Gallagher-Moszkowski (GM) doublet bands in ^{162}Ho

Guodong Liang, Shouyu Wang, Yunzuo Liu, Yingjun Ma, Jingbin Lu,
Mingfei Li, Xingzhu Cui, Guangyi Zhao, and Xianfeng Li
Department of Physics, Jilin University, Changchun 130023, People's Republic of China

Xiaoguang Wu, Lihua Zhu, Guangshen Li, Shuxian Wen, and Chunxiang Yang
China Institute of Atomic Energy, P.O. Box 275, Beijing 102413, People's Republic of China
(Received 16 July 2005; published 9 December 2005)

High-spin states in ^{162}Ho have been populated in the reaction ^{160}Gd(^{7}Li, 5n) at a beam energy of 49 MeV. The $K^\pi = 1^-$ band, the low-K Gallagher-Moszkowski (GM) partner band of known high-K($K^\pi = 6^-$) band, based on the configuration $\pi 7/2^-[523] \otimes \nu 5/2^+[642]$, and the $K^\pi = 6^+$ band, the high-K GM partner band of known low-K($K^\pi = 1^+$) band, based on the configuration $\pi 7/2^-[523] \otimes \nu 5/2^-[523]$, have been identified. GM splitting energies, defined as $\Delta E_{\mathrm{GM}} = E_{\mathrm{int}}^{K_\langle} - E_{\mathrm{int}}^{K_\rangle}$, 80 keV and −135 keV were extracted from these two sets of GM doublet bands, respectively. They are comparable with 65 keV and −145 keV, reported recently by Hojman *et al.* for the corresponding configurations $\pi 7/2^-[523] \otimes \nu 5/2^+[642]$ and $\pi 7/2^-[523] \otimes \nu 5/2^-[523]$ in ^{164}Ho, respectively.

DOI: 10.1103/PhysRevC.72.067301 PACS number(s): 21.10.Re, 23.20.Lv, 27.70.+q

The recent experimental studies on high-spin states in ^{160}Ho [1] and ^{164}Ho [2] make ^{162}Ho the less studied nucleus among the deformed holmium odd-odd isotopes. This report presents the new experimental results of high-spin states in ^{162}Ho.

Hign-spin states in ^{162}Ho were populated using the reaction ^{160}Gd(^{7}Li, 5n) at a beam energy of 49 MeV. The beam was delivered by the Tandem Accelerator at the China Institute of Atomic Energy in Beijing. The target was a self-supporting foil of 4.5mg/cm^2 in thickness. Gamma-ray coincidences were measured with 11 Compton-suppressed HPGe-BGO detectors. About 120 million events requiring two or more detectors to be fired within 200 ns were accumulated. In the offline analysis, the data were sorted into a symmetrized $E\gamma$-$E\gamma$ matrix. To obtain information on γ-ray multipolarities, two asymmetric matrices were constructed and ADO ratios (γ-ray angular distribution from oriented nuclei) were evaluated using the method as described in Ref. [3]. Figure 1 shows the level scheme of ^{162}Ho proposed in the present study and it was constructed by combining the previous results [1,4,5,6,7,8] and the new results of the present study. Figure 2 shows the sample spectra supporting the level scheme of Fig. 1.

The decay of 67 min $I^\pi = 6^-$ isomeric state at ≈106 keV in ^{162}Ho was studied by Jϕrgensen *et al.* [4] and Harmatz *et al.* [5] and as results of these studies, the first two members, 2^+ and 3^+ states of the ground-state band, were established and the 6^- isomeric state was linked to the 3^+ state of the ground-state band through a ≈10 keV transition with $E3$ multipolarity. Schilling *et al.* [6] established the $K^\pi = 1^-$ bandhead at 179.8 keV with the configuration $\pi 7/2^-[523] \otimes \nu 5/2^+[642]$ by means of ^{162}Dy(p, n)^{162}Ho reaction. Excited levels of the $K^\pi = 6^-$ yrast band with the configuration $\pi 7/2^-[523] \otimes \nu 5/2^+[642]$ were observed up to $I^\pi = 15^-$ by Leigh *et al.* [7] in the ^{160}Gd(^{7}Li, 5n) reaction. All these previously obtained results were integrated into a partial level scheme as presented in Ref. [8]. Very recently, the excited levels of the yrast band were extended to $I^\pi = 28^-$ by Escrig *et al.* [1], while no information on other rotational bands in ^{162}Ho was provided in Ref. [1].

In the present work, the excited levels of ground-state band have been extended from 6^+ [8] to 14^+ with minor changes, namely the energies of the γ-transitions 114.0 keV($6^+ \rightarrow 5^+$) and 99.6 keV($5^+ \rightarrow 4^+$) have been replaced by 115.9 keV and 98.2 keV, respectively. For the yrast band, we can only reach the level with $I^\pi = 24^-$ in the present study and, for completeness, the levels above $I^\pi = 24^-$in Fig. 1 are adopted from Ref. [1].

Band 4 was identified for the first time in the present study. The placement of band 4 in the level scheme was fixed by the linking transitions between band 3 and band 4. These linking transitions are weak, but they can be seen in the sum spectrum gated by the 141.5 and 179.8 keV γ-rays as indicated in Fig. 2. Strong coincidences were observed between γ-transitions in band 4 and the 141.5 and 179.8 keV deexciting γ-rays of the $K^\pi = 1^-$ bandhead with configuration $\pi 7/2^-[523] \otimes \nu 5/2^+[642]$, which most probably suggest that band 4 is the upper part of the $K^\pi = 1^-$ band with configuration $\pi 7/2^-[523] \otimes \nu 5/2^+[642]$. A similar situation had occurred in the case of ^{164}Ho [2], except that the low-lying levels between 1^- and 6^- in ^{164}Ho were established by combining the careful analysis of low-energy spectra and known information from particle-transfer reactions while the later information is not available in the case of ^{162}Ho. The spin values of the levels in band 4 were tentatively assigned on the basis of the arguments: (i) Considering that the parities of band 3 and band 4 are different, the observed linking transitions between band 3 and band 4 can only be of $E1$ character and thus the spin of level in band 4 can be deduced by the spin of the related level in band 3. (ii) The level structure of band 4 is similar to that of the upper part (above 6^-level) of $K^\pi = 1^-$ band with configuration $\pi 7/2^-[523] \otimes \nu 5/2^+[642]$ in ^{164}Ho (band 5 of Fig. 4 in Ref. [2]) and the correspondence between the levels of

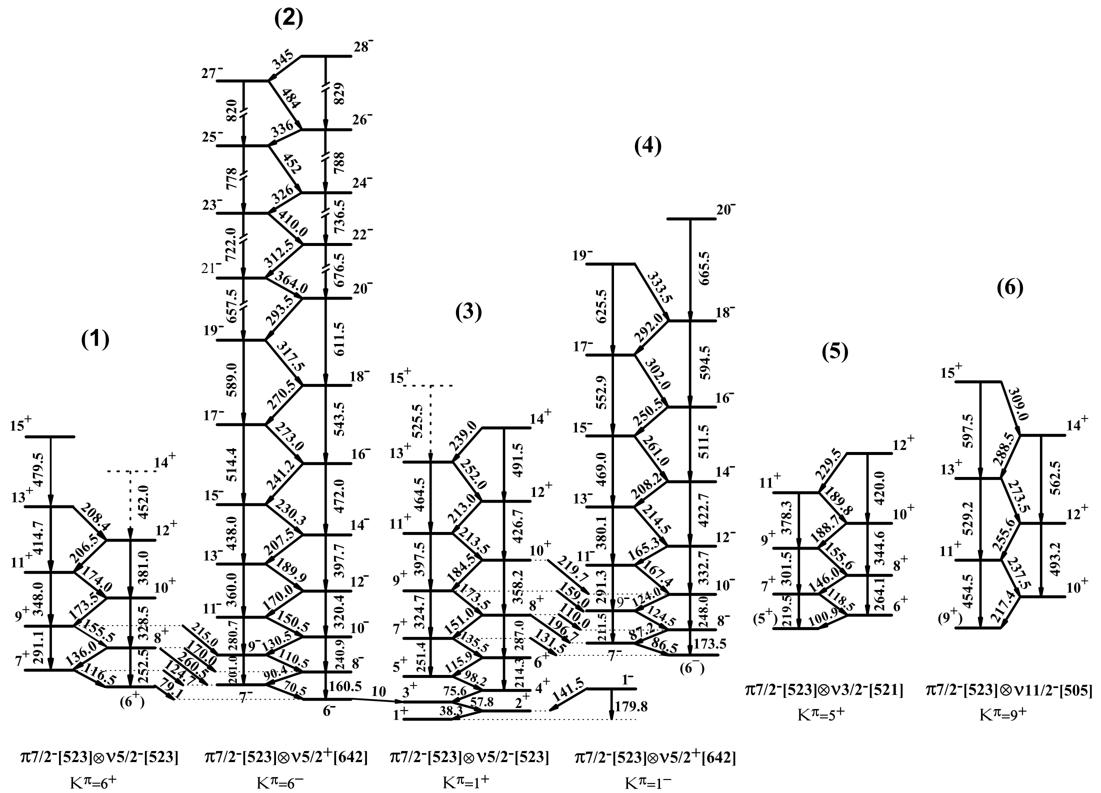

FIG. 1. Level scheme of ^{162}Ho proposed in the present work. I^π assignments to the levels of bands 1, 4, 5, and 6 are considered to be tentative as indicated by placing the I^π of the lowest observed states of these bands in the brackets.

$K^\pi = 1^-$ band (band 4) in ^{162}Ho and those of $K^\pi = 1^-$ band in ^{164}Ho can easily be found. The configuration assignment of band 4 is supported by the reasonably well agreement between the experimental and theoretical $B(M1)/B(E2)$ ratios, as shown in Fig. 3(a). The experimental in-band $B(M1)/B(E2)$ ratios were computed from the γ branching ratios assuming pure dipole character for the $\Delta I = 1$ transitions and the theoretical values were predicted by the geometrical model [10]. The level structure of band 4 has previously been reported in Ref. [1] and it was tentatively assigned to ^{161}Ho and no discussion on I^π and configuration assignments was given Ref. [1].

Band 1 was established in the present study. The placement of band 1 in the level scheme was fixed by the linking transitions (79.1, 124.7, 260.5, 170.0, and 215.0 keV) between band 1 and band 2. These linking transitions are indicated in the sum spectrum gated by the 414.7 and 479.5 keV γ-rays as shown in Fig. 2. The ADO ratio 0.45(11) of the 79.1 keV decay out transition suggests that it has the character of $\Delta I = 1$. Schilling *et al.* [6] reported an unplaced 78.7 keV transition with $T_{1/2} = 25$ ns in their ^{162}Dy$(p, n)^{162}$Ho reaction study. Assuming the 79.1 keV decay out transition observed in the present study corresponds to the 78.7 keV delayed transition reported by Schilling *et al.* [6], the hindrance factor relative to the Weisskopt estimate $F_w \approx 10^5$ is obtained for the 79.1 keV γ-transition, which falls within the systematics for an $E1$, $\Delta K = 0$ transition [9]. Based on this argument, $I^\pi = 6^+$ is tentatively assigned to the bandhead of band 1 and the I^π assignments for the member states of band 1 are tentatively suggested as shown in Fig. 1.

The configurations of bands in ^{162}Ho resulted from the coupling of the low-lying proton orbitals, such as $\pi 7/2^-[523]$, $\pi 7/2^+[404]$, $\pi 1/2^+[411]$, and $\pi 1/2^-[541]$, as observed in ^{161}Ho [1] and neutron orbitals, such as $\nu 5/2^+[642]$, $\nu 5/2^-[523]$, $\nu 3/2^-[521]$, and $\nu 11/2^-[505]$, as observed in ^{161}Dy [12]. $\pi 7/2^-[523] \otimes \nu 5/2^-[523]$ and $\pi 7/2^+[404] \otimes \nu 5/2^+[642]$ are the possible candidates for the configuration of band 1. Both of these configurations can provide $I^\pi = 6^+$ for the bandhead of band 1 through the antiparallel coupling of intrinsic spins of proton and neutron. However, the later configuration is not favored by the $B(M1)/B(E2)$ ratios as shown in Fig. 3(b). Therefore configuration of $\pi 7/2^-[523] \otimes \nu 5/2^-[523]$ was assigned to band 1.

Band 5 and band 6 were not linked to the rest part of the level scheme. The assignment of band 5 to ^{162}Ho was mainly based on systematic comparison with the similar band $\pi 7/2^-[523] \otimes \nu 3/2^-[521]$ reported in ^{160}Ho [1] and ^{164}Ho [2]. The assignment of band 6 to ^{162}Ho was mainly based on the systematic comparison with the similar band $\pi 7/2^-[523] \otimes \nu 11/2^-[505]$ reported in ^{156}Ho [15], ^{158}Ho [16] and ^{160}Ho [1]. A detailed discussion on the assignments of spins, parites, and configurations of bands 5 and 6 will appear elsewhere.

For each pair of proton and neutron orbitals, there are two possible couplings, the low-K, $K_< = |\Omega_p - \Omega_n|$, and the high-$K$, $K_> = \Omega_p + \Omega_n$, couplings. When the intrinsic spins

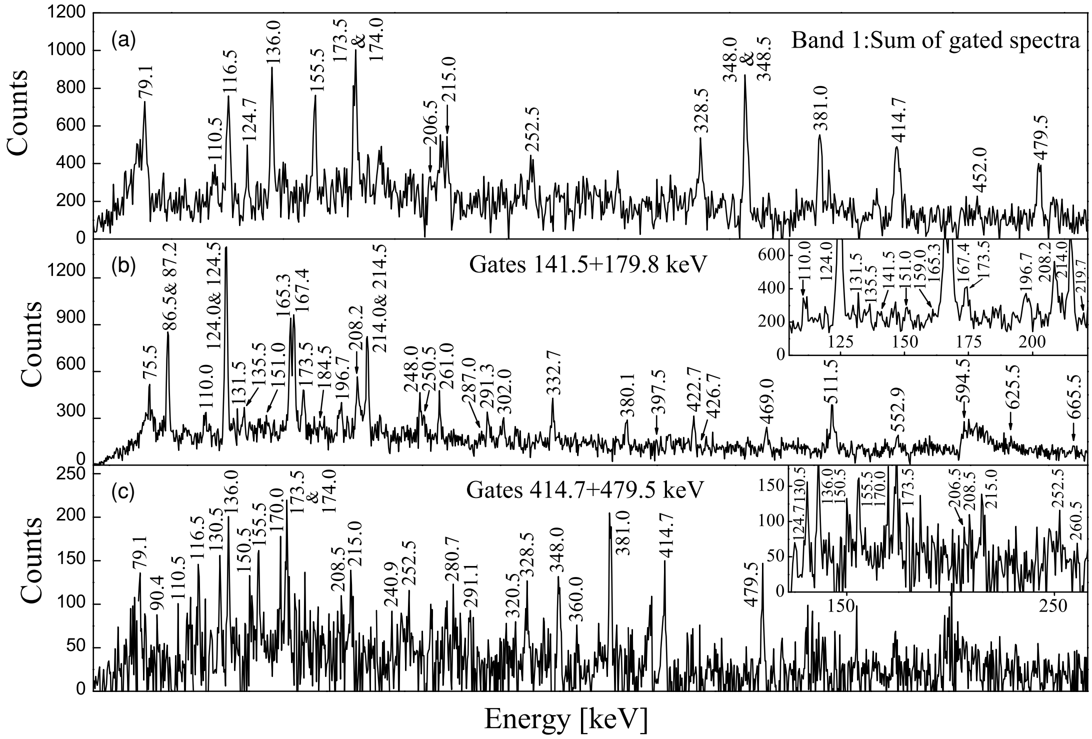

FIG. 2. Examples of γ-γ coincidence spectra in ^{162}Ho. Inset of (a) is produced by a sum of spectra gated on the 116.5, 136.0, 155.5, 328.5, 348.0, and 414.7 keV transitions. Inset of (b) displays linking transitions between bands 3 and 4. Inset of (c) displays linking transitions between band 1 and band 2.

of proton and neutron are coupled in parallel ($\Sigma = \pm 1$) or in antiparallel ($\Sigma = 0$), the corresponding states are placed lower or higher in energy, respectively, according to the Gallagher-Moszkowski (GM) coupling rules [13]. These two $K_>$ and $K_<$ bands form the so-called GM doublet. K-values, parities, and configurations of the bandhead of bands 2, 3, and 4 are adopted from the previous studies as summarized in Ref. [8], namely, the K-value of the bandhead of band 2 is a result of the high-K coupling, $K_> = 7/2 + 5/2$, of the proton orbital 7/2$^-$[523] and neutron orbital 5/2$^+$[642], and thus bandhead of band 2 is the high-K member of the GM doublet based on the $\pi 7/2^-[523] \otimes \nu 5/2^+[642]$ configuration. Similarly, the bandhead of band 3 is the low-K, $K_< = 7/2 - 5/2$, member of the GM doublet based on the $\pi 7/2^-[523] \otimes \nu 5/2^-[523]$ configuration, and the bandhead of band 4 is the low-K, $K_< = 7/2 - 5/2$, member of the GM doublet based on the $\pi 7/2^-[523] \otimes \nu 5/2^+[642]$ configuration.

Bands 1, 2, 3, and 4 in ^{162}Ho form two pairs of GM doublets. The $K^\pi = 6^-$ band (band 2) and $K^\pi = 1^-$ band (band 4) are the $K_>$ and $K_<$ members of the GM doublet based on $\pi 7/2^-[523] \otimes \nu 5/2^+[642]$ configuration, respectively. The 6^- and 1^- bands correspond to parallel and antiparrallel couplings of intrinsic spins of proton and neutron, respectively, and thus the 6^- bandhead lies lower in energy. The $K^\pi = 6^+$ band (band 1) and $K^\pi = 1^+$ band (band 3) are the $K_>$ and $K_<$ members of the GM doublet based on $\pi 7/2^-[523] \otimes \nu 5/2^-[523]$ configuration, respectively. The

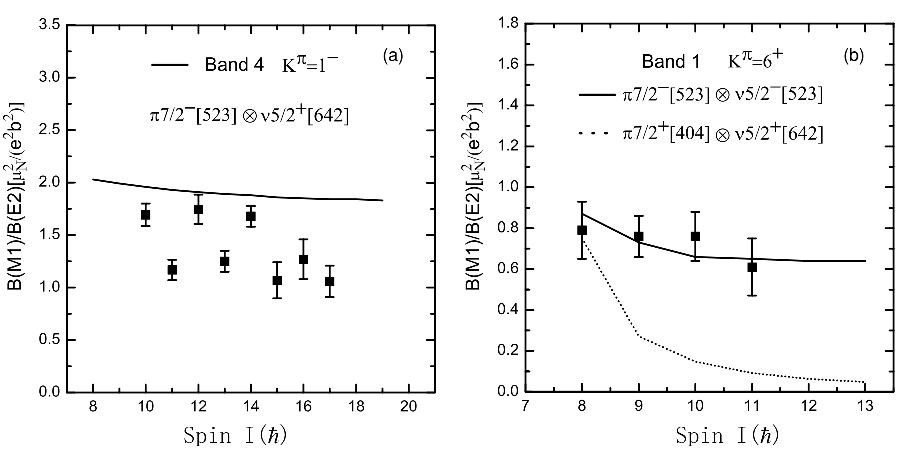

FIG. 3. Experimental and predicted $B(M1)/B(E2)$ ratios as a function of spin for bands 1 and 4 of ^{162}Ho. Parameters used in the calculations of the predicted $B(M1)/B(E2)$ values: $Q_0 = 0.72e$b, $g_R = 0.3$, $g(\pi 7/2^-[523]) = 1.35$, $g(\pi\ 7/2^+\ [404]) = 0.73$, $g(\nu 5/2^+ [642]) = -0.34$, $g(\nu 5/2^-[523]) = 0.20$, $i(\pi 7/2^-[523]) = 1.4$, $i(\pi\ 7/2^+\ [404]) = 0.8$, $i(\nu 5/2^+[642]) = 3.0$, $i(\nu 5/2^-[523]) = 0.50$. The gyromagnetic factors were taken from Ref. [11].

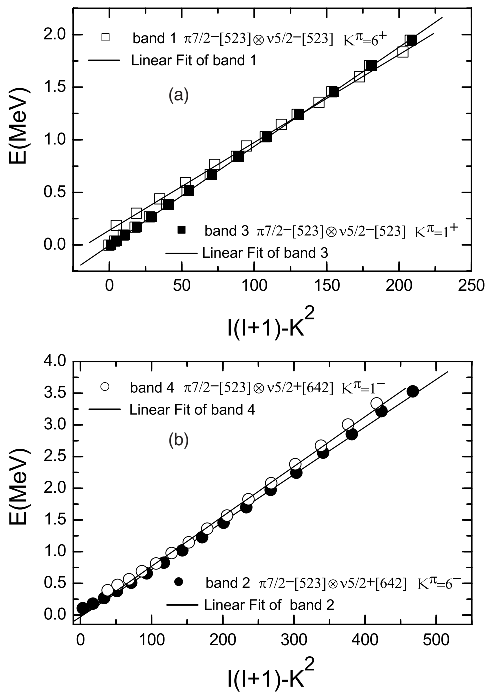

FIG. 4. Experimental level energies of GM doublets of ^{162}Ho and the linear fits (straight lines) according to the rotational formula.

$K^\pi = 6^+$ and $K^\pi = 1^+$ bands correspond to antiparrallel and parallel couplings of intrinsic spins of proton and neutron, respectively, and thus the $K^\pi = 1^+$ band lies lower in energy.

In the case of $K \neq 0$, the energy of a state with spin I in a rotational band of an odd-odd nucleus, neglecting the nondiagonal contributions of the Coriolis and of the *p*-*n* residual interaction, can be written as [14]

$$E_{IK} = E_p + E_n + \frac{\hbar^2}{2J}[I(I+1) - K^2] + E_{\rm int}^K, \qquad (1)$$

where $E_{\rm int}^K$ is the diagonal part of the *p*-*n* interaction. The energy separation between the two $K_>$ and $K_<$ members of the GM doublet, appropriately corrected for the zero-point rotational energy, is called the GM splitting energy of a GM doublet and is defined by the expression: $\Delta E_{\rm GM} = E_{\rm int}^{K_\langle} - E_{\rm int}^{K_\rangle}$. In the plot of E_{IK} vs $I(I+1) - K^2$, Eq. (1) is a straight line characterized by two parameters $E_p + E_n + E_{\rm int}^K$ and $\hbar^2/2J$. These two parameters can be obtained by a least-square fitting. The GM splitting energy $\Delta E_{\rm GM} = E_{\rm int}^{K_\langle} - E_{\rm int}^{K_\rangle}$ of a GM doublet can be obtained as the difference between the parameters $E_p + E_n + E_{\rm int}^K$ of the two rotational bands constituting the GM doublet, the contribution from $E_p + E_n$ cancels out when the difference is taken.

Figure 4(a) shows the E_{IK} vs $I(I+1) - K^2$ plots of the $K^\pi = 6^+$ and $K^\pi = 1^+$ rotational bands of the GM doublet based on the $\pi 7/2^-[523] \otimes \nu 5/2^-[523]$ configuration. $\Delta E_{\rm GM} = E_{\rm int}^{K_\langle} - E_{\rm int}^{K_\rangle} = -135$ keV is obtained from the difference of $E_p + E_n + E_{\rm int}^{K_\langle}$ and $E_p + E_n + E_{\rm int}^{K_\rangle}$, which were extracted from the linear fits of the data.

The plots of the two rotational bands of the GM doublet based on $\pi 7/2^-[523] \otimes \nu 5/2^+[642]$ deviate from straight line in the low-spin region as shown in Fig. 4(b). The appearance of this distortion is consistent with the presence of the $i_{13/2}$ neutron for which the Coriolis effects are more important as discussed in the case of ^{164}Ho [2]. The experimental data were fitted in the energy range $0.5 \sim 2.0$ MeV and the $\Delta E_{\rm GM}$ for this GM doublet was determined to be 80 keV. These two GM splitting energies, -135 keV and 80 keV, obtained in the present study are comparable with -145 keV and 65 keV obtained in Ref. [2] for the GM doublets based on configurations $\pi 7/2^-[523] \otimes \nu 5/2^-[523]$ and $\pi 7/2^-[523] \otimes \nu 5/2^+[642]$ in ^{164}Ho, respectively.

In summary, hign-spin states of ^{162}Ho have been studied through the reaction ^{160}Gd(^{7}Li, 5*n*). The band with $K^\pi = 1^-$ and configuration $\pi 7/2^-[523] \otimes \nu 5/2^+[642]$, and the band with $K^\pi = 6^+$ and configuration $\pi 7/2^-[523] \otimes \nu 5/2^-[523]$ have been identified for the first time in ^{162}Ho. Combining with previously known rotational bands, two pairs of GM doublet bands with configurations $\pi 7/2^-[523] \otimes \nu 5/2^+[642]$ and $\pi 7/2^-[523] \otimes \nu 5/2^-[523]$ were established, and GM splitting energies 80 keV and -135 keV were extracted, respectively.

This study was supported by the National Natural Science Foundation (Grant Nos. 10275028, 10205006, and 10105003) and the Major State Research Development Programme (No. G2000077405) of China.

[1] D. Escrig *et al.*, Eur. Phys. J. A **21**, 67 (2004).
[2] D. Hojman *et al.*, Eur. Phys. J. A **21**, 383 (2004).
[3] M. Piiparinen *et al.*, Nucl. Phys. **A605**, 191 (1996).
[4] M. Jϕrgensen, O. B. Nielsen, and O. Skilbreid, Nucl. Phys. **24**, 443 (1961).
[5] B. Harmatz and T. H. Handley, Phys. Rev. **123**, 1758 (1961).
[6] K. D. Schilling, L. Käubler, W. Andrejtscheff, T. M. Muminov, V. G. Kalinnikov, N. Z. Marupov, F. R. May, and W. Seidel, Nucl. Phys. **A299**, 189 (1978).
[7] J. R. Leigh, F. S. Stephens, and R. M. Diamond, Phys. Lett. **B33**, 410 (1970).
[8] R. G. Helmer and C. W. Reich, Nucl. Data Sheets **87**, 317 (1999).
[9] K. E. G. Löbner, Phys. Lett. **B26**, 369 (1968).
[10] F. Dönau, S. Frauendorf, in *Proceedings of the Conference on High Angular Momentum Properties of Nuclei, Oak Ridge, USA, 1982*, edited by N. Johnson (Harwood Academic, Chur, Switzerland, 1982), p. 143.
[11] W. Reviol *et al.*, Phys. Rev. C **59**, 1351 (1999).
[12] A. Jungclaus *et al.*, Phys. Rev. C **67**, 034302 (2003).
[13] C. J. Gallagher and S. A. Moszkowski, Phys. Rev. **111**, 1282 (1958).
[14] A. K. Jain, R. K. Sheline, D. M. Headly, P. C. Sood, D. G. Burke, I. Hrívnácová, J. Kvasil, D. Nosek, and R. W. Hoff, Rev. Mod. Phys. **70**, 843 (1998).
[15] D. M. Cullen, C.-H. Yu, D. Cline, M. Simon, D. C. Radford, M. A. Riley, and J. Simpson, Phys. Rev. C **57**, 2170 (1998).
[16] Jingbin Lu *et al.*, Phys. Rev. C **59**, 3461 (1999).