

# Magnetic rotation in $^{106}\text{Ag}^*$

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**Abstract** The high spin states of  $^{106}\text{Ag}$  were populated via the fusion-evaporation reaction  $^{100}\text{Mo}(^{11}\text{B},5\text{n})^{106}\text{Ag}$  at a beam energy of 60 MeV. A new level scheme of  $^{106}\text{Ag}$  is presented. The positive parity band based on the configuration of  $\pi g_{9/2} \otimes \nu [h_{11/2}^2(g_{7/2}/d_{5/2})]$  is assigned to magnetic rotation band of shears mechanism. Theoretical calculation of the effective interaction on the basis of TAC mode were also performed, the calculated results agrees well with the value extracted from the experiment.

**Key words** high spin states, shears mechanism, magnetic rotation band, valence nucleon

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## 1 Introduction

Recently, magnetic rotation has been observed around the predicted  $A \sim 110$  mass region, such as neutron deficient Cd<sup>[1-3]</sup>, In<sup>[4]</sup> and Sn<sup>[5, 6]</sup> nuclei. The magnetic rotation bands in these nuclei are thought to be based on the configuration of one or more holes in the  $g_{9/2}$  proton orbital and particles in the  $h_{11/2}$ ,  $g_{7/2}$ ,  $d_{5/2}$  neutron orbitals. With valence nucleon number increasing, the deformation of nuclei is becoming larger and the shears mechanism will gradually disappear, so it is very important to investigate these nuclei which are at the boundary of magnetic rotation. At  $A \sim 110$  mass region, many examples of magnetic rotation bands have been found, as listed above, it is seldom reported in Ag isotopes. Ag isotopes have 47 protons, less than Sn, In and Cd isotopes, it is very good to take Ag isotopes as the sub-

ject to quest for the boundary of magnetic rotation at  $A \sim 110$  mass region.

$^{106}\text{Ag}$  has 47 protons and 59 neutrons, its proton Fermi surface lies in the upper  $g_{9/2}$  orbital, while the valence neutrons populate  $g_{7/2}$  or  $d_{5/2}$  orbital, and they also can excite to  $h_{11/2}$  orbital. All the configurations in  $^{106}\text{Ag}$  agree with the qualification for magnetic rotation. Some results about  $^{106}\text{Ag}$  have been reported<sup>[7]</sup> before this experiment. In Ref. [8], the given values of  $J^{(2)}/B(E2)$  on the basis of lifetime measurement for the positive parity band are between  $120 \text{ } \hbar^2\text{MeV}^{-1} \cdot \text{eb}^{-2}$  and  $290 \text{ } \hbar^2\text{MeV}^{-1} \cdot \text{eb}^{-2}$ . TAC calculations for the reduced M1 transition strength  $B(M1)$  with the configuration of  $\pi g_{9/2} \otimes \nu [h_{11/2}^2(g_{7/2}/d_{5/2})]$  agreed well with the experimental results, a small deformation  $\varepsilon_2 \sim 0.18$  was also given out by the TAC mode calculation. These results suggested that the positive parity band in  $^{106}\text{Ag}$  is on

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the ground of shears mechanism. In this paper, besides a new level scheme, both the property analysis of magnetic rotation and semi-classical TAC calculation for effective interaction between valence nucleus are presented. The study gives a more convincing evidence for the shears coupling of the positive band of  $^{106}\text{Ag}$ .

## 2 Experiment and results

The high-spin states of  $^{106}\text{Ag}$  were populated via the fusion-evaporation reaction  $^{100}\text{Mo}(^{11}\text{B},5\text{n})^{106}\text{Ag}$  at a beam energy of 60 MeV delivered by the HI-13 tandem accelerator of the China Institute of Atomic Energy (CIAE). The target was composed of a  $2.5\text{ mg/cm}^2$  layer of  $^{100}\text{Mo}$  enriched to 97.4% with a  $11\text{ mg/cm}^2$  lead backing. The beam energy was chosen to maximize the yield of  $^{106}\text{Ag}$ , which should be about 47.7% of the total cross section as predicted by the statistical evaporation code CASCADE.  $\gamma$ - $\gamma$  coincidence events were collected using a multi-detector array consisting of 15 HPGe detectors, each of which was equipped with a BGO-Compton background. In the detector array, five detectors were placed at  $90^\circ$ , five at about  $48^\circ$  and five at about  $132^\circ$

with respect to the beam direction. Each detector had an energy resolution of about 2 keV for 1332.5 keV  $\gamma$  rays. The relative efficiency of the detector array was calibrated using a  $^{152}\text{Eu}$  standard radioactive source mounted at the target position. A total of  $130 \times 10^6$   $\gamma$ - $\gamma$  coincidence events were collected in the experiment in event-by-event mode. After careful energy calibration and gain matching of each detector, the  $\gamma$ - $\gamma$  coincidence data were sorted offline into conventional  $E_\gamma$ - $E_\gamma$  matrices. In addition, a directional correlation from oriented states (DCO) analysis was also carried out using the  $\gamma$ - $\gamma$  coincidence data between detectors at forward and backward angles ( $\theta_{\text{eff}} = 48^\circ$ ) and those placed at  $90^\circ$ . These matrices were analyzed by using the RADWARE package<sup>[9]</sup> based on a Linux-PC system. A new level scheme of  $^{106}\text{Ag}$  has been established from the present experiment<sup>[10]</sup>. From the present work, the positive and negative bands have been extended to  $22^+$  and  $19^-$  respectively, therinto, the positive parity bands are presented in Fig. 1.

## 3 Discussion

The positive parity band 1 of odd-odd  $^{106}\text{Ag}$  is expected to be built on the  $\pi g_{9/2} \otimes \nu [h_{11/2}^2 (g_{7/2}/d_{5/2})]$  configuration where the odd proton occupies the positive parity high  $j$  high  $\Omega$  orbital and two of the three neutrons occupy the negative parity high  $j$  low  $\Omega$  orbital. This perpendicular coupling of valance nucleus meets the needs of magnetic rotation. On the ground of this configuration, the angular momentum evolves at  $18^+ \hbar$ . After  $\hbar\omega \sim 0.59\text{ MeV}$  ( $\hbar\omega \sim E_\gamma$ ), the angular momentum is increased about  $2\hbar$  because of a band-crossing. By considering the magnetic rotation bands with the same configuration in  $^{108}\text{In}$  and  $^{110}\text{In}$ , a band crossing with the similar rotation frequency has also been reported respectively, band 1 in  $^{106}\text{Ag}$  should have the similar band structure with them. In Ref. [4], the band-crossing was explained by the alignment of a  $\nu d_{5/2}$  or  $\nu g_{7/2}$  pair.

Long sequence of M1 transitions in band 1 of  $^{106}\text{Ag}$  have been observed. On the basis of the perpendicular coupling of the valence proton and valence neutrons, the M1 transitions are greatly enhanced. A comparison with the observed M1 bands in  $A \sim 200$  mass region, these cascades share several similar signatures with the bands in Pb isotopes<sup>[11–13]</sup>: (1) The

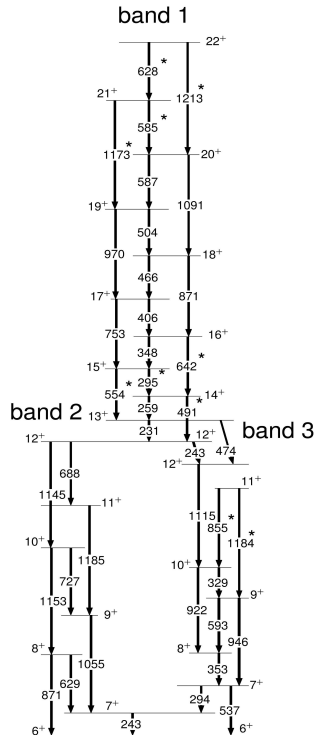


Fig. 1. Partial level scheme of  $^{106}\text{Ag}$  deduced from the present experiment. Energies are in keV. (New  $\gamma$  transitions are indicated by\*)

states in band 1 have energies that follow the pattern of  $E(I) - E_0 \sim A(I - I_0)^2$ ,  $E_0$  and  $I_0$  are the energy and angular momentum of band head of band 1 respectively. This is a slightly different expression from the  $I(I+1)$  relation described from the rotational bands in well deformed nuclei; (2) The structures have small deformation ( $\varepsilon \sim 0.18$ )<sup>[7, 8]</sup>; (3) There is no signature splitting (Fig. 2); (4) The total angular momentum in band 1 are main attributed to the intrinsic configuration; (5) The dynamic moment of inertia ( $J^{(2)}$ ) of this band is far smaller than that of superdeformed band<sup>[14]</sup>, as showing in Fig. 3.

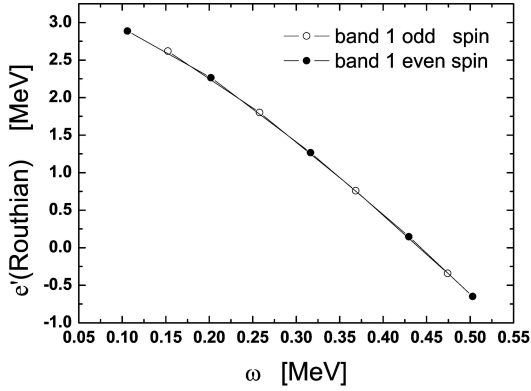


Fig. 2. Experimental routhians for band 1 in  $^{106}\text{Ag}$  with the harries parameters  $J_0=8.9 \hbar^2\text{MeV}^{-1}$ ,  $J_1=15.7 \hbar^4\text{MeV}^{-3}$ .

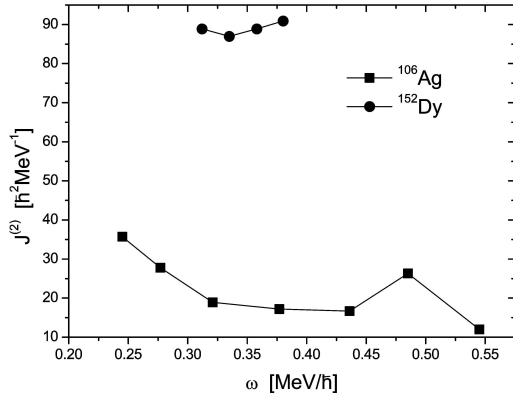


Fig. 3. Dynamical momentum inertia of band 1 in  $^{106}\text{Ag}$  and superdeformation band in  $^{152}\text{Dy}$ .

As magnetic rotation bands are building on shears mechanism, we will use the semiclassical approach<sup>[15]</sup> with the TAC mode, which is based on a schematic model of the coupling of two long  $\mathbf{j}$  vectors ( $\mathbf{j}_\pi$  and  $\mathbf{j}_\nu$ ) with the aim of extracting information on the effective interaction between the nucleus which are involved in the shears behavior. The shears angle  $\theta$ , between  $\mathbf{j}_\pi$  and  $\mathbf{j}_\nu$  for a given state with the total angular momentum  $\mathbf{I}_{\text{shear}} = \mathbf{j}_\pi + \mathbf{j}_\nu$ , can be derived

using the simple expression<sup>[15]</sup>:

$$\cos\theta = \frac{\mathbf{j}_\pi \cdot \mathbf{j}_\nu}{|\mathbf{j}_\pi||\mathbf{j}_\nu|} = \frac{I_{\text{shear}}(I_{\text{shear}+1}) - j_\pi(j_\pi+1) - j_\nu(j_\nu+1)}{2\sqrt{j_\pi(j_\pi+1)j_\nu(j_\nu+1)}}. \quad (1)$$

Based on the perpendicular coupling of the valence particles, the band head spin ( $I_{\text{bh}} = 12\hbar$ ) is well reproduced by the valence protons and neutrons, and the effect due to an increasing contribution from the core is also considered by decomposing the total spin as  $I = I_{\text{shear}} + R_{\text{core}}$  and using a linear relation

$$R_{\text{core}}(I) = \frac{(\Delta R - R_{\text{core-bh}})I}{I_{\text{max}} - I_{\text{bh}}} + \frac{I_{\text{max}}R_{\text{core-bh}} - \Delta R I_{\text{bh}}}{I_{\text{max}} - I_{\text{bh}}}, \quad (2)$$

where  $\Delta R$  is determined from the difference between the maximum observed spin  $I_{\text{max}}$  and the sum of  $j_\pi$  and  $j_\nu$ ;  $I_{\text{bh}}$  and  $R_{\text{core-bh}}$  are the spin of the band head and angular momentum coming from core rotation at the band head respectively. This analysis of the competition between the shears mechanism and the core rotation in a classical particles-plus-rotor model has also been done in Pb nuclei<sup>[16]</sup>.

The effective interaction between the valence protons and neutrons can be expanded in terms of even legendre polynomials. The relative energies of interactions is expressed by the function of the following form:

$$V_{\pi\nu}(\theta) - V_{\pi\nu}(90^\circ) \propto \frac{3V_2 \cos^2\theta}{2}. \quad (3)$$

The energies of effective interactions can also be extracted by using the next expressions from the experiment:

$$V_{\text{ex}}[I(\theta)] = E[I(\theta)] - E_{\text{bh}}, \quad (4)$$

where  $V_{\text{ex}}[I(\theta)]$ ,  $E[I(\theta)]$  and  $E_{\text{bh}}$  are the interactions coming from the shears mechanism, the energy of each level in band 1 and the band head energy. As the nuclei have a small deformation, so the energy contributed by core rotation of each level should be subtracted. The energy of the core rotation contribution is coming from the following hypothesis:

$$E_{\text{core}}[I(\theta)] \approx E[I(\theta)] \frac{R_{\text{core}}^2(I)}{[I(\theta)]^2}. \quad (5)$$

Finally, the effective interaction between valence nucleus is deduced:

$$V[I(\theta)] = [E(I(\theta)) - E_{\text{core}}(I(\theta))] - [E_{\text{bh}}(I(90^\circ)) - E_{\text{core}}(I(90^\circ))]. \quad (6)$$

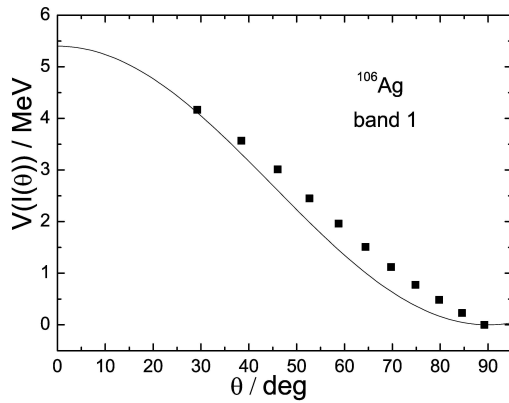


Fig. 4. The square dots show the effective interaction between the valence protons and neutrons subtracted from the present experiment. The solid curve is theoretical simulation result.

The calculated results before band-crossing is shown in Fig. 4, where the solid squares indicates the values extracted from the present experiment, and the solid line indicates the semi-classical approach calculated result. The strength of the effective interaction is determined here by the  $V_2$  value. In the case of band 1 in  $^{106}\text{Ag}$ , the obtained strength of effective in-

teraction  $V_2$  is about 1.38 MeV. Taking into account one proton hole and three neutron particles as two blades of a pair of shears, we estimate that the interaction strength per proton/neutron pair is about 0.46 MeV. It is comparable to the value of  $\sim 0.5$  MeV for  $^{110}\text{Cd}$ <sup>[17]</sup>. This result is consistent with the  $1/A$  dependence of the interaction strength suggested in Ref. [15].

## 4 Summary

In conclusion,  $A$  dipole positive band (band 1) building on shears mechanism has been observed in  $^{106}\text{Ag}$ . It consists of strong M1 transitions and its level energies follow a rotation-like pattern based on a small deformation. The semiclassical approach of with TAC mode has been used to calculate the value of per p-n interaction. Our results are consistent with the results which have been calculated from  $^{110}\text{Cd}$ . All these signatures give more convincing evidence that band 1 in  $^{106}\text{Ag}$  is a good magnetic rotation band.

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