Nuclear structure studies with the EUROBALL cluster detectors: EURICA and GALILEO

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Overview

- **Neutron-rich**
  - β delayed γ-ray spectroscopy: $^{55}$Ca $\rightarrow$ $^{55}$Sc
  - β delayed γ-ray spectroscopy: $^{75,77}$Ni $\rightarrow$ $^{75,77}$Cu
  - Isomer spectroscopy: $^{110}$Zr

- **Proton-rich**
  - Isomer spectroscopy: $^{71}$Kr

- The GALILEO project at LNL
Ductu naturae

$\nu f_{7/2}$

$\pi f_{p}$

$\nu g_{9/2}$

$\pi g_{9/2}$

$\nu f_{7/2}$

$\nu g_{9/2}$

$\nu s d g$

$\nu h_{11/2}$

$\nu f_{p}$

$\nu g_{9/2}$

$\nu s d g$

$\nu h_{11/2}$

$^{71}\text{Kr}$

$^{55}\text{Sc}$

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

$^{110}\text{Zr}$
β delayed γ-ray spectroscopy: $^{55}\text{Ca} \rightarrow ^{55}\text{Sc}$

Spokepersons: J.J. Valiente-Dobón, D. Mengoni, …
N=34 subshell gap

Monopole effect of the tensor interaction in shell evolution

- Possible subshell closure between $p_{3/2} - p_{1/2}$ and $f_{5/2}$
- Attraction between the $f_{7/2}$ and $f_{5/2}$
- Does $^{54}$Ca present N=34 subshell?

T. Otsuka et al., PRL95 232502 (2005)
Energies and B(E2) values

Indication of shell gaps

Energies and B(E2) values are complementary to study in detail shell evolution.


Indication of three body forces NNN

Evidence of NNN forces in the Binding Energies in light nuclei

Courtesy of C. Pipier, Argonne National lab.
Microscopic calculations with well-established two-nucleon NN, do not reproduce N=28.

However NN and NN+3N forces predict a high 2$^+$ energy in $^{54}$Ca, 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)
States with predominant $v_{f_{5/2}}$ predict that the $p_{1/2}$-$f_{5/2}$ energy difference might be smaller that the one predicted by GXPF1A. Nevertheless this does not rule out the possible N=34 shell gap, since the change in the gap still gives good description of $^{54}\text{Ca}$.

B.Fornal et al., PRC77, 014304 (2008)
A SM interpretation of the experimental levels shows that the energy spacing between the $p_{1/2}$ and $f_{5/2}$ is almost constant up to $^{52}$Ca, and when extrapolated to $^{53,54}$Ca shows that N=34 might not be a magic number.

M. Rejmund et al., PRC76 021304(R) (2007)
Investigating the N=34 with β decay

We propose the study of the β decay $^{55}\text{Ca} \rightarrow ^{55}\text{Sc}$ in order to disentangle the evolution of $\pi f_{7/2} - \nu f_{5/2}$ monopole tensor interaction and NNN forces, that might give rise to the subshell closure N=34.

P.F. Mantica et al., PRC77, 014313 (2008)
Possible beam time request

- Beam $^{86}$Kr - 30pnA - 345MeV/nucleon
- Setting $^{55}$Ca
- Be primary target $\sim$2.5 g/cm$^2$
- BigRIPS fragment separator
- EURICA eff $\sim$10%
- Nine-layer double-sided silicon-strip detector (DSSSD) PRL106, 052502 (2011)
- Production $\sim$0.5pps $^{55}$Ca
- 8 days $\rightarrow$ 34000 gamma if $\beta$ has a $\sim$ 100% efficiency
- Complementary measurement to the GSI AGATA in beam experiment with knockout reactions.
β delayed γ-ray spectroscopy: $^{75,77}\text{Ni} \rightarrow ^{75,77}\text{Cu}$

Spokespersons: E. Sahin, V. Modamio, …
Systematic variation of effective single-particle energies due to the tensor interaction

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

T. Otsuka et al. PRL 95, 232502 (2005)
Magnetic moment measurement confirmed the inversion of the $f_{5/2}$ with the $p_{3/2}$ in $^{75}\text{Cu}$
Study of $^{71,73,75}$Cu at CLARA+PRISMA

$^{82}$Se + $^{238}$U @ 515 MeV  CLARA-PRISMA  $\Theta_{PRISMA} = 64^\circ$

States involving the $\pi f_{7/2}^{-1}$ might allow to have a hint on the $Z=28$ shell gap.
Experiment Performed in middle June 2010 Multi-nucleon transfer reaction: $^{76}\text{Ge} + ^{238}\text{U} @ E(^{76}\text{Ge})=577 \text{ MeV}$

Data analysis is ongoing!!

AGATA demonstrator + PRISMA

: Levels to measure lifetimes!
Beyond $^{73}\text{Cu} - ^{75,77}\text{Cu}$ with $\beta$ decay

Proton induced fission $^{238}\text{U}$ Louvain-la-Neuve

S. Franchoo et al PRC64, 054308 (2001)

FIG. 8. Decay scheme of $^{77}\text{Ni}$. For discussion, see text.
Possible beam time request

- Beam $^{86}$Kr - 30pnA - 345MeV/nucleon
- Setting $^{77}$Ni
- Be primary target $\sim$2 g/cm$^2$
- BigRIPS fragment separator
- EURICA eff $\sim$10%
- Nine-layer double-sided silicon-strip detector (DSSSD) PRL106, 052502 (2011)
- $N(^{75}$Ni$)= 1.0$ pps
- $N(^{77}$Ni$)= 0.5$ pps
- 8 days $^{75}$Ni $\rightarrow$ 68000 gamma if $\beta$ has a $\sim$ 100% efficiency
- 8 days $^{77}$Ni $\rightarrow$ 34000 gamma if $\beta$ has a $\sim$ 100% efficiency
Isomer spectroscopy: $^{110}\text{Zr}$

Spokesperson: G. de Angelis, J. Dudek, D. Curien, F. Haas, …
Tetrahedral symmetry

New nuclear deformation never observed: **tetrahedral** shape

The tetrahedron is a Platonic solid with 24 symmetries

The corresponding symmetry group for nuclei (fermionic hamiltonian) has 48 symmetries

\[ R(\theta, \varphi) = \sum_{\lambda,\mu} \alpha_{\lambda\mu} Y_{\lambda\mu} \]

A tetrahedral deformation is a kind of non-axial octupole shape: \( \alpha_{32} \)

The presence of a symmetry in the Hamiltonian leads to the appearance of new magic numbers $Z=40$; $N=70$.

N. Schunck et al., PRC69 061305(R) 2004
Tetrahedral magic numbers

- From a WS potential:
  
  20, 32, 40, 56-58, 64, 70, 90, 100, 112, ...

- Existence of $T_d$ magic numbers independent of the realization of the mean-field = Universality

Best candidates: proton-rich or neutron-rich nuclei...

Highly accurate measurement with a Bragg spectrometer and the GRID technique.

- Lifetime of the $5^-$ level at 1.408 MeV
- Intensity of the 132 keV $5^- \rightarrow 3^- \gamma$ ray

The measurend lifetime gives an intrinsic $Q_0 = 7.104(35) b$ is obtained $\rightarrow$ Large quadrupole collectivity. Therefore the negative parity band incompatible with a tetrahedral symmetry.
Coullex to access Tetrahedral shapes

Electromagnetic transition matrix elements and quadrupole moment (with sign) accessible by low energy Coulomb excitation
One might expect isomers from non axial octupole bands to normally deformed bands.

The spherical N=70 sub-shell gap is not having a large effect at N=68 $^{108}$Zr

The isomeric state of $^{108}$Zr is proposed to be the candidate for a tetrahedral shape.

Possible beam time request

- Beam $^{238}$U – 5pnA - 345MeV/nucleon
- Setting $^{110}$Zr
- Be primary target ~1 g/cm$^2$
- BigRIPS fragment separator
- EURICA eff ~10%
- Nine-layer double-sided silicon-strip detector (DSSSD) PRL 106, 052502 (2011)
- Production ~7pps $^{110}$Zr
- Isomeric ratio ~10%
- 8 days $\rightarrow$ 5 $10^4$ gamma
Isomer spectroscopy: $^{71}$Kr

Spokespersons: F. Recchia, G. de Angelis, …
The isospin symmetry in the $f_{7/2}$

- Isospin symmetry manifest better along the $N=Z$ nuclei
- Coulomb Energy Differences CED, difference in excitation energies between isobaric analog states.
Isospin symmetry in collective structures

If isospin is conserved, the E1 transitions in mirror nuclei should have the same strength.
Measured $B(E1)$

**$^{67}$Se**

- $9/2^+ \rightarrow 7/2^-$ analogue transitions

**$^{67}$As**

- Two pairs of $9/2^+ \rightarrow 7/2^-$ analogue transitions
- To determine $B(E1)$
  - branching ratios
  - lifetime of $9/2^+$ state
- Multipolarities and mixing ratios

<table>
<thead>
<tr>
<th>Energy (KeV)</th>
<th>$B(E1)$ ($10^{-6}$ wu)</th>
<th>$B(E1)$ ($10^{-6}$ wu)</th>
<th>Energy (KeV)</th>
</tr>
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<tbody>
<tr>
<td>717</td>
<td>0.4(4)</td>
<td>1.4(4)</td>
<td>725</td>
</tr>
<tr>
<td>303</td>
<td>&lt;1.4(9)</td>
<td>8.3(2.4)</td>
<td>319</td>
</tr>
</tbody>
</table>
The B(E1) isoscalar/isovector

Both transitions consistent with large isoscalar/isovector ratio: IS/IV~ 0.35(20)

\[ \begin{align*}
B(E1) \left( T_z = \pm \frac{1}{2} \right) &= \langle J_f; T_f T_z | M(E1)_{IS} \pm M(E1)_{IV} | J_i; T_i T_z \rangle^2
\end{align*} \]

- Selection Rules for charge-symmetric nuclear interaction
  - E1 pure isovector (but different sign in mirror nuclei)
  - E1 transitions in \( T_z = \frac{1}{2} \) nuclei should exhibit same strength
- If differences, may arise from interference between IV and non-zero IS term
  - \( 10^{-4} \) in IS/IV for the neglected terms in the long-wave approximation
  - Coulomb mixing with close lying 7/2⁻ levels
  - Mixing via Isovector Giant Monopole Resonance (IVGMR)

Detailed calculations in a forthcoming publication P.G Bizzeti
Shape effects in the $A=70$ mass

$CED(J) = E_x(J,T=1,T_z>) - E_x(J,T=1,T_z<)$

- $A=70^{(70\text{Br}/70\text{Se})}$ – large negative CED has been explained as resulting from:
  - Prolate stretching in both nuclei (B S Nara Singh et al., PRC 75, 061301(R) (2007))
  - Also speculated that it may be due to diff (obl/ prol) shapes for the two nuclei (R. Wadsworth et al., Act. Pol. B40, 611 (2009), G. de Angelis et al. PRC (R) (to be published))

G. de Angelis et al., EPJ A12, 51 (2001)
D.G. Jenkins et al., PRC 65, 064307 (2002)
Shape effects in CED

- Beyond mean-field approach with symmetry projection
- Successfully used to describe analogue states in mass 70 region, Petrovici et al., Nucl Phys A728, 396 (2003)
- Takes into account: Oblate/ prolate shape co-existence and n-p pairing correlations in both the T=0 and T=1 channels
- Calculations performed using the isospin symmetric G matrix based on Bonn A potential and Coulomb interaction between the valence protons.

• $^{70}$Se is predominantly oblate GS (J. Ljungvall et al., PRL100 102502 (2008))
• $^{70}$Br is predominantly prolate GS
Character 9/2$^+$ transition in $^{71}$Kr

\[ T_z = +1/2 \]

\[ \tau = 33\text{ns isomer in } ^{71}\text{Br} \]

Predicted $\tau \sim 100\text{ns isomer in } ^{71}\text{Kr}$

- measurement of the decay branches in $^{71}$Br and $^{71}$Kr

S.M. Fischer et al., PRC72, 024321 (2005)
Possible beam time request

- Beam $^{78}$Kr - 30pnA - 345MeV/nucleon (not in the list)
- Setting $^{71}$Kr
- Be primary target 2g/cm$^2$
- BigRIPS fragment separator
- EURICA eff $\sim$10%
- Nine-layer double-sided silicon-strip detector (DSSSD) PRRL106, 052502 (2011)
- Production $\sim$1500pps $^{71}$Kr
- Isomeric ratio 10%
- 5 days $\rightarrow$ 3 $10^5$ gamma
The GALILEO project at LNL

Project manager: C.A. Ur
The GALILEO project

2012 after AGATA

GALILEO – a new gamma–ray array spectroscopy

- takes advantage of the developments made for AGATA
  - preamplifiers
  - digital sampling
  - preprocessing
  - DAQ

- uses the EUROBALL cluster detectors capsules
  - improved efficiency
  - development of a new cluster detector with 3 capsules

Detector configuration
- 30 GASP detectors @ 22.5cm
  5 5 5 5 5 5
  29° 51° 59° 121° 129° 131°
- 10 triple cluster detectors @ 24 cm
  90°

\[ e_{ph} \approx 8\% \quad P/T \approx 50\% \]
GALILEO physics case

2009 – call for Letters of Intent
15 LolIs (30 institutes, 11 countries)

The proposed physics cases can be grouped in the following categories
• structure of N~Z nuclei
• isospin symmetry
• study of neutron–rich nuclei
• exotic decay of high–spin states
• nuclear structure close to $^{100}\text{Sn}$
• cluster and highly deformed states in sd–shell nuclei
• giant resonances and warm rotations
• symmetries and shape–phase transitions in nuclei
• shape coexistence in neutron–deficient nuclei
• magnetic moments measurement
GALILEO Triple Cluster

- Development of the triple cryostat
- Design of the anti–Compton shield
- Design of the support structure
- New digital electronics
R&D anti-Compton shields

Recovery from EUROBALL Anti Compton
Ancillary detectors for GALILEO

• Light charged particle detectors
  • EUCLIDES, LUSIA, TRACE
• Neutron detector
  • n–Ring, N–Wall, NEDA
• Binary reaction products detection
  • DANTE, MW-PPAC
• Recoil detectors
  • RFD
• High–energy gamma–rays detector
  • HECTOR
• Fast timing
  • LaBr3 detectors
• Mass spectrometer
  • PRISMA

Study of weak reaction channels stable beams & SPES beams

• High efficiency
• High resolving power
Summary

• Proposals to study neutron-rich nuclei
  • Address the N=34 subshell gap via $\beta$ delayed $\gamma$-ray spectroscopy: $^{55}\text{Ca} \rightarrow ^{55}\text{Sc}$
  • Address shell evolution $Z=28$ nearby $N=50$ via $\beta$ delayed $\gamma$-ray spectroscopy: $^{75,77}\text{Ni} \rightarrow ^{75,77}\text{Cu}$
  • Doubly magic tetrahedral nucleus $^{110}\text{Zr}$ via isomer spectroscopy
• Proposal to study proton-rich nuclei
  • Address IS/IV component and CED via isomer spectroscopy of $^{71}\text{Kr}$
• GALILEO project at LNL for gamma spectroscopy using Triple Clusters from EUROBALL 7-clusters