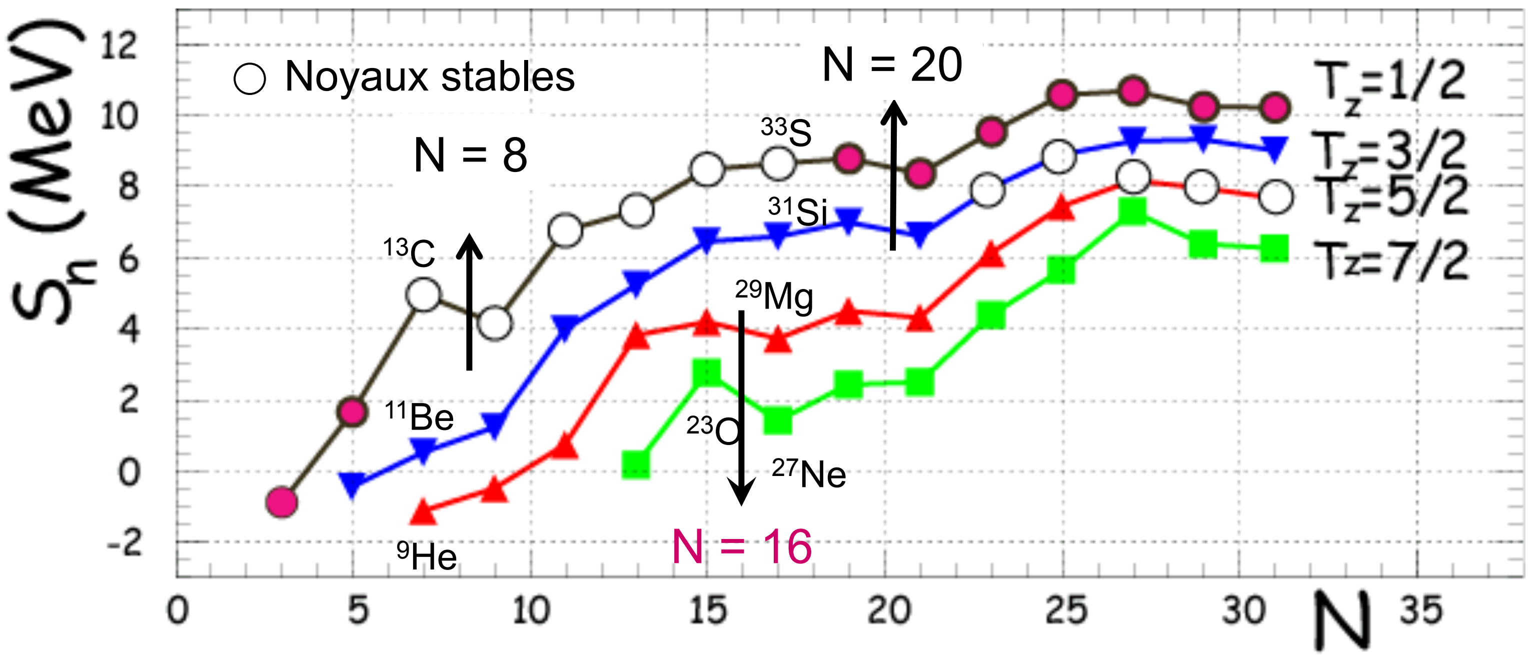


Self-Consistent Green's Function theory

Courtesy C. Barbieri, University of Surrey

N=16, a new magic number

$T_z = (N-Z)/2$



⇒ N=16 ? Ozawa *et al.*, Phys. Rev. Lett. **84**, 5493 (2000)

N=16, a new magic number

- RIPS, RIKEN
- $^{24}O(p,p')^{23}O+n$ @ 62 MeV/u
- 20-mm liquid H_2 target

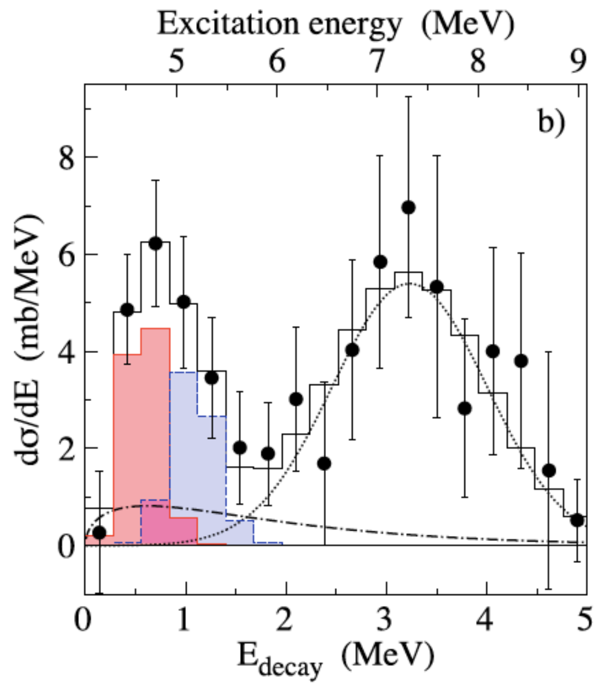
- $S_n(^{24}O)=4.09\pm0.13$ MeV

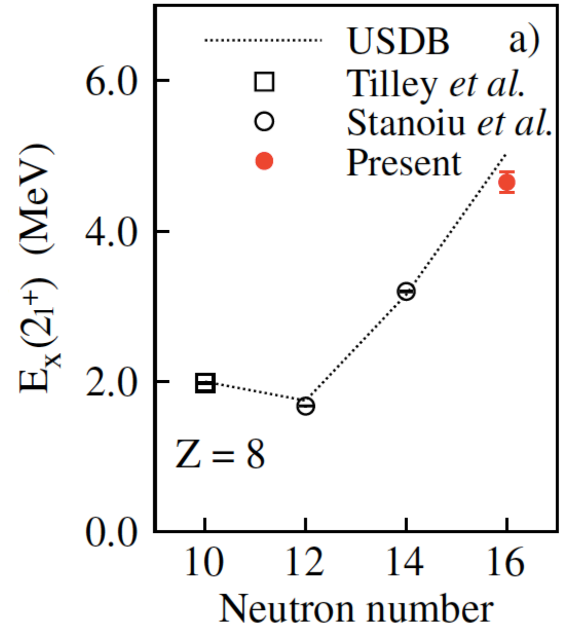
- Invariant mass measurement:

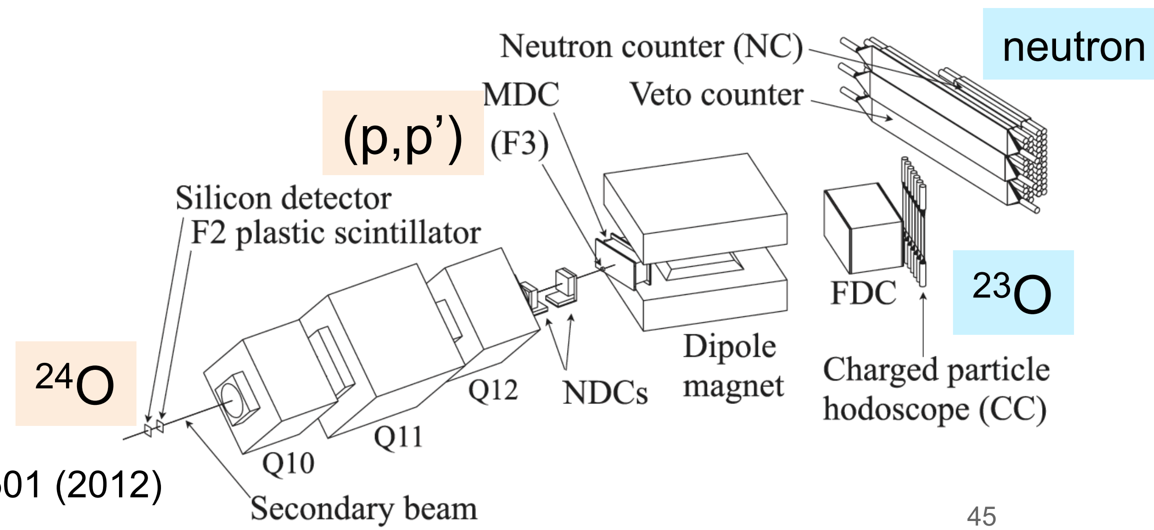
$$E_{decay} = \sqrt{(E_f + E_n)^2 - |p_f + p_n|^2} - (M_f + M_n)$$

- $E_{decay}(2^+)=0.56\pm0.05$ MeV

- **High 2^+_1 excitation energy**: $E(2^+_1)=4.65\pm0.14$ MeV



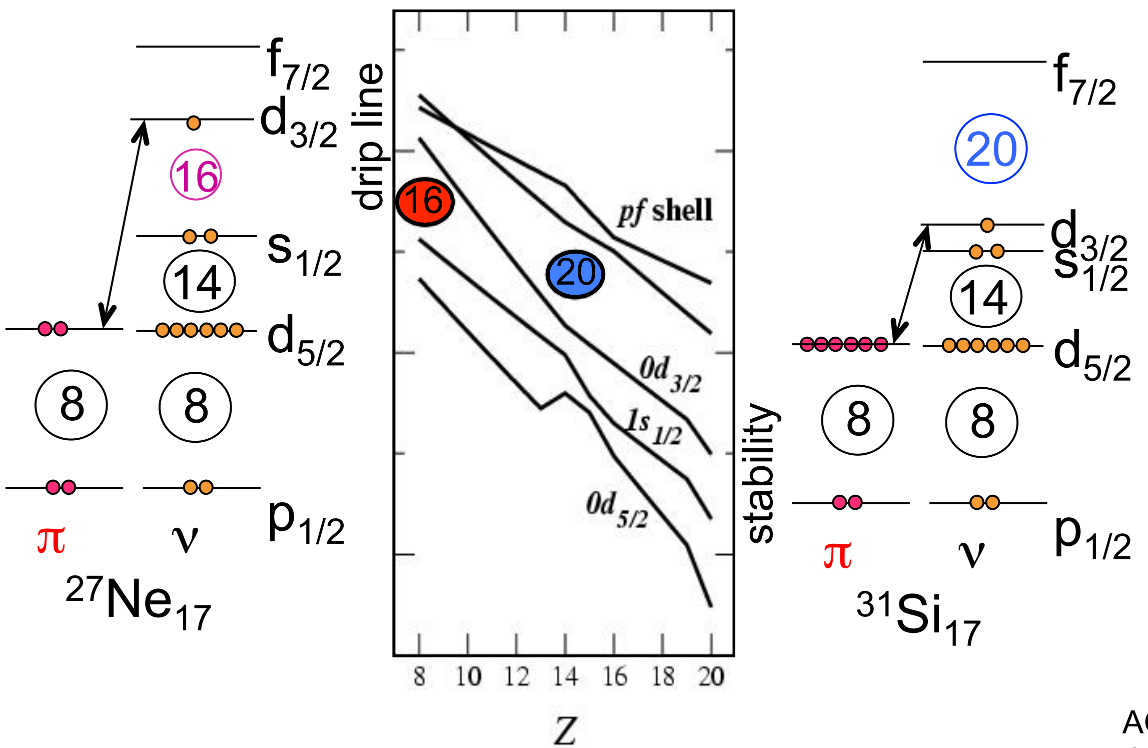


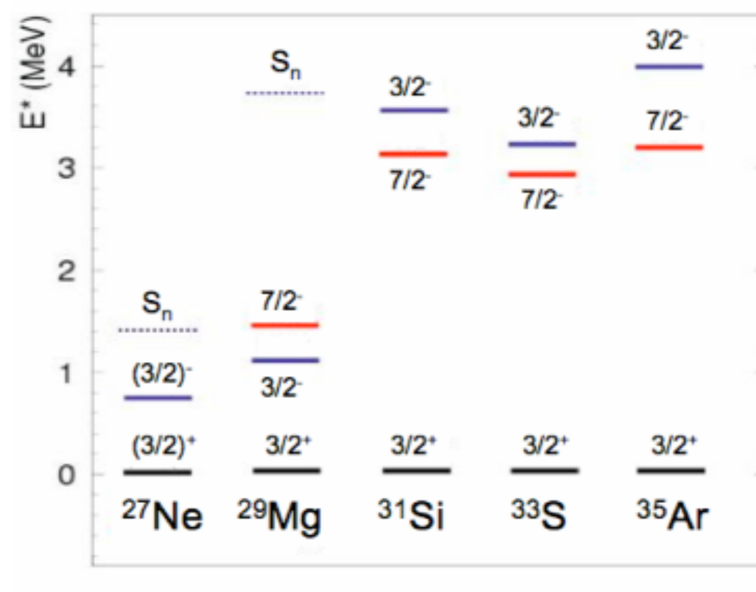


K. Tshoo et al., Phys. Rev. Lett. 109, 022501 (2012)

N=16, N=20: joint spin-isospin mechanism

- Intrusion of negative-parity states in neutron-rich N=17 isotones
- « measure » of the lowering of the *sd-fp* shell gap



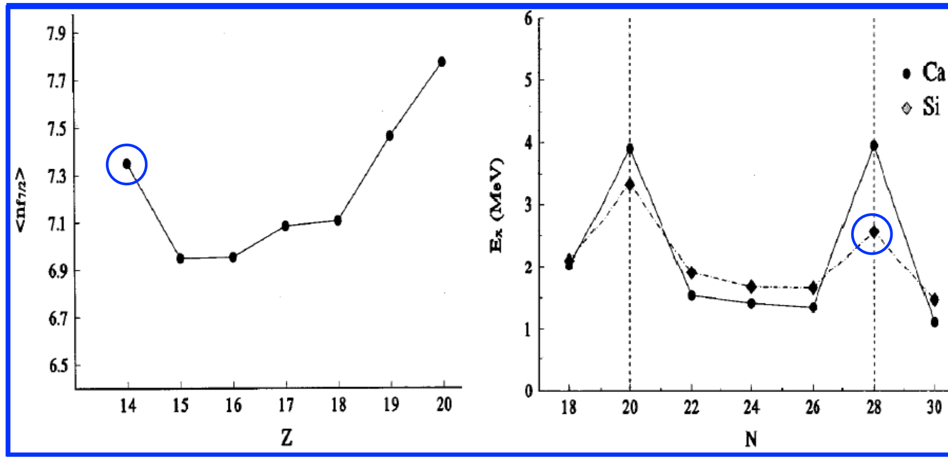


AO *et al.*, Phys. Lett. B **633**, 33 (2006)
J.R. Terry *et al.*, Phys. Lett. B **640**, 86 (2006)
S.M. Brown *et al.*, Phys. Rev. C **85**, 011302(R) (2012)

Evolution of the N=28 spin-orbit shell closure

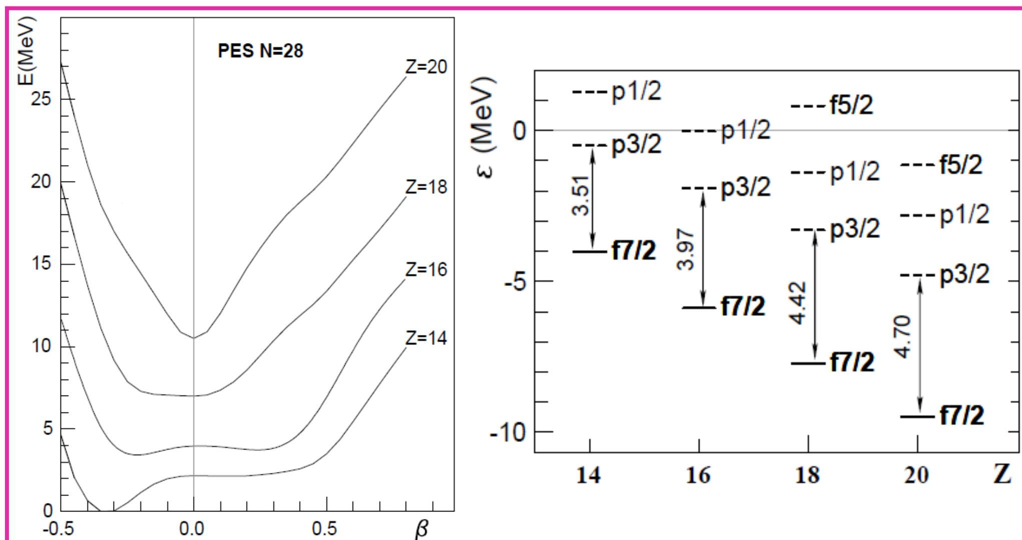
- Shell model, 1997
  Shell gap at N=28 smaller in Si than in Ca
  - ^{42}Si still predicted to be **magic**

J. Retamosa, E. Caurier, F. Nowacki and A. Poves, PRC47(1997)



- Shell model, 2004
  E. Caurier, F. Nowacki and A. Poves, NPA742(2004)
  Adjustment of interaction on ^{35}Si data
  Moderate decrease of the N=28 gap
  - Shape coexistence in ^{44}S
  - ^{42}Si very sensitive to details of the interaction

S. Peru, M. Girod and J.F. Berger, EPJA9(2000)



- Mean field (Gogny D1S, 5DCH), 2000
  Strong decrease of the N=28 gap
  - ^{44}S: shape coexistence
  - ^{42}Si: **very deformed** (oblate: β=0.4)

Doubly magic ^{42}Si?

nature   Vol 435|16 June 2005|**doi:10.1038/nature03619**

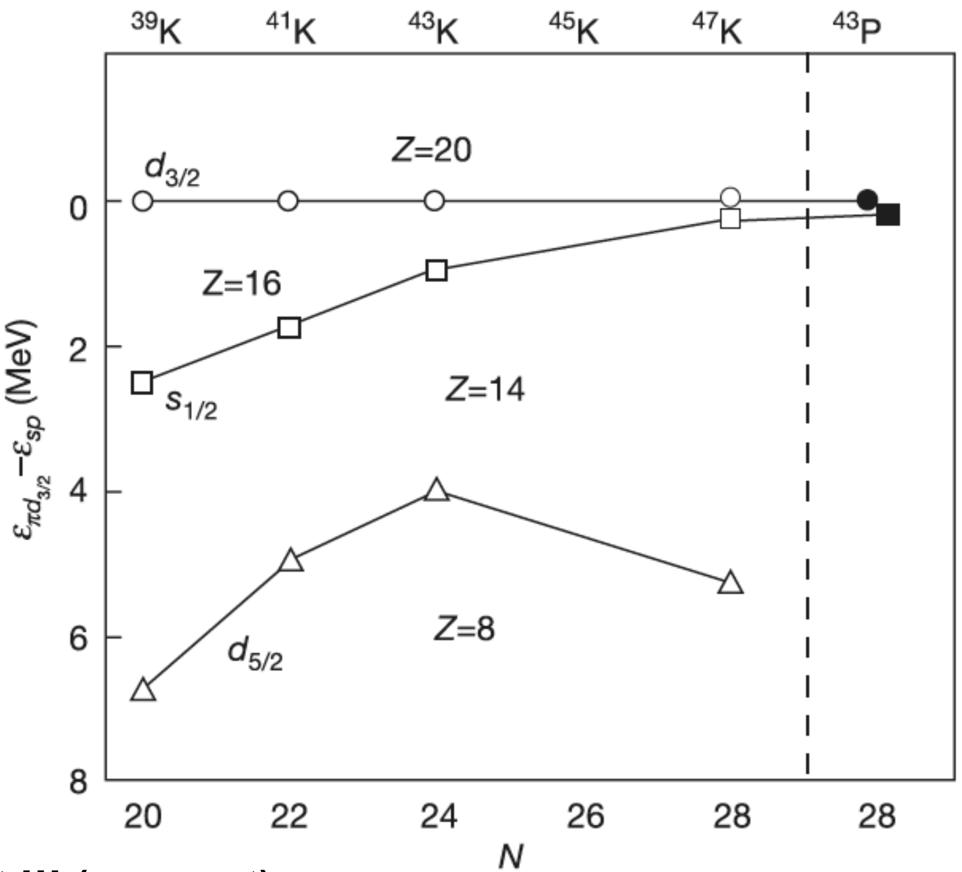
LETTERS

'Magic' nucleus ^{42}Si

- ❑ ^{42}Si,^{43}P produced from 1,2-proton removal
- ❑ Low statistics
- ❑ In-beam γ spectroscopy
- ❑ SeGA Ge array (efficiency 2.5%)

- ❑ no γ observed in ^{42}Si
  interpreted as no bound excited state
- ❑ small 2-proton cross section
  interpreted as a sign of shell closure

- ❑ Conclusion of a closed shell ^{42}Si in contradiction with previous β decay lifetime
  S. Grévy *et al.* Phys. Lett. B **594** (2004)



!!! Wrong interpretation of the measurement !!! (see next)

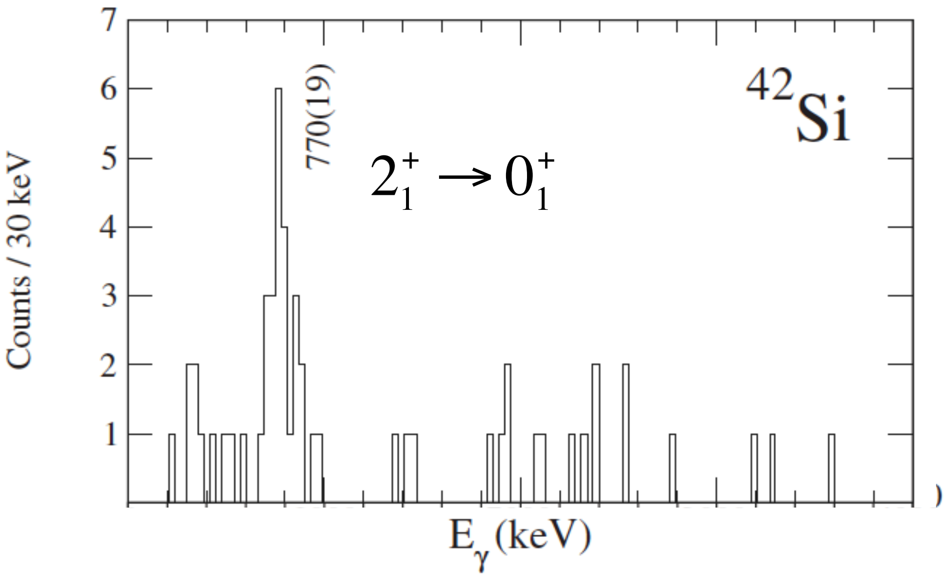
Collapse of the N=28 shell closure

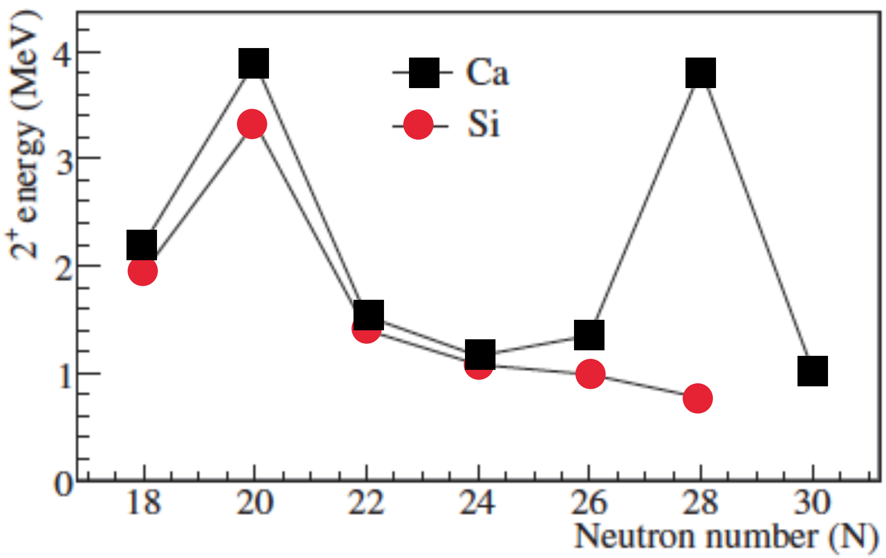
- **^{42}Si not magic… but very deformed**

- GANIL experiment, LISE
- ^{42}Si produced from 1,2 proton removal at 39 A MeV
- in-beam γ with high photopeak efficiency (38%, NaI array « Château de crystal »)
- first 2^+ of ^{42}Si at low energy: 770(19) keV

- Results later confirmed with additional transitions (4_1^+ state ar 2173(14) keV) at RIBF

S. Takeuchi *et al.*, Phys. Rev. Lett. **109**, 182501 (2012)

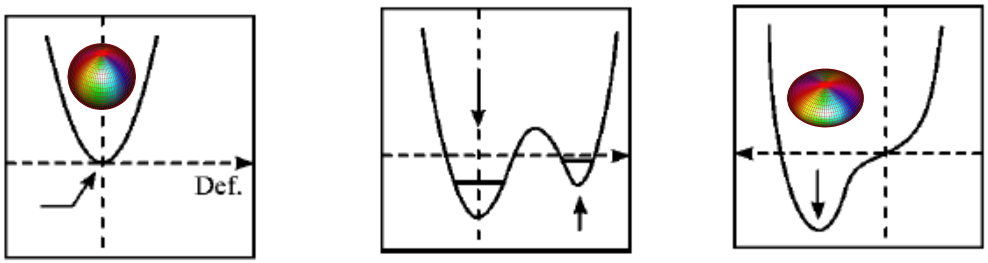




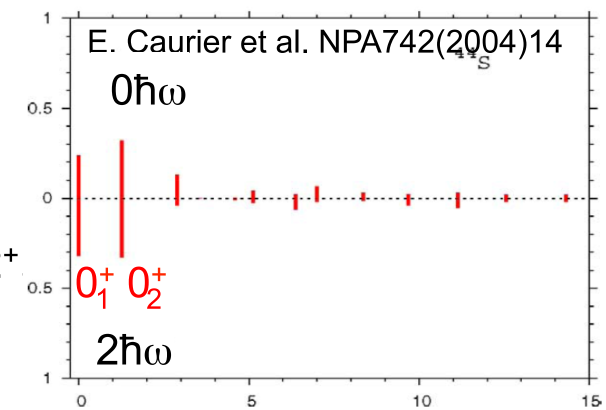
B. Bastin et al., Phy. Rev. Lett. **99**, 022503 (2007)

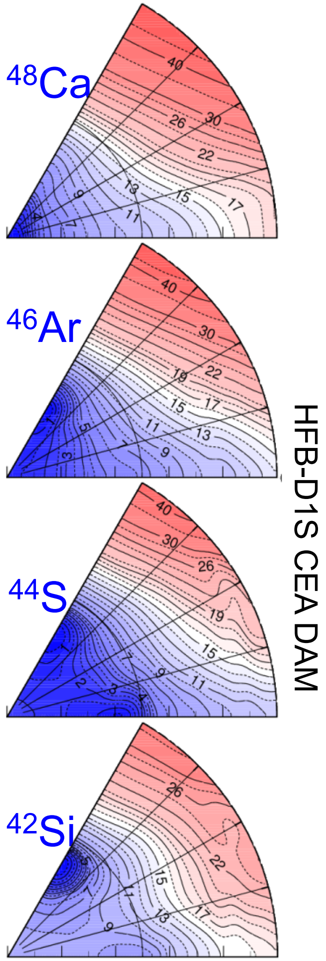
Shape coexistence in ^{44}S

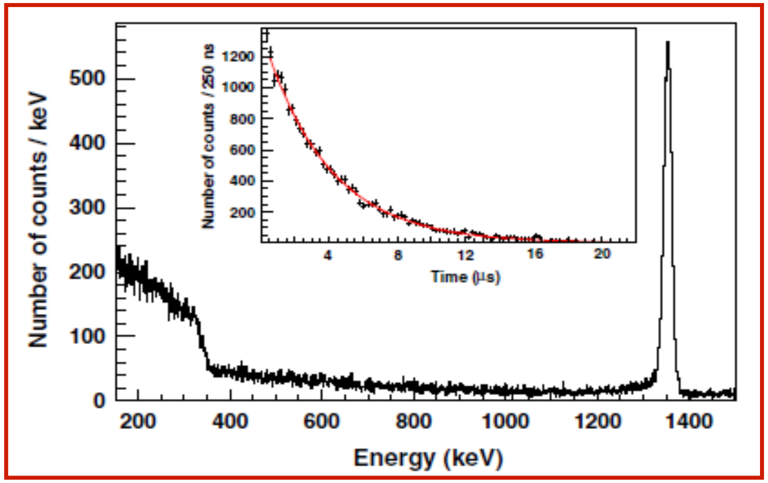
- transition between spherical and deformed ground-state configurations

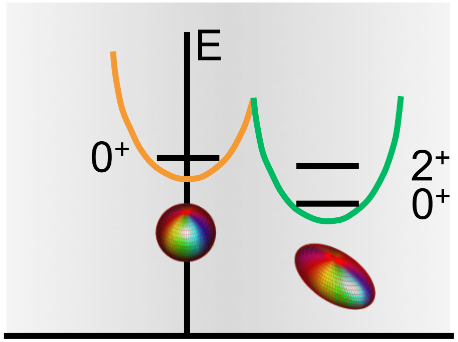


- Mean field approaches
  - prolate oblate shape coexistence
- Shell model approaches
  - prolate-spherical coexistence
  - prediction of a 0^+_2 state above the 2^+









The merging of the N=20 & N=28 regions of deformation

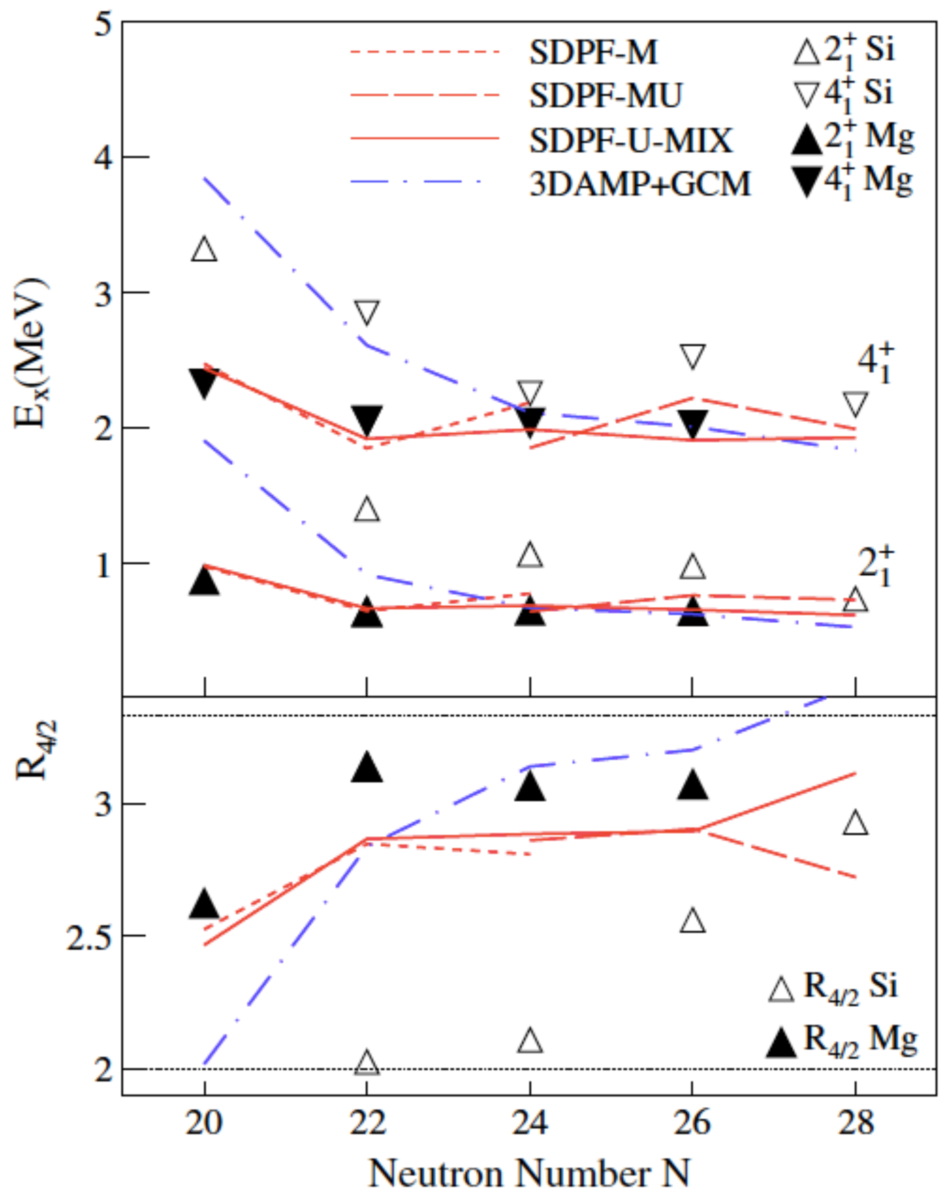
- RIBF, RIKEN
- in-beam γ spectroscopy of $^{34,36,38}Mg$

- Flat systematics of 2^+_1,4^+_1
- Low 2^+_1 energies (about 500 keV)
- R_{42}>3, consistent with deforemd nuclei

- Merging of the N=20 island of inversion with the N=28 region of deformation

P. Doornenbal, Phys. Rev. Lett. 111, 212502 (2013)

- Spectroscopy of ^{40}Mg measured in 2016 under analysis



"Second" island of inversion at N=40, an old story

From A. Poves

The Physics around the doubly-magic ^{78}Ni Nucleus

Leuven, Belgium
November 4-5, 1996

^{64}Cr

$g(0ph - 2ph) = 5.70$
$g(0ph - 4ph) = 8.30$

$Q = -9.0\ b^2$ $\quad$ CS < 1%

$BE2 = 19.8\ b^4$ $\quad$ $n(d_{5/2}) = 1.1$

$\frac{E(4^+)}{E(2^+)} = 2.7$ $\quad$ $\left[\frac{E(4^+)}{E(2^+)} = (3.2)(3.4)\right]$ in the intruder configurations.

A SITUATION THAT REMINDS WHAT IS KNOWN AT N=20 FFS.

!

“Second” island of inversion at N=40, an old story

Eur. Phys. J. A **16**, 55–61 (2003)
DOI 10.1140/epja/i2002-10069-9

THE EUROPEAN PHYSICAL JOURNAL A

New region of deformation in the neutron-rich $^{60}_{24}Cr_{36}$ and $^{62}_{24}Cr_{38}$

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Abstract. The neutron-rich nuclei $^{60-63}_{23}V$ have been produced at GANIL via interactions of a 61.8 A · MeV ^{76}Ge beam with a ^{58}Ni target. Beta-decay to $^{60-63}_{24}Cr$ has been investigated using combined β- and γ-ray spectroscopy. Half-lives of the $^{60-63}V$ nuclei have been determined, and the existence of a beta-decay isomer in the ^{60}V nucleus is strongly supported. The observation of low-energy 2^+ states in ^{60}Cr (646 keV) and ^{62}Cr (446 keV) suggests that these isotopes are strongly deformed with $\beta_2 \sim 0.3$. This is confirmed by shell model calculations which show the dominant influence of the intruder g and d orbitals to obtain low 2^+ energies in the neutron-rich Cr isotopes.

Fe and Cr isotopes

MSU

PHYSICAL REVIEW C **81**, 051304(R) (2010)

RAPID COMMUNICATIONS

Collectivity at *N* = 40 in neutron-rich ^{64}Cr

A. Gade,[1,2] R. V. F. Janssens,[3] T. Baugher,[1,2] D. Bazin,[1] B. A. Brown,[1,2] M. P. Carpenter,[3] C. J. Chiara,[3,4] A. N. Deacon,[5] S. J. Freeman,[5] G. F. Grinyer,[1] C. R. Hoffman,[3] B. P. Kay,[3] F. G. Kondev,[6] T. Lauritsen,[3] S. McDaniel,[1,2] K. Meierbachtol,[1,7] A. Ratkiewicz,[1,2] S. R. Stroberg,[1,2] K. A. Walsh,[1,2] D. Weisshaar,[1] R. Winkler,[1] and S. Zhu[3]

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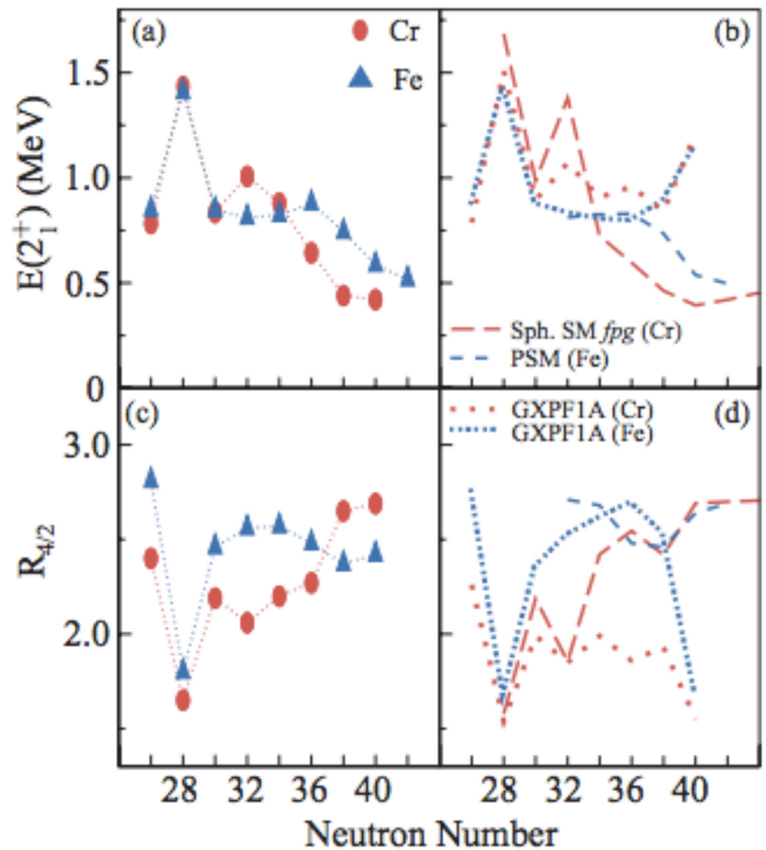
- ❑ in-beam gamma at the NSCL
- ❑ 2^+ energy and R_{42} of ^{64}Cr indicate strong deformation

- ❑ Shell model in *fp* valence space fails
- ❑ Onset of collectivity requires *1g* orbital (*fpg* space)



Fe and Cr isotopes

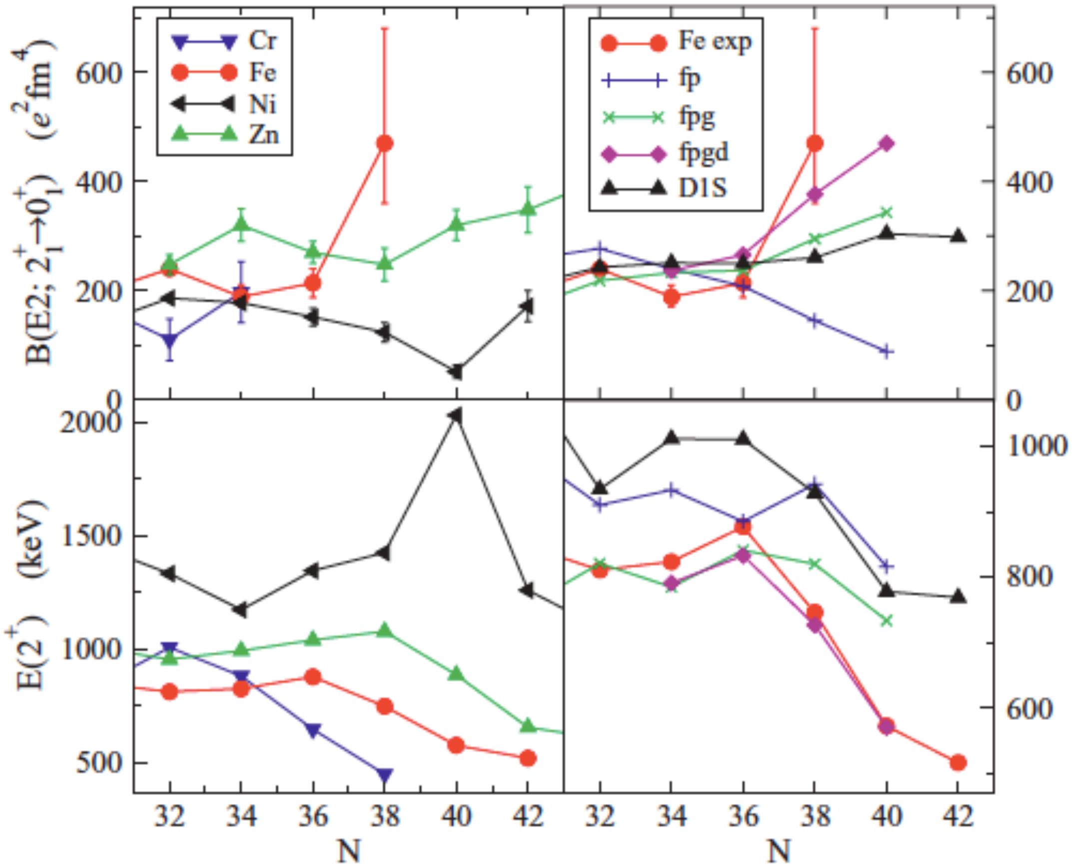
GANIL

RAPID COMMUNICATION

PHYSICAL REVIEW C **81**, 061301(R) (2010)

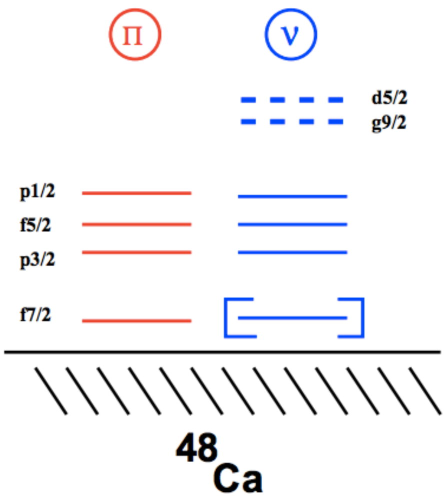
Onset of collectivity in neutron-rich Fe isotopes: Toward a new island of inversion?

J. Ljungvall,[1,2,3] A. Görgen,[1] A. Obertelli,[1] W. Korten,[1] E. Clément,[2] G. de France,[2] A. Bürger,[4] J.-P. Delaroche,[5] A. Dewald,[6]

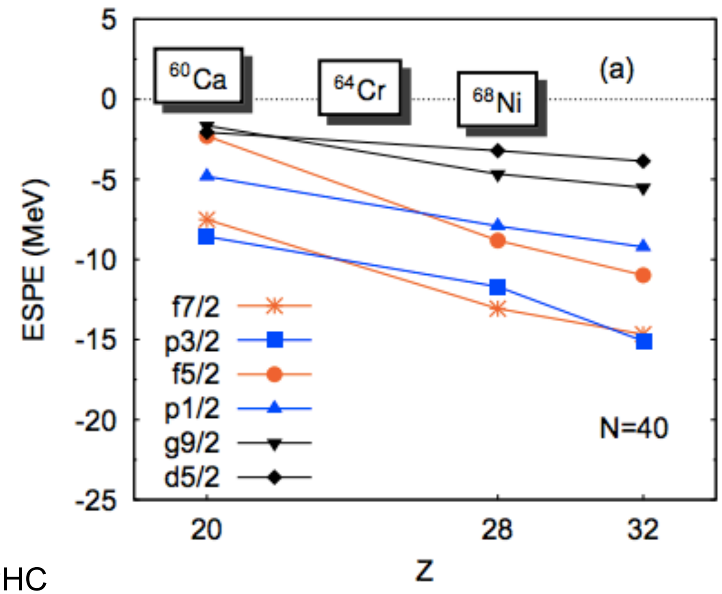


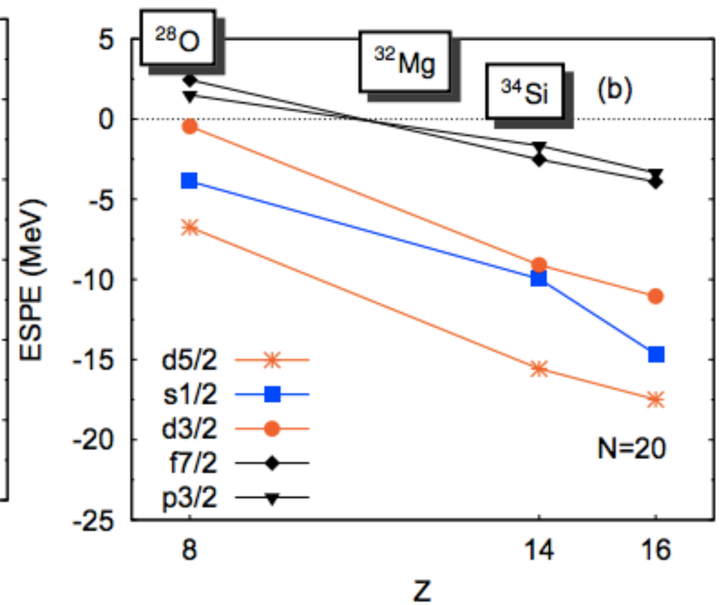
A new Island of inversion?

S.M. Lenzi *et al.,* Phys. Rev. C **82**, 054301 (2010)



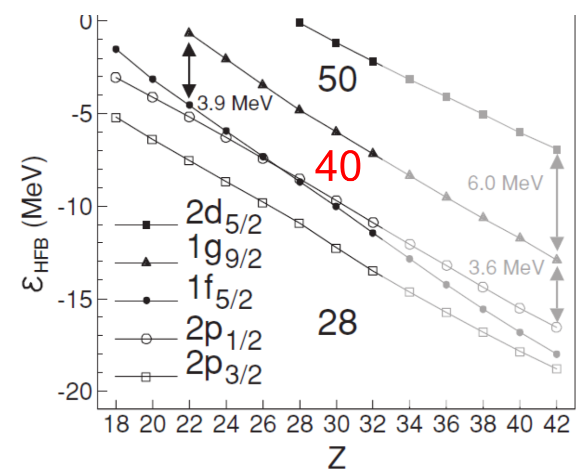
Sketch from F. Nowacki, IPHC





- Reduction of the fp-gds gap towards the neutron dripline
- strong similarities to the N=20 shell gap behavior
- Difference between shell-model and mean-field for the neutron spherical shell gap at N=40

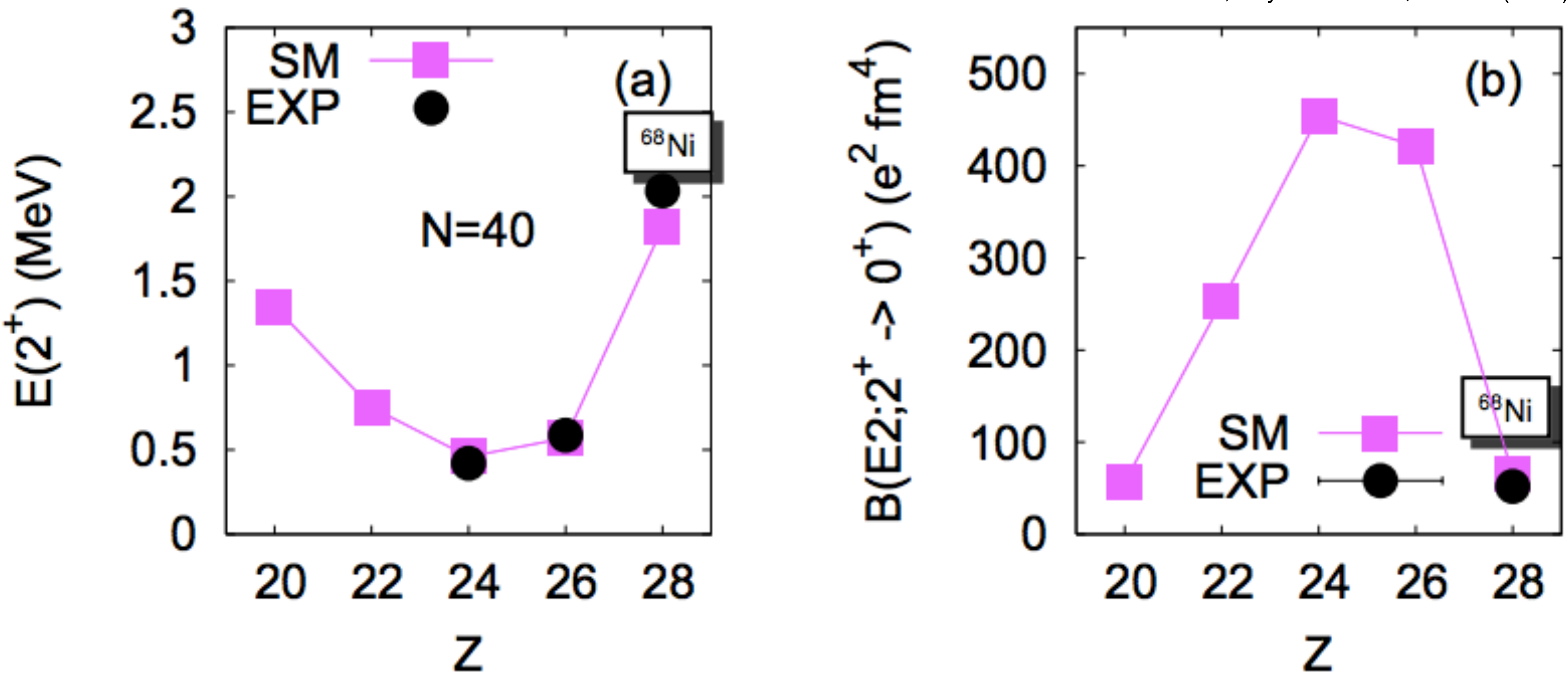
L. Gaudefroy *et al.,* Phys. Rev. C **80**, 064313 (2009)



Mean-field + Gogny D1S

Shell model description of N=40 isotones

S.M. Lenzi *et al.,* Phys. Rev. C **82**, 054301 (2010).

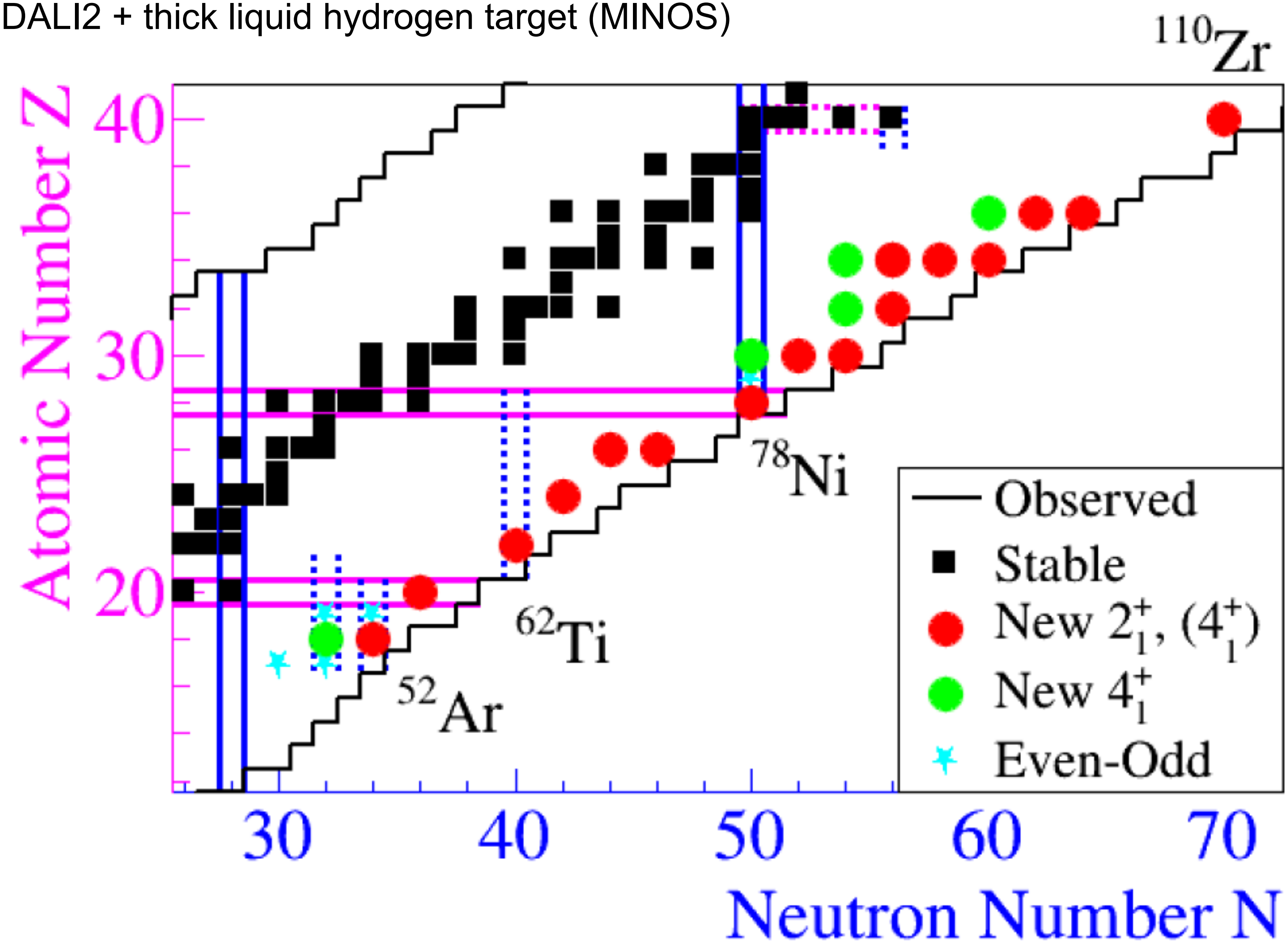


Nucleus	$\nu g_{9/2}$	$\nu d_{5/2}$	configuration
^{68}Ni	0.98	0.10	0p0h(51%)
^{66}Fe	3.17	0.46	4p4h(26%)
^{64}Cr	3.41	0.76	6p6h(23%)
^{62}Ti	3.17	1.09	4p4h(48%)

Slide by F. Nowacki, IPHC

The SEASTAR program at the RIBF

- RIBF is the laboratory where the spectroscopy of the most exotic species can be accessed
- Dedicated program of search for new 2^+ states: experimental campaigns in 2014, 215 and 2017
- DALI2 + thick liquid hydrogen target (MINOS)



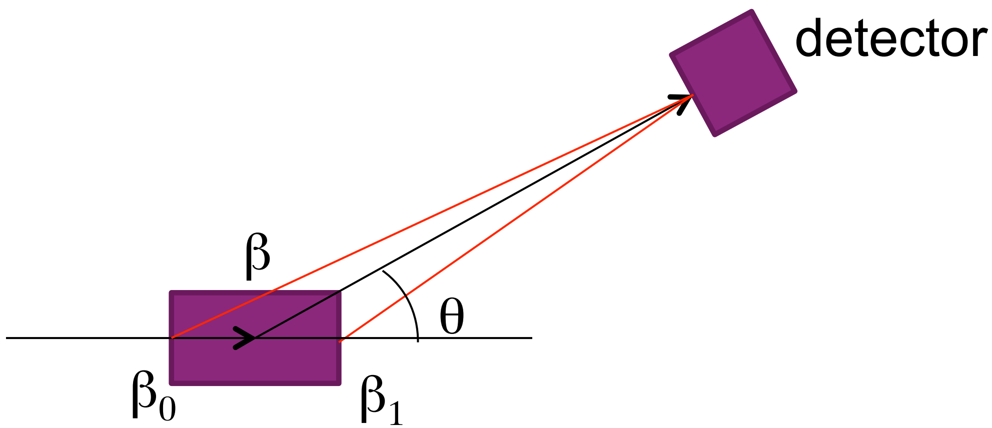
Features of in-beam gamma spectroscopy

$$E_0 = \gamma(1 - \beta\cos\theta_{lab})E_{lab}$$

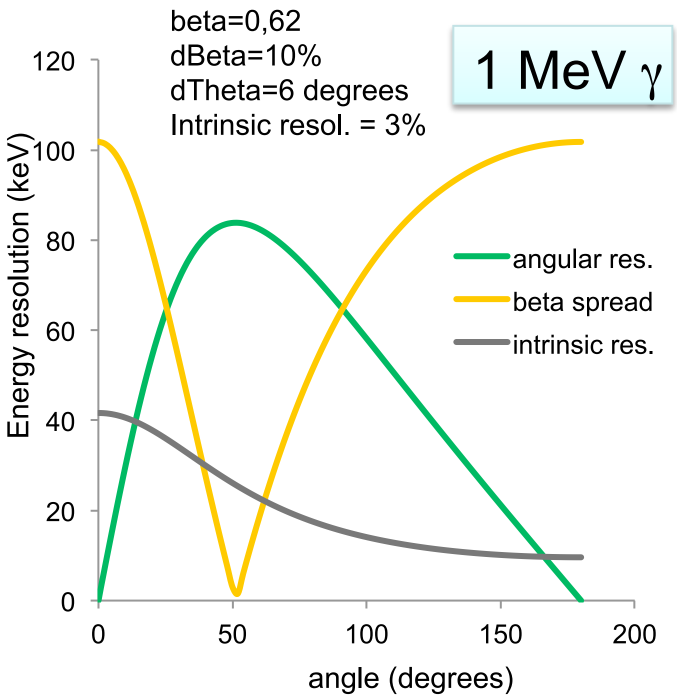
$$\left(\frac{\delta E_0}{E_0}\right)^2 = \left(\frac{\beta\sin\theta_{lab}}{1-\beta\cos\theta_{lab}}\right)^2(\delta\theta_{lab})^2 + \left(\frac{\beta\gamma^2(\beta-\cos\theta_{lab})}{1-\beta\cos\theta_{lab}}\right)^2\left(\frac{\delta\beta}{\beta}\right)^2 + \left(\frac{\delta E_{lab}}{E_{lab}}\right)^2$$

Angular resolution
(detector geometry / technology)

Intrinsic resolution
few % for scintillators

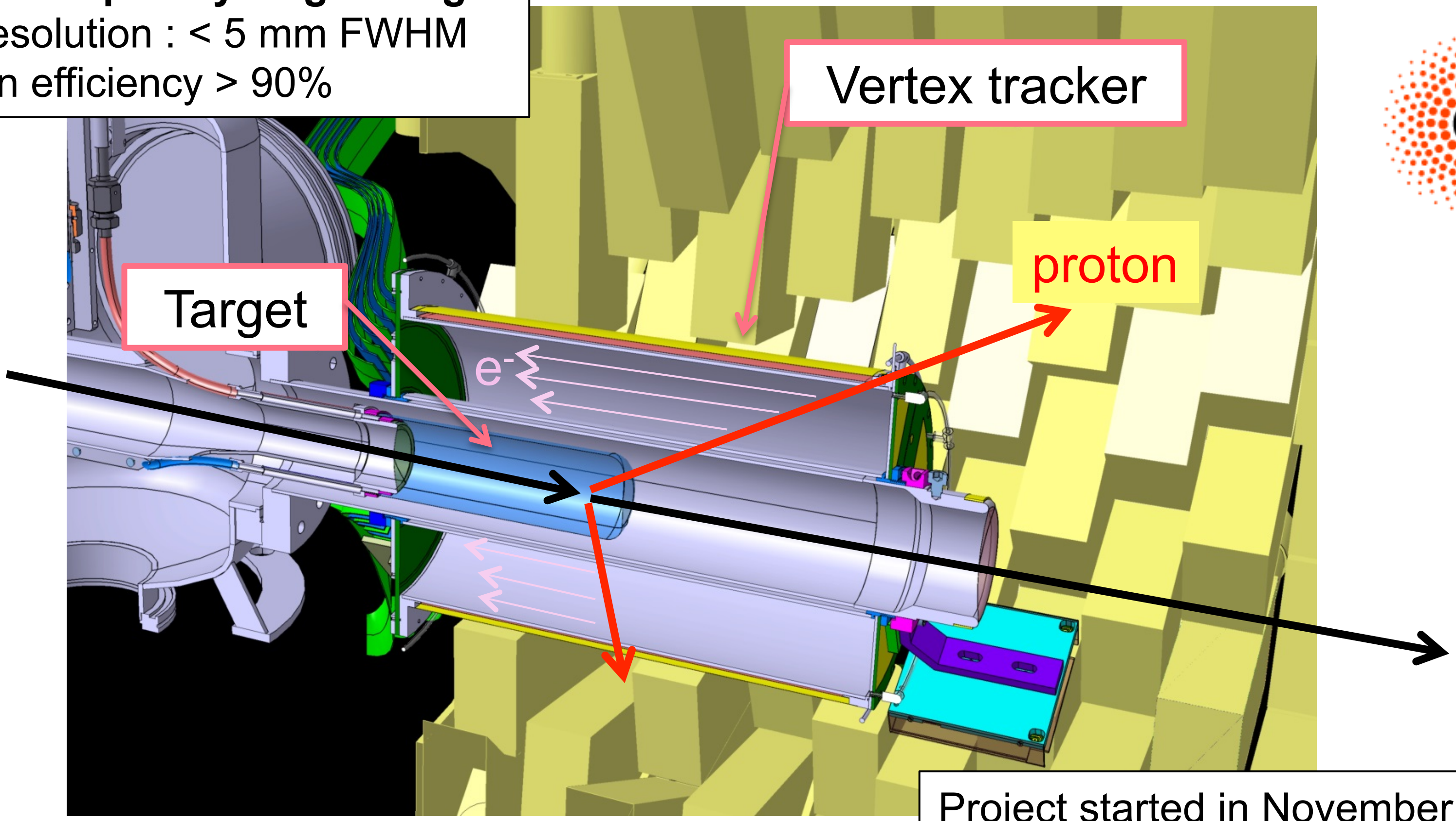


Thick target induces Δβ and Δθ



Program based on (p,2p), (p,pn), (p,3p)

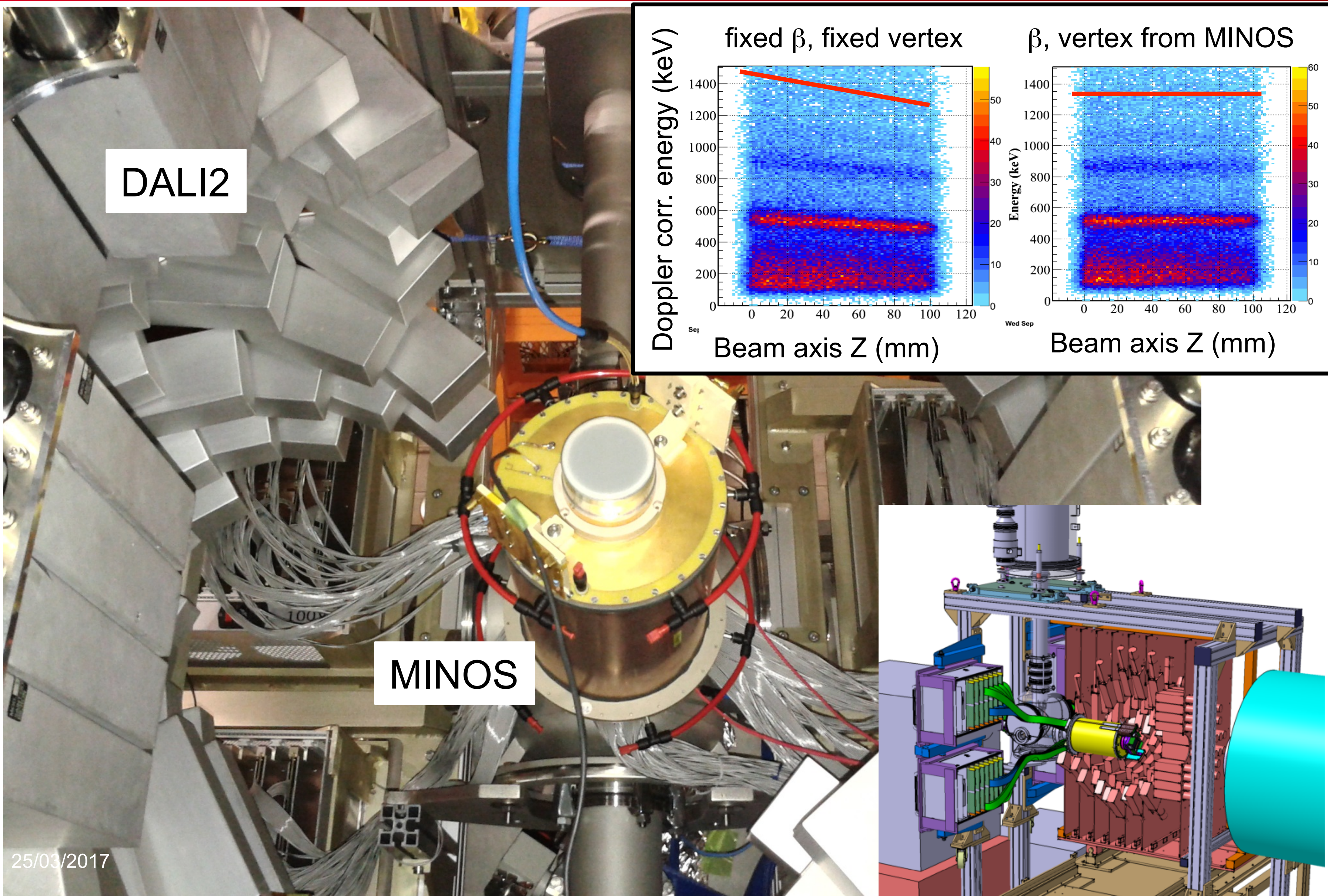
60-200 mm **liquid hydrogen target**
Vertex resolution : < 5 mm FWHM
Detection efficiency > 90%



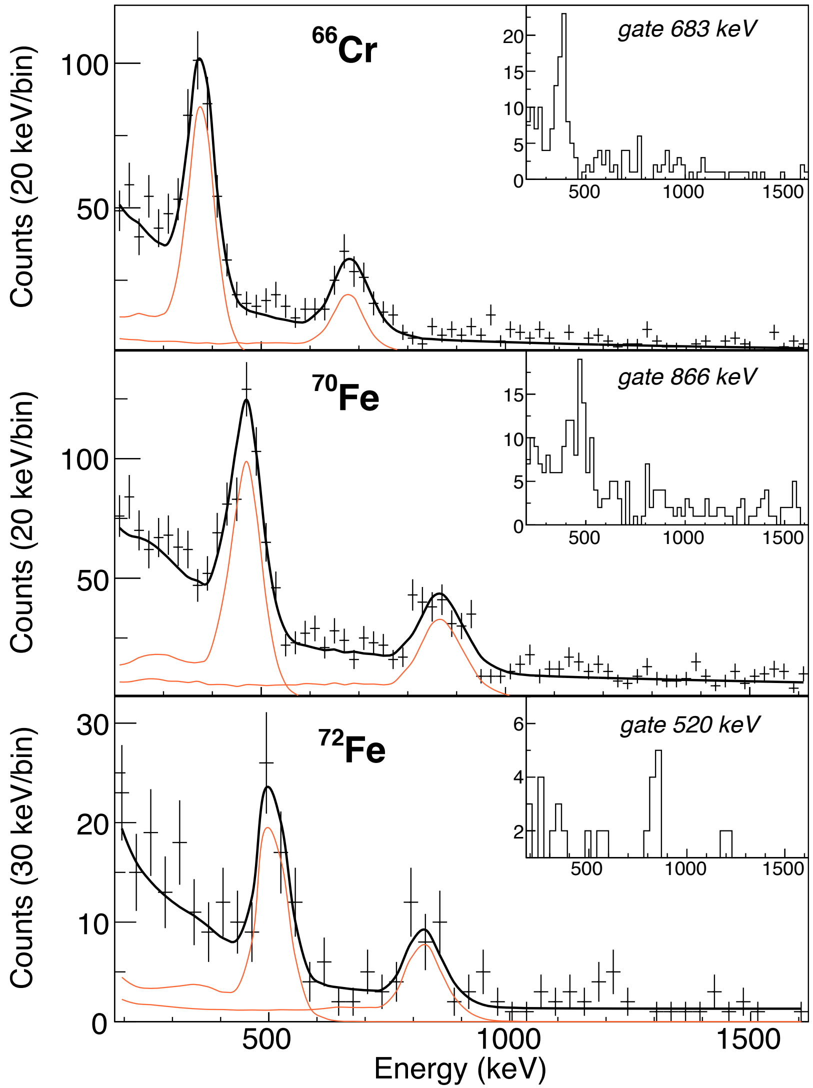
Project started in November 2010
In use at the RIBF since 2014

A. Obertelli *et al.,* Eur. Phys. Jour. A **50**, 8 (2014)

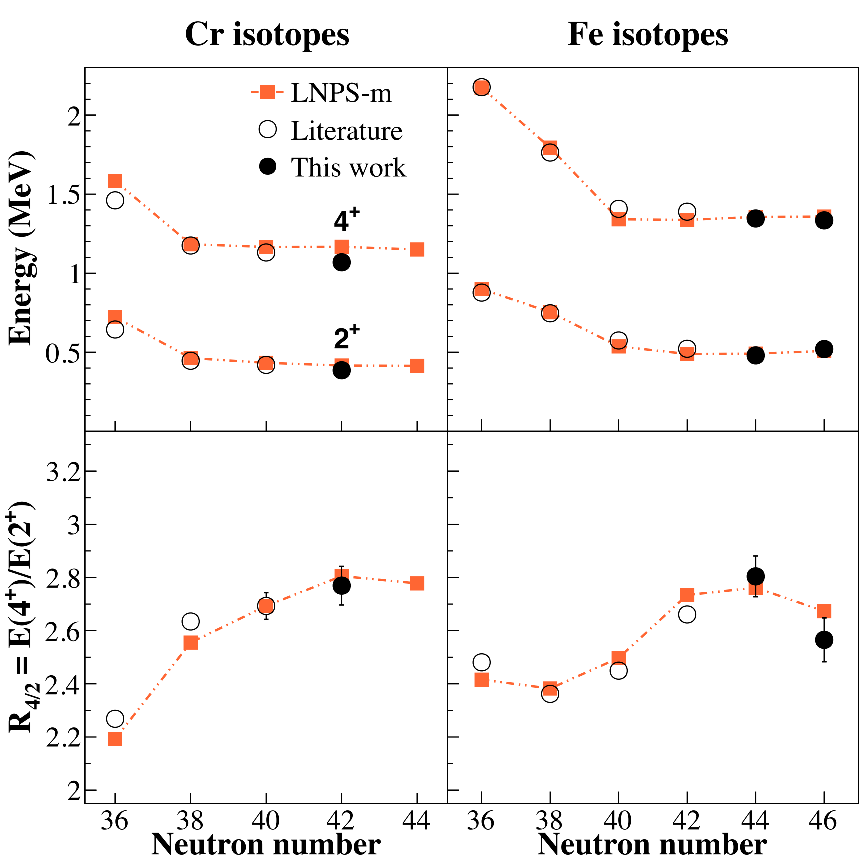
Setup


DALI2
MINOS
fixed β, fixed vertex
β, vertex from MINOS
Doppler corr. energy (keV)
Energy (keV)
Beam axis Z (mm)
Beam axis Z (mm)

Fe and Cr isotopes

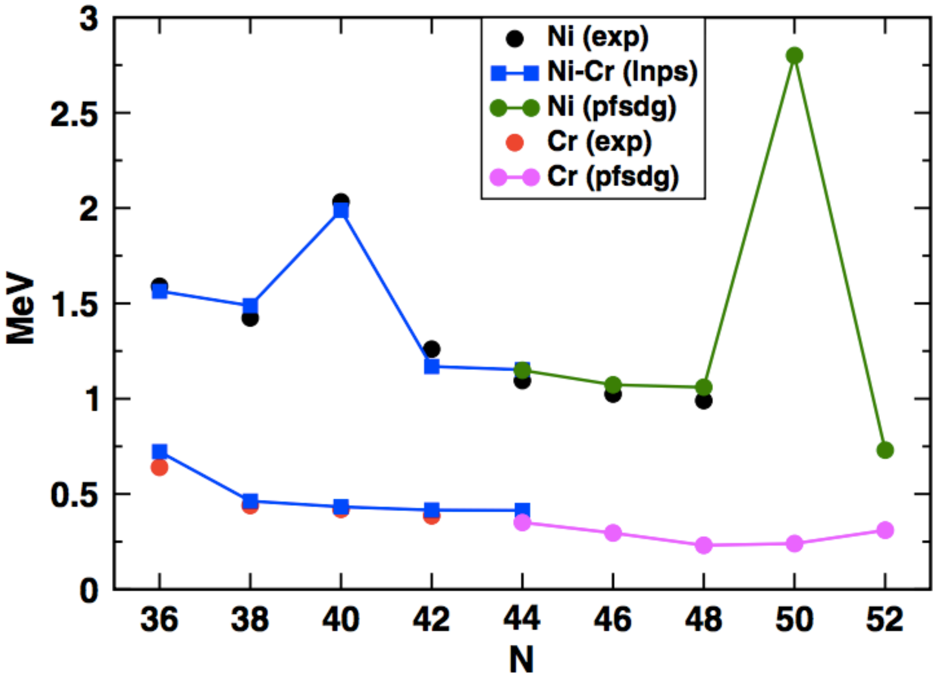


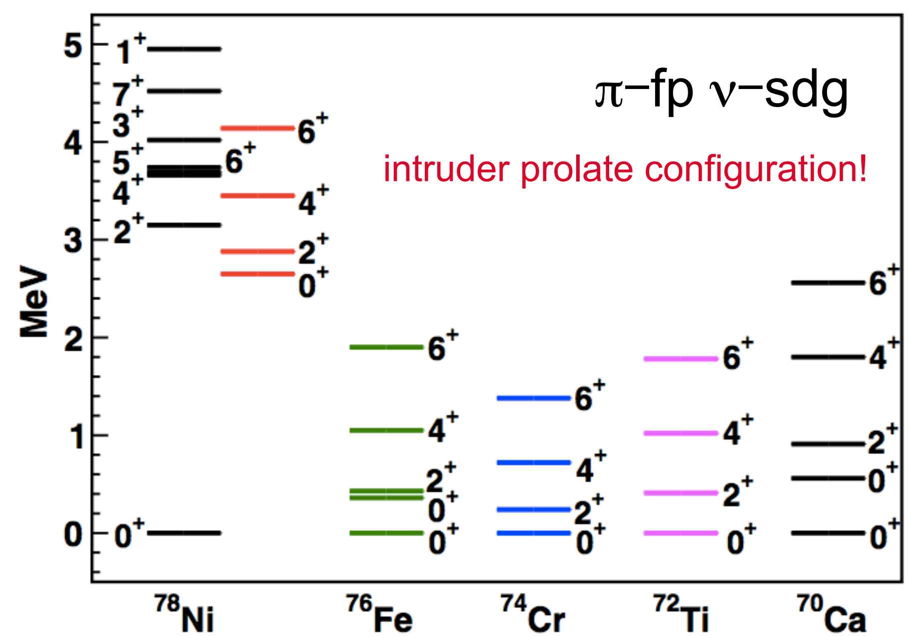
« **Second** » island of inversion



C. Santamaria *et al.*, Phys. Rev. Lett. 115, 192501 (2015).

Extension of the N=40 IoI towards N=50





- ❑ Full *fp* for protons, full *sdg* for neutrons
- ❑ First 2^+ excited state predicted to be intruder state
- ❑ Prediction of **dissapearance of N=50 shell closure below ^{78}Ni**

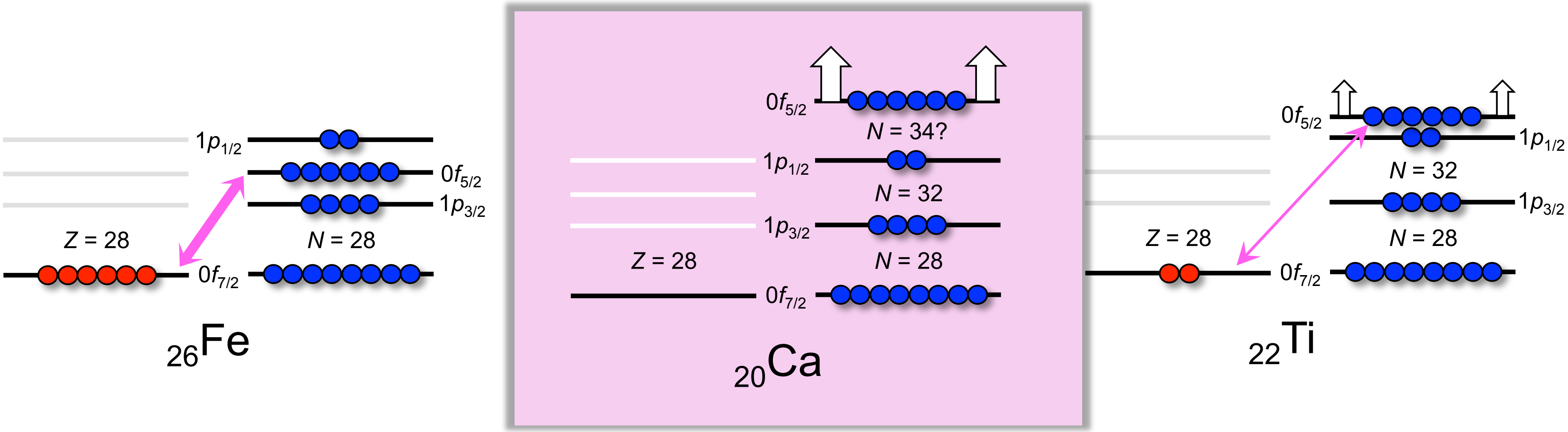
F. Nowacki et al., Phys. Rev. Lett. **117**, 272501 (2016)

N=32 and N=34: shell closures ?

- Neutron-rich *fp* shell
- Attractive interaction between $\pi 1f_{7/2}$ and $\nu 1f_{5/2}$ orbitals is important; responsible for some features of nuclear shell evolution in this mass region

  T. Otsuka *et al*., Phys. Rev. Lett. **95** (2005) 232502

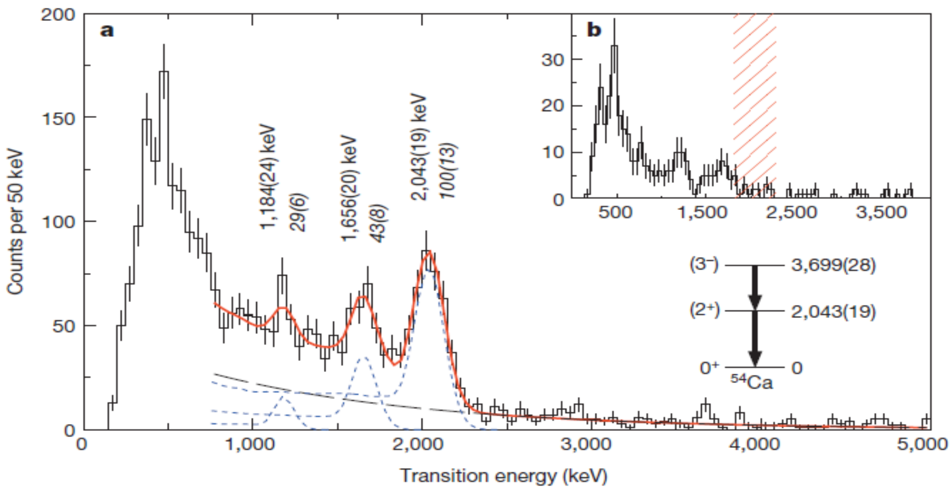
- As protons are removed from the $\pi f_{7/2}$ orbital (i.e., from $_{28}$Ni to $_{20}$Ca) the strength of the π-ν interaction weakens, causing the $\nu f_{5/2}$ orbital to shift up in energy relative to $\nu p_{1/2}$ and $\nu p_{3/2}$

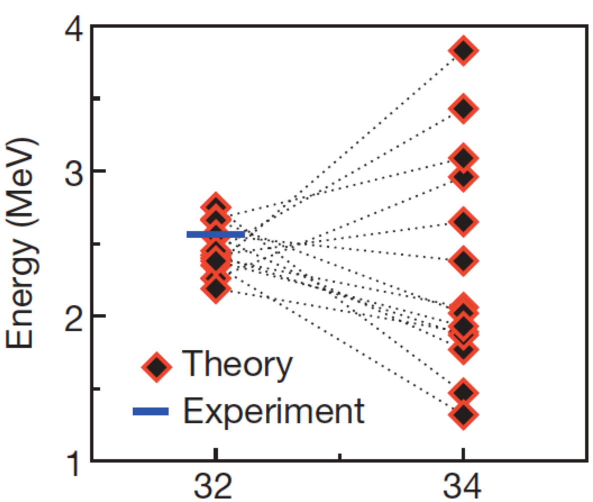


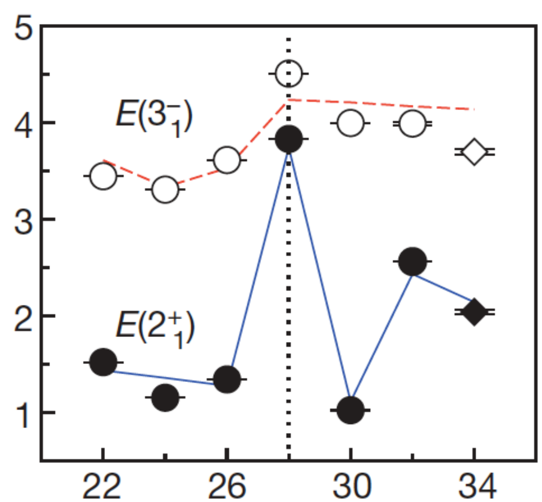
Spectroscopy of ^{54}Ca

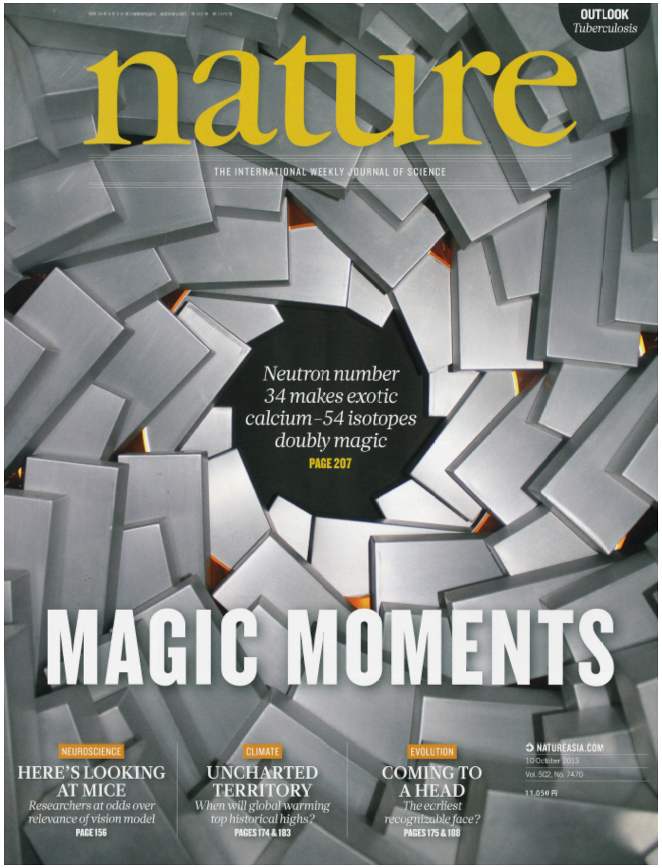
^{56}Ti, ^{55}Sc + Be -> ^{54}Ca + X at the RIBF (DALI2)
^{70}Zn primary beam (100 pnA max)
^{56}Ti 120 pps/pnA, ^{55}Sc 12 pps/pnA

D. Steppenbeck *et al.*, Nature **502** (2013)

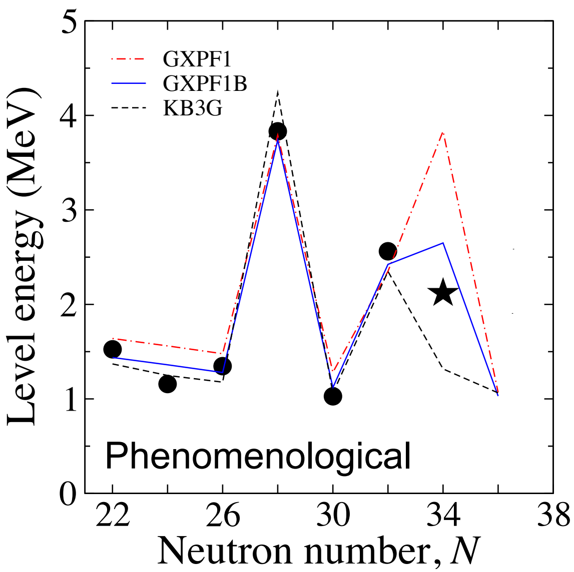


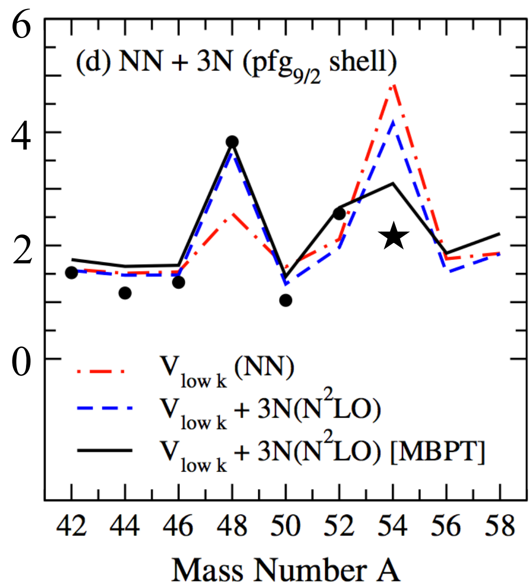




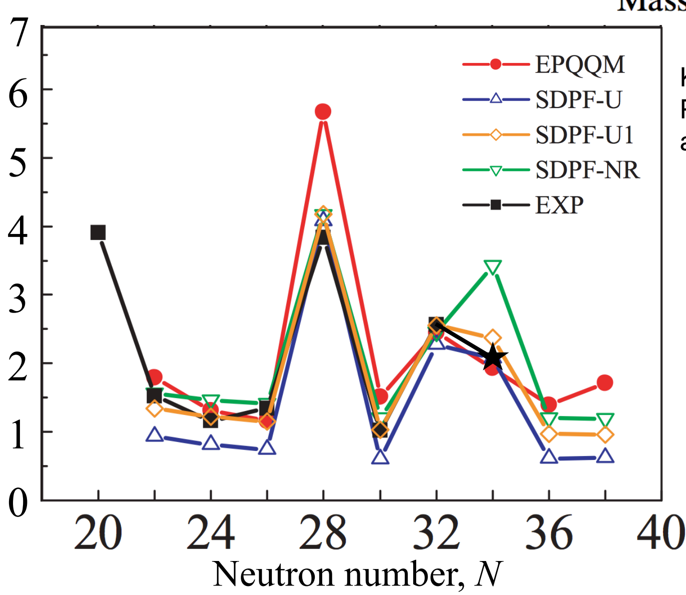


Shell model calculations for ^{54}Ca



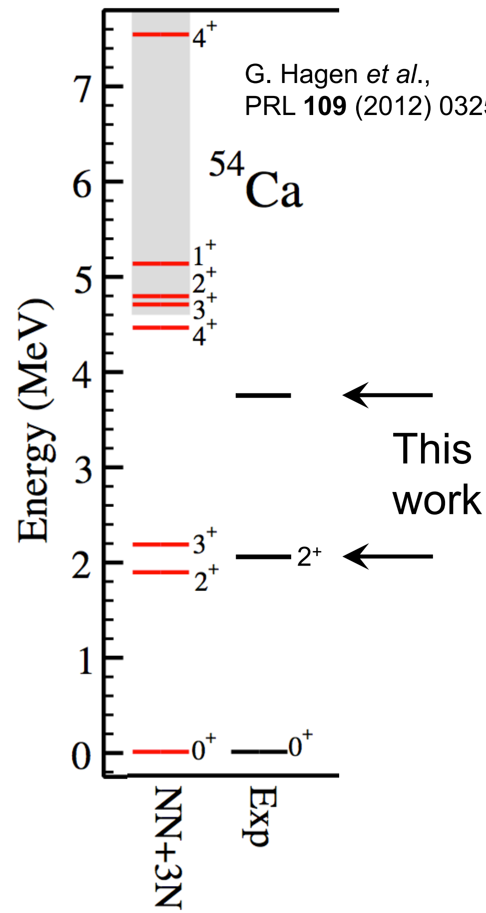


J.D. Holt *et al.*, JPG:NPP **39** (2012) 085111



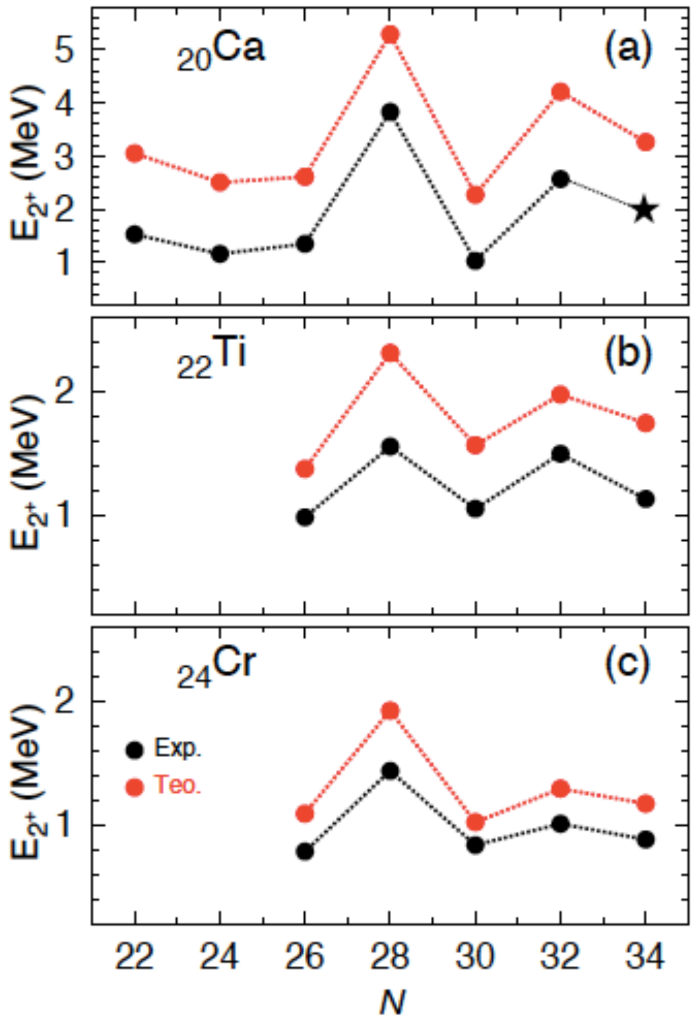
K. Kaneko *et al.*, PRC **83** (2011) 014320, and references therein

G. Hagen *et al.*, PRL **109** (2012) 032502

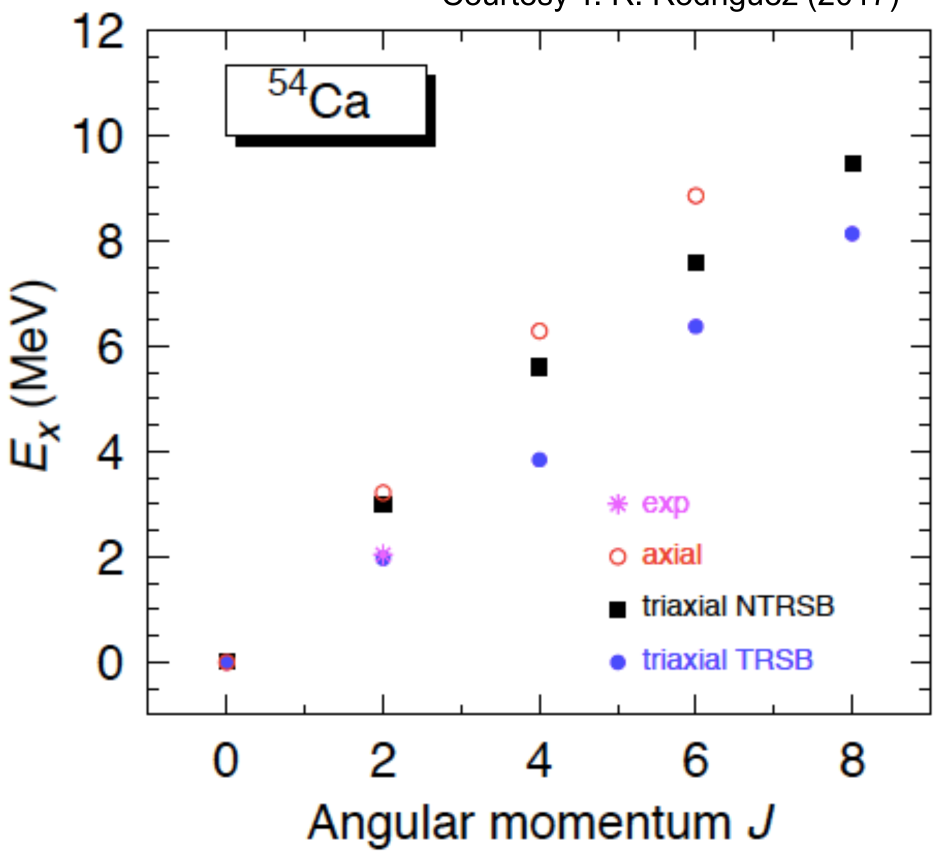


Beyond mean-field calculations for neutron-rich Ca

- overall proper predictions from GCM with Gogny D1S
- cranking necessary for a proper prediction of absolute excitation energies



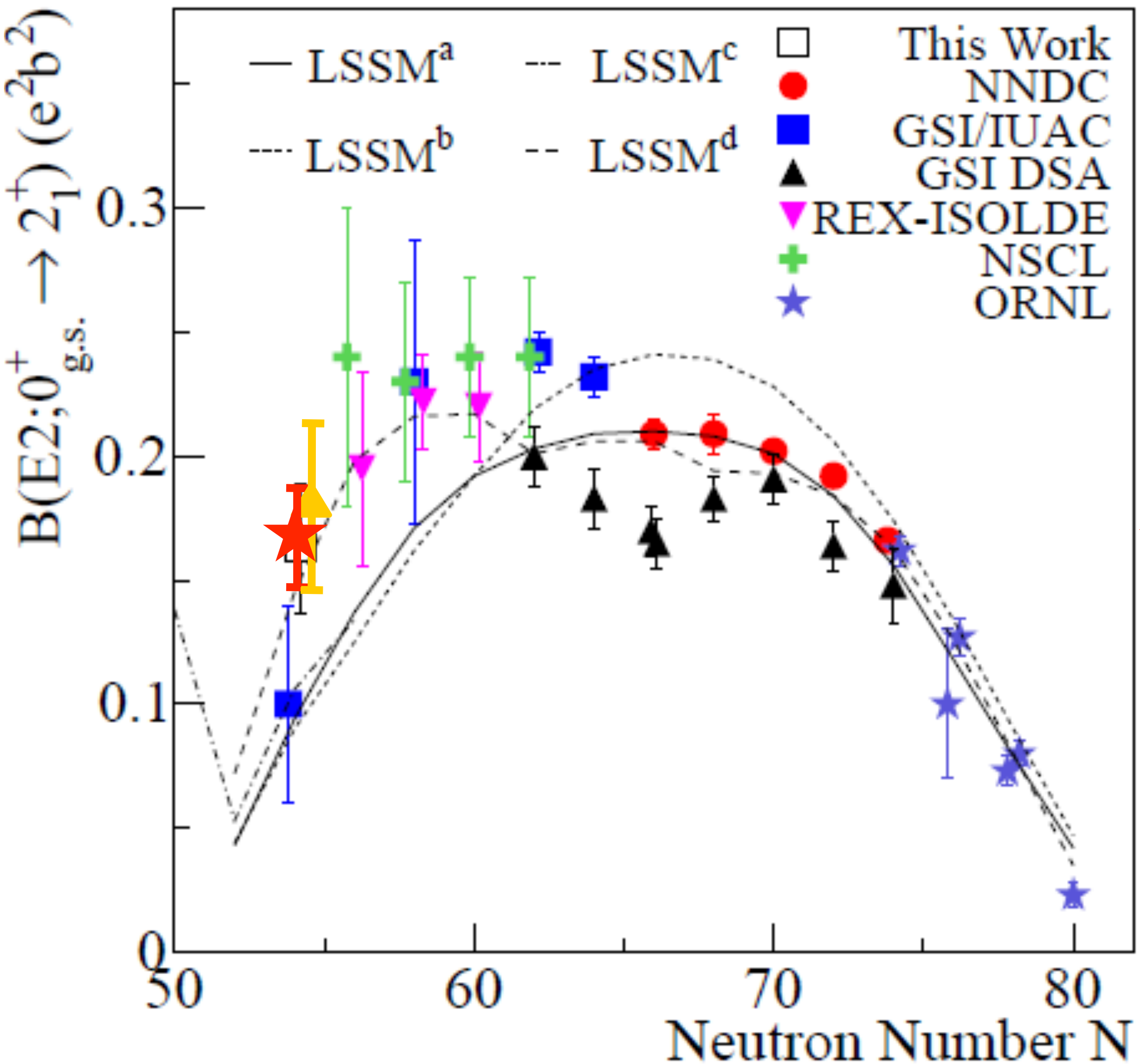
Courtesy T. R. Rodriguez (2017)



T. R. Rodriguez, Phys. Rev. Lett. **99**, 06201 (2007)

- The shell model and shell closures
- Origins of shell evolution
  - diffusiveness of the nuclear surface
  - spin-isospin and tensor terms of the NN interaction
  - reduction of spin-orbit
  - 3N forces
- RI beam production and future facilities
- The N=16 “new magic number”, collapse of N=20, 28 shell closures
- Mirror region: the N=40 island of inversion and the ^{78}Ni region
- Are N=32 and 34 “new” magic numbers?
- **Heavier doubly-magic nuclei: ^{100}Sn and ^{132}Sn**

Collectivity in the ^{100}Sn region



Measurements for ^{104}Sn

GSI

G.Guastalla *et al*., PRL **110**, 172501 (2013)

$B(E2)=0.10(4)e^2b^2$

RIKEN

P. Doornenbal *et al*., PRC **90**, 061302(R) (2014)

$B(E2)=0.173(28)e^2b^2$

NSCL

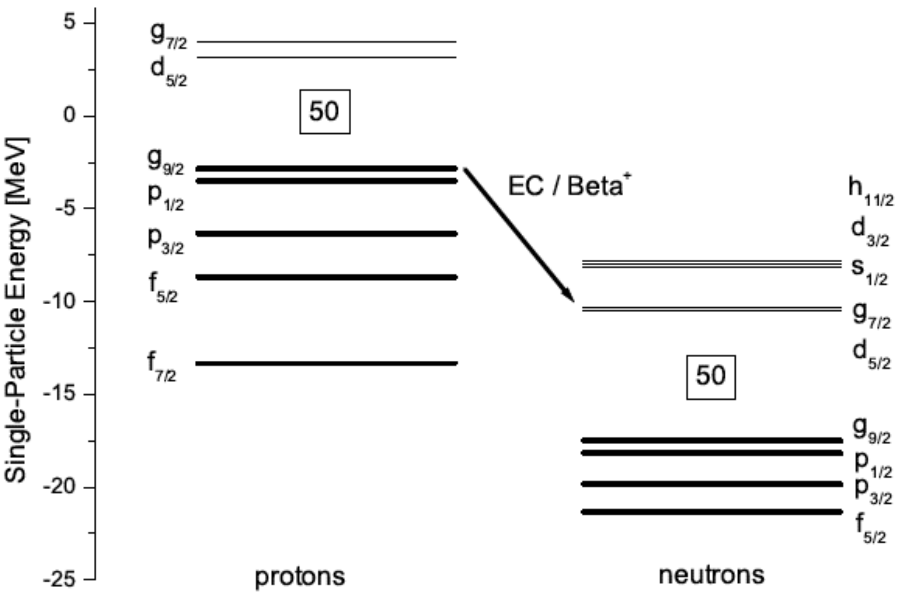
V.Bader et al. PRC **88**, 051301(R) (2013)

$B(E2)=0.180(37)e^2b^2$

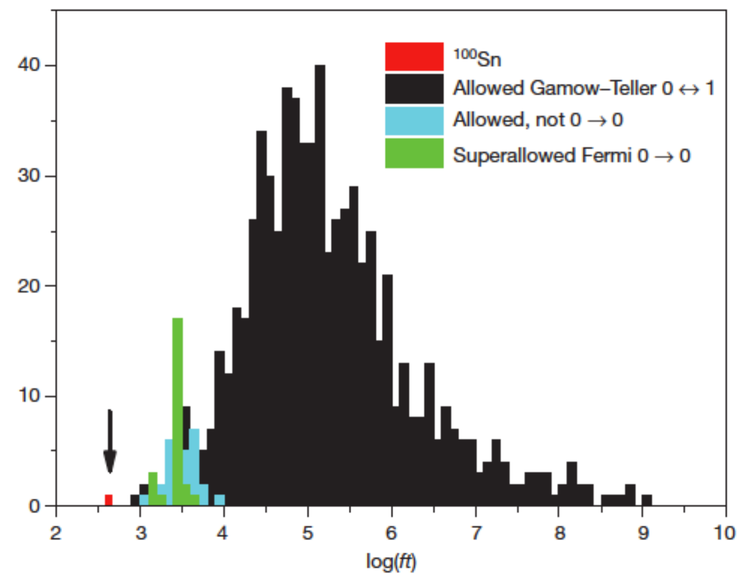
Collectivity in the ^{100}Sn region

- Gamow-Teller transition change proton into neutron
- Experimental probes: charge exchange reactions, **beta-decay**, EC decay
- Gamow-Teller strength $B_{GT} \sim 1/ft$
- Gamow-Teller strenght **sensitive to shell closure**

$$B_{GT}^{ESM} = \frac{4\ell}{2\ell+1} \cdot \left(1 - \frac{N_{\nu g7/2}}{8}\right) \cdot N_{\pi g9/2}$$



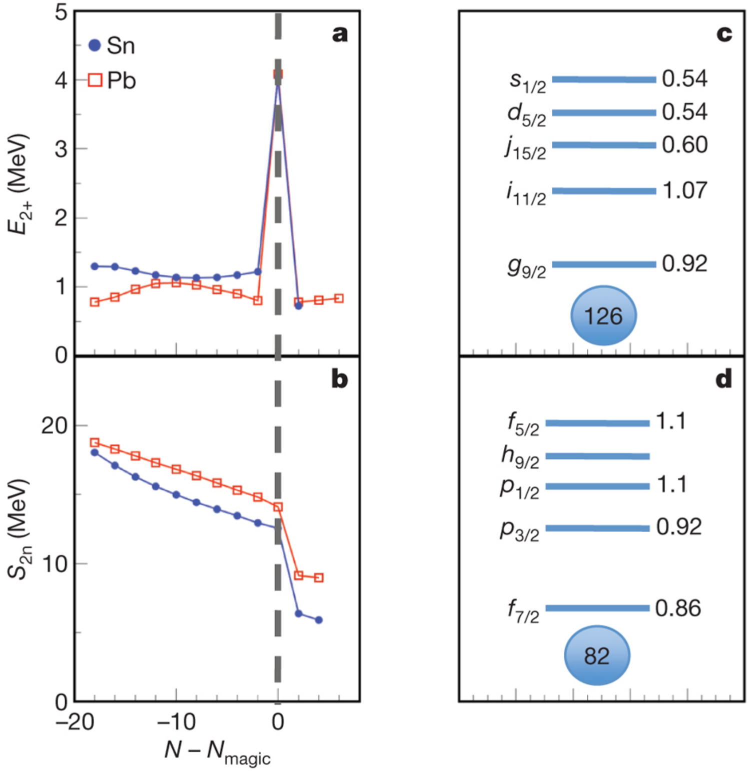
Hinke, PhD Thesis, Univ. Munchen (2010)
Hinke, Nature 486, 341 (2012)



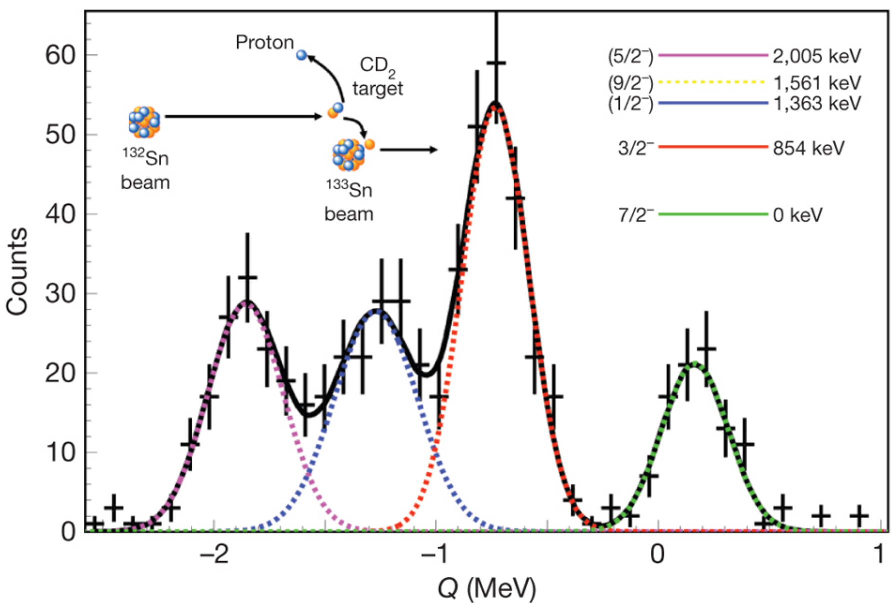
- All GT strenght on one final state ^{100}In(1^+)
- B_{GT}=9.1 exceptionally large
- **strong shell closure at ^{100}Sn**

Structure of ^{132}Sn

- Holifield RIB facility at Oak Ridge: re-accelerated fission fragment beam, 4.5 MeV/nucleon
- Machine is decommissionned today
- ^{132}Sn(d,p)^{133}Sn via missing mass
- Single-particle nature of neutron states in ^{133}Sn confirmed. **Validates ^{132}Sn as magic** [Neutron transfer: see tomorrow's lecture]



Q-value spectrum for the ^{132}Sn(d,p)^{133}Sn reaction at 54° in the centre of mass.



KL Jones *et al. Nature* **465**, 454-457 (2010)

Summary

- ❑ The picture of the nuclear shell structure has been explored since 40 years
- ❑ The nuclear shell model offers a succesfull framework to interpretate observed structure changes
- ❑ EDF-based approaches give overall sucessfull predictions
- ❑ **No breakdown of first-developped models**

- ❑ In the shell model picture, **monopole drifts** (spin-orbit,spin-isospin, tensor) develop and modify « spherical mean-field » gaps, while **the interplay with correlations** (pairing, quadrupole) drives the physics

- ❑ **Three-body forces** necessary for a quantitative understanding of shell structure and evolution

- Disappearance of **N=20, 28** as shell closures in the neutron-rich region
- Joint appearance of **N=16** as a new magic number
- **N=32,34** intepreted as new shell closure (at least show subshell effects)
- Island of inversion at N=20, N=40 (mirror phenomena)
- prediction of disappearance of the **N=50** shell closure below ^{78}Ni
- ^{100}Sn (**N=Z=50**) (unknown spectroscopy yet) and ^{132}Sn (**N=82**) seem doubly closed shell nuclei

- ❑ **Shape / configuration coexistence** exist everywhere across the nuclear landscape.