Coulomb excitation of ^{165}Ho

K. P. Singh, D. C. Tayal,* Gulzar Singh, and H. S. Hans
Physics Department, Panjab University, Chandigarh, India
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Six low-lying negative parity levels of ^{165}Ho, up to 688.5 keV excitation energy, were observed to be Coulomb excited with 4.32 MeV protons. Eleven deexcitation transitions from these levels were identified in the singles gamma-ray spectra recorded with a 57 cm^3 Ge(Li) detector. The 515.5, 566.8, 638, and 688.5 keV levels have been Coulomb excited with protons for the first time. Level energies, branching ratios, $B(E2)$ transition probabilities, and the multipole mixing ratios (δ) were obtained. Existing ambiguities in the reported measurements of $B(E2)$ were resolved. The angular distributions of the nine deexcitation transitions were analyzed to extract the angular distribution coefficients A_2, and the δ values for the mixed 115.1, 543.3, 566.8, and 593.8 keV transitions. The results have been discussed in light of the previously reported results.

I. INTRODUCTION

The levels of the strongly deformed odd-proton ^{165}Ho nucleus have been investigated experimentally by several workers.[1–5] The radioactive decay,[1–3] and inelastic scattering reactions like (p,p′), (^{10}B, ^{10}B′γ), (n,n′), and (n,n′γ) have been studied to construct the level scheme of ^{165}Ho up to about 1.98 MeV excitation energy.[1] The angular distributions of the gamma rays from the (n,n′γ) reactions were analyzed to assign J^{π} to several levels,[1] while the radioactive studies provided the multipolarities of many deexcitation transitions, as well as the firm assignments of several Nilsson configurations.[1–3,6] Single nucleon transfer data on the level structure of ^{165}Ho had also been interpreted on the basis of the Nilsson model with pairing and Coriolis mixing effects included.[4,5] Previously suggested[1–3] bands based on various Nilsson orbitals were observed and the level assignment to some of the bands was improved.[1]

Coulomb excitations with protons,[7,8] deuterons,[9,10] alphas,[11] and heavy ions[12–14] like ^{16}O and ^{35}Cl have furnished more information on the level properties of this nucleus. The first few negative parity levels of ^{165}Ho were characterized as the members of the ground state[7–11] rotational band $\frac{7}{2}^-$[523], and the two γ-vibrational[12–14] bands $\frac{3}{2}^-\{\frac{7}{2}[523],2^+\}$ and $\frac{11}{2}^-\{\frac{7}{2}[523],2^+\}$. The $\frac{9}{2}^-$ and $\frac{11}{2}^-$ members of the ground state band have been assigned 94.7 and 209.8 keV excitation energy,[6] while the $\frac{3}{2}^-$, $\frac{5}{2}^-$, and $\frac{7}{2}^-$ members of the $\frac{3}{2}^-\{\frac{7}{2}[523],2^+\}$ γ band have been assigned energies of 515.5, 566.8, and 638 keV, respectively.[12–14] The 688.5 keV level was suggested to be the $\frac{11}{2}^-\{\frac{7}{2}[523],2^+\}$ γ bandhead.[5,12–14] The $\frac{11}{2}^-$ level of the ground state band has been found to be strongly admixed with higher lying members arising from the $h_{11/2}$ shell model state.[5]

Coulomb investigations of the low-lying levels have been carried out either by recording the spectra with a magnetic spectrometer for the conversion electrons[8,9–12] or the inelastically scattered charged particles,[10] or by recording the γ-ray spectra with a scintillation counter[7,11] as for the case of 94.7 and 209.8 keV levels, or with a relatively small sized (3 cm^3) Ge(Li) detector,[13,14] as for the case of 515.4, 566.8, 638, and 688.5 keV levels. The last four levels have been Coulomb investigated only with heavy ions,[12–14] but for the last three levels the deduced $B(E2)\uparrow$ values were not corrected for multiple Coulomb excitation.[1] Also the corresponding values of the reduced quadrupole transition probabilities $B(E2)$ for the 94.7 and 209.8 keV levels,[1,7–11] as well as for the 515.5, 566.8, 638, and 688.5 keV levels[1,12,13] reported by different workers, have significant discrepancies. Besides, in the case of the last four levels, no angular distribution measurements of the deexcitation transitions have been carried out.[1,12–14] Keeping these facts in view, we decided to perform the Coulomb excitation measurements on ^{165}Ho as part of our general program[15–17] to investigate low-lying levels in the mass region $A>100$ through Coulomb excitation with protons. The possibility of multiple Coulomb excitation with protons is negligible, resulting in the enhanced accuracy of the extracted nuclear information. Eleven deexcitation transitions were observed with a 57 cm^3 Ge(Li) detector, from the six levels up to 688.5 keV excitation energy, populated in the present work. The $B(E2)$, the angular distribution coefficients A_2, and the multipole mixing ratios (δ) were deduced from the gamma-ray yields and angular anisotropy measurements. The A_2 coefficients for the eight transitions and δ values for 543.3, 566.8, and 593.8 keV transitions have been extracted for the first time from the angular distributions.

II. EXPERIMENTAL PROCEDURE

The experimental procedure followed has been described in detail elsewhere.[15,16] An isotopically pure thick metallic foil of ^{165}Ho was bombarded with 4.32 MeV protons available from the variable energy cyclotron at Panjab University, Chandigarh.[18] The beam current on the target was maintained around 200 nA to avoid the pileup in the electronic circuit, and to minimize the dead time correction for the multichannel analyzer. The deexcitation gamma rays were detected at a distance of about

8.8 cm from the target, with a 57 cm^3 Ge(Li) detector having an energy resolution of about 2.0 keV for the 1.332 MeV line from the ^{60}Co source. The spectra were recorded at three angles of 0°, 55°, and 90° to the beam direction, to provide the data for the anisotropy treatment. The data at 55°, being independent of angular distribution effects, were used to extract $B(E2)$ values.

III. EXPERIMENTAL RESULTS AND ANALYSIS

A. Gamma-ray yields

The gamma-ray spectrum recorded at 55° to the beam direction, and displaying the well-resolved peaks, is shown in Fig. 1. Eleven gamma-ray peaks at 94.7, 115.1, 154, 209.8, 428.2, 472.1, 515.5, 543.3, 566.8, 593.8, and 688.5 keV energies, have been assigned to the transitions from the Coulomb excited levels in ^{165}Ho, on the basis of their well-known energies.[1] The remaining gamma-ray peaks arise from the background. As described in our previous papers[15,16] the experimental thick-target gamma-ray yields per incident proton, for each transition, were compared with the theoretical gamma-ray yields obtained by integrating the theoretical excitation function[19] along the path of the proton in the target. The $B(E2)$ values were extracted from the comparison of theoretical and experimental gamma-ray yields for various transitions. The compound nucleus contribution at 4.32 MeV proton energy, computed with code CINDY (Ref. 20) was found to be negligible (less than 0.5 percent of the Coulomb excitation) compared to the experimental yield, confirming the prevailing reaction mechanism to be Coulomb excitation. The present $B(E2)\uparrow$ values along with their comparison with the previous results are shown in Table I. The errors assigned to the $B(E2)\uparrow$ values result from the uncertainties in the peak area, the calibrated efficiency of the Ge(Li) detector, and the stopping power of Ho for protons.

B. Angular distributions

The angular distributions of the gamma rays were determined from the spectra taken with 4.32 MeV protons

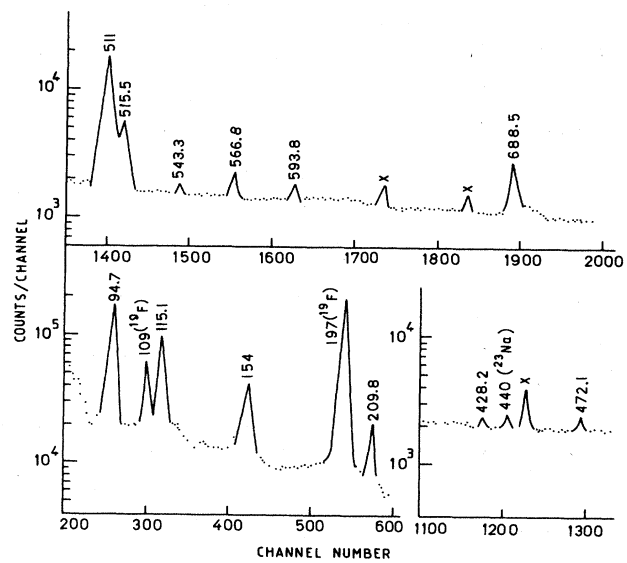

FIG. 1. Gamma-ray spectrum observed with 4.32 MeV protons. The peaks marked × correspond to background gamma rays.

at 0° and 90° relative to the beam direction. The results were fitted to the equation

$$W(\theta)=1+a_2g_2A_2P_2(\cos\theta)+a_4g_4A_4P_4(\cos\theta) ,$$

where a_2 and a_4 are the thick target particle parameters,[19] and g_2 and g_4 are the finite solid angle correction factors. The coefficients A_2 and A_4 are a function of spin sequence and the multipole mixing ratio. The last term in the preceding equation has been neglected since a_4 is very small. The measurement of the ratio

$$R \equiv W(0°)/W(90°)$$

determines A_2 uniquely and thereby the multipole mixing ratio[21] allowed for a particular transition. The results of our measurements are summarized in Table II.

The quoted errors in δ values were estimated from the uncertainties in A_2 coefficients propagated from the measured gamma-ray yields.

TABLE I. Comparison of $B(E2)\uparrow$ values with the previous Coulomb excitation studies of ^{165}Ho.

Level energy (keV)	Measured $B(E2)\uparrow$ ($10^{-50}e^2$cm^4) Present	Seaman (Ref. 13)	Diamond (Ref. 12)	Bernstein (Ref. 8)	Martin (Ref. 7)
94.7	230 ±46			280±40	320
209.8	62 ±8			65±13	119
515.5	3.0 ±0.3	4.44 ±0.053	2.89 ±0.35		
566.8	1.3 ±0.2	2.1 ±0.2	1.4 ±0.2		
638	0.095±0.017/ϵ	0.248±0.055/ϵ[a]	0.0020±0.0006/ϵ[a]		
688.5	4.0 ±0.4	7.3 ±0.7	4.2 ±0.5		

[a]Not corrected for multiple Coulomb excitation (Ref. 1).

TABLE II. Summary of gamma-ray anisotropy results from the Coulomb excitation of ^{165}Ho.

E_γ (keV)	$R=\dfrac{W(0°)}{W(90°)}$	a_2	A_2	Mixing ratios
115.1	1.010±0.013	0.414	0.016±0.021	0.18 ±0.03
209.8	1.183±0.007	0.414	0.283±0.010	
428.2	1.317±0.100	0.830	0.235±0.067	
472.1	1.270±0.061	0.790	0.214±0.044	
515.5	1.270±0.021	0.753	0.231±0.016	
543.3	0.917±0.044	0.830	−0.07 ±0.04	−0.35 ±0.17
566.8	0.818±0.017	0.790	−0.167±0.017	−0.09 ±0.05
593.8	0.926±0.026	0.854	−0.062±0.022	0.073±0.023
688.5	1.369±0.036	0.854	0.270±0.023	

IV. DISCUSSION OF THE LEVEL PROPERTIES

The level scheme incorporating the results of the present investigation and previous[1] studies for ^{165}Ho is displayed in Fig. 2. Except for the 478.6 and 638 keV transitions, all other eleven transitions, from the six low-lying levels reported previously,[1] were observed in the present experiment. The 478.6 keV transition with the reported 3% photon branching ratio[1] is expected to be very weak. Our photon branching ratios for other transitions are in reasonable agreement with the previously reported results.[1] The observed 154 keV transition has been characterized as the $M2$ transition[12–14] as it links the 515.5 keV with $J=\frac{3}{2}^-$ to the 361.7 keV level with $J=\frac{3}{2}^+$. The latter level is not populated through direct Coulomb excitation. In the extraction of $B(E2)$ values the feeding, as well as the deexcitation of each level through the intermediate transitions, has been taken into account. A brief discussion of the properties of various levels follows.

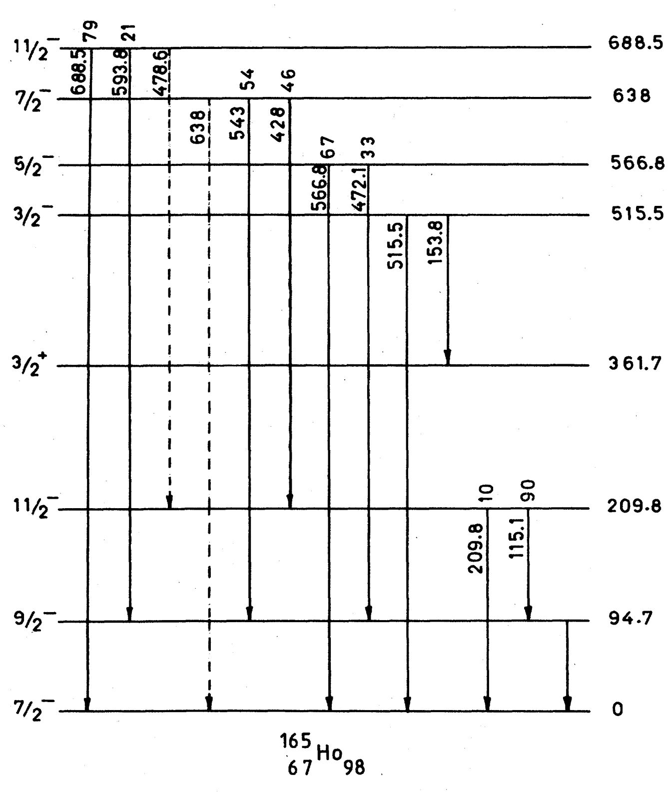

FIG. 2. Energy level diagram of states in ^{165}Ho Coulomb excited with protons. The numbers on each level give the relative intensities of gamma rays from that level.

A. The 94.7 and 209.8 keV levels

These levels have been studied earlier through Coulomb excitations with protons,[7,8] deuterons,[9,10] and alphas.[11] The corresponding reduced quadrupole transition probabilities, reported by different workers,[1] for both these levels have significant discrepancies. These differences may arise because of the uncertainties introduced by the poor energy resolution of the NaI detectors used. The present $B(E2)$ values of these levels, however, agree with the results of some of the workers.[1]

These levels have been characterized,[1] respectively, as the $\frac{9}{2}^-$ and $\frac{11}{2}^-$ members of the ground state band $\frac{7}{2}^-[523]$. The relatively large values of $B(E2)$ for these levels, suggesting their strong collective nature, support such assignment. The higher members of the ground state rotational band could not be excited because of the spin selection rule. For the 115.1 keV transition, the present values of the A_2 coefficient and mixing ratio are 0.016±0.021 and 0.18±0.03, respectively. These values are in reasonable agreement with the reported values in the literature.[1] The present A_2 value for the pure $E2$, 209.8 keV transition is the first time measurement for this transition.

B. The 515.5, 566.8, 638, and 688.5 keV levels

These levels have previously been Coulomb excited only with heavy ions.[12–14] The respective $B(E2)$ values for these levels, provided by the two different research groups,[12,13] differ significantly. In the case of the last three levels, these workers did not apply the necessary corrections to their $B(E2)$ values for the possible multiple Coulomb excitation.[1] These results may also carry some uncertainties because of the relatively small detection efficiencies of gamma-ray detectors used by the previous workers. Besides, because of the unknown gamma-ray branching ratios, the $B(E2)$ values for the 638 keV level, as determined by different workers from the 543.3 keV transition gamma-ray yields, were not completely defined.[1]

In the present work the 638 keV γ-ray transition was also not observed, and the $B(E2)$ value for the 638 keV level was deduced from the gamma-ray yield of the 543.3 keV transition. We have, however, lesser uncertainties here due to multiple Coulomb excitation and detector efficiency.

Our $B(E2)$ value for the 638 keV level seems to differ from the results of Diamond *et al.*[12] as well as Seaman *et al.*[13] For the other three levels, our results are in excellent agreement with the values by Diamond *et al.*[12] The values by Seaman *et al.*,[13] however, seem to be somewhat larger than the corresponding present results.

These levels are known to be members of $K=\frac{7}{2}\pm 2$ γ-vibrational bands on the ground state.[1] The relatively smaller values of $B(E2)$ for these levels, however, suggest that their collective nature is not as predominant as that for the 94.7 and 209.8 keV levels.

The angular distribution coefficients A_2 for the pure $E2$, 428.2, 472.1, 515.5, and 688.5 keV transitions, as well as the mixing ratios (δ) for the 543.2, 566.8, and 593.8 keV transitions determined in the present work have been listed in Table II. The previously reported δ values of $5.5^{+\infty}_{-3.8}$ and $2.6^{+\infty}_{-1.2}$, respectively, for the 566.8 and 593.8 keV transitions were estimated from the results of internal conversion coefficient measurements.[12] These results, however, cannot be very reliable because of their large sensitivity to changes in the poorly determined internal conversion coefficients and the photon branching ratios. So the present results from the angular distributions provide new information for most of the cases. For the 566.8 and 593.8 keV transitions, the present values supersede the previously poorly defined values.

V. CONCLUSION

Our measurements upgrade the data on Coulomb excitation of ^{165}Ho with protons. The 515.5, 566.8, 638, and 688.5 keV levels were Coulomb excited for the first time with protons. All the known levels of the ground state rotational band $\frac{7}{2}^-[523]$ and the γ-vibrational bands $\frac{3}{2}^-\{\frac{7}{2}[523],2^+\}$ and $\frac{11}{2}^-\{\frac{7}{2}[523],2^+\}$, permitted by the spin selection rule, were populated. Because of the use of a high resolution Ge(Li) detector of greater efficiency, the recording of data with improved statistics and the absence of multiple Coulomb excitation with protons, our results are expected to be more reliable. Present values have resolved the discrepancies in the reported values of $B(E2)$. The angular distribution results for the 115.1 keV transition agree with the previously reported values. The angular distribution coefficients A_2 for the four pure $E2$ transitions and multipole mixing ratios (δ) for the three mixed transitions constitute our contribution to the nuclear data on ^{165}Ho levels.

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*Permanent address: Physics Department, N.R.E.C. College, Khurja 203131, India.

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