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Excited states of the odd-mass nucleus ^{173}Yb with different deformation- dependent mass coefficients

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-In this work, we have studied the properties of the low-lying collective states of the odd nucleus ^{173}Yb by using a new generalized version of the collective quadrupole Bohr Hamiltonian with deformation-dependent mass coefficients.

- Moreover, we investigate the effect of the deformation-dependent mass parameter on energy spectra and transition rates in both cases, namely when the mass coefficients are different and when they are equal.

- We used the asymptotic iteration method (AIM) to solve the radial and angular equations of the Bohr Hamiltonian.

- Finally we compared the obtained results with the experimental values.

1-Bohr Hamiltonian with mass parameters:

- for an odd-mass nucleus, and for small harmonic β and γ oscillations of a deformed nuclear surface with respect to the equilibrium values $\beta_0 \neq 0$ and $\gamma_0 \approx 0$, the corresponding Hamiltonian with three different mass parameters, can be written as :

$$\mathrm{H}=\mathrm{H}_{vib} + H_{rot} + H_{int} \quad (1)$$

where the operator describing the β and γ vibrations of the nuclear core surface is

$$H_{vib} = -\frac{\hbar^2}{2}\left(\frac{1}{B_\beta}\frac{\partial^2}{\partial\beta^2} + \frac{2}{B_\gamma}\frac{1}{\beta}\frac{\partial}{\partial\beta} + \frac{2}{B_\beta}\frac{1}{\beta}\frac{\partial}{\partial\beta} + \frac{1}{B_\gamma\beta^2}\frac{1}{\gamma}\frac{\partial}{\partial\gamma}(\gamma\frac{\partial}{\partial\gamma}) - \frac{1}{B_\gamma}\frac{1}{4\beta^2}.(\frac{1}{\gamma^2}+\frac{1}{3})(L_3 - j_3)^2\right) + V(\beta,\gamma) \quad (2)$$

$$V(\beta,\gamma) = V_0\left(\frac{\beta}{\beta_0} - \frac{\beta_0}{\beta}\right)^2 + \frac{1}{2}\frac{\beta_0^4}{\beta^2}C_\gamma\gamma^2$$

The nuclear rotational energy operator can conveniently be represented as

$$H_{rot} = \frac{\hbar^2}{6B_{rot}\beta^2}(L^2 + j^2 - L_3^2 - j_3^2) \quad (3)$$

and the interaction operator which takes into account non-spherical part of the field of the core is given by the expression

$$H_{int} = -\beta_0 < T(r) > (3j_3^2 - j^2) \quad (4)$$

where $B_{\rm rot}$, B_β and B_γ are three different mass coefficients for rotational, β-, γ- motion, respectively. L is the total angular momentum, where L_3 is the eigenvalue of the projection of angular momentum on the principal axis of nucleus, j and j_3 are the angular momentum operator of a single nucleon, and its projection. β_0 is the equilibrium value of the nuclear surface β-oscillations and $T(r)$ is a function of the distance between the single nucleon and the center of the nuclear core, while $\langle T \rangle$ is its average value over internal states of the external nucleon and zero nuclear surface oscillations

2-Deformation-dependent mass and different mass parameters:

To construct a Bohr equation with three deformation-dependent mass coefficients, in accordance with the DDM formalism , the mass tensor of the collective Hamiltonian becomes

$$B = \frac{\langle i|B_0|i\rangle}{(f(\beta))^2}, \tag{5}$$

where $i =$ g.s., β or γ (g.s. is often replaced by *rot*) corresponding to three separable state bands of nuclei, namely : the g.s band, the β and γ vibrational bands, each one of these will have its own mass coefficient equal to its average value over the wave function of the considered state, such as : $\langle g.s.|B_0|g.s.\rangle \equiv B_{\text{rot}}$, $\langle\gamma|B_0|\gamma\rangle \equiv B_\gamma$ and $\langle\beta|B_0|\beta\rangle \equiv B_\beta$ defined for each band. f is the deformation function depending only on the radial coordinate β. Therefore, only the β part of the resulting equation will be affected.

The explicit equation reads as

$$\frac{\hbar^2}{2\langle i|B_0|i\rangle}\Big(-\frac{\sqrt{f}}{\beta^4}\frac{\partial}{\partial\beta}\beta^4 f\frac{\partial}{\partial\beta}\sqrt{f}-\frac{f^2}{\beta^2\sin 3\gamma}\frac{\partial}{\partial\gamma}\sin 3\gamma\frac{\partial}{\partial\gamma} + \frac{f^2}{4\beta^2}\sum_{k=1,2,3}\frac{(Q_k-j_k)^2}{\sin^2(\gamma-\frac{2}{3}\pi k)}\Big)\Psi - f^2\beta\langle T\rangle(3j_3^2-j^2)\Psi + V_{eff}\Psi = E\Psi, \quad (6)$$

with,

$$V_{eff} = V(\beta,\gamma)+\frac{\hbar^2}{2\langle i|B_0|i\rangle}\Big(\frac{1}{2}(1-\delta-\lambda)f\bigtriangledown^2 f + (\frac{1}{2}-\delta)(\frac{1}{2}-\lambda)(\bigtriangledown f)^2\Big), \quad (7)$$

The total wave function can be constructed as :

$$\Psi = F(\beta)\chi(\gamma)|LMjKm\rangle, \quad (8)$$

where the rotational wave function $|LMjKm\rangle$ has been expanded in terms of the Wigner $D(\theta_i)$-function of the Euler angles, and $\varphi(x_i)$ the eigenfunction of the single-particle states, in the following form

$$|LMjKm\rangle = \sqrt{\frac{2L+1}{16\pi^2}}\Big[D^L_{MK}(\theta_i)\varphi^j_{K-2m}(x_i) + (-1)^{L-j}D^L_{M-K}(\theta_i)\varphi^j_{-K+2m}(x_i)\Big], \quad (9)$$

As a result, Eq. (6) can be separated into three equations

$$\Big[\frac{\hbar^2}{2\langle i|B_0|i\rangle}\Big(-\tfrac{\sqrt{f}}{\beta^4}\tfrac{\partial}{\partial\beta}\beta^4 f\tfrac{\partial}{\partial\beta}\sqrt{f} + \tfrac{f^2}{\beta^2}\Lambda + \frac{1}{2}(1-\delta-\lambda)f\bigtriangledown^2 f + (\frac{1}{2}-\delta)(\frac{1}{2}-\lambda)(\bigtriangledown f)^2\Big) + V(\beta)\Big]F(\beta) = EF(\beta), \quad (10)$$

$$\left[-\frac{\hbar^2}{2B_\gamma}\left(\frac{1}{\sin 3\gamma}\frac{\partial}{\partial\gamma}\sin 3\gamma\frac{\partial}{\partial\gamma}-\frac{1}{4}\left(\frac{1}{\gamma^2}+\frac{1}{3}\right)\left(L_3-j_3\right)^2\right)\right.$$
$$\left.+W(\gamma)\right]\chi_{n_\gamma|m|}(\gamma)=\Lambda'\chi_{n_\gamma|m|}(\gamma), \quad (11)$$

$$\left[\frac{\hbar^2}{6B_{rot}}\left(L^2+j^2-L_3^2-j_3^2\right)\right.$$
$$\left.-\beta^3\langle T\rangle\left(3j_3^2-j^2\right)\right]|LMjKm\rangle=\bar{\Lambda}|LMjKm\rangle, \quad (12)$$

With

$$\frac{B_\beta}{\hbar^2}\bar{\Lambda}=\frac{B_\beta}{6B_{rot}}\Big(L(L+1)+j(j+1)-K^2$$
$$-(K-2m)^2\Big)-\frac{1}{6\xi}\Big(3(K-2m)^2-j(j+1)\Big), \quad (13)$$

The corresponding analytical solution of Eq. (11) is given with eigenvalues

$$\frac{B_\beta}{\hbar^2}\Lambda' = \frac{2}{g}\frac{B_\beta}{B_\gamma}\Big(1+n_\gamma\Big) + \frac{m^2}{3}\frac{B_\beta}{B_\gamma}, \qquad (14)$$

then

$$\begin{aligned}\frac{B_\beta}{\hbar^2}\Lambda = \frac{2}{g}\frac{B_\beta}{B_\gamma}(1+n_\gamma) + \frac{m^2}{3}\frac{B_\beta}{B_\gamma} + \frac{1}{3}\frac{B_\beta}{B_{rot}}\Big(L(L+1)\\ +j(j+1) - K^2 - (K-2m)^2\Big) \qquad (15)\\ -\frac{1}{3\xi}\Big(3(K-2m)^2 - j(j+1)\Big),\end{aligned}$$

and the corresponding eigenfunctions, are obtained in terms of the Laguerre polynomials as

$$\chi_{n_\gamma|m|}(\gamma) = N_{n_\gamma,|m|}\gamma^{|m|}e^{\frac{-\gamma^2}{2g}}L_{\tilde{n}_\gamma}^{|m|}\Big(\frac{\gamma^2}{g}\Big), \qquad (16)$$

with $g = \frac{1}{\beta_0^2}\frac{\hbar}{\sqrt{B_\gamma C_\gamma}}$. $\tilde{n}_\gamma = \frac{n_\gamma - |m|}{2}$, n_γ is the quantum number related to γ-oscillations

$$N_{n_\gamma,|m|} = \left(\frac{2}{3}g^{-1-|m|}\frac{\tilde{n}_\gamma!}{\Gamma(|m|+\tilde{n}_\gamma+1)}\right)^{\frac{1}{2}}, \tag{17}$$

- Thus, the energy spectrum of the radial equation is determined by the following expression,

$$E_{n_\beta n_\gamma L|m|} = \frac{\hbar^2}{2B_\beta}\Big(k_0 + \frac{a}{2}(2 + \frac{B_\beta}{B_\gamma} + 2p + 2q + pq) + 2a(2+p+q)n_\beta + 4an_\beta^2\Big), \tag{18}$$

where n_β is the principal quantum number of β vibrations, and

$$\begin{aligned} q \equiv q_{n_\gamma}(L,|m|) &= \sqrt{1+4k_{-2}}, \\ p \equiv p_{n_\gamma}(L,|m|) &= \sqrt{4\frac{B_\beta}{B_\gamma} - 3 + 4\frac{k_2}{a^2}}, \end{aligned} \tag{19}$$

$$
\begin{aligned}
k_2 =& \frac{a^2}{2}\left[\left(1+\frac{B_\beta}{B_\gamma}\right)\left(6\frac{B_\beta}{B_\gamma}+(1-2\delta)(1-2\lambda)\right.\right. \\
&\left.\left.+5(1-\delta-\lambda)\right)+\frac{2B_\beta}{\hbar^2}\Lambda\right]+\frac{2g_\beta}{\beta_0^4}, \\
k_0 =& \frac{a}{2}\left[\left(1+\frac{B_\beta}{B_\gamma}\right)\left(8\frac{B_\beta}{B_\gamma}+5(1-\delta-\lambda)\right)\right. \\
&\left.+\frac{4B_\beta}{\hbar^2}\Lambda\right]-\frac{4g_\beta}{\beta_0^2}, \\
k_{-2} =& \frac{B_\beta}{B_\gamma}\left(1+\frac{B_\beta}{B_\gamma}\right)+\frac{B_\beta}{\hbar^2}\Lambda+2g_\beta,
\end{aligned}
\tag{20}
$$

where $g_\beta = \frac{B_\beta V_0 \beta_0^2}{\hbar^2}$

If $a = 0$, i.e., the dependence of the mass on the deformation is canceled, then one has from Eq. (20)

$$k_2 = \frac{2g_\beta}{\beta_0^4}, \qquad k_0 = -4\frac{g_\beta}{\beta_0^2},$$
$$k_{-2} = \frac{B_\beta}{B_\gamma}\left(1 + \frac{B_\beta}{B_\gamma}\right) + \frac{B_\beta}{\hbar^2}\Lambda + 2g_\beta. \tag{21}$$

In this case, the energy spectrum formula reads

$$E_{n_\beta n_\gamma L|m|} = \sqrt{2\frac{V_0^2}{g_\beta}}\left[1 + 2n_\beta + \frac{1}{2}q_{n_\gamma}(L,|m|) - \sqrt{2g_\beta}\right], \tag{22}$$

with

$$\frac{1}{2}q_{n_\gamma}(L,|m|) = \sqrt{\frac{1}{4} + \frac{B_\beta}{B_\gamma}\left(1 + \frac{B_\beta}{B_\gamma}\right) + \frac{B_\beta}{\hbar^2}\Lambda + 2g_\beta}, \tag{23}$$

In the case of $a = 0$ and $B_\beta = B_\gamma = B_{rot}$, our formula Eq. (18) becomes

$$E_{n_\beta n_\gamma L|m|} = \sqrt{2\frac{V_0^2}{g_\beta}}\left(1 + 2n_\beta + \sqrt{\frac{9}{4} + \Lambda + 2g_\beta}\right) - 2V_0, \quad (24)$$

3-B(E2) transition probabilities: The B(E2) transition rates from an initial to a final state are given by ,

$$B(E2; L_iK_i \longrightarrow L_fK_f) = \frac{5}{16\pi} \frac{|\langle L_fK_f||T^{(E2)}||L_iK_i\rangle|^2}{2L_i+1}, \tag{25}$$

and the reduced matrix element can be obtained by using the Wigner-Eckrat theorem ,

$$\langle L_fM_fK_f|T_M^{(E2)}|L_iM_iK_i\rangle = \frac{(L_i2L_f|M_iMM_f)}{\sqrt{2L_f+1}}\langle L_fK_f||T^{(E2)}||L_iK_i\rangle. \tag{26}$$

The final result reads

$$B(E2; n_\beta L n_\gamma K|m| \longrightarrow n'_\beta L' n'_\gamma K'|m'|) = \frac{5}{16\pi}\langle L, K, 2, K'-K|L', K'\rangle^2 I^2_{n_\beta L, n'_\beta L'} C^2_{n_\gamma,|m|,n'_\gamma,|m'|}, \tag{27}$$

Where

$$
\begin{aligned}
I_{n_\beta L, n'_\beta L'} &= \int \beta F_{L,n_\beta}(\beta) F_{L',n'_\beta}(\beta) \beta^{2+2\frac{B_\beta}{B_\gamma}} \, \mathrm{d}\beta \\
&= \int \beta R_{L,n_\beta}(\beta) R_{L',n'_\beta}(\beta) \, \mathrm{d}\beta,
\end{aligned} \tag{28}
$$

with

$$
\begin{aligned}
R(t) =& N_{n_\beta} 2^{-(1+\frac{B_\beta}{B_\gamma})/2-(q+p)/4} a^{-(1+q)/4} \\
& (1-t)^{(1+2\frac{B_\beta}{B_\gamma}+p)/4} (1+t)^{(q+1)/4} P_{n_\beta}^{(q/2,p/2)}(t), \\
t =& \frac{-1+a\beta^2}{1+a\beta^2}.
\end{aligned} \tag{29}
$$

$P_n^{(\alpha,\beta)}(t)$ denotes the Jacobi polynomials , while the normalization coefficient N_{n_β} is given by

$$
\begin{aligned}
N_{n_\beta} &= \left(2a^{q/2+1} n_\beta!\right)^{\frac{1}{2}} \\
& \left[\frac{\Gamma\left(n_\beta + \frac{q+p}{2} + 1\right) \Gamma\left(2n_\beta + \frac{q+p}{2} + 1 + \frac{B_\beta}{B_\gamma}\right)}{\Gamma\left(n_\beta + \frac{q}{2} + 1\right) \Gamma\left(n_\beta + \frac{B_\beta}{B_\gamma} + \frac{p}{2}\right) \Gamma\left(2n_\beta + \frac{q+p}{2} + 1\right)} \right]^{\frac{1}{2}}.
\end{aligned} \tag{30}
$$

and $C_{n_\gamma,|m|,n'_\gamma,|m'|}$ contains the integral over γ. For $\Delta m = 0$ corresponding to transitions (g.s.$\longrightarrow$ g.s.), $(\gamma \longrightarrow \gamma)$, $(\beta \longrightarrow \beta)$ and $(\beta \longrightarrow g.s.)$, the γ-integral part reduces to the orthonormality condition of the γ-wave functions : $C_{n_\gamma,|m|,n'_\gamma,|m'|} = \delta_{n_\gamma,n'_\gamma}\delta_{m,m'}$. For $|\Delta m| = 1$ corresponding to transitions $(\gamma \longrightarrow g.s.)$, $(\ \gamma \longrightarrow \beta)$, this integral takes rather the form.

$$C_{n_\gamma,|m|,n'_\gamma,|m'|} = \int \sin\gamma\ \chi_{n_\gamma|m|}\chi_{n'_\gamma|m'|}|\sin 3\gamma|\mathrm{d}\gamma. \qquad (31)$$

The excitation energies 18 depend on five quantum numbers,namely: n_β, n_γ, L, K and m, and nine parameters : g, g_β, ξ, B_β/B_γ, B_β/B_{rot} ratio of the mass coefficients, a the deformation mass parameter, β_0 the minimum of the potential and the free parameters δ and λ coming from the DDM formalism.

- In the special case without DDM formalism (i.e. $a = 0$), we have determined the optimal values of the free parameters B_β/B_γ, B_β/B_{rot}, g and g_β by fitting the energy formula (22) on the available experimental data
- The free parameters are adjusted to reproduce the experimental data by applying a least-squares fitting procedure

$$\sigma = \sqrt{\frac{\sum_{i=1}^{n}(E_i(exp) - E_i(th))^2}{(n-1)E(\frac{7}{2}{}_1^-)^2}} \tag{32}$$

$\rightarrow$ $E_i(exp)$:
$\rightarrow$ $E_i(th)$:
$\rightarrow$ n:
$\rightarrow$ $E(\frac{7}{2}{}_1^-)$:
- In DDM The optimal values of both parameters a and β_0 are evaluated through r.m.s fits of energy levels by making use of Eq. (18) for each band of nucleus.

Nucleus	g	g_β	B_β/B_γ	B_β/B_{rot}	$g(B_\beta = B_\gamma = B_{\text{rot}})$	$g_\beta(B_\beta = B_\gamma = B_{\text{rot}})$
^{173}Yb	0.0094	1033.26	1.3008	7.5	0.0464	0.3643

- The values of free parameters fitted to experimental data by using Eqs. (22) and (24) in the case where $B_\beta \neq B_\gamma \neq B_{\text{rot}}$ and $B_\beta = B_\gamma = B_{\text{rot}}$, respectively.

	$B_\beta \neq B_\gamma \neq B_{\text{rot}}$		$B_\beta = B_\gamma = B_{\text{rot}}$	
	$a = 0$	DDM	$a = 0$	DDM
g.s				
σ	0.0399	0.0253	1.2419	0.0235
a		0.001		0.0881
β_0		6.94		1.029
β				
σ	0.6839	0.6837	1.1682	1.1682
a		0.1724		$1.94 \cdot 10^{-11}$
β_0		0.0913		3.8091
γ				
σ	0.347	0.347	1.01	0.9828
a		$1.14 \cdot 10^{-7}$		0.00064
β_0		0.3703		1.8036
σ_{total}	0.4135	0.4134	1.0974	1.0009
a		0.0099		0.0037
β_0		0.3251		1.3531

β_0 and a the position of the minimum of Davidson potential and the deformation dependence of the mass parameter respectively for the ^{173}Yb nucleus, while σ is the quality measure Eq 32 .

$B_\beta \neq B_\gamma \neq B_{rot}$				$B_\beta = B_\gamma = B_{rot}$	
L	Exp	$a=0$	DDM	$a=0$	DDM
g.s.					
$9/2^-$	2.27	2.28	2.28	2.25	2.28
$11/2^-$	3.84	3.84	3.84	3.74	3.83
$13/2^-$	5.68	5.67	5.67	5.43	5.66
$15/2^-$	7.78	7.76	7.77	7.32	7.76
$17/2^-$	10.07	10.12	10.13	9.37	10.12
$19/2^-$	12.76	12.73	12.75	11.58	12.74
$21/2^-$	15.63	15.58	15.63	13.91	15.62
$23/2^-$	18.75	18.68	18.74	16.37	18.76
β					
$9/2^-$	13.46	13.44	13.42	14.40	14.40
$11/2^-$	14.75	15.00	14.98	15.89	15.89
$13/2^-$	16.38	16.83	16.81	17.58	17.58
$15/2^-$	19.48	18.92	18.90	19.47	19.47
$17/2^-$	20.73	21.28	21.26	21.52	21.52
$19/2^-$	23.27	23.89	23.87	23.73	23.73
$21/2^-$	27.99	26.74	26.73	26.06	26.06
γ					
$9/2^-$	18.59	18.69	18.69	19.94	20.09
$11/2^-$	20.61	20.16	20.16	21.01	21.18
$13/2^-$	22.22	21.88	21.88	22.26	22.45
$15/2^-$	23.40	23.86	23.86	23.67	23.88
$17/2^-$	25.85	26.09	26.09	25.23	25.47
$19/2^-$	28.56	28.56	28.56	26.93	27.21

The theoretical predictions of energy levels 18 of the $g.s$ band,the β and γ bands normalized to the energy of the first excited state $E(7/2^-_{g.s.})$

$B_\beta \neq B_\gamma \neq B_{rot}$				$B_\beta = B_\gamma = B_{rot}$	
	Exp. [28]	$a=0$	DDM	$a=0$	DDM
$\frac{B(E2; L^i_{g.s.} \to L_{g.s.})}{B(E2; \frac{9}{2}^-_{g.s.} \to \frac{5}{2}^-_{g.s.})}$					
$11/2^- \longrightarrow 7/2^-$	2.03	1.70		1.74	1.72
$13/2^- \longrightarrow 9/2^-$	2.06	2.18		2.27	2.23
$15/2^- \longrightarrow 11/2^-$	2.31	2.51		2.68	2.60
$17/2^- \longrightarrow 13/2^-$	2.93	2.76		3.02	2.89
$21/2^- \longrightarrow 17/2^-$	3.21	3.10		3.60	3.33
$23/2^- \longrightarrow 19/2^-$	3.26	3.23		3.86	3.51
$25/2^- \longrightarrow 21/2^-$	3.37	3.34		4.11	3.66
$\frac{B(E2; L'_\beta \to L_{g.s.})}{B(E2; \frac{9}{2}^-_{g.s.} \to \frac{5}{2}^-_{g.s.})} \times 10^3$					
$9/2^- \longrightarrow 5/2^-$		1.74		11.81	11.81
$13/2^- \longrightarrow 9/2^-$		1.66		14.47	14.47
$17/2^- \longrightarrow 13/2^-$		0.55		9.78	9.78
$9/2^- \longrightarrow 9/2^-$		0.76		4.65	4.65
$13/2^- \longrightarrow 13/2^-$		4.82		29.55	29.55
$17/2^- \longrightarrow 17/2^-$		7.45		45.80	45.81
$5/2^- \longrightarrow 9/2^-$		16.63	16.61	97.81	97.81
$9/2^- \longrightarrow 13/2^-$		39.24	39.21	220.25	220.25
$13/2^- \longrightarrow 17/2^-$		56.40	56.35	296.76	296.77
$\frac{B(E2; L'_\gamma \to L_{g.s.})}{B(E2; \frac{9}{2}^-_{g.s.} \to \frac{5}{2}^-_{g.s.})} \times 10^3$					
$9/2^- \longrightarrow 5/2^-$		9.19		41.03	41.30
$9/2^- \longrightarrow 9/2^-$		1.42		6.79	6.82
$9/2^- \longrightarrow 13/2^-$		28.84		150.41	150.92
$11/2^- \longrightarrow 9/2^-$		21.66		102.63	103.23
$11/2^- \longrightarrow 13/2^-$		19.95		103.17	103.57
$13/2^- \longrightarrow 9/2^-$		19.91		93.00	93.61
$13/2^- \longrightarrow 13/2^-$		9.10		46.53	46.75
$13/2^- \longrightarrow 17/2^-$		33.70		188.55	189.04
$15/2^- \longrightarrow 13/2^-$		13.29		67.06	67.42

The theoretical predictions of B(E2) in units of $B(E2; 9/2^-_{g.s.} \to 5/2^-_{g.s.})$

- In the present work, we have studied the deformed odd-mass nuclei, ^{173}Yb , in the framework of the Bohr Hamiltonian with deformation-dependent mass coefficients using Davidson potential in β shape and the harmonic oscillator in γ potential.

- Analytical expressions have been obtained for the excited-state energies, wave functions and E2 transition probabilities.

- We have studied the effect of the deformation mass parameter on energy spectra and transition rates in both above-cited cases. Moreover, we have shown the importance of the mass parameter to be introduced in numerical calculations

- The obtained results of the excitation energies and B(E2) reduced transition probabilities show an overall agreement with the experimental data.

Thank you for your attention