Nuclear Superdeformation

Paul Fallon NS06

Outline

• Introduction
  • basic physics
  • the early days
  • review - what we have learned

• Selected Topics
  • Decays
  • C4
  • Identical Bands
  • New regions $^{40}$Ca
  • Triaxial SD
  • Hyperdeformed
    - $^{108}$Cd ….

• Future

P. Twin et. al
The discovery of “high-spin” superdeformation was a major motivation and justification for the large $4\pi$ arrays Gammasphere and Euroball
“Top unexpected physics discoveries of the last five years!”

PHYSICS TODAY December 1991

High temperature superconductivity

Atom cooling and atom optics

Large-scale structure of the universe

Supernova 1987A

Superdeformed nuclei

Buckyballs

Daniel Kleppner
Lester Wolfe Professor of Physics at MIT

J. Garrett
“Superdeformation - Nuclear Physics’ Supernova”

B. Mottelson
…one of Nuclear Structures finest hours ..
First Observed $^{242}\text{Am}$

25yrs later $^{152}\text{Dy}$ (1986)

Since then …

Rapid progress—Large detector arrays
Deformed Minima/Shell gaps

- Coulomb Energy
- Rotational Energy

If gaps due to symmetry
- deformation independent of A
Deformed analog of spherical gaps
SD distinct from normal defs
Nuclear Deformations

\[ \frac{Q}{2/5ZR^2} \]

Normalized Quadrupole Moment (Deformation)

Mass A

1/A^{1/3}
surface/volume

ground states

208\text{Pb}
Nuclear Deformations

\[ \frac{Q}{2\sqrt{5}ZR^2} \]

- Normalized Quadrupole Moment (Deformation)
- Mass A
- Ground states
- \(1/A^{1/3}\)
- \(1/3\)
- \(36\) Ar, \(40\) Ca, \(60\) Zn, \(82\) Sr, \(108\) Cd, \(132\) Ce, \(152\) Dy, \(192\) Hg, \(208\) Pb, \(236\) U

\(c/a \sim 2:1\)
\(c/a \sim 3:2\)
Table of Superdeformed Nuclear Bands and Fission Isomers* Third Edition (July 2002)

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Deformations Shell Structure and Intruders

Classify the Intruder by the number of major oscillator shells it has moved

Classify the Structure by the Intruder Occupation

<table>
<thead>
<tr>
<th>Intruder</th>
<th>ND</th>
<th>SD</th>
<th>HD</th>
</tr>
</thead>
<tbody>
<tr>
<td>Z~50</td>
<td>g\textsubscript{9/2}</td>
<td>h\textsubscript{11/2}</td>
<td>i\textsubscript{13/2}</td>
</tr>
</tbody>
</table>

Has some benefits compared with definition based strictly on axis ratio
The early days (1986-1992)

- Observation
  \( A \sim 130, 150, 190 \)

- Structure – \( J^{(2)} \)

- Identical Bands
Mapping the single-particle (high-j intruder) configurations


Theoretical by T. Bengsston, et al. PLB 208 (1988) 39,
1990: Identical Superdeformed bands

T. Bryski et al, PRL 64(90) 1650
W. Nazarewicz et al, PRL 64 (90) 1654

(a) $E_\gamma(^{151}\text{Tb}:\text{SD Excited}) - E_\gamma(^{152}\text{Dy}:\text{SD Yrast})$

(b) $E_\gamma(^{150}\text{Gd}:\text{SD Excited}) - E_\gamma(^{151}\text{Tb}:\text{SD Yrast})$

F. S. Stephens et al., PRL 64 (1990) 2626

Heroic? New insight? Pseudo-spin alignment (1 Unit Spin Difference!)
or
Non-Heroic? : Chance cancellations between pairing & deformation effects?
Superdeformation and the large arrays

- Data explosion – new regions, multiple bands – new physics

- Precision measurements (Transition energies and rates, deformations, linking the normal and superdeformed minima)

- New phenomena – C4, Triaxial, order-to-chaos
Superdeformation – highly polarized systems

Tool to study many aspects of nuclear structure - Elementary Modes of Excitation

Shell Structure; Exotic states; Extreme Single-Particle Motion (shell model); Collective Modes; Pairing

**Extreme single-particle motion**
Residual correlations are washed out

\[ Q_0[abcd] = Q_c - a \cdot \overline{q}_a - b \cdot \overline{q}_b - c \cdot \overline{q}_c - d \cdot \overline{q}_d \]

**Pairing Correlations**

Quasiparticle alignment
\[ \pi_{13/2} \nu_{15/2} \]

SD-1 band

[Graph showing data and distribution]
Excitations

• ~ 250 SD bands – most involve excitations within the second minimum

• Vast majority are single-particle excitations

• limited number of collective excitations (vibrations)  
  — concentrated in heavier systems.

• Identical bands (very stringent test of theory – def. pairing, alignments)
Collective excitations

\[ M. \text{ Hunyadi et al.} / \text{Physics Letters B 505 (2001) 27–35} \]

**inner barrier**

\[ E_A = 5.8 \text{ MeV} \]

**Quadrupole phonons:**

\[ (K^\pi = 0^+) \]

\[ \begin{align*}
  \sim 5.05 & \quad \sim 2.80(20) \\
  4.625 & \quad 2.38(20) \\
  4.526 & \quad 3 \hbar \omega_\beta \\
  4.434 & \\
\end{align*} \]

\[ 4 \hbar \omega_\beta \]

\[ 3 \hbar \omega_\beta \]

\[ 2 \hbar \omega_\beta \]

**outer barrier**

\[ E_B = 5.45 \text{ MeV} \]

**Octupole phonons:**

\[ \begin{align*}
  (-3.85) & \quad (-1.6) \\
  3.02(20) & \quad 0.77 \\
\end{align*} \]

\[ \beta\text{-band} \]

\[ \hbar \omega_\beta \]

\[ \begin{align*}
  1.345 & \\
  1.345 & \\
  0.836 & \\
  0.806 & \\
  0.555 & \\
\end{align*} \]

\[ \begin{align*}
  K^z = 1^- & \\
  K^z = 1^- & \\
  K^z = 2^- & \\
  K^z = 0^- & \\
\end{align*} \]

\[ 3.7 \text{ ns} \]

**A = 240**

Quadrupole and Octupole Vibrations

\[ ^{240}\text{Pu} \]

**A = 190**

Octupole Vibrations

\[ ^{190,194}\text{Hg}, \ ^{196,198}\text{Pb} \]

**A = 150**

Octupole Vibrations

\[ ^{152}\text{Dy} \]
Superdeformation Physics and Phenomena

- Identical Bands – Decay out (links)
- $Q_0$’s
- C4
- Triaxiality
- $A=40$
- $^{108}$Cd Towards Hyperdeformation
- ....
Identical Bands - Spins

- Increase in SD Data – identical band systematics in A=150, A190 regions

- Key development – establish spins in $^{194}\text{Hg}$, an identical band

- Confirm existence of unit spin difference

→ What is origin of unit alignment?

**Systematic Study**
- Comparison – Data and Theory

  - Suggests – Quasiparticle alignment and Pairing

P. Fallon et al, PRC 60 (1999) 04431

G. Hackman et al, PRL 79 (1997) 4100
Decays from the second minimum

**Distinct States (two minima)**

- Tunneling
- Statistical (compound) ?
- Dependence on excitation energy ? (mass region)
- Status
  - A~40 “All” linked
  - A~60 (~50% linked)
  - A~80 (1 linked)
  - A~130 (~50% linked)
  - A~150 (\(^{149}\)Gd, \(^{152}\)Dy)
  - A~190 (\(^{194}\)Hg, \(^{194}\)Pb, \(^{192}\)Pb)
  - A~240 (\(^{236,238}\)U)
$^{152}$Dy Fifteen Years …

T. Lauritsen et al., PRL 88 (2002) 042501

4011 keV Determines Ex. Energy
Dipole Character (E1)
$\tau \sim 2.9$ ps
$B(E1) \sim 2 \times 10^{-6}$ WU

Other gammas placed $> \text{Fixed spins}$
- $2 \text{ hbar}$ higher than original estimate
- Can test calculations

E1 decays (similar for $^{194}$Hg)
$\Delta I = 4$ bifurcation occurs when alternate levels in a superdeformed band are perturbed by one part in a million, in opposite directions.

The transitions in these neighboring nuclei are nearly identical, but the direction of the tiny shift is reversed.

When the small shifts in three bands are plotted as a function of spin, they show a remarkable correlation which is not understood at this time.

S. Flibotte et al., PRL 71 (93) 4299
D. Haslip et al., PRL 78, (1997) 3447
D. Haslip et al., PRC 58 (98) R2649
Identical Bands and C4

GS expt by Haslip et al., PRL 78 (1997) 3447

\[ ^{29}\text{Si} + ^{124}\text{Sn} \rightarrow ^{148}\text{Eu} + \text{p4n} \]
\[ ^{148}\text{Gd} + 5\text{n} \]

 Lots of new bands!

We can use other bands as a reference!

See also Haslip et al., PRC 58 (1998) R2649 for systematic survey
Precision Measurements: A~130 Quadrupole Moments


Graph showing quadrupole moments for different elements.
New regions - new physics
A~40 Superdeformed Nuclei

- Microscopic understanding of collective motion
  - Connect deformed intrinsic states (rotational motion) with microscopic wavefunctions (lab system) – $^{20}$Ne, $^{24}$Mg (sd), $^{48}$Cr (pf)

- Truncations/approximations (theory) are necessary - must be tested by experiment
- Nuclei around A~40 are an ideal place to carry out these studies
  - Deformed shell gaps ($f_{7/2}$ intruder, N=3)
Data on A~40

- $^{32}\text{S}$, not seen 4p-12h
  C.E.Svensson et al., PRL 85 (2000) 2693
- $^{36}\text{Ar}$, 4p-8h ($\pi^2\nu^2$)
  D.Rudolph et al., PRC 65 (2002) 034305
- $^{38}\text{Ar}$, 4p-6h ($\pi^2\nu^2$)
  E.Ideguchi et al., PRL 85 (2001) 222501
- $^{40}\text{Ca}$, 8p-8h ($\pi^4\nu^4$)
  C.O’Leary et al., PRC 61 (2000) 064314
- $^{44}\text{Ti}$, 8p-4h ($\pi^4\nu^4$)

Determined - Energies, Spins, Parities, B(E2).

Observed to Band head (excited O$^+$)

Allows detailed comparison with theory.
E. Ideguchi et al., PRL 87 222501 (2001); C.J. Chiara et al., PRC 67 041303 (2003)

\[ ^{40}\text{Ca} \]

- \(^{28}\text{Si}(^{20}\text{Ne},2\alpha)^{40}\text{Ca}\)
- 8p-8h structure identified as \(\pi^3\nu^3\)

\[ Q_t = 1.30 \pm 0.05 \text{ e b} \quad \beta_2 \sim 0.59 \]

- New expt \(^{24}\text{Mg}(^{24}\text{Mg},2\alpha)^{40}\text{Ca}\)

\[ Q_t(\text{high}) = 1.81^{+0.41}_{-0.26} \text{ e b} \]
\[ Q_t(\text{low}) = 1.18^{+0.06}_{-0.05} \text{ e b} \]
Triaxial Shapes and The Wobbling Mode

Robust triaxial shapes have been sought after for decades!

\[ {^{163}\text{Lu}} \]

- Triaxial nucleus allows rotation about all 3 axes
- Total ang. momentum vector lies off principal axis - precession
- Amount it lies off axis quantized into wobbling phonons \( (n_w) \)
- See a family of bands based on same configuration \( (n_w) \)
- Bands are linked together
  - \( \Delta I = 1 \) have dominant E2 nature
- Bands have similar properties
  - Moments of inertia, quadrupole moment, alignment

"the rotational families contain an added dimension, and the rotational relationships are correspondingly more complex .. it is potentially a field of broad scope."
Bohr and Mottelson Vol. 2 page 176

D.R. Jensen et al., PRL 89, 142503 (02)
A Brief Status of TSD

- Best evidence for triaxiality is in $^{163}\text{Lu}$
  - See “wobbling” excitations based on $\pi i_{13/2}$ structure
- Evidence of wobbling seen in $^{165}\text{Lu}$ & $^{167}\text{Lu}$
- Ultimate Cranker predicts $^{164,166}\text{Hf}$ are good candidates
  - But no TSD bands found
- Multiple bands in heavier Hf (yet no definite evidence for wobbling)

Questions - role of triaxial N=94 gap, is odd-proton doing at all?

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<td>$^{172}\text{Lu}$</td>
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<tr>
<td>$N = 94$</td>
<td>93</td>
<td>94</td>
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M.K. Djongolov *et al.*, PLB 560, 24 (03)

G. Schönwaßer *et al.*, PLB 552, 9 (03)

H. Amro *et al.*, PLB 553, 197 (03)

S.W. Ødegård *et al.*, PRL 86, 5866 (01)
The $^{108}$Cd Superdeformed Bands


High spin (multiplicity) states selected by a “K” cut

Deformation $\beta_2 \sim 0.6$ (lower limit)
108Cd: Towards Hyperdeformed Nuclei

Woods Saxon Potential

235U: “normal-intruder”

152Dy: “super-intruder”

108Cd: i_{13/2} “hyper-intruder”

Fig. 1

(a) Single Particle Levels (MeV) vs. Quadrupole Deformation

(b) Moment of Inertia vs. Spin

Exp. + Th.

J(1) and J(2)
For Z~50 and A~110 the $\pi i_{13/2}$ and $\nu j_{15/2}$ are the “hyper-intruder” (N+3) states 

$\pi i_{13/2}$ “hyper-intruder” occupied in $^{108}\text{Cd}$

Calculations suggest $\nu j_{15/2}$ occupied at N=64 (close to $^{108}\text{Cd}$, N=60)

Exciting possibility for Hyperdeformation (both N+3 intruders !)
Future Prospects “where do we go from here”

Future Progress (example from super to hyper)
- Tools (apart from imagination)
  - Beams
    - RIBS
  - Detectors
    - Gamma-ray tracking arrays

- RIB Beams (not usually discussed in this context)
  - Extend towards the n-rich (back to the Cd story)
    - Even a few (6) extra neutrons can make a difference in observed physics (hyperintruders - need neutron levels)
    - More neutrons, more spin

- Gamma-ray detectors
  - Ge Shell (GRETA) – increased efficiency, inverse reactions
Hyperdeformation: Production and Population

An example...

A New Region and Increasing the Spin limit

<table>
<thead>
<tr>
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<th>60</th>
<th>62</th>
<th>64</th>
<th>66</th>
<th>68</th>
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<tbody>
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<td>50</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>48</td>
<td></td>
<td></td>
<td>108Cd</td>
<td></td>
<td>114Cd</td>
</tr>
</tbody>
</table>

limit with favorable stable-beam reactions

Hyperdeformation

94Kr + 26Mg -> 120Cd*
“Dream Experiment”

- \( l_{\text{max}} \sim 62 \hbar \) in \(^{108}\text{Cd}\) and \( 70 \hbar \) in \(^{114}\text{Cd}\)
- \(^{108}\text{Cd}\) produced with stable beams: \(^{48}\text{Ca} + ^{64}\text{Ni}\) at 207 MeV
- \(^{114}\text{Cd}\) produced with “RIA” beams: \(^{94}\text{Kr} + ^{26}\text{Mg}\) at 500 MeV

Also 170-180 region \(^{132}\text{Sn} + ^{48}\text{Ca} \rightarrow ^{180}\text{Yb}\*)
130-140 region \(^{94}\text{Kr} + ^{48}\text{Ca} \rightarrow ^{142}\text{Ba}\*)
Angular Momentum Limit

Gain 1-2 hbar per neutron

new spin regime

- Compound Nucleus using stable beams
- Compound Nucleus using RIA
Gamma-ray Detector Development

Central Role in Nuclear Physics

- Advances in detector technology have resulted in new discoveries.
- Innovations have improved detector performance.
  - Energy resolution
  - Efficiency
  - Peak-to-total ratio
  - Position resolution
  - Directional information
  - Polarization
  - Auxiliary detectors
- Tracking is feasible, will provide new opportunities and meet the challenges of new facilities.
The $4\pi$ Array GRETA
GRETA High spin state from fusion reactions

\[ {^{64}\text{Ni}} \left( ^{48}\text{Ca}, 4n \right) ^{108}\text{Cd}, \text{Gammasphere} \]

- Simulation GS, \( \epsilon = 0.09 \)
  - 3-fold, \( I = 10^{-4} \)

- Simulation GS
  - 3-fold, \( I = 10^{-3} \)

- Simulation GRETA, \( \epsilon = 0.25 \)
  - 4-fold, \( I = 10^{-5} \)

\( v/c = 0.04 \)
Future Directions

• Hyperdeformation
  — location, new physics
• Higher Temperatures (SD unique – shell gap)
  — feeding, damped nucleonic and rotational motions
  — GDR
• Decay
• Fission Isomers
• Connections to cluster states
• Periodic orbits (Semi-classical approaches)
Concluding observations…

Just as the discovery of Superdeformation had a major impact, so too has Gammasphere built a community, a base for the future.

Gammasphere (Euroball) - The best of a kind. Can’t build a better spectrometer using this technology.

What’s next - The Ge shell – built on the new technology of highly segmented Ge.

Tools – (i) Beams (stable and RIBS). (ii) Instruments (+ imagination)
As we maximize our capabilities, advanced Instrumentation can give the competitive edge
→ important today, maybe more so than ever …

• A $4\pi$ tracking array (GRETA) is essential for these studies
Thanks ...

Still going ...
END