Spectroscopy of exotic nuclei in the $^78$Ni region

E. Sahin$^1$, F. Bello$^1$, K. Hadynska$^{1,2}$, V. Modamio$^1$, L. Gaard Pedersen$^1$

and EURICA/SEASTAR/SUNFLOWER Collaborations

$^1$ University of Oslo, Norway.
$^2$ University of Surrey, UK.
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$^1$ University of Oslo, Norway.
$^2$ University of Surrey, UK.

Young Research Talents Grant from The Research Council of Norway
4 years - $\sim$1 M€ (Researcher + Postdoctoral fellow)
Project manager: Dr. Eda Sahin
Project Title: Nuclear shell evolution towards the “terra incognita”
$^{78}\text{Ni}$ region & Shell evolution

$Z=28$ Gap towards $N=50$

With tensor

Without tensor

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

Inversion
Reduction
Deformation

$p_{3/2}$ is raised due to the repulsion between $pp_{3/2}-ng_{9/2}$

$f_{5/2}$ is lowered due to the attraction between $pf_{5/2}-ng_{9/2}$

$f_{7/2}$ is raised due to the repulsion between $pf_{7/2}-ng_{9/2}$
Cu nuclei emerge as good probes

\[ ^{78}\text{Ni} \] region & Shell evolution

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

\[ ^{69}\text{Cu} \quad ^{79}\text{Cu} \]

\[ p_{3/2} \] is raised due to the repulsion between \( pp_{3/2} - ng_{9/2} \)

\[ f_{5/2} \] is lowered due to the attraction between \( pf_{5/2} - ng_{9/2} \)

\[ f_{7/2} \] is raised due to the repulsion between \( pf_{7/2} - ng_{9/2} \)

\[ \begin{array}{cccc}
N/Z: & 1.0 & \sim 1.43 & \sim 1.79 \\
0.97 & \sim 1.38 & \sim 1.72 \\
\end{array} \]

Ni

Cu
Spectroscopy of Cu nuclei @ RIKEN

Level schemes of odd-A Cu nuclei.

- $^{67,69,71,73,75,77,79,81}$Cu
- $^{70,72,74,76,78,80}$Zn
- $^{66,68,70,72}$Zn
- $^{67,69,71,73,75,77,79}$Cu
- $^{64,66,68,70,72}$Cu
- $^{64,66,68,70,72}$Ni
- $^{65,67,69,71,73,75}$Ni
- $^{64,66,68,70,72}$Co
- $^{64,66,68,70,72}$Fe

Selected to be dominated by single-particle states:
- $^3_2^1\pi f_{7/2}$
- $^3_2^1\pi p_{3/2}$
- $^3_2^1\pi p_{1/2}$
- $^3_2^1\pi f_{5/2}$

$^{67,69}$Cu transfer reactions:
- B. Zeidman et al., PRC 18, 2122 (1978).

$^{69,71,73}$Cu, $\beta$-decay:
- S. Franchoo et al., PRL 81, 3100(1998);
- S. Franchoo et al., PRC 64, 054308(2000);
EURICA Campaign @RIKEN

Excited states of $^{75,77}\text{Cu}$ via beta-delayed gamma-ray spectroscopy

2012-2013
Beta decay
EUROICA Campaign
$^{75}\text{Ni} \rightarrow ^{75}\text{Cu}$ & $^{77}\text{Ni} \rightarrow ^{77}\text{Cu}$

2014
(p,2p) knock-out
SEASTAR Campaign
$^{78}\text{Zn} (p,2p)$
$^{77}\text{Cu} \rightarrow ^{75}\text{Cu}$
$^{76}\text{Zn} (p,2p) ^{75}\text{Cu}$

2015
Coulomb excitation
DALI Spring 2015 Campaign
$^{77}\text{Cu} + ^{197}\text{Au} \rightarrow (^{77}\text{Cu})^*$

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2015
Coulomb excitation
DALI Spring 2015 Campaign
$^{77}\text{Cu} + ^{197}\text{Au} \rightarrow (^{77}\text{Cu})^*$
From single to coincidence spectra: $^{77}\text{Cu}$

5
lowered relative to the correlation effects are stronger for the SM calculations is also shown (right panel).

\[ \sum_{j} C_{j}^{2} = 1 \]

C. Petrone et al.,
PRC 94, 024319 (2016)

\[ \left[ 1/2^{-}, 3/2^{-} \right] \]
\[ T_{1/2} = 149(5) \text{ ms} \]
\[ E_{\gamma} = 66.2 \text{ keV} \]
\[ (1/2^{-}, 3/2^{-}) \]
\[ T_{1/2} = 310(8) \text{ ns} \]
\[ E_{\gamma} = 61.7 \text{ keV} \]


F. Bello, E.S. et al., to be published.
MCSM Calculations
Model space: pf9g9d5
Core: $^{40}\text{Ca}$
A3DA interaction

The present calculations give an improved description of this inversion by including correlation effects due to multipole interaction.

5/2 ground-state spin in $^{75}\text{Cu}$:
K.T. Flanagan et al., PRL 103, 142501 (2009)

Evolution of the Shell evolution

2005

Proton Single Particle Levels

2010

Z=28 Gap

2010

Energy (MeV)

2017 Present work

(a) proton SPE of Ni isotopes

Z=28 Gap

Energy (MeV)

6.5 MeV

5 MeV
Systematics of Cu isotopes:
dominated by single-particle and core-coupling excitations

\[ \begin{align*}
\text{Intruder states} & \quad \text{Core coupled states} \\
\text{Single-particle states} &
\end{align*} \]

\[ \begin{align*}
\text{np}_{3/2}/nf_{5/2} & \otimes 2^+ \\
(\text{nf}_{7/2})^{-1} & \quad 7/2^- \\
\text{np}_{5/2} & \quad 5/2^- \\
\text{np}_{3/2} & \quad 3/2^- \\
69\text{Cu} & \quad 71\text{Cu} & \quad 73\text{Cu} & \quad 75\text{Cu} & \quad 77\text{Cu}
\end{align*} \]

\[ \begin{align*}
(\text{nf}_{7/2})^{-1} & \quad 7/2^- \\
5/2^- & \quad 7/2^- \\
3/2^- & \quad 7/2^- \\
\end{align*} \]

\[ \begin{align*}
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5/2^- & \quad 7/2^- \\
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\end{align*} \]

69Cu, transfer reactions:
B. Zeidman et al., PRC 18, 2122, (1978).

71Cu, deep inelastic:

69,71,73Cu, beta decay:
S. Franchoo et al., PRL 81,3100, (1998).

69,71,73Cu, Coulomb exc.:
I. Stefanescu et al., PRL100,112502,(2008).

71Cu, deep inelastic:
I. Stefanescu et al., PRC 79,034319,(2009).

69,71,73Cu, deep inelastic:

75Cu, delayed g spect.:
C. Petrone et al., PRC94,024319,(2016).

75Cu, beta decay, RIKEN/EURICA:
F. Bello et al., to be submitted.

77Cu, beta decay, RIKEN/EURICA:
E.S. et al., PRL 118,242502,(2017).
Systematics of Cu isotopes:
dominated by single-particle and core-coupling excitations

$^{69,71,73}$Cu, transfer reactions:
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$^{71}$Cu, deep inelastic:

$^{69,71,73}$Cu, beta decay:

$^{69,71,73}$Cu, Coulomb exc.: 

$^{71}$Cu, deep inelastic:

$^{69,71,73}$Cu, deep inelastic:

$^{75}$Cu, beta decay, RIKEN/EURICA: 
F. Bello et al., to be submitted.

$^{77}$Cu, beta decay, RIKEN/EURICA: 

$^{75}$Cu, delayed g spect.: 
First spectroscopy of very exotic nuclei through one-proton knockout reaction

Projectile \rightarrow \text{Knockout residue}

\begin{align*}
\text{76,78Zn} & \rightarrow 50g_{9/2} \\
\text{28p1/2} & \rightarrow 40p_{1/2} \\
\text{20f7/2} & \rightarrow 50p_{3/2} \\
\text{f5/2} & \rightarrow \text{gamma ray}
\end{align*}

\text{75,77Cu}

\text{78Zn} (p,2p) \text{ 77Cu} \quad \text{76Zn} (p,2p) \text{ 75Cu}
SEASTAR Project

The "Shell Evolution And Search for Two-plus energies At RIBF" (SEASTAR)

High primary beam intensity \( ^{238}\text{U},^{70}\text{Zn} \)
BiGRIPS fragment separator for PID
DALI2 array for the gamma detection
MINOS target (at least 10 cm thick)

MINOS (proton tracker)

Exp. & Particle identification

BigRIPS

ZeroDegree Spectrometer

In-flight fission

$^{238}\text{U}$

$^9\text{Be}$

$^{78,76}\text{Zn}$

$^{77,75}\text{Cu}$

LH$_2$ MINOS target

186 NaI detectors

@ 345 MeV/A

> 10 pnA

$^{9}\text{Be}$ → $^{238}\text{U}$ in-flight fission

(p,2p) selection

PID before target

PID after target

$^{76}\text{Zn}$

$^{78}\text{Zn}$

$^{75}\text{Cu}$

$^{77}\text{Cu}$
2.2 Gamma coincidence examples

In the case of the spectrum gated on 950 keV in Figure 3a, we believe that under the peak area of 490 keV due to the fact that 950- and 990-keV peaks are lying closer than the resolution limit of DALI. The same applies to the gated spectrum on 490 keV.

Figure 3b shows the relation between the transitions 490 and 990 keV. Like the case above, here there is a contribution from 530 keV under peak at 530 keV there is a contribution from 490 keV which is in coincidence with 990 keV.

Appendix A.

TimeO

Gamma-single spectra for Cu after the target. The spectra are doppler corrected and with addback.

Counts (16 keV/bin)

Counts (20 keV/bin)

Energy (keV)

Energy (keV)
The wave function is rather mixed with the particle-core coupled states $2p_{3/2} \otimes 1f_{5/2}$

E.S., K. Hadynska et al., in preparation.
2p-2h excitations above Z=28: Prolate deformation

\[ \pi f_{7/2}^{-1} \otimes \sigma_{7/2}(^{76}\text{Ni}) \]

2p-1h excitations above Z=28:

Prolate deformation
**Shape coexistence along Cu-Ni chain**

![Energy diagram and shape coexistence](image)

**Shape Coexistence**

- 3/2⁻ or 5/2⁻: Spherical
- 7/2⁻: Prolate

*2p-2h excitations above Z=28: Prolate deformation*

*2p-1h excitations above Z=28: Prolate deformation*

πf7/2⁻⊗02⁺(76Ni)

Type II shell evolution

**MCSM calculations**

Viewpoint: “Peaceful coexistence of nuclear shapes”

Paul Mantica, National Superconducting Cyclotron Laboratory, Michigan State University, East Lansing, MI 48824, USA
March 2, 2009 • Physics 2, 18

Viewpoint: “Islands of insight in the nuclear chart”

B. Alex Brown, Michigan State University, East Lansing, MI 48824, USA
December 13, 2010 • Physics 3, 104

Viewpoint: “Doubly Magic Nickel”

Daniel Bazin, National Superconducting Cyclotron Laboratory, Michigan State University, East Lansing, MI 48824-1321, USA
November 6, 2017 • Physics 10, 121

Shape coexistence
Coulomb excitation of $^{77}$Cu @RIKEN

BE2 transition strength of "2+" in $^{77}$Cu via intermediate-energy coulomb excitation

- **2012-2013**
  - Beta decay EURICA Campaign
  - $^{75}$Ni $\rightarrow$ $^{75}$Cu & $^{77}$Ni $\rightarrow$ $^{77}$Cu

- **2014**
  - (p,2p) knock-out SEASTAR Campaign
  - $^{78}$Zn (p,2p) $^{77}$Cu & $^{76}$Zn (p,2p) $^{75}$Cu

- **2015**
  - Coulomb excitation DALI Spring 2015 Campaign
  - $^{77}$Cu $+$ $^{197}$Au $\rightarrow$ ($^{77}$Cu)*

**Equipment and Conditions**

- **BigRIPS**
  - In-flight fission
  - $^{238}$U $\rightarrow$ $^{9}$Be
  - @ 345 MeV/A
  - ~ 20 pnA

- **DALI**
  - 186 NaI detectors

- **ZeroDegree Spectrometer**
  - Gold target
  - 900 mg/cm²

**Campaigns**

- **2012-2013**
  - Beta decay EURICA Campaign
  - $^{75}$Ni $\rightarrow$ $^{75}$Cu & $^{77}$Ni $\rightarrow$ $^{77}$Cu

- **2014**
  - (p,2p) knock-out SEASTAR Campaign
  - $^{78}$Zn (p,2p) $^{77}$Cu & $^{76}$Zn (p,2p) $^{75}$Cu

- **2015**
  - Coulomb excitation DALI Spring 2015 Campaign
  - $^{77}$Cu $+$ $^{197}$Au $\rightarrow$ ($^{77}$Cu)*
Particle-core coupling

\( (8^+) \quad 143 \)
\( (6^+) \quad 143 \)
\( (4^+) \quad 356 \)

\( ^{76}\text{Ni} \)

\( 930 \)

\( ^{77}\text{Cu} \)

\( 831 \)

\( 5/2^- \quad 946 \)

\( 9/2^- \quad 991 \)

\( 0^+ \)

\( \Pi f_{5/2} \otimes 2^+ (^{76}\text{Ni}) \)

- How well the MCSM predictions are
- \( B(E2; 2^+ \rightarrow 0^+) \) in \(^{76}\text{Ni}\) will be estimated from \(^{77}\text{Cu}\)
**BigRIPS setting #1: $^{77}\text{Cu}$**

- **Au target Coulomb ex**
- **$^{77}\text{Cu}$**
- **(77Cu)$^*$**
- **200 MeV/A**
- **C target Inelastic**

**BigRIPS setting #2: $^{73}\text{Cu}$**

- **Au target Coulomb ex**
- **$^{73}\text{Cu}$**
- **(73Cu)$^*$**
- **C target Inelastic**

---

The Gamma-ray spectrum of $^{77}\text{Cu}$ with different energy values and particle identification before and after the target.
73Cu @ ISOLDE (2008) & 72Ni at NSCL-MSU (2016)

Coulomb excitation of 73Cu and 72Ni @RIKEN

73Cu @ ISOLDE (2008) & 72Ni at NSCL-MSU (2016)

I. Stefanescu et al., PRL 100, 112502 (2008)
K. Kolos et al., PRL 116, 122502 (2016)

73Cu -> B(E2) = 14.9 (18) W.u. (Safe-energy Coulex)
72Ni -> B(E2) = 4.0 (5) W.u. at NSCL/MSU (Plunger lifetime)

V. Modamio et al., to be published, Univ. Of Oslo
$N=50$ Gap towards $Z=28$ via spectroscopy
the chain has been done for investigate the proposed shape coexistence in the doubly-magic \( ^{92}Zn, ^{78}_{76}Cu, ^{80}_{78}Ni \) and change sign as seen in Fig. 24. This evolution of the correlation values in the copper chain as a function of the number of hole excitations across the \( N = 50 \) isotonic shell nuclides. The extent of quadrupole correlations in the single particle excitations is intimately connected to the sizes of the shell gaps essentially due to the strong attractive interaction whose main active components are described. Recent results from laser spectroscopy of Cu isotopes. Returning to the question of the same proton number \( Z, N \) having two neutrons less than the magic number: without exception, for each maximum in the proton orbital occupancies plotted in Fig. 3(c) the peaked structure of the empirical shell gaps was explained in Ref. 69,167(1988). However, a local maximum for \( \Delta = 2 \) \( p \) is perfectly accounted for by the same proton number \( Z, N \) \( \Delta = 2 \) \( f \) \( \geq 69 \), \( \leq 79 \). This evolution of the correlation energies for the \( (d) \) PFSDG-U correlation energies for the \( 82_{28}Zn, 77,79,81_{28}Cu, 76,78,80_{28}Ni \) etc. from \(+\) energies, the proton gap is considerably reduced from the effective single particle excitations between the two calculations, we represent the evolution of the correlation energies for the \( (d) \) PFSDG-U and JUN45 (open green squares) interactions with experimental data are from Atomic Mass Evaluation 2016 model calculations using the PFSDG-U interaction (crosses). The experimental data are from Atomic Mass Evaluation 2016 model calculations using the PFSDG-U interaction (crosses). The correlations describe an inverse parabolic energy is well reflected in the experimental two-neutron separation energies along particle-hole excitations across the \( N = 50 \) conjugation. The correlations describe an inverse parabolic evolution of the correlation energies for the \( (d) \) PFSDG-U correlation energies for the \( 82_{28}Zn, 77,79,81_{28}Cu, 76,78,80_{28}Ni \) etc. from \(+\) energies, the proton gap is considerably reduced from the effective single particle excitations between the two calculations, we represent the evolution of the correlation energies for the \( (d) \) PFSDG-U and JUN45 (open green squares) interactions with experimental data are from Atomic Mass Evaluation 2016 model calculations using the PFSDG-U interaction (crosses). The correlations describe an inverse parabolic energy is well reflected in the experimental two-neutron separation energies along particle-hole excitations across the \( N = 50 \) conjugation. The correlations describe an inverse parabolic
The resulting states arising from the (\(d_{5/2} - g_{9/2}\)) interaction are significant component of \(\Sigma = 1\) neutron-proton excitations above the Coulomb barrier, which slightly shifts the maximum correlation position of the \(2^{+}\) level at \(\Delta E = 2\) MeV.

Returning to the question of the \(N=50\) shell gap evolution on the neutron drip line but also as inputs to the theory to pin down the nuclear interactions between \(Z, N\) and \(\Sigma = 1\) in the upper curve. The doubly magic nuclei show a local shell strength, and pairing correlations as explained in Ref. [9]. In this respect, it is not diode-like.

One also notices the slight reduction of the proton gap in the proton orbital occupancies plotted in Fig. 46. Moreover, recent \(\Sigma = 2\) and \(\Sigma = 3\) excitations above the Coulomb barrier, which slightly shifts the maximum correlation position of the \(2^{+}\) level at \(\Delta E = 2\) MeV.

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To understand the differences observed in Fig. 46, one needs to consider the role of the proton gap in the proton orbital occupancies plotted in Fig. 46. Moreover, recent \(\Sigma = 2\) and \(\Sigma = 3\) excitations above the Coulomb barrier, which slightly shifts the maximum correlation position of the \(2^{+}\) level at \(\Delta E = 2\) MeV.

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One also notices the slight reduction of the proton gap in the proton orbital occupancies plotted in Fig. 46. Moreover, recent \(\Sigma = 2\) and \(\Sigma = 3\) excitations above the Coulomb barrier, which slightly shifts the maximum correlation position of the \(2^{+}\) level at \(\Delta E = 2\) MeV.
TRIUMF EEC New Letter of Intent Detailed Statement of Proposed Research for Experiment #: 1835

Neutron sp states in \( ^{82}\text{Ge} \) have been done for the N=50 shell gap evolution on the neutron drip line but also as inputs to the theory to pin down states above the N=50 gap: 6.7 MeV at \([\text{Fig. 4}](\text{image link})\]

Correlation energies for the \( ^{40}\text{Zr} \) reflect two features: the neutron shell closures at midshell for \( n \) and \( p \) hole excitations across the \( N\) behavior whose derivative should vanish at midshell.

A complete identification of these multiplets along the N=50 isotonic chain was explained in Ref. 76/\( Z; N \). The doubly magic nuclei show a local \( \Delta S/\Delta Z; N \) towards \( ^{200}\text{Ni} \). In addition, when it comes to the more exotic members of the isotonic chain, this complete identification of \( ^{200}\text{Zr} \) isotopes depends strongly on inverse kinematics.

\( \text{(d,p) reaction} \)

\( ^{81}\text{Ge}(d,p)^{82}\text{Ge} \quad \text{I}^{(81}\text{Ge})=10^5\text{pps} \)

\( \text{Next:}^{80}\text{Zn} \)
Loi submitted to TRIUMF May 2018
Neutron sp states in $^{62}$Ge
$^{81}\text{Ge}(d,p)^{82}\text{Ge}$

(d,p) reaction
Inverse kinematics

Mass measurements

$\gamma$-ray spectroscopy

(ISOLDE/TRIUMF)
ISOL beam production
Proton angular distribution

5-10 MeV/u
$^{81}\text{Ge}$
$^{79}\text{Zn}$
$10^5$ pps

$^{82}\text{Zn}$

$^{80}\text{Zn}$

T-REX + MINIBALL
SHARC + TIGRESS

RIKEN/MSU/GSI
Fragmentation
Luminosity
$\gamma$-ray tagging
$^{d(77}\text{Ni, }^{78}\text{Ni}+\gamma)p$

$^{77}\text{Ni}$
$3$ pps
$^{78}\text{Cu}$
$200$ pps
$^{79}\text{Zn}$
$10^3$ pps

$^{78}\text{Ni}$
$^{79}\text{Zn}$
$^{80}\text{Zn}$

The LD2 target
$700$ mg/cm$^2$
LoI submitted to TRIUMF May 2018

Neutron sp states in $^{82}$Ge

$^{81}$Ge(d,p)$^{82}$Ge

(d,p) reaction
Inverse kinematics

"A Simple Way to Fish an Olive Out of One of Those Long-necked Bottles"

In future
K. Hadynska
Univ. Of Surrey
SEASTAR
$^{75}\text{Cu},^{77}\text{Cu}$

F. Bello
Univ. of Oslo
EURICA
$^{75}\text{Cu},^{77}\text{Cu}$

V. Modamio
Univ. of Oslo
SUNFLOWER
$^{72}\text{Ni},^{73}\text{Cu}$

L. Gaard Pedersen
Univ. of Oslo
EURICA
$^{74,76}\text{Cu}$
EURICA 2012-2013 Collaborations:

SEASTAR 2014 Collaboration


Thank you
EURICA 2012-2013 Collaborations:

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SEASTAR 2014 Collaboration

SUNFLOWER-SPRING 2015 Collaboration
$^{75}\text{Cu}$ & $^{77}\text{Cu}$ - identification in (p,2p)

Figure 3: (a) Gated spectra on 530, 880, and 950 keV, respectively. (b) Gated spectra on 490 and 990 keV, respectively.

2.3 Level schemes

Level scheme of $^{75}\text{Cu}$ is built on the coincidence relations in the present work. Figure 4 shows the level scheme from the present experiment.

Due to the insufficient statistics no coincidence data were available to build the level scheme for $^{77}\text{Cu}$. We tentatively assigned our states through the comparison to the level scheme of $^{77}\text{Cu}$ from the EURICA experiment. Figure 4 shows the level scheme from the present experiment.