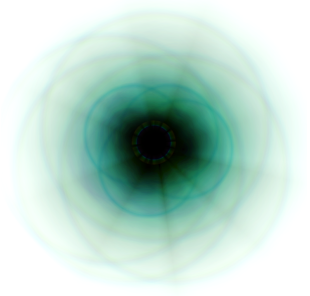
High-resolution spectroscopy of exotic nuclei through direct reactions

A. Matta for the direct reactions community

Nuclear Physics and Nuclear Astrophysics Town Hall Meeting,
Abbaye aux Dames, Caen,
30-31th January 2020

What is nuclear physics?

How to predict nuclear structure?

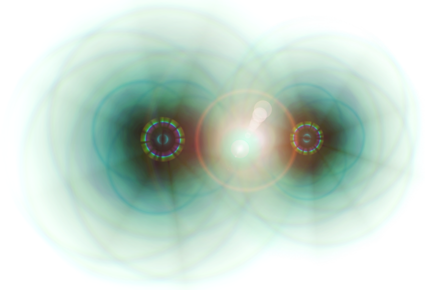


N neutrons + Z protons

- predict all eigen states
- predict any obervable: E, J^{π}, g,...

→ Getting the underlying W.F. right

How to predict nuclear dynamics?



Nuclei A + Nuclei B at Energy E

- predict all final states
- predict C.S. for each one

→ Getting the underlying W.F. right

A daunting task?

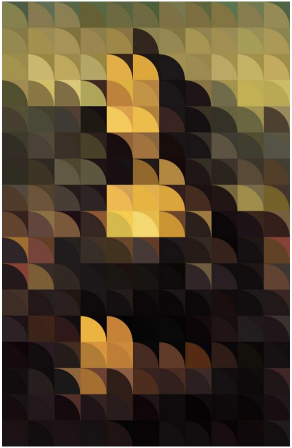
Solving the "too many / not enough" body problem with an unknown interaction

Current model doing OK:

→ Predict trends

→ Need to tune per region

→ Fail at predicting details



"You know what I mean" by Rafa Jenn

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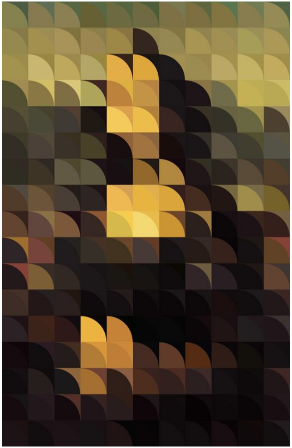
Hang on people!

- First 70% of a task in 30% of time
- 39 years from Nucleus to S.M.

→ All done in 2041



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Using directe reactions

Any reaction that occure in a single-step

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Any reaction that occure (mostly) in a single-step

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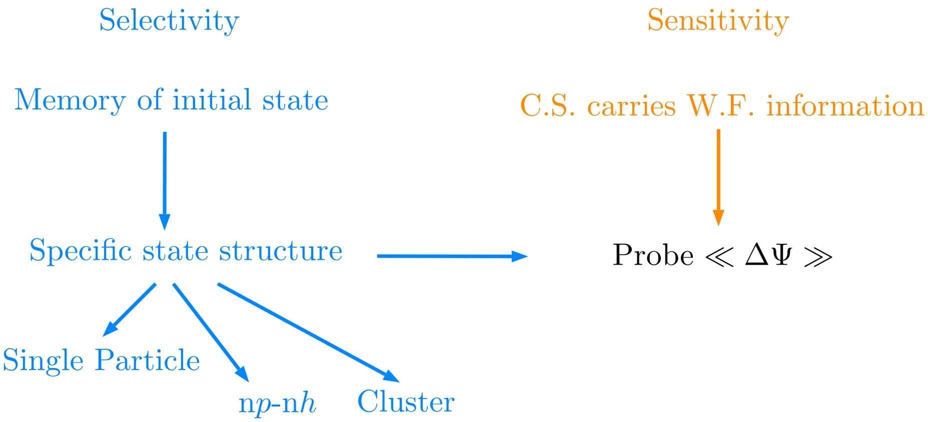


Using directe reactions

Any reaction that occure (mostly) in a single-step

Selectivity

Memory of initial state

Specific state structure

Single Particle

np-nh

Cluster

Sensitivity

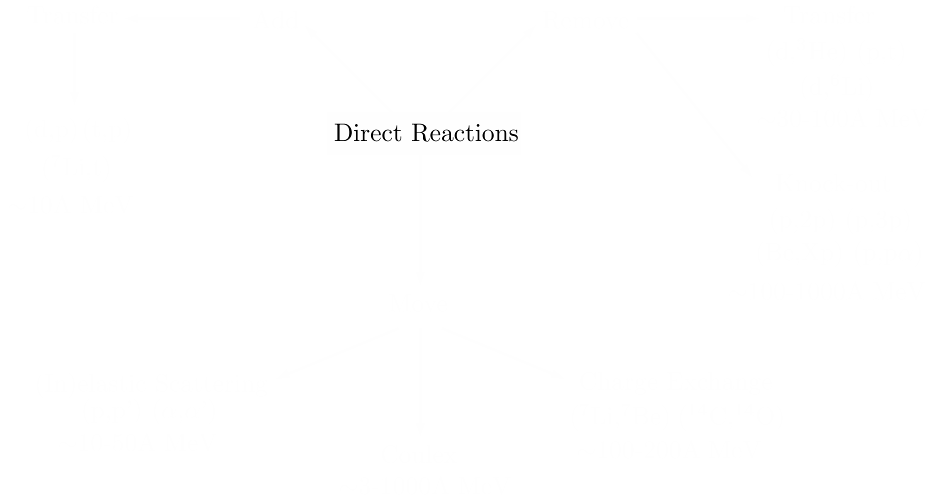
C.S. carries W.F. information

Probe $\ll \Delta\Psi \gg$

price to pay ⇒ small cross section

Using directe reactions

Any reaction that occure (mostly) in a single-step



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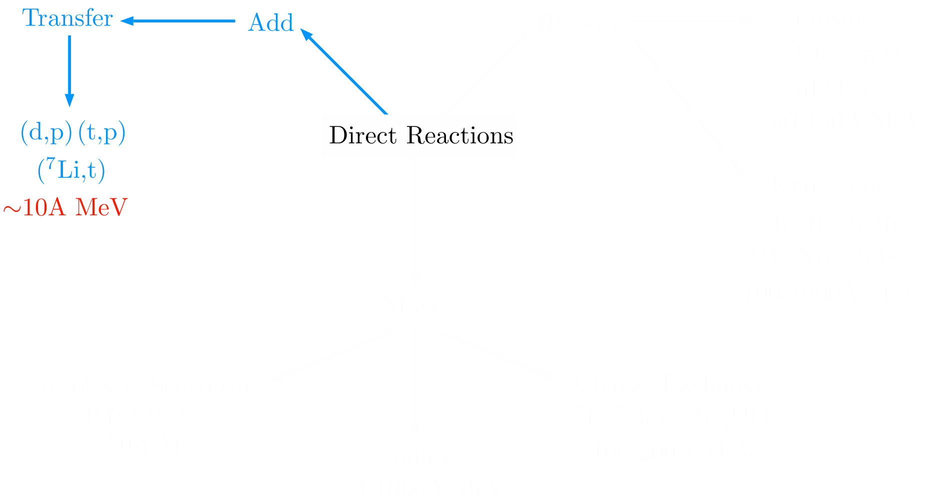

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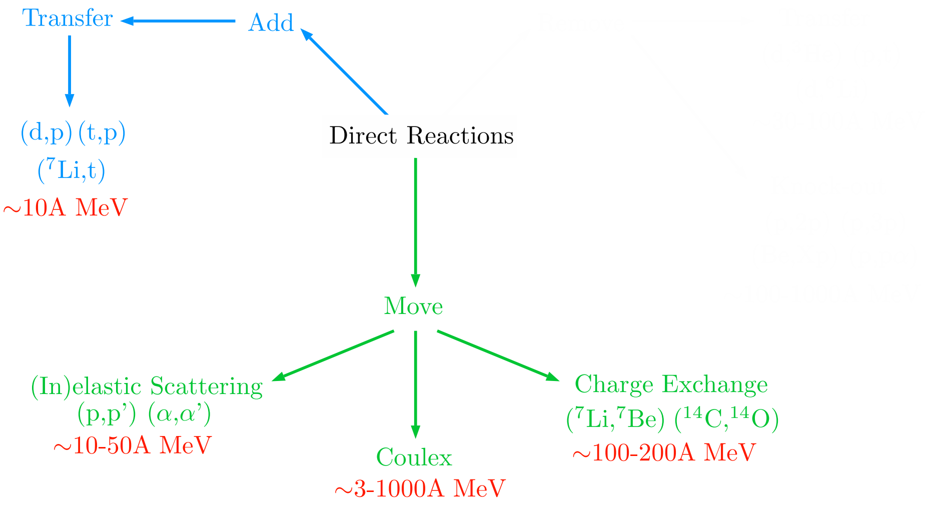

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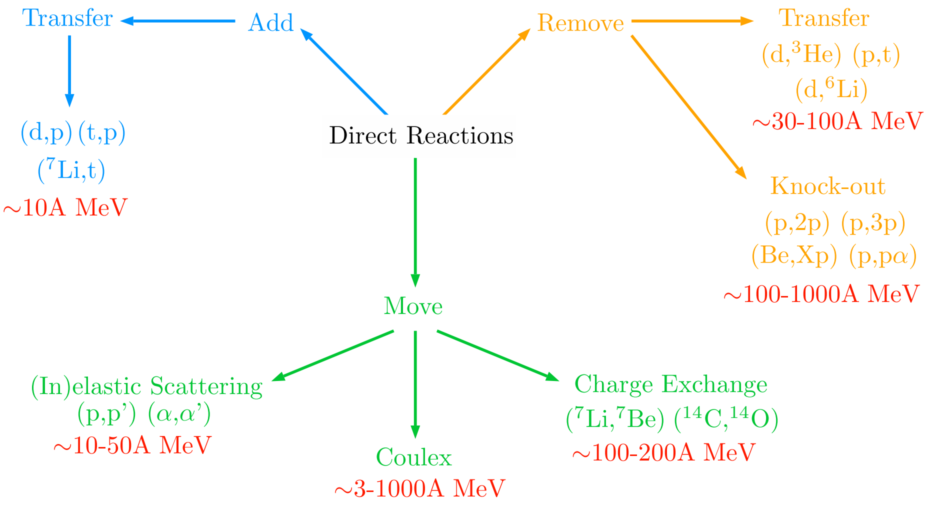

Extracting structure information from transfer

DWBA Formalism A(a,b)B

$$\frac{d\sigma}{d\Omega} = \frac{\mu_\alpha \mu_\beta}{(2\pi\hbar^2)^2} \frac{k_\beta}{k_\alpha} \frac{1}{(2J_a+1)(2J_A+1)} \sum_{M_\alpha M_\beta} |T_{\alpha\beta}|^2$$

$$T_{\alpha\beta} = \int \chi^*_\beta(\vec{r_{Bb}}, \vec{k_b}) \langle \Psi_f | \Psi_i \rangle \cdot \langle \phi_b | V_{na} | \phi_a \rangle \chi_\alpha(\vec{r_{Aa}}, \vec{k_a}) d\vec{r}_{Aa} d\vec{r}_{Bb}$$

Transition Matrix element

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Optical Potential describing elastic scattering

- Assume elastic scattering is dominant
- Imaginary part summed all other process
- Valid only at "small" CM angle
- Non-unicity of the solution

→ Need for large data set in the region

→ cf M. Grasso for theory driven one

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ab-initio calculation
or phenomenologic prescription

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Structure Input : nuclear overlap function

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Spectroscopic factor:

$$S = \int r^2 \langle \Psi_f | \Psi_i \rangle^2 d\vec{r} \approx \int r^2 |\phi_n|^2 d\vec{r}$$

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Overlap injected directly:

- Correct shape :
  → correct overlap (ΔL)
  → correct potentials (Real)
- Correct amplitude:
  → correct overlap (Binding)
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→ typical ∼20% incertitude on S
(d,^{3}He) vs (e,e'p)

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Extracting structure information from Coulex

Cline's criteria

Large impact parameter → Small scattering angle → "Safe" Coulex

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Low energy Coulex formalism

$$\frac{d\sigma_{if}}{d\Omega} = \frac{d\sigma_{ruth}}{d\Omega} P_{if} \rightarrow P_{if} = (\sum_n a^{(n)})^2$$

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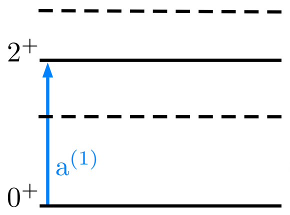
First Order

$a^{(1)} \propto \langle \Psi_f | M(E2) | \Psi_i \rangle \propto B(E2) \iff T_{1/2}$



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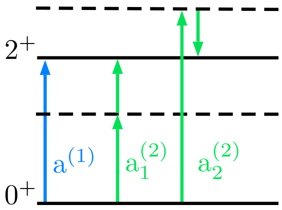

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For $j = f$ → reorientation effect

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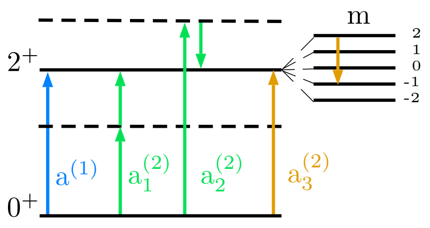

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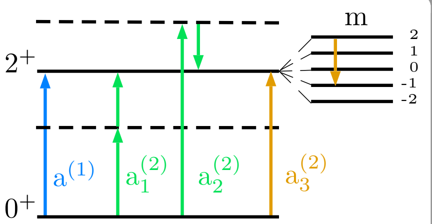

→ typical ~5% incertitude on M.E.

→ down to ~1% with $T_{1/2}$

Extracting structure information from Coulex

High-energy Coulex formalism

$$\sigma_{E\lambda} \approx \frac{Z_c e^2}{\hbar c} \frac{\pi}{e^2 b_0^2} \mathrm{B}(\mathrm{E}\lambda)$$

- **sensible to all B(Eλ)**
- single step only

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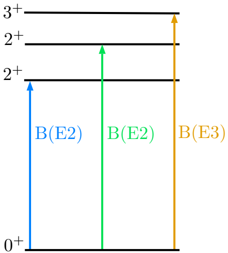
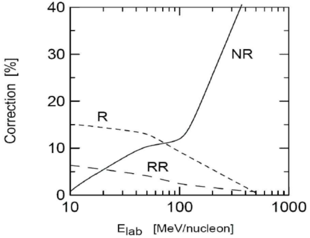
Recoil Relativist (RR) correction

$$b \rightarrow b + \frac{\pi a}{2\gamma}$$

$$a = \frac{Z_p Z_c e^2}{m_0 c^2 \beta^2}$$





C.A. Bertulani *et al*, Phys.Rev. C68 (2003) 044609

Extracting structure information from Knock-out

Knock-out formalism for $N^{A}(T,X)N^{A-1}$

$$\text{Core + nucleon } n \Rightarrow |\Psi_i\rangle = |\Psi_f\rangle \otimes |\phi_n\rangle$$

$$\sigma_{sp} = \sigma_{absorbtion} + \sigma_{diffraction}$$

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Glauber formalism

$$\sigma_{absorbtion} = \int b|S_C|^2(1-|S_n|^2)db$$

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$$S_C(\vec{b}) = e^{i\sigma_{NN}\int \rho_{Core}(|\vec{b}-\vec{r}|)\rho_{Target}(|\vec{r}|)d^2\vec{r}_\perp}$$

Eikonal approximation

+

$$\sigma_{NN}(\rho) \approx \sigma_{NN}$$

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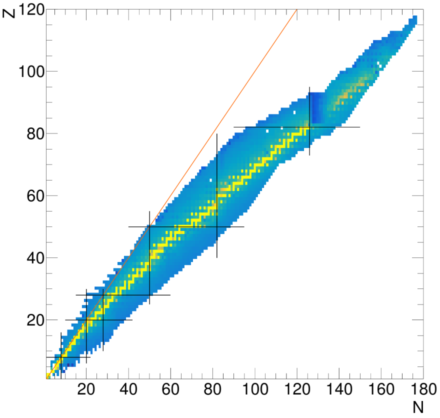
(Be,X) vs (e,e'p) $\Rightarrow$ typical ~20% incertitude on S

Shell evolution

Breaking the shell

Archipelago of shell breaking



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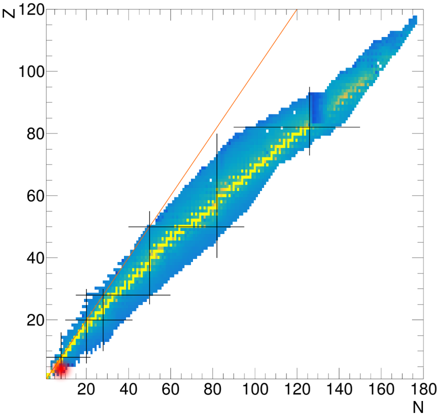

Branding in nuclear physics

A brief history:

- N=8 : "Parity inversion"

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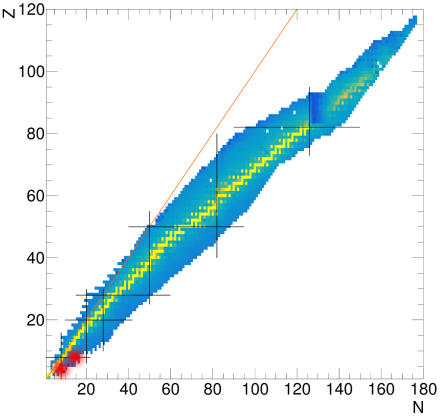

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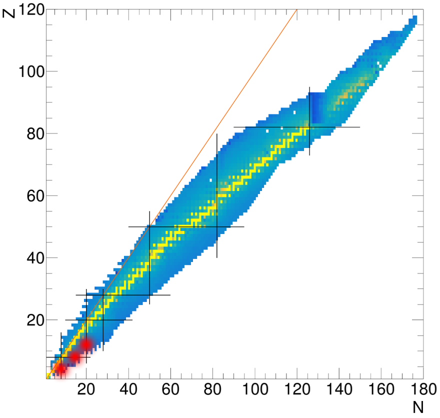

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- N=20 : "The Island of Inversion"

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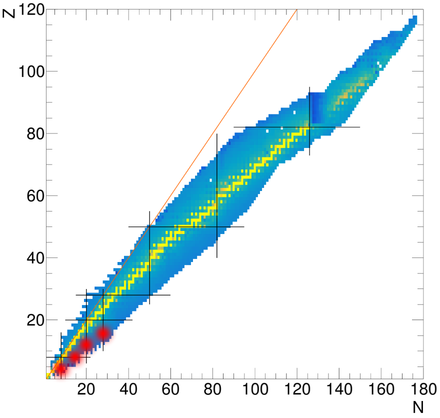

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- N=28 : "Shaping nuclei"

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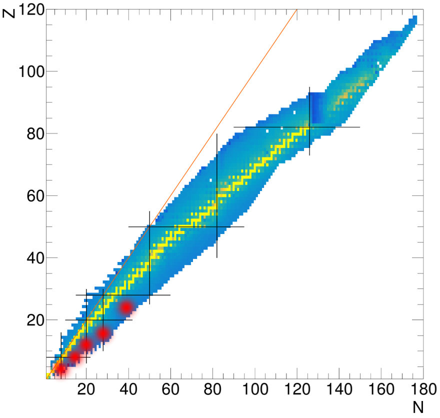

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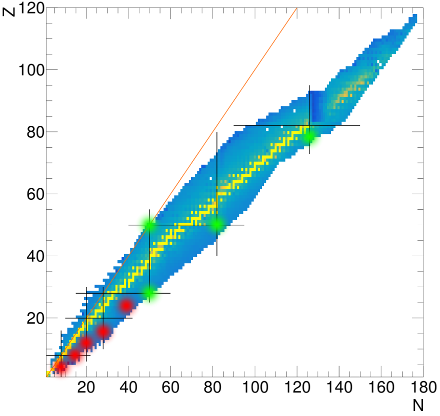

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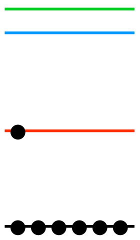
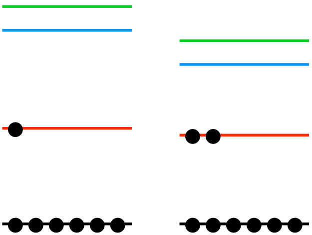
Open Territory:

- N=50 & Z=28
- N=50 & Z=50
- N=82 & Z=50
- N=126

Breaking the shell: a naively monopolar view



Breaking the shell: a naively monopolar view



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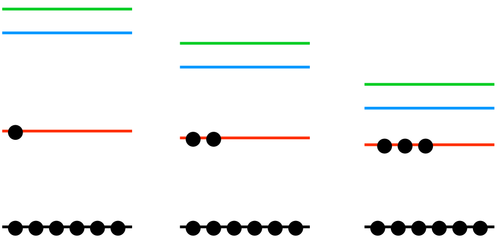
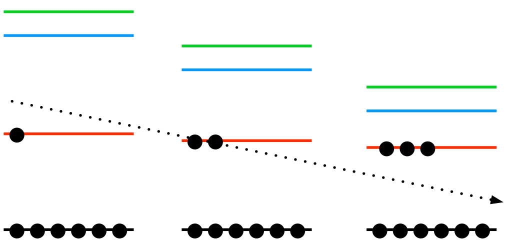


Breaking the shell: a naively monopolar view

Mainly Single Particle



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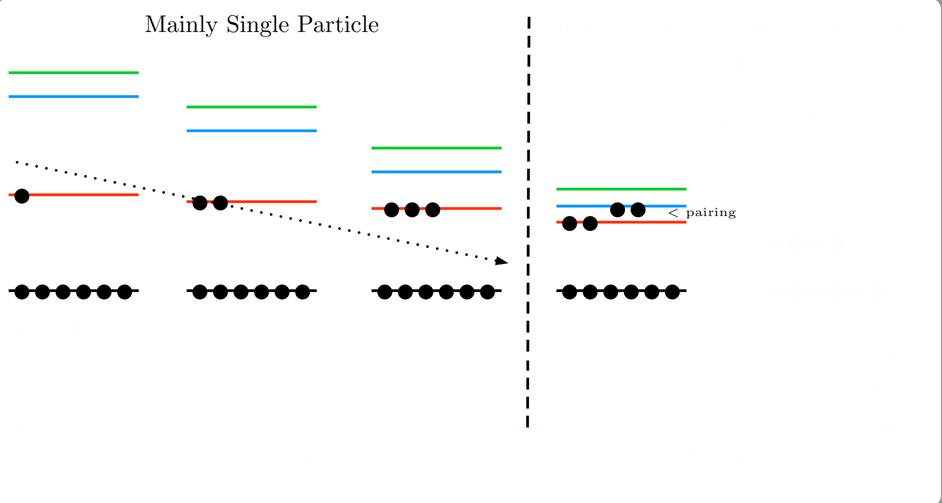
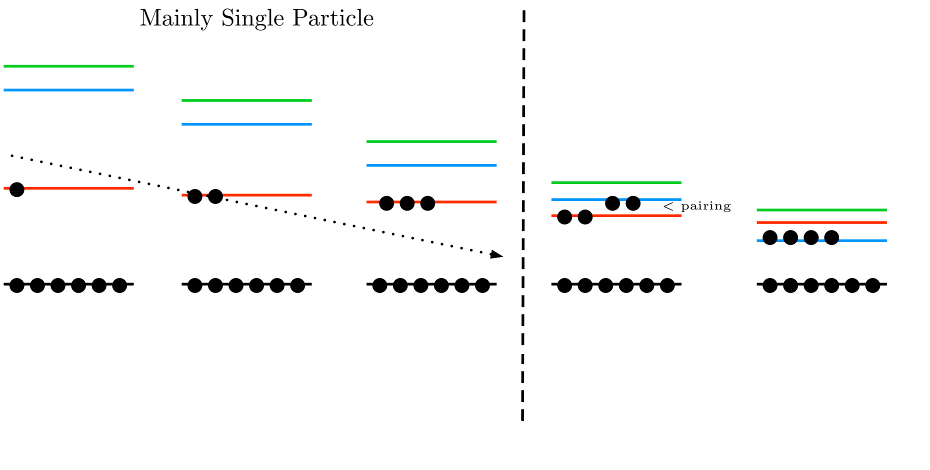


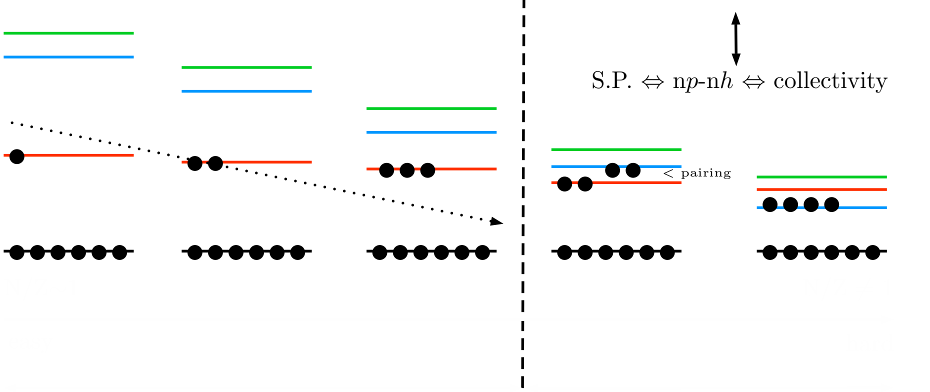
Breaking the shell: a naively monopolar view



Breaking the shell: a naively monopolar view

Mainly Single Particle

Intruder states & Shapes coexistence



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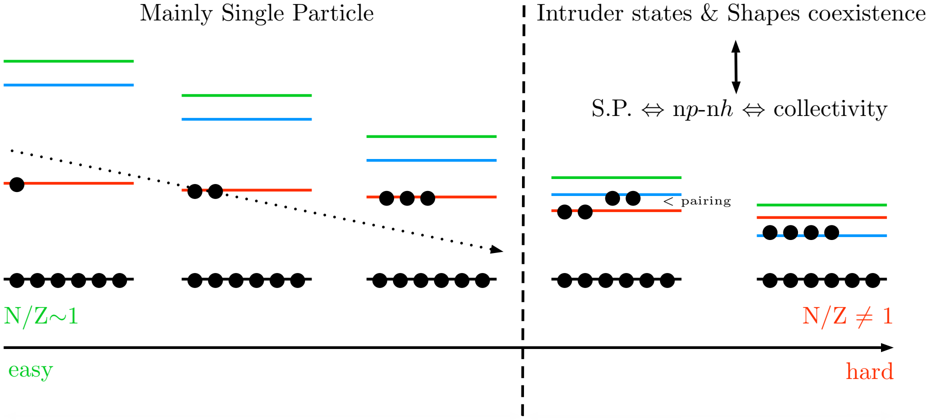

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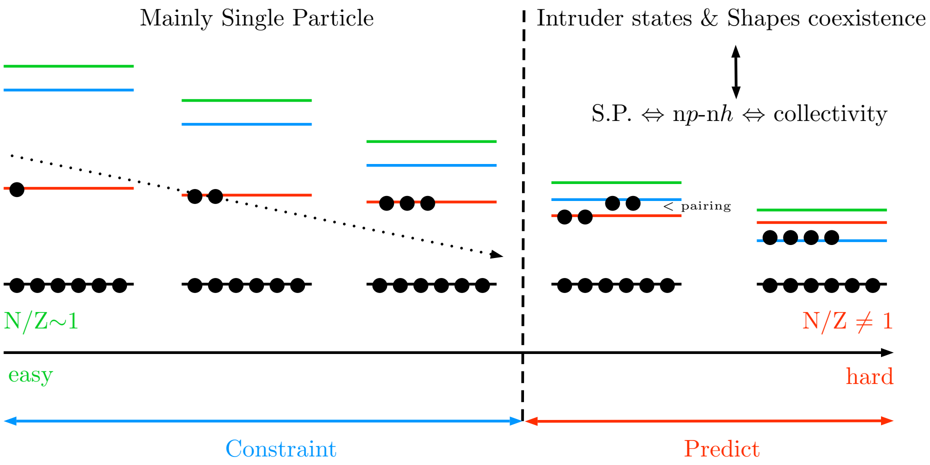

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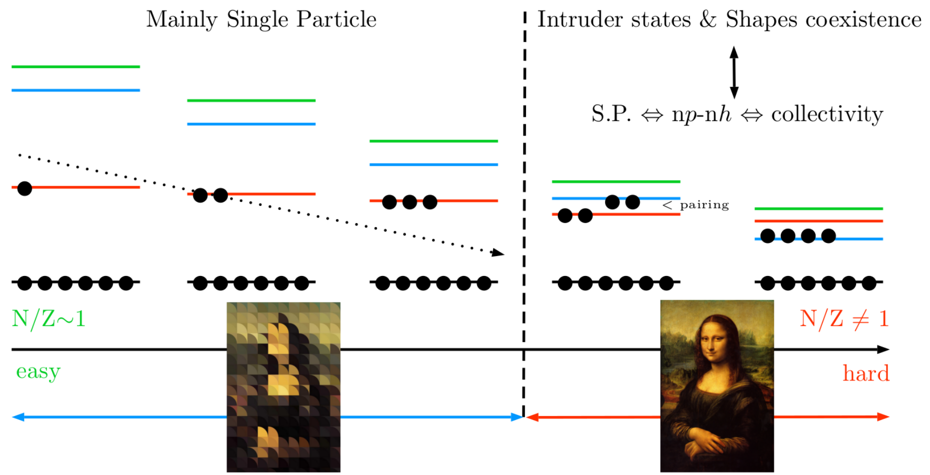
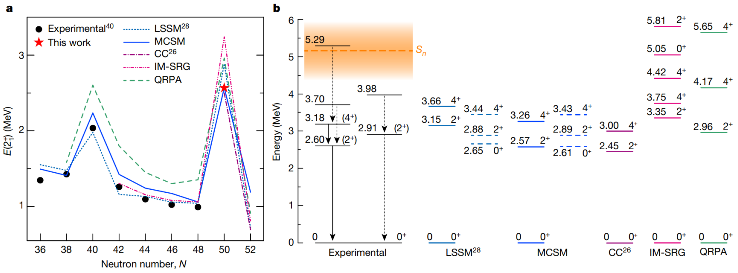


Shell evolution around ^{78}Ni

^{78}Ni identity card

- ✓ Doubly magic: N=50, Z=28, yet not a good core
- ✓ Low $2_1^+ \Longrightarrow np\text{-}nh \Longrightarrow$ Gap ? Valence Space? Interaction?
- ✓ Hints 0_2^+ $2_2^+ \Longrightarrow$ Spherical/Prolate

Recent result from RIKEN: a Japanese-French collaboration



R. Taniuchi *et al*, Nature 569, 53-58 (2019)

Shell evolution around ^{78}Ni

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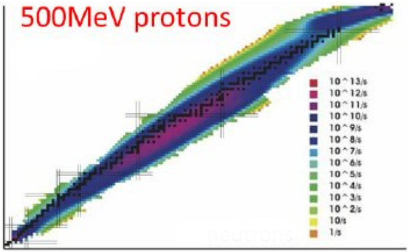
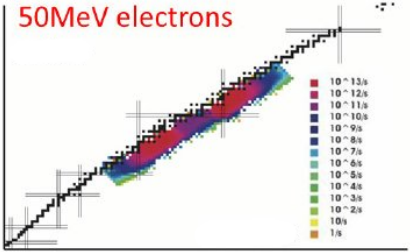
- ✓ Low $2_1^+ \Longrightarrow np\text{-}nh \Longrightarrow$ Gap ? Valence Space? Interaction?
- ✓ Hints 0_2^+ $2_2^+ \Longrightarrow$ Spherical/Prolate
- ✗ Difficult to produce : hard for fragmentation, out of reach for ISOL

Triumf ISOL production yield





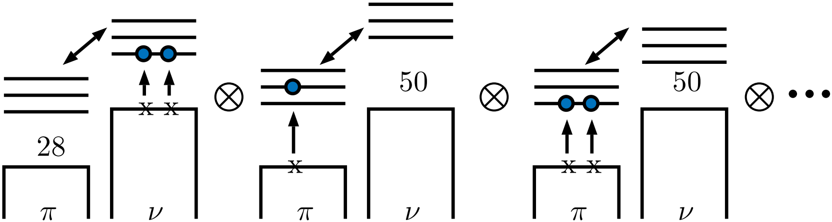
M. Narchetto *et al*, International Particle Accelerator 2015 (IPAC 2015)

Shell evolution around ^{78}Ni: Short term

High energy knock-out at RIKEN

Limited to specific np-nh states

Intruder

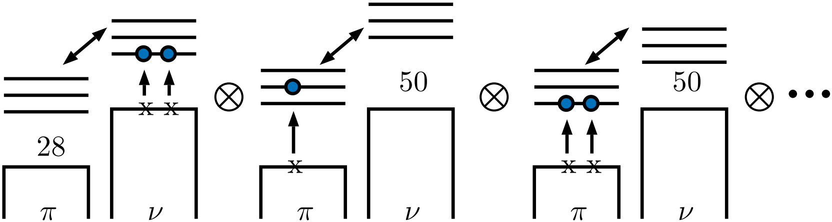


Shell evolution around ^{78}Ni: Short term

High energy knock-out at RIKEN

Limited to specific n*p*-n*h* states

Intruder



$^{80}Ni(p,p2n)$

Shell evolution around ^{78}Ni: Short term

High energy knock-out at RIKEN

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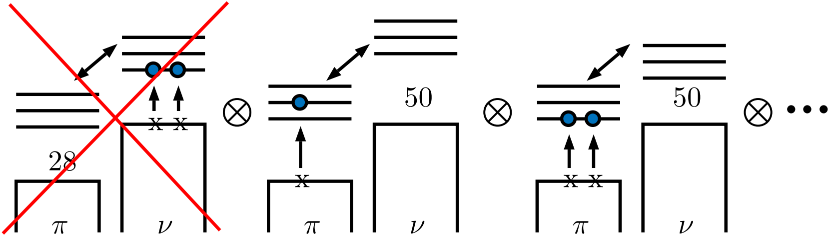
Intruder



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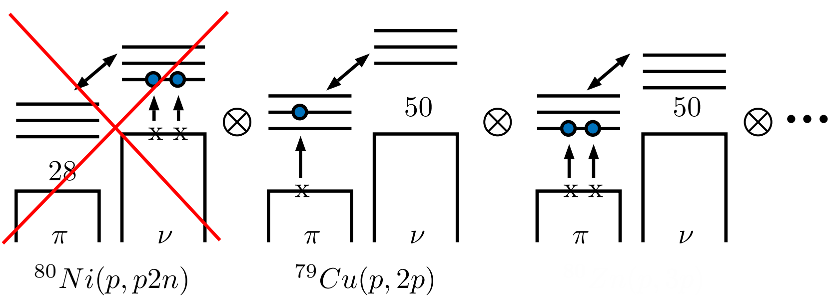

Shell evolution around ^{78}Ni: Short term

High energy knock-out at RIKEN

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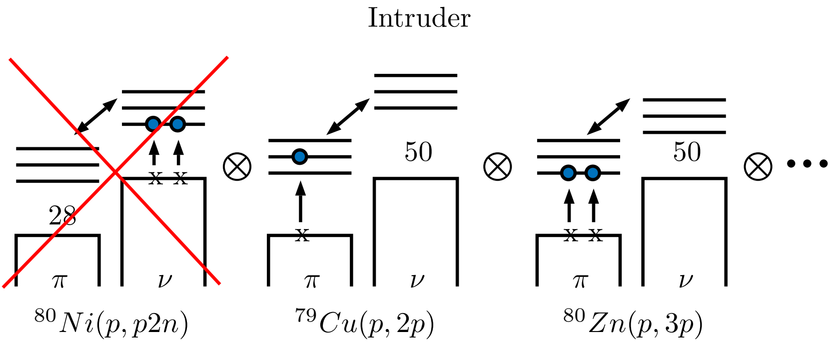
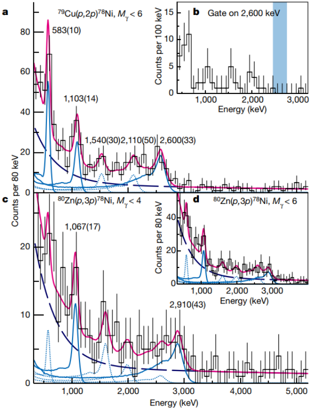


Shell evolution around ^{78}Ni: Short term

High energy knock-out at RIKEN

SEASTAR

- 5 pps ^{79}Cu
- 290 pps ^{80}Zn
- 26% efficency
- 10 cm LH_2 target



R. Taniuchi *et al*, Nature 569, 53-58 (2019)

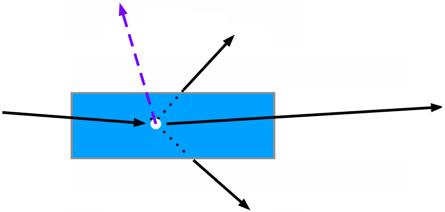
Shell evolution around ^{78}Ni: Short term

High energy knock-out at RIKEN

Typical Setup

- High energy beam
  → Thick target

Conceptual design



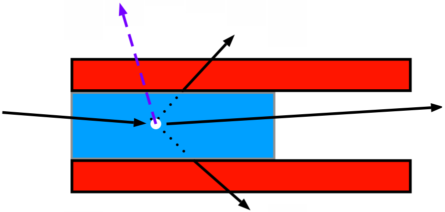
Shell evolution around ^{78}Ni: Short term

High energy knock-out at RIKEN

Typical Setup

- High energy beam
  - → Thick target
- (p,2p) (p,3p) (p,pn)
  - → Tracker

Conceptual design



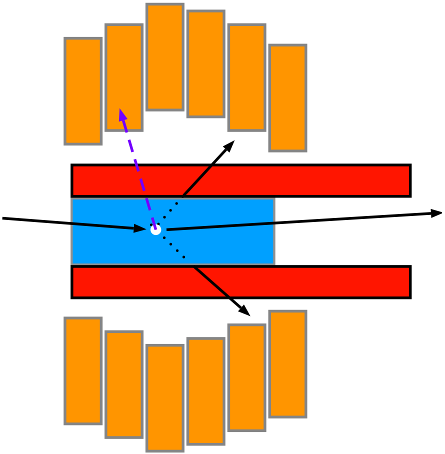
Shell evolution around ^{78}Ni: Short term

High energy knock-out at RIKEN

Typical Setup

- High energy beam
  - → Thick target
- (p,2p) (p,3p) (p,pn)
  - → Tracker
- Building level scheme
  - → NaI detector
  - → High-Efficiency
  - → $\gamma-\gamma$ coinc.

Conceptual design



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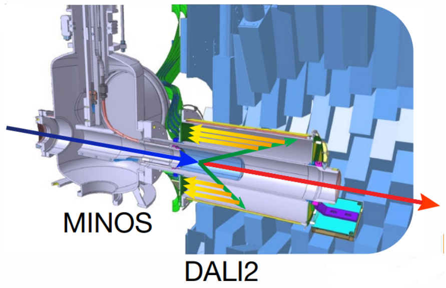

R. Taniuchi *et al*, Nature 569, 53-58 (2019)

Shell evolution around ^{78}Ni: Short term

High energy knock-out at RIKEN

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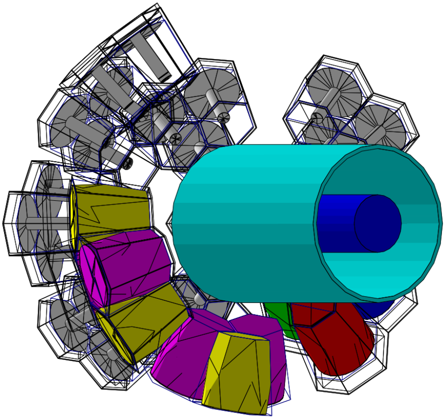
  - → High-Efficiency
  - → $\gamma - \gamma$ coinc.
- Detail spectroscopy
  - → Ge Tracking array
  - → High state density
  - → Low Eff. but good FWHM

HiCARI (RIKEN 2020)



Bootstrap MINOS-MINIBALL-GRETINA

Shell evolution around ^{78}Ni: Short term

High energy knock-out at RIKEN

Typical Setup

- High energy beam
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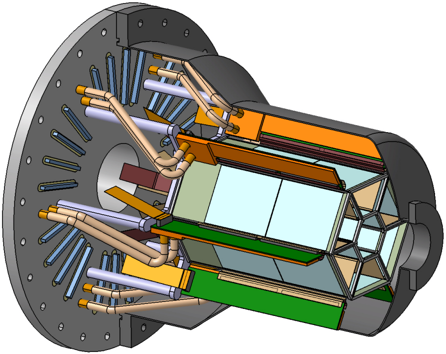
STRASSE (RIKEN/FAIR)

Silicon tracker + LH_2
DALI/CALIFA and/or AGATA



Darmstadt, RIKEN, LPC, FAIR

Shell evolution around ^{78}Ni: Short term

High energy knock-out at RIKEN

Typical Setup

- High energy beam
  - $\rightarrow$ Thick target
- (p,2p) (p,3p) (p,pn)
  - $\rightarrow$ Tracker
- Building level scheme
  - $\rightarrow$ NaI detector
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  - $\rightarrow$ Ge Tracking array
  - $\rightarrow$ High state density
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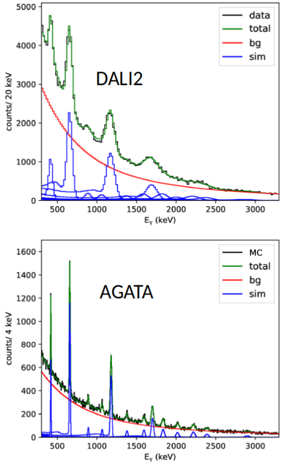
HPGe vs Calo



Shell evolution around ^{78}Ni: Short term

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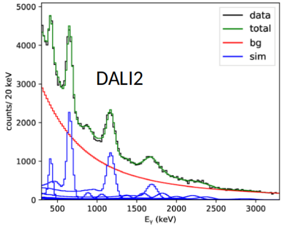
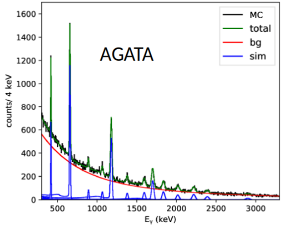
  - → Spectrometer

HPGe vs Calo

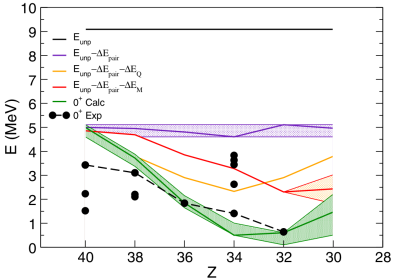




Shell evolution around ^{78}Ni: mid-term

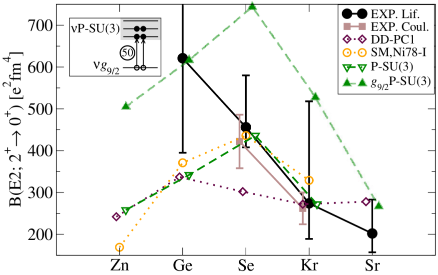
Transfer and coulex at SPES-TRIUMF-ISOLDE

Footprint in less exotic nuclei



A. Gottardo *et al*, PRL 121, 192502 (2018)

β-decay ^{80}Ga⇒^{80}Ge at ALTO



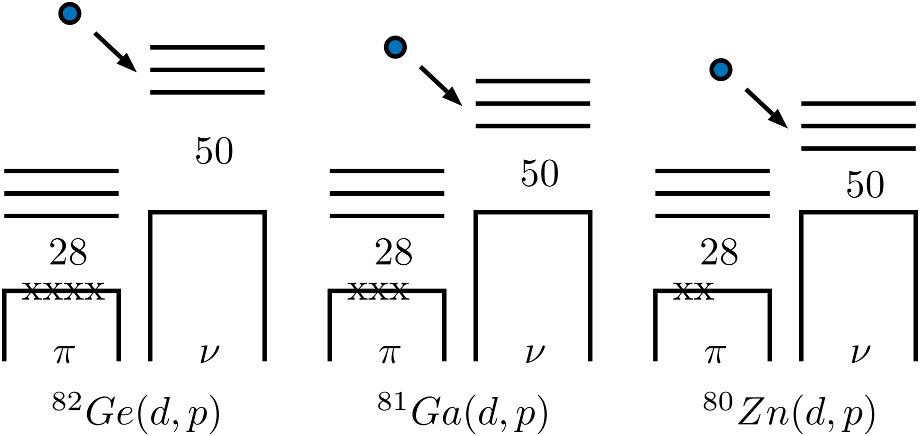
C. Delafosse *et al*, PRL 116, 182501 (2016)

Fusion and transfer-fission of U-Be at GANIL

Shell evolution around ^{78}Ni: mid-term

Transfer and coulex at SPES-TRIUMF-ISOLDE

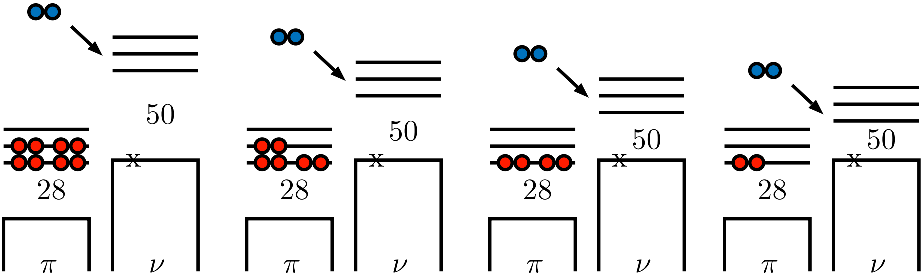
Single-nucleon transfer (d,p): direct probe of monopole shift



Shell evolution around ^{78}Ni: mid-term

Transfer and coulex at SPES-TRIUMF-ISOLDE

Two-nucleon transfer (t,p): direct probe of n*p*-n*h*



$^{85}Kr(t,p)$ $^{83}Se(t,p)$ $^{81}Ge(t,p)$ $^{79}Zn(t,p)$

Shell evolution around ^{78}Ni: mid-term

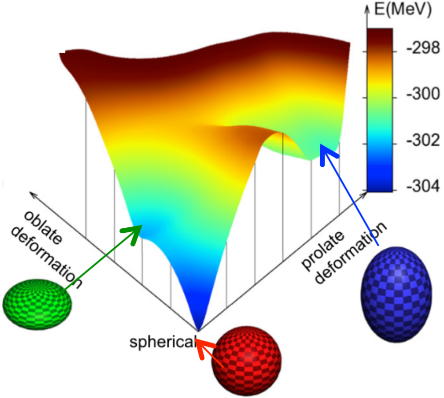
Transfer and coulex at SPES-TRIUMF-ISOLDE

Low-energy Coulex: direct probe of collectivity

Locating deformed 2^+ in Zn and Ge

- Small B(E2) spherical-deformed
- Large B(E2) deformed-deformed
- Quadrupolar moment $\Rightarrow \beta$
- Life-Time by DSAM

Coulex of ^{80,82,84}Ge and ^{78,80,82}Zn



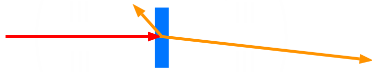
Shell evolution around ^{78}Ni: mid term

Transfer and coulex at SPES-TRIUMF-ISOLDE

Typical Setup

- Low energy beam
  - → Thin target
  - → Compound foil (CD_2)
  - → Implanted (Ti-t)
  - → Cryogenic (CHyMEN)

Conceptual design



Shell evolution around ^{78}Ni: mid term

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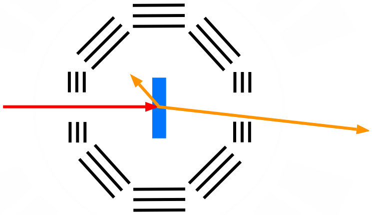
  - → 4π Silicon array

Conceptual design



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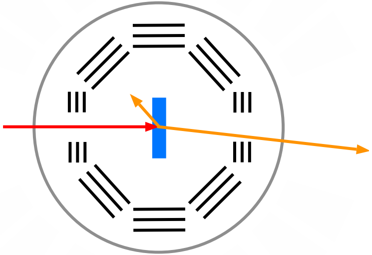

Shell evolution around ^{78}Ni: mid term

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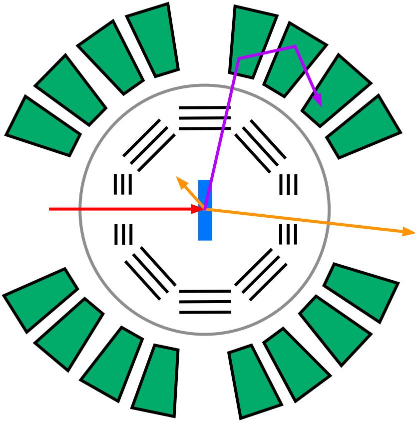
- Detail spectroscopy
  - → Ge Tracking array
  - → High state density
  - → Low Eff. but good FWHM

Conceptual design



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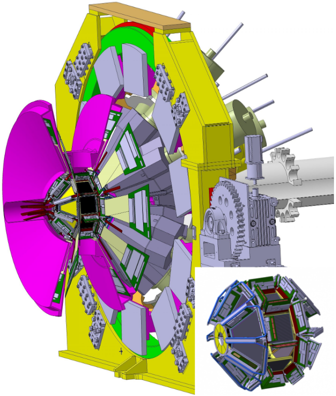
GRIT-AGATA



GRIT: IN2P3-INFN

Shell evolution around ^{78}Ni: mid term

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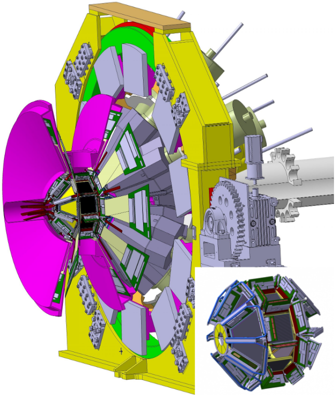
GRIT-AGATA



GRIT: IN2P3-INFN

Shell evolution around ^{78}Ni: long-term

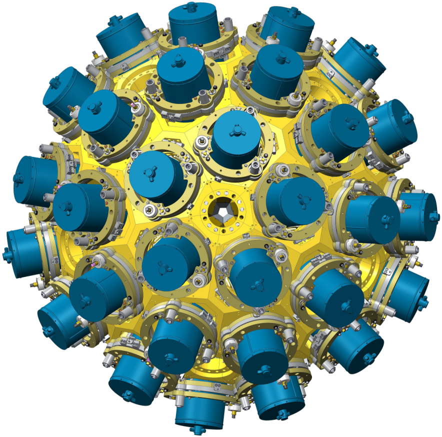
Coulex of ^{78}Ni and beyond at RIKEN and/or FAIR

A technical challenge

Probing physics beyond 2_1^+

- Stat:
  - $\rightarrow$ need x10 beams
  - $\rightarrow$ need high-efficiency
- Density of states:
  - $\rightarrow$ need high-resolution
- High velocity:
  - $\rightarrow$ need tracking

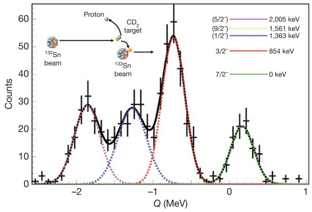
$\Rightarrow$ **Best tool: AGATA 4π**
$\Rightarrow$ **Realistic $\sim 3\pi$**



Shell Evolution at ^{132}Sn and ^{100}Sn

^{132}Sn

- ✓ Doubly magic, but a good core?
- ✓ ISOL/Frag accessible
- ⇒ Result to be improved
- ⇒ Whole region to be mapped
- ⇒ Removal: RIKEN/FAIR
- ⇒ Addition: SPES/TRIUMF/ISOLDE



K.L. Jones, Nature 465, 454-457(2010)

Shell Evolution at ^{132}Sn and ^{100}Sn

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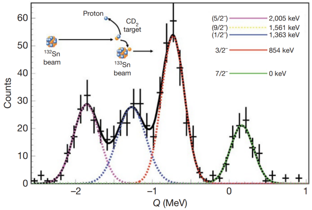


K.L. Jones, Nature 465, 454-457(2010)

^{100}Sn

- ✗ Out of reach today
- ✓ N=Z ⇒ Effect of p-n pairing
- ⇒ ISOL accessible?

nucleon-nucleon interactions

p-n pairing

Key points

Nature of $p-n$ pairing:

- isovector $\Rightarrow$ isospin symmetry
- isoscalar $\Rightarrow$ a lot of uncertainties

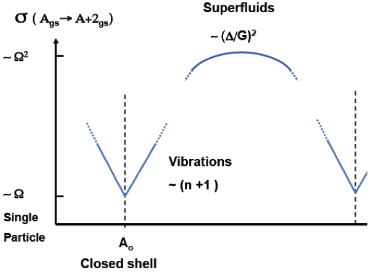
^{2}H bound:

- J=1^+, T=0
- T=0 $\gg$ T=1

T=0 superfluid phase?

- collective mode

Theoretical effect



pn transfer as an ideal probe

- isoscalar $\Rightarrow$ (d,^{4}He),(^{4}He,d)
- isovector $\Rightarrow$ (p,^{3}He),(^{3}He,p)
- Max effect in N=Z
- Max effect mid-shell

p-n pairing

Experimental program

Recently done:

- ^{56}Ni(p,^{3}He)^{54}Co (LISE)
- ^{52}Fe(p,^{3}He)^{50}Mn (LISE)

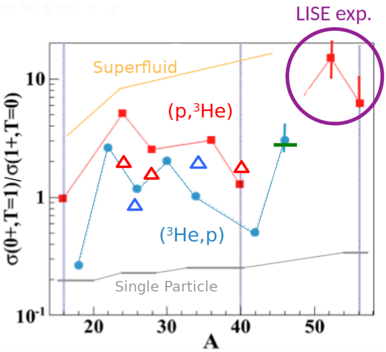
To be done:

- ^{56}Ni(^{3}He,p)^{58}Cu (SPIRAL1+)
- ^{48}Cr(^{3}He,p)^{50}Mn (SPIRAL1+)
- ^{48}Cr(p,^{3}He)^{46}V (LISE)

Setup:

- GRIT-AGATA-ZDS + cryo target

Experimental measures



pn transfer as an ideal probe

- isoscalar ⇒ (d,^{4}He),(^{4}He,d)
- isovector ⇒ (p,^{3}He),(^{3}He,p)
- Max effect in N=Z
- Max effect mid-shell

3-body forces in light nuclei

life time as a probe

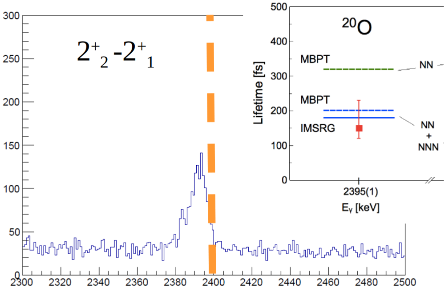
ab initio

- MBPT & IMSRG
- LT $\Rightarrow$ B(M1)
- sensible to NNN

First AGATA result:

- encouraging
- DSAM technique
- ^{18}O+Tl
- difficult due to BR

^{20}O AGATA results



M. Ciemala (ifj-PAN) *et al*, to be submitted to PRL

3-body forces in light nuclei

life time as a probe

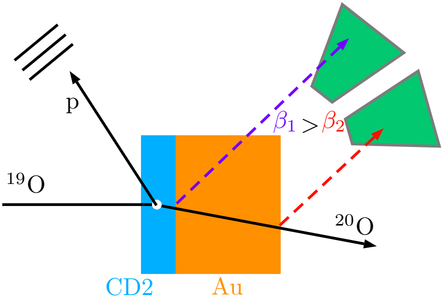
Next step: ^{19}O(d,p)

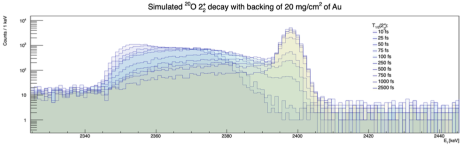
- Selectivity
- Fine tune sensibility
- GRIT-AGATA-VAMOS

Next next: ^{15}C(d,p)

- Hints VAMOS-AGATA
- Possible at LISE
- Specific setup

(d,p)+DSAM





E.Clement e775s MUGAST-AGATA-VAMOS 2020

3-body forces in light nuclei

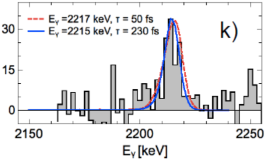
life time as a probe

Next step: $^{19}O(d,p)$

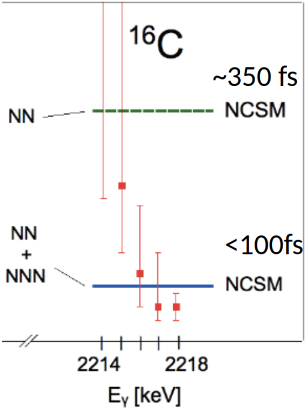
- Selectivity
- Fine tune sensibility
- GRIT-AGATA-VAMOS

Next next: $^{15}C(d,p)$

- Hints VAMOS-AGATA
- Possible at LISE
- Specific setup



^{16}C sensibility



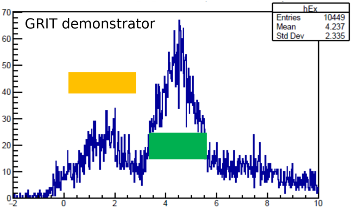
even more sensitive

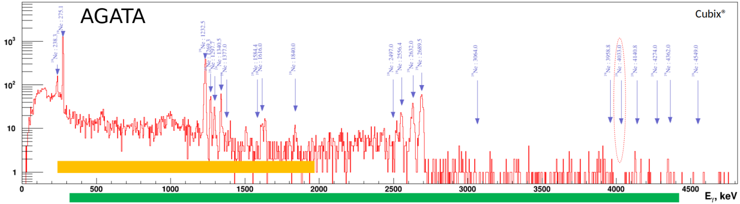
Cluster study ⇔ np-nh

Phenomena of custering is emerging in n-rich nuclei ⇒ *cf* O.Sorlin talk

Recent MUGAST(GRIT)-AGATA-VAMOS results

- $^{15}O(^{7}Li,t)^{19}Ne$:
  - → Hot-CNO cycle
  - → α capture rate
- Selectivity:
  - → Only cluster state
  - → Ex observable





C. Diget and N. de Sereville

The collaboration

LPC:

- Achouri
- Delaunay
- Flavigny
- Gibelin
- Marques
- Matta
- Orr
- Parlog

GANIL:

- Clement
- de France
- Lemasson
- Roger
- Sorlin
- Rejmund

IJCLab:

- Assié
- Astier
- Beaumel
- Bluemenfeld
- Franchoo
- Georgiev
- Ljungvall
- Lozeva
- Matea

IPHC:

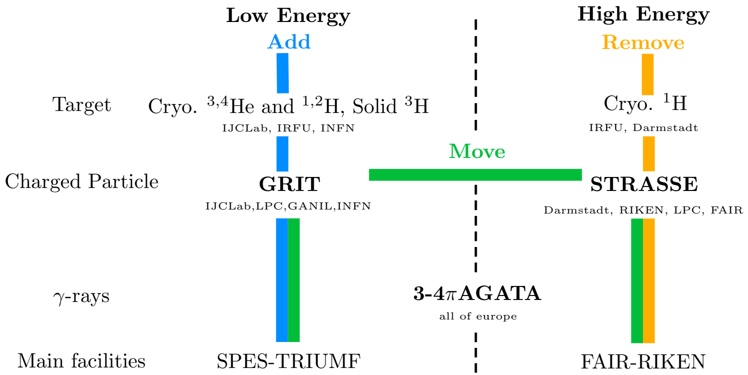
- Duchene
- Didierjean
- Moukaddam

IP2I:

- Dudouet

Many more things not mentionned

Technical developments



Synergies GT2

Theory:

- Nowacki
- Grasso
- Blender
- Hupin
- Lacroix

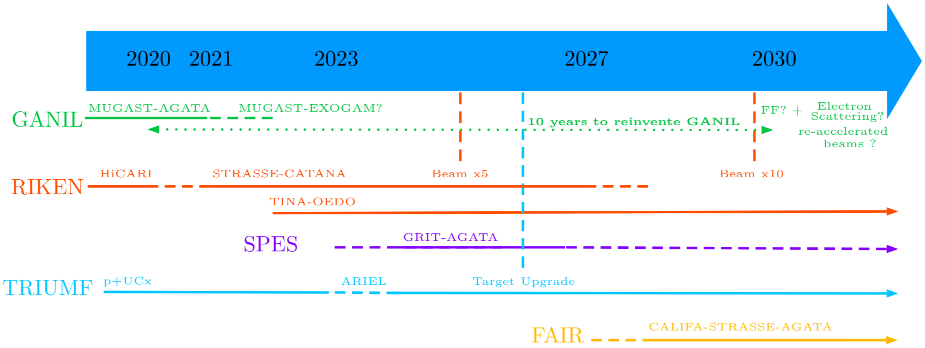
Physics:

- Caceres
- Flavigny
- Sorlin
- Hammache
- Gulminelli

Technical:

- Lopez-Martens
- Duchene
- Jurado

Direct reactions timeline



not mentionning ISOLDE, FRIB, RAON