Effective theory for deformed nuclei

Thomas Papenbrock

and OAK RIDGE NATIONAL LABORATORY

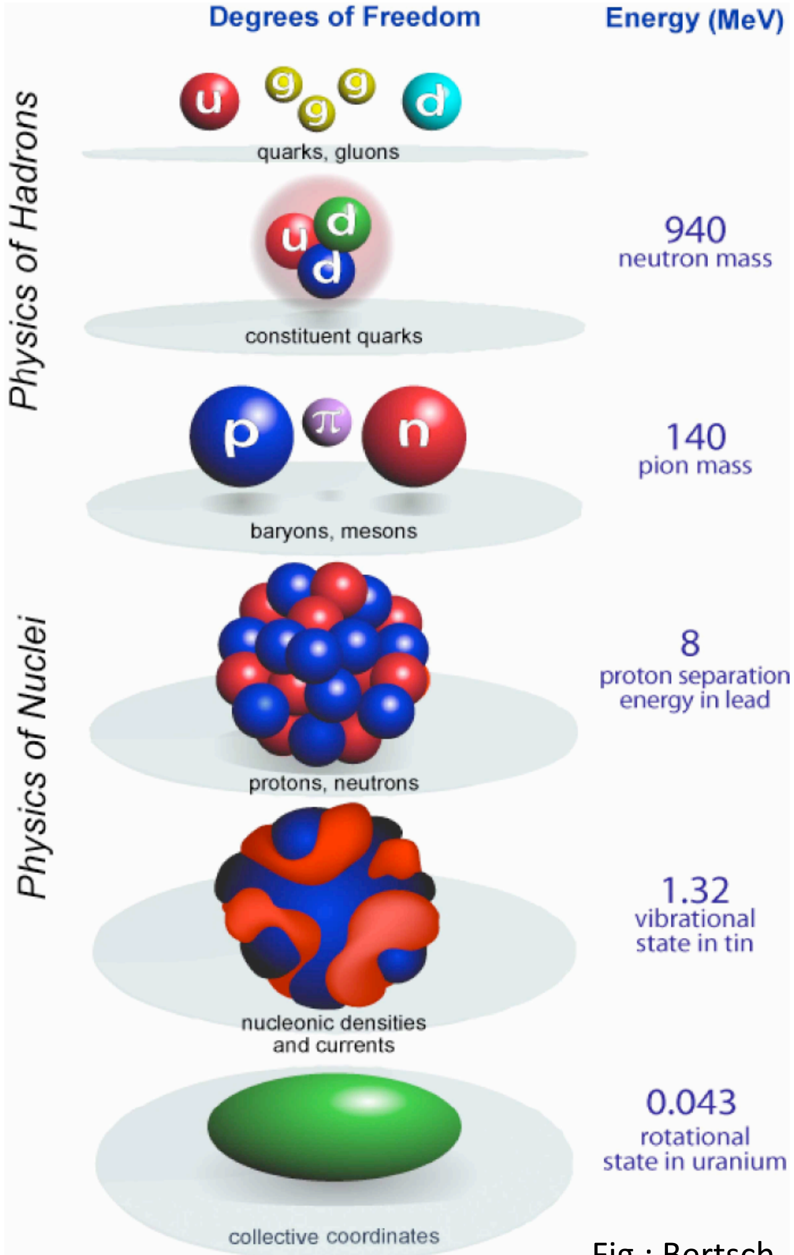
TP, Nucl. Phys. A 852, 36 (2011); arXiv:1011.5026
Jialin Zhang and TP, Phys. Rev. C 87, 034323 (2013); arXiv:1302.3775
TP and H. Weidenmüller, arXiv.1307.1181
Toño Coello and TP, in preparation

EFT for many body systems — Madrid 1.16.2014

Research partly funded by the US Department of Energy

Separation of scales in nuclear physics

Energy or Resolution



Chiral effective field theory

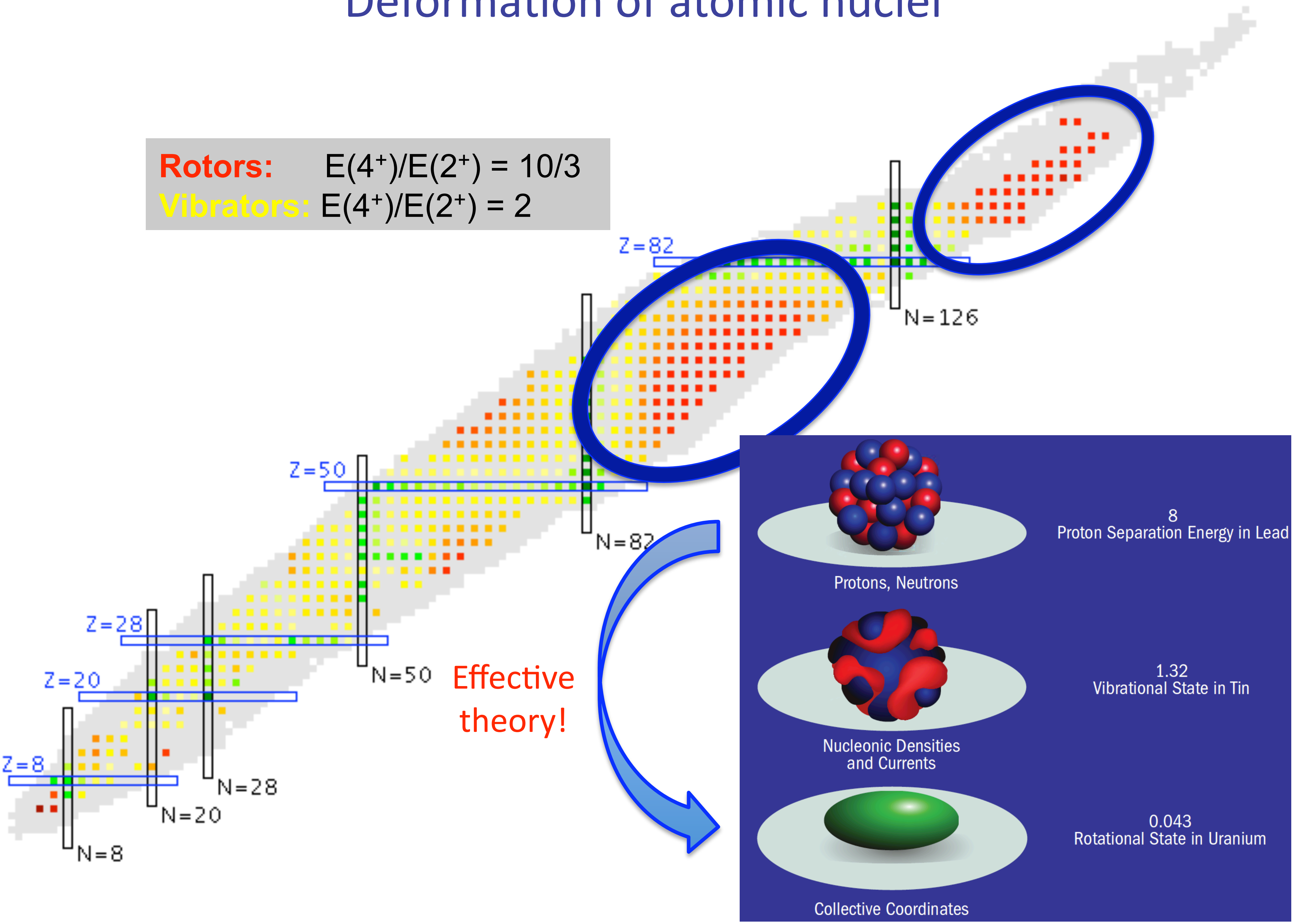
Effective theories provide us with model independence

Effective theory of deformed nuclei

Fig.: Bertsch, Dean, Nazarewicz, SciDAC review (2007)

Deformation of atomic nuclei

Rotors: $E(4^+)/E(2^+) = 10/3$
Vibrators: $E(4^+)/E(2^+) = 2$



Models for nuclear rotations

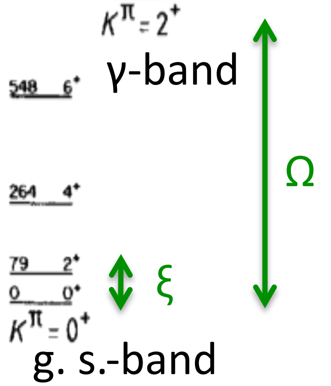
1. Bohr Hamiltonian (1952), Bohr & Mottelson's collective model (1953).
   - five quadrupole degrees of freedom model surface deformations → three Euler angles and two shape parameters
2. General collective model "Frankfurt model" [Gneuss, Mosel & Greiner (1969); Hess, Maruhn, Greiner (1981)]
3. Arima & Iachello's Interacting Boson Model (1976)
   - *s* and *d* boson are degrees of freedom; algebraic approach with symmetries imposed on Hamiltonian in limiting cases

- The existing models describe many aspects of vast sets of data quite well.
- They are difficult to generalize in a tractable way due to the difficulties in coupling of angular momenta and the computation of matrix elements.
- Renewed interest in computationally tractable models [M.A. Caprio, Phys. Rev. C 68, 054303 (2003); D.J. Rowe, Nucl. Phys. A 735, 372 (2004)]

Approach within an effective field theory possible.

Spectrum of a deformed nucleus

“Complete” spectrum of ^{168} Er [Davidson *et al.*, J. Phys. G 7, 455 (1981)]



Key features: rotational bands on top of “vibrational” band heads

Typical deformed even-even nuclei: lowest vibrational state has $J^{\pi} = 0^{+}, 2^{+}$

Separation of scale: $\xi << \Omega$

Similarly complete: spectrum of ^{162}Dy

A. Aprahamian *et al.*, Nucl. Phys. A 764, 42 (2006)

EFT for finite systems with "emergent symmetry breaking"*

Consider energy scales in an atomic nucleus with mass number A

Radius $\propto A^{1/3}$

Moment of inertia $\text{mass} \times (\text{length})^2 \propto A^{5/3}$

→Rotational energy ~ $A^{-5/3}$

Typical wave number of NG mode $\propto A^{-1/3}$

Thus, for A >> 1 there is a regime where rotational motion is a correction to NG modes

Related work: Corrections to partition functions of infinite systems from finite simulations. [Horsch & von der Linden, Z. Phys. B 72, 181 (1988); H. Leutwyler, Phys. Lett. B 189, 197 (1987); Gasser & Leutwyler, Nucl. Phys. B 307, 763 (1988); Hasenfratz & Niedermayer, Z. Phys. B 92, 91 (1993), hep-lat/9212022.]

Coset SO(3)/SO(2) in infinite systems: [Leutwyler, Phys. Rev. D 49, 3033 (1994); Roman & Soto, Int. J. Mod. Phys. B 13, 755 (1999); Hofmann, Phys. Rev. B 60, 388 (1999); Bär, Imboden & Wiese, Nucl. Phys. B 686, 347 (2004).]

* Yannouleas & Landman, Rep. Progr. Phys. 70, 2067 (2007)

Key step: single out the zero mode

[Leutwyler, Phys. Lett. B 189, 197 (1987)]

Coset space for molecules and deformed nuclei: $SO(3)/SO(2)$

Parameterization in terms of time-dependent angles (α,β) and Nambu-Goldstone fields (x,y).

$$
\begin{aligned}
U &= g(\alpha,\beta)u(x,y) \ , \\
g(\alpha,\beta) &= \exp\left\{-i\alpha(t)J_z\right\}\exp\left\{-i\beta(t)J_y\right\} \ , \\
u(x,y) &= \exp\left\{-ix(\theta,\phi,t)J_x - iy(\theta,\phi,t)J_y\right\}
\end{aligned}
$$

Properties of NG fields:

$$|x|, |y| \ll 1$$

$$\int \mathrm{d}\Omega \ x(\theta,\phi,t) = 0 = \int \mathrm{d}\Omega \ y(\theta,\phi,t)$$

Upon quantization, angles (α,β) restore spherical symmetry (good angular momentum) while (x,y) become intrinsic quantized excitation modes.

Behavior under rotations

Behavior of U = gu under rotations r, with $h(\gamma) = \exp\{-i\gamma J_z\}$

$$\begin{aligned} rU &= g(\alpha', \beta')h(\gamma')u \\ &= g(\alpha', \beta')\ [h(\gamma')uh^\dagger(\gamma')]\ h(\gamma') \end{aligned}$$

→(α,β) transform nonlinearly (like angles on the sphere).
→(x,y) are intrinsic variables and transform linearly (with a complicated angle)

Steps:

- identify invariants
- power counting: rotations << vibrations << breakup scale (100 keV << 1MeV << 3 MeV)
- Expansion of fields (x,y) in normal modes and canonical quantization
- Quantum Numbers: Total angular momentum J, intrinsic projection K
- Key difference between nuclei and molecules: Nuclei are paired in their ground state. This excludes low-energy excitations with positive parity and odd K
- Result: Rotational bands on top of vibrational (spin K) band heads

TP and H. Weidenmüller, arXiv.1307.1181 (v2 soon), → Phys. Rev. C (2014)

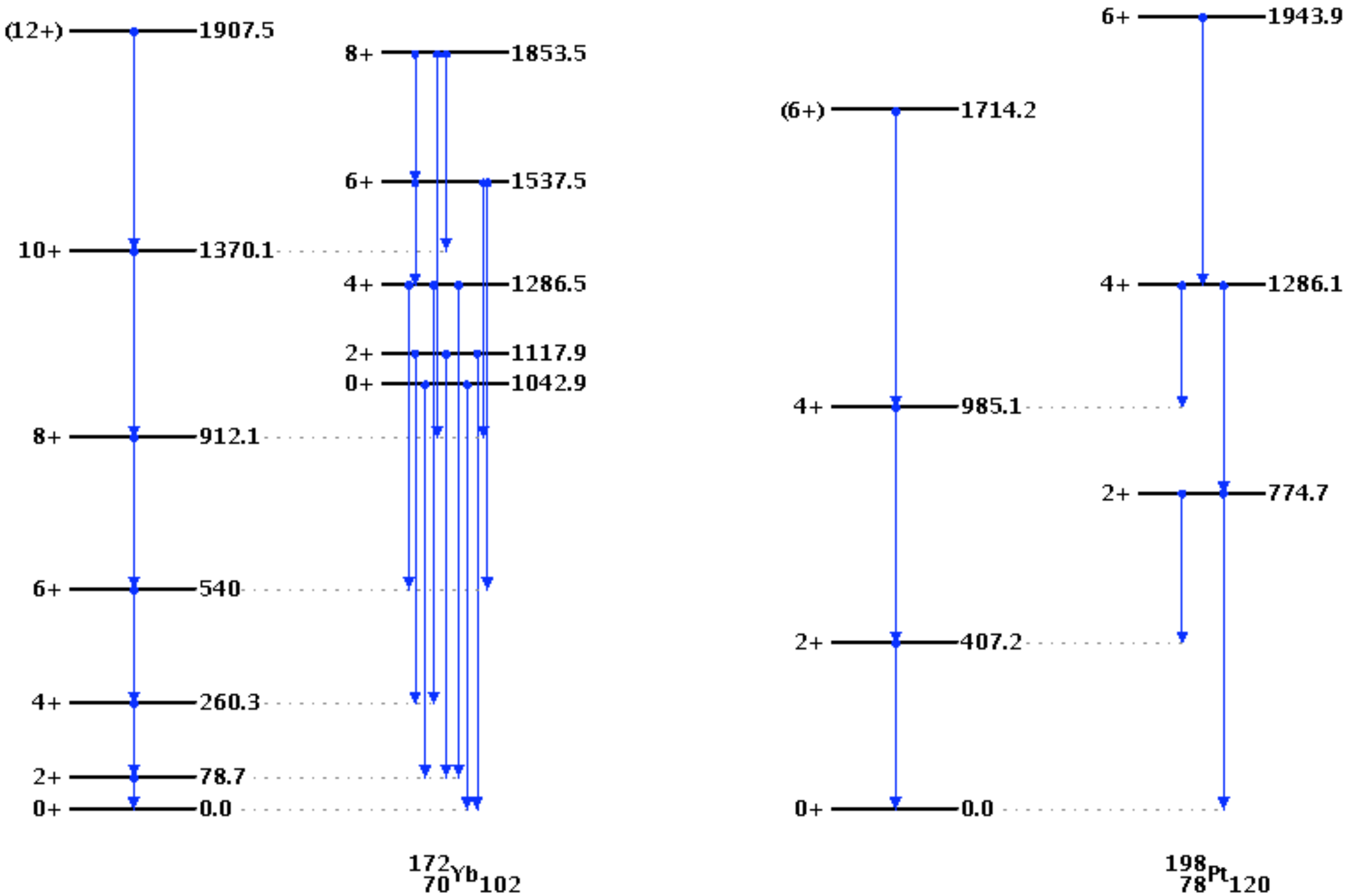
Construction of a simpler effective theory for deformed nuclei

Stay within QM, consider effective theory for angles (α,β), and add physics of intrinsic quadrupole degrees of freedom with SSB.

Quadrupole field

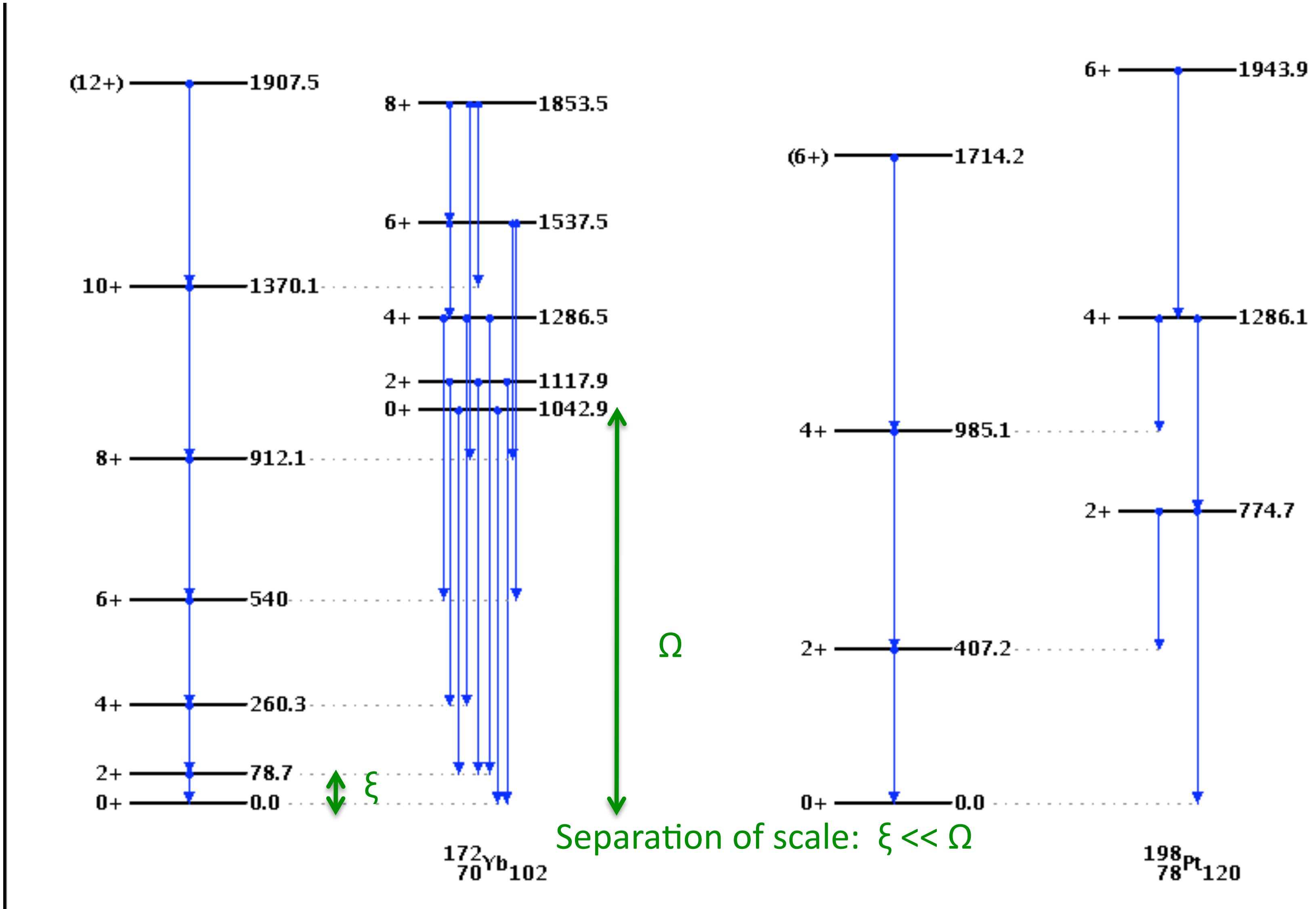
- can be viewed as one of the normal modes of the intrinsic fields (x,y)
- taken from phenomenological approach by looking at low-energy states

1. Identify relevant degrees of freedom



Quadrupole degrees of freedom describe spins and parity of low-energy spectra

2. Identify relevant symmetries and symmetry breaking



Symmetry: Rotational invariance

Very low energy excitations ("zero modes") indicate emergent symmetry breaking

Nonlinear realization of the rotational symmetry: Quantities with definite symmetry properties

1. E_x and E_y transform as the x and y-components of a vector under rotations. (These are the velocity components of a particle on the sphere)

$$\begin{aligned} E_x &= \dot{\alpha} \sin\beta \\ E_y &= -\dot{\beta} \end{aligned}$$

2. The "covariant derivative" D_t transforms as the z-component of a vector under rotations. (This is the covariant derivative on the sphere)

$$D_t \equiv \partial_t - i E_z J_z$$

$$E_z = -\dot{\alpha} \cos\beta$$

Any Lagrangian consisting of combinations of E_x, E_y, and D_t (acting on other fields) **that is formally invariant under SO(2)** (i.e. axially symmetric) **is indeed invariant under SO(3)**.

Weinberg (1967); Coleman, Wess, Zumino (1969); Callan, Coleman, Wess & Zumino (1969).
Pedagogical reviews: S. Weinberg, The Quantum Theory of Fields, Vol.II, chap. 19;
C. P. Burgess, Physics Reports 330 (2000) 193; T. Brauner, Symmetry 2, 2010; arXiv:1001.5212.

Physics of zero modes

Lagrangian

$$L = \frac{C_0}{2}(\partial_t \vec{n}) \cdot (\partial_t \vec{n}) = \frac{C_0}{2}(\dot{\beta}^2 + \dot{\alpha}^2 \sin^2 \beta)$$

Hamiltonian

$$H = \frac{p_\beta^2}{2C_0} + \frac{p_\alpha^2}{2C_0 \sin^2 \beta}$$

Quantization

$$p_\beta^2 = -\frac{1}{\sin \beta} \partial_\theta \sin \beta \partial_\beta \; ,$$

$$p_\alpha = -i\partial_\alpha \; .$$

Spectrum

$$\hat{H} Y_{lm}(\beta, \alpha) = \frac{l(l+1)}{2C_0} Y_{lm}(\beta, \alpha)$$

Rotational bands are quantized Nambu-Goldstone modes.
Low-energy constant C_0 is moment of inertia and fit to data.

Nuclei with nonzero ground-state spins: WZ terms

A finite ground-state spin breaks time reversal invariance.
→ Consider terms that are first order in the time derivative
→ No such terms are invariant under rotations.
BUT: Action remains essentially invariant under one particular combination (corresponds to magnetic monopole inside sphere)

Lagrangian

$$\begin{aligned} L_{\rm LO} &= L_{\rm LO}^{(ee)} + L_{\rm WZ} \\ &= \frac{C_0}{2}\left(\dot\beta^2 + \dot\alpha^2 \sin^2\beta\right) - q\dot\alpha\cos\beta \end{aligned}$$

Hamiltonian

$$\boxed{H_{\rm LO} = \frac{p_\beta^2}{2C_0} + \frac{(p_\alpha + q\cos\beta)^2}{2C_0\sin^2\beta}}$$

Eigenvalues and eigenfunctions (Identify q with ground-state spin!)

$$\hat H_{\rm LO}\, d^l_{mq}(\beta)e^{-i\alpha m} = E_{\rm LO}(q,l) d^l_{mq}(\beta)e^{-i\alpha m}$$

$$\boxed{E_{\rm LO}(q,l) = \frac{l(l+1)-q^2}{2C_0}} \qquad l = |q|, |q|+1, |q|+2, \ldots$$

$$D^l_{mq}(\alpha,\beta,\gamma) \equiv e^{-im\alpha} d^l_{mq}(\beta) e^{-iq\gamma}$$ (Wigner D functions)

Chandrasekharan, Jiang, Pepe, & Wiese, Phys. Rev. D 78, 077901 (2008)

Power counting and beyond leading order

Estimates
(naïve dimensional analysis)
$H_{LO} \sim \xi$

$$C_0 \sim \xi^{-1} \,,$$
$$p_\beta \sim p_\alpha \sim q \sim \xi^0 \,,$$
$$\dot\beta \sim \dot\alpha \sim E_{x,y,z} \sim \xi \,.$$

Lagrangian at NLO

$$L_{\rm NLO} = L_{\rm LO} + \frac{C_2}{4}\left(E_x^2 + E_y^2\right)^2$$

Power counting

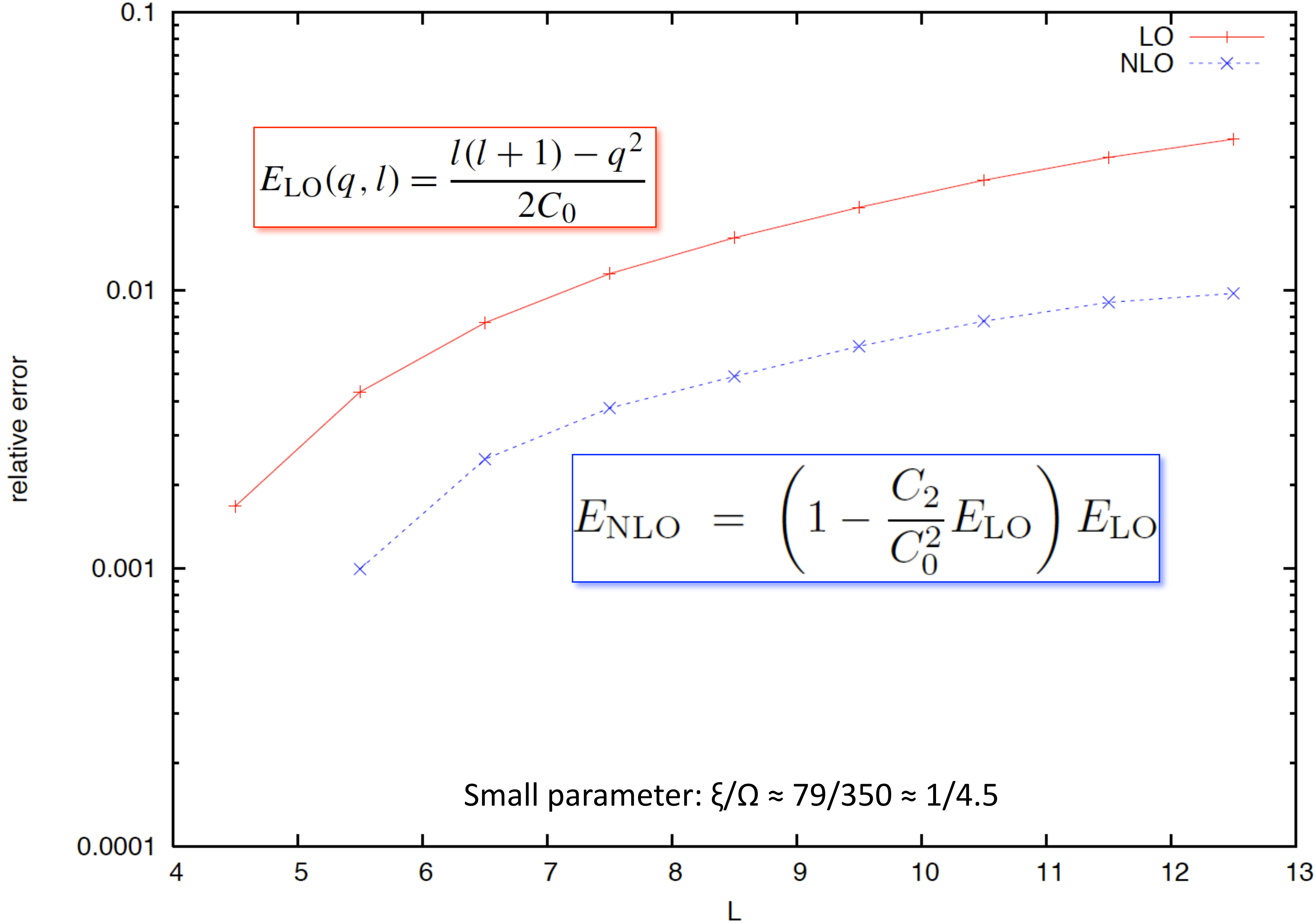
Main idea: higher-oder term due to neglected couplings between NG modes and vibrations. $[C_2/C_0]$= energy^{-2}

$$\frac{C_2}{C_0} \sim \Omega^{-2} \quad \Longrightarrow \quad \frac{C_2}{C_0}\left(E_x^2 + E_y^2\right) \sim \left(\frac{\xi}{\Omega}\right)^2 \ll 1$$

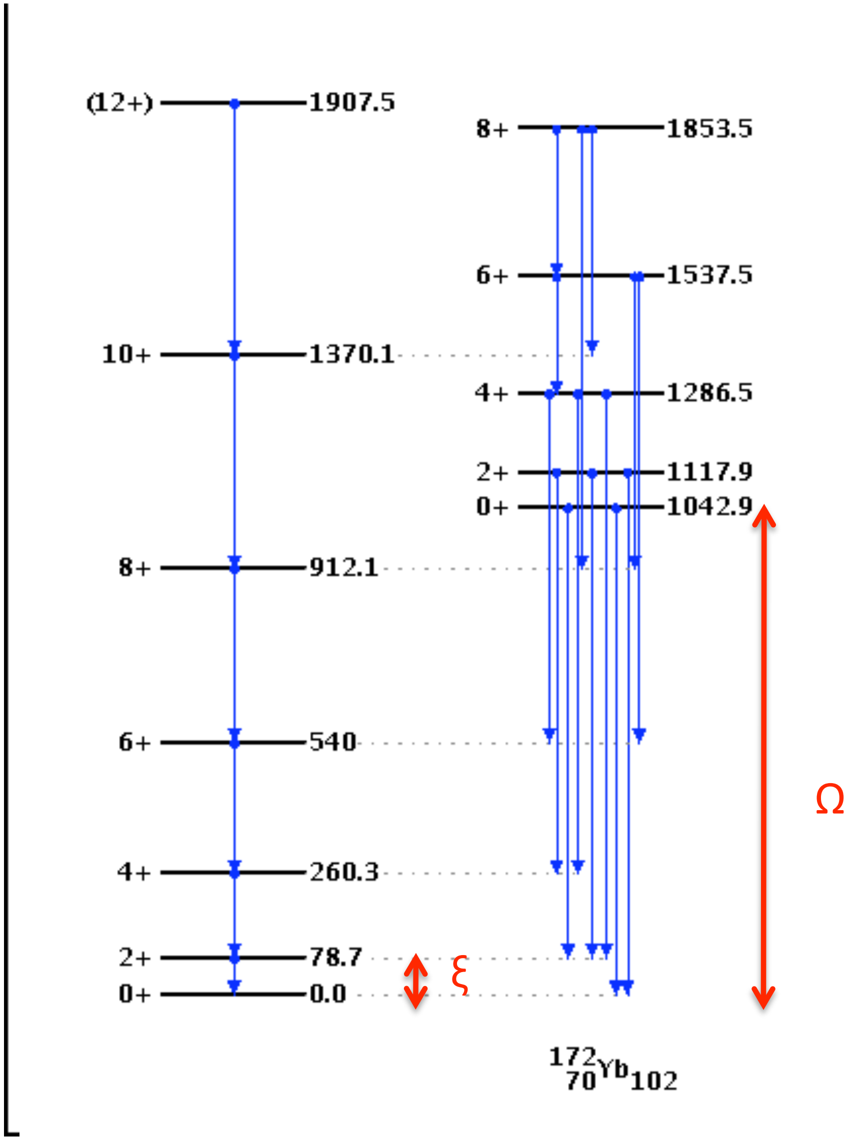
Spectrum: $AI(I+1) + B(I(I+1))^2$ for even-even nuclei. (Bohr & Mottelson)
In general:

$$E_{\rm NLO} = \left(1 - \frac{C_2}{C_0^2} E_{\rm LO}\right) E_{\rm LO}$$

^{173}Yb: Relative error in LO and NLO



Beyond NG modes: coupling to vibrations



Higher energetic degrees of freedom need to be included.

Quadrupole field exhibits spontaneous symmetry breaking.

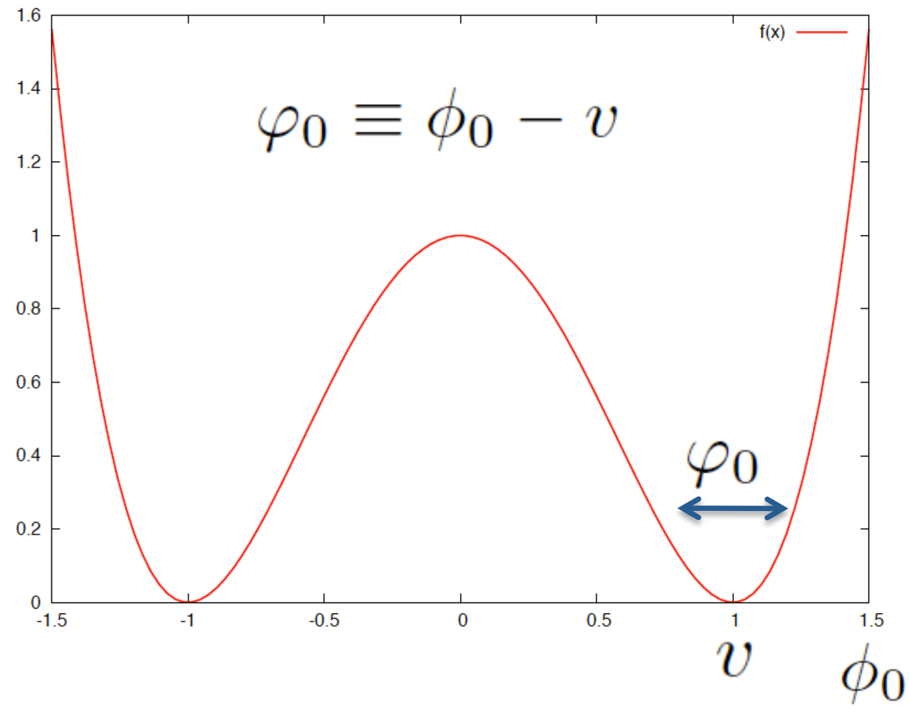
→5 DoF – 2NG = 3DoF

$$\phi = \begin{pmatrix} \phi_2 \\ 0 \\ \phi_0 \\ 0 \\ \phi_2^* \end{pmatrix}$$

Separation of scale: ξ << Ω

Couplings to vibrations: power counting

Low energy scale ξ
High energy scale Ω>>ξ



Dimensional analysis

$$\begin{aligned} v \sim \phi_0 &\sim \xi^{-1/2} \,, \\ \varphi_0 \sim \phi_2 &\sim \Omega^{-1/2} \,, \\ \dot{\varphi}_0 = \dot{\phi}_0 \sim \dot{\phi}_2 &\sim \Omega^{1/2} \,. \end{aligned}$$

Potential expanded around miniumum

$$V_2(\phi) = \frac{\omega_0^2}{2}(\phi_0 - v)^2 + \frac{\omega_2^2}{4}|\phi_2|^2$$

$$V = V_2 + \sum_{k+2l>2} v_{kl}\varphi_0^k|\phi_2|^{2l}$$

Power counting: large amplitudes $\phi_0 \approx v$ restore rotational symmetry → breakdown of EFT

$$v_{kl}\varphi_0^k|\phi_2|^{2l} \sim \Omega\left(\frac{\xi}{\Omega}\right)^{l-1+k/2}$$

Leading order ~O(Ω)

Lagrangian at leading order:

$$L_{\mathrm{LO}} = \frac{1}{2}\dot{\varphi_0}^2 + |\dot{\phi}_2|^2 - \frac{\omega_0^2}{2}\varphi_0^2 - \frac{\omega_2^2}{4}|\phi_2|^2$$

$$H_{\mathrm{LO}} = \frac{1}{2}p_0^2 + \frac{1}{4}\left(p_{2r}^2 + p_{2i}^2\right) + \frac{\omega_0^2}{2}\varphi_0^2 + \frac{\omega_2^2}{4}\left(\phi_{2r}^2 + \phi_{2i}^2\right)$$

Spectrum

$$E(n_0, n_2, m_l) = \omega_0\left(n_0 + \frac{1}{2}\right) + \frac{\omega_2}{2}(2n_2 + |m_l| + 1)$$

β vibration γ vibration

Leading order Lagrangian yields the band heads as harmonic vibrations

Lagrangian consists of E_x, E_y, $D_t\varphi_0$, $D_t\phi_2$, ϕ_0, ϕ_2, and needs to be formally invariant under SO(2) (axial symmetry) only.

Next-to-leading order ~O(ξ)

Lagrangian

$$L_{\rm NLO} = L_{\rm LO} + \frac{3}{2}v^2\left(E_x^2 + E_y^2\right) - 4E_z {\rm Im}\left(\dot{\phi}_2\phi_2^*\right) - \sum_{k+2l=3,4} v_{kl}\varphi_0^k|\phi_2|^{2l} \; .$$

Hamiltonian (kinetic energy)

$$H_{\rm NLO} = H_{\rm LO} + \frac{1}{6v^2}\left(p_\beta^2 + \frac{1}{\sin^2\beta}\left[p_\alpha^2 + 2p_\alpha l_z\cos\beta\right]\right)$$

Spectrum: harmonic vibrations & rotational band on every vibrational band head

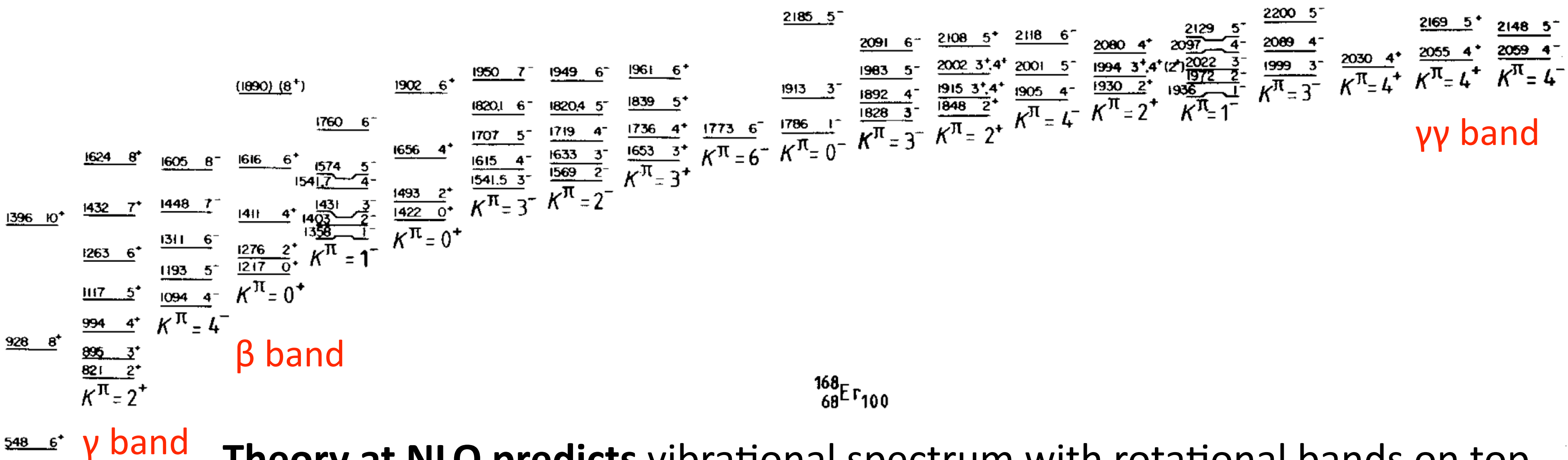
$$E(n_0, n_2, m_l, l) = \omega_0\left(n_0 + \frac{1}{2}\right) + \frac{\omega_2}{2}(2n_2 + |m_l| + 1) + \frac{1}{6v^2}\left(l(l+1) - (2m_l)^2\right)$$

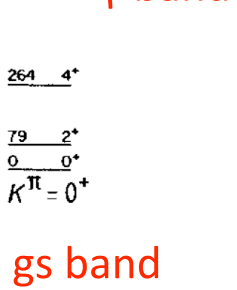
(Corrections ~ξ of band heads due to anharmonicities in the potential neglected.)

In next-to-leading order, the results of the rotational-vibrational model are reproduced.

Multi-phonon excitations

W. F. Davidson *et al.*, J. Phys. G **7**, 455 (1981)





Theory at NLO predicts vibrational spectrum with rotational bands on top (and constant moment of inertias/rotational constants)

Data

- Vibrational band heads clearly not harmonic
- Moments of inertia exhibit smaller, band-head-dependent variations
- Many band heads (neg. parity) not accounted for (octupole, hexadecupole, …)

Multi-phonon bands in deformed nuclei

Multi-phonon γ bands unambiguously* observed in ^{166,68}Er, ^{232}Th

^{168}Er [H. G. Börner *et al*., Phys. Rev. Lett. 66, 691 (1991); M. Oshima *et al*., Phys. Rev. C 52, 3492 (1995); T. Härtlein *et al*., Eur. Phys. J. A 2, 253 (1998).]

^{166}Er [C. Fahlander *et al*., Phys. Lett. B 388, 475 (1996); P. E. Garrett *et al*., Phys. Rev. Lett. 78, 4545 (1997).]

^{232}Th [W. Korten *et al*., Phys. Lett. B 317, 19 (1993); A. Martin *et al*., Phys. Rev. C 62, 067302 (2000)].

	^{168}Er			^{166}Er			^{232}Th		
E	0	821	2056	0	786	2028	0	785	1414
K	0	2	4	0	2	4	0	2	4
A	13.17	12.33	11.37	13.43	12.25	10.56	8.23	7.38	7.27

Energies of rotational bands $$A[I(I+1)-K^2]$$

Rotational constants of two-phonon γγ bands from NNLO corrections

- Nonlinear terms in the vibrations only (→ anharmonicities; sufficient parameters)
- Couplings between rotational and vibrational degrees of freedom

Methods: Fukuda's inversion method for perturbative Legendre transformations

Result: rotational constants are linearly in the excited vibrational quanta

$$A_{\text{theo}} = A_{\text{g.s.}} - a_\beta n_0 - a_\gamma (2n_2 + |K|/2)$$

	^{168}Er			^{166}Er			^{232}Th		
E	0	821	2056	0	786	2028	0	785	1414
K	0	2	4	0	2	4	0	2	4
A	13.17	12.33	11.37	13.43	12.25	10.56	8.23	7.38	7.27
A_{theo}	13.17	12.33	11.49	13.43	12.25	11.07	8.23	7.38	6.53

Predictions in good agreement for ^{168}Er, fair agreement for ^{166}Er, and correct trend in ^{232}Th

The theory's account for small variations in the moment of inertia overcomes a smaller but long-standing problem of the IBM and collective models. Origin of success: coupling between kinetic terms of rotor and vibrations.

Electromagnetic transitions in deformed nuclei

Key features of geometric collective model

✓ Rotational bands on top of vibrational band heads
✓ Strong in-band E2 transitions
✓ Weaker inter-band E2 transitions

✗ Inter-band transitions are factors 2-10 too strong [Garrett, J. Phys. G 27 (2001) R1; Rowe & Wood "Fundamentals of Nuclear Models" (2010)]

Isotope	$\frac{y}{x}$	$\frac{E_{2_1}}{2\hbar\omega_\beta}$	$\frac{z}{x}$	$\frac{E_{2_1}}{\hbar\omega_\gamma}$
^{154}Sm	0.005	0.037	0.018	0.057
^{156}Gd	0.003	0.043	0.025	0.078
^{158}Gd	0.002	0.033	0.018	0.066
^{160}Gd		0.028	0.019	0.075
^{158}Dy	0.011	0.039	0.032	0.084
^{160}Dy	0.004	0.034	0.023	0.090
^{162}Dy		0.030	0.023	0.090
^{164}Dy			0.019	0.096
^{162}Er	0.008	0.048	0.032	0.114
^{164}Er	0.001	0.037	0.024	0.105
^{166}Er			0.026	0.102
^{168}Er	0.0003	0.033	0.023	0.096
^{170}Er	0.001	0.045	0.018	0.084
^{168}Yb	0.009	0.039	0.022	0.090
^{170}Yb	0.005	0.040	0.013	0.075
^{172}Yb	0.001	0.038	0.0063	0.054
^{174}Yb		0.026	0.0087	0.048
^{176}Yb			0.0093	0.066
^{174}Hf	0.014	0.057	0.032	0.075
^{176}Hf	0.006	0.039	0.022	0.066
^{178}Hf	0.005	0.039	0.025	0.078
^{180}Hf		0.044	0.025	0.078
^{182}W	0.007	0.044	0.025	0.081
^{184}W	0.002	0.049	0.037	0.111
^{186}W		0.067	0.042	0.165

Collective model confronts data

$x = B(E2, 2^+_{g.s.} \rightarrow 0^+_{g.s.})$

$y = B(E2, 2^+_{0_2^+} \rightarrow 0^+_{g.s.})$

$z = B(E2, 2^+_{\gamma} \rightarrow 0^+_{g.s.})$

- The problem lies with the absolute strengths of inter-band transitions.
- Ratios of inter-band transitions ok
- In-band transitions ok

Rowe & Wood, *Fundamentals of nuclear models*, World Scientific (2010)

Lagrangian expansion in powers of ξ/Ω

Ω

$$L = \frac{1}{2}\dot{\psi}_0^2 + \dot{\psi}_2^2 + \dot{\gamma}^2\psi_2^2 - \frac{\omega_0^2}{2}\psi_0^2 - \frac{\omega_2^2}{4}\psi_2^2$$

ξ

$$+ \frac{C_0}{2}(\dot{\theta}^2 + \dot{\phi}^2\sin^2\theta) + 4\dot{\gamma}\dot{\phi}\psi_2^2\cos\theta$$

Ω(ξ/Ω)$^{3/2}$

$$+ \frac{C_1}{2}(\dot{\theta}^2 + \dot{\phi}^2\sin^2\theta)\psi_0$$

$$+ \frac{C_2}{2}(\dot{\theta}^2 - \dot{\phi}^2\sin^2\theta)\psi_2\cos\gamma + 2C_2\dot{\theta}\dot{\phi}\psi_2\sin\gamma\sin\theta$$

$$+ \frac{C_3}{2}(\dot{\theta}^2 - \dot{\phi}^2\sin^2\theta)\psi_2\sin\gamma - 2C_3\dot{\theta}\dot{\phi}\psi_2\cos\gamma\sin\theta$$

$$+ \dots$$

Gauging yields

$$L_{EM} = L + Q\dot{\psi}_0 A_r + q\dot{\theta}A_\theta + q\dot{\phi}\sin\theta A_\phi$$

Electromagnetic transitions

• Add electromagnetic terms to the Lagrangian

$$L_{EM} = L + Q\dot{\psi}_0 A_r + q\dot{\theta} A_\theta + q\dot{\phi}\sin\theta A_\phi$$

• A Legendre transformation yield the corresponding Hamiltonian

• The interaction Hamiltonian defines the transition operators and transition probabilities

$$B(E2, i \rightarrow f) = \frac{1}{2l_i + 1} |\langle f || H_{EM} || i \rangle|^2$$

Gauged Hamiltonian

$$H_{EM} = H + \frac{Q}{2}(p_0 A_r + A_r p_0)$$
$$- \frac{q}{2C_0}\left[p_\theta A_\theta + A_\theta p_\theta + \left(\frac{p_\phi - 2p_\gamma \cos\theta}{\sin\theta}\right) A_\phi + A_\phi \left(\frac{p_\phi - 2p_\gamma \cos\theta}{\sin\theta}\right)\right]$$

Richer electromagnetic structure than collective models: “Radial” charge, and “angular” charge.

Results for ^{168}Er

Effective theory:

- Gauging of Lagrangian yields EM currents consistent with Hamiltonian
- Power counting also for EM couplings
- Richer structure than geometric model; more parameters in a systematic expansion

B(E2, i→f) in e^2b^2

$i \to f$	$B(E2)^{a}_{exp}$	$B(E2)_{ET}$	Adiabatic Bohr model
$0^+_{g.s.} \to 2^+_{g.s.}$	5.72 (20)	5.92[c]	5.92
$2^+_{g.s.} \to 4^+_{g.s.}$	3.07 (19)	3.04 (30)	
$4^+_{g.s.} \to 6^+_{g.s.}$	3.30 (20)	2.69 (26)	
$6^+_{g.s.} \to 8^+_{g.s.}$	2.57 (15)	2.55 (25)	
$3^+_{\gamma} \to 2\gamma^+$	1.65 (37)	2.11 (21)	
$2^+_{\gamma} \to 4\gamma^+$	1.66 (10)	1.26 (12)	
$4^+_{\gamma} \to 3\gamma^+$	2.78 (71)	1.57 (15)	
$0^+_{g.s.} \to 2^+_{\gamma}$	0.129 (4)	0.143 (14)	0.568
$2^+_{\gamma} \to 2^+_{g.s.}$	0.0442 (38)	0.0410[c]	
$2^+_{\gamma} \to 4^+_{g.s.}$	0.00242 (22)	0.00200 (20)	
$3^+_{\gamma} \to 2^+_{g.s.}$	0.042 (11)	0.051 (5)	
$3^+_{\gamma} \to 4^+_{g.s.}$	0.028 (12)	0.020 (2)	
$4^+_{\gamma} \to 2^+_{g.s.}$	0.0114 (7)	0.0171 (17)	
$4^+_{\gamma} \to 4^+_{g.s.}$	0.0576 (32)	0.0503 (50)	
$4^+_{\gamma} \to 6^+_{g.s.}$	0.0049 (26)	0.0043 (4)	
$6^+_{\gamma} \to 4^+_{g.s.}$	0.00481 (27)	0.0140 (14)	
$6^+_{\gamma} \to 6^+_{g.s.}$	0.0421 (45)	0.0521 (52)	
$6^+_{\gamma} \to 8^+_{g.s.}$	0.0110 (80)	0.0055 (5)	
$2^+_{\beta} \to 0^+_{g.s.}$	0.0022[b]	0.0022[c]	0.0391
$2^+_{\beta} \to 2^+_{g.s.}$	0.0027[b]	0.0031 (3)	
$2^+_{\beta} \to 4^+_{g.s.}$	0.0121[b]	0.0056 (5)	

a Baglin, Nucl. Data Sheets 111, 1807 (2010)
b Lehmann et al., Phys. Rev. C 57, 569 (1998)
c Value employed to adjust low-energy constant

[Toño Coello and TP, in preparation]

Summary

Effective theory for deformed nuclei

- EFT developed for finite system (single out the symmetry-restoring coset modes)
  - rotations are large-amplitude zero-modes
  - vibrational states are quantized Nambu-Goldstone modes
- exploits separation of energy between rotations and vibrations
- essentially reproduces spectra of phenomenological models at NLO
- allows for small variations in rotational constants of band heads
- predictions for rotational constants of multi-phonon γ vibrations in reasonable agreement with data
- electromagnetic coupling via gauging promising: consistent and richer structure than collective models; improved strengths of inter-band transitions