New high spin level scheme of ^{87}Sr *

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Abstract: High spin states of the odd-A ^{87}Sr were populated by the fusion-evaporation reaction ^{82}Se(^{9}Be,4n) ^{87}Sr at a beam energy of 46 MeV. Excited levels of ^{87}Sr have been extended up to an excitation energy of 7.4 MeV at spin $31/2\hbar$. The coupling of a $g_{9/2}$ neutron hole to the yrast states of the ^{88}Sr core can account for the low-lying states in ^{87}Sr. The structure of the higher spin states is discussed by analogy with those of the neighboring odd-A $N=49$ isotones and possible configurations are proposed.

Key words: high spin state, fusion-evaporation reaction, $N=49$ isotone

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1 Introduction

The excited states of nuclei around the $N=50$ closed shell have aroused many theoretical and experimental studies. The nuclei in this region show many interesting characters, such as spherical shape, irregular de-excited energy and intrinsic particles excitation. The level structure study of ^{87}Sr is very interesting because it has 38 protons at the $Z=38$ semimagic shell closure and a neutron hole at the $N=50$ closed shell as a non-deformed nucleus. High spin states in ^{87}Sr have previously been investigated using ^{84}Kr(α,n) ^{87}Sr and ^{86}Kr(α,3n) ^{87}Sr reactions [1]. The level scheme of ^{87}Sr has been extended up to an excitation energy of 4.44 MeV at spin $23/2\hbar$. An assignment of $13/2^{+}$ for the 1740 keV level and the dipole natures of the yrast cascade were suggested by the analysis of the angular distributions. The following structure of ^{87}Sr has been studied by Ekström et al using the reaction ^{84}Kr(α,nγ) ^{87}Sr [2]. The mean lifetime measurements have been made for some levels by using the DSA method. Angular distribution and linear polarization measurements have been made for several levels of spin and parity assignments.

The aim of the present work is to extend the existing level scheme of ^{87}Sr to higher spins and excitation energies, and investigate the structure of the high spin states of ^{87}Sr.

2 Experimental details

The experiment was performed at the HI-13 tandem accelerator of the China Institute of Atomic Energy. High spin states of the odd-A ^{87}Sr were populated via the heavy ion fusion-evaporation reaction ^{82}Se(^{9}Be,4n) ^{87}Sr at a beam energy of 46 MeV. A detector array consisting of nine Compton-suppressed HPGe detectors, two planar HPGe detectors, and one Clover detector was used to measure the in-beam γ-ray. The target consisted of an 0.85 mg/cm^2 foil of ^{82}Se evaporated on a 4.45 mg/cm^2 natural gold backing. The detectors were calibrated for efficiency using the standard γ sources of ^{133}Ba and ^{152}Eu. A total of 1.1×10^{8} γ-γ coincidence events were recorded.

The data have been sorted into a γ-γ symmetrized and an asymmetric directional correlation of oriented states (DCO) coincidence matrices for off-line analysis. The asymmetric DCO matrix between the detectors at 40° (140°) and at 90° was constructed and used for the

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DCO ratio analysis [3] to distinguish between quadrupole and dipole transitions. For the present detector geometry, if one gates on a quadrupole transition then the $R_{\rm DCO}$ value is close to 1.0 for stretched quadrupole transitions and close to 0.5 for stretched dipole transitions. Similarly, using a dipole gating transition, the $R_{\rm DCO}$ value is close to 1.6 and 1.0 for quadrupole and dipole transitions, respectively. However, the stretched quadrupole transitions cannot be distinguished from $\Delta I=0$ dipole transitions. In these cases, cross-checks from crossover or parallel transitions could provide supplementary arguments for the spin and parity assignments.

3 Results and discussion

In comparison with earlier work on the nucleus ^{87}Sr [1, 2], a new partial level scheme including 21 new γ-ray transitions and 10 new levels deduced in the present work is shown in Fig. 1. The obtained γ-ray transitions energies, relative intensities, DCO ratios, and spin parity assignments of the initial and final states are listed in Table 1. The positive parity states are extended to 7441.9 keV at spin $31/2\hbar$. The 1739.6 keV gated spectrum shown in Fig. 2(a) displays the transitions, feeding the $13/2^+$ state of ^{87}Sr. Several new transitions with energies 100.4, 501.9, 711.6, 488.8, 299.4, 300.5, 767.9, 1322.1 and 954.0 keV decaying from positive parity states are indicated in this spectrum. This spectrum also shows the known transitions with energies 1090.9, 418.2, 141.5, 220.1 and 829.7 keV decaying from negative parity states. In addition, 299.4 keV transitions can be observed in Fig. 2(b) gated by a 300.5 keV transition, which shows that the γ transition labeled by 299.4 and 300.5 keV is a doublet peak in Fig. 2. The DCO ratio of the 1090.9 keV transition indicates its dipole character. Thus, I=15/2 is assigned to the 2830.5 keV and is consistent with the DCO ratios of the 235.2 keV $\Delta I=1$ and 855.7 keV $\Delta I=0$ transitions. In Ref. [2], angular distribution and linear polarization measurements have been used to obtain definite spin and parity assignments for the 2595.3 and 2830.5 keV levels with I^π=$13/2^-$ and $15/2^-$, respectively. Based on the DCO ratios deduced for the other γ transitions of Sequence 1, we assign I^π=$17/2^{(-)}$, $19/2^{(-)}$ up to $23/2^{(-)}$ for the 3248.7, 3390.2 to 4440.0 keV levels, respectively, which is in agreement with Ref. [1, 2].

Sequence 2 is built on the $17/2^{(+)}$ level at 4171.3 keV. The 4171.3 keV and 4570.8 keV levels have been assigned to I=17/2 and 19/2, respectively, according to the dipole characters of 1322.1 keV ($R_{\rm DCO}$=0.41) and 399.5 keV ($R_{\rm DCO}$=0.65) transitions, although the DCO values of 2431.7 and 1340.8 keV transitions could not be extracted because of their lower intensity. The 4671.2 keV level has been assigned to I=21/2 by considering the dipole character of the 954.0 and 1281.0 keV transitions. On the basis of quadrupole character of 1945.8 keV transition with DCO ratios of 0.82, I=17/2 has been assigned to the 3685.4 keV level. The strong transitions with energies 501.9, 711.6, 901.0 up to 767.9 keV show a dipole character from the DCO ratio analysis. As a result, the spin assignments of Sequence 2 are confirmed. By comparing the level structure in the isotope ^{85}Sr [4] with ^{87}Sr, this new structure of ^{87}Sr in the present work looks similar to the positive parity sequence of ^{85}Sr. Thus, we consider these new levels as a positive parity level sequence for ^{87}Sr.

Table 1. Energies, relative intensities, DCO ratios, and spin parity assignments of the initial and final states assigned to ^{87}Sr in the present work.

E_γ/keV$^{\rm a}$	$I_\gamma^{\rm b}$	$R_{\rm DCO}^{\rm c}$	$I_{\rm i}^\pi \rightarrow I_{\rm f}^\pi$
100.4	11.6(10)		$21/2^{(+)}\rightarrow 19/2^{(+)}$
141.5	33.8(18)	0.68(14)	$19/2^{(-)}\rightarrow 17/2^{(-)}$
220.1	25.5(13)	0.57(7)	$21/2^{(-)}\rightarrow 19/2^{(-)}$
235.2	1.0(3)	0.33(13)	$15/2^-\rightarrow 13/2^-$
299.4	6.9(7)		$27/2^{(+)}\rightarrow 25/2^{(+)}$
300.5	14.2(6)	0.88(22)$^{\rm d}$	$29/2^{(+)}\rightarrow 27/2^{(+)}$
327.0	7.5(4)	0.89(19)	$19/2^{(-)}\rightarrow 19/2^{(-)}$
399.5	6.2(7)	0.65(11)	$19/2^{(+)}\rightarrow 17/2^{(+)}$
418.2	58.9(28)	0.54(4)	$17/2^{(-)}\rightarrow 15/2^-$
488.8	7.6(6)	0.49(8)	$27/2^{(+)}\rightarrow 25/2^{(+)}$
501.9	22.5(14)	0.47(5)	$23/2^{(+)}\rightarrow 21/2^{(+)}$
711.6	11.8(7)	0.40(7)	$25/2^{(+)}\rightarrow 23/2^{(+)}$
767.9	12.0(10)	0.97(16)$^{\rm d}$	$31/2^{(+)}\rightarrow 29/2^{(+)}$
829.7	9.6(10)	0.87(7)$^{\rm d}$	$23/2^{(-)}\rightarrow 21/2^{(-)}$
855.7$^{\rm e}$	5.1(3)	1.05(44)	$13/2^-\rightarrow 13/2^+$
885.4	<0.5		$19/2^{(+)}\rightarrow 17/2^{(+)}$
901.0	10.1(9)	0.30(4)	$25/2^{(+)}\rightarrow 23/2^{(+)}$
954.0	6.2(8)	0.45(18)	$21/2^{(+)}\rightarrow 19/2^{(-)}$
985.8	<0.5		$21/2^{(+)}\rightarrow 17/2^{(+)}$
1060.9	2.5(3)		$21/2^{(+)}\rightarrow 21/2^{(-)}$
1090.9$^{\rm e}$	67.5(33)	0.44(4)	$15/2^-\rightarrow 13/2^+$
1180.6	3.9(5)	1.40(30)$^{\rm d}$	$19/2^{(+)}\rightarrow 19/2^{(-)}$
1281.0	2.9(4)	0.91(25)$^{\rm d}$	$21/2^{(+)}\rightarrow 19/2^{(-)}$
1322.1	8.5(5)	0.41(8)	$19/2^{(+)}\rightarrow 17/2^{(-)}$
1340.8	1.1(2)		$17/2^{(+)}\rightarrow 15/2^-$
1562.8	2.4(5)		$23/2^{(+)}\rightarrow 21/2^{(-)}$
1634.1	1.0(2)		$25/2^{(+)}\rightarrow 23/2^{(-)}$
1739.6$^{\rm e}$	100.0(17)		$13/2^+\rightarrow 9/2^+$
1945.8	3.1(4)	0.82(29)	$17/2^{(+)}\rightarrow 13/2^+$
2431.7	1.7(3)		$17/2^{(+)}\rightarrow 13/2^+$

(a) The uncertainty in strong γ-ray energies is less than 0.4 keV; for weak γ-ray energies, it is about 0.7 keV. (b) Intensities are corrected for detector efficiency and normalized to 100 for the 1739.6 keV transition. (c) DCO ratios from a gate on the quadrupole transition. (d) DCO ratios from a gate on the dipole transition. (e) γ-ray multipolarities adopted from previous work [1, 2].

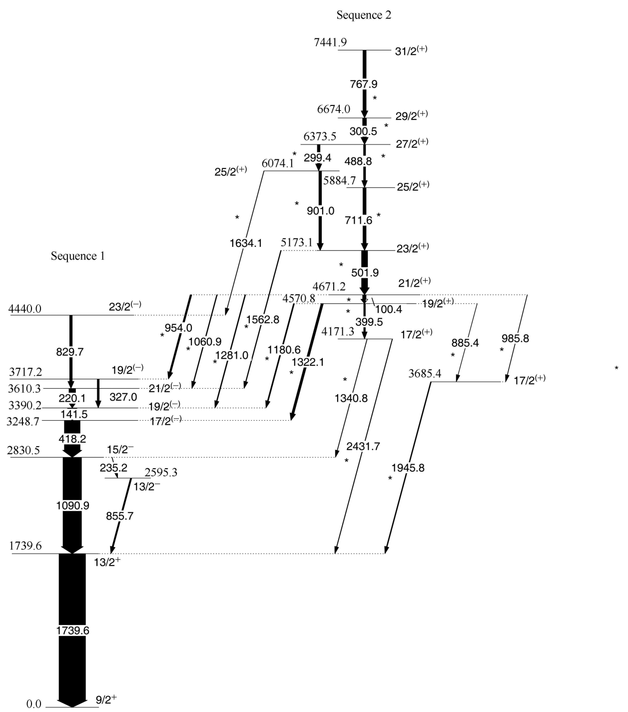

Fig. 1. The partial level scheme of ^{87}Sr obtained from the present work. The γ-ray energies are in keV. New γ transitions are marked by asterisks.

In Fig. 1, Sequence 1 is mainly constructed from several $\Delta I=1$ transitions, and the irregular level energies do not show any rotational behavior, which is the same as that at higher spin levels in Sequence 2. For the origin of the low-lying levels in ^{87}Sr, the possible ways that can be used all have a $g_{9/2}$ neutron hole coupled to the excited states of the even-even ^{88}Sr. This kind of analysis has been successfully applied to the structures of low-lying levels of ^{85}Kr [5], ^{91}Nb [6], ^{87}Rb [7] and ^{87}Zr [8]. Fig. 3 shows the low-lying states of ^{87}Sr and its neighboring isotope ^{88}Sr [9, 10], and a systematic comparison with their neighboring ^{85}Kr [5] and ^{86}Kr [5], respectively. The corresponding level energies are very close at between ^{87}Sr and ^{88}Sr, as well as ^{85}Kr and ^{86}Kr, respectively, because of the weakly coupling interaction. By comparing with the corresponding low-lying levels of ^{87}Sr and ^{88}Sr, the states of $9/2^+$ and $13/2^+$ for ^{87}Sr are perhaps formed by coupling a $g_{9/2}$ neutron hole to the 0^+ and 2^+ states of ^{88}Sr, respectively. Analogously, the $13/2^-$ and $15/2^-$ states may be characterized by coupling a $g_{9/2}$ neutron hole to the 3^- state. The 5^- or 6^- states of ^{88}Sr should dominate the $17/2^-$, $19/2^-$, $21/2^-$ states, and the 7^-

Table 2. Main configurations of low-lying level in ^{87}Sr relative to the ^{88}Sr core.

$E_{\rm i}$/keV	I^π	proposed configuration (s)
0	$9/2^+$	$\nu g_{9/2}^{-1}$
1739.6	$13/2^+$	$\pi(p_{3/2}^{-1}p_{1/2}^{1})\otimes\nu g_{9/2}^{-1}$
2595.3, 2830.5	$13/2^-$, $15/2^-$	$\pi(p_{3/2}^{-1}g_{9/2}^{1})\otimes\nu g_{9/2}^{-1}$
3248.7, 3390.2	$17/2^{(-)}$, $19/2^{(-)}$	$\pi(p_{3/2}^{-1}g_{9/2}^{1})\otimes\nu g_{9/2}^{-1}$
and 3610.3	and $21/2^{(-)}$	or $\pi(f_{5/2}^{-1}g_{9/2}^{1})\otimes\nu g_{9/2}^{-1}$
4440.0	$23/2^{(-)}$	$\pi(f_{5/2}^{-1}g_{9/2}^{1})\otimes\nu g_{9/2}^{-1}$

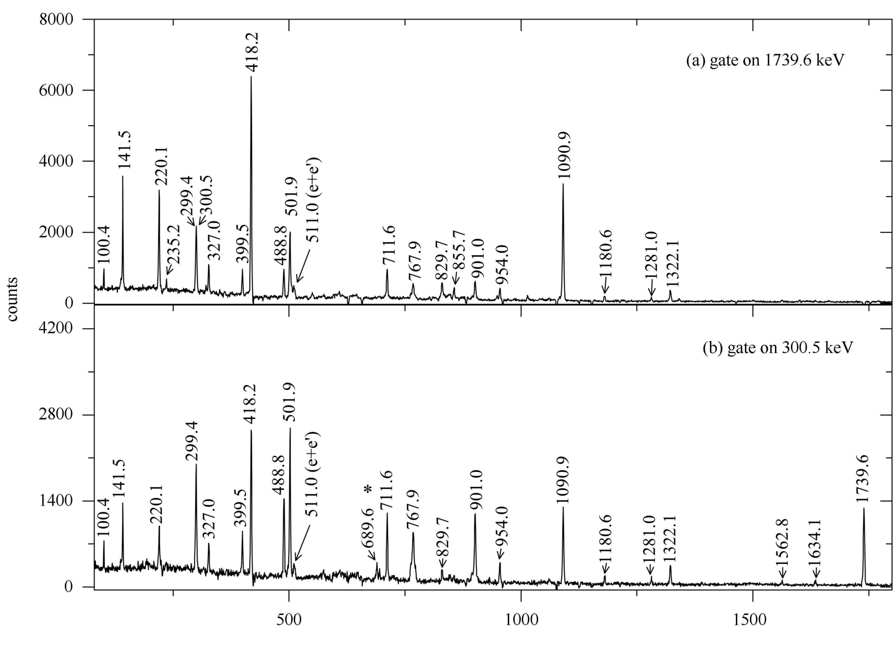

Fig. 2. The γ-ray coincidence spectra gated on the (a) 1739.6 keV, (b) 300.5 keV. γ-ray transitions associated with ^{87}Sr are labeled with their energies in keV. ∗ represents the contaminated peaks of ^{203}Bi. ^{203}Bi comes from the ^{197}Au(^{9}Be,3n) ^{203}Bi reaction.

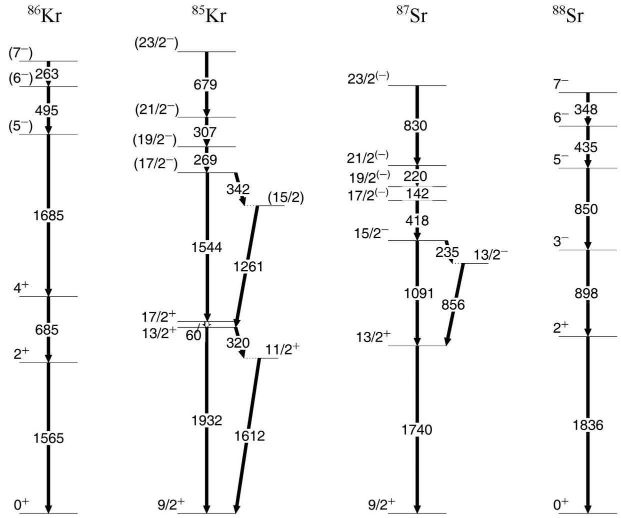

Fig. 3. Partial level schemes of ^{86}Kr [5], ^{85}Kr [5], ^{87}Sr [present work] and ^{88}Sr [9, 10]. γ-ray transitions energies are given in keV.

state dominates the $23/2^-$ state, respectively. The suggested configurations of the low-lying of ^{87}Sr are summarized in Table 2. On the other hand, the structure of ^{87}Sr resembles the neighboring isotone ^{85}Kr, although the states of $17/2^+$ with a long lifetime($T_{1/2}=1.2$ μs) and $11/2^+$ are not observed in ^{87}Sr.

The higher spin states in Sequence 2 have a different structure. By comparing similar positive parity sequences of several isotones ^{89}Zr [11], ^{91}Mo [12] and ^{93}Ru [13], it can be seen that they could be generated from $2p$-$2h$ protons excitation coupled to a $g_{9/2}$ neutron hole or neutron core excitation coupled to protons excitation. The shell-model calculations showed that the positive parity states of ^{89}Zr [11] were well described as $\pi[(p_{3/2}f_{5/2}p_{1/2})^{-2}(g_{9/2})^2]\otimes\nu g_{9/2}^{-1}$. The ^{87}Sr with 38 protons has two protons less than ^{89}Zr, which indicates that their Fermi surface should be very close and the protons should occupy the same orbits. Therefore, the configurations for new positive parity states in ^{87}Sr are tentatively assigned as $\pi[(p_{3/2}f_{5/2}p_{1/2})^{-2}(g_{9/2})^2]\otimes\nu g_{9/2}^{-1}$ contributing maximally. In Ref. [12], neutron core excitation in the calculations for ^{91}Mo was observed at the $37/2^+$ state with energy 8279 keV involving a neutron in $g_{9/2}$ orbits excited to $d_{5/2}$ orbits, similar behavior also existed in ^{93}Ru [13]. The excited ^{87}Sr may break the $N=50$ neutron core above $37/2^+$ state with an excitation energy of about 9 MeV.

4 Summary

In summary, the level structure in ^{87}Sr has been investigated using the ^{82}Se(^{9}Be,4n)^{87}Sr reaction. The level scheme of ^{87}Sr has been extended to 7441.9 keV at spin $31/2\hbar$. The structure of the low-lying levels is well described by a $g_{9/2}$ neutron hole weakly coupling with an even-even ^{88}Sr core. The positive parity states are dominated by proton excitation coupled to a $g_{9/2}$ neutron hole by comparing with the neighboring isotones.

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