Shell Model Far From Stability: IoI Mergers

Frédéric Nowacki

NUSPIN 2017, June 26th-29th 2017
The Archipelago of Islands of Inversion

N=8  N=20  N=28  N=40  N=50

$^{11}\text{Li}$  $^{32}\text{Mg}$  $^{42}\text{Si}$  $^{64}\text{Cr}$  $^{74}\text{Cr}$
Landscape of medium mass nuclei: Mergers
Evolution of nuclear shells due to Tensor force


$$\Delta V_{Tj} = \left\{ \begin{array}{ll}
(2j_2 + 1) V^T_{j \geq ,j'} + (2j_1 + 1) V^T_{j < ,j'} = 0,
\end{array} \right.$$  

- reduction of spin-orbit partners splitting while filling $j'$ shell

FIG. 4 (color). Proton (neutron) ESPE as a function of $N$ ($Z$). Lines in (a)–(c) show the change of ESPE’s calculated from the $\pi + \rho$ tensor force. Points represent the corresponding experimental data. (a) Proton ESPE’s in Ca isotopes relative to 1d$_{3/2}$. Points are from [13]. (b) Proton ESPE’s in Ni isotopes; calculations only. See [19] for related experimental data. (c) Neutron ESPE’s in $N = 51$ isotones relative to 2d$_{5/2}$; points are from [21]. (d) Proton ESPE’s in Sb isotopes; points are from [18]. Lines include a common shift of ESPE as well as the tensor effect (see the text).
Spin-orbit shell closure far from stability

- Evolution of $Z=14$ from $N=20$ to $N=28$
- Evolution of $Z=28$ from $N=40$ to $N=50$
- Evolution of $N=50$ from $Z=40$ to $Z=28$

- $^\Pi^+$
- $^\Pi^-$
- $^{14}_{\text{d}}d_{5/2}$
- $^{28}_{\text{f}}f_{7/2}$
- $^{42}_{\text{Si}}_{28}$
- $^{78}_{\text{Ni}}$ ???
- $^{132}_{\text{Sn}}$ doubly magic

- sd-pf: $^{42}_{\text{Si}}$ deformed

H. O.
Spin-orbit shell closure far from stability

- $\Pi^-$
- $\Pi^+$
- $\Pi^-$

H. O.

- $\Pi^+$
- $\Pi^-$
- $\Pi^-$

H. O.

- sd-pf: $^{42}$Si deformed
- pf-sdg: $^{78}$Ni ??
- sdg-phf: $^{132}$Sn doubly magic

- Evolution of Z=14 from N=20 to N=28
- Evolution of Z=28 from N=40 to N=50
- Evolution of N=50 from Z=40 to Z=28
Spin-orbit shell closure far from stability

- $\Pi^+$
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- sd-pf: $^{42}$Si deformed
- $^{78}$Ni ???
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- Evolution of Z=14 from N=20 to N=28
- Evolution of Z=28 from N=40 to N=50
- Evolution of N=50 from Z=40 to Z=28
Physics around $^{78}\text{Ni}$

**PFSDG-U interaction:**
- realistic TBME
- pf shell for protons and gds shell for neutrons
- monopole corrections (3N forces)
- proton and neutrons gap $^{78}\text{Ni}$ fixed to phenomenological derived values

**Calculations:**
- excitations across $Z=28$ and $N=50$ gaps
- up to $5 \times 10^{10}$ Slater Determinant basis states
- m-scheme code ANTOINE (non public version)
- J-scheme code NATHAN (parallelized version): $0.5 \times 10^9$ J basis states
Physics around $^{78}\text{Ni}$

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Neutron intruders constraints

PFSDG-U mix
Exp.

82Zn

N=50 Gap + V_{d5d5}
Neutron intruders constraints

RIKEN MINOS experiment
C. Shand, Z. Podolyak, et al. to be published
Neutron intruders constraints

RIKEN MINOS experiment
M. Lettman, V. Werner, N. Pietralla, accepted in Phys. Rev. C
### Neutron intruders constraints

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<th>Neutron number</th>
<th>PFSDG-U</th>
<th>NNDC</th>
<th>RIKEN</th>
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</tbody>
</table>

**RIKEN MINOS experiment**

M. Lettman, V. Werner, N. Pietralla, accepted in Phys. Rev. C

**Graph: S2n (MeV) vs. Neutron number**

- **Ge**
  - E(2+) (MeV)
  - PFSDG-U
  - NNDC
  - RIKEN

**Plot Details:**
- Neutron number range: 38 to 56
- Energy levels: 2+, 4+
Neutron intruders constraints

**Graph:**
- **Y-axis:** $S_2n$ (MeV)
- **X-axis:** Neutron number
- **Lines:**
  - JUN45
  - PFSDG-U
  - AME2016
  - ISOLTRAP
- **Data Points:**
  - Copper ($Cu$) is marked.

**Text:**
- Data: AME2016 and ISOLTRAP Collaboration 2017
NpNh excitations

[Graph showing energy levels (S2n) vs. Neutron number for different isotopes with Cu as a marker.]

- theory PFSDG-U
- data: AME2016 and ISOLTRAP Collaboration 2017
NpNh excitations

Cu

S2n (MeV)

Neutron number

2p2h

AME2016

ISOLTRAP

Cu

theory PFSDG-U

data: AME2016 and ISOLTRAP Collaboration 2017
NpNh excitations

\[ \begin{align*}
\text{Neutron number} & \quad 4p4h \\
\text{AME2016} & \quad \text{ISOLTRAP} \\
\text{theory PFSDG-U} & \quad \text{data: AME2016 and ISOLTRAP Collaboration 2017}
\end{align*} \]
NpNh excitations

![Graph showing the relationship between neutron number and S2n (MeV). The graph includes data points for theory PFSDG-U and data from AME2016 and ISOLTRAP Collaboration 2017.](image)

- theory PFSDG-U
- data: AME2016 and ISOLTRAP Collaboration 2017
NpNh excitations

![Graph showing Neutron number vs. S2n (MeV)]

- **8p8h**
- **AME2016**
- **ISOLTRAP**

- **Cu**

- **Theory PFSDG-U**
- **Data: AME2016 and ISOLTRAP Collaboration 2017**
NpNh excitations

\[ S_{2n} \text{ (MeV)} \]

\[ \text{Neutron number} \]

Theory PFSDG-U

Data: AME2016 and ISOLTRAP Collaboration 2017

F. Nowacki and ISOLTRAP COLLABORATION, to be published
NpNh excitations

Figure 5. Experimental moments compared to calculations for odd-odd isotopes. Where possible, the weighted mean of this work and literature values are plotted.

R. P. de Groote and the CRIS collaboration
in preparation
Spherical structure of $^{78}\text{Ni}$

Structure of $^{78}\text{Ni}$ from First-Principles Computations

G. Hagen,$^{1,2}$ G. R. Jansen,$^{3,1}$ and T. Papenbrock$^{1,2}$

$^1$Physics Division, Oak Ridge National Laboratory, Oak Ridge, Tennessee 37831, USA
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(Received 4 May 2016; revised manuscript received 18 August 2016; published 17 October 2016)

FIG. 2. Correlation between the energies of the $2^+_1$ excited state in $^{48}\text{Ca}$ and $^{78}\text{Ni}$, obtained from the interactions NNLO$_{sat}$ (circle), “2.0/2.0 (PWA)” (square), “2.0/2.0 (EM)” (diamond), “2.2/2.0 (EM)” (triangle up), and “1.8/2.0 (EM)” (triangle down). The error bars estimate uncertainties from enlarging the model space from $N = 12$ to $N = 14$. The thin horizontal line marks the known energy of the $2^+_1$ state in $^{48}\text{Ca}$.

FIG. 3. Convergence of the first $2^+_1$ excited state of $^{48}\text{Ca}$ and $^{78}\text{Ni}$ with increasing model-space size and compared to the data for the interaction 1.8/2.0 (EM) of Ref. [33].
Spherical structure of $^{78}\text{Ni}$

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Spherical structure of $^{78}$Ni

$^{78}$Ni

$E$ (MeV) vs. $p\hbar$ excitations

GS and $2^+_{ph}$ in $^{78}$Ni
Spherical structure of $^{78}\text{Ni}$

$\text{Ni}$

$E (\text{MeV})$

$\text{ph excitations}$

$^{78}\text{Ni}$

GS and $2^+_{\text{ph}}$ in $^{78}\text{Ni}$
Nilsson-SU3 self-consistency in heavy $N = Z$ nuclei

A. P. Zuker, A. Poves, F. Nowacki, and S. M. Lenzi

- monopole + quadrupole model
- proton gap (5MeV) and neutron gap (5 MeV) estimates
- Quasi-SU3 (protons) and Pseudo-SU3 (neutrons) blocks
- $Q_s = (\langle q_{20} \rangle + 3.5 b^2)^2 / 3.5$
- $E_n = G_n^{mp}(50) - \hbar \omega \kappa \left( \frac{\langle Q_0^m(\pi) \rangle}{15 b^2} + \frac{\langle Q_0^m(\nu) \rangle}{23 b^2} \right)^2$
- $G_n^{mp}(50) = n \left( \frac{3.0}{8} n_f + 2.25 \right) + \Delta(n) + \delta_p(n)$

Prediction of Island of strong collectivity below $^{78}$Ni !!!
Shape coexistence in $^{78}$Ni

- At first approximation, $^{78}$Ni has a double closed shell structure for GS
- But very low-lying competing structures
- From the diagonalization, the first excited states in $^{78}$Ni are:
  - $0^{+}_2-2^{+}_1$ predicted at 2.6-2.9 MeV and to be deformed intruders of a rotationnal band !!!
  - "1p1h" $2^{+}_2$ predicted at $\sim 3.1$ MeV
- Necessity to go beyond $(fpg_9 d_5^2)$ LNPS space and beyond ab-initio description
- Portal to a new Island of Inversion

Constrained deformed HF in the SM basis
(B. Bounthong, PhD Thesis, Strasbourg)
At first approximation, $^{78}\text{Ni}$ has a double closed shell structure for GS.

But very low-lying competing structures.

From the diagonalization, the first excited states in $^{78}\text{Ni}$ are:
- $0^+_{2} \rightarrow 2^+$ predicted at 2.6-2.9 MeV and to be deformed intruders of a rotationnal band !!!
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Portal to a new Island of Inversion.
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- Portal to a new Island of Inversion.

### Energy Levels and Properties

<table>
<thead>
<tr>
<th>State</th>
<th>$\Delta E^*$ (th.)</th>
<th>$Q_s$</th>
<th>$BE2\downarrow$ (th.)</th>
<th>$Q_i(e.f.m^2)$ from $Q_s$</th>
<th>$Q_i(e.f.m^2)$ from BE2</th>
<th>$\beta_2^e$</th>
<th>$\sim 0.3$ prolate</th>
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<tbody>
<tr>
<td>$2^+_1$</td>
<td>0.229</td>
<td>-39</td>
<td>516</td>
<td>135</td>
<td>195</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
At first approximation, $^{78}\text{Ni}$ has a double closed shell structure for GS.

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Necessity to go beyond ($fpg_9d_5$) LNPS space and beyond ab-initio description.

Portal to a new Island of Inversion.
Island of Deformation below $^{78}$Ni: PES’s

- $^{72}$Fe
- $^{74}$Fe
- $^{76}$Fe
- $^{70}$Cr
- $^{72}$Cr
- $^{74}$Cr
Island of Deformation below $^{78}$Ni: PES’s

<table>
<thead>
<tr>
<th></th>
<th>$E^* (2^+_1)$ (MeV)</th>
<th>$Q_s$ (e.fm$^2$)</th>
<th>$\text{BE}2_{↓}$ (e$^2$.fm$^4$)</th>
<th>$Q_{i}^m$ (e.fm$^2$)</th>
<th>$\beta^m$</th>
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<td>420</td>
<td>340</td>
<td>0.26</td>
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<tr>
<td>$^{72}$Cr</td>
<td>0.23</td>
<td>-48</td>
<td>549</td>
<td>407</td>
<td>0.30</td>
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<tr>
<td>$^{74}$Cr</td>
<td>0.24</td>
<td>-51</td>
<td>630</td>
<td>552</td>
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<tr>
<td>$^{72}$Fe</td>
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<td>$^{74}$Fe</td>
<td>0.47</td>
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<td>330</td>
<td>308</td>
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<tr>
<td>$^{76}$Fe</td>
<td>0.35</td>
<td>-39</td>
<td>346</td>
<td>320</td>
<td>0.25</td>
</tr>
</tbody>
</table>

Predicted New IoI centered at $^{74}$Cr
Shape Coexistence in $^{78}$Ni as the Portal to the Fifth Island of Inversion

F. Nowacki,1,2 A. Poves,3 E. Caurier,1,2 and B. Bounthong1,2
1Université de Strasbourg, IPHC, 23 rue du Loess 67037 Strasbourg, France
2CNRS, UMR7178, 67037 Strasbourg, France
3Departamento de Física Teórica e IFT-UAM/CSIC, Universidad Autónoma de Madrid, E-28049 Madrid, Spain and Institute for Advanced Study, Université de Strasbourg, France
(Received 30 May 2016; revised manuscript received 14 July 2016; published 27 December 2016)
The N=40 and N=50 IoI's Merge

MeV

N

36 38 40 42 44 46 48 50 52

Ni (exp)
Ni-Cr (lnps)
Ni (pfsdg)
Cr (exp)
Cr (pfsdg)

\( ^{68}\text{Ni} \)
\( ^{78}\text{Ni} \)
\( ^{64}\text{Cr} \)
\( ^{74}\text{Cr} \)
Like the N=20 and N=28 IoI's did
Shell evolution and Tensor mechanism in mid-mass nuclei

(c) Neutron ESPE

Energy (MeV)

1h11/2
2d3/2
1g7/2
2d5/2

(c) neutron SPE at N=51

1h11/2
1g7/2
2d3/2
2d5/2

T. Otsuka, et al.

K. Sieja, et al.

T. Otsuka, et al.

PRL 104, 012501 (2010)

Selected for a Viewpoint in Physics

PHYSICAL REVIEW LETTERS
week ending 8 JANUARY 2010

Novel Features of Nuclear Forces and Shell Evolution in Exotic Nuclei

Takaharu Otsuka,1,2 Toshio Suzuki,3 Michio Honma,4 Yutaka Utsuno,5 Naofumi Tsunoda,1
Koshiroh Tsukiyama,1 and Morten Hjorth-Jensen6

1Department of Physics, University of Tokyo, Hongo, Bunkyo-ku, Tokyo 113-0033, Japan
2Center for Nuclear Study, University of Tokyo, Hongo, Bunkyo-ku, Tokyo 113-0033, Japan
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5Japan Atomic Energy Agency, Tokai, Ibaraki, 319-1195 Japan
6Department of Physics and Center of Mathematics for Applications, University of Oslo, N-0316 Oslo, Norway

(Received 29 September 2009; published 4 January 2010)
Effective Single Particle Energies: Trends

Silicium chain

![Graph showing trends in effective single particle energies for Si isotopes.]

- Neutron number
- ESPE (MeV)

Isotopes:
- $^{34}$Si
- $^{42}$Si

Lines represent different orbitals:
- d5/2
- s1/2
- d3/2
Spin-Tensor decomposition

\[ V = \sum V_k = \sum U^k.S^k \]

<table>
<thead>
<tr>
<th>( k )</th>
<th>( S )</th>
<th>( S' )</th>
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<td>0</td>
<td>0</td>
<td>C=Central</td>
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<td>ALS=antisymmetric spin-orbit</td>
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<td>1</td>
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<td>LS=spin-orbit</td>
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<td>1</td>
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<td>T=Tensor</td>
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Effective Single Particle Energies: Trends

Silicium chain

\[ \Delta \left( d_{5/2} - d_{3/2} \right) \text{ filling } f_{7/2} \text{ between } ^{34}\text{Si and } ^{42}\text{Si} \]

<table>
<thead>
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<th>G matrix</th>
<th>SDPF-U</th>
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<tr>
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<td>Central</td>
<td>+0.24</td>
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<td>-0.35</td>
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<td>Vector</td>
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<td>LS</td>
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<td>Tensor</td>
<td>-2.65</td>
<td>-2.77</td>
<td>+0.12</td>
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Neutron number
**Effective Single Particle Energies: Trends**

### Δ \( (f_{7/2} - f_{5/2}) \) filling \( g_{9/2} \) between \(^{68}\text{Ni}\) and \(^{78}\text{Ni}\)

<table>
<thead>
<tr>
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<tr>
<td>Tensor</td>
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<td>-2.38</td>
<td>+0.46</td>
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</table>

**Neutron number**
Effective Single Particle Energies: Trends

\[ \Delta \left( f_{7/2} - f_{5/2} \right) \text{ filling } g_{9/2} \text{ between } ^{68}\text{Ni} \text{ and } ^{78}\text{Ni} \]

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<td>-3.70</td>
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<tr>
<td>Tensor</td>
<td>-2.84</td>
<td>-2.38</td>
<td>+0.46</td>
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Neutron number

ESPE (MeV)

\[ f_{5/2}, p_{3/2}, p_{1/2}, g_{9/2}, f_{7/2} \]
Effective Single Particle Energies: Trends

ESPE (MeV) vs Neutron number

- g9/2
- d5/2
- g7/2
- s1/2
- d3/2
- h11/2

Sn

120Sn

132Sn

5.9

5.2
Effective Single Particle Energies: Trends

\[ \Delta (g_{9/2} - g_{7/2}) \text{ filling } h_{11/2} \text{ between } ^{120}\text{Sn and } ^{132}\text{Sn} \]

<table>
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<th>NNSP</th>
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<tr>
<td>Vector</td>
<td>+0.12</td>
<td>+1.55</td>
<td>+1.43</td>
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<td>LS</td>
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<tr>
<td>ALS</td>
<td>+0.49</td>
<td>+1.61</td>
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<tr>
<td>Tensor</td>
<td>-2.30</td>
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</table>
Effective Single Particle Energies: Trends

$\Delta (g_{9/2} - g_{7/2})$ filling $h_{11/2}$ between $^{120}\text{Sn}$ and $^{132}\text{Sn}$

<table>
<thead>
<tr>
<th></th>
<th>$V_{lowk}$</th>
<th>NNSP</th>
<th>diff.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tot</td>
<td>-2.15</td>
<td>+0.89</td>
<td>+3.04</td>
</tr>
<tr>
<td>Central</td>
<td>-0.034</td>
<td>+0.30</td>
<td>+0.33</td>
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<tr>
<td>Vector</td>
<td>+0.12</td>
<td>+1.55</td>
<td>+1.43</td>
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<tr>
<td>LS</td>
<td>-0.038</td>
<td>-0.06</td>
<td>-0.022</td>
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<tr>
<td>ALS</td>
<td>+0.49</td>
<td>+1.61</td>
<td>+1.12</td>
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<tr>
<td>Tensor</td>
<td>-2.30</td>
<td>-0.96</td>
<td>+1.34</td>
</tr>
</tbody>
</table>

Neutron number

ESPE (MeV)
The physics around magic or semi-magic closures depends of subtle balances between the spherical mean field and the (very large) correlation energies of the open shell configurations at play.

There is a common mechanism explaining the appearance of "islands of inversion/deformation" (IoI’s) in nuclei with large neutron excess, and shape coexistence usually shows up as a its portal.

The IoI’s at N=20 and N=28 merge in the Magnesium isotopes.

Shape coexistence in $^{78}$Ni is the portal to a new IoI at N=50.

The IoI’s at N=40 and N=50 merge in the Chromium isotopes.

Increasing role of spin-orbit force in intermediate mass region.
Summary

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- B. Bounthong, E. Caurier, H. Naidja, A. Zuker
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- J. Herzfeld