# Revised interpretations for $K^\pi = 1^+$ bands in $^{166}$Ho

P.C. Sood
*Department of Physics and Astronomy, McMaster University, Hamilton, Ontario, Canada L8S 4M1*
*and Department of Physics, Banaras Hindu University, Varanasi 221005, India*

D.G. Burke
*Department of Physics and Astronomy, McMaster University, Hamilton, Ontario, Canada L8S 4M1*
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Experimental data from the $^{165}$Ho$(d,p)^{166}$Ho reaction were analyzed using the distorted-wave Born approximation formalism and Nilsson model wave functions with Coriolis mixing. It is concluded that the $K^\pi = 1^+$ bands at 426 and 568 keV in $^{166}$Ho have the $\frac{7}{2}^-[523]_\pi - \frac{5}{2}^-[512]_\nu$ and the $\frac{7}{2}^-[523]_\pi - \frac{5}{2}^-[523]_\nu$ two-quasiparticle configurations, respectively. These assignments interchange the ones currently adopted for these two bands, but are in agreement with phenomenological and theoretical predictions. In addition, the $(d,p)$ data suggest a tentative $\frac{7}{2}^-[523]_\pi - \frac{1}{2}^-[510]_\nu$ assignment for the $K^\pi = 3^+$ band based at 814 keV in $^{166}$Ho.

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The nuclide $^{166}_{67}$Ho$_{99}$ offers one of the best known level schemes among the odd-odd deformed nuclei. Over 330 energy levels and 20 rotational bands have been identified [1] in this nucleus, based on $\beta^-$ decay [2], single-nucleon-transfer reactions [3,4], and $(n,\gamma)$ studies [5–10]. Fifteen of the known bands have been assigned two-quasiparticle (2qp) Nilsson model configurations based on $(d,p)$ [3] and $(t,\alpha)$ [4] reaction studies. However, for the other bands [1], such detailed assignments are either missing (e.g., the 814 keV $K^\pi = 3^+$ band) or have been suggested on plausibility arguments or model considerations [6,7,9–11]. The purpose of this Brief Report is to point out that existing $(d,p)$ data [3] provide direct evidence for interchanging the currently adopted 2qp interpretations for the two $K^\pi = 1^+$ bands at 426 keV and 568 keV. At the time these early $(d,p)$ data [3] were published the level structure was not well known, and it was impossible to interpret all the peaks in the low energy region of the spectrum, as many of these peaks were unresolved doublets or multiplets. Since then, many $(n,\gamma)$ studies [5–10] have provided much information on the energies, spins, parities, and band structures for levels in this region. This knowledge now makes it possible to understand better the early $(d,p)$ results, and to extract additional new information from them, using the well-known feature that in a single-nucleon-transfer reaction the relative cross sections within a rotational band have a characteristic pattern or "fingerprint" [12–14].

The level with $I^\pi = 1^+$ at 426 keV was populated through allowed $\beta$ decay of $^{166}$Dy by Helmer and Burson [2] who deduced log*ft*=4.8 for this beta branch. Low energy $(n,\gamma)$ studies by Motz *et al.* [6] identified rotational levels up to spin 6 in the $K^\pi = 1^+$ band based on this level. The low log*ft* value led them to characterize this beta transition as allowed unhindered (AU) [15], and hence to suggest the $\frac{7}{2}^-[523]_\pi - \frac{5}{2}^-[523]_\nu$ configuration for this $K^\pi = 1^+$ band. Bollinger and Thomas [7] proposed another $K^\pi = 1^+$ band based on a level at 568 keV, and assigned it as the $\frac{7}{2}^-[523]_\pi - \frac{5}{2}^-[512]_\nu$ 2qp state, as this was the only other configuration expected to produce a $K^\pi = 1^+$ band in the low energy spectrum. These assignments, one based on the assumed AU classification for a beta transition (with a currently adopted [1] log*ft*=5.12) and the other by default, have persisted [1] even though various physical arguments and microscopic structure calculations [11,16] have strongly suggested interchange of their 2qp assignments.

An exhaustive survey [17] of all beta transitions with log*ft*≤5.2 in deformed nuclei revealed that in several cases AU strength could be distributed over a number of daughter states. Also, other channels obeying modified selection rules [18] could result in log*ft* values overlapping the AU domain [11]. Further microscopic calculations [16] quantitatively established that an admixture of only 10% of the $\frac{7}{2}^-[523]_\pi - \frac{5}{2}^-[523]_\nu$ strength in the 426 keV $1^+$ state of $^{166}$Ho yields log*ft*=5.1 for its beta population, and that the dominant component of the 426 keV state is the $\frac{7}{2}^-[523]_\pi - \frac{5}{2}^-[512]_\nu$ configuration. The $1^+$ state at 568 keV, which probably contains the main $\frac{7}{2}^-[523]_\pi - \frac{5}{2}^-[523]_\nu$ component, lies at too high an energy to be populated in the $\beta$ decay of $^{166}$Dy ($Q_\beta$=487 keV). This interpretation is more consistent with considerations of bandhead energies and Gallagher-Moszkowski (GM) splitting energies [11] than the one currently adopted [1]. Hence, a new examination of the available $(d,p)$ data [3] has been undertaken to see whether they could help resolve this controversy.

For this purpose, results from the $^{165}$Ho$(d,p)^{166}$Ho study of Struble *et al.* [3] are considered. These experiments used 12 MeV deuterons from the Florida State University tandem Van de Graaff accelerator to bombard a metal holmium target. Reaction products were analyzed with a Browne-Buechner-type magnetic spectrograph and detected with photographic plates. Figure 1 shows a spectrum, adapted from the data reported for $\theta$=45°, labeled according to the interpretation given in the present work. The energy resolution reported for this spectrum was 10.7 keV full width at half maximum.

 

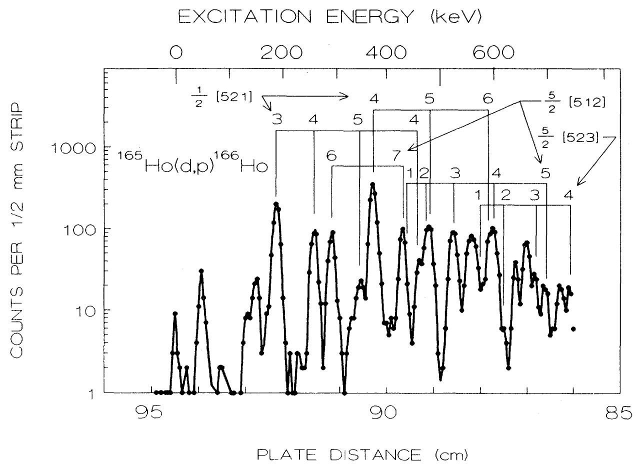


FIG. 1. Partial spectrum of protons from the $^{165}$Ho$(d,p)^{166}$Ho reaction with a deuteron energy of 12 MeV and $\theta$=45°, adapted from data of Struble *et al.* [3]. The bands are labeled by the neutron which couples with the $\frac{7}{2}^-[523]$ proton of the target ground state to form the respective GM doublets. The spin values indicated for band members are from the Nuclear Data Sheets [1], and are adopted from previous works. Levels in the ground state band have very small cross sections, and are located among some impurity peaks; so these negative-parity states have not been labeled in this figure.

The assignments indicated in Fig. 1 for positive-parity levels were made by comparing excitation energies from the $(d,p)$ experiment with the presently available precise level energies and adopted spin parities. These are consistent with the assignments originally made by Struble *et al.* [3], but it is now possible to extend the interpretation to a larger number of bands. The corresponding experimental intensities (normalized to 100 for the large 191 keV $I,K^\pi = 3,3^+$ peak) are listed in Table I for comparison with predicted values obtained from calculations described below.

The intrinsic single-neutron transfer cross sections were obtained from distorted-wave Born approximation (DWBA) calculations with the program [19] DWUCK4, using optical model parameters obtained from global fits, and which had been used in a study of the $^{167}$Er$(d,p)$ reaction [13]. Theoretical wave functions for states of interest were obtained by performing a Nilsson model calculation, and then incorporating Coriolis mixing effects with the program GREATER [20]. These calculations included all configurations obtained by coupling the $\frac{7}{2}^-[523]$ proton with the $\frac{7}{2}^+[633]$, $\frac{5}{2}^-[523]$, $\frac{3}{2}^-[521]$, $\frac{1}{2}^-[521]$, $\frac{5}{2}^-[512]$, $\frac{1}{2}^-[510]$, and $\frac{3}{2}^-[512]$ neutrons. An attenuation factor of 0.75 was applied to the Coriolis matrix elements.

TABLE I. Comparison of experimental $(d,p)$ cross sections with predicted values for configurations involved in the two $K^\pi = 1^+$ bands discussed.

| Configuration | Energy (keV) | | Intensity[c] ($\theta$=45°) | |
|---|---|---|---|---|
| | Adopted[a] | Experiment[b] ($\theta$=45°) | Experiment[b] | Calculated |
| $\frac{7}{2}^-[523]_\pi + \frac{5}{2}^-[512]_\nu$ | | | | |
| $K^\pi=6^+$, $I=6$ | 295.1 | 293.6 | 44±2 | 45 |
| 7 | 421.1 | 422.7 | 48±2 | 46 |
| $\frac{7}{2}^-[523]_\pi - \frac{5}{2}^-[512]_\nu$ | | | | |
| $K^\pi=1^+$, $I=1$ | 426.0 | 422.7 | Obscured[d] | 8 |
| 2 | 464.5 | 468.2 | ≤52[e] | 23 |
| 3 | 522.0 | 515.6 | 38±6 | 30 |
| 4 | 598.3 | 596.0 | 42±6 | 22 |
| 5 | (693) | 690.7 | 10±1 | 10 |
| 6 | 807.3 | — | — | 2 |
| $\frac{7}{2}^-[523]_\pi - \frac{5}{2}^-[523]_\nu$ | | | | |
| $K^\pi=1^+$, $I=1$ | 567.6 | 571.2 | ≤7[f] | 1.8 |
| 2 | 605.1 | 613±4 | 2±1 | 3.0 |
| 3 | 662.2 | 668.1 | 8±2 | 3.4 |
| 4 | 736.5 | 738.0 | 8±1 | 2.6 |
| 5 | 832.2 | — | — | 1.4 |

[a]From the Nuclear Data Sheets [1].
[b]From Struble *et al.* [3].
[c]Relative cross sections at $\theta$=45°, normalized to 100 for the strong 191 keV peak. Experimental values are from Struble *et al.* [3] and theoretical values are from DWBA and Nilsson model calculations, with Coriolis mixing, from the present work.
[d]Obscured by the large peak for the $I,K^\pi = 7,6^+$ level.
[e]The peak at 468.2 keV with an observed intensity of 52±3 includes contributions from the 464.5 keV $I,K^\pi = 2,1^+$ level (calculated intensity =23) and the 470.9 keV $I,K^\pi = 5,4^+$ level of the $7/2^-[523]_\pi+1/2^-[521]_\nu$ band (calculated intensity =30).
[f]The 571.2 keV peak includes contributions from the 567.6 keV $I,K^\pi = 1,1^+$ level (calculated intensity =2) and the 577.2 keV $I,K^\pi = 7,3^+$ level of the $7/2^-[523]_\pi-1/2^-[521]_\nu$ band (calculated intensity =5).

The $(d,p)$ reaction populates configurations that can be formed by coupling the transferred neutron to the $\frac{7}{2}^-[523]$ proton, which forms the $^{165}$Ho ground state. The $K^\pi = 1^+$ band with $\frac{7}{2}^-[523]_\pi - \frac{5}{2}^-[512]_\nu$ character is expected to have much larger cross sections than the $\frac{7}{2}^-[523]_\pi - \frac{5}{2}^-[523]_\nu$ one. This is because the $\frac{5}{2}^-[512]$ neutron contains large amplitudes of the $2f_{7/2}$ shell model state and therefore has dominant $\ell = 3$ components, which have much larger cross sections than the $\ell = 5$ ones from the $h_{9/2}$ shell that dominate the $\frac{5}{2}^-[523]$ orbital. This difference is clearly evident in the predictions shown in the last column of Table I.

The only levels occurring below 190 keV belong to the $K^\pi = 0^-$ and $7^-$ bands arising from transfer of the $\frac{7}{2}^+[633]$ neutron, which originates from the $i_{13/2}$ shell and thus involves mainly $\ell$=6 transfers. These have very small cross sections, which are further complicated by peaks in the spectrum due to light impurities, and therefore have not been labeled in Fig. 1. The large peaks for the $K^\pi = 3^+$ and $K^\pi = 4^+$ bands formed by transfer of a $\frac{1}{2}^-[521]$ neutron dominate the low energy portion of the spectrum. These bands were correctly interpreted by Struble *et al.* [3] and will not be discussed further here. Similarly, the $K^\pi = 6^+$ band with the $\frac{7}{2}^-[523]_\pi + \frac{5}{2}^-[512]_\nu$ configuration was also previously assigned [3]. For this study, discussion is focussed on the remaining two bands shown in Fig. 1 with $K^\pi = 1^+$, which were not assigned by Struble *et al.* [3]. As mentioned above, the adopted [1] assignments for these two $K^\pi = 1^+$ bands have been seriously questioned [11,16]. Information for these bands, and the $K^\pi = 6^+$ band, which is a GM partner to the $K^\pi = 1^+$, $\frac{7}{2}^-[523]_\pi - \frac{5}{2}^-[512]_\nu$ band of interest, is summarized in Table I.

An important sum rule for a single-nucleon-transfer reaction on an odd-mass target is that to a first approximation the total strength to the triplet (spins coupled parallel) band should be the same as that to the singlet (spins coupled antiparallel) band formed with the same nucleons. In practice, the summed cross sections can differ slightly for the two bands because of the $Q$-value dependence of the intrinsic cross sections as calculated by the DWBA. Also, there are cases where one of the two bands in a GM pair may mix significantly with nearby levels, and this can cause deviations from the "first approximation" given above. However, in most cases the expectation is satisfied reasonably well. The effect of this rule can be seen in Table I for transfer of the $\frac{5}{2}^-[512]$ neutron. The total predicted intensity for the $K^\pi = 6^+$ triplet band is 91 units, while that for the $K^\pi = 1^+$ singlet band is 95. The Coriolis calculation does not predict serious mixing for either of these bands. Table I shows that the experimental intensities for the $K^\pi = 6^+$ band are in excellent agreement with those predicted, and so it is expected that the summed intensity for the $K^\pi = 1^+$, $\frac{7}{2}^-[523]_\pi - \frac{5}{2}^-[512]_\nu$ band should be of the order of 90–100 units. It can be seen immediately from Table I that the total intensity for members of the $K^\pi = 1^+$ band at 568 keV is $\leq$25 units, which is much too small to be consistent with the $\frac{7}{2}^-[523]_\pi - \frac{5}{2}^-[512]_\nu$ assignment presently adopted [1]. Moreover, the intensity for the $I^\pi = 2^+$ band member at 605 keV has an intensity of only 2$\pm$1 units, compared to the predicted value of $\sim$23 for the spin-2 member of a pure $K^\pi = 1^+$, $\frac{7}{2}^-[523]_\pi - \frac{5}{2}^-[512]_\nu$ band. This indicates that the admixture of this configuration in the 568 keV band can be no larger than $\sim$10%. Thus, even though many of the peaks in the $(d,p)$ spectrum include unresolved levels, the upper limits which can be placed on observed intensities (by simply taking the entire cross section present at that energy) are small enough to show unambiguously that the main $K^\pi = 1^+$, $\frac{7}{2}^-[523]_\pi - \frac{5}{2}^-[512]_\nu$ strength is not in the 568 keV band. On the other hand, the small observed intensities in this band are large enough for the $K^\pi = 1^+$, $\frac{7}{2}^-[523]_\pi - \frac{5}{2}^-[523]_\nu$ configuration to be present in this band.

In contrast, the observed intensities for the $K^\pi = 1^+$ band at 426 keV are seen in Table I to be large enough to include the predicted values for the $\frac{7}{2}^-[523]_\pi - \frac{5}{2}^-[512]_\nu$ band, in terms of both the total cross section and its distribution among the band members. Therefore, these results provide clear and direct evidence that the $\frac{7}{2}^-[523]_\pi - \frac{5}{2}^-[512]_\nu$ band should be assigned at 426 keV, and the $\frac{7}{2}^-[523]_\pi - \frac{5}{2}^-[523]_\nu$ one at 568 keV, as suggested by several authors [11,16], but opposite to the interpretation adopted in the Nuclear Data Sheets [1]. Of course, it is quite likely that some $\Delta K = 0$ mixing occurs between these bands, and so the labels given here refer only to the dominant components.

The $K^\pi = 6^+$ GM partner of the 568 keV $1^+$ band is expected at $\sim$700 keV with a small $(d,p)$ cross section. With the resolution of the $(d,p)$ data used here, these weak peaks cannot be identified.

In summary, the present analysis of $^{165}$Ho$(d,p)^{166}$Ho reaction data unambiguously establishes the $\frac{7}{2}^-[523]_\pi - \frac{5}{2}^-[512]_\nu$ 2qp configuration for the 426 keV $1^+$ band and the $\frac{7}{2}^-[523]_\pi - \frac{5}{2}^-[523]_\nu$ configuration for the 568 keV $1^+$ band in $^{166}$Ho. The data are consistent with a mixing of $\sim$10% for the two bands, and this was found adequate [16] to explain the observed log*ft*=5.12 for the beta branch populating the 426 keV bandhead. The empirical values of GM splittings are used to extract parameters of the residual neutron-proton interaction, and the interchange of assignments described here is important in that it removes a spurious data point from analyses of this interaction [11].

It would be very useful to have $(d,p)$ data with better resolution to provide more stringent limits on these admixtures and to help interpret some of the other peaks in the spectrum. For example, large peaks are predicted for the $K^\pi = 4^+$ and $3^+$, $\frac{7}{2}^-[523]_\pi \pm \frac{1}{2}^-[510]_\nu$ bands, and it is likely that the 814.3 keV ($3^+$), 889.8 keV ($4^+$), and 984.6 keV ($5^+$) levels assigned as a $K^\pi = 3^+$ band [7], but not given a 2qp interpretation, are actually this expected $K^\pi = 3^+$ band. The large peaks observed in the $(d,p)$ spectrum at these energies appear to be consistent with this tentative assignment, but better $(d,p)$ data are highly desirable to confirm this, and to elucidate other structures in $^{166}$Ho.

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