Chirality in atomic nuclei: 2013

Jie Meng 孟 杰

北京大学物理学院

School of Physics, Peking University

Outline

- ☐ Introduction
- ☐ Chirality in atomic nuclei
- ☐ Experimental progress
- ☐ Theoretical progress
- ☐ Summary and perspectives

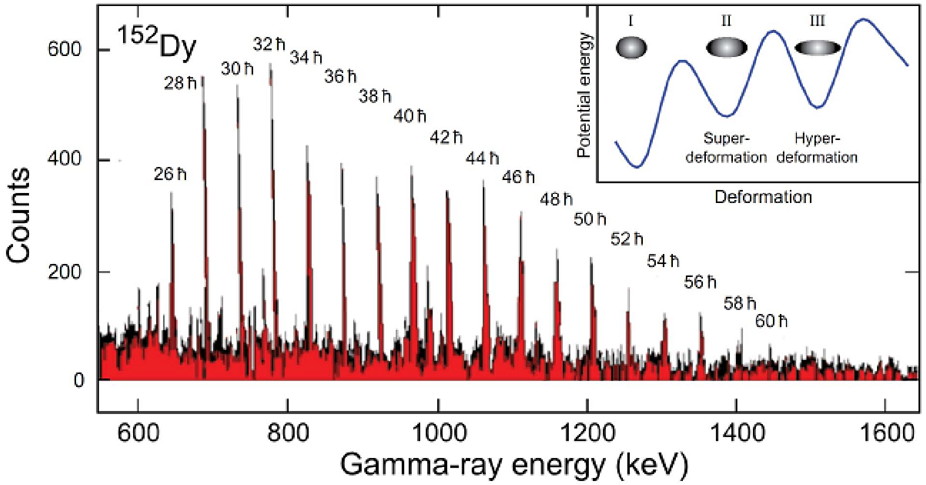
Chiral symmetries exist commonly in nature

- Macroscopic spirals of snail shells and the Human hands...
- In geometry, a figure is chiral if it is not identical to its mirror image, or it cannot be mapped onto its mirror image by rotations and translations alone
- Particle physics, chirality is a dynamic property distinguishing between the parallel and anti-parallel orientations of the intrinsic spin with respect to the momentum of the massless particle.
- Chemistry, the study of chirality is a very active in inorganic, organic, physical, biochemistry and supramolecular chemistry.
- Nobel Prize in Chemistry for 2001: the development of catalytic asymmetric synthesis
- …

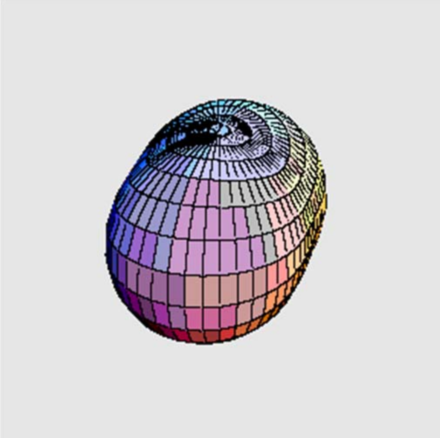
Electric & Magnetic Rotation

ΔI = 2

E2 Transitions

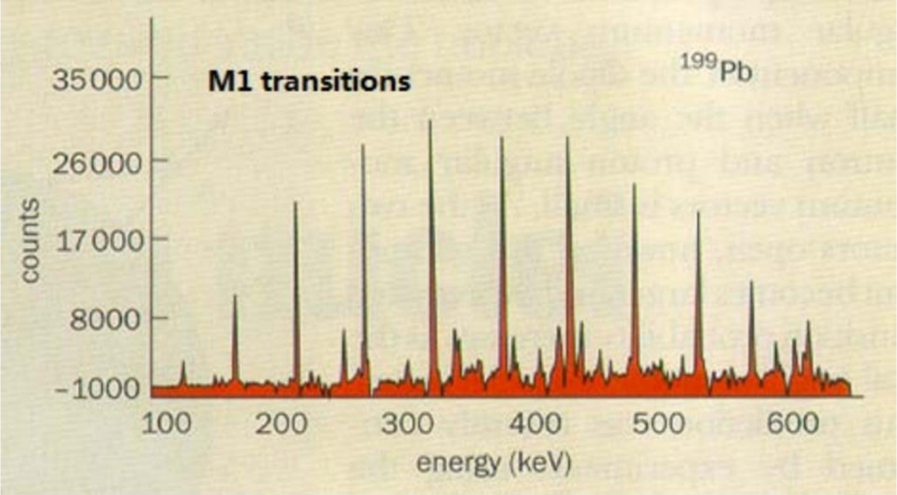


Twin PRL1986

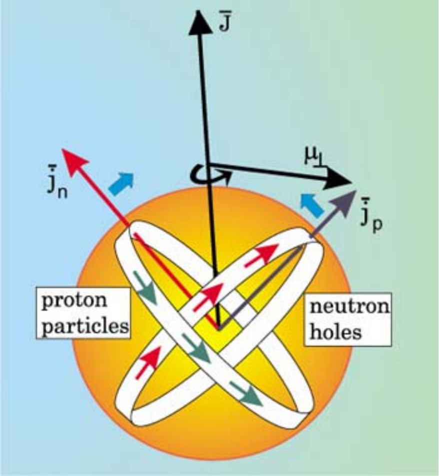


ΔI = 1

M1 Transitions



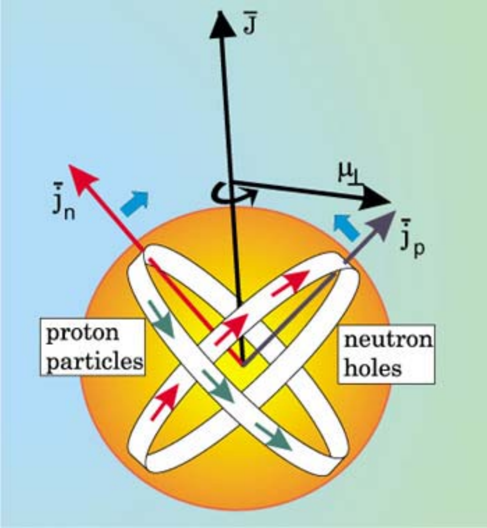
Hübel PPNP2005



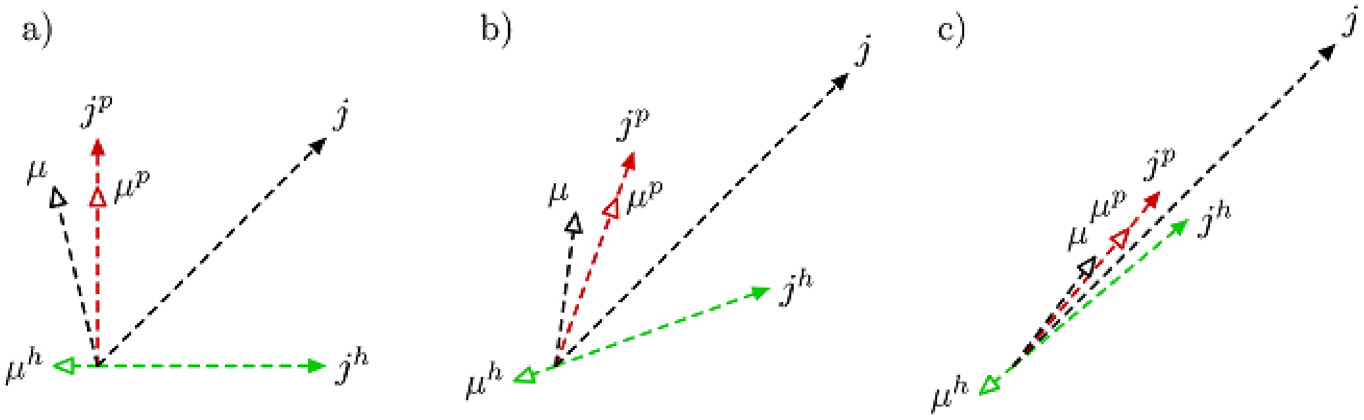
Magnetic rotation

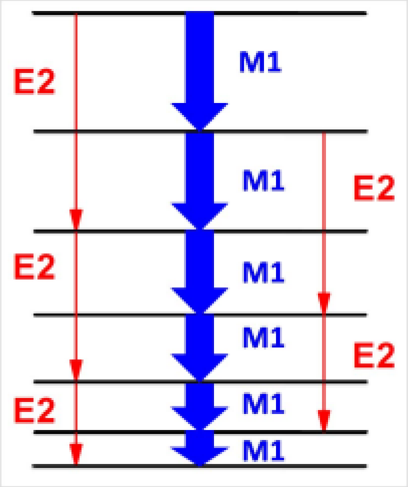
S . Frauendorf, Nuclear Physics A557 (1993) 259c-276c

- ✓ **near spherical or weakly deformed nuclei**
- ✓ **strong M1 and very weak E2 transitions**
- ✓ **rotational bands with ΔI = 1**
- ✓ **shears mechanism**



Frauendorf, Rev. Mod. Phys. 73, 463 (2001).
Frauendorf, Meng, Reif, in Proc. Large γ -Ray Detector Arrays (Berkeley, 1994),



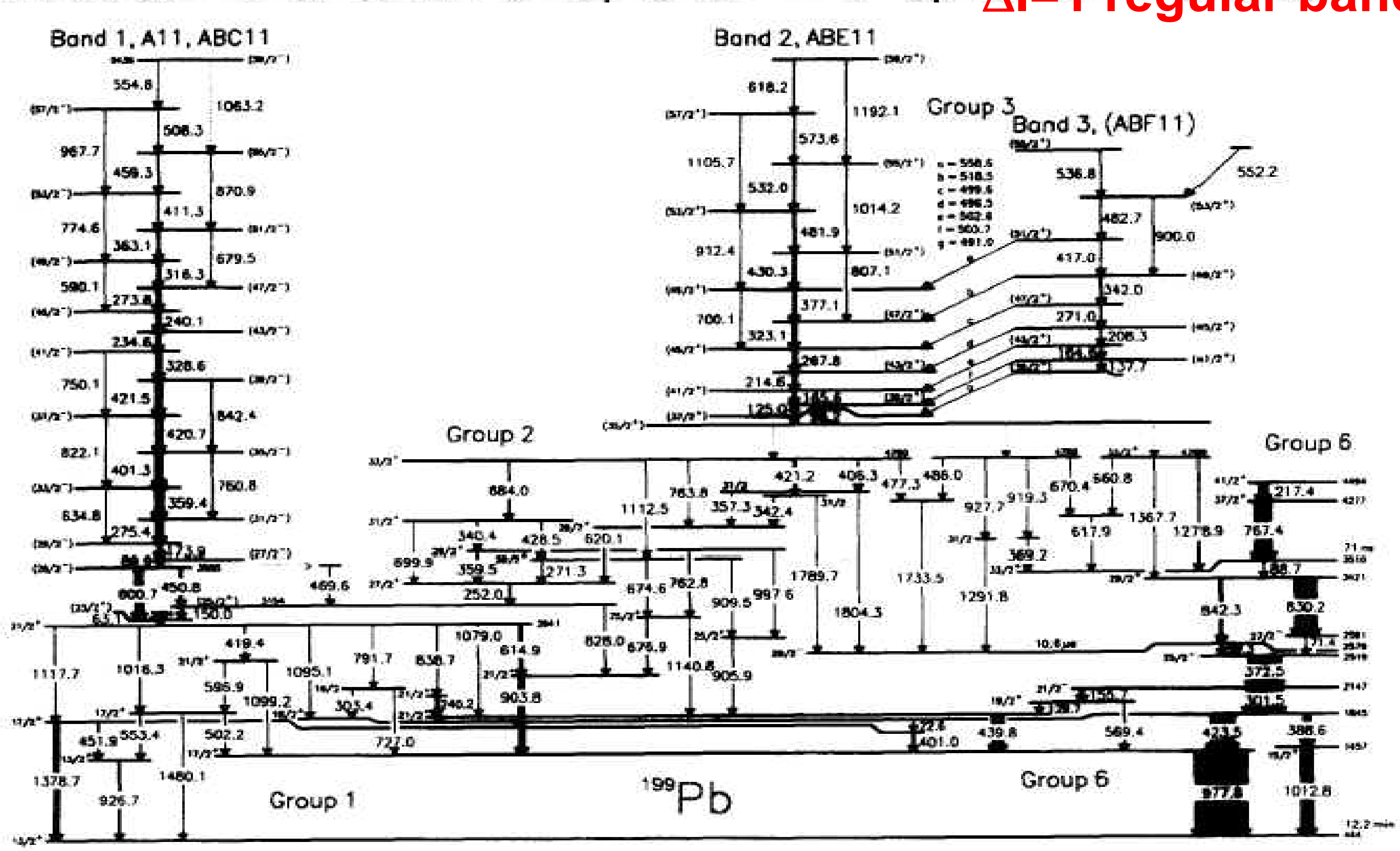


ELSEVIER

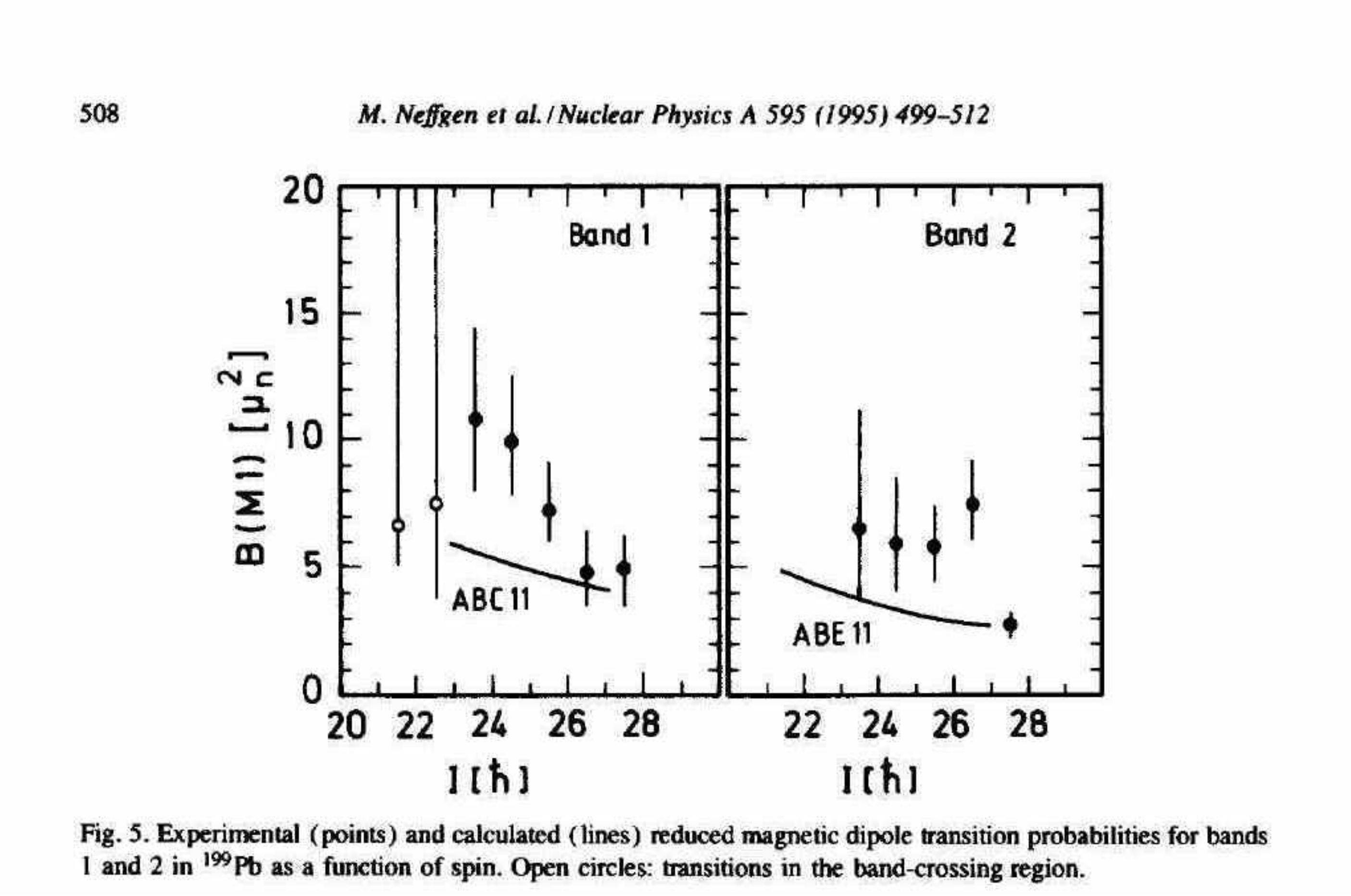
Nuclear Physics A 595 (1995) 499–512

Lifetimes of shears bands in ^{199}Pb

ΔI=1 regular bands



ΔI = 1 Enhanced magnetic dipole transition

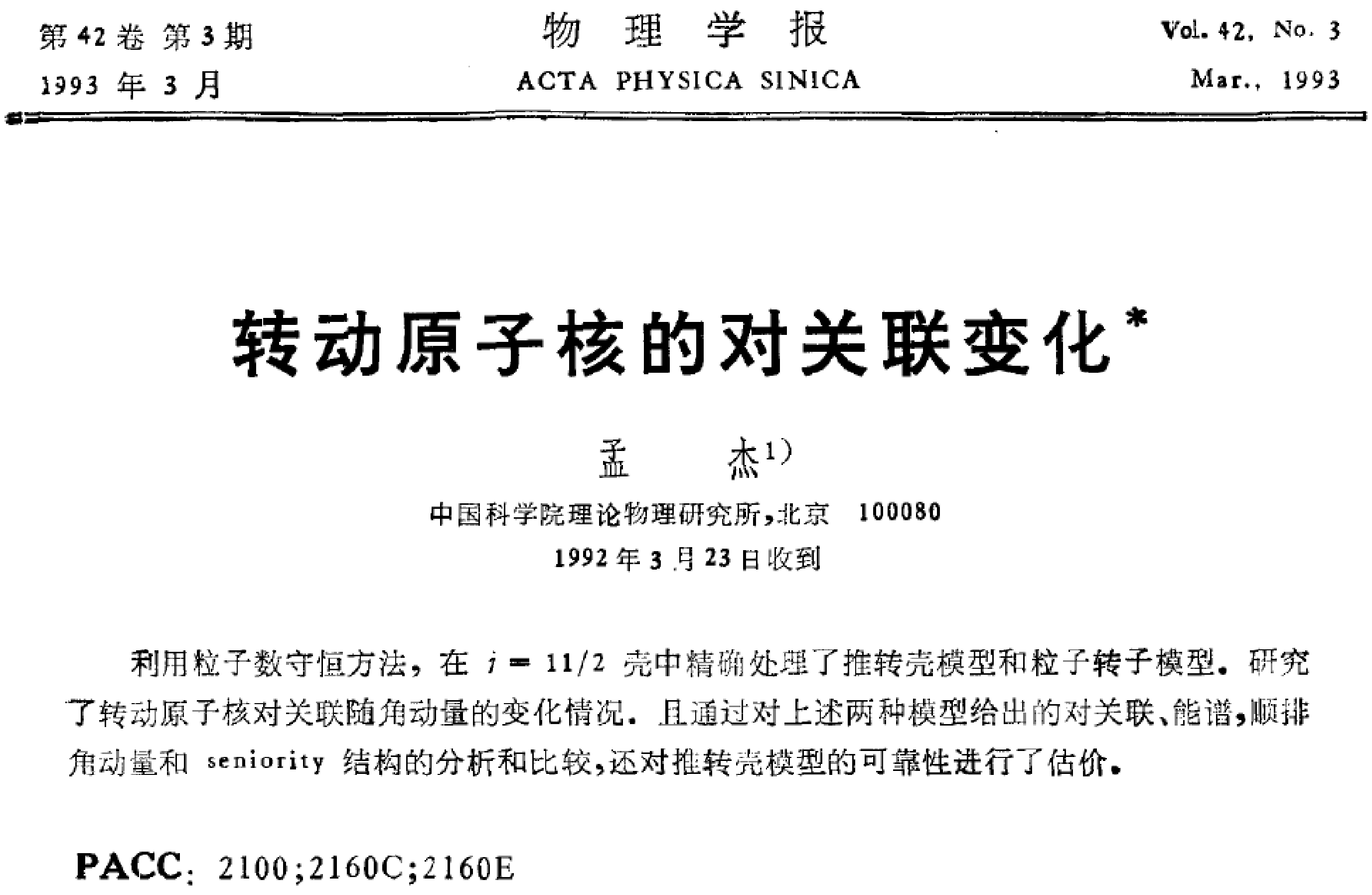


508 M. Neffgen et al. / Nuclear Physics A 595 (1995) 499–512

Fig. 5. Experimental (points) and calculated (lines) reduced magnetic dipole transition probabilities for bands 1 and 2 in ^{199}Pb as a function of spin. Open circles: transitions in the band-crossing region.

How does B(M1) change with spin I ?

Possible problems: mean field approximation / semi-classic approach



第 42 卷 第 3 期
1993 年 3 月

物 理 学 报
ACTA PHYSICA SINICA

Vol. 42, No. 3
Mar., 1993

转动原子核的对关联变化*

孟 杰¹⁾
中国科学院理论物理研究所，北京 100080

1992 年 3 月 23 日收到

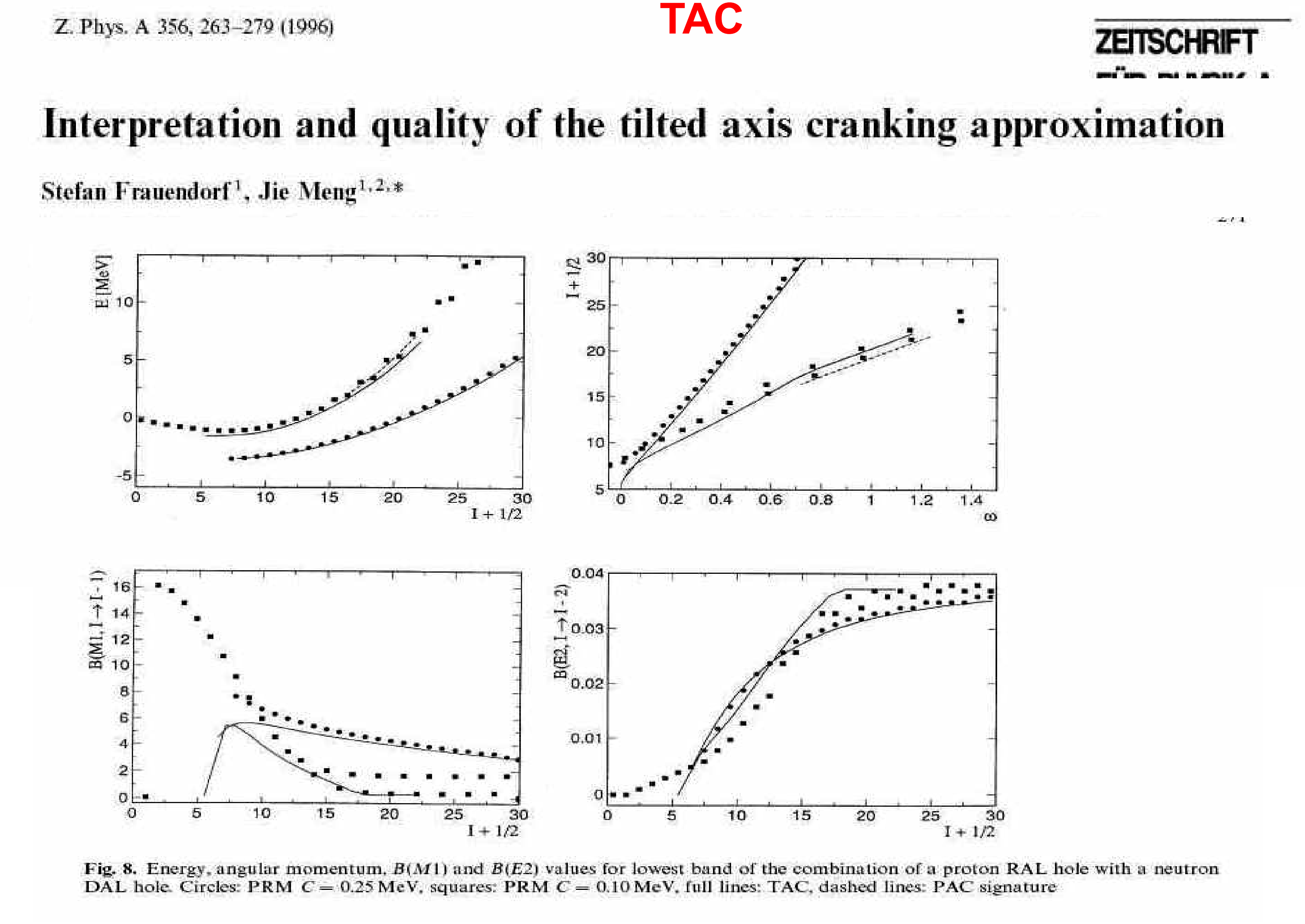
利用粒子数守恒方法，在 $j = 11/2$ 壳中精确处理了推转壳模型和粒子转子模型。研究了转动原子核对关联随角动量的变化情况。且通过对上述两种模型给出的对关联、能谱，顺排角动量和 seniority 结构的分析和比较，还对推转壳模型的可靠性进行了估价。

PACC: 2100;2160C;2160E

Semi-classic cranking model versus quantum Particle-rotor model PAC

Good agreement between TAC and PRM

Semi-classic cranking model versus quantum Particle-rotor model
TAC



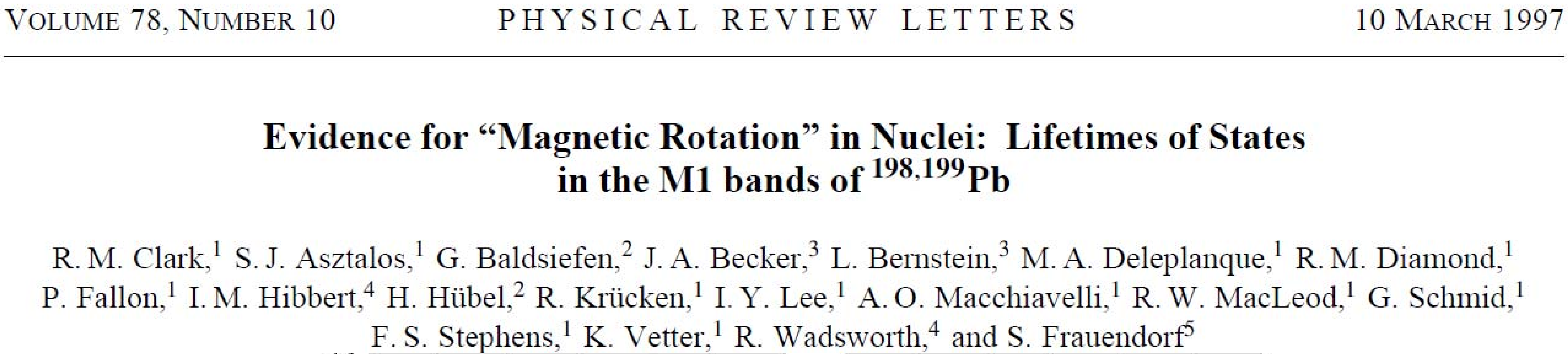
Z. Phys. A 356, 263–279 (1996)

ZEITSCHRIFT

Interpretation and quality of the tilted axis cranking approximation

Stefan Frauendorf[1], Jie Meng[1,2,*]

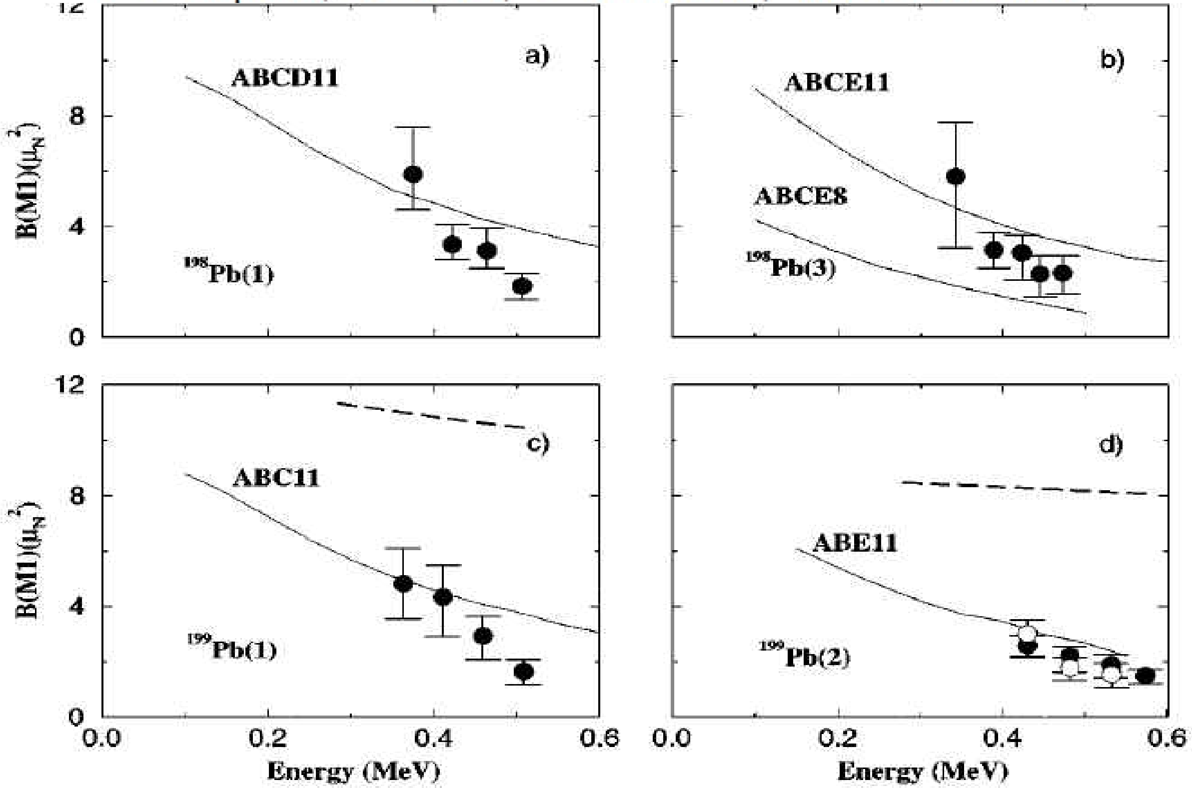
Fig. 8. Energy, angular momentum, $B(M1)$ and $B(E2)$ values for lowest band of the combination of a proton RAL hole with a neutron DAL hole. Circles: PRM $C = 0.25$ MeV, squares: PRM $C = 0.10$ MeV, full lines: TAC, dashed lines: PAC signature



VOLUME 78, NUMBER 10 PHYSICAL REVIEW LETTERS 10 MARCH 1997

Evidence for “Magnetic Rotation” in Nuclei: Lifetimes of States in the M1 bands of ^{198,199}Pb

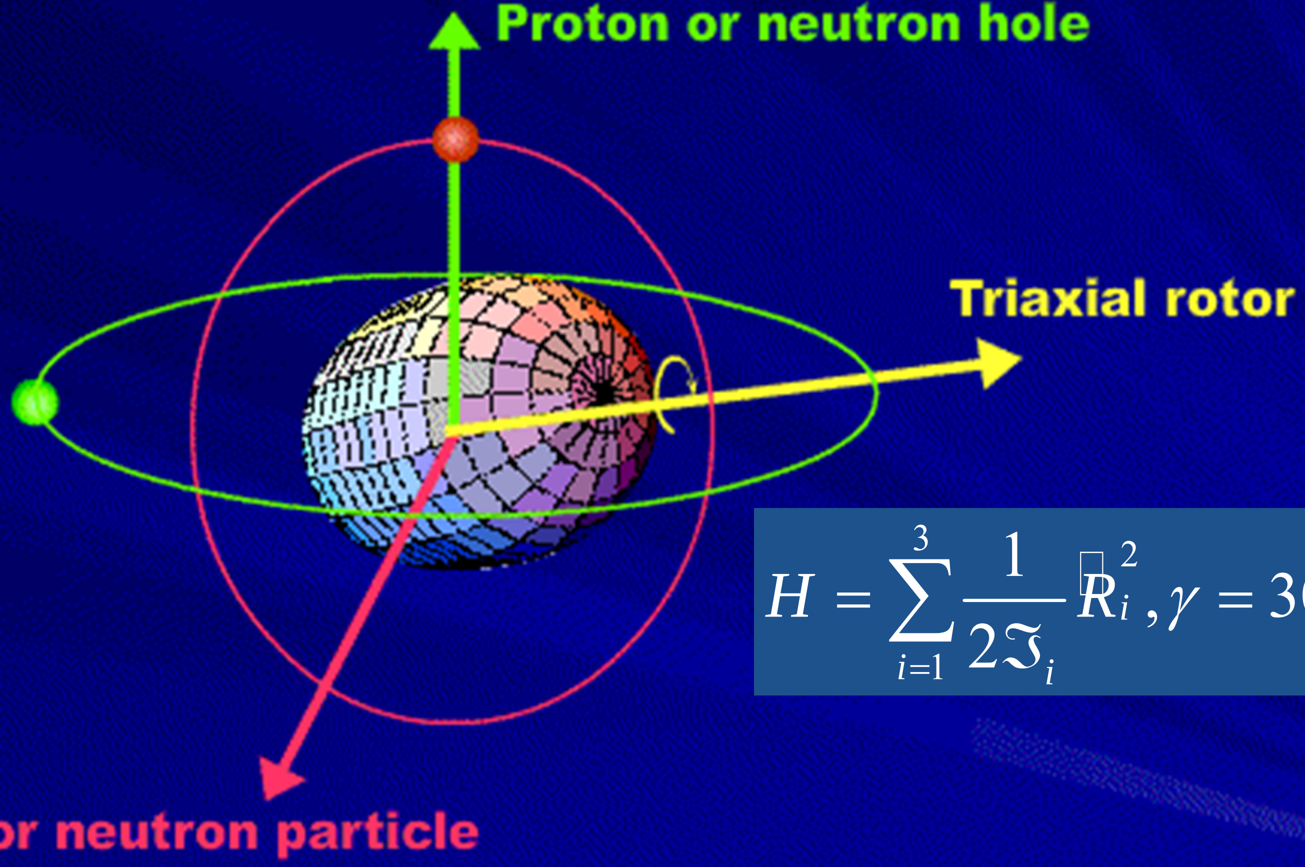
R. M. Clark,[1] S. J. Asztalos,[1] G. Baldsiefen,[2] J. A. Becker,[3] L. Bernstein,[3] M. A. Deleplanque,[1] R. M. Diamond,[1]
P. Fallon,[1] I. M. Hibbert,[4] H. Hübel,[2] R. Krücken,[1] I. Y. Lee,[1] A. O. Macchiavelli,[1] R. W. MacLeod,[1] G. Schmid,[1]
F. S. Stephens,[1] K. Vetter,[1] R. Wadsworth,[4] and S. Frauendorf[5]



Good agreement with prediction for BM1 versus I

Semi-classic cranking model versus quantum Particle-rotor model: Aplanar rotation

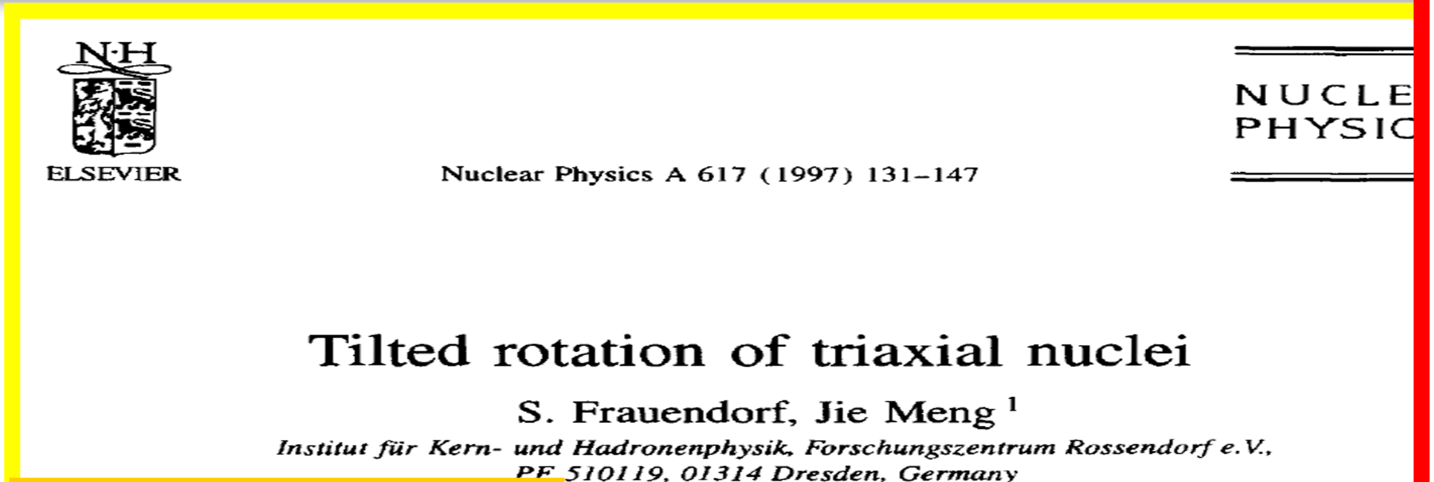
$$H_{sp} = -\frac{1}{2}C\left\{\cos\gamma\left\{j_3^2 - \frac{j(j+1)}{3}\right\} + \frac{\sin\gamma}{2\sqrt{3}}\left(j_+^2 + j_-^2\right)\right\}$$



$$H = \sum_{i=1}^{3}\frac{1}{2\Im_i}R_i^2, \gamma = 30^o$$

$$H_{sp} = \frac{1}{2}C\left\{\cos\gamma\left\{j_3^2 - \frac{j(j+1)}{3}\right\} + \frac{\sin\gamma}{2\sqrt{3}}\left(j_+^2 + j_-^2\right)\right\}$$

Chiral symmetry in atomic



ELSEVIER

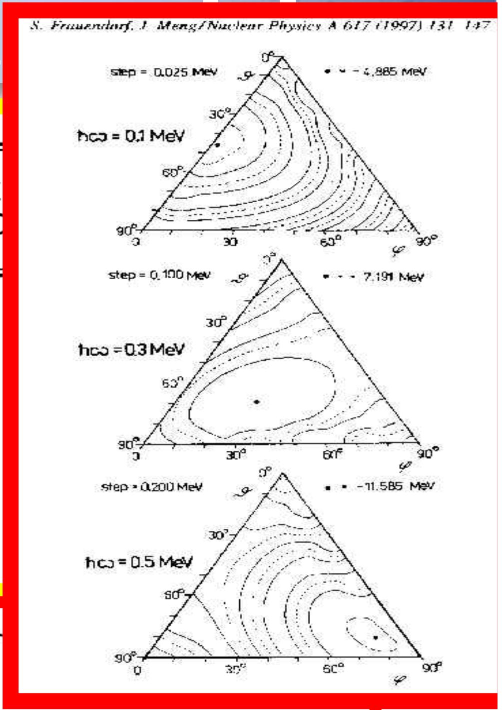
Nuclear Physics A 617 (1997) 131–147

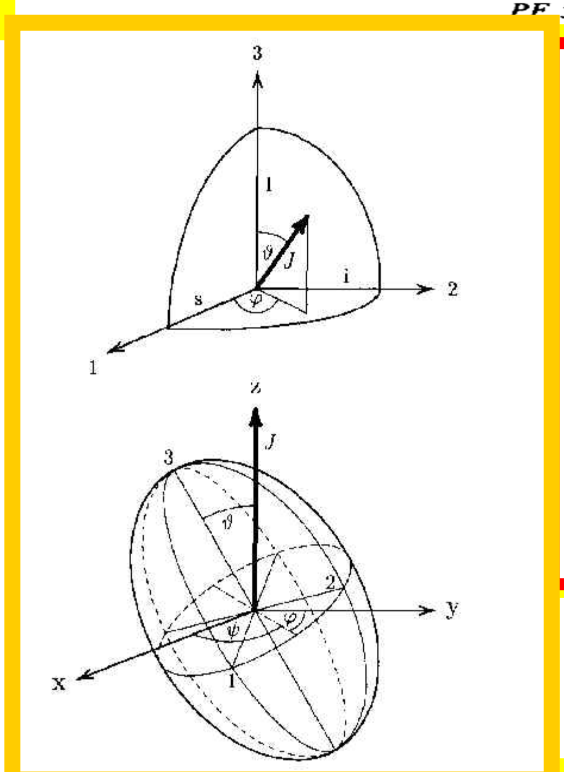
NUCLE
PHYSIC

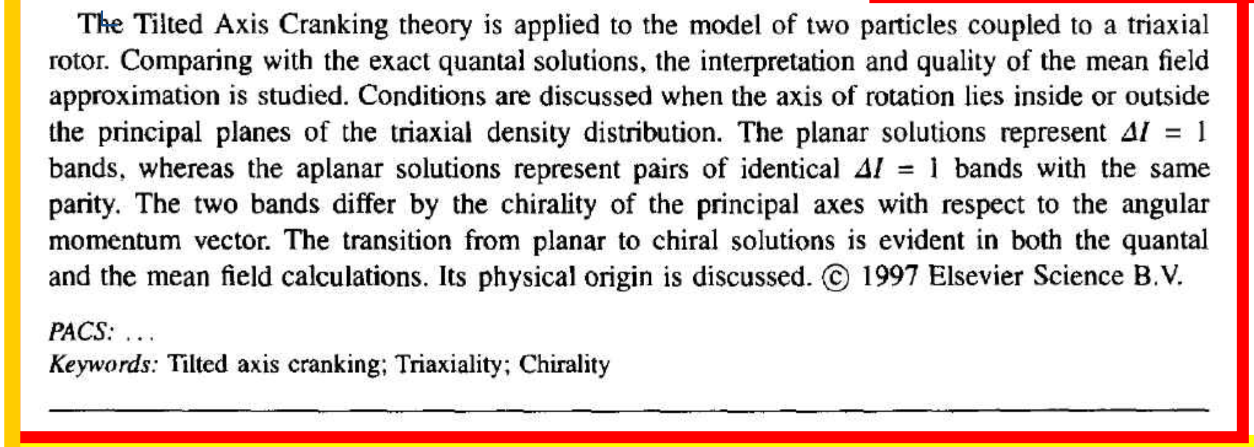
Tilted rotation of triaxial nuclei

S. Frauendorf, Jie Meng[1]

Institut für Kern- und Hadronenphysik, Forschungszentrum Rossendorf e.V., PF 510119, 01314 Dresden, Germany



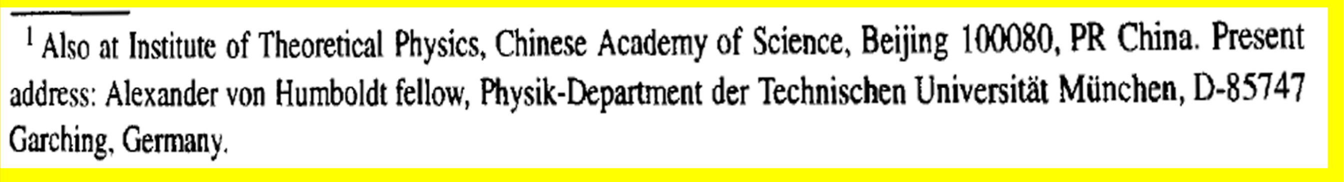




Abstract

The Tilted Axis Cranking theory is applied to the model of two particles coupled to a triaxial rotor. Comparing with the exact quantal solutions, the interpretation and quality of the mean field approximation is studied. Conditions are discussed when the axis of rotation lies inside or outside the principal planes of the triaxial density distribution. The planar solutions represent $\Delta I = 1$ bands, whereas the aplanar solutions represent pairs of identical $\Delta I = 1$ bands with the same parity. The two bands differ by the chirality of the principal axes with respect to the angular momentum vector. The transition from planar to chiral solutions is evident in both the quantal and the mean field calculations. Its physical origin is discussed. © 1997 Elsevier Science B.V.

PACS: . . .
Keywords: Tilted axis cranking; Triaxiality; Chirality

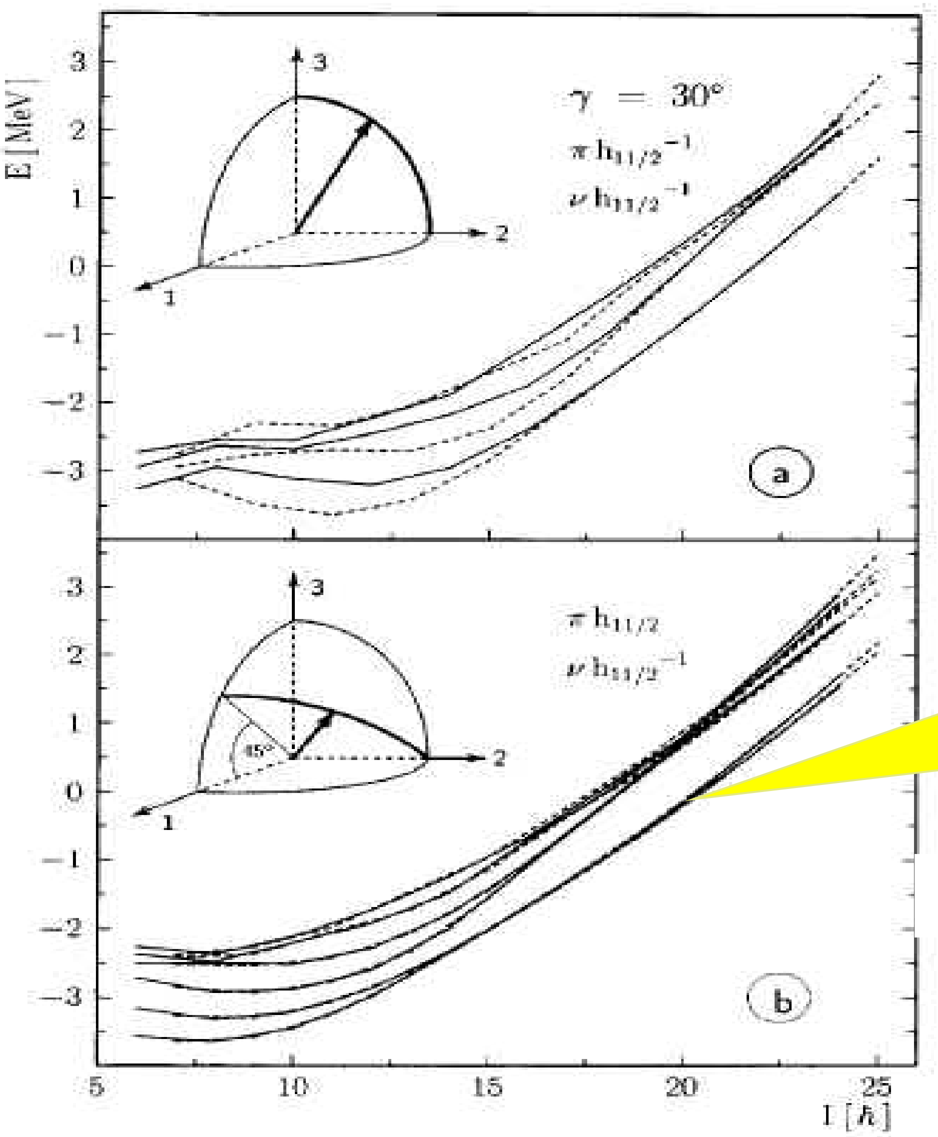


---

[1] Also at Institute of Theoretical Physics, Chinese Academy of Science, Beijing 100080, PR China. Present address: Alexander von Humboldt fellow, Physik-Department der Technischen Universität München, D-85747 Garching, Germany.

Chiral doublets bands: experimental signal

S. Frauendorf, J. Meng/Nuclear Physics A 617 (1997) 131–147



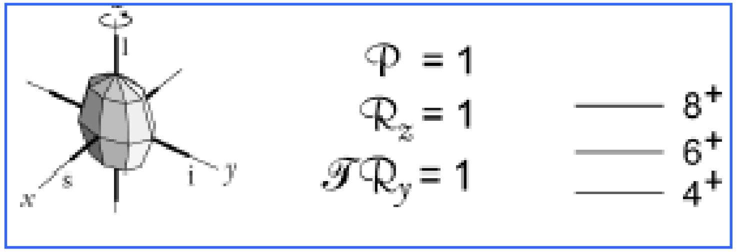
h+h+triaxial rotor=MR

两条简并的磁转动带，由于量子PRM模型导致分裂从而可以从实验上进行观测。

p+h+triaxial rotor=Chiral doublets

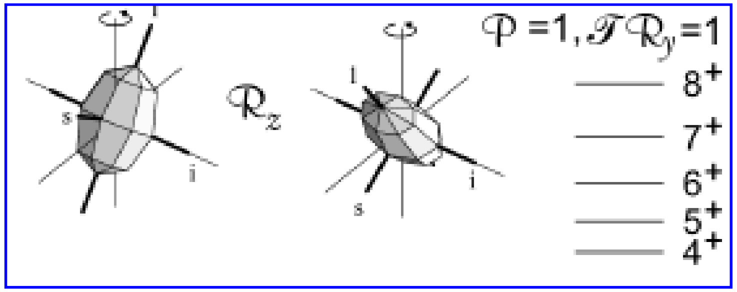
Chiral doublets bands, Why ?

1. J lies along a principal axis

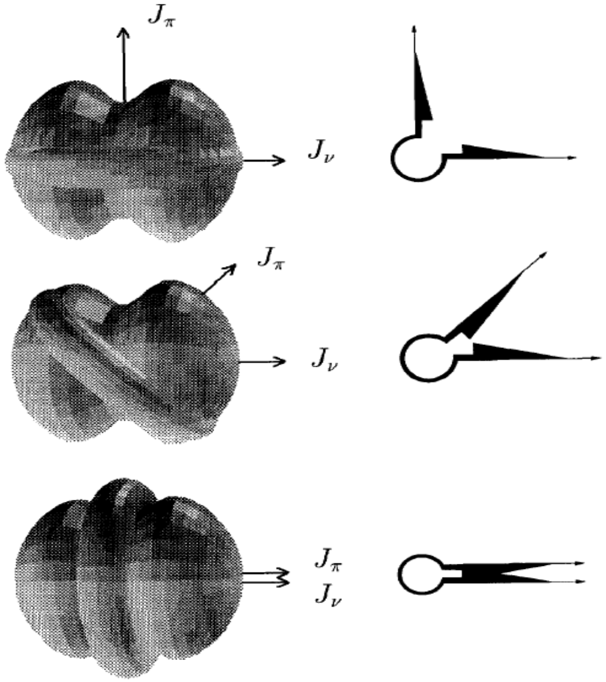


△I=2 rotational bands

2. J lies in a principal plane

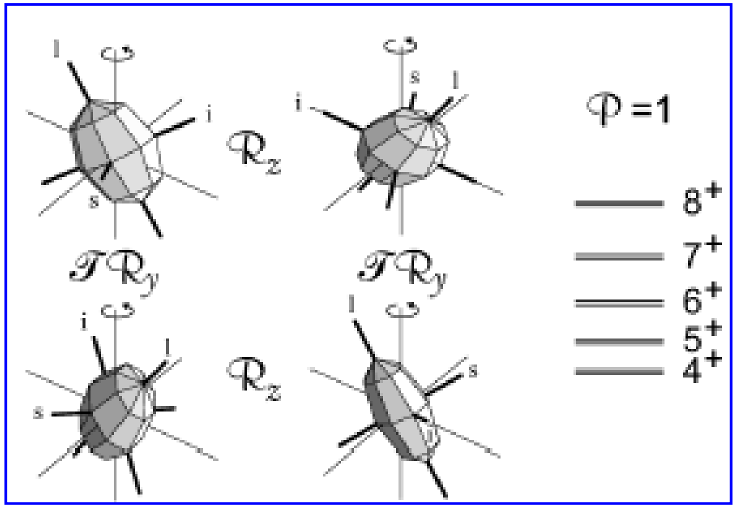


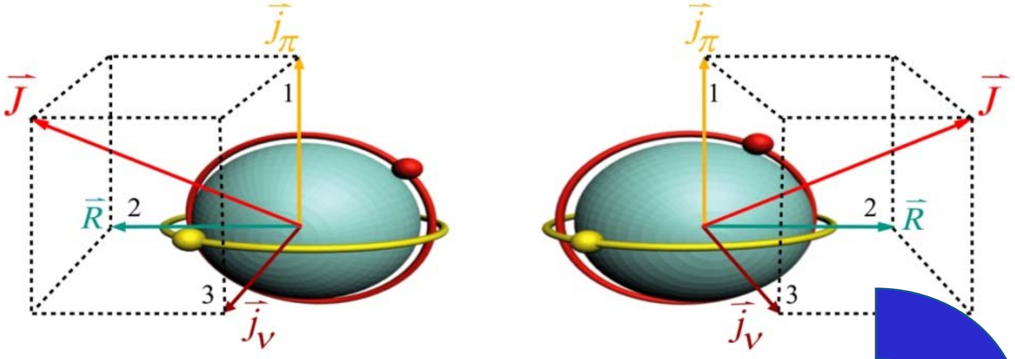
△I= 1 magnetic
rotational bands
Shears bands



Chiral doublets bands, Why ?

3. J does not lie in any of principal plane





Chiral bands
Experimental signature:
Degenerate pairs of △ I=1 bands

$\Xi = T\,Py(\pi)$

Frauendorf, Meng, Nucl. Phys. A 617, 131(1997)

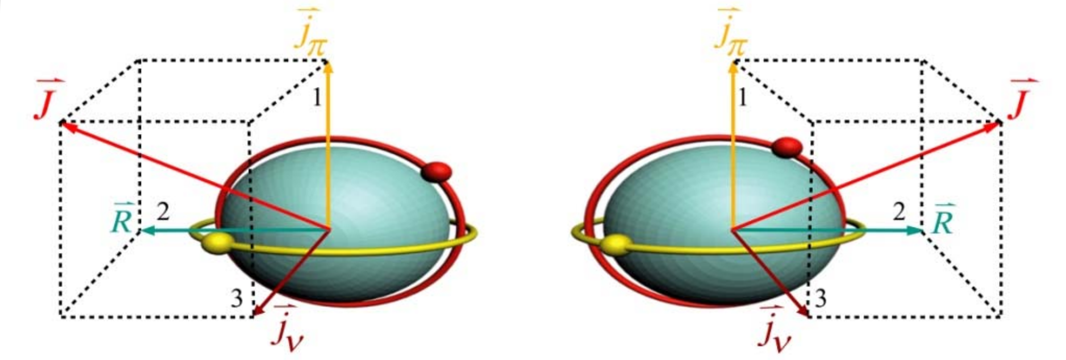
Spontaneous Symmetry Breaking of Chiral symmetry

$$[\chi, H] = 0, \chi = TR_y(\pi)$$

$$H|R\rangle = \varepsilon_R|R\rangle, H|L\rangle = \varepsilon_L|L\rangle$$

$$|R\rangle = \chi|L\rangle, |L\rangle = \chi|R\rangle$$

$$\varepsilon_R = \varepsilon_L$$



Ground State (vacuum) ⇛ Chiral

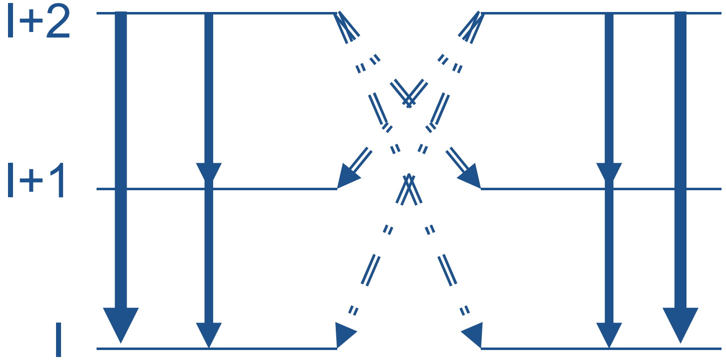
$$|IM+\rangle = \frac{1}{\sqrt{2}}(|R\rangle + |L\rangle)$$

$$|IM-\rangle = \frac{i}{\sqrt{2}}(|R\rangle - |L\rangle)$$

$$H|IM\pm\rangle = \varepsilon_{\pm}^{IM}|IM\pm\rangle$$

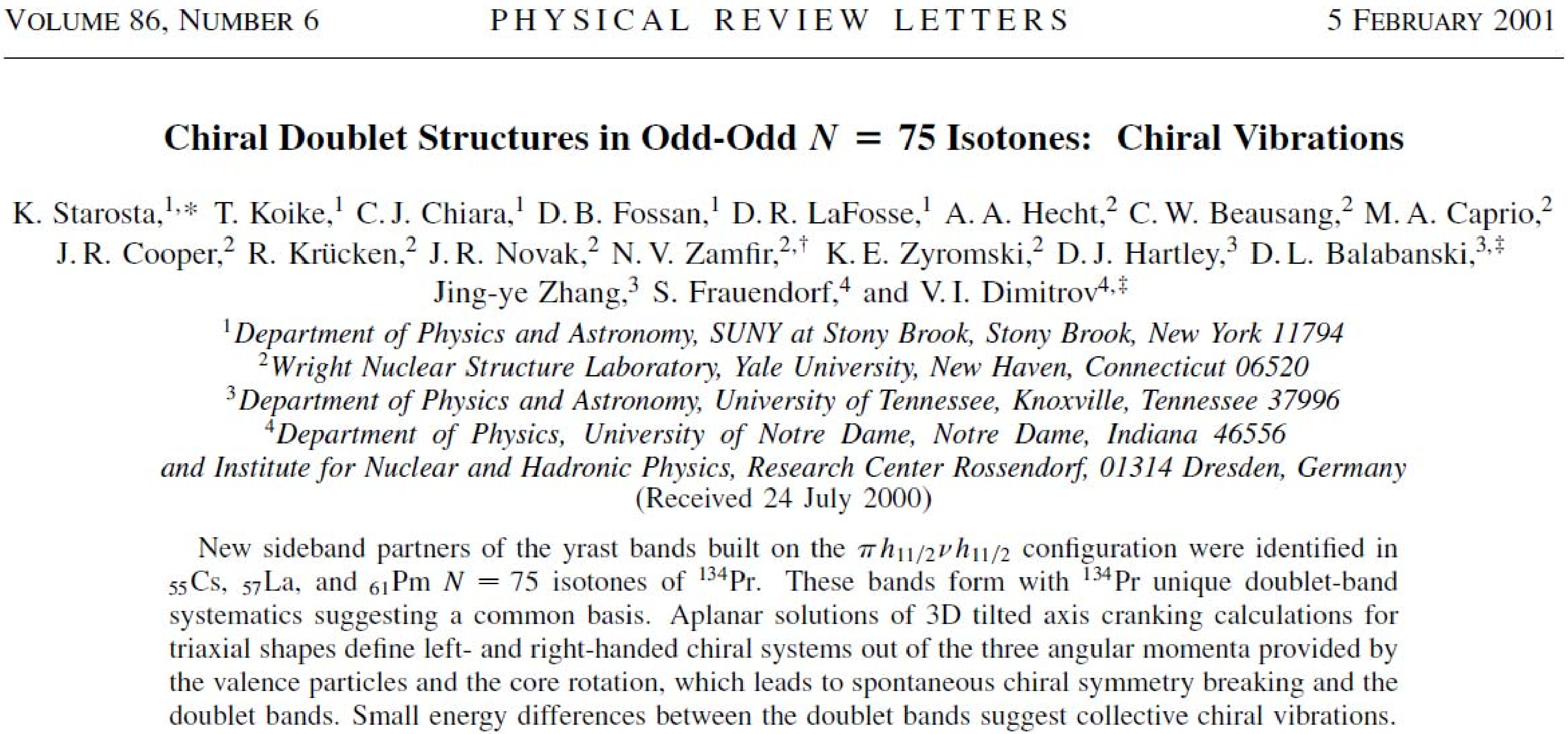
$$\chi|IM\pm\rangle = |IM\pm\rangle$$

$$\varepsilon_{+}^{IM} = \varepsilon_{-}^{IM}.$$



Chiral doublet ⇛ Restoration

First Observations of the Chiral doublets bands



VOLUME 86, NUMBER 6 PHYSICAL REVIEW LETTERS 5 FEBRUARY 2001

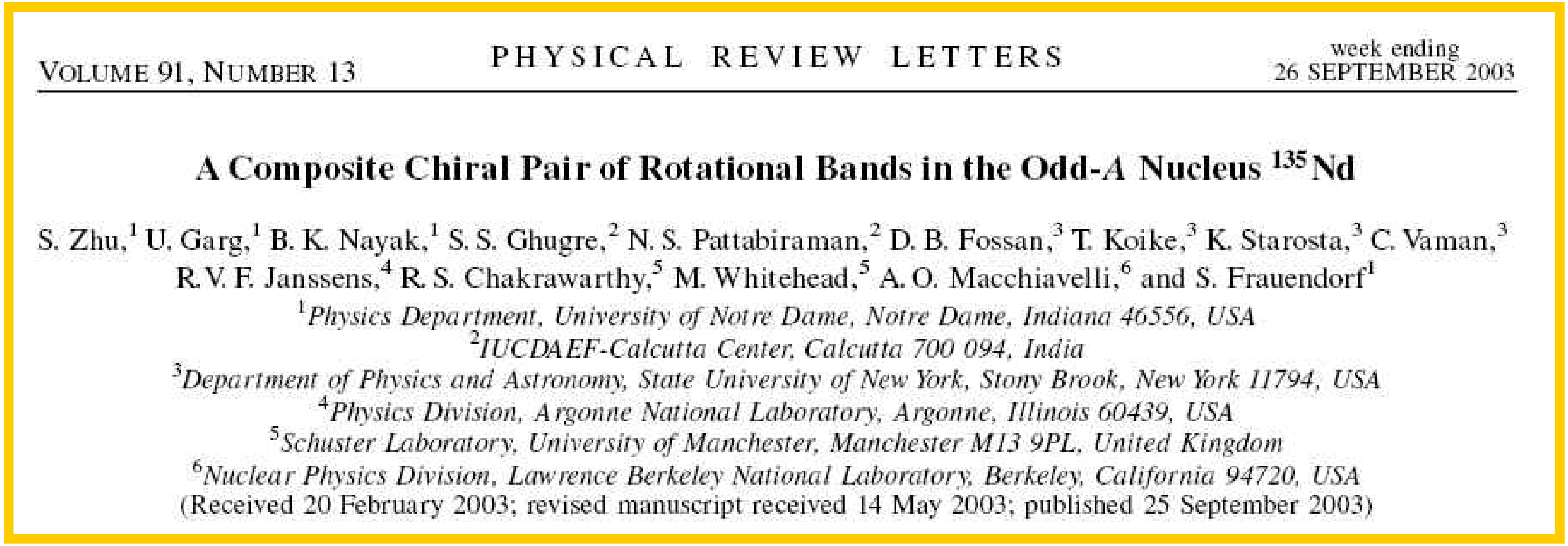
Chiral Doublet Structures in Odd-Odd $N = 75$ Isotones: Chiral Vibrations

K. Starosta,[1,*] T. Koike,[1] C. J. Chiara,[1] D. B. Fossan,[1] D. R. LaFosse,[1] A. A. Hecht,[2] C. W. Beausang,[2] M. A. Caprio,[2]
J. R. Cooper,[2] R. Krücken,[2] J. R. Novak,[2] N. V. Zamfir,[2,†] K. E. Zyromski,[2] D. J. Hartley,[3] D. L. Balabanski,[3,‡]
Jing-ye Zhang,[3] S. Frauendorf,[4] and V. I. Dimitrov[4,‡]
[1]*Department of Physics and Astronomy, SUNY at Stony Brook, Stony Brook, New York 11794*
[2]*Wright Nuclear Structure Laboratory, Yale University, New Haven, Connecticut 06520*
[3]*Department of Physics and Astronomy, University of Tennessee, Knoxville, Tennessee 37996*
[4]*Department of Physics, University of Notre Dame, Notre Dame, Indiana 46556*
and Institute for Nuclear and Hadronic Physics, Research Center Rossendorf, 01314 Dresden, Germany

(Received 24 July 2000)

New sideband partners of the yrast bands built on the $\pi h_{11/2} \nu h_{11/2}$ configuration were identified in $_{55}$Cs, $_{57}$La, and $_{61}$Pm $N = 75$ isotones of ^{134}Pr. These bands form with ^{134}Pr unique doublet-band systematics suggesting a common basis. Aplanar solutions of 3D tilted axis cranking calculations for triaxial shapes define left- and right-handed chiral systems out of the three angular momenta provided by the valence particles and the core rotation, which leads to spontaneous chiral symmetry breaking and the doublet bands. Small energy differences between the doublet bands suggest collective chiral vibrations.

Observations in Odd-A Nucleus



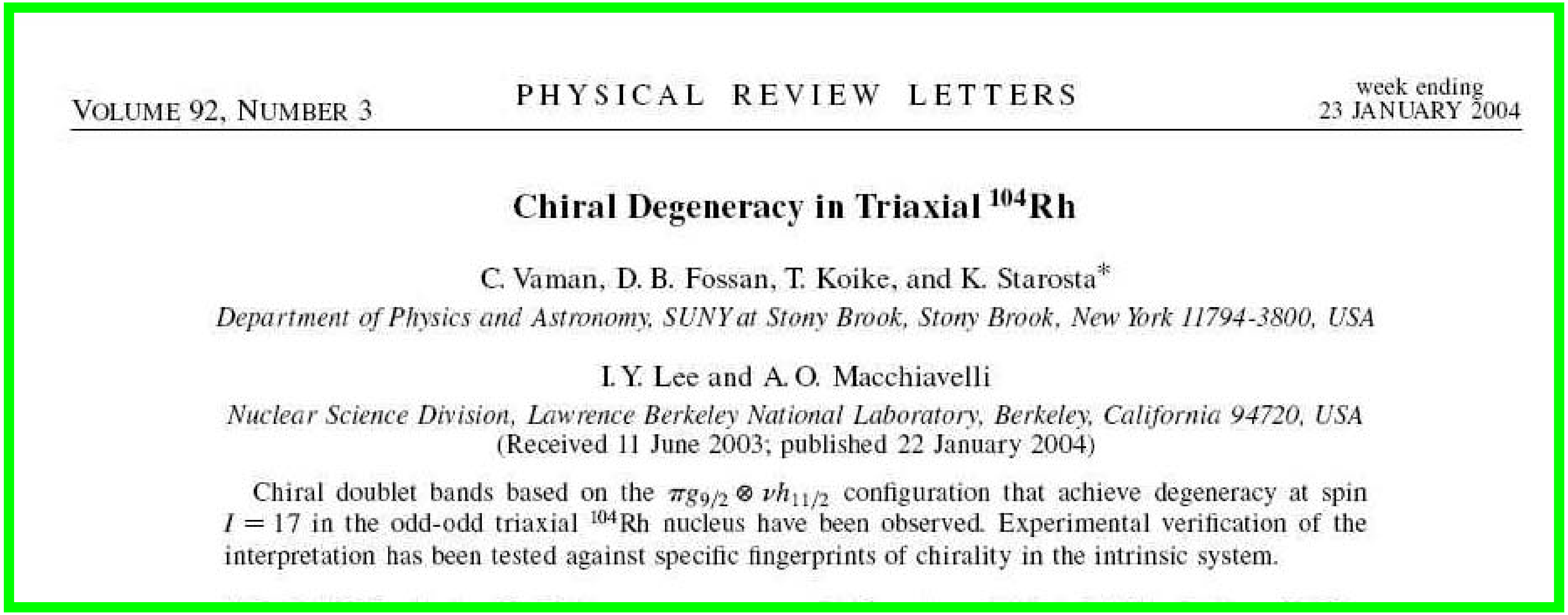
VOLUME 91, NUMBER 13 PHYSICAL REVIEW LETTERS week ending 26 SEPTEMBER 2003

A Composite Chiral Pair of Rotational Bands in the Odd-A Nucleus ^{135}Nd

S. Zhu,[1] U. Garg,[1] B. K. Nayak,[1] S. S. Ghugre,[2] N. S. Pattabiraman,[2] D. B. Fossan,[3] T. Koike,[3] K. Starosta,[3] C. Vaman,[3]
R. V. F. Janssens,[4] R. S. Chakrawarthy,[5] M. Whitehead,[5] A. O. Macchiavelli,[6] and S. Frauendorf[1]
[1]*Physics Department, University of Notre Dame, Notre Dame, Indiana 46556, USA*
[2]*IUCDAEF-Calcutta Center, Calcutta 700 094, India*
[3]*Department of Physics and Astronomy, State University of New York, Stony Brook, New York 11794, USA*
[4]*Physics Division, Argonne National Laboratory, Argonne, Illinois 60439, USA*
[5]*Schuster Laboratory, University of Manchester, Manchester M13 9PL, United Kingdom*
[6]*Nuclear Physics Division, Lawrence Berkeley National Laboratory, Berkeley, California 94720, USA*

(Received 20 February 2003; revised manuscript received 14 May 2003; published 25 September 2003)

Observations in A~100 Nucleus



VOLUME 92, NUMBER 3 PHYSICAL REVIEW LETTERS week ending 23 JANUARY 2004

Chiral Degeneracy in Triaxial ^{104}Rh

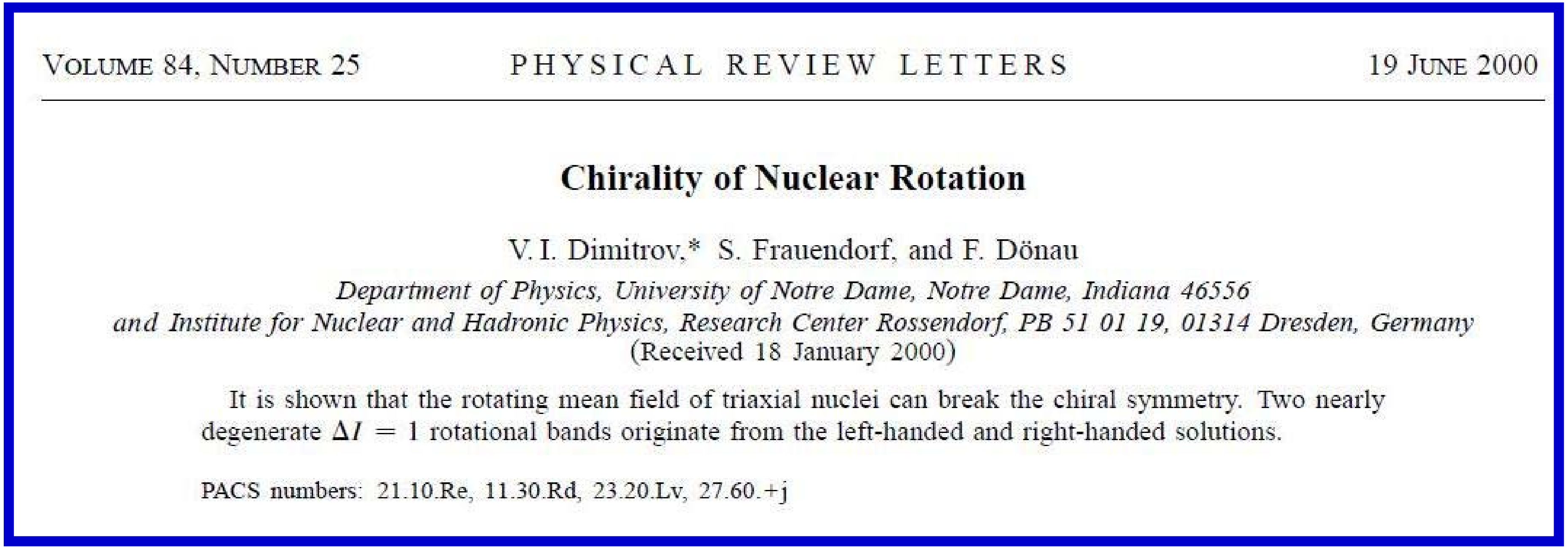
C. Vaman, D. B. Fossan, T. Koike, and K. Starosta*
Department of Physics and Astronomy, SUNY at Stony Brook, Stony Brook, New York 11794-3800, USA

I. Y. Lee and A. O. Macchiavelli
Nuclear Science Division, Lawrence Berkeley National Laboratory, Berkeley, California 94720, USA

(Received 11 June 2003; published 22 January 2004)

Chiral doublet bands based on the $\pi g_{9/2} \otimes \nu h_{11/2}$ configuration that achieve degeneracy at spin $I = 17$ in the odd-odd triaxial ^{104}Rh nucleus have been observed. Experimental verification of the interpretation has been tested against specific fingerprints of chirality in the intrinsic system.

Self- consistent rotating mean field chiral solutions



VOLUME 84, NUMBER 25 PHYSICAL REVIEW LETTERS 19 JUNE 2000

Chirality of Nuclear Rotation

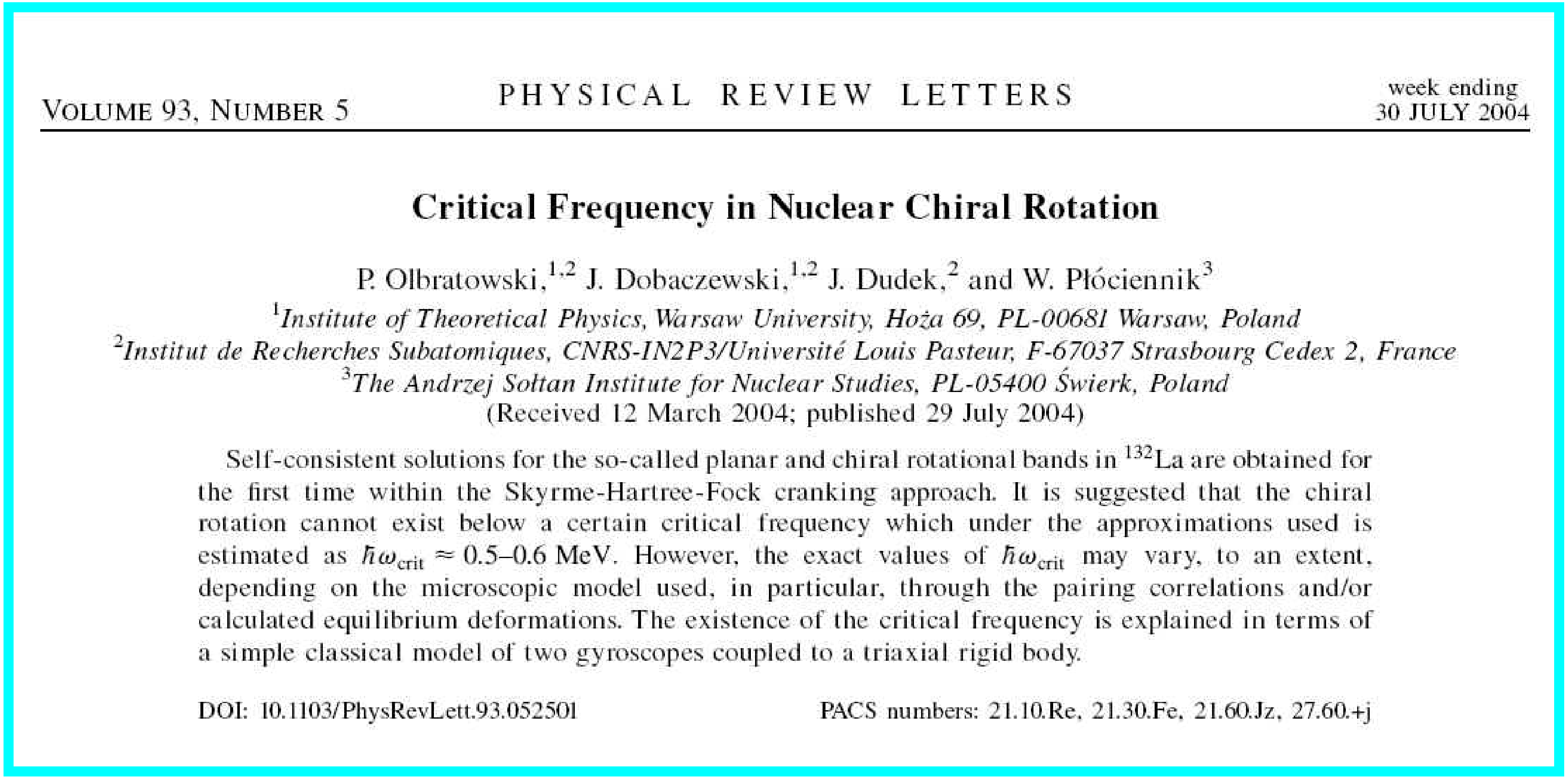
V. I. Dimitrov,* S. Frauendorf, and F. Dönau
Department of Physics, University of Notre Dame, Notre Dame, Indiana 46556
and Institute for Nuclear and Hadronic Physics, Research Center Rossendorf, PB 51 01 19, 01314 Dresden, Germany

(Received 18 January 2000)

It is shown that the rotating mean field of triaxial nuclei can break the chiral symmetry. Two nearly degenerate $\Delta I = 1$ rotational bands originate from the left-handed and right-handed solutions.

PACS numbers: 21.10.Re, 11.30.Rd, 23.20.Lv, 27.60.+j

Critical frequency in Chiral rotations



VOLUME 93, NUMBER 5 PHYSICAL REVIEW LETTERS week ending 30 JULY 2004

Critical Frequency in Nuclear Chiral Rotation

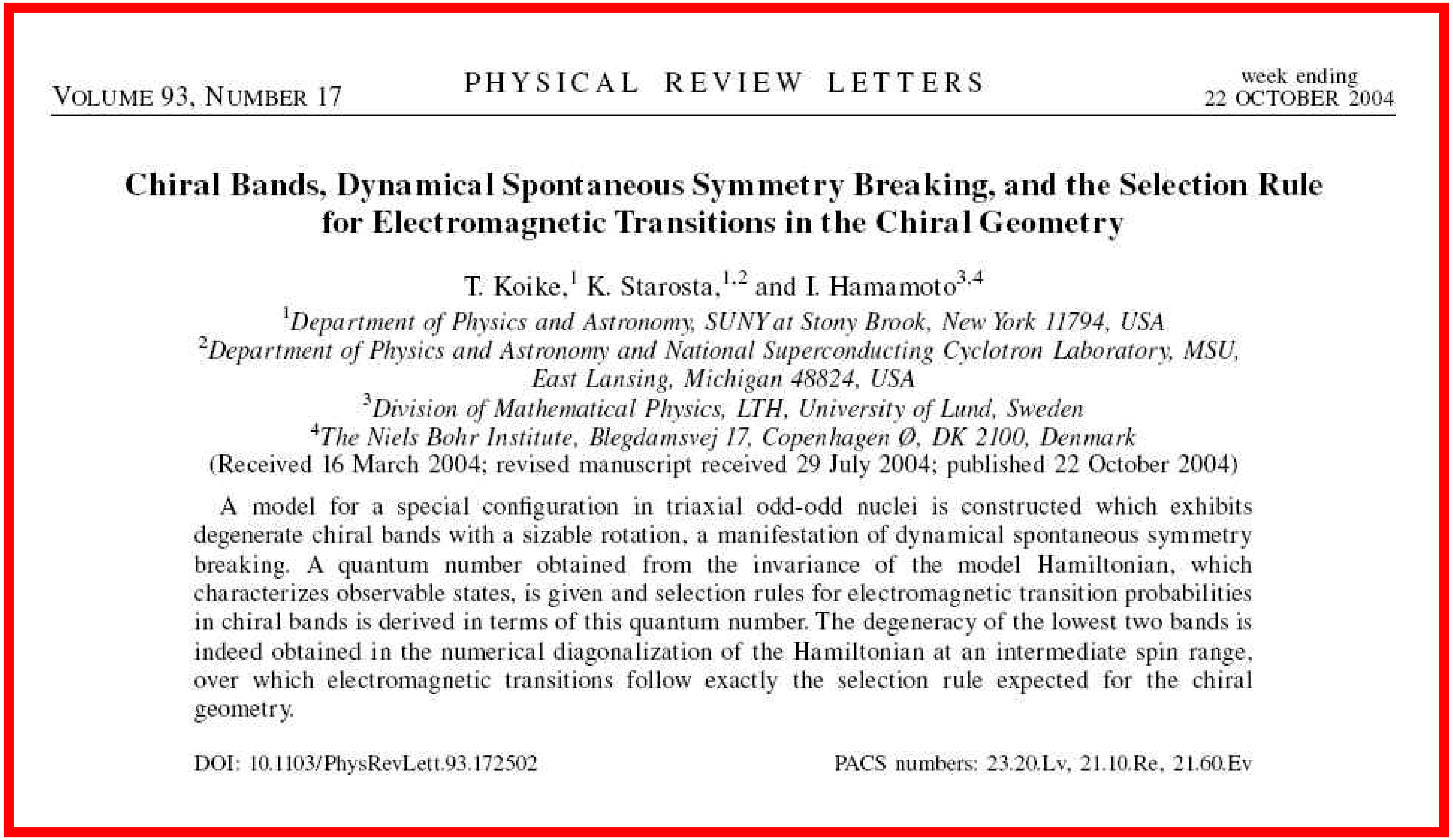
P. Olbratowski,[1,2] J. Dobaczewski,[1,2] J. Dudek,[2] and W. Płóciennik[3]
[1] *Institute of Theoretical Physics, Warsaw University, Hoża 69, PL-00681 Warsaw, Poland*
[2] *Institut de Recherches Subatomiques, CNRS-IN2P3/Université Louis Pasteur, F-67037 Strasbourg Cedex 2, France*
[3] *The Andrzej Sołtan Institute for Nuclear Studies, PL-05400 Świerk, Poland*

(Received 12 March 2004; published 29 July 2004)

Self-consistent solutions for the so-called planar and chiral rotational bands in ^{132}La are obtained for the first time within the Skyrme-Hartree-Fock cranking approach. It is suggested that the chiral rotation cannot exist below a certain critical frequency which under the approximations used is estimated as $\hbar\omega_{\mathrm{crit}} \approx 0.5$–$0.6$ MeV. However, the exact values of $\hbar\omega_{\mathrm{crit}}$ may vary, to an extent, depending on the microscopic model used, in particular, through the pairing correlations and/or calculated equilibrium deformations. The existence of the critical frequency is explained in terms of a simple classical model of two gyroscopes coupled to a triaxial rigid body.

DOI: 10.1103/PhysRevLett.93.052501 PACS numbers: 21.10.Re, 21.30.Fe, 21.60.Jz, 27.60.+j

Selection rule of EM transitions in Chiral rotations



VOLUME 93, NUMBER 17 PHYSICAL REVIEW LETTERS week ending 22 OCTOBER 2004

Chiral Bands, Dynamical Spontaneous Symmetry Breaking, and the Selection Rule for Electromagnetic Transitions in the Chiral Geometry

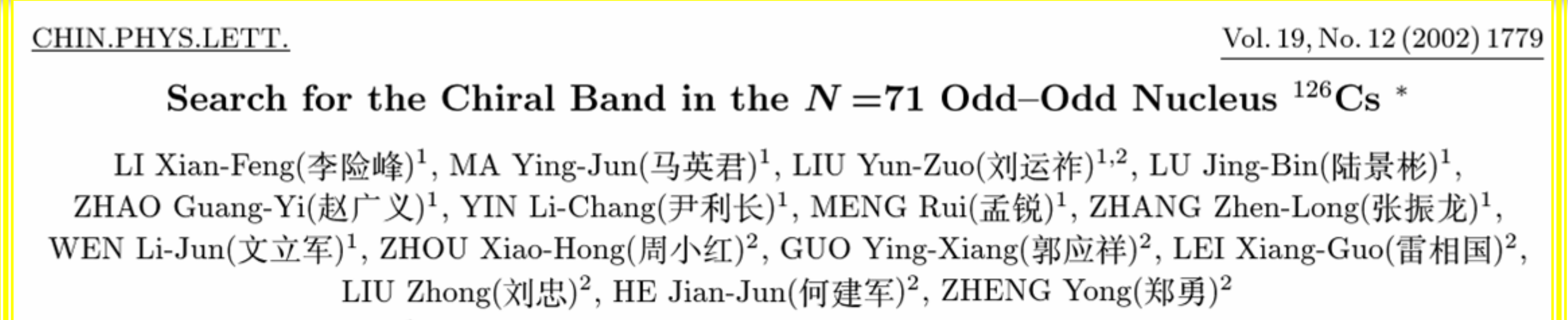
T. Koike,[1] K. Starosta,[1,2] and I. Hamamoto[3,4]
[1]*Department of Physics and Astronomy, SUNY at Stony Brook, New York 11794, USA*
[2]*Department of Physics and Astronomy and National Superconducting Cyclotron Laboratory, MSU, East Lansing, Michigan 48824, USA*
[3]*Division of Mathematical Physics, LTH, University of Lund, Sweden*
[4]*The Niels Bohr Institute, Blegdamsvej 17, Copenhagen Ø, DK 2100, Denmark*

(Received 16 March 2004; revised manuscript received 29 July 2004; published 22 October 2004)

A model for a special configuration in triaxial odd-odd nuclei is constructed which exhibits degenerate chiral bands with a sizable rotation, a manifestation of dynamical spontaneous symmetry breaking. A quantum number obtained from the invariance of the model Hamiltonian, which characterizes observable states, is given and selection rules for electromagnetic transition probabilities in chiral bands is derived in terms of this quantum number. The degeneracy of the lowest two bands is indeed obtained in the numerical diagonalization of the Hamiltonian at an intermediate spin range, over which electromagnetic transitions follow exactly the selection rule expected for the chiral geometry.

DOI: 10.1103/PhysRevLett.93.172502 PACS numbers: 23.20.Lv, 21.10.Re, 21.60.Ev

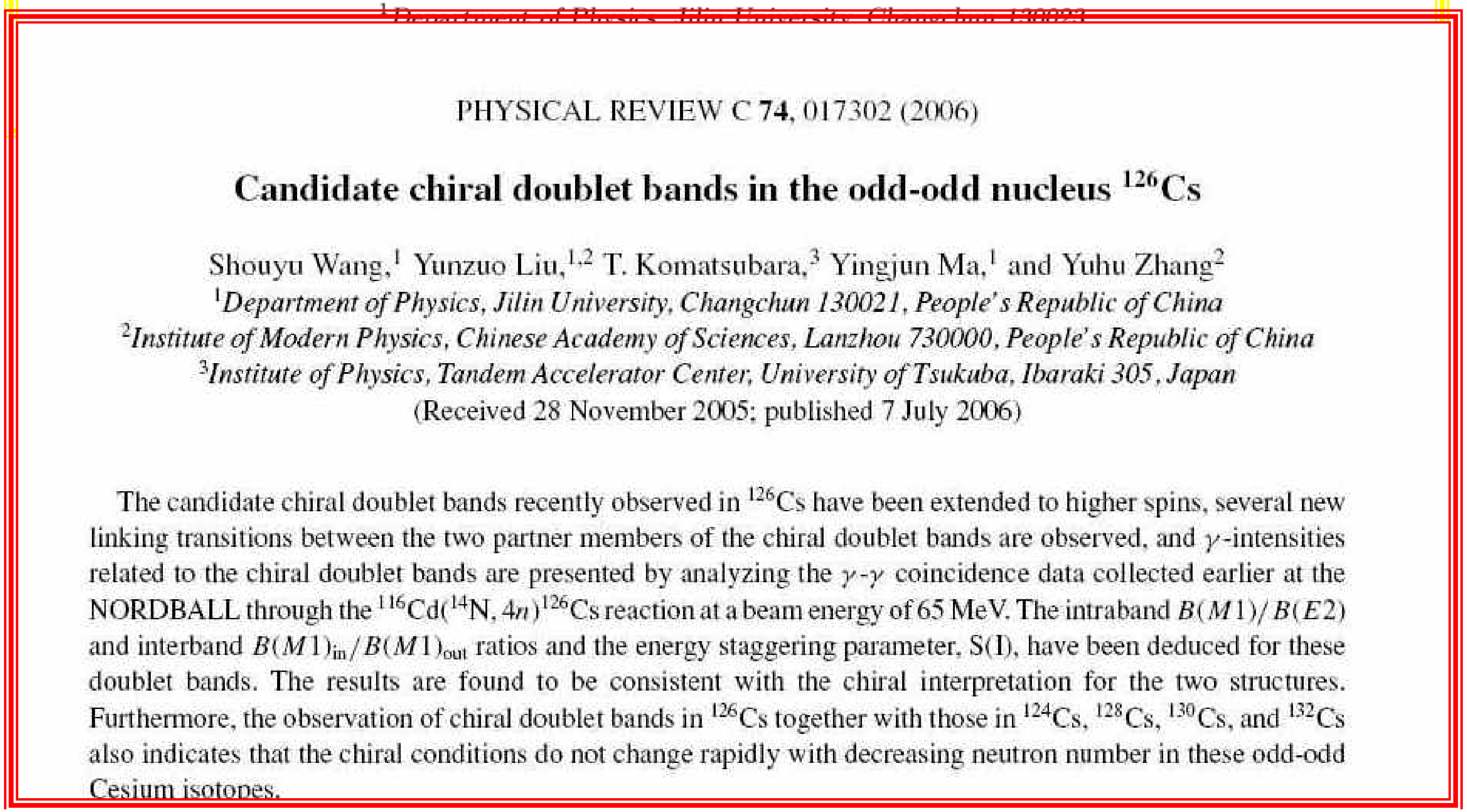
Observations of the Chiral doublets bands in China



CHIN.PHYS.LETT. Vol. 19, No. 12 (2002) 1779

Search for the Chiral Band in the $N = 71$ Odd–Odd Nucleus ^{126}Cs *

LI Xian-Feng(李险峰)[1], MA Ying-Jun(马英君)[1], LIU Yun-Zuo(刘运祚)[1,2], LU Jing-Bin(陆景彬)[1],
ZHAO Guang-Yi(赵广义)[1], YIN Li-Chang(尹利长)[1], MENG Rui(孟锐)[1], ZHANG Zhen-Long(张振龙)[1],
WEN Li-Jun(文立军)[1], ZHOU Xiao-Hong(周小红)[2], GUO Ying-Xiang(郭应祥)[2], LEI Xiang-Guo(雷相国)[2],
LIU Zhong(刘忠)[2], HE Jian-Jun(何建军)[2], ZHENG Yong(郑勇)[2]



PHYSICAL REVIEW C **74**, 017302 (2006)

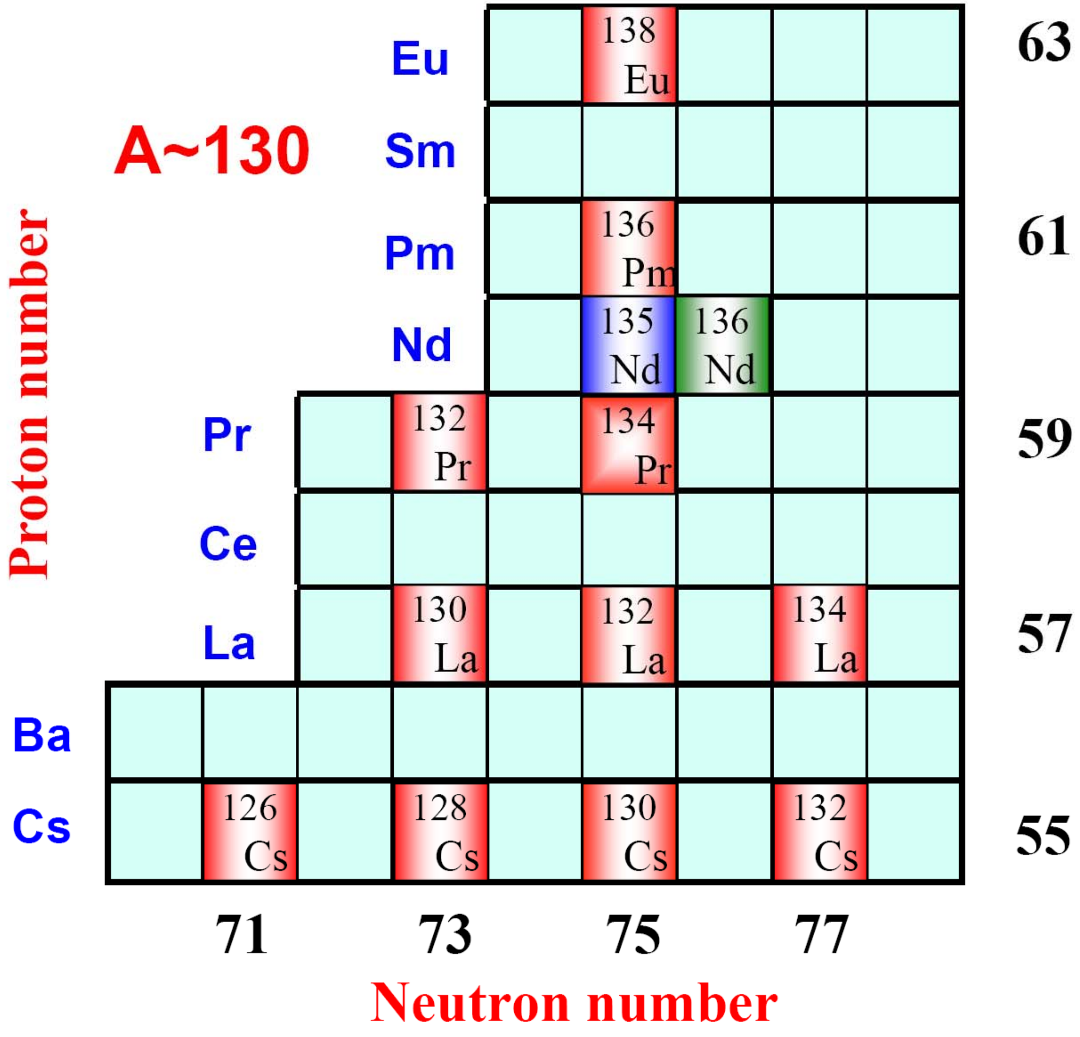
Candidate chiral doublet bands in the odd-odd nucleus ^{126}Cs

Shouyu Wang,[1] Yunzuo Liu,[1,2] T. Komatsubara,[3] Yingjun Ma,[1] and Yuhu Zhang[2]
[1]*Department of Physics, Jilin University, Changchun 130021, People's Republic of China*
[2]*Institute of Modern Physics, Chinese Academy of Sciences, Lanzhou 730000, People's Republic of China*
[3]*Institute of Physics, Tandem Accelerator Center, University of Tsukuba, Ibaraki 305, Japan*

(Received 28 November 2005; published 7 July 2006)

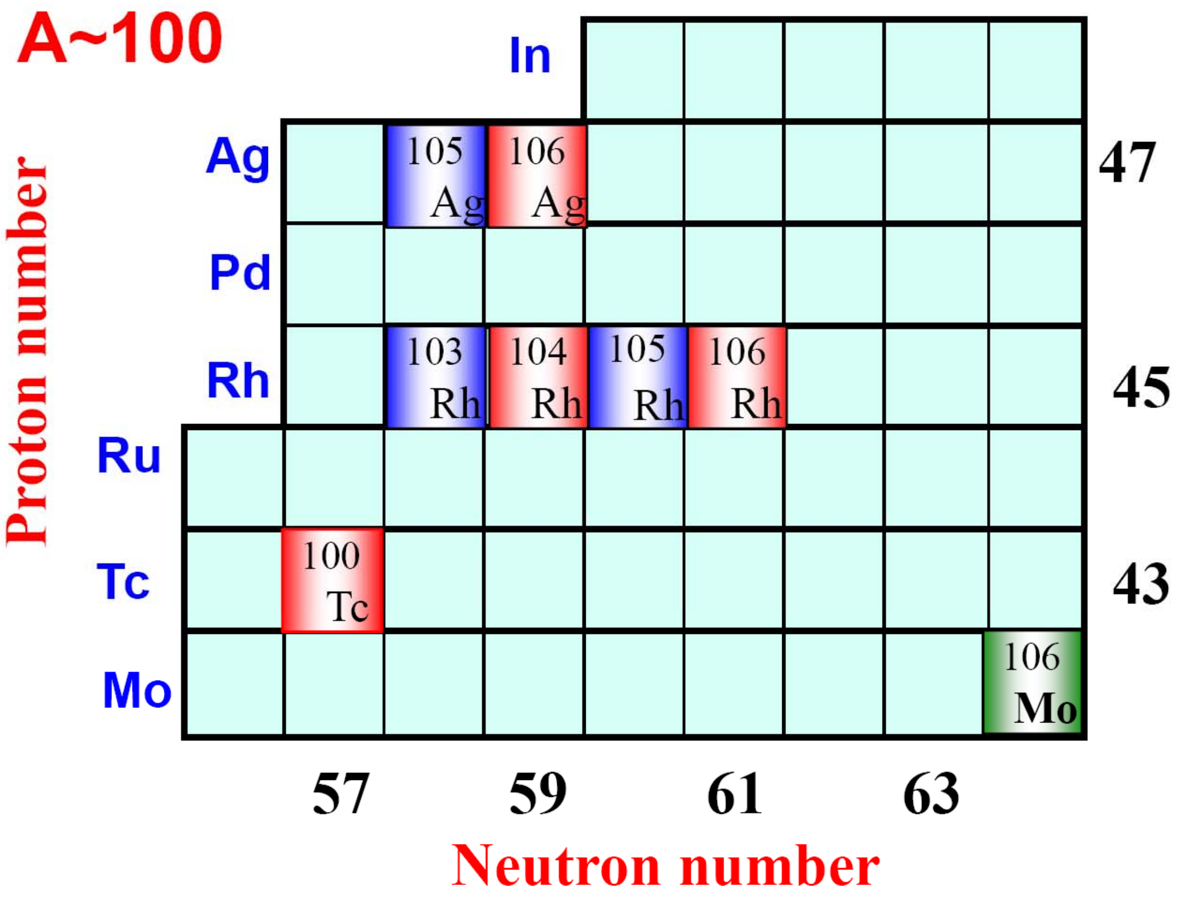
The candidate chiral doublet bands recently observed in ^{126}Cs have been extended to higher spins, several new linking transitions between the two partner members of the chiral doublet bands are observed, and γ-intensities related to the chiral doublet bands are presented by analyzing the γ-γ coincidence data collected earlier at the NORDBALL through the ^{116}Cd(^{14}N, $4n$)^{126}Cs reaction at a beam energy of 65 MeV. The intraband $B(M1)/B(E2)$ and interband $B(M1)_{\mathrm{in}}/B(M1)_{\mathrm{out}}$ ratios and the energy staggering parameter, S(I), have been deduced for these doublet bands. The results are found to be consistent with the chiral interpretation for the two structures. Furthermore, the observation of chiral doublet bands in ^{126}Cs together with those in ^{124}Cs, ^{128}Cs, ^{130}Cs, and ^{132}Cs also indicates that the chiral conditions do not change rapidly with decreasing neutron number in these odd-odd Cesium isotopes.

Candidate Chiral bands in *A~130 region*



^{138}Eu: Hecht 2001
^{136}Pm: Starosta 2001
Hecht 2001
^{135}Nd: Zhu 2003
^{136}Nd: Mergel 2002
^{132}Pr: Koike 2001
^{134}Pr: Petrache 1996
^{130}La: Koike 2001
^{132}La: Starosta 2001
^{134}La: Bark2001
^{126}Cs: Li 2002
Wang 2006
^{128}Cs: Koike 2001
^{130}Cs: Starosta 2001
^{132}Cs: Koike 2003
Rainovski 2003

Candidate Chiral bands in *A~100 region*



^{105}Ag: Timár 2007

^{106}Ag: He 2006

Joshi 2007

^{103}Rh: Timár 2006

^{104}Rh: Vaman 2004

^{105}Rh: Alcátara 2004

Timár 2004

^{100}Tc: Joshi 2005

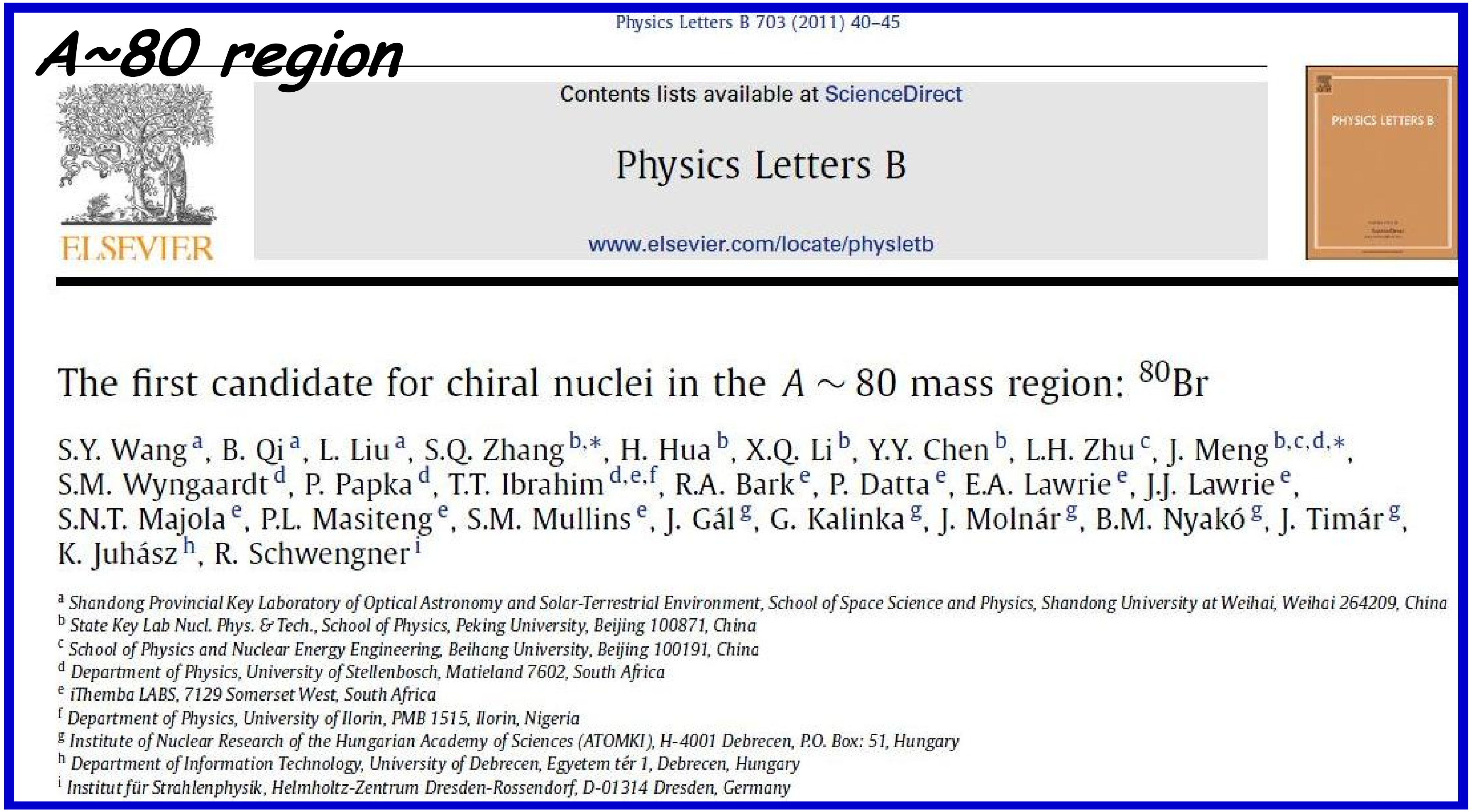
^{106}Mo: Zhu 2005

Chiral bands in *other region*

A~190 region

^{188}Ir: Balabanski 2004
^{198}Tl: Lawrie2008

A~80 region



Physics Letters B 703 (2011) 40–45

Contents lists available at ScienceDirect

Physics Letters B

www.elsevier.com/locate/physletb

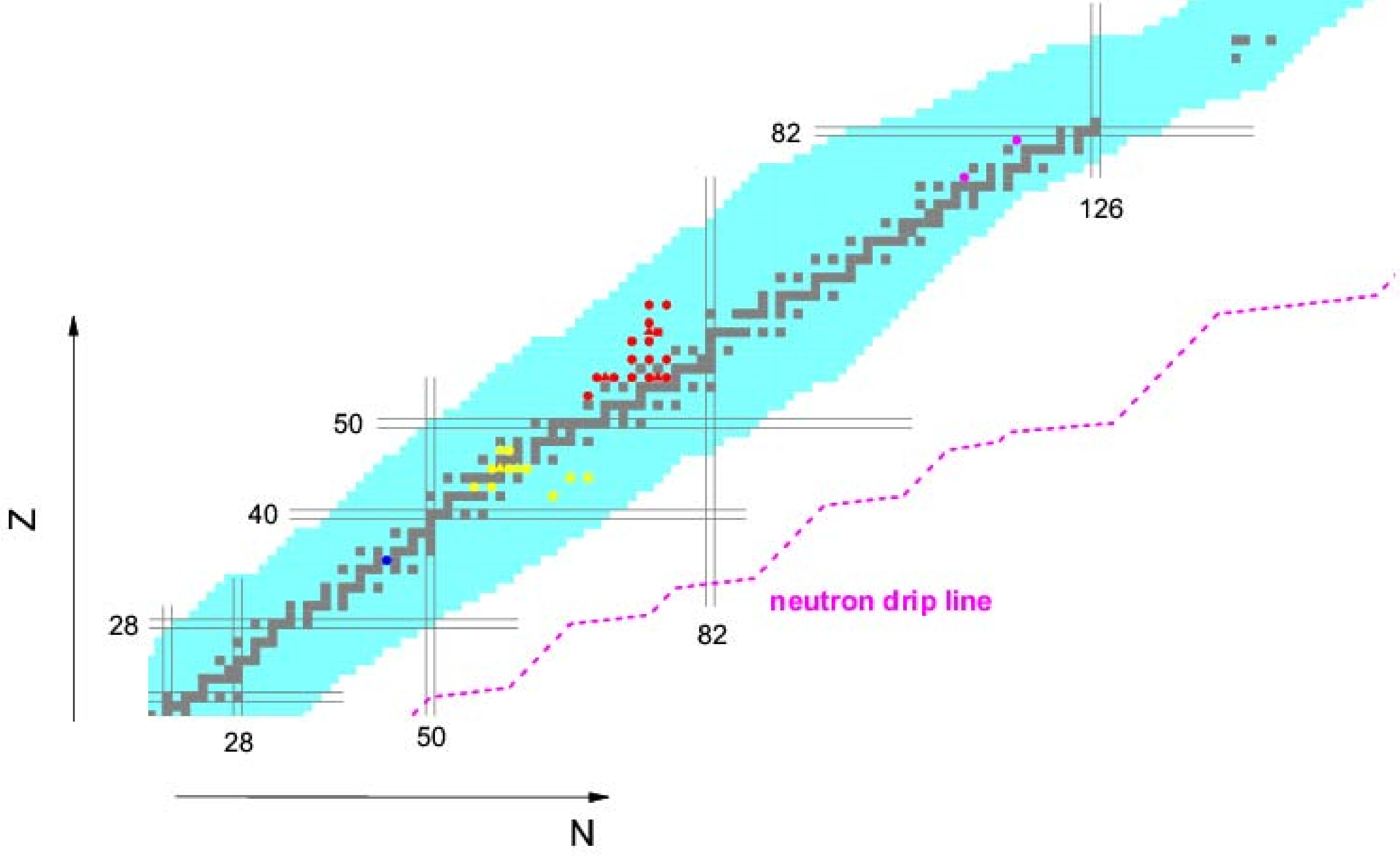
The first candidate for chiral nuclei in the $A \sim 80$ mass region: ^{80}Br

S.Y. Wang[a], B. Qi[a], L. Liu[a], S.Q. Zhang[b,*], H. Hua[b], X.Q. Li[b], Y.Y. Chen[b], L.H. Zhu[c], J. Meng[b,c,d,*], S.M. Wyngaardt[d], P. Papka[d], T.T. Ibrahim[d,e,f], R.A. Bark[e], P. Datta[e], E.A. Lawrie[e], J.J. Lawrie[e], S.N.T. Majola[e], P.L. Masiteng[e], S.M. Mullins[e], J. Gál[g], G. Kalinka[g], J. Molnár[g], B.M. Nyakó[g], J. Timár[g], K. Juhász[h], R. Schwengner[i]

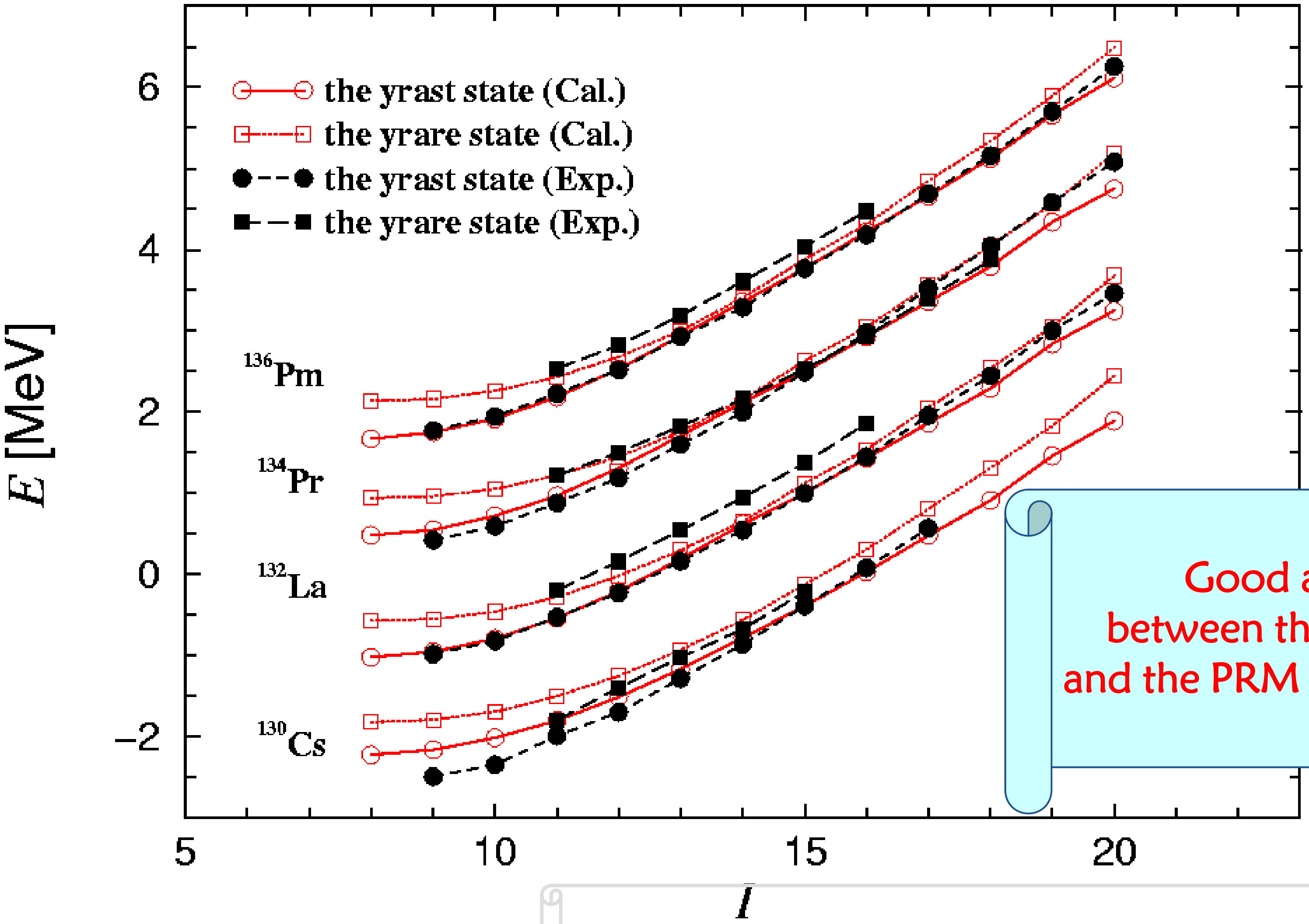
[a] *Shandong Provincial Key Laboratory of Optical Astronomy and Solar-Terrestrial Environment, School of Space Science and Physics, Shandong University at Weihai, Weihai 264209, China*
[b] *State Key Lab Nucl. Phys. & Tech., School of Physics, Peking University, Beijing 100871, China*
[c] *School of Physics and Nuclear Energy Engineering, Beihang University, Beijing 100191, China*
[d] *Department of Physics, University of Stellenbosch, Matieland 7602, South Africa*
[e] *iThemba LABS, 7129 Somerset West, South Africa*
[f] *Department of Physics, University of Ilorin, PMB 1515, Ilorin, Nigeria*
[g] *Institute of Nuclear Research of the Hungarian Academy of Sciences (ATOMKI), H-4001 Debrecen, P.O. Box: 51, Hungary*
[h] *Department of Information Technology, University of Debrecen, Egyetem tér 1, Debrecen, Hungary*
[i] *Institut für Strahlenphysik, Helmholtz-Zentrum Dresden-Rossendorf, D-01314 Dresden, Germany*

Nuclear Chiral chart

- **Up till now, more than 30 candidate have been reported in the A~80, 100, 130, and 190 mass regions. [Meng and Zhang2010JPG]**
- **Multiple chiral doublets (MχD) were predicted in 2006 [Meng2006PRC] and experimentally observed in 2013 [Ayangeakaa2013PRL]**



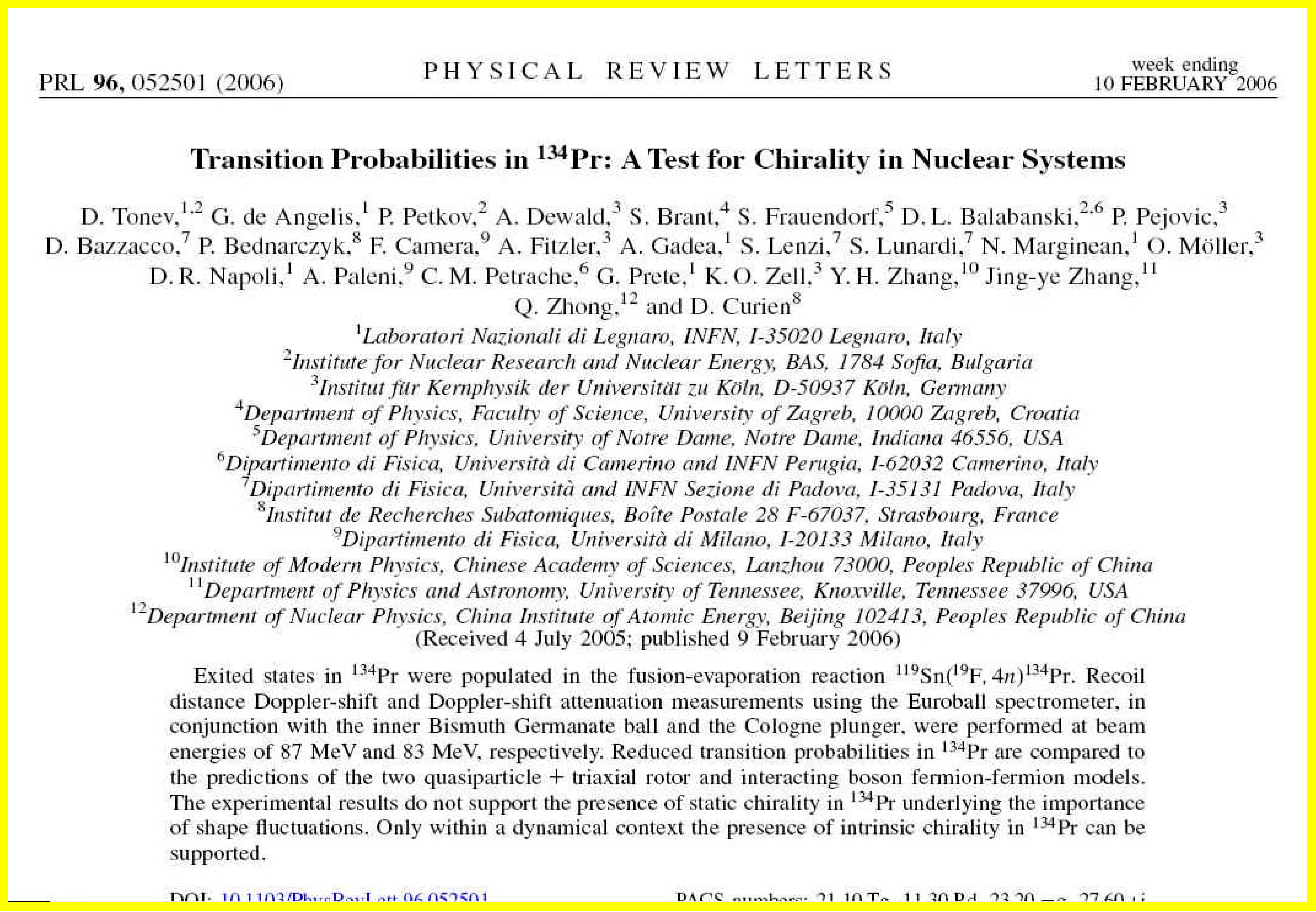
Chiral criteria: Near energy degeneracy?



Good agreement between the experimental and the PRM calculated results

Peng, Meng, Zhang,Phys. Rev.C68, 044324 (2003)

Near energy degeneracy - chirality?



PRL **96,** 052501 (2006) PHYSICAL REVIEW LETTERS week ending
10 FEBRUARY 2006

Transition Probabilities in ^{134}Pr: A Test for Chirality in Nuclear Systems

D. Tonev,[1,2] G. de Angelis,[1] P. Petkov,[2] A. Dewald,[3] S. Brant,[4] S. Frauendorf,[5] D. L. Balabanski,[2,6] P. Pejovic,[3] D. Bazzacco,[7] P. Bednarczyk,[8] F. Camera,[9] A. Fitzler,[3] A. Gadea,[1] S. Lenzi,[7] S. Lunardi,[7] N. Marginean,[1] O. Möller,[3] D. R. Napoli,[1] A. Paleni,[9] C. M. Petrache,[6] G. Prete,[1] K. O. Zell,[3] Y. H. Zhang,[10] Jing-ye Zhang,[11] Q. Zhong,[12] and D. Curien[8]

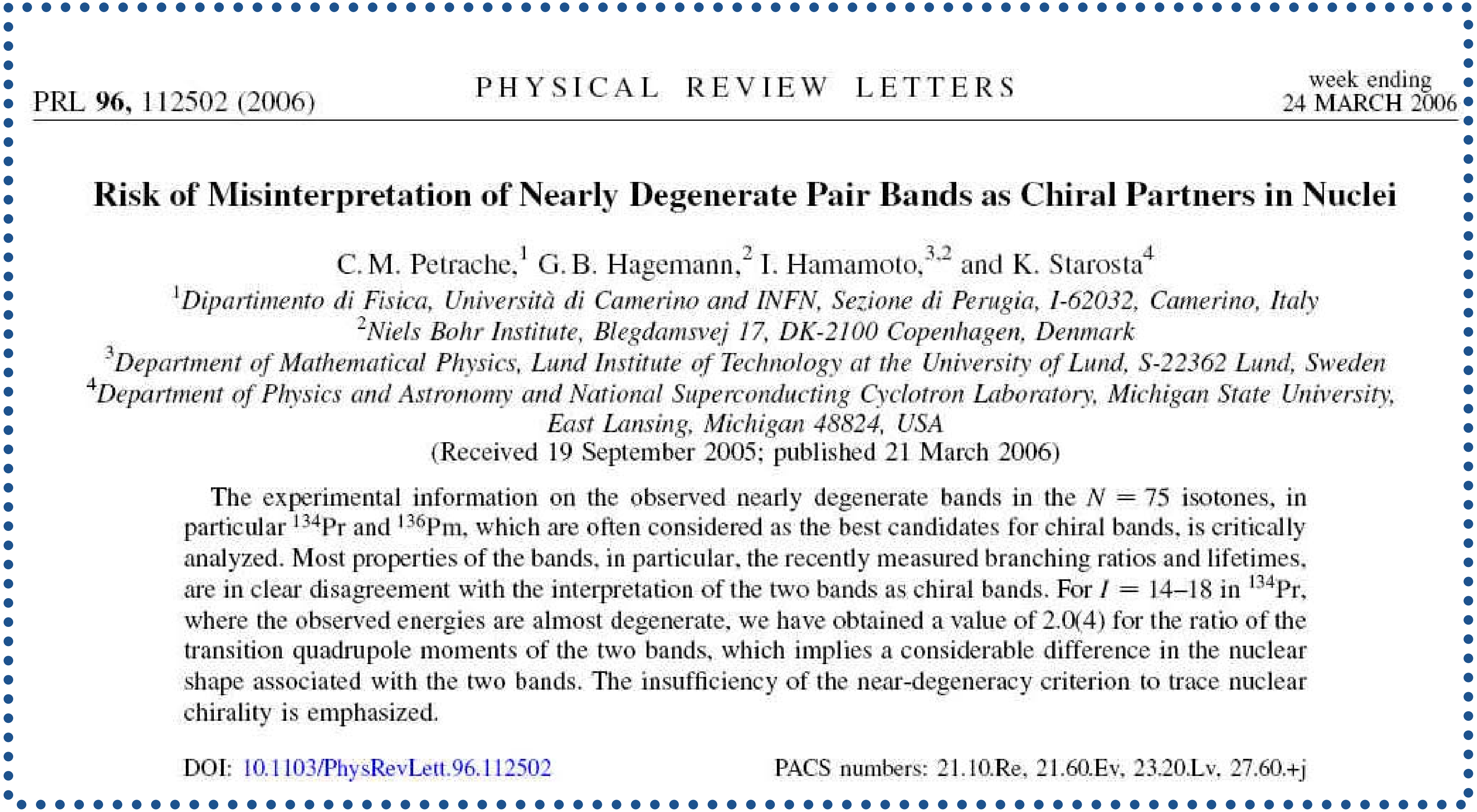
[1]*Laboratori Nazionali di Legnaro, INFN, I-35020 Legnaro, Italy*
[2]*Institute for Nuclear Research and Nuclear Energy, BAS, 1784 Sofia, Bulgaria*
[3]*Institut für Kernphysik der Universität zu Köln, D-50937 Köln, Germany*
[4]*Department of Physics, Faculty of Science, University of Zagreb, 10000 Zagreb, Croatia*
[5]*Department of Physics, University of Notre Dame, Notre Dame, Indiana 46556, USA*
[6]*Dipartimento di Fisica, Università di Camerino and INFN Perugia, I-62032 Camerino, Italy*
[7]*Dipartimento di Fisica, Università and INFN Sezione di Padova, I-35131 Padova, Italy*
[8]*Institut de Recherches Subatomiques, Boîte Postale 28 F-67037, Strasbourg, France*
[9]*Dipartimento di Fisica, Università di Milano, I-20133 Milano, Italy*
[10]*Institute of Modern Physics, Chinese Academy of Sciences, Lanzhou 73000, Peoples Republic of China*
[11]*Department of Physics and Astronomy, University of Tennessee, Knoxville, Tennessee 37996, USA*
[12]*Department of Nuclear Physics, China Institute of Atomic Energy, Beijing 102413, Peoples Republic of China*

(Received 4 July 2005; published 9 February 2006)

Exited states in ^{134}Pr were populated in the fusion-evaporation reaction ^{119}Sn(^{19}F, $4n$)^{134}Pr. Recoil distance Doppler-shift and Doppler-shift attenuation measurements using the Euroball spectrometer, in conjunction with the inner Bismuth Germanate ball and the Cologne plunger, were performed at beam energies of 87 MeV and 83 MeV, respectively. Reduced transition probabilities in ^{134}Pr are compared to the predictions of the two quasiparticle + triaxial rotor and interacting boson fermion-fermion models. The experimental results do not support the presence of static chirality in ^{134}Pr underlying the importance of shape fluctuations. Only within a dynamical context the presence of intrinsic chirality in ^{134}Pr can be supported.

DOI: 10.1103/PhysRevLett.96.052501 PACS numbers: 21.10.Tg, 11.30.Rd, 23.20.−g, 27.60.+j

^{134}Pr - Chiral candidate ? ? ?



PRL **96,** 112502 (2006) PHYSICAL REVIEW LETTERS week ending 24 MARCH 2006

Risk of Misinterpretation of Nearly Degenerate Pair Bands as Chiral Partners in Nuclei

C. M. Petrache,[1] G. B. Hagemann,[2] I. Hamamoto,[3,2] and K. Starosta[4]
[1] *Dipartimento di Fisica, Università di Camerino and INFN, Sezione di Perugia, I-62032, Camerino, Italy*
[2] *Niels Bohr Institute, Blegdamsvej 17, DK-2100 Copenhagen, Denmark*
[3] *Department of Mathematical Physics, Lund Institute of Technology at the University of Lund, S-22362 Lund, Sweden*
[4] *Department of Physics and Astronomy and National Superconducting Cyclotron Laboratory, Michigan State University, East Lansing, Michigan 48824, USA*

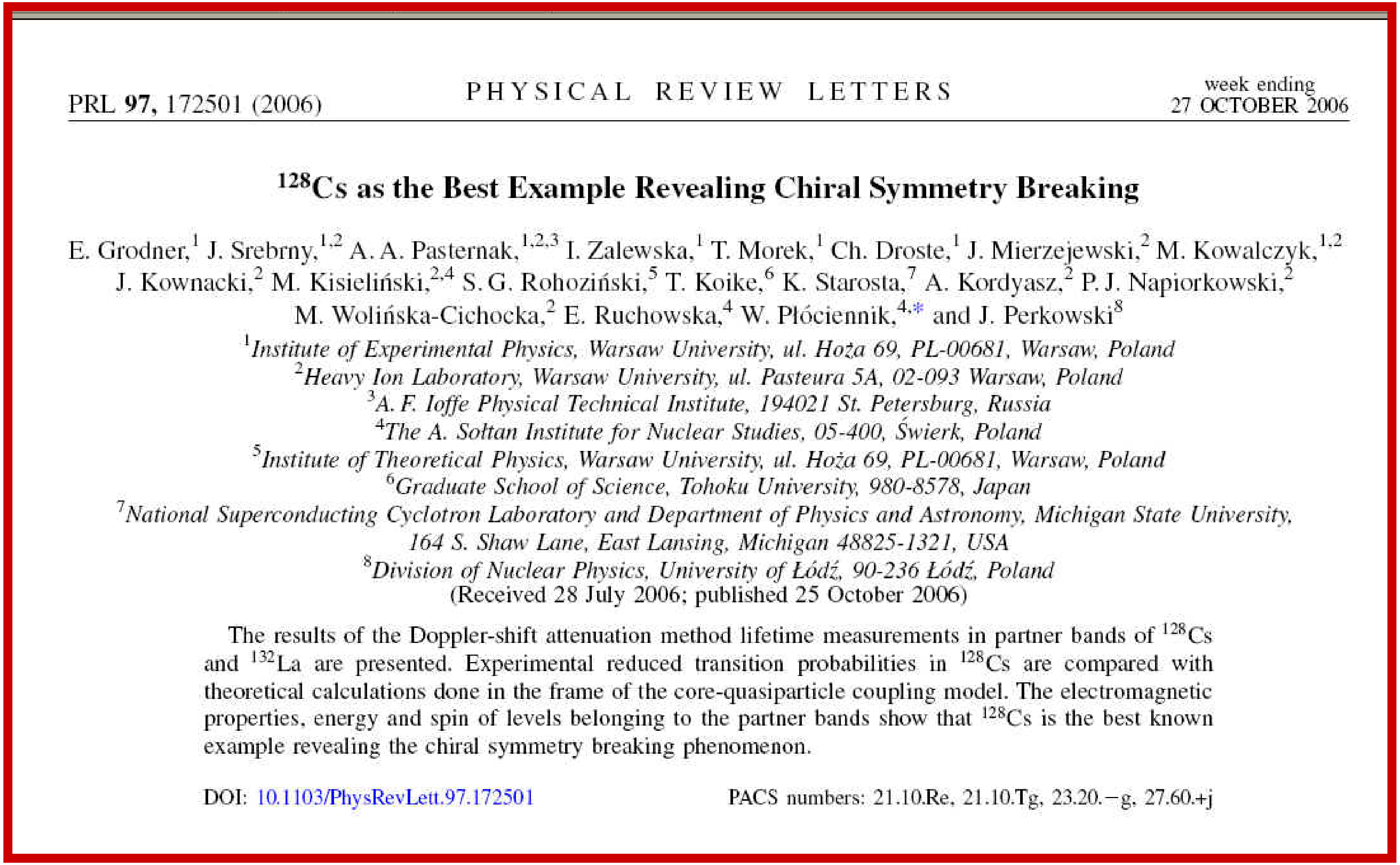
(Received 19 September 2005; published 21 March 2006)

The experimental information on the observed nearly degenerate bands in the $N = 75$ isotones, in particular ^{134}Pr and ^{136}Pm, which are often considered as the best candidates for chiral bands, is critically analyzed. Most properties of the bands, in particular, the recently measured branching ratios and lifetimes, are in clear disagreement with the interpretation of the two bands as chiral bands. For $I = 14$–18 in ^{134}Pr, where the observed energies are almost degenerate, we have obtained a value of 2.0(4) for the ratio of the transition quadrupole moments of the two bands, which implies a considerable difference in the nuclear shape associated with the two bands. The insufficiency of the near-degeneracy criterion to trace nuclear chirality is emphasized.

DOI: 10.1103/PhysRevLett.96.112502 PACS numbers: 21.10.Re, 21.60.Ev, 23.20.Lv, 27.60.+j

End of the story ?

手征原子核：another best example！？



PRL **97,** 172501 (2006) PHYSICAL REVIEW LETTERS week ending
27 OCTOBER 2006

^{128}Cs as the Best Example Revealing Chiral Symmetry Breaking

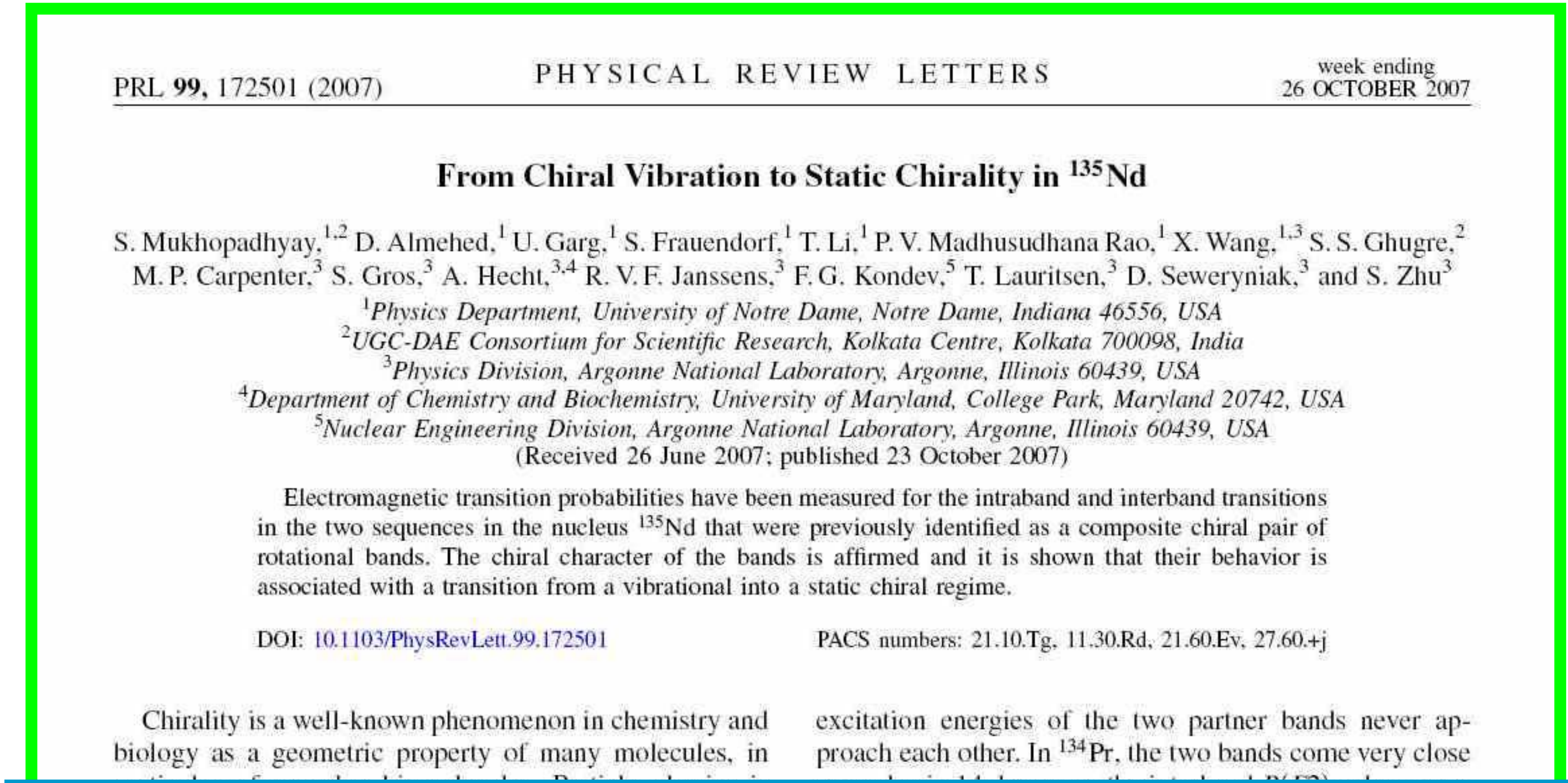
E. Grodner,[1] J. Srebrny,[1,2] A. A. Pasternak,[1,2,3] I. Zalewska,[1] T. Morek,[1] Ch. Droste,[1] J. Mierzejewski,[2] M. Kowalczyk,[1,2]
J. Kownacki,[2] M. Kisieliński,[2,4] S. G. Rohoziński,[5] T. Koike,[6] K. Starosta,[7] A. Kordyasz,[2] P. J. Napiorkowski,[2]
M. Wolińska-Cichocka,[2] E. Ruchowska,[4] W. Płóciennik,[4,*] and J. Perkowski[8]
[1]*Institute of Experimental Physics, Warsaw University, ul. Hoża 69, PL-00681, Warsaw, Poland*
[2]*Heavy Ion Laboratory, Warsaw University, ul. Pasteura 5A, 02-093 Warsaw, Poland*
[3]*A. F. Ioffe Physical Technical Institute, 194021 St. Petersburg, Russia*
[4]*The A. Sołtan Institute for Nuclear Studies, 05-400, Świerk, Poland*
[5]*Institute of Theoretical Physics, Warsaw University, ul. Hoża 69, PL-00681, Warsaw, Poland*
[6]*Graduate School of Science, Tohoku University, 980-8578, Japan*
[7]*National Superconducting Cyclotron Laboratory and Department of Physics and Astronomy, Michigan State University,*
164 S. Shaw Lane, East Lansing, Michigan 48825-1321, USA
[8]*Division of Nuclear Physics, University of Łódź, 90-236 Łódź, Poland*

(Received 28 July 2006; published 25 October 2006)

The results of the Doppler-shift attenuation method lifetime measurements in partner bands of ^{128}Cs and ^{132}La are presented. Experimental reduced transition probabilities in ^{128}Cs are compared with theoretical calculations done in the frame of the core-quasiparticle coupling model. The electromagnetic properties, energy and spin of levels belonging to the partner bands show that ^{128}Cs is the best known example revealing the chiral symmetry breaking phenomenon.

DOI: 10.1103/PhysRevLett.97.172501 PACS numbers: 21.10.Re, 21.10.Tg, 23.20.−g, 27.60.+j

手征原子核：another best example！ ？



PRL **99,** 172501 (2007) PHYSICAL REVIEW LETTERS week ending 26 OCTOBER 2007

From Chiral Vibration to Static Chirality in ^{135}Nd

S. Mukhopadhyay,[1,2] D. Almehed,[1] U. Garg,[1] S. Frauendorf,[1] T. Li,[1] P. V. Madhusudhana Rao,[1] X. Wang,[1,3] S. S. Ghugre,[2] M. P. Carpenter,[3] S. Gros,[3] A. Hecht,[3,4] R. V. F. Janssens,[3] F. G. Kondev,[5] T. Lauritsen,[3] D. Seweryniak,[3] and S. Zhu[3]

[1]*Physics Department, University of Notre Dame, Notre Dame, Indiana 46556, USA*
[2]*UGC-DAE Consortium for Scientific Research, Kolkata Centre, Kolkata 700098, India*
[3]*Physics Division, Argonne National Laboratory, Argonne, Illinois 60439, USA*
[4]*Department of Chemistry and Biochemistry, University of Maryland, College Park, Maryland 20742, USA*
[5]*Nuclear Engineering Division, Argonne National Laboratory, Argonne, Illinois 60439, USA*

(Received 26 June 2007; published 23 October 2007)

Electromagnetic transition probabilities have been measured for the intraband and interband transitions in the two sequences in the nucleus ^{135}Nd that were previously identified as a composite chiral pair of rotational bands. The chiral character of the bands is affirmed and it is shown that their behavior is associated with a transition from a vibrational into a static chiral regime.

DOI: 10.1103/PhysRevLett.99.172501 PACS numbers: 21.10.Tg, 11.30.Rd, 21.60.Ev, 27.60.+j

Chirality is a well-known phenomenon in chemistry and biology as a geometric property of many molecules, in

excitation energies of the two partner bands never approach each other. In ^{134}Pr, the two bands come very close

Question: Chiral bands ?

Reproduction of Spectra & transition in 2qp coupled with triaxial rotor ! Examine the orientation of the AM

Nuclear Chirality: Based on the geometry for one particle and one hole coupled to a triaxial rotor with gamma=30^0

1. nearly degenerate doublet bands

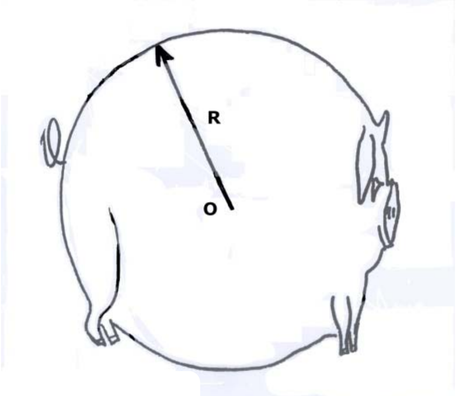
2. S(I) independent of spin

3. identical spin alignments

4. identical B(M1), B(E2) values

5. staggering of B(M1)/B(E2) ratios

6. interband B(E2)=0 at high spin



chiral bands

A microscopic quantum many-body model with n-particles and n-holes !

S.Y. Wang, S.Q. Zhang, B. Qi, and J. Meng, Examining the Chiral Geometry in ^{104}Rh and ^{106}Rh, Chinese Physics Letters 2007 24 (3): 664-667

Theoretical models for nuclear chirality

- **Tilted axis cranking** (*intrinsic frame; microscopic; mean-field; self-consistent; semi-classical; no quantum tunneling;*)
  - Single-j model Frauendorf and Meng NPA(1997);
  - Hybird Woods-Saxon and Nilsson model Dimitrov et al PRL(2000)
  - Skyrme Hartree-Fock model Olbratowski et al PRL(2004), PRC(2006)
  - Relativistic mean field (RMF) theory Madokoro et al PRC(2000); Peng et al PRC (2008)
  - TAC+RPA (135Nd) S. Mukhopadhyay et al PRL2007;

Theoretical tools for nuclear chirality

Tilted Axis Cranking

Advantage:

- Easily extended to the multi-particle case.
- microscopic method

Problems:

- The cranking model is a semi-classical approach, where the total angular momentum is not a good quantum number and the electromagnetic transitions are calculated in semiclassical approximation.
- The description of quantum tunneling of chiral partners is beyond the mean field approximation .

Theoretical models for nuclear chirality

- **Particle Core Coupling** (*lab frame; phenomenological; quantum; with quantum tunneling;*)

– Triaxial Particle Rotor Model

Frauendorf and Meng NPA(1997); Peng et al PRC(2003); Koike et al PRL(2004); Zhang et.al PRC(2007); Lawrie et al PRC (2008); Qi et al PLB(2009)

– Core-quasiparticle coupling model, which follows the KKDF method

T. Koike, K. Starosta, and I. Hamamoto, Phys. Rev. Lett. 93, 172502 (2004)

K. Starosta et al., Phys. Rev. C65 044328 (2004)

– Interacting Boson Fermion Fermion Model (IBFFM)

Brant, Vretenar, and Ventura, Phys. Rev. C 69, 017304 (2004)

– Interacting Vector Boson Model (IVBM)

Ganev, Georgieva, Brant, and Ventura, Phys. Rev. C 79, 044322 (2009)
Tonev et al PRL(2006)

– Pair Truncated Shell Model / Quadrupole Coupling Model

Higashiyama, Yoshinaga, and Tanabe, Phys. Rev. C 72, 024315 (2005)
Yoshinaga and Higashiyama, Eur. Phys. J A 30,343 (2006)

Theoretical tools for nuclear chirality

Particle Rotor Model

Advantage

- A quantum-mechanical model with the angular momentum as a good quantum number.
- In the laboratory frame and yields directly the energy splitting and tunneling between doublet bands.

Problem

- In PRM calculation, the quadrupole deformation parameters β and γ are inputs.

Theoretical tools for nuclear chirality

Particle Rotor Model beyond one particle one hole configuration

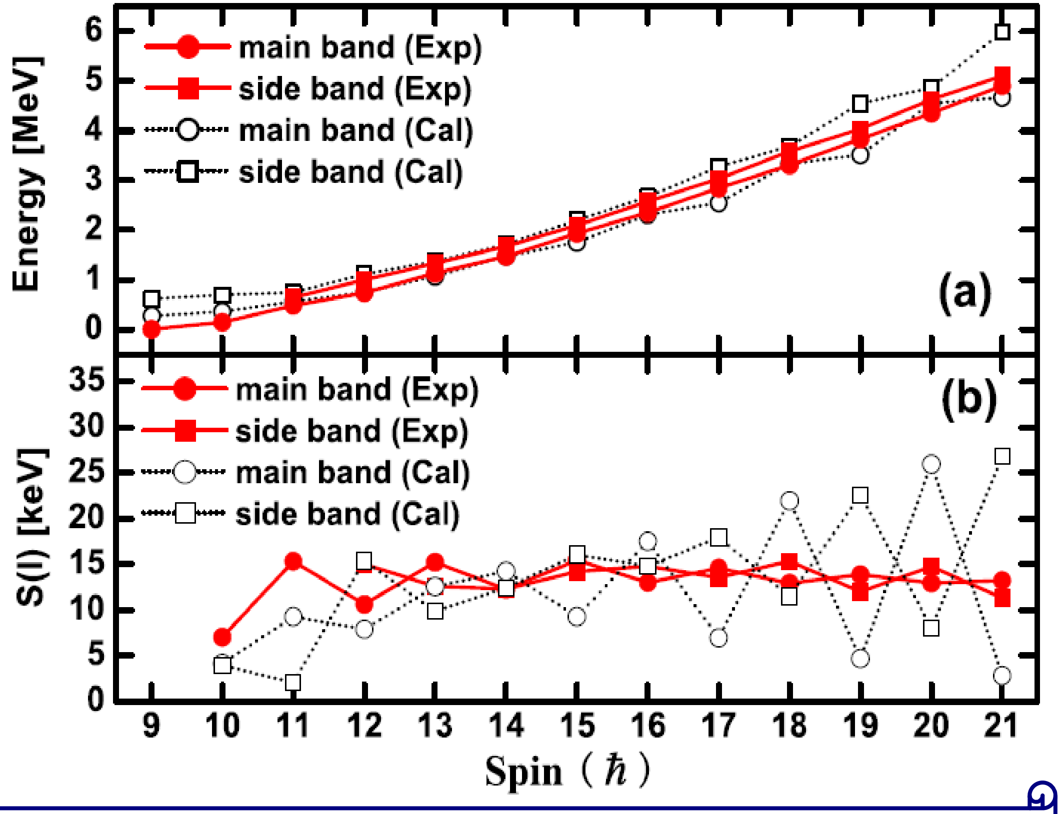
Simulating n-particles-n-holes by pairing

configuration:

one proton in $h_{11/2}$

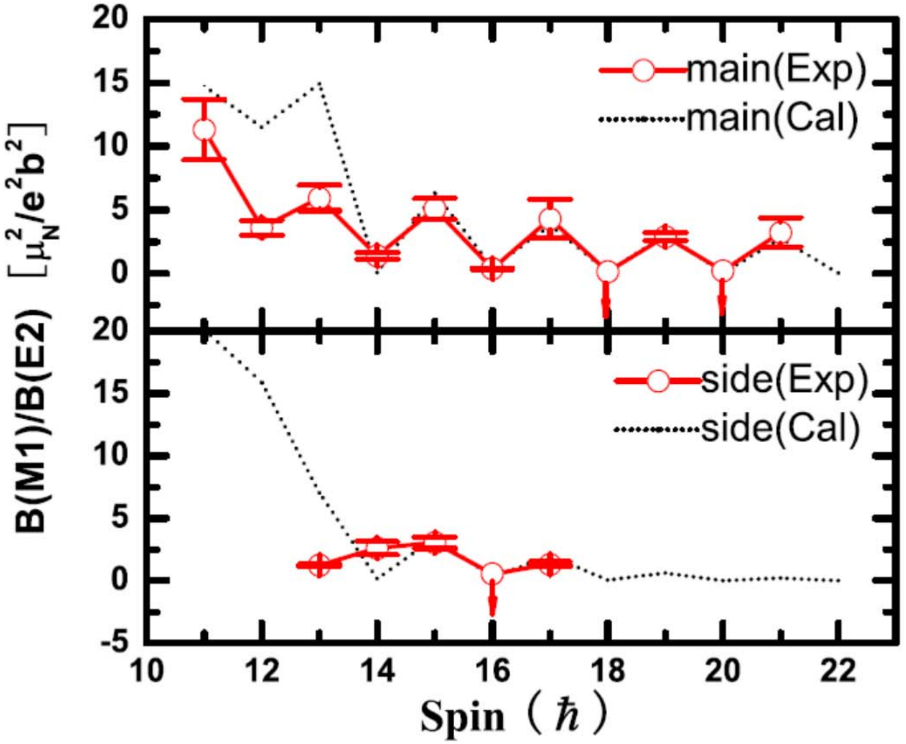
one quasi-neutron in $h_{11/2}$: simulate n-neutron holes

Energy spectra of ^{126}Cs

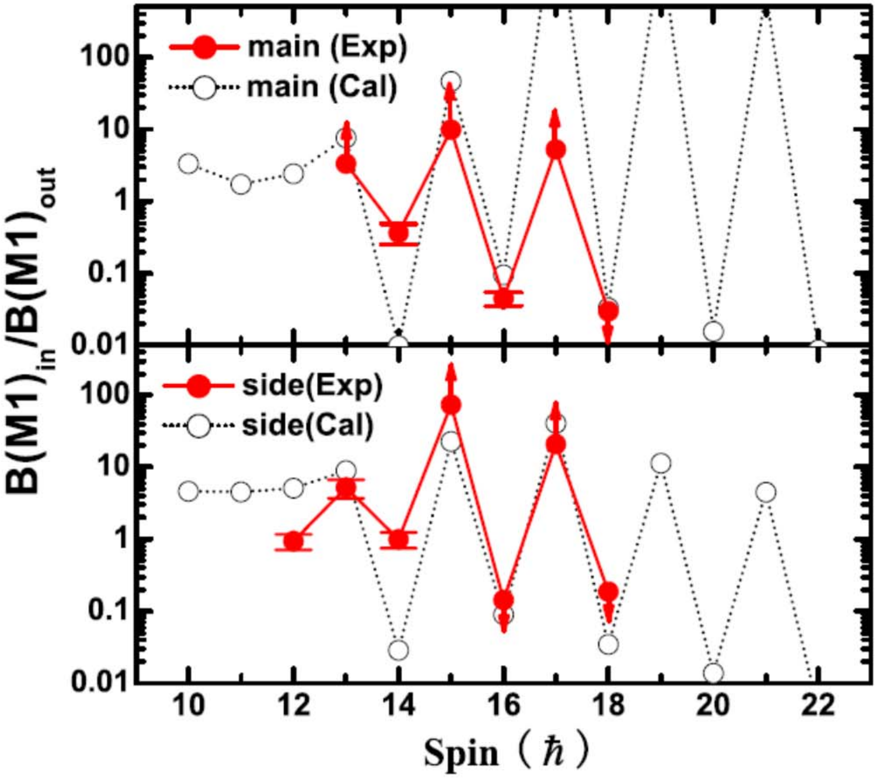


S.Y. Wang, S.Q. Zhang, B. Qi, and J. Meng, Phys. Rev. C 75, 024309 (2007)

Simulating n-particles-n-holes by pairing



S.Y. Wang, S.Q. Zhang, B. Qi, J. Meng,
Phys. Rev. C 75, 024309 (2007)



Electromagnetic properties of ^{126}Cs

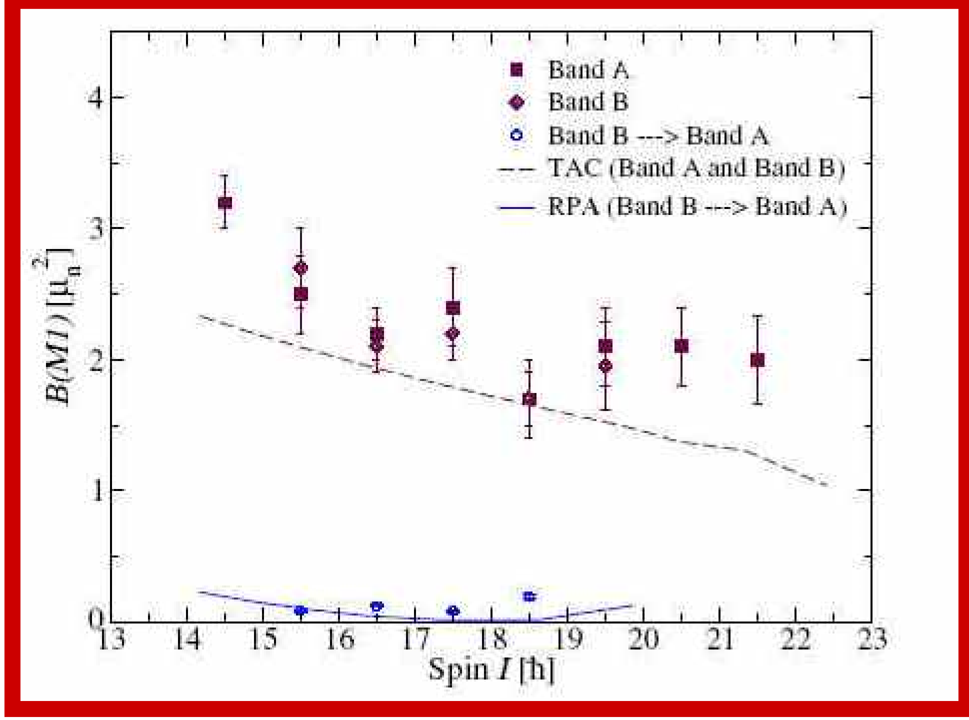
^{135}Nd as an example

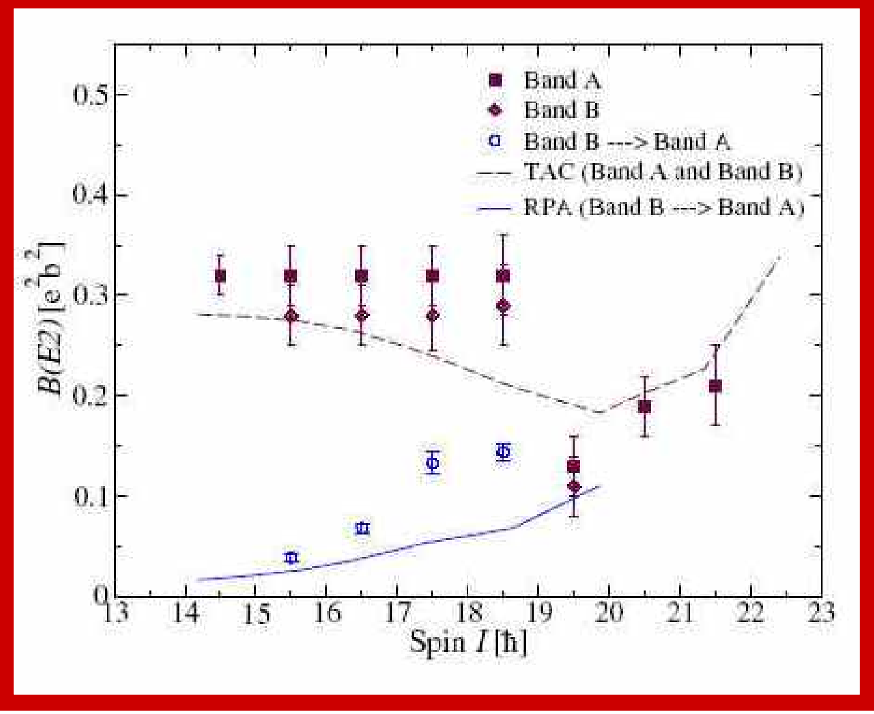
PRL **99,** 172501 (2007) PHYSICAL REVIEW LETTERS week ending 26 OCTOBER 2007

From Chiral Vibration to Static Chirality in ^{135}Nd

S. Mukhopadhyay,[1,2] D. Almehed,[1] U. Garg,[1] S. Frauendorf,[1] T. Li,[1] P. V. Madhusudhana Rao,[1] X. Wang,[1,3] S. S. Ghugre,[2] M. P. Carpenter,[3] S. Gros,[3] A. Hecht,[3,4] R. V. F. Janssens,[3] F. G. Kondev,[5] T. Lauritsen,[3] D. Seweryniak,[3] and S. Zhu[3]

[1]*Physics Department, University of Notre Dame, Notre Dame, Indiana 46556, USA*
[2]*UGC-DAE Consortium for Scientific Research, Kolkata Centre, Kolkata 700098, India*
[3]*Physics Division, Argonne National Laboratory, Argonne, Illinois 60439, USA*





Odd-A Chiral Nucleus ^{135}Nd

Many-particle-many-hole & triaxial rotor

Numerical details

☐ **Config:** $\pi h_{11/2}^{2} \otimes \nu h_{11/2}^{-1}$

☐ **deformation** $\beta = 0.235, \ \gamma = 22.4^{\circ}$ **from RMF**

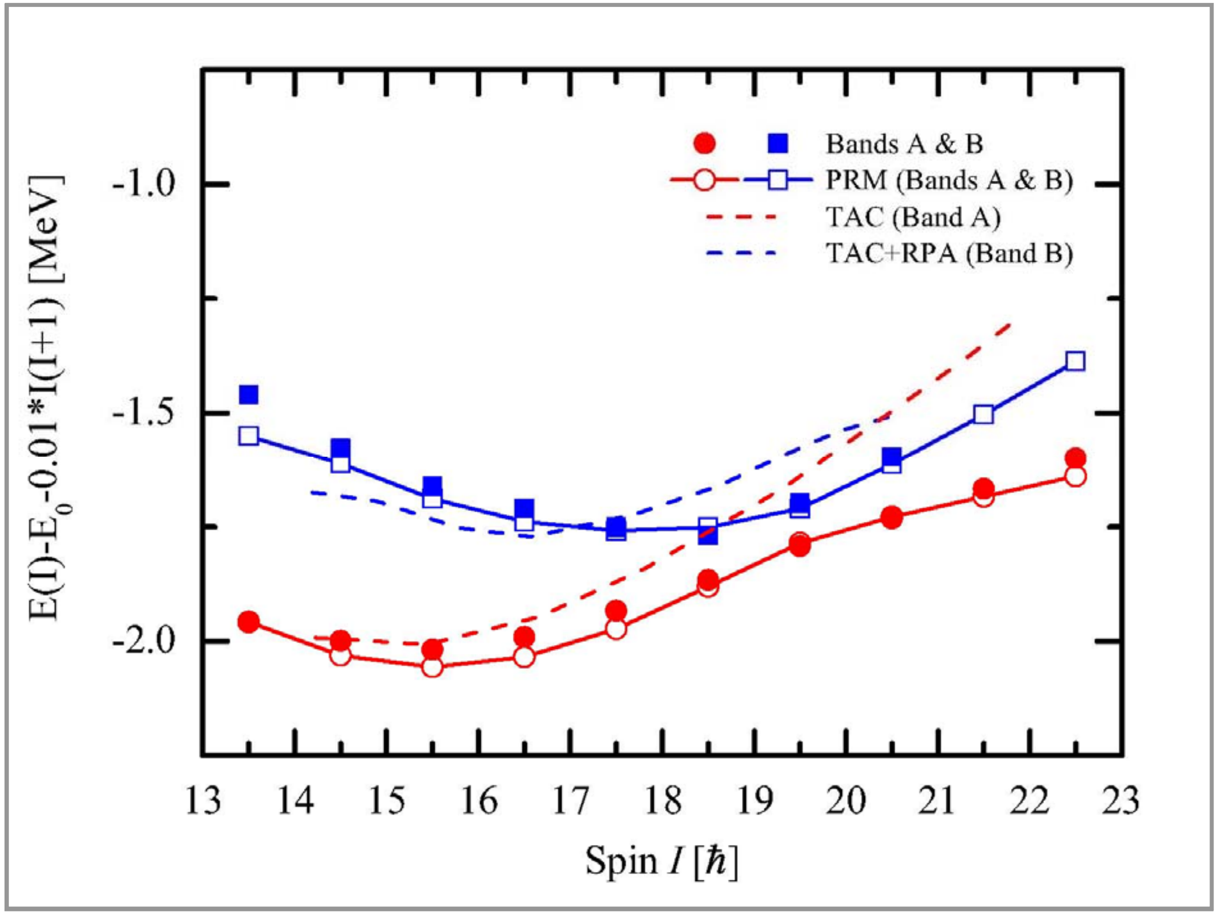
☐ **MOI** $29\hbar^2 / MeV$ **justified by data**

☐ **intrinsic Q** $Q_0 = (3/\sqrt{5\pi})R_0^2 Z\beta = 4.0eb$

☐ **g-factor** $g_R = Z/A, \quad g_p = 1.21, \quad g_n = -0.21$

Odd-A Chiral Nucleus ^{135}Nd

奇-A 核^{135}**Nd**中候选手征带的能谱

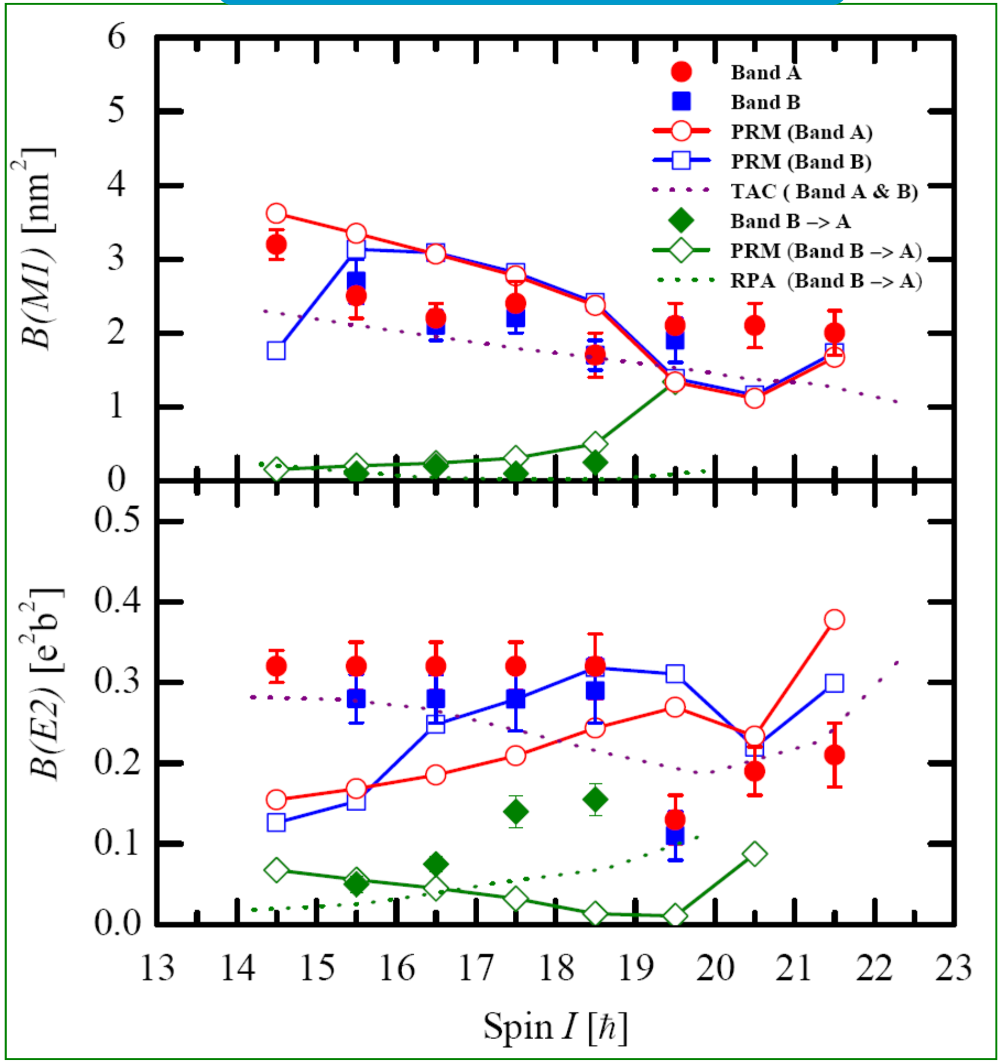


Data: Zhu *PRL* 2003
TAC: Mukhopahyay *PRL* 2007

Chirality in odd-A nucleus ^{135}Nd in particle rotor model,
B.Qi, S.Q. Zhang, J. Meng, S.Y. Wang, S. Frauendorf, Phys. Lett. B 675 (2009) 175–180

Odd-A Chiral Nucleus ^{135}Nd

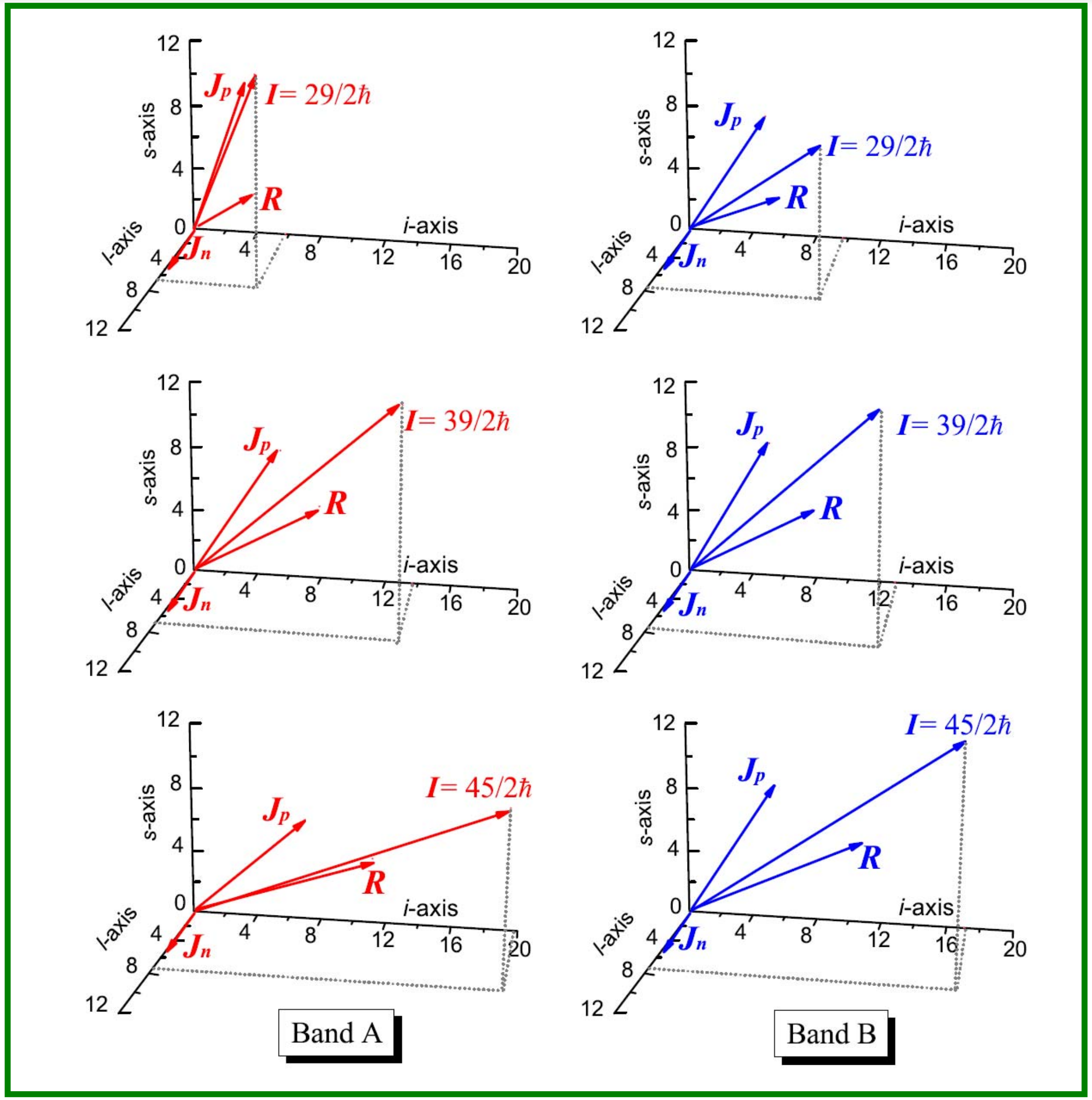
B(M1) & B(E2)



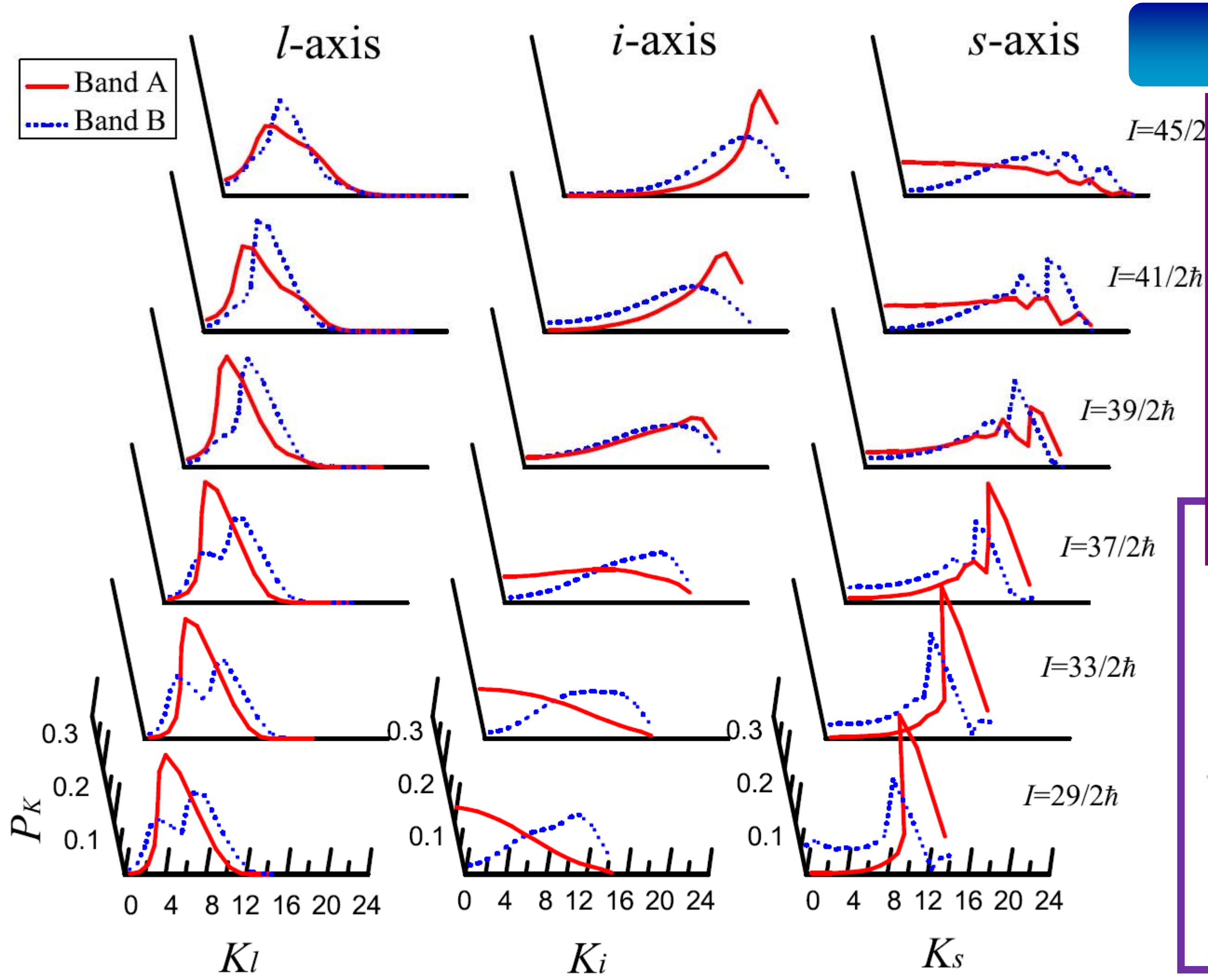
B(M1) & B(E2)的实验特征被很好的再现

Odd-A Chiral Nucleus ^{135}Nd

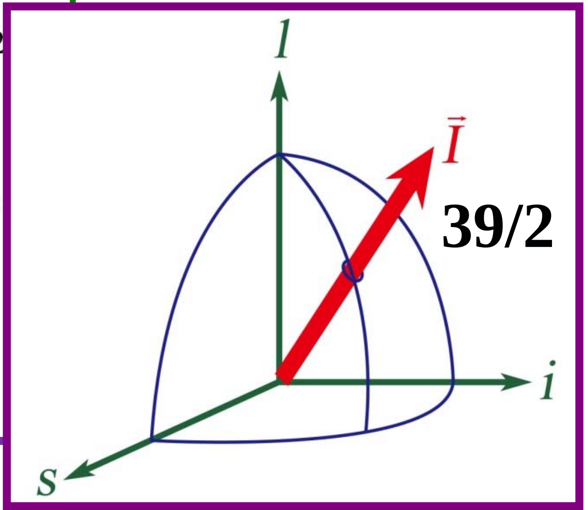
角动量期待值

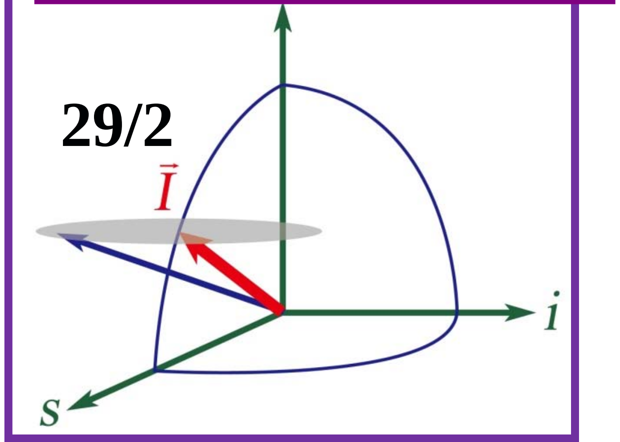


Odd-A Chiral Nucleus ^{135}Nd



角动量投影值





动态手性 ⟶ **I=39/2**附近的静态手性 ⟶ 动态手性

Beyond phenomenological Cranking approach

- **Collective Hamiltonian based on the TAC solutions is developed for chiral rotation and chiral vibration.**

  Chen, Zhang, Zhao, Jolos, Meng, Phys. Rev. C87, 024314 (2013).

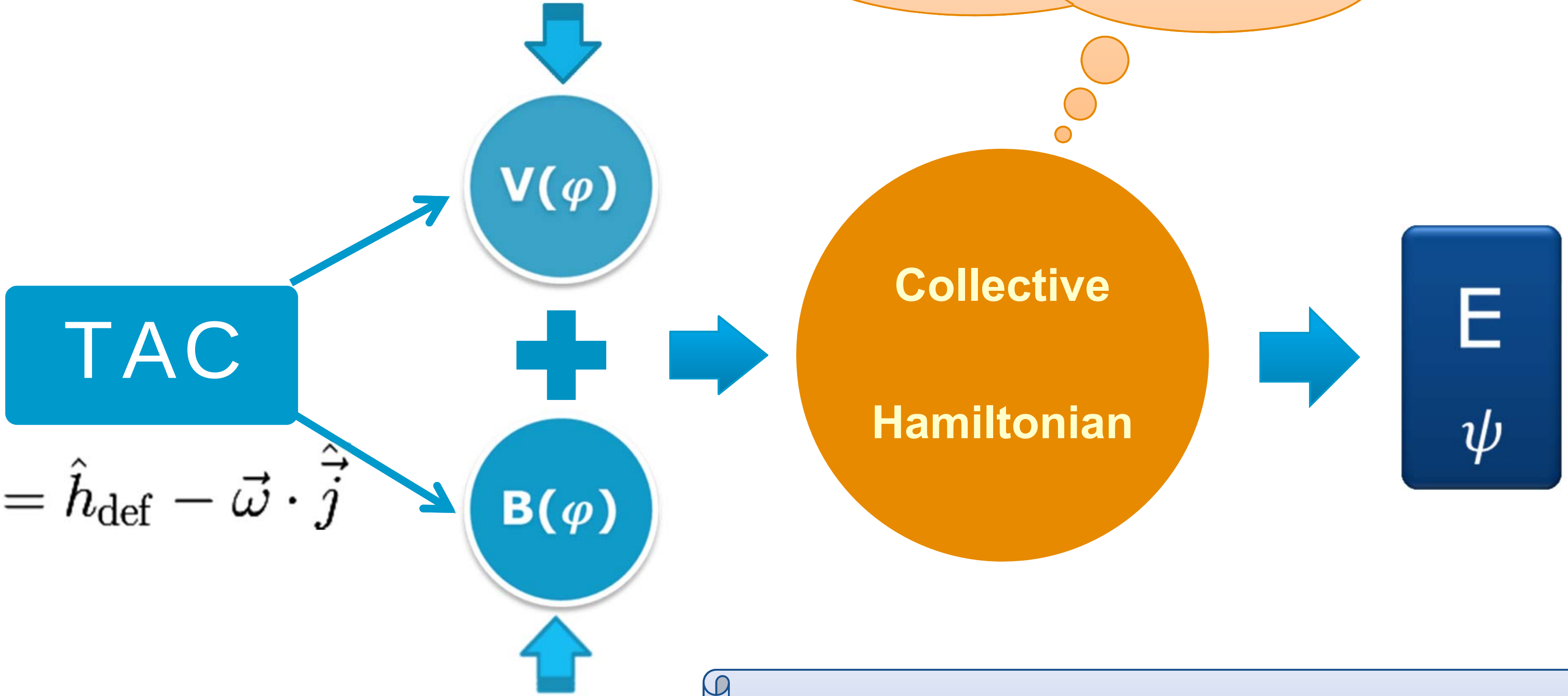
- **Covariant density functional: configuration constraint and cranking**

Collective Hamiltonian for Chiral Modes

minimize

$$E' = \langle h' \rangle - \frac{1}{2}\sum_{k=1}^{3} \mathcal{J}_k \omega_k^2$$

$$\hat{H}_{\mathrm{coll}} = -\frac{\hbar^2}{2\sqrt{B(\varphi)}}\frac{\partial}{\partial\varphi}\frac{1}{\sqrt{B(\varphi)}}\frac{\partial}{\partial\varphi} + V(\varphi)$$



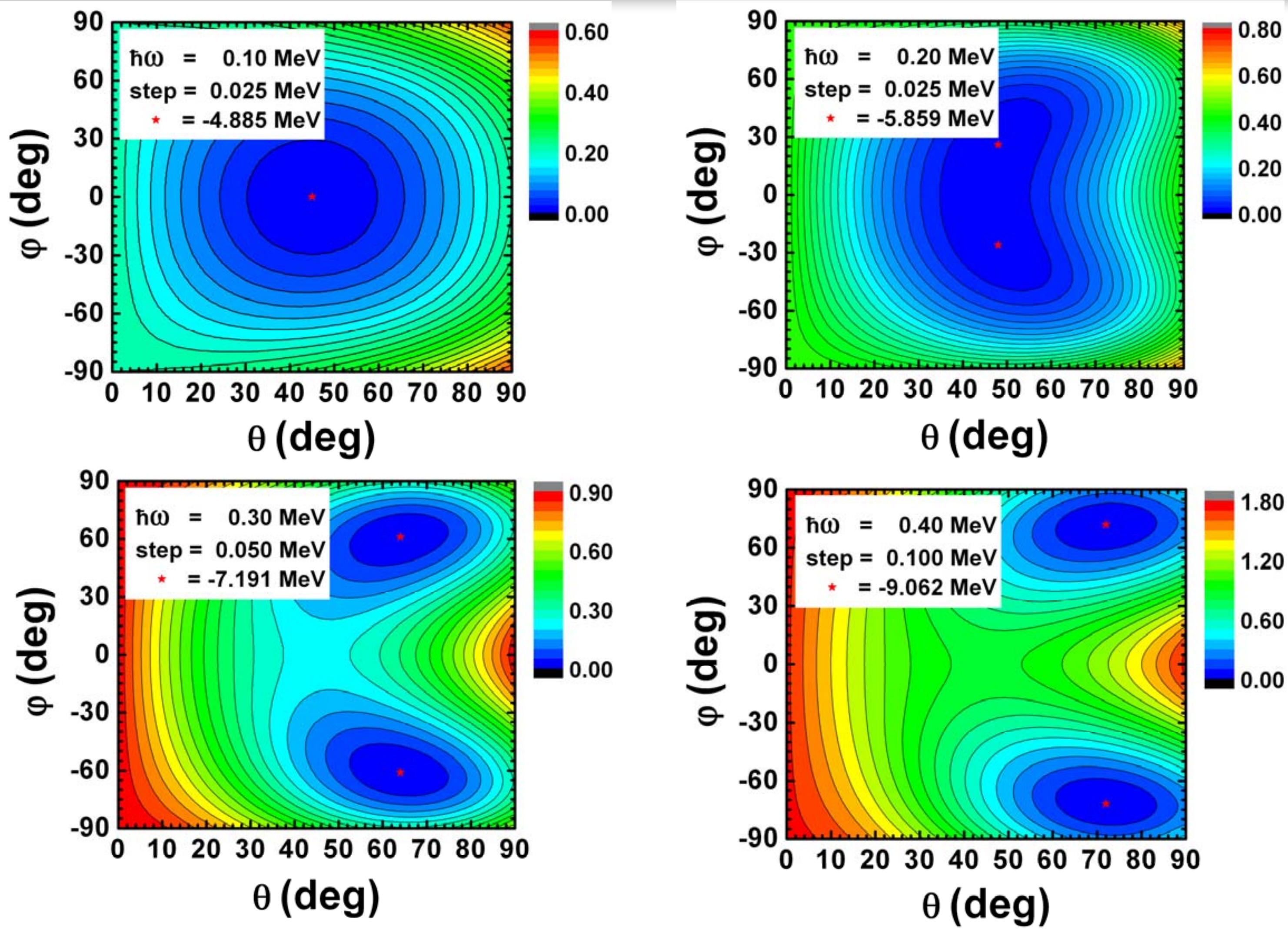
$$\hat{h}' = \hat{h}_{\mathrm{def}} - \vec{\omega}\cdot\hat{\vec{j}}$$

$$B = 2\hbar^2 \sum_{l\neq 0} \frac{(E_l - E_0)\left|\frac{\partial\vec{\omega}}{\partial\varphi}\langle l|\hat{\vec{j}}|0\rangle\right|^2}{\left[(E_l - E_0)^2 - \hbar^2\Omega^2\right]^2}$$

Q. B. Chen, S. Q. Zhang, P. W. Zhao, R. V. Jolos, J. Meng

Phys. Rev. C87, 024314 (2013).

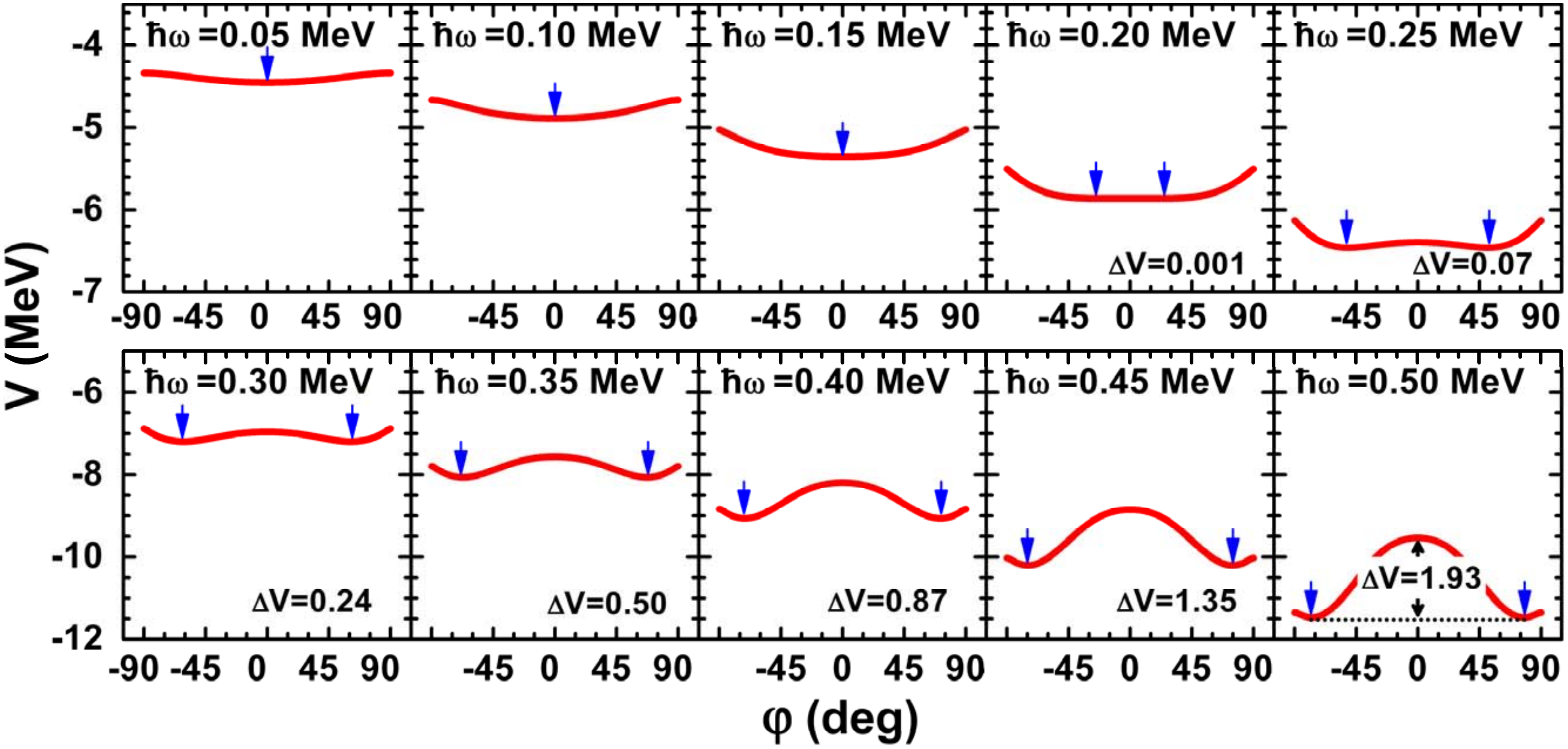
Total Routhian



Minima: $\varphi = 0 \Rightarrow \varphi \neq 0$; one ⇒ two

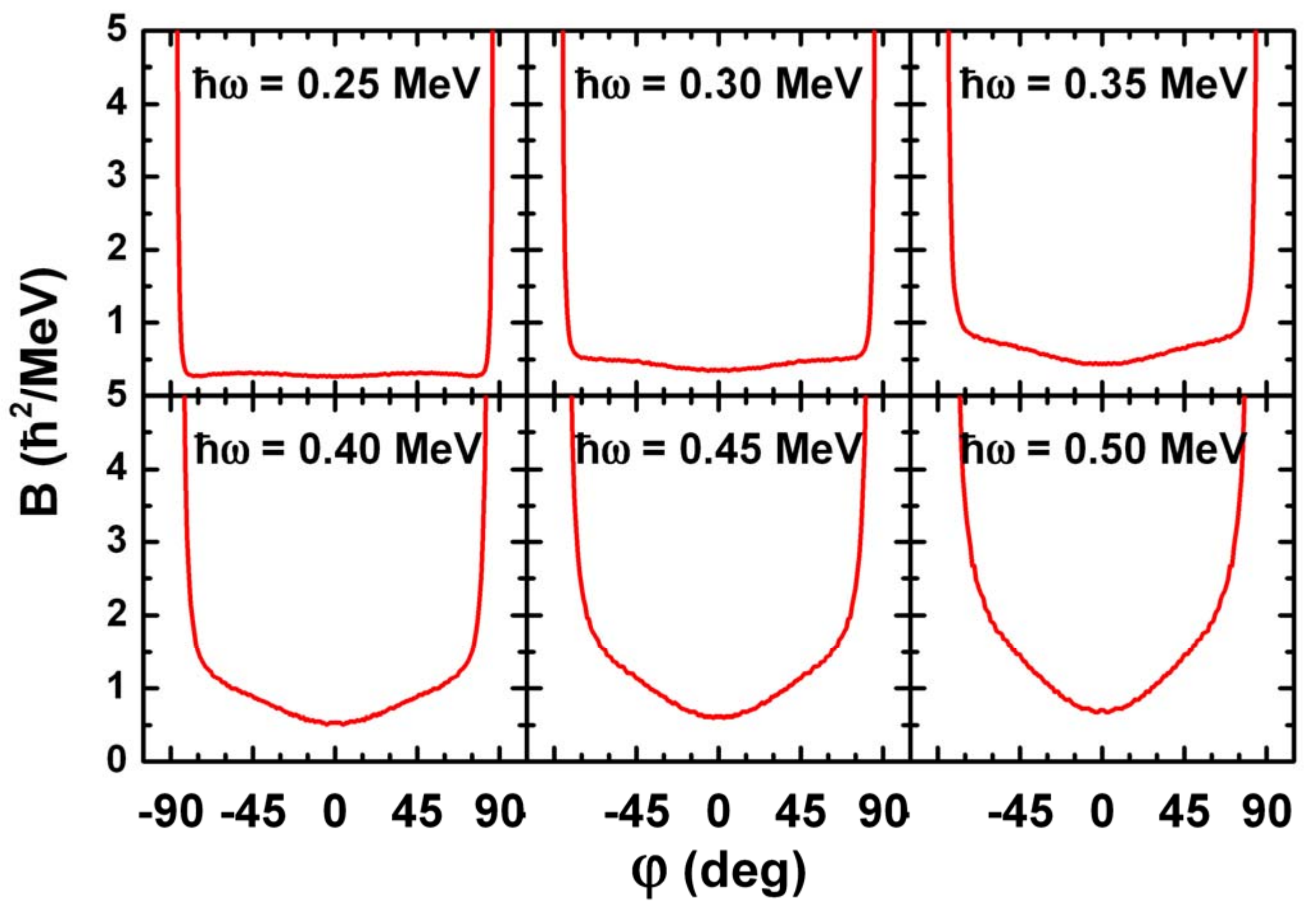
Rotating mode: planar ⇒ aplanar

Potential energy



With the increasing frequency, the potential barrier

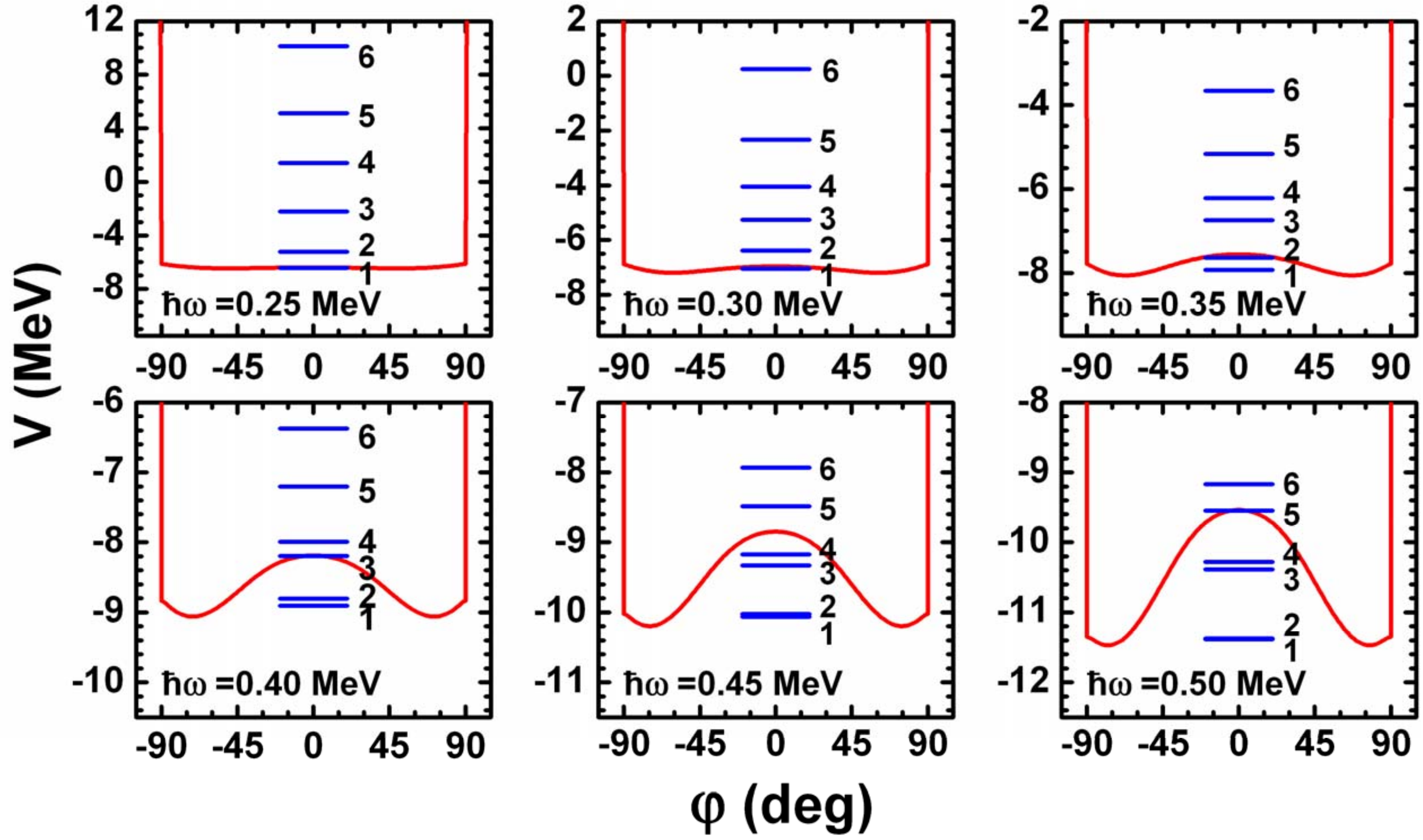
Mass parameter



For the case of chiral rotation, the chiral vibration frequency is

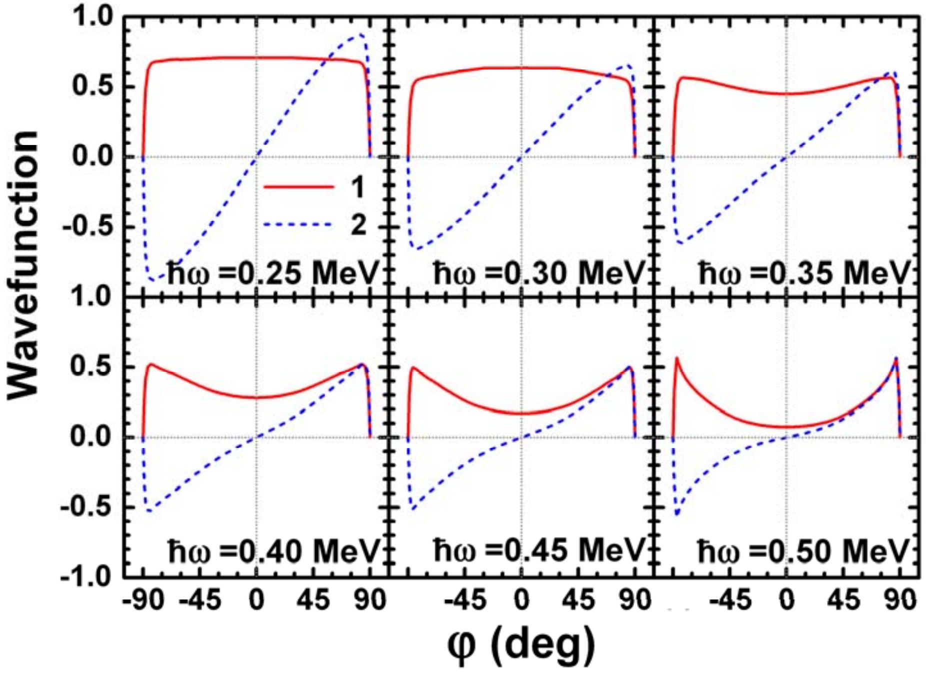
$$B = 2\hbar^2 \sum_{l\neq 0} \frac{|\frac{\partial \vec{\omega}}{\partial \varphi}\langle l|\hat{\vec{j}}|0\rangle|^2}{(E_l - E_0)^3}$$

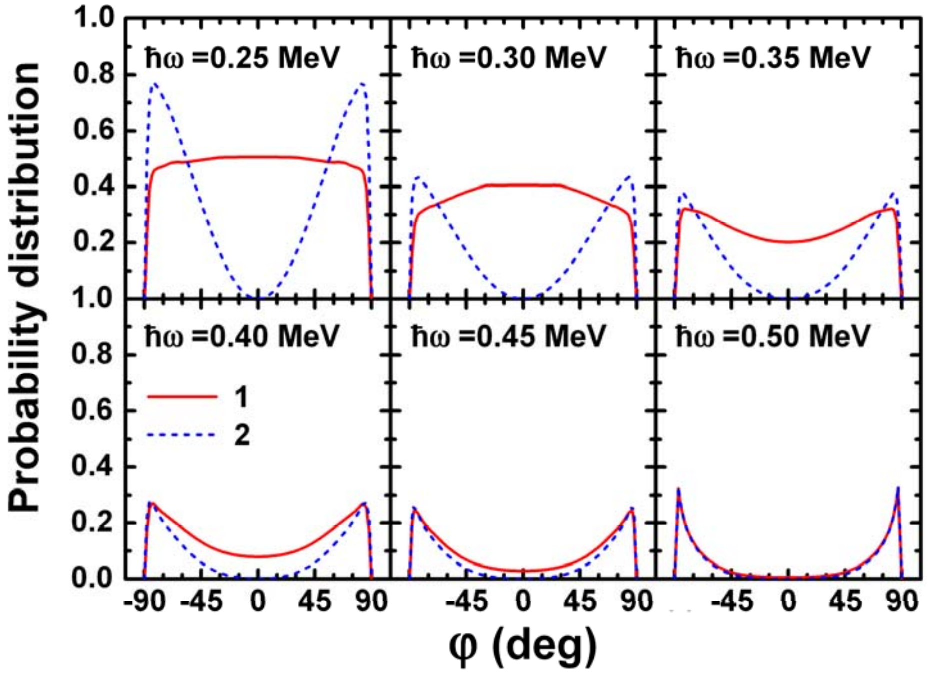
Energy levels



With the increasing frequency, the energy difference between levels 1 and 2 decreases.

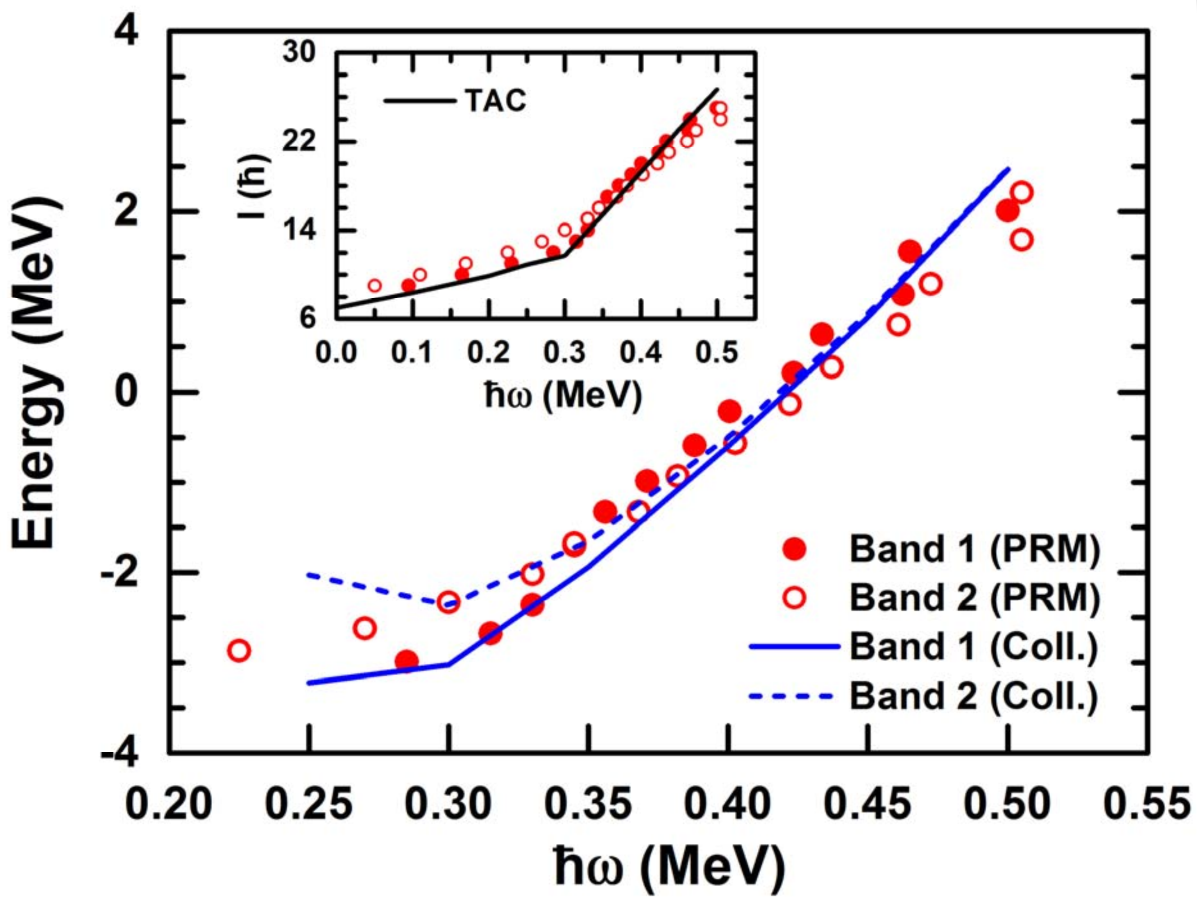
Wave function and probability distributions





- **The wave functions are symmetric for level 1 and antisymmetric for level 2 with respect to φ to $-\varphi$.**
- **When the cranking frequency increases, the wave functions of levels 1 and 2 tend to show similar pattern.**

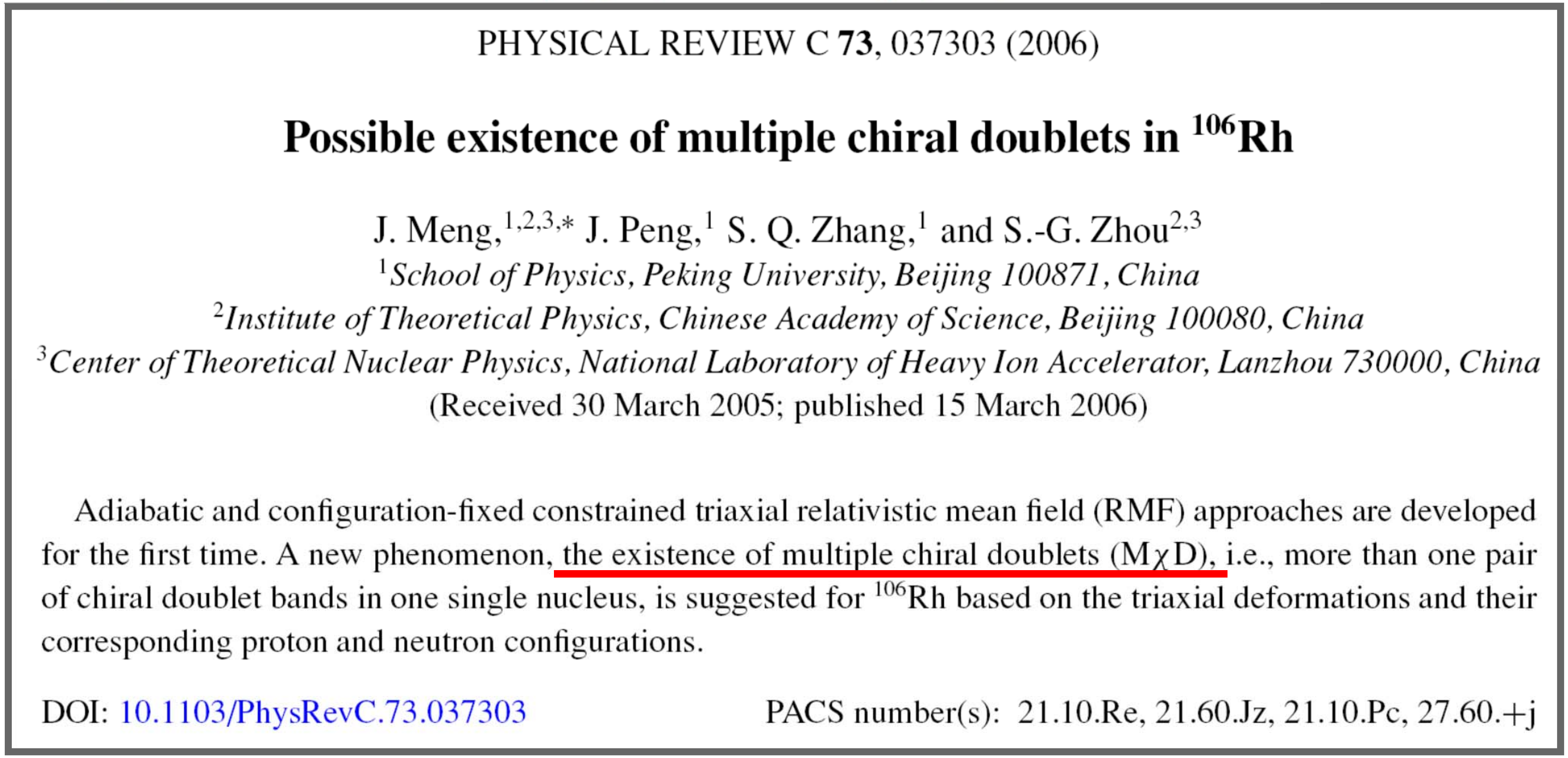
Comparison with exact solutions



- Apart from the agreement of collective Hamiltonian and PRM results for the yrast band, the partner band of PRM can also be reasonably reproduced by the collective Hamiltonian.

Multiple chiral doublets

Multiple chiral doublets (MχD) was firstly proposed in 2006



PHYSICAL REVIEW C **73**, 037303 (2006)

Possible existence of multiple chiral doublets in ^{106}Rh

J. Meng,[1,2,3,*] J. Peng,[1] S. Q. Zhang,[1] and S.-G. Zhou[2,3]
[1]*School of Physics, Peking University, Beijing 100871, China*
[2]*Institute of Theoretical Physics, Chinese Academy of Science, Beijing 100080, China*
[3]*Center of Theoretical Nuclear Physics, National Laboratory of Heavy Ion Accelerator, Lanzhou 730000, China*
(Received 30 March 2005; published 15 March 2006)

Adiabatic and configuration-fixed constrained triaxial relativistic mean field (RMF) approaches are developed for the first time. A new phenomenon, the existence of multiple chiral doublets (MχD), i.e., more than one pair of chiral doublet bands in one single nucleus, is suggested for ^{106}Rh based on the triaxial deformations and their corresponding proton and neutron configurations.

DOI: 10.1103/PhysRevC.73.037303 PACS number(s): 21.10.Re, 21.60.Jz, 21.10.Pc, 27.60.+j

The investigation followed by:

- ***Prediction for other odd-odd Rh isotopes:*** **J. Peng et al., PRC77, 024309 (200**
- ***Confirmed with time-odd fields included:*** **J. M. Yao et al., PRC79, 067302 (20**
- ***Prediction for the odd-A Rh isotopes:*** **J. Li et al., PRC83, 037301 (2011)**

Microscopic deformation calculation for chiral Nucleus

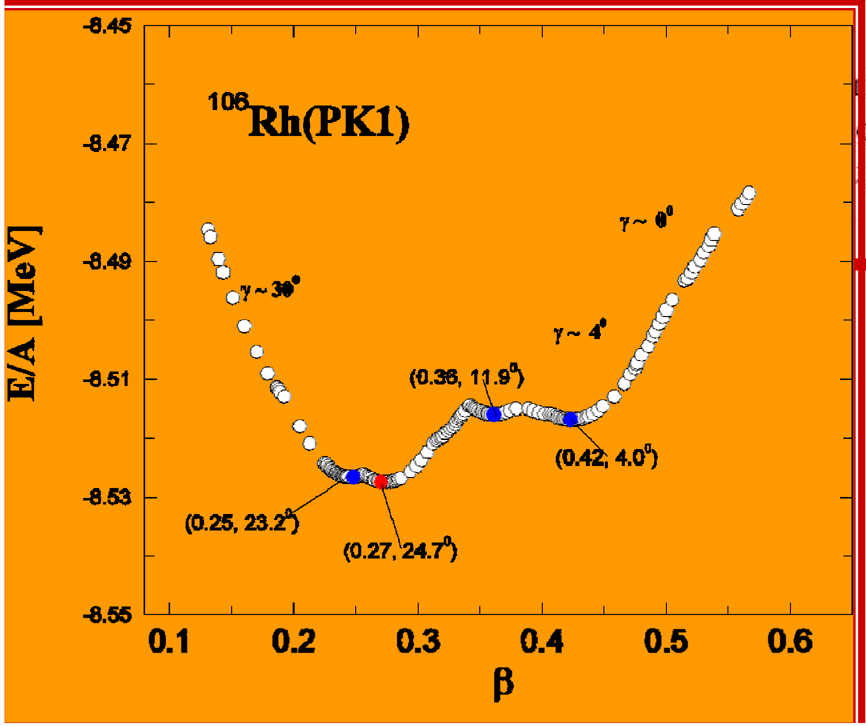
PHYSICAL REVIEW C **73**, 037303 (2006)

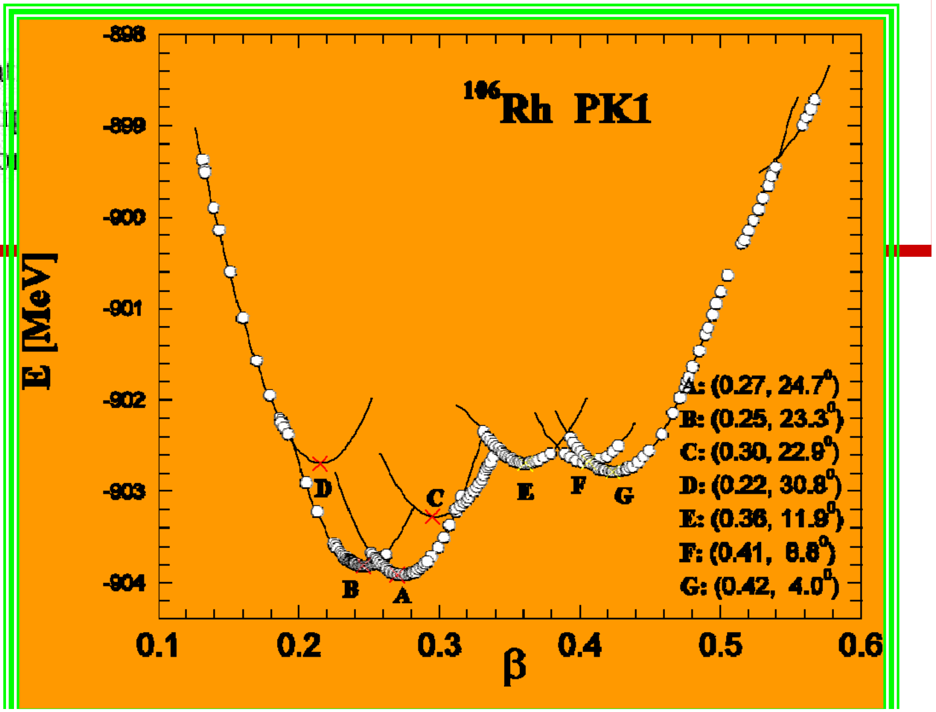
Possible existence of multiple chiral doublets in ^{106}Rh

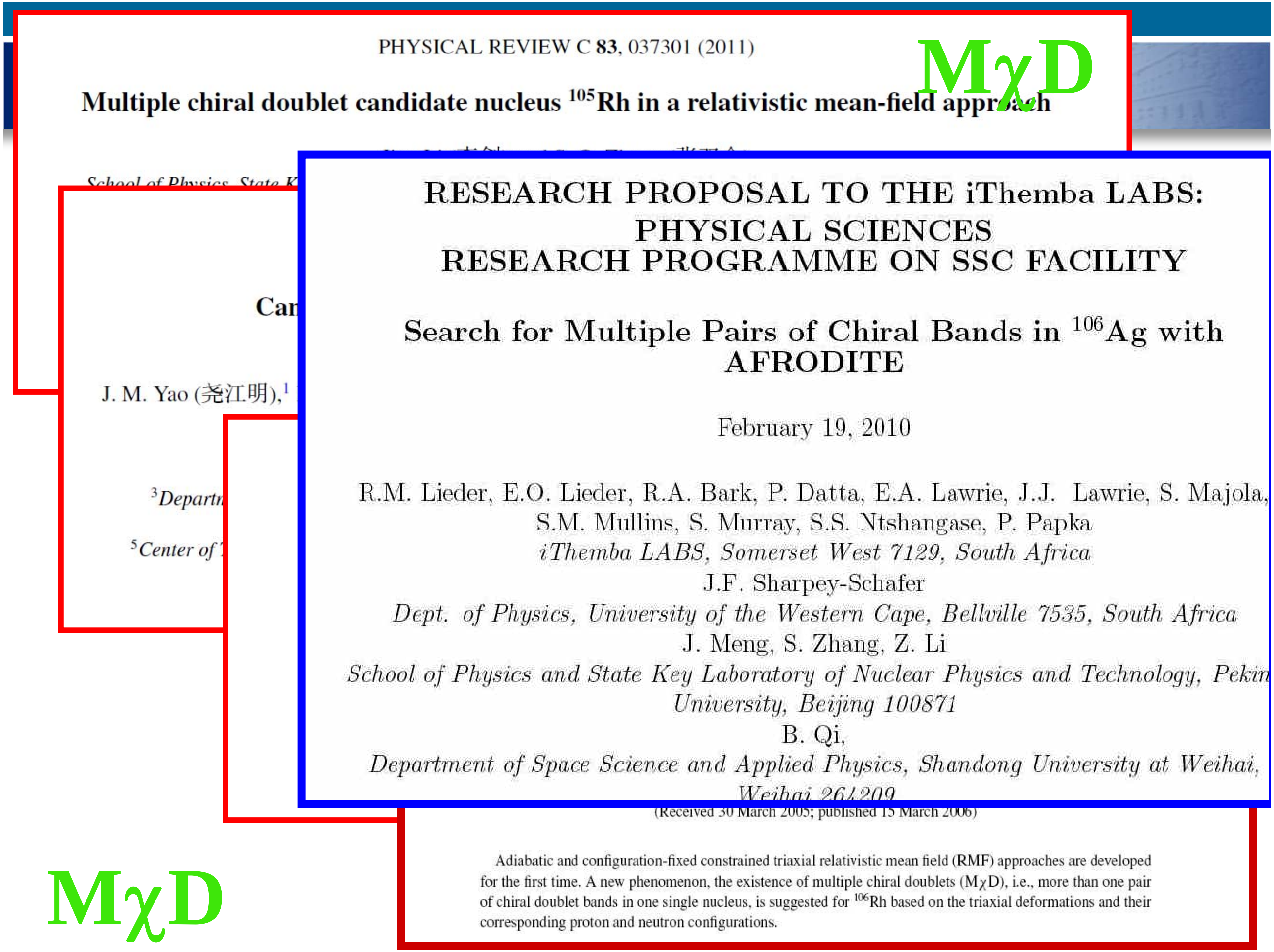
J. Meng,[1,2,3,*] J. Peng,[1] S. Q. Zhang,[1] and S.-G. Zhou[2,3]
[1]*School of Physics, Peking University, Beijing 100871, China*
[2]*Institute of Theoretical Physics, Chinese Academy of Science, Beijing 100080, China*
[3]*Center of Theoretical Nuclear Physics, National Laboratory of Heavy Ion Accelerator, Lanzhou 730000, China*
(Received 30 March 2005; published 15 March 2006)

MχD

iaxial relat
ce of multi
ggested fo







MχD

PHYSICAL REVIEW C **83**, 037301 (2011)

Multiple chiral doublet candidate nucleus ^{105}Rh in a relativistic mean-field approach

School of Physics, State K

Can

J. M. Yao (尧江明),[1]

[3]Departm

[5]Center of

RESEARCH PROPOSAL TO THE iThemba LABS: PHYSICAL SCIENCES RESEARCH PROGRAMME ON SSC FACILITY

Search for Multiple Pairs of Chiral Bands in ^{106}Ag with AFRODITE

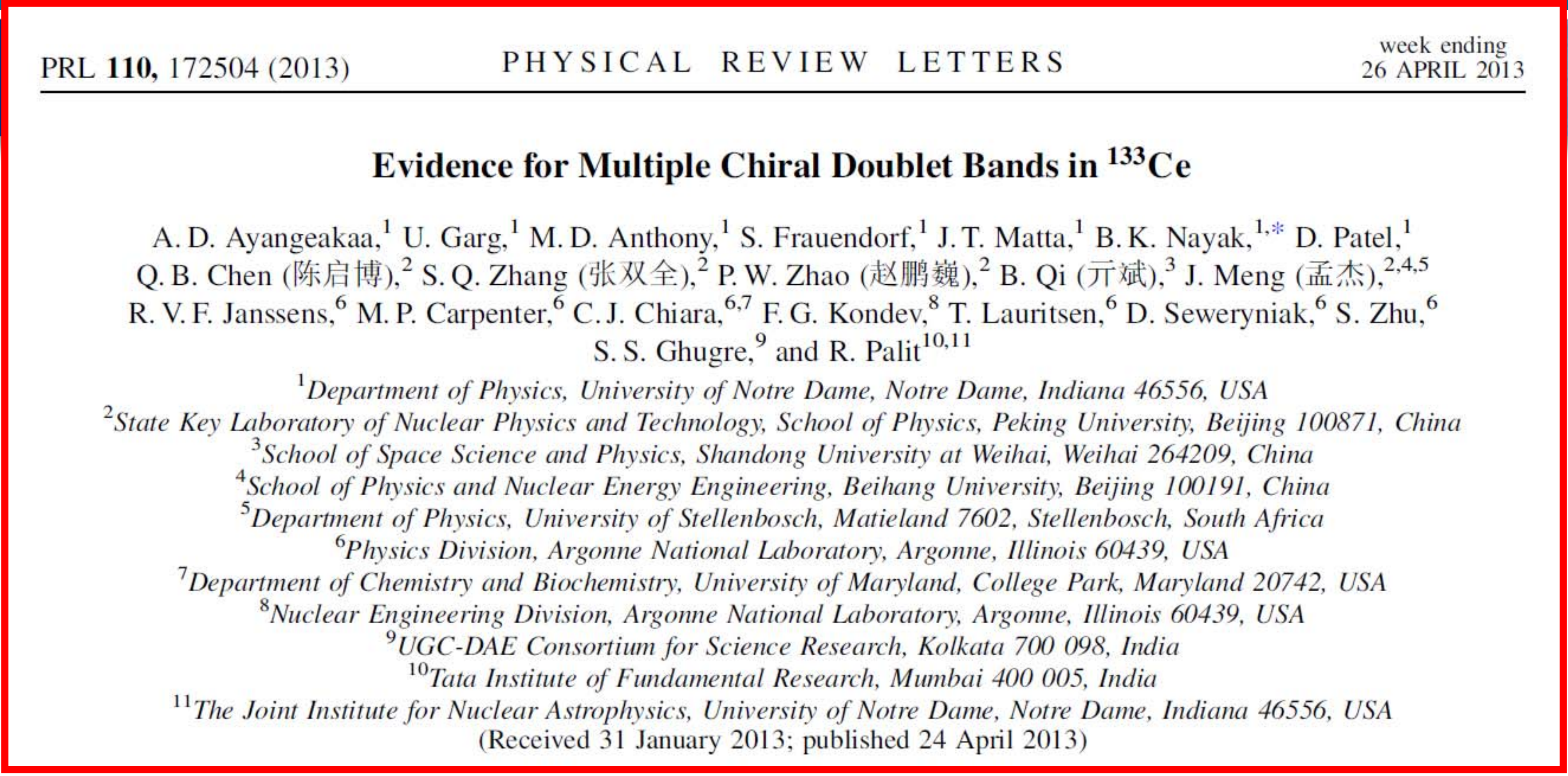
February 19, 2010

R.M. Lieder, E.O. Lieder, R.A. Bark, P. Datta, E.A. Lawrie, J.J. Lawrie, S. Majola,
S.M. Mullins, S. Murray, S.S. Ntshangase, P. Papka
iThemba LABS, Somerset West 7129, South Africa
J.F. Sharpey-Schafer
Dept. of Physics, University of the Western Cape, Bellville 7535, South Africa
J. Meng, S. Zhang, Z. Li
School of Physics and State Key Laboratory of Nuclear Physics and Technology, Pekin
University, Beijing 100871
B. Qi,
Department of Space Science and Applied Physics, Shandong University at Weihai,
Weihai 264209

(Received 30 March 2005; published 15 March 2006)

Adiabatic and configuration-fixed constrained triaxial relativistic mean field (RMF) approaches are developed for the first time. A new phenomenon, the existence of multiple chiral doublets (MχD), i.e., more than one pair of chiral doublet bands in one single nucleus, is suggested for ^{106}Rh based on the triaxial deformations and their corresponding proton and neutron configurations.

MχD



PRL **110,** 172504 (2013) PHYSICAL REVIEW LETTERS week ending 26 APRIL 2013

Evidence for Multiple Chiral Doublet Bands in ^{133}Ce

A. D. Ayangeakaa,[1] U. Garg,[1] M. D. Anthony,[1] S. Frauendorf,[1] J. T. Matta,[1] B. K. Nayak,[1,*] D. Patel,[1]
Q. B. Chen (陈启博),[2] S. Q. Zhang (张双全),[2] P. W. Zhao (赵鹏巍),[2] B. Qi (亓斌),[3] J. Meng (孟杰),[2,4,5]
R. V. F. Janssens,[6] M. P. Carpenter,[6] C. J. Chiara,[6,7] F. G. Kondev,[8] T. Lauritsen,[6] D. Seweryniak,[6] S. Zhu,[6]
S. S. Ghugre,[9] and R. Palit[10,11]

[1]*Department of Physics, University of Notre Dame, Notre Dame, Indiana 46556, USA*
[2]*State Key Laboratory of Nuclear Physics and Technology, School of Physics, Peking University, Beijing 100871, China*
[3]*School of Space Science and Physics, Shandong University at Weihai, Weihai 264209, China*
[4]*School of Physics and Nuclear Energy Engineering, Beihang University, Beijing 100191, China*
[5]*Department of Physics, University of Stellenbosch, Matieland 7602, Stellenbosch, South Africa*
[6]*Physics Division, Argonne National Laboratory, Argonne, Illinois 60439, USA*
[7]*Department of Chemistry and Biochemistry, University of Maryland, College Park, Maryland 20742, USA*
[8]*Nuclear Engineering Division, Argonne National Laboratory, Argonne, Illinois 60439, USA*
[9]*UGC-DAE Consortium for Science Research, Kolkata 700 098, India*
[10]*Tata Institute of Fundamental Research, Mumbai 400 005, India*
[11]*The Joint Institute for Nuclear Astrophysics, University of Notre Dame, Notre Dame, Indiana 46556, USA*

(Received 31 January 2013; published 24 April 2013)

- 2013年4月24日：Evidence for Multiple Chiral Doublet Bands in 133Ce【Phys. Rev. Lett. 110, 172504 (2013)】。
- 美国圣母大学的核物理实验组在美国Argonne国家实验室先后于2008和2011年进行。
- 2012年3月至5月，实验组负责人 U. Garg 教授获得北京大学海外学者讲学计划资助访问中国，
- 中国负责物理分析和理论解释，共同合作完成该文章。

MχD: Multi Chiral Pair-Bands

- Q. B. Chen, J. M. Yao, S. Q. Zhang, B. Qi, Chiral geometry of higher excited bands in triaxial nuclei with particle-hole configuration, Phys.Rev.C82, 067302(2010)
- Ikuko Hamamoto, Possible Presence and Properties of Multi Chiral Pair-Bands in Odd-Odd Nuclei with the Same Intrinsic Configuration, arXiv:1307.2970

DFT: Cranking version

TAC based on Covariant Density Functional Theory

✓ **Meson exchange version:**

3-D Cranking: ***Madokoro, Meng, Matsuzaki, Yamaji, PRC 62, 061301 (2000)***

2-D Cranking: ***Peng, Meng, Ring, Zhang, PRC 78, 024313 (2008)***

✓ **Point coupling version:** Simple and more suitable for systematic investigations

2-D Cranking: ***Zhao, Zhang, Peng, Liang, Ring, Meng, PLB 699, 181 (2011)***

TAC based on Skyrme Density Functional Theory

3-D Cranking: ***Olbratowski, Dobaczewski, Dudek, Płóciennik, PRL 93, 052501(2004)***

2-D Cranking: ***Olbratowski, Dobaczewski, Dudek, Rzaca-Urban, Marcinkowska, Lieder, APPB 33, 389(2002)***

Fully self-consistent microscopic investigations

- fully taken into account polarization effects
- self-consistently treated the nuclear currents
- without any adjustable parameters for rotational excitations

Tilted axis cranking CDFT

General Lagrangian density

$$
\begin{aligned}
L = {} & \bar{\psi}(i\gamma_\mu\partial^\mu - m)\psi \\
& -\frac{1}{2}\alpha_S(\bar{\psi}\psi)(\bar{\psi}\psi) - \frac{1}{2}\alpha_V(\bar{\psi}\gamma_\mu\psi)(\bar{\psi}\gamma^\mu\psi) - \frac{1}{2}\alpha_{TV}(\bar{\psi}\vec{\tau}\gamma_\mu\psi)(\bar{\psi}\vec{\tau}\gamma^\mu\psi) \\
& -\frac{1}{3}\beta_S(\bar{\psi}\psi)^3 - \frac{1}{4}\gamma_S(\bar{\psi}\psi)^4 - \frac{1}{4}\gamma_V[(\bar{\psi}\gamma_\mu\psi)(\bar{\psi}\gamma^\mu\psi)]^2 \\
& -\frac{1}{2}\delta_S\partial_\nu(\bar{\psi}\psi)\partial^\nu(\bar{\psi}\psi) - \frac{1}{2}\delta_V\partial_\nu(\bar{\psi}\gamma_\mu\psi)\partial^\nu(\bar{\psi}\gamma^\mu\psi) - \frac{1}{2}\delta_{TV}\partial_\nu(\bar{\psi}\vec{\tau}\gamma_\mu\psi)\partial^\nu(\bar{\psi}\vec{\tau}\gamma_\mu\psi) \\
& -e\frac{1-\tau_3}{2}\bar{\psi}\gamma^\mu\psi A_\mu - \frac{1}{4}F^{\mu\nu}F_{\mu\nu}
\end{aligned}
$$

Transformed to the frame rotating with the uniform velocity

$$\Omega = (\Omega_x, 0, \Omega_z) = (\Omega\cos\theta_\Omega, 0, \Omega\sin\theta_\Omega)$$

$$x^\alpha = \begin{pmatrix} t \\ \mathbf{x} \end{pmatrix} \rightarrow \tilde{x}^\alpha = \begin{pmatrix} \tilde{t} \\ \tilde{\mathbf{x}} \end{pmatrix} = \begin{pmatrix} 1 & 0 \\ 0 & \mathbf{R} \end{pmatrix} \begin{pmatrix} t \\ \mathbf{x} \end{pmatrix}$$

Koepf NPA1989; Kaneko PLB1993; Madokoro PRC1997

TAC RMF:equations of motion

Dirac Equation

$$\left[\alpha\cdot\left(-i\nabla-\vec{V}(\mathbf{r})\right)+\beta\left(M+S(\mathbf{r})\right)+V(\mathbf{r})-\Omega\cdot J\right]\psi_i=\varepsilon_i\psi_i$$

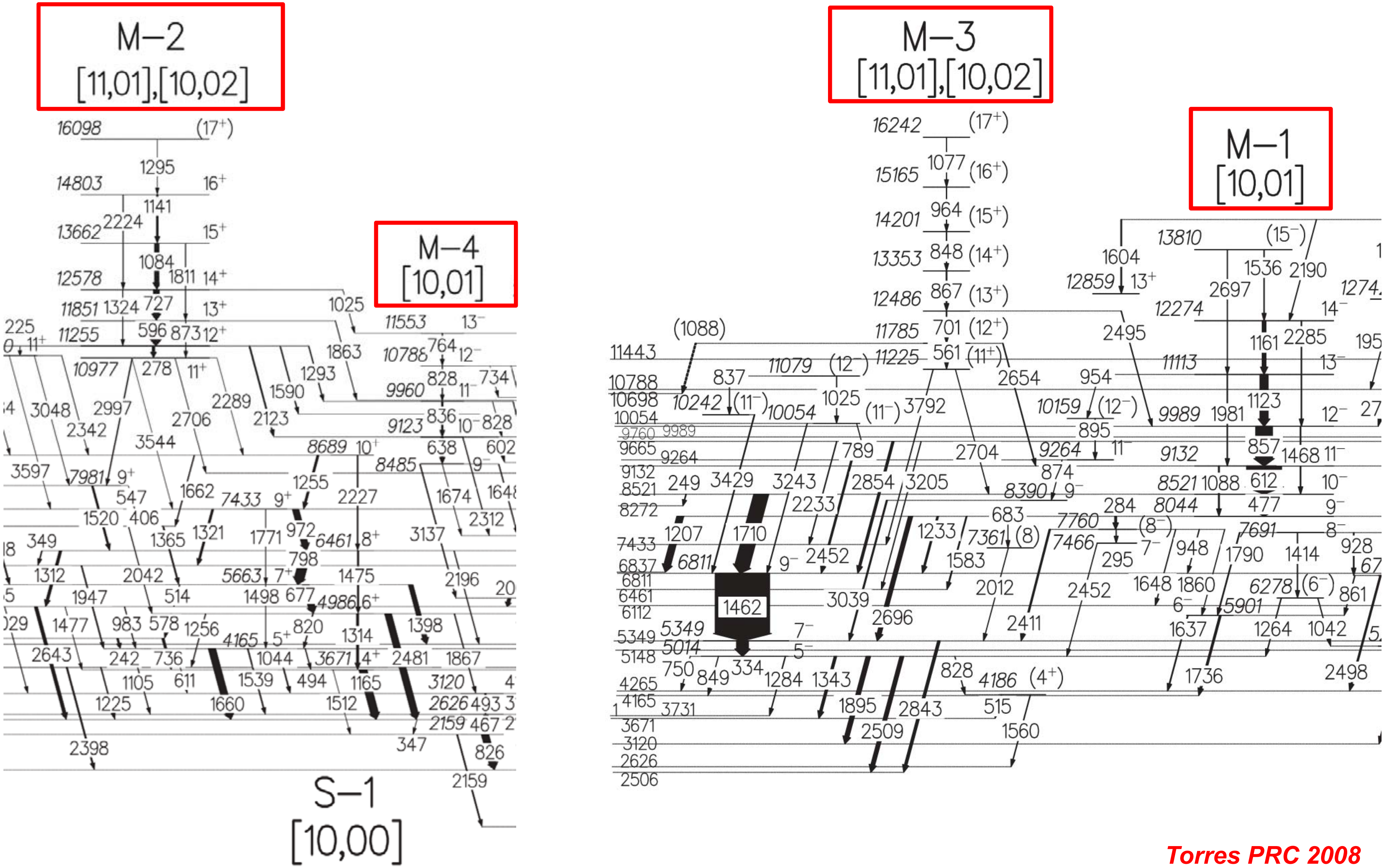
Potential

$$\begin{cases} S(r)=\alpha_S\rho_S+\beta_S\rho_S^2+\gamma_S\rho_S^3+\delta_S\Delta\rho_S \\ V^\mu(\mathbf{r})=\alpha_V j_V^\mu(\mathbf{r})+\gamma_V(j_V^\mu)^3(\mathbf{r})+\delta_V\Delta j_V^\mu(\mathbf{r})+\tau_3\alpha_{TV} j_{TV}^\mu(\mathbf{r})+\tau_3\delta_{TV}\Delta j_{TV}^\mu(\mathbf{r})+e\frac{1-\tau_3}{2}A^\mu(\mathbf{r}) \end{cases}$$

Spatial components of vector field are included due to the violation of the time-reversal invariance

MR: ^{60}Ni

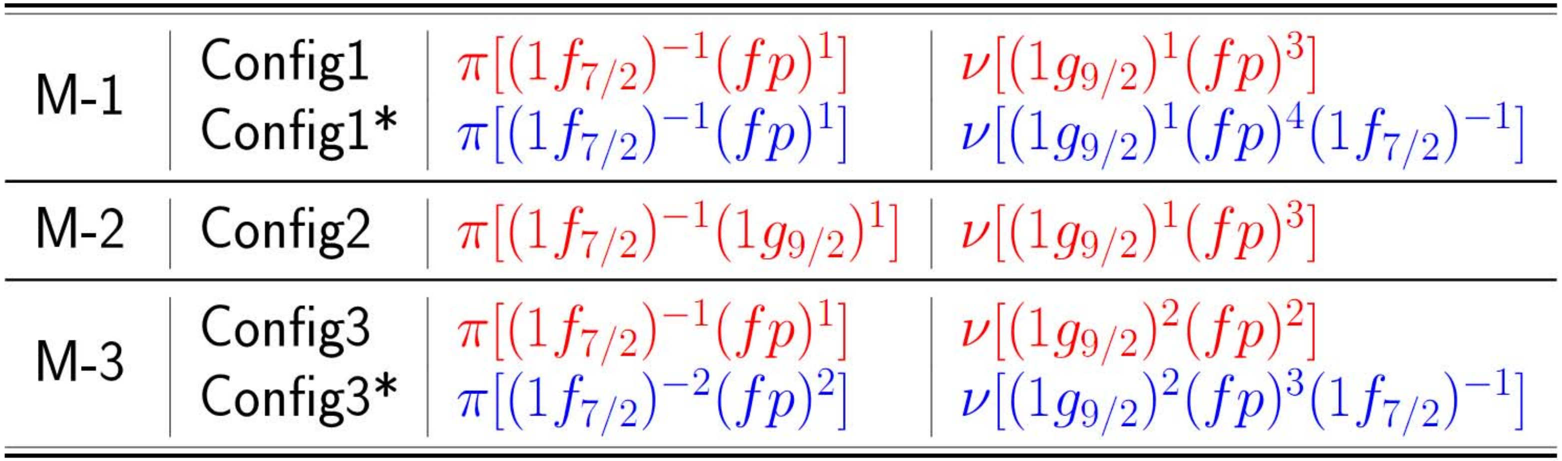
lightest nucleus with magnetic rotation



Torres PRC 2008

MR: ^{60}Ni

- Harmonic oscillator shells: Nf = 10
- Parameter set: PC-PK1
- Configurations:



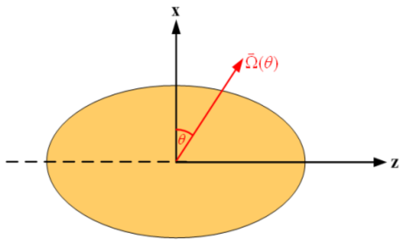
M-1	Config1	$\pi[(1f_{7/2})^{-1}(fp)^{1}]$	$\nu[(1g_{9/2})^{1}(fp)^{3}]$
	Config1*	$\pi[(1f_{7/2})^{-1}(fp)^{1}]$	$\nu[(1g_{9/2})^{1}(fp)^{4}(1f_{7/2})^{-1}]$
M-2	Config2	$\pi[(1f_{7/2})^{-1}(1g_{9/2})^{1}]$	$\nu[(1g_{9/2})^{1}(fp)^{3}]$
M-3	Config3	$\pi[(1f_{7/2})^{-1}(fp)^{1}]$	$\nu[(1g_{9/2})^{2}(fp)^{2}]$
	Config3*	$\pi[(1f_{7/2})^{-2}(fp)^{2}]$	$\nu[(1g_{9/2})^{2}(fp)^{3}(1f_{7/2})^{-1}]$

Zhao, Zhang, Peng, Liang, Ring, Meng, PLB 699, 181 (2011)

Numerical Details

◆ **Symmetry**

	$\mathcal{P}$	$\mathcal{P}_x\mathcal{T}$	$\mathcal{P}_x$	$\mathcal{P}_z\mathcal{T}$	$\mathcal{P}_z$	$\mathcal{P}_y\mathcal{T}$	$\mathcal{P}_y$
J_x	√	×	√	√	×	√	×
J_z	√	√	×	×	√	√	×



$(\mathcal{P}_y = \mathcal{P}\mathcal{R}_y(\pi))$

◆ **Identification of the energy levels**

$$|n_x\ n_y\ n_z\ n_s\rangle \rightarrow |nljm_z\rangle \rightarrow |nljm_x\rangle$$

Cartesian basis **Spherical basis**

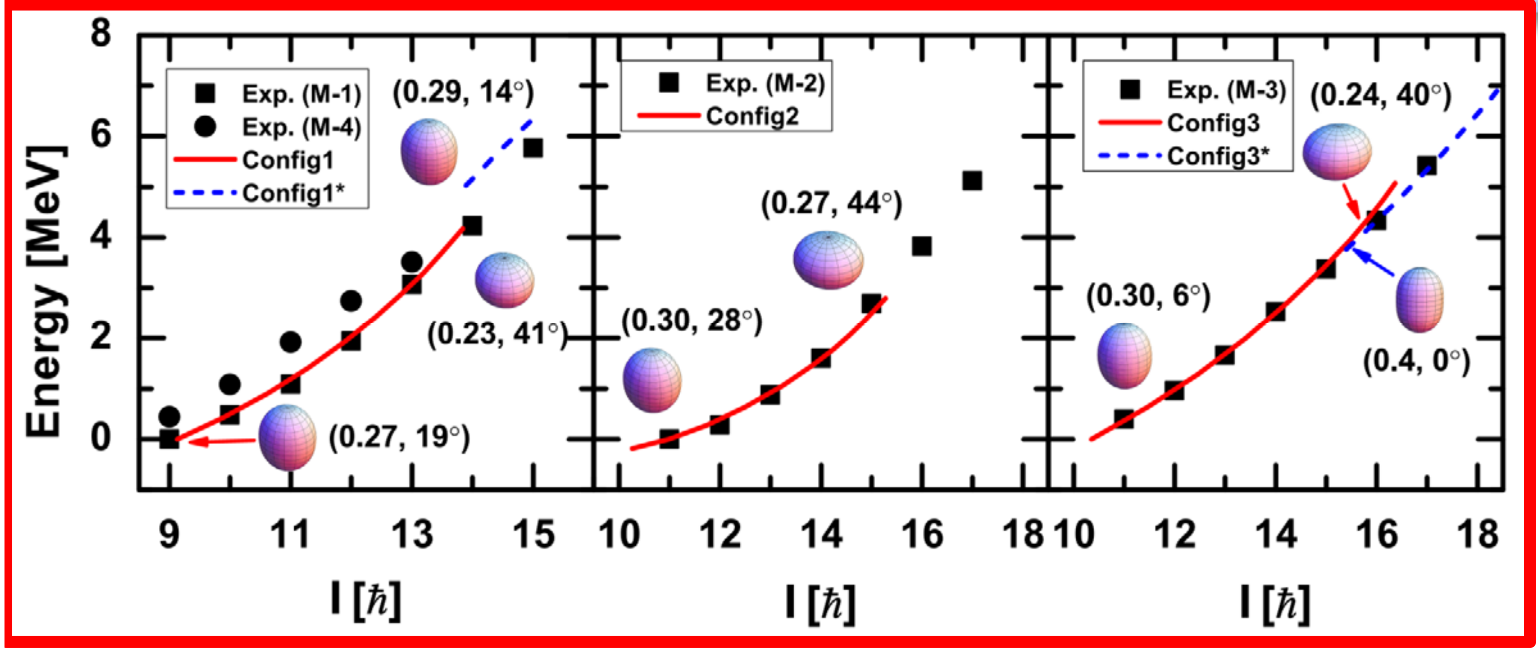
◆ **Constrained intrinsic framework:** principal axes identical with the x, y, z axis.

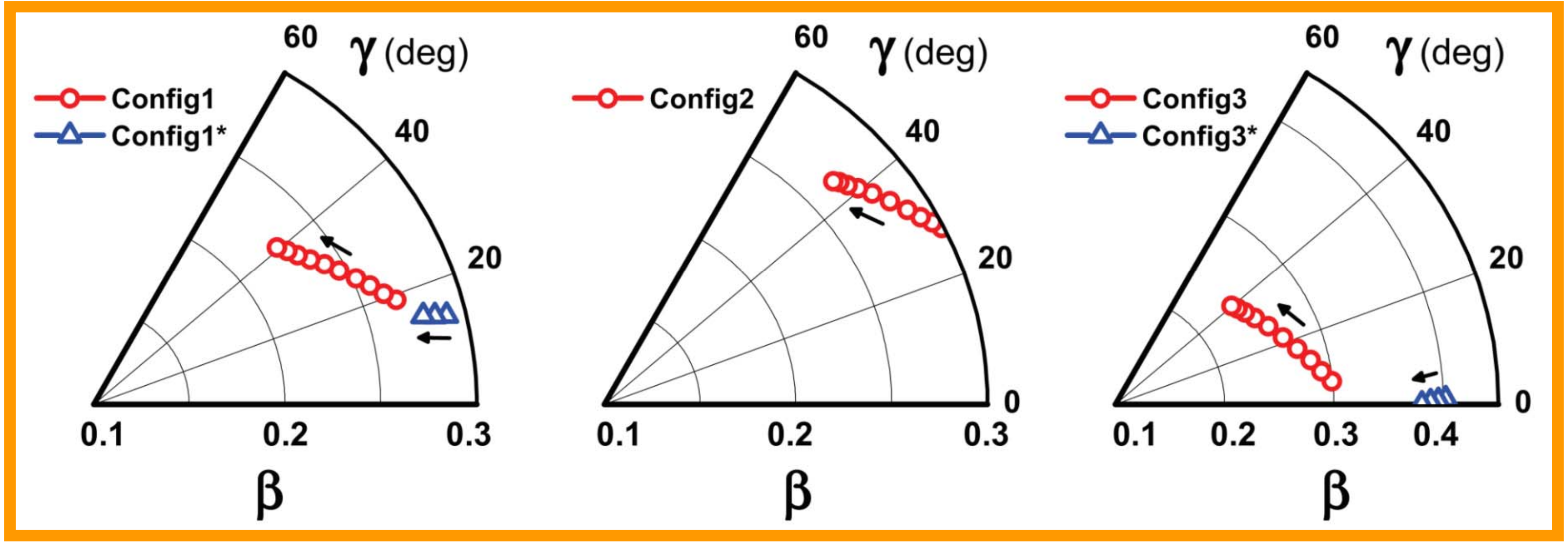
$$\langle H'\rangle = \langle H\rangle + \frac{1}{2}C\left(\langle Q_{2-1}\rangle - a_{2-1}\right)^2 \qquad a_{2-1} = 0$$

◆ **Parallel transport principle: fixed the configuration**

$$\left\langle \phi_j(\Omega + \delta\Omega)\middle|\phi_i(\Omega)\right\rangle \approx 1$$

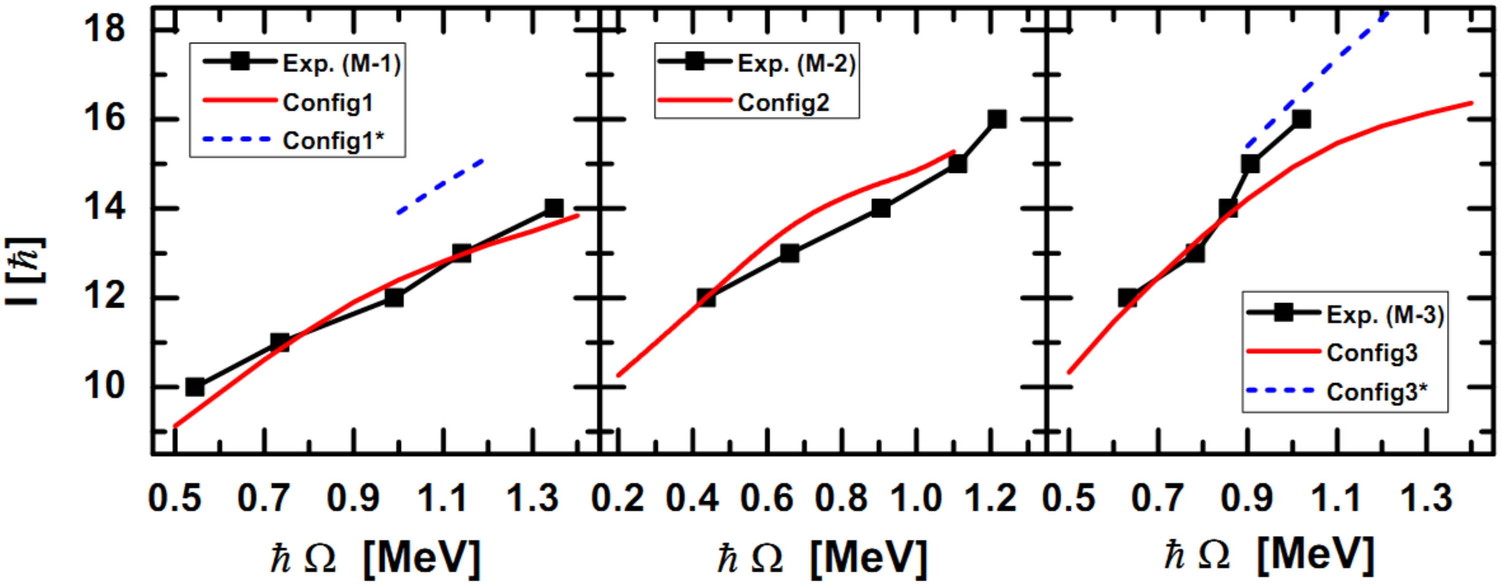
MR: ^{60}Ni





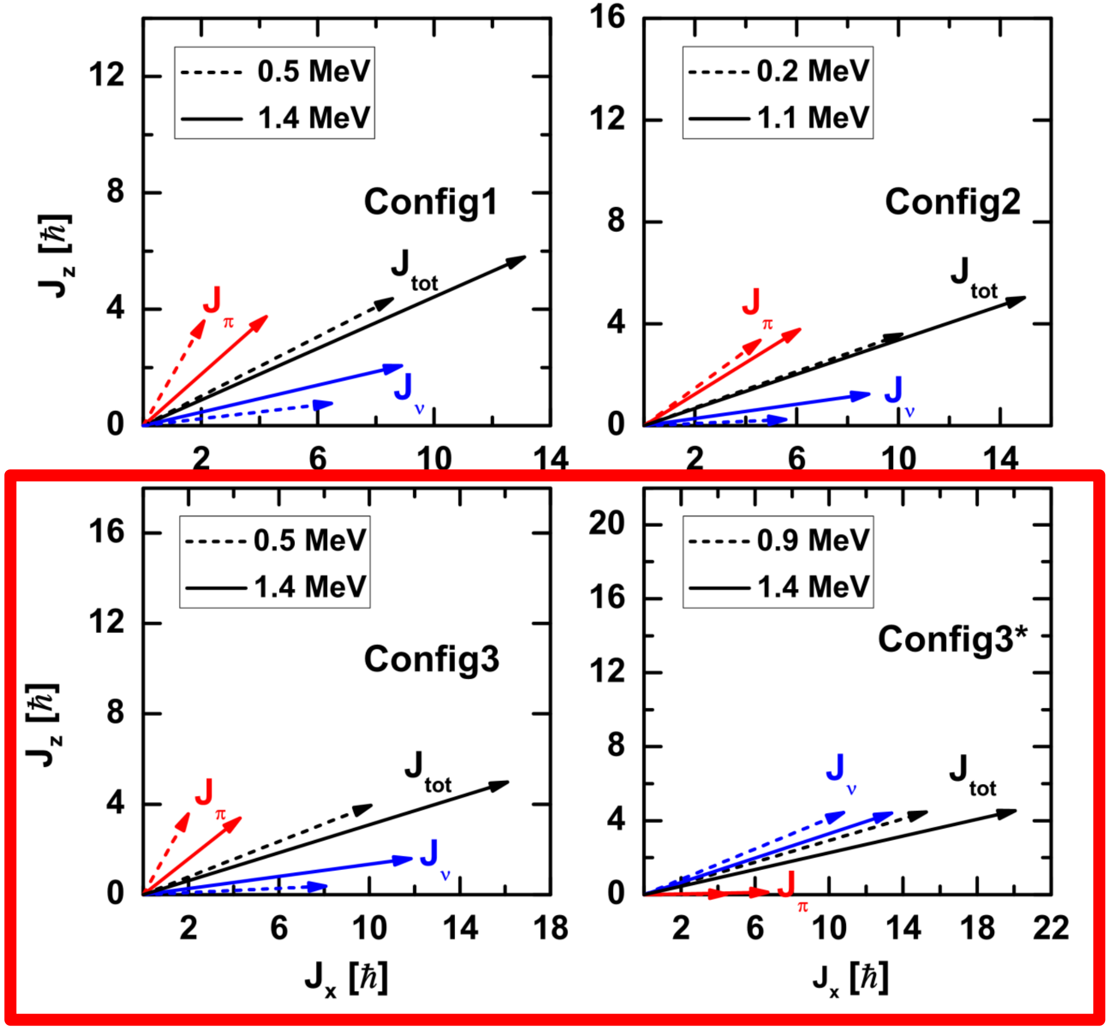
Zhao, Zhang, Peng, Liang, Ring, Meng, PLB 699, 181 (2011)

MR: ^{60}Ni



Zhao, Zhang, Peng, Liang, Ring, Meng, PLB 699, 181 (2011)

MR: ^{60}Ni



Magnetic Rotation

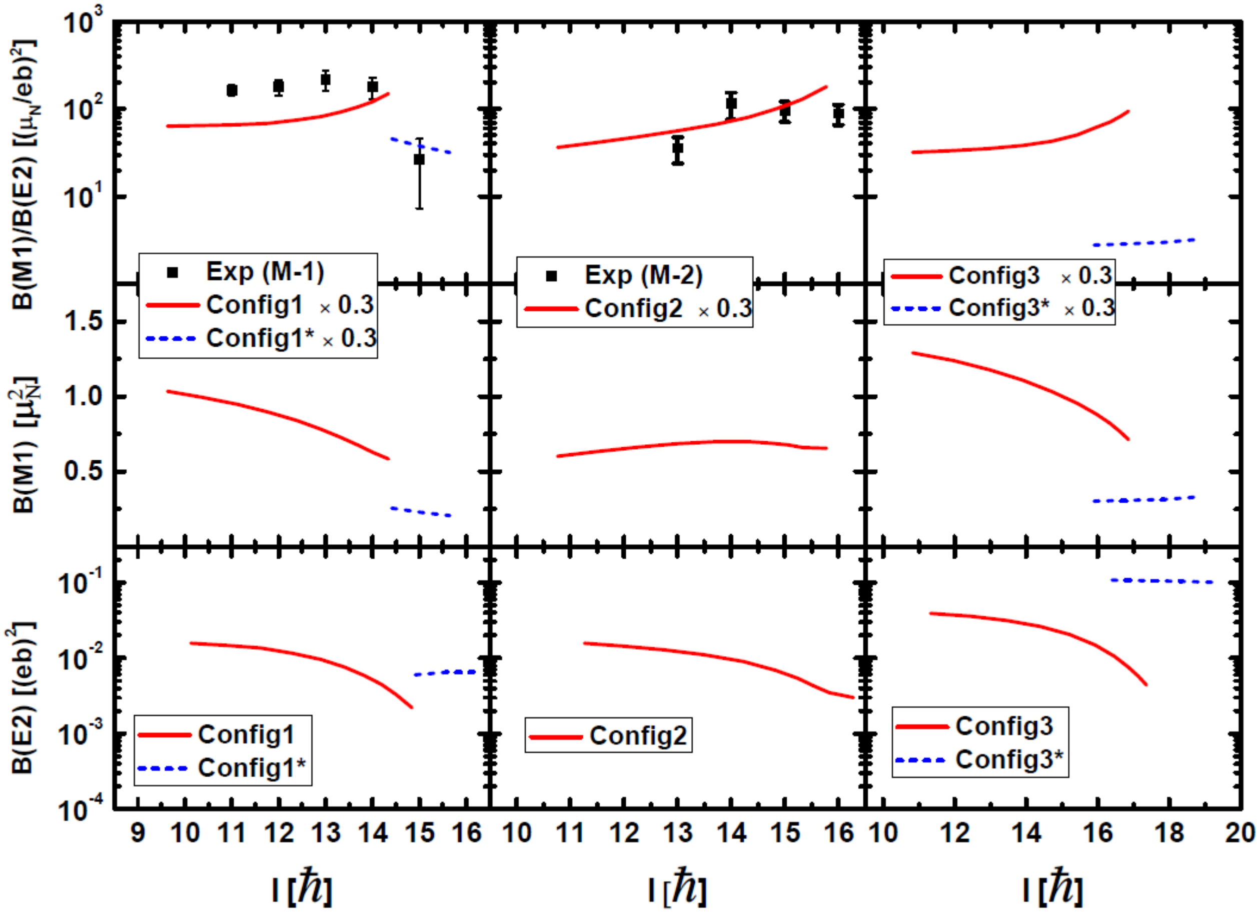
↓

Electric Rotation

Shears mechanism

Zhao, Zhang, Peng, Liang, Ring, Meng, PLB 699, 181 (2011)

MR: ^{60}Ni



Electromagnetic transition properties

Zhao, Zhang, Peng, Liang, Ring, Meng, PLB 699, 181 (2011)

- ^{198}Pb and ^{199}Pb: MR Yu, Zhao, Zhang, Ring, Meng, PRC 85, 024318 (2012)
- ^{58}Fe: MR Steppenbeck et al, PRC 85, 044316 (2012)

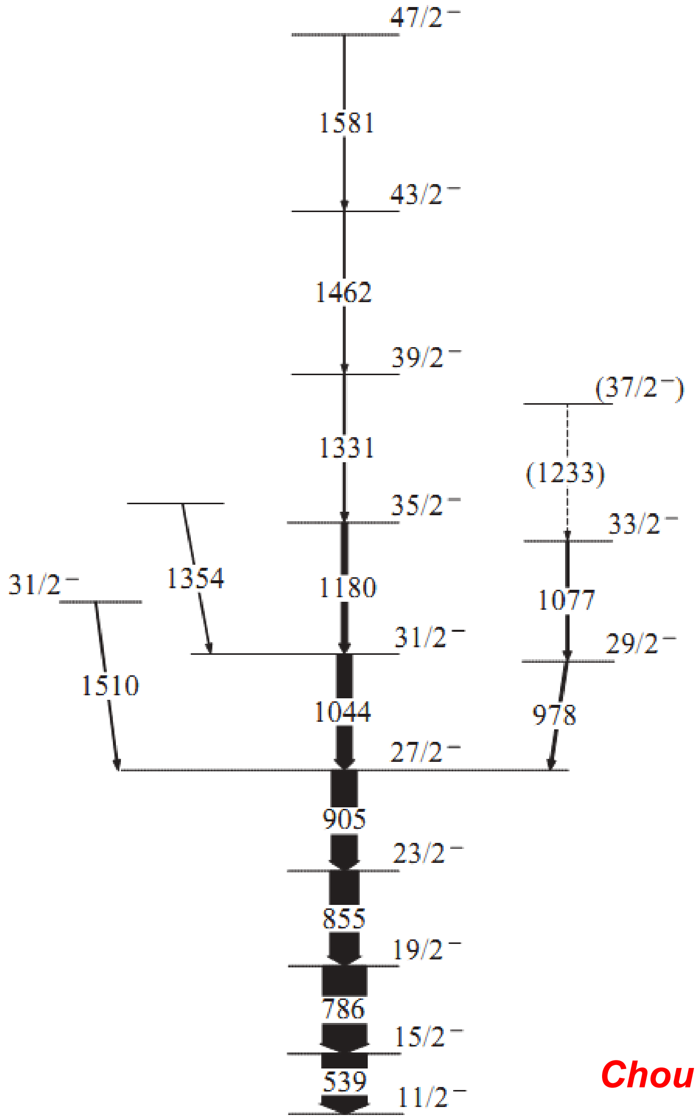
Meng, Peng, Zhang, Zhao,

Progress on tilted axis cranking covariant density functional theory for nuclear magnetic and antimagnetic rotation

Frontiers of Physics 8: 1, 55-79 (2013)

AMR: ^{105}Cd

first odd-A nucleus with antimagnetic rotation



Choudhury et al., Phys. Rev. C 82, 061308 (2010).

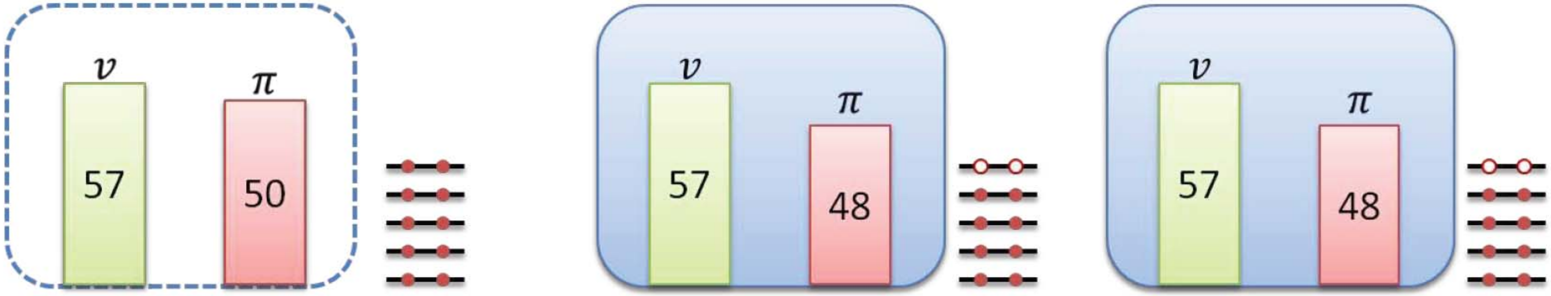
AMR: ^{105}Cd

- **Harmonic oscillator shells: Nf = 10**
- **Parameter set: PC-PK1**
- **Configurations:** $\nu[h_{11/2}(g_{7/2})^2] \otimes \pi[(g_{9/2})^{-2}]$ *Choudhury PRC2010*
- **Polarizations:**

Without Polarization
Self-consistency

Without Polarization
Without Self-consistency

With Polarization
Self-consistency



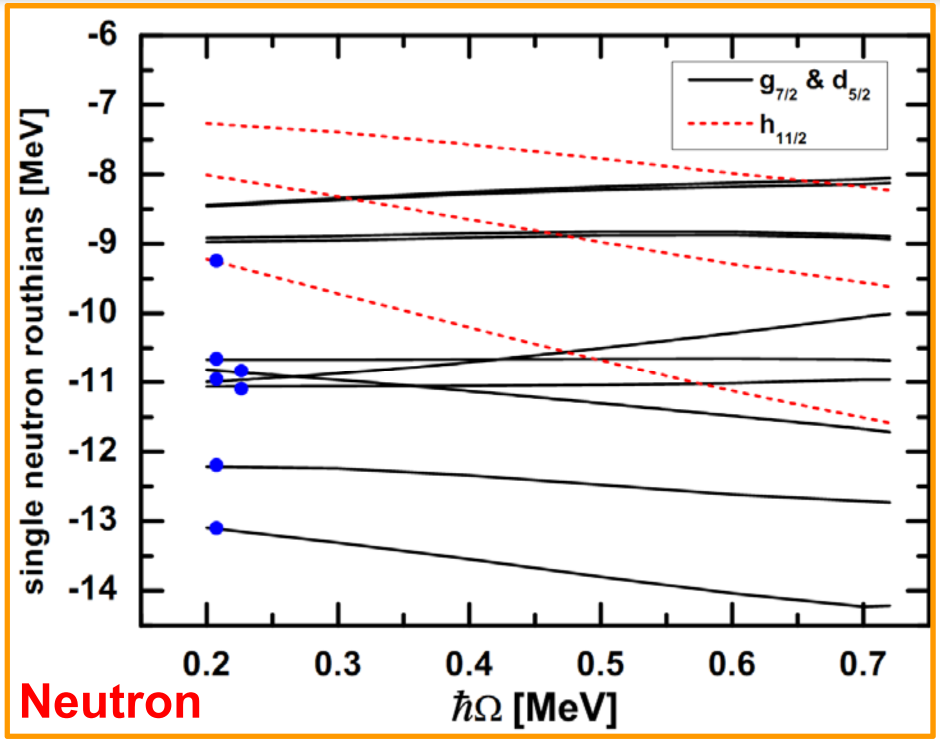
^{107}Sn

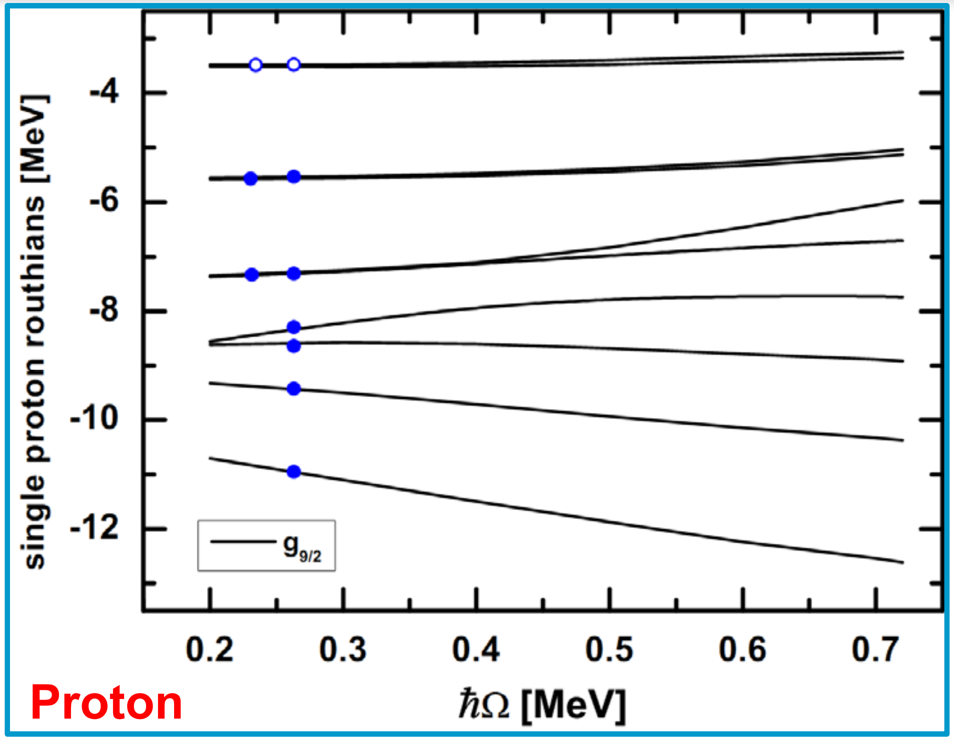
^{107}Sn + $\pi[(g_{9/2})^{-2}]$

^{105}Cd

Zhao, Peng, Liang, Ring, Meng PRL 107, 122501(2011)

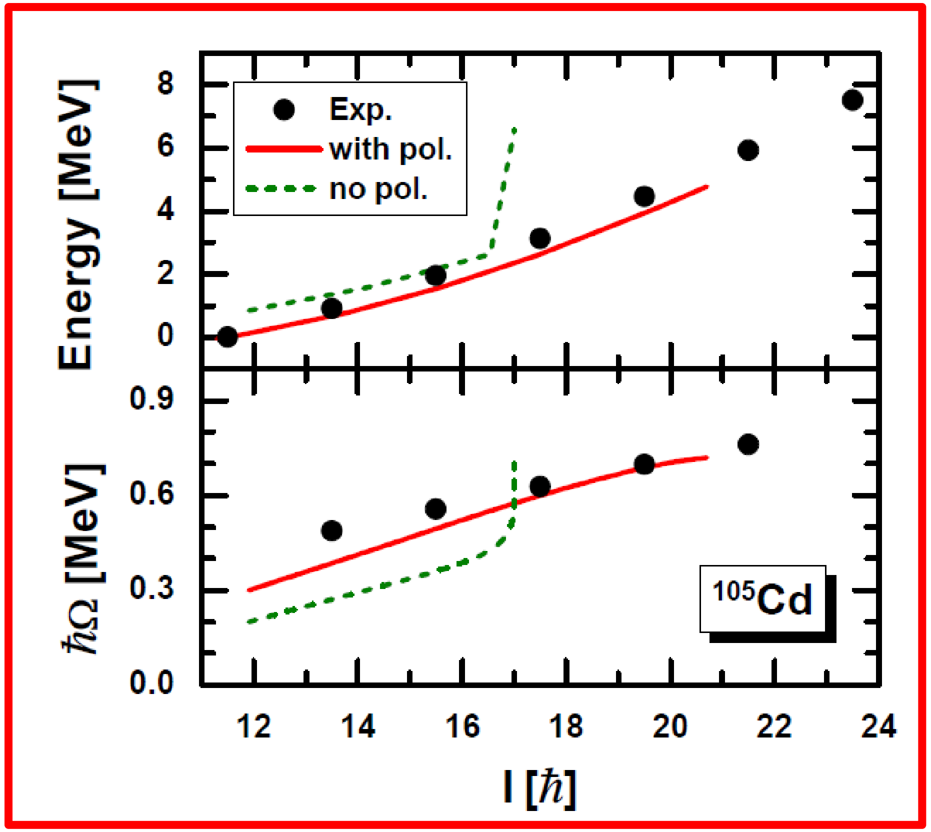
AMR: Single particle routhians

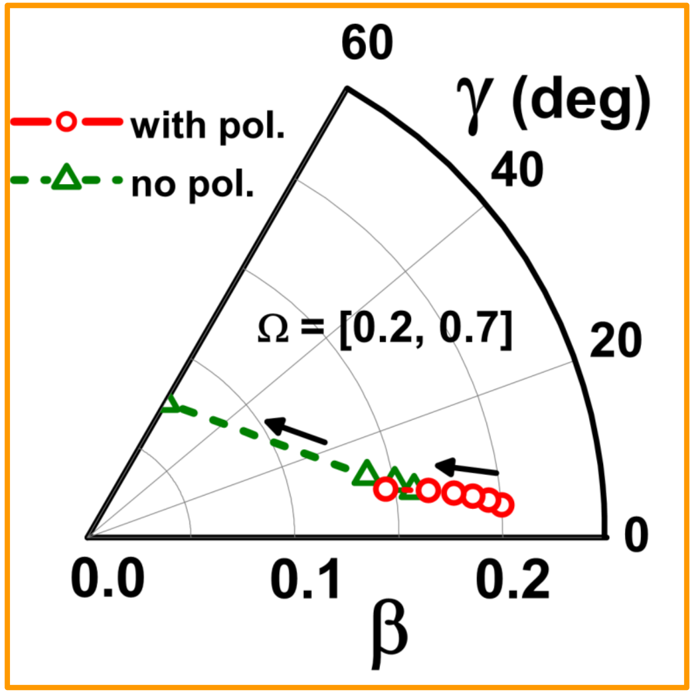




- Time reversal symmetry broken ⟹ energy splitting
- For proton, two holes in the top of $g_{9/2}$ shell
- For neutron, one particle in the bottom of $h_{11/2}$ shell, the other six are distributed over the (gd) shell with strong mixing
- This configuration is similar to $\nu[h_{11/2}(g_{7/2})^2] \otimes \pi[(g_{9/2})^{-2}]$, but not exactly

AMR: ^{105}Cd

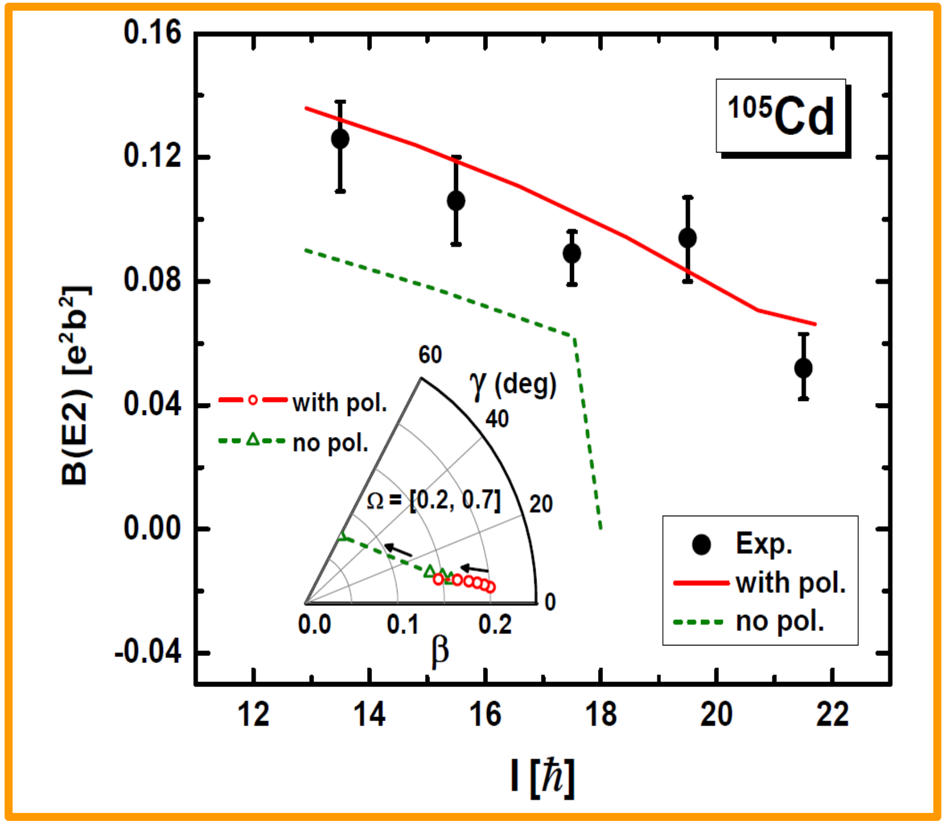




Zhao, Peng, Liang, Ring, Meng   PRL 107, 122501(2011)

Zhao, Peng, Liang, Ring, Meng PRC 85, 054310 (2012)

AMR: ^{105}Cd

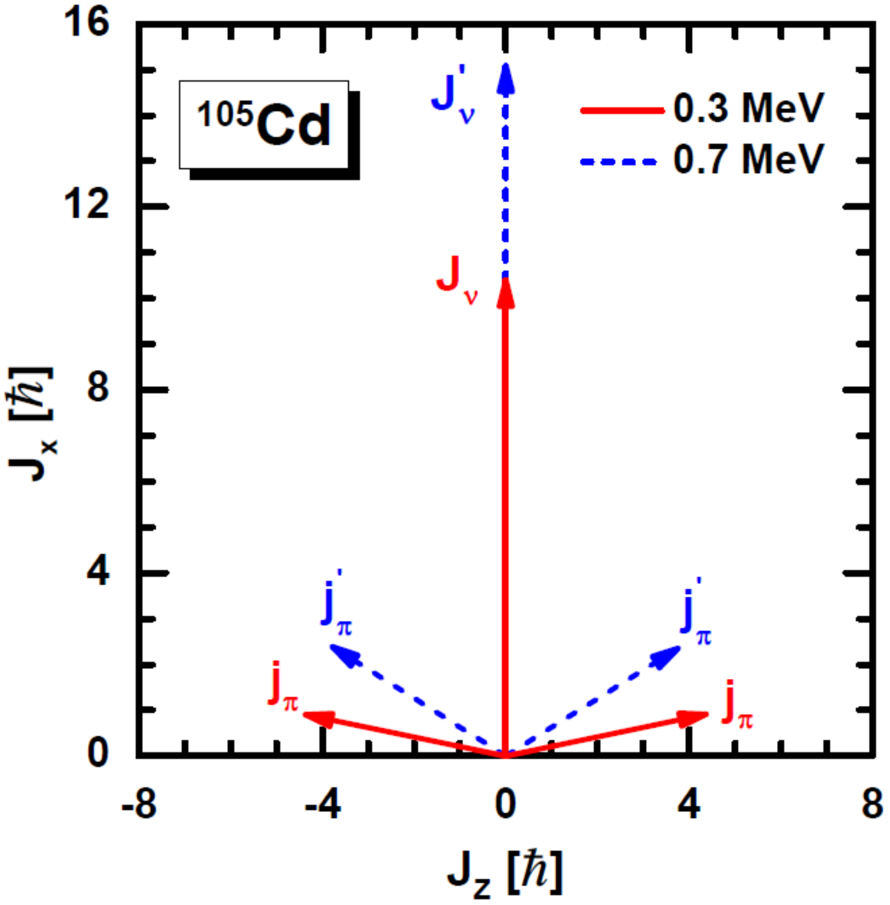


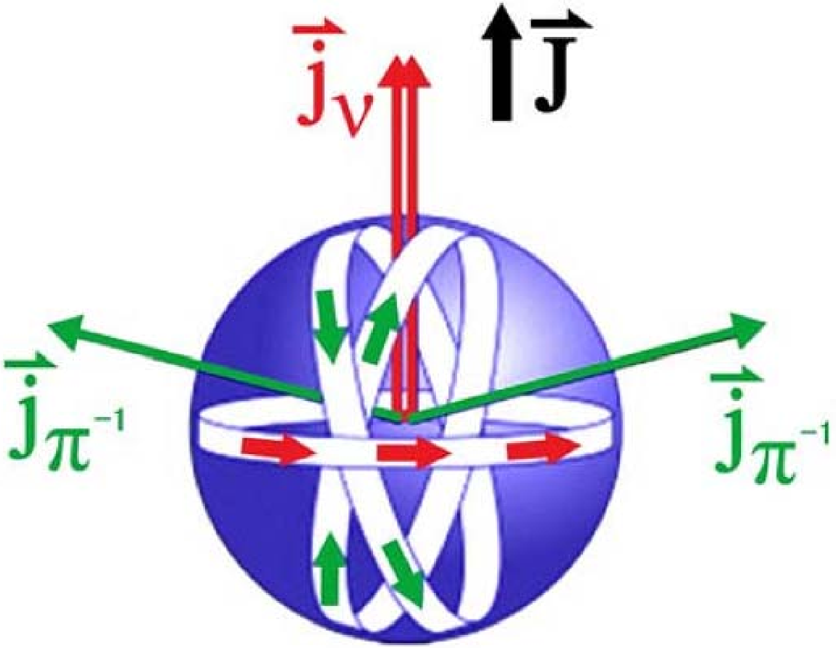
Polarization effects play important roles in the description of AMR, especially for E2 transitions.

Zhao, Peng, Liang, Ring, Meng PRL 107, 122501(2011)

Zhao, Peng, Liang, Ring, Meng PRC 85, 054310 (2012)

AMR: ^{105}Cd



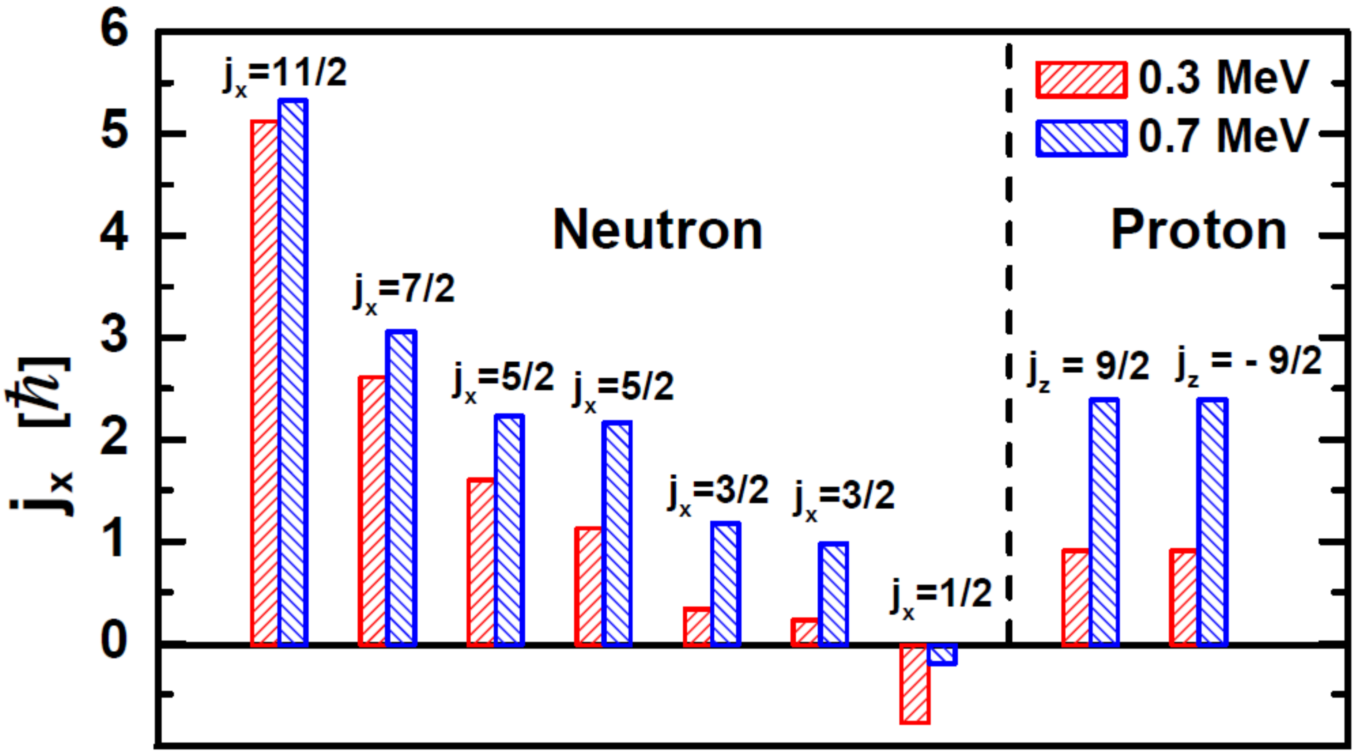


Two "shears-like" mechanism

Zhao, Peng, Liang, Ring, Meng   PRL 107, 122501(2011)

Zhao, Peng, Liang, Ring, Meng PRC 85, 054310 (2012)

AMR: ^{105}Cd



In the microscopic point of view, increasing angular momentum results from the alignment of the proton holes and the mixing within the neutron orbitals.

Zhao, Peng, Liang, Ring, Meng   PRL 107, 122501(2011)

Zhao, Peng, Liang, Ring, Meng PRC 85, 054310 (2012)

Summary & Perspectives

IOP PUBLISHING JOURNAL OF PHYSICS G: NUCLEAR AND PARTICLE PHYSICS

J. Phys. G: Nucl. Part. Phys. 37 (2010) 064025 (11pp) doi:10.1088/0954-3899/37/6/064025

Open problems in understanding the nuclear chirality

Jie Meng[1,2,3] **and S Q Zhang**[2]

[1] School of Physics and Nuclear Energy Engineering, Beihang University, Beijing 100191, People's Republic of China
[2] State Key Laboratory of Nuclear Physics and Technology, School of Physics, Peking University, Beijing 100871, People's Republic of China
[3] Department of Physics, University of Stellenbosch, Stellenbosch, South Africa

E-mail: mengj@pku.edu.cn

- ☐ Chirality in atomic nuclei is a hot topic
- ☐ Lots of theoretical and experimental progress on chirality in atomic nuclei are achieved
- ☐ Efforts to understand nuclear chirality more are appreciated

Thank you！