不稳定核结构涉及的新问题

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湖州暑期讲习班，2021.07.09-24

内 容

I. 针对核多体系统的“不稳定”特征
— 内卷还是开拓?

II. 奇特结构新自由度的处理

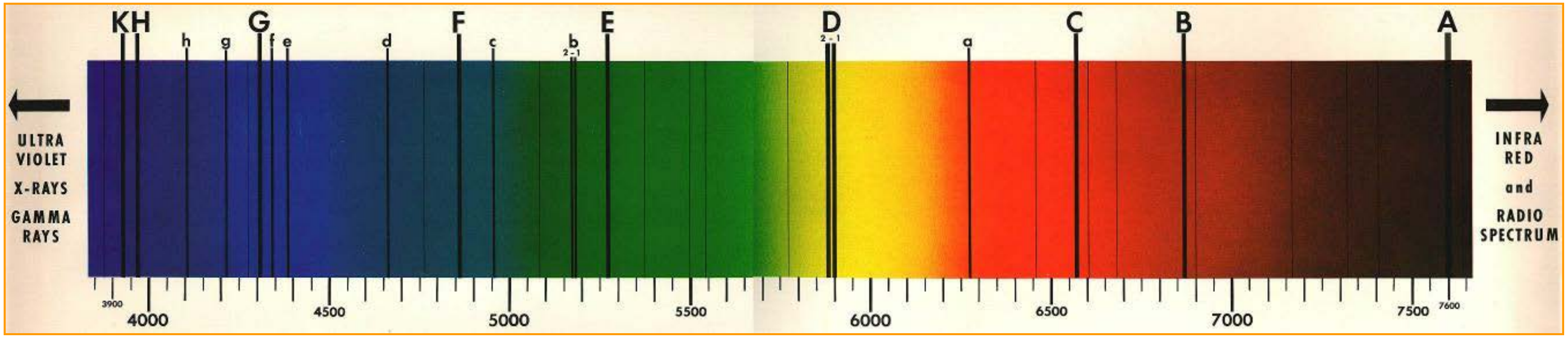
III. 壳演化(新幻数)、连续态和闯入态

IV. 展望和期待

谱：理论和实验的交汇

Spectroscopy: probability distribution with respect to certain physics quantity

光谱引发的革命：



连续谱：紫外发散问题？普朗克的光量子解释

线谱(line spectra)：原子的核式模型；电子轨道量子化

Kirchhoff and Bunsen, 1860: "The different bodies with which the metals were combined, the variety in the nature of chemical process occurring in the several flames, and the wide differences of temperature which these flames exhibit, produce no effect upon the position of the bright lines in the spectrum which are characteristic of each metal."

Schuster, 1882: "It is ambitious object of spectroscopy to study the vibrations of atoms and molecules in order to obtain what information we can about the nature of forces which bind them together (内卷?). …But we must not too soon expect the discovery of any grand and very general law, for the constitution of what we call a molecule is no doubt a very complicated one, and the difficulty of the problem is so great that was it not for the primary importance of the result which we may finally hope to obtain, all but the most sanguine might well be discouraged to engage in an inquiry which, even after many years of work, may turn out to have been fruitless."

Plank, 1902: “If the question concerning the nature of white light may thus be regarded as being solved, the answer to a closely related but no less important question — the question concerning the nature of the spectral line — seems to belong among the most difficult and complicated problems, which have ever been posed in optics or electrodynamics.”

around 1860: characteristic discrete spectrum for each chemical substance.

Wollaston, 1802: dark line in solar spectrum.

1885: Balmer’s formular (60 years old school teacher in a high school for girls)

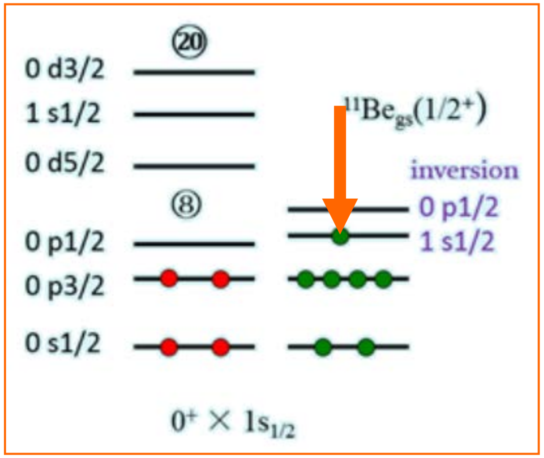
1913-1915: Bohr-Sommerfeld theory of atomic stucture

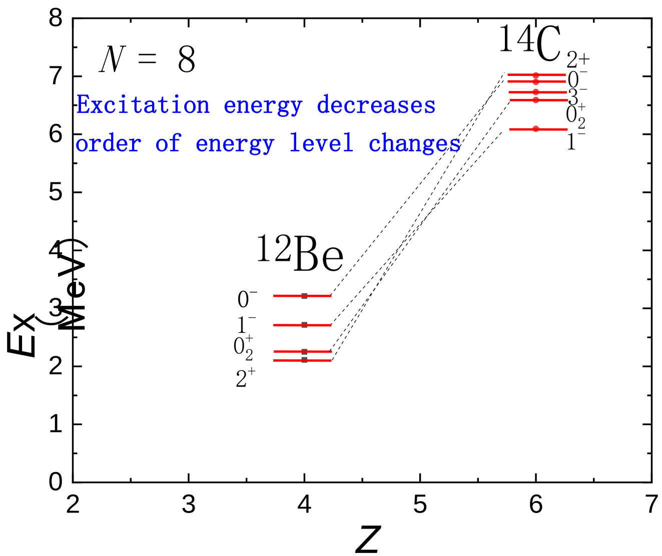
What's science?

- "If science is to progress, what we need is the ability to experiment, honesty in reporting results – the results must be reported without somebody saying what they would like the results to have been – and finally – an important thing – the intelligence to interpret the results.

From 《The Character of Physics Law》
- Richard Feynman, The MIT Press, 1965

不稳定核基态和低激发态— 例如N = 8幻数附近





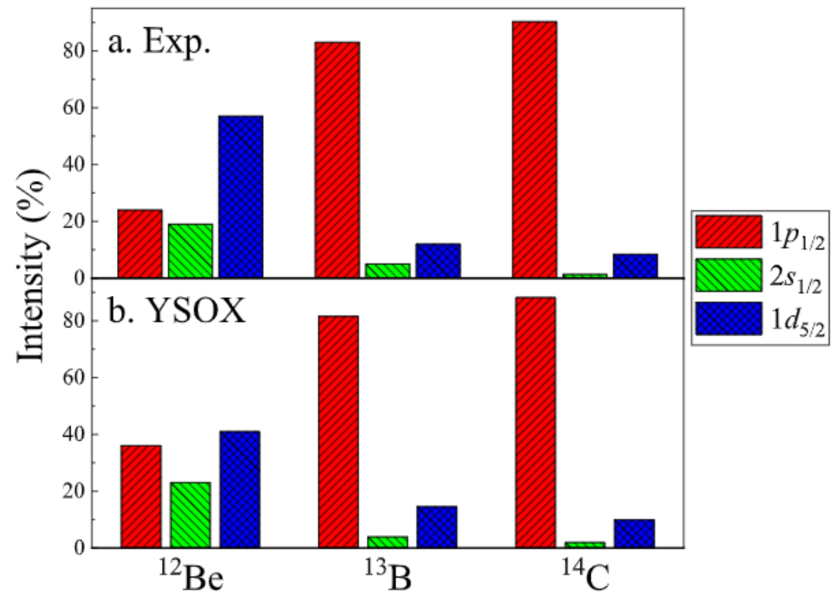
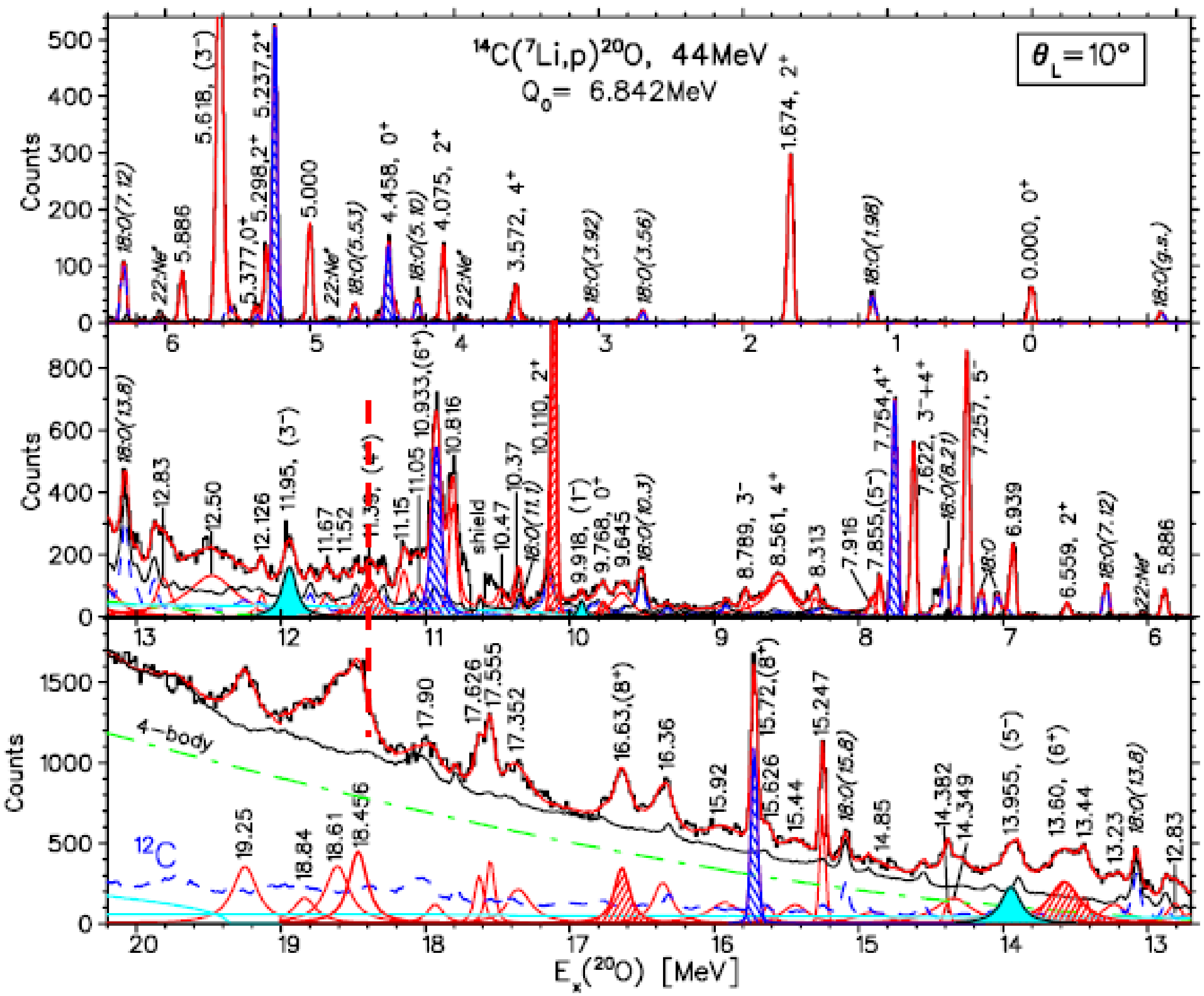


FIG. 10. (a)Individual *p*-, *s*-, and *d*-wave intensities in the ground state of ^{12}Be [5], ^{13}B (this work) and ^{14}C [16]. (b) Shell model calculations with YSOX interaction in full *p*-*sd* model space. The results for ^{12}Be are from Ref. [5].

W. Liu, J.L.Lou et al.

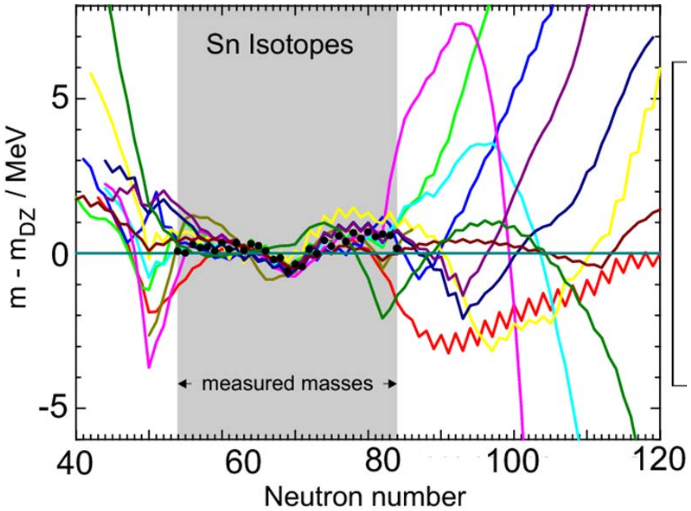
不稳定核高激发态？



Members of the $K = 0^+_2$, 1^-_2 , and 0^+_4 bands of ^{20}O (with tentative assignments) are marked by downward hatched (blue), filled (cyan), and upward hatched (red) areas, respectively.

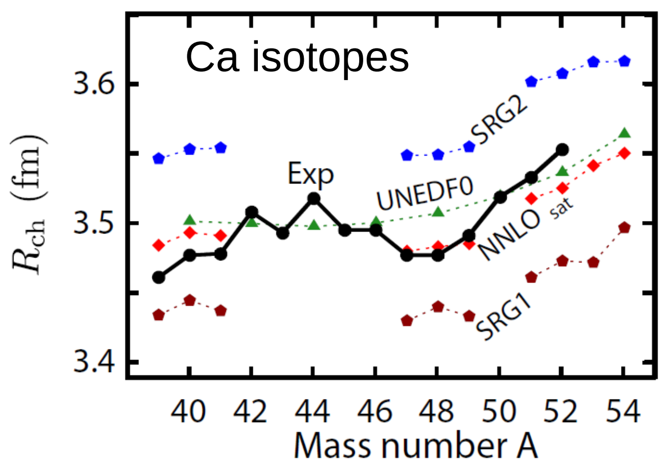
Eur. Phys. J. A (2011) **47**: 44

离开稳定线的理论预言？

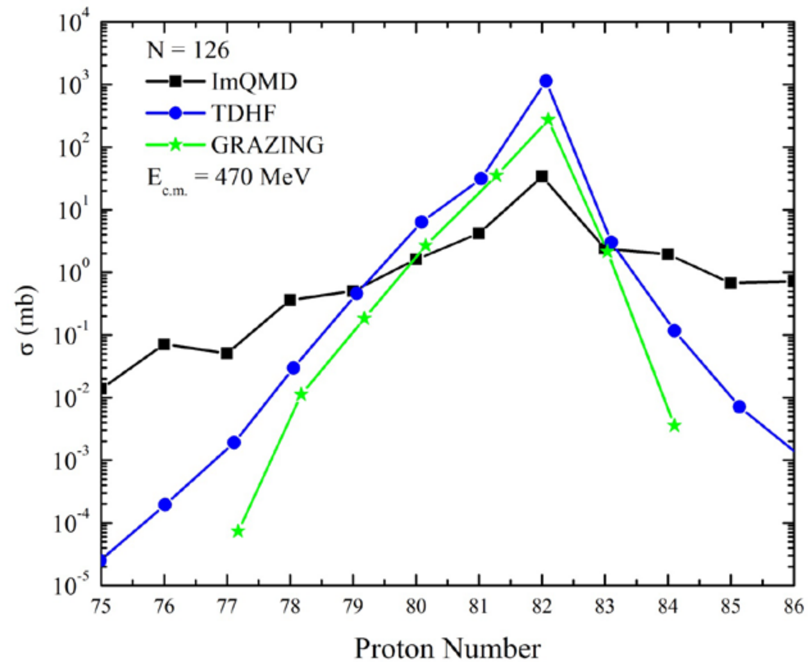


From Y.H. Zhang et al.

Nature Physics 12, 594 (2016)



Large mass transfer reaction .



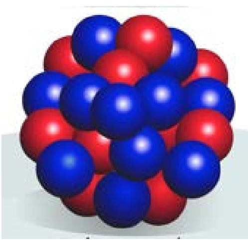
^{132}Sn+^{208}Pb @ Ec.m.=470 MeV

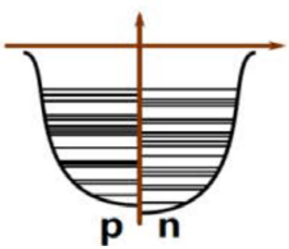
王楠等，2019年长春全国核反应大会

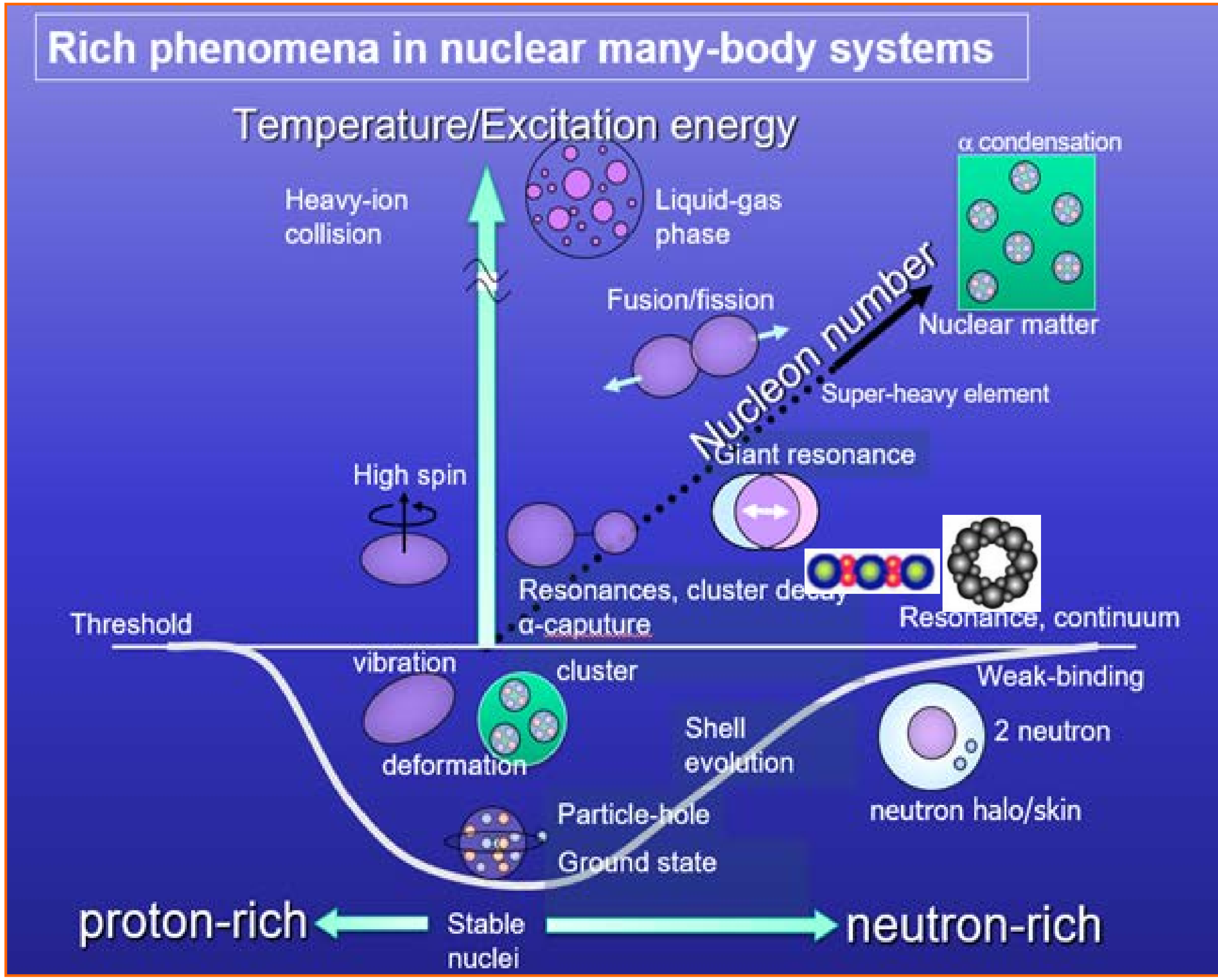
难有捷径可走！

你心目中的原子核结构?

原子核?







PTEP,2012,01A202

Why？（不稳定特征-核力的管控本事不够？）

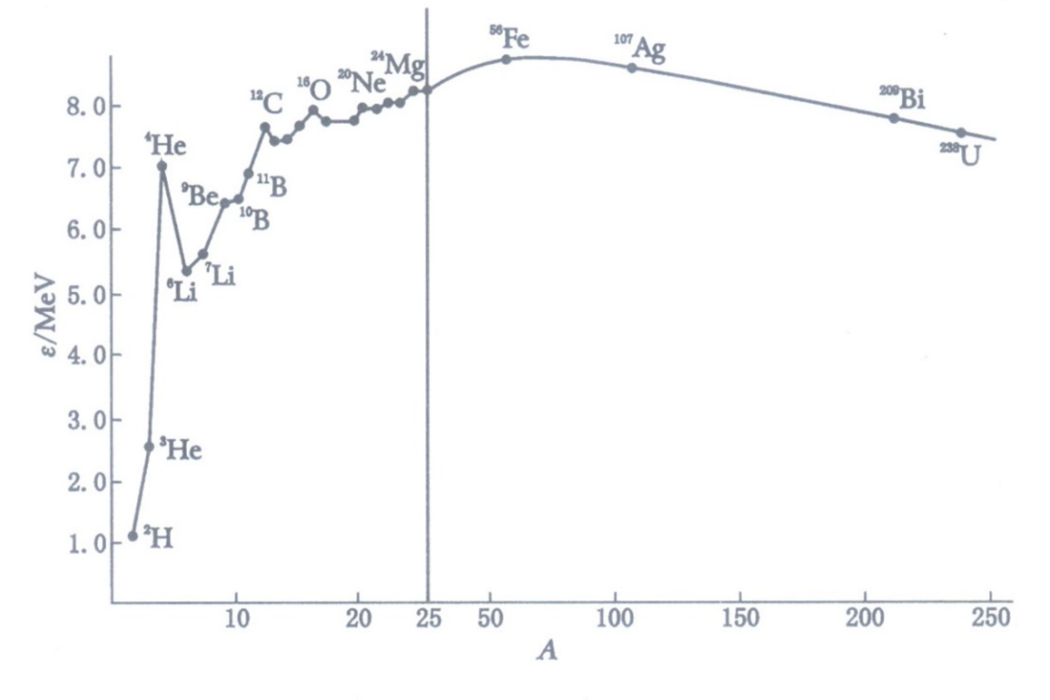


图 2-10 比结合能曲线

核力的饱和性(短程)

(不同于原子)

同位旋-滴线；

激发-阈效应；

奇异自由度；

非核子自由度；

......

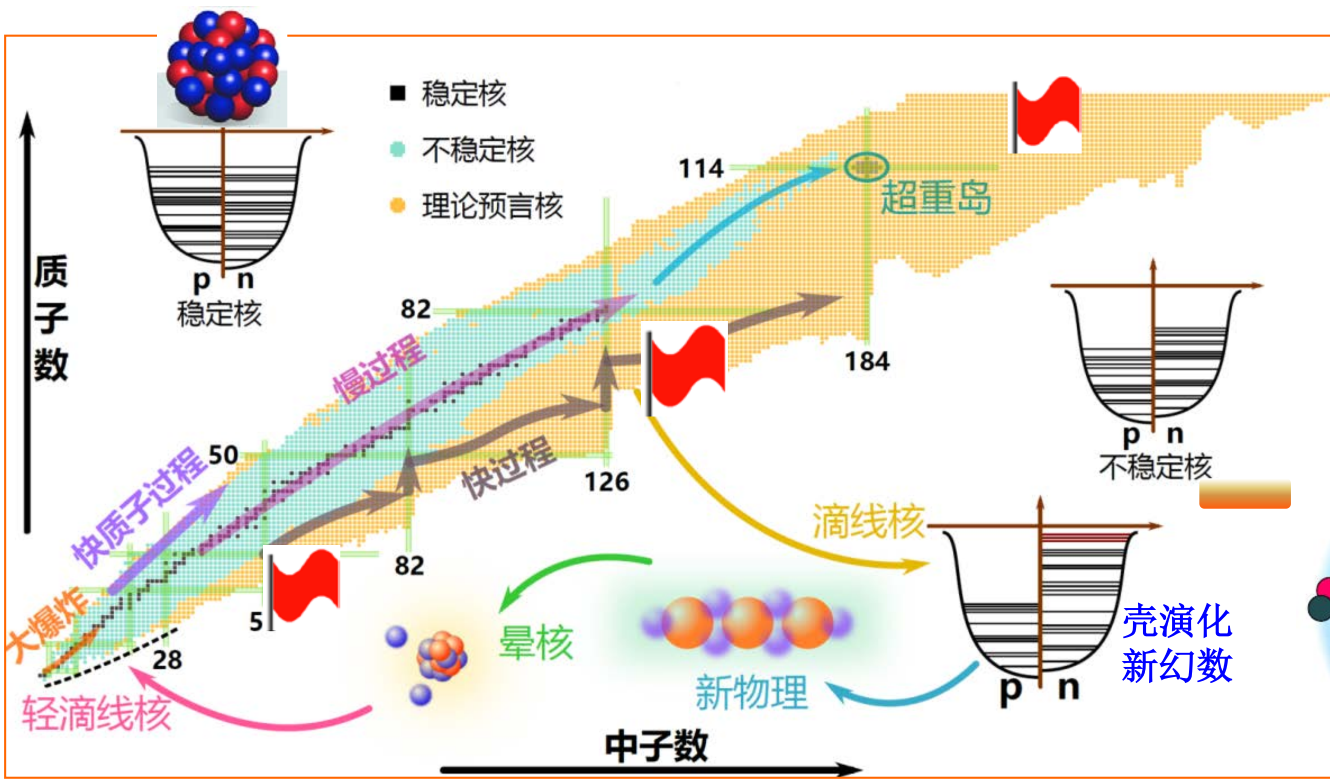
研究生《高等原子核物理》，

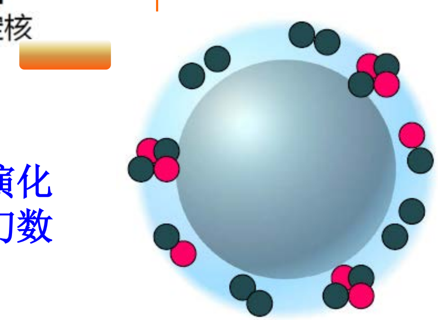
国科大、北大...新开设

核素版图扩大面临的重大科学问题

- 滴线区新物理（系统性突破）
- 宇宙中重元素的生成（巨大未知数）
- 攀登超重岛（挑战极限）

说不清才是机会！





走出内卷、开疆拓土：学术思想、方法、领域、交叉...

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RGM：Resonating Group Method (共振群方法)

DECEMBER 1, 1937 PHYSICAL REVIEW VOLUME 52

On the Mathematical Description of Light Nuclei by the Method of Resonating Group Structure

JOHN A. WHEELER
University of North Carolina, Chapel Hill, North Carolina

(Received August 17, 1937)

(1912-2008)

处理一个体系的不同结构自由度。

N (m protons + n neutrns) particles sorted into groups in a particular way (configuration).

$$\Psi(12\cdots \mathbf{N})=(k_{\mathrm{I}}{}^1!\cdots l_{\mathrm{I}}{}^1!\cdots m!n!)^{-\frac{1}{2}}$$

$$\times\sum_{\text{perm}}(\pm 1)\sum_{m^1}F^1(\mathbf{X}_{\mathrm{I}}{}^1, m_{\mathrm{I}}{}^1; \mathbf{X}_{\mathrm{II}}{}^1, m_{\mathrm{II}}{}^1; \cdots).$$

$$\Phi_{\mathrm{I}}{}^1,{}_{m_{\mathrm{I}}}(1, 2, \cdots \mathbf{k}_{\mathrm{I}}{}^1; \mathbf{m}+1, \mathbf{m}+2, \cdots \mathbf{m}+\mathbf{l}_{\mathrm{I}}{}^1)$$

$$\times\Phi_{\mathrm{II}}{}^1,{}_{m_{\mathrm{II}}}(\mathbf{k}_{\mathrm{I}}{}^1+1, \cdots; \mathbf{m}+\mathbf{l}_{\mathrm{I}}{}^1+1, \cdots)\cdots$$

$$+(k_{\mathrm{I}}{}^2!\cdots l_{\mathrm{I}}{}^2!\cdots m!n!)^{-\frac{1}{2}}\sum_{\text{perm}}(\pm 1)$$

$$\sum_{m^2}F^2(\mathbf{X}_{\mathrm{I}}{}^2, m_{\mathrm{I}}{}^2; \cdots)\Phi^2{}_{\mathrm{I}},{}_{m_{\mathrm{I}}}(1, 2, \cdots \mathbf{k}_{\mathrm{I}}{}^2; \cdots)\cdots$$

$$+\text{terms in } F^3, F^4, \cdots F^c. \quad (1)$$

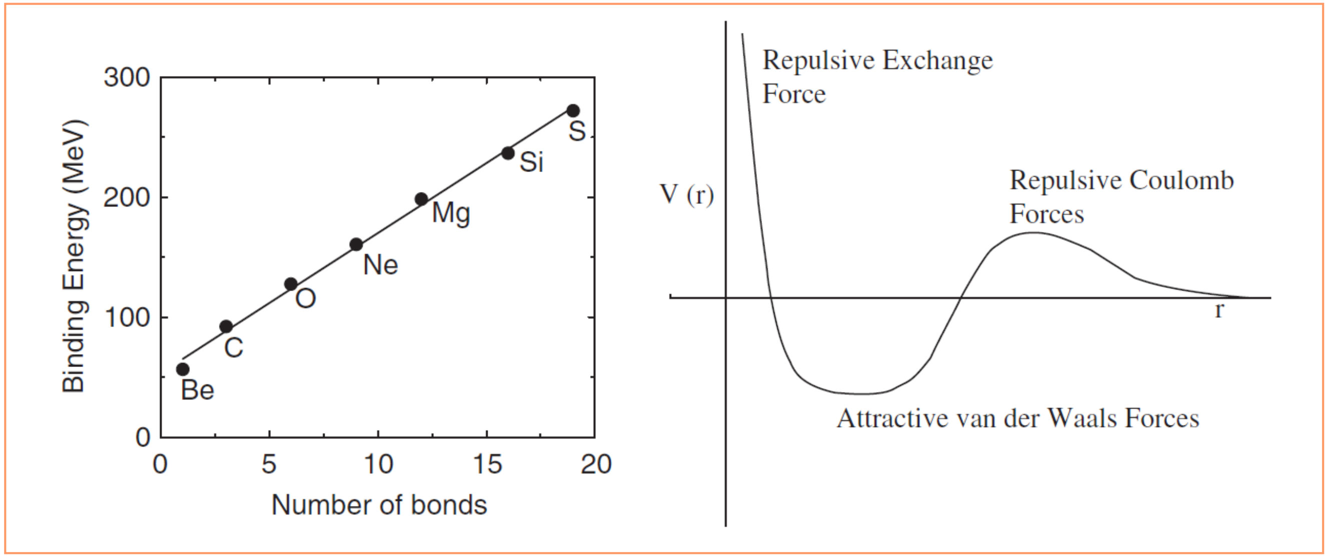
Outline of procedure

The problem centers on the calculation of the functions F^i, which we determine uniquely by the condition that they shall give the best possible wave function of the form (1) in the sense of the variation principle:

$$\delta E=0 \quad \left(E=\int \Psi^* H\Psi d\tau \Big/ \int \Psi^*\Psi d\tau\right). \quad (3)$$

Our program is as follows: We express (Eq. (13)) $\int \Psi^* H\Psi d\tau$ and $\int \Psi^*\Psi d\tau$ in terms of the F^i and certain quantities representing the Hamiltonians of the individual configurations and the interactions responsible for the resonance of the nucleus between different configurations; then

基于实验观察- 谱学中的未知



α集团之间相互作用给出的附加结合能。

PR54(1938)681;Phys. Report 432(2006)43

物理学家约翰惠勒（John A. Wheeler）去世，终年96岁

文 . 2008-4-15 19:48:45

约翰惠勒（John A. Wheeler），美国著名物理学家，"黑洞"的命名者，曾与爱因斯坦和尼尔斯玻尔争论自然的真实性，2008年4月13日早晨因为肺炎而在新泽西的家中去世，享年96岁。

约翰惠勒师从玻尔，是"黑洞"和"虫洞"这两个物理学术语的创造者，他推广了广义相对论的研究，著名的学生有肯尼斯福特（Kenneth Ford）和理查费曼。惠勒主要从事原子核结构、量子理论、广义相对论及宇宙学等研究。他27岁就与丹麦科学家玻尔发展出核分裂理论，后与学生理查德·费曼改写了电磁理论，并提出时光回溯移动的构想。惠勒的性格严厉却不失风趣，而且他时常会说出一些精辟的甚至接近禅语的话，来表达他深邃的观点和思考："It from bit"（万物源于比特），"Mass without Mass"。MIT的宇宙学家Max Tegmark如此评论惠勒，"对我来说，他是最后的巨人，物理学最后的超级英雄。"

背景资料

ADDRESS OF H. A. ROWLAND OF BALTIMORE, MD., VICE-PRESIDENT OF SECTION B, AUG. 15, 1883.

A PLEA FOR PURE SCIENCE.[1]

SCIENCE.

[VOL. II., No. 29. 242

AUGUST 24, 1883.

为纯科学呼吁

A Plea for Pure Science

亨利-奥古斯特-罗兰/Henry Augustus Rowland

编者按：1883 年 8 月 15 日，美国著名物理学家、美国物理学会第一任会长亨利·奥古斯特·罗兰(1848－1901)在美国科学促进会(AAAS)年会上做了题为“为纯科学呼吁”的演讲。该演讲的文字后发表在 1883 年 8 月 24 日出版的 *Science* 杂志上，并被誉为“美国科学的独立宣言”。中科院科学时报社主办的《科学新闻》杂志 2005 年第 5 期全文发表了这篇演讲的中译文（王丹红译，王鸿飞校，小标题为译者所加）。一百多年后重读罗兰的“为纯科学呼吁”演讲，可以感觉到今日中国的科学发展与美国当年颇有相似之处。在当前我国科技界尚存在许多急功近利、浮躁浮夸以及学术不端行为等现象的情况下，罗兰先生的文章更是具有洞穿历史的警世作用。它山之石，可以攻玉，征得科学时报社同意，我刊特将演讲译文全文转发，以期对我国科学发展和现代化建设提供一定的借鉴。

为了应用科学，科学本身必须存在。假如我们停止科学的进步而只留意科学的应用，我们很快就会退化成中国人那样，多少代人以来他们（在科学上）都没有什么进步，因为他们只满足于科学的应用，却从来没有追问过他们所做事情中的原理。这些原理就构成了纯科学。中国人知道火药的应用已经若干世纪，如果他们用正确的方法探索其特殊应用的原理，他们就会在获得众多应用的同时发展出化学，甚至物理学。因为只满足于火药能爆炸的事实，而没有寻根问底，中国人已经远远落后于世界的进步。我们现在只是将这个所有民族中最古老、人口最多的民族当成野蛮人。然而，我们的国家也正处于同样的状况。不过，我们可以做得更好，因为我们获得了欧洲世界的科学，并将它们应用到生活的方方面面。我们就像接受从天空中落下的雨水那样理所应当地接过这些科学知识，既不问它们究竟从哪里来，也没有感激为我们提供这些知识的伟大、无私的人们的恩情。就像天堂之雨一样，纯科学降临到我们的国家，让我们的国家更加伟大、富裕和强壮。

To have the applications of a science, the science itself must exist. Should we stop its progress, and attend only to its applications, we should soon degenerate into a people like the Chinese, who have made no progress for generations, because they have been satisfied with the applications of science, and have never sought for reasons in what they have done. The reasons constitute pure science. They have known the application of gunpowder for centuries; and yet the reasons for its peculiar action, if sought in the proper manner, would have developed the science of chemistry, and even of physics, with all their numerous applications. By contenting themselves with the fact that gunpowder will explode, and seeking no farther, they have fallen behind in the progress of the world; and we now regard this oldest and most numerous of nations as only barbarians. And yet our own country is in this same state. But we have done better; for we have taken the science of the old world, and applied it to all our uses, accepting it like the rain of heaven.

Second Series. *January, 1913.* *Vol. I., No. 1*

THE

PHYSICAL REVIEW.

ANNOUNCEMENT OF THE TRANSFER OF THE REVIEW TO THE AMERICAN PHYSICAL SOCIETY.[1]

WITH the present number the AMERICAN PHYSICAL SOCIETY takes over the PHYSICAL REVIEW and assumes the entire responsibility for its conduct. In so doing the society wishes to give expression to its deep appreciation of the great service done to physics and physicists in America by the editors who, in July-August, 1893, put forth the first number of a new journal, and to Cornell University, which assumed the financial risk. There was at that time no journal in this country entirely devoted to physics, and there was no national society. During nearly twenty years the original editors have carried on the arduous task of maintaining this journal on a high standard, and it is difficult to estimate the value of their efforts in furthering the cause of physics in America. In this manner the way for the foundation of the American Physical Society was prepared, and early in its history the society and the REVIEW entered into relations which have continually become closer. The former editors have now thought best to complete their task by transferring their control to the American Physical Society, and the PHYSICAL REVIEW now becomes the journal of that society, national in scope, and looks for the coöperation of all American physicists. A. G. W.

1931年， Sloan*和Lawrence*建立线性加速器。
1932年,Lawrence*和Livingston建立回旋加速器。

GCM - Generating Coordinate Method (坐标生成法)

PHYSICAL REVIEW VOLUME 108, NUMBER 2 681 OCTOBER 15, 1957

Collective Motions in Nuclei by the Method of Generator Coordinates*

JAMES J. GRIFFIN,† *Princeton University, Princeton, New Jersey, and Institute for Theoretical Physics, Copenhagen, Denmark*

AND

JOHN A. WHEELER, *Palmer Physical Laboratory, Princeton University, Princeton, New Jersey*

(Received June 20, 1957)

* Based in part upon the thesis submitted by James J. Griffin to Princeton University in June, 1955, in partial fulfillment of the requirements for the degree of Ph.D.

We consider a system of A-particles with coordinates $\mathbf{x}_1, \mathbf{x}_2, \cdots \mathbf{x}_A$ with a Hamiltonian function,

$$H=(\mathbf{p}_1^2/2M)+(\mathbf{p}_2^2/2M)+\cdots(\mathbf{p}_A^2/2M)+\sum_{i<k} V(r_{ik}). \quad (1)$$

We construct the trial wave function of the variational method in the following way: we replace the actual potential felt by a particle by a fictitious potential, characterized by a shape parameter, α. We solve the wave equation for individual particles moving in this potential. Out of these individual particle wave functions, we construct by formation of a determinant or otherwise a many-particle wave function

the *nucleonic wave function*, $\varphi_n(\mathbf{x}_1\cdots\mathbf{x}_A;\alpha)$. (2)

$$\Psi(\mathbf{x}_1,\cdots\mathbf{x}_n)=\int \varphi_n(\mathbf{x};\alpha)f(\alpha)d\alpha. \quad (3)$$

Here the quantity, α, may be given the name of *generator coordinate*, because it serves to generate the wave function of the system. It should be emphasized, how-

the *generator wave function*, $f(\alpha)$, a so far undetermined function of α. We next determine this collective wave function by the requirement that the *expectation value* of the energy of the A-particle system shall be an extremum with respect to choice of the generator wave function, $f(\alpha)$:

$$\delta E=0; \quad \text{or} \quad \delta E/\delta f(\alpha)=0. \quad (4)$$

处理集体和独立粒子的关联，可以转动、振动、裂变等等。

Brink wave function (1966)

EX: Brink wave function for the C + k(2n)-cluster system consisting of a core (C) and k dineutrons (2n)

PRC76(2007)044323

$$\Phi_{\rm Brink}(\mathbf{S}_C, \mathbf{S}_1, \mathbf{S}_2, \ldots, \mathbf{S}_k),$$
$$\equiv \mathcal{A}\{\phi^{\rm C}(\mathbf{S}_C)\phi^{2n}(\mathbf{S}_1)\phi^{2n}(\mathbf{S}_2)\cdots\phi^{2n}(\mathbf{S}_k)\}.$$

$$\phi^{2n}(\mathbf{S}) = \mathcal{A}\left\{\phi_{\mathbf{S}}^{0s}(\mathbf{r}_1)\chi_\uparrow\phi_{\mathbf{S}}^{0s}(\mathbf{r}_2)\chi_\downarrow\right\},$$
$$\phi_{\mathbf{S}}^{0s}(\mathbf{r}_i) = \frac{1}{(b^2\pi)^{\frac{3}{4}}}\exp\left[-\frac{1}{2b^2}(\mathbf{r}_i - \mathbf{S})^2\right].$$

[32] D. M. Brink, in *Proceedings of the International School of Physics "Enrico Fermi,"* Course 36, Varenna, 1965, edited by C. Bloch (Academic, New York, 1966), p. 247.

灵活地扩大
集团态空间。

THSR wave function (BEC)

PRL87(2001)192501

受Hoyle state 启发；
所有玻色集团都处在内外
S-wave，用于描写BEC态

Alpha Cluster Condensation in ^{12}C and ^{16}O

A. Tohsaki,[1] H. Horiuchi,[2] P. Schuck,[3] and G. Röpke[4]
[1]Department of Fine Materials Engineering, Shinshu University, Ueda 386-8567, Japan
[2]Department of Physics, Kyoto University, Kyoto 606-8502, Japan
[3]Institut de Physique Nucléaire, F-91406 Orsay Cedex, France
[4]FB Physik, Universität Rostock, D-18051 Rostock, Germany

$$C_\alpha^\dagger = \int d^3R\, e^{-\mathbf{R}^2/R_0^2} \int d^3r_1 \cdots d^3r_4 \times \varphi_{0s}(\mathbf{r}_1 - \mathbf{R}) a_{\sigma_1\tau_1}^\dagger(\mathbf{r}_1) \cdots \varphi_{0s}(\mathbf{r}_4 - \mathbf{R}) a_{\sigma_4\tau_4}^\dagger(\mathbf{r}_4),$$

$$\varphi_{0s}(\mathbf{r}) = (1/(\pi b^2))^{3/4} e^{-\mathbf{r}^2/(2b^2)}$$

$$|\Phi_{n\alpha}\rangle = (C_\alpha^\dagger)^n |\mathrm{vac}\rangle,$$

C + k(2n)-cluster system

$$\Psi_{\mathrm{cond}}(B) \equiv n_0 \int \prod_{i=1}^{k} \left\{ d^3\mathbf{S}_i \exp\left(-\frac{(\mathbf{S}_i - \mathbf{S}_C)^2}{B^2} \right) \right\} \times \Phi_{\mathrm{Brink}}(\mathbf{S}_C, \mathbf{S}_1, \mathbf{S}_2, \ldots, \mathbf{S}_k),$$

OCM-Orthogonality Condition Method (正交条件法)

Prog. Theor. Phys. Vol. 40 (1968), No. 4 893

Effect of Pauli Principle in Scatterings of Two Clusters

Sakae SAITO

Department of Physics, Hokkaido University Sapporo

May 6, 1968

by the integro-differential equation. Several numerical analyses show that the relative radial functions are almost energy-independent in the fully overlapping region of two α particles and have characteristic inner oscillations in S and D states.[1] Thus, the repulsive core of effective α-α potentials[2] is understood from the outermost energy-independent nodes of the wave functions.

$$(E - T_r - V_D(\boldsymbol{r}))u(\boldsymbol{r}) = -\Sigma_\alpha u_\alpha(\boldsymbol{r})(u_\alpha, (T + V_D)u), \quad (5)$$

the solutions of which are always orthogonal to the states $u_\alpha(\boldsymbol{r})$.

ed behavior. It is concluded that, as a simple model, the inner behavior can be understood by the orthogonal conditions for the excluded states, and that the relative motion is essentially described by Eq. (5).

GCM的发展，相对运动部分F(a)与各组内部占有部分在一定条件下正交！

α之间作用势的π介子场理论

Prog. Theo. Phys. Volume 25 ,1961 , P853

Interaction between Alpha Particles

Ichirô Shimodaya, Ryozo Tamagaki
and Hajime Tanaka

Department of Physics
Hokkaido University
Sapporo

February 18, 1961

applying the pion-theoretical potentials recently verified in two-nucleon problems,[2] interactions between α-particles are investigated from the viewpoint of the cluster model, without taking account of the polarization effects of α-particles.

亚层次自由度的
有效相互作用

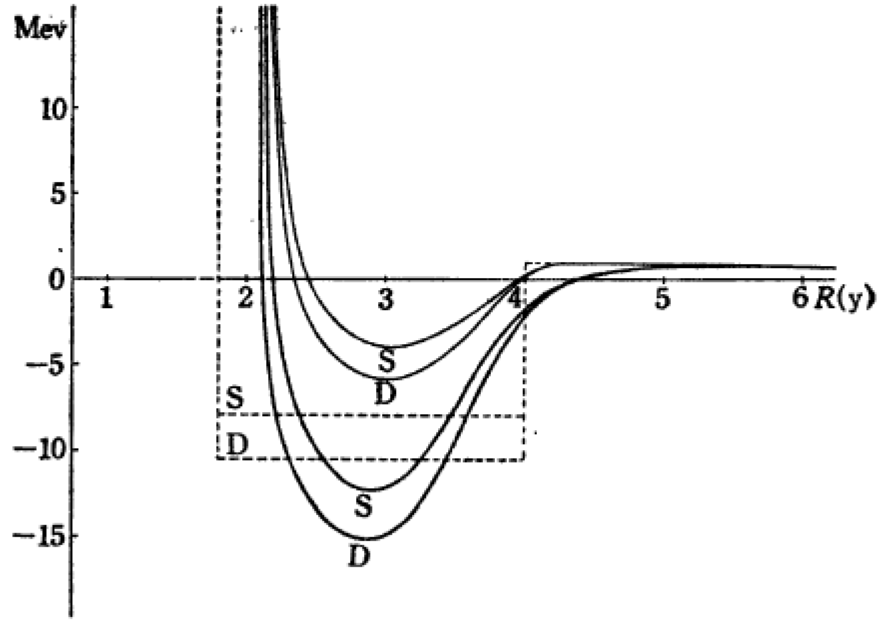


Fig. 1. The dashed lines represent the phenomenologically determined α-α interactions for S- and D-states.[3] The upper curves are obtained from the potential with an attractive TPEP only in the singlet even state and the lower curves from the potential with an additional attractive TPEP in the triplet even and triplet odd states.

PHYSICAL REVIEW VOLUME 101, NUMBER 1 254 JANUARY 1, 1956

Interpretation of Some of the Excited States of 4n Self-Conjugate Nuclei*

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PHYSICAL REVIEW VOLUME 103, NUMBER 2 358 JULY 15, 1956

α-Particle Model of O^{16}†*

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PHYSICAL REVIEW VOLUME 103, NUMBER 3 701 AUGUST 1, 1956

Alpha-Particle Model of C^{12}

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AND

A. GALONSKY, *Oak Ridge National Laboratory, Oak Ridge, Tennessee*

(Received March 5, 1956)

The α-particle model for C^{12} has been re-examined. In addition to correlating the 0^+, 2^+, and 0^+ states at 0, 4.43, and 7.65 Mev, respectively, two possible identifications are given for the 9.61-Mev level: 1^- or 2^+. These levels completely determine the model, and the position and character of all levels up to 15 Mev are given. The main defect of the model is its prediction of a 3^- state at 5.53 Mev which has never been observed. The separation of the α particles in C^{12} is 3.7×10^{-13} cm and the mean zero-point kinetic energy per vibrational degree of freedom is about 2 Mev.

The Systematic Structure-Change into the Molecule-like Structures in the Self-Conjugate 4*n* Nuclei

Kiyomi IKEDA,*) Noboru TAKIGAWA and Hisashi HORIUCHI

Department of Physics, University of Tokyo, Tokyo

Ikeda diagram Threshold rule

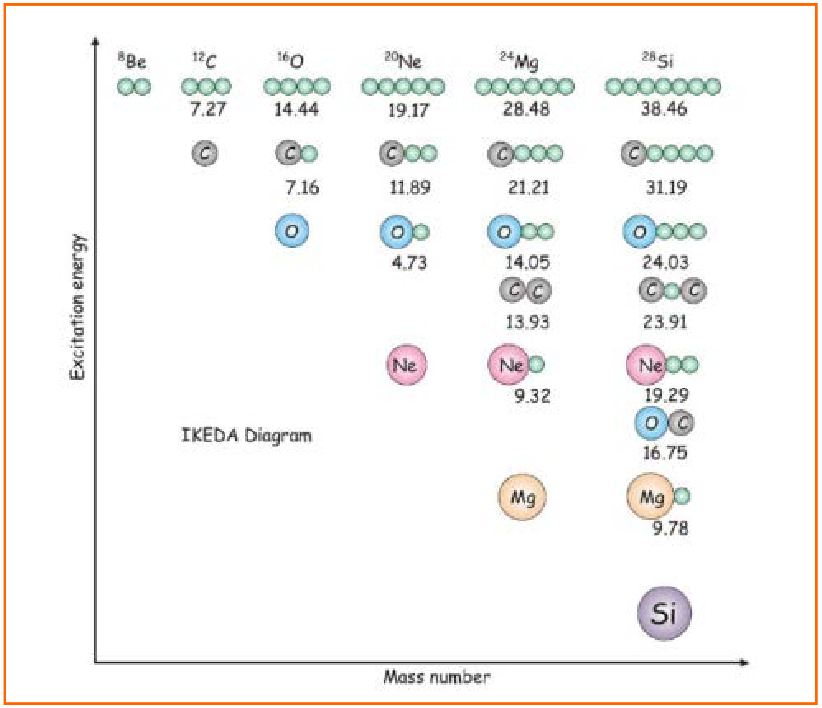


Fig. 1. Threshold energy for each decay mode. In the figure, the threshold energy for each decay mode is given in MeV. The systematics suggests the possible molecular nature around each energy. Some of the molecular states are already found and are represented in Fig. 2.

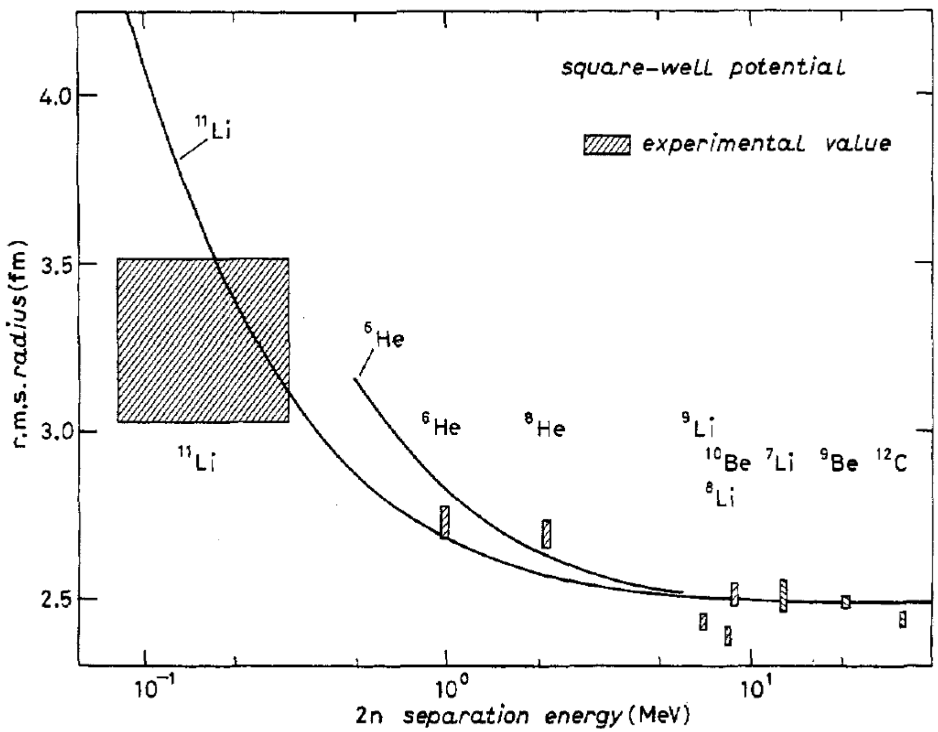
Dineutron halo – decoupling

Europhys. Lett., **4** (4), pp. 409-414 (1987)

The Neutron Halo of Extremely Neutron-Rich Nuclei.

P. G. HANSEN (*) (§) and B. JONSON (**)

$$\rho = \hbar/(2\mu B)^{1/2},$$



不稳定核结团效应！

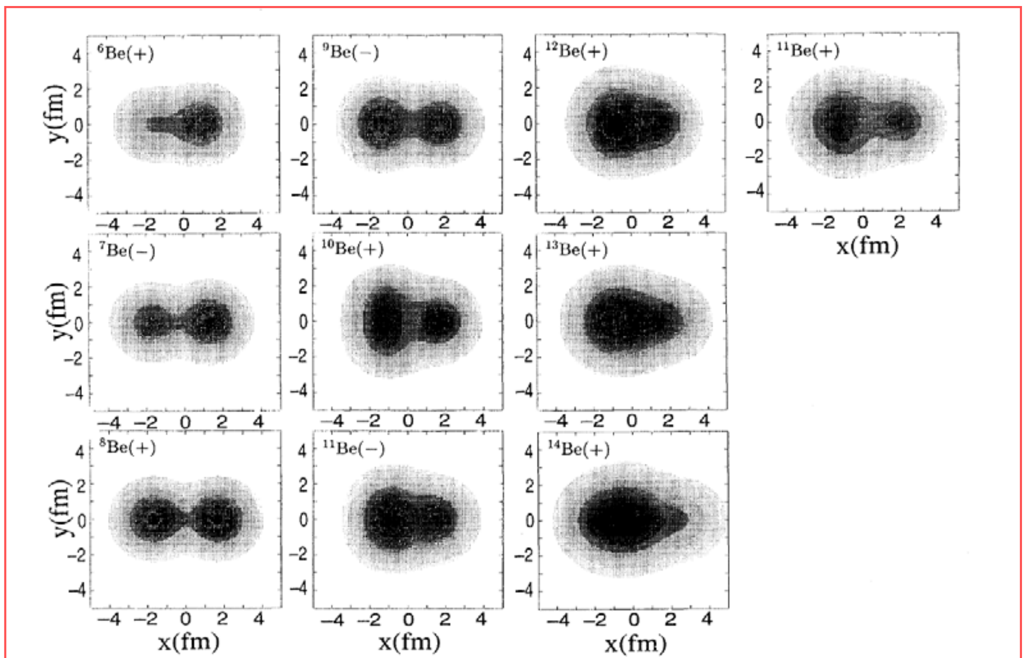
AMD (反对称分子动力学模型)

PHYSICAL REVIEW C VOLUME 52, NUMBER 2 628 AUGUST 1995

Structure of Li and Be isotopes studied with antisymmetrized molecular dynamics

Yoshiko Kanada-En'yo, Hisashi Horiuchi, and Akira Ono
Department of Physics, Kyoto University, Kyoto 606-01, Japan

FIG. 9. Matter density distribution of AMD states of Be isotopes. The intrinsic density before parity projection is shown. Density is projected to a x-y plane and integrated along the z axis perpendicular to the plane. Units of x and y axes are in fm.



适用于组态复杂核。单粒子波包为基础，有利于描写结团效应。

II. FORMULATION OF AMD

A. Wave function of AMD

$$|\Phi(\mathbf{Z})\rangle = \frac{1}{\sqrt{A!}}\det[\varphi_j(i)], \quad \varphi_j = \phi_{\mathbf{Z}_j}\chi_{\alpha_j} \ , \qquad (1)$$

$$\langle \mathbf{r}|\phi_{\mathbf{Z}_j}\rangle = \left(\frac{2\nu}{\pi}\right)^{3/4} \exp\left[-\nu\left(\mathbf{r} - \frac{\mathbf{Z}_j}{\sqrt{\nu}}\right)^2 + \frac{1}{2}\mathbf{Z}_j^2\right] \ ,$$

$$\propto \exp\left[-\nu(\mathbf{r} - \mathbf{D}_j)^2 + \frac{i}{\hbar}\mathbf{K}_j \cdot \mathbf{r}\right] \ , \qquad (2)$$

$$\mathbf{Z}_j = \sqrt{\nu}\mathbf{D}_j + \frac{i}{2\hbar\sqrt{\nu}}\mathbf{K}_j \ ,$$

Gaussian wave-packet;
Frictional cooling(正交条件等);
Projection;
Superposition(GCM);
NN interaction

$$|\Phi^{\pm}(\mathbf{Z}_1, \mathbf{Z}_2, \ldots, \mathbf{Z}_A)\rangle = (1 \pm P)|\Phi(\mathbf{Z}_1, \mathbf{Z}_2, \ldots, \mathbf{Z}_A)\rangle \ ,$$

$$\frac{\langle P^J_{MK}\Phi^{\pm}|\widehat{T}^k_{q=0}|P^J_{MK}\Phi^{\pm}\rangle}{\langle P^J_{MK}\Phi^{\pm}|P^J_{MK}\Phi^{\pm}\rangle} = \frac{\mathcal{T}}{\mathcal{N}} \ ,$$

$$|\Phi^{\pm}(\mathbf{Z}_1, \ldots, \mathbf{Z}_A\mathbf{Z}'_1, \ldots, \mathbf{Z}'_A, C)\rangle$$

$$= |\Phi^{\pm}(\mathbf{Z}_1, \ldots, \mathbf{Z}_A)\rangle + C|\Phi^{\pm}(\mathbf{Z}'_1, \ldots, \mathbf{Z}'_A)\rangle \ . \quad (4)$$

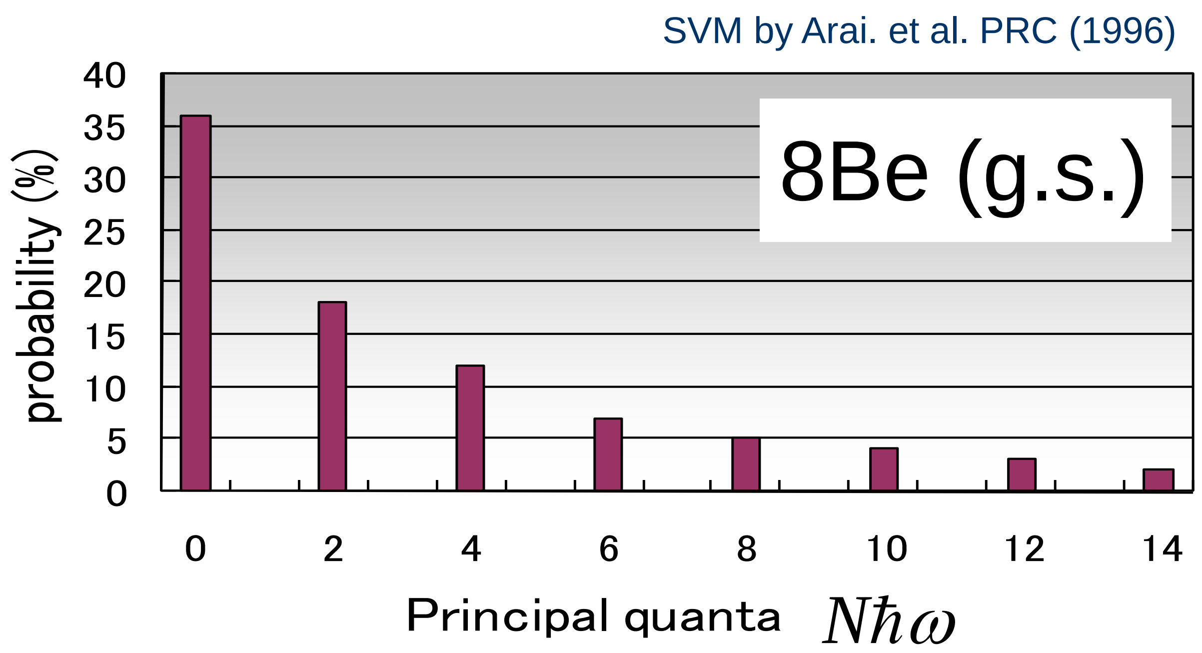
GCM

From Y. Kanada-En'yo

8Be (g.s.)

Developed 2α

Strong spatial correlation involves higher-shell components.



Developed cluster states are usually beyond mean-field

理论应用例：Linear Chain State

PHYSICAL REVIEW C **94**, 044303 (2016)

Structure and decay pattern of the linear-chain state in ^{14}C

T. Baba and M. Kimura

Department of Physics, Hokkaido University, 060-0810 Sapporo, Japan

II. THEORETICAL FRAMEWORK

A. Variational calculation and generator coordinate method

$$H = \sum_{i=1}^{A} t_i + \sum_{i<j}^{A} v_{ij}^N + \sum_{i<j}^{Z} v_{ij}^C - t(\text{c.m.}),$$

Brink-type

$$\Phi_{\text{int}} = \mathcal{A}\{\varphi_1, \varphi_2, \ldots, \varphi_A\} = \frac{1}{\sqrt{A!}}\det[\varphi_i(\boldsymbol{r}_j)],$$

$$\varphi_i(\boldsymbol{r}) = \phi_i(\boldsymbol{r}) \otimes \chi_i \otimes \xi_i,$$

$$\phi_i(\boldsymbol{r}) = \exp\left\{-\sum_{\sigma=x,y,z} \nu_\sigma \left(r_\sigma - \frac{Z_{i\sigma}}{\sqrt{\nu_\sigma}}\right)^2\right\},$$

$$\chi_i = a_i\chi_\uparrow + b_i\chi_\downarrow, \quad \xi_i = \text{proton or neutron}.$$

$$\Phi^\pi = P^\pi \Phi_{\text{int}} = \frac{1 + \pi P_x}{2}\Phi_{\text{int}}, \quad \pi = \pm,$$

GCM：β、γ

$$E'^\pi = \frac{\langle\Phi^\pi|H|\Phi^\pi\rangle}{\langle\Phi^\pi|\Phi^\pi\rangle} + v_\beta(\langle\beta\rangle - \beta_0)^2 + v_\gamma(\langle\gamma\rangle - \gamma_0)^2,$$

$$\Phi_{MK}^{J\pi}(\beta,\gamma) = P_{MK}^J \Phi^\pi(\beta,\gamma) = \frac{2J+1}{8\pi^2}\int d\Omega D_{MK}^{J*}(\Omega)R(\Omega)\Phi^\pi(\beta,\gamma).$$

$$\Psi_{Mn}^{J\pi} = \sum_i \sum_K c_{Kin}^{J\pi}\Phi_{MK}^{J\pi}(\beta_i,\gamma_i),$$

nth J^π state

B. Single-particle orbits

$$\widetilde{\varphi}_\alpha = \frac{1}{\sqrt{\lambda_\alpha}} \sum_{i=1}^{A} g_{i\alpha}\varphi_i .$$

$$h_{\alpha\beta} = \langle\widetilde{\varphi}_\alpha|t|\widetilde{\varphi}_\beta\rangle + \sum_{\gamma=1}^{A}\langle\widetilde{\varphi}_\alpha\widetilde{\varphi}_\gamma|v^N + v^C|\widetilde{\varphi}_\beta\widetilde{\varphi}_\gamma - \widetilde{\varphi}_\gamma\widetilde{\varphi}_\beta\rangle,$$

$$+ \frac{1}{2}\sum_{\gamma,\delta=1}^{A}\langle\widetilde{\varphi}_\gamma\widetilde{\varphi}_\delta|\widetilde{\varphi}_\alpha^*\widetilde{\varphi}_\beta\frac{\delta v^N}{\delta\rho}|\widetilde{\varphi}_\gamma\widetilde{\varphi}_\delta - \widetilde{\varphi}_\delta\widetilde{\varphi}_\gamma\rangle. \qquad (13)$$

The eigenvalues ϵ_s and eigenvectors $f_{\alpha s}$ of $h_{\alpha\beta}$ give the single-particle energies and the single-particle orbits, $\widetilde{\phi}_s = \sum_{\alpha=1}^{A} f_{\alpha s}\widetilde{\varphi}_\alpha$. We also calculate the amount of the

$$\widetilde{\phi}_s = \sum_{\alpha=1}^{A} f_{\alpha s}\widetilde{\varphi}_\alpha .$$

$$p^+ = \left|\langle\widetilde{\phi}_s|\frac{1+P_x}{2}|\widetilde{\phi}_s\rangle\right|^2,$$

$$j(j+1) = \langle\widetilde{\phi}_s|j^2|\widetilde{\phi}_s\rangle, \quad |j_z| = \sqrt{\langle\widetilde{\phi}_s|j_z^2|\widetilde{\phi}_s\rangle},$$

$$l(l+1) = \langle\widetilde{\phi}_s|l^2|\widetilde{\phi}_s\rangle, \quad |l_z| = \sqrt{\langle\widetilde{\phi}_s|l_z^2|\widetilde{\phi}_s\rangle},$$

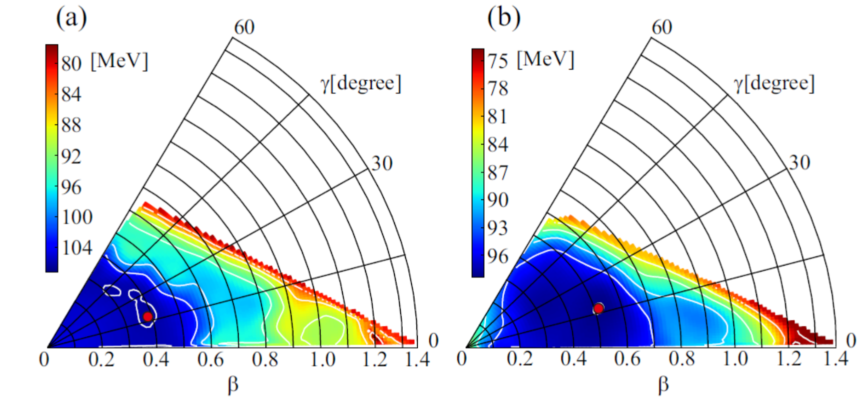
C. α reduced width amplitude and decay width

$$y_{lj^{\pi'}}(r) = \sqrt{\frac{A!}{4!(A-4)!}}\langle\phi_\alpha[\phi_{\rm Be}(j^{\pi'})Y_{l0}(\hat{r})]_{J^\pi M}\big|\Psi^{J^\pi}_{Mn}\rangle,$$

$$\gamma^2_{lj^{\pi'}}(a) = \frac{\hbar^2}{2\mu a}[a y_{lj^{\pi'}}(a)]^2.$$

$$\Gamma^\alpha_{lj^{\pi'}} = 2P_l(a)\gamma^2_{lj^{\pi'}}(a), \quad P_l(a) = \frac{ka}{F_l^2(ka) + G_l^2(ka)}, \qquad (18)$$

III. RESULTS



A. Energy surface and intrinsic structures

FIG. 1. The angular-momentum projected energy surface for (a) the $J^{\pi} = 0^{+}$ state and (b) $J^{\pi} = 1^{-}$ state as functions of quadrupole deformation parameters β and γ. The circles show the position of the energy minima.

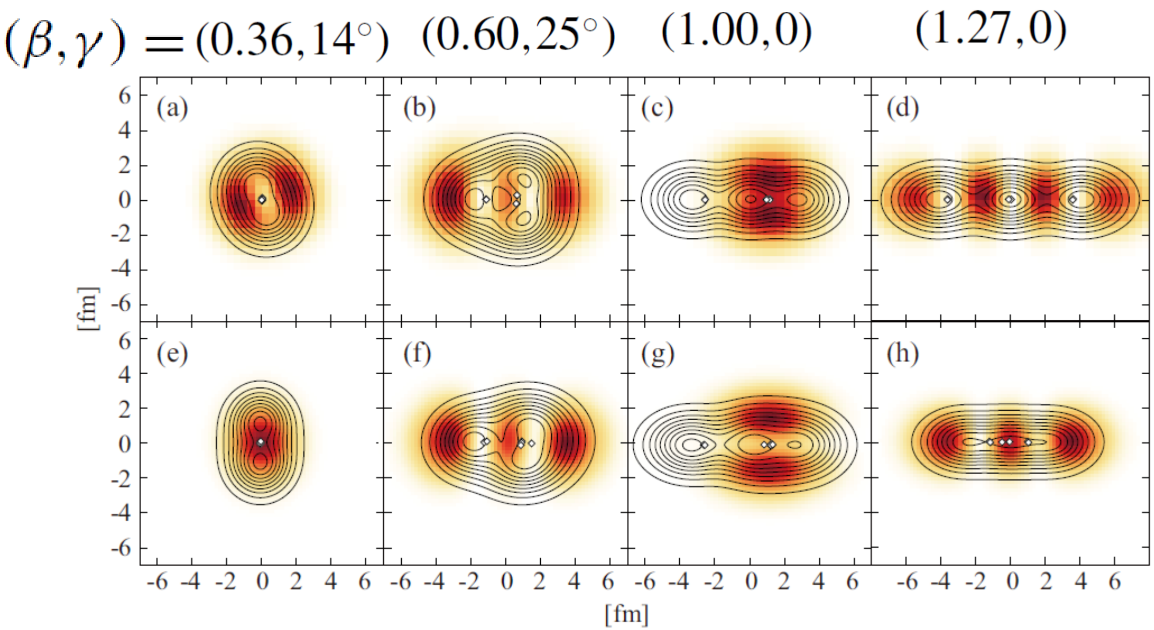


FIG. 2. The density distribution of (a)–(d) the positive states and (e)–(h) negative parity states. The contour lines show the proton density distributions. The color plots show the single-particle orbits occupied by the most weakly bound neutron. Open boxes show the centroids of the Gaussian wave packets describing protons.

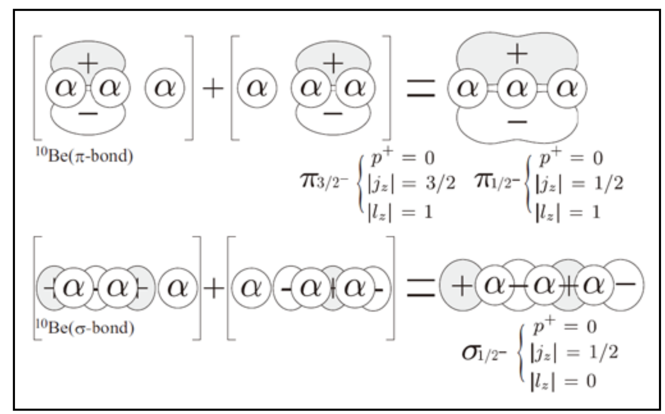


FIG. 3. The schematic figure showing the π and σ orbits around the linear chain. The combination of the p orbits perpendicular to the symmetry axis generates π orbits, while the combination of parallel orbits generates σ orbits.

B. Excitation spectrum

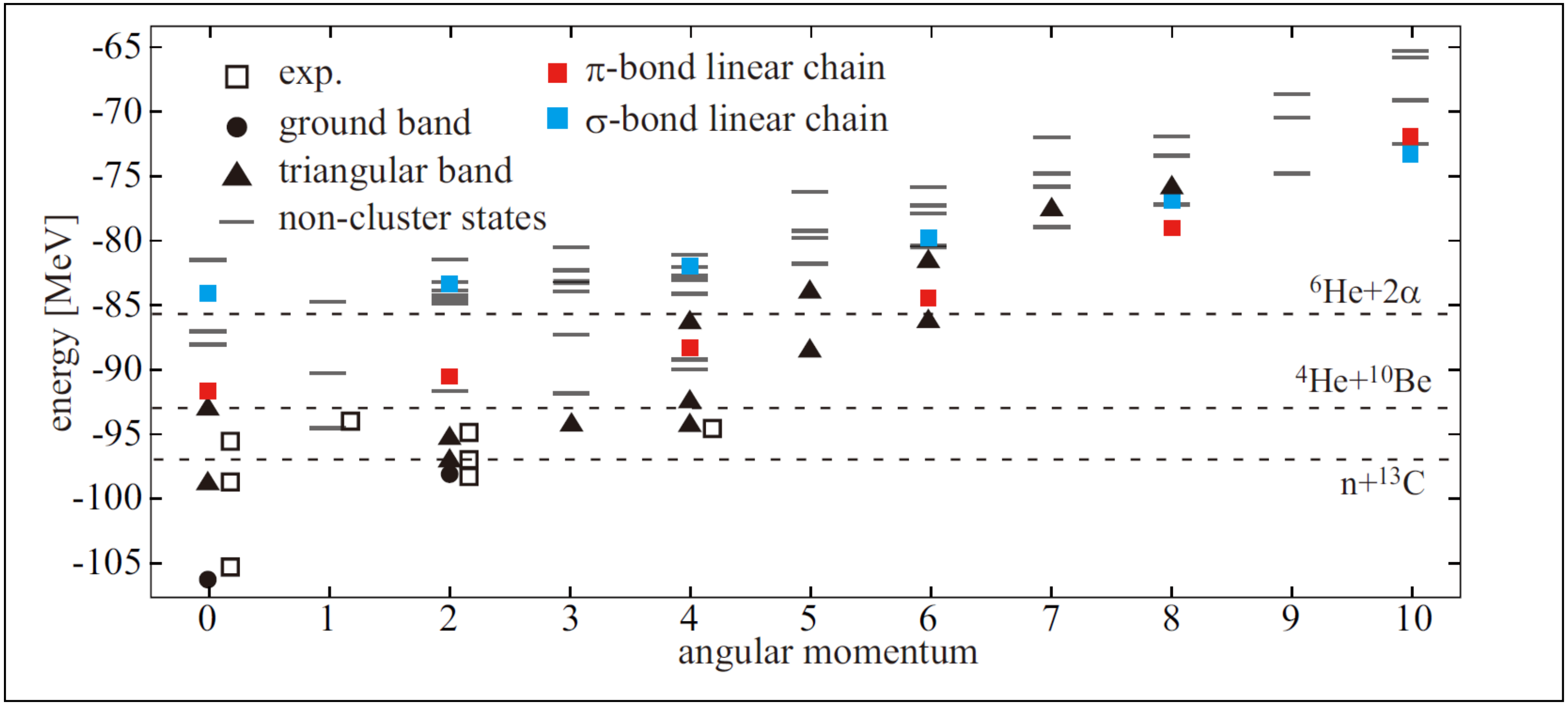


FIG. 4. The positive-parity energy levels up to $J^\pi = 10^+$. Open boxes show the observed states with the definite spin-parity assignments taken from Ref. [41], and other symbols show the calculated result. The filled circles, triangles and filled boxes show the ground, triangular, and linear-chain bands, while lines show the noncluster states which have the reduced widths less than 0.08 $\mathrm{MeV}^{1/2}$.

TABLE II. Excitation energies (MeV) and proton and neutron root-mean-square radii (fm) of several selected states. Numbers in the parentheses are the observed data [41,42].

Band	J^π	E_x	r_p	r_n
Ground	0_1^+	0.00	2.53	2.58
	2_1^+	8.41	2.58	2.69
		(7.01)	(2.34)	
Triangular	0_2^+	7.49	2.67	2.92
$K^\pi = 0^+$	2_2^+	9.26	2.64	2.83
	4_1^+	12.00	2.65	2.89
Triangular	2_3^+	10.99	2.68	2.92
$K^\pi = 2^+$	3_1^+	12.03	2.68	2.92
	4_2^+	13.83	2.68	2.92
π-bond	0_4^+	14.64	3.27	3.20
Linear chain	2_5^+	15.73	3.37	3.28
	4_5^+	17.98	3.33	3.24
	6_2^+	21.80	3.39	3.30
σ-bond	0_7^+	22.16	3.91	4.12
Linear chain	2_{10}^+	22.93	4.02	4.21
	4_{11}^+	24.30	3.97	4.15

TABLE III. The calculated in-band $B(E2)$ strengths for the low-spin positive-parity states in units of $e^2\text{fm}^4$. For the negative-parity states, the transitions between the low-spin cluster states (diamonds in Fig. 5) are shown and the transitions less than $10e^2\text{fm}^4$ are not shown. The number in parentheses is the observed data [43].

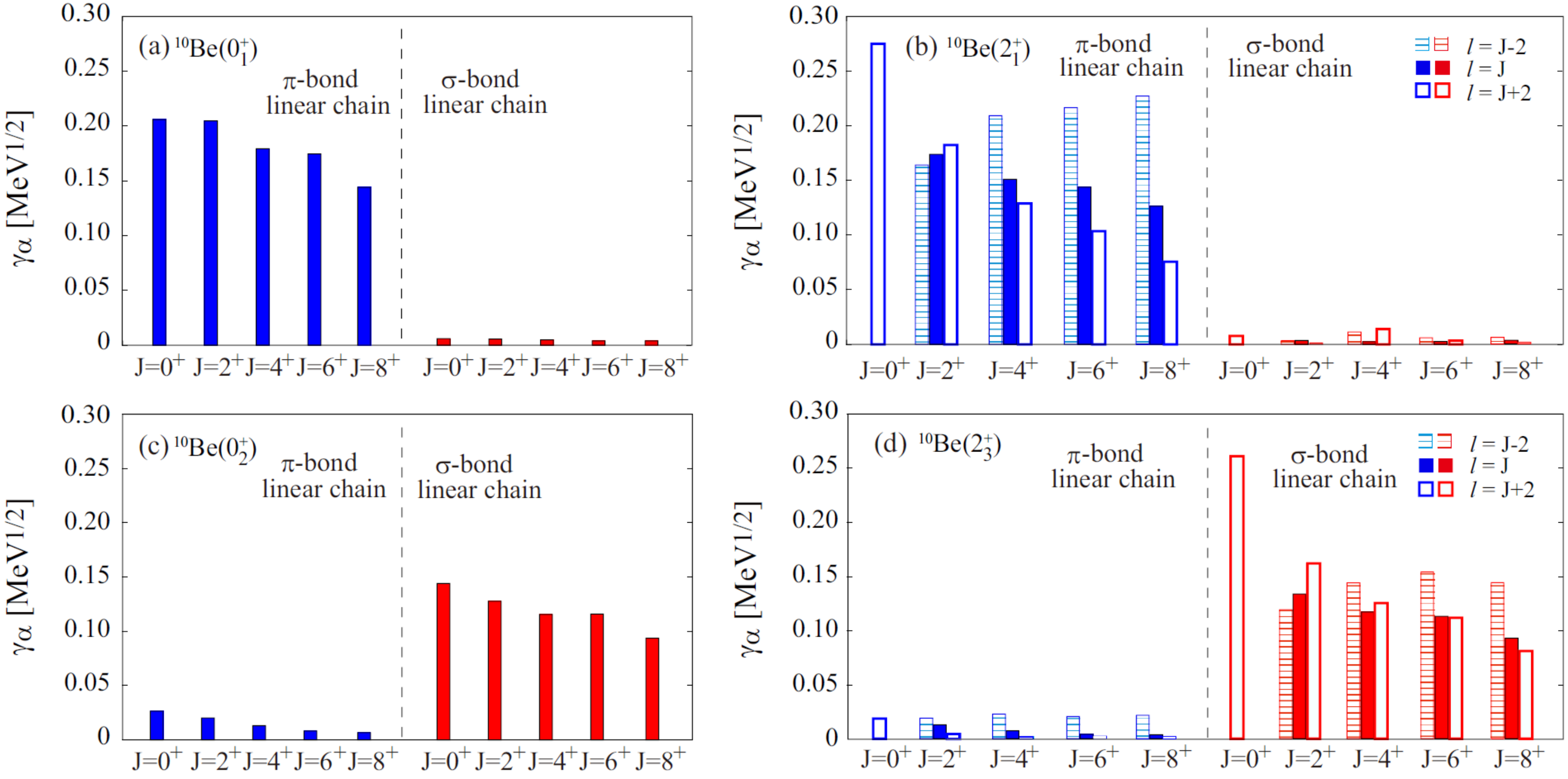
	$J_i \rightarrow J_f$	$B(E2; J_i \rightarrow J_f)$
Ground $\rightarrow$ ground	$2_1^+ \rightarrow 0_1^+$	8.1(3.74)
Triangular $K^\pi = 0^+$	$2_2^+ \rightarrow 0_2^+$	7.6
$\rightarrow$ triangular $K^\pi = 0^+$	$4_1^+ \rightarrow 2_2^+$	7.9
	$6_1^+ \rightarrow 4_2^+$	19.8
Triangular $K^\pi = 2^+$	$3_1^+ \rightarrow 2_3^+$	17.6
$\rightarrow$ triangular $K^\pi = 2^+$	$4_2^+ \rightarrow 3_1^+$	8.5
	$4_2^+ \rightarrow 2_3^+$	5.4
π-bond linear chain	$2_5^+ \rightarrow 0_4^+$	165.5
$\rightarrow$ π-bond linear chain	$4_5^+ \rightarrow 2_5^+$	257.4
	$6_2^+ \rightarrow 4_5^+$	276.5
σ-bond linear chain	$2_{10}^+ \rightarrow 0_7^+$	441.9
$\rightarrow$ σ-bond linear chain	$4_{11}^+ \rightarrow 2_{10}^+$	655.9
Negative parity states	$3_4^- \rightarrow 1_3^-$	21.9
	$3_5^- \rightarrow 1_3^-$	32.4
	$3_6^- \rightarrow 1_5^-$	60.1
	$3_{10}^- \rightarrow 1_5^-$	31.5
	$5_2^- \rightarrow 3_4^-$	63.0
	$5_4^- \rightarrow 3_5^-$	54.5
	$5_7^- \rightarrow 3_6^-$	53.9

PHYSICAL REVIEW C **95**, 064318 (2017)

Three-body decay of linear-chain states in ^{14}C

T. Baba[1] and M. Kimura[1,2]
[1]*Department of Physics, Hokkaido University, 060-0810 Sapporo, Japan*
[2]*Reaction Nuclear Data Centre, Faculty of Science, Hokkaido University, 060-0810 Sapporo, Japan*

Reduced widths



理论应用例：α + 2n + 2n Condensate (BEC)

PHYSICAL REVIEW C **88**, 034321 (2013)

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Dineutron formation and breaking in ^{8}He

A. Framework

1. Extended ^{6}He + 2n cluster wave function

GCM on $\{\lambda, \boldsymbol{R}_\lambda, b_\lambda\}$

$$\Phi_{2n}(\boldsymbol{R}, b) = \mathcal{A}\{\phi_n(\boldsymbol{r}_1; \boldsymbol{R}, b)\chi_\uparrow(1)\phi_n(\boldsymbol{r}_2; \boldsymbol{R}, b)\chi_\downarrow(2)\},$$

$$\phi_n(\boldsymbol{r}; \boldsymbol{R}, b) \propto \exp\left[-\frac{1}{2b^2}(\boldsymbol{r}-\boldsymbol{R})^2\right],$$

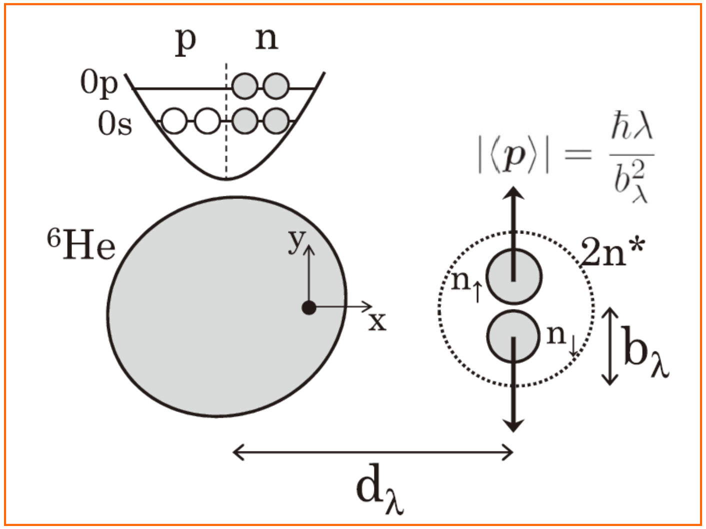
$$\boldsymbol{R}_{\uparrow/\downarrow} = \boldsymbol{R}_\lambda \pm i\lambda \boldsymbol{e}_\lambda. \qquad \langle \boldsymbol{r}\rangle = \mathrm{Re}[\boldsymbol{R}],$$

$$\boldsymbol{e}_\lambda = \boldsymbol{e}_{spin} \times \hat{\boldsymbol{R}}_\lambda \qquad \langle \boldsymbol{p}\rangle = \frac{\hbar}{b^2}\mathrm{Im}[\boldsymbol{R}].$$

$$\Phi_{^6\mathrm{He}+2n^*}(\kappa; \lambda, d_\lambda, b_\lambda)$$

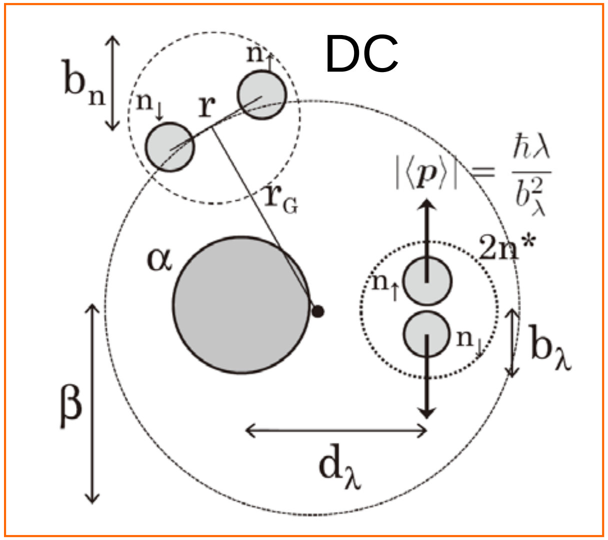
$$= \frac{1}{\sqrt{8!}}\mathcal{A}\left\{\Phi_{^6\mathrm{He}}\left(\kappa, \boldsymbol{R}_{^6\mathrm{He}} = -\frac{1}{4}d_\lambda \boldsymbol{e}_x, b_\alpha\right)\right.$$

$$\left.\times\, \Phi_{2n^*}\left(\lambda, \boldsymbol{R}_\lambda = \frac{3}{4}d_\lambda \boldsymbol{e}_x, b_\lambda = b_\alpha\right)\right\}.$$



Shell-like

2. ^{8}He DC wave function



$$\Phi_{DC}(\lambda, d_\lambda, b_\lambda; B_n, b_n) = \frac{1}{\sqrt{8!}} \int d^3\boldsymbol{R} \exp\left[-\frac{R^2}{B_n^2}\right] \mathcal{A}\left\{\Phi_\alpha\left(\boldsymbol{R}_\alpha = -\frac{1}{3}d_\lambda \boldsymbol{e}_x, b_\alpha\right) \times \Phi_{2n^*}\left(\lambda, \boldsymbol{R}_\lambda = \frac{2}{3}d_\lambda \boldsymbol{e}_x, b_\lambda = b_\alpha\right) \Phi_{2n}(\boldsymbol{R}, b_n)\right\}. \quad (7)$$

$$\Phi_{2n_{DC}}(\beta, b_n) = \int d^3\boldsymbol{R} \exp\left[-\frac{R^2}{B_n^2}\right] \Phi_{2n}(\boldsymbol{R}, b_n) = \mathcal{A}\{\psi_r(b_n)\psi_G(\beta)\,\chi_\uparrow(n1)\chi_\downarrow(n2)\}, \quad (8)$$

$$\psi_r(\boldsymbol{r}; b_n) \propto \exp\left[-\frac{r^2}{4b_n^2}\right] \boldsymbol{r} = \boldsymbol{r}_{n1} - \boldsymbol{r}_{n2}, \quad (9)$$

$$\psi_G(\boldsymbol{r}_G; \beta) \propto \exp\left[-\frac{r_G^2}{\beta^2}\right] \boldsymbol{r}_G = \frac{\boldsymbol{r}_{n1} + \boldsymbol{r}_{n2}}{2}, \quad (10)$$

$$\beta^2 = B_n^2 + b_n^2$$

GCM:

	2n*			2n_DC	
$\Phi_{^6\mathrm{He}+2n^*}$	$\lambda = 0.0, 0.4$	$d_\lambda = 1, 2, 3, 4$	$b_\lambda = b_\alpha$		
Φ_{DC}	$\lambda = 0.0$	$d_\lambda = 1, 2, \ldots, 8$	$b_\lambda = b_n$	$\beta = 2, 3, \ldots, 8$	$b_n = b_i\ (i = 1, \ldots, 5)$
	$\lambda = 0.4$	$d_\lambda = 1, 2, 3, 4$	$b_\lambda = b_\alpha$	$\beta = 2, 3, \ldots, 8$	$b_n = b_i\ (i = 1, \ldots, 5)$

3. *Description of $^8He(0^+)$*

RGM+GCM: $i = \{\kappa; \lambda, d_\lambda\} \qquad j = \{\lambda, d_\lambda, b_\lambda; \beta, b_n\}.$

$$\Psi_{^8\mathrm{He}(0^+)} = \sum_i c_i \, \mathcal{P}^{0+}_{00} \Phi_{^6\mathrm{He}+2n^*}(\kappa; \lambda, d_\lambda, b_\lambda = b_\alpha)$$

Shell-like

$$+ \sum_j c_j \, \mathcal{P}^{0+}_{00} \Phi_{\mathrm{DC}}(\lambda, d_\lambda, b_\lambda; \beta, b_n), \qquad (12)$$

DC-like

4. *Description of $^6He(0^+)$*

$$\Psi_{^6\mathrm{He}(0^+)} = \sum_i c_i \, \mathcal{P}^{0+}_{00} \Phi_{\alpha+2n^*}(\lambda, d_\lambda, b_\lambda = b_\alpha)$$

$$+ \sum_j c_j \, \mathcal{P}^{0+}_{00} \Phi_{\mathrm{DC}}(\beta, b_n),$$

5. *Quantization of the dineutron component*

类似谱因子式展开系数

$$\mathcal{N}^{^8\mathrm{He}}_{\mathrm{DC}}(\beta, b_n) = \left| \left\langle \mathcal{P}^{0+}_{00} \Phi_{\mathrm{DC}}(\lambda = \lambda_0, d_\lambda = d_0, b_\lambda = b_\alpha; \beta, b_n) \middle| \Psi_{^8\mathrm{He}(0^+)} \right\rangle \right|^2.$$

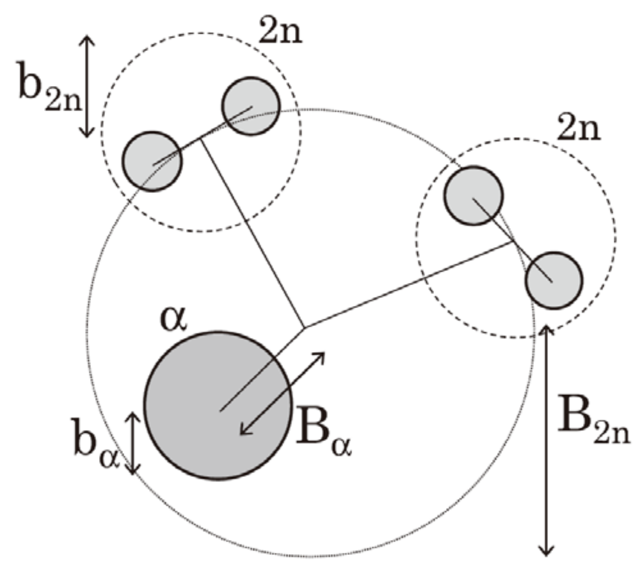
$$\Phi_{2\mathrm{DC}}^{\mathrm{norecoil}} = \frac{1}{\sqrt{8!}} \int d^3\boldsymbol{R}_{2n_1}\, d^3\boldsymbol{R}_{2n_2}\, \exp\left[-\frac{\boldsymbol{R}_{2n_1}^2}{B_{2n_1}^2} - \frac{\boldsymbol{R}_{2n_2}^2}{B_{2n_2}^2}\right] \mathcal{A}\left\{\Phi_\alpha(\boldsymbol{R}_\alpha = 0, b_\alpha)\Phi_{2n}\left(\boldsymbol{R}_{2n_1}, b_{2n}\right)\Phi_{2n}\left(\boldsymbol{R}_{2n_2}, b_{2n}\right)\right\}$$

$$= \frac{1}{\sqrt{8!}} \int d^3\boldsymbol{R}_{2n_1}\, d^3\boldsymbol{R}_{2n_2}\, \exp\left[-\frac{\boldsymbol{R}_{2n_1}^2}{B_{2n_1}^2} - \frac{\boldsymbol{R}_{2n_2}^2}{B_{2n_2}^2}\right] \mathcal{A}\left\{ \exp\left[-\frac{4}{2b_\alpha^2}\boldsymbol{X}_\alpha^2 - \frac{2}{2b_{2n}^2}\left(\boldsymbol{X}_{2n_1} - \boldsymbol{R}_{2n_1}\right)^2 - \frac{2}{2b_{2n}^2}\left(\boldsymbol{X}_{2n_2} - \boldsymbol{R}_{2n_2}\right)^2\right] \psi_\alpha \psi_{2n} \psi_{2n} \right\},$$

$$\mathcal{N}_{2\mathrm{DC}}(\beta, b_n) = \left|\langle \Phi_{2\mathrm{DC}}(\beta, b_n) | \Psi_{^8\mathrm{He}(0^+)} \rangle\right|^2,$$

$$\Psi_{\alpha\mathrm{DC}}(B_\alpha, b_\alpha, B_{2n}, b_{2n})$$

$$= \frac{1}{\sqrt{8!}} \mathcal{A}\left\{ \int d^3\boldsymbol{R}_1 \exp\left[-\frac{\boldsymbol{R}_1^2}{B_\alpha^2}\right] \Phi_\alpha(\boldsymbol{R}_1, b_\alpha) \times \prod_{c=2}^{3} \left(\int d^3\boldsymbol{R}_c \exp\left[-\frac{\boldsymbol{R}_c^2}{B_{2n}^2}\right] \Phi_{2n}(\boldsymbol{R}_c, b_{2n}) \right) \right\}.$$



B. Hamiltonian

$$H = T - T_G + V_{\text{cent}} + V_{\text{LS}} + V_{\text{Coul}},$$

m55 interaction: good for n-n but too strong for core-n;
m59 interaction: good for core-n but too strong for n-n

C. Result

1. Energy spectra and characteristics

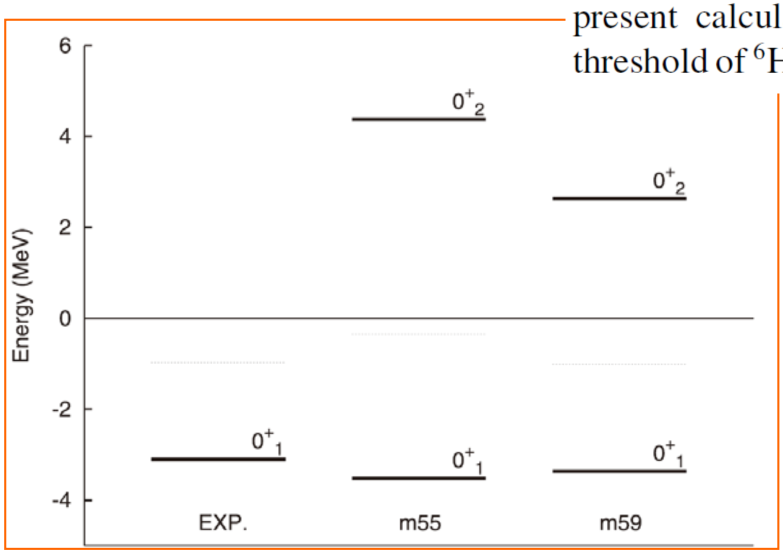
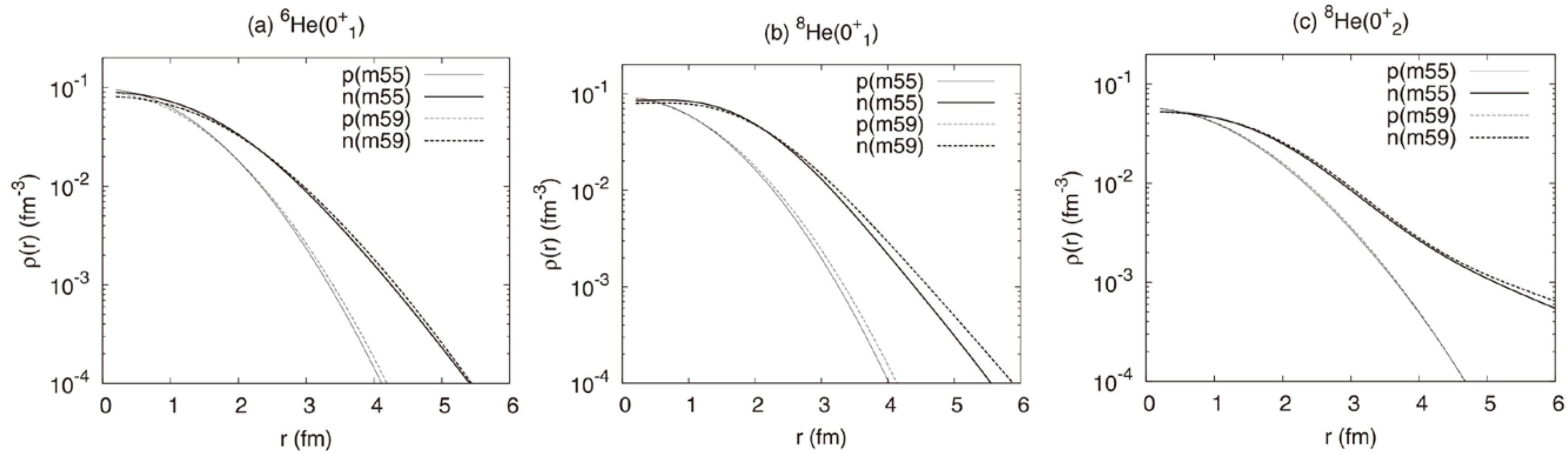
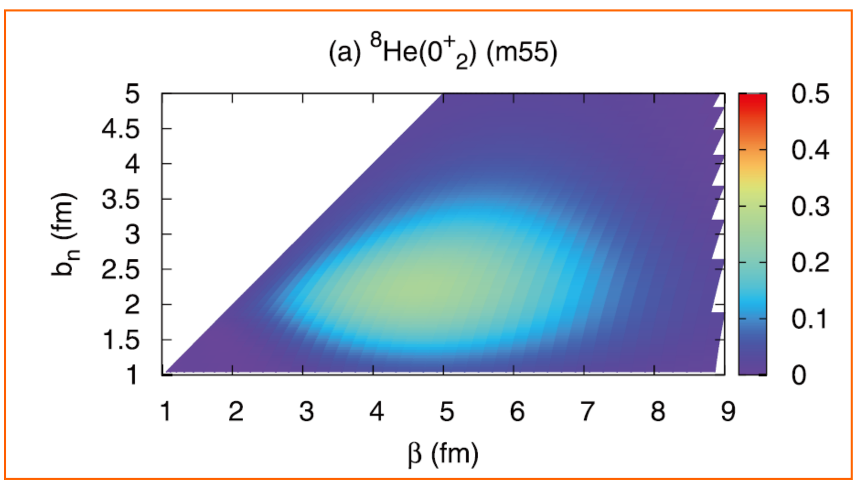


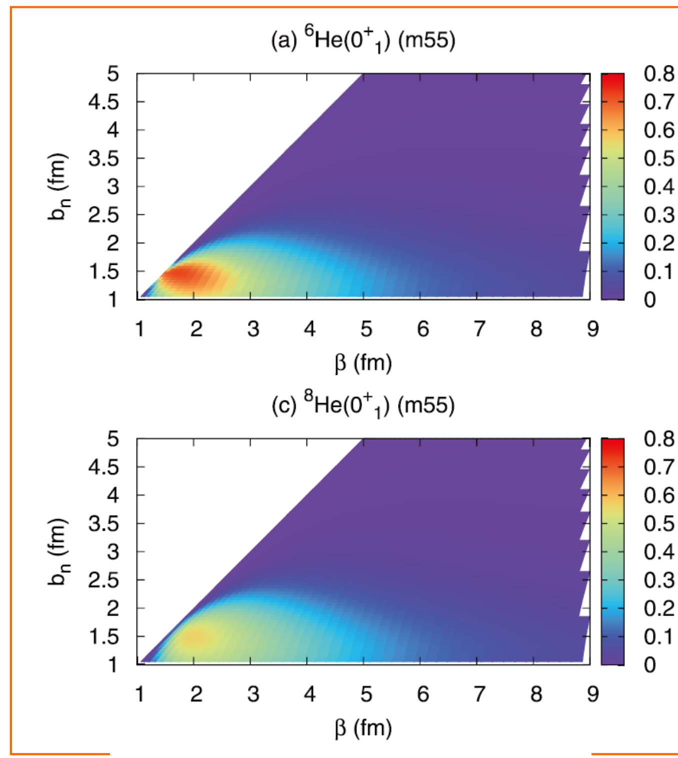
FIG. 3. Energy spectra of the 0^+ states in experiments and the present calculation measured from the threshold of $\alpha + 4n$. The threshold of ^{6}He $+ 2n$ is shown with the dotted line in each spectrum.



2. *Component of one dineutron in the S wave in $^8He(0^+_1)$ and $^6He(0^+_1)$*



2DC wave function on the β-b_n plane.



DC wave function on the β-b_n plane.

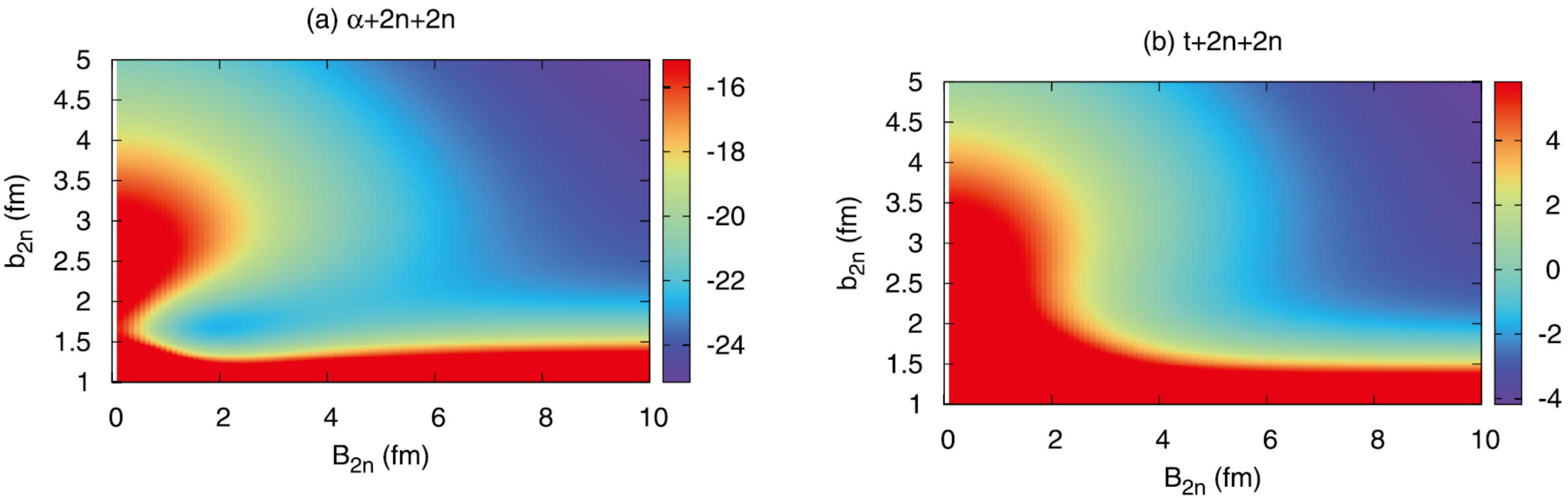


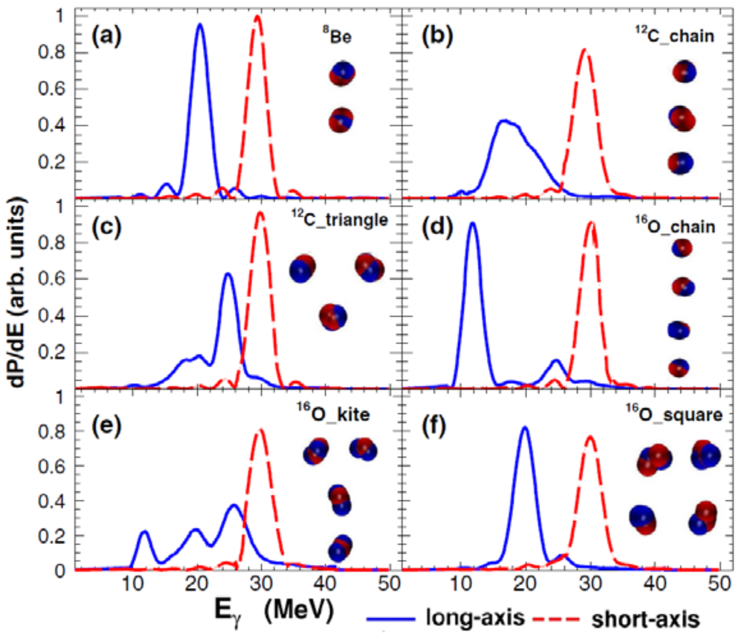
FIG. 9. (Color online) The energy surface on the B_{2n}-b_{2n} plane calculated with the $\alpha + 2n + 2n$ and $t + 2n + 2n$ αDC wave functions [(a) and (b)]. Each of them are plotted by energy region from the energy at $(B_{2n}, b_{2n}) = (10.0, 5.0)$ to that +10 MeV.

GDR中的结团效应— 复旦大学组工作例

PRL **113,** 032506 (2014) PHYSICAL REVIEW LETTERS week ending 18 JULY 2014

Giant Dipole Resonance as a Fingerprint of α Clustering Configurations in ^{12}C and ^{16}O

W. B. He (何万兵),[1,2] Y. G. Ma (马余刚),[1,3,*] X. G. Cao (曹喜光),[1,†] X. Z. Cai (蔡翔舟),[1] and G. Q. Zhang (张国强)[1]
[1]*Shanghai Institute of Applied Physics, Chinese Academy of Sciences, Shanghai 201800, China*
[2]*University of the Chinese Academy of Sciences, Beijing 100080, China*
[3]*Shanghai Tech University, Shanghai 200031, China*



is well established that the centroid energy of this resonance can provide direct information about nuclear sizes and the nuclear equation of state [16]. Meanwhile, the GDR width closely relates with nuclear deformation, temperature, and angular momentum [16–18]. The GDR strength

FIG. 2 (color online). ^{8}Be, ^{12}C, and ^{16}O GDR spectra with different cluster configurations. The corresponding α cluster configuration in the present EQMD model calculation is drawn in each panel, in which blue and red balls indicate protons and neutrons, respectively. The dynamical dipole evolution of ^{8}Be, ^{12}C, and ^{16}O with linear-chain configurations are shown in [50].

集团间相互作用的有效场论处理— 同济大学组工作例

PHYSICAL REVIEW C **103**, 044316 (2021)

α-cluster structures above double shell closures via double-folding potentials from chiral effective field theory

Dong Bai[1,*] and Zhongzhou Ren[1,2,†]
[1]*School of Physics Science and Engineering, Tongji University, Shanghai 200092, China*
[2]*Key Laboratory of Advanced Micro-Structure Materials, Ministry of Education, Shanghai 200092, China*

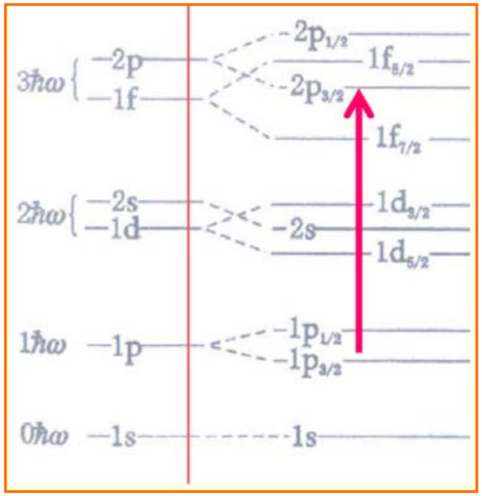
α-cluster structures above double shell closures are among the cornerstones for nuclear α-cluster physics. Semimicroscopic cluster models (SMCMs) are important theoretical models to study their properties. A crucial ingredient of SMCMs is the effective potential between the alpha cluster and the doubly magic nucleus. We derive new double-folding potentials between α clusters and doubly magic nuclei from soft local chiral nucleon-nucleon potentials given by chiral effective field theory (χEFT) at the next-to-next-to-leading order. The α-cluster structures in ^{8}Be, ^{20}Ne, ^{44,52}Ti, and ^{212}Po are explored to validate these new double-folding potentials. The α decay of ^{104}Te is also studied in the light of recent experimental results. Our study shows that double-folding potentials from χEFT are the new reliable effective potentials for the SMCM approach to α-cluster structures above double shell closures, with both conceptual and phenomenological merits.

单极跃迁强度增强：激发潜在的cluster结构自由度

Progress of Theoretical Physics, Vol. 120, No. 6, December 2008

Monopole Excitation to Cluster States

Taiichi Yamada,[1,*] Yasuro Funaki,[2] Hisashi Horiuchi,[3,4]
Kiyomi Ikeda[2] and Akihiro Tohsaki[3]



a strong monopole strength comparable to the typical single-particle strength (e.g. a matrix element of 3.37 fm2 for the 0p →1p transition [32]) for excited states below 20 MeV signals the formation of cluster structure.

Bayman-Bohr theorem,

Shell-like vs cluster-like

$$\frac{1}{\sqrt{16!}}\det|(0s)^4(0p)^{12}| = N_g\frac{1}{\sqrt{_{16}C_4}}\mathcal{A}\{[\mathcal{R}_4(\boldsymbol{r},3\nu_N)\phi(^{12}\mathrm{C})]_{(0,0)}\phi(\alpha)\}\phi_G(\boldsymbol{r}_G), \quad (2\cdot1)$$

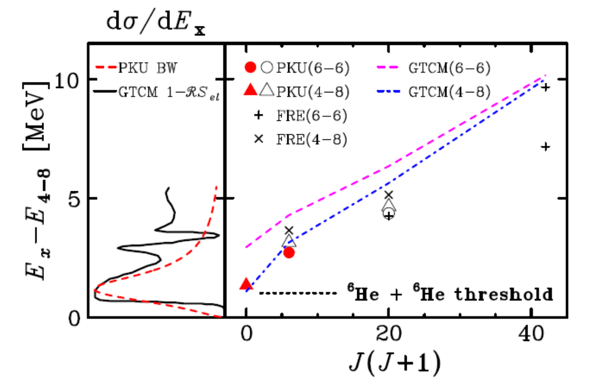
$$[\mathcal{R}_4(\boldsymbol{r},3\nu_N)\phi(^{12}\mathrm{C})]_{(\lambda,\mu)=(0,0)} = \sum_{L=0,2,4} C_L\,[\mathcal{R}_{4L}(\boldsymbol{r},3\nu_N)\phi_L(^{12}\mathrm{C})]_{J=0}, \quad (2\cdot2)$$

$$\phi_G(\boldsymbol{r}_G) = \left(\frac{32\nu_N}{\pi}\right)^{3/4}\exp\left(-16\nu_N\boldsymbol{r}_G^2\right), \quad \boldsymbol{r}_\mathrm{G} = \frac{1}{16}\sum_{i=1}^{16}\boldsymbol{r}_i, \quad (2\cdot3)$$

$$C_L = \langle(4,0)L,(0,4)L||(0,0)0\rangle, \quad {}_{16}C_4 = \frac{16!}{12!4!}. \quad (2\cdot4)$$

实验例1：^{12}Be集团结构 — HIRFL/RIBLL1上的实验研究

采用独特的零度测量技术，首次在不稳定核中测定增强的单极跃迁强度，结合自旋和谱因子的测定，从而清楚发现了丰中子核^{12}Be中10.3 MeV近阈分子态，确定了^{12}Be中的集团结构。



PRL 112, 162501 (2014) PHYSICAL REVIEW LETTERS week ending 25 APRIL 2014

Observation of Enhanced Monopole Strength and Clustering in ^{12}Be

Z. H. Yang (杨再宏),[1] Y. L. Ye (叶沿林),[1,*] Z. H. Li (李智焕),[1] J. L. Lou (楼建玲),[1] J. S. Wang (王建松),[2] D. X. Jiang (江栋兴),[1] Y. C. Ge (葛愉成),[1] Q. T. Li (李奇特),[1] H. Hua (华辉),[1] X. Q. Li (李湘庆),[1] F. R. Xu (许甫荣),[1] J. C. Pei (裴俊琛),[1] R. Qiao (乔锐),[1] H. B. You (游海波),[1] H. Wang (王赫),[1,3] Z. Y. Tian (田正阳),[1] K. A. Li (李阔昂),[1] Y. L. Sun (孙叶磊),[1] H. N. Liu (刘红娜),[1,3] J. Chen (陈洁),[1] J. Wu (吴锦),[1,3] J. Li (李晶),[1] W. Jiang (蒋伟),[1] C. Wen (文超),[1,3] B. Yang (杨彪),[1] Y. Y. Yang (杨彦云),[2] P. Ma (马朋),[2] J. B. Ma (马军兵),[2] S. L. Jin (金仕纶),[2] J. L. Han (韩建龙),[2] and J. Lee (李晓菁)[3]

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- PRC91,024304(2015); SC-PMA57, 1613(2014)
- NIMA728(2013)47； IEEE-NS61(2014)59

实验例2：发现^{16}C中的π构型链状分子转动带—HIRFL/RIBLL1上的实验研究

PHYSICAL REVIEW LETTERS **124**, 192501 (2020)

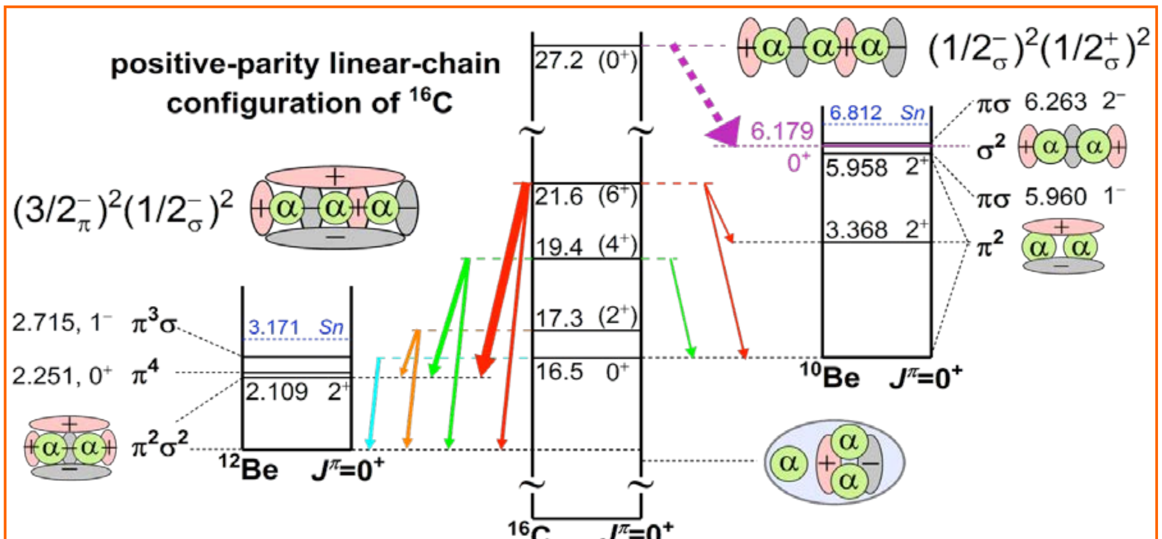
Positive-Parity Linear-Chain Molecular Band in ^{16}C

Y. Liu,[1] Y. L. Ye,[1,*] J. L. Lou,[1] X. F. Yang,[1] T. Baba,[2] M. Kimura,[3] B. Yang,[1] Z. H. Li,[1] Q. T. Li,[1] J. Y. Xu,[1] Y. C. Ge,[1] H. Hua,[1] J. S. Wang,[4,5] Y. Y. Yang,[5] P. Ma,[5] Z. Bai,[5] Q. Hu,[5] W. Liu,[1] K. Ma,[1] L. C. Tao,[1] Y. Jiang,[1] L. Y. Hu,[6] H. L. Zang,[1] J. Feng,[1] H. Y. Wu,[1] J. X. Han,[1] S. W. Bai,[1] G. Li,[1] H. Z. Yu,[1] S. W. Huang,[1] Z. Q. Chen,[1] X. H. Sun,[1] J. J. Li,[1] Z. W. Tan,[1] Z. H. Gao,[5] F. F. Duan,[5] J. H. Tan,[6] S. Q. Sun,[6] and Y. S. Song[6]

[1]*School of Physics and State Key Laboratory of Nuclear Physics and Technology, Peking University, Beijing 100871, China*
[2]*Kitami Institute of Technology, 090-8507 Kitami, Japan*
[3]*Department of Physics, Hokkaido University, 060-0810 Sapporo, Japan*
[4]*School of Science, Huzhou University, Huzhou 313000, China*
[5]*Institute of Modern Physics, Chinese Academy of Science, Lanzhou 730000, China*
[6]*Fundamental Science on Nuclear Safety and Simulation Technology Laboratory, Harbin Engineering University, Harbin 150001, China*

(Received 13 January 2020; revised manuscript received 31 March 2020; accepted 22 April 2020; published 12 May 2020)

首次在PF型实验中得到高分辨的Q值谱，从而清楚识别衰变路径；区分0度望远镜相邻硅条真假信号的来源，提高约6倍可用的真实事件率；首次实验发现完整的线性链状核分子转动带。



实验例3 - ^{14}C的链状分子结构— CIAE和RIBLL1实验

RAPID COMMUNICATIONS

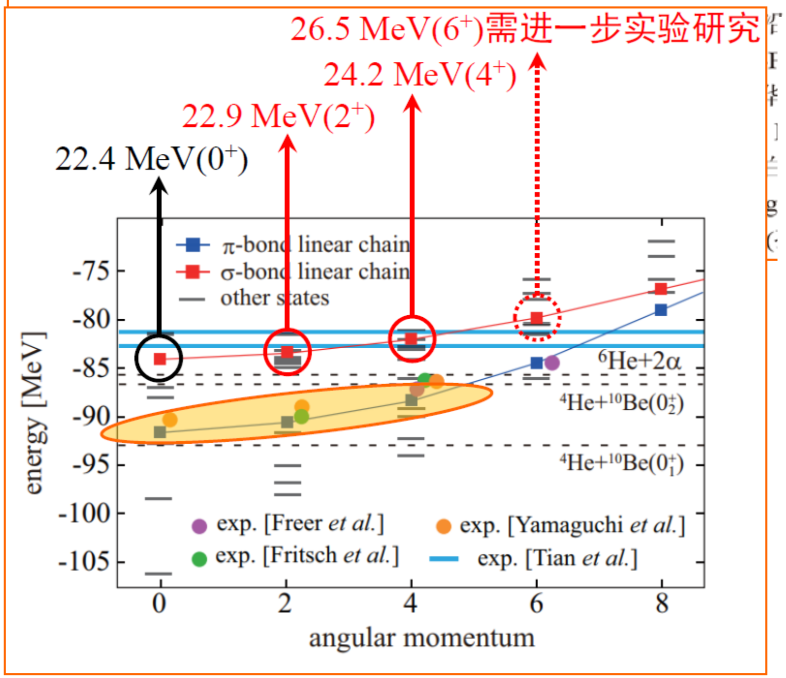
PHYSICAL REVIEW C **95**, 021303(R) (2017)

Selective decay from a candidate of the σ-bond linear-chain state in ^{14}C

J. Li,[1] Y. L. Ye,[1,*] Z. H. Li,[1] C. J. Lin,[2] Q. T. Li,[1] Y. C. Ge,[1] J. L. Lou,[1] Z. Y. Tian,[1] W. Jiang,[1] Z. H. Yang,[3] J. Feng,[1] P. J. Li,[1] J. Chen,[1] Q. Liu,[1] H. L. Zang,[1] B. Yang,[1] Y. Zhang,[1] Z. Q. Chen,[1] Y. Liu,[1] X. H. Sun,[1] J. Ma,[1] H. M. Jia,[2] X. X. Xu,[2] L. Yang,[2] N. R. Ma,[2] and L. J. Sun[2]

Chinese Physics C Vol. 45, No. 8 (2021)

New evidences for the σ-bond linear-chain molecular structure in ^{14}C*



对^{14}C的σ构型的线性链状分子带提供了系列的实验证据。

最近对π构型的线性链状分子带的研究有重要进展，确定了三个态的自旋，可能产生比较大影响。

实验例4：稀薄中子物质中的α集团

Science 371,260 (2021)

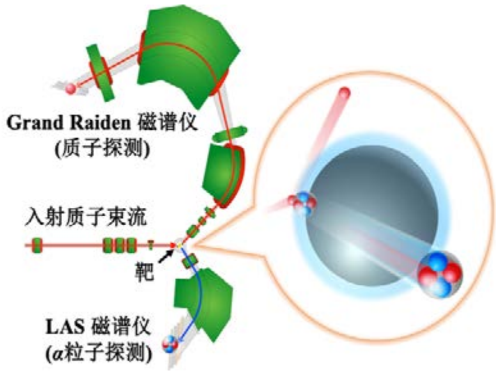
Science Contents News Careers Journals

REPORT

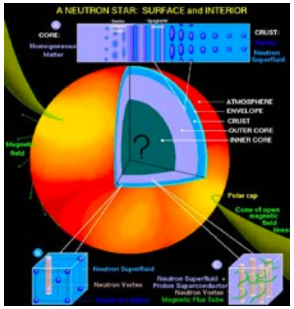
Formation of α clusters in dilute neutron-rich matter

Junki Tanaka[1,2,3,*], Zaihong Yang[3,4,*], Stefan Typel[1,2], Satoshi Adachi[4], Shiwei Bai[5], Patrik van Beek[1], Didier Beaumel[6], Yuki Fujikawa[7], Jiaxing Han[5], Sebastian Heil[1], Siwei Huang[5], Azusa Inoue[4], Ying Jiang[5], Marco Knösel[1], Nobuyuki Kobayashi[4], Yuki Kubota[3], Wei Liu[5], Jianling Lou[5], Yukie Maeda[8], Yohei Matsuda[9], Kenjiro Miki[10], Shoken Nakamura[4], Kazuyuki Ogata[4,11], Valerii Panin[3], Heiko Scheit[1], Fabia Schindler[1], Philipp Schrock[12], Dmytro Symochko[1], Atsushi Tamii[4], Tomohiro Uesaka[3], Vadim Wagner[1], Kazuki Yoshida[13], Juzo Zenihiro[3,7], Thomas Aumann[1,2,14]

*Corresponding author. Email: zhyang@ribf.riken.jp (Z.Y.); junki.tanaka@riken.jp (J.T.)



In star



In nucleus

实验例5：^{214}U中的α集团形成因子显著增强

PHYSICAL REVIEW LETTERS **126,** 152502 (2021)

Editors' Suggestion Featured in Physics

New α-Emitting Isotope ^{214}U and Abnormal Enhancement of α-Particle Clustering in Lightest Uranium Isotopes

Z. Y. Zhang (张志远),[1,2] H. B. Yang (杨华彬),[1] M. H. Huang (黄明辉),[1,2] Z. G. Gan (甘再国),[1,2,*] C. X. Yuan (袁岑溪),[3] C. Qi (亓冲),[4] A. N. Andreyev,[5,6] M. L. Liu (柳敏良),[1,2] L. Ma (马龙),[1] M. M. Zhang (张明明),[1] Y. L. Tian (田玉林),[1] Y. S. Wang (王永生),[1,2,7] J. G. Wang (王建国),[1] C. L. Yang (杨春莉),[1] G. S. Li (李广顺),[1] Y. H. Qiang (强赟华),[1] W. Q. Yang (杨维青),[1] R. F. Chen (陈若富),[1] H. B. Zhang (张宏斌),[1] Z. W. Lu (卢子伟),[1] X. X. Xu (徐新星),[1,2] L. M. Duan (段利敏),[1,2] H. R. Yang (杨贺润),[1,2] W. X. Huang (黄文学),[1,2] Z. Liu (刘忠),[1,2] X. H. Zhou (周小红),[1,2] Y. H. Zhang (张玉虎),[1,2] H. S. Xu (徐瑚珊),[1,2] N. Wang (王宁),[8] H. B. Zhou (周厚兵),[8] X. J. Wen (温小江),[8] S. Huang (黄山),[8] W. Hua (滑伟),[3] L. Zhu (祝龙),[3] X. Wang (王翔),[9] Y. C. Mao (毛英臣),[10] X. T. He (贺晓涛),[11] S. Y. Wang (王守宇),[12] W. Z. Xu (许文政),[12] H. W. Li (李弘伟),[12] Z. Z. Ren (任中洲),[13] and S. G. Zhou (周善贵)[14,15]

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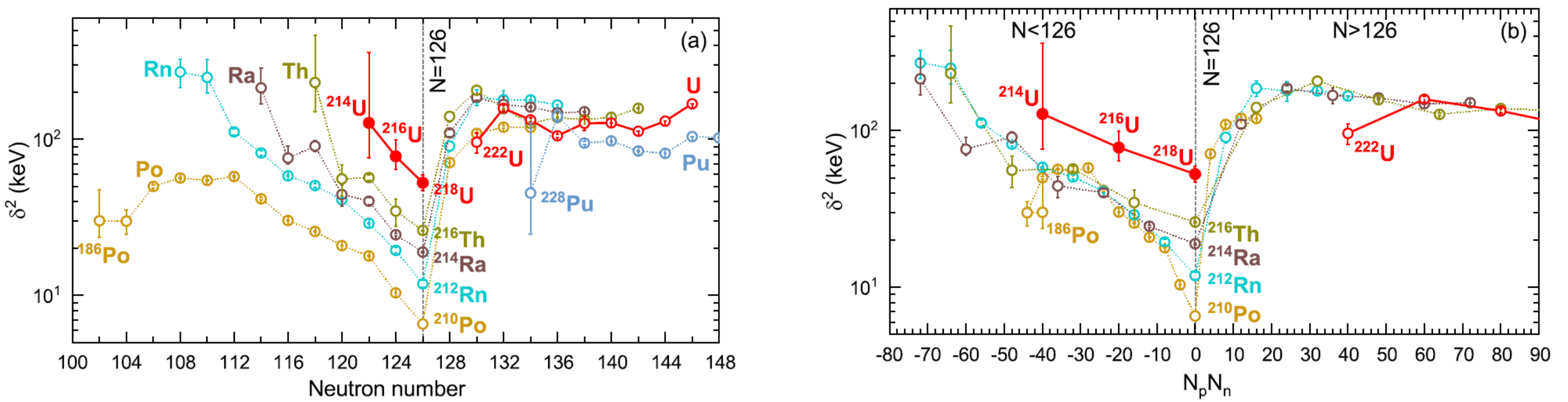
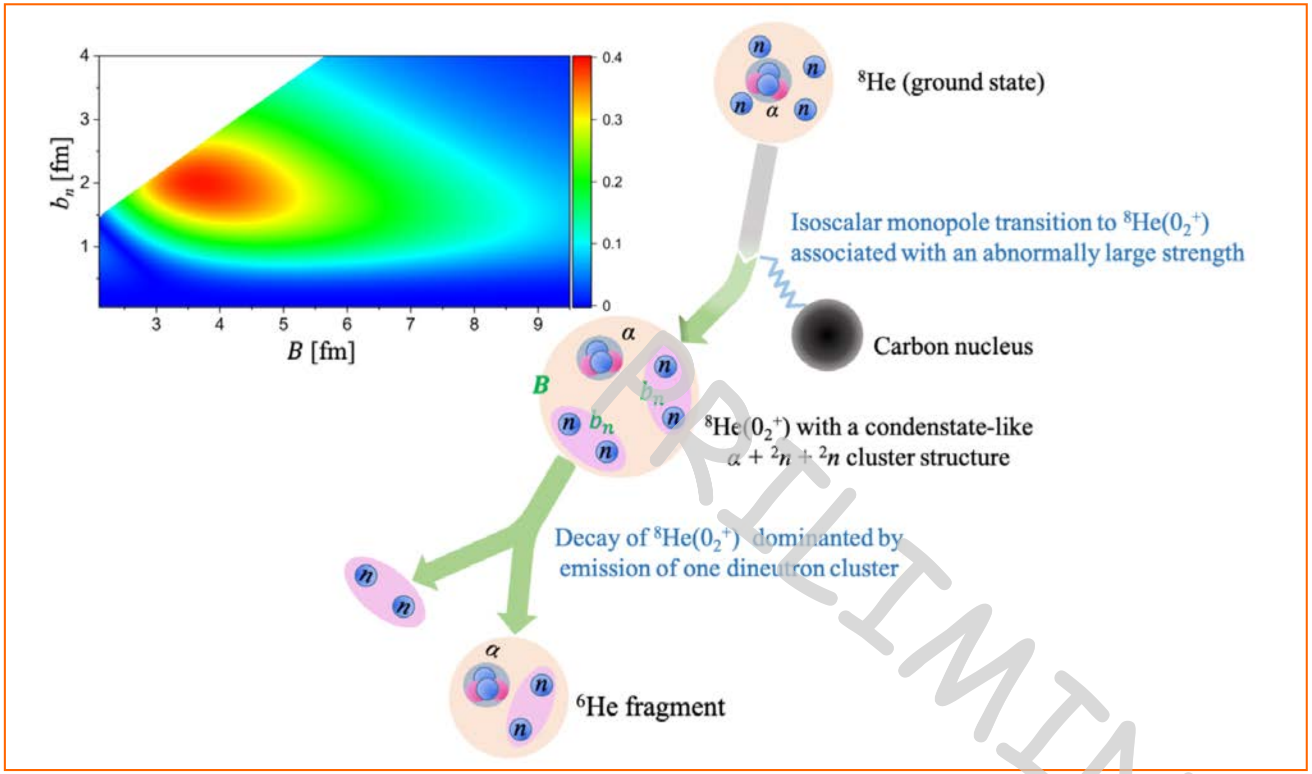
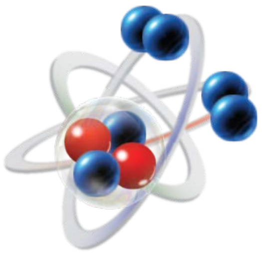
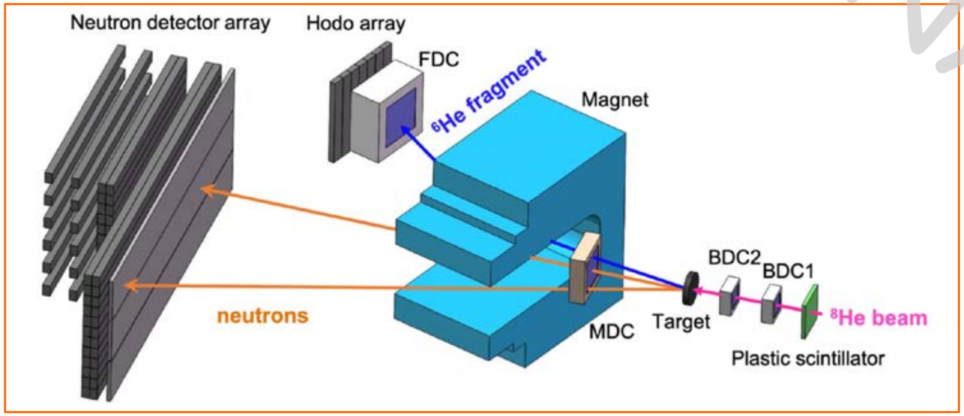


FIG. 3. (a) Systematics of reduced widths for g.s.-to-g.s. α decays of even-even $84 \leq Z \leq 94$ isotopes as a function of neutron number. The decay properties are taken from Refs. [11,12,42,50–53]. The values for ^{214,216,218}U from this work are shown by filled circles. The errors of reduced widths are only determined by half-life uncertainties. (b) Same as (a) but against N_pN_n for even-even Po to U isotopes. The N_p and N_n values are calculated relative to $Z = 82$ and $N = 126$ closed shells, respectively, with an exception of $^{186}_{84}Po_{102}$, for which $N_n = -20$, relative to the closest $N = 82$ neutron shell.

实验例6: possible α- and dineutron-condensate state







PRELIMINARY

内 容

I. 针对核多体系统的“不稳定”特征
— 内卷还是开拓?

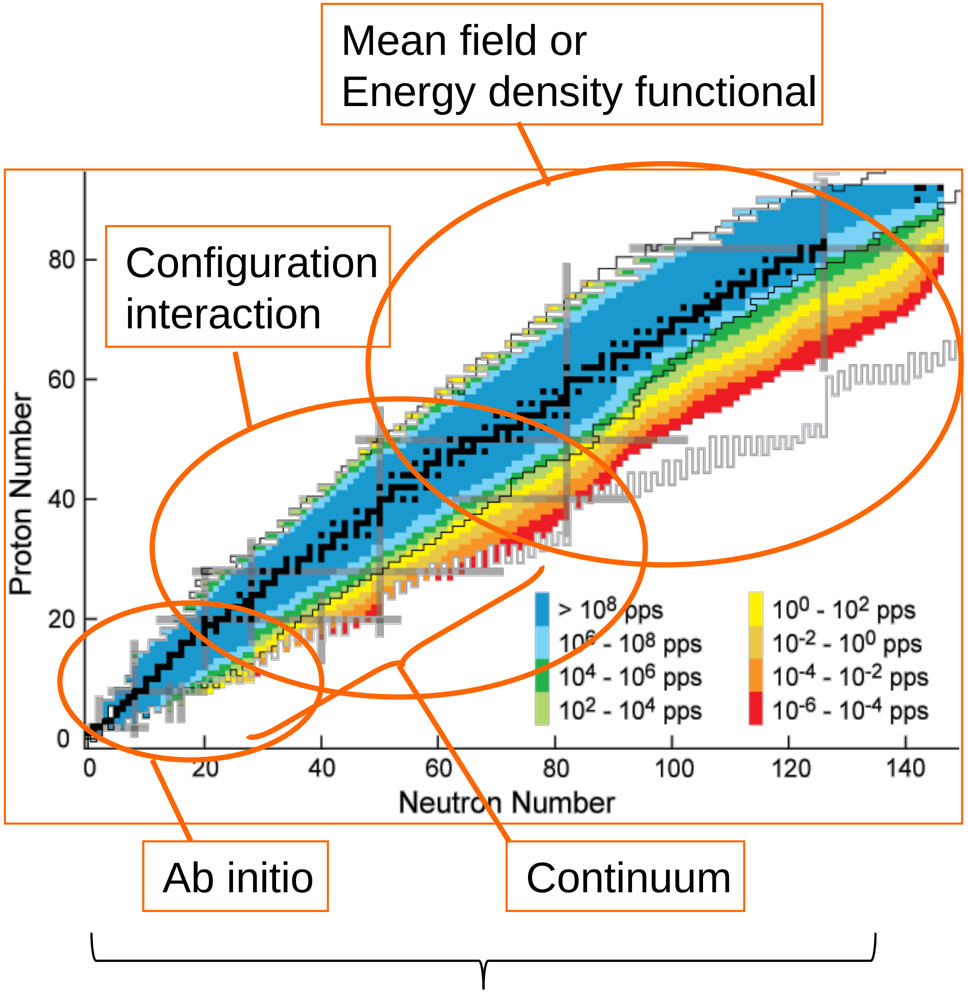
II. 奇特结构新自由度的处理

III. 壳演化(新幻数)、连续态和闯入态

IV. 展望和期待

核力与核多体理论的发展

- –Ab initio models: study of neutron-rich, light nuclei helps determine the force to use in models, especially the N-N interactions derived from χEFT
- –Configuration-interaction theory: study of shell and effective interactions
- –The universal energy density functional (DFT) : determine parameters
- – The role of the continuum and reactions and decays of nuclei



Relationship to QCD (LQCD)

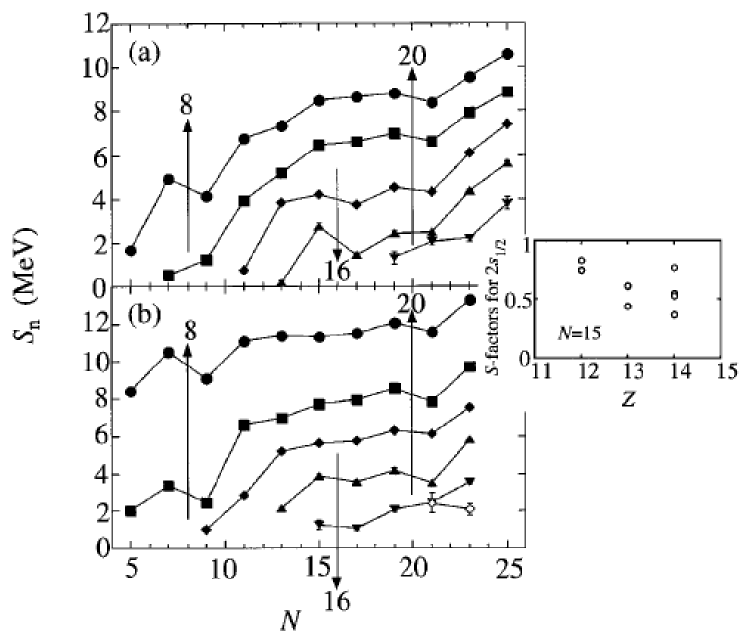
新幻数的概念和研究进展

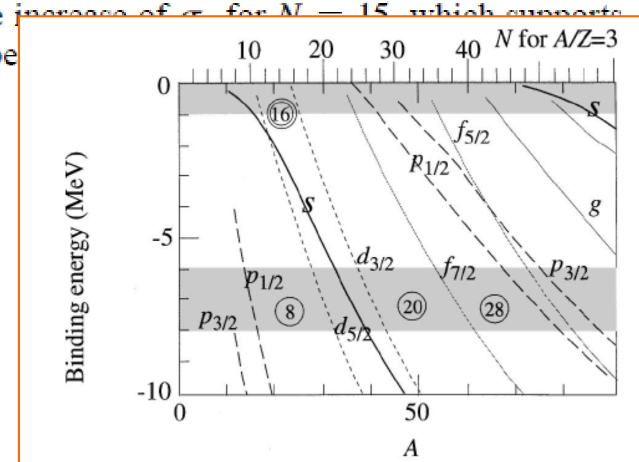
VOLUME 84, NUMBER 24 PHYSICAL REVIEW LETTERS 12 JUNE 2000

New Magic Number, $N = 16$, near the Neutron Drip Line

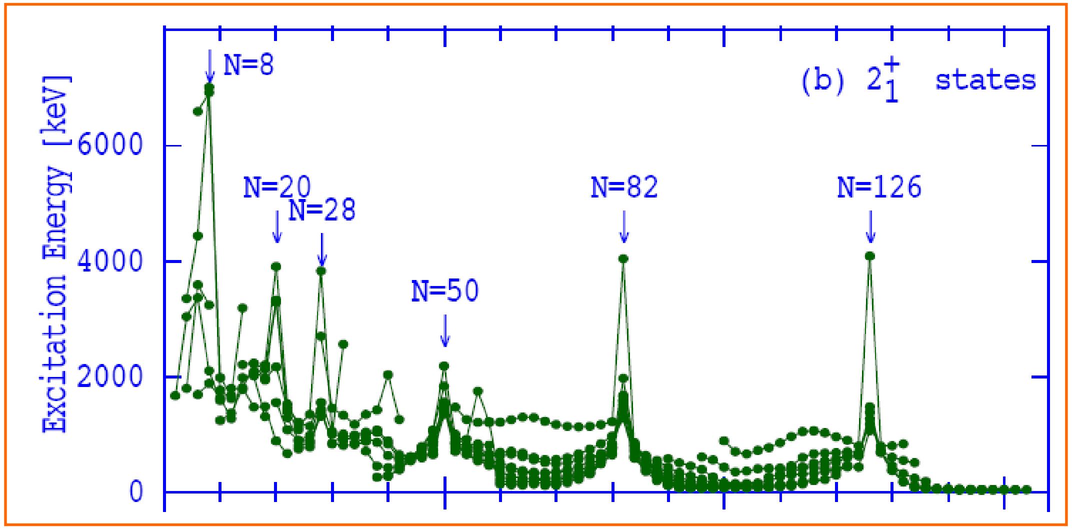
A. Ozawa,[1] T. Kobayashi,[2] T. Suzuki,[3] K. Yoshida,[1] and I. Tanihata[1]
[1] *The Institute of Physical and Chemical Research (RIKEN), Hirosawa 2-1, Wako-shi, Saitama 351-0198, Japan*
[2] *Department of Physics, Tohoku University, Miyagi 980-8578, Japan*
[3] *Department of Physics, Niigata University, Niigata 950-2181, Japan*
(Received 15 February 2000)

We have surveyed the neutron separation energies (S_n) and the interaction cross sections (σ_I) for the neutron-rich p-sd and the sd shell region. Very recently, both measurements reached up to the neutron drip li
A neutron-number dependence of S_n shows clear b
), which shows the creation of a new magic numbe
increase of σ_I for $N = 15$ which supports the ne
pe





在束γ $E(2^+)$、$B(E2)$测量



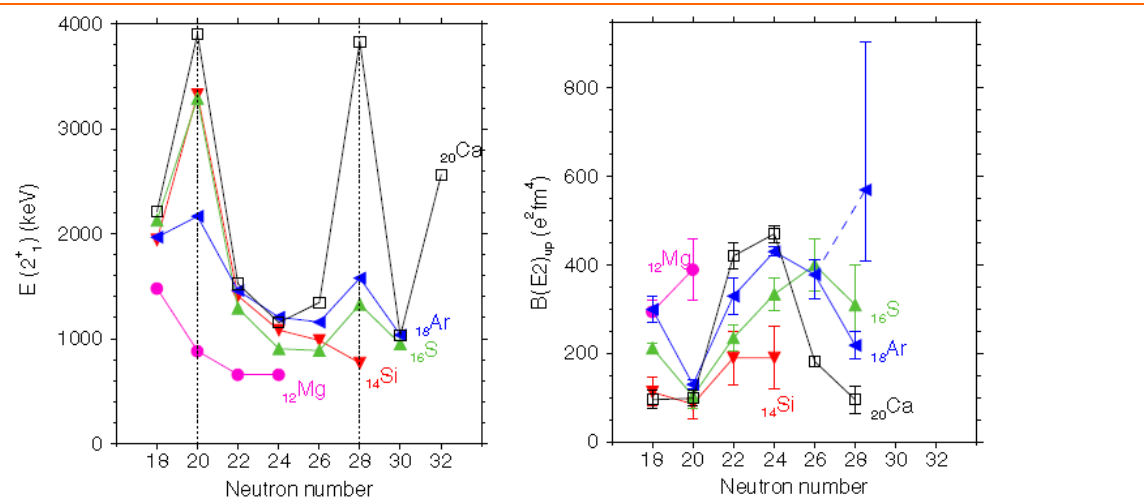


Figure 3. Experimental $E(2_1^+)$ energies (left) and $B(E2; 0_1^+ \to 2_1^+)$ values, also denoted as $B(E2)_{\rm up}$ or $B(E2)\uparrow$, (right) in the $_{12}$Mg to $_{20}$Ca isotopic chains as a function of the neutron number N. Data are taken from the compilation of [6], except for ^{38}Si [7], ^{40}Si [8], ^{42}Si [9], ^{40}S [10], ^{46}S [11], ^{44}Ar [12], ^{46}Ar [13, 14] and ^{48}Ar [15].

New “magicity” of N=34 in Ca isotopes

Nature502(2013)207

Evidence for a new nuclear ‘magic number’ from the level structure of ^{54}Ca

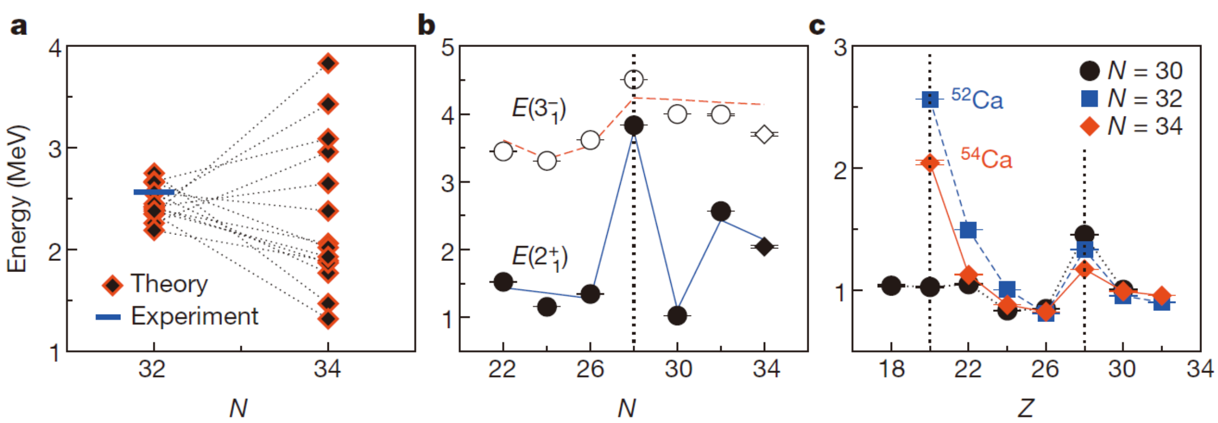


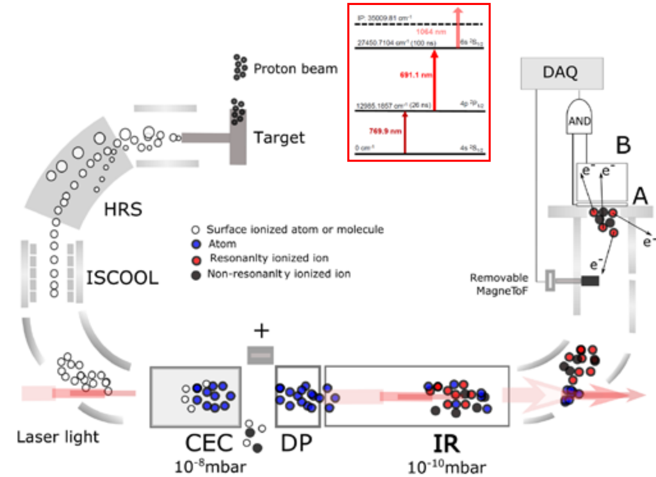
Figure 2 | Systematics of excited-state energies in even–even Ca isotopes and neighbouring nuclei. **a**, Theoretical predictions of the energy of the first 2^+ state for ^{52}Ca ($N = 32$) and ^{54}Ca ($N = 34$) (refs 14–16, 19–24). The solid blue line represents the experimental result for ^{52}Ca (refs 6, 7). **b**, Energies of the first 2^+ (filled symbols) and 3^- (open symbols) levels for even–even $^{42-54}$Ca isotopes. The results of the present study are indicated by diamonds at $N = 34$. The solid and dashed lines are shell-model predictions of the first 2^+ and 3^- energies, respectively (see text for details). **c**, $E(2_1^+)$ along the $N = 30$, 32 and 34 isotonic chains. The solid and dashed lines are intended to guide the eye. Vertical dotted lines represent the standard magic numbers.

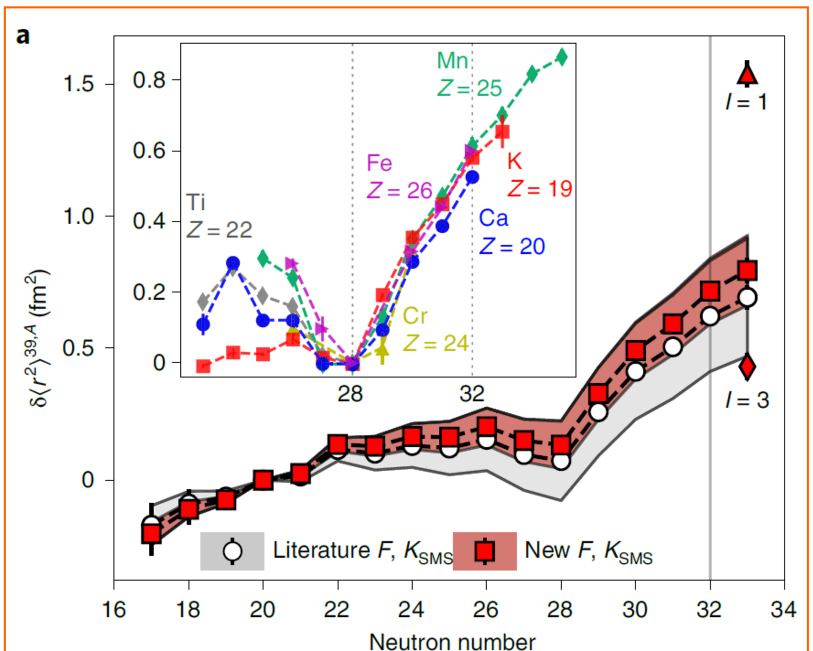
A.Koszorus, X. F. Yang et al., Nature Physics 17 (2021) 439

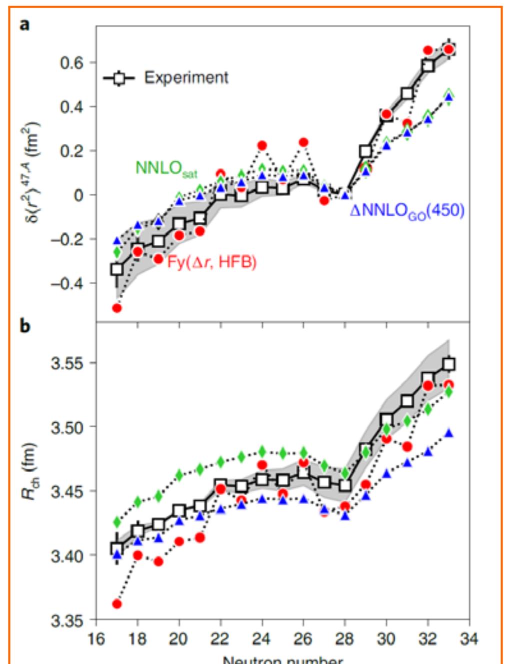
Charge radii of exotic potassium isotopes challenge nuclear theory and the magic character of $N = 32$

Á. Koszorús[1,17]✉, X. F. Yang[1,2]✉, W. G. Jiang[3,4,5], S. J. Novario[3,4], S. W. Bai[2], J. Billowes[6], C. L. Binnersley[6], M. L. Bissell[6], T. E. Cocolios[1], B. S. Cooper[6], R. P. de Groote[7,8], A. Ekström[5], K. T. Flanagan[6,9], C. Forssén[5], S. Franchoo[10], R. F. Garcia Ruiz[11,12], F. P. Gustafsson[1], G. Hagen[4], G. R. Jansen[4], A. Kanellakopoulos[1], M. Kortelainen[7,8], W. Nazarewicz[13], G. Neyens[1,12], T. Papenbrock[3,4], P.-G. Reinhard[14], C. M. Ricketts[6], B. K. Sahoo[15], A. R. Vernon[1,6] and S. G. Wilkins[16]

Correspondence and requests for materials should be addressed to X.F.Y. or Á.K.







首次将质子幻数核钙附近电荷半径的测量拓展到N=32之上。实验结果没有表现出N=32中子幻数特征；附近所有同位素链的电荷半径趋势一致

Soft "magicity" of *N* = 50 for ^{78}Ni

^{78}Ni revealed as a doubly magic stronghold against nuclear deformation

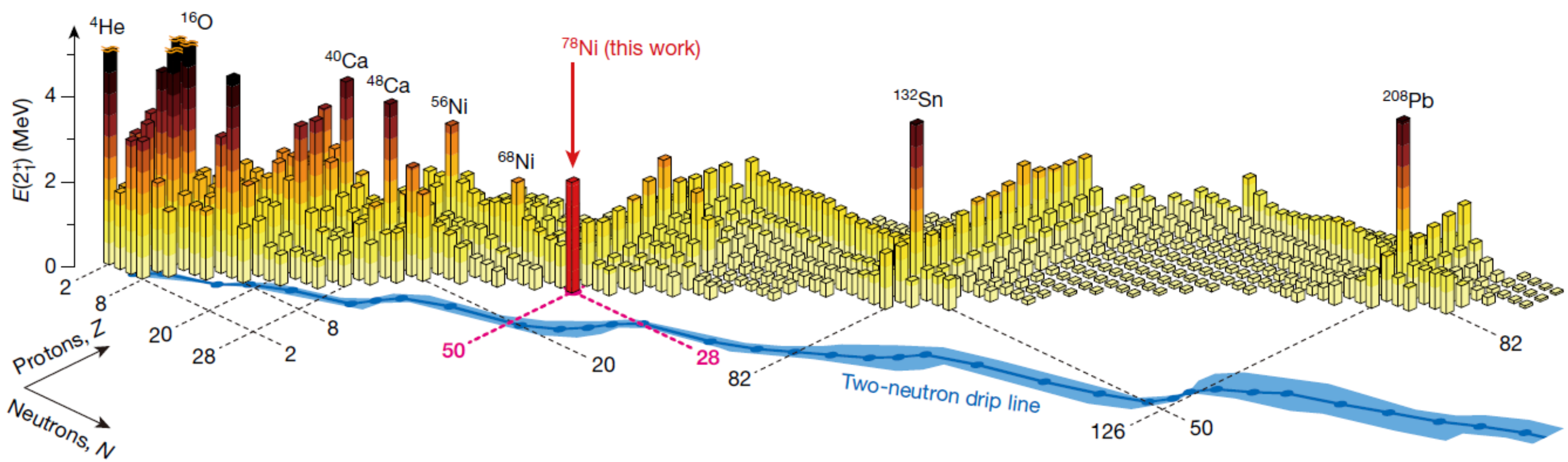


Fig. 1 | Experimental $E(2_1^+)$ systematics of the even–even nuclear landscape. Shown are known $E(2_1^+)$ of even–even isotopes[40] and the value for ^{78}Ni obtained in the present study. Canonical magic numbers are indicated by dashed lines and doubly magic nuclei are labelled. ^{68}Ni, for which the number of neutrons, $N = 40$, matches the harmonic-oscillator shell closure, is also marked. The predicted two-neutron drip line and its uncertainties[3] are shown in blue.

连续态耦合(GSM、GCC…)：处理Open-system 新问题

PHYSICAL REVIEW C **96**, 044307 (2017)

Structure and decays of nuclear three-body systems: The Gamow coupled-channel method in Jacobi coordinates

S. M. Wang (王思敏),[1] N. Michel,[2] W. Nazarewicz,[3] and F. R. Xu (许甫荣)[4]
[1] *FRIB/NSCL Laboratory, Michigan State University, East Lansing, Michigan 48824, USA*

PHYSICAL REVIEW C **99**, 054302 (2019)

Structure and decay of the extremely proton-rich nuclei ^{11,12}O

S. M. Wang (王思敏),[1] W. Nazarewicz,[2] R. J. Charity,[3] and L. G. Sobotka[3,4]
[1] *FRIB/NSCL Laboratory, Michigan State University, East Lansing, Michigan 48824, USA*

First Observation of Unbound ^{11}O, the Mirror of the Halo Nucleus ^{11}Li

T. B. Webb,[1,*] S. M. Wang (王思敏),[2] K. W. Brown,[2] R. J. Charity,[3] J. M. Elson,[3] J. Barney,[2] G. Cerizza,[2] Z. Chajecki,[4] J. Estee,[2] D. E. M. Hoff,[3] S. A. Kuvin,[5] W. G. Lynch,[2] J. Manfredi,[2] D. McNeel,[5] P. Morfouace,[2] W. Nazarewicz,[6] C. D. Pruitt,[3] C. Santamaria,[2] J. Smith,[5] L. G. Sobotka,[1,3] S. Sweany,[2] C. Y. Tsang,[2] M. B. Tsang,[2] A. H. Wuosmaa,[5] Y. Zhang,[2] and K. Zhu[2]
[1] *Department of Physics, Washington University, St. Louis, Missouri 63130, USA*

Open quantum systems

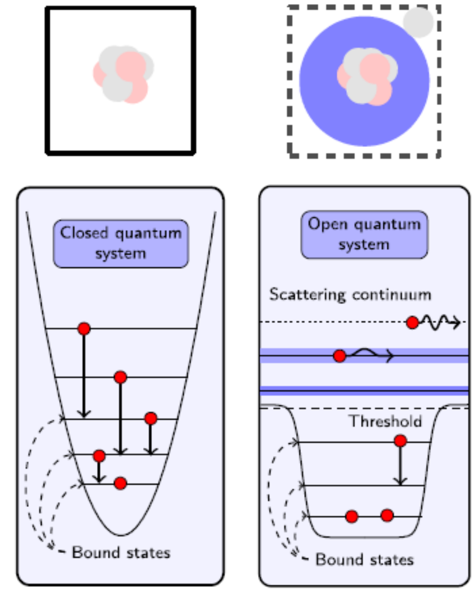
- Quantum systems coupled to the environment of scattering states and decay channels.

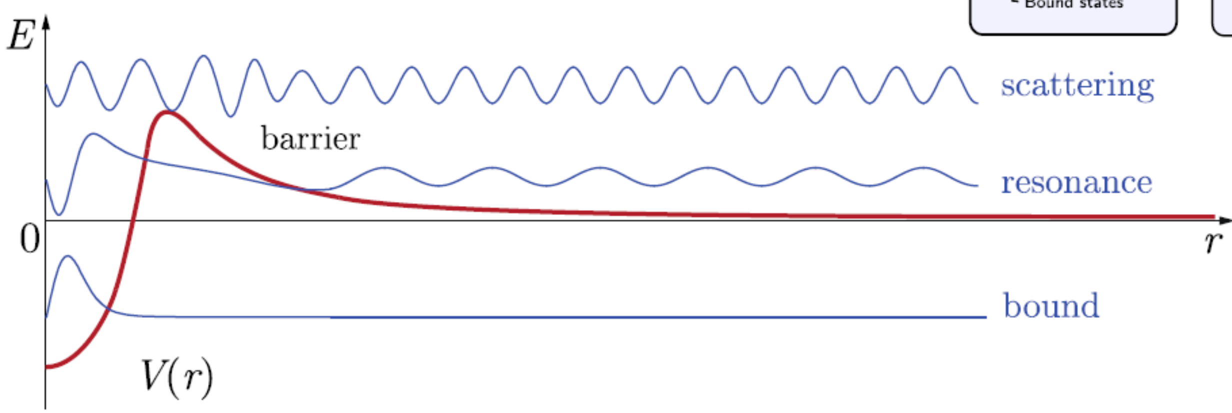
1. **Bound state** $\varphi_l(k,r) \xrightarrow[r\to\infty]{} C(k)e^{-k}$
2. **Scattering state**

$$\varphi_l(k,r) \xrightarrow[r\to\infty]{} C^{+}(k)H^{+}(k,r) + C^{-}(k)H^{-}(k,r)$$

3. **Resonance (Gamow state)** with outgoing boundary conditions

$$\varphi_l(k,r) \xrightarrow[r\to\infty]{} C^{+}(k)H^{+}(k,r)$$





From S.M. Wang

2N发射的有趣问题：structure-dynamics-FSI

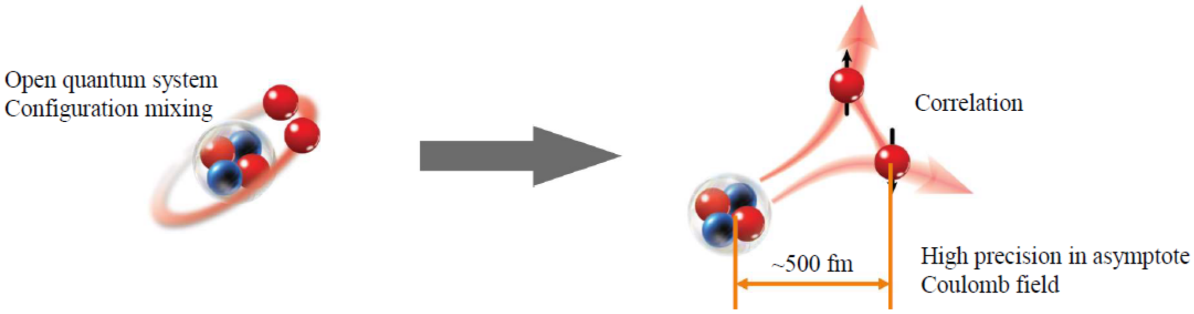


Fig. From S.M. Wang

HBT-FSI; Dalitz-plot; Diffraction; Time-dependent ?

PHYSICAL REVIEW C **97**, 034605 (2018)

Exploring the manifestation and nature of a dineutron in two-neutron emission using a dynamical dineutron model

L. V. Grigorenko,[1,2,3] J. S. Vaagen,[4] and M. V. Zhukov[5]

[1] *Flerov Laboratory of Nuclear Reactions, JINR, RU-141980 Dubna, Russia*

RU-115409 Moscow, Russia

123182 Moscow, Russia

7 Bergen, Norway

96 Göteborg, Sweden

J. Phys. G: Nucl. Part. Phys. **46** (2019) 03LT02

Chronology of the three-body dissociation of ^{8}He

B Laurent[1,10], F M Marqués[1], C Angulo[2,11], N I Ashwood[3],

持续30年的探索！

闯入态举例：$2s_{1/2}$ 态闯入-晕结构

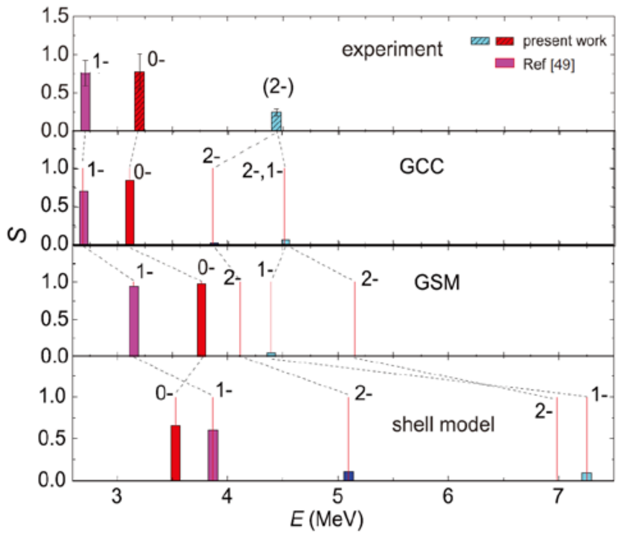
Letter

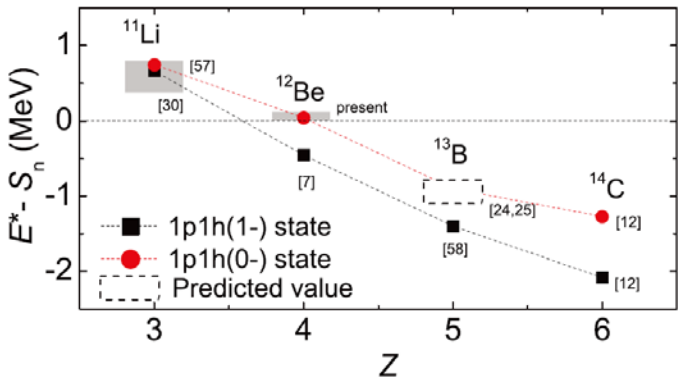
PHYSICAL REVIEW C **103**, L031302 (2021)

Observation of the near-threshold intruder 0^- resonance in ^{12}Be

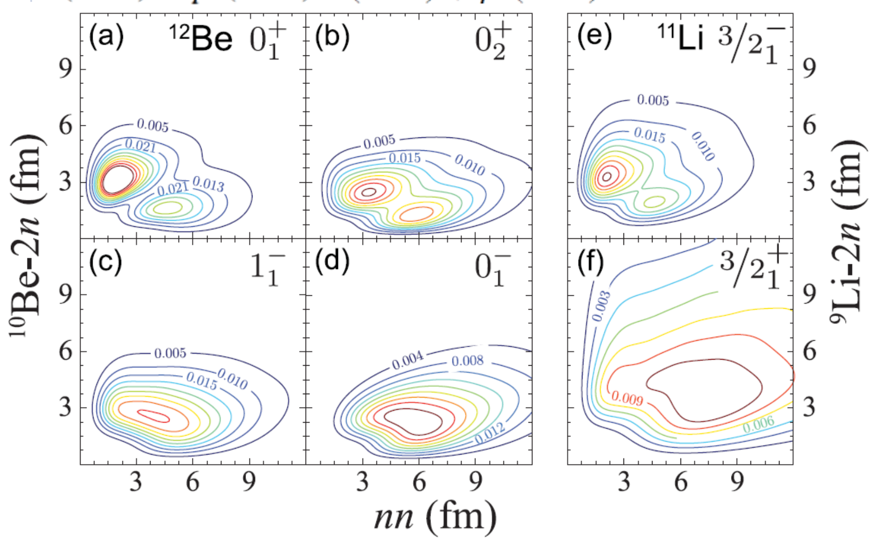
J. Chen,[1,2] S. M. Wang,[2] H. T. Fortune,[3] J. L. Lou,[1,*] Y. L. Ye,[1] Z. H. Li,[1] N. Michel,[4,5] J. G. Li,[1] C. X. Yuan,[6] Y. C. Ge,[1] Q. T. Li,[1] H. Hua,[1] D. X. Jiang,[1] X. F. Yang,[1] D. Y. Pang,[1] F. R. Xu,[1] W. Zuo,[4,5] J. C. Pei,[1] J. Li,[1] W. Jiang,[1] Y. L. Sun,[1] H. L. Zang,[1] N. Aoi,[7] H. J. Ong,[4,7] E. Ideguchi,[7] Y. Ayyad,[7,2] K. Hatanaka,[7] D. T. Tran,[7] D. Bazin,[2] J. Lee,[8] Y. N. Zhang,[9] J. Wu,[1,8] H. N. Liu,[1,8] C. Wen,[1,8] T. Yamamoto,[7] M. Tanaka,[7] and T. Suzuki[7]

[1]*School of Physics and State Key Laboratory of Nuclear Physics and Technology, Peking University, Beijing 100871, China*





$s^2(16\%) + p^2(57\%)$ $s^2(25\%) + p^2(63\%)$

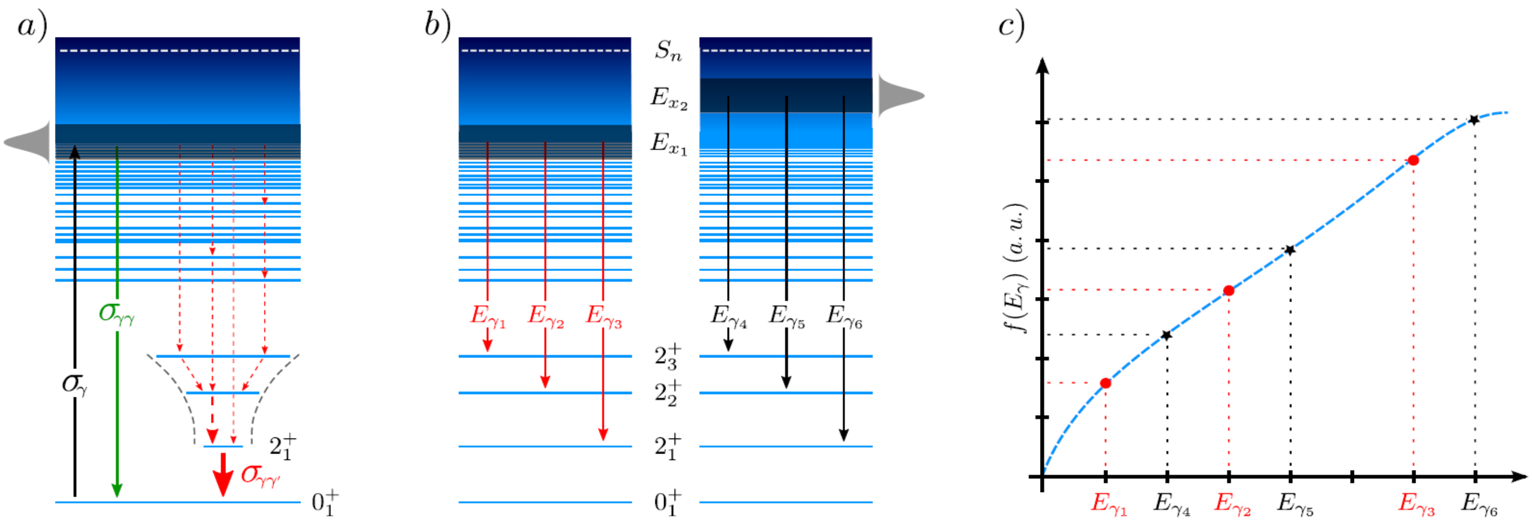


(s, p) with 78% and 82%

FIG. 4. Two-nucleon density distributions (in fm^{-2}) in Jacobi coordinates predicted by GCC for the g.s. and low-lying states in (a)–(d) ^{12}Be and (e), (f) ^{11}Li.

Investigations of nuclear photon strength functions (PSF)

Open quantum system



- 阈附近结构(PDR, Cluster, Intrusion...)
- 核天体(只有粗略假定)
- 核能系统(数据：运行设计、废料处置...)
- γ产生和关联探测系统(新技术)

Using photosbsorption σ_γ

$$f_{\lambda L}(E_\gamma) = \frac{1}{g(\pi\hbar c)^2} \cdot \frac{\sigma_\gamma}{E_\gamma^{2L-1}}$$

Using primary γ-decay strengths

$$\frac{\sigma_{ik}}{\sigma_{ij}} = \frac{f(E_i - E_k)}{f(E_i - E_j)} \cdot \frac{(E_i - E_j)^3}{(E_i - E_k)^3} \quad (k, j) \neq 0,$$

J.Isaak et al., PLB788(2019)225;
N.Pietralla et al., EPJA55(2019)237
J. Okołowicz et al., PRL124(2020)042502

内 容

I. 针对核多体系统的“不稳定”特征
— 内卷还是开拓?

II. 奇特结构新自由度的处理

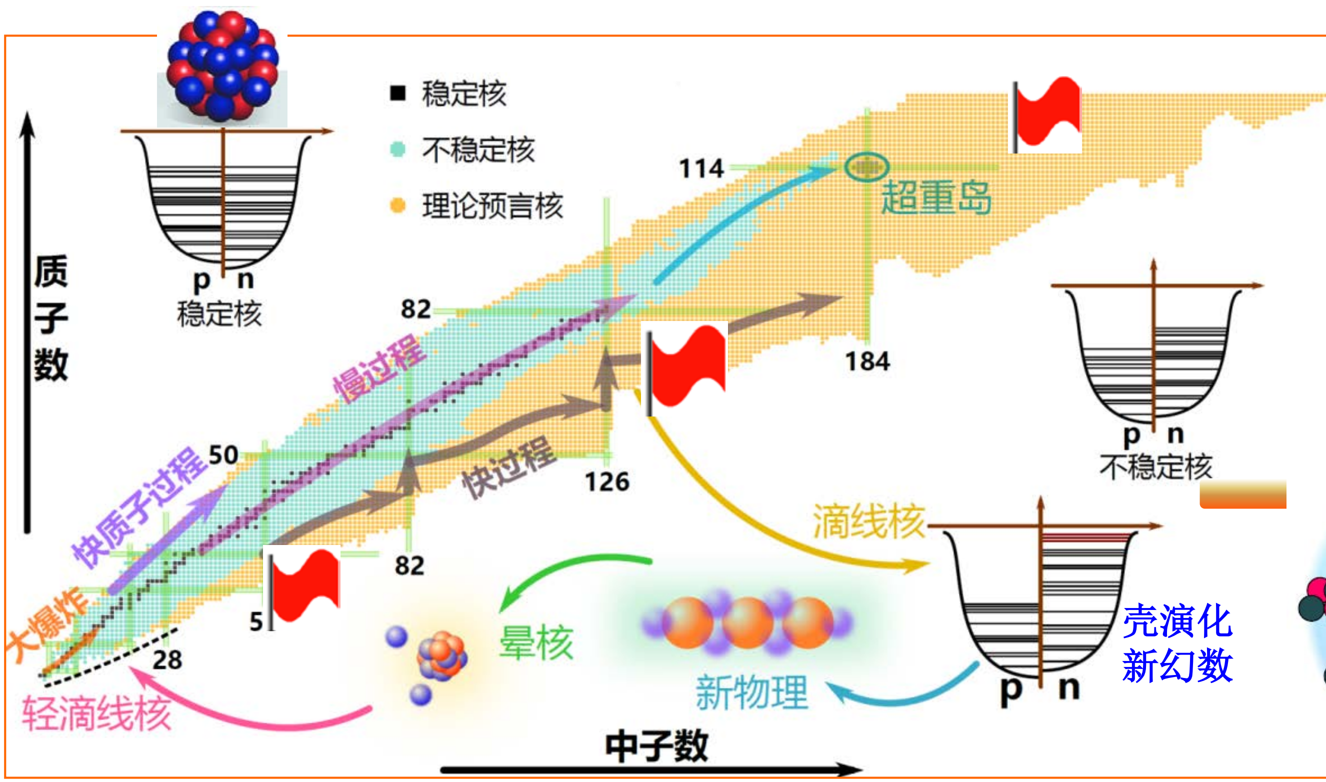
III. 壳演化(新幻数)、连续态和闯入态

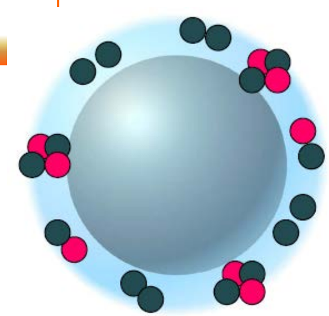
IV. 展望和期待

核素版图扩大面临的重大科学问题

- 滴线区新物理（系统性突破）
- 宇宙中重元素的生成（巨大未知数）
- 攀登超重岛（挑战极限）

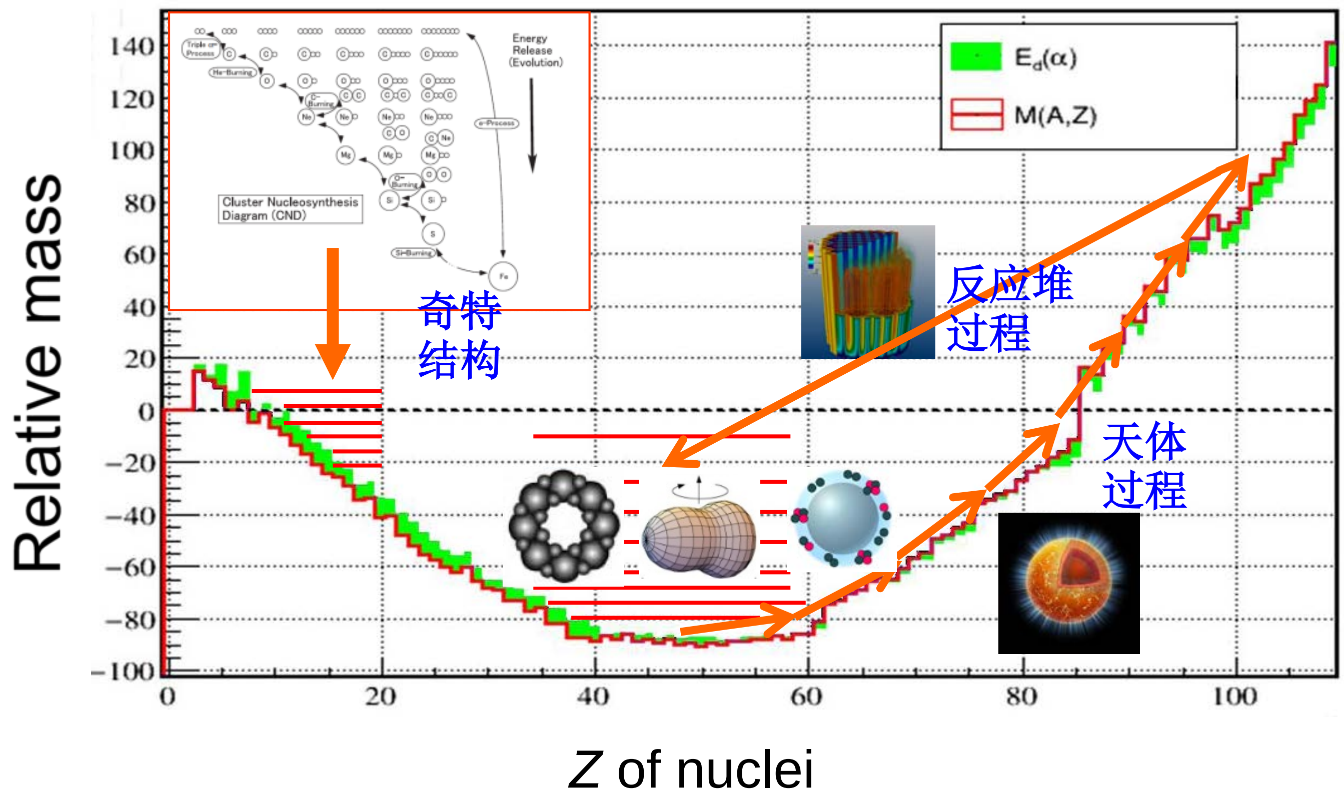
Involution？
Evolution？
Revolution？





走出内卷、开疆拓土：学术思想、方法、领域、交叉...

核物质和能量循环中的奇特结构与效应——中等质量区？



中等质量区不稳定核高激发态可能形成各种奇特结构（如八级形变、同核异能素、集团分子态…）、发射复杂的衰变粒子！目前测量和认识刚刚起步。

创新模式

以100多年核物理-粒子物理发展为例（达到诺贝尔奖提名以上）

- 探索型（靠制度、环境、兴趣、运气） （~56项，59%）
- 目标型（靠大投入） （~17项，18%）
- 智慧型（靠小环境和天才群体） （~22项，23%）

"An atomic nucleus is an elephant"-*Prof. Jacek Dobaczewski*

More Is Different

Broken symmetry and the nature of the hierarchical structure of science.

P. W. Anderson, Science 177(1972) 393

Complementary and exclusive

探索低密度区(open system)新问题

低密度区结构自由度(BCS-BEC)?

低密度区作用力和关联 (2N、4N...)

新集体运动(链、环、新巨共振...) ?

较重核里的RGM、GCM...?

连续态和共振态强耦合 (OS)

多核子怎么转移(超重生成)?

核天体r过程的中子行为? ;

中子物质?

……

结语：年青的几代人：

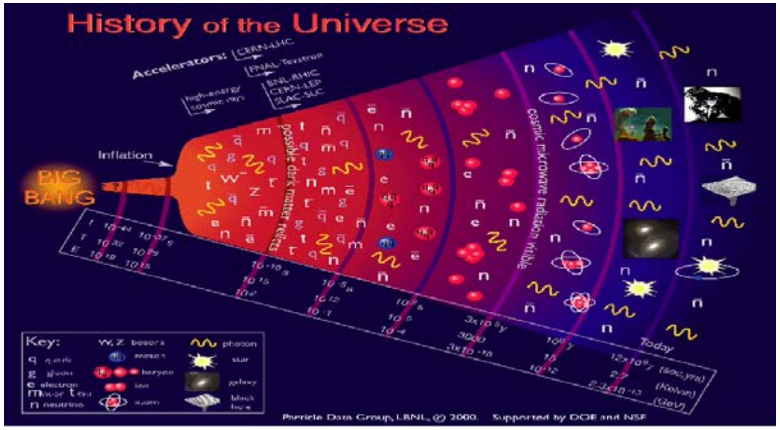
- 良好的训练、良好的条件、较大的人员规模
- 多方面学术的思想、方法的来源和交叉
- 面对大量新问题
- 重要的是：

  新的视野、新的理解、

  新的创造

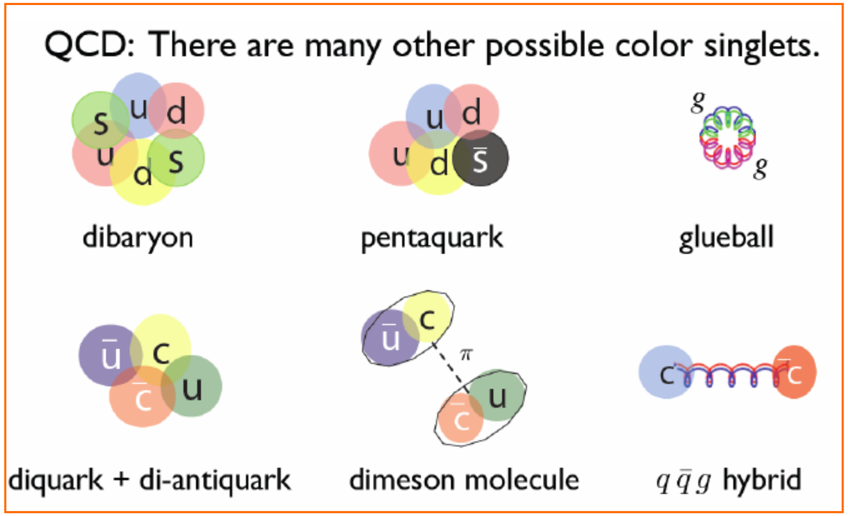
Thank you for your attention !

Clustering in the universe



Annu.Rev. Astron. Astrophysics 41(2003)57

Clustering in hadrons



Shi-Lin Zhu, FB20, Fukuoka, August 20, 2012