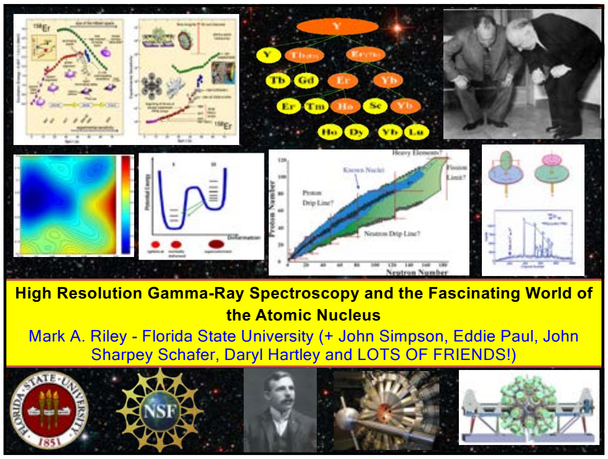
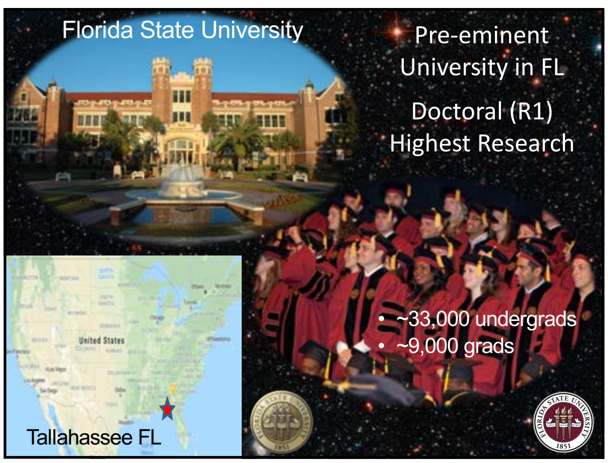
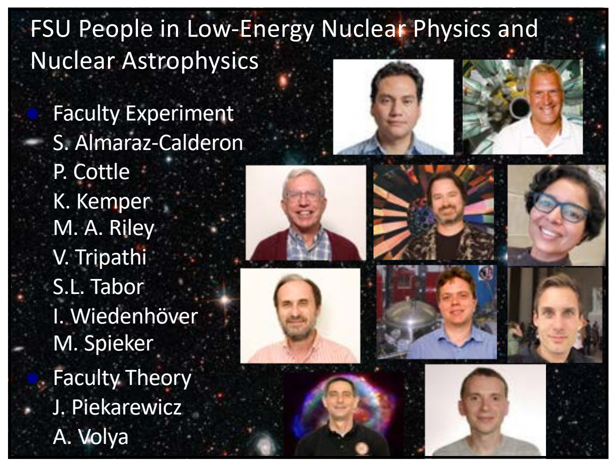
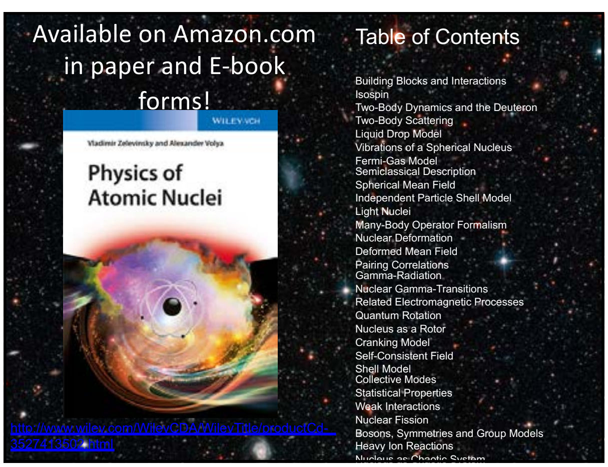
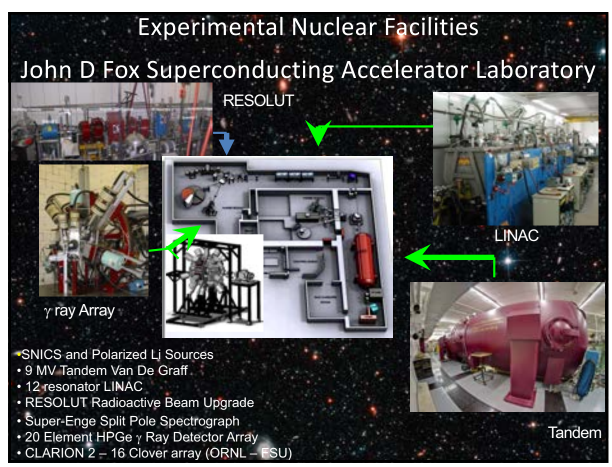

High Resolution Gamma-Ray Spectroscopy and the Fascinating World of the Atomic Nucleus
Mark A. Riley - Florida State University (+ John Simpson, Eddie Paul, John Sharpey Schafer, Daryl Hartley and LOTS OF FRIENDS!)
NSF

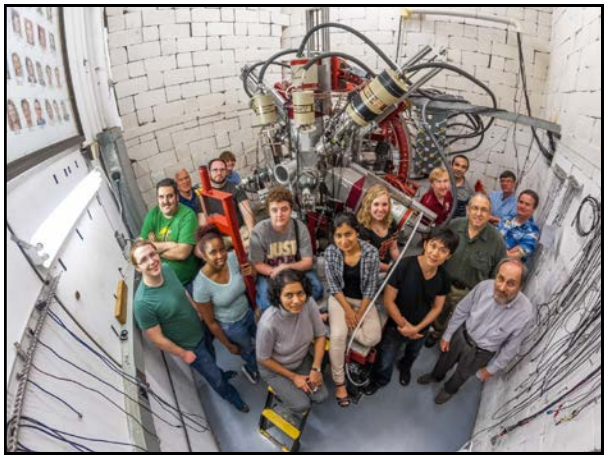

Widowisko z muzyką Józefa Skrzeka
oraz narracją filmową Jerzego Gręboszа
15/09/2019
Na styku dwóch nieskończoności
Koncepcja i reżyseria: Adam Maj
45. ZJAZD FIZYKÓW POLSKICH
Auditorium Maximum UJ, Kraków; 15 września 2019 r., godz. 20
https://www.ifj.edu.pl/en/popularization/spectacle-mgs/


Florida State University
Pre-eminent University in FL
Doctoral (R1) Highest Research
• ~33,000 undergrads
• ~9,000 grads
Tallahassee FL


FSU People in Low-Energy Nuclear Physics and Nuclear Astrophysics
Faculty Experiment
S. Almaraz-Calderon
P. Cottle
K. Kemper
M. A. Riley
V. Tripathi
S.L. Tabor
I. Wiedenhöver
M. Spieker
Faculty Theory
J. Piekarewicz
A. Volya

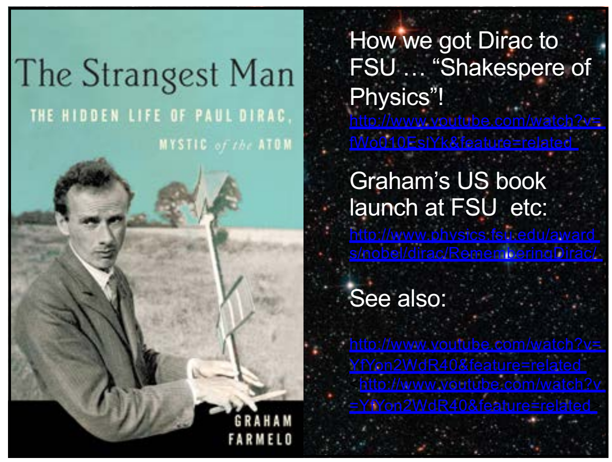

Available on Amazon.com in paper and E-book forms!
Physics of Atomic Nuclei
Vladimir Zelevinsky and Alexander Volya
WILEY-VCH
http://www.wiley.com/WileyCDA/WileyTitle/productCd-3527413502.html
Table of Contents
Building Blocks and Interactions
Isospin
Two-Body Dynamics and the Deuteron
Two-Body Scattering
Liquid Drop Model
Vibrations of a Spherical Nucleus
Fermi-Gas Model
Semiclassical Description
Spherical Mean Field
Independent Particle Shell Model
Light Nuclei
Many-Body Operator Formalism
Nuclear Deformation
Deformed Mean Field
Pairing Correlations
Gamma-Radiation
Nuclear Gamma-Transitions
Related Electromagnetic Processes
Quantum Rotation
Nucleus as a Rotor
Cranking Model
Self-Consistent Field
Shell Model
Collective Modes
Statistical Properties
Weak Interactions
Nuclear Fission
Bosons, Symmetries and Group Models
Heavy Ion Reactions

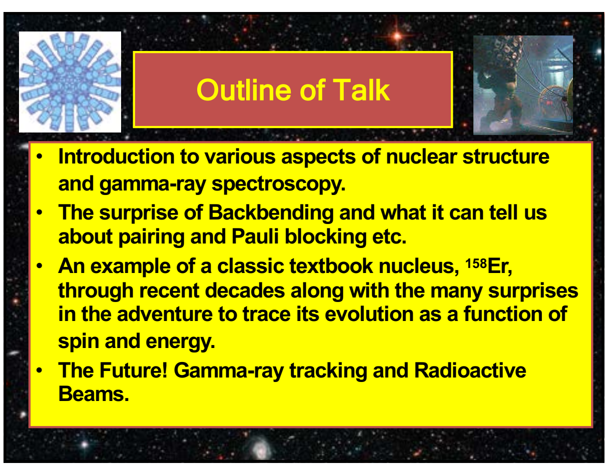

Experimental Nuclear Facilities
John D Fox Superconducting Accelerator Laboratory
RESOLUT
LINAC
γ ray Array
Tandem
• SNICS and Polarized Li Sources
• 9 MV Tandem Van De Graff
• 12 resonator LINAC
• RESOLUT Radioactive Beam Upgrade
• Super-Enge Split Pole Spectrograph
• 20 Element HPGe γ Ray Detector Array
• CLARION 2 – 16 Clover array (ORNL – FSU)

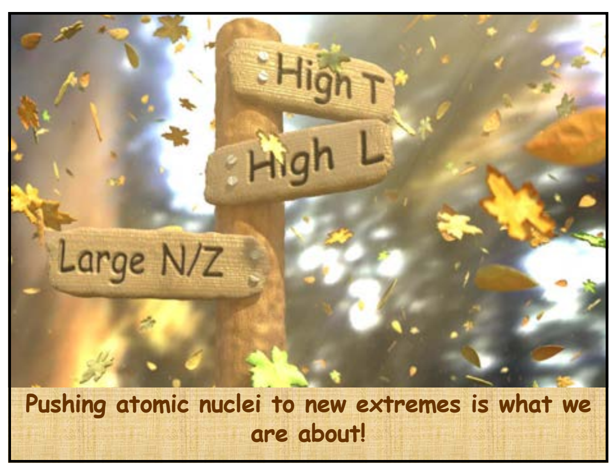


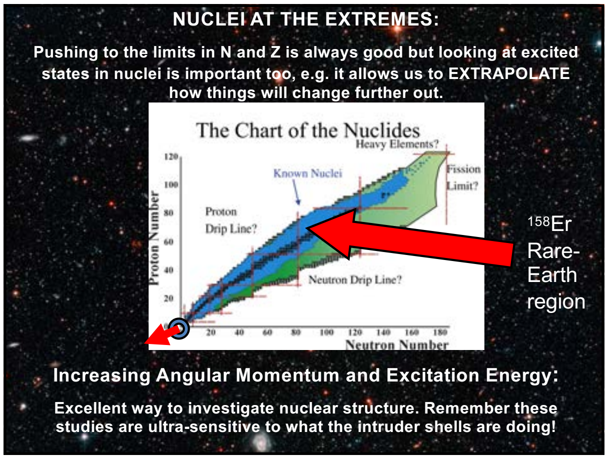

College "Football" at FSU!
National Champs 1993, 1999, 2013
FLORIDA STATE

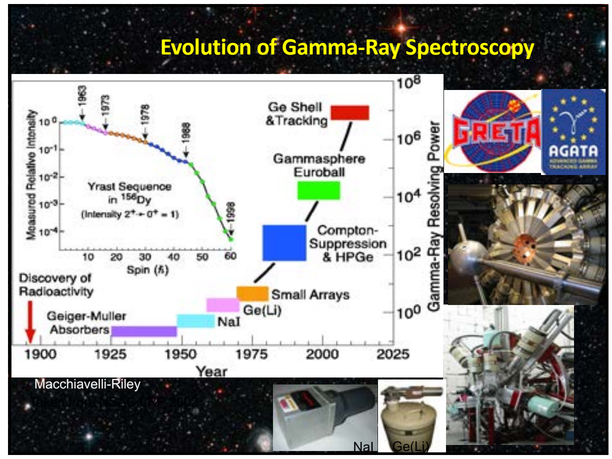

What they will say about
Tallahassee in 1000 years!
DIRAC
PAUL ADRIEN MAURICE
DIRAC
AUGUST 8, 1902
OCTOBER 20, 1984

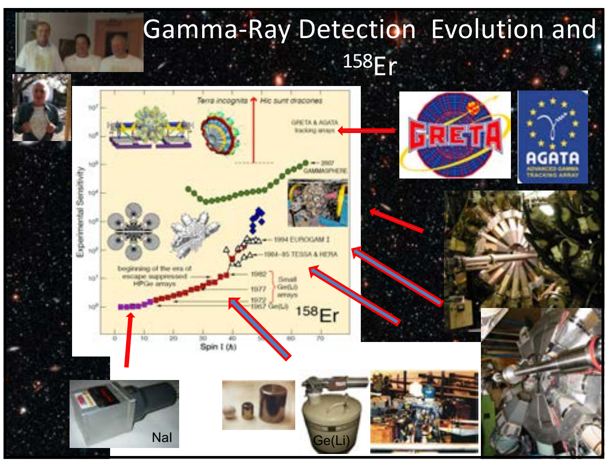

The Strangest Man
THE HIDDEN LIFE OF PAUL DIRAC, MYSTIC of the ATOM
GRAHAM FARMELO
How we got Dirac to FSU … "Shakespere of Physics"!
http://www.youtube.com/watch?v=fWo010EsiYk&feature=related
Graham's US book launch at FSU etc:
http://www.physics.fsu.edu/awards/nobel/dirac/RememberingDirac/
See also:
http://www.youtube.com/watch?v=YfYon2WdR40&feature=related
<http://www.youtube.com/watch?v=YfYon2WdR40&feature=related>

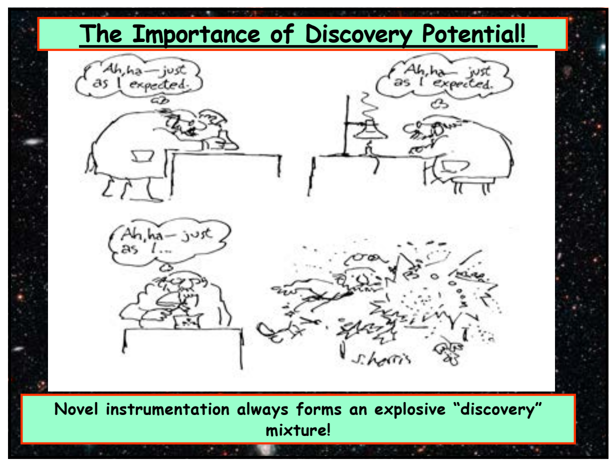

Outline of Talk
• Introduction to various aspects of nuclear structure and gamma-ray spectroscopy.
• The surprise of Backbending and what it can tell us about pairing and Pauli blocking etc.
• An example of a classic textbook nucleus, ¹⁵⁸Er, through recent decades along with the many surprises in the adventure to trace its evolution as a function of spin and energy.
• The Future! Gamma-ray tracking and Radioactive Beams.

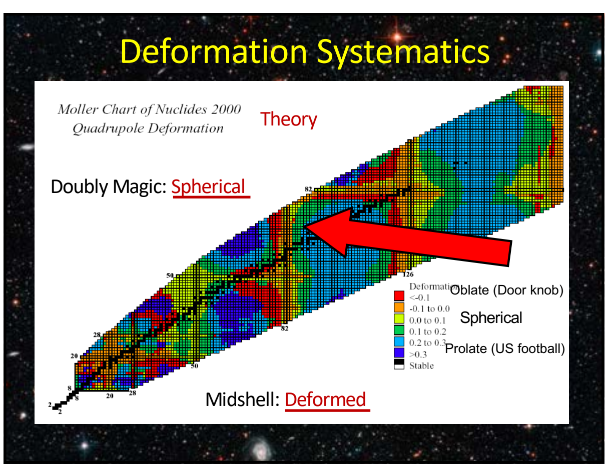

High T
High L
Large N/Z
Pushing atomic nuclei to new extremes is what we are about!

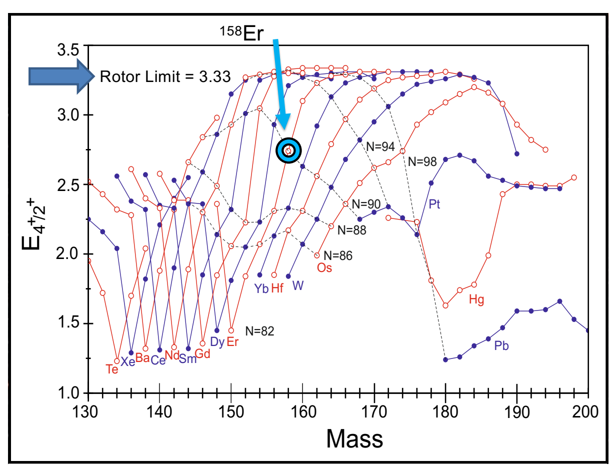

NUCLEI AT THE EXTREMES:
Pushing to the limits in N and Z is always good but looking at excited states in nuclei is important too, e.g. it allows us to EXTRAPOLATE how things will change further out.
The Chart of the Nuclides
Heavy Elements?
Known Nuclei
Fission Limit?
Proton Drip Line?
Neutron Drip Line?
Proton Number
Neutron Number
158Er
Rare-Earth region
Increasing Angular Momentum and Excitation Energy:
Excellent way to investigate nuclear structure. Remember these studies are ultra-sensitive to what the intruder shells are doing!

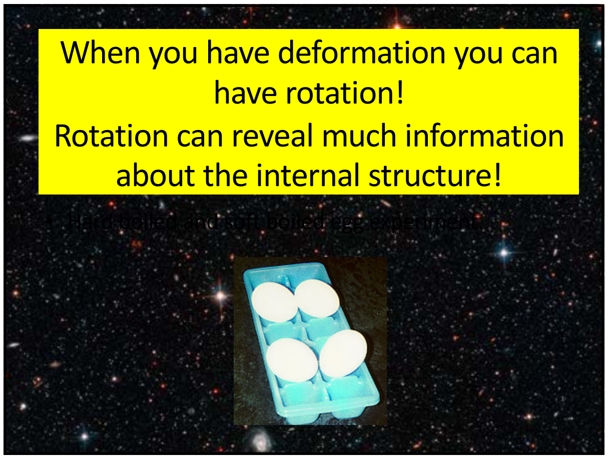

Evolution of Gamma-Ray Spectroscopy
Measured Relative Intensity
Yrast Sequence in 156Dy
Spin (ħ)
Ge Shell &Tracking
Gammasphere Euroball
Compton-Suppression & HPGe
Small Arrays
Ge(Li)
NaI
Geiger-Muller Absorbers
Discovery of Radioactivity
Year
Gamma-Ray Resolving Power
Macchiavelli-Riley
GRETA
AGATA
NaI
Ge(Li)


Gamma-Ray Detection Evolution and 158Er
GRETA
AGATA
Experimental Sensitivity
Spin I (ħ)
158Er
NaI
Ge(Li)

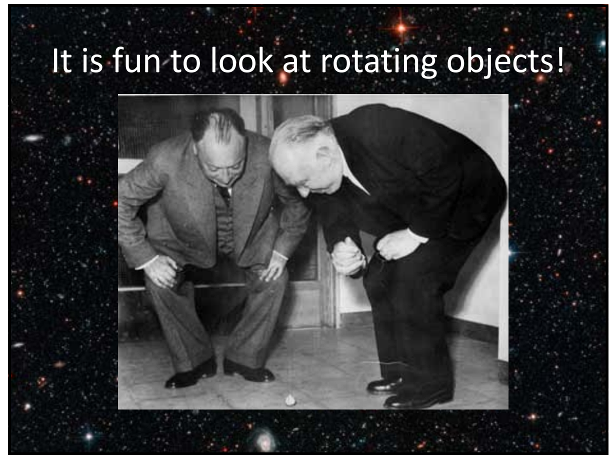

The Importance of Discovery Potential!
Ah, ha — just as I expected.
Ah, ha — just as I expected.
Ah, ha — just as I...
S. harris
Novel instrumentation always forms an explosive "discovery" mixture!


Deformation Systematics
Moller Chart of Nuclides 2000
Quadrupole Deformation
Theory
Doubly Magic: Spherical
Oblate (Door knob)
Spherical
Prolate (US football)
Midshell: Deformed

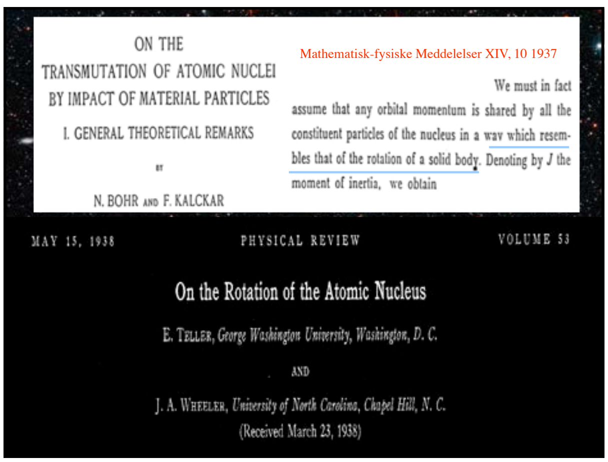

158Er
Rotor Limit = 3.33
E4+/2+
Mass
N=94
N=98
N=90
N=88
N=86
N=82
Te
Xe
Ba
Ce
Nd
Sm
Gd
Dy
Er
Yb
Hf
W
Os
Pt
Hg
Pb



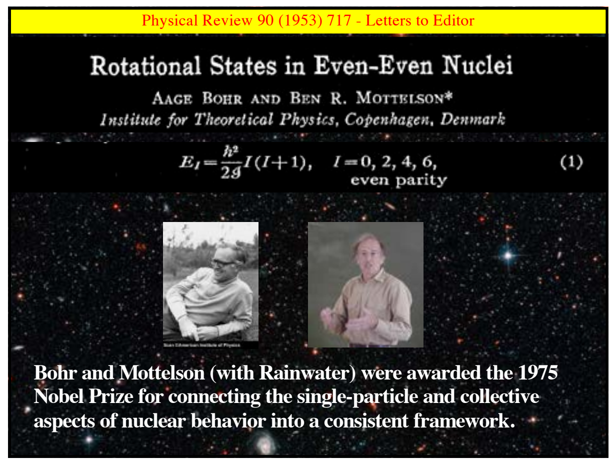
When you have deformation you can have rotation!
Rotation can reveal much information about the internal structure!
• Hard boiled and soft boiled egg experiment



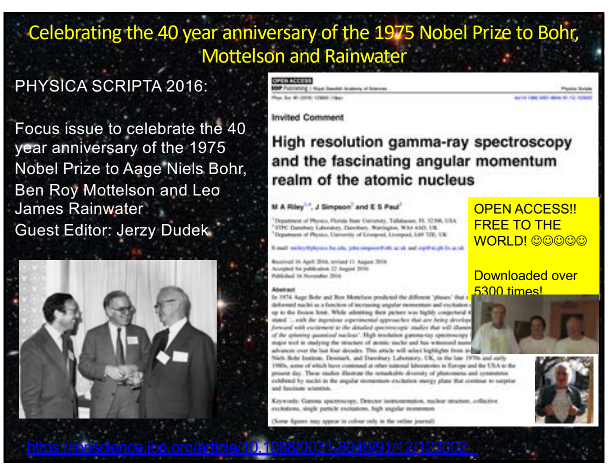
It is fun to look at rotating objects!



ON THE TRANSMUTATION OF ATOMIC NUCLEI BY IMPACT OF MATERIAL PARTICLES
I. GENERAL THEORETICAL REMARKS
BY
N. BOHR AND F. KALCKAR
Mathematisk-fysiske Meddelelser XIV, 10 1937
We must in fact assume that any orbital momentum is shared by all the constituent particles of the nucleus in a way which resembles that of the rotation of a solid body. Denoting by J the moment of inertia, we obtain
MAY 15, 1938 PHYSICAL REVIEW VOLUME 53
On the Rotation of the Atomic Nucleus
E. Teller, George Washington University, Washington, D. C.
AND
J. A. Wheeler, University of North Carolina, Chapel Hill, N. C.
(Received March 23, 1938)

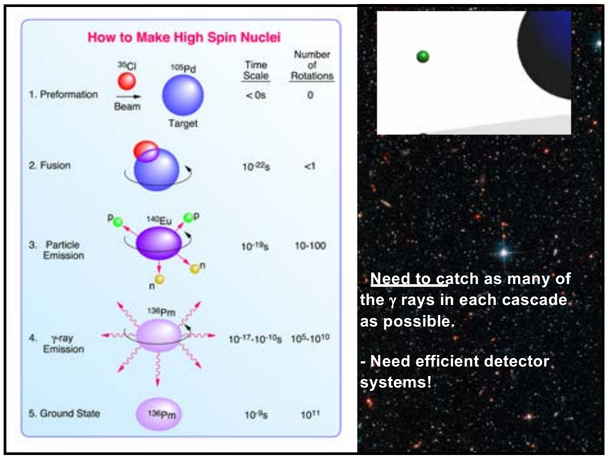


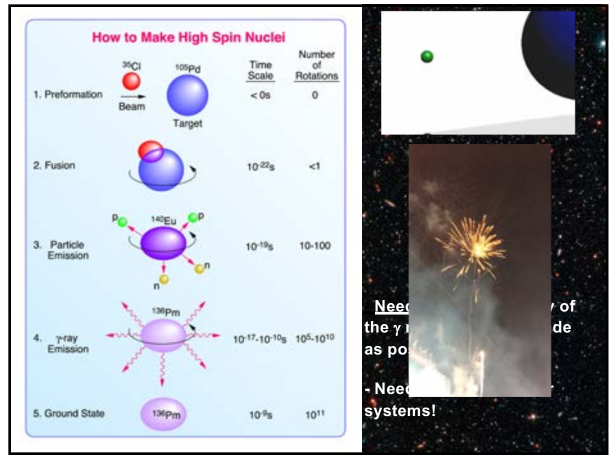
Physical Review 90 (1953) 717 - Letters to Editor
Rotational States in Even-Even Nuclei
Aage Bohr and Ben R. Mottelson*
Institute for Theoretical Physics, Copenhagen, Denmark
$E_I=\frac{\hbar^2}{2\mathcal{J}}I(I+1),\quad I=0,2,4,6,$ even parity (1)
Bohr and Mottelson (with Rainwater) were awarded the 1975 Nobel Prize for connecting the single-particle and collective aspects of nuclear behavior into a consistent framework.

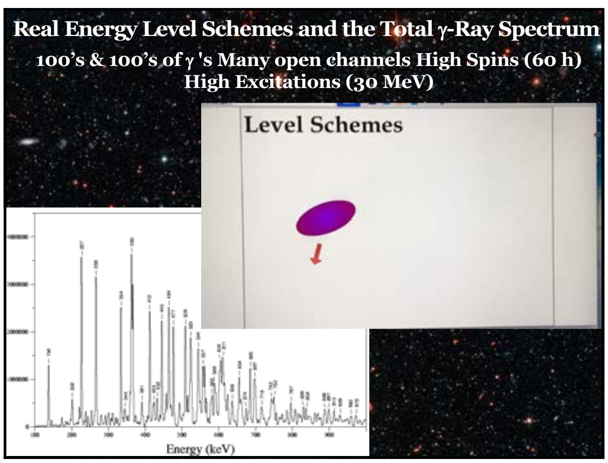


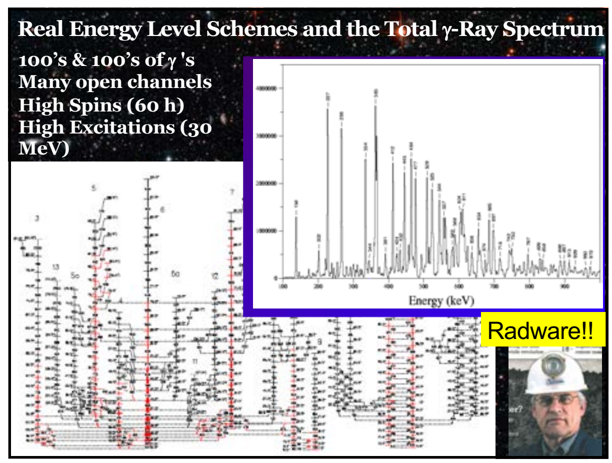
Celebrating the 40 year anniversary of the 1975 Nobel Prize to Bohr, Mottelson and Rainwater
PHYSICA SCRIPTA 2016:
Focus issue to celebrate the 40 year anniversary of the 1975 Nobel Prize to Aage Niels Bohr, Ben Roy Mottelson and Leo James Rainwater
Guest Editor: Jerzy Dudek
Invited Comment
High resolution gamma-ray spectroscopy and the fascinating angular momentum realm of the atomic nucleus
M A Riley, J Simpson and E S Paul
OPEN ACCESS!! FREE TO THE WORLD! ☺☺☺☺☺
Downloaded over 5300 times!
https://iopscience.iop.org/article/10.1088/0031-8949/91/12/123002

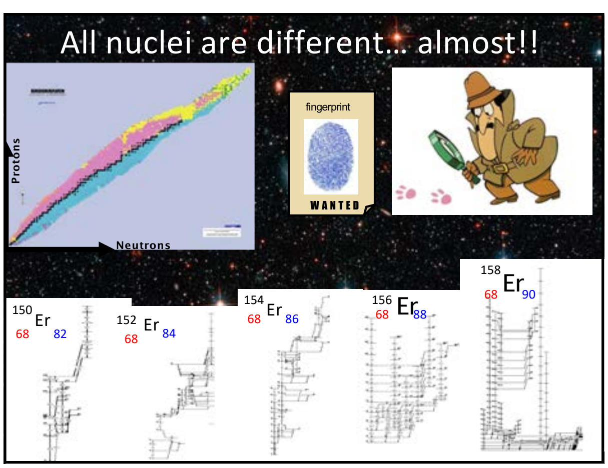
So many epic gatherings at the NBI!

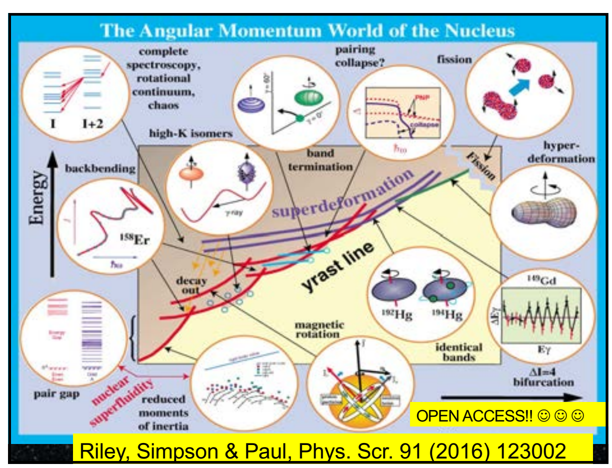

How to Make High Spin Nuclei
Time Scale
Number of Rotations
1. Preformation
Beam
Target
< 0s
0
2. Fusion
10-22s
<1
3. Particle Emission
10-19s
10-100
4. γ-ray Emission
10-17-10-10s
105-1010
5. Ground State
10-9s
1011
Need to catch as many of the γ rays in each cascade as possible.
- Need efficient detector systems!

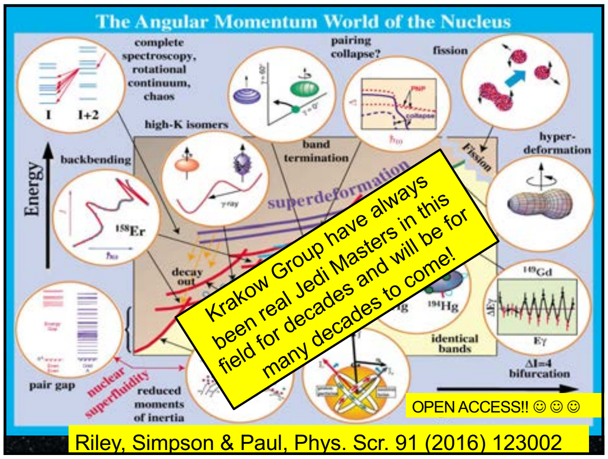

How to Make High Spin Nuclei
Time Scale
Number of Rotations
1. Preformation
Beam
Target
< 0s
0
2. Fusion
10-22s
<1
3. Particle Emission
10-19s
10-100
4. γ-ray Emission
10-17-10-10s
105-1010
5. Ground State
10-9s
1011
systems!

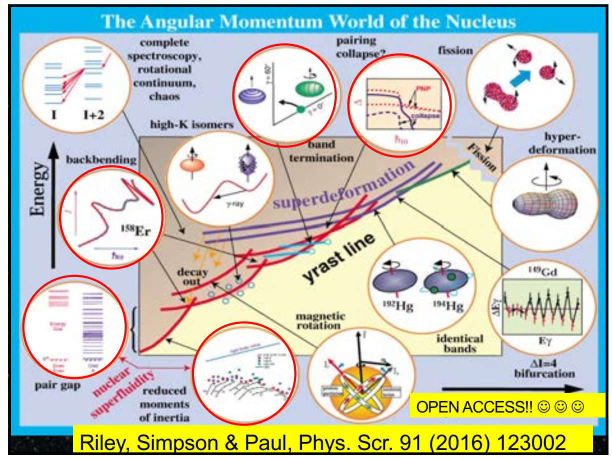

Real Energy Level Schemes and the Total γ-Ray Spectrum
100's & 100's of γ 's Many open channels High Spins (60 h) High Excitations (30 MeV)
Level Schemes
Energy (keV)

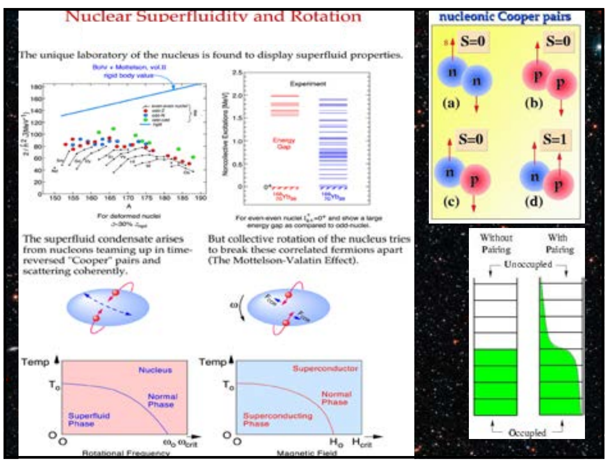

Real Energy Level Schemes and the Total γ-Ray Spectrum
100's & 100's of γ 's
Many open channels
High Spins (60 h)
High Excitations (30 MeV)
Energy (keV)
Radware!!

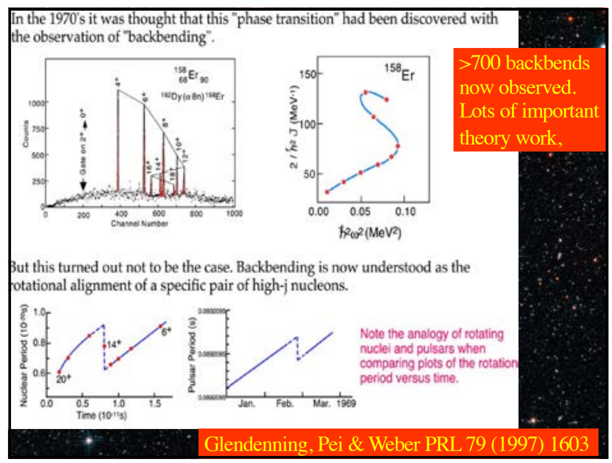

All nuclei are different… almost!!
Protons
Neutrons
fingerprint
WANTED
150 Er 68 82
152 Er 68 84
154 Er 68 86
156 Er 68 88
158 Er 68 90

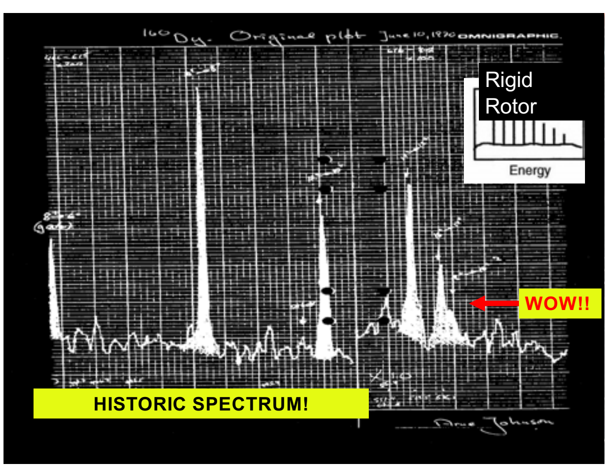

The Angular Momentum World of the Nucleus
complete spectroscopy, rotational continuum, chaos
pairing collapse?
fission
high-K isomers
backbending
band termination
hyper-deformation
Energy
superdeformation
yrast line
decay out
magnetic rotation
identical bands
ΔI=4 bifurcation
pair gap
nuclear superfluidity
reduced moments of inertia
OPEN ACCESS!! ☺☺☺
Riley, Simpson & Paul, Phys. Scr. 91 (2016) 123002











16 October, 1970

Dear Arne and Hans,

Thank you for the preprint of your note which indeed makes a very exciting story. It appears that you have rather convincing evidence for the occurrence of something quite remarkable for angular momentum values in the region I ≈ 16; this is exhibited, perhaps, even more dramatically in a plot of the moment of inertia as a function of the rotational frequency (see the enclosed figure). The frequency is defined by the canonical relation appropriate for an axial symmetric rotor

$$\omega = \frac{dE}{d\sqrt{I(I+1)}}$$

or

$$\omega^2 = 4I(I+1)\left(\frac{dE}{dI(I+1)}\right)^2$$

In the last expression, the energy derivative is taken from the observed transition energies

$$\left(\frac{dE}{dI(I+1)}\right)_{I(I+1)=I_1^2-I_1+1^*} = \frac{E(I_1)-E(I_1-2)}{4I_1-2}$$

The moment of inertia is also defined in terms of the derivative of the observed energy

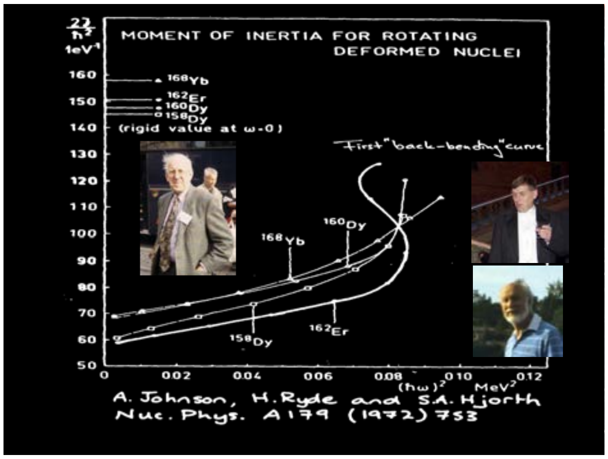
$$\frac{2\mathcal{J}}{\hbar^2} = \left(\frac{dE}{dI(I+1)}\right)^{-1}$$

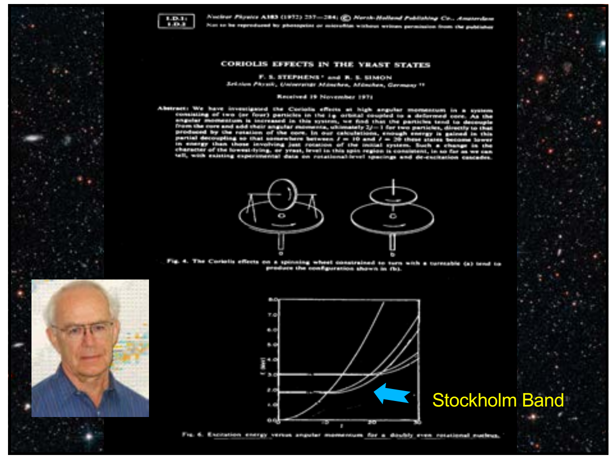
Another interesting feature of your data concerns the value of $\mathcal{J}$ at the singular point. If the pairing correlation were to completely disappear, one would expect $\mathcal{J} \approx \mathcal{J}_{rig}$. However, since the transition frequency for neutrons and protons may be quite different, the value of $\mathcal{J}$ is likely to be somewhat below $\mathcal{J}_{rig}$ after the first transition.

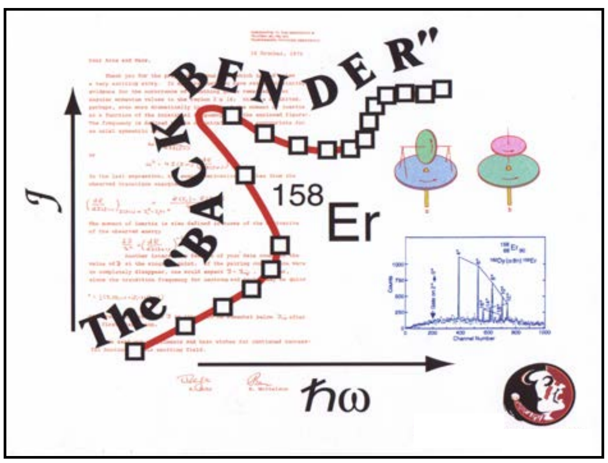
$* = \frac{1}{2}(I_1(I_1+1)+(I_1-2)(I_1-1))$

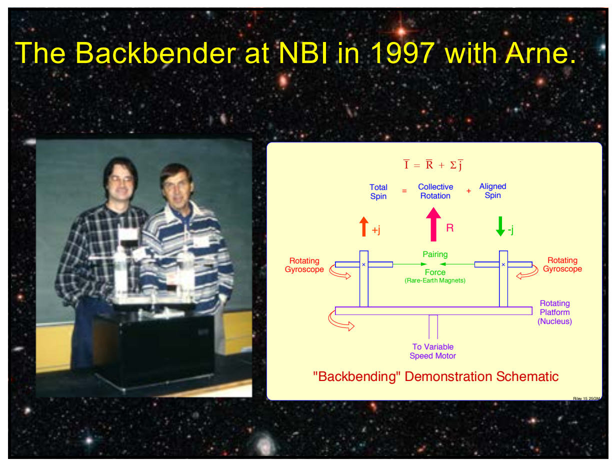
We send our compliments and best wishes for continued successful hunting in this exciting field.

A. Bohr B. Mottelson

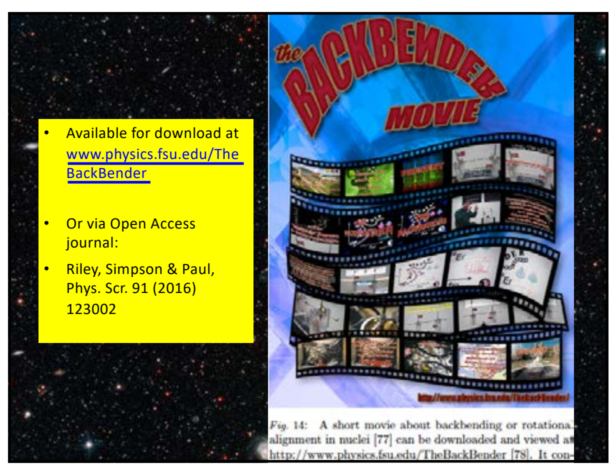

MOMENT OF INERTIA FOR ROTATING DEFORMED NUCLEI
(rigid value at ω=0)
First "back-bending" curve
A. Johnson, H. Ryde and S.A. Hjorth
Nuc. Phys. A179 (1972) 753

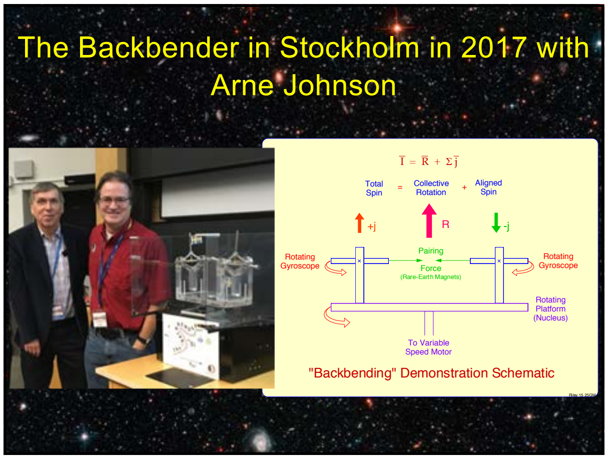

CORIOLIS EFFECTS IN THE YRAST STATES
Stockholm Band

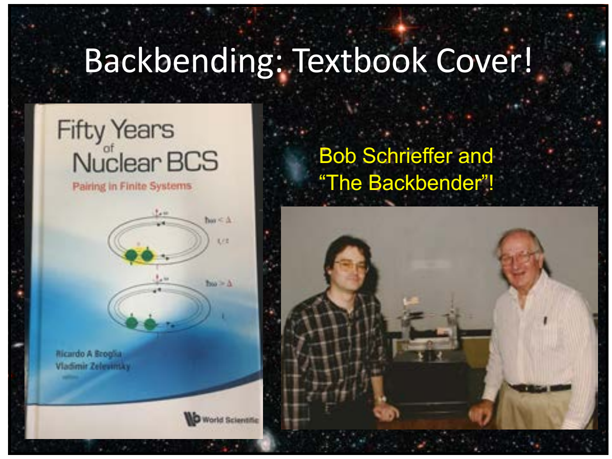

The "BACKBENDER"
158 Er
ħω

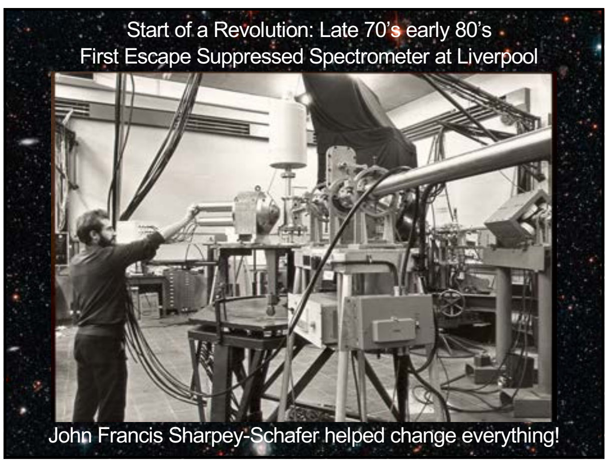

The Backbender at NBI in 1997 with Arne.
Total Spin
Collective Rotation
Aligned Spin
Rotating Gyroscope
Pairing
Force
Rotating Gyroscope
Rotating Platform (Nucleus)
To Variable Speed Motor
"Backbending" Demonstration Schematic

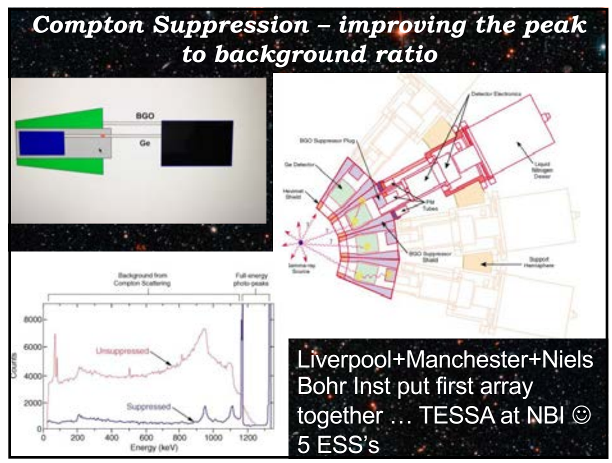

Backbender Movie
THE PHYSICS DEPARTMENT OF FLORIDA STATE UNIVERSITY

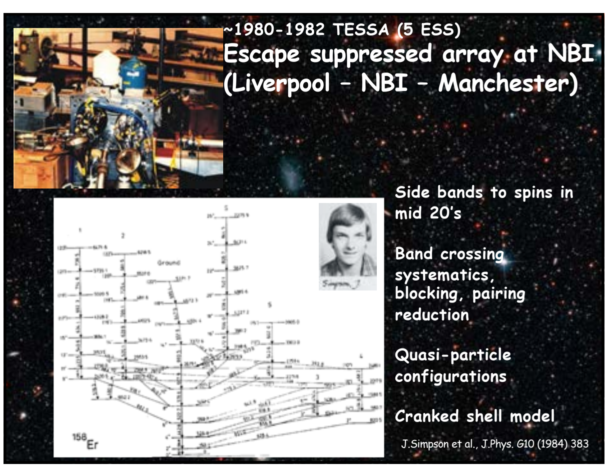

Available for download at www.physics.fsu.edu/TheBackBender
Or via Open Access journal:
Riley, Simpson & Paul, Phys. Scr. 91 (2016) 123002
the BACKBENDER MOVIE
Fig. 14: A short movie about backbending or rotationa
alignment in nuclei [77] can be downloaded and viewed at
http://www.physics.fsu.edu/TheBackBender [78]. It con-

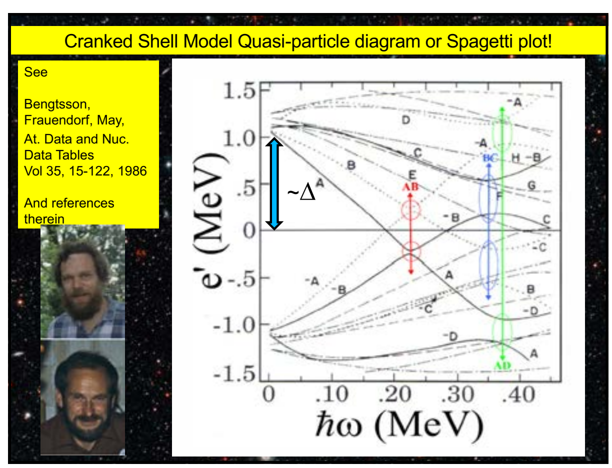

The Backbender in Stockholm in 2017 with Arne Johnson
Total Spin = Collective Rotation + Aligned Spin
Rotating Gyroscope
Pairing Force (Rare-Earth Magnets)
Rotating Platform (Nucleus)
To Variable Speed Motor
"Backbending" Demonstration Schematic

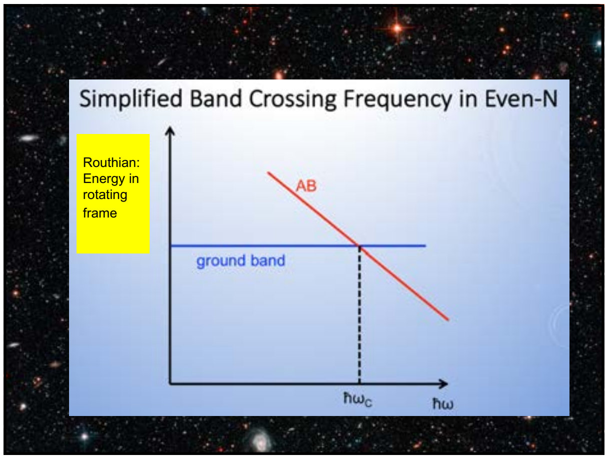

Backbending: Textbook Cover!
Fifty Years of Nuclear BCS
Pairing in Finite Systems
Ricardo A Broglia
Vladimir Zelevinsky
World Scientific
Bob Schrieffer and "The Backbender"!

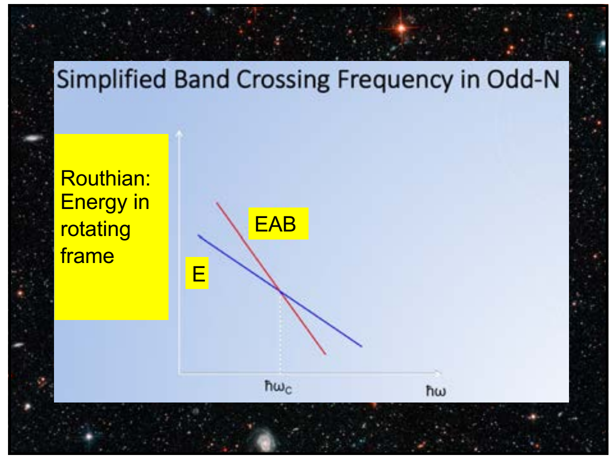

Start of a Revolution: Late 70's early 80's
First Escape Suppressed Spectrometer at Liverpool
John Francis Sharpey-Schafer helped change everything!

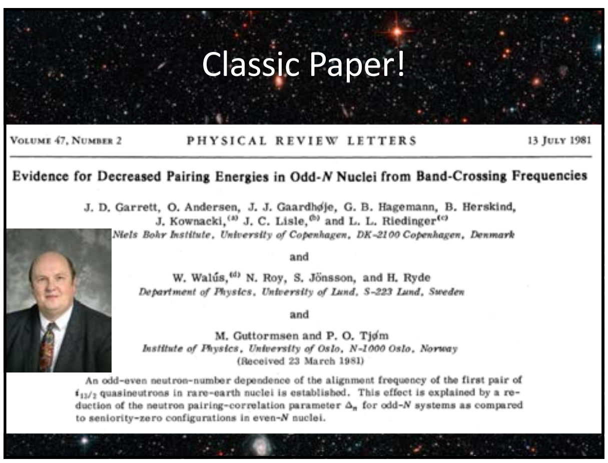

Compton Suppression – improving the peak to background ratio
BGO
Ge
Unsuppressed
Suppressed
Energy (keV)
Liverpool+Manchester+Niels Bohr Inst put first array together … TESSA at NBI ☺
5 ESS's


~1980-1982 TESSA (5 ESS)
Escape suppressed array at NBI
(Liverpool – NBI – Manchester)
Side bands to spins in mid 20's
Band crossing systematics, blocking, pairing reduction
Quasi-particle configurations
Cranked shell model
J.Simpson et al., J.Phys. G10 (1984) 383


Cranked Shell Model Quasi-particle diagram or Spagetti plot!
See
Bengtsson, Frauendorf, May, At. Data and Nuc. Data Tables Vol 35, 15-122, 1986
And references therein
e' (MeV)
ħω (MeV)







VOLUME 47, NUMBER 2 PHYSICAL REVIEW LETTERS 13 JULY 1981

Evidence for Decreased Pairing Energies in Odd-N Nuclei from Band-Crossing Frequencies

J. D. Garrett, O. Andersen, J. J. Gaardhøje, G. B. Hagemann, B. Herskind, J. Kownacki,[a] J. C. Lisle,[b] and L. L. Riedinger[c]
Niels Bohr Institute, University of Copenhagen, DK-2100 Copenhagen, Denmark

and

W. Walús,[d] N. Roy, S. Jönsson, and H. Ryde
Department of Physics, University of Lund, S-223 Lund, Sweden

and

M. Guttormsen and P. O. Tjøm
Institute of Physics, University of Oslo, N-1000 Oslo, Norway
(Received 23 March 1981)

An odd-even neutron-number dependence of the alignment frequency of the first pair of $i_{13/2}$ quasineutrons in rare-earth nuclei is established. This effect is explained by a reduction of the neutron pairing-correlation parameter Δ_n for odd-N systems as compared to seniority-zero configurations in even-N nuclei.

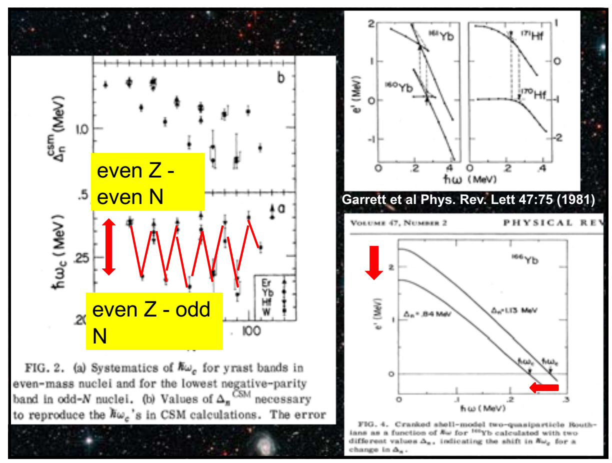
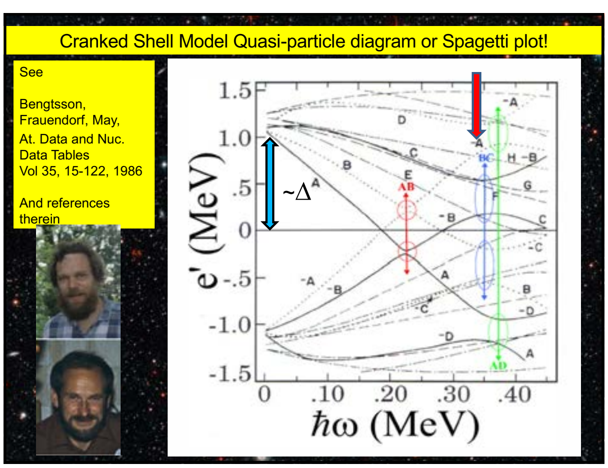
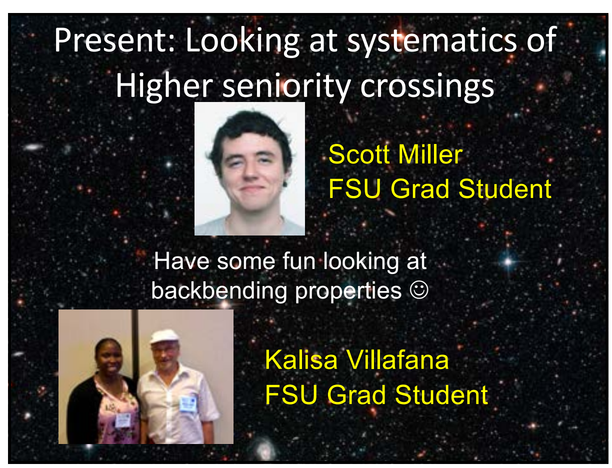
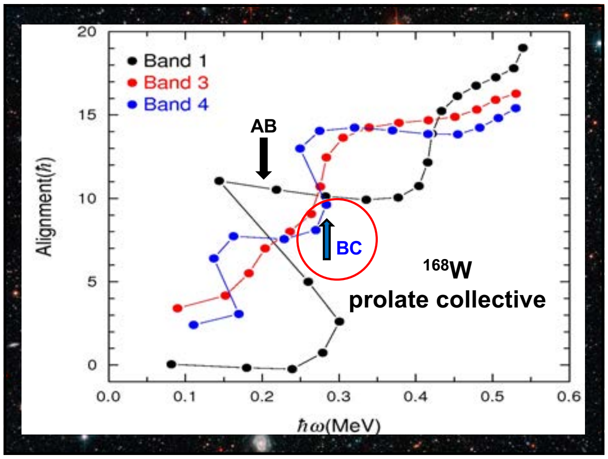
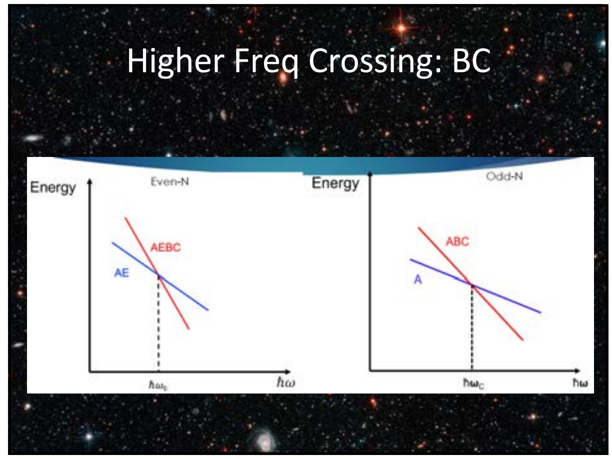


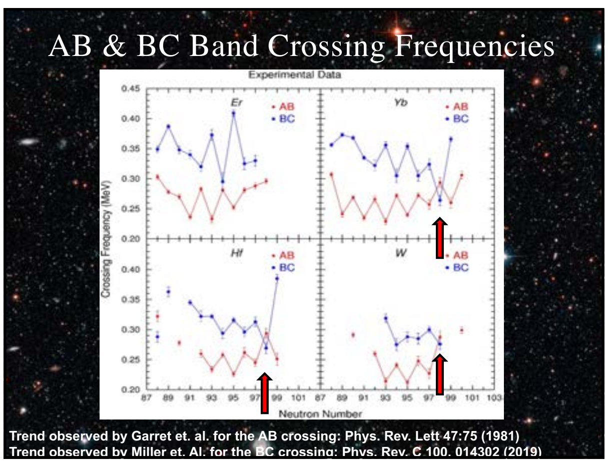
FIG. 2. (a) Systematics of $\hbar\omega_c$ for yrast bands in even-mass nuclei and for the lowest negative-parity band in odd-N nuclei. (b) Values of Δ_n^{CSM} necessary to reproduce the $\hbar\omega_c$'s in CSM calculations. The error

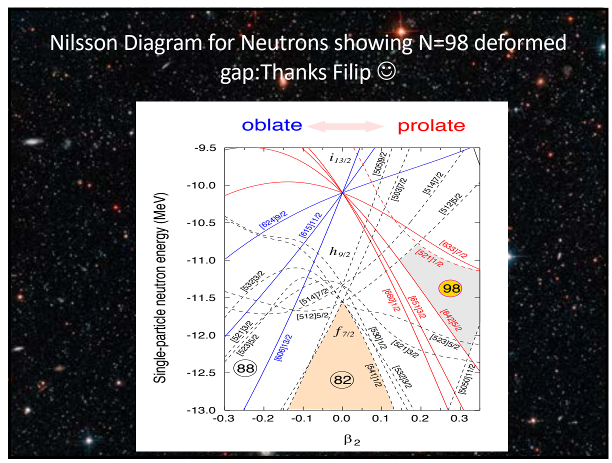


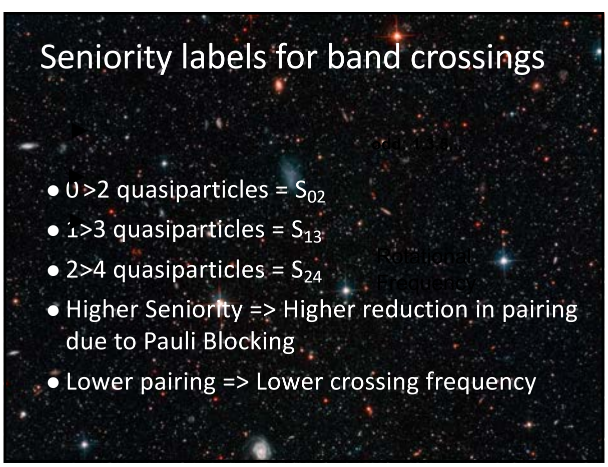


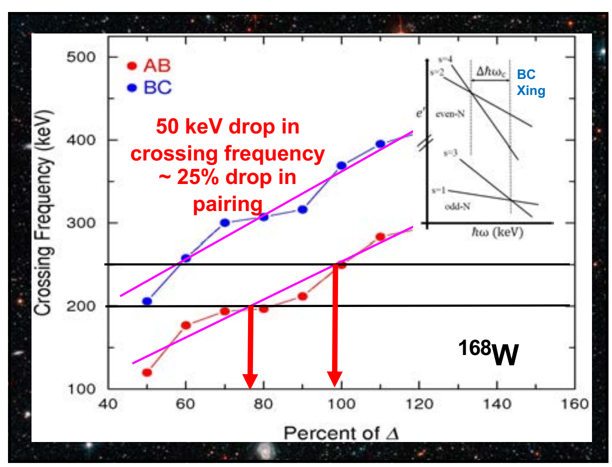

Band 1
Band 3
Band 4
AB
BC
168W
prolate collective
Alignment(ħ)
ħω(MeV)

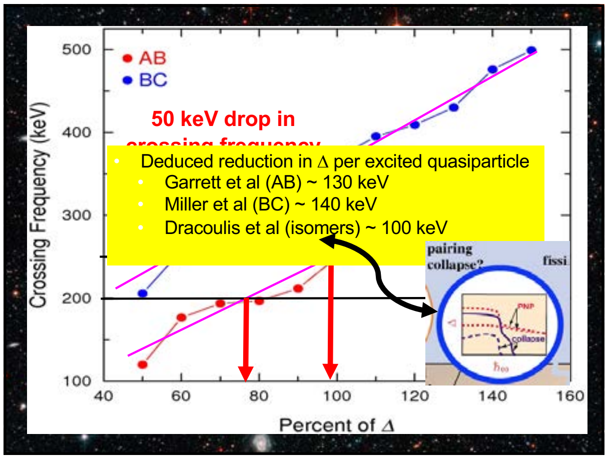

Higher Freq Crossing: BC
Energy
Even-N
AEBC
AE
Energy
Odd-N
ABC
A
ħω


AB & BC Band Crossing Frequencies
Experimental Data
Er
Yb
Hf
W
AB
BC
Crossing Frequency (MeV)
Neutron Number
Trend observed by Garret et. al. for the AB crossing: Phys. Rev. Lett 47:75 (1981)
Trend observed by Miller et. Al. for the BC crossing: Phys. Rev. C 100, 014302 (2019)


Nilsson Diagram for Neutrons showing N=98 deformed gap:Thanks Filip ☺
oblate
prolate
Single-particle neutron energy (MeV)
98
88
82
β2


Seniority labels for band crossings
0>2 quasiparticles = S02
1>3 quasiparticles = S13
2>4 quasiparticles = S24
Higher Seniority => Higher reduction in pairing due to Pauli Blocking
Lower pairing => Lower crossing frequency


AB
BC
50 keV drop in crossing frequency ~ 25% drop in pairing
BC Xing
even-N
odd-N
ħω (keV)
168W
Crossing Frequency (keV)
Percent of Δ




Backbending, Seniority, and Pauli Blocking of Pairing Correlations at High Rotational Frequency in Rapidly Rotating Nuclei

S. L. Miller, K. A. Villafana, M. A. Riley, J. Simpson, D. J. Hartley, E. S. Paul, A. D. Ayangeakaa, J. S. Baron, P. F. Bertone, M. P. Carpenter, J. J. Carroll, J. Cavey, C. J. Chiara, P. Chowdhury, U. Garg, S. S. Hota, E. G. Jackson, R. V. F. Janssens, F. G. Kondev, T. Lauritsen, M. Litz, W. C. Ma, J. Matta, E. A. McCutchan, S. Mukhopadhyay, E. E. Pedicini, L. L. Riedinger, J. F. Sharpey-Schafer, J. R. Vanhoy, A. Volya, X. Wang, and S. Zhu

(Dated: March 15, 2019)

Phys. Rev. C 100, 014302 (2019)

☺

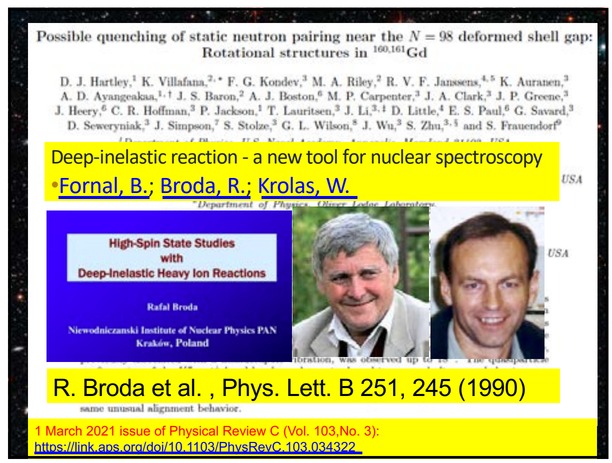

Possible quenching of static neutron pairing near the $N = 98$ deformed shell gap: Rotational structures in ^{160,161}Gd

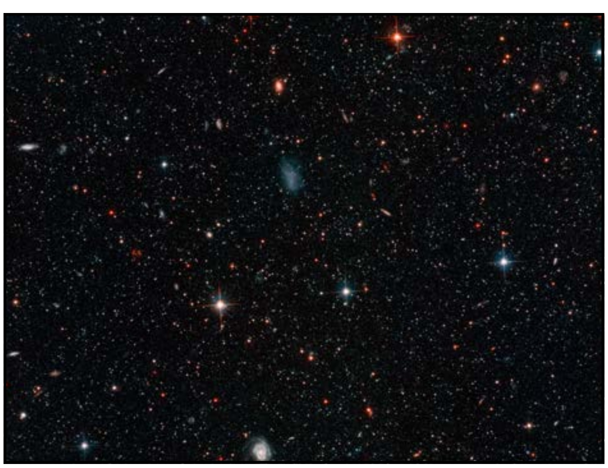
D. J. Hartley, K. Villafana, F. G. Kondev, M. A. Riley, R. V. F. Janssens, K. Auranen, A. D. Ayangeakaa, J. S. Baron, A. J. Boston, M. P. Carpenter, J. A. Clark, J. P. Greene, J. Heery, C. R. Hoffman, P. Jackson, T. Lauritsen, J. Li, D. Little, E. S. Paul, G. Savard, D. Seweryniak, J. Simpson, S. Stolze, G. L. Wilson, J. Wu, S. Zhu, and S. Frauendorf

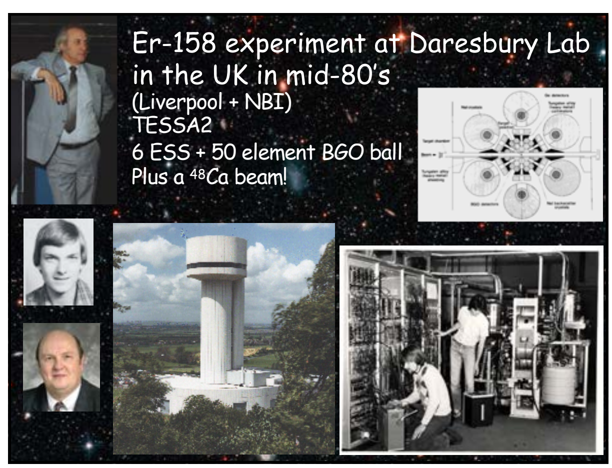
(Dated: March 8, 2021)

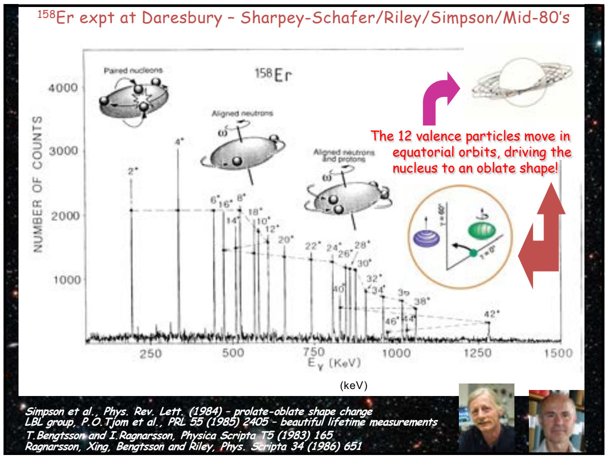
A ^{160}Gd beam was accelerated to an energy of 1000 MeV and, separately, bombarded thick targets of ^{154}Sm and ^{164}Dy in order to observe neutron-rich, rare-earth nuclei via deep-inelastic collision processes. Gammasphere was utilized to observe γ-ray emissions. Many new states and transitions were observed in ^{160}Gd as a result of so-called "unsafe" Coulomb excitation. The ground-state band in ^{160}Gd has been extended to $I^\pi = 20^+$ and a rotational band based on the $K^\pi = 4^+$ state, previously associated with a hexadecapole vibration, was observed up to 18^+. The quasiparticle configuration of the $K^\pi = 4^+$ band has been determined, and its unusual alignment behavior may result from a possible quenching of static neutron pairing. In addition, the band based on the [523]5/2 quasineutron orbital in ^{161}Gd was extended from $11/2^-$ to $33/2^-$, and also displays the same unusual alignment behavior.

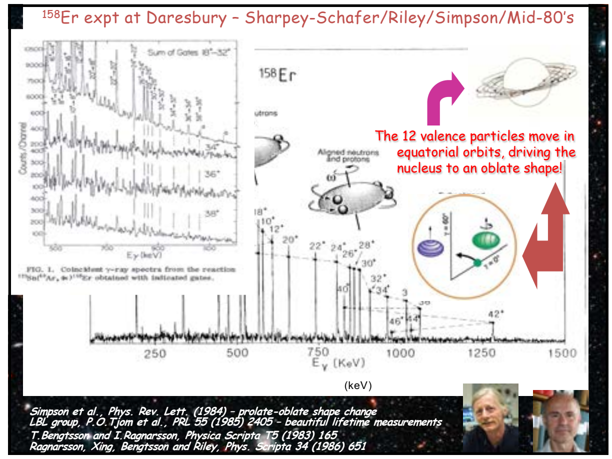
1 March 2021 issue of Physical Review C (Vol. 103, No. 3):
https://link.aps.org/doi/10.1103/PhysRevC.103.034322

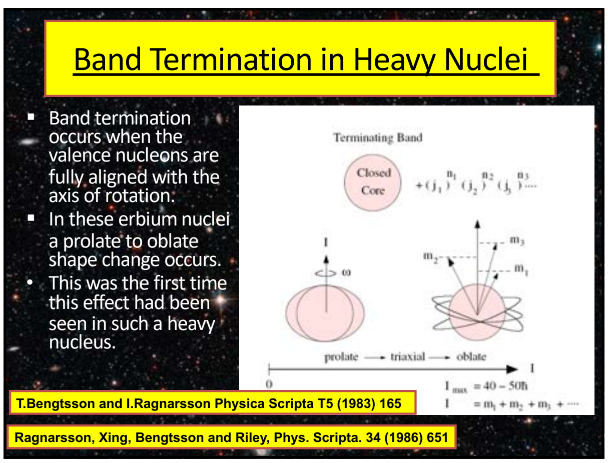


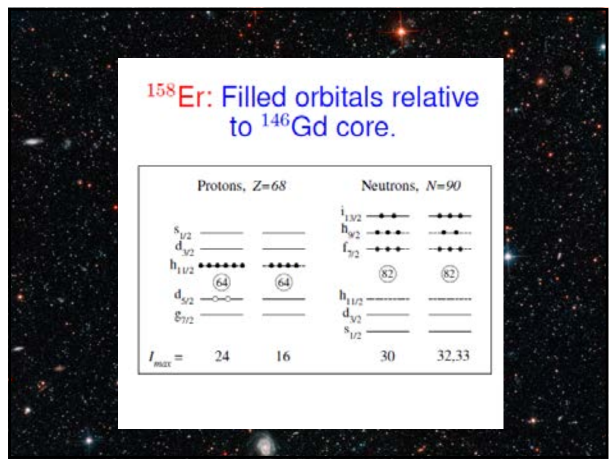


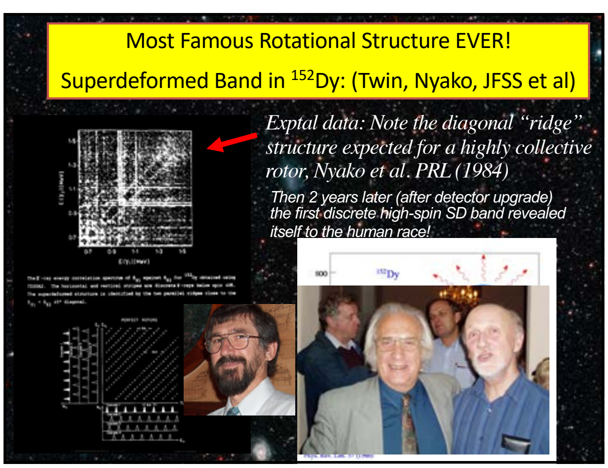


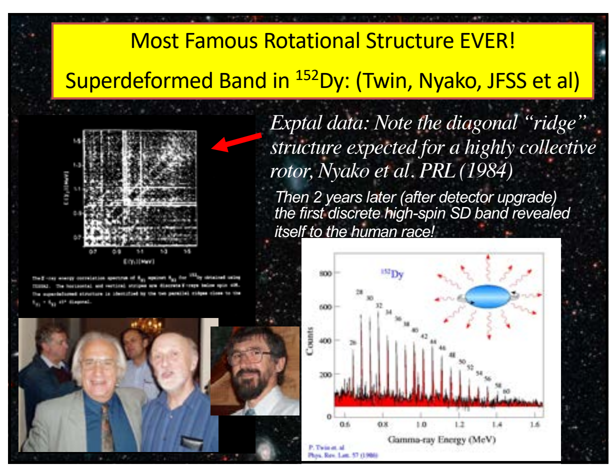

158Er expt at Daresbury – Sharpey-Schafer/Riley/Simpson/Mid-80's
158Er
Paired nucleons
Aligned neutrons
Aligned neutrons and protons
The 12 valence particles move in equatorial orbits, driving the nucleus to an oblate shape!
NUMBER OF COUNTS
Eγ (KeV)
(keV)
Simpson et al., Phys. Rev. Lett. (1984) – prolate-oblate shape change
LBL group, P.O.Tjøm et al., PRL 55 (1985) 2405 – beautiful lifetime measurements
T.Bengtsson and I.Ragnarsson, Physica Scripta T5 (1983) 165
Ragnarsson, Xing, Bengtsson and Riley, Phys. Scripta 34 (1986) 651


158Er expt at Daresbury – Sharpey-Schafer/Riley/Simpson/Mid-80's
Sum of Gates 18+–32+
158Er
Aligned neutrons and protons
The 12 valence particles move in equatorial orbits, driving the nucleus to an oblate shape!
Eγ (KeV)
(keV)
Simpson et al., Phys. Rev. Lett. (1984) – prolate-oblate shape change
LBL group, P.O.Tjøm et al., PRL 55 (1985) 2405 – beautiful lifetime measurements
T.Bengtsson and I.Ragnarsson, Physica Scripta T5 (1983) 165
Ragnarsson, Xing, Bengtsson and Riley, Phys. Scripta 34 (1986) 651

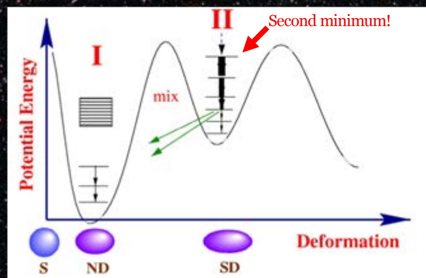

Band Termination in Heavy Nuclei
Band termination occurs when the valence nucleons are fully aligned with the axis of rotation.
In these erbium nuclei a prolate to oblate shape change occurs.
This was the first time this effect had been seen in such a heavy nucleus.
Terminating Band
Closed Core
prolate — triaxial — oblate
T.Bengtsson and I.Ragnarsson Physica Scripta T5 (1983) 165
Ragnarsson, Xing, Bengtsson and Riley, Phys. Scripta. 34 (1986) 651


158Er: Filled orbitals relative to 146Gd core.
Protons, Z=68
Neutrons, N=90
Imax = 24 16 30 32,33


Most Famous Rotational Structure EVER!
Superdeformed Band in 152Dy: (Twin, Nyako, JFSS et al)
Exptal data: Note the diagonal "ridge" structure expected for a highly collective rotor, Nyako et al. PRL (1984)
Then 2 years later (after detector upgrade) the first discrete high-spin SD band revealed itself to the human race!


Most Famous Rotational Structure EVER!
Superdeformed Band in 152Dy: (Twin, Nyako, JFSS et al)
Exptal data: Note the diagonal "ridge" structure expected for a highly collective rotor, Nyako et al. PRL (1984)
Then 2 years later (after detector upgrade) the first discrete high-spin SD band revealed itself to the human race!
152Dy
Counts
Gamma-ray Energy (MeV)

The Nucleus at Extreme Deformation



Second minimum in the nuclear potential energy!

Extremely deformed nucleus - 2:1 prolate (football shaped)

Can we create such states to investigate this new world?

Large array of escape-suppressed spectrometers led to a revolution in gamma-ray spectroscopy – A frenzy of activity and new physics!

~1990

Many array world wide
10-20 ESS
TESSA, Nordball, Chateau de Cristal, HERA, ORIRIS, MIPAD, 8π, ANL,….

Efficiency ~ 0.5% - 1.5%

Structure features ~1% of total nuclear intensity
- Superdeformation
- Shape Changes
- Alignments
- N=Z nuclei to Mo
- Damping
- Fission fragment spectroscopy
- Pairing collapse
- Octupole shapes

Physics programme required a much more efficiency array with high resolving power to lower the intensity limit by orders of magnitude

---

Increase the detection efficiency

Use more Ge detectors

Use large Ge detectors 70% - 80%

Composite Ge detectors (Clovers, Clusters)

GaSp, Legnaro, Italy 40 detectors

Eurogam 1 Daresbury UK/France 45 detectors

Euroball Strasbourg, Legnaro

Gammasphere E.L. 30-100 detectors, LBNL ANL

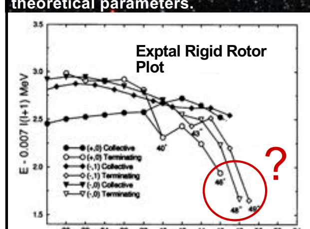
---

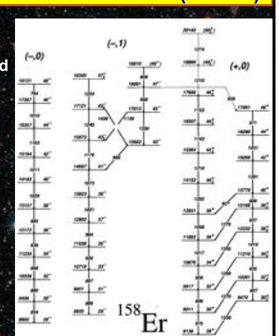
10 years later (1994)
– ^{158}Er again at Daresbury but now with EUROGAM (37 ESS)

Terminating states in the side bands too

Now see BT states at 46⁺, 48⁻ and 49⁻ and single particle states at 40⁺ and 43⁻

Special BT states were used to help set theoretical parameters.





Simpson, Riley, JFSS et al., Phys. Lett. B327 (1994) 187

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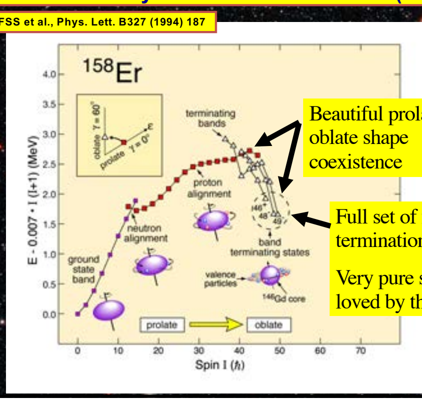
10 years later (1994)
– ^{158}Er again at Daresbury but now with EUROGAM (37 ESS)

Simpson, Riley, JFSS et al., Phys. Lett. B327 (1994) 187

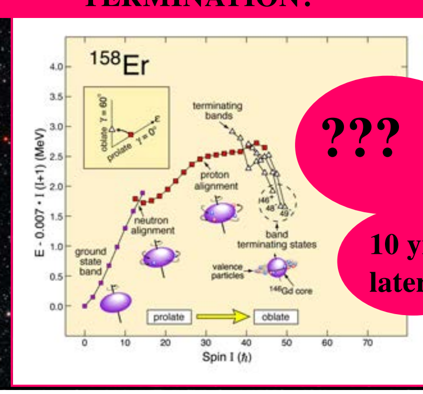


Beautiful prolate – oblate shape coexistence

Full set of favored terminations!

Very pure states – loved by theorists

BUT WHAT LIES ABOVE BAND TERMINATION?

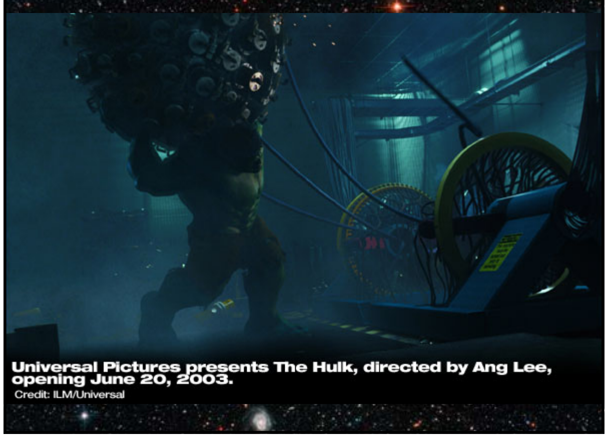


???

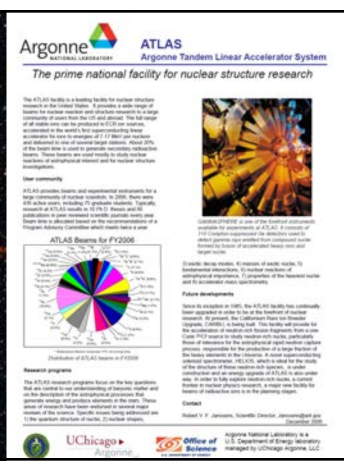
10 yrs later …

The GAMMASPHERE Spectrometer at Berkeley National Laboratory

~100 institutions, ~25 nations



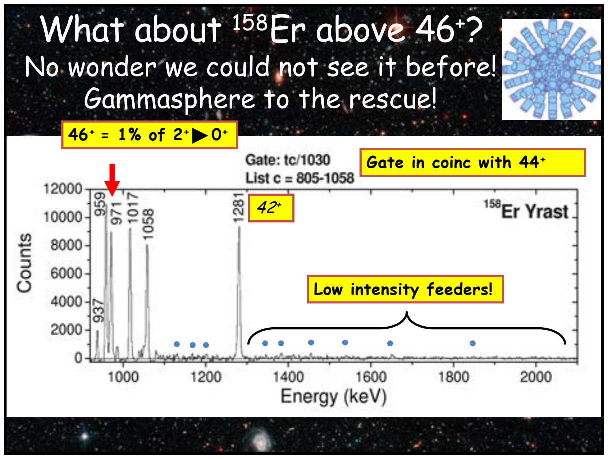
BIG BANG THEORY TV SHOW!
Every serious physicist has the ATLAS beam list and Gammasphere on his wall

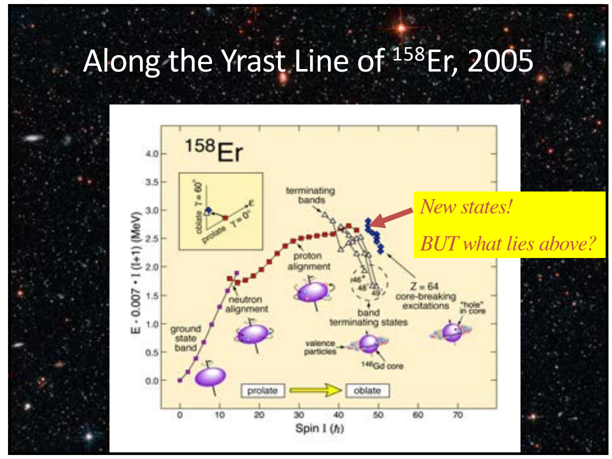


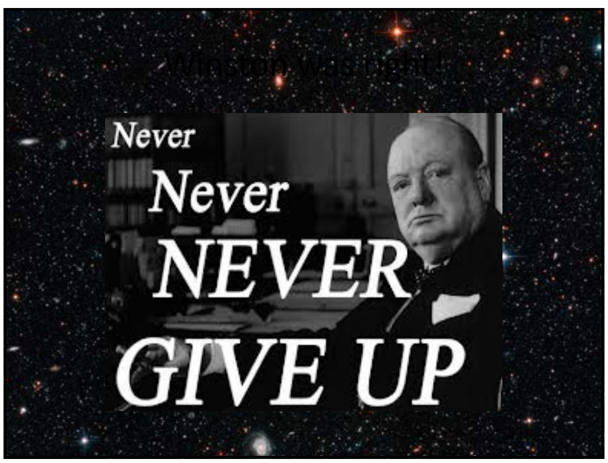
So 10 years later: GS = 97 ESS's! BEYOND BAND TERMINATION in ^{157,158}Er!

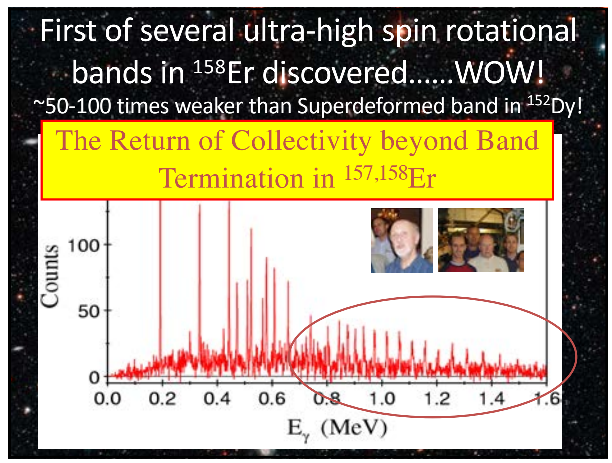
- ^{114}Cd(^{48}Ca,4,5n) @ 215MeV GS Triggered on clean fold 7+
- FSU + Daresbury + Liverpool + LBNL + Lund
- ^{158}Er has taken time to crack! See below.
- But we had wonderful early success with ^{157}Er:

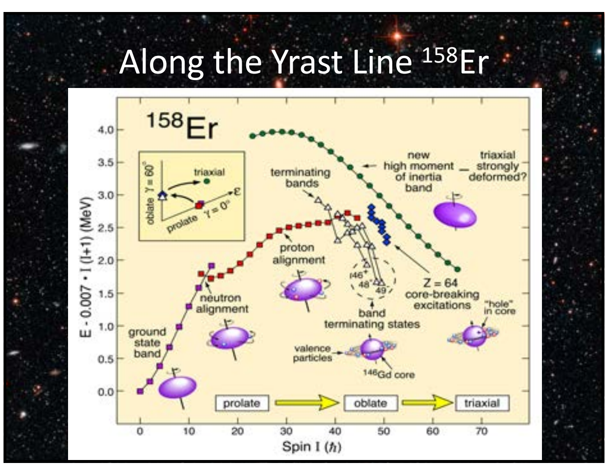
A.O. Evans et al., PRL 92, 252502 (2004)

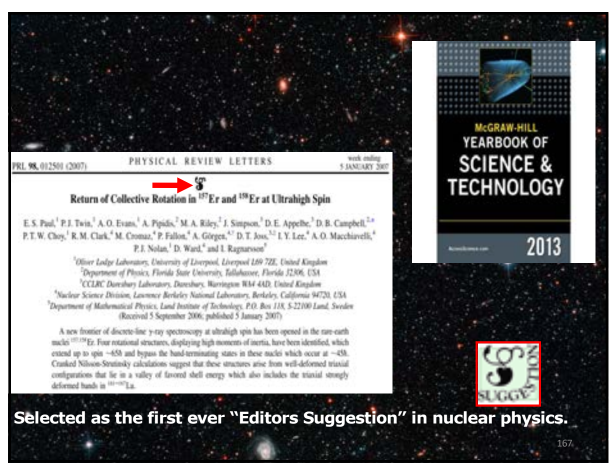

What about 158Er above 46+?
No wonder we could not see it before!
Gammasphere to the rescue!
46+ = 1% of 2+▶0+
Gate: tc/1030
List c = 805-1058
Gate in coinc with 44+
959
971
1017
1058
937
1281
42+
158Er Yrast
Low intensity feeders!
Counts
Energy (keV)

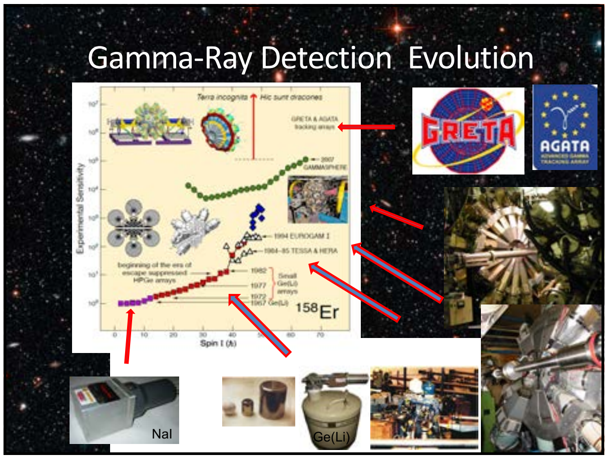

Along the Yrast Line of 158Er, 2005
158Er
New states!
BUT what lies above?
terminating bands
proton alignment
neutron alignment
ground state band
band terminating states
Z = 64 core-breaking excitations
"hole" in core
valence particles
146Gd core
prolate
oblate
E - 0.007 • I (I+1) (MeV)
Spin I (ħ)


Winston was right!
Never
Never
NEVER
GIVE UP

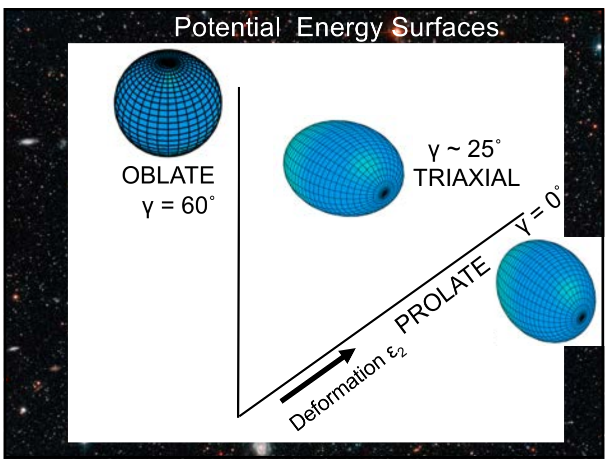

First of several ultra-high spin rotational bands in 158Er discovered……WOW!
~50-100 times weaker than Superdeformed band in 152Dy!
The Return of Collectivity beyond Band Termination in 157,158Er
Counts
Eγ (MeV)

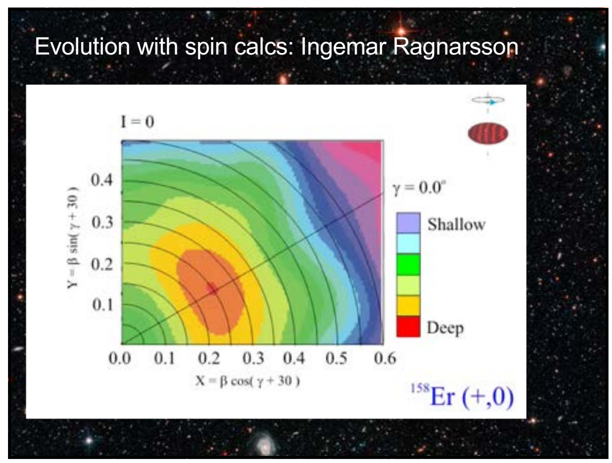

Along the Yrast Line 158Er
158Er
triaxial
terminating bands
new high moment of inertia band
triaxial strongly deformed?
proton alignment
neutron alignment
ground state band
band terminating states
Z = 64 core-breaking excitations
"hole" in core
valence particles
146Gd core
prolate
oblate
triaxial
E - 0.007 • I (I+1) (MeV)
Spin I (ħ)


PHYSICAL REVIEW LETTERS
Return of Collective Rotation in 157Er and 158Er at Ultrahigh Spin
McGRAW-HILL YEARBOOK OF SCIENCE & TECHNOLOGY 2013
Selected as the first ever "Editors Suggestion" in nuclear physics.

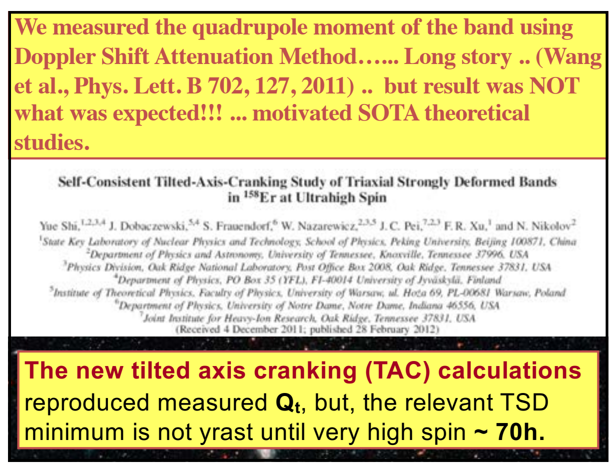

Gamma-Ray Detection Evolution
GRETA
AGATA
158Er
NaI
Ge(Li)

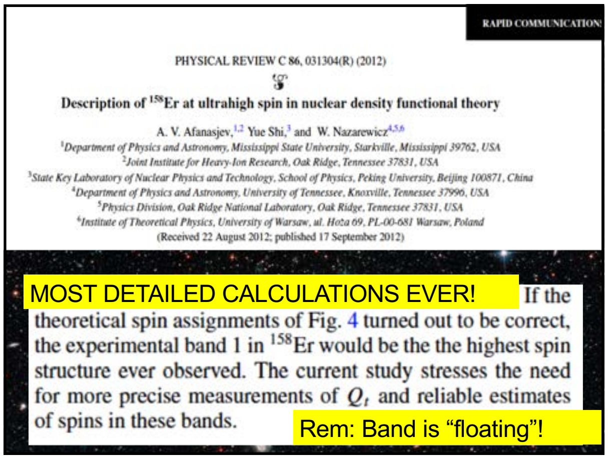

IMAGINE
06-14
158 ERB


Potential Energy Surfaces
OBLATE
γ = 60˚
γ ~ 25˚
TRIAXIAL
γ = 0˚
PROLATE
Deformation ε2

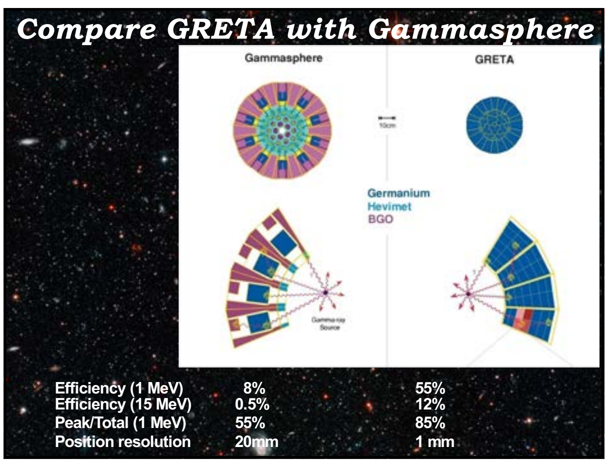

Evolution with spin calcs: Ingemar Ragnarsson
I = 0
γ = 0.0˚
Shallow
Deep
Y = β sin(γ + 30)
X = β cos(γ + 30)
158Er (+,0)

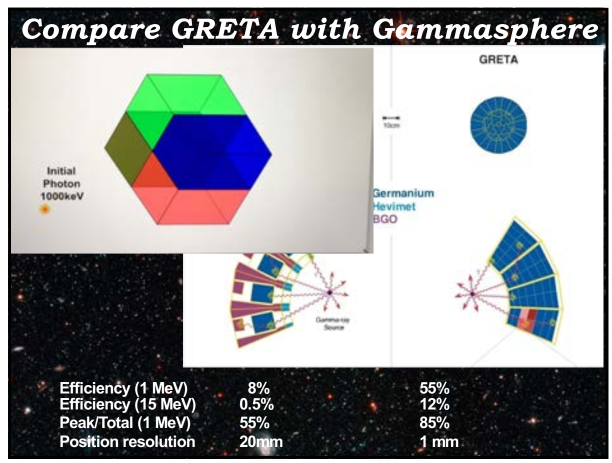

Quadrupole Moment Measurements in 158Er: Our team
North America,
FSU: X. Wang, M. A. Riley, C. Teal;
ANL: M. P. Carpenter, C. J. Chiara, R. V. F. Janssens, F. G. Kondev, T. Lauritsen, S. Zhu
USNA: D. J. Hartley; UTK: L. L. Riedinger;
ND: A. D. Ayangeakaa, U. Garg, J. Matta; LBNL: P. Fallon, M. K. Petri
Europe,
Liverpool: E. S. Paul, A. J. Boston, H. C. Boston, D. Judson, P. J. Nolan,
J. Revill, S. V. Rigby, C. Unsworth;
Daresbury: J. Simpson, J. Ollier; Lund: I. Ragnarsson
South Africa, iThemba: J. F. Sharpey-Schafer

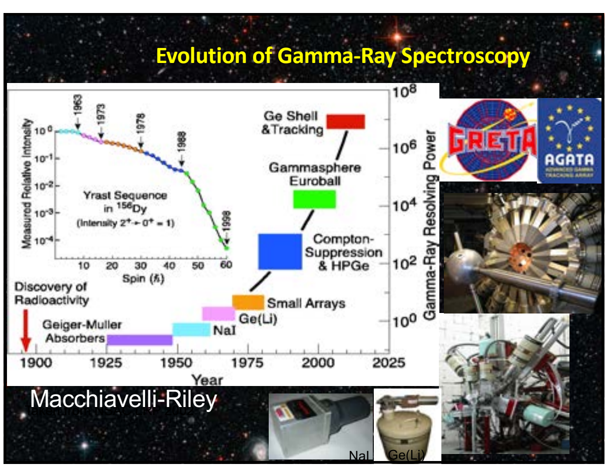

We measured the quadrupole moment of the band using Doppler Shift Attenuation Method…... Long story .. (Wang et al., Phys. Lett. B 702, 127, 2011) .. but result was NOT what was expected!!! ... motivated SOTA theoretical studies.
Self-Consistent Tilted-Axis-Cranking Study of Triaxial Strongly Deformed Bands in 158Er at Ultrahigh Spin
Yue Shi, J. Dobaczewski, S. Frauendorf, W. Nazarewicz, J. C. Pei, F. R. Xu, and N. Nikolov
(Received 4 December 2011; published 28 February 2012)
The new tilted axis cranking (TAC) calculations
reproduced measured Qt, but, the relevant TSD minimum is not yrast until very high spin ~ 70h.

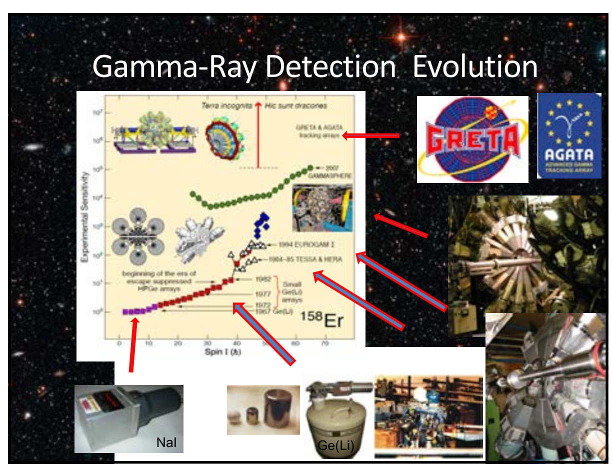

RAPID COMMUNICATIONS
PHYSICAL REVIEW C 86, 031304(R) (2012)
Description of ^{158}Er at ultrahigh spin in nuclear density functional theory
A. V. Afanasjev,[1,2] Yue Shi,[3] and W. Nazarewicz[4,5,6]
[1]Department of Physics and Astronomy, Mississippi State University, Starkville, Mississippi 39762, USA
[2]Joint Institute for Heavy-Ion Research, Oak Ridge, Tennessee 37831, USA
[3]State Key Laboratory of Nuclear Physics and Technology, School of Physics, Peking University, Beijing 100871, China
[4]Department of Physics and Astronomy, University of Tennessee, Knoxville, Tennessee 37996, USA
[5]Physics Division, Oak Ridge National Laboratory, Oak Ridge, Tennessee 37831, USA
[6]Institute of Theoretical Physics, University of Warsaw, ul. Hoża 69, PL-00-681 Warsaw, Poland
(Received 22 August 2012; published 17 September 2012)
MOST DETAILED CALCULATIONS EVER!
If the theoretical spin assignments of Fig. 4 turned out to be correct, the experimental band 1 in ^{158}Er would be the the highest spin structure ever observed. The current study stresses the need for more precise measurements of Q_t and reliable estimates of spins in these bands.
Rem: Band is “floating”!


What Next?
GAMMA-RAY TRACKING!!!!
US community (and European friends) has been working on this revolutionary technology since mid-late-90’s ....


Compare GRETA with Gammasphere
Gammasphere
GRETA
10cm
Germanium
Hevimet
BGO
Gamma-ray Source
Efficiency (1 MeV) 8% 55%
Efficiency (15 MeV) 0.5% 12%
Peak/Total (1 MeV) 55% 85%
Position resolution 20mm 1 mm

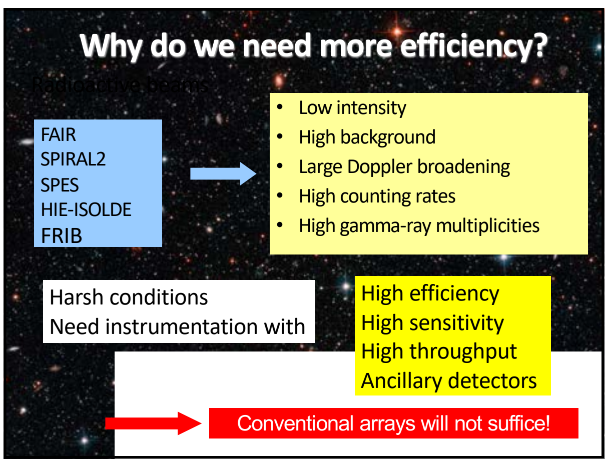

Compare GRETA with Gammasphere
GRETA
Initial Photon 1000keV
10cm
Germanium
Hevimet
BGO
Efficiency (1 MeV) 8% 55%
Efficiency (15 MeV) 0.5% 12%
Peak/Total (1 MeV) 55% 85%
Position resolution 20mm 1 mm

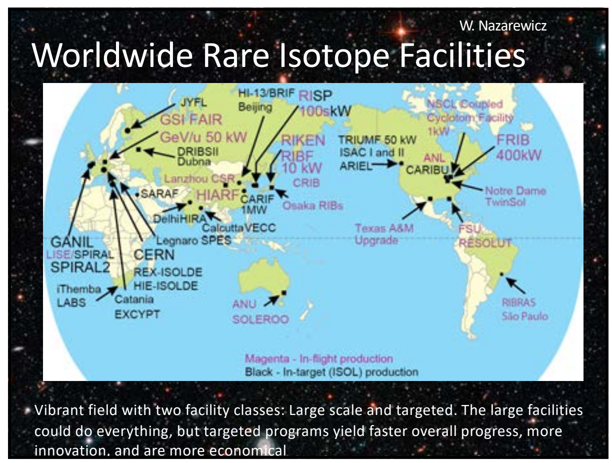

Evolution of Gamma-Ray Spectroscopy
Measured Relative Intensity
Yrast Sequence in ^{156}Dy
Spin (ħ)
Ge Shell &Tracking
Gammasphere Euroball
Compton-Suppression & HPGe
Small Arrays
Ge(Li)
NaI
Geiger-Muller Absorbers
Discovery of Radioactivity
Year
Gamma-Ray Resolving Power
GRETA
AGATA
Macchiavelli-Riley
NaI
Ge(Li)

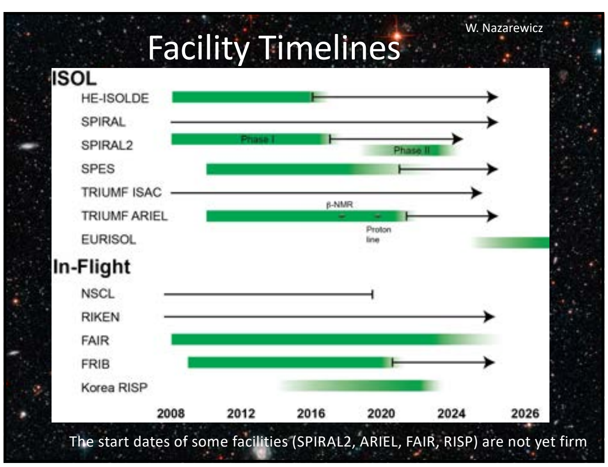

Gamma-Ray Detection Evolution
Terra incognita
Hic sunt dracones
GRETA & AGATA tracking arrays
GAMMASPHERE
EUROGAM I
TESSA & HERA
Experimental Sensitivity
Spin I (ħ)
^{158}Er
GRETA
AGATA
NaI
Ge(Li)


Path to GRETA
'96
'02
2002 NSAC LRP "The detection of γ-ray emissions from excited nuclei plays a vital and ubiquitous role in nuclear science .."
GRETA
The 2015 LONG RANGE PLAN for NUCLEAR SCIENCE
2007 NSAC LRP "Construction of GRETA should begin immediately upon successful completion of the GRETINA array"
concept endorsed – GRETA identified as a key instrument for FRIB


THE FUTURE OF HIGH RESOLUTION NUCLEAR SPECTROSCOPY LOOKS VERY BRIGHT INDEED!!! ☺
The Gamma-Ray Energy Tracking Array -GRETA
GRETA
The Advanced Gamma Tracking Array AGATA
AGATA


Why do we need more efficiency?
FAIR
SPIRAL2
SPES
HIE-ISOLDE
FRIB
Low intensity
High background
Large Doppler broadening
High counting rates
High gamma-ray multiplicities
Harsh conditions
Need instrumentation with
High efficiency
High sensitivity
High throughput
Ancillary detectors
Conventional arrays will not suffice!


W. Nazarewicz
Worldwide Rare Isotope Facilities
JYFL
HI-13/BRIF Beijing
RISP 100skW
GSI FAIR GeV/u 50 kW
DRIBSII Dubna
RIKEN
RIBF 10 kW
CRIB
TRIUMF 50 kW ISAC I and II
ARIEL
CARIBU
ANL
NSCL Coupled Cyclotron Facility 1kW
FRIB 400kW
Notre Dame TwinSol
Lanzhou CSR
SARAF
HIARF
CARIF 1MW
Osaka RIBs
DelhiHIRA
Calcutta VECC
Legnaro SPES
Texas A&M Upgrade
FSU RESOLUT
GANIL LISE/SPIRAL SPIRAL2
CERN REX-ISOLDE HIE-ISOLDE
iThemba LABS
Catania EXCYPT
ANU SOLEROO
RIBRAS São Paulo
Magenta - In-flight production
Black - In-target (ISOL) production
Vibrant field with two facility classes: Large scale and targeted. The large facilities could do everything, but targeted programs yield faster overall progress, more innovation, and are more economical


W. Nazarewicz
Facility Timelines
ISOL
HE-ISOLDE
SPIRAL
SPIRAL2
Phase I
Phase II
SPES
TRIUMF ISAC
TRIUMF ARIEL
β-NMR
EURISOL
Proton line
In-Flight
NSCL
RIKEN
FAIR
FRIB
Korea RISP
2008
2012
2016
2020
2024
2026
The start dates of some facilities (SPIRAL2, ARIEL, FAIR, RISP) are not yet firm


New facilities + new detectors!!!
Their discovery potential is phenomenal!!!
Great time for nuclear physics!!!
GAMMA-RAY SPECTROSCOPY CONTINUES TO PLAY A CENTRAL AND VITAL ROLE!!!
THE KRAKOW GROUP WILL BE IN THE MIDDLE OF IT ALL!!
THANK YOU!

THANK YOU!

Exploration of the Mid-Shell Neutron-Rich, Rare-Earth Region
Via Deep-Inelastic Collisions

209

D.J. Hartley (US Naval Academy), K.A. Villafana, M.A. Riley (FSU), F. Kondev, M.P. Carpenter, S. Zhu (ANL), R.V.F. Janssens (UNC), J. Simpson (Daresbury), E.S. Paul (Liverpool)

- Use deep-inelastic collisions to populate excited states in neutron-rich nuclei and observe sequences up to medium spin.
- Beam and target interact and exchange particles that can create neutron-rich species at medium spins.
- Recent theoretical study suggested ^{160}Gd + ^{154}Sm reaction may produce more than 40 neutron-rich nuclei.
  - Wang & Guo, PLB **760**, 236 (2016)

Exploration of the Mid-Shell Neutron-Rich, Rare-Earth Region
Via Deep-Inelastic Collisions

210

D.J. Hartley (US Naval Academy), K.A. Villafana, M.A. Riley (FSU), F. Kondev, M.P. Carpenter, S. Zhu (ANL), R.V.F. Janssens (UNC), J. Simpson (Daresbury), E.S. Paul (Liverpool)

- Use d... states in neutro... to medium spin.
- Beam ...es that can create...
- Recen... eaction may produc...
  - War...

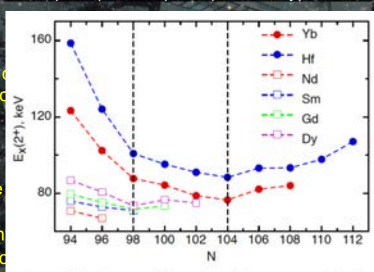
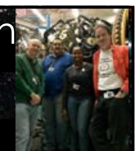
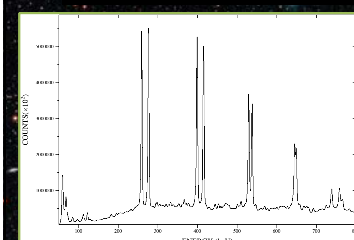


Figure 1: Excitation energy of the lowest 2+ states in even-even, rare-earth nuclei.

Deep-inelastic experiment details

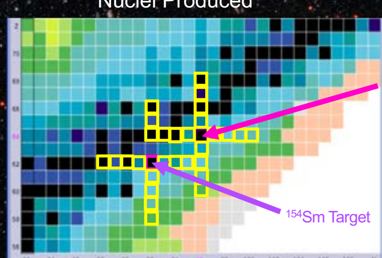


- ATLAS + GAMMASPHERE
- Used ^{160}Gd beam with E = 1000 MeV
- Directed beam onto ^{154}Sm and ^{164}Dy targets (>200 mg/cm^2)



-Is GAMMASPHERE double-peaking?
-No – both beam and target
-Coulex peaks dominate spectra
-Complex analysis

^{160}Gd + ^{154}Sm reaction
Nuclei Produced

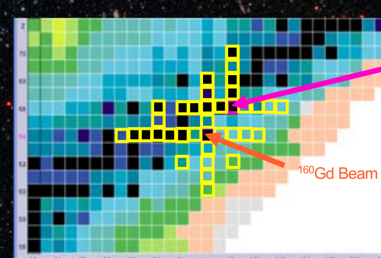


^{160}Gd Beam

^{154}Sm Target

^{160}Gd + ^{164}Dy reaction
Nuclei Produced

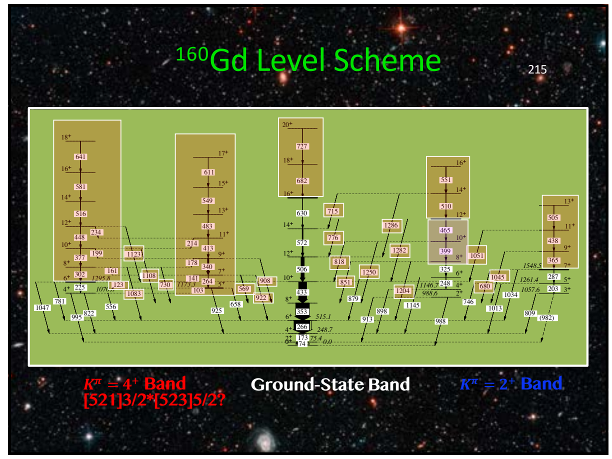
213

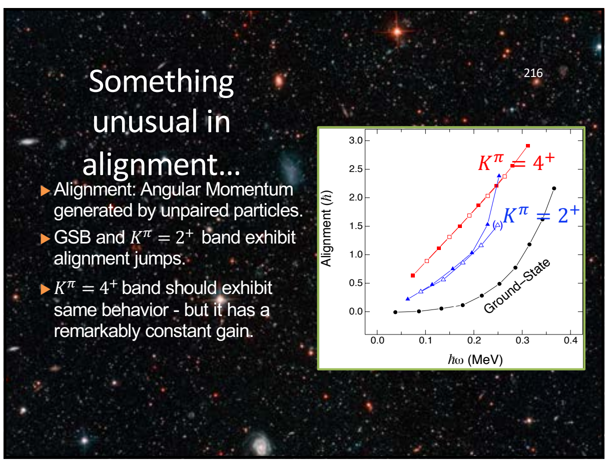


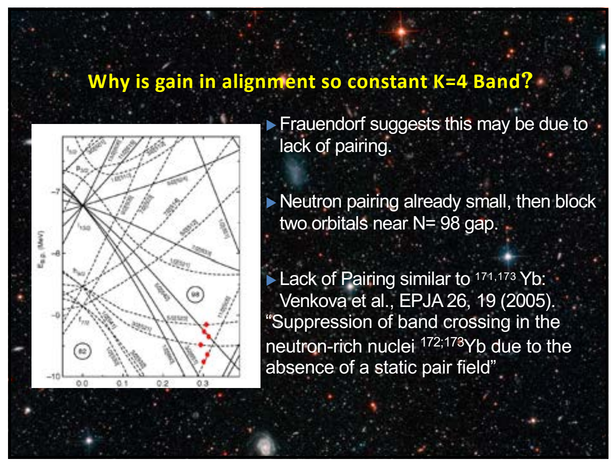
^{164}Dy Target

^{160}Gd Beam

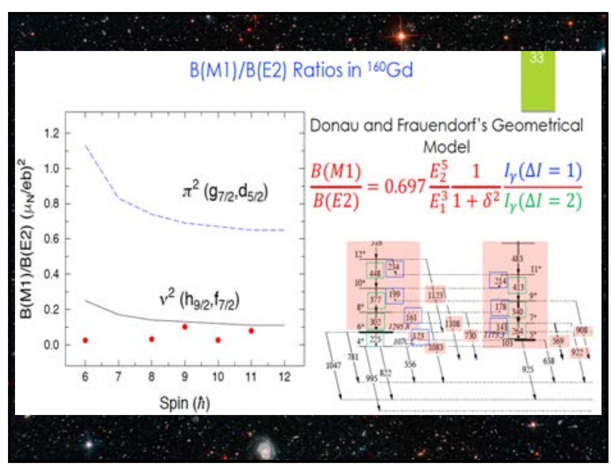

And then there were gamma-rays!

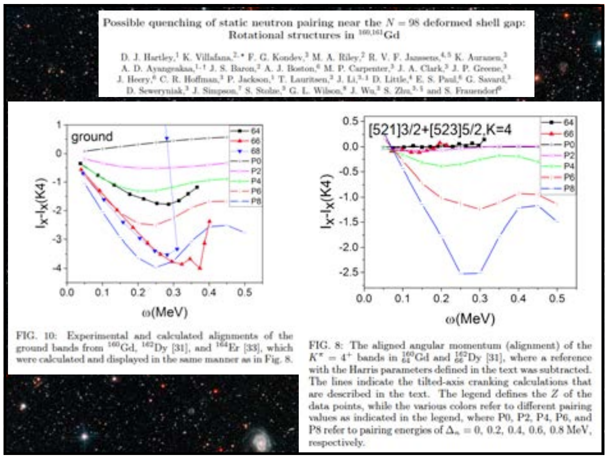

160Gd Level Scheme
215
Kπ = 4+ Band
[521]3/2*[523]5/2?
Ground-State Band
Kπ = 2+ Band


Something unusual in alignment...
216
Alignment: Angular Momentum generated by unpaired particles.
GSB and Kπ = 2+ band exhibit alignment jumps.
Kπ = 4+ band should exhibit same behavior - but it has a remarkably constant gain.
Kπ = 4+
Kπ = 2+
Ground-State
Alignment (ℏ)
ℏω (MeV)


Why is gain in alignment so constant K=4 Band?
Frauendorf suggests this may be due to lack of pairing.
Neutron pairing already small, then block two orbitals near N= 98 gap.
Lack of Pairing similar to 171,173 Yb: Venkova et al., EPJA 26, 19 (2005).
"Suppression of band crossing in the neutron-rich nuclei 172;173Yb due to the absence of a static pair field"


Odd-Even Mass Differences: Already Low at 160Gd
Δ
Neutron Number
Sm
Gd
Dy
Er
Yb
Hf
W


B(M1)/B(E2) Ratios in 160Gd
33
Donau and Frauendorf's Geometrical Model
B(M1)/B(E2) = 0.697 E₂⁵/E₁³ 1/(1+δ²) Iγ(ΔI = 1)/Iγ(ΔI = 2)
π² (g7/2,d5/2)
ν² (h9/2,f7/2)
B(M1)/B(E2) (μN/eb)²
Spin (ℏ)


Possible quenching of static neutron pairing near the $N = 98$ deformed shell gap: Rotational structures in $^{160,161}Gd$

D. J. Hartley,[1] K. Villafana,[2,*] F. G. Kondev,[3] M. A. Riley,[2] R. V. F. Janssens,[4,5] K. Auranen,[3] A. D. Ayangeakaa,[1,†] J. S. Baron,[2] A. J. Boston,[6] M. P. Carpenter,[3] J. A. Clark,[3] J. P. Greene,[3] J. Heery,[6] C. R. Hoffman,[3] P. Jackson,[1] T. Lauritsen,[3] J. Li,[3,‡] D. Little,[4] E. S. Paul,[6] G. Savard,[3] D. Seweryniak,[3] J. Simpson,[7] S. Stolze,[3] G. L. Wilson,[8] J. Wu,[3] S. Zhu,[3,§] and S. Frauendorf[9]

FIG. 10: Experimental and calculated alignments of the ground bands from ^{160}Gd, ^{162}Dy [31], and ^{164}Er [33], which were calculated and displayed in the same manner as in Fig. 8.

FIG. 8: The aligned angular momentum (alignment) of the $K^{\pi} = 4^{+}$ bands in $^{160}_{64}Gd$ and $^{162}_{66}Dy$ [31], where a reference with the Harris parameters defined in the text was subtracted. The lines indicate the tilted-axis cranking calculations that are described in the text. The legend defines the Z of the data points, while the various colors refer to different pairing values as indicated in the legend, where P0, P2, P4, P6, and P8 refer to pairing energies of $\Delta_n = 0, 0.2, 0.4, 0.6, 0.8$ MeV, respectively.

Deep Inelastic collaboration

D. J. Hartley, A. D. Ayangeakaa, J. Cavey, E. Pedicini, J. Vanhoy, United States Naval Academy

K. A. Villafana, M. A. Riley, J. Baron, Florida State University

F.G. Kondev, G. Savard, M. Carpenter, P. Copp, S. Zhu, K. Auranen, D. Ayangeakaa, S. Bottoni, J. Clark, J. Greene, C. Hoffman, T. Lauritsen, J. Li, J. Sethi, D. Seweryniak, S. Stolze, G. Wilson, and J. Wu, Argonne National Laboratory

- R. Orford, McGill University
- R. V.F. Janssens, D. Little, University of North Carolina
- A. Boston, J. Henry, E. S. Paul, University of Liverpool
- J. Simpson, Daresbury Laboratory
- S. Frauendorf, University of Notre Dame