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New rotational bands in ^{166}Ho

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The $K^\pi=1^-$ and 0^- bands from the $(\frac{1}{2}^+[411]\pm\frac{1}{2}^-[521])$ configuration, and the $K^\pi=1^-$ and 2^- bands from the $(\frac{3}{2}^+[411]\pm\frac{1}{2}^-[521])$ configuration have been identified for the first time largely using known but previously unused gamma transitions from the ^{165}Ho(n,γ) reaction. A remarkable similarity is shown to exist between the level structures of the $K^\pi=1^-$ and 0^- bands from the $(\frac{1}{2}^+[411]\pm\frac{1}{2}^-[521])$ configurations in ^{170}Tm and ^{166}Ho.

Holmium in nature is monoisotopic ^{165}Ho. Therefore the odd-odd nucleus ^{166}Ho has been conveniently studied using neutron insertion reactions, such as the (d,p) reaction[1,2] and especially the (n,γ) reaction,[3-9] using thermal neutrons, average resonance capture, polarized neutrons, and the (n,e^-) reaction. It has also been possible to study ^{166}Ho using the (t,α) proton pickup reaction[10] on the stable target ^{167}Er. Finally the low spin states in ^{166}Ho have been characterized following the β^- decay of 81.6 h ^{166}Dy.[11-15]

This prodigious experimental effort has led to the observation of 309 levels from which it is possible to construct 18 rotational bands.[16] In this investigation we report on three more rotational bands or band heads involving 11 additional new levels and the reassignment of one rotational band. The rotational level structure for ^{166}Ho below 1250 keV, which includes all except two of these rotational bands, is presented in Fig. 1. The three new rotational bands and the reassigned band are shown in the shaded rectangle in the center of the diagram. The energies of the states, except those in the shaded area, in Fig. 1 are from Nuclear Data Sheets[16] and the two-particle configurations are from our recent analysis.[17] The negative parity bands, shaded in Fig. 1, are presented in more detail in Fig. 2.

Two quasiparticle states in an odd-odd deformed nucleus are created by adding an odd proton (Ω_p) and an odd neutron (Ω_n) to the deformed even-even core (with $Z-1$ and $A-2$). Each combination of Ω_p and Ω_n gives two rotational bands with $K^\pm=|\Omega_p\pm\Omega_n|$. The calculated energies of these rotational bands are approximately given by the expression

$$E_K(\Omega_p,\Omega_n)=E_p(\Omega_p)+E_n(\Omega_n)+(\hbar^2/2\mathcal{J})[I(I+1)-K^2] -(\tfrac{1}{2}-\delta_{\Sigma,0})E_{\rm GM}-\delta_{K,0}(-1)^{\pi}\pi E_N \ . \quad (1)$$

The level structure in neighboring odd-proton and odd-neutron nuclei is used to evaluate E_p and E_n, respectively. The inverse moment of inertia $(\hbar^2/2\mathcal{J})$ is obtained by adding small incremental contributions determined from neighboring odd-proton and odd-neutron nuclei to the inverse moment of inertia of the even-even core. The Gallagher-Moszkowski GM splitting energies $E_{\rm GM}$ between K^+ and K^-, and the Newby splitting energy E_N for the $K=0$ bands can be obtained from existing experimental values, or if necessary, calculated assuming a zero range interaction.

Using this formalism for calculating the position of two-quasiparticle states in ^{166}Ho, we obtain 52 two-quasiparticle bands from the single-particle orbitals with the summed neutron and proton energies up to 1 MeV.[17] The number of observed rotational bands is therefore even less than half of which we might expect in ^{166}Ho. This suggests that, within the existing data, there may be previously unidentified levels and rotational bands. It is quite clear where we might expect to find this additional level structure. Since reaction spectroscopy populates either neutron excited configurations or proton excited configurations, but not both neutron and proton excited configurations, we can expect that the most likely configurations to be missed would involve both excited proton and neutron configurations. All configurations in Fig. 1, except those in the shaded rectangle, which are first observed and/or assigned in this paper, involve either ground-state proton or neutron configurations.

If we look at the excitation spectrum in ^{165}Dy we find the two lowest neutron configurations are the 108-keV $\frac{1}{2}^-[521]$ and the 184-keV $\frac{5}{2}^-[512]$ above the $\frac{7}{2}^+[633]$ ground state. Similarly in ^{165}Ho the two lowest excited proton configurations are the 362-keV $\frac{3}{2}^+[411]$ and the 429-keV $\frac{1}{2}^+[411]$ above the $\frac{7}{2}^-[523]$ ground state. In zeroth order, therefore, the lowest-lying configurations with both excited neutron and proton configurations would be $(\frac{3}{2}^+[411]\pm\frac{1}{2}^-[521])$ at 470 keV with $K^\pi=1^-$

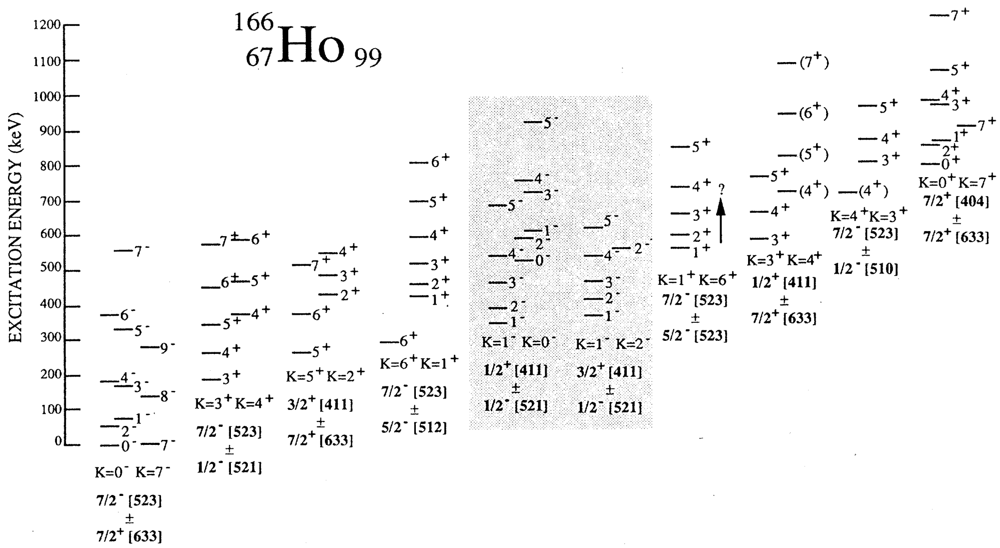

FIG. 1. The band structure of ^{166}Ho below 1250 keV. Energies of most of the states are from Ref. 16. However, three of the bands in the shaded rectangle in the center of the figure are observed here for the first time and are presented in more detail in Fig. 2. The fourth band in the shaded area had previously been observed, but is reassigned in this paper. K^{π} values and Nilsson configurations are given under each band.

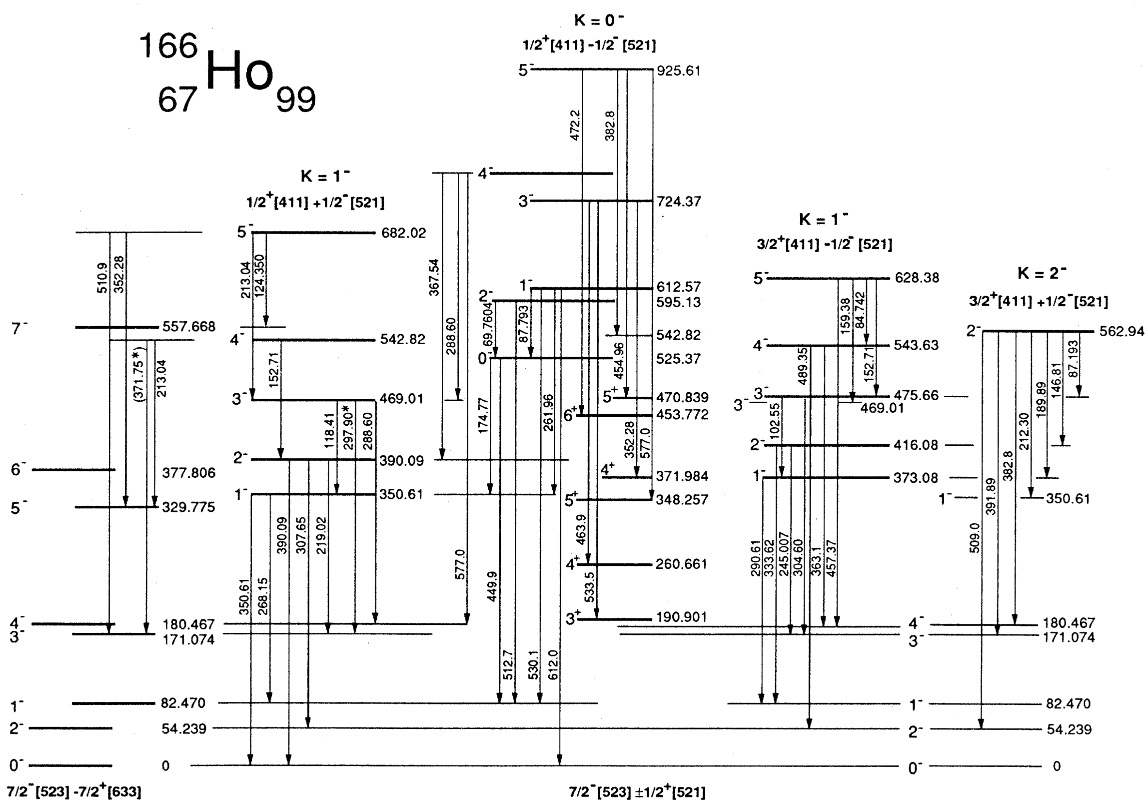

FIG. 2. The energies and γ decay patterns of the $K^{\pi}=1^-$ and 0^- bands from the $(\frac{1}{2}^+[411]\pm\frac{1}{2}^-[521])$ configuration and the $K^{\pi}=1^-$ and 2^- bands from the $(\frac{3}{2}^+[411]\pm\frac{1}{2}^-[521])$ configuration. The 373.1-keV $K^{\pi}=1^-$ band, assigned here as $(\frac{3}{2}^+[411]-\frac{1}{2}^-[521])$, had previously been assigned the $K^{\pi}=1^-$ $(\frac{1}{2}^+[411]+\frac{1}{2}^-[521])$ configuration. See text for details. An asterisk after a transition indicates that it has also been used elsewhere in the total ^{166}Ho decay scheme.

TABLE I. The calculated excitation energies for the lowest-lying band heads for configurations in ^{166}Ho in which both the proton and neutron are excited.

Configuration	Zeroth-order energy (keV)	First-order calculations K_1^π	Energy of K_1 (keV)	K_2^π	Energy of K_2 (keV)
$\frac{3}{2}^+[411]\pm\frac{1}{2}^-[521]$	470	1^-	375	2^-	553
$\frac{1}{2}^+[411]\pm\frac{1}{2}^-[521]$	537	1^-	440	0^-	590
$\frac{3}{2}^+[411]\pm\frac{5}{2}^-[512]$	546	4^-	425	1^-	635
$\frac{1}{2}^+[411]\pm\frac{5}{2}^-[512]$	613	2^-	500	3^-	720

and 2^-; ($\frac{1}{2}^+[411]\pm\frac{1}{2}^-[521]$) at 537 keV with $K^\pi=1^-$ and 0^-; ($\frac{3}{2}^+[411]\pm\frac{5}{2}^-[512]$) at 546 keV with $K^\pi=4^-$ and 1^-; and ($\frac{1}{2}^+[411]\pm\frac{5}{2}^-[512]$) at 613 keV with $K^\pi=2^-$ and 3^-. The first-order calculations of the energies for the band heads, as determined using Eq. (1), are given in Table I.

It is interesting to note that the $K^\pi=1^-$ band beginning at 373.1 keV with rotational band members up to the 4^- has been assigned[6,16] as the ($\frac{1}{2}^+[411]+\frac{1}{2}^-[521]$) configuration of Table I. However this band is seen to have very regular energy spacings, whereas we find that in the ground state of ^{170}Tm the $K^\pi=1^-$ band with the configuration ($\frac{1}{2}^+[411]+\frac{1}{2}^-[521]$) coriolis couples with, and therefore mirrors to some extent, the energy staggering caused by the Newby shift of the $K^\pi=0^-$ band having the same configuration but with antiparallel coupling. We expect a similar effect for the corresponding band in ^{166}Ho. In consequence this configurational assignment

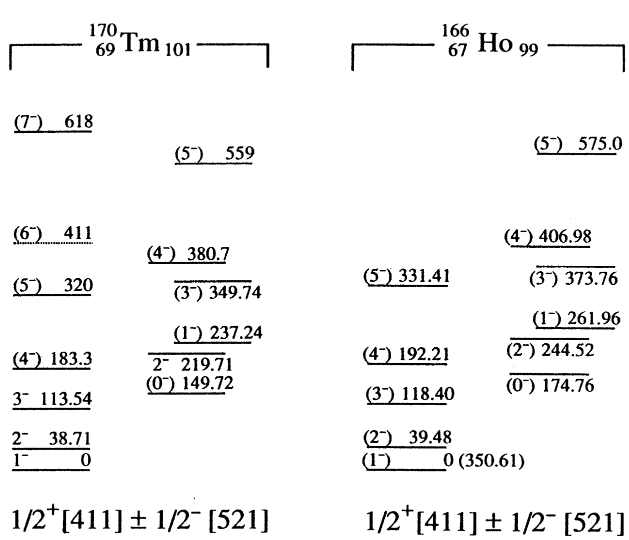

FIG. 3. Comparison of the level structure of the $K^\pi=1^-$ and 0^- bands of the ($\frac{1}{2}^+[411]\pm\frac{1}{2}^-[521]$) configuration of ^{170}Tm (left) with ^{166}Ho (right). To facilitate the direct comparison 350.61 keV has been subtracted from all of the level energies in ^{166}Ho in this figure.

for the 373.1-keV $K^\pi=1^-$ band must be seriously questioned, although the existence of this $K^\pi=1^-$ band is not in doubt.

One way to confirm this suspicion of a wrong configurational assignment for the 373.1-keV $K^\pi=1^-$ band is to identify the correct $K^\pi=1^-$ band. Since the low-energy (n,γ) and (n,e^-) studies are expected to populate states with excited neutron and excited proton configurations, we look at the existing low-energy γ and electron transitions following neutron capture in ^{165}Ho. The unusually high precision and reasonable completeness of the low-energy bent crystal γ-ray transitions[3] can be used to determine new energy levels especially when they are based on the firmly established existing levels in ^{166}Ho. The energy coincidences of a number of energy loops give us confidence in the method.

The application of this method resulting in three new bands or band heads is shown in Fig. 2. Also shown is the existing $K^\pi=1^-$ beginning at 373.1 keV. All γ-ray transitions are shown, including those previously and newly assigned in the $K^\pi=1^-$ band beginning at 373.1 keV. Figure 2 identifies the configurations and the corresponding bands for all four level structures. They are ($\frac{1}{2}^+[411]\pm\frac{1}{2}^-[521]$) with a $K^\pi=1^-$ band beginning at 350.61 keV and a $K^\pi=0^-$ at 525.37 keV, and ($\frac{3}{2}^+[411]\pm\frac{1}{2}^-[521]$) with a $K^\pi=1^-$ at 373.08 keV and a $K^\pi=2^-$ band head at 562.94 keV.

In Fig. 3 the level structure of the ($\frac{1}{2}^+[411]\pm\frac{1}{2}^-[521]$) configuration for the nucleus ^{166}Ho, observed and assigned for the first time in this study, is compared with that for the nucleus ^{170}Tm where it is the ground state configuration and has previously been assigned.[18] In order to make a direct comparison with ^{170}Tm, 350.61 keV has been subtracted from all ^{166}Ho level energies. The similarity between the level structures in ^{166}Ho and ^{170}Tm in Fig. 3 is indeed remarkable, and gives us additional confidence in the ^{166}Ho assignments. The Gallagher-Moszkowski splittings between the $K^\pi=1^-$ and 0^- bands in the two nuclei differ by only 25 keV. Even more remarkable is the extremely similar Newby splitting between the odd and even members of the $K^\pi=0^-$ bands. Finally, this Newby splitting is transferred into the $K^\pi=1^-$ bands via the Coriolis force resulting in an almost identical staggering in both nuclei.

The success in identifying these three new bands gives us hope that we might find other low-lying configurations with both excited neutron and proton configurations. The best opportunities for these observations probably lie in the third and fourth configurations listed in Table I, namely the ($\frac{3}{2}^+$[411]$\pm\frac{5}{2}^-$[512]) with $K^\pi=4^-$ and 1^- and ($\frac{1}{2}^+$[411]$\pm\frac{5}{2}^-$[512]) with $K^\pi=2^-$ and 3^-. All four of these bands are reasonably expected to be strongly populated in the (n,γ) reaction and their band heads should be observed in the energy region between $\sim$400 and $\sim$750 keV. However, in the absence of any distinctive or corroborative features for these bands, their identification from the presently available data alone can only be speculative and is not attempted here.

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