'Nuclear Structure of the Neutron-Rich Region around Z=28 towards and beyond N=50'

WOG workshop Leuven March 9 - 11, 2009
Mark Huyse
# The program

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<th>Time</th>
<th>Name</th>
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<th>Affiliation</th>
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<tbody>
<tr>
<td>14.00</td>
<td>Flanagan Kieran</td>
<td>Reordering of quantum states in neutron rich copper isotopes</td>
<td>IPN Orsay</td>
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<td>Cheal Bradley</td>
<td>Laser spectroscopy of neutron-rich gallium isotopes at ISOLDE</td>
<td>University of Manchester</td>
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<td>Thomas Cocolios</td>
<td>In-source laser spectroscopy in a gas cell: the magnetic moment of 57-</td>
<td>IKS-K.U.Leuven</td>
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<td>Fe isotopes - updated</td>
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<td>16.00</td>
<td>Herlitz Alexander</td>
<td>Mass measurements on neutron-rich nuclei around N=50</td>
<td>CERN</td>
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<td>16.30</td>
<td>Jokinen Ari</td>
<td>Investigation of Z=28 and N=50 shell gaps with precision mass</td>
<td>University of Jyvaskyla</td>
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<td>Block Michael</td>
<td>High-resolution mass measurements of neutron-rich Fe and Co isotopes</td>
<td>GSI</td>
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<td>Mantica Paul</td>
<td>Nuclear structure studies near Ni-78 at NSCL</td>
<td>NSCL/MSU</td>
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## Tuesday March 10

*Theory (Chair: Kris Heyde)*

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<tr>
<th>Time</th>
<th>Name</th>
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<tbody>
<tr>
<td>9.00</td>
<td>Grawe Hipert</td>
<td>The N=50 shell gap from 100Sn to 78Ni</td>
<td>GSI Darmstadt</td>
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<td>Nowacki Frederic</td>
<td>The story of 44Sc, 78Ni and 122Sn</td>
<td>IFIC, Strasbourg</td>
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<td>10.30</td>
<td>Coffee break</td>
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<td>11.00</td>
<td>Van Isacker Piet</td>
<td>Towards a shell-model interaction for neutron-rich Ni, Cu and Zn isotopes</td>
<td>GANIL</td>
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<td>Heenen Paul-Henri</td>
<td>Shell effects in mean-field approaches</td>
<td>Universite Libre de Bruxelles</td>
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## Tuesday March 10

*Decay studies and systematics (Chair: Gerda Leyren)*

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<tr>
<td>14.00</td>
<td>Rykaczewski Krzysztof</td>
<td>Decay studies of neutron-rich Cu, Zn and Ga isotopes at Oak Ridge</td>
<td>Physics Division, Oak Ridge National Laboratory</td>
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<td>Duchene Gilbert</td>
<td>Beta-decay of the odd 71-75 copper isotopes</td>
<td>IPHC-CNRS/Strasbourg</td>
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<td>Verney David</td>
<td>Contribution to the study of the N=50 shell effect from beta-decay experiments at PARRNc and ALTO</td>
<td>IPN Orsay, CNRS/IN2P3-U. Paris Sud</td>
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<td>Sean Lidick</td>
<td>First results on the decay of 81Zn from LeRiSS</td>
<td>Lawrence Livermore National Laboratory</td>
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<td>Coffee break</td>
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<td>16.30</td>
<td>Fauvels Dieter</td>
<td>Intruder states around 68Ni: comparison to the 60Zr region and nuclear-structure considerations for the region below Z=28 and beyond N=40</td>
<td>KS - K.U.Leuven</td>
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## Wednesday March 11

*Coulomb excitation and reactions (Chair: Mark Huyse)*

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<tr>
<td>9.30</td>
<td>Van de Walle Jarro</td>
<td>Coulomb excitation of Zn and Fe and comparison to shell model calculations</td>
<td>CERN</td>
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<td>Oinken Jan</td>
<td>Coulomb excitation of 71,73Ga and of the odd mass Cu isotopes</td>
<td>KU-Leuven</td>
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<td>Javier Valente Dobon Jose</td>
<td>Approaching 78Ni via deep-inelastic collisions with the CLARA-PRISMA setup</td>
<td>INFN-LNS</td>
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<td>11.30</td>
<td>Chapman Robert</td>
<td>Probing the N=50 shell gap near 78Ni</td>
<td>University of the West of Scotland</td>
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<td>Ili Farkas</td>
<td>Recent and aberrant n-beam experiment at GANIL around Z=78</td>
<td>GANIL</td>
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Theory
Shell gaps along \( N=50 \) from \(^{100}_{50}\text{Sn}_{50}\) to \(^{78}_{28}\text{Ni}_{50}\)

H. Grawe, GSI Darmstadt

Arbitrary choice of recent statements on shell evolution

- ... “that magic numbers are actually not immutable occurred only during the past 10 years”.  **Known since almost 50 years!**
- ...“nuclear orbits change their ordering in regions far away from stability”.  **Occurs everywhere, but ´´far away´´ is now accessible experimentally!**
- ...”the proton - neutron monopole is determined by the tensor force“.
  **The tensor force is only one ingredient!**
- ...“the largest \((N=50\) neutron) gap is found close to the stability valley at \(Z=40\)“ (with linearly extrapolated values of 3.0(5) for \(^{78}\text{Ni}\) and \(^{100}\text{Sn}\)).
- ...“this \((Z=50\) proton) gap is decreasing below \(N=64\), ... (which) could increase collectivity (towards \(^{100}\text{Sn}\))“.
- ...“this \(Z=28\) proton gap in \(^{78}\text{Ni}\) could decrease down to 2.5 MeV only“....

**See results and summary!**
Summary and conclusions

- Precision spectroscopy of exotic nuclei → tuning/extraction of effective NN interaction (mainly monopoles)

- Monopoles determine shell evolution from "known" to "unknown" regions

- $^{78}_{28}\text{Ni}_{50}$ and $^{100}_{50}\text{Sn}_{50}$ have well developed shell gaps $\Delta$ for both protons and neutrons

  - $\Delta(N=50,\text{Ni}) = 4.05(18) \text{ MeV}$; $\Delta(N=50,\text{Sn}) = 6.35(13) \text{ MeV}$
  - $\Delta(Z=28,\text{Ni}) = 5.08(42) \text{ MeV}$; $\Delta(Z=50,\text{Sn}) = 5.96(35) \text{ MeV}$

- Beware of shell gap extrapolation from mid-shell to double CS and vice versa!

- "Pre"-mass shell gap determination by core excited isomers

- Valence mirror symmetry and good seniority are distorted by core excitation
Summary

- Continuous Progress in computational "standard" diagonalization, and understanding of monopole corrections to 2N forces to provide good spectroscopy

- Tensor mechanism develops in different regions

- The physics emerging is quite different: deformation at N=28 for $^{42}$Si, shell weakening at N=28 for $^{78}$Ni and strong shell closure at N=82 for $^{132}$Sn

- Spin-Tensor analysis of the effective interactions under progress
The influence of FF transitions on half-lives is up to 20% in SM calculations for N=50 and 82
Shell-model calculations
“north by north-west” of $^{78}\text{Ni}$

P. Van Isacker, GANIL, France

The curious case of orbit $g_{9/2}$
L. Zamick (Rutgers), S. Heinze (Cologne)

Large-scale shell-model calculations
P.C. Srivastava (GANIL & Allahabad)

Partial conservation of seniority
Shell Effects in Mean-Field Approach

Based on Lesinski et al PRC 76 014312, Bender, Bertsch and Heenen PRC 73 034322, Bender, Heenen et al., in preparation

- Correlations beyond mean-field must be included explicitly
- Tensor interaction is a second order effect
- Dangerous to change interactions perturbatively!
- New terms in EDF seem unavoidable
- Z around 28 and N=28 to N=50 seem to be a difficult test
Laser spectroscopy
Detecting $\beta$ delayed neutrons can clean Ga background (until $^{79}\text{Cu}$)

RILIS laser scanned across the $^{2}\text{S}_{1/2} - ^{2}\text{P}_{1/2}$

Scans of $^{75,77,78}\text{Cu}$ were made with stable references.
Yield of $^{75}$Cu ~ 5E4/uC
5 out of 6 peaks resolved

\[ A\left( ^2S_{1/2}\right) = +1592(1) \text{ MHz} \]
\[ B\left( ^2P_{3/2}\right) = -34(2) \text{ MHz} \]
Laser spectroscopy on n-rich Ga isotopes

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8,000 MHz
(New) Spin assignments

\( \chi^2 \) minimisation

Spin 2

Spin 1/2
The moments of $^{28+1}_{\text{Cu}28}$
Probing the $Z = 28$ magicity with a single proton

$$\mu_{Schmidt}(p_{3/2}) = +3.79\mu_N$$


Thomas E. Coccolios 57−59 Cu moments
The 'Shadow' cell
A dual-chamber recoil gas cell for purity and laser spectroscopy

- Natural Ni thin target:
  - $^{58}\text{Ni}(p, 2n)^{57}\text{Cu}$,
  - $^{60}\text{Ni}(p, 2n)^{59}\text{Cu}$,
  - $^{58}\text{Ni}(^{3}\text{He}, pn)^{59}\text{Cu}$
- Buffer gas at 100 mbar
- 1 mm diameter exit hole
- Lasers repetition rate at 200 Hz

Thomas E. Cocolios
$^{57} - ^{59}\text{Cu moments}$
Experimental data
Spectra of $^{57,59,63,65}\text{Cu}$
A unique tool for laser spectroscopy
Fast, chemically unselective, good resolution, ...

Hot cavity vs. Gas catcher
- Better resolution in spite of the pressure;
- Faster release => More exotic.

Sonoda et al., to be published.
Kudryavtsev et al., to be published.
Masses
A. Herlert

ISOLTRAP

neutrons

protons

K
Ca
Sc
Ti
V
Cr
Mn
Fe
Co
Ni
Cu
Zn
Ga
Ge
As
Se
Br
Kr
Rb
Mass measurements of 30 n-rich Zn, Ga, Ge, As and Se at JYFLTRAP
J. Hakala et al. PRL 101 (2008) 052502

+ $^{81}$Zn-isotope at ISOLTRAP
S. Baruah et al., PRL 101 (2008) 262501
Sub-shell closure at N=40

Spectroscopic data for Ni:
Reduction of B(E2) and increase of E(2+) implies the sub-shell closure at N=40 (only for Ni chain !)
Shell-model calculations:
K. Kaneko et al., PRC 74 (2006) 024321

No signature of the gap in S_{2n}(N) data
No visible N=40 gap in S_{2n}(Z) graph
Change of the slope at N=40 ↔ tensor-force and the role of the filling of g_{9/2} neutron-orbit?
S. Rahaman et al., EPJ A34 (2007) 5
High-Precision Mass Measurements of Neutron-rich Fe and Co Isotopes at LEBIT

- Introduction
- The LEBIT setup and its performance
- LEBIT results at a glance
- Mass measurements of neutron-rich nuclides
- Conclusions

Michael Block, GSI for the LEBIT collaboration
Isomer studies with Penning traps

Penning trap mass measurements can provide complimentary information to decay spectroscopy for the study of long-lived isomers

- Pin down excitation energy accurately
- Determine level ordering
  (in combination with laser ionization or for different half-lives)

Exc. Energy 402(5) keV

Decay spectroscopy
Fast RIB from fragmentation:
• no decay losses
• any beam can be produced
• multiple measurements in one
• high sensitivity
Results for the main goal: $^{78}\text{Ni}$ (14 neutrons added to stable Ni)

$^{78}\text{Ni}$ : major bottle-neck for synthesis of heavy elements in the r-process

Managed to create 11 of the doubly magic $^{78}\text{Ni}$ nuclei in ~ 5 days

Result for half-life: $110^{+100}_{-60}$ ms

Compare to theoretical estimate used: 470 ms

→ Acceleration of the entire r-process
→ Models need to be adjusted to explain observed abundance distribution
$^{73}\text{Co}$ beta decay

S. Liddick

$^{73}\text{Co}$ decay

Counts/keV

Energy (keV)

Time (ms)

$^{73}\text{Co}$ - decay
$T_{1/2} = 42(6)\text{ms}$

$^{73}\text{Co}$ - 239keV
$T_{1/2} = 42(2)\text{ms}$

$^{73}\text{Co}$ - 774keV
$T_{1/2} = 48(9)\text{ms}$
Decay studies of neutron-rich Cu, Zn and Ga isotopes at Oak Ridge
Krzysztof P. Rykaczewski, ORNL Physics Division, Oak Ridge

among our motivations:

- understanding the evolution of nuclear structure

-beta-decay properties are needed for the analysis of post r-process isotopic distributions (in particular the data around “waiting-point” nuclei) half-lives, beta-delayed neutron rates, low-energy isomers …

- the decay properties of fission products are among the parameters needed for the operation of nuclear reactors, e.g., during a shut-down process, and for the nuclear spent fuel/waste handling
factor 2 to 4 higher $P_n$ values in comparison to the “current $\beta n$-reference”
B. Pfeiffer, K.-L. Kratz, P. Möller (PKM)

67Fe and 67Co decay

Correlate in long time ranges with:
- β-gated 189-keV events
- β-gated 694-keV events

Lasers on Fe
Lasers OFF

Long-lived isomer in Co or Ni?

Correlate in long time ranges with:
- β-gated 189-keV events
- β-gated 694-keV events
Construction of correlations

- **a)** $\beta$-189 keV correlated single $\gamma$ events
- **b)** $\beta$-189 keV randomly correlated single $\gamma$ events
- **c)** $\beta$-189 keV randoms-subtracted single $\gamma$ events
- **d)** $\beta$-694 keV randoms-subtracted single $\gamma$ events

Isomer confirmed by Penning-trap mass measurements (Dec., 2008)

See talk of M. Block
492-keV isomer established with correlations

492-keV events coming after $\beta^{-}$-189 keV

$T_{1/2}=483\ (56)\ ms$

$\text{Int.}(0\rightarrow\text{inf.})=172\ (14)$

492-keV events coming before $\beta^{-}$-694 keV

$T_{1/2}=329\ (28)\ ms$

$\text{Int.}(0\rightarrow\text{inf.})=204\ (14)$

Isomer confirmed by Penning-trap mass measurements (Dec., 2008)

See talk of M. Block
67Fe decay scheme

**Ground state:**
L. Weissman et al., PRC 59, 2004 (1999)

**492 keV:**
T_{1/2}(492)=0.50(3) s
\[=800 \text{ E3(492)}\]
\[=15 \text{ M3(492)}\]
\[=0.001 \text{ E4(492)}\]

**680 keV:**
I(680)/I(189)=0.08(3)
\[=10^{-11} \text{ E1(680)/M2(680)}\]
\[=10^{-8} \text{ M1(680)/E2(680)}\]
\[=5.7 \text{ E2(680)/M1(189)}\]
\[=10^{4} \text{ M2(680)/E1(189)}\]
Interpretation $^{67}$Co

- **Outline**: 
  - Z=28, N=40
  - Setup
  - Correlations
  - Decay schemes
  - Interpretation
  - Discussion
  - Conclusions

- **Discussion**
  - Pair scattering
  - $\pi(1p-2h)$

- **Conclusions**
  - $f^1_{7/2} \otimes 2^+: 3/2^- - 11/2^-$
  - $4^+ 3149$
  - $2^+ 2034$
  - $0^+ 1770$

- **Single-Proton Energies (MeV)**

- **Spheroidal Deformation $\epsilon_2$**

- **492 keV**: $\pi f^{-2}_{7/2} \pi p_{3/2}^+ \bm{(0.25<\epsilon_2<0.4)}$

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**D. Pauwels**

**WOG-workshop**

**Leuven**

**March 5, 2009**
N=50 and Z=28 shell-gaps evolution close to $^{78}\text{Ni}$
Conclusion

Systematic study of Ge and Zn n-rich isotopes

- Deep-inelastic reactions at LNL with CLARA-PRISMA and GASP arrays
- N=50 shell gap is significantly large close to $^{78}$Ni

β-decay study of odd n-rich Cu isotopes

- Laser ionisation at ISOLDE
- Comparison of exp and theo B(GT) evidence for a 5/2- ground state in $^{75}$Cu
- Recent ISOLDE g.s. magnetic moment measurements confirm this result
- The $\pi f_{5/2}$ and $\pi p_{3/2}$ energy difference is reduced by $\sim 2$ MeV in $^{73}$Cu and will be further affected by the tensor force. However, the Z=28 shell gap will likely not be reduced enough to enable deformation to sets in in $^{78}$Ni
Reactions
Approaching $^{78}$Ni via deep inelastic collisions with the CLARA-PRISMA setup

Jose Javier Valiente Dobón (INFN-LNL, Italy)

On behalf of the CLARA-PRISMA collaboration
Summary

- Grazing reactions are a good tool to populate n-rich nuclei at medium spins.
- DIC give complementary information to β decay and Coulex when going to exotic systems. $^{83}$As, $^{82}$Ge and $^{81}$Ga suggest that $^{78}$Ni is a magic nucleus.
- Copper isotopes up to $^{75}$Cu populated in DIC.
- Novel method to measure lifetimes that combines the traditional RDDS method with the CLARA-PRISMA spectrometers. Lifetimes of the N=30 isotones $^{50}$Ca and $^{51}$Sc and $^{44,46}$Ar isotopes.
- Future at LNL: The AGATA demostrator.
Coulomb excitation of $^{74-80}$Zn, $^{80}$Ga, $^{61}$Mn, $^{61}$Fe and $^{62}$Fe at REX-ISOLDE and some comparison to existing shell model calculations

Jarno Van De Walle
The Coulex program

The Coulex program is a method used in nuclear physics to study the stability of atomic nuclei. The diagram illustrates the nuclear chart with various isotopes and elements labeled, such as Mg, Cu, Ni, Zn, Cd, Xe, Sn, Ba, Sr, Kr, Hg, and Rn. The chart shows the distribution of elements across different atomic numbers (Z) and atomic masses (N), highlighting the stability regions of these elements.
Beam manipulation in REXTRAP and REX-EBIS
Coulomb excitation of the neutron rich odd-A Cu isotopes and $^{71,73}$Ga

J. Diriken  I. Stefanescu

Observation

- At $N = 40$ ($^{69}$Cu), $5/2^-$ state undergoes a significant loss in collectivity.
- The change in structure does not affect the excitation energy which stays similar to that in $^{67}$Cu.
- The low $B(E2; 5/2^- \rightarrow 3/2^-)$ value from $N = 40$ onwards indicates that the $5/2^-$ state is essentially of single-particle character.
- The proposed $1/2^-$ shows an important increase in collectivity beyond $N = 40$.
- Onset of collectivity related to the filling of the $\nu g_{9/2}$-orbital.

[Robinson, 1964]
[Stefanescu, 2008]
Recent and future experiment at GANIL in the $Z=28$ $N=40-50$ vicinity

Emmanuel Clement
GANIL
Leuven – March 2009
On going program

E553 – Fe plunger (Ljungvall & Korten et al)
E507 – Ni (d,p) (Duchene et al)
E588 - Ni plunger (Clement et al.)
E572 - Cu spectroscopy (Sahin, De France et al)
E552 – Cu plunger (Franchoo et al)
Probing the N=50 shell gap near $^{78}\text{Ni}$

Spectroscopy of single-particle states in $^{79}\text{Zn}$

Robert Chapman

University of the West of Scotland

WOG workshop: Nuclear Structure of the Neutron-Rich Region around Z=28 towards and beyond N=50

Leuven  March 9 – 11 2009
$^{79}$Zn via $^2$H($^{78}$Zn, $^1$H) $^{79}$Zn  3MeV/u
at REX-ISOLDE

- INTC approved experiment

Riccardo Orlandi (UWS) spokesperson
The Ni region is one of the most active regions of the nuclear chart

Many experimental and theoretical efforts are devoted to its study

The fpg shell possesses an extraordinarily rich structure that ranges over shell & subshell closures, pairing phases and different shapes

Understanding how all these phenomena emerges from a fully microscopic many-body approach to fpg nuclei will result in a major advance in nuclear structure and many-body quantum mechanics

The fpg shell impacts other basic physics issues

-its structure needs to be understood because of the role of $^{78}\text{Ni}$ and $^{80}\text{Zn}$ in the r-process

-$^{76}\text{Ge}$ and $^{76}\text{Se}$ are parent and daughter of one of the best candidate pairs for the study of neutrinoless double-beta decay

(Thanks to John Wood)