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Excited states of ^{139}Ce from $(p,n\gamma)$ reactions on lanthanum

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The $N=81$ odd-mass ^{139}Ce nucleus has been studied from the $(p,n\gamma)$ reaction on lanthanum to look for the single neutron-hole states and also the states arising from hole-core coupling. Ten excited states of ^{139}Ce have been studied by gamma-ray singles measurements at different angles with Ge(Li) detectors following the bombardment of a lanthanum target with protons of energies 4.00 to 6.50 MeV. A level scheme for ^{139}Ce has been proposed from the in-beam gamma-ray spectroscopy. The A_2 and A_4 parameters of the transitions have been measured from the angular distributions of the gamma rays. Relative excitation functions of the states with respect to the 1347.4 keV $\frac{7}{2}^+$ state have been measured. The experimentally measured excitation cross sections of the individual states have been compared with the values obtained from theoretical calculation on the basis of the compound nuclear statistical theory of Hauser and Feshbach.

I. INTRODUCTION

The excited states in ^{139}Ce are of interest from the point of view of the neutron-hole excitations in the vicinity of the $N=82$ shell closure. The low-lying states of ^{139}Ce have been studied earlier from the decay of $^{139}_{59}$Pr$_{80}$ by Zalutsky *et al.*[1] The reaction studies on this particular nucleus were carried out earlier to excite neutron-hole states from the closed shell $^{140}_{58}$Ce$_{82}$ nucleus through (p,d), $(^3\mathrm{He},\alpha)$, and (d,t) reactions[2,3] and the high spin states from the ^{138}Ba$(\alpha,3n\gamma)$ reaction.[4] However, the study of ^{139}Ce from the ^{139}La(p,n) reaction has not been carried out prior to this investigation.

The (p,n) reaction in the sub-Coulomb region is a compound nuclear process and as such does not have preferential excitation for the residual states. Residual states in (p,n) reactions are usually excited regardless of their structural configurations. The $^{139}_{58}$Ce nucleus is expected to have a number of single neutron-hole states as well as a few states arising from the coupling of a neutron-hole motion with the phonon vibrations of the neighboring even-even core. The compound nuclear statistical theory[5] can be used in this reaction as the spectroscopic tool for assigning spins of the residual states. This aspect has been exploited earlier,[6–9] particularly in the studies of (p,n) reactions in medium weight nuclei in the sub-Coulomb energy region. If the incident proton energy is chosen to be a few MeV above the threshold and below the Coulomb barrier, the compound nucleus thus formed decays mostly through emission of neutrons to the low-lying levels of the residual nucleus. This process is expected to dominate over the direct process. The emission of protons are inhibited to a great extent by the Coulomb barrier. The present investigation has been initiated to excite the low-lying states of ^{139}Ce because of the reasons stated above.

II. EXPERIMENTAL PROCEDURE

A foil of natural lanthanum of thickness 0.051 cm having an isotopic abundance of 99.91% of ^{139}La was bombarded with protons of energies 4.00–6.50 MeV from the 7.5 MV Van de Graaff accelerator of the Université Laval, Canada. The deexcited gamma rays were observed with two absolute efficiency calibrated Ge(Li) detectors of 50 cm^3 volume (resolutions $\sim$3.0 keV for 1.33 MeV) following the bombardment of the lanthanum target with $\sim$20 nA of proton beam current. The absolute efficiencies of these detectors have been measured with an accuracy better than 5% using ^{152}Eu, ^{56}Co, and a calibrated ^{60}Co source. The gamma-ray singles and angular distribution measurements have been carried out at a proton energy of 5.50 MeV by taking the spectra at 0°, 21°, 30°, 45°, 55°, 75°, and 90° with respect to the beam direction using the mobile Ge(Li) detector. The studies of excitation functions have been carried out at proton energies 4.00–6.50 MeV in steps of 0.500 MeV. The spectra were recorded using the on-line PDP 15 system and analyzed with computer program SPECT.[10]

III. RESULTS AND DISCUSSIONS

The Q value for the ^{139}La(p,n) reaction is -1.057 MeV. Hence, it is possible to excite the low-lying states of ^{139}Ce from the (p,n) reaction at $E_p=4.00-6.50$ MeV. The spectrum in Fig. 1 shows the gamma-rays from the bombardment of a La target with 5.50 MeV protons. In the present work gamma rays up to 2015.5 keV have been observed and are assigned to ^{139}Ce on the basis of energy measurement and known information from other studies.[11] The intensities of the gamma transitions from the ^{139}Ce states have been measured after taking into consideration the effects of angular distribution and internal conversion. A tentative level scheme for ^{139}Ce has been constructed and shown in Fig. 2. Most of the low-lying levels reported earlier[11] have been observed. The 1818.3, 1842.9, 1965.5, and 1984.81 keV levels reported from the decay study[1] have not been included in the present work as most of the transitions from these levels have not been observed. The 1729.7 keV gamma ray in Fig. 2 cannot be a transition from the 1984.81 keV level because a stronger transition of energy 354.0 keV from this level re-

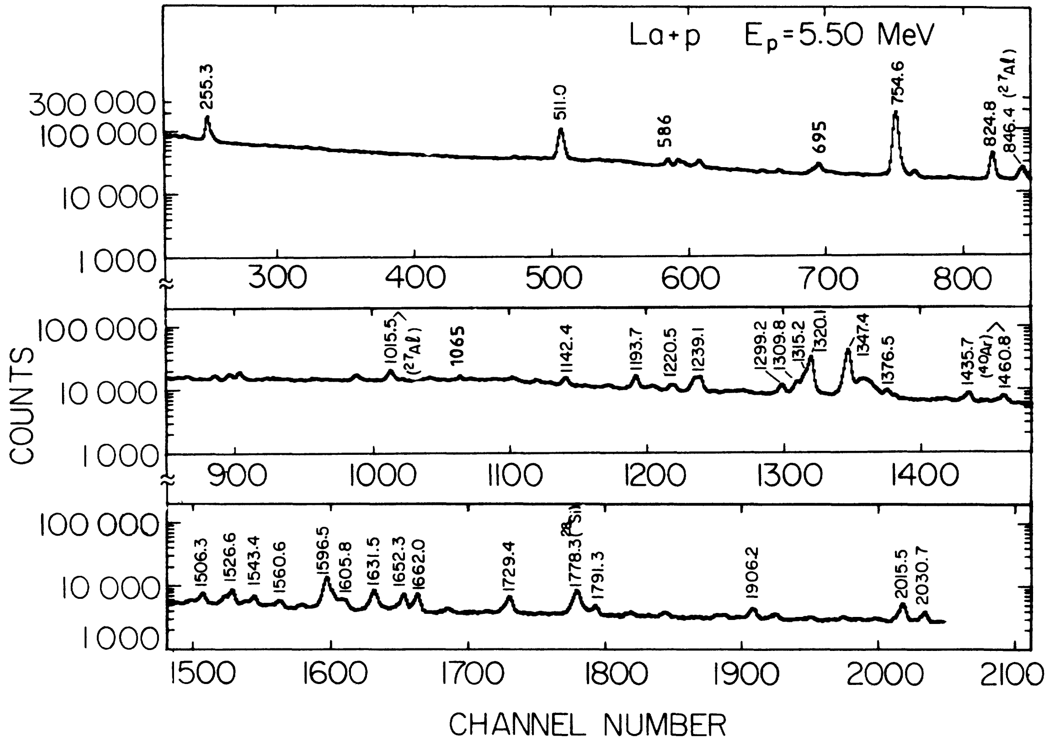

FIG. 1. Gamma-ray spectrum observed with a 50 cm^3 Ge(Li) detector following the bombardment of a lanthanum target with 5.50 MeV protons.

ported[1] has not been observed. However, the 1729.7 keV gamma ray could be a transition from the 2484.0 keV level which may correspond to the 2.47 MeV state observed earlier from the (p,d) reaction.[3] No spin parity could be assigned to this state from the earlier (p,d) work.[3] However, spin of this state could be assigned tentatively as $(\frac{13}{2}^-, \frac{15}{2}^-)$. The $\frac{15}{2}^-$ state at 2360.4 keV assigned in this work has also been observed by Ludziejewski and Arnold[4] from the $(\alpha,3n\gamma)$ reaction. The excitation of such high spin states are not unlikely in $(p,n\gamma)$ reaction from the $\frac{7}{2}^+$ ground state of ^{139}La.

Excitation cross sections for the individual states have been measured considering the absolute yield of the gamma rays populating and depopulating the states. The effect of target thickness has been taken into consideration in measuring the excitation cross section. Excitation cross sections of the individual states relative to the 1347.4 keV $\frac{7}{2}^+$ state, shown in Fig. 3, have been utilized for the determination of spins. Relative excitation functions were used earlier for the determination of spins in several nuclei by Glenn *et al.*,[6] Chatterjee *et al.*,[7] and Kajrys *et al.*[8] From the slope of the relative excitation function, positive or negative with increasing proton energy, spin of the state greater or less than $\frac{7}{2}$ can be determined. Such studies together with the known l transfer from (p,d) work have been very useful in determining the most probable spin parities of the excited states of ^{139}Ce. The only discrepancy observed in the relative excitation function is that of the 1320.1 keV state; it is almost parallel to the 1347.4 keV state. The spin parity of this state

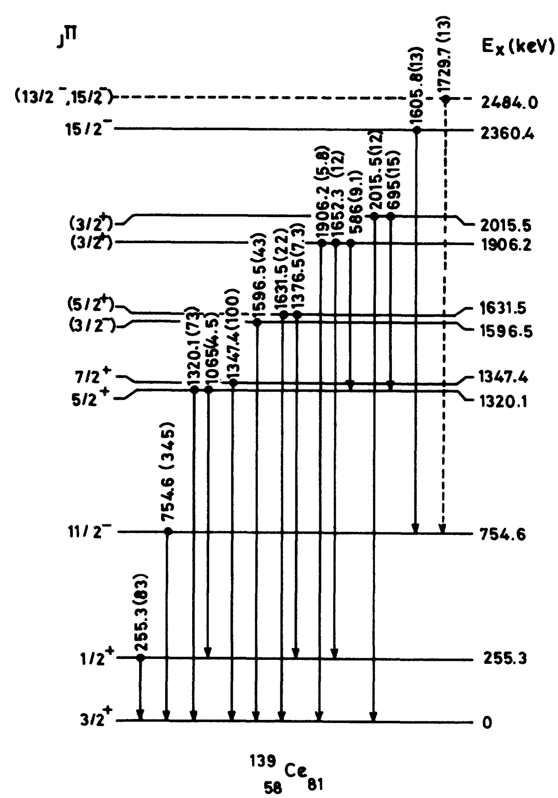

FIG. 2. Level scheme for ^{139}Ce from the present $(p,n\gamma)$ work.

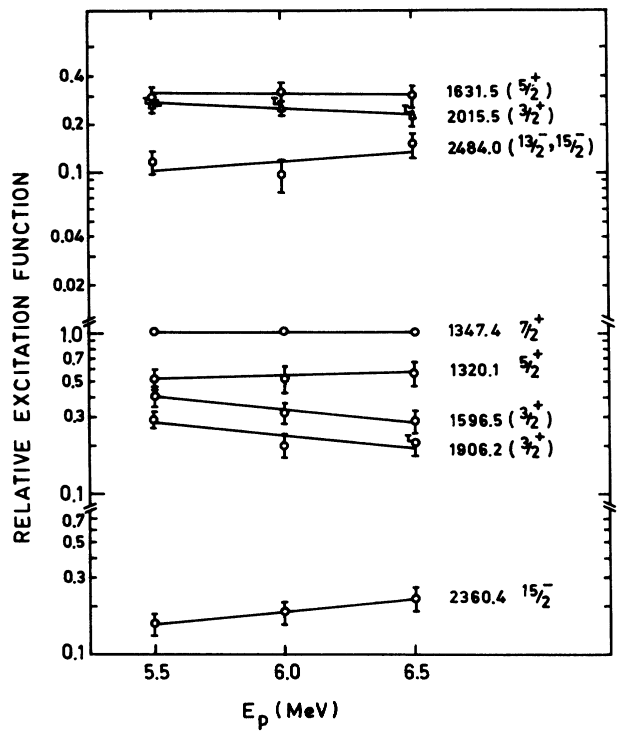

FIG. 3. Relative excitation cross sections of the various states of ^{139}Ce with respect to the 1347.4 keV state. The solid lines through the data points are the least-squares fitted straight lines.

has been assigned as $\frac{5}{2}^+$ from the observed $l=2$ transfer in the (p,d) reaction and the 1065 keV transition between this level and a $\frac{1}{2}^+$ level.

In the present work, gamma-ray angular distribution measurements have been carried out at 5.50 MeV incident proton energy. The angular distribution of the gamma rays were fitted to

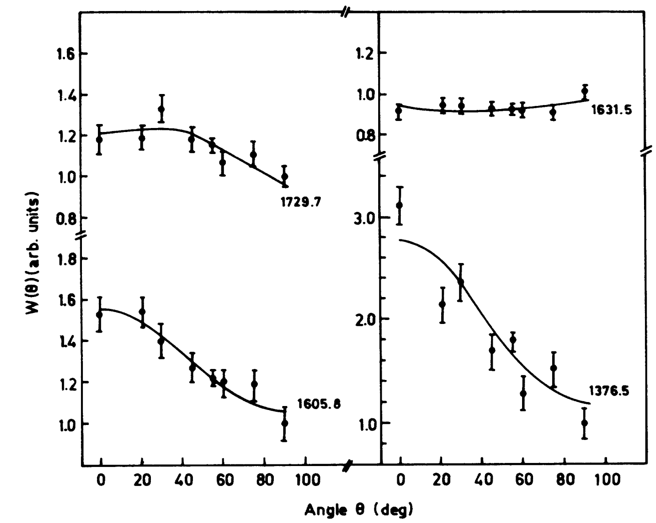

FIG. 4. Angular distribution of a few gamma rays of ^{139}Ce. The solid lines are the least-squares fitted distribution functions.

$$W(\theta)=A_0+g_2A_2P_2(\cos\theta)+g_4A_4P_4(\cos\theta)$$

after normalizing the yield of the gamma rays at different angles with respect to the 255.3 keV gamma ray from the $\frac{1}{2}^+$ state. A_0, A_2, A_4 are the angular distribution coefficients of the Legendre polynomial and g_2, g_4 are the geometrical attenuation coefficients. The angular distributions of a few gamma rays are shown in Fig. 4. The experimentally measured A_2/A_0, A_4/A_0 coefficients of the transitions are shown in Table I. The A_2 value of 0.28 ± 0.04 of the 1605.8 keV transition from the 2360.4 keV level is in good agreement with the corrected A_2 value of 0.45 ± 0.15 measured earlier.[4] This confirms the $E2$ character of the 1605.8 keV transition from the 2360.4 keV state.

TABLE I. Energies, intensities, and angular distribution parameters of the deexcited gamma rays from the ^{139}Ce levels following the ^{139}La$(p,n\gamma)$ reaction at 5.50 MeV proton energy.

Level energies (keV)	Deexcited gamma rays (keV)	Intensities	A_2/A_0	A_4/A_0	Assignments $I_i \to I_f$
255.3	255.3	83±6			$\frac{1}{2}^+ \to \frac{3}{2}^+$
754.6	754.6	345±24			$\frac{11}{2}^- \to \frac{3}{2}^+$
1320.1	1320.1	73±5	0.031±0.009	−0.015±0.010	$\frac{5}{2}^+ \to \frac{3}{2}^+$
	1065	4.5±0.4			$\frac{5}{2}^+ \to \frac{1}{2}^+$
1347.4	1347.4	100	0.16±0.01	−0.01±0.01	$\frac{7}{2}^+ \to \frac{3}{2}^+$
1596.5	1596.5	43±3	0.01±0.01	−0.004±0.014	$\frac{3}{2}^+ \to \frac{3}{2}^+$
1631.5	1631.5	22±2	−0.03±0.03	0.03±0.03	$\frac{5}{2}^+ \to \frac{3}{2}^+$
	1376.5	7.3±0.6	0.64±0.08	0.05±0.08	$\frac{5}{2}^+ \to \frac{1}{2}^+$
1906.2	1906.2	5.8±0.4	0.10±0.08	−0.05±0.09	$\frac{3}{2}^+ \to \frac{3}{2}^+$
	1652.3	12±1	−0.06±0.03	0.10±0.04	$\frac{3}{2}^+ \to \frac{1}{2}^+$
	586	9.1±0.7			$\frac{3}{2}^+ \to \frac{7}{2}^+$
2015.5	2015.5	12±1	−0.01±0.04	0.07±0.05	$\frac{3}{2}^+ \to \frac{3}{2}^+$
	695	15±1			
2360.4	1605.8	13±1	0.28±0.04	0.004±0.05	$\frac{15}{2}^- \to \frac{11}{2}^-$
2484.0	1729.4	13±1	0.15±0.04	−0.09±0.04	$\frac{13}{2}^-, \frac{15}{2}^- \to \frac{11}{2}^-$

The theoretical cross section for the individual states as well as the total (p,n) reaction cross section have been calculated on the basis of Hauser-Feshbach formalism considering the (p,n) and (p,p_0) elastic channels. The (p,α), (p,γ), and other reaction channels have been neglected since they usually provide an insignificant contribution at these energies. The eleven states of ^{139}Ce, including the ground state observed in the present work, were used in the calculation with their most probable spin parities. The excitation cross sections of the individual states may be found from

$$\sigma(p,n)=\frac{\pi\lambda\!\!\!^{-2}}{2(2i+1)}\sum_J(2J+1)\frac{T^p_{lj}T^n_{l'j}}{\Sigma T_{lj}}\ , \qquad (1)$$

where the indicated summation includes all possible J, l, and j corresponding to the excitation of a particular state of spin i'. i and J are the spins of the target and compound nuclei and j is the channel spin. T_l is the partial transmission coefficient of the associated particle such as neutron and proton for the orbital angular momentum l.

In order to calculate the (p,n) cross section, the tabulated values[12,13] of the partial transmission coefficients of protons and neutrons have been used. The orbital angular momenta for both incoming protons and outgoing neutrons have been considered up to $5\hbar$. Such a restriction seems to be quite reasonable because the partial transmission coefficients of low-energy protons and neutrons corresponding to $l=5$ are very small. No appreciable change in cross sections has been observed with an increase in l values from 4 to 5.

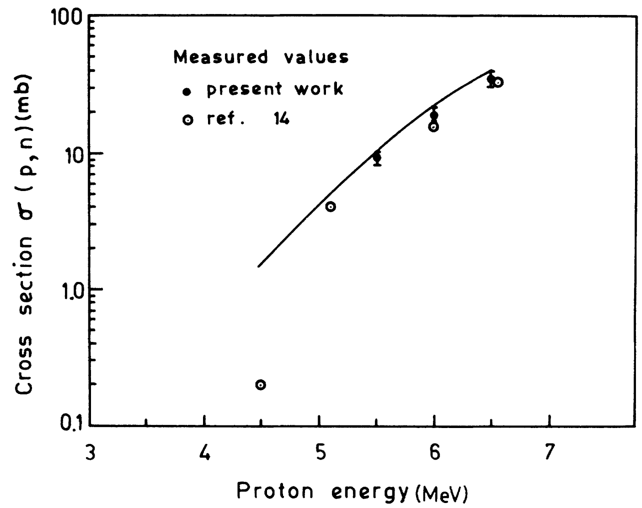

FIG. 5. Comparison of the theoretical (p,n) cross section (shown as a solid line) calculated from Hauser-Feshbach formalism with the experimentally measured cross section.

Excitation cross sections of the individual states have been measured at 5.5, 6.0, and 6.5 MeV proton energies. The experimentally measured cross sections summed over the excited states $\Sigma^{\sigma_{i'}}_{\rm exp}(p,n)$ will always be less than the total $\sigma_{\rm exp}(p,n)$ due to the exclusion of the contribution of the ground state which cannot be accounted for in the gamma-spectroscopic study. However, even this summed cross section $\Sigma^{\sigma_{i'}}_{\rm exp}(p,n)$ measured in the present work is

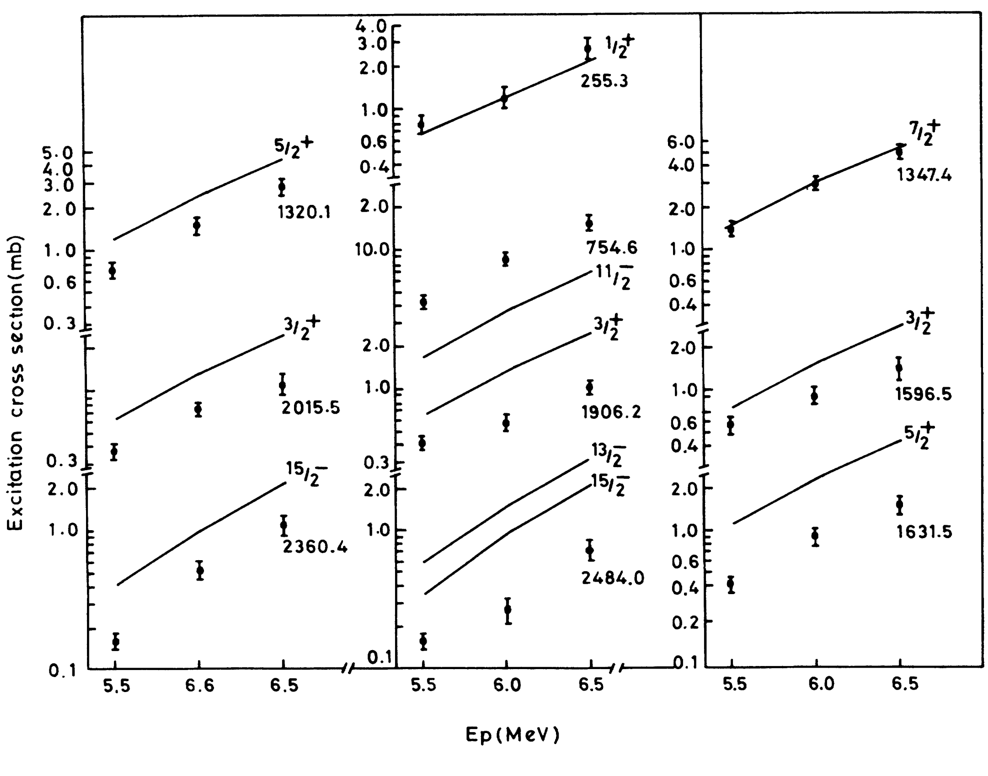

FIG. 6. Excitation cross sections of the states of ^{139}Ce. The solid lines are the theoretical curves with the most probable spin parities.

slightly more than the total $\sigma_{\rm exp}(p,n)$ measured earlier.[14] Hence, no attempt has been made to reproduce the total cross-section data with different values of partial transmission coefficients of protons and neutrons. The calculated total $\sigma_{\rm calc}(p,n)$ is slightly more than the $\sum_{\rm exp}^{\sigma^{i'}}(p,n)$ measured in the present work, which is consistent with what has been stated above. The calculated and measured cross sections are shown in Fig. 5.

The measured cross sections of the individual states in ^{139}Ce have been compared with the calculated cross sections in Fig. 6. These have not been normalized with the calculated cross sections. Excellent agreement between the measured and calculated cross sections have been observed for the 255.3 keV ($\frac{1}{2}^+$) and 1347.4 keV ($\frac{7}{2}^+$) states. A reasonably good agreement has also been observed for the 1320.1 keV state. However, the calculated cross sections for the $\frac{11}{2}^-$ state at 754.6 keV are considerably less than the measured values while those for the other states are more. Such enhancement of cross sections has also been observed earlier in other nuclei.[7] This effect may be due to the correlation of structural configuration of a state in a residual nucleus with the states in the compound nucleus.

The nuclei with $N=81$ neutrons can be considered to be a neutron hole in the $N=82$ shell closure. Such nuclei show single neutron-hole states in their low-lying spectra. The single neutron-hole states in this region are $2d_{3/2}$, $3s_{1/2}$, $1g_{7/2}$, and $2d_{5/2}$. However, the positions of these states in odd nuclei of $N=81$ isotones vary from Xe to Sm. In the case of the ^{139}Ce nucleus, the ground state and the first and second excited states at 255.3 keV and 754.6 keV have properties consistent with the excitation of a single neutron hole to the $2d_{3/2}$, $3s_{1/2}$, and $1h_{11/2}$ orbitals. The single neutron-transfer reaction[3] shows the splitting of $2d_{5/2}$ and $1g_{7/2}$ states and fragmentations of spectroscopic strengths. The number of levels observed arise from the coupling of the single neutron hole with the phonon vibration of the neighboring core nucleus. Such a description was used by Heyde and Brussaard.[15]

The coupling of the single neutron hole with the phonon vibrations considering the core excitations of up to three quadrupole phonons was done to describe the states in ^{139}Ce.[15] The levels and the branching ratios of the transitions obtained from the theoretical calculation are in very good agreement with the experimental levels observed in the present work. The level observed at 2360.4 keV having spin and parity $\frac{15}{2}^-$ has been identified as one of the members of the multiplet of negative parity states arising from the configuration of $2^+\otimes h_{11/2}$ from the weak and intermediate coupling calculations by Ludziejewski and Arnold *et al.*[4] considering hole-core vibration. The state at 2484.0 keV may be a member of that multiplet.

Finally, it is concluded that the low-lying states having single neutron-hole configurations as well as more complicated configurations such as coupling of a neutron hole with a core, can be excited in ^{139}Ce from the (p,n) reaction in the sub-Coulomb energy region. Such reaction studies sometimes give considerable information regarding the properties of the excited states.

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