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High-spin Level Structure of the Neutron-rich Nucleus ^{91}Y

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Abstract: High-spin level structure of the neutron-rich nucleus ^{91}Y has been reinvestigated via the ^{82}Se(^{13}C, p3n)^{91}Y reaction. A newly constructed level scheme including several key levels clarifies the uncertainties in the earlier studies. These levels are characterized by the breaking of the $Z = 38$ and $N = 56$ subshell closures, which involves in tensor force and the spin-isospin dependent central force.

Key words: neutron-rich nucleus; level scheme; tensor force; spin-isospin dependent central force
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1 Introduction

It is well known that the high-spin states of near-spherical nuclei can be constructed by the aligned angular momentum of open shell nucleons. The maximum spin occurs at the configuration termination in the valence space. To generate higher-spin states, the shell closure should be broken. A number of studies have revealed such excitation process for nuclei around the quasidoubly magic nucleus ^{88}Sr[1–4].

The low-lying levels of nuclei with $38 < Z < 50$ and $50 < N < 56$ are dominated by the valence-nucleon excitations within the $\pi(p_{1/2}, g_{9/2})$ and $\nu d_{5/2}$ shell-model orbitals. The medium- or high-spin levels can be understood as the particle-hole excitations. Federman *et al.* [5–6] have theoretically studied the proton $p_{3/2} \rightarrow p_{1/2}$ and neutron $d_{5/2} \rightarrow g_{7/2}$ excitations and given the reasonable explanations for the reductions of the $Z = 38$ and $N = 56$ energy gaps. The proton-neutron interaction includes tensor force and the spin-isospin dependent central force[7–8]. In the picture of tensor force[7], the enhanced $\pi p_{1/2}$−$\nu d_{5/2}$ and reduced $\pi p_{3/2}$−$\nu d_{5/2}$ monopole interaction may arise from the tensor component if the others contribute the same interactional values. Hence, when the $\nu d_{5/2}$ orbital is occupied by more neutrons, the $\pi p_{1/2}$ orbital goes down while $\pi p_{3/2}$ orbital comes up, that is, the $Z = 38$ energy gap becomes smaller. Likewise, the reduction of the $N = 56$ gap can be associated with the spin-orbital partners $\pi g_{9/2}$ and $\nu g_{7/2}$[6], between which the interaction is the so-called spin-isospin dependent central force[8].

The production of neutron-rich nucleus ^{91}Y is problematic via the conventional (HI, xn) reaction. High-spin states of ^{91}Y have been initially investigated via fusion-evaporation reaction ^{82}Se(^{12}C, p2n)^{91}Y[9]. It was not until recently that an extended level scheme is constructed by means of the fission of ^{221}Pa produced by a ^{24}Mg beam impinging on a ^{173}Yb target[10]. In this work, the high-spin level structure is reinvestigated and the configurations are figured out, in analogy to our earlier study of the $N = 52$ isotone ^{92}Zr[11].

2 Experiment

High-spin states of ^{91}Y were populated through the ^{82}Se(^{13}C, p3n)^{91}Y reaction. The ^{13}C beam was provided by the HI-13 Tandem Accelerator of the China Institute of Atomic Energy(CIAE), and the target was 2.11 mg/cm^2 isotopically enriched ^{82}Se on 8.56

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mg/cm^2 natural lead backing. The emitted γ rays from the reaction products were detected by an array consisting of 2 planar and 12 Compton-suppressed HPGe detectors. The energy and efficiency calibrations were made using the ^{60}Co, ^{133}Ba, and ^{152}Eu standard sources and the typical energy resolution was 2.0～2.5 keV at full width at half-maximum (FWHM) for the 1332.5- keV γ ray of ^{60}Co. Events were collected when at least 2 detectors were fired within the prompt 80 ns coincidence time window. Under these conditions, a total of 2.5×10^7 coincidence events were recorded and the data was sorted into a symmetrized E_γ-E_γ matrix for subsequent off-line analysis.

In order to obtain multipolarity information of the emitted γ rays, two asymmetric coincidence matrices were constructed using the γ rays detected at all angles (as y axis) against those observed at ～34° (or ～146°) and 90° angles (as x axis) respectively. The ADO (γ ray angular distribution from oriented nuclei) ratio[12] is defined as $R_{\rm ADO}(\gamma)=\frac{I_\gamma(34^\circ)}{I_\gamma(90^\circ)}=\frac{N_\gamma(34^\circ)/\epsilon_\gamma(34^\circ)}{N_\gamma(90^\circ)/\epsilon_\gamma(90^\circ)}$ (here γ refers to a particular energy value.). By setting gates on the y-axis with all the detectors, the γ ray intensities $I_\gamma(34^\circ)$ and $I_\gamma(90^\circ)$ were extracted from the coincidence spectra regardless of the multipole character of the gating transition. Generally, one transition is adopted as stretched quadrupole transition if its $R_{\rm ADO}(\gamma)$ is significantly larger than 1.0 or adopted as dipole transition if its $R_{\rm ADO}(\gamma)$ is less than 1.0.

3 Experimental results

We have noticed a significant difference between the level schemes given in the earlier studies[9–10]. To the extent of our knowledge, it is difficult to understand the identified strong γ rays in Ref. [10] not listed in Ref. [9]. In order to clarify the uncertainties, we have carefully checked the γ-γ coincidence relationships and construct a new level scheme shown in Fig. 1. Except for 3 569.1-, 5 579.9-, 5 781.2- keV levels and 1 411.9-, 953.5-, 1 094.5-, 1 297.8- keV γ rays (see Fig. 2 for γ-γ coincidence relationships), the other levels and γ rays in Ref. [10] can not be confirmed in the present work. It is worth pointing out that the 766.8- and 579.3- keV γ rays are weak in Fig. 2 but can be confirmed in coincidence with the 672.3-, 335.0- and 327.7- keV lines.

On referring to the prior studies[9–10], an obvious contribution of our work is the revisional or tentative assignment of the spin-parity values of the 3 734.4-, 4 483.4- and 4 811.1- keV levels. According to the ADO ratios of γ rays listed in Table 1, the 1 577.0- keV γ ray is a quadrupole transition and the spin of the 3734.4- keV level is therefore (21/2). Accepting the spins and parities of 3 528.4- and 4148.4- keV levels in Ref. [9], the intensity ratio between the 415.3- and 619.6- keV lines proposes that the former is an electric quadrupole(E2) rather than magnetic quadrupole(M2) transition and the parity of the 3 734.4- keV level is therefore positive. It can be seen from Fig. 3 that the 327.7- and 335- keV lines are obviously dipole transitions if the 619.6-, 929.5-, 1371.0- and 1 577.0- keV lines are quadrupole ones. Hence, the 4 483.4- keV level is (27/2). Considering the intensity ratio of the 335.0- and 953.5- keV γ rays, the 953.5- keV γ ray should be an E3 rather than M3 transition and the parity of the 4483.4- keV level is of course negative. (29/2) is tentatively adopted for the 4811.1- keV level according to the dipole character of the 327.7- keV line.

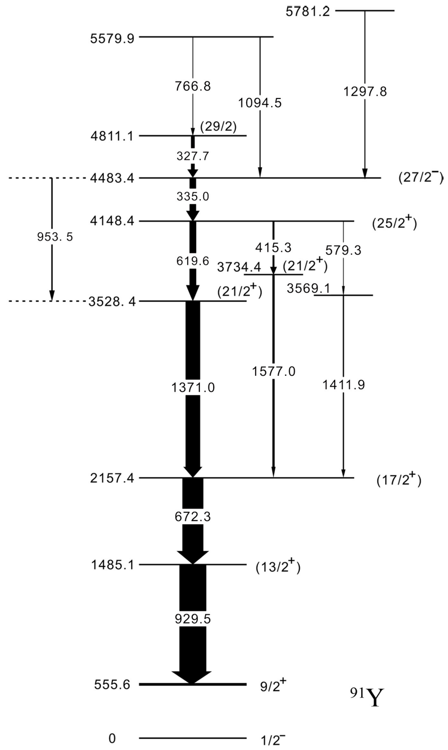

Fig. 1 The revised level scheme of ^{91}Y deduced from the present work. The 579.3-, 1 411.9-, 953.5-, 1 297.8-, 766.8- and 1 094.5- keV γ rays are newly added into the level scheme compared with that in Ref. [9].

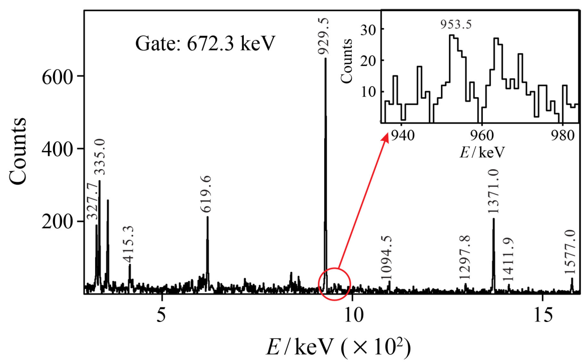

Fig. 2 Typical coincidence spectrum for ^{91}Y gated on the 672.3- keV line.

Table 1　The γ ray transition energies, relative intensities, ADO ratios, and their assignments in ^{91}Y.

E_γ/keV [a]	I_γ [b]	$R_{\rm ADO}$	$E_{\rm i}\rightarrow E_{\rm f}$/keV [c]	$J_{\rm i}^{\pi}\rightarrow J_{\rm f}^{\pi}$ [d]
327.7	17.7	0.42(5)	4811.2 → 4483.5	(29/2) → (27/2$^-$)
335.0	31.0	0.46(7)	4483.5 → 4148.5	(27/2$^-$) → (25/2$^+$)
415.3	9.1	1.45(19)	4148.5 → 3734.3	(25/2$^+$) → (21/2$^+$)
579.3	7.1		4148.5 → 3569.7	(25/2$^+$) →
619.6	32.0	1.06(15)	4148.5 → 3528.4	(25/2$^+$) → (21/2$^+$)
672.3	100	1.29(13)	2157.4 → 1485.1	(17/2$^+$) → (13/2$^+$)
766.8	3.8		5578.0 → 4811.2	→ (29/2)
929.5	⩾127.6	1.41(13)	1485.1 → 555.6	(13/2$^+$) → 9/2$^+$
953.0	6.6		2131.1 → 1882.4	(27/2$^-$) → (21/2$^+$)
1 094.5	5.0		5578.0 → 4483.5	→ (27/2$^-$)
1 297.8	4.9		5781.3 → 4483.5	→ (27/2$^-$)
1 371.0	69.3	1.27(23)	3528.4 → 2157.4	(21/2$^+$) → (17/2$^+$)
1 411.9	6.0		3569.1 → 2157.4	→ (17/2$^+$)
1 577.0	11.1	1.30(43)	3734.3 → 2157.4	(21/2$^+$) → (17/2$^+$)

a　Uncertainties are within 0.5 keV.
b　Uncertainties are within 30%.
c　Excitation energies of initial $E_{\rm i}$ and final $E_{\rm f}$ states.
d　Proposed spin and parity assignments for the initial $J_{\rm i}^{\pi}$ and final $J_{\rm f}^{\pi}$ levels.

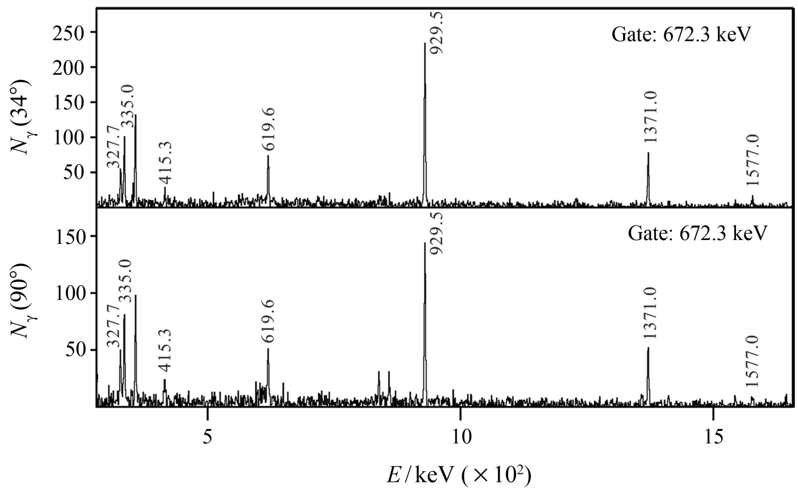

Fig. 3　γ ray counts $N_\gamma(34°)$ and $N_\gamma(90°)$ of the two asymmetry matrices at 34° and 90° angles respectively gated on the 672- keV line. It's very clear that the 327.7- and 335.0- keV γ rays are dipole transitions for their ADO ratios are smaller than 1.0 while the 619.6-, 929.5-, 1 371.0- and 1 577.0- keV lines are quadrupole transitions for their ADO ratios are larger than 1.0.

4　Discussion

Since the Fermi levels of ^{91}Y lie at the $\pi p_{1/2}$ and $\nu d_{5/2}$, the active proton and neutron orbitals are $(f_{5/2}, p_{3/2}, p_{1/2}, g_{9/2})$ and $(d_{5/2}, s_{1/2}, d_{3/2}, g_{7/2}, h_{11/2})$, respectively (for the single-particle energies see Ref. [11]). The $9/2^+$ state is naturally the $g_{9/2}$ proton coupled with two $d_{5/2}$ neutrons in pair. It is expected that the $(13/2^+)$ level above the $9/2^+$ can be associated with the $\pi g_{9/2}\otimes\nu(d^2_{5/2})_{2^+}$. The three-particle $\pi g_{9/2}\otimes\nu d^2_{5/2}$ configuration may persist till the $(17/2^+)$. The $(17/2^+)$ is the maximum spin for the termination of the configuration in the space $\pi(p_{1/2}, g_{9/2})$ and $\nu d_{5/2}$.

Above the fully aligned $(17/2^+)$, the states should therefore arise from the competition of one proton and one neutron excitations across the respective $Z=38$, $N=56$ subshell closures. It has been pointed out in our previous results[11] that the low-energy one is attributed to the neutron excitation. In the same way, we propose that the excitation from the 2 157.4 keV $(17/2^+)$ to 3 528.4 keV $(21/2^+)$ level is $\nu(d_{5/2}\rightarrow g_{7/2})$ and the 3 528.4 keV state has the $\pi g_{9/2}\otimes\nu(d_{5/2}g_{7/2})$ configuration. The $\nu g_{7/2}$ single-particle excitation energy relative to the $\nu d_{5/2}$ decreases from ∼2.19 MeV in ^{91}Zr to ∼ 0.17 MeV in ^{101}Sn [13], namely ∼ 0.2 MeV lowered by adding a proton into the $g_{9/2}$ orbital. The energy of the $\nu(d_{5/2}\rightarrow g_{7/2})$ excitation in ^{92}Zr $((12^+)\rightarrow(14^+_1))$ is 1 098.4 keV. Thus we can predict the excitation energy of the $\pi g_{9/2}\otimes\nu d^2_{5/2}\rightarrow\pi g_{9/2}\otimes\nu(d_{5/2}g_{7/2})$ in ^{91}Y to be ∼1 298.4(=1 098.4+200) keV;

the 1 371- keV energy (see Fig. 1) agrees reasonably well with this value. The lowered $\nu(d_{5/2} \to g_{7/2})$ excitation energy reflects the dramatic reduction of the $N = 56$ energy gap due to the spin-isospin dependent central force.

Given the 3 528.4 keV state as neutron particle-hole excitation, the other $(21/2^+)$ at 3 734.4 keV is naturally attributed to the proton particle-hole excitation. Since the $Z = 38$ energy gap is separated by the $\pi p_{3/2}$ and $\pi p_{1/2}$, the particle-hole excitation might be $\pi(p_{3/2} \to p_{1/2})$. Thus the energy gap in ^{91}Y (1 577.0 keV) is ~ 0.233 MeV lower than $\sim$1.8 MeV to break the $Z = 38$ subshell closure in ^{88}Sr which is demonstrated by the excitation energy of the 2^+ state[13]. This indicates a possible reduction of the energy gap when two neutron goes into the $d_{5/2}$ orbital. From the introduction part, the reduction may be associated with the proton-neutron tensor force[8]. To generate the (25/2) spin value, both of the $Z = 38$ and $N = 56$ subshell closures should be broken. Therefore, the $\pi(p^{-1}_{3/2}p_{1/2}g_{9/2}) \otimes \nu(d_{5/2}g_{7/2})$ configuration is proposed for the $(25/2^+)$ state.

For achieving higher-spin state, the proton should be further excited to the $g_{9/2}$, namely $\pi(p_{3/2}/f_{5/2} \to g_{9/2})$. The $(27/2^-)$ and (29/2) states appear to be associated with the $\pi(p^{-1}_{3/2}g^2_{9/2}) \otimes \nu(d_{5/2}g_{7/2})$ and $\pi(f^{-1}_{5/2}g^2_{9/2}) \otimes \nu(d_{5/2}g_{7/2})$ configurations, respectively.

5 Summary

The high-spin level structure of ^{91}Y has been reinvestigated through the ^{82}Se(^{13}C, $p3n$)^{91}Y fusion-evaporation reaction. The level scheme has been modified. The spin-parity values of states in ^{91}Y above the fully aligned $(17/2^+)$ state have been proposed. The configuration of high-spin states above the fully aligned $(17/2^+)$ state are figured out in terms of the breaking of the $Z = 38$ and $N = 56$ subshell closures. The tensor force and spin-isospin dependent central force play an important role in breaking the subshells.

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丰中子核 ^{91}Y的高自旋能级结构

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摘要： 再次研究了丰中子核^{91}Y 的高自旋能级结构通过^{82}Se(^{13}C, p3n)^{91}Y 反应。新建立的包含几条关键能级的能级纲图澄清了以前研究中的几点不确定的地方。这几条能级具有$Z = 38$和$N = 56$子闭壳打破的特征，这涉及到张量力和自旋-同位旋依赖的中心力。

关键词： 丰中子核；能级纲图；张量力；自旋-同位旋依赖的中心力

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