北京大学 PEKING UNIVERSITY
iTHES workshop on "Exploration of hidden symmetries in atomic nuclei"
Saturday, 27 July 2013 from 9:00 to 18:00
at RIKEN Wako Campus

Hidden symmetries in atomic nuclei: a brief introduction

Jie Meng 孟 杰

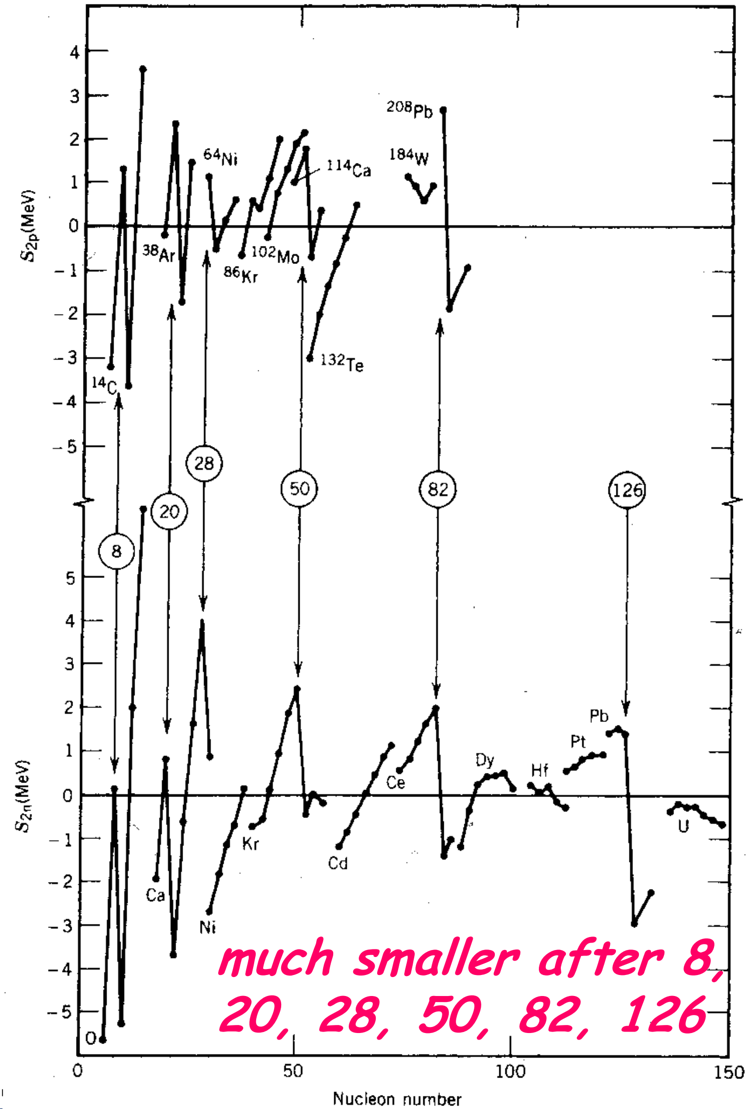
北京大学物理学院
School of Physics, Peking University
mengj@pku.edu.cn

Nuclear magic number

Nuclear properties change periodically with proton or neutron number

原子核性质随中子数或质子数周期性地变化

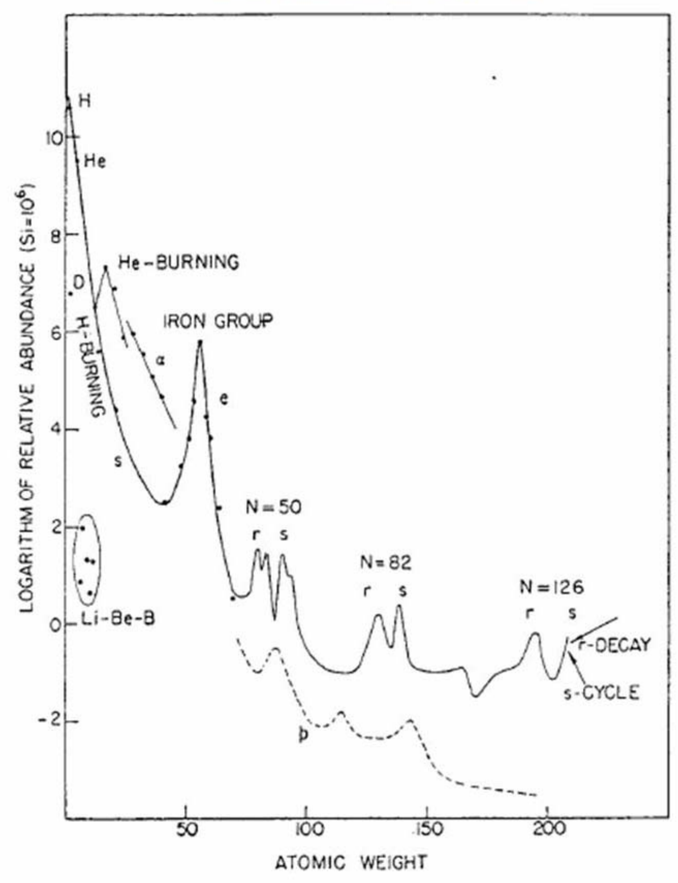
two-nucleon separation energy



ΔS_{2p}

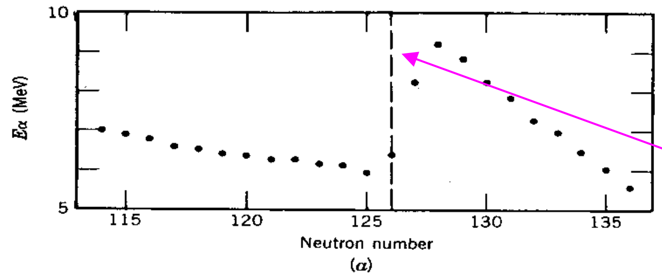
ΔS_{2n}

Abundance curve



Nuclear magic number

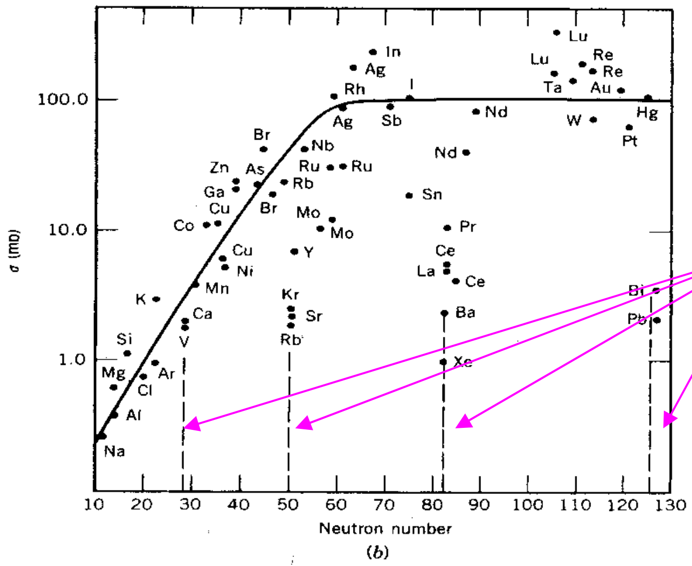
T_α



$^{A}Rn \rightarrow \alpha + {}^{A-4}Po$

Sudden rise at N = 126

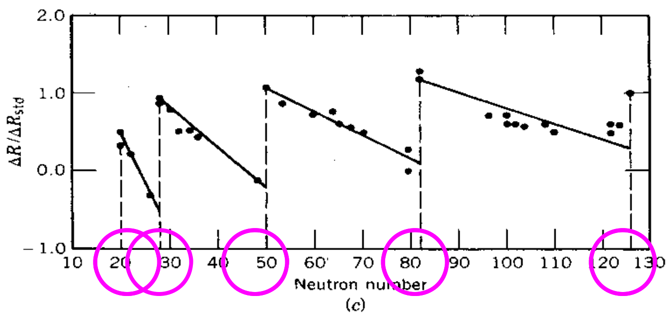
σ



Neutron capture cross section σ

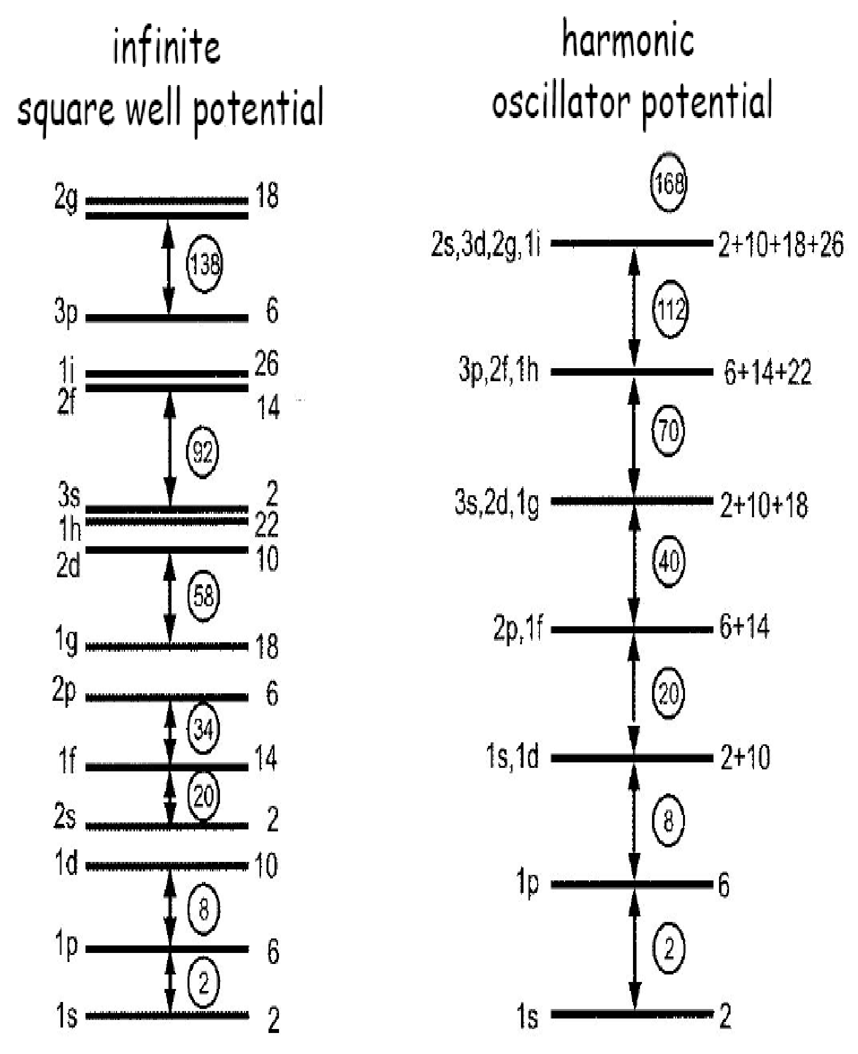
Very small σ at N = 28, 50, 82, 126

$\frac{\Delta R}{\Delta R_{avg}}$



Abrupt change in nuclear radius at N = 20, 28, 50, 82, 126

原子核壳结构 Nuclear Shell Model



Only smallest magic numbers are reproduced. Why ?

Spin-orbit term is necessary

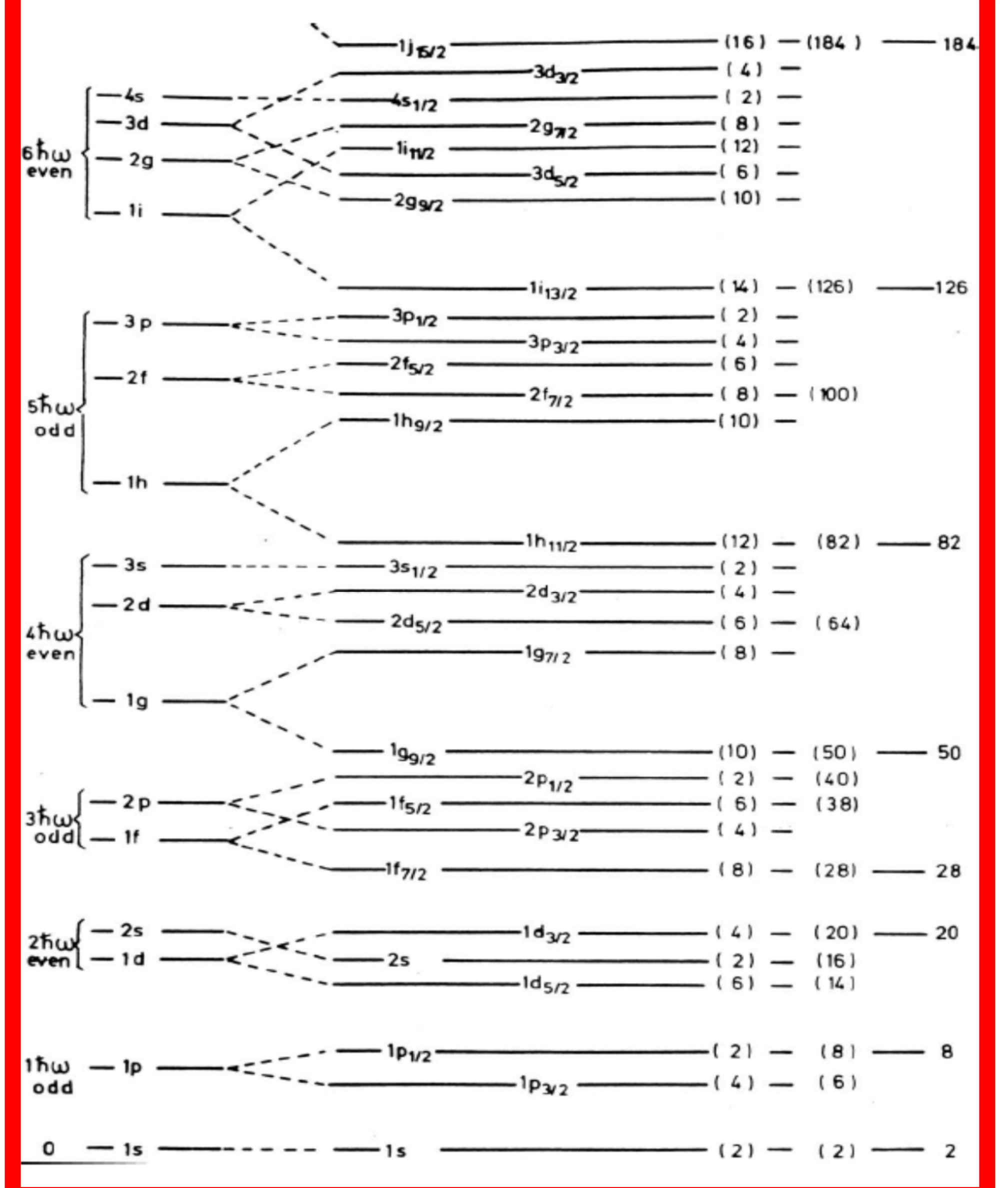
Mayer and Jensen et al., 1949

$$V_{so} = -V_{\ell s}\frac{1}{r}\frac{\partial V(r)}{\partial r}\underline{\ell}.\underline{s}$$

M. G. Mayer, Phys. Rev. 75(1949)1969; 78(1950).
O. Haxel, J. H. D. Jensen, and H. E. Suess, Phys. Rev. 75(1949)1766;Z. Phys. 128(1950)295;

北京大學 PEKING UNIVERSITY

原子核壳结构 Nuclear Shell Model



Great for:

magic numbers

ground state properties

some low lying excited states

强自旋-轨道壳模型是原子核结构的所有微观理论的出发点

S. G. Nilsson的轴对称变形核的强自旋-轨道壳模型能级系

S. G. Nilsson, Mat. Fys. Medd. Dan. Vid. Selsk. 29, No.16(1955).

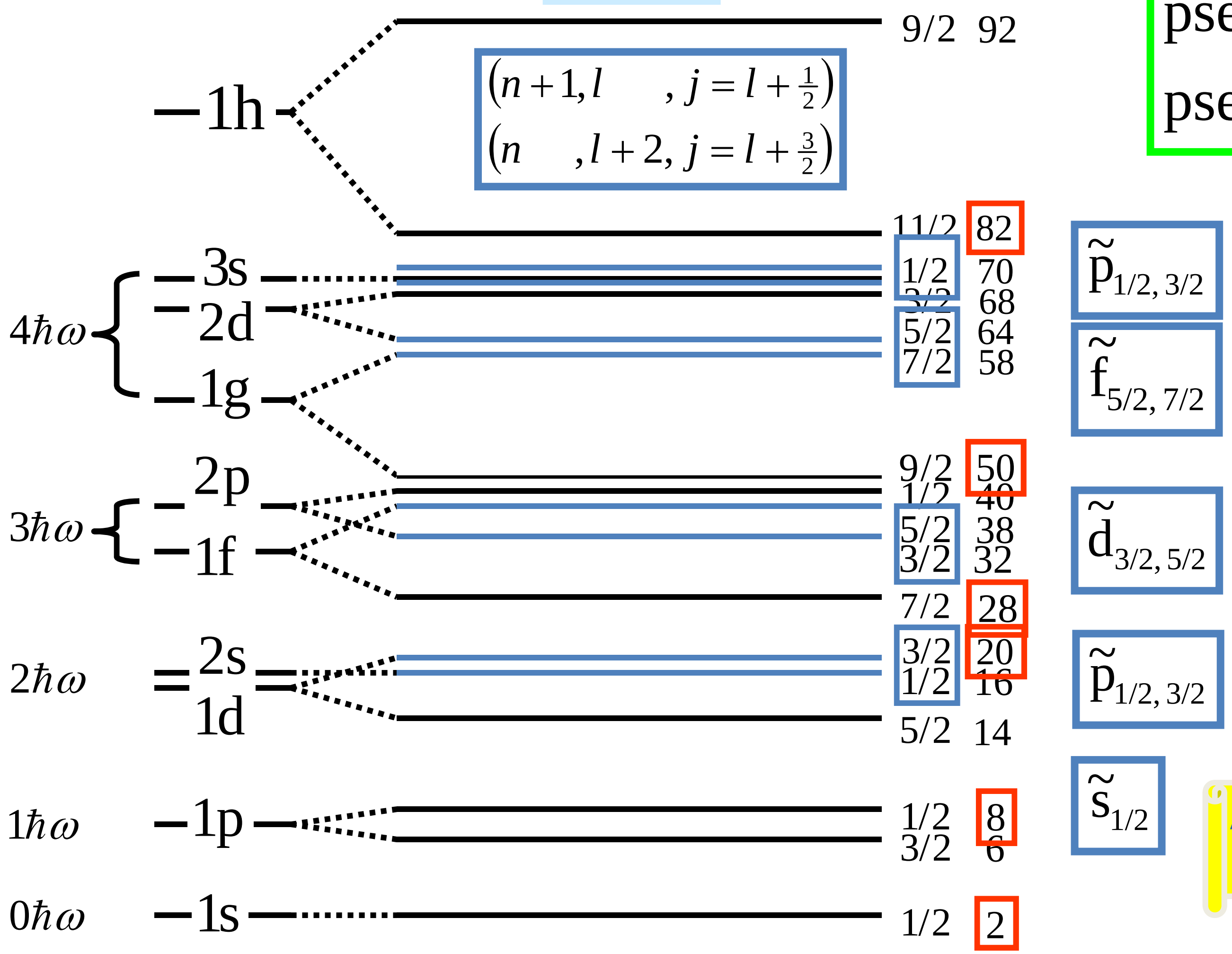
S. G. Nilssion, et al., Nucl. Phys. A131(1969) 1.

Spin and pseudospin symmetry in atomic nuclei

Woods-Saxon

$\kappa \vec{l} \cdot \vec{s}$

$$\text{pseudo-orbit}: \ \tilde{l} = l + 1$$
$$\text{pseudo-spin}: \ \tilde{s} = 1/2$$



Hecht & Adler
NPA137(1969)129

Arima, Harvey & Shimizu
PLB30(1969)517

Earlier attempt to understand PSS

Physica Scripta. Vol. 26, 267–272, 1982

Pseudospin in Rotating Nuclear Potentials

A. Bohr, I. Hamamoto and Ben R. Mottelson

The Niels Bohr Institute, Blegdamsvej 17, DK-2100 Copenhagen Ø, Denmark

and

NORDITA, Blegdamsvej 17, DK-2100 Copenhagen Ø, Denmark

Received July 7, 1982; accepted July 10, 1982

Abstract

It is found that the concept of pseudo-spin and pseudo-oscillator quantum numbers, introduced by previous authors, can be helpful in understanding the qualitative features of quasiparticle motion in rotating potentials, for the orbits with normal parity (excluding the high j orbits). In the first part of the paper, the use of pseudo-spin in static deformed potentials is briefly reviewed.

A. Bohr, I. Hamamoto, and B. R. Mottelson, Phys. Scr. 26,267 1982

Earlier attempt to understand PSS

VOLUME 68, NUMBER 14 PHYSICAL REVIEW LETTERS 6 APRIL 1992

Pseudospin Symmetry in Nuclear Physics

C. Bahri and J. P. Draayer

Department of Physics and Astronomy, Louisiana State University, Baton Rouge, Louisiana 70803

S. A. Moszkowski

Department of Physics, University of California, Los Angeles, Los Angeles, California 90024

(Received 12 November 1991)

The origin and consequences of pseudospin symmetry in nuclear physics, which is exact for an oscillator potential with one-body orbit-orbit (v_{ll}) and spin-orbit (v_{ls}) interaction strengths in the ratio $\mu \equiv 2v_{ll}/v_{ls} = 0.5$, are considered. Specifically, the $v_{ls} \approx 4v_{ll}$ condition is consistent with relativistic mean-field results and a pseudo LS coupling scheme. When deformation dominates, pseudospin extends to pseudo SU(3), which is applicable to superdeformation.

Since PSS was suggested, lots of nuclear phenomena have been interpreted in connection with the PSS, for example …

Nuclear superdeformed configurations

VOLUME 59, NUMBER 13 PHYSICAL REVIEW LETTERS 28 SEPTEMBER 1987

Abundance and Systematics of Nuclear Superdeformed States; Relation to the Pseudospin and Pseudo-SU(3) Symmetries

J. Dudek
Center de Recherches Nucléaires et Université Louis Pasteur, F-67037 Strasbourg Cedex, France

W. Nazarewicz
Institute of Physics, Technical University, PL-00-662 Warsaw, Poland

Z. Szymanski
Centre de Recherches Nucléaires, F-67037 Strasbourg Cedex, France, and Institute of Theoretical Physics, Warsaw University, PL-00-681 Warsaw, Poland

and

G. A. Leander
Oak Ridge Associated Universities, Oak Ridge, Tennessee 37830
(Received 31 December 1986)

Results of a multidimensional (β_2, γ, β_4, ω, Z, and N) search for nuclear superdeformed configurations are presented. Calculations based on a realistic deformed average field give a relatively strong dependence of the "super" elongation on the particle number. This dependence is shown to be a cyclic function of the particle number. It originates from the pseudospin and pseudo-SU(3) symmetries which are obeyed approximately in a realistic average field.

PACS numbers: 21.10.Gv, 21.60.Fw

Interpretation of the identical bands

VOLUME 64, NUMBER 14 PHYSICAL REVIEW LETTERS 2 APRIL 1990

Natural-Parity States in Superdeformed Bands and Pseudo SU(3) Symmetry at Extreme Conditions

W. Nazarewicz,[1] P. J. Twin,[2] P. Fallon,[2] and J. D. Garrett[3]

[1]*Institute of Physics, Warsaw University of Technology, ul. Koszykowa 75, PL-00662 Warsaw, Poland*
[2]*Oliver Lodge Laboratory, University of Liverpool, Liverpool L69 3BX, United Kingdom*
[3]*Oak Ridge National Laboratory, Oak Ridge, Tennessee 37831*

(Received 18 December 1989)

RAPID COMMUNICATIONS

PHYSICAL REVIEW C VOLUME 44, NUMBER 5 NOVEMBER 1991

Spin determination and quantized alignment in the superdeformed bands in ^{152}Dy, ^{151}Tb, and ^{150}Gd

J. Y. Zeng,[1,2,3] J. Meng,[2,3] C. S. Wu,[1,2,3] E. G. Zhao,[1,3]
Z. Xing,[4] and X. Q. Chen[4]

[1]*China Center of Advanced Science and Technology (World Laboratory), Center of Theoretical Physics, P.O. Box 8730, Beijing 100080, China*
[2]*Department of Physics, Peking University, Beijing 100871, China**
[3]*Institute of Theoretical Physics, Chinese Academy of Science, Beijing 100080, China*
[4]*Department of Modern Physics, Lanzhou University, Lanzhou 730000, China*

(Received 13 May 1991)

The spin of the lowest level observed in the superdeformed band in ^{152}Dy is determined to be $I_0=25$ rather than the previously assigned $I_0=22$. As a result, we have $\mathcal{J}^{(1)} > \mathcal{J}^{(2)}$ and both $\mathcal{J}^{(1)}$ and $\mathcal{J}^{(2)}$ decrease very slowly with rotational frequency. From the spin determination of the two pairs of identical bands in ^{152}Dy and ^{151}Tb*, ^{151}Tb and ^{150}Gd*, evidence has been obtained to support the assumption of quantized alignments in units of $\hbar/2$.

Observation of the PSS partner bands…

Meng and Zhang, JPG37, 064025 (2010)

PHYSICAL REVIEW C **80**, 034303 (2009)

Properties of the rotational bands in the transitional nucleus ^{189}Pt

W. Hua and X. H. Zhou*
Institute of Modern Physics, Chinese Academy of Sciences, Lanzhou 730000, People's Republic of China and
Graduate School of the Chinese Academy of Sciences, Beijing 100049, People's Republic of China

Y. H. Zhang, Y. Zheng, M. L. Liu, F. Ma, S. Guo, L. Ma, S. T. Wang, N. T. Zhang, Y. D. Fang, X. G. Lei, and Y. X. Guo
Institute of

School of Physics, a

(Received

High-spin st
of 88 and 95 M
Rotational ban
shape and a nea
transition seque
the $\nu i_{13/2}^{-2} \nu f_{5/2}$(
as a pair of pse
theoretical calc

PHYSICAL REVIEW C **78**, 064301 (2008)

Identification of pseudospin partner bands in ^{108}Tc

Q. Xu (徐强),[1] S. J. Zhu (朱胜江),[1,2,*] J. H. Hamilton,[2] A. V. Ramayya,[2] J. K. Hwang,[2] B. Qi (亓斌),[3] J. Meng (孟杰),[3] J. Peng (彭靖),[4] Y. X. Luo,[2,5] J. O. Rasmussen,[5] I. Y. Lee,[5] S. H. Liu,[2] K. Li,[2] J. G. Wang (王建国),[1] H. B. Ding (丁怀博),[1] L. Gu (顾龙),[1] E. Y. Yeoh (杨韵颐),[1] and W. C. Ma[6]
[1]*Department of Physics, Tsinghua University, Beijing 100084, People's Republic of China*
[2]*Department of Physics, Vanderbilt University, Nashville, Tennessee 37235, USA*
[3]*School of Physics, Peking University, Beijing 100871, People's Republic of China*
[4]*Department of Physics, Beijing Normal University, Beijing 100875, People's Republic of China*
[5]*Lawrence Berkeley National Laboratory, Berkeley, California 94720, USA*
[6]*Department of Physics, Mississippi State University, Mississippi State, Mississippi 39762, USA*
(Received 31 July 2008; published 8 December 2008)

High-spin structures in the neutron-rich ^{108}Tc nucleus have been reinvestigated by measuring the prompt γ-rays from spontaneous fission of ^{252}Cf. A previously known collective band has been extended up to higher spin states and a new side band has been identified. These doublet bands are proposed as pseudospin partner bands with configurations $\pi 1/2^+[431] \otimes \nu[\widetilde{312}\, 5/2^+, 3/2^+]$, which is a first identification in $A \sim 100$ region. The particle-rotor model (PRM) was applied to calculate levels and $B(M1)/B(E2)$ ratios of the bands in ^{108}Tc. The calculated results are in good agreement with the experimental values.

Even for Magnetic moments, transitions and γ-vibrational states

- On the validity of the pseudo-spin concept for axially symmetric deformed nuclei

  D. Troltenier, W. Nazarewicz, Z. Szymański, J.P. Draayer, Nucl. Phys. A 567, 591 (1994).

- l-forbidden M1 transitions and pseudospin symmetry

  P. von Neumann-Cosel and J. N. Ginocchio, Phys. Rev. C 62, 014308 (2000)

- Neutron number dependence of the energies of the γ-vibrational states in nuclei with Z∼100 and the manifestation of pseudospin symmetry

  R. V. Jolos, N. Yi. Shirikova, and A. V. Sushkov, Phys. Rev. C 86, 044320 (2012)

Nuclear Physics A522 (1991) 1c-12c
North-Holland, Amsterdam

Some themes in the study of very deformed rotating nuclei

Ben Mottelson
Nordita
Blegdamsvej 17

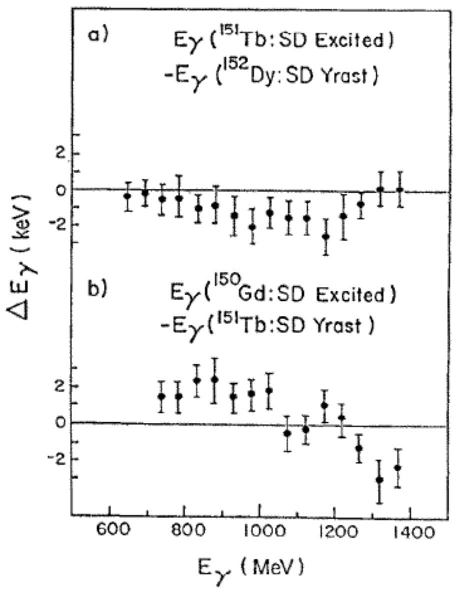


Fig.6: Comparison of transition energies for super-deformed rotational bands in ^{152}Dy, ^{151}Tb, and ^{150}Gd.

Very briefly the concept of psudo-spin is built on the following observations (Hecht and Adler, Nucl.Phys. A137, 129 (69); Arima, Harvey, and Shimizu, Phys.Lett. 30B, 517 (69)) :

a) The observed single particle spectra in spherical nuclei exhibit a number of approximate degeneracies of orbits with the same parity and $\Delta j=1$:

$$\left.\begin{matrix}(g_{7/2}, d_{5/2}) \\ (d_{3/2}, s_{1/2})\end{matrix}\right\} \text{ for N} = 50 - 82$$

$$\left.\begin{matrix}(h_{9/2}, f_{7/2}) \\ (f_{5/2}, p_{3/2})\end{matrix}\right\} \text{ for N} = 82 - 126$$

$$\left.\begin{matrix}(i_{11/2}, g_{9/2}) \\ (g_{7/2}, d_{5/2}) \\ (d_{3/2}, s_{1/2})\end{matrix}\right\} \text{ for N} > 126$$

Nucleon Dirac Equations

Relativistic mean field / Covariant density functional theory

$$\left[\alpha\cdot\boldsymbol{p}+V(\boldsymbol{r})+\beta\left(M+S(\boldsymbol{r})\right)\right]\psi_i=\varepsilon_i\psi_i$$

$$\begin{cases} V(\boldsymbol{r})=g_\omega\omega(\boldsymbol{r})+g_\rho\tau_3\rho(\boldsymbol{r})+e\dfrac{1-\tau_3}{2}A(\boldsymbol{r}) \\ S(r)=g_\sigma\sigma(\boldsymbol{r}) \end{cases}$$

Dirac Spinor quantum numbers

$$\psi^N_{n\kappa m}(\boldsymbol{r}) = \frac{1}{r}\begin{pmatrix} i\ G_{n\kappa}(r)\, Y^l_{jm}(\Omega) \\ -F_{\tilde{n}\kappa}(r)\, Y^{\tilde{l}}_{jm}(\Omega) \end{pmatrix}$$

$$\begin{cases} j = l \pm 1/2 \\ \kappa = (-)^{j+l+1/2}(j+1/2) \\ \tilde{l} = l + (-)^{j+l-1/2} \end{cases}$$

$$n = \text{node number} + 1$$

$$(2\text{s}_{1/2}, 1\text{d}_{3/2}) \Rightarrow (\tilde{\text{p}}_{1/2,\,3/2})$$

$$(\tilde{n} = 2)\ \tilde{\text{p}}_{1/2,3/2}$$

$$2\text{s}_{1/2} = \begin{pmatrix} n = 2,\ l = 0,\ j = l + \frac{1}{2} \\ \tilde{n} = 2, \tilde{l} = 1,\ j = \tilde{l} - \frac{1}{2} \end{pmatrix}$$

$$1\text{d}_{3/2} = \begin{pmatrix} n = 1,\ l = 2,\ j = l - \frac{1}{2} \\ \tilde{n} = 2, \tilde{l} = 1,\ j = \tilde{l} + \frac{1}{2} \end{pmatrix}$$

Pseudo quantum numbers are nothing
but the quantum numbers of the lower component.

Ginocchio PRL78(97)436

Origin of the symmetry - Nucleons

$$V_\pm(r) = V(r) \pm S(r)$$

$$M_\pm(\varepsilon_N, r) = M \pm \varepsilon_N \mp V_\mp(r)$$

$$\psi^N_{n\kappa m}(\mathbf{r}) = \frac{1}{r}\begin{pmatrix} i\; G_{n\kappa}(r)\, Y^l_{jm}(\Omega) \\ -F_{\tilde{n}\kappa}(r)\, Y^{\tilde{l}}_{jm}(\Omega) \end{pmatrix}$$

$$\left[-\frac{1}{2M_+}\left(\frac{d^2}{dr^2} + \frac{1}{2M_+}\frac{dV_-}{dr}\frac{d}{dr} - \frac{l(l+1)}{r^2}\right) - \frac{1}{4M_+^2}\frac{\kappa}{r}\frac{dV_-}{dr} + M - V_+\right]G = +\varepsilon_N G$$

$$\left[-\frac{1}{2M_-}\left(\frac{d^2}{dr^2} - \frac{1}{2M_-}\frac{dV_+}{dr}\frac{d}{dr} + \frac{\tilde{l}(\tilde{l}+1)}{r^2}\right) + \frac{1}{4M_-^2}\frac{\tilde{\kappa}}{r}\frac{dV_+}{dr} + M - V_-\right]F = -\varepsilon_N F$$

For nucleons,
✖ $d[V(r)-S(r)]/dr=0$ ⇒ spin symmetry
✓ $d[V(r)+S(r)]/dr=0$ ⇒ pseudo-spin symmetry

Meng, Sugawara-Tanabe, Yamaji, Ring, Arima, PRC58 (1998) 628R
Meng, Sugawara-Tanabe, Yamaji, Arima, PRC59 (1999) 154

北京大学 PEKING UNIVERSITY

Origin of the symmetry - Anti-nucleons

$$V_{\pm}(r) = V(r) \pm S(r)$$

$$M_{\pm}(\varepsilon_A, r) = M \mp \varepsilon_A \mp V_{\mp}(r)$$

$$\psi^{A}_{n\kappa m}(\mathbf{r}) = \frac{1}{r}\begin{pmatrix} -F_{n\kappa}(r)\, Y^{l}_{jm}(\Omega) \\ i\;G_{\tilde{n}\kappa}(r)\, Y^{\tilde{l}}_{jm}(\Omega) \end{pmatrix}$$

$$\left[-\frac{1}{2M_-}\left(\frac{d^2}{dr^2} - \frac{1}{2M_-}\frac{dV_+}{dr}\frac{d}{dr} + \frac{l(l+1)}{r^2}\right) + \frac{1}{4M_-^2}\frac{\kappa}{r}\frac{dV_+}{dr} + M - V_-\right]F = -\varepsilon F$$

$$\left[-\frac{1}{2M_+}\left(\frac{d^2}{dr^2} + \frac{1}{2M_+}\frac{dV_-}{dr}\frac{d}{dr} - \frac{\tilde{l}(\tilde{l}+1)}{r^2}\right) - \frac{1}{4M_+^2}\frac{\tilde{\kappa}}{r}\frac{dV_-}{dr} + M - V_+\right]G = +\varepsilon G$$

For anti-nucleons,

✘ $d[V(r) - S(r)]/dr = 0$ ⇒ pseudo-spin symmetry

✓ $d[V(r) + S(r)]/dr = 0$ ⇒ spin symmetry

Zhou, Meng & Ring PRL92(03)262501

Origin of the symmetry

Zhou,Meng&Ring
PRL92(03)262501

For nucleons, the smaller component *F*

$$\left[-\frac{\vec{\nabla}^2}{2M_-^*}-\left[V(r)-S(r)\right]+\frac{1}{4M_-^2}\frac{1}{r}\frac{d}{dr}\left[V(r)+S(r)\right]\left(1+\vec{\tilde{l}}\cdot\vec{\tilde{\sigma}}\right)+M\right]F=-\varepsilon_N F$$

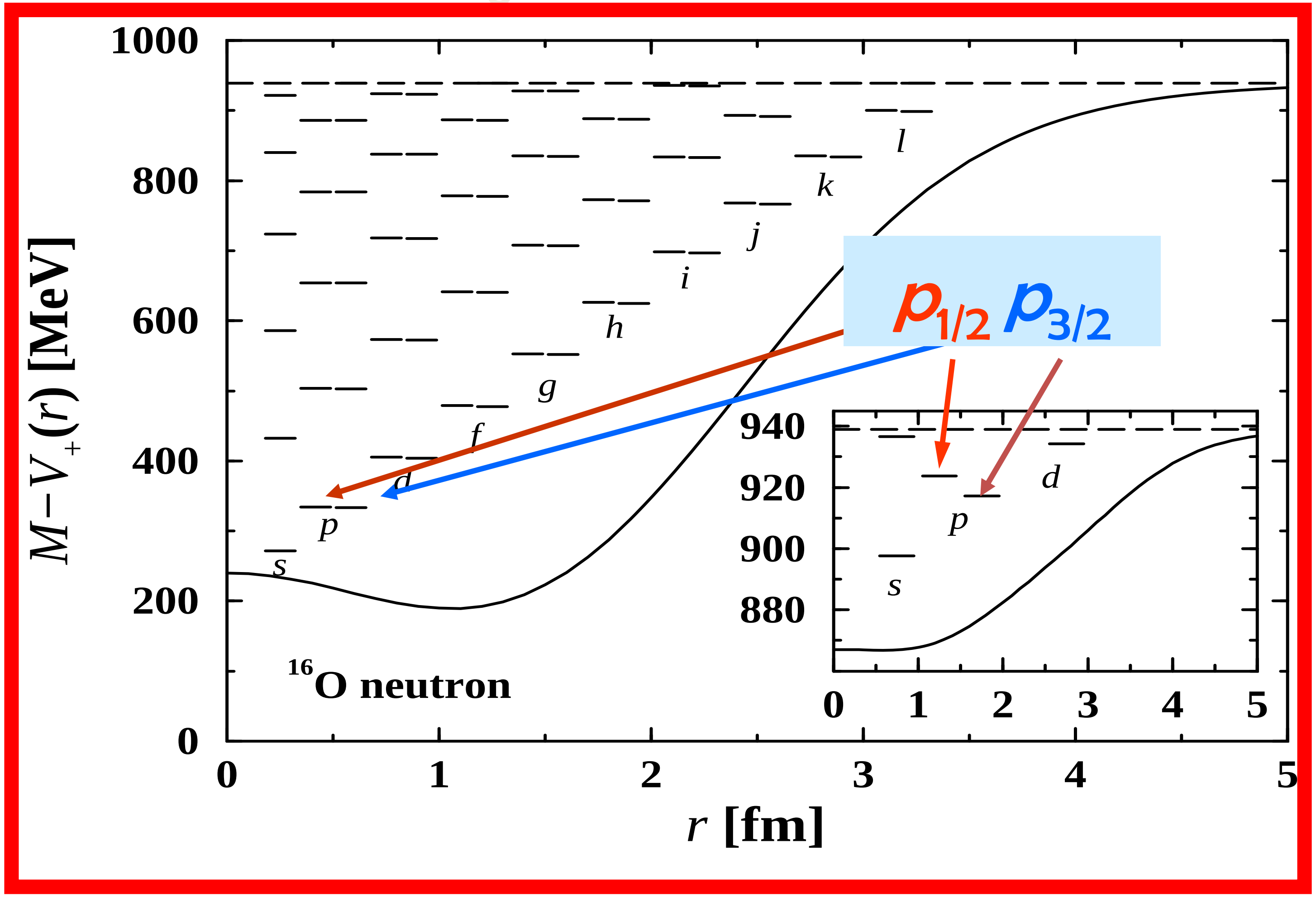
For anti-nucleons, the larger component *F*

$$\left[-\frac{\vec{\nabla}^2}{2M_-^*}-\left[V(r)-S(r)\right]+\frac{1}{4M_-^2}\frac{1}{r}\frac{d}{dr}\left[V(r)+S(r)\right]\left(1+\vec{l}\cdot\vec{\sigma}\right)+M\right]F=+\varepsilon_A F$$

The factor $1/4M_-^2$ is ~400 times smaller for anti nucleons!

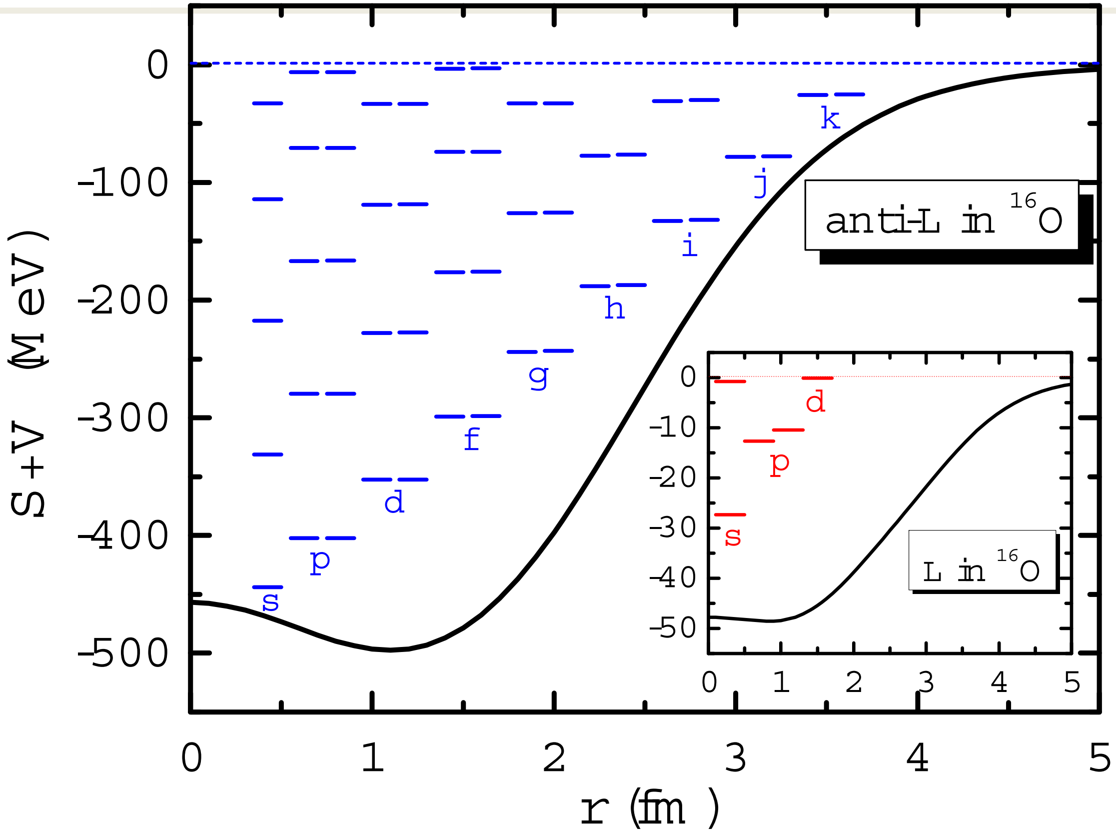
Origin of the symmetry - Anti-nucleons

Zhou, Meng & Ring, PRL92 (03) 262501



Experimental verification: Anti-Λ in ^{16}O

Song, Yao, Meng, CHIN. PHYS. LETT. Vol. 26, No. 12 (2009) 122102



Experiment: exploration of the relativistic symmetry by hyperon

PEKING UNIVERSITY 北京大學

Summary / Introduction

Kenichiro Arita (Nagoya Institute of Technology)
Haozhao Liang (RIKEN)
Shan-Gui Zhou (Institute of Theoretical Physics, CAS, China)
…

- Origins of nuclear shell structure
- Spin symmetry in Dirac negative energy spectrum
- Perturbative interpretation of relativistic symmetries possible
- Pseudospin symmetry in resonances
- Pseudospin symmetry in supersymmetric quantum mechanics
- Pseudospin for deformed nucleus
- …

- Liang, Shen, Zhao, Meng, Phys. Rev. C 87, 014334 (2013) [13 pages]
- B.-N. Lu, E.-G. Zhao, and S.-G. Zhou, Phys. Rev. Lett. 109, 072501 (2012).
- Bing-Nan Lu, En-Guang Zhao, Shan-Gui Zhou arXiv:1305.1524

Thank you for your attention!