一些近期发现的同核异能态的壳模型解释

袁岑溪 刘梦兰 葛育霖

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在线阅读 View online: https://doi.org/10.11804/NuclPhysRev.37.2019CNPC18

引用格式:
袁岑溪, 刘梦兰, 葛育霖. 一些近期发现的同核异能态的壳模型解释[J]. 原子核物理评论, 2020, 37(3):447–454. doi: 10.11804/NuclPhysRev.37.2019CNPC18
YUAN Cenxi, LIU Menglan, GE Yulin. Shell–Model Explanation on Some Newly Discovered Isomers[J]. Nuclear Physics Review, 2020, 37(3):447–454. doi: 10.11804/NuclPhysRev.37.2019CNPC18

第 37 卷 第 3 期　　原 子 核 物 理 评 论　　Vol.37, No.3
2020 年 9 月　　Nuclear Physics Review　　Sep. , 2020

Article ID: 1007-4627(2020)03–0447–08

Shell-Model Explanation on Some Newly Discovered Isomers

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Abstract: Recently, isomeric states are discovered for the first time in ^{101}In, ^{123,125}Ag, and ^{218}Pa. The nuclear shell model is used to explain the underlying physics in these and related isomers in In, Ag isotopes, and the $N=127$ isotones. The observed excitation energies of the $1/2^-$ isomeric states in odd-A In isotopes, $^{101\text{-}109}$In, are rather similar among five isotopes, which can be explained by introducing the strong neutron configuration mixing between the $0g_{7/2}$ and $1d_{5/2}$ orbitals. In addition, from the $9/2^+$ ground state to the $1/2^-$ isomeric state in these odd-A In isotopes, a proton moves from the $1p_{1/2}$ orbital to the $0g_{9/2}$ orbital, which may induce the change on the single particle energies of the neutron $0g_{7/2}$ and $1d_{5/2}$ orbitals. Such configuration dependent shell evolution in one nucleus is called the type II shell evolution. Similar to In isotopes, the isomeric states in ^{123,125}Ag are found to be the $1/2^-$ states, which correspond to a proton hole in $1p_{1/2}$ orbital. But $1/2^-$ states are ground states in ^{115,117}Ag, which indicates an inversion of the proton $1p_{1/2}$ and $0g_{9/2}$ orbitals around $N=72$. The shell-model analysis shows that the tensor force is the key reason of the inversion of the two orbitals. A 1^- ground state and a high spin isomeric state are observed previously along the odd-odd $N=127$ isotones, ^{210}Bi, ^{212}At, ^{214}Fr, and ^{216}Ac. However, the ground state and the newly discovered isomeric state of ^{218}Pa are suggested to be 8^- and 1^-, respectively, based on the properties of α decay and the shell-model calculations. The evolution of the ground states and isomeric states along the odd-odd $N=127$ isotones are caused by the transition of the proton-neutron interaction from particle-particle type to hole-particle type and the proton configuration mixing. In general, the nuclear shell model gives nice descriptions on these newly discovered isomeric states in nuclei around the doubly magic nuclei ^{100}Sn, ^{132}Sn, and ^{208}Pb. The isomeric states in nuclei around doubly magic nuclei, so called the shell-model isomers, are of high importance in the nuclear structure study, because they often provide the first spectroscopic properties in the extreme neutron-rich and neutron-deficient nuclei in the medium and heavy mass region and include a plenty of information in physics, such as the proton-neutron interaction and its role in shell evolution.

Key words: nuclear shell model; isomer; shell evolution; configuration mixing; nuclear interaction

CLC number: O532.33　　**Document code:** A　　**DOI:** 10.11804/NuclPhysRev.37.2019CNPC18

1 Introduction

Isomeric states are of great importance for nuclear structure investigations. For example, the isomeric states in nuclei around doubly magic nuclei, so called the shell-model isomers, often provide the first spectroscopic properties in the extreme neutron-rich and neutron-deficient nuclei in the medium and heavy mass region and include a plenty of information, such as the proton-neutron interaction and its role in shell evolution. Recent years, many isomeric states are newly discovered in extreme neutron-rich and neutron-deficient nuclei around doubly magic, ^{100}Sn, ^{132}Sn, and ^{208}Pb. Because of relatively long half-lives, the properties of the isomeric states are easier to be observed and provide the first spectroscopic properties. Just in the year of 2019, discoveries on isomeric states are firstly reported in ^{101}In[1], ^{123,125}Ag[2], ^{134}In[3], and ^{218}Pa[4].

Fruitful discussions are made on the underlying

Received date: 22 Dec. 2019;　**Revised date:** 03 Apr. 2020

Foundation item: National Natural Science Foundation of China(11775316); Tip-top Scientific and Technical Innovative Youth Talents of Guangdong Special Support Program(2016TQ03N575); Computational Resources from SYSU and National Supercomputer Center in Guangzhou

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physics behind the observed isomeric states. The strong neutron configuration mixing between the $0g_{7/2}$ and $1d_{5/2}$ orbitals is introduced to explain the similarity among the excitation energies of the newly observed $1/2^-$ isomeric states in ^{101}In and those in odd-A In isotopes, $^{103\text{-}109}$In[1]. A six-nucleon noncollective isomeric state is found beyond a chiral-like pair band of ^{120}I[5]. Many isomeric states are found in ^{122}I and the corresponding configurations are identified by comparing with the calculations[6]. The evolution of the isomeric states from ^{117}Ag to ^{123}Ag is found to be caused by the tensor part of the nuclear interaction[2]. The isomeric state in ^{134}In is suggested to be 5^-[3] because its decay energy and reduced transition rate are close to the previous shell-model prediction on a 5^- isomeric state[7]. Based on the observations and shell-model calculations, the spin and parity of the ground states and the isomeric states are suggested to be inverted from ^{216}Ac to ^{218}Pa due to the proton-neutron interaction and the proton configuration mixing[4].

In the present work, the nuclear shell model is used to provide more detailed investigations on the newly discovered isomeric states in ^{101}In, ^{123,125}Ag, and ^{218}Pa, including Type I and II shell evolution and configuration mixing. A brief introduction is presented in Section 2 on the shell model and Hamiltonians used to investigate these isomeric states. The isomeric states in ^{101}In, ^{123,125}Ag, and ^{218}Pa are discussed in Sections 3, 4, 5, respectively. The present work is concluded in Section 6.

2 Nuclear shell model and hamiltonians

The nuclear shell model solves the many body Schrodinger equations with the full considerations of the configuration mixing in a truncated model space. It provides nice descriptions on the spectroscopic properties of the atomic nuclei, such as the binding energies (relative to the core), the levels, the electromagnetic properties, the β transitions, and the spectroscopic factors. Because the shell model is implemented in a truncated model space, it is of great importance to choose a proper model space and the corresponding Hamiltonian. During decades, a lot of shell model Hamiltonians are suggested for many model spaces. For example, the USD family provides the wonderful Hamiltonians for the *sd* region. But if the mirror nuclei are considered, the modified USD family with the weakly bound effect should be used to describe the mirror energy differences in the nuclei around $A=20$[8], which further explain the recent observations on the decay properties of ^{22}Si[9], ^{26}P[10], and ^{27}S[11–12].

The phenomenological nuclear force, the monopole based universal interaction V_{MU}[13] plus the M3Y spin-orbit interaction[14], is used as the cross shell interaction for the *psd* region[15], the ^{132}Sn region[7], and the ^{208}Pb[16] region. The *psd* Hamiltonian, YSOX, provides nice descriptions on the levels and the spectroscopic properties of ^{11}Be[17], the cross-shell components in ^{12}Be[18−19], the levels and the transition rates of ^{14}C[20], and the spectroscopic factors of C isotopes[21−22]. The Hamiltonian for the southeast region of ^{132}Sn, jj46Y16, predicted an isomeric state in ^{134}In, which is found in a recent work in RIKEN[3].

Encouraged by the nice performance of V_{MU} plus the M3Y spin-orbit interaction, it is possible to use it not only as the cross-shell interaction, but also as the full parts of the Hamiltonian. It is found in the previous works that one central part of V_{MU}, C10 with T, $S=1$, 0, should be enhanced by 15% for the proton-proton interaction and 5% for the neutron-neutron interaction[23−24]. The original V_{MU} plus the M3Y spin-orbit interaction with the modified proton-proton and neutron-neutron parts is used to calculate the Hamiltonian for investigations of ^{101}In, ^{123,125}Ag, and nearby nuclei, while the one for ^{101}In has been slightly modified. The model space for investigating ^{101}In and ^{123,125}Ag includes the proton $0f_{5/2}$, $1p_{3/2}$, $1p_{1/2}$, $0g_{9/2}$ orbitals and the neutron $0g_{7/2}$, $1d_{5/2}$, $1d_{3/2}$, $2s_{1/2}$, $0h_{11/2}$ orbitals.

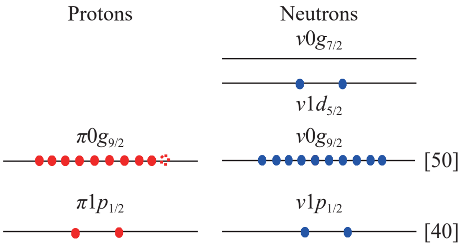
The isomeric states of ^{218}Pa and the $N=127$ isotopes are examined through the KHPE Hamiltonian[25], which is based on the Kuo-Herling interaction[26−27]. KHPE is recently used to identify the spin and parity of the ground state of ^{223}Np. The model space includes the proton $0h_{9/2}$, $1f_{7/2}$, $1f_{5/2}$, $2p_{3/2}$, $2p_{1/2}$, $0i_{13/2}$ orbitals and the neutron $0i_{11/2}$, $1g_{9/2}$, $1g_{7/2}$, $2d_{5/2}$, $2d_{3/2}$, $3s_{1/2}$, $0j_{15/2}$ orbitals. All the shell-model calculations are performed through the code KSHELL[28]. It should be noted that all calculations in the present work do not take into account the uncertainty of the shell-model Hamiltonians. Some uncertainty analyses are performed for the liquid drop model[29−30]. Although there are some analyses on the shell-model uncertainty[23, 31], they are still preliminary and need further investigations.

3 ^{101}In

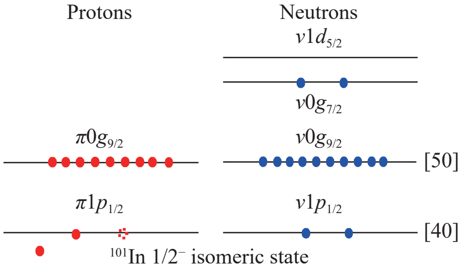
Recently, an isomeric $1/2^-$ state in ^{101}In is observed[1]. Compared through the previously observed data, the excitation energies of the isomeric $1/2^-$ states in odd-A isotopes, $^{101\text{-}109}$In, are close to each other. For the $^{101\text{-}109}$In isotopes, the $9/2^+$ ground state corresponds to a proton hole in the $0g_{9/2}$ orbital, while the $1/2^-$ isomeric state corresponds to a proton hole in the $1p_{1/2}$ orbital. From the single particle states of ^{101}Sn, It is found that the neutron $0g_{7/2}$ and $1d_{5/2}$ orbitals locate just beyond the $N=50$ magic number, while the other three orbitals, $1d_{3/2}$, $2s_{1/2}$, and $0h_{11/2}$ locate much higher[32]. The excitation energies of isomeric $1/2^-$ states in odd-A isotopes reflect the proton $Z=40$ subshell evolution as the function of neutron numbers.

It should be noted that the shell evolution is generally induced by the proton-neutron interactions. As discussed in Ref. [13], the $j=l\pm1/2$ neutron generally attracts the $j'=l'\mp1/2$ proton more than the $j''=l''\pm1/2$ proton, where j, j', j'' are the total angular momentum of certain orbitals and l, l', l'' are orbital angular momentum of certain orbitals. For example, the $1d_{5/2}$ ($0g_{7/2}$) neutron attracts the $1p_{1/2}$ ($0g_{9/2}$) proton more than the $0g_{9/2}$ ($1p_{1/2}$) proton. The occupancy of the $1d_{5/2}$ ($0g_{7/2}$) neutron increases (decreases) the $Z=40$ subshell gap and the excitation energies of the isomeric $1/2^-$ states. Such analysis is supported by the shell-model calculation[1]. Thus, the similar excitation energies of the isomeric $1/2^-$ states among the odd-A In isotopes, $^{101\text{-}109}$In, are caused by the strong neutron configuration mixing between the $0g_{7/2}$ and $1d_{5/2}$ orbitals. The neutrons occupy both these two orbitals with the increasing neutron number, which changes little on the $Z=40$ subshell gap.

On the other hand, the change of the proton configuration can induce the neutron shell evolution. A schematic picture is presented in Fig. 1 for the type II shell evolution in ^{101}In. The two neutrons above the $N=50$ shell are schematically presented for simplicity because they have strong configuration mixing between the $0g_{7/2}$ and $1d_{5/2}$ orbitals. The $1p_{1/2}$ ($0g_{9/2}$) proton attracts the $1d_{5/2}$ ($0g_{7/2}$) neutron more than the $0g_{7/2}$ ($1d_{5/2}$) neutron. From the $9/2^+$ ground state to the $1/2^-$ isomeric state in odd-A In isotopes, a proton moves from the $1p_{1/2}$ orbital to the $0g_{9/2}$ orbital. One more proton on the $0g_{9/2}$ orbital decreases the shell gap between the neutron $0g_{7/2}$ and $1d_{5/2}$ orbitals, while one less proton on the $1p_{1/2}$ orbital has a similar effect. Due to the proton-neutron interactions among four orbitals, it is thus expected that the shell gap between the neutron $0g_{7/2}$ and $1d_{5/2}$ orbitals can change a lot or even invert from the $9/2^+$ ground state to the $1/2^-$ isomeric state in the odd-A In isotopes. The shell-model calculations show that the neutrons occupy more on the $1d_{5/2}$ orbital in the $9/2^+$ ground state but more on the $0g_{7/2}$ orbital in the $1/2^-$ isomeric state[1]. From the calculated effective single particle energies (ESPE) of $^{99\text{-}105}$In, the $0g_{7/2}$ orbital locates higher than the $1d_{5/2}$ orbital in the $9/2^+$ ground state and lower in the $1/2^-$ isomeric state[1]. It is called type I shell evolution that the proton (neutron) shell evolves as the function of the neutron (proton) number. The proton (neutron) shell evolution in different states with different configurations in one nuclei is called type II shell evolution, which is suggested in ^{68}Ni firstly[33] and identified in some neutron-rich even-even and odd-odd nuclei, such as ^{96}Zr[34] and ^{70}Co[35]. The discovery of isomeric state in ^{101}In and the corresponding analysis on the possible type II shell evolution in a odd-A neutron-deficient nucleus provide a unique and novel candidate for type II shell evolution, of which the inversion of two neutron orbitals is induced by a single proton movement.



^{101}In 9/2$^+$ ground state



^{101}In 1/2$^-$ isomeric state

Fig. 1　(color online)Schematic configurations for $9/2^+$ ground state and $1/2^-$ isomeric state of ^{101}In.

Following above analysis, the excitation energies of the isomeric states in the odd-A In isotopes are rather sensitive to the proton-neutron interaction. As shown in Fig. 2, the monopole term between the proton $0g_{9/2}$ orbital and the neutron $0g_{7/2}$ orbital strongly affects the excitation energies of the isomeric states in the odd-A In isotopes with increasing neutron number. Only a 0.025 MeV change on this monopole results a change more than 0.5 MeV on the excitation energy of the isomeric state in ^{113}In when that in ^{101}In is fixed. The flat energies from ^{101}In to ^{109}In are induced by the balance of four proton-neutron interactions among the proton $1p_{1/2}$, $0g_{9/2}$ orbitals and the neutron $0g_{7/2}$, $1d_{5/2}$ orbitals. The Hamiltonian discussed in Section 2 can not exactly describe the balance. The mentioned monopole term between the $0g_{9/2}$ proton and the $0g_{7/2}$ neutron is modified to be 0.475 MeV more attractive, where the relative single particle energy between the proton $1p_{1/2}$ and the $0g_{9/2}$ are fitted to reproduce the excitation energy of the isomeric state in ^{101}In. Although it is difficult to judge which term of the proton-neutron interaction should be modified based on the present observables, the preset work provides a possible modification to reproduce the observed data and shows the sensitivity between the interaction and the levels.

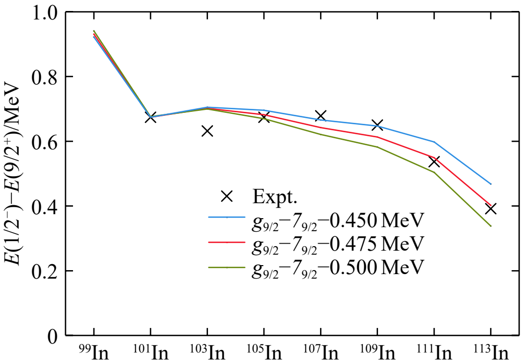


Fig. 2 (color online)The excitation energies of the isomeric states in the odd-A In isotopes, $^{101\text{-}113}$In. The proton-neutron interaction between the proton $0g_{9/2}$ orbital and the neutron $0g_{7/2}$ orbital is modified to be 0.450, 0.475, and 0.500 MeV more attractive, respectively, than the Hamiltonian described in Section 2.

4 ^{123,125}Ag

Nuclei around the ^{132}Sn region are of great interest because of their importance in both the fission products and the r-process. Recently, the level of ^{140}Te[36] is analysed based on the β decay of ^{140}I[37] through the EURICA collaboration. As discussed in Ref. [2], the ground states and the isomeric states are $9/2^+$ and $1/2^-$, respectively, in the odd-A Ag isotopes, $^{99\text{-}103}$Ag. But for the odd-A Ag isotopes, $^{105\text{-}117}$Ag, inversions are found while the ground states and the isomeric states become $1/2^-$ and $9/2^+$, respectively. Similar to the discussions in the odd-A In isotopes, the $9/2^+$ and $1/2^-$ states correspond to proton holes in $0g_{9/2}$ and $1p_{1/2}$ orbitals, respectively. But the situation is more complicated in the Ag isotopes because of their three proton holes rather than the one proton hole in the In isotopes. The spin-parities of the ground states and the isomeric states with their energy differences reflect the size of the $Z=40$ subshell gap in the odd-A Ag isotopes. The $Z=40$ subshell exists in $^{99\text{-}103}$Ag because of the $9/2^+$ ground states and the $1/2^-$ isomeric states. The $Z=40$ subshell disappears with the almost degenerate $1/2^-$ ground states and $9/2^+$ isomeric states in $^{105\text{-}117}$Ag. It should be noted that it is difficult to identify the $Z=40$ subshell gap purely from the $9/2^+$ and $1/2^-$ states because the $9/2^+$ state can be obtained by both the proton $(0g_{9/2})^{-3}$ and $(0g_{9/2})^{-1}(1p_{1/2})^{-2}$ configurations, while the proton firstly occupy the $1p_{1/2}$ orbital in the former case and the $0g_{9/2}$ orbital in the latter case. Both from the observed data and the shell-model calculations, the odd-A Ag isotopes always have a rather low lying or even ground $7/2^+$ states, which can not be coupled by the proton $(0g_{9/2})^{-1}(1p_{1/2})^{-2}$ configuration. It is thus concluded that the $9/2^+$ and the $1/2^-$ states in odd-A Ag isotopes are dominated by the $(0g_{9/2})^{-3}$ and the $(0g_{9/2})^{-2}(1p_{1/2})^{-1}$ configurations, respectively. The $(0g_{9/2})^{-3}$ configuration becomes more favourable when the $Z=40$ subshell exists. The $(0g_{9/2})^{-2}(1p_{1/2})^{-1}$ configuration becomes more favourable when the $Z=40$ subshell disappears.

It is of great interest to know whether the $Z=40$ subshell exists or not in the neutron-rich odd-A Ag isotopes, such as ^{123,125}Ag. The answer is found that the isomeric states in ^{123,125}Ag are discovered to be $1/2^-$ states but with rather small excitation energies[2]. The $Z=40$ subshell recovers with a small shell gap in ^{123,125}Ag. An inversion between the $1p_{1/2}$ and $0g_{9/2}$ orbitals is found from ^{117}Ag to ^{123}Ag. A schematic picture of the shell evolution is presented in Fig. 3 for comparison between ^{117}Ag and ^{123}Ag. The shell-model calculations with the Hamiltonian discussed in Section 2 well reproduce the levels of ^{123,125}Ag[2]. ESPE are calculated with and without the tensor interaction to further investigate which part of

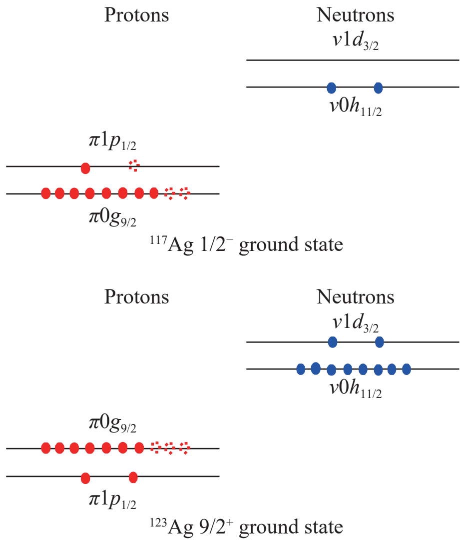


Fig. 3 (color online)Schematic configurations for $1/2^-$ and $9/2^+$ ground states of ^{117}Ag and ^{123}Ag, resepctively.

the nuclear interaction contributes to the inversion of the proton $1p_{1/2}$ and $0g_{9/2}$ orbitals around $N=72$. It is found that the $1p_{1/2}$ orbital locates always below $0g_{9/2}$ orbital without the tensor interaction, while with the tensor interaction it locates above $0g_{9/2}$ orbital around $N=68$ and below $0g_{9/2}$ orbital around $N=76$. The tensor interaction is the key reason to explain the inversion of the two orbitals around $N=72$.

As mentioned in Section 3, the $j=l\pm1/2$ neutron generally attracts the $j'=l'\mp1/2$ proton more than the $j''=l''\pm1/2$ proton. The $0h_{11/2}$ neutron attracts more the $1p_{1/2}$ proton rather than the $0g_{9/2}$ proton. From ^{117}Ag to ^{123}Ag, the neutrons mainly occupy the $0h_{11/2}$ orbital, which is the reason for the recovery of the $Z=40$ subshell. As observed and discussed in Ref. [2], the $Z=40$ subshell recovers with a small shell gap, which is because of the neutron configuration mixing between the $0h_{11/2}$ and $1d_{3/2}$ orbitals. The occupancy of the neutron $1d_{3/2}$ orbital has an opposite effect on the $Z=40$ subshell gap to that of the neutron $0h_{11/2}$ orbital. From ^{117}Ag to ^{123}Ag, the neutrons mainly occupy the $0h_{11/2}$ orbital but with certain mixing occupancy on the $1d_{3/2}$ orbital, which explains the recovery of the small $Z=40$ subshell gap.

It is worth using the present Hamiltonian for the further investigations on the astrophysical interested $N=82$ isotones because of its nice description on ^{123,125}Ag. Fig. 4 presents the low lying levels of the even $N=82$ isotones from ^{130}Cd to ^{120}Sr. It is clearly seen that the excitation energies of the 2^+, 4^+, 6^+, 8^+, 4^-, and 5^- states increase as the proton number decreases, while those of the 0_2^+ states decrease from ^{130}Cd to ^{122}Zr. If only the proton $1p_{1/2}$ and $0g_{9/2}$ orbitals are considered, the 2^+, 4^+, 6^+, and 8^+ states can only be coupled by the even protons on the $0g_{9/2}$ orbital and the 4^- and 5^- states can only be coupled by the odd protons on the $0g_{9/2}$ orbital and the single proton on the $1p_{1/2}$ orbital. The ground state and the 0_2^+ state are from different configuration mixing between the proton pairs on these two orbitals. The results in Fig. 4 show that the protons favour to couple to pairs with zero angular momentum. Actually, the protons also remove from the $1p_{3/2}$ orbital and even the $0f_{5/2}$ orbital from ^{130}Cd to ^{120}Sr. The proton $1p_{1/2}$ and $0g_{9/2}$ orbitals still have considerable occupancies of 0.678 and 2.251 in the ground state of ^{120}Sr, respectively. The $Z=38$ and 40 subshell gaps are not kept in the extreme neutron rich $N=82$ isotones, such as ^{122}Zr and ^{120}Sr, based on the present study.

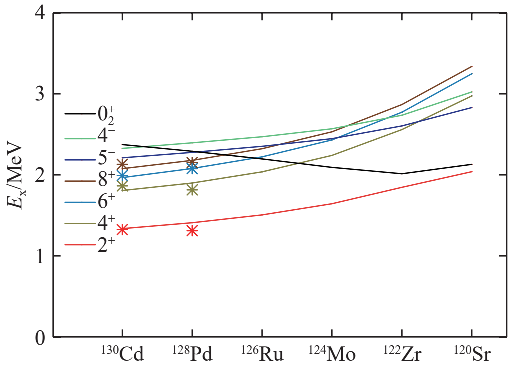


Fig. 4 (color online)Observed (points) and calculated (lines) levels of the even $N=82$ isotones from ^{130}Cd to ^{120}Sr.

5 ^{218}Pa

A 1^- ground state and a high spin isomeric state are observed along the odd-odd $N=127$ isotones, ^{210}Bi, ^{212}At, ^{214}Fr, and ^{216}Ac[32]. In these odd-odd $N=127$ isotones, both the 1^- ground state and the high spin isomeric state are from the multiplet coupled by the odd $0h_{9/2}$ protons and the single $1g_{9/2}$ neutron. Recently the isomeric state in ^{218}Pa is discovered for the first time[4]. It is not possible to identify the spin-parity of both the ground state and the isomeric state due to the limited statistics of the data. It is very natural to assume that the ground state is a 1^- state and the isomeric state is a high spin state following the systematics of the other $N=127$ isotones.

However, some facts from the observations and the shell-model calculations show deviations from such assumptions. Firstly, the excitation energies of the high spin isomers decrease from ^{210}Bi to ^{216}Ac. The newly discovered isomeric state in ^{218}Pa has a larger excitation energy than that of ^{216}Ac, which deviates from the systematic trend of the odd-odd $N=127$ isotones[4]. Secondly, the shell-model calculations reproduce the observed spins and parities of the ground states and the isomeric states of ^{210}Bi, ^{212}At, ^{214}Fr, and ^{216}Ac but predict a 8^- ground state for ^{218}Pa. Following the α decay properties and the shell-model calculations, the ground state and isomeric state of ^{218}Pa are suggested to be 8^- state and 1^- state, respectively[4].

It is worth investigating further the mechanism which induces the evolution of the ground states and the isomeric states among $N=127$ isotones. As shown in Fig. 5, constrained calculations, of which protons are constrained with $(0h_{9/2})^n$ configuration or with $(0h_{9/2}1f_{7/2}0i_{13/2})^n$ configuration, are performed to identify the important configurations for the evolution. Along the $N=127$ isotones from ^{210}Bi to ^{218}Pa, the increasing protons mainly occupy the $0h_{9/2}$ orbital. However, if only the $0h_{9/2}$ protons are included in the model space while the other proton orbitals are excluded, it is found from Fig. 5 that the excitation energies of the high spin isomer decrease very quickly and become the ground state in ^{214}Fr. It should be noted that KHPE interaction fixed the proton-neutron interaction to reproduce the multiplet in ^{210}Bi, while the evolution from ^{210}Bi should be investigated. From ^{210}Bi to ^{218}Pa, the proton-neutron particle-particle interaction in the $(0h_{9/2})^1(1g_{9/2})^1$ configuration changes to the proton-neutron hole-particle interaction in the $(0h_{9/2})^{-1}(1g_{9/2})^1$ configuration when the protons only occupy the $0h_{9/2}$ orbital. The transition from the particle-particle interaction to the hole-particle interaction drives the decreasing energy between the high spin 8^- state and the 1^- state but much more quickly than the observations. If the $0h_{9/2}$, $1f_{7/2}$, and $0i_{13/2}$ orbitals are included in the model space, the calculated results are rather close to the calculations with the full model space. From ^{210}Bi to ^{218}Pa, the protons occupy not only the $0h_{9/2}$ orbital but also the $1f_{7/2}$ and $0i_{13/2}$ orbitals. The protons on the $1f_{7/2}$ and $0i_{13/2}$ orbitals generally couple to pairs which contribute little on the spin but some on the energy.

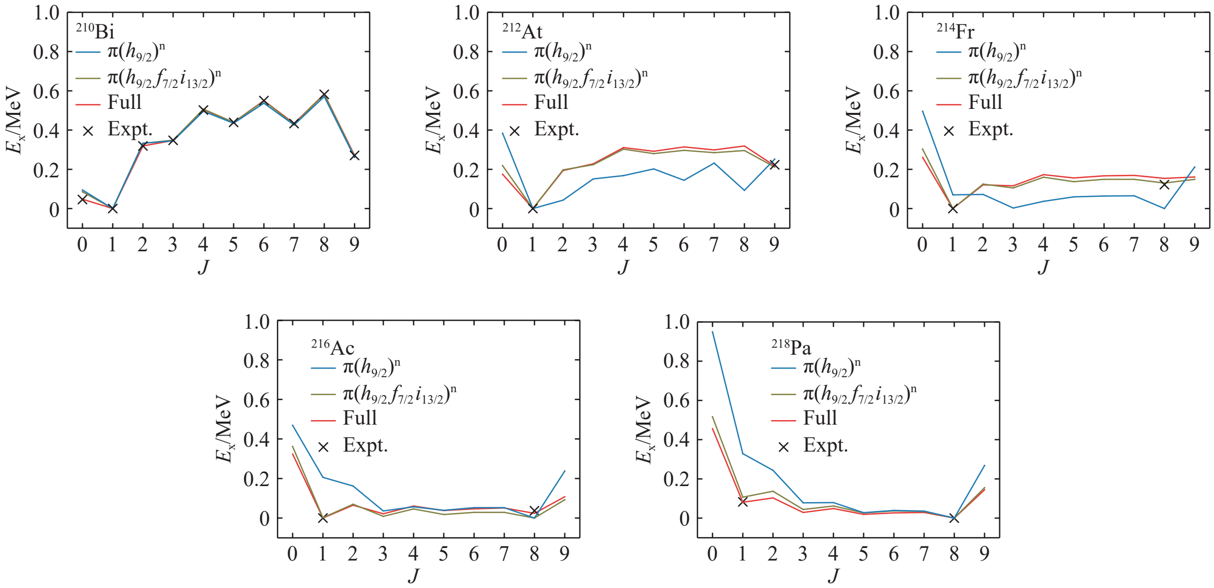


Fig. 5 (color online)Observed (points) and calculated (lines) levels of the odd-odd $N=127$ isotones from ^{210}Bi to ^{218}Pa.

6 Conclusion

In summary, the newly discovered isomeric states in ^{101}In, ^{123,125}Ag, and ^{218}Pa are well reproduced by the shell-model calculations, which provides a nice basis to investigate the underlying physics in these isomeric states.

The neutron configuration mixing is introduced to explain the similar excitation energies of the isomeric states in the odd-A In isotopes, $^{101\text{-}109}$In. The type II shell evolution is suggested for these isotopes that the relative positions between neutron $1d_{5/2}$ and $0g_{7/2}$ orbitals are different in the ground $9/2^+$ states and the isomeric $1/2^-$ states in these In isotopes. The shell-model calculations also show strong sensitivity between the proton-neutron interaction and the excitation energies of the isomeric states.

The newly discovered isomeric states in ^{123,125}Ag indicate the recovery of the $Z=40$ subshell. The tensor interaction is found to be the key components in the nuclear interaction to reproduce the $Z=40$ subshell evolution from ^{117}Ag to ^{123}Ag. Based on the nice description on ^{123,125}Ag, the same Hamiltonian is used to investigate the levels of the $N=82$ isotones. The $Z=38$ and 40 subshell are found to be not kept in the extreme neutron-rich $N=82$ isotones.

Based on the observed α decay properties and the shell-model calculations, the ground state and the newly discovered isomeric state of ^{218}Pa are suggested to be the 8^- and 1^- states, respectively, which differ from the previous observed odd-odd $N=127$ isotones ^{210}Bi to ^{216}Ac with the ground 1^- states and the high spin isomeric states. The transition of the proton-neutron interaction from the particle-particle type to the hole-particle type is found to be the key interaction contributed to the rapid evolution between the ground states and the isomeric states in the odd-odd $N=127$ isotones. The configuration mixing from the other two proton orbitals, $1f_{7/2}$ and $0i_{13/2}$, slows the evolution and reproduces well the observed data.

It is expected that V_{MU} plus the M3Y spin-orbit interaction can provide a universal interaction for the nuclear structure study, which are preliminarily investigated in the present work and Refs. [23–24]. It is more reliable to perform the shell-model calculations based on one effective interaction, while the Gogny interaction is also a potential one[38–39].

Acknowledgement Prof. Zhang Yuhu, Prof. Wang Meng, Prof. Xu Xing, Prof. Yang Huabin, and Prof. Zhang Zhiyuan from the Institute of Modern Physics, CAS and Prof. Li Zhihuan, Prof. Hua Hui, and Dr. Chen Zhiqiang from Peking University are appreciated for their helpful discussions.

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一些近期发现的同核异能态的壳模型解释

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摘要:　近期，在 ^{101}In、^{123,125}Ag 和 ^{218}Pa 等核中，首次观测到同核异能态。本工作通过原子核壳模型解释 In、Ag 同位素和 $N=127$ 同中素中的这些同核异能态及相关的同核异能态背后的物理原因。$^{101\text{-}109}$In 这五个奇 A 核 In 同位素中，观测到的 $1/2^-$ 同核异能态的激发能非常接近。这可以通过引入中子 $0g_{7/2}$ 和 $1d_{5/2}$ 轨道间的很强的组态混合来解释。更进一步分析表明，这些奇 A 核 In 同位素中，从 $9/2^+$ 基态到 $1/2^-$ 同核异能态，一个质子从 $1p_{1/2}$ 轨道激发到 $0g_{9/2}$ 轨道。这一质子组态变化可能引发中子 $0g_{7/2}$ 和 $1d_{5/2}$ 轨道的单粒子能变化。这样一个原子核内的组态依赖的壳演化被称为第二类壳演化。与 In 同位素类似，^{123,125}Ag 的同核异能态被发现是 $1/2^-$ 态，对应着一个质子空穴在 $1p_{1/2}$ 轨道。但之前观测到的 ^{115,117}Ag 的 $1/2^-$ 态是基态。这意味着质子 $1p_{1/2}$ 轨道和 $0g_{9/2}$ 轨道在 $N=72$ 附近发生了反转。壳模型分析表明张量力是造成这两个轨道反转的决定性原因。之前观测到的奇奇核 $N=127$ 同中素 ^{210}Bi、^{212}At、^{214}Fr 和 ^{216}Ac 中，基态是 1^- 态，同时存在高自旋的同核异能态。然而，基于 α 衰变性质和壳模型计算，推荐 ^{218}Pa 中的基态和新发现的同核异能态分别为 8^- 态和 1^- 态。奇奇核 $N=127$ 同中素基态和同核异能态的演化是由质子中子相互作用从粒子粒子形式转化为空穴粒子形式以及质子组态混合所导致。总的来说，壳模型对这些双幻核 ^{100}Sn、^{132}Sn 和 ^{208}Pb 附近核中新发现的同核异能态有较好的描述。双幻核附近核中的同核异能态，也称为壳模型同核异能态，是核结构研究中非常重要的。因为这些同核异能态常常提供了中重质量区域极端丰中子和缺中子原子核中的第一个谱学性质，并包含了丰富的物理信息，比如质子中子相互作用及其在壳演化中的作用。

关键词:　原子核壳模型；同核异能态；壳演化；组态混合；核相互作用

收稿日期: 2019-12-22；　**修改日期:** 2020-04-03

基金项目: 国家自然科学基金资助项目 (11775316)；广东特支计划科技创新青年拔尖人才项目 (2016TQ03N575)；中山大学和广州超算中心的计算资源

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