原子核集团结构和衰变研究进展

任中洲
同济大学 物理科学与工程学院

北京 核物理前沿与交叉 2022. 08. 26

报告提纲

一 轻原子核的集团态（结团态）研究：

^{20}Ne ,^{12}Be…

二 重原子核的集团效应：

重核 alpha衰变和集团放射性等

Z=119和Z=120衰变性质

三 小 结

原子核结构理论简述

- 原子核内核子运动已有研究集中在：单粒子运动和集体运动。
- 单粒子运动：壳模型或平均场模型描述。集体运动：Bohr-Mottelson模型，互作用玻色子模型（IBM）描述等。　徐躬耦先生，王顺金老师，……
- 对核内核子间结团结构和结团态（集团态）研究稀少（相对上述两种模式）
- 近来研究表明，一些稳定核和不稳定核有集团态。这些态无法用壳模型或集体模型给出，如^{12}C的Hoyle态。

集团结构研究的新进展

- 在轻核中，一些状态集团运动模式起主导作用。

- 在重核中存在alpha衰变和集团放射性，所以集团态的研究也很重要。

- 到目前为止，人们对于不稳定核的集团结构和集团态还不是非常清楚，预期新现象，新规律。
- 因此，原子核集团结构的研究最近是核物理和核天体物理的一个热点课题。

LETTER

How atomic nuclei cluster

J.-P. Ebran[1], E. Khan[2], T. Nikšić[3] & D. Vretenar[3]

Nucleonic matter displays a quantum-liquid structure, but in some cases finite nuclei behave like molecules composed of clusters of protons and neutrons. Clustering is a recurrent feature in light nuclei, from beryllium to nickel[1–3]. Cluster structures are typically observed as excited states close to the corresponding decay threshold; the origin of this phenomenon lies in the effective nuclear interaction, but the detailed mechanism of clustering in nuclei has not yet been fully understood. Here we use the theoretical framework of energy-density functionals[4,5], encompassing both cluster and quantum liquid-drop aspects of nuclei, to show that conditions for cluster formation can in part be traced back to the depth of the confining nuclear potential. For the illustrative example of neon-20, we show that the depth of the potential determines the energy spacings between single-nucleon orbitals in deformed nuclei, the localization of the corresponding wavefunctions and, therefore, the degree of nucleonic density clustering. Relativistic functionals, in particular, are characterized by deep single-nucleon potentials. When compared to non-relativistic functionals that yield similar ground-state properties (binding energy, deformation, radii), they predict the occurrence of much more pronounced cluster structures. More generally, clustering is considered as a transitional phenomenon between crystalline and quantum-liquid phases of fermionic systems.

举例一：欧洲科学家，能量密度泛函研究原子核集团态

Energy density functional theory

***Nature* 487, 341–344 (2012)**

RESEARCH LETTER

Ebran, Khan, Nikšić & Vretenar， Nature：
核子大小和核子间距相当时，集团主导

Use the theoretical framework of energy density functionals, encompassing both cluster and quantum liquid-drop aspects of nuclei

$a=b/r_0$

LETTER RESEARCH

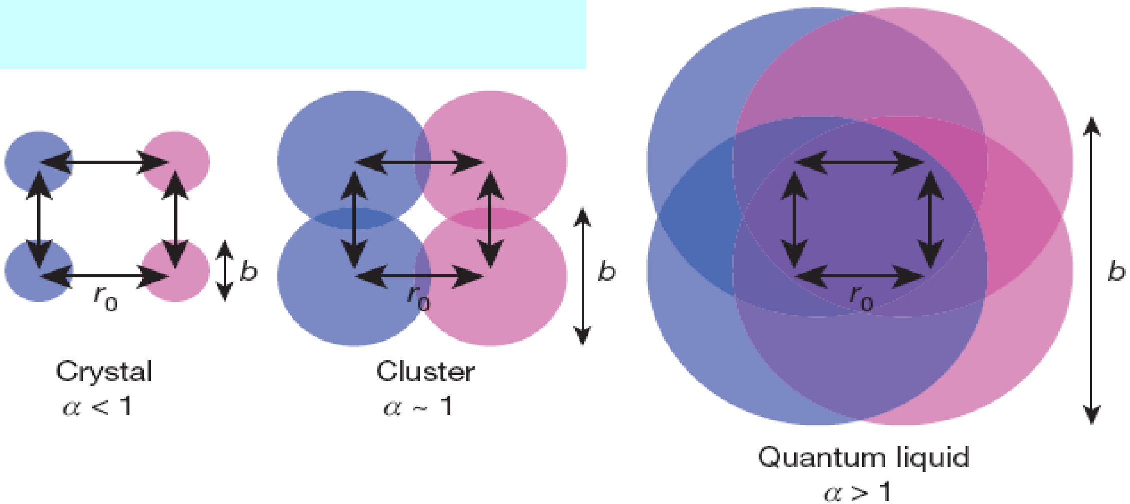

Figure 4 | Schematic illustration of the transition from a crystalline to a quantum liquid phase, including the cluster phase. The dimensionless parameter $\alpha = b/r_0$, where b is the dispersion of the fermion wavefunction and r_0 the typical inter-fermion distance, quantifies nuclear clustering. For a harmonic oscillator $\alpha = (\hbar R)^{1/2}(2mV_0)^{-1/4}r_0^{-1}$, where V_0 is the depth of the potential, R the radius of the system, m the mass of the nucleon and $\hbar$ Planck's constant/2π.

我们2012研究^{20}Ne Phys. Rev. C 86 (2012) 014301

PHYSICAL REVIEW C **86**, 014301 (2012)

New concept for the ground-state band in ^{20}Ne within a microscopic cluster model

Bo Zhou,[1,2,*] Zhongzhou Ren,[1,3,†] Chang Xu,[1,‡] Y. Funaki,[4] T. Yamada,[5] A. Tohsaki,[2] H. Horiuchi,[2,6]
P. Schuck,[7,8] and G. Röpke[9]

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[4]*Nishina Center for Accelerator-Based Science, The Institute of Physical and Chemical Research (RIKEN), Wako 351-0198, Japan*
[5]*Laboratory of Physics, Kanto Gakuin University, Yokohama 236-8501, Japan*
[6]*International Institute for Advanced Studies, Kizugawa 619-0225, Japan*
[7]*Institut de Physique Nucléaire, CNRS, UMR 8608, F-91406 Orsay, France*
[8]*LPMMC, UMR 5493, F-38042 Grenoble 9, France*
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(Received 30 March 2012; revised manuscript received 24 May 2012; published 3 July 2012)

We propose a generalized wave function based on the flexible original THSR (Tohsaki, Horiuchi, Schuck, Röpke) wave function [A. Tohsaki *et al.*, Phys. Rev. Lett. **87**, 192501 (2001)], which is applicable to studies of general cluster structures in nuclei. The ground-state band in ^{20}Ne is investigated by using this generalized wave function and the energies obtained agree well with the experimental values. Moreover, it is found that the single generalized THSR wave functions almost completely coincide with the exact solutions of the $\alpha+^{16}$O resonating group method for the ground-state band in ^{20}Ne. For the ground state, for instance, the squared overlap between them is 99.3%. This indicates that the THSR model can also be extended to study more compact cluster states in nuclei such as, e.g., the ground-state band in ^{20}Ne.

2013年4月，任中洲等在北京Kavli理论物理研究所举办原子核结团物理会议，推动这方面研究

中国科学院卡弗里理论物理研究所(Kavli)

Program: Clustering Aspects in Nuclei

- **Date : from 2013-04-01 to 2013-04-26**
- **Local coordinators : Zhongzhou Ren (Chair, Nanjing University), Chang Xu (Nanjing University), Furong Xu (Peking University), Zaiguo Gan (Institute of Modern Physics), Shan-Gui Zhou (KITPC/ITP-CAS)**
- **International coordinators : Zhongzhou Ren (Chair, Nanjing University), Yanlin Ye (Peking University), W. Mittig (Michigan State University), P. Van Isacker (GANIL), G. Audi (Université de Paris Sud)**

国内 2013.6--2014.7：集团研究三篇PRL (南大，北大--兰州所，上海所)， rare

1. Bo Zhou(周波), Y. Funaki, H. Horiuchi, Zhongzhou Ren (任中洲), G. Röpke, P. Schuck, A. Tohsaki, Chang Xu(许昌), and T. Yamada，

   PRL 110, 262501 (2013)

2. Z. H. Yang (杨再宏), Y. L. Ye (叶沿林), Z. H. Li (李智焕), J. L. Lou (楼建玲), J. S. Wang (王建松)…

   PRL 112, 162501 (2014)

3. W. B. He (何万兵), Y. G. Ma (马余刚), X. G. Cao (曹喜光),X. Z. Cai (蔡翔舟),and G. Q. Zhang (张国强)

   PRL 113, 032506 (2014)

南京大学任中洲课题组

PRL 110, 262501 (2013): 非局域集团观点

PRL **110,** 262501 (2013) PHYSICAL REVIEW LETTERS week ending 28 JUNE 2013

Nonlocalized Clustering: A New Concept in Nuclear Cluster Structure Physics

Bo Zhou,[1,2,3,*] Y. Funaki,[3,†] H. Horiuchi,[2,4] Zhongzhou Ren,[1,5,‡] G. Röpke,[6] P. Schuck,[7,8] A. Tohsaki,[2] Chang Xu,[1] and T. Yamada[9]

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[3]*Nishina Center for Accelerator-Based Science, The Institute of Physical and Chemical Research (RIKEN), Wako 351-0198, Japan*
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[6]*Institut für Physik, Universität Rostock, D-18051 Rostock, Germany*
[7]*Institut de Physique Nucléaire, Université Paris-Sud, IN2P3-CNRS, UMR 8608, F-91406, Orsay, France*
[8]*Laboratoire de Physique et Modélisation des Milieux Condensés, CNRS-UMR 5493, F-38042 Grenoble Cedex 9, France*
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(Received 5 April 2013; revised manuscript received 17 May 2013; published 24 June 2013)

We investigate the $\alpha + {}^{16}O$ cluster structure in the inversion-doublet band ($K^\pi = 0_1^\pm$) states of ^{20}Ne with an angular-momentum-projected version of the Tohsaki-Horiuchi-Schuck-Röpke (THSR) wave function, which was successful "in its original form" for the description of, e.g., the famous Hoyle state. In contrast with the traditional view on clusters as localized objects, especially in inversion doublets, we find that these *single* THSR wave functions, which are based on the concept of nonlocalized clustering, can well describe the $K^\pi = 0_1^-$ band and the $K^\pi = 0_1^+$ band. For instance, they have 99.98% and 99.87% squared overlaps for 1^- and 3^- states (99.29%, 98.79%, and 97.75% for 0^+, 2^+, and 4^+ states), respectively, with the corresponding exact solution of the $\alpha + {}^{16}O$ resonating group method. These astounding results shed a completely new light on the physics of low energy nuclear cluster states in nuclei: The clusters are nonlocalized and move around in the whole nuclear volume, only avoiding mutual overlap due to the Pauli blocking effect.

在新构造的集团波函数中引入可以描述集团关联的新自由度。

在两种极端条件下可以变为传统的局域集团波函数和非局域的凝聚波函数。

将这个新的集团波函数应用到^{20}Ne的结团结构计算中，发现新波函数可以很好地描述^{20}Ne的正宇称转动带和负宇称转动带。

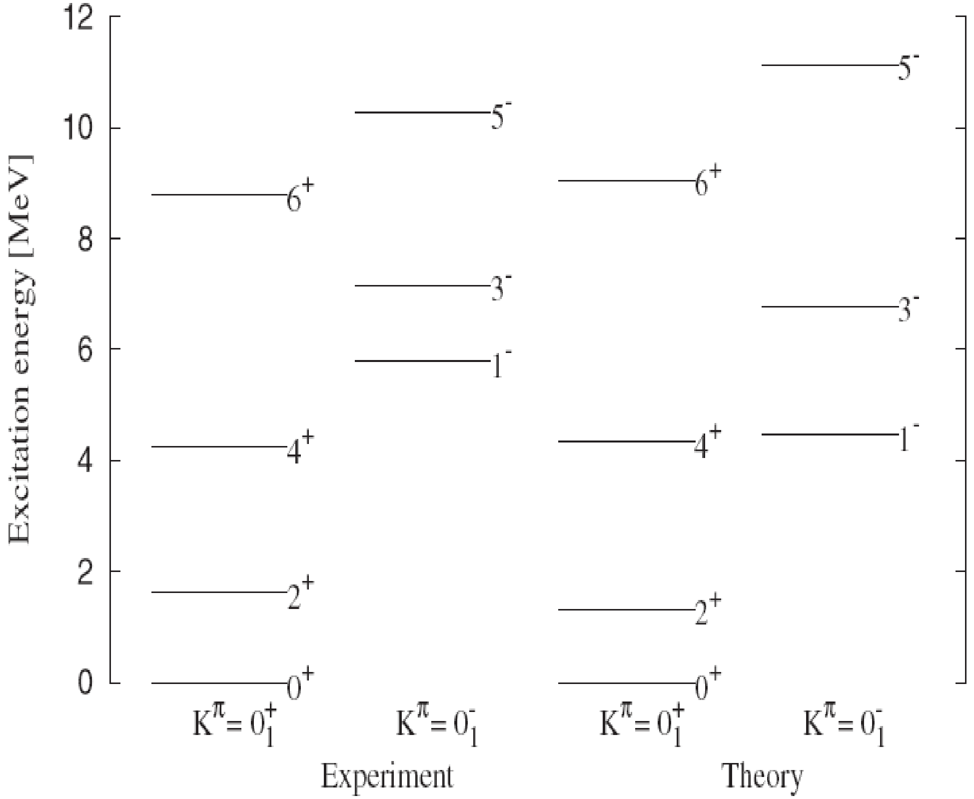

FIG. 4. The energy levels of the inversion doublet bands in ^{20}Ne reproduced by the hybrid wave function compared with the experimental levels.

PRL 110, 262501 (2013)

- Zhou, …, Ren,…　PRL(2013) 论文结论：

- 研究发现^{20}Ne的微观波函数是具有非局域特点的集团凝聚波函数。

- 在此之前，人们一直认为轻核中的集团结构具有类刚体的特点，这些集团在原子核中做局域的集团运动。

- 我们的研究清楚地表明，^{20}Ne中的^{4}He集团和^{16}O集团实际在做非局域集团运动，而非通常认为的局域运动。

国内研究组成果举例：PRL 2014， 北大叶沿林+兰州王建松课题组： ^{12}Be中集团态实验研究

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]

[1]*State Key Laboratory of Nuclear Physics and Technology, School of Physics, Peking University, Beijing 100871, China*
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北大叶沿林PRL:虽然集团态理论研究有大进展[4,6-8]，但实验仅证实少数集团态，主要是关于稳定核。

Recently it has been recognized that, compared to usual α-conjugate nuclei [5], a much larger number of cluster (molecular) configurations can be formed in an unstable nucleus, owing to numerous combinations of valence nucleons with the cluster cores [4]. Studies on such a new aspect of nuclear clustering have acquired strong interest in recent years [4,6]. However, although remarkable progress has been made from the theoretical side [4,6–8], only a few cluster states have been experimentally justified, focusing mainly on the stable nuclei [9].

[8] B. Zhou, Y. Funaki, H. Horiuchi, Z. Ren, G. Röpke, P. Schuck, A. Tohsaki, C. Xu, and T. Yamada, Phys. Rev. Lett. **110**, 262501 (2013).

上海所马余刚组结团研究　ＰＲＬ论文

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]
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[3]*Shanghai Tech University, Shanghai 200031, China*

ground state [36]. There are also many different configurational descriptions implying the α cluster structure in ^{20}Ne and ^{24}Mg, such as three-dimensional shuttle shape [5,13] or chain states [37,38] as well as nonlocalized cluster states [39]. Therefore, it is highly necessary and important [40] to look for new probes to diagnose different configurations for α-conjugate nuclei around the cluster decay threshold.

[39] B. Zhou, Y. Funaki, H. Horiuchi, Z. Ren, G. Röpke, P. Schuck, A. Tohsaki, C. Xu, and T. Yamada, Phys. Rev. Lett. **110**, 262501 (2013).

在20Ne和24Mg中，有很多显示alpha结团结构的工作，例如三维形状的描述[5,13]或链式态[37,38]，以及非局域化结团态[39]。

IOP Publishing Reports on Progress in Physics
Rep. Prog. Phys. **77** (2014) 096301 (46pp) doi:10.1088/0034-4885/77/9/096301

Review Article

Ikeda等的综述文章引用

Unified studies of chemical bonding structures and resonant scattering in light neutron-excess systems, ^{10,12}Be

Makoto Ito[1,2,3] **and Kiyomi Ikeda**[2,3]

[1] Department of Pure and Applied Physics, Kansai University, Yamatecho, 3-3-35, Suita, Japan
[2] Research Center for Nuclear Physics (RCNP), Osaka University, Mihogaoka 10-1, Suita 567-0047, Japan
[3] RIKEN Nishina Center for Accelerator-based Science, RIKEN, Wako,351-0198, Saitama, Japan

[22] Bo Zhou, Funaki Y, Horiuchi H, Zhongzhou Ren, Röpke G, Schuck P, Tohsaki A, Chang Xu and Yamada T 2013 *Phys. Rev. Lett.* **110** 262501

我们论文被美国耶鲁大学Iachello教授等引用

PRL 114, 192504 (2015) PHYSICAL REVIEW LETTERS week ending 15 MAY 2015

Origin of Low-Lying Enhanced $E1$ Strength in Rare-Earth Nuclei

M. Spieker,[1,*] S. Pascu,[1,2] A. Zilges,[1] and F. Iachello[3]
[1]*Institut für Kernphysik, Universität zu Köln, Zülpicher Straße 77, D-50937 Köln, Germany*
[2]*National Institute for Physics and Nuclear Engineering, R-77125 Bucharest-Magurele, Romania*
[3]*Center for Theoretical Physics, Sloane Physics Laboratory, Yale University, New Haven, Connecticut 06520-8120, USA*
(Received 16 October 2014; revised manuscript received 5 March 2015; published 12 May 2015)

Recently, an exploratory calculation for ^{212}Po was presented [31], indicating the existence of ^{208}Pb + α configurations when four-particle correlations are added to the shell-model calculations. This calculation provided a first hint at how to extend the well-established Tohsaki-Horiuchi-Schuck-Röpke wave function concept used for α-like condensates in light nuclei [21,32–34] to heavier nuclei. However, the general existence of α clustering in

这个计算提供了第一个线索，关于如何扩展轻核集团模型（THSR波函数）

[31] G. Röpke, P. Schuck, Y. Funaki, H. Horiuchi, Z. Ren, A. Tohsaki, C. Xu, T. Yamada, and B. Zhou, Phys. Rev. C **90**, 034304 (2014).

[34] B. Zhou, Y. Funaki, H. Horiuchi, Z. Ren, G. Röpke, P. Schuck, A. Tohsaki, C. Xu, and T. Yamada, Phys. Rev. Lett. **110**, 262501 (2013).

[31]Roepke…Ren…, PRC90, 034304(2014)
[34]Zhou…Ren…, PRL110, 262501(2013)

^{9}B，发展结团模型，新程序，丰Z，库仑势，计入质子自由度和集团自由度耦合

PHYSICAL REVIEW C **97**, 054323 (2018)

Investigation of the ^{9}B nucleus and its cluster-nucleon correlations

Qing Zhao,[1,*] Zhongzhou Ren,[2,†] Mengjiao Lyu,[3,‡] Hisashi Horiuchi,[3,4] Yasuro Funaki,[5] Gerd Röpke,[6] Peter Schuck,[7,8] Akihiro Tohsaki,[3] Chang Xu,[1] Taiichi Yamada,[5] and Bo Zhou[9,10]

[1]*School of Physics and Key Laboratory of Modern Acoustics, Institute of Acoustics, Nanjing University, Nanjing 210093, China*
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[3]*Research Center for Nuclear Physics (RCNP), Osaka University, Osaka 567-0047, Japan*
[4]*International Institute for Advanced Studies, Kizugawa 619-0225, Japan*
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[6]*Institut für Physik, Universität Rostock, D-18051 Rostock, Germany*
[7]*Institut de Physique Nucléaire, Université Paris-Sud, IN2P3-CNRS, UMR 8608, F-91406, Orsay, France*
[8]*Laboratoire de Physique et Modélisation des Milieux Condensés, CNRS-UMR 5493, F-38042 Grenoble Cedex 9, France*
[9]*Institute for International Collaboration, Hokkaido University, Sapporo 060-0815, Japan*
[10]*Department of Physics, Hokkaido University, 060-0810 Sapporo, Japan*

^{9}B集团能谱与实验比较，高激发能也符合好

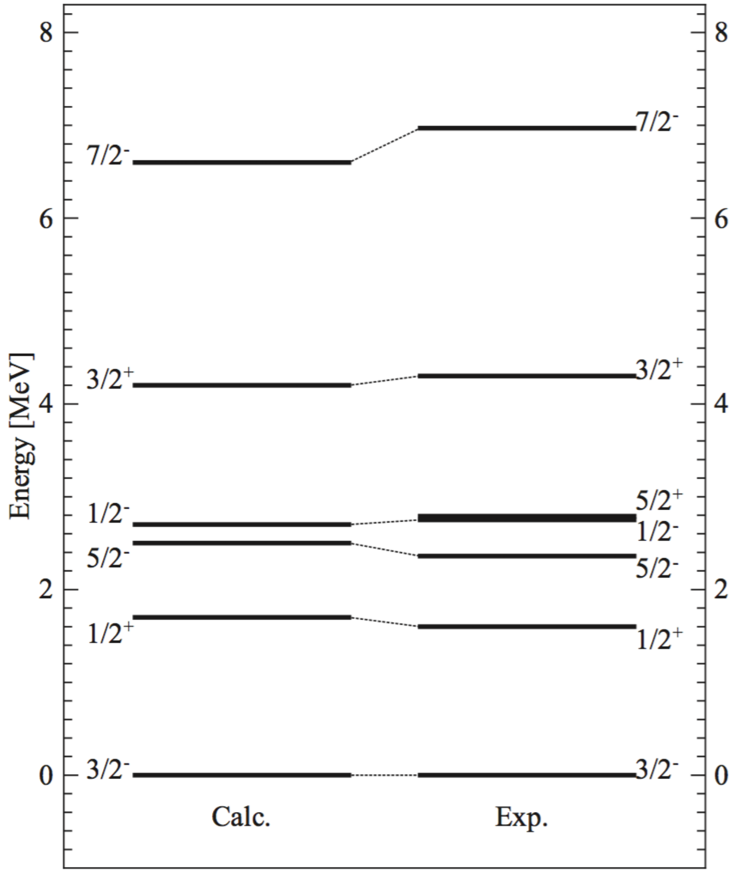
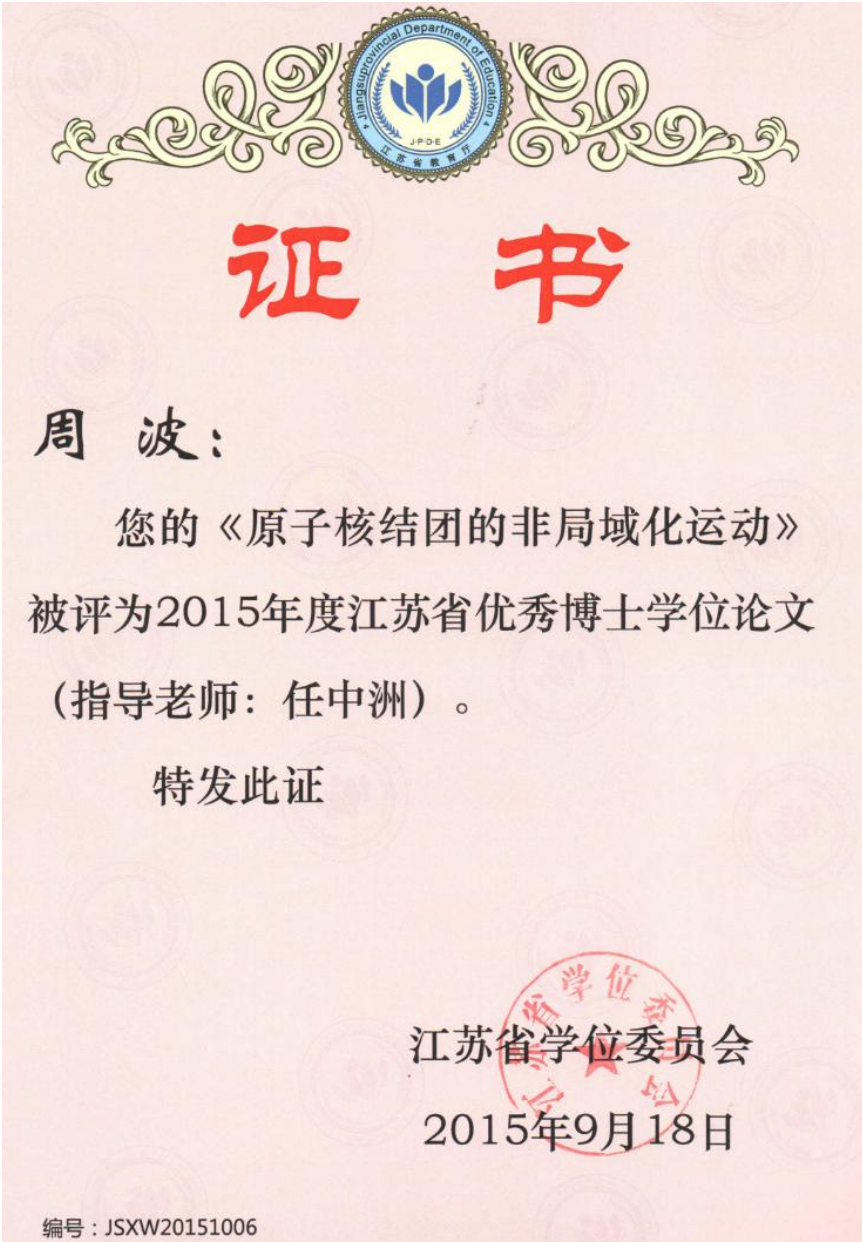


FIG. 8. Theoretical and experimental energy spectra of ^{9}B. The states with higher energy, which are found in experiment, are not considered in our calculation because of the limitation of computation power.

2016年 KITPC活动 任中洲 等组织



证书

周 波：

您的《原子核结团的非局域化运动》被评为2015年度江苏省优秀博士学位论文（指导老师：任中洲）。

特发此证

江苏省学位委员会

2015年9月18日

编号：JSXW20151006

人才培养：

指导的博士生周波获
2015
江苏省优博论文

我们轻核结团研究：
2020，周波青年千人

下面：重核结团研究

我们组对重
核结团研究背景（徐先生—我---学生…）

- 源于我在兰州大学硕士二年级（1984.9—1985.7），寒假。
- 在南京大学读博期间，逐渐有了成果。1987， PRC；1988，PRC。1989，JPG. 1990, PLB, 两篇。

- 再后来研究超重核alpha衰变：1999-2003， → PRC, NPA

- 2003-- →建立模型，计算alpha衰变寿命：DDCM, MCCM等。

任中洲，徐躬耦，PRC 36 (1987) 456：重核 alpha clustering

PHYSICAL REVIEW C VOLUME 36, NUMBER 1 JULY 1987

Reduced alpha transfer rates in a schematic model

Ren Zhong-zhou and Xu Gong-ou
Department of Physics, Nanjing University, Nanjing, China
(Received 27 January 1987)

The reduced alpha transfer rates are studied microscopically with a schematic model. Results for ground state to ground state alpha transfer reactions are given.

The model Hamiltonian is as follows:

$$H = H_0(+) + H_0(-) + H_1(+,-) , \tag{1}$$

where

$$H_0(\pm) = \pm\epsilon A(\pm) - 2\lambda_0 \left[\sum_\alpha B_\alpha^\dagger(\sigma,\pm) B_\alpha(\sigma,\pm) + \sum_\mu B_\mu^\dagger(\tau,\pm) B_\mu(\tau,\pm) \right] , \tag{2a}$$

任中洲，徐躬耦，PRC 36 (1987) 456

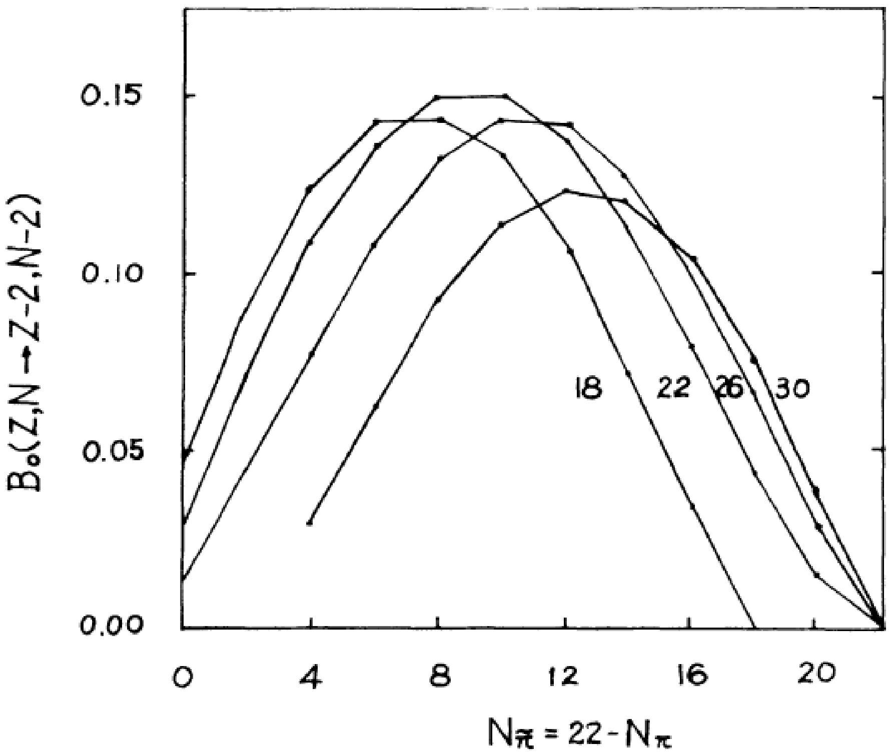


FIG. 2. Reduced α-transfer rates $B(Z,N\rightarrow Z-2,N-2)$ between ground states of nuclei with same value of $N_\nu - N_\pi$ as indicated in the figure, $N_\pi < 4l(-)+2$, $N_\nu > 4l(-)+2$. $\epsilon = 3.5$ MeV, $\lambda_0 = 1.0$ MeV, $\lambda_1 = 0.5$ MeV, $l(-)=5$, $l(+)=6$.

- 约化Alpha转移率

任中洲，徐躬耦， PRC 38 (1988) 1078

PHYSICAL REVIEW C VOLUME 38, NUMBER 2 AUGUST 1988

Evidence of α correlation from binding energies in medium and heavy nuclei

Ren Zhong-zhou
Department of Physics, Nanjing University, Nanjing, China

Xu Gong-ou
Department of Physics, Nanjing University, Nanjing, China
and Department of Modern Physics, Lanzhou University, Lanzhou, China

(Received 23 March 1988)

If the effect of α clustering due to the interaction of the excited correlated proton pair with correlated neutron pairs in medium and heavy nuclei were taken into consideration, quasiparticle energies would not be simply additive. The empirical values of the extra term $\delta(\alpha)$ indicate that α correlations exist to a certain extent in these nuclei.

$$\delta B = \begin{cases} \Delta & \text{even-even nuclei} \\ 0 & \text{even-odd or odd-even nuclei} \\ -\Delta & \text{odd-odd nuclei} \end{cases} \tag{3}$$

$$\delta B = \begin{cases} \Delta + \delta(\alpha) & \text{even-even nuclei} \\ 0 & \text{even-odd or odd-even nuclei} \\ -\Delta & \text{odd-odd nuclei} \end{cases} \tag{4}$$

系统研究奇Z超重核的基态性质，
预言未知超重核衰变能和寿命.

PHYSICAL REVIEW C **67**, 064302 (2003)

Ground state properties of odd-Z superheavy nuclei

Zhongzhou Ren,[1,2,*] Ding-Han Chen,[1] Fei Tai,[1] H. Y. Zhang,[3] and W. Q. Shen[3]
[1]*Department of Physics, Nanjing University, Nanjing 210008, People's Republic of China*
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(Received 21 January 2003; published 5 June 2003)

The ground state properties of odd-Z superheavy nuclei in the mass range of $Z=97$–115 and $N=140$–190 are systematically investigated in deformed relativistic mean-field (RMF) theory. Special emphasis is placed on nuclear shell effect around $N=184$. Calculations clearly show that the RMF model can reliably reproduce the data of binding energy and α decay energy of known nuclei and can also be used to predict the binding energy of unknown nuclei. It is found that deformation plays an important role for many superheavy nuclei. For $N=184$ isotones, the lighter ones are approximately spherical but the heavier ones are deformed. The α-decay energies of $N=184$ isotones are lower than those of neighboring nuclei in some cases and higher in other cases. This demonstrates that there is a complicated structural behavior for $N=184$ isotones.

Oganessian et al, PRC72 2005

PHYSICAL REVIEW C 72, 034611 (2005)

Synthesis of elements 115 and 113 in the reaction ^{243}Am + ^{48}Ca

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(Received 21 March 2005; published 29 September 2005)

The results of two experiments designed to synthesize element 115 isotopes in the ^{243}Am + ^{48}Ca reaction are presented. Two new elements with atomic numbers 113 and 115 were observed for the first time. With 248-MeV ^{48}Ca projectiles, we observed three similar decay

Predictions of SHF and RMF compare well with MM results [12,13]

[13] Z. Ren *et al.*, Phys. Rev. C 67, 064302 (2003).

In our experiments, α-decay properties proposed by the MM nuclear model [6,7] were used for setting the initial experimental parameters. One should note that the predictions of other models within the Skyrme-Hartree-Fock-Bogoliubov (SHFB) and the relativistic mean-field (RMF) approaches compare well with the MM results (see, e.g., [12,13]). Unfortunately, calculations of the probability of spontaneous fission and electron capture for odd nuclei are rather scarce.

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Oganessian et al, PRC72 2005

V. DISCUSSION

The experimental α-decay energies Q_α^{exp} of the synthesized isotopes and previously known odd-Z nuclei with $Z \geqslant 103$ are plotted in Fig. 9(a). The Q_α^{exp} of even-Z nuclei, including those produced in our experiments [1,2,20], are plotted in Fig. 9(b) for comparison. The α-decay energies attributed to the isotopes of Mt and Bh coincide well with theoretical values [7], also plotted in the figures. The same can be seen for the last nuclei in the decay chain ^{275}Hs → ^{271}Sg → ^{267}Rf.

The trend of the $Q_\alpha(N)$ systematics predicted by the MM model [6,7] and confirmed by experimental data for odd-Z

SHF [12, 49-51] and RMF [13, 52-57] compare well with the experimental results

considerable increase in T_α for the new heavier isotopes ... Db

[54] Z. Ren, Phys. Rev. C **65**, 051304(R) (2002).

[55] S. Das and G. Gangopadhyay, J. Phys. G **30**, 957 (2004).

[56] Z. Ren *et al.*, Phys. Rev. C **67**, 064302 (2003).

For the isotopes ^{279,280}Rg and ^{283,284}113 the difference between theoretical and experimental Q_α values is 0.6–0.9 MeV. Some part of this energy can be accounted for by γ-ray emission from excited levels populated during α decay. For the even-Z nuclei as well, the agreement between theory and experiment becomes somewhat worse as one moves from the deformed nuclei in the vicinity of neutron shells $N = 152$ and $N = 162$ to the more neutron-rich nuclides with $N \geqslant 169$. In this region, experimentally measured values of Q_α are less than the values calculated from the model by ⩽0.5 MeV. Although the predicted Q_α values for the heaviest nuclei observed in our experiments are systematically larger than the experimental data as a whole, the trends of the predictions are in good agreement for the 23 nuclides with $Z = 106$–118 and $N = 165$–177, especially considering that the theoretical predictions of the MM model match the experimental data over a broad previously unexplored region of nuclides.

One should note that the predictions of other models for even-Z and odd-Z nuclei within the Skyrme-Hartree-Fock-Bogoliubov [12,49–51] and the relativistic mean-field [13,52–57] methods also compare well with the experimental results. These models predict the same spherical neutron shell at $N = 184$, but different proton shells, $Z = 114$ (MM) and $Z = 120$, 124, or 126 (SHFB, RMF), yet all describe the experimental data equally well. Such insensitivity with respect

15. Ren, Z. Shape coexistence in even-even superheavy nuclei. Phys. Rev. C65, 051304 (2002)

Cited: shape coexistence, Ref. [15]

Nature, 433 (2005) 705

review article

Shape coexistence and triaxiality in the superheavy nuclei

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Superheavy nuclei represent the limit of nuclear mass and charge; they inhabit the remote corner of the nuclear landscape, whose extent is unknown. The discovery of new elements with atomic numbers $Z \geq 110$ has brought much excitement to the atomic and nuclear physics communities. The existence of such heavy nuclei hangs on a subtle balance between the attractive nuclear force and the disruptive Coulomb repulsion between protons that favours fission. Here we model the interplay between these forces using self-consistent energy density functional theory; our approach accounts for spontaneous breaking of spherical symmetry through the nuclear Jahn–Teller effect. We predict that the long-lived superheavy elements can exist in a variety of shapes, including spherical, axial and triaxial configurations. In some cases, we anticipate the existence of metastable states and shape isomers that can affect decay properties and hence nuclear half-lives.

Letters to nature

Nature 422, 876 (2003)

重核alpha衰变：^{209}Bi。

典型的壳模型核(Z=83)，但有alpha衰变（集团）

- **Experimental detection of α-particles from the radioactive decay of natural bismuth**

- **PIERRE DE MARCILLAC, NOËL CORON, GÉRARD DAMBIER, JACQUES LEBLANC & JEAN-PIERRE MOALIC**

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我们从2003年开始对重核的alpha衰变进行研究：on 209Bi Nature

PHYSICAL REVIEW C **68**, 034319 (2003)

α decay of odd-A nuclei with an extra nucleon outside a closed shell

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(Received 19 May 2003; published 18 September 2003)

The newly discovered α decay of ^{209}Bi [Marcillac *et al.*, Nature (London) **422**, 876 (2003)] is investigated in the cluster model of α decay. It is found that the cluster model can reproduce the data of this longest-lived α emitter in all known α-decay nuclei. This decay belongs to a special class of α decays occurring in odd-A nuclei with an extra nucleon outside a closed shell. By combining the cluster model of α decay with a microscopic model of preformation α cluster, we can successfully describe the half-lives of odd-A $N=127$ isotones. The cluster model of the favored α decays is interestingly generalized to the hindered α decays of odd-A nuclei.

Ren et al., PRC 70 (2004) 034304, Density-Dependent Cluster Model (DDCM): new model ^{4}He, ^{14}C decay

PHYSICAL REVIEW C **70**, 034304 (2004)

New perspective on complex cluster radioactivity of heavy nuclei

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Experimental data of complex cluster radioactivity (^{14}C–^{34}Si) are systematically analyzed and investigated with different models. The half-lives of cluster radioactivity are well reproduced by a new formula between half-lives and decay energies and by a microscopic density-dependent cluster model with the renormalized M3Y nucleon-nucleon interaction. The formula can be considered as a natural extension of both the Geiger-Nuttall law and the Viola-Seaborg formula from simple α decay to complex cluster radioactivity where different kinds of clusters are emitted. It is useful for experimentalists to analyze the data of cluster radioactivity. A new linear relationship between the decay energy of cluster radioactivity and the number of α particles in the cluster is found where the increase of decay energy for an extra α particle is between 15 and 17 MeV. The possible physics behind this new linear relationship is discussed.

^{212}Po，轻核结团模型思想（N=Z）到重核区

RAPID COMMUNICATIONS

PHYSICAL REVIEW C **93**, 011306(R) (2016)

α-decay width of ^{212}Po from a quartetting wave function approach

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present computer capabilities. The approach is inspired by the THSR wave function concept that has been successfully applied to light nuclei. Shell model calculations are improved by including four-particle (α-like) correlations that are of relevance when the matter density becomes low. A closer relation of the calculation presented here to the THSR calculations is of great interest; see the calculations for ^{20}Ne [16,17]. Related calculations are performed in Ref. [18]. A comparison with THSR calculations would lead to a better understanding of the microscopic calculations, in particular the c.m. potential, the c.m. wave function, and the preformation factor.

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[17] B. Zhou, Y. Funaki, H. Horiuchi, Z. Ren, G. Röpke, P. Schuck, A. Tohsaki, C. Xu, and T. Yamada, Phys. Rev. C **89**, 034319 (2014).

集团模型近似推广到中重核是一个大的发展，论文被同行引用及好评

同行指出我们结果和实验符合好

PHYSICAL REVIEW C **93**, 054326 (2016)

Microscopic description of superallowed α-decay transitions

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(Received 4 March 2016; published 26 May 2016)

larger than the corresponding experimental value. In effective theories, where the preformation probability is a parameter extracted from fittings to previous experimental values, theory and experiment agree reasonably well, as seen in Refs. [18,19].

[18] C. Xu, Z. Ren, G. Röpke, P. Schuck, Y. Funaki, H. Horiuchi, A. Tohsaki, T. Yamada, and B. Zhou, Phys. Rev. C **93**, 011306 (2016).
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PHYSICAL REVIEW C **97**, 064616 (2018)

Systematic studies of α and heavy-cluster emissions from superheavy nuclei

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It should be noted that microscopic calculations [29,30] are very important for the determination of the cluster preformation probabilities. Recently Deng *et al.* [29] calculated the α preformation factors of medium-mass nuclei as well as their behavior in the vicinity of $Z = 82$ shell closure by the cluster-formation model (CFM). The CFM was found to be effective in the evaluation of α preformation factors in the heavy-mass region and the authors claimed that the CFM is also valid for medium-mass nuclei because it reproduced reasonable features of the variation of α preformation probability, especially the $Z = 82$ shell effects, which were made evident in a recent experiment. Xu *et al.* [30] performed a microscopic calculation of α-cluster preformation probability and α-decay width in the ^{212}Po nucleus by improving a recent approach to describe α preformation in ^{212}Po [31] implementing four-nucleon correlations (quartetting). It was seen that, using the actually measured density distribution of the ^{208}Pb core, the calculated α-decay width of ^{212}Po agrees fairly well with the measured one.

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我们预言^{104}Te阿尔法衰变；实验PRL2018

PHYSICAL REVIEW C **74**, 037302 (2006)

Half lives of α-emitters approaching the $N = Z$ line

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(Received 13 July 2006; published 21 September 2006)

PHYSICAL REVIEW LETTERS **121**, 182501 (2018)

Editors' Suggestion | Featured in Physics

Superallowed α Decay to Doubly Magic ^{100}Sn

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suddenly. The present data are in agreement with this linear trend, and therefore with the extrapolated values of $Q_\alpha(^{104}\mathrm{Te}) = 5.053$ MeV and $Q_\alpha(^{108}\mathrm{Xe}) = 4.440$ MeV [29]. Furthermore, the folding potential calculations

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PHYSICAL REVIEW C **89**, 014308 (2014)

α decay of the new neutron-deficient isotope ^{205}Ac

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(Received 1 December 2013; published 13 January 2014)

The new neutron-deficient isotope ^{205}Ac was synthesized in the complete-fusion reaction ^{169}Tm(^{40}Ca, $4n$)^{205}Ac. The evaporation residues were separated in-flight by the gas-filled recoil separator SHANS in Lanzhou and subsequently identified by the α-α position and time correlation method. The α-decay energy and half-life of ^{205}Ac were determined to be 7.935(30) MeV and 20^{+97}_{-9} ms, respectively. Previously reported decay properties of the ground state in ^{206}Ac were confirmed.

In Refs. [16,17], a new version of the Geiger-Nuttall law including the quantum numbers of α-core relative motion was proposed, which reproduces the α-decay half-lives of heavy nuclei with $N \leqslant 126$ very well. In Fig. 3(b), a calculation using this law is carried out for the favored α-decay transitions, and the results are compared with experimental values. The calculated 15-ms half-life of ^{205}Ac is in good agreement with the value measured in the present experiment.

The calculated half-life (15 ms) with the new Geiger-Nuttall law [16,17] agrees well with the measured data (20 $^{+97}_{-9}$ms).

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轻—中重核：α预形成因子，中重核区计算

Physics Letters B 777 (2018) 298–302

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PHYSICS LETTERS B

New insight into α clustering of heavy nuclei via their α decay

Check for updates

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Physics Letters B 786 (2018) 5–10

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PHYSICS LETTERS B

Cluster-daughter overlap as a new probe of alpha-cluster formation in medium-mass and heavy even–even nuclei

Check for updates

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PRL 122, 192503 (2019) 产生一个新核素^{220}Np，
研究了N = 126幻数对应的闭壳效应。PRL编辑建议文章。
同济大学任中洲教授 (作者之一)

PHYSICAL REVIEW LETTERS **122,** 192503 (2019)

Editors' Suggestion

New Isotope ^{220}Np: Probing the Robustness of the $N = 126$ Shell Closure in Neptunium

Z. Y. Zhang (张志远),[1,2] Z. G. Gan (甘再国),[1,2,*] H. B. Yang (杨华彬),[1] L. Ma (马龙),[1] M. H. Huang (黄明辉),[1,2] C. L. Yang (杨春莉),[1,2] M. M. Zhang (张明明),[1,2] Y. L. Tian (田玉林),[1,2] Y. S. Wang (王永生),[1,2,3] M. D. Sun (孙明道),[1,2,3,†] H. Y. Lu (卢洪洋),[1,2] W. Q. Zhang (张文强),[1,2] H. B. Zhou (周厚兵),[4] X. Wang (王翔),[5] C. G. Wu (武晨光),[5] L. M. Duan (段利敏),[1,2] W. X. Huang (黄文学),[1,2] Z. Liu (刘忠),[1,2] Z. Z. Ren (任中洲),[6] S. G. Zhou (周善贵),[7,8] X. H. Zhou (周小红),[1,2] H. S. Xu (徐瑚珊),[1,2] Yu. S. Tsyganov,[9] A. A. Voinov,[9] and A. N. Polyakov[9]

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PRL 125, 032502 (2020) 在兰州产生另一个新核素 ^{222}Np，深入研究N = 126闭壳附近阿尔法衰变。
同济大学任中洲教授 (作者之一)

PHYSICAL REVIEW LETTERS **125,** 032502 (2020)

Short-Lived α-Emitting Isotope ^{222}Np and the Stability of the $N = 126$ Magic Shell

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Phys. Rev. Lett **126**, 152502 (2021)： new isotope ^{214}U

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

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A new α-emitting isotope ^{214}U, produced by the fusion-evaporation reaction $^{182}W(^{36}Ar, 4n)^{214}U$, was identified by employing the gas-filled recoil separator SHANS and the recoil-α correlation technique. More precise α-decay properties of even-even nuclei $^{216,218}U$ were also measured in the reactions of ^{40}Ar, ^{40}Ca beams with $^{180,182,184}W$ targets. By combining the experimental data, improved α-decay reduced widths δ^2 for the even-even Po-Pu nuclei in the vicinity of the magic neutron number $N = 126$ are deduced. Their systematic trends are discussed in terms of the N_pN_n scheme in order to study the influence of proton-neutron interaction on α decay in this region of nuclei. It is strikingly found that the reduced widths of $^{214,216}U$ are significantly enhanced by a factor of two as compared with the N_pN_n systematics for the $84 \leq Z \leq 90$ and $N < 126$ even-even nuclei. The abnormal enhancement is interpreted by the strong monopole interaction between the valence protons and neutrons occupying the $\pi 1f_{7/2}$ and $\nu 1f_{5/2}$ spin-orbit partner orbits, which is supported by the large-scale shell model calculation.

Shen,Guo…PLB， 2019，原子能院+…+同济大学+中大

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First experimental constraint of the spectroscopic amplitudes for the α-cluster in the ^{11}B ground state

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ABSTRACT

We present the first experimental determination on the spectroscopic amplitudes (SAs) for the α-cluster in the ^{11}B ground state via the ^{7}Li(^{6}Li, d)^{11}B reaction using a high-precision magnetic spectrograph. This

Phys. Rev. C 105, 024327 (2022) , DDCM+ by Wang, Bai, Ren

Improved density-dependent cluster model in α-decay calculations within anisotropic deformation-dependent surface diffuseness

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The density-dependent cluster model (DDCM) is one of the successful theoretical models for α-decay studies. It gives a good description of the experimental α-decay half-lives for a wide range of α emitters. Nuclear surface diffuseness, one important quantity in determining the nucleon density profiles, is extremely sensitive to deformation, Bohr, Mottelson *et al.* proposed an anisotropic feature of the surface diffuseness for the deformed nuclei. In this work, an improved version of the density-dependent cluster model, abbreviated as DDCM+, is developed to optimize α-decay calculations on half-lives, by accounting for the anisotropy and polarization effects of surface diffuseness due to nuclear deformation. Within a deformation-dependent diffuseness correction, the response of α-decay dynamics to the diffuseness anisotropy is first investigated in detail. It demonstrates that such an anisotropic deformation-dependent diffuseness would change the shape of nucleon density profile and effective α-core interactions, yielding longer calculated α-decay half-lives, as well as suggesting larger estimated α-preformation factors. The systematic calculations on α-decay half-lives are subsequently performed for 157 even-even nuclei with $52 \leqslant Z \leqslant 118$, which reproduce the experimental data within an average factor of 1.88, and drastically reduce the root-mean-square deviations between theoretical results and experimental data by about 41.4% in contrast to conventional DDCM. Noticeably, the theoretical result of new isotope ^{214}U [Zhang *et al.*, Phys. Rev. Lett. **126**, 152502 (2021)] given by DDCM+ also shows good agreement with the latest reported experimental data, demonstrating the high reliability of the improved model. It is expected that this improved model could be useful for future experimental and theoretical studies of α decays.

New version of density-dependent cluster model

(DDCM+)

- include the surface effect of nucleon density and deformation for nuclei： Bohr,Mottelson, *Nuclear Structure Vol. 2* (1998).
- Different density distributions of protons and neutrons
- to solve quasi-bound state Schroedinger-equations

Numerical results （^{214}U 、 ^{216}U、 ^{218}U ）

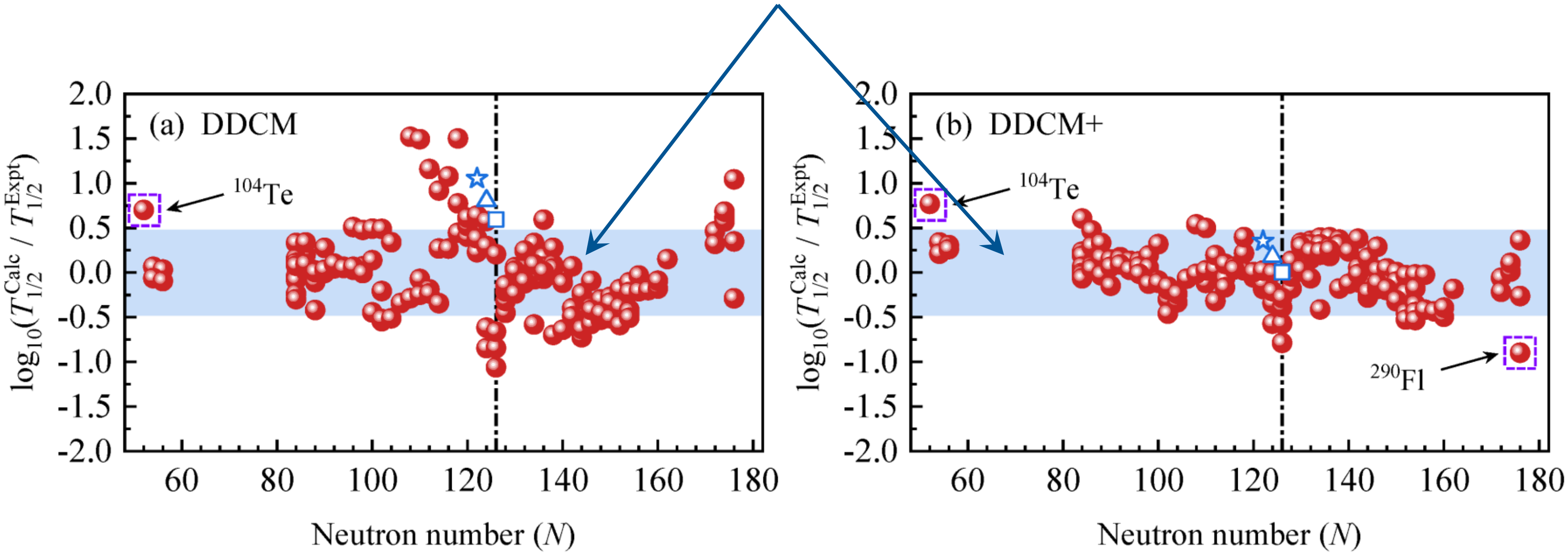
DDCM+ is in better agreement with data for new isotopes ^{214}U , ^{216}U and ^{218}U

核素	$T_{1/2}^{\mathrm{Expt}}$ (s)	$T_{1/2}^{\mathrm{DDCM}}$ (s)	δ_1	$T_{1/2}^{\mathrm{DDCM+}}$ (s)	δ_2
^{214}U	5.20×10^{-4}	5.87×10^{-3}	1.053	1.17×10^{-3}	0.352
^{216}U	2.25×10^{-3}	1.43×10^{-2}	0.804	3.41×10^{-3}	0.181
^{218}U	6.50×10^{-4}	2.55×10^{-3}	0.594	6.57×10^{-4}	0.0045

Deviation between logrithms of calculated half-lives and data

Deviations between calculated half-lives and data (157 even-even nuclei)

Blue region: less than 3 times



RMS is reduced by 41.3% ↓ (data is from NUBASE2020)

Z=119, 120新元素α衰变寿命预言

- α衰变半衰期对于α衰变能具有较强的敏感性和依赖性，而现阶段对于α衰变能的精确预言是较为困难的。因此，在预言α衰变寿命时，需考虑不同α衰变能(质量)模型的不确定性。Lg T ~ Q

- 为提供可靠的α衰变寿命预言，供实验参考，我们考虑了3种不同的理论模型给出的α衰变能，对新核素α衰变寿命进行计算和预言。

Q_α^{th1}: Dong's formula [T. Dong *et al*., Phys. Rev. C 82, 034320(2010)]

Q_α^{th2}: FRDM2012 [P. Möller *et al*., Atom. Data Nucl. Data. Tabl. 125, 1 (2019)]

Q_α^{th3}: Valence correlation scheme [Y. Qian *et al*., Phys. Rev. C 103, 024314(2021)]

Z=119, 120新元素α衰变寿命预言

- α衰变半衰期T_{α}^{th1}, T_{α}^{th2}由改进的密度依赖的结团模型DDCM+计算得到， α衰变半衰期T_{α}^{th3}以及自发裂变寿命T_{SF}^{th}由Y. Qian提供。

T_{α}^{th1}, T_{α}^{th2}: DDCM+ [Z. Wang, Z. Ren *et al.*, Phys. Rev. C 105, 024327(2022)]

T_{SF}^{th}: [A. V. Karpov *et al.*, Int. J. Mod. Phys. E 21, 1250013(2012)]

[Y. Qian, Z. Ren *et al.*, Phys. Rev. C 90, 064308(2014)]

- 此外，其他老师利用WS4质量模型[N. Wang *et al.*, Phys. Lett. B 734, 215 (2014)]等给出的α衰变能，采用不同α衰变理论模型也计算预言了一些新核素的α衰变半衰期，供实验参考。

新表1：^{293}119、^{294}119新元素α衰变链衰变能、α衰变寿命、自发裂变寿命理论预言(by Z. Ren, Z. Wang and Y. Qian) 核梦：新元素

核素	Q_α^{th1} (MeV)	T_α^{th1} (s)	Q_α^{th2} (MeV)	T_α^{th2} (s)	Q_α^{th3} (MeV)	T_α^{th3} (s)	T_{SF}^{th} (s)
^{293}119	12.30	1.40×10^{-4}	12.92	7.31×10^{-6}	12.53	7.44×10^{-5}	1.86×10^{1}
^{289}Ts	11.83	4.17×10^{-4}	11.98	1.93×10^{-4}	11.87	5.66×10^{-4}	1.21×10^{3}
^{285}Mc	11.47	7.20×10^{-4}	10.30	6.42×10^{-1}	11.20	5.17×10^{-3}	6.26×10^{3}
^{281}Nh	11.16	6.69×10^{-4}	10.76	6.37×10^{-3}	11.65	1.20×10^{-4}	1.62×10^{1}
^{294}119	12.15	3.82×10^{-4}	12.85	1.35×10^{-5}	12.40	2.25×10^{-4}	4.38×10^{1}
^{290}Ts	11.62	1.63×10^{-3}	11.85	4.97×10^{-4}	11.73	1.79×10^{-3}	3.71×10^{3}
^{286}Mc	11.21	4.07×10^{-3}	10.21	1.53×10^{0}	11.06	1.72×10^{-2}	2.92×10^{4}
^{282}Nh	10.88	3.80×10^{-2}	10.02	7.23×10^{0}	10.39	2.08×10^{-1}	1.03×10^{2}

根据P. Möller等人FRDM2012预言的结果，$T_\beta^{th}(^{293}119) = 1.01 \times 10^2\ s$，$T_\beta^{th}(^{294}119) = 1.10 \times 10^2\ s$

新表2：^{294}120、^{295}120新核素α衰变链衰变能、α衰变寿命、自发裂变寿命理论预言(by Z. Ren, Z. Wang and Y. Qian) 核梦：新元素

核素	Q_α^{th1} (MeV)	T_α^{th1} (s)	Q_α^{th2} (MeV)	T_α^{th2} (s)	Q_α^{th3} (MeV)	T_α^{th3} (s)	T_{SF}^{th} (s)
^{294}120	12.71	2.32×10^{-5}	13.49	7.15×10^{-7}	13.01	1.14×10^{-5}	7.62×10^{-4}
^{290}Og	12.25	6.27×10^{-5}	12.67	8.47×10^{-6}	12.34	7.58×10^{-5}	6.33×10^{-2}
^{286}Lv	11.90	1.07×10^{-4}	11.68	3.35×10^{-4}	11.67	6.01×10^{-4}	5.55×10^{0}
^{282}Fl	11.60	9.30×10^{-5}	9.96	1.30×10^{0}	12.14	1.57×10^{-5}	1.72×10^{0}
^{295}120	12.57	6.79×10^{-5}	13.46	1.22×10^{-6}	12.87	2.90×10^{-5}	3.74×10^{-1}
^{291}Og	12.05	2.58×10^{-4}	12.55	2.21×10^{-5}	12.20	2.02×10^{-4}	9.48×10^{1}
^{287}Lv	11.64	5.81×10^{-4}	11.20	6.22×10^{-3}	11.53	1.66×10^{-3}	3.82×10^{3}
^{283}Fl	11.32	6.29×10^{-4}	9.83	4.81×10^{0}	10.86	1.68×10^{-2}	1.22×10^{3}

根据P. Möller等人FRDM2012预言的结果，$T_\beta^{th}(^{294}120) = 1.65 \times 10^{1}\ s$，$T_\beta^{th}(^{295}120) = 2.43 \times 10^{1}\ s$

Wang and Ren，Phys. Rev. C 106, 024311 (2022)将DDCM+推广到奇-A核与奇奇核：

预言Z=119，120衰变性质

Favored α-decay half-lives of odd-A and odd-odd nuclei using an improved density-dependent cluster model with anisotropic surface diffuseness

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We extend the improved density-dependent cluster model (DDCM+) of our recent work [Wang *et al.*, Phys. Rev. C **105**, 024327 (2022)] to study the favored α decays of odd-A and odd-odd nuclei with $Z \geqslant 82$. In this work, the effective α-core interactions are determined using the double-folding potential with a realistic M3Y-Reid nucleon-nucleon interaction plus proton-proton Coulomb interaction, in which a deformation-dependent diffuseness correction is validated to address the surface anisotropy and polarization effects in nucleon density distribution. It is found that calculations within the anisotropic diffuseness would yield longer calculated α decay half-lives and suggest larger estimated α-preformation factors, which is quite consistent with the conclusions obtained for the even-even α emitters. Meanwhile, the theoretical half-lives agree very well with the experimental data for the favored α decays of the odd-A and odd-odd nuclei with a mean factor of 1.94 and 1.61, respectively. Remarkably, the experimental α-decay half-life of the new thorium isotope ^{207}Th [Yang *et al.*, Phys. Rev. C **105**, L051302 (2022)] is also well reproduced with a factor of about 2.50. Furthermore, we present the quantitative predictions on the favored α-decay half-lives of $^{293,294}119$ and $^{294,295}120$ α-decay chains in this work, which are expected to serve as useful references for the synthesis of new isotopes in the future.

DOI: 10.1103/PhysRevC.106.024311

Summary

- **Develop the cluster model of light nuclei**
- **Density-Dependent Cluster Model (DDCM)**
- **New version of Density-Dependent Cluster Model (DDCM+) for calculations of alpha-decay half-lives :**
  S-eq. for quasi-bound states.
- **By including nuclear deformation and surface effect we reach good agreement with experimental half-lives.**
- **New predictions on Z=119, Z=120**
- **中国： 合成新元素 Chinium （金龙）（中国）：Ci**

三. 中文小 结

首先，回顾了国内外核集团态理论研究的一些新成果。

对原子核集团态的研究少，国内关于集团态的PRL论文（轻核区集团态）。还回顾了重核的alpha衰变和集团放射性等的模型，209Bi。新核素220Np等。不稳定原子核做为复杂的量子多体系统，会有不少结团有关新现象和新规律有待研究。DDCM+(新版密度依赖结团模型），MCCM

新元素Z=119，Z=120衰变性质。

一批优秀留学回国青年人才。

轻核集团研究：1青千。

重核集团研究：2优青。

谢谢清华大学物理系肖志刚教授的邀请！

祝贺清华大学物理系复系**40**年！
祝愿清华大学物理系取得更多新成果，培养更多优秀人才！

很高兴做报告，进行科研交流。

Variation of reduced alpha transfer rates with valence protons and neutrons

$$B_0(Z,N\to Z-2,N-2)=B_0(Z-2,N-2\to Z,N)$$

$$=(N_{\tilde{\pi}}+2)\left[1-\frac{N_{\tilde{\pi}}}{2[2l(-)+1]}\right]N_{\nu}\left[1-\frac{N_{\nu}-2}{2[2l(+)+1]}\right]$$

$$\times\frac{1}{3}\lambda_1^2\left[\frac{1}{\Delta E_{\alpha}(N_{\tilde{\pi}},N_{\nu})}\left[1+\frac{2}{2l(+)+1}\right]+\frac{1}{\Delta E_{\tilde{\alpha}}(N_{\tilde{\pi}}+2,N_{\nu}-2)}\left[1+\frac{2}{2l(-)+1}\right]\right]$$

where

$$\Delta E_{\alpha}(N_{\tilde{\pi}},N_{\nu})=4(\epsilon-\lambda_0)-\frac{8\lambda_0}{2l(+)+1}+\frac{12\lambda_0}{2l(-)+1}+\frac{2\lambda_0 N_{\tilde{\pi}}}{2l(-)+1}$$

$$\Delta E_{\tilde{\alpha}}(N_{\tilde{\pi}},N_{\nu})=4(\epsilon-\lambda_0)+\frac{4\lambda_0}{2l(-)+1}+\frac{2\lambda_0 N_{\nu}}{2l(+)+1}\ .$$

Ren and Xu, PRC 1988: alpha correlation

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PHYSICAL REVIEW C　VOLUME 38, NUMBER 2　AUGUST 1988

Evidence of α correlation from binding energies in medium and heavy nuclei

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(Received 23 March 1988)

If the effect of α clustering due to the interaction of the excited correlated proton pair with correlated neutron pairs in medium and heavy nuclei were taken into consideration, quasiparticle energies would not be simply additive. The empirical values of the extra term $\delta(\alpha)$ indicate that α correlations exist to a certain extent in these nuclei.

系统研究奇Z超重核的基态性质，

预言未知超重核衰变能和寿命.

PHYSICAL REVIEW C **67**, 064302 (2003)

Ground state properties of odd-*Z* superheavy nuclei

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The ground state properties of odd-Z superheavy nuclei in the mass range of $Z=97-115$ and $N=140-190$ are systematically investigated in deformed relativistic mean-field (RMF) theory. Special emphasis is placed on nuclear shell effect around $N=184$. Calculations clearly show that the RMF model can reliably reproduce the data of binding energy and α decay energy of known nuclei and can also be used to predict the binding energy of unknown nuclei. It is found that deformation plays an important role for many superheavy nuclei. For $N=184$ isotones, the lighter ones are approximately spherical but the heavier ones are deformed. The α-decay energies of $N=184$ isotones are lower than those of neighboring nuclei in some cases and higher in other cases. This demonstrates that there is a complicated structural behavior for $N=184$ isotones.

Oganessian et al, PRC72 2005

PHYSICAL REVIEW C **72**, 034611 (2005)

Synthesis of elements 115 and 113 in the reaction ^{243}Am + ^{48}Ca

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(Received 21 March 2005; published 29 September 2005)

The results of two experiments designed to synthesize element 115 isotopes in the ^{243}Am + ^{48}Ca reaction are presented. Two new elements with atomic numbers 113 and 115 were observed for the first time. With 248-MeV ^{48}Ca projectiles, we observed three similar decay

Predictions of SHF and RMF compare well with MM results [12,13]

In our experiments, α-decay properties proposed by the MM nuclear model [6,7] were used for setting the initial experimental parameters. One should note that the predictions of other models within the Skyrme-Hartree-Fock-Bogoliubov (SHFB) and the relativistic mean-field (RMF) approaches compare well with the MM results (see, e.g., [12,13]). Unfortunately, calculations of the probability of spontaneous fission and electron capture for odd nuclei are rather scarce.

[13] Z. Ren *et al.*, Phys. Rev. C **67**, 064302 (2003).

Oganessian et al, PRC72 2005

V. DISCUSSION

The experimental α-decay energies Q_α^{exp} of the synthesized isotopes and previously known odd-Z nuclei with $Z \geqslant 103$ are plotted in Fig. 9(a). The Q_α^{exp} of even-Z nuclei, including those produced in our experiments [1,2,20], are plotted in Fig. 9(b) for comparison. The α-decay energies attributed to the isotopes of Mt and Bh coincide well with theoretical values [7], also plotted in the figures. The same can be seen for the last nuclei in the decay chain ^{275}Hs → ^{271}Sg → ^{267}Rf.

The trend of the $Q_\alpha(N)$ systematics predicted by the MM model [6,7] and confirmed by experimental data for odd-Z isotopes of Mt and Bh along with even-Z isotopes of Ds can

SHF [12， 49-51] and RMF [13， 52-57] compare well with the experimental results

considerable increase in T_α for the new heavier isotopes [illegible] Db

[54] Z. Ren, Phys. Rev. C **65**, 051304(R) (2002).

[55] S. Das and G. Gangopadhyay, J. Phys. G **30**, 957 (2004).

[56] Z. Ren *et al.*, Phys. Rev. C **67**, 064302 (2003).

For the isotopes ^{279,280}Rg and ^{283,284}113 the difference between theoretical and experimental Q_α values is 0.6–0.9 MeV. Some part of this energy can be accounted for by γ-ray emission from excited levels populated during α decay. For the even-Z nuclei as well, the agreement between theory and experiment becomes somewhat worse as one moves from the deformed nuclei in the vicinity of neutron shells $N = 152$ and $N = 162$ to the more neutron-rich nuclides with $N \geqslant 169$. In this region, experimentally measured values of Q_α are less than the values calculated from the model by $\leqslant 0.5$ MeV. Although the predicted Q_α values for the heaviest nuclei observed in our experiments are systematically larger than the experimental data as a whole, the trends of the predictions are in good agreement for the 23 nuclides with $Z = 106$–118 and $N = 165$–177, especially considering that the theoretical predictions of the MM model match the experimental data over a broad previously unexplored region of nuclides.

One should note that the predictions of other models for even-Z and odd-Z nuclei within the Skyrme-Hartree-Fock-Bogoliubov [12,49–51] and the relativistic mean-field [13,52–57] methods also compare well with the experimental results. These models predict the same spherical neutron shell at $N = 184$, but different proton shells, $Z = 114$ (MM) and $Z = 120$, 124, or 126 (SHFB, RMF), yet all describe the experimental data equally well. Such insensitivity with respect

Letters to

Nature 422, 876

重核alpha衰变：^{209}Bi。

典型的壳模型核(Z=83)，但有alpha衰变（集团）

- Experimental detection of α-particles from the radioactive decay of natural bismuth

- PIERRE DE MARCILLAC, NOËL CORON, GÉRARD DAMBIER, JACQUES LEBLANC & JEAN-PIERRE MOALIC

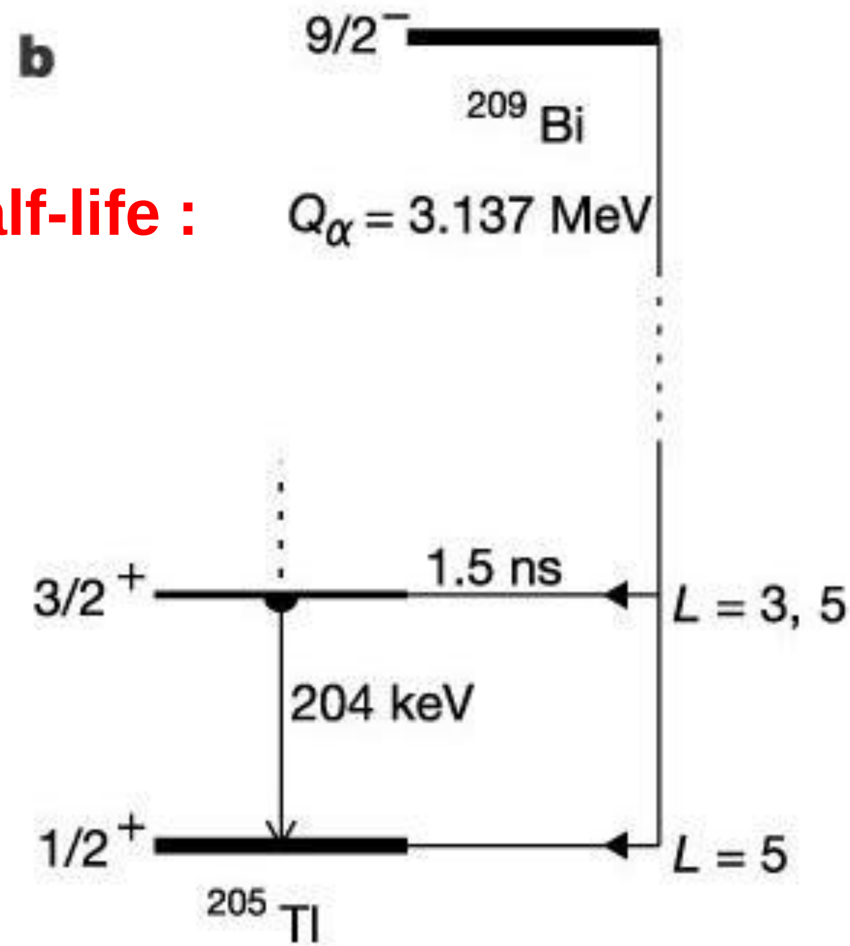
- Institut d'Astrophysique Spatiale, CNRS & Université Paris Sud, UMR 8617, Bât. 121, 91405 Orsay Cedex, France

α-decay scheme of ^{209}Bi

Exceptionally long half-life :

decay energy

angular momentum



我们从2003年开始对重核的alpha衰变进行研究：on 209Bi Nature

PHYSICAL REVIEW C **68**, 034319 (2003)

α decay of odd-A nuclei with an extra nucleon outside a closed shell

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[2]*Center of Theoretical Nuclear Physics, National Laboratory of Heavy-Ion Accelerator, Lanzhou 730000, China*
(Received 19 May 2003; published 18 September 2003)

The newly discovered α decay of ^{209}Bi [Marcillac *et al.*, Nature (London) **422**, 876 (2003)] is investigated in the cluster model of α decay. It is found that the cluster model can reproduce the data of this longest-lived α emitter in all known α-decay nuclei. This decay belongs to a special class of α decays occurring in odd-A nuclei with an extra nucleon outside a closed shell. By combining the cluster model of α decay with a microscopic model of preformation α cluster, we can successfully describe the half-lives of odd-A $N=127$ isotones. The cluster model of the favored α decays is interestingly generalized to the hindered α decays of odd-A nuclei.

Preformation factor P_α=0.004 (Z-82): PRC1987

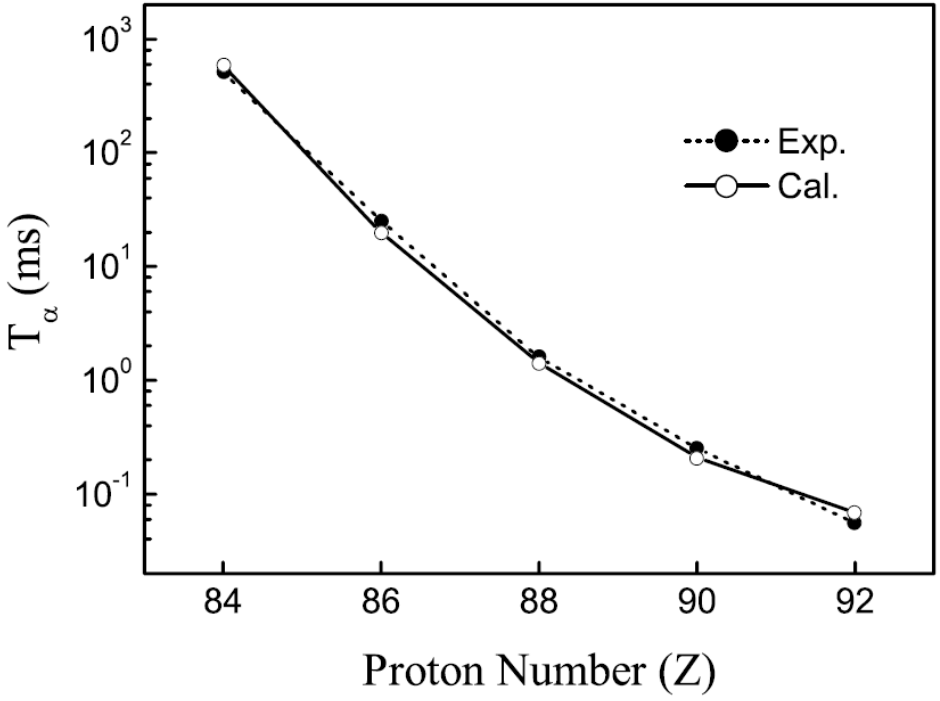

FIG. 2. The variation of theoretical half-life of α decay with proton number where the nuclear structure effect of the preformation α cluster is included. $G=23$ is chosen for $N=127$ isotones. The black circles are experimental half-lives. The hollow circles are theoretical half-lives.

Xu and Ren, PRC 73, 041301(R) 2006

建立新形变模型（DDCM）：密度依赖集团模型（ Density-Dependent Cluster Model）

RAPID COMMUNICATIONS

PHYSICAL REVIEW C **73**, 041301(R) (2006)

New deformed model of α-decay half-lives with a microscopic potential

Chang Xu[1] and Zhongzhou Ren[1,2,3,*]

[1]*Department of Physics, Nanjing University, Nanjing 210008, China*

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(Received 19 January 2006; published 6 April 2006)

The α-decay half-lives of deformed nuclei are investigated in a new version of the density-dependent cluster model. By the multipole expansion method, the deformation- and orientation-dependent double-folding potential is derived to calculate the α-decay width through a deformed Coulomb barrier. We perform systematic calculations for the ground-state α transitions of even-even nuclei with $Z = 52-104$. The theoretical results are in good agreement with the experimental data. This is, to our knowledge, the first deformed calculation of α-decay half-lives within the framework of microscopic double-folding potentials. A unified description of α-decay half-lives of both spherical and deformed nuclei is obtained by the microscopic potentials.

Ni and Ren, PRC 81, 064318 (2010)…建立多道集团模型：Multi-channel cluster model (MCCM)

PHYSICAL REVIEW C **81**, 064318 (2010)

New approach for α-decay calculations of deformed nuclei

Dongdong Ni[1,2,*] and Zhongzhou Ren[1,2,3,†]
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[2]*Kavli Institute for Theoretical Physics China, Beijing 100190, China*
[3]*Center of Theoretical Nuclear Physics, National Laboratory of Heavy-Ion Accelerator, Lanzhou 730000, China*
(Received 31 March 2010; published 22 June 2010)

We present a new theoretical approach to evaluate α-decay properties of deformed nuclei, namely the multichannel cluster model (MCCM). The deformed α-nucleus potential is taken into full account, and the coupled-channel Schrödinger equation with outgoing wave boundary conditions is employed for quasibound states. Systematic calculations are carried out for well-deformed even-even nuclei with $Z \geqslant 98$ and isospin dependence of nuclear potentials is included in the calculations. Fine structure observed in α decay is well described by the four-channel microscopic calculation, which is performed for the first time in α-decay studies. The good agreement between experiment and theory is achieved for both total α-decay half-lives and branching ratios to the ground-state rotational band of daughter nuclei. Predictions on the branching ratios to high-spin daughter states are presented for superheavy nuclei, which may be important to interpret future observations.

建立和发展重核衰变结团模型

1 系统性研究工作：建立和发展多道结团模型到5道和25道。

研究范围：偶偶核—奇A核—奇奇核alpha衰变精细结构

创新点：1) 4道→5道→25道，新编写更多道计算程序

2) 完成奇A核和奇奇核的耦合道模型（求解准束缚态耦合薛定谔方程），研究形变重核 alpha 衰变精细结构现象，解决了半经典近似计算的缺陷。

2 这是计算形变重核alpha衰变寿命和分支比的微观模型—多道结团模型（MCCM）。Period：2010—2015.

耦合道计算系列工作 (PRC3篇)

该系列工作第一篇 —— 偶偶核五道耦合计算

调试新程序（多级展开），并解决半经典近似的缺陷

PHYSICAL REVIEW C **83**, 067302 (2011)

Coupled-channels study of fine structure in the α decay of well deformed nuclei

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(Received 14 March 2011; revised manuscript received 8 June 2011; published 21 June 2011)

We formulate a theoretical model for the α decay of well-deformed even-even nuclei based on the coupled-channel Schrödinger equation. The α-decay half-lives and fine structures observed in α decay are well described by the five-channel microscopic calculations. Since the branching ratios to high-spin states are hard to understand in the traditional α-decay theories, this success could be important to interpret future observations of heavier nuclei. It is also found that the α transition to high-spin states is a powerful tool to probe the energy spectrum and deformation of daughter nuclei.

系列工作第二篇 —— 奇A核多道耦合计算（最多25道）

耦合道数目多，数值计算难度大（未见他人研究）

PHYSICAL REVIEW C **86**, 054608 (2012)

Systematic calculation of fine structure in the α decay of heavy odd-mass nuclei

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[2]*Center of Theoretical Nuclear Physics, National Laboratory of Heavy-Ion Accelerator, Lanzhou 730000, China*

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(Received 28 October 2012; published 28 November 2012)

系列工作第三篇 —— 奇奇核多道耦合计算

实验数据稀少，理论与实验符合很好（未见他人研究）

PHYSICAL REVIEW C **87**, 027602 (2013)

Theoretical description of fine structure in the α decay of heavy odd-odd nuclei

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(Received 1 February 2013; published 28 February 2013)

5道计算结果：偶偶Cm核（PRC2011）

^{242}Cm	Exp. (%)	Cal. (%)
8^+	2.0×10^{-5}	3.8×10^{-5}
6^+	0.0046	0.0053
4^+	0.035	0.077
2^+	25.92	31.04
0^+	74.08	68.87
$T_{1/2}$(s)	1.41×10^{7}	1.32×10^{7}

^{244}Cm	Exp. (%)	Cal. (%)
8^+	4.0×10^{-5}	2.8×10^{-5}
6^+	0.00352	0.00733
4^+	0.0204	0.0479
2^+	23.1	28.60
0^+	76.9	71.34
$T_{1/2}$(s)	5.72×10^{8}	5.68×10^{8}

73

PHYSICAL REVIEW C **89**, 014308 (2014)

α decay of the new neutron-deficient isotope ^{205}Ac

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T. H. Huang (黄天衡),[1] G. S. Li (李广顺),[1] Y. L. Tian (田玉林),[1] Y. S. Wang (王永生),[1] X. X. Xu (徐新星),[4]
X. L. Wu (吴晓蕾),[1] M. H. Huang (黄明辉),[1,5] C. Luo (罗成),[1] Z. Z. Ren (任中洲),[6,7] S. G. Zhou (周善贵),[7,8]
X. H. Zhou (周小红),[1] H. S. Xu (徐瑚珊),[1] and G. Q. Xiao (肖国青)[1]

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(Received 1 December 2013; published 13 January 2014)

The new neutron-deficient isotope ^{205}Ac was synthesized in the complete-fusion reaction ^{169}Tm(^{40}Ca, $4n$)^{205}Ac. The evaporation residues were separated in-flight by the gas-filled recoil separator SHANS in Lanzhou and subsequently identified by the α-α position and time correlation method. The α-decay energy and half-life of ^{205}Ac were determined to be 7.935(30) MeV and 20^{+97}_{-9} ms, respectively. Previously reported decay properties of the ground state in ^{206}Ac were confirmed.

In Refs. [16,17], a new version of the Geiger-Nuttall law including the quantum numbers of α-core relative motion was proposed, which reproduces the α-decay half-lives of heavy nuclei with $N \leqslant 126$ very well. In Fig. 3(b), a calculation using this law is carried out for the favored α-decay transitions, and the results are compared with experimental values. The calculated 15-ms half-life of ^{205}Ac is in good agreement with the value measured in the present experiment.

The calculated half-life (15 ms) with the new Geiger-Nuttall law [16,17] agrees well with the measured data (20 $^{+97}_{-9}$ms).

[16] Yuejiao Ren and Zhongzhou Ren, Phys. Rev. C **85**, 044608 (2012).

[17] Yuejiao Ren and Zhongzhou Ren, Nucl. Sci. Tech. **24**, 050518 (2013), http://www.j.sinap.ac.cn/nst/EN/Y2013/V24/I5/50518.

三. 小 结

首先，回顾了国内外核集团态理论研究的一些新成果，特别是发表在Nature和PRL上的重要论文。

对原子核集团态的研究少，国内2013.6-2014.7有三篇关于集团态的PRL论文（轻核区集团态）。还回顾了重核的alpha衰变和集团放射性等的模型,209Bi。

不稳定原子核做为复杂的量子多体系统，会有不少结团有关新现象和新规律有待研究。

谢谢各位同行！

祝愿 兰州大学核学院更大发展！

南京大學
Nanjing University

原子核结团研究新进展

任中洲

南京大学 物理学院

2017年4月27日， 兰州大学 核学院

Microscopic calculation of preformation factor in a two level model

Ren and Xu, PRC 36, 456,1987…

PHYSICAL REVIEW C VOLUME 36, NUMBER 1 JULY 1987

Reduced alpha transfer rates in a schematic model

Ren Zhong-zhou and Xu Gong-ou
Department of Physics, Nanjing University, Nanjing, China
(Received 27 January 1987)

The reduced alpha transfer rates are studied microscopically with a schematic model. Results for ground state to ground state alpha transfer reactions are given.

Outline

(1) A brief review of researches on alpha cluster …

(2) Alpha decay emitters with proton numbers 52<=Z<=118

Three typical regions of alpha emitters

"Light island" : near doubly magic nucleus ^{100}Sn

Alpha emitters: near doubly magic nuclei ^{208}Pb

"Superheavy island": next doubly magic nucleus ^{298}114?

(3) Microscopic calculations with a quartetting wave function approach

(4) Summary

任中洲，徐躬耦，PRC 36 (1987) 456

PHYSICAL REVIEW C　　VOLUME 36, NUMBER 1　　JULY 1987

Reduced alpha transfer rates in a schematic model

Ren Zhong-zhou and Xu Gong-ou
Department of Physics, Nanjing University, Nanjing, China
(Received 27 January 1987)

The reduced alpha transfer rates are studied microscopically with a schematic model. Results for ground state to ground state alpha transfer reactions are given.

The model Hamiltonian is as follows:

$$H = H_0(+) + H_0(-) + H_1(+,-) , \tag{1}$$

where

$$H_0(\pm) = \pm\epsilon A(\pm) - 2\lambda_0 \left[\sum_\alpha B_\alpha^\dagger(\sigma,\pm) B_\alpha(\sigma,\pm) + \sum_\mu B_\mu^\dagger(\tau,\pm) B_\mu(\tau,\pm) \right] , \tag{2a}$$

任中洲，徐躬耦，PRC 36 (1987) 456

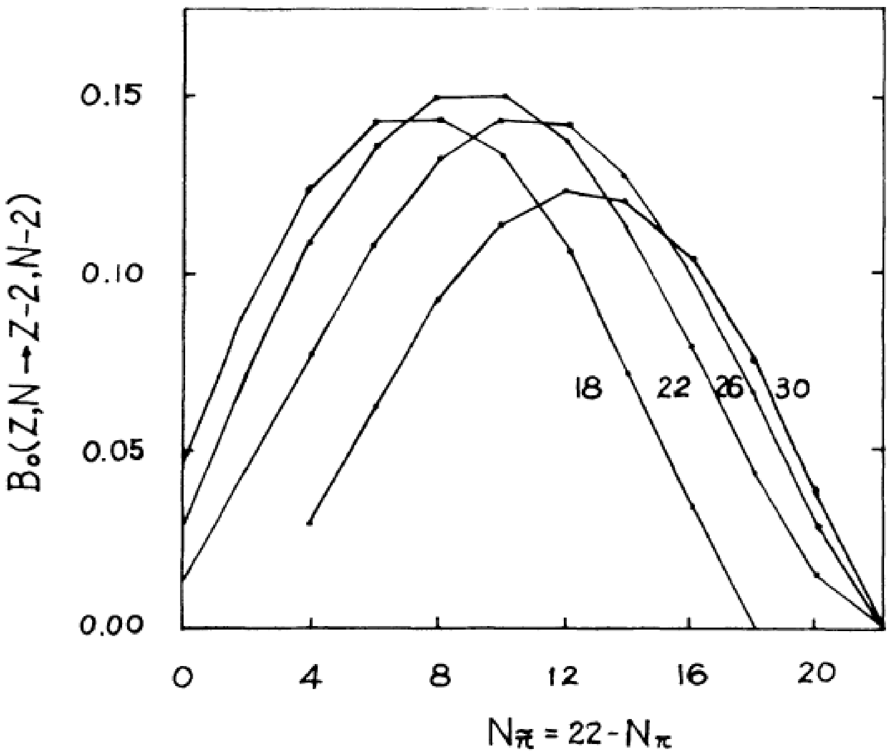

FIG. 2. Reduced α-transfer rates $B(Z,N \rightarrow Z-2,N-2)$ between ground states of nuclei with same value of $N_\nu - N_\pi$ as indicated in the figure, $N_\pi < 4l(-)+2$, $N_\nu > 4l(-)+2$. $\epsilon = 3.5$ MeV, $\lambda_0 = 1.0$ MeV, $\lambda_1 = 0.5$ MeV, $l(-)=5$, $l(+)=6$.

- 约化Alpha转移率

任中洲，徐躬耦， PRC 38 (1988) 1078

PHYSICAL REVIEW C VOLUME 38, NUMBER 2 AUGUST 1988

Evidence of α correlation from binding energies in medium and heavy nuclei

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Xu Gong-ou
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and Department of Modern Physics, Lanzhou University, Lanzhou, China

(Received 23 March 1988)

If the effect of α clustering due to the interaction of the excited correlated proton pair with correlated neutron pairs in medium and heavy nuclei were taken into consideration, quasiparticle energies would not be simply additive. The empirical values of the extra term $\delta(\alpha)$ indicate that α correlations exist to a certain extent in these nuclei.

$$\delta B = \begin{cases} \Delta & \text{even-even nuclei} \\ 0 & \text{even-odd or odd-even nuclei} \\ -\Delta & \text{odd-odd nuclei} \end{cases} \tag{3}$$

$$\delta B = \begin{cases} \Delta + \delta(\alpha) & \text{even-even nuclei} \\ 0 & \text{even-odd or odd-even nuclei} \\ -\Delta & \text{odd-odd nuclei} \end{cases} \tag{4}$$

任中洲，徐躬耦，PRC 38 (1988) 1078

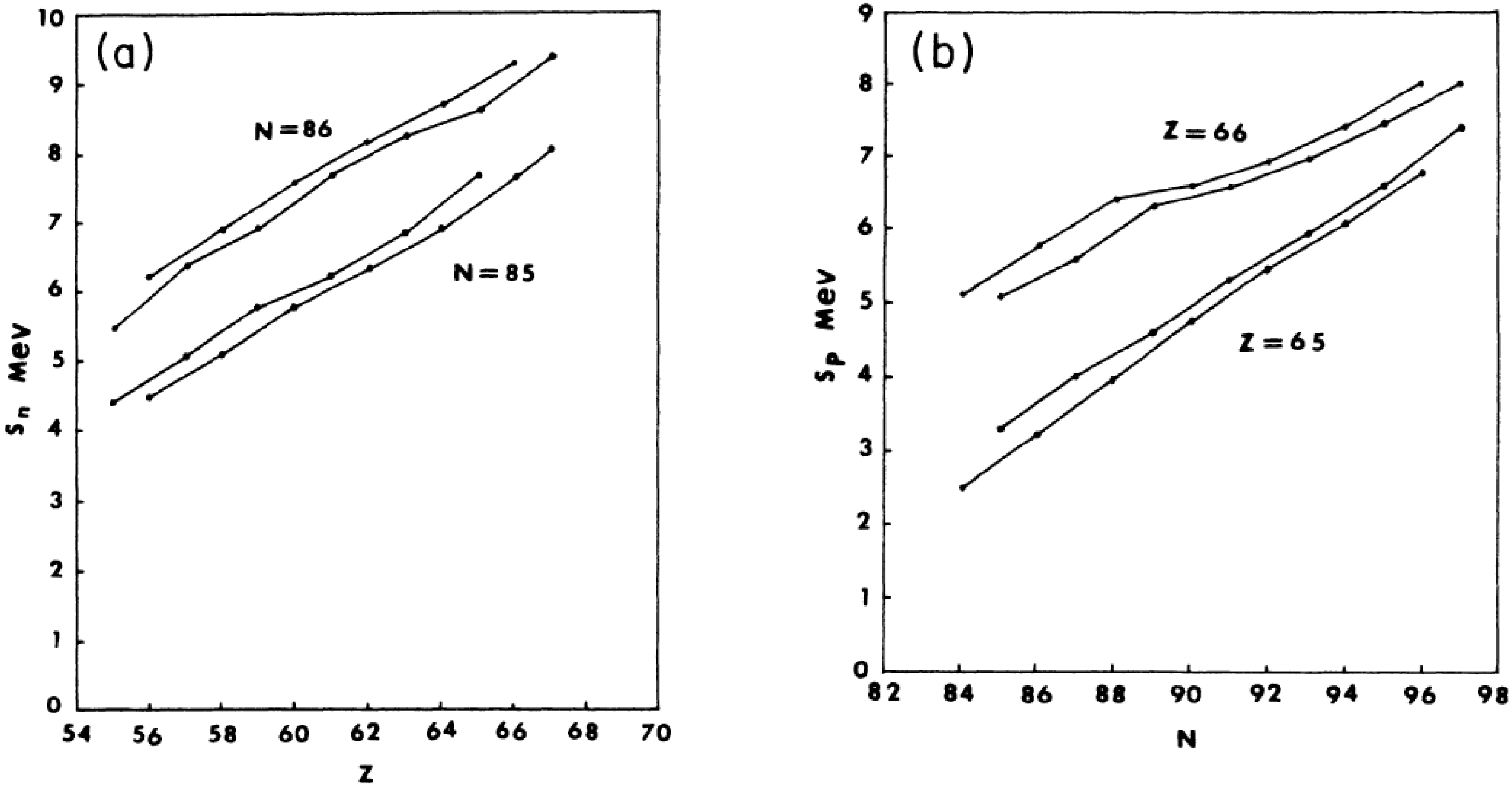

FIG. 1. (a) Neutron separation energies for nuclei with fixed *N*; (b) proton separation energies for nuclei with fixed *Z*.

任中洲，徐躬耦， JPG 15 (1989) 465

J. Phys. G: Nucl. Part. Phys. **15** (1989) 465–472. Printed in the UK

Shell and blocking effects in α-transfer reactions†

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Received 18 July 1988

Abstract. Using a two-level pairing force model and assuming that α-clustering in ground states of medium and heavy nuclei is mainly the result of configuration mixing of cross-shell excitation of correlated pairs, shell and blocking effects in α-transfer reactions can be reasonably explained.

任中洲，徐躬耦， JPG 15 (1989) 465

2. The two-level pairing force model and the reduced pair transfer rates

The two levels of the model are introduced for representing the energy levels around proton and neutron Fermi energies in neighbouring shells. Nucleons in these two levels are interacting with each other with pairing forces. The model Hamiltonian is

$$H = H_0(+) + H_0(-) + H_1(+, -) \tag{1}$$

where

$$H_0(\pm) = \pm \varepsilon N_F(\pm) - \lambda_0 \sum_{\nu=0, \pm 1} B_\nu^\dagger(\pm) B_\nu(\pm) \tag{2}$$

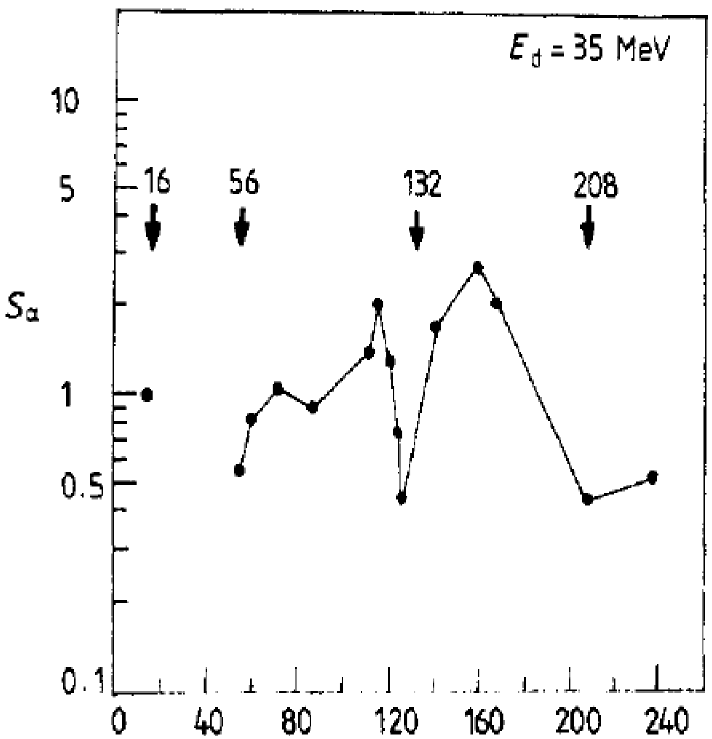
$$H_1(+, -) = -\lambda_1 \sum_{\nu=0, \pm 1} B_\nu^\dagger(+) B_\nu(-) + \mathrm{HC} \tag{3}$$

$\pm\varepsilon$ represent the single-particle energies of upper and lower levels; λ_0, λ_1 represent the intensities of pairing forces related to the same level and to different levels; and

$$N_F(\pm) = \sum_{m, m_t} a_{m, m_t}^\dagger(\pm) a_{m, m_t}(\pm) \tag{4}$$

$$B_\nu^\dagger(\pm) = \frac{1}{\sqrt{2}} [a^\dagger(\pm) a^\dagger(\pm)]_{M=0\ \ M_T=\nu}^{J=0\ \ T=1} \qquad B_\nu(\pm) = (B_\nu^\dagger(\pm))^\dagger \tag{5}$$

任中洲，徐躬耦， JPG 15 (1989) 465



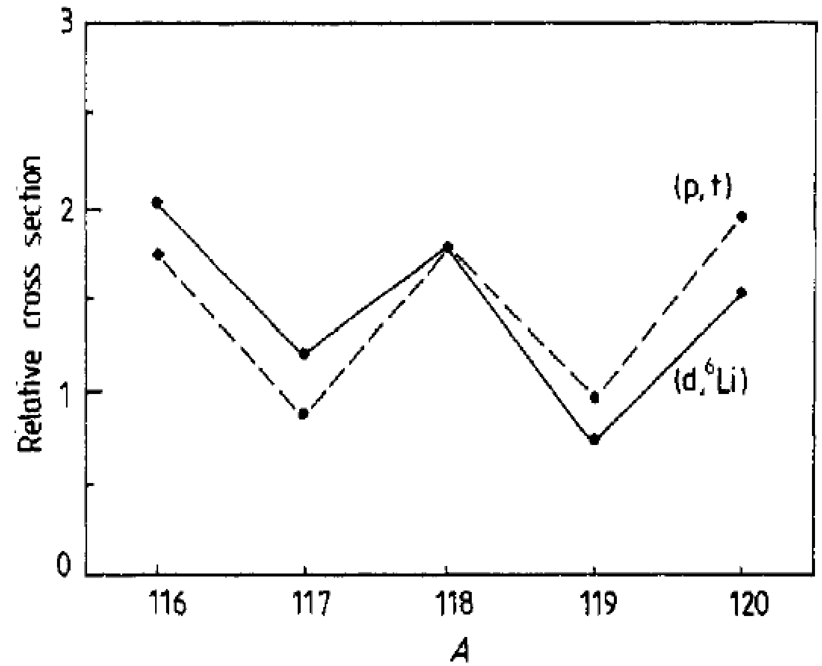
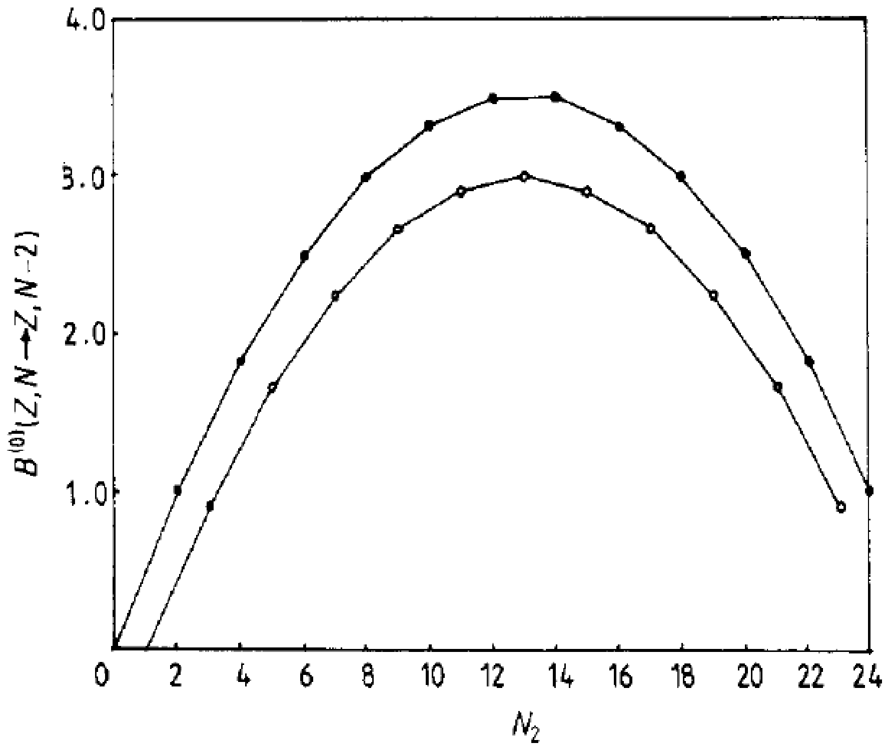


Figure 1. Alpha-particle spectroscopic factor S_α obtained from analysis of (d, Li) reactions normalised to unity at ^{16}O and plotted as a function of target mass (Becchetti *et al* 1975 *Phys. Rev. Lett.* **34** 225).

Figure 2. Comparison between the relative cross section of (p, t) and (d, Li) reactions as a function of *A* for some tin isotopes (Becchetti *et al* 1975 *Phys. Rev. Lett.* **35** 268).

任中洲，徐躬耦， JPG 15 (1989) 465



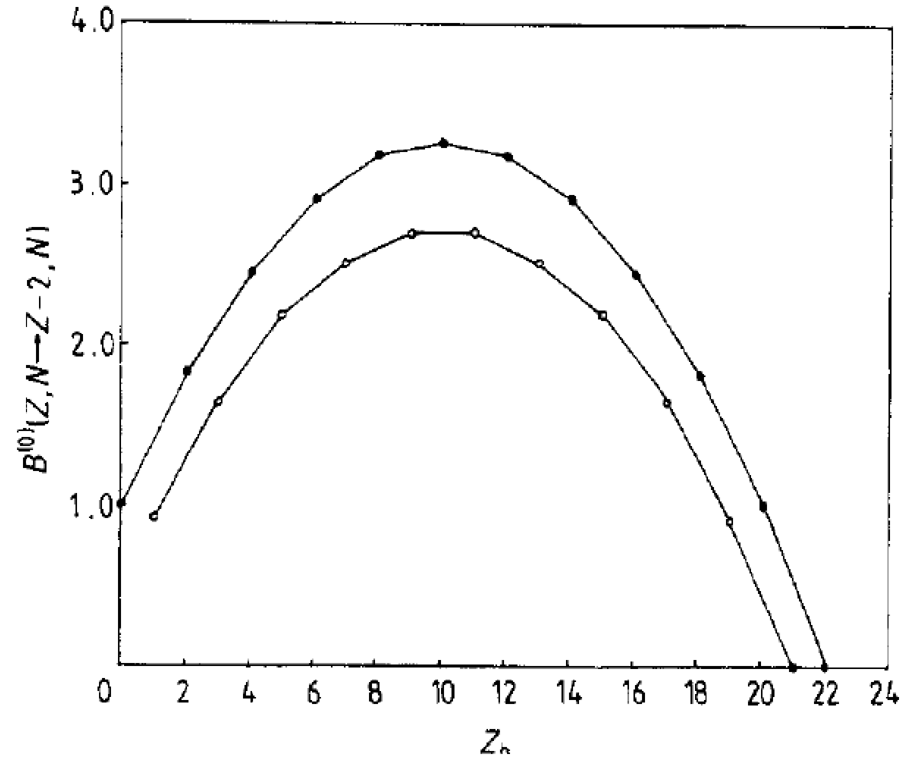
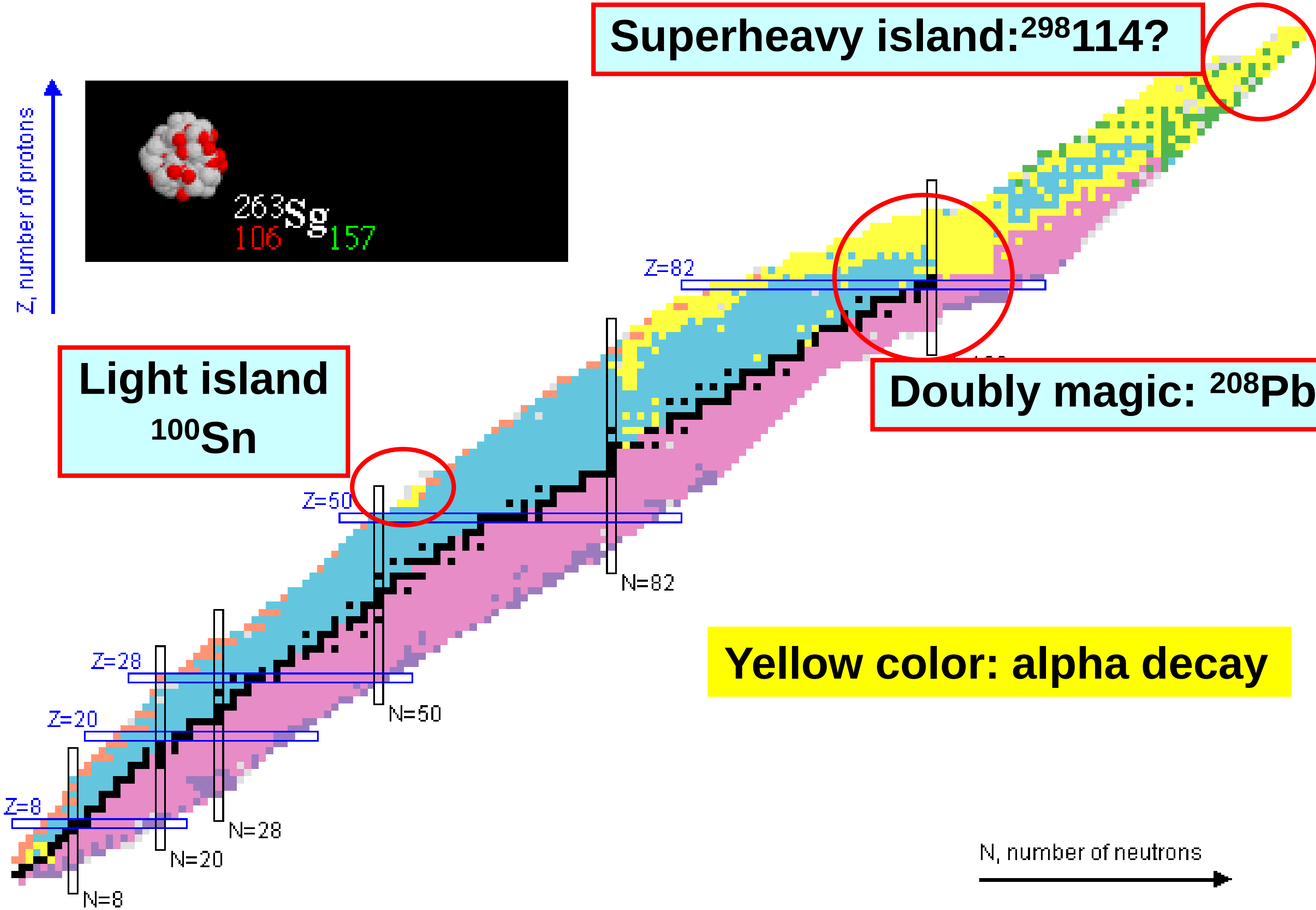


Figure 3. Reduced neutron-pair transfer rates $B^{(0)}(Z, N\rightarrow Z, N-2)$ as a function of N_2 for $Z<\Omega_1$: ○, odd N; ●, even N.

Figure 4. Reduced proton-pair transfer rates $B^{(0)}(Z, N\rightarrow Z, N-2, N)$ as a function of Z_h for $N>\Omega_1$: ○, odd Z; ●, even Z.

(1) A brief review of alpha cluster decay

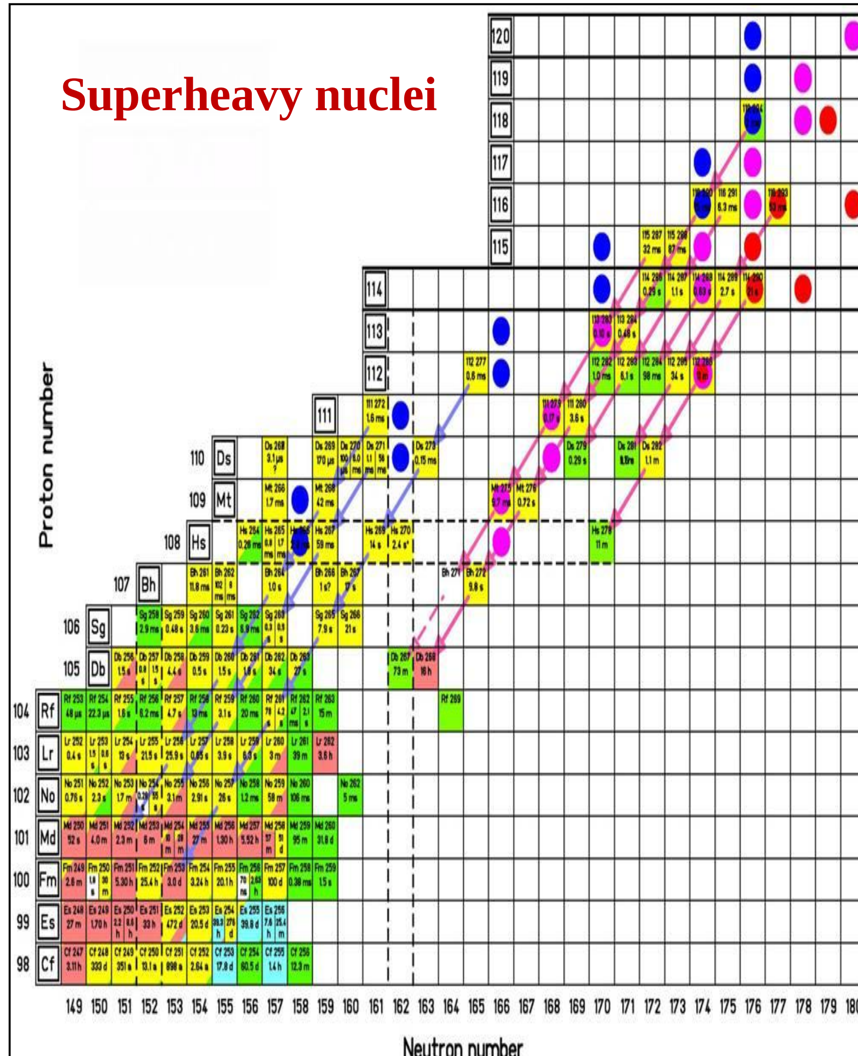


(1) A brief review of alpha cluster decay

- **Alpha decay: an old problem with renewed interest in recent years, still not fully solved**

- **Nuclear properties:**
  - ➢ **Energy and Lifetime**
  - ➢ **Spin and parity**
  - ➢ **Nuclear interaction**
  - ➢ **Shell effect**
  - ➢ **Superheavy nuclei**

- **Alpha clustering (most difficult)**



Alpha decay : theoretical calculations

1. Phenomenological Formulas:

(1) The Geiger-Nuttall law

(2) The Viola-Seaborg formula

(3) Other alpha-decay formulas

2. Theoretical Approaches:

(1) Shell model

(2) Cluster model

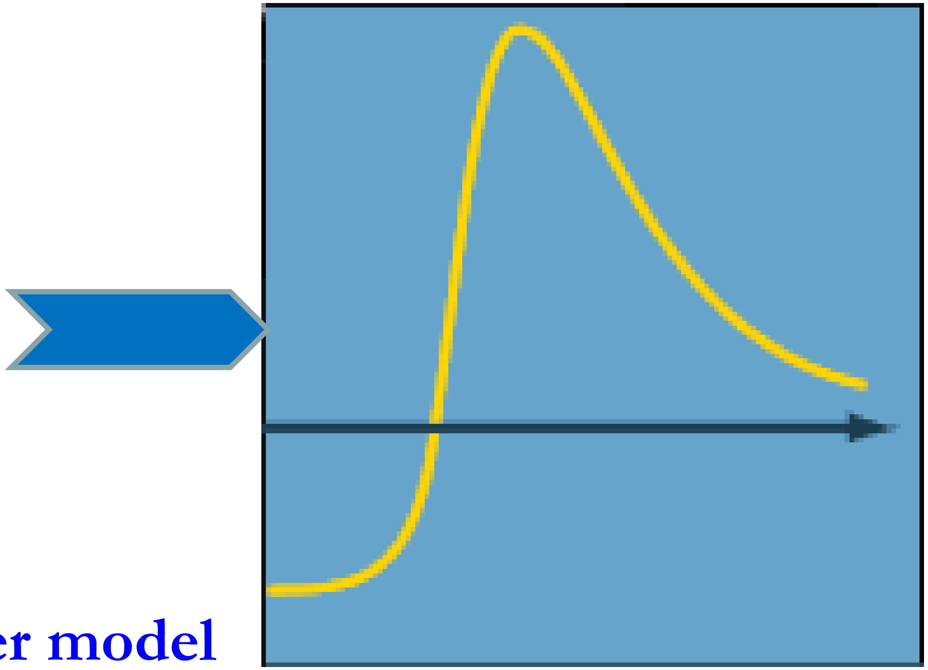
(3) Fission-like model

(4) A mixture of shell and cluster model

(5) A density-dependent cluster model

(6) A quartetting wave function approach

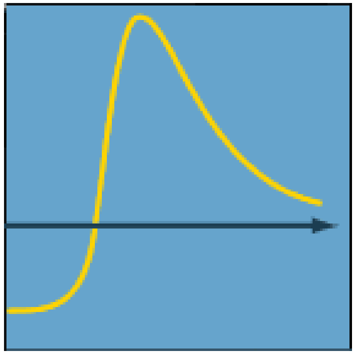
(7) ……



Alpha-decay theory in nuclear textbooks

(1) Preformation probability
(2) Frequency
(3) Penetration probability

p_α, ν, and $\mathcal{T}$



Energy and mass dependence. Using p_α, ν, and $\mathcal{T}$ obtained above, we can write the transition probability as

$$\mathcal{W} = p_\alpha \nu \mathcal{T}$$

To put this expression into a form so that it can be compared with the Geiger-Nuttall law of Eq. (4-61), we take the logarithm in the base 10 for both sides and obtain the result

$$\begin{aligned} \log_{10} \mathcal{W} &= \log_{10} p_\alpha + \log_{10} \nu + \log_{10} \mathcal{T} \\ &= 20.46 + \log_{10} \frac{\sqrt{E_\alpha}}{A^{1/3}} + 1.42\sqrt{ZA^{1/3}} - 1.72\frac{Z}{\sqrt{E_\alpha}} \end{aligned} \quad (4\text{-}65)$$

The dominant energy dependence comes from the last term, in agreement with the empirical result of the Geiger-Nuttall law.

Alpha-decay theory in textbooks

(1)Preformation probability (open problem)

The probability W for α-particle emission from a heavy nucleus by tunneling may be separated into a product of three factors. The first is the probability p_α to find an α-particle inside the nucleus. In a heavy nucleus, there is a good chance for two protons and two neutrons to form an α-like entity. We shall call such an object an α-cluster. However, this is only one of the many possible components of the wave function for such a nucleus. As a result, it is not easy to make an estimate for the value of p_α. A crude way is to say that it must be essentially of the same order of magnitude for all heavy nuclei, as there are only small fractional differences in their masses and we shall take $p_\alpha \sim 0.1$ as a rough guide.

This is only a rough guide!!!

Phenomenological

Alpha-decay theory in textbooks

(2) Frequency (Pre-exponential factor)

Once an α-cluster is formed inside the nucleus, it must come to the surface before it can tunnel through the barrier. The frequency ν with which it appears at the edge of the potential well depends on the velocity v it travels and the size of the potential well. A reasonable way to estimate ν is to take the well size as twice the nuclear radius R. With this assumption we obtain the result,

$$\nu = \frac{v}{2R} = \frac{\sqrt{2K/M_\alpha}}{2R}$$

Phenomenological

where K is the kinetic energy of the α-cluster inside the well and M_α its mass. The precise value of K depends on the depth of the potential well and is not well known.

$E_\alpha = 5.6$ MeV. It is about an order of magnitude larger than the best values deduced from measurements. Part of the reason for the poor agreement comes from the fact that heavy nuclei do not have the simple spherical shape assumed here. Furthermore, the replacement of K by E_α may also have cost some loss of accuracy.

Microscopic calculation of "frequency"

VOLUME 59, NUMBER 3 PHYSICAL REVIEW LETTERS 20 JULY 1987

Decay Width and Shift of a Quasistationary State

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and

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The Hebrew University of Jerusalem, 91904 Jerusalem, Israel

The decay width of a metastable state in the quasiclassical limit was found long ago by Gamow.[3] Even in this treatment the preexponential factor appearing in the width formula was hard to estimate except for the case of high-lying states. Since then, little progress has been made towards finding a general formula that embodies the quasiclassical result of Gamow including the energy shift in closed form.

$$N = \left[\int_{r_0}^{r_1} \frac{1}{p(r)} \cos^2 \left[\int_{r_0}^{r} p(r')dr' - \frac{\pi}{4} \right] dr \right]^{-1} . \qquad (3.7)$$

If the contribution from the classically forbidden regions is not small, these regions should also be taken into account in Eq. (3.7). Substituting Eq. (3.6) into Eqs. (3.3) and (3.4) we obtain for the quasiclassical width and shift

$$\Gamma = \frac{\hbar^2 N}{4m} \exp \left[-2 \int_{r_1}^{r_2} |p(r)| \, dr \right] , \qquad (3.8)$$

Frequency
Vs
Well defined
pre-factor

For the high-lying states where $\varphi_0(r)$ oscillates strongly, one can replace the cosine term in Eq. (3.7) by $\frac{1}{2}$. Then

$$N^{-1} = \frac{1}{2m} \int_{r_0}^{r_1} \frac{m}{p(r)} dr = \frac{T\hbar}{4m} , \qquad (3.10)$$

where T is the classical period of motion. Substituting Eq. (3.10) into Eq. (3.8) we obtain the famous Gamow formula for the width of the quasistationary state with preexponential Gamow factor $\hbar/T$. However, our prefactor factor $N\hbar^2/4$ in Eq. (3.8) is more general and can also be used as soon as the quasiclassical approximation is applicable to the bound-state wave function in a classically forbidden region, which is correct even for low-lying bound states.

Alpha-decay theory in textbooks

(3) Exponential factor

$$\Gamma = \nu \times \mathcal{T} = \frac{4\hbar^2\alpha^2}{\mu k}|\Phi(r_{\text{sep}})\chi_k(r_{\text{sep}})|^2,$$

to calculate. In this limit, $\kappa b \to \infty$, and $\sinh \kappa b \longrightarrow e^{\kappa b}$. The transmission coefficient in Eq. (4-62) simplifies to the form

$$\mathcal{T} \longrightarrow e^{-2\kappa b} \tag{4-63}$$

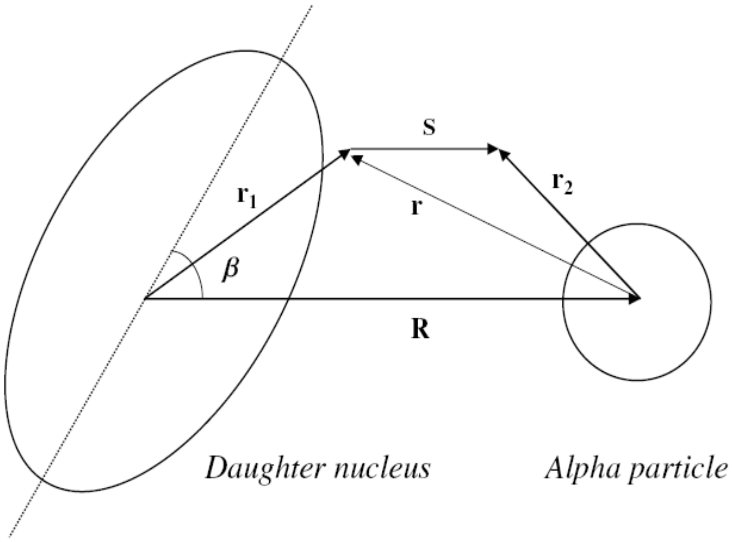
The factor $e^{-\kappa b}$ expresses the attenuation of the amplitude of the wave in going through the barrier, and it is quite reasonable to expect that the transmission coefficient is essentially given by the square of this factor. For our case of $V_0 \approx 30$ MeV and E_α in

The form of the solution, however, remains very similar to that given in Eq. (4-63) if we make the replacement

$$\kappa b \longrightarrow \int_R^{R_1} \sqrt{\frac{2\mu}{\hbar^2}}\left\{V_b(r) - E_\alpha\right\}^{1/2} dr$$

A density-dependent cluster model: all alpha emitters

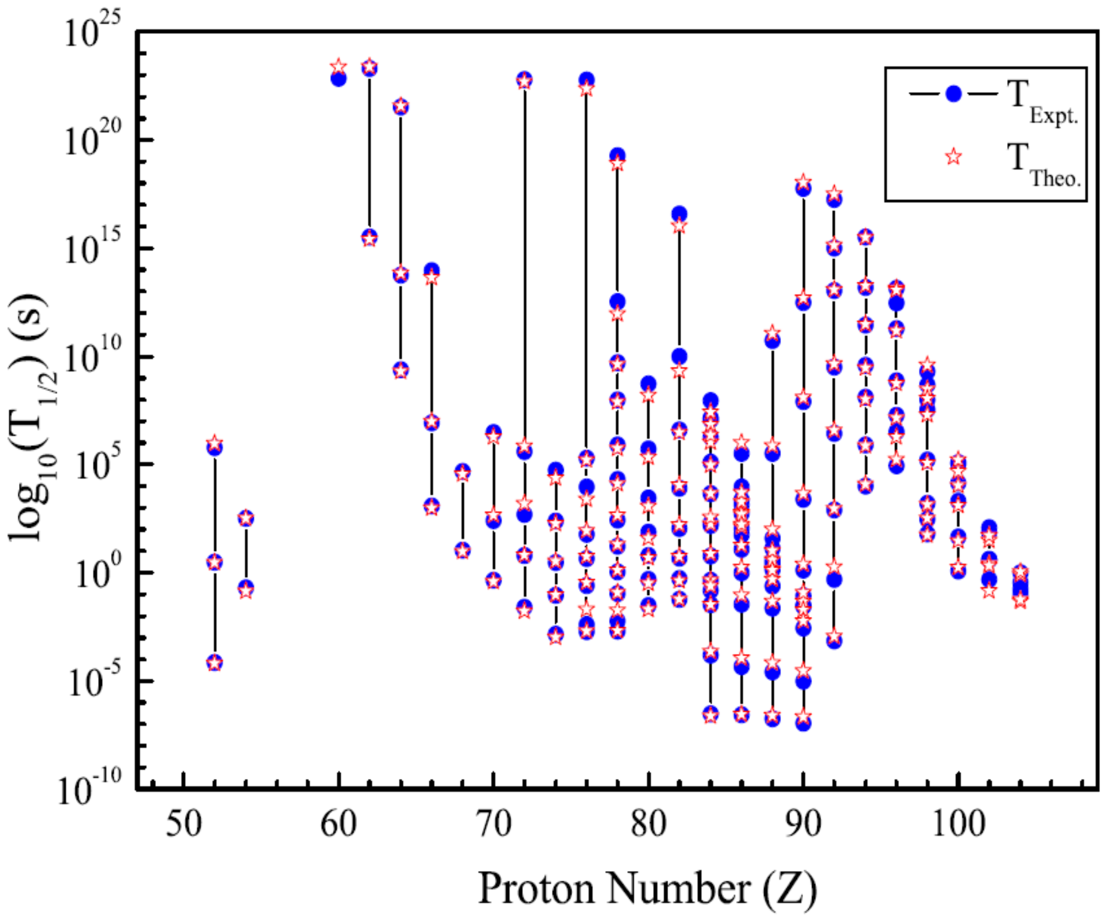
Preformation probability
Pre-exponential factor
Exponential factor



p_{α}, ν, and $\mathcal{T}$

- **Potential with doubly folding procedure**
- **Finite-size of the alpha particle and core**
- **Nuclear deformation**
- **Centrifugal potential**
- **Bohr-Sommerfeld quantization condition**
- **……**

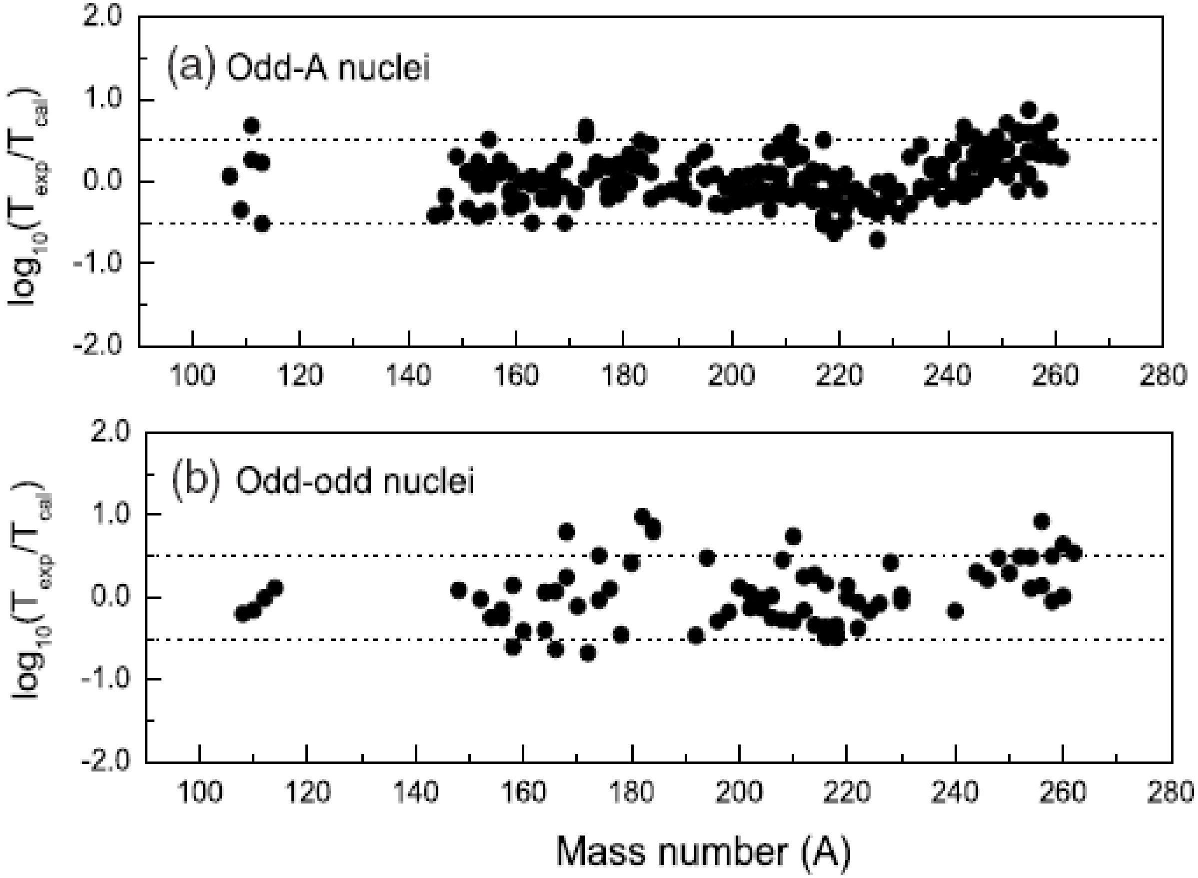
Alpha-decay half-lives of even-even nuclei of ground-state transitions (Z=52-104)



Circles : Experiment

Stars : Theory

The factor of agreement for odd nuclei of ground-state transitions (Z=52-105)



Circles :

HF=Texp / Tcal between experiment and theory

TABLE I. Comparison of average and rms deviations of DDCM and GLDM.

Nuclide	Number	Average deviation	rms deviation
Even-even	157 (131)	0.209	0.267(0.35)
Odd-*A*	231 (192)	0.229	0.285(0.57/0.71)
Odd-odd	79 (50)	0.318	0.435(0.99)

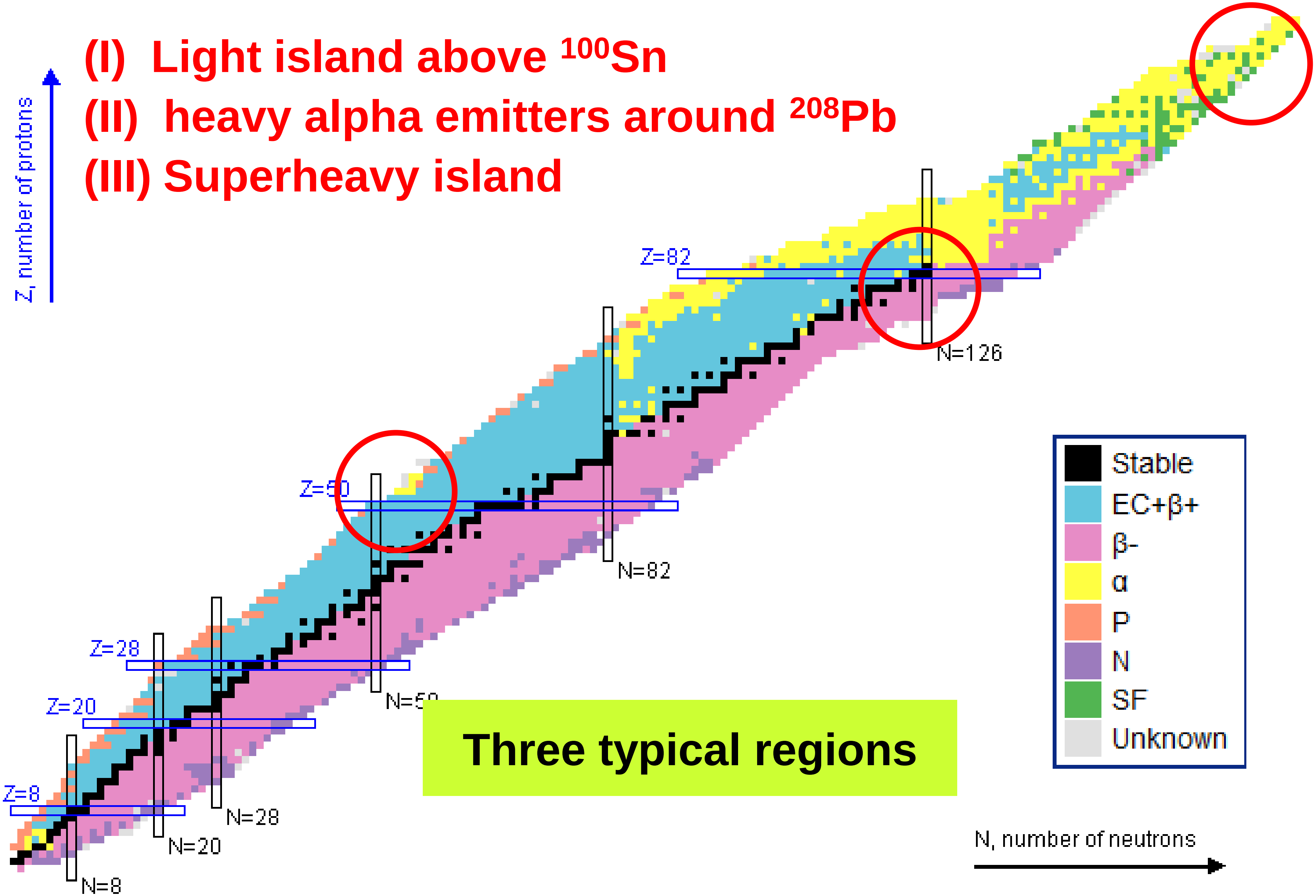
To further improve the agreement, microscopic calculations of preformation factors are needed.

A constant alpha preformation factor is OK for open shell nuclei, but not for shell region nuclei!

(I) Light island above ^{100}Sn

(II) heavy alpha emitters around ^{208}Pb

(III) Superheavy island



Three typical regions

(I) Light island: Theory and Experiment

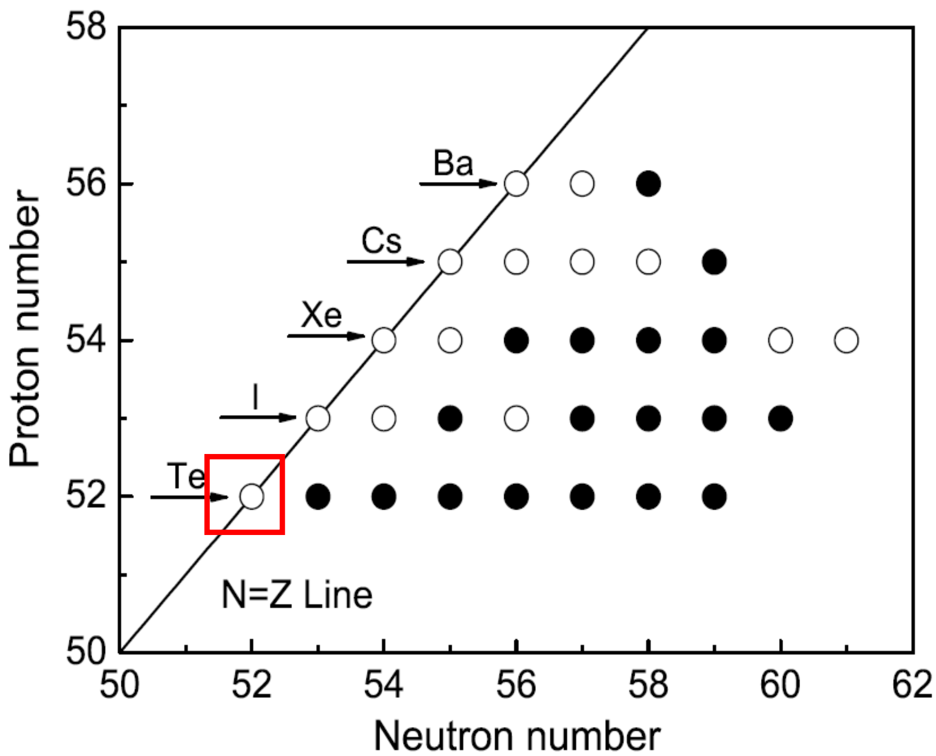


FIG. 1: Alpha emitters close to the N=Z line.

^{104}Te: alpha particle on top of doubly magic core ^{100}Sn

α decay of ^{105}Te

PHYSICAL REVIEW C **73**, 061301(R) (2006)

closest to the N=Z line

Extrapolated alpha-decay energy for ^{104}Te

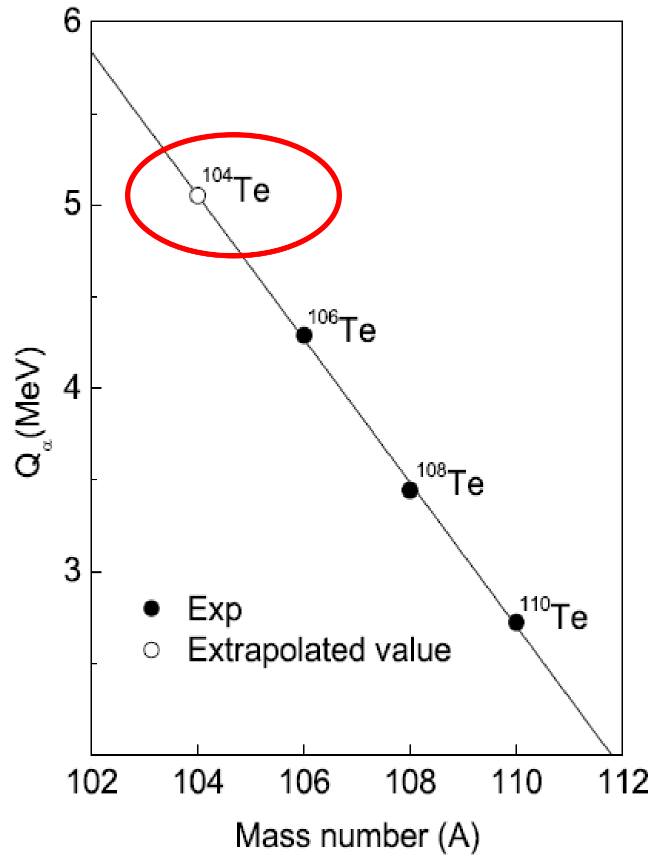
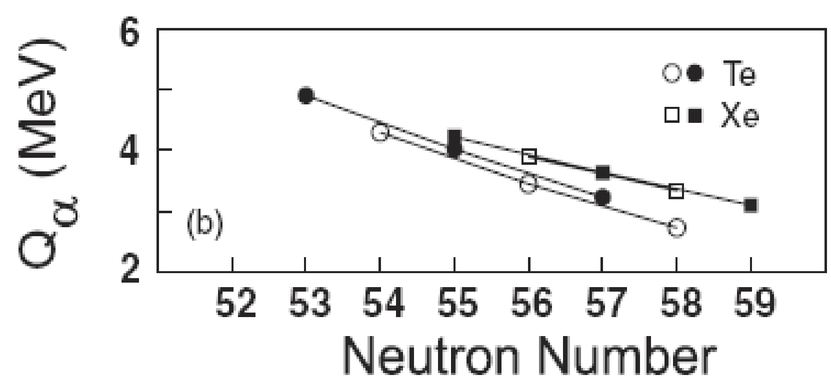


FIG. 2: Extrapolation of α-decay energy for ^{104}Te.

Nuclei	Q_α(MeV)
$^{104}Te \rightarrow ^{100}Sn + \alpha$	5.053*
$^{105}Te \rightarrow ^{101}Sn + \alpha$	4.900
$^{106}Te \rightarrow ^{102}Sn + \alpha$	4.290
$^{107}Te \rightarrow ^{103}Sn + \alpha$	4.008
$^{108}Te \rightarrow ^{104}Sn + \alpha$	3.445
$^{109}Te \rightarrow ^{105}Sn + \alpha$	3.230
$^{110}Te \rightarrow ^{106}Sn + \alpha$	2.723
$^{111}Te \rightarrow ^{107}Sn + \alpha$	2.576



Preformation probability: important

of α clusterization in the DDCM. Delion and co-workers systematically analyzed the α-clustering effect in heavy and superheavy nuclei [6,7] and they pointed out the suppression of the α-clusterization process with increasing proton-neutron asymmetry along the isotopic chains [7]. To improve the agreement between experiment and theory, we therefore use the isospin-dependent preformation factor $P_\alpha = c_1 + c_2(N - Z)$ instead of the constant one [19] for each kind of nuclei [e.g., a linear dependence $P_\alpha^{ee} = 0.73 - 0.09 \times (N - Z)$ for the even-even nuclei]. As expected, the corresponding theoretical lifetimes [T_α(Cal2)] show a significantly better agreement with the experimental data. The root-mean-square deviation is reduced from 0.319 to 0.242 for the available α-emitters. Thus

(II) Shape Coexistence : Pb and Po isotopes

Preformation factor is also important!

letters to nature

A triplet of differently shaped spin-zero states in the atomic nucleus ^{186}Pb

A. N. Andreyev*, M. Huyse*, P. Van Duppen*, L. Weissman*, D. Ackermann†, J. Gerl†, F. P. Heßberger†, S. Hofmann†, A. Kleinböhl†, G. Münzenberg†, S. Reshitko†, C. Schlegel†, H. Schaffner†, P. Cagarda‡, M. Matos‡, S. Saro‡, A. Keenan§, C. Moore§, C. D. O'Leary§, R. D. Page§, M. Taylor§, H. Kettunen‖, M. Leino‖, A. Lavrentiev¶, R. Wyss# & K. Heyde☆

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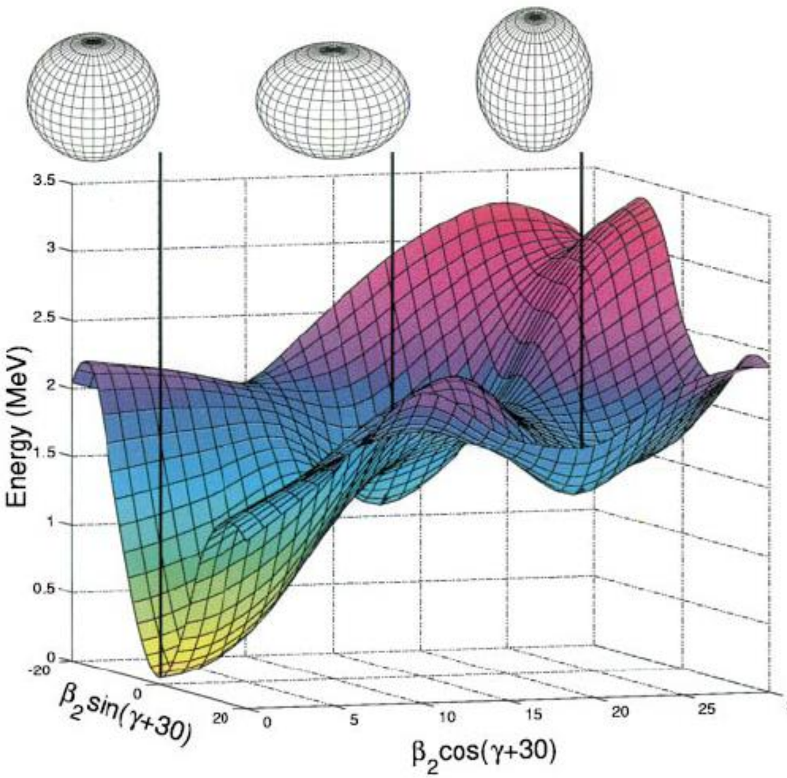
† Gesellschaft fur Schwerionenforschung Darmstadt, Postfach 110541, D-6100 Darmstadt, Germany
‡ Department of Nuclear Physics, Comenius University, Bratislava, Slovakia
§ Department of Physics, Oliver Lodge Laboratory, University of Liverpool, Liverpool L69 7ZE, UK
‖ Department of Physics, University of Jyväskylä, FIN-40351 Jyväskylä, Finland
¶ Flerov Laboratory of Nuclear Reactions, Joint Institute for Nuclear Research, 141980 Dubna, Russia
 # Department of Physics, Royal Institute of Technology, 104 05 Stockholm, Sweden, and Department of Technology, Kalmar University, Box 905, 391 29 Kalmar, Sweden
☆ Vakgroep Subatomaire en Stralingsfysica, Institute for Theoretical Physics, B-9000 Gent, Belgium



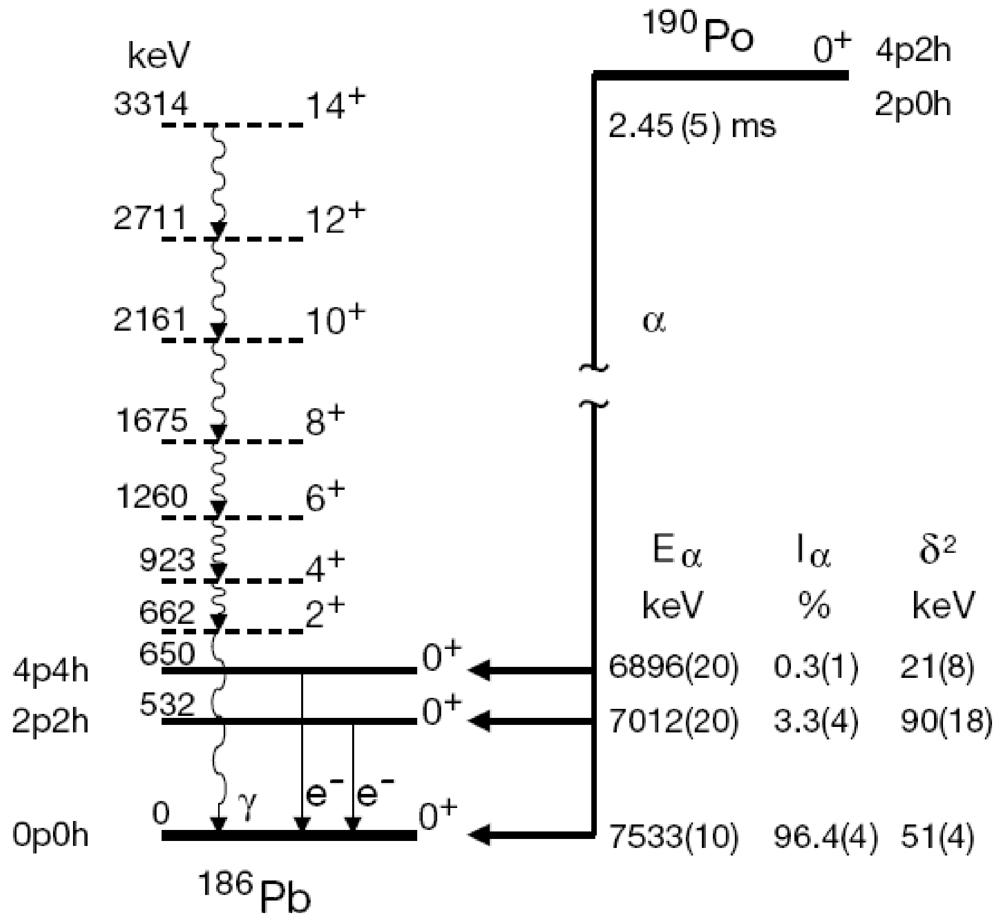
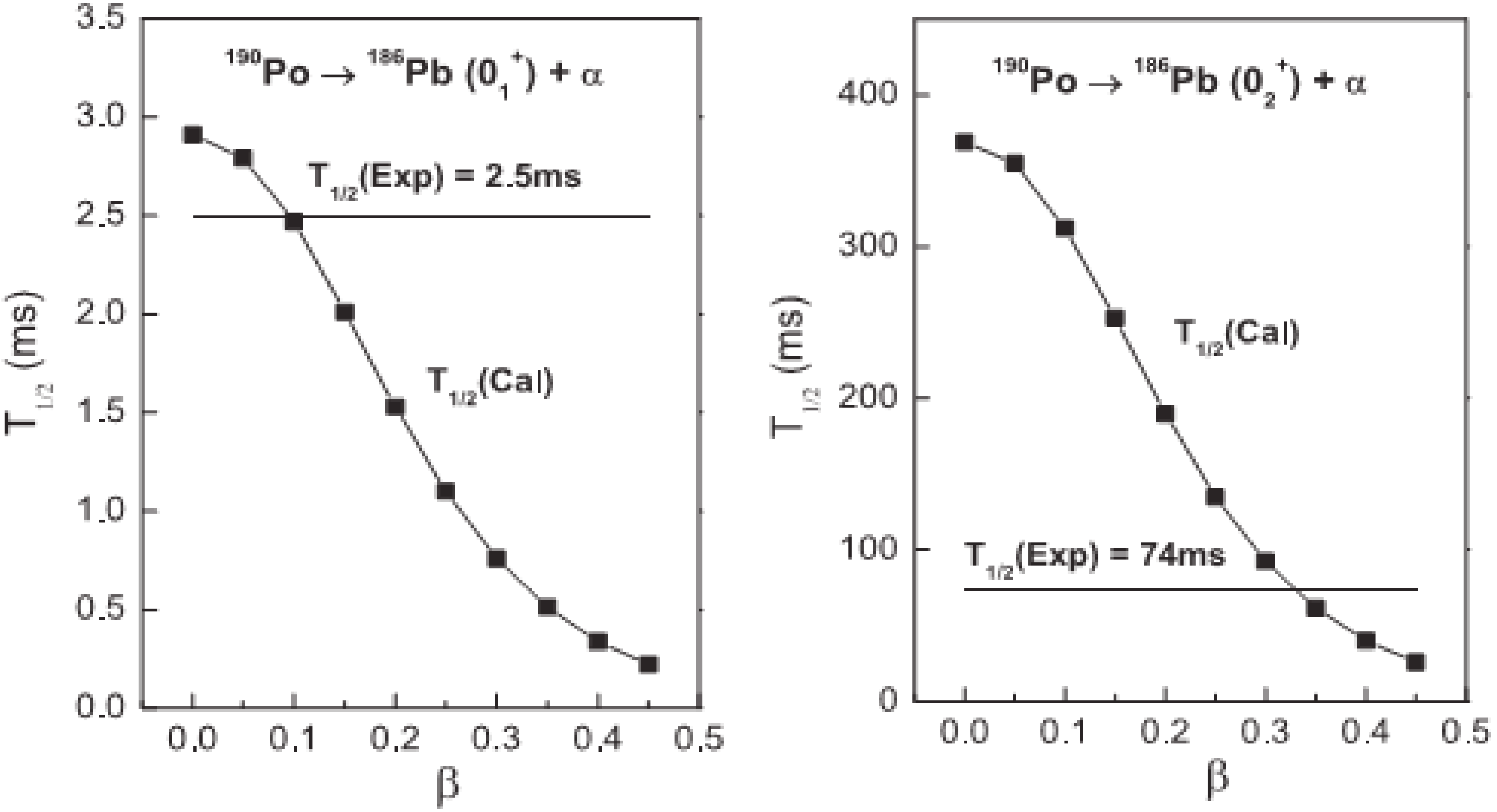


Figure 4 The decay pattern of ^{190}Po and the level scheme of ^{186}Pb. Indicated are α-decay energies E_α, intensities I_α, reduced α-widths δ^2, and configuration assignments. As

Alpha-transitions to coexisting 0+ states



Preformation probability: important

are involved. This is also evidenced by our previous analysis of α-decay branching ratios where the excitation probabilities of the daughter nucleus after disintegration were found to obey the Boltzmann distribution approximately [36]

$$w_\ell(\mathrm{E}_\ell^*) = \exp[-c\mathrm{E}_\ell^*], \quad (9)$$

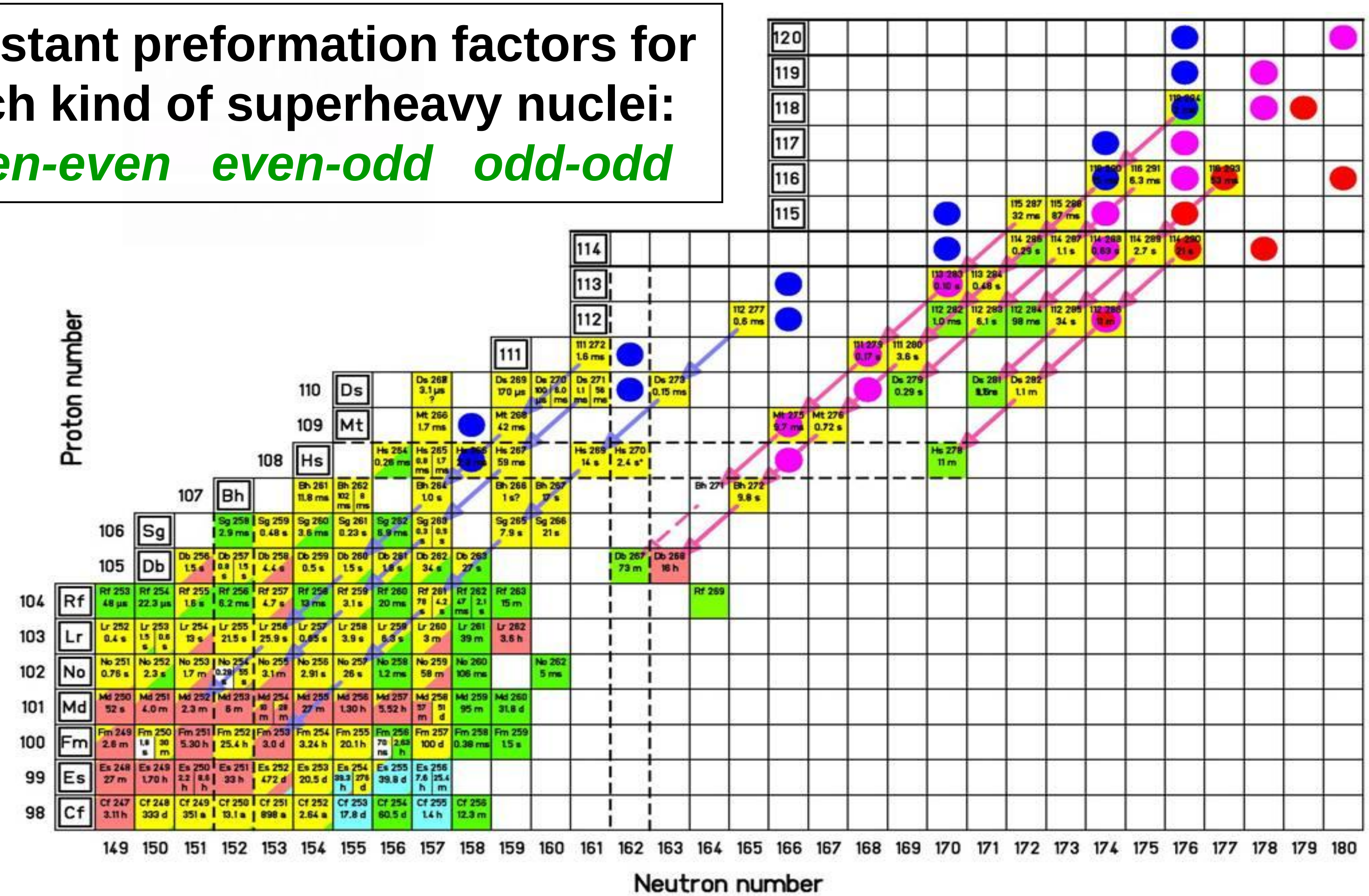
where E_ℓ^* is the excitation energy of ℓ state in the daughter nucleus and c is a free parameter. The excitation probability

α-decay branching ratios [36]. In present study, we describe the α-cluster preformation probabilities for different α-transitions by the product of the constant formation factor and the Boltzmann distribution function $[\mathrm{P}_\alpha \times w_\ell(\mathrm{E}_\ell^*)]$. It is easy to find that the preformation factor of the α-particle is fixed to a constant value of 0.38 for the ground-state transitions ($0^+ \rightarrow 0_1^+$). For α-transitions to the excited 0^+ states, a smaller value

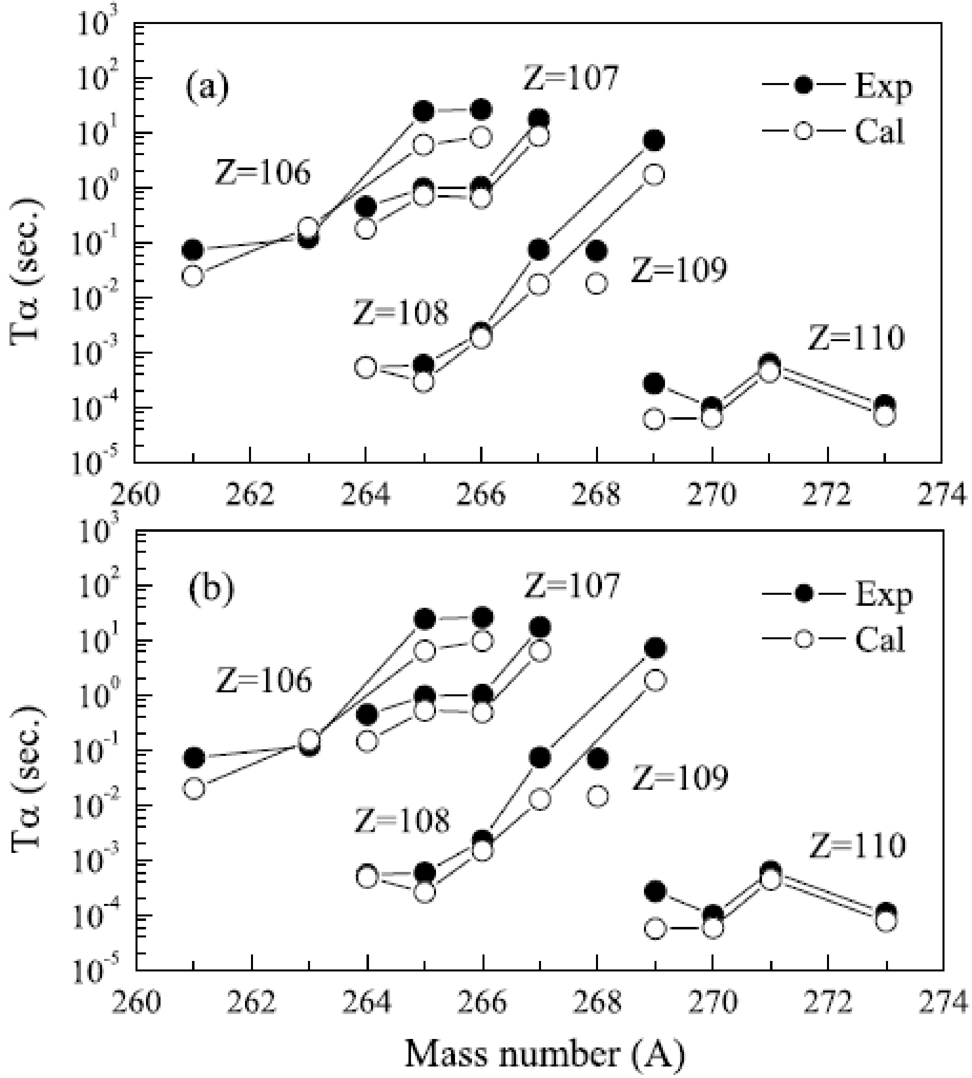
(III) Superheavy island: Theory and Experiment

Constant preformation factors for each kind of superheavy nuclei:

even-even even-odd odd-odd



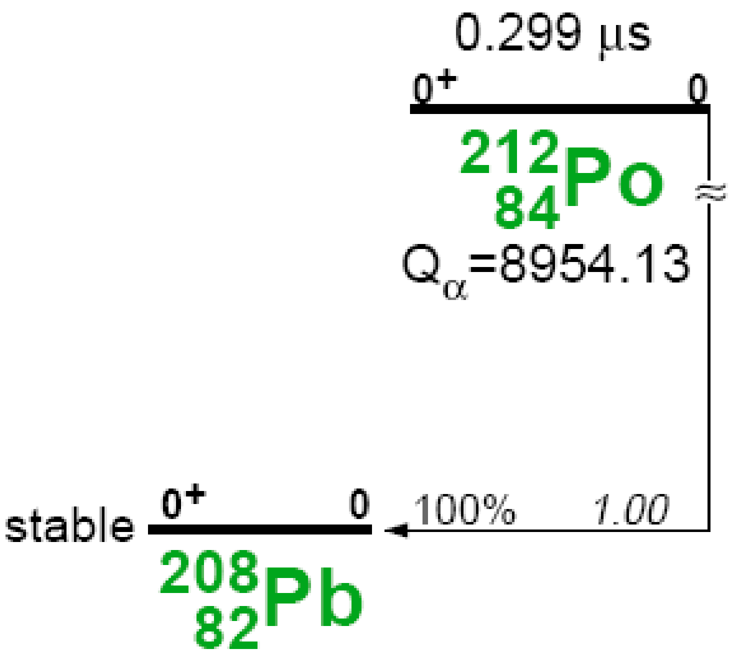
The experimental and calculated alpha-decay half-lives of nuclei with Z=106-110



Deformation: the macroscopic-microscopic model (MM)

Deformation: RMF

Preformation probability and Penetration probability of ^{212}Po



Spherical
Doubly magic
Only one decay channel
Accurate experimental data
……

Microscopic calculation of the preformation and penetration probability simultaneously

Alpha decay: a quartetting wave function approach

PHYSICAL REVIEW C **93**, 011306(R) (2016)

α-decay width of ^{212}Po from a quartetting wave function approach

Chang Xu,[1,*] Zhongzhou Ren,[1,2,†] G. Röpke,[3,‡] P. Schuck,[4,5,§] Y. Funaki,[6] H. Horiuchi,[7,8] A. Tohsaki,[7] T. Yamada,[9] and Bo Zhou[10]

[1]*Department of Physics and Key Laboratory of Modern Acoustics, Nanjing University, Nanjing 210093, China*
[2]*Center of Theoretical Nuclear Physics, National Laboratory of Heavy-Ion Accelerator, Lanzhou 730000, China*
[3]*Institut für Physik, Universität Rostock, D-18051 Rostock, Germany and National Research Nuclear University (MEPhI), 115409 Moscow, Russia*
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[5]*Laboratoire de Physique et Modélisation des Milieux Condensés, CNRS- UMR 5493, F-38042 Grenoble Cedex 9, France*
[6]*RIKEN Nishina Center, Wako 351-0198, Japan*
[7]*Research Center for Nuclear Physics (RCNP), Osaka University, Osaka 567-0047, Japan*
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[10]*Faculty of Science, Hokkaido University, Sapporo 060-0810, Japan*

A microscopic calculation of α-cluster preformation probability and α-decay width in the typical α emitter ^{212}Po is presented. Results are obtained by improving a recent approach to describe α preformation in ^{212}Po [Phys. Rev. C **90**, 034304 (2014)] implementing four-nucleon correlations (quartetting). Using the actually measured density distribution of the ^{208}Pb core, the calculated α-decay width of ^{212}Po agrees fairly well with the measured one.

PHYSICAL REVIEW C **93**, 011306(R) (2016) **RAPID COMMUNICATIONS**

α-decay width of ^{212}Po from a quartetting wave function approach

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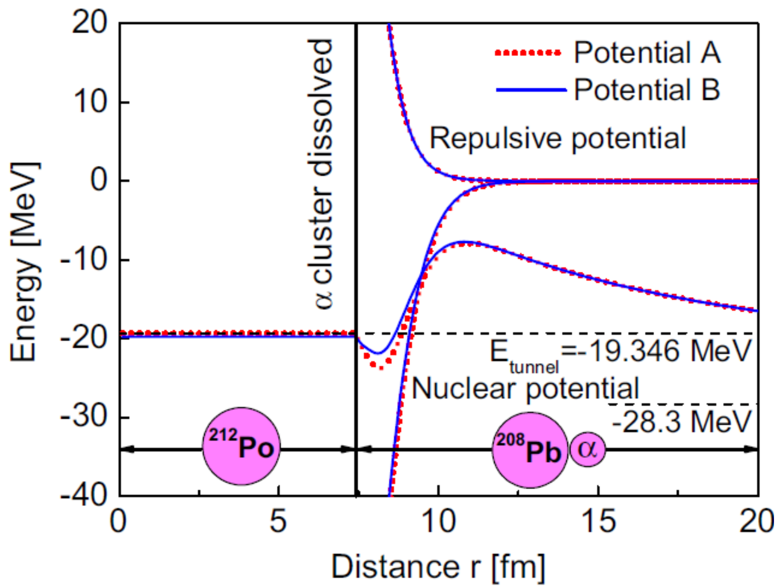

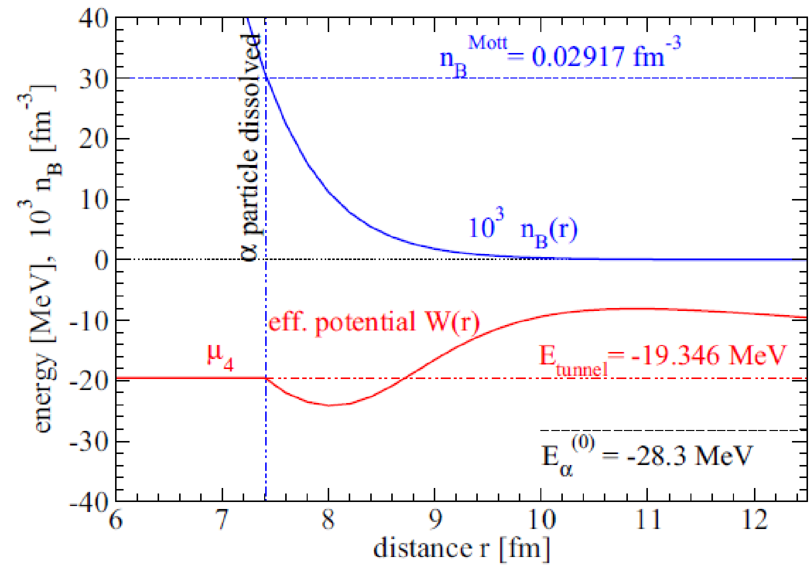

Potential A: Thomas-Fermi model for the core region.

Potential B: Discrete energy level structure of the core nucleus.

$$P_\alpha = \int_0^\infty d^3r |\Phi(r)|^2 \Theta[n_B^{\text{Mott}} - n_B(r)].$$

$$\Gamma = \nu \times \mathcal{T} = \frac{4\hbar^2\alpha^2}{\mu k} |\Phi(r_{\text{sep}})\chi_k(r_{\text{sep}})|^2,$$

PHYSICAL REVIEW C **93**, 011306(R) (2016) RAPID COMMUNICATIONS

α-decay width of ^{212}Po from a quartetting wave function approach

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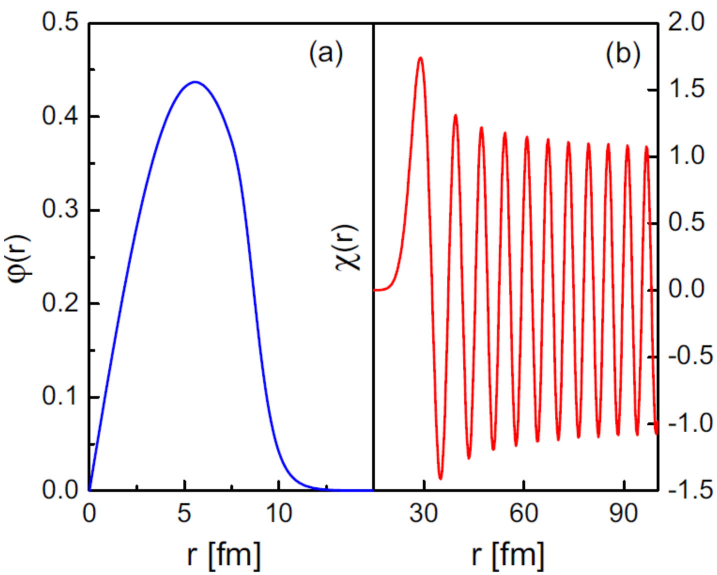

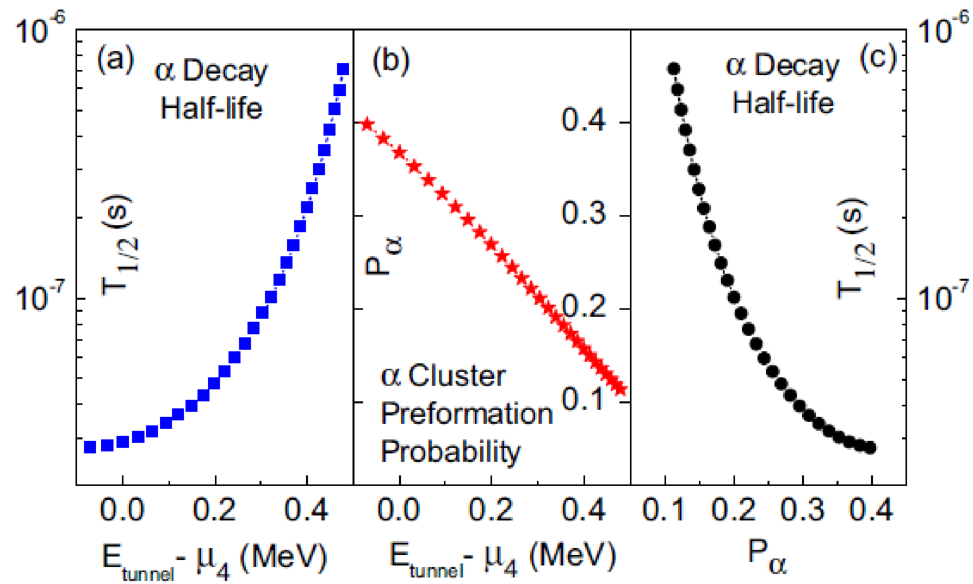

TABLE I. The calculated preformation probability and decay half-life of ^{212}Po using different sets of effective c.m. potentials.

Potential	c (MeV fm)	d (MeV fm)	E_{tunnel} (MeV)	Fermi energy μ_4 (MeV)	$E_{\text{tunnel}} - \mu_4$ (MeV)	Preform. factor P_α	Decay half-life $T_{1/2}$ (s)
A	13866.30	4090.51	−19.346	−19.346	0	0.367	2.91×10^{-8}
B	11032.08	3415.56	−19.346	−19.771	0.425	0.142	2.99×10^{-7}

PHYSICAL REVIEW C VOLUME 42, NUMBER 2 AUGUST 1990

Systematics of alpha decay half-lives

Yuichi Hatsukawa
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Hiromichi Nakahara
Department of Chemistry, Tokyo Metropolitan University, Setagaya, Tokyo 158, Japan

Darleane C. Hoffman
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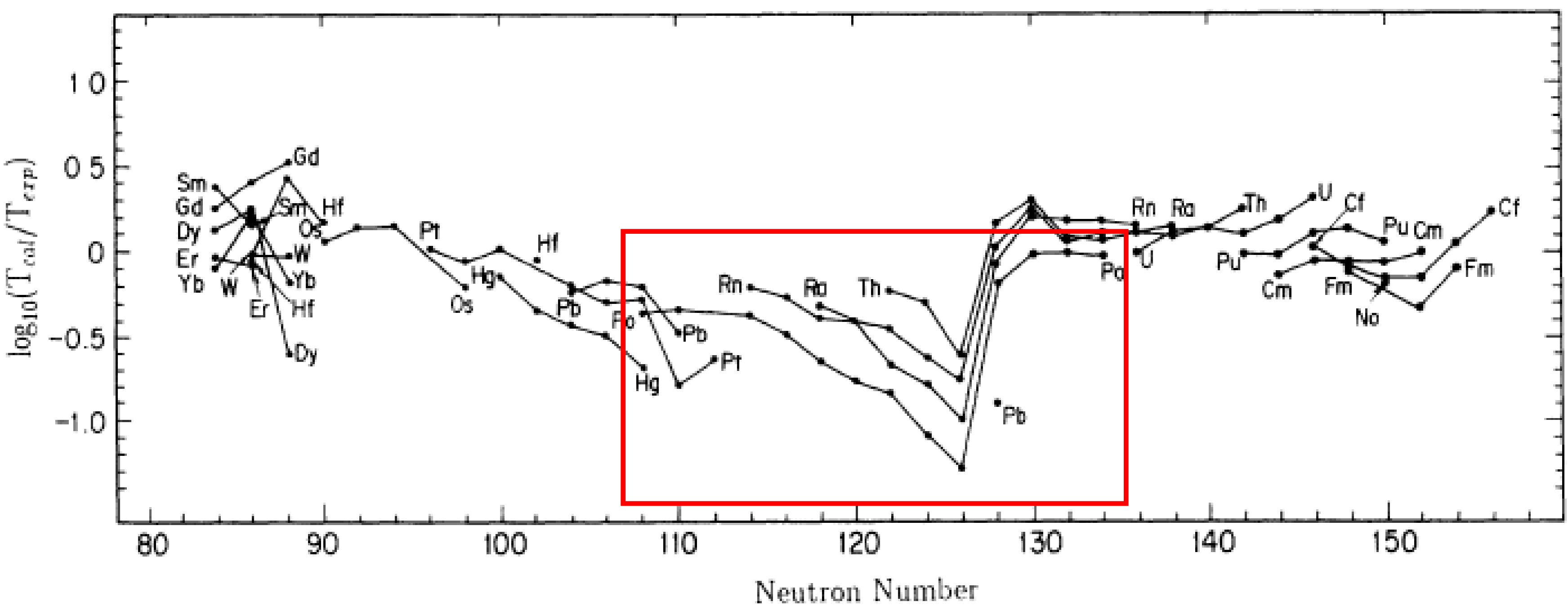

PHYSICAL REVIEW C VOLUME 46, NUMBER 2 AUGUST 1992

Simple relation for alpha decay half-lives

B. Alex Brown
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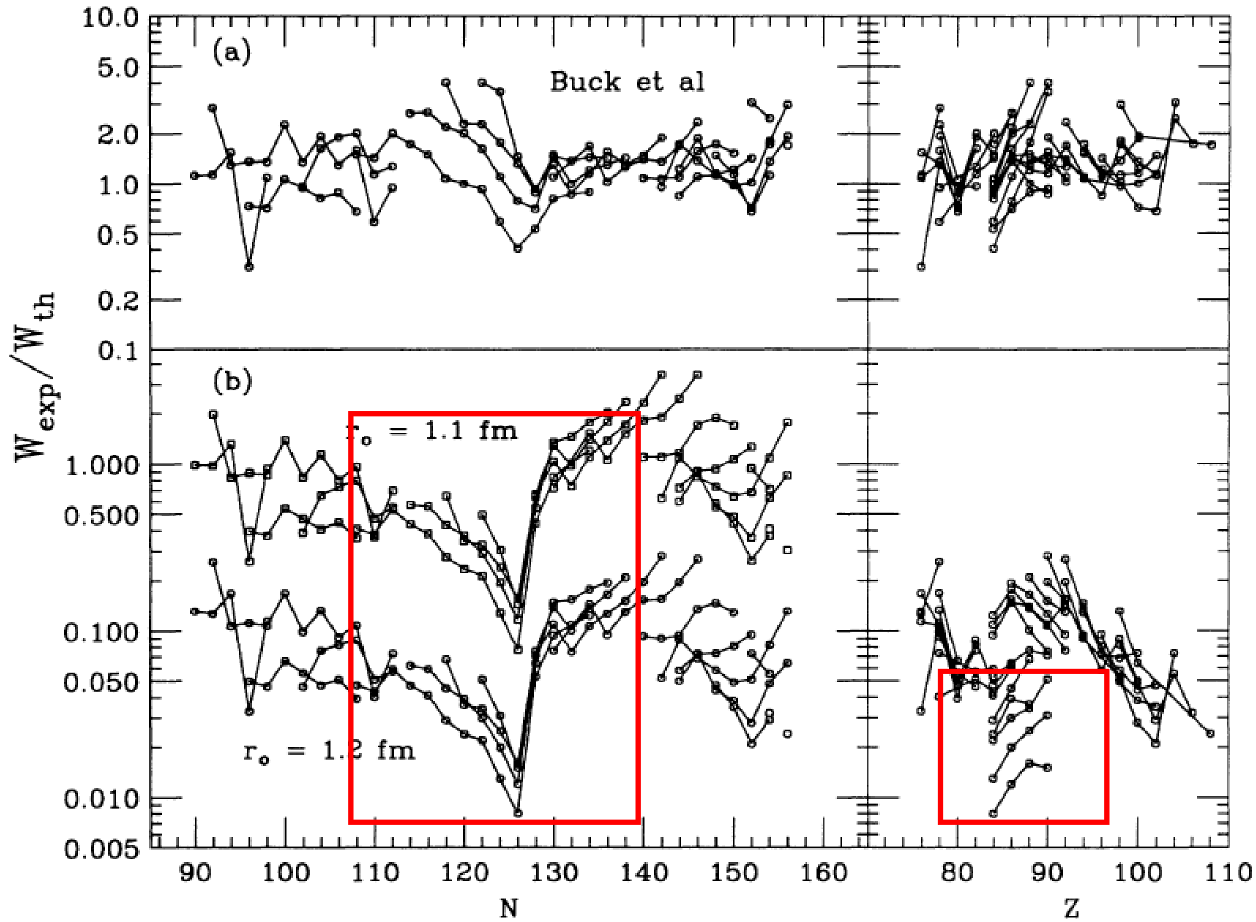

PHYSICAL REVIEW C VOLUME 42, NUMBER 2 AUGUST 1990

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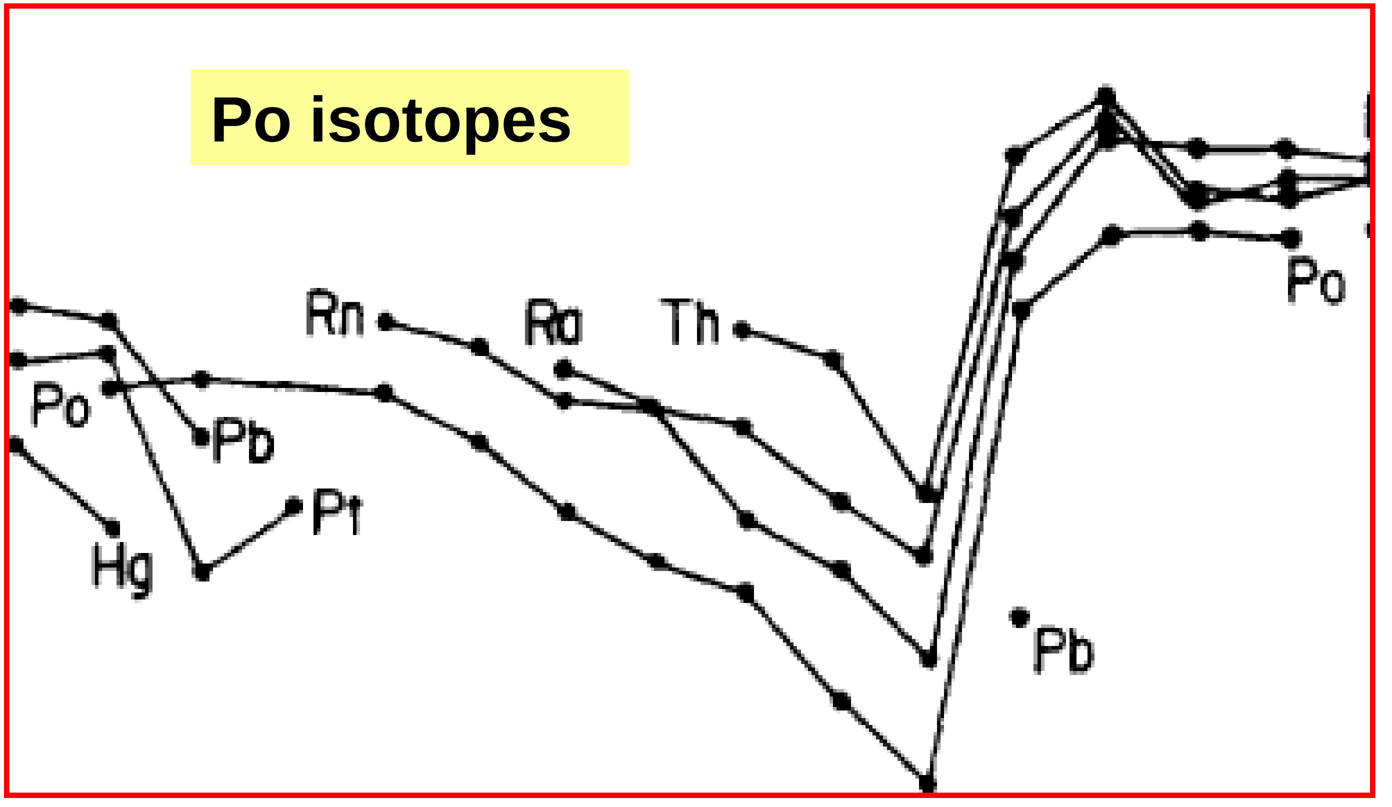
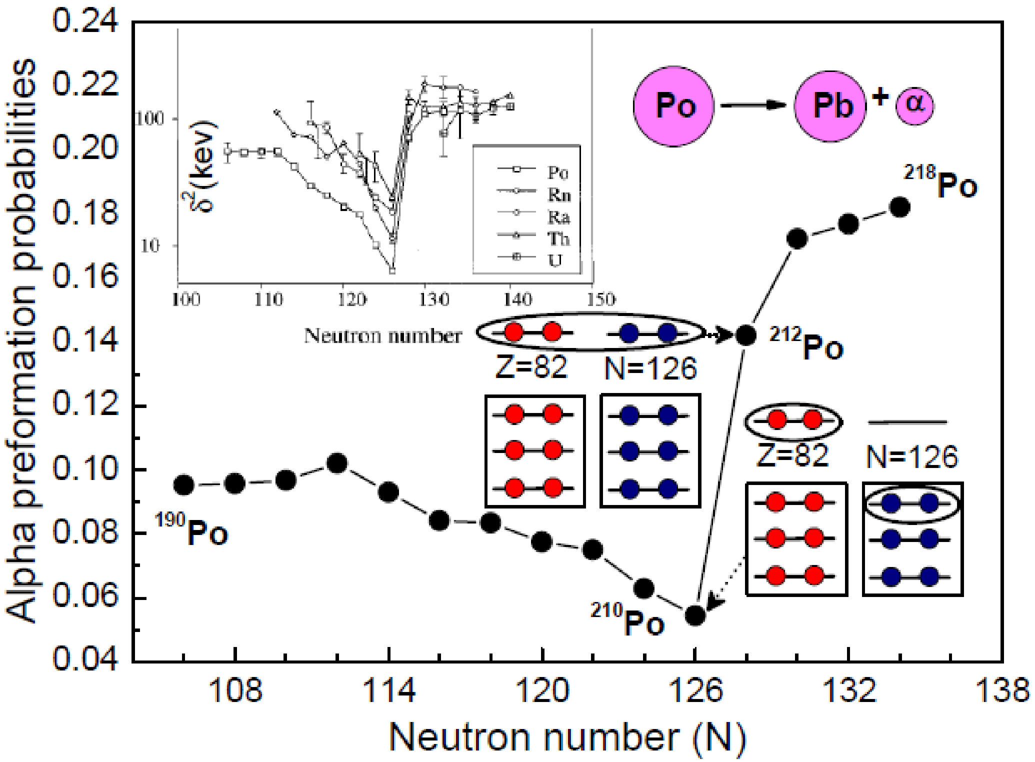


Microscopic results of alpha cluster preformation probabilities
Daughter nuclei: Z=82 isotopes



Experimental data:
Qa and Ta (well measured)

c and *d* fitted to Qa and Ta

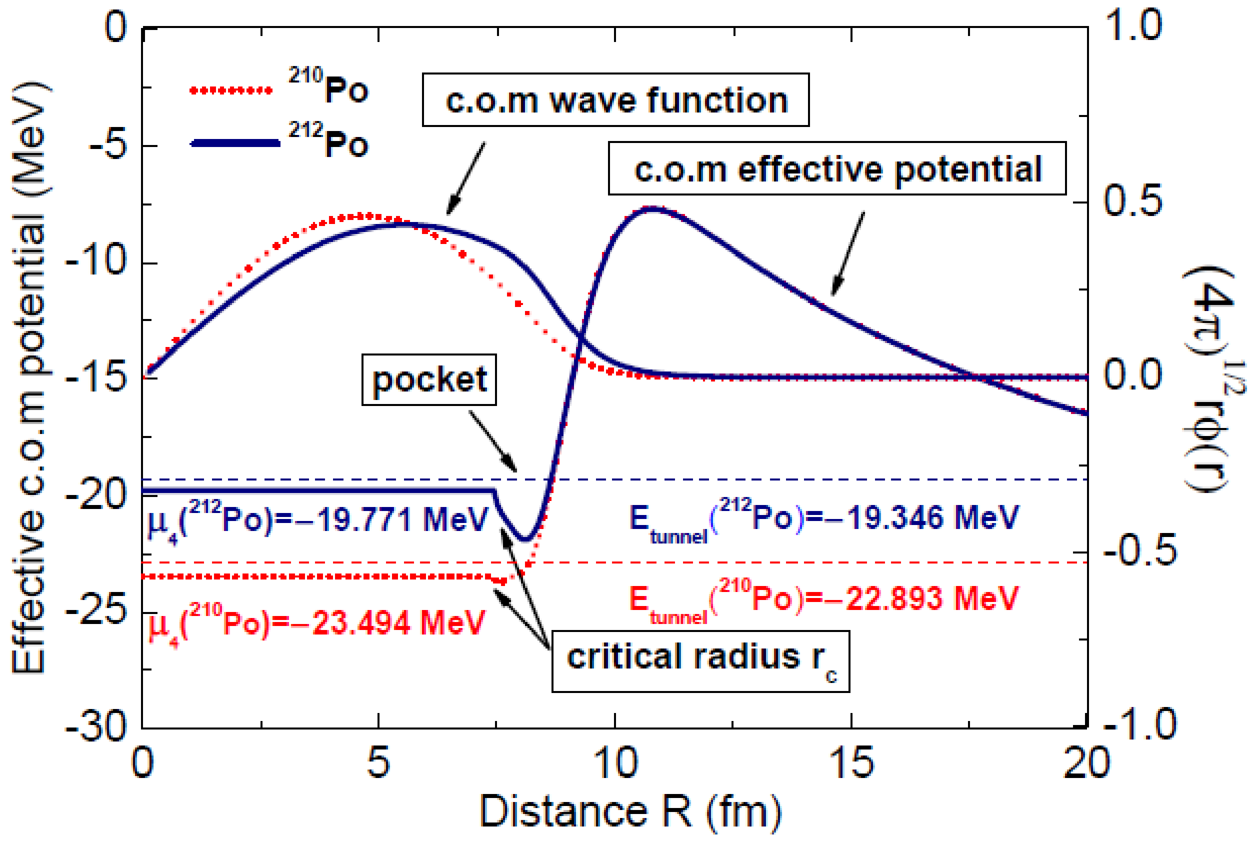
Preformation probabilities are obtained for each nucleus

shell effect: important

$$v(s) = c\exp(-4s)/(4s) - d\exp(-2.5s)/(2.5s)$$

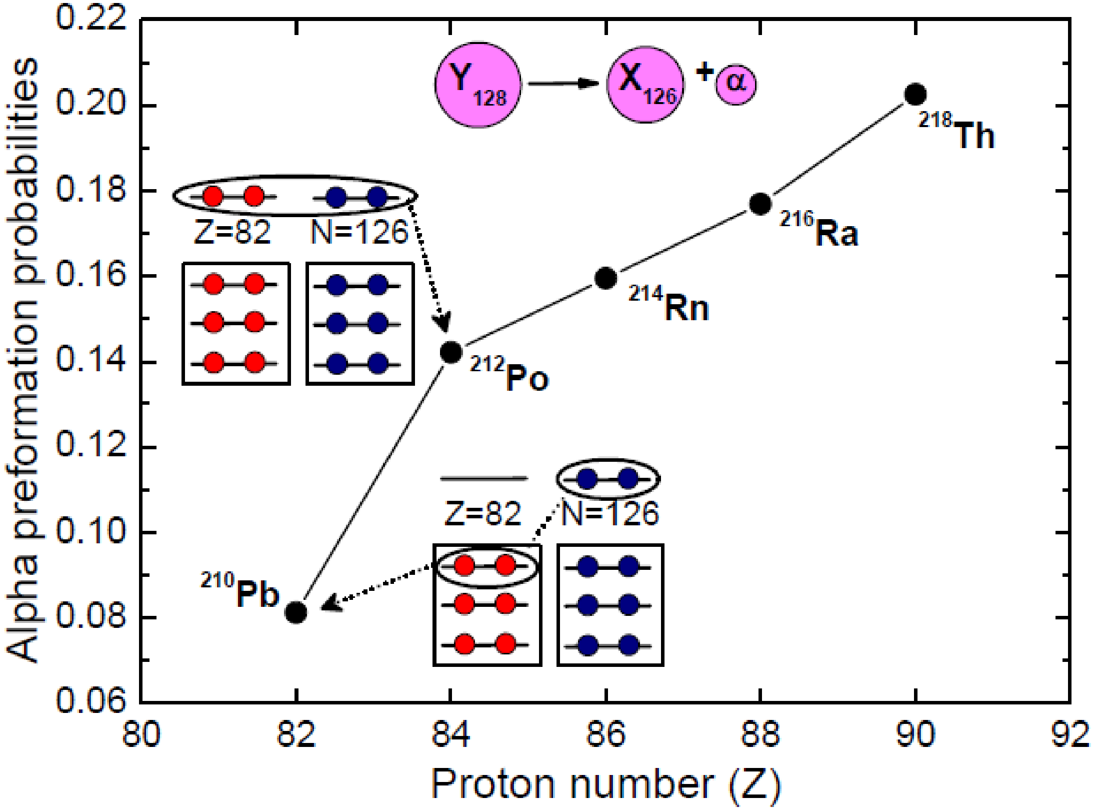
describing a short-range repulsion (*c*) and a long-range attraction (*d*);
S denotes the nucleon-nucleon distance.

Microscopic results of alpha cluster preformation probabilities
Daughter nuclei: Z=82 isotopes



Comparison of the c.o.m. effective potentials, the c.o.m. wave functions, and the Fermi energies for two neighbouring alpha-emitters

Microscopic results of alpha cluster preformation probabilities
Daughter nuclei: N=126 isotones



Experimental data:
Qa and Ta (well measured)

c and *d* fitted to Qa and Ta

Preformation probabilities are obtained for each nucleus

shell effect: important

$$v(s) = c\exp(-4s)/(4s) - d\exp(-2.5s)/(2.5s)$$

describing a short-range repulsion (*c*) and a long-range attraction (*d*);
S denotes the nucleon-nucleon distance.

Microscopic results of alpha preformation probabilities Superheavy nuclei

Mass	Z	N	Q_α MeV	Half-life $T_{1/2}$[s]	c [MeV fm]	d [MeV fm]	Fermi energy μ_4[MeV]	E_{tunnel} [MeV]	$E_{\text{tunnel}} - \mu_4$ [MeV]	P_α
294	118	176	11.810	1.4×10^{-3}	17066.70	4847.61	-16.889	-16.490	0.399	0.110
292	116	176	10.774	2.4×10^{-2}	19237.20	5365.62	-17.772	-17.526	0.246	0.197
290	116	174	10.990	8.0×10^{-3}	19027.50	5315.41	-17.568	-17.310	0.258	0.191
288	114	174	10.072	7.5×10^{-1}	18743.70	5251.07	-18.549	-18.228	0.320	0.156
286	114	172	10.370	3.5×10^{-1}	17237.40	4892.79	-18.349	-17.930	0.419	0.104
270	**110**	**160**	11.117	2.1×10^{-4}	17079.10	4847.45	-17.547	-17.183	**0.364**	**0.144**
268	**108**	**160**	9.623	1.4×10^{0}	15653.10	4516.39	-19.171	-18.677	**0.494**	**0.077**
264	108	156	10.591	1.1×10^{-3}	17054.60	4843.76	-18.088	-17.709	0.379	0.140
260	106	154	9.901	1.2×10^{-2}	17488.80	4948.93	-18.759	-18.399	0.360	0.152

A brief summary of my talk

1. Alpha decay: old problem but still not fully solved

challenge: alpha cluster preformation

- **Light island (doubly magic ^{100}Sn)**
- **doubly magic ^{208}Pb**
- **Superheavy island (next doubly magic nucleus)**

2. Preformation probability of ^{212}Po: a quartetting wave function approach

3. Microscopic calculations on more alpha emitters around Z=82 and N=126 region, superheavy nuclei

谢谢!

Collaborators: C. Xu, G. Roepke, P. Schuck, T. Yamada, Y. Funaki, H. Horiuchi, A. Tohsaki，B. Zhou, Mengjiao Lyu

Towards a fully microscopic calculation of the alpha decay problem!!!

Microscopic calculation of preformation factor in a two level model

Ren and Xu, PRC 36, 456,1987…

PHYSICAL REVIEW C VOLUME 36, NUMBER 1 JULY 1987

Reduced alpha transfer rates in a schematic model

Ren Zhong-zhou and Xu Gong-ou
Department of Physics, Nanjing University, Nanjing, China
(Received 27 January 1987)

The reduced alpha transfer rates are studied microscopically with a schematic model. Results for ground state to ground state alpha transfer reactions are given.