Spectroscopy studies around $^{78}\text{Ni}$ via transfer reactions at SPES and short term plans.

J. J. Valiente Dobón (INFN-LNL, Padova, Italy)
A. Gadea (IFIC, Valencia, Spain)
E. Clement (GANIL, Caen, France)
R. Orlandi (CSIC, Madrid, Spain)
Overview

- Study of nuclei in the region of $^{78}\text{Ni}$
- Physics cases and apparata for SPES
- Short term plans: $^{70}\text{Ni}(d,t)^{69}\text{Ni}$ at ISOLDE
- Summary/Remarks
- Possible points to consider in the discussion
Magic numbers and their evolution as a direct consequence of the character of the nuclear force.
The “spin-orbit” magic numbers

N=4

\[ 40 \]

N=3

\[ 20 \]

N=2

\[ 8 \]

N=1

\[ 8 \]

N=8 collapses at \(^{12}\text{Be}\)

Triggered by the \(\pi p_{3/2}-\nu p_{1/2}\) interaction

Reduction of N=20 triggered by \(\pi d_{5/2}-\nu d_{3/2}\)

Island of inversion, large collectivity

Reduction of N=28 gap by tensor force \(\pi d_{3/2}-\nu f\)

strongly deformed \(^{42}\text{Si}\)

Reduction of N=50 gap by tensor force \(\pi f_{5/2}-\nu g\)

Behaviour of \(^{78}\text{Ni}\) ?

H.O + L\(^2\) + → L.S
Systematic variation of effective single-particle energies due to the tensor interaction

\[ V_T = (\tau_1 \tau_2) \left( [\sigma_1 \sigma_2]^{(2)} Y^{(2)}(\Omega) \right) Z(r) \]

T. Otsuka et al. PRL 95, 232502 (2005)
Quadrupole deformation can be generated by using a 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 representing this relevant subspace a quasi-SU3.
Indication of three body forces NNN

Evidence of NNN forces in the Binding Energies in light nuclei

Argonne $v_{18}$

With Illinois-2 GFMC Calculations

Courtesy of C. Pipier, Argonne National lab.
NNN in the Ca region

Microscopic calculations with well-established two-nucleon NN, do not reproduce N=28.

However NN and NN+3N forces predict the N=28 shell gap, but with quantitative differences.

The changes due to 3N forces are amplified in neutron-rich nuclei and will play a crucial role for matter at the extremes.

T. Otsuka et al., PRL105, 032501 (2010)
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N=50
Co isotopes, Z=27

Lifetime measurement at AGATA+PRISMA of the neutron-rich Co isotopes, a way to study the evolution of the Ni isotopes.

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

\[ \pi f_{7/2}^1 \otimes 2^+ (\text{Fe}) \]

A. Dijon et al. PRC83, 064321 (2011)

F. Recchia et al. to be published

V. Modamio et al., PRC (to be submitted)
Evolution along $Z=28$ - $^{78}\text{Ni}$

- Softening of the $Z=28$ core
- Quasi-$SU(3)$ symmetry involvement of the $d_{5/2}$ orbital to explain the collectivity

O. Sorlin et al. PRL 88 (2002) 092501
O. Perru et al. PRL 96 (2006) 232501
G. Kraus et al. PRL 73 (1994) 1773.

B(E2) values towards $^{78}$Ni


Preliminary Coulex: G. de Angelis

N. Aoi (p,p’)

Courtesy of K. Sieja Vietri sul Mare (2010)
ESPE towards $^{78}\text{Ni}$

$^{56}\text{Ni}$: well doubly-magic, gap 6.5 MeV

$^{68}\text{Ni}$ mixture of magic and superfluid. O. Sorlin $\text{PRL88 092501 (2002)}$

$^{78}\text{Ni}$ is supposed to be doubly-magic with a proton gap 5.0 MeV and neutron 4.6 MeV

The rigidity of the gap in $^{78}\text{Ni}$ is also an important issue in astrophysics because it is a waiting point in the r-process.

K. Sieja et al., $\text{PRC81, 061303 (2010)}$
Cu isotopes, Z=29

Collectivity of the $7/2^-$ state probe the $B(E2:0^+\rightarrow 2^+)$ in $^{76}\text{Ni}$

Magnetic moment measurement confirmed the inversion of the $f_{5/2}$ with the $p_{3/2}$ in $^{75}\text{Cu}$

Along the N=50

Highly precision mass measurements

Two neutron shell gap energies

J. Hakala et al., PRL101, 052502 (2008)
J. Van de Walle et al., PRL99, 142501 (2007)
The N=50 isotones

Shell Model calculations: 2p-2h excitations across the N=50 shell to 2d_{5/2}^{-1}g_{7/2}^{-1}3s_{1/2}^{-1} (Lisetsky) for 4.7 MeV of the shell gap value → No reduction of the shell gap

E. Sahin and G. De Angelis PLB (to be published)
Physics cases and apparata for SPES
Transfer reactions

What can we learn from transfer reactions:
- Evolution of ESPE
- Spectroscopic factors, etc.

ISOLDE and GANIL:
- $^{78}$Zn(d,p) R. Orlandi et al., (to be published)
- $^{68}$Ni(d,p) G. Duchene et al., (to be published) – Thesis.
- $^{66}$Ni(d,p) J. Diriken et al., (to be published).
Physics cases considered for SPES

• (d,p) \(^{81,82}\text{Ga}, \, ^{79,80}\text{Zn}\) – single particle orbital around N=50 g\(_{9/2}\), d\(_{5/2}\), s\(_{1/2}\), d\(_{3/2}\) and g\(_{7/2}\). Gap stability

• (t,α) \(^{74,76,78,80}\text{Zn}\) to selectively populate single proton states in odd-A \(^{73,75,77,79}\text{Cu}\) isotopes- p\(_{3/2}\), f\(_{5/2}\) and f\(_{7/2}\). Proton removal from the GS of Zn.
Challenges:
- Required beam (10^5 – 10^6 pps, purity > 40-60%)
- High-energy of secondary beams ~ 5-10MeV/u
- Tritium loaded Ti target ➔ safety issues to be considered
- Efficient instrumentation: gamma and charged particles.
- Effective interactions for shell-model calculations ➔ Energies and SF
- Cross sections calculations: DWBA calculations
Detection systems

Gamma ray arrays
- AGATA
- GALILEO

Charged particle/heavy ion detectors
- TRACE
- SPIDER
Short term plans: $^{70}\text{Ni}(d,t)^{69}\text{Ni}$ at ISOLDE

Proposal to be presented next INTC ISOLDE meeting: 31 Oct-1 Nov 2012
D. Mengoni, R. Orlandi and JJVD
Large-scale shell-model calculations

- The $d_{5/2}$ orbital is essential to describe the B(E2) values.
- quasi-SU3 symmetry
- Region of Fe and Cr: the $d_{5/2}$ orbital is essential to describe this deformation region (S. Lenzi et al., Phys. Rev. C 82, 054301 (2010))

Deduced from N. Aoi PLB692 302 (2010)
$\delta = 1.04(16) \text{ fm}$

Courtesy of K. Sieja Vietri sul Mare (2010)
The role of the $g_{9/2}$ and $d_{5/2}$ orbitals

The GS of $^{70}$Ni

$\text{GS of } ^{70}\text{Ni has according to SM calculations 0.25 particles in } d_{5/2}$

We consider the $5/2^+$ state at 2.5 MeV (G. Duchene et al., Acta Phys. Pol.)

The Q value of the reaction is $-0.985\text{MeV}$

$Q(5/2^+) = -3.485\text{MeV}$

SM valence space:
- $pf$-shell for protons
- $f_{5/2}, p, g_{9/2}, d_{5/2}$ for neutrons.

Study of $^{70}\text{Ni}$ ground state

Beam: $^{70}\text{Ni} @ 5.5\text{MeV/u}$
Target: 1 mg/cm$^2$ of Deuterated Polyethylene (C2D4)

Fusion evaporation of $^{12}\text{C}$ with $^{70}\text{Ni}$ (PACE4)
$^{12}\text{C} + ^{70}\text{Ni} \rightarrow ^{82}\text{Se} \rightarrow t\ (2n+p) + ^{79}\text{As} \quad \sigma=0.14\ \text{mb} \rightarrow \text{Most } 2n+p\ \text{and not triton}$
Summary

• Study of the low-lying properties of isotopes near by $^{78}\text{Ni}$ with the SPES beams.
• Shell evolution in the region – Tensor interaction, rigidity of the gaps when going towards $^{78}\text{Ni}$
• Changes due to 3N forces are amplified in neutron-rich nuclei and will play a crucial role for matter at the extremes.
• Use of (d,p) and (t,α) reactions to study the region
• Sensitive detection systems to be used like: AGATA, GALILEO, TRACE, SPIDER
• There is no a universal technique to measure the physical properties along an isotopic chain
• Concerns: beam purity $> 40\%$, intensity $10^5$-$10^6$, energy $10\sim \text{MeV/u}$
• Short-term range plans: Proposal for an experiment at ISOLDE $^{70}\text{Ni}(d,t)^{69}\text{Ni}$ at ISOLDE
Points to consider in the discussion

- **SPES beams** ➔ Important to know the intensity and beam purity
- **Targets** ➔ Is there a general strategy to include radioactive targets such as tritium in the general SPES project? Who should take care of this?
- **Detector systems** ➔ AGATA/GALILEO+TRACE ✔️ Lacking any others instrumentation? For example, IC for beam purity check at the end of the line. Is there a general strategy?
- **Before SPES** ➔ General strategy (INFN) to collaborate with other laboratories with larger experience ISOLDE/GANIL? Not only a single proposal.
- Theoretical support ➔ Is there a more general umbrella of theoreticians working on this kind of projects? Within NuPNET?
- Etc.
Reactions and 3-body force

Study of Three-Body Force in Nuclear Physics

- Which reactions (and systems) to study?
  - Electromagnetic interaction on 3B systems
  - 3B (and more bodies?) Bound states
  - 3B Elastic scattering in large parts of phase space
  - 3B Break-up reaction in different kinematics
  - Many-body systems $\rightarrow$ Nuclear matter

$N + d \rightarrow N + d$
$N + d \rightarrow N + N + N$
$N + d \rightarrow ^3He(^3H) + \gamma(\ast)$
$\gamma(\ast) + ^3He(^3H) \rightarrow N + d$
$\gamma(\ast) + ^3He(^3H) \rightarrow N + N + N$

Courtesy of N. Kalantar-Nayestanaki
Reactions and 3-body force

pd elastic scattering cross sections

\[ p + d \rightarrow p + d \]

K. Ermisch et al., PRC 68, 054004 (2003), PRC 71, 064004 (2005)

Courtesy of N. Kalantar-Nayestanaki


\( ^{74}\text{Ni} (p,p') \) measurement

- Softening of the Z=28 core
- Quasi-SU(3) symmetry involvement of the \( d_{5/2} \) orbital to explain the collectivity
Beyond N=50 - Deformation

Involvement of the quasi-SU(3) in the explanation of the deformation in the N=40 region

- **78,80,82 Ge Coulex**
- **84 Se(d,p)85 Se (N=51)**

Proton angular distributions for GS and 462keV Ex

- **Coulex**: 78,80,82 Ge E. Padilla-Rodal et al., PRL94, 122501 (2005)
- **Relativistic Coulex + knockout**: 82 Ge and 84 Se A. Gade et al., PRC81, 064326 (2010)
- **(d,p)**: 83 Ge and 85 Se: J.S. Thomas et al., PRC76, 044302 (2007)
- 8 sectors of Si strip detectors arranged in a pie-shaped array
- The front surface (junction side) is segmented into 8 strips
- The thickness of the Si detector is around 300μm
- Dead layer 50nm

θ coverage when the detector is mounted at 5 cm distance from the target: 18 to 60 degrees