Nuclear structure far from stability

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Outline

• Introduction
• Island of inversion at N~40
• Shape coexistence: shell model description
• Beyond Z=28, N=40
• Conclusions
New phenomena far from stability

Nuclei known

0+\text{T}=1

T=1

0+

Nuclear SHELL Structure

1949

Neutron Star

Proton Single Particle Levels

\text{Neutron rich}

N/Z - 3

\text{N/Z} - 1.6

around the valley of nuclear stability

0+\text{T}=1

0+

T=1

126

r-process

p-process

s-process

supernova cores

neutron star processes

Number of Neutrons
The neutron-rich side

- How does the shell structure change far from stability?
- How do new regions of deformation develop at “magic” numbers?
- How does the effective interaction describe shape evolution and shape coexistence?
- Will new excitation/decay modes be observed far from stability?
- New dynamical symmetries or new shapes?
- Connection with Astrophysics
Atomic nuclei are characterized by a specific shell structure. How do the magic numbers depend on isospin?

Data on exotic nuclei put in evidence the role of specific terms of the nuclear interaction and demand an improved modelling.
The effective interaction

A multipole expansion

\[ V = V_m + V_M \]

- represents a spherical mean field extracted from the interacting shell model
- determines the single particle energies or ESPE

- correlations
- energy gains

Deformation

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Understanding monopole effects

The monopole matrix element of an operator $V$ can be written as:

$$V_{jj'}^T = \sum_J (2J + 1) \langle jj' | V | jj' \rangle_{JT} / \sum_J (2J + 1)$$

→ Averaged over possible orientations

As the orbit $j'$ becomes occupied, the single-particle energy of an orbit $j$, $e_j$ changes linearly:

$$\Delta e_j = V_{jj'} n_{j'}$$

T. Otsuka et al., PRL 104, 012501 (2010)

O. Sorlin and M.G. Porquet
PPNP 61 (2008) 602-673

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The monopole tensor force and the spe

Central part: global variation of the single-particle energies
Tensor part: characteristic behavior of spin–orbit partners, etc.

\[ j_\uparrow = l + \frac{1}{2} \]
\[ j_\downarrow = l - \frac{1}{2} \]

![Graphs showing variation of single-particle energies](image)

T. Otsuka et al., PRL 104, 012501 (2010)
N. A. Smirnova et al., PLB 686, 109 (2010)
Interplay: Monopole and Multipole

The interplay of the monopole with multipole terms, like pairing and quadrupole, determines the different phenomena we observe.

In particular, far from stability new magic numbers appear and new regions of deformation develop giving rise to new phenomena such as islands of inversion, shape phase transitions, shape coexistence, haloes, etc.
The islands of inversion (N=8,20,28)

At N=8 and N=20 the h.o. shell gap vanishes for very neutron rich nuclei.

Deformed intruder configurations fall below the spherical ones.

T. Otsuka EPJ S. Top. 156, 169 (2008)

A. Poves, 2011
Subshell closure at N=40

The increase of the $^{68}\text{Ni} \, 2^+$ excitation energy indicates a significant shell closure at N=40.
New island of inversion at N=40

S. Lunardi et al., PRC76, 034303 (2007).
S. M. Lenzi et al., PRC82, 054301 (2010).
W. Rother et al., PRL106, 022502 (2011).
Neutron excess and shell migration

Monopole shifts

T. Otsuka

\[ Z = 28 \]

\[ Z = 20 \]

protons

neutrons

protons

neutrons

Monopole shifts

\[ \pi f_{7/2} \]

\[ \nu g_{9/2} \]

\[ \nu f_{5/2} \]

\[ \nu p_{1/2} \]

\[ \nu p_{3/2} \]
The island of inversion at N~40:
Cr and Fe isotopic chains
Cr isotopic chain: data

**Beta decay @ GANIL**

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

- O. Sakrin et al.
- C. Donzaud
- F. Nowacki
- J.C. Angélil
- F. Azaiez
- C. Bourgeois
- V. Chita
- Z. Dlouhy
- S. Grévy
- D. Guillouard-Mueller
- F. Ibrahim
- K.-L. Krawczyk
- M. Lewitowicz
- S.M. Lukyanov
- J. Mraak
- Yu. E. Penionzhkevich
- F. de Oliveira Santos
- B. Pfeiffer
- F. Pougheon
- A. Poves
- M.G. Saint-Laurent
- and M. Stancik

**Inelastic scattering @ NSCL (MSU)**

**Multinucleon transfer @ ANL**

**Multinucleon transfer @ LNL**

**Shape transitions far from stability: The nucleus $^{58}\text{Cr}$**

- N. Marginean
- M. Lonzi
- A. Gadea
- E. Famaey
- S.J. Freeman
- D.R. Napoli
- D. Bazzacco
- S. Beshini
- B.R. Behera
- P.G. Bizzi
- A. Bizzeti-Sonè
- B. Bucurescu
- R. Chapman
- L. Corradi
- A.N. Deacon
- G. de Angelis
- F. della Vedova
- E. Fioett
- M. Ionescu-Bujor
- A. Iordache
- T. Król
- A. Latina
- X. Liang
- S. Lunardi
- G. Montagnoli
- N. Marginean
- M. Nespoli
- G. Pollarolo
- C. Rusu
- F. Scarlassara
- J.F. Smith
- K. Spohr
- A.M. Stefanini
- S. Szilner
- M. Trottet
- C.A. Ur
- B.J. Varley
- W. Zhimin

**Level structure of the neutron-rich $^{56,58,60}\text{Cr}$ isotopes: Single-particle and collective aspects**

- S. Zhu
- A.N. Deacon
- S.J. Freeman
- R.V. F. Janssens
- B. Fornal
- M. Honma
- F.R. Xu
- R. Broda
- I.R. Calderin
- M.P. Carpenter
- P. Chowdhury
- F.G. Kondev
- W. Królas
- T. Lauritsen
- S.N. Liddick
- C.J. Lister
- P.F. Mantica
- T. Pawlak
- D. Sekanina
- J.E. Smith
- S.J. Teber
- R.E. Tomlin
- B.J. Verder
- J. Waczyński
The CLARA+PRISMA setup at Legnaro

A & Z identification

“in-beam” γ-ray

25 Euroball Clover detectors for $E_\gamma = 1.3\text{MeV}$
Efficiency $\sim 3\%$
Peak/Total $\sim 45\%$
FWHM $\sim 10\text{keV}$
(at $v/c = 10\%$)
Cr isotopic chain

at the shape phase transition critical point?


Recent plunger experiment at MSU to measure the lifetimes and test the E(5).

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Fe isotopes and the shell model

Approaching N=40, Fe and Cr isotopes become deformed

Shell model calculations
Core $^{48}$Ca
valence space: full $fp$ for protons
$p_{3/2}, f_{5/2}, p_{1/2}, g_{9/2}$ for neutrons

The inclusion of the $g_{9/2}$ orbital is not enough
to allow a good theoretical description of $^{66}$Fe

S. Lunardi et al.,
PRC 76, 034303 (2007)
At and beyond N=40

The fpg model space is not able to reproduce the increase of collectivity of Cr and Fe isotopes approaching N=40.


Clara+Prisma

The fpg model space is not able to reproduce the increase of collectivity of Cr and Fe isotopes approaching N=40.
Rotational features are determined by the interplay of the quadrupole force with the central field in the subspace spanned by a sequence of $\Delta j = 2$ orbits that come lowest by the spin-orbit splitting.
Islands of inversion and symmetries

Islands of Inversion at the magic numbers can be understood in terms of symmetries.

A.P. Zuker et al., PRC 52 (1995)
The new interaction in the fpgd space

**LNPS interaction:** renormalized realistic interaction + monopole corrections

**48Ca core**
protons: full pf shell
neutrons: \( p_{3/2}, f_{5/2}, p_{1/2}, g_{9/2}, d_{5/2} \)

- KB3gr for the pf-shell
- renormalized G-matrix with monopole corrections for the remaining matrix elements involving the \( p_{3/2}, p_{1/2}, f_{5/2} \) and \( g_{9/2} \) neutron orbits
- the G-matrix based on the Kahana-Lee-Scott potential for the matrix elements involving the \( d_{5/2} \) orbit
- monopole corrections to reproduce the \( Z=28 \) and \( N=50 \) gaps in \( 78\text{Ni} \) based on data of neighboring nuclei

SML, F. Nowacki, A. Poves and K. Sieja (LNPS), PRC 82, 054301 (2010)
ESPE in N=20 and N=40

Note: the ground-state deformation properties result from the total balance between the monopole and the correlation energies

LNPS, PRC 82, 054301 (2010)
The N=40 isotones

A change of structure is observed along the isotonic chain in good agreement with the available data.

Occupation of intruder orbitals and percentage of p-h in g.s. configurations.

<table>
<thead>
<tr>
<th>Nucleus</th>
<th>$v_{g9/2}$</th>
<th>$v_{d5/2}$</th>
<th>0p0h</th>
<th>2p2h</th>
<th>4p4h</th>
<th>6p6h</th>
<th>$E_{\text{corr}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{68}\text{Ni}$</td>
<td>0.98</td>
<td>0.10</td>
<td>55.5</td>
<td>35.5</td>
<td>8.5</td>
<td>0.5</td>
<td>-9.03</td>
</tr>
<tr>
<td>$^{66}\text{Fe}$</td>
<td>3.17</td>
<td>0.46</td>
<td>1</td>
<td>19</td>
<td>72</td>
<td>8</td>
<td>-23.96</td>
</tr>
<tr>
<td>$^{64}\text{Cr}$</td>
<td>3.41</td>
<td>0.76</td>
<td>0</td>
<td>9</td>
<td>73</td>
<td>18</td>
<td>-24.83</td>
</tr>
<tr>
<td>$^{62}\text{Ti}$</td>
<td>3.17</td>
<td>1.09</td>
<td>1</td>
<td>14</td>
<td>63</td>
<td>22</td>
<td>-19.62</td>
</tr>
<tr>
<td>$^{60}\text{Ca}$</td>
<td>2.55</td>
<td>1.52</td>
<td>1</td>
<td>18</td>
<td>59</td>
<td>22</td>
<td>-12.09</td>
</tr>
</tbody>
</table>

LNPS, PRC 82, 054301 (2010)
Cr, Fe and Ni isotopic chains

\[ E(2^+) \]

\[ B(E2) \]

\[ \beta \approx 0.35 \]

\[ \beta \approx 0.3 \]

LNPS, PRC 82, 054301 (2010)

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The choice of the effective charges

By combining the results of cex and (p,p') (Aoi et al) the ratio of the neutron and proton transition matrix elements can be obtained and compared with the calculations → discriminate the best effective charges

It is suggested that the effective charges need to be reduced

V. Modamio et al., AGATA lifetimes measurement. Confirms the reduction of the effective charges for 63-65Co
Silvia M. Lenzi – Italy - Japan 2012, Milano 20 – 22 November 2012

Shape coexistence: the Co isotopic chain
Spectroscopy of odd-mass cobalt isotopes toward the $N = 40$ subshell closure and shell-model description of spherical and deformed states
Evolution of yrast levels in Co isotopes

F. Recchia et al., PRC 85, 064305 (2012)
Inversion of the multiplets

In the weak coupling limit, the energy shifts between the states in the multiplet can be obtained.

\[ \Delta E = k_2 \langle L \parallel Q \parallel L \rangle \langle j \parallel q \parallel j \rangle (-)^{j+L+j} \left\{ \begin{array}{ccc} L & j & J \\ j & L & 2 \end{array} \right\} \]

L. Trache et al., PRC54, 2361 (1996)

\[ \pi f_{7/2}^{-1} \otimes 2^+ {^{64}}Ni \]

\[ {^{63}}Co \]

\[ \pi f_{7/2}^{-1} \otimes 2^+ {^{66}}Ni \]

\[ {^{65}}Co \]

\[ Q(2^+, {^{64}}Ni) < 0 \]

\[ Q(2^+, {^{66}}Ni) > 0 \]
65Co: weak coupling interpretation

Can we explain 67Co in a similar way?

F. Recchia et al., PRC 85, 064305 (2012)
Proton intruder states and shape coexistence in \(^{67}\text{Co}\)

The \(1/2^-\) state lowers due to deformation increase at \(Z<28\ N=40\)

D. Pauwels et al., PRC 78, 041307 (2008) and PRC 79, 044309 (2009)

Courtesy D. Pauwels and P. Van Duppen
Shape coexistence in $^{67}$Co and $^{68}$Ni

The deformation driven by the neutrons induces a reduction of the Z=28 gap and gives rise to a deformed low-lying $1/2^-$ state.

The $1/2^-$ state in $^{67}$Co gains a total of ~8 MeV of correlation energy and ~5 MeV relative to the ground state.

The LNPS interaction is able to reproduce these structures.
Shape coexistence in $^{67}\text{Co}$

The largest $B(E2)$ in the region

$^{68}\text{Ni}$

$^{67}\text{Co}$

Exp

Theo

F. Recchia et al., PRC 85, 064305 (2012)
Beyond $Z=28$ and $N=40$
Transition probability measurements with AGATA at LNL

AGATA Demonstrator
4 Triple Cluster

\[ d = 18 \text{ cm}, 135 - 175^\circ \]
\[ \varepsilon = 2.4 \% @ 600 \text{ keV} \]
\[ 60 \text{ KHz per crystal} \]

Plunger (Univ. Köln)

5 distances:
- 100 – 1900 μm
- 20 hours each

A. Goergen,
EGAN 2012 Workshop
Lifetime measurements in Zn isotopes

A. Goergen, EGAN 2012 Workshop
The Zn isotopic chain

Calculations using the LNPS give good results for the excitation energy of Zn isotopes. New results for transition probabilities are needed.
The N=50 isotonic chain

The LNPS interaction is able to reproduce the available data for N=50 isotones towards $^{78}\text{Ni}$.

No reduction of the N=50 gap is predicted.
Three body forces

Theoretical efforts to include 3N forces in the Shell Model calculations. Need a clear signature.

Realistic NN

Chiral effective field theory

T. Otsuka et al., PRL105, 032501 (2010)
J.D. Holt et al., in preparation

S.M. Lenzi et al., PRC82, 054301 (2010)
Conclusions

The mass region studied shows a development of collectivity towards N=40 with rapid changes of shape along the isotopic chains.

The LNPS effective interaction in the fpgd space is able to describe the rapid changes of structure, the development of quadrupole collectivity and shape coexistence phenomena in this island of inversion.

$^{67}$Co shows very different shapes at low excitation energy. Gamma-gamma data needed to construct the level scheme, together with the measurement of transition probabilities to study the evolution of deformation → provide a stringent test for the effective interactions.

The model space and interaction are suitable for describing the structure of nuclei beyond Z=28, N=40, towards N=50. The effect of three body forces may be important. This needs experimental efforts to find clear signatures.