Nucleon clustering and decay of nuclei

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- 同济大学, 上海, 中国

- Thank NSFC, MOST for support

Outline

- **Introduction**
- **Nucleon clustering in light and medium nuclei**
- **Density-dependent cluster model (DDCM) and generalized DDCM for alpha-decay half-lives**
- **New version of Density-dependent cluster model (DDCM+) : solve quasi-bound state Schrödinger--equations for alpha-decay half-lives**
- **Summary**

2013.4，Zhongzhou REN (任中洲) et al organize workshop in KAVLI in Beijing on cluster physics

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)**

Cluster on ^{20}Ne : PRC 86 (2012) 014301

(China-Japan-France-Germany Collaboration)

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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(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.

PRL 110, 262501 (2013): nolocalized cluster

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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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.

good description both on positive and negative bands

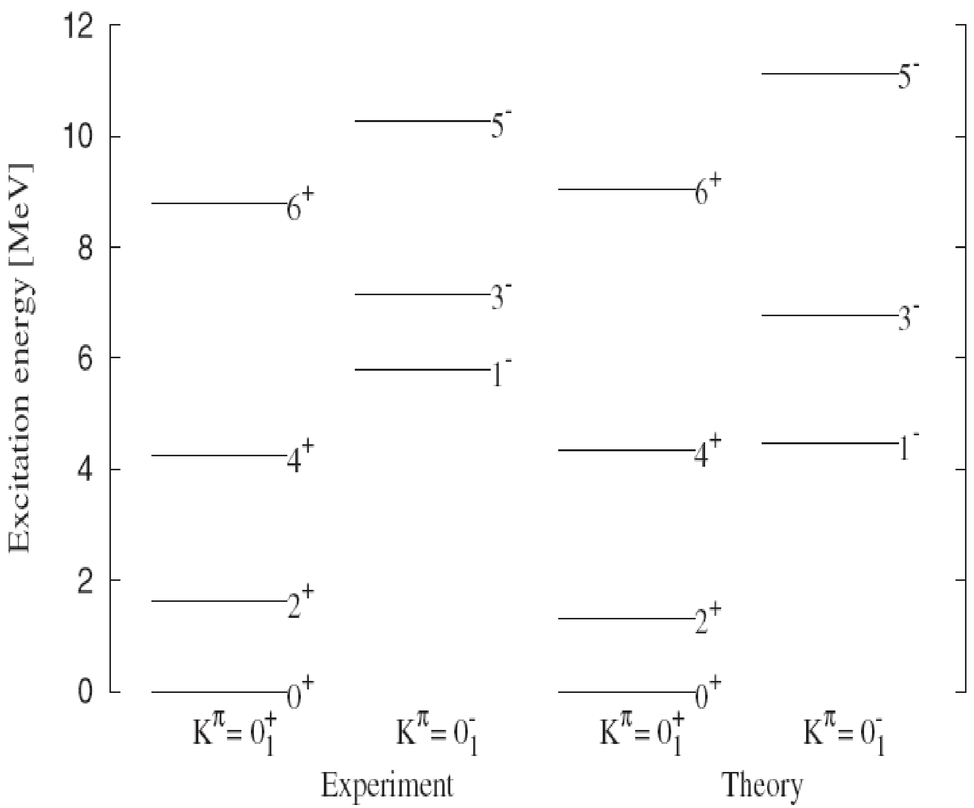

FIG. 4. The energy levels of the inversion doublet bands in ^{20}Ne reproduced by the hybrid wave function compared with the experimental levels.

PRL 110, 262501 (2013)

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doi:10.1088/0034-4885/77/9/096301

Review Article

^{20}Ne artcle is cited by Ito and Ikeda

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]

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[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

Research from Prof. Iachello and collaborators

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

Origin of Low-Lying Enhanced *E*1 Strength in Rare-Earth Nuclei

M. Spieker,[1,*] S. Pascu,[1,2] A. Zilges,[1] and F. Iachello[3]
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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

[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).

Extend THSR wave function

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

2016.3-4, KITPC, by Zhongzhou Ren …

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Clustering effects of nucleons in nuclei and quarks in multi-quark states

Date : From 2016-03-28 To 2016-04-22

Advisory committee :

Local coordinators : Qiang Zhao (Institute of High Energy Physics, CAS), Shan-Gui Zhou (Institute of Theoretical Physics, CAS), Chang Xu (Nanjing University),Feng-Kun Guo(Institute of Theoretical Physics, CAS)

International coordinators : Zhongzhou Ren (Chair, Nanjing University), Ulf-G. Meiβner (University of Bonn, Germany), Bing-Song Zou (Institute of Theoretical Physics, CAS), Hisashi Horiuchi (Osaka Univeristy, Japan), Peter Schuck (IN2P3-CNRS,

We develop cluster model (THSR) from N=Z=Even nuclei (previous researches) to N=Z+1 nuclei (^{9}Be…, Lyu, Ren,..Horiuchi,…PRC 2015). Schematic Fig.:

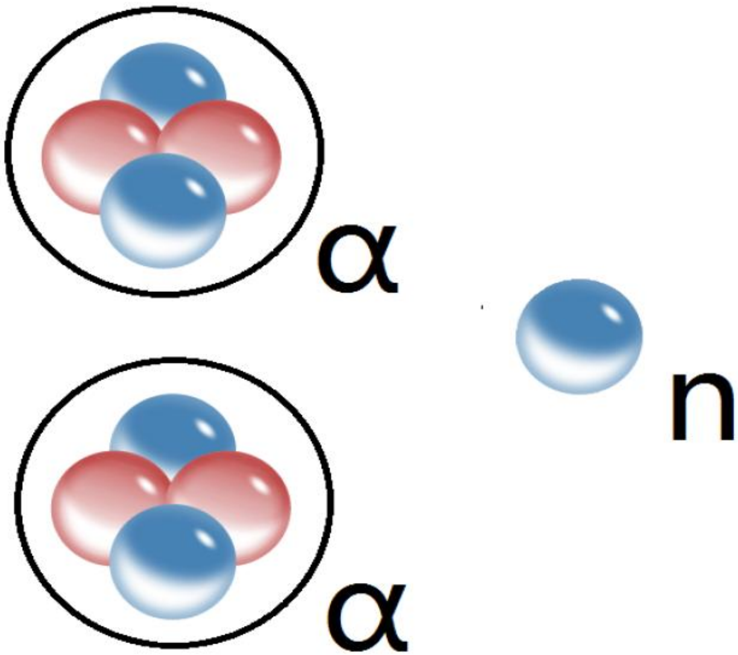

Figure: Cluster structure of ^{9}Be.

The effective nucleon-nucleon interaction of ^{9}Be : the Volkov potential + spin-orbit potential

- The Hamiltonian of ^{9}Be

$$H = \sum_{i=1}^{9} T_i - T_{c.m.} + \sum_{i<j}^{9} V_{ij}^N + \sum_{i<j}^{9} V_{ij}^C + \sum_{i<j}^{9} V_{ij}^{ls}$$

- Volkov No. 2 used as the central force of nucleon-nucleon potential.

$$V_{ij}^N = \{V_1 e^{-\alpha_1 r_{ij}^2} - V_2 e^{-\alpha_2 r_{ij}^2}\}\{W - M\hat{P}_\sigma \hat{P}_\tau + B\hat{P}_\sigma - H\hat{P}_\tau\}$$

- Two-body type G3RS term taken as the spin-orbit interaction.

$$V_{ij}^{ls} = V_0^{ls}\{e^{-\alpha_1 r_{ij}^2} - e^{-\alpha_2 r_{ij}^2}\}\mathbf{L}\cdot\mathbf{S}\hat{P}_{31}$$

Low energy states of ^{9}Be in cluster model (THSR),
PRC 2015 , Lyu, Ren, …, Horiuchi,…

Excitation energy

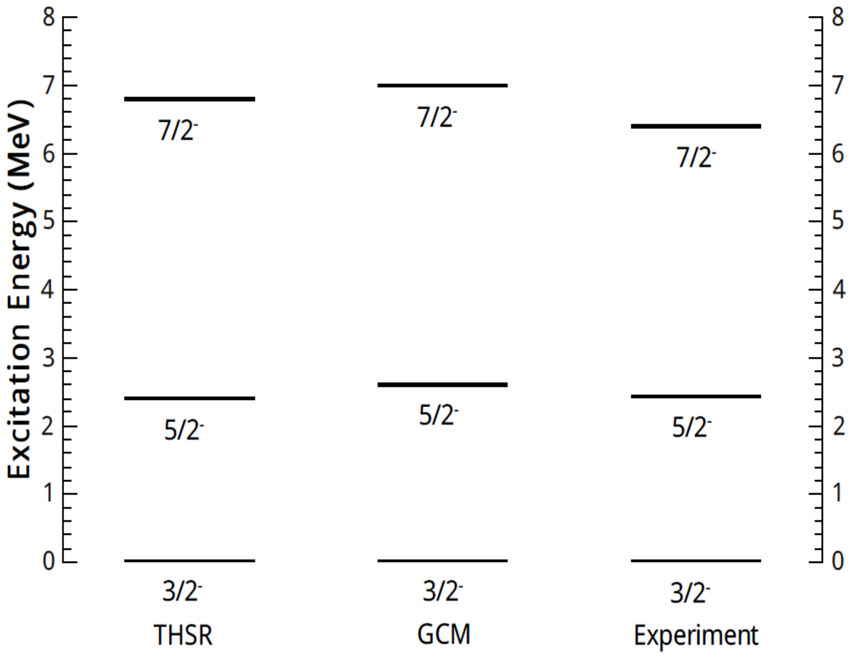

Figure: Excitation energy calculated with both the THSR wave function and the GCM method for the $3/2^{-}$ rotational band head.

Lyu, Ren,… PRC2015: ^{9}Be(α+α+n) coupling of single-particle and cluster motions

PHYSICAL REVIEW C **91**, 014313 (2015)

Investigation of ^{9}Be from a nonlocalized clustering concept

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

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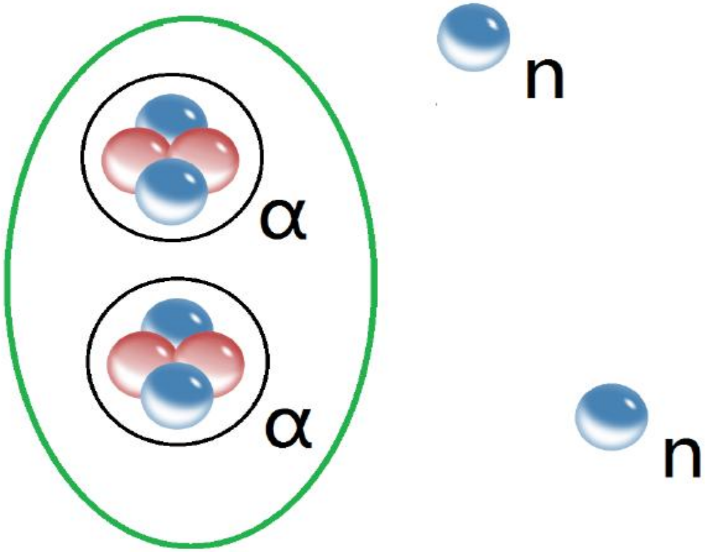
The nonlocalized aspect of clustering, which is a new concept for self-conjugate nuclei, is extended for the investigation of the $N \neq Z$ nucleus ^{9}Be. A modified version of the Tohsaki-Horiuchi-Schuck-Röpke (THSR) wave function is introduced with a new phase factor. It is found that the constructed negative-parity THSR wave function is very suitable for describing the cluster states of ^{9}Be. Namely, the nonlocalized clustering is shown to prevail in ^{9}Be. The calculated binding energy and radius of ^{9}Be are consistent with calculations in other models and with experimental values. The squared overlaps between the single THSR wave function and the Brink + generator coordinate method wave function for the $3/2^{-}$ rotational band of ^{9}Be are found to be near 96%. Furthermore, by showing the density distribution of the ground state of ^{9}Be, the π-orbit structure is naturally reproduced by using this THSR wave function.

We develop cluster model (THSR) from N=Z=Even nuclei (previous researches) to N=Z+2 or N=Z=odd nuclei (^{10}Be, ^{10}B…, Lyu, Ren, Horiuchi,…Zhao…, PRC2016, PRC2018).



Schematic Fig.: **Cluster structure of ^{10}Be**

PHYSICAL REVIEW C **93**, 054308 (2016)

Investigation of ^{10}Be and its cluster dynamics with the nonlocalized clustering approach

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

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We extend the concept of nonlocalized clustering to the nucleus ^{10}Be with proton number $Z = 4$ and neutron number $N = 6$ ($N = Z + 2$). The Tohsaki-Horiuchi-Schuck-Röpke (THSR) wave function is formulated for the description of different structures of ^{10}Be. Physical properties such as energy spectrum and root-mean-square

^{10}Be: compare exp. data with cal. ones

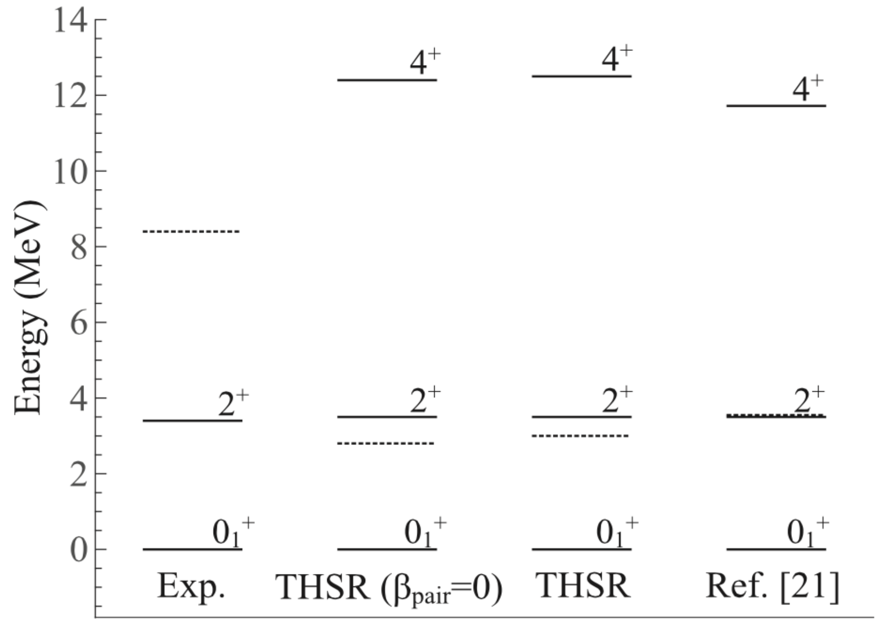

FIG. 3. The 0^+ ground state of ^{10}Be and its rotational band. "THSR" denotes calculated results with the THSR wave function. "THSR ($\beta_{\text{pair}} = 0$)" denotes calculated results with the THSR wave function and the $\beta_{\text{pair}} = 0$ limit. "Ref. [21]" denotes the results of the AMD method [21]. "Exp." denotes the experimental result. The dashed lines indicate the corresponding $\alpha + \alpha + n + n$ threshold -55.2 MeV.

REVIEWS OF MODERN PHYSICS, VOLUME 90, JULY–SEPTEMBER 2018

Microscopic clustering in light nuclei

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Freer et al. cited our work in RMP： ^{10}Be article

3. Neutron-rich Be isotopes

Extended THSR wave functions have also been applied to neutron-rich nuclei. Since the container describing valence neutrons will have size parameters different from the container for the core part of the system, the use of the extended THSR wave function for neutron-rich nuclei is quite natural. Here we report the work of Lyu *et al.* (2015, 2016) which treats ^{9}Be and ^{10}Be, respectively.

In the case of ^{9}Be, the valence-neutron wave function $F(\vec{r})$ in the extended THSR wave function should have negative parity, and it is given by

$$F_n(\vec{r}) = \int d\vec{R} \exp\left(-\sum_{k=x}^{z} \frac{R_k^2}{\beta_k^2}\right) \exp(i\phi_R) \exp\left[-\frac{(\vec{r}-\vec{R})^2}{2b^2}\right]. \quad (5.31)$$

The phase factor $\exp(i\phi_R)$ makes the parity of $F_n(\vec{r})$ negative. Lyu *et al.* (2015) treated the ground rotational-band levels $3/2^-$, $5/2^-$, and $7/2^-$ and found that the extended THSR wave functions of these levels have about 95% squared overlaps with the wave functions obtained by the GCM calculation by using $2\alpha + n$ three-body Brink wave functions.

In the case of ^{10}Be, the energy spectra of two rotational bands upon the ground state and the 0_2^+ state were calculated using single extended THSR wave functions and were compared with those obtained by AMD calculations (Suhara and Kanada-En'yo, 2010; Kobayashi and Kanada-En'yo, 2012). For the ground band, the extended THSR wave functions where two valence neutrons occupy the orbit $F_n(\vec{r})$ were used. The modifications of these extended THSR wave functions were also made by introducing the distance parameter $\vec{R}_{\rm pair}$ between the c.m. of the 2α system and the c.m. of the $2n$ system. It was reported that both kinds of extended THSR wave functions give very similar energy spectra compared to that of the AMD calculation (Kobayashi and Kanada-En'yo, 2012). For the excited band, the extended THSR wave functions were constructed by accommodating two valence neutrons into the σ-orbit-type single-neutron orbit. The obtained energy spectrum is very similar to but a little higher than the AMD energy spectra (Suhara and Kanada-En'yo, 2010; Kobayashi and Kanada-En'yo, 2012). The extended THSR wave function of the 0_2^+ state is not orthogonalized to that of the ground state, but the squared overlap between them is as small as 1.4%. We see thus that the wave functions as simple as the single extended THSR wave functions give very good results quite similar to AMD calculations.

Lyu, M., Z. Ren, B. Zhou, Y. Funaki, H. Horiuchi, G. Röpke, P. Schuck, A. Tohsaki, C. Xu, and T. Yamada, 2015, "Investigation of 9Be from a nonlocalized clustering concept," Phys. Rev. C **91**, 014313.

Lyu, M., Z. Ren, B. Zhou, Y. Funaki, H. Horiuchi, G. Röpke, P. Schuck, A. Tohsaki, C. Xu, and T. Yamada, 2016, "Investigation of 10Be and its cluster dynamics with the nonlocalized clustering approach," Phys. Rev. C **93**, 054308.

Both ^{9}Be and ^{10}Be cited

^{9}B， develop cluster model by including coupling between proton and clusters

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]

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^9B: comparison between calculated and experimental levels

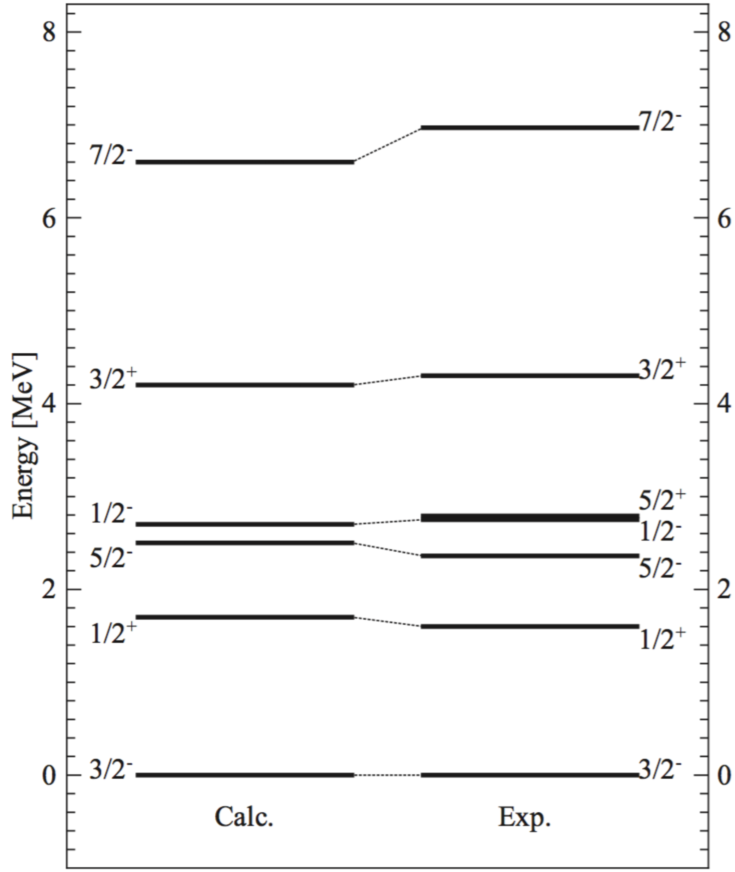

FIG. 8. Theoretical and experimental energy spectra of ^9B. The states with higher energy, which are found in experiment, are not considered in our calculation because of the limitation of computation power.

Extended cluster model to study A=10 nuclei (PRC 100, 014306(2019))

PHYSICAL REVIEW C **100**, 014306 (2019)

Investigation of isospin-triplet and isospin-singlet pairing in the $A = 10$ nuclei ^{10}B, ^{10}Be, and ^{10}C with an extension of the Tohsaki-Horiuchi-Schuck-Röpke wave function

Qing Zhao,[1,*] Zhongzhou Ren,[2,†] Mengjiao Lyu,[3,‡] Hisashi Horiuchi,[3,4] Yoshiko Kanada-En'yo,[5,§] Yasuro Funaki,[6] Gerd Röpke,[7] Peter Schuck,[8,9] Akihiro Tohsaki,[3] Chang Xu,[1] Taiichi Yamada,[6] and Bo Zhou[10,11]

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In order to study the nucleon-nucleon pairing effects in clustering nuclei, we formulate a superposed Tohsaki-Horiuchi-Schuck-Röpke (THSR) wave function, which includes both molecular-orbit and pairing configurations explicitly. With this new wave function, we investigate the anomalous deuteronlike *pn*-pairing effect in ^{10}B with $T = 0$ and $S = 1$ (isoscalar) by comparing with isovector *NN* pairs ($T = 1, S = 0$) in ^{10}Be and ^{10}C. Energies are calculated for the ground states of ^{10}Be, ^{10}B and ^{10}C nuclei, and the 1_1^+0 excited state of ^{10}B. These energies are essentially improved comparing with studies using a previous version of THSR wave function. Furthermore, overlaps between the total wave function and the pairing component indicate that the *NN* pairing effect is more visible in ^{10}B than in ^{10}Be and ^{10}C. By analyzing the energies and the overlaps between wave function components, we observe two different mechanisms enhancing the formation of deuteronlike pairs in ^{10}B. We also discuss the pairing effect by showing average distances between components in each nucleus and density distributions of valence nucleons.

PHYSICAL REVIEW C **99**, 051303(R) (2019)

Rapid Communications

Nonlocalized motion in a two-dimensional container of α particles in 3^- and 4^- states of ^{12}C

Bo Zhou,[1,2] Yasuro Funaki,[3] Hisashi Horiuchi,[4] Masaaki Kimura,[2,5] Zhongzhou Ren,[6] Gerd Röpke,[7] Peter Schuck,[8] Akihiro Tohsaki,[4] Chang Xu,[9] and Taiichi Yamada[10]

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The first 3^- and 4^- states of ^{12}C are studied in the present container model, in which the shift parameter is introduced to break the parity symmetry for projecting out the negative-parity states. Taking the limit as the shift parameter approaches zero and by variational calculations for one-deformed size parameter, the local energy minima are obtained for the 3^- and 4^- states. It is found that the obtained *single* Tohsaki-Horiuchi-Schuck-Röpke (THSR) wave functions for 3^- and 4^- states are 96% and 92% equivalent to the corresponding generator coordinate method (GCM) wave functions, respectively. The calculated intrinsic densities further show that these negative-parity states of three clusters, different from the traditional understanding of a rigid triangle structure, are found to have nonlocalized clustering structure in the two-dimensional container picture.

alpha transfer reaction of light nuclei：PLB2019

Physics Letters B 797 (2019) 134820

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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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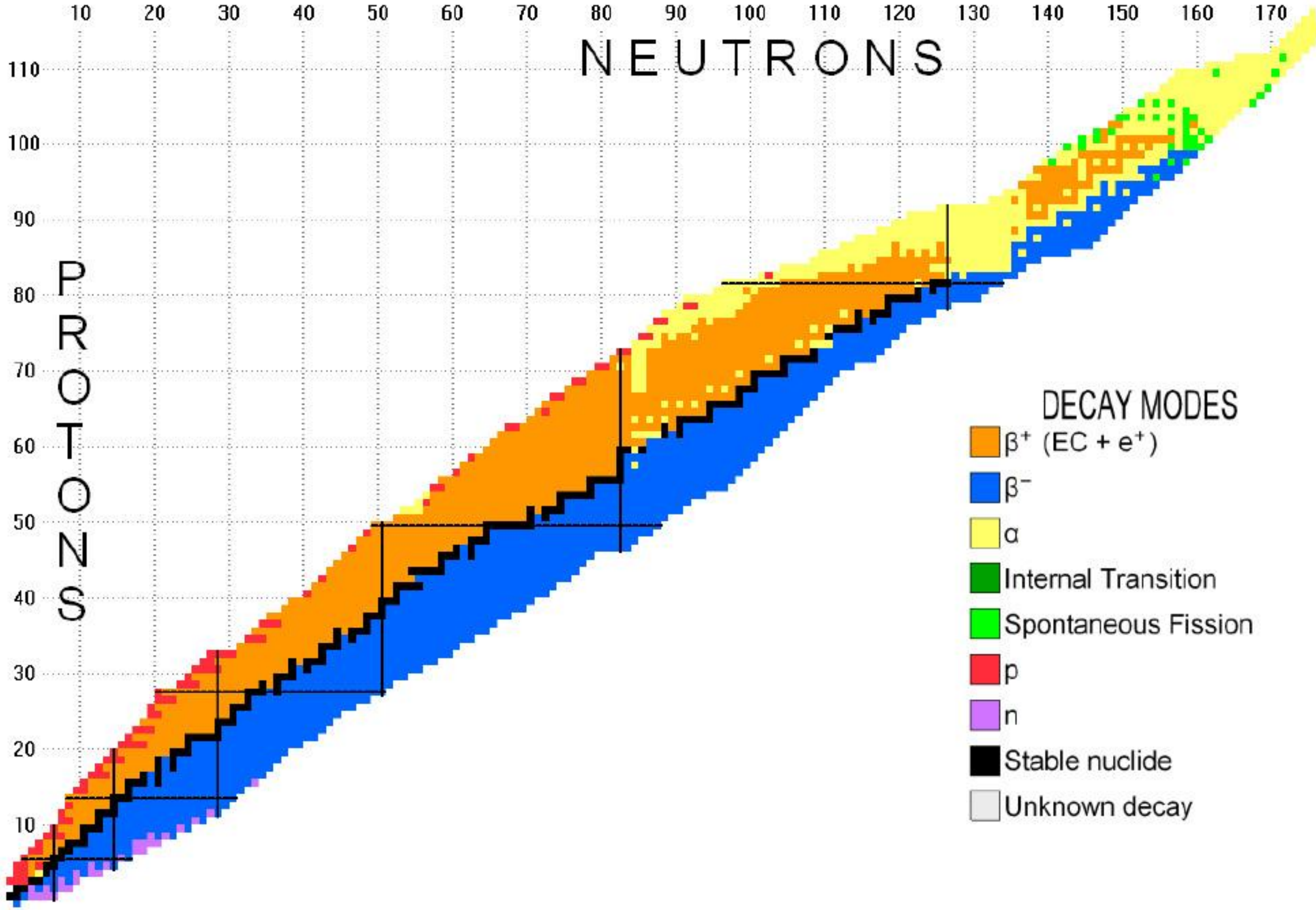
ABSTRACT

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

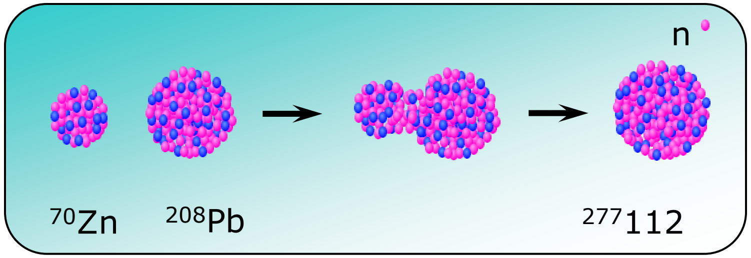
Now move to alpha decay of nuclei: importance of alpha decay

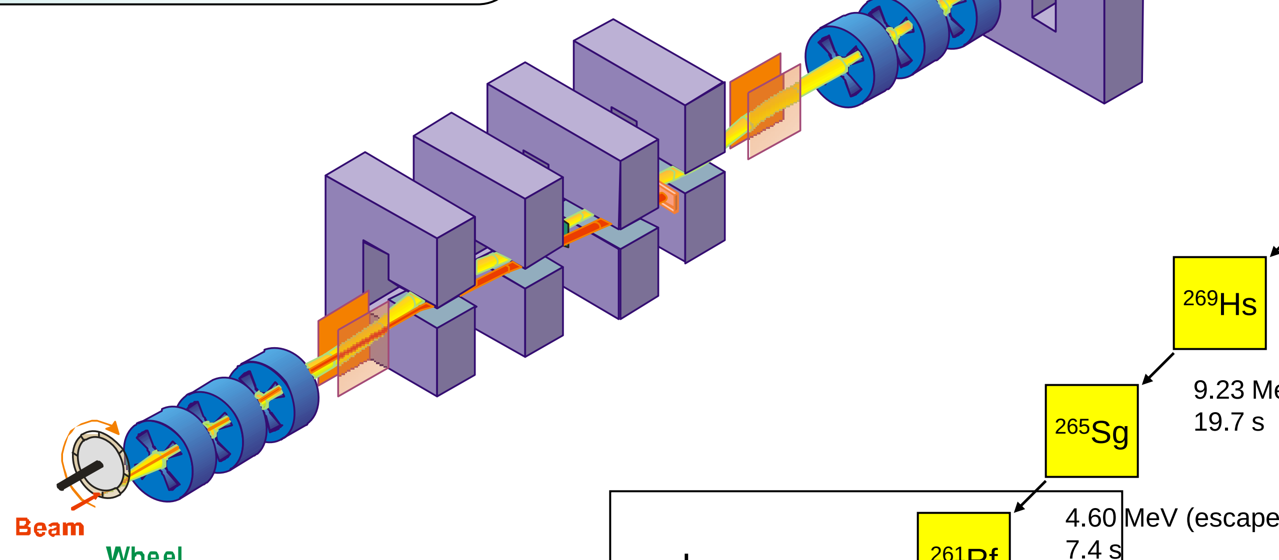
- Origin of nuclear physics 1896: Becquerel
- Identify new elements (Po and Ra) by stronger radioactivity: Curies. Z=105-118…
- Identify the core of atom (nucleus): Rutherford
- Validity of quantum mechanics for nuclear Physics: Gamow in 1928

There are more than 400 nuclei that exhibit the alpha-decay phenomenon (yellow one).

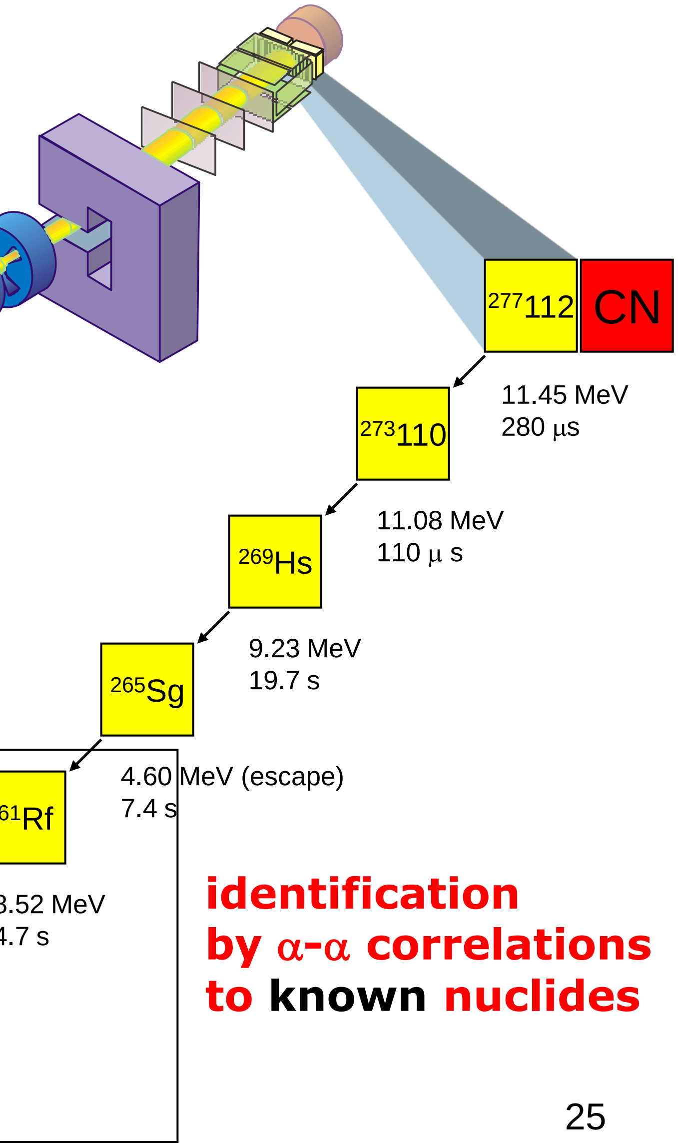


Synthesis of Z=112 SHE at SHIP





kinematic separation
in flight



identification
by α-α correlations
to known nuclides

Date: 09-Feb-1996
Time: 22:37 h

Z=113,115,117,118 identified by alpha decay

- Z=113: Nihonium, Nh. (produced in RIKEN).
- Z=115: Moscovium, Mc. (produced in Dubna).
- Z=117: Tennessine, Ts. (produced in Dubna).
- Z=118: Oganesson; Og. (produced in Dubna).

I and my teacher, PRC 36 (1987) 456. heavy nuclei :alpha transfer

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:

$$H = H_0(+) + H_0(-) + H_1(+,-) , \quad (1)$$

where

$$H_0(\pm) = \pm\epsilon A(\pm) - 2\lambda_0 \left[\sum_\alpha B^\dagger_\alpha(\sigma,\pm) B_\alpha(\sigma,\pm) + \sum_\mu B^\dagger_\mu(\tau,\pm) B_\mu(\tau,\pm) \right] , \quad (2a)$$

ZZ Ren，GO Xu，PRC 36 (1987) 456

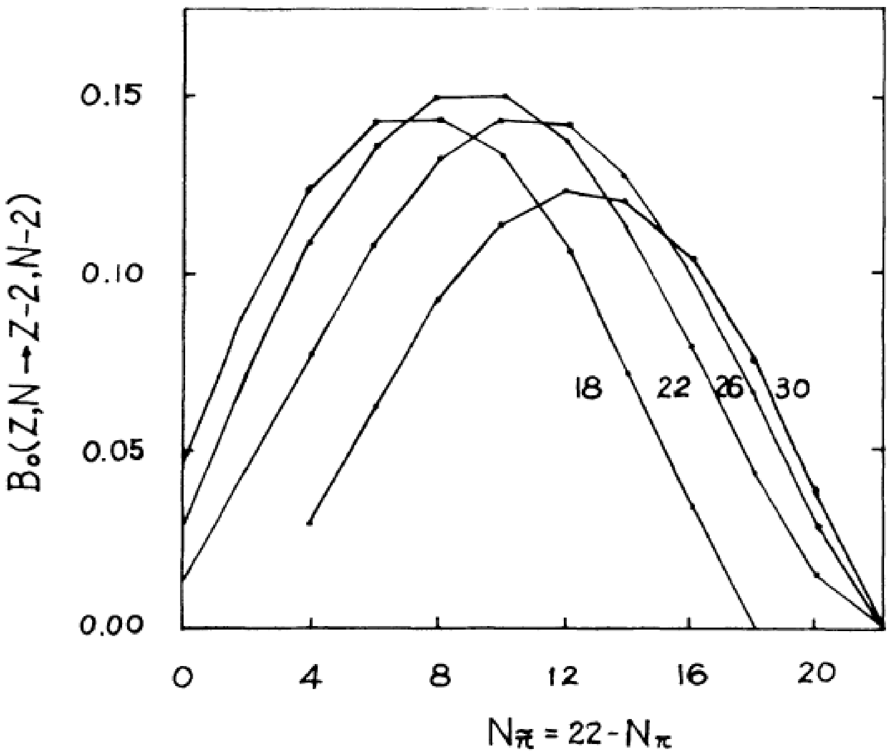


FIG. 2. Reduced α-transfer rates $B(Z,N \to Z-2,N-2)$ between ground states of nuclei with same value of $N_\nu - N_\pi$ as indicated in the figure, $N_\pi < 4l(-)+2$, $N_\nu > 4l(-)+2$. $\epsilon = 3.5$ MeV, $\lambda_0 = 1.0$ MeV, $\lambda_1 = 0.5$ MeV, $l(-)=5$, $l(+)=6$.

- **Reduced alpha transfer rates**

ZZ Ren, GO Xu， 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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(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.

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

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

Our: alpha decay of ^{104}Te (^{100}Sn+…); Exp.

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

[29] C. Xu and Z. Ren, Phys. Rev. C **74**, 037302 (2006).

Nuclei around A=208: ^{212}Po ($^{208}Pb+^{4}He$)

RAPID COMMUNICATIONS

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]

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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.

[16] B. Zhou, Z. Ren, C. Xu, Y. Funaki, T. Yamada, A. Tohsaki, H. Horiuchi, P. Schuck, and G. Röpke, Phys. Rev. C **86**, 014301 (2012).

[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).

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).
[19] Y. Ren and Z. Ren, Phys. Rev. C **85**, 044608 (2012).

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.

[27] Z. Ren, C. Xu, and Z. Wang, Phys. Rev. C **70**, 034304 (2004)
[28] Y. Qian and Z. Ren, J. Phys. G: Nucl. Part. Phys. **39**, 015103 (2012).
[29] D. Deng and Z. Ren, Phys. Rev. C **93**, 044326 (2016).
[30] C. Xu, Z. Ren, G. Röpke, P. Schuck, Y. Funaki, H. Horiuchi, A. Tohsaki, T. Yamada, and B. Zhou, Phys. Rev. C **93**, 011306(R) (2016).
[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).

Oganessian et al, PRC72, 034611 (2005)

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

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

Yu. Ts. Oganessian, V. K. Utyonkov, S. N. Dmitriev, Yu. V. Lobanov, M. G. Itkis, A. N. Polyakov, Yu. S. Tsyganov, A. N. Mezentsev, A. V. Yeremin, A. A. Voinov, E. A. Sokol, G. G. Gulbekian, S. L. Bogomolov, S. Iliev, V. G. Subbotin, A. M. Sukhov, G. V. Buklanov, S. V. Shishkin, V. I. Chepygin, G. K. Vostokin, N. V. Aksenov, M. Hussonnois, K. Subotic, and V. I. Zagrebaev
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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 chains consisting of five consecutive α decays, all detected

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.

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 $\rightarrow$ ^{271}Sg $\rightarrow$ ^{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 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

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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[3] *Department of Physics and Astronomy, The University of Tennessee, Knoxville, Tennessee 37996, USA*
[4] *Physics Division, Oak Ridge National Laboratory, PO Box 2008, Oak Ridge, Tennessee 37831, USA*
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* Deceased

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.

New isotope in China: ^{265}Bh (Z=107)

Eur. Phys. J. A **20**, 385–387 (2004)

THE EUROPEAN PHYSICAL JOURNAL A

Letter

New isotope ^{265}Bh

Z.G. Gan[1,a], J.S. Guo[1], X.L. Wu[1], Z. Qin[1], H.M. Fan[1], X.G. Lei[1], H.Y. Liu[1], B. Guo[1], H.G. Xu[1], R.F. Chen[1], C.F. Dong[1], F.M. Zhang[1], H.L. Wang[1], C.Y. Xie[1], Z.Q. Feng[1], Y. Zhen[1], L.T. Song[1], P. Luo[1], H.S. Xu[1], X.H. Zhou[1], G.M. Jin[1], and Zhongzhou Ren[2]

[1] Institute of Modern Physics, Chinese Academy of Sciences, Lanzhou 730000, PRC
[2] Department of Physics, Nanjing University, Nanjing 210008, PRC

Data of ^{265}Bh agree with Ren et al [12,13]

. The derived Q_α from the measured α energy for ^{265}Bh was 9.38 MeV, which was in agreement with the expected Q_α value by Zhongzhou Ren *et al.* [12,13]. The experimental half-life of ^{265}Bh also agrees with the calculations [13] $T_{1/2} = 2.6$

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

Zhongzhou Ren,[1,2] Chang Xu,[1] and Zaijun Wang[1]
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[2]*Center of Theoretical Nuclear Physics, National Laboratory of Heavy-Ion Accelerator, Lanzhou 730000, China*
(Received 15 June 2004; published 14 September 2004)

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.

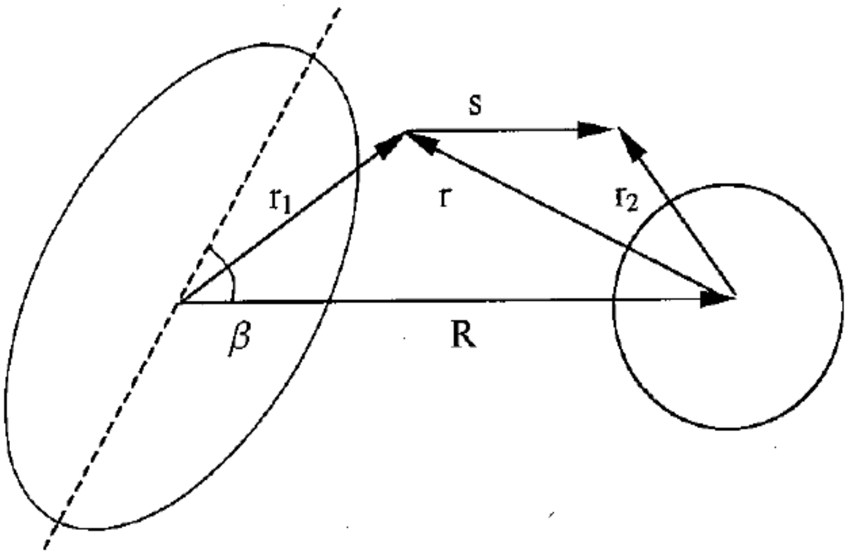
Density-Dependent Cluster Model

- DDCM: model of alpha and cluster decay:
- 1) N-N effective potential: from Reid potential
- 2) Double folding with density: alpha+nucleus
- 3) low density behavior--exchange included
- 4) agree well with experimental half-lives

- Z Ren, C Xu, Z Wang, PRC 70: 034304 (2004)
- C Xu, Z Ren, NPA 753: 174 ,NPA 760: 303 (2005)
- C Xu, Z Ren, PRC 73: 041301(R) (2006)…
- D. Ni, Z. Ren, PRC , (2009), (2010), GDDCM…..

Schematic Fig.: double folding potential or Woods-Saxon potential

We consider a spherical alpha-particle interacts with a deformed core nucleus which has an axially symmetric nuclear shape.



The decay process is described by the tunneling of the alpha particle through a deformed potential barrier, which is approximated by an axially deformed potential.

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

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

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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.

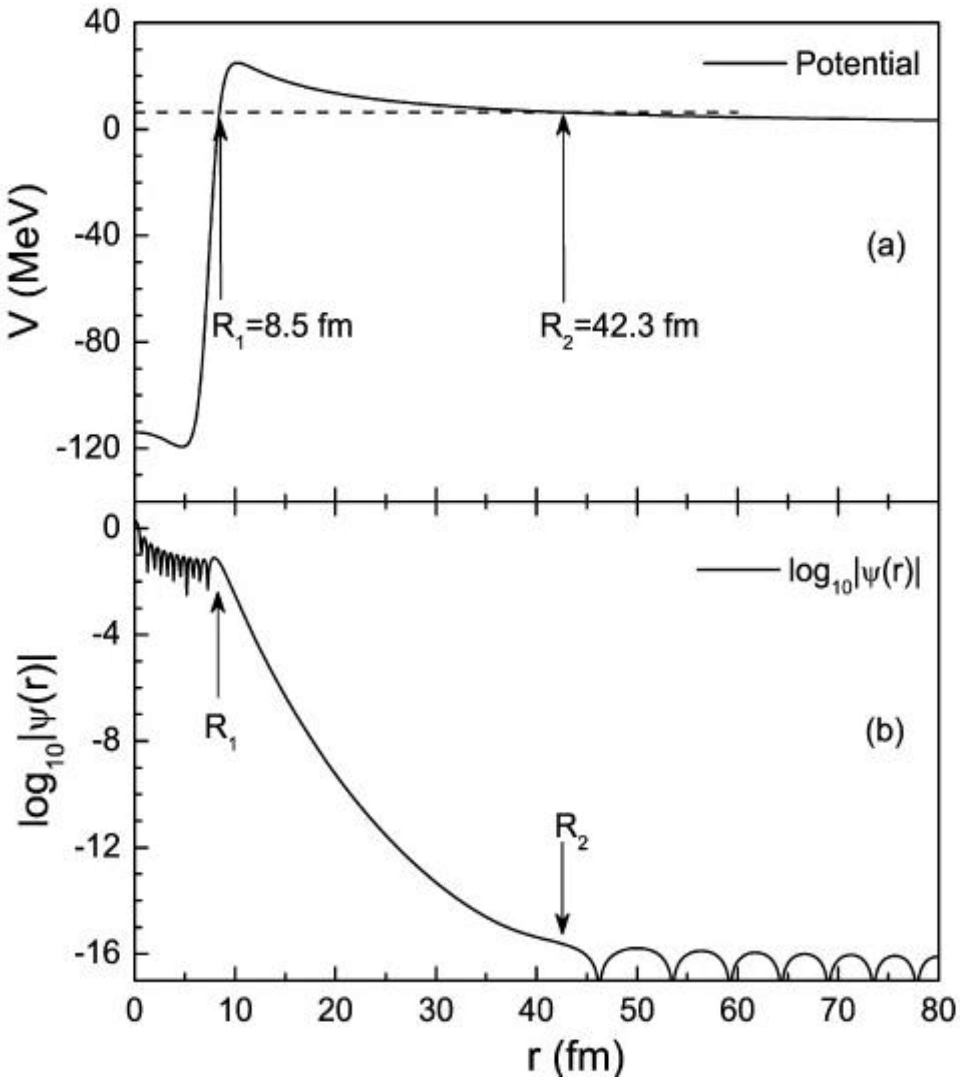
alpha decay and quantum mechanics

- **Quantum mechanics: originated from atomic physics. Two kinds of states in textbook: bound, scattering**
  1928，Gamow: quantum tunnel
- **Unstable nuclei (^{238}U): finite lifetime: Quasi-Bound State (QBS)**

- **Our DDCM: WKB, Bohr-Sommerfeld quantization, semi-classical approximation**
- **alpha-decay : quantum effect. To solve Schroedinger-eq. for QBS**

- **Generalized Density-Dependent Cluster Model**
- **Multi-Channel Cluster Model (MCCM)**

QBS: wave function of Woods-Saxon potential, tail

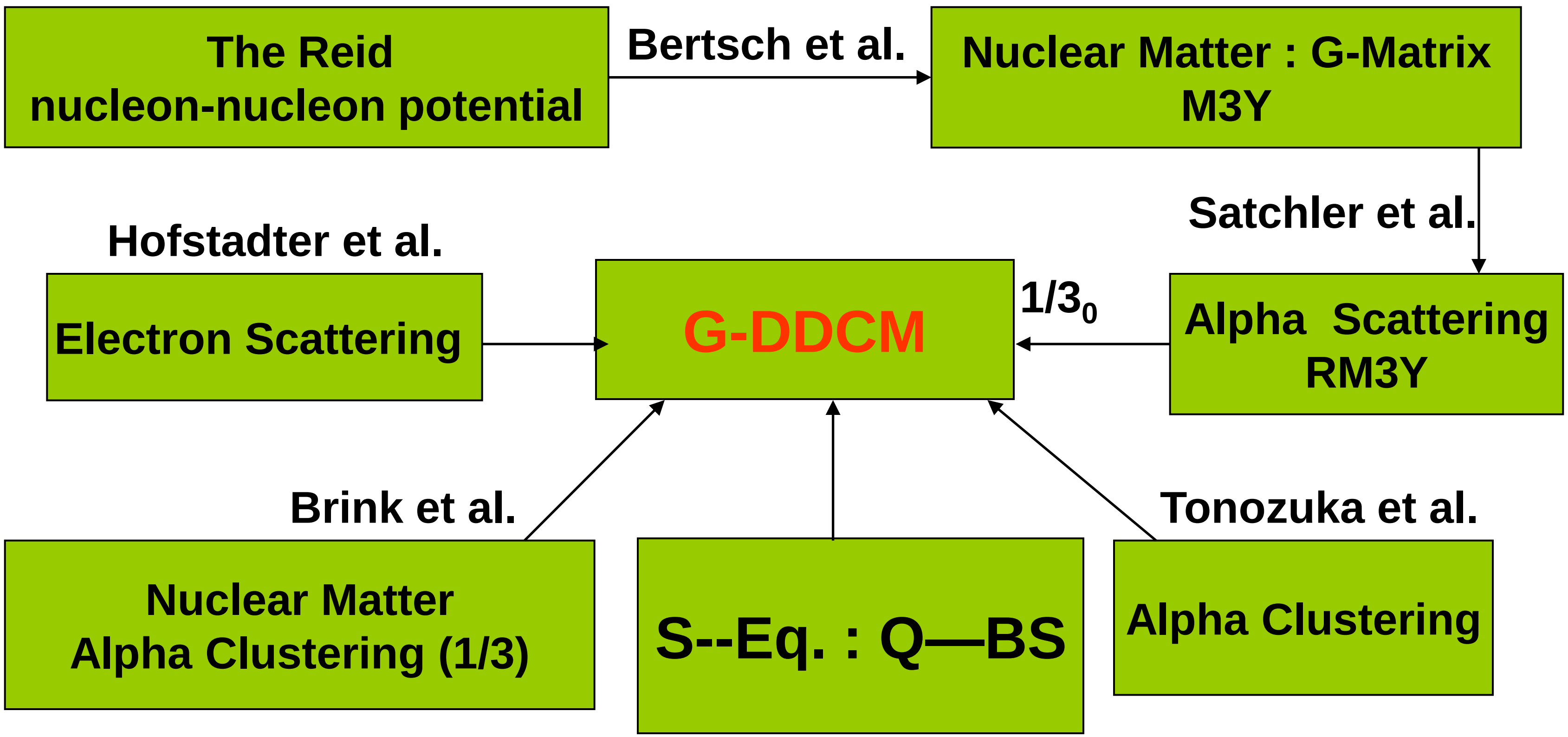


Woods-Saxon shape nuclear potentials

$$V_N(r) = \frac{V_0}{1 + \exp\left(\frac{r - r_0 A^{1/3}}{a}\right)}$$

V_0 is determined by the characteristic of the alpha-cluster quasibound state.

Generalized Density-Dependent Cluster Model



Generalized Density-Dependent Cluster Model PRC 80 014314 (2009)

PHYSICAL REVIEW C **80**, 014314 (2009)

Exotic α decays around the $N = 126$ magic shell

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We investigate the α-decay half-lives of the exotic $N = 125, 126, 127$ isotones by the generalized density-dependent cluster model (GDDCM) in combination with the microscopic two-level model. The decay widths are calculated using the overlap integral of the quasibound state wave function, the scattering state wave function, and the difference of potentials, instead of using the simple semiclassical WKB method along with the Bohr-Sommerfeld quantization condition. The α-preformation factors are evaluated by the Z-dependent formula based on the two-level model, where the closed-shell effect is included. The calculated half-lives of α transitions to both ground states and excited states are found to be in good agreement with the experimental data.

DOI: 10.1103/PhysRevC.80.014314 PACS number(s): 23.60.+e, 21.10.Tg, 21.60.Gx, 27.80.+w

PHYSICAL REVIEW C **87**, 024310 (2013)

Nuclear charge radii of heavy and superheavy nuclei from the experimental α-decay energies and half-lives

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[2]*Center of Theoretical Nuclear Physics, National Laboratory of Heavy-Ion Accelerator, Lanzhou 730000, China*
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(Received 10 December 2012; revised manuscript received 18 January 2013; published 13 February 2013)

The radius of a nucleus is one of the important quantities in nuclear physics. Although there are many researches on ground-state properties of superheavy nuclei, researches on charge radii of superheavy nuclei are rare. In this article, nuclear root-mean-square (rms) charge radii of heavy and superheavy nuclei are extracted from the experimental α-decay data. α-decay calculations are performed within the generalized density-dependent cluster model, where α-decay half-lives are evaluated using quasibound state wave functions. The charge distribution of daughter nuclei is determined in the double-folding model to reproduce the experimental α-decay half-lives. The rms charge radius is then calculated using the resulting charge distribution. In addition, a simple formula is also

First result on charge radii of superheavy nuclei by decay data

The two different methods show good agreement with the experimental data for even-even nuclei, and the deduced results are consistent with other theoretical models. Moreover, nuclear radii of heavy and superheavy nuclei with $Z = 98$–116 are extracted from the α-decay data, for which α decay is a unique tool to probe nuclear sizes at present. This is the first result on nuclear charge radii of superheavy nuclei based on the experimental α-decay data.

PRC 89 (2014) 024318: Nuclear charge radii of superheavy odd-mass and odd-odd nuclei from α-decay data

PHYSICAL REVIEW C **89**, 024318 (2014)

Tentative probe into the nuclear charge radii of superheavy odd-mass and odd-odd nuclei

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The root-mean-square (rms) nuclear charge radii of superheavy odd-A and odd-odd nuclei are tentatively pursued by the deduction of experimental α decay data. The framework of calculating α decay half-lives is constructed via the combination of the improved two-potential approach with the density-dependent cluster model. In this procedure, the charge distribution of daughter nuclei is determined to exactly reproduce the measured α decay half-lives. Next, the rms charge radius of daughter nuclei is obtained by using the corresponding charge distribution. For comparison, the previously proposed formula of our group is employed to estimate the rms charge radii as well. Besides the reasonable agreement between the extracted nuclear charge radii and the available experimental values, the nuclear radii of heaviest odd-A and odd-odd nuclei are extracted from the α decay energies and half-lives. This can be considered as an effective attempt in terms of the nuclear size in the superheavy mass region.

Microscopic calculation of α preformation factor ^{212}Po (PRC 2016, Xu, Ren,…Horiuchi...)

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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Cluster in medium and heavy nuclei

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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Cluster conferences in China and in Japan

2014.12 Nanjing U
2015.08 Hokkaido U &
Osaka-RCNP

2016.11 Yokohama

2016.07 PKU

2017.11 Hokkaido U
2018.11 Chengdu, China

2018 cluster conference at Chengdu, China

PRL 122, 192503 (2019), New isotope: ^{220}Np, N = 126 shell effect. Editor's suggestion

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

Editors' Suggestion

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

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PRL 125, 032502 (2020)： new isotope ^{222}Np

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.

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 ）

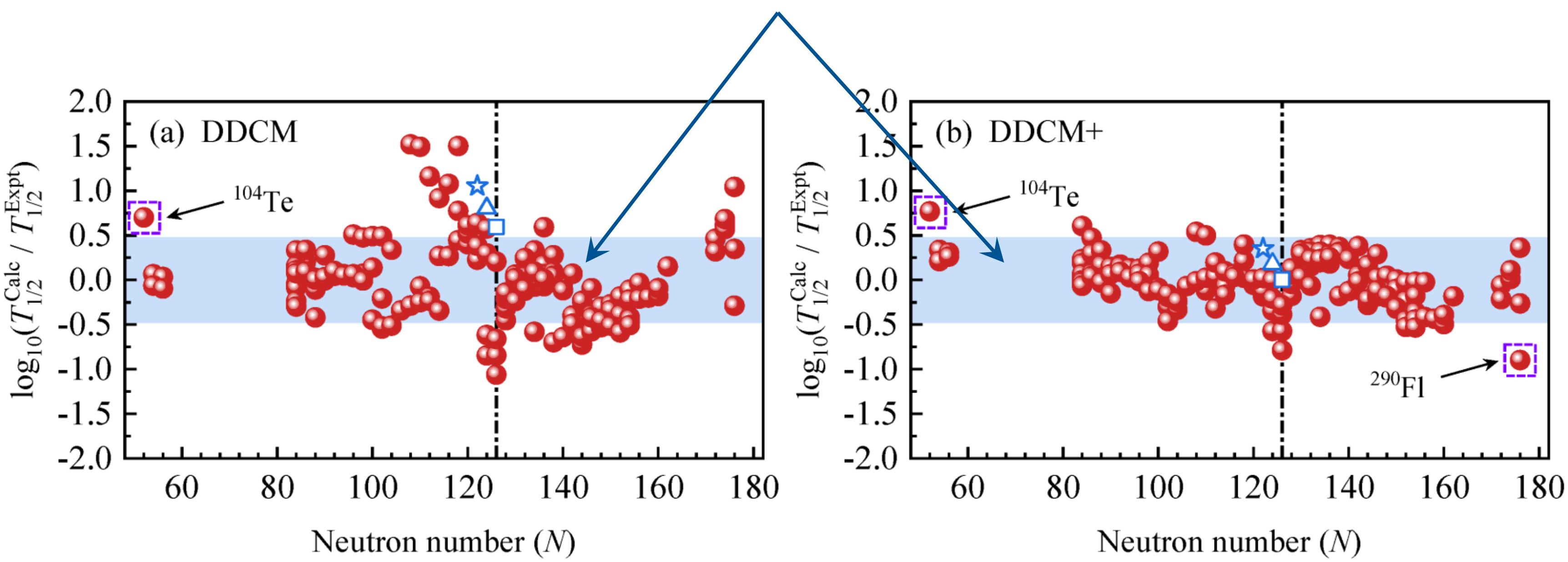
DDCM+ is in better agreement with data for new isotopes ^{214}U, ^{216}U and ^{218}U

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)

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 isotopes ^{216}U, ^{219,220,222}Np**

Thanks

- **Collaborators: C.Xu, D.Ni, X.P. Zhang, Y.Qian, Bo Zhou, Mengjiao Lyu, Q. Zhao， D. Bai, Z.Wang… Z.Gan…;**

  H. Horiuchi, Tohsaki, Funaki, Yamada，

  En'yo, P. Schuck, G. Roepke, M. Kimura, H.Toki, Ito…
- **happy to attend YKIS2022b (online).**
- **Thanks for your attention ….**