Neutron-proton correlation phenomena in N=Z nuclei around $^{100}$Sn

- An experimental perspective

Bo Cederwall
Royal Institute of Technology (KTH), Stockholm

NORDITA Conference on Chiral Bands in Nuclei, Stockholm, 20-24 April 2015
Challenges in Nuclear Structure (selection!)

Shell structure in nuclei (general)
- Structure of doubly magic nuclei
- Changes in the (effective) interactions
- Development of collective excitations

Proton drip line and N=Z nuclei
- Spectroscopy beyond the drip line
  - influence from continuum
- Neutron-proton pair modes
- Isospin symmetry
- Superallowed α-decays
- GT strengths
- exotic decays

Neutron rich heavy nuclei (N/Z → 2)
- Large neutron skins (rν-rπ → 1fm)
- New coherent excitation modes
- Shell quenching

Nuclei at the neutron drip line (Z→25)
- Very large proton-neutron asymmetries
- Resonant excitation modes
- Neutron Decay

Limits of nuclear existence
- Driplines
- Superheavy island
- Shape coexistence
- Transfermium nuclei
- Exotic shapes and isomers
- Hyperdeformation
- Coexistence and transitions

Challenges in Nuclear Structure (selection!)

Bo Cederwall, NORDITA Conference on Chiral Bands in Nuclei, Stockholm, 20-24 April 2015
Nuclear structure around $^{100}$Sn – near the “top” of the N=Z line

Moller Chart of Nuclides 2000
Quadrupole Deformation

N=Z line coincides with a doubly-magic system and the proton dripline

- Neutron-proton correlations in identical orbitals
- Neutron-proton (isoscalar) pairing / Spin-aligned np coupling scheme
- Superallowed $\alpha$-decays
- Emergence of “collectivity”; B(E2), B(E3) strength
- LSSM calculations (eff. charges, interactions) can be applied and tested
Astrophysical interest:
End point of the rp-process path in X-ray bursts and steady-state hydrogen burning on accreting neutron stars*

Region of interest I

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Proton separation energy (MeV)

Courtesy M. Palacz

Bo Cederwall, NORDITA Conference on Chiral Bands in Nuclei, Stockholm, 20-24 April 2015
Structure data is lacking → new generation detector arrays and facilities

Number of excited states known

adapted from M. Palacz

Bo Cederwall, NORDITA Conference on Chiral Bands in Nuclei, Stockholm, 20-24 April 2015
What is the nature of nuclear pair correlations near N=Z?
- A long-standing, open question in nuclear structure physics

When approaching N=Z, “normal” pair correlations may remain or even be extended as neutrons and protons occupy identical quantum states:

\[ T=1, \ J=0 \ ("\text{isovector}") \ \text{nn, pp} \]
\[ \text{as well as np Cooper pairs} \quad (\text{neutrons and protons occupy identical orbits}) \]

In addition: \[ T=0, \ J=1 \ldots \ ("\text{isoscalar}") \ \text{np pairing?} \]

(We know the isoscalar effective NN interaction is strongly attractive but can it produce a correlated np pairing condensate?)
Effective (residual) interactions between nucleons in a j-shell

\[ \theta_{12} = \frac{J(J+1)}{2j(j+1)} - 1 \]

- effective force between particles, orbital overlap
- Pauli principle

Bo Cederwall, NORDITA Conference on Chiral Bands in Nuclei, Stockholm, 20-24 April 2015
The isoscalar (np) pair gap is predicted to increase sharply as $N \rightarrow Z$

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"Isospin-generalized" BCS-type calculation by W. Satula, R. Wyss
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Does isoscalar (np) pairing *in the BCS sense* exist in Nature? (i.e. can we find an isoscalar pairing “deuteron” condensate somewhere?)

The experimental search for $T=0$ np pairing has focused on special features:

- g.s. binding energies of $N=Z$ (even-even vs odd-odd) nuclei
- high-spin properties of deformed $N=Z$ nuclei (reduced CAP, delayed alignments?)
- deuteron transfer reactions in inverse kinematics (e.g. measure branching to $T=1$ and $T=0$ states in odd-odd $N=Z$ nuclei)

Need for (reaction) theory to develop sharp predictions

**Status:** No convincing evidence for so far
But much more to be done ...
Evidence for isovector np pairing is claimed from nuclear binding energies, rotational alignments, charge radii etc.


“Overview of neutron-proton pairing”
Frauendorf, S., Macchiavelli, A.O.
Progress in Particle and Nuclear Physics volume 78, 2014, pp. 24 - 90

“Excludes” $T=0$ pairing in g.s
Note: Data end at $N=Z\approx30$!
Symmetry energy?
Precision mass data is crucially lacking for N=Z!

Precision of known masses in the $^{100}$Sn region.

T. Faestermann, M. Górska, and H. Grawe, Prog. Part. Nucl.Phys. 69, 85 (2013)
Delayed (or absent) paired (T=1) bandcrossings in deformed N=Z nuclei?

Data end crucially here!

Ru - a superdeformed self-conjugate system? The perfect "laboratory" for investigating nuclear pairing effects? Deep SD minimum persists down to zero rot frequency, low excitation energy.

TRS calculation by R. Wyss

Bo Cederwall, NORDITA
Conference on Chiral Bands in Nuclei, Stockholm, 20-24 April 2015

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Strong T=0 neutron-proton (np) pair correlations may lead to something different from a BCS-type of pairing condensate:

**“Isoscalar spin-aligned coupling scheme”** *

predicted for N=Z nuclei close below $^{100}$Sn.

- Unique signature of “vibrational-like” yrast energies and “rotational-like” B(E2) strengths. B(E2;0$^+\rightarrow 2^+$)s develop differently compared with standard seniority scheme along isotopic chain as N$\rightarrow$ Z

- A new manifestation of strong np-pair correlations

* ’Evidence for a spin-aligned neutron-proton paired phase from the level structure of $^{92}$Pd’
  B. Cederwall et al., Nature 469, 68 (2011)

’Spin-aligned neutron-proton pair mode in atomic nuclei’
C. Qi, J. Blomqvist, T. Bäck, B. Cederwall, A. Johnson, R. J. Liotta, and R. Wyss
Observation of excited states in the $N=Z=46$ nucleus $^{92}\text{Pd}$

EXOGAM + Neutron Wall + Diamant experiment

B. Cederwall et al., Nature 469, 68 (2011)
Calculations performed in several model spaces, i.e., $0g_{9/2}$, $0g_{9/2}-1p_{1/2}$ and $0g_{9/2}-1p_{1/2}-0f_{5/2}-1p_{3/2}$ which all give very similar results.

Int. parameters determined to reproduce exp energies in $^{94,95}$Pd, $^{93,94}$Rh

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<tr>
<th>State</th>
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<td>92Pd</td>
<td>93Pd</td>
<td>94Pd</td>
<td>95Pd</td>
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</table>

B. Cederwall et al., Nature 469, 68 (2011)
Strong residual np interactions $\Rightarrow$ Spin-aligned T=0 np coupling scheme for N=Z nuclei below $^{100}$Sn

"Spin-aligned T=0 np paired phase"
Not pairing as a BCS condensate

The diagonal SM interaction matrix element that corresponds to the isoscalar $\nu\pi(g_{9/2})^2$ aligned np pair ($J^\pi = 9^+$),
$V_9 = <g^2_{9/2}; J=9|V|g^2_{9/2}; J=9>$, is strongly attractive, with $V_9 \sim -2$ MeV

Aligned isoscalar np coupling:
$\Psi_{G.S.} = [\{\nu g_{9/2}^{-1} \times \pi g_{9/2}^{-1}\}_{9^+}]^2_{0^+} \times [\{\nu g_{9/2}^{-1} \times \pi g_{9/2}^{-1}\}_{7^+}]^2_{0^+}$
Different from the standard textbook description of the ground states in even-even nuclei!
Generation of angular momentum in the isoscalar spin-aligned coupling scheme ($^{92}$Pd)

Similarities with “stretch scheme”
M. Danos and V. Gillet, Phys. Rev. 161 (1967) 1034
Upper: Shell model spectra of $^{92}$Pd calculated within the $1p_{3/2}0f_{5/2}1p_{1/2}0g_{9/2}$ space [10] (fpg) and the $1p_{1/2}0g_{9/2}$ space (pg).

Lower: $B(E2; I \rightarrow I-2)$ values in $^{92}$Pd calculated within the fpg and pg spaces. The two dashed lines show the predictions of the geometric collective model normalized to the $2^+_1$ state.

C.Qi, J.Blomqvist, T.Bäck, B. Cederwall, A. Johnson, R. J. Liotta, and R. Wyss, PRC 84, 021301(R) (2011)
LSSM calculation, \( fpg (f5/2, p3/2, p1/2, g9/2) \)
(all shells between 28 and 50)  C. Qi

\[
B(E2; 2^+; 0^+) (e^2fm^4)^* \]

\* 1 W.U. \( \sim 25 \ e^2fm^4 \) here

- Green: Only T=1/no np
- Purple: Only T=0
- White: Full np

\[ ^{92}_{\text{Pd}} \]  \[ ^{94}_{\text{Pd}} \]  \[ ^{96}_{\text{Pd}} \]
C. Qi, priv. comm., Z.X. Xu et al., Nuclear Physics A 877 (2012) 51–58

Bo Cederwall, NORDITA Conference on Chiral Bands in Nuclei, Stockholm, 20-24 April 2015
LSSM calculation, fpg (f5/2, p3/2, p1/2, g9/2) (all shells between 28 and 50)  C. Qi

B(E2;2^+\rightarrow0^+) (e^2\text{fm}^4)\times 1 \text{ W.U.} \approx 25 \text{ e}^2\text{fm}^4 \text{ here}

Only T=1 np
Only T=0 np
Full np

0  20  40  60  80  100  120  140  160  180

0  20  40  60  80  100  120  140  160  180

only T=1 np
only T=0 np
Full np

96Cd
98Cd

* 1 W.U. \approx 25 e^2\text{fm}^4 \text{ here}
Critical test of LSSM interactions: Precision spectroscopy of E1 transitions in semimagic nuclei

- All low-lying states in this region are well described within the $f_{5/2}$, $p_{3/2}$, $p_{1/2}$ and $g_{9/2}$ model space.

- $E1$ transitions are “forbidden” within this space since the matrix elements $\langle f | E1 | i \rangle$ vanish for all possible combinations of initial states $i$ and final states $f$.

- Presence of $E1$ transitions $\rightarrow$ other (higher or deeper lying) single-particle states are active.

- A sensitive probe of SM parameters: Even a minute admixture of such configurations in the wave function may greatly increase the probability of $E1$ decay since the $E1$ single-particle matrix element is very large in comparison with any other multipole mode.

- The observed $E1$ transition strengths serve as a critical test of the shell-model wave function with respect to the model subspace from which it is constructed. In particular for core excited states.
### E1 hindrance factors in N=50 nucleus $^{94}$Ru

<table>
<thead>
<tr>
<th>$E_{\gamma}$ (keV)</th>
<th>$J_i^\pi \rightarrow J_f^\pi$</th>
<th>$H \times 10^5$ (W.u.)$^{-1}$</th>
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<tr>
<td>257</td>
<td>$13^+ \rightarrow 12^-_1$</td>
<td>0.006 (1)</td>
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<td>462</td>
<td>$15^-_2 \rightarrow 14^+_2$</td>
<td>0.051 (5)</td>
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<td>402</td>
<td>$18^-_1 \rightarrow 18^+$</td>
<td>0.188 (25)</td>
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<td>$15^-_2 \rightarrow 14^+_1$</td>
<td>0.451 (32)</td>
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<td>227</td>
<td>$12^+ \rightarrow 11^-$</td>
<td>0.57 (27)</td>
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<td>887</td>
<td>$18^-_1 \rightarrow 17^+$</td>
<td>1.09 (12)</td>
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<td>438</td>
<td>$5^- \rightarrow 4^+$</td>
<td>1.90 (17)</td>
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<td>498</td>
<td>$11^- \rightarrow 10^+$</td>
<td>4.27 (19)</td>
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</table>

\[ a \quad H = \frac{A^{2/3}}{15.5 \times B(E1)} . \]

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Moradi, Qi, Cederwall et al., PRC, 014301 (2014)
E1 hindrance in $^{95}$Rh$_{50}$

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<tr>
<th>$E_\gamma$ (keV)</th>
<th>$J_i^\pi \rightarrow J_f^\pi$</th>
<th>$H \times 10^5$ (W.u.)$^{-1}$</th>
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<td>29/2$^+$ $\rightarrow$ 27/2$^-$</td>
<td>0.11(1)</td>
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<tr>
<td>1031</td>
<td>37/2$^-$ $\rightarrow$ 35/2$^+$</td>
<td>0.29(1)</td>
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<td>770</td>
<td>35/2$^-$ $\rightarrow$ 35/2$^+$</td>
<td>0.35(1)</td>
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<td>169</td>
<td>17/2$^-$ $\rightarrow$ 17/2$^+_1$</td>
<td>2.8(2)</td>
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Table II of this work, there are a number of weak E1 transitions present, even at low excitation energies (below 5 MeV). We evaluated all possible E1 transitions among states within the expanded shell model space. Considering first the E1 decay from the first 17/2$^-$ state to the yраст 17/2$^+_1$ state, these states are predominantly of $\pi(1p_{1/2}^{-1}0g_{9/2}^{-4})$ and $\pi(0g_{7/2}^{-5})$ character, respectively, as discussed above; i.e., without possibility of E1 decay. This transition has the largest hindrance, $2.8 \times 10^5$ W.u.$^{-1}$ among the E1 decays observed in $^{95}$Rh which is reflected by the long ($\sim$19 ns) half-life of the 17/2$^-$ state [2]. The core-excitation components in these two states are mainly of a one-neutron character. In our calculation the contribution to the transition in terms of occupation probability from the high lying shells 1$d_{5/2}$ and 0$g_{7/2}$ is 0.02, while the corresponding contribution from the deep-lying shells 1$p_{3/2}$ and 0$f_{5/2}$ is approximately $10^{-4}$. Therefore the E1 hindrance factor is of the order $5 \times 10^5$ W.u.$^{-1}$, which is consistent with the value given in Table II. The absence of E1 transitions depopulating the following negative-parity states up to 25/2$^-$ indicates that the influence of the core excited configurations is limited in these states as predicted in Ref. [8]. E1 decays observed from the higher-lying negative-parity states as well as from the 29/2$^+_1$ state signal significant contributions from core-excited configurations with one neutron being excited from below the $N = 50$ shell closure to the 1$d_{5/2}$ or 0$g_{7/2}$ orbits, in agreement with the calculations presented in Ref. [20].
### Region of interest II: Island of α and p radioactivity “NE” of $^{100}$Sn

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<td>7.6 s</td>
</tr>
<tr>
<td>Sb 108</td>
<td>16.7 s</td>
</tr>
<tr>
<td>Sb 109</td>
<td>24.0 s</td>
</tr>
<tr>
<td>Sb 111</td>
<td>75 s</td>
</tr>
<tr>
<td>Te 105</td>
<td>0.70 µs</td>
</tr>
<tr>
<td>Te 106</td>
<td>70 µs</td>
</tr>
<tr>
<td>Te 107</td>
<td>3.1 ms</td>
</tr>
<tr>
<td>Te 108</td>
<td>2.1 s</td>
</tr>
<tr>
<td>Te 109</td>
<td>4.6 s</td>
</tr>
<tr>
<td>Te 110</td>
<td>18.6 s</td>
</tr>
<tr>
<td>Te 111</td>
<td>26.2 s</td>
</tr>
<tr>
<td>Te 112</td>
<td>2.0 m</td>
</tr>
<tr>
<td>I 108</td>
<td>36 ms</td>
</tr>
<tr>
<td>I 109</td>
<td>100 µs</td>
</tr>
<tr>
<td>I 110</td>
<td>0.65 s</td>
</tr>
<tr>
<td>I 111</td>
<td>2.5 s</td>
</tr>
<tr>
<td>I 112</td>
<td>3.42 s</td>
</tr>
<tr>
<td>I 113</td>
<td>5.9 s</td>
</tr>
<tr>
<td>Xe 109</td>
<td>13 ms</td>
</tr>
<tr>
<td>Xe 110</td>
<td>105 ms</td>
</tr>
<tr>
<td>Xe 111</td>
<td>0.95 s</td>
</tr>
<tr>
<td>Xe 112</td>
<td>2.7 s</td>
</tr>
<tr>
<td>Xe 113</td>
<td>2.8 s</td>
</tr>
<tr>
<td>Xe 114</td>
<td>10 s</td>
</tr>
<tr>
<td>Ba 113</td>
<td>100 ms</td>
</tr>
<tr>
<td>Ba 114</td>
<td>0.43 s</td>
</tr>
<tr>
<td>Ba 115</td>
<td>0.45 s</td>
</tr>
<tr>
<td>Ba 116</td>
<td>1.3 s</td>
</tr>
<tr>
<td>Cs 112</td>
<td>500 µs</td>
</tr>
<tr>
<td>Cs 113</td>
<td>17 µs</td>
</tr>
<tr>
<td>Cs 114</td>
<td>0.57 s</td>
</tr>
<tr>
<td>Cs 115</td>
<td>1.4 s</td>
</tr>
</tbody>
</table>

- **N=x**: Stable nuclides
- **N≠x**: Stable nuclides

**Note:** The table indicates the decay lifetimes for various isotopes, with some elements having halflives in the range of milliseconds to hours. The decay modes include α-decay and β-decay, which are critical for understanding the stability and properties of these nuclides.
Recoil-decay tagging (RDT) *) has become a crucial tool for structural studies of heavy, proton rich nuclei

- Recoil-decay tagging spectroscopy (as we know it nowadays) started in the $A \sim 100$ ($^{108,109}$Te) region E.S. Paul et al.

- Extremely low production cross sections prevented further exploration

- Technical advances (RITU + GREAT, TDR ...) were needed to proceed further

- Technique now getting ready for high-intensity beams

*) R.S. Simon et al., Z.P.A. 325, 197 (1986): NaI + SHIP @ GSI
E.S. Paul et al., P.R.C. 51, 78 (1995): Eurogam (45 HPGe) + DRS @ Daresbury
Experimental set-up at JYFL; Univ. of Jyväskylä Cyclotron Laboratory

Bo Cederwall, NORDITA Conference on Chiral Bands in Nuclei, Stockholm, 20-24 April 2015
**Gamma Recoil Electron Alpha Tagging - GREAT**

**MWPC - Multi Wire Proportional Counter:** Recoil discriminator
**PIN-diodes:** Detection of \(\beta\)-particles and conversion \(e^-\)
**DSSD - Double-sided Silicon Strip Detector:** Charged particle detection (alpha, proton)
**Planar Ge and Clover:** Detection of delayed gamma rays following radioactive decays or from isomeric states

Bo Cederwall, NORDITA Conference on Chiral Bands in Nuclei, Stockholm, 20-24 April 2015
RDT selectivity

γ

γ − recoil

γ − recoil − α
Evidence for enhanced collective strength in Te and Xe nuclei approaching N=Z?

Xe experimental $E(2^+)$ and $B(E2; 2^+ \rightarrow 0^+)$ systematics

Te experimental $E(2^+)$ and $B(E2; 2^+ \rightarrow 0^+)$ systematics

Xe and Te energy ratios

$$\frac{E_{4^+}}{E_{2^+}}$$

$\gamma$-soft rotor

harm. vibration

Bo Cederwall, NORDITA Conference on Chiral Bands in Nuclei, Stockholm, 20-24 April 2015
Evidence for weakening of the $N=Z=50$ shell closure?

Systematics of $B(E2)$ for Sn isotopes

Status pre 2013

$B(E2; 0^+_\text{gs} \rightarrow 2^+)^\uparrow \left[ e^2 b^2 \right]$
Systematics of $B(E2)^\uparrow$ for Te and Sn isotopes


Including $\nu g_{9/2}(-6 \text{ MeV})$: $(g,d,s,h_{11/2})$

$B(E2; 0_{gs}^+ \rightarrow 2^+) \uparrow [e^2 b^2]$

$N$

52 54 56 58 60 62 64 66 68 70 72 74 76 78 80 82

0 0.1 0.2 0.3 0.4 0.5 0.6 0.7 0.8

Te

$^{108}\text{Te}$

stable beams

radioactive beams

$g_{7/2} < d_{5/2}$

Banu s.p.e. 2005 ($g_{7/2}, d, s, h_{11/2}$)

stable beams

SNDC

ISOLDE

GSI

NSCL

ORNL

Banu

SM$^a$

SM$^b$

SM$^c$
Doornenbal et al., arXiv:1305.2877 [nucl-ex]

$^{104}$Sn, PRESPEC, Guastalla et al., PRL 110, 172501 (2013)
Enhanced octupole deformation and correlations near N=Z

<table>
<thead>
<tr>
<th>202</th>
<th>134</th>
<th>88</th>
<th>56</th>
<th>34</th>
</tr>
</thead>
<tbody>
<tr>
<td>184</td>
<td>126</td>
<td>82</td>
<td>50</td>
<td>28</td>
</tr>
<tr>
<td>2h 11/2</td>
<td>4s 1/2</td>
<td>3p 1/2</td>
<td>1g 9/2</td>
<td>1f 7/2</td>
</tr>
<tr>
<td>1k 17/2</td>
<td>3d 3/2</td>
<td>3p 3/2</td>
<td>2p 1/2</td>
<td>1d 3/2</td>
</tr>
<tr>
<td>1j 15/2</td>
<td>2g 7/2</td>
<td>3l 13/2</td>
<td>3h 9/2</td>
<td>1f 3/2</td>
</tr>
<tr>
<td>1l 11/2</td>
<td>2g 9/2</td>
<td>1i 13/2</td>
<td>2f 7/2</td>
<td>1d 5/2</td>
</tr>
</tbody>
</table>

**Strong octupole correlations are expected in nuclei where normal-parity single-particle states and intruder states differing by $\Delta l = \Delta j = 3$ are near the Fermi surface.**


<table>
<thead>
<tr>
<th>112</th>
<th>Ba</th>
</tr>
</thead>
<tbody>
<tr>
<td>56</td>
<td></td>
</tr>
</tbody>
</table>

**Coherent octupole correlations for neutrons and protons should occur near N=Z. Can we observe additional enhancement due to dynamic np correlations?**
Enhanced octupole correlations in light Te-Xe nuclei due to dynamical np coupling $(\pi(\nu)d_{5/2} - \nu(\pi)h_{11/2})$?

Next to $^{112}\text{Ba}$ (inaccessible with current state-of-the-art) $^{110}\text{Xe}_{56}$ and $^{109}\text{I}_{56}$ might have the largest octupole stability

$^{112}\text{Xe}$

$^{110}\text{Xe}_{56}$ and $^{109}\text{I}_{56}$ might have the largest octupole stability

$^{80}\text{W.u.}$

$\approx 80$ W.u. !


Bo Cederwall, NORDITA Conference on Chiral Bands in Nuclei, Stockholm, 20-24 April 2015
The “island” of alpha and proton radioactivity “NE” of $^{100}$Sn → opportunity for RDT spectroscopy of exotic N~Z nuclei

Challenges

- Difficult separating fusion-evaporation residues: Can only be populated in near-symmetric reactions.
- Large fusion cross section, many evaporation channels open → rate limited by focal plane detectors (until now).

Bo Cederwall, NORDITA Conference on Chiral Bands in Nuclei, Stockholm, 20-24 April 2015
\[ ^{58}\text{Ni} (^{52}\text{Cr}, 3n) ^{107}\text{Te}^* @ 187\text{MeV} \]

Recoil-correlated \(\alpha\) decays @ RITU focal plane

4\(\times\)10\(^{15}\) A, \(~5\) days

Alpha-decay branching ratio : 70%  
Half life : 3.1 ms  
\(\sigma = 1\) \(\mu\)b

---

C. Fahlander et al.  
(Euroball)

D. Seweryniak et al.  
(Gammasphere + FMA)
Recoil-decay correlated gamma-ray spectrum

Tentative level scheme

D. Schardt et al.,

B. Hadinia et al.,
Phys. Rev. C. 2004

Bo Cederwall,  NORDITA Conference on Chiral Bands in Nuclei, Stockholm, 20-24 April 2015
The predicted rp-process end point in X-ray bursters and accreting neutron stars

Companion star (H and He envelope)

Accretion disk (H and He fall onto neutron star)

Peak temperature
\[ T \sim 1 \text{ GK} \]
\[ kT \sim 100 \text{ keV} \]

$^{54}\text{Fe} + ^{54}\text{Fe} \rightarrow ^{106}\text{Te}^* + 2\text{n}$

$(E_b = 182 \text{ MeV}, I_b = 10 \text{ pnA}, 5 \text{ days})$

Alpha decay branching ratio : 100%
Halflife : 70μs

Time between recoil implantation and $^{106}\text{Te}$ alpha decay

$^{106}$Te gamma rays
\[ \sigma = 25 \text{ nb} \] - (Then) a new limit for in-beam $\gamma$-ray spectroscopy!

Recoil-gated triples projection spectrum

Recoil-decay correlated gamma-ray spectrum

Selectivity: $\sim 10^{-7}$

Tentative level structure of $^{106}$Te


Bo Cederwall, NORDITA Conference on Chiral Bands in Nuclei, Stockholm, 20-24 April 2015
Gamma-gamma coincidences at $\sigma \sim 25$ nb

$^{106}$Te $\gamma$ rays
Recoil–$\alpha$ correlated

$^{106}$Te recoil-alpha gated gamma singles
$^{106}$Te recoil-alpha gated gamma-gamma
(sum of 4 gates)
Identification of excited states in $^{110}\text{Xe}$


β-delayed protons

First evidence for superallowed α-decay at $T_z=1$
Clean mother–daughter correlations essential for selecting the $^{110}$Xe nuclei

β-delayed protons

$^{110}$Xe mother–daughter correlated, sum $\gamma\gamma$

$^{110}$Xe mother–daughter correlated

Total recoil-tagged

Bo Cederwall, NORDITA Conference on Chiral Bands in Nuclei, Stockholm, 20-24 April 2015
Comparing theory with experimental $B(E2)$ values (Raman estimates) for extremely neutron deficient Xe isotopes

$B(E2)$ values are a measure of nuclear collectivity

Theoretical models predict a decrease in $B(E2)$ values for decreasing $N$

The empirically deduced values* reveal a leveling off and even a small increase of the $B(E2)$ value for $^{110}$Xe

$B(E2; 2^+_1 \rightarrow 0^+_1) \approx 0.66 E(2^+_1)^{-1} Z^2 A^{-0.69}$

Bo Cederwall, NORDITA Conference on Chiral Bands in Nuclei, Stockholm, 20-24 April 2015
Decay spectroscopy: “High-intensity” stable beams and new detection schemes

$^{109}\text{Xe}\to^{105}\text{Te}\to^{101}\text{Sn}$

**Exp I**
Liddick et al., PRL 97 082501 (2006)

$^{54}\text{Fe}+^{58}\text{Ni}\to^{112}\text{Xe}^*(3n)^{109}\text{Xe}$
$\sim 8 \text{ part. nA}$
standard target

$^{54}\text{Fe}+^{58}\text{Ni}\to^{112}\text{Xe}^*(3n)^{109}\text{Xe}$
$\sim 50 \text{ part. nA}$
rotating target

DSSD (40x40, 65 $\mu$m)
+ veto detectors
+ HPGe (11.2% @ 123 keV)

Digital DAQ: alpha catcher mode

Chiara Mazzocchi, UW, 2011
Superallowed alpha decay: enhanced preformation
- Strongly connected to np correlations in N=Z systems

Chiara Mazzocchi, UW, 2011
$T_{1/2} \ (\text{th}) \sim 100-150 \ \mu s$

$Q_\alpha \ (\text{th}) = 4.44 - 4.65(15) \ \text{MeV}$

$T_{1/2} \ (\text{th}) \sim 5 - 50 \ \text{ns}$

$Q_\alpha \ (\text{th}) = 5.05 - 5.42(7) \ \text{MeV}$

$Q_\alpha \ (\text{extr}) > 5.0 - 5.2 \ \text{MeV}$

Chiara Mazzocchi, UW, 2011

**Theory:**
Xu and Ren, PRC74, 2006;
Mohr, EPJA31, 2007

**Extrapolated limits:**
Liddick et al., PRL97, 2006;
Seweryniak et al., PRC73, 2006
Experimental opportunities at the end of the N-Z line:

**AGATA @ GANIL → SPIRAL2**
- RDT/RDDS using VAMOS in gas-filled mode
- L.E. Coulex
- Spectroscopy
- np-transfer

**RIKEN (DALI2+ZDS)?**
**AGATA-HISPEC @ FAIR**
- H.E. Coulex, knockout
Proton rich and $N=Z$ nuclei – major potential for important discoveries

- Neutron-proton correlation effects
  - isoscalar pair modes
  - superallowed alpha decays
  - development of collective excitations
- GT strengths Not discussed here
- Isospin symmetry Not discussed here
- Exotic particle decay modes (2p, ...) Not discussed here
- Influence from proton state continuum on structure and correlations Not discussed here
- High-spin physics Discussed only briefly here
- ...

“High-intensity” stable beams coupled to improved detector instrumentation one important route forward!
np pair modes - outlook

- $^{100}\text{Sn}$ region a prime “laboratory” for investigating effects of strong residual neutron-proton correlations including $T=0$ pairing

- Strong need for mass measurements in $N=Z$ nuclei beyond $A\approx 60$ to pin down ground-state isoscalar pairing issue

- Deuteron transfer reactions with RIBs (inverse kinematics) another promising route

- Angular momentum response in (super) deformed $N=Z$ systems

- Isoscalar spin-aligned coupling scheme is a possible, different “paired phase” with characteristic features that need further experimental verification at the new facilities

- Need sharper theoretical predictions for reactions & structure
Thank You