Low energy 0^+ excitations in ^{158}Gd

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High precision (p,t) studies of the deformed nucleus ^{158}Gd allowed the observation of 13 excited 0^+ states below an excitation energy of 3.1 MeV. This high density of low energy states, and particularly their measured B(E2) transition strengths to the first excited 2^+ state challenge nuclear models. The pseudo SU(3) model, which successfully describes many excited bands in Dy isotopes, is used to analyze this nuclei. We have fairly good reproduction of most of the states but the absence of actively including nucleons occupying intruders orbits may be the reason for the observed limitations of the model.

Keywords: Algebraic models; nuclear structure; deformed nuclei.

Estudios de alta precision (p,t) del nucleo deformado 158Gd han permitido la observacion de 13 estados excitados 0+ a una energia abajo de 3.1 MeV. Esta alta densidad de estados de baja energia y particularmente la medida de sus transiciones B(E2) al primer estado 2+ representa un desafio para cualquier modelo nuclear. Se utiliza el modelo pseudo SU(3), que describe adecuadamente un gran numero de bandas excitadas en los isotopos de Dy, para estudiar el 158Gd. Encontramos que el modelo describe adecuadamente la mayoria de los estados, sin embargo, es posible que el hecho de excluirÃlos nucleones ocupando estados de paridad intrusa sea la principal limitante del modelo.

Descriptores: Modelos algebraicos; estructura nuclear; nucleos deformados.

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1. Introduction

Recent experiments had provided clear evidence of the existence of many low lying $K^+ = 0^+$ bands in deformed nuclei. Using a Q3D spectrometer in high-precision (p,t) studies 13 excited 0^+ states have been identified below 3.1 MeV in ^{158}Gd, seven of them for the first time [1]. The new 0^+ assignments were strengthened by the placement of γ rays that were identified to belong to the ^{158}Gd nucleus with no previous level assignments. Such an abundance of 0^+ states had not previously been seen in nuclei.

This high density of 0^+ states challenges the simplest theoretical descriptions, which usually predict very few bands below 3 MeV. This is true for the earlier studies using the geometrical collective model (GCM) [2], and the *sd*-IBM [3], which could account for only 5 excited 0^+ states below 3 MeV. The inclusion of the octupole degree of freedom in IBA calculations allows the prediction of 10 excited 0^+ states below 3 MeV and 14 below 4 MeV, a number of them having a strong collective two-phonon octupole character [4]. The Projected Shell Model (PSM) [5], using as building blocks angular-momentum-projected two- and four-quasiparticle (qp) states, is also able to reproduce reasonably well the energies of all observed 0^+ states [6]. Most of the states are dominated by one 2-qp or 4-qp state, coming from the near-Fermi Nilsson levels with low excitation energies. The qp nature of these excited states is quite different from the collective octupole vibration introduced in [4].

A microscopic calculation within the quasiparticle-phonon model (QPM) [7] offered a less biased criterion for determining the nature of these 0^+ states. In this model the microscopic phonons, both collective and noncollective, are generated in the random-phase approximation (RPA), and are used to diagonalize a separable Hamiltonian containing different multipoles. The study of the 0^+ states in ^{158}Gd found many low energy states, which in most cases have large, if not dominant, two-phonon octupole components [8], in agreement with the previous IBA predictions [4].

Measured electromagnetic transition strengths are extremely useful to distinguish between different theoretical models. A strong $B(E2 : K = 0_2^+ \rightarrow \gamma)$ had been determined in ^{158}Gd using the GRID technique [9].The authors associated this with band mixing rather than with a double-γ phonon. Other $B(E2)$ values for the decay of the $K = 2_1^+$

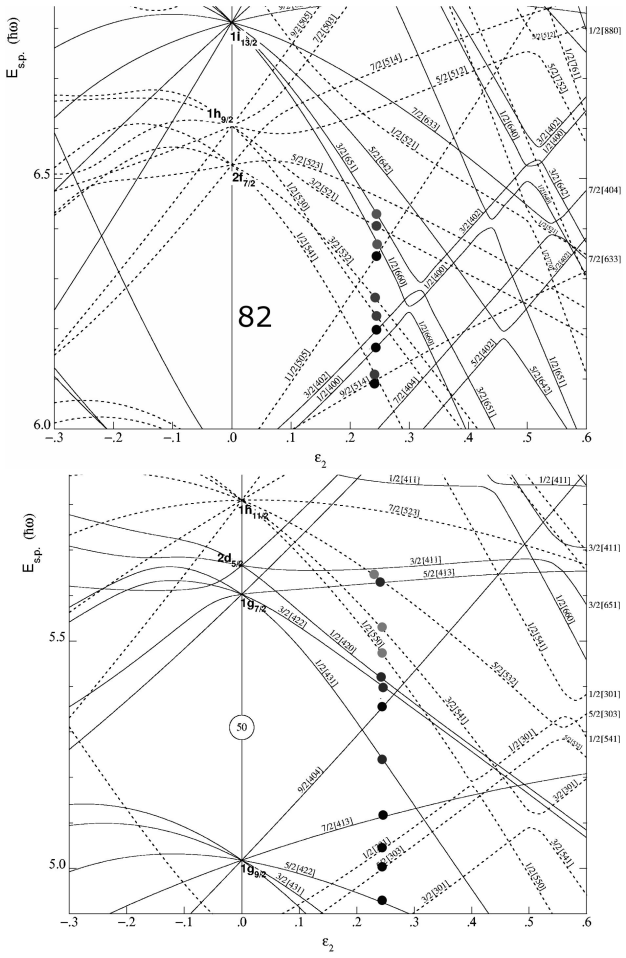

FIGURE 1. The occupancies for neutrons (top) and protons (bottow) as determined by the filling of the the deformed Nilsson levels.

TABLE I. γ-ray energies, excitation energies of the state J^π_x and the extracted $B(E2: K=0_x \rightarrow 2_1)$ values in ^{158}Gd, taken from Ref. 10

E_γ (keV)	E_x (keV)	J^π_x	B(E2) (W.u.)
1116.48	1196.10	0^+_2	2.3± 0.9
1372.90	1452.30	0^+_3	3.1± 1.1
1878.3	1957.8	0^+_7	4.1± 1.9
2196.61	2277.0	0^+_8	4.2± 1.6
2260.47	2338.0	0^+_9	1.0± 0.3
2564.67	2643.4	0^+_{10}	6.4± 3.7
2605.8	2687.1	0^+_{11}	4.5± 3.5
2832.0	2911.2	0^+_{12}	0.9± 0.9
2997.0	3076.7	0^+_{13}	1.7± 0.5
3026.2	3109.9	0^+_{14}	1.9± 0.6

and $K=0^+_2$ bands were also reported in [9]. The study of 0^+ excitations with the $(n,n'\gamma)$ reaction allowed the determination of $B(E2: K=0^+_x \rightarrow 2_1)$ values for ten of the previously measured excited 0^+ states [10]. They all have values between one and a few W.u., suggesting the presence of a significant fragmentation of the collectivity in these excited states.

The theoretical description of these large but fragmented B(E2) values has not been possible up to now. From the 18 0^+ states predicted in the PSM to have energies below 3.25 MeV [4], only two states have B(E2) transition strengths larger than 1 W.u. In the QPM calculation only the first excited 0^+ state is predicted to decay with a $B(E2)$ strength larger than 1 W.u..

In the present contribution we report on an attempt to describe the observed 0^+ excited states and their $B(E2)$ transition strengths in ^{158}Gd using the pseudo SU(3) model [11–13]. We were strongly motivated by the success of this model in describing the energy levels and electromagnetic transition strengths in many excited bands in ^{157}Gd, ^{163}Dy and ^{169}Tm [14]. The same model allowed also the description of up to 8 rotational bands in ^{158,160,162,164}Dy [15]. In what follows we will briefly review the main ideas behind the pseudo SU(3) model, present the results for ^{158}Gd, and discuss them critically.

2. Pseudo SU(3) basis

The pseudo SU(3) model [16] has been widely used in recent years in the description of even-even [17–19] and odd-mass nuclei [20–22]. The first step in any application of the pseudo SU(3) model is to build the many-body basis. For the pseudo SU(3) scheme the proton and neutron valence Nilsson single-particle levels are filled from below for a fixed deformation, which in the case of ^{158}Gd is $\epsilon_2 = 0.25$ [23]. It allows the determination of the most probable normal and unique parity orbital occupancies, as shown in Fig. 1.

Of the 14 valence protons, 8 occupy normal parity orbitals, and 6 intruder orbitals. Of the 12 valence neutrons, 8 are in normal parity orbitals and 4 in intruder orbitals.

TABLE II. Case 1: The SU(3) irreps (obtained by coupling all the pseudo-spin zero proton and neutron irreps) with $C_2 > C_{2cut}$, ordered by decreasing C_2 values, used to describe the low-energy spectra in ^{158}Gd.

(λ_π,μ_π)	(λ_ν,μ_ν)	(λ,μ)
(10,4)	(18,4)	(28,8), (29,6), (30,4), (31,2), (32,0), (26,9), (27,7)
(10,4)	(20,0)	(30,4)
(10,4)	(16,5)	(26,9),(27,7)
(10,4)	(17,3)	(27,7)
(10,4)	(13,8)	(23,12)
(12,0)	(18,4)	(30,4)
(12,0)	(20,0)	(32,0)
(8,5)	(18,4)	(26,9),(27,7)
(9,3)	(18,4)	(27,7)
(5,8)	(18,4)	(23,12)

TABLE III. Case 2: The SU(3) irreps (obtained by coupling all the pseudo-spin zero and one proton and neutron irreps) with $C_2 > C_{2cut}$, the same as in the first case, ordered by decreasing C_2 values, used to describe the low-energy spectra in ^{158}Gd.

(λ_π, μ_π)	S_π	(λ_ν, μ_ν)	S_ν	(λ, μ)	S	(λ_π, μ_π)	S_π	(λ_ν, μ_ν)	S_ν	(λ, μ)	S
(10,4)	0	(18,4)	0	(28,8)	0	(10,4)	0	(18,4)	0	(29,6)	0
(10,4)	0	(19,2)	1	(29,6)	1	(11,2)	1	(18,4)	0	(29,6)	1
(10,4)	0	(18,4)	0	(30,4)	0	(10,4)	0	(19,2)	1	(30,4)	1
(10,4)	0	(20,0)	0	(30,4)	0	(11,2)	1	(18,4)	0	(30,4)	1
(11,2)	1	(19,2)	1	(30,4)	0	(11,2)	1	(19,2)	1	(30,4)	1
(11,2)	1	(19,2)	1	(30,4)	2	(12,0)	0	(18,4)	0	(30,4)	0
(10,4)	0	(18,4)	0	(31,2)	0	(10,4)	0	(19,2)	1	(31,2)	1
(11,2)	1	(18,4)	0	(31,2)	1	(11,2)	1	(19,2)	1	(31,2)	0
(11,2)	1	(19,2)	1	(31,2)	1	(11,2)	1	(19,2)	1	(31,2)	2
(11,2)	1	(20,0)	0	(31,2)	1	(12,0)	1	(19,2)	1	(31,2)	1
(10,4)	0	(18,4)	0	(32,0)	0	(11,2)	1	(19,2)	1	(32,0)	0
(11,2)	1	(19,2)	1	(32,0)	1	(11,2)	1	(19,2)	1	(32,0)	2
(12,0)	0	(20,0)	0	(32,0)	0	(10,4)	0	(18,4)	0	(26,9)	0
(10,4)	0	(16,5)	0	(26,9)	0	(10,4)	0	(16,5)	1	(26,9)	1
(8,5)	0	(18,4)	0	(26,9)	0	(8,5)	1	(18,4)	0	(26,9)	1
(10,4)	0	(18,4)	0	(27,7)	0	(10,4)	0	(19,2)	1	(27,7)	1
(10,4)	0	(16,5)	0	(27,7)	0	(10,4)	0	(16,5)	1	(27,7)	1
(10,4)	0	(17,3)	0	(27,7)	0	(11,4)	0	(17,3)	1	(27,7)	1
(11,2)	1	(18,4)	0	(27,7)	1	(11,2)	1	(16,5)	0	(27,7)	1
(11,2)	1	(16,5)	1	(27,7)	0	(11,2)	1	(16,5)	1	(27,7)	1
(11,2)	1	(16,5)	1	(27,7)	2	(8,5)	0	(18,4)	0	(27,7)	0
(8,5)	1	(18,4)	0	(27,7)	1	(8,5)	0	(19,2)	1	(27,7)	1
(8,5)	1	(19,2)	1	(27,7)	0	(8,5)	1	(19,2)	1	(27,7)	1
(8,5)	1	(19,2)	1	(27,7)	2	(9,3)	0	(18,4)	0	(27,7)	0
(9,3)	1	(18,4)	0	(27,7)	1	(10,4)	0	(13,8)	0	(23,12)	0
(10,4)	0	(13,8)	1	(23,12)	1	(5,8)	0	(18,4)	0	(23,12)	0
(5,8)	1	(18,4)	0	(23,12)	1						

Many-particle states are built as pseudo-SU(3) coupled states with a well-defined particle number (of nucleons in normal parity orbits) and good total angular momentum. Nucleons occupying the intruder orbits are considered implicitly through the use of effective charges. The explicit inclusion of the unique-parity sector configurations remains an open challenge that, while under investigation, is still not available.

Since in a quadrupole-quadrupole driven Hamiltonian, the states corresponding to highest deformation are the most important, we extract from this scheme the proton and neutron SU(3) irreps corresponding to the highest C_2 values which, in turn, are coupled to final SU(3) irreps that have good total angular momentum [16, 20]. The configuration space was generated from the strong coupling of the eight protons and eight neutrons in the normal parity states. Two sets of calculations were performed. In the first case proton and neutron states with only pseudo-spin zero were considered and, in the second case, the configuration space was enlarged by considering proton and neutron states with both pseudo-spin zero and one. In both cases the configuration space was truncated by considering all the coupled SU(3) irreps with a C_2 greater than the same value for the C_{2cut}. The SU(3) irreps considered in the two cases are given in Table I and II.

Any state $|J_i M\rangle$, where J is the total angular momentum, M its projection and i an integer index which enumerates the states with the same J, M starting from the one with the lowest energy, is built as a linear combination

$$|J_i M\rangle = \sum_\beta C_\beta^{Ji} |\beta J M\rangle \tag{1}$$

of the strong coupled proton-neutron states

$$
\begin{aligned}
|\beta JM\rangle \equiv |\{\tilde{f}_\pi\}(\lambda_\pi\mu_\pi)\tilde{S}_\pi, \{\tilde{f}_\nu\}(\lambda_\nu\mu_\nu)\tilde{S}_\nu; \rho(\lambda\mu)\kappa\tilde{L}, \tilde{S}\ JM\rangle \\
= \sum_{M_L M_S} (\tilde{L}M_L, \tilde{S}M_S|JM) \sum_{M_{S\pi}M_{S\nu}} (\tilde{S}_\pi M_{S\pi}, \tilde{S}_\nu M_{S\nu}|\tilde{S}M_S) \\
\times \sum_{k_\pi\kappa_\nu\tilde{L}_\pi\tilde{L}_\nu M_\pi M_\nu} \langle(\lambda_\pi\mu_\pi)\kappa_\pi\tilde{L}_\pi M_\pi; (\lambda_\nu\mu_\nu)\kappa_\nu\tilde{L}_\nu M_\nu|(\lambda\mu)\kappa\tilde{L}M\rangle_\rho |\{\tilde{f}_\pi\} \\
\times (\lambda_\pi\mu_\pi)\kappa_\pi\tilde{L}_\pi M_\pi, \tilde{S}_\pi M_{S\pi}\rangle |\{\tilde{f}_\nu\}(\lambda_\nu\mu_\nu)\kappa_\nu\tilde{L}_\nu M_\nu, \tilde{S}_\nu M_{S\nu}\rangle. \qquad (2)
\end{aligned}
$$

In the above expression $(-,-|-)$ and $\langle -;-|-\rangle$ are the SU(2) and SU(3) Clebsch Gordan coefficients, respectively.

In this article we consider the Hilbert space spanned by the states with $\tilde{S}_{\pi,\nu}$ = 0 and 1 in Eq. (2). The main difference with the pseudo SU(3) basis used in previous pseudo SU(3) descriptions of even-even nuclei [18] is the inclusion of states with $\tilde{S}_{\pi,\nu}$ = 1 in the proton and neutron wave functions. They have a non negligible contribution to excited rotational bands. The goodness of the pseudo SU(3) symmetry is preserved by imposing that states with $\tilde{S}_{\pi,\nu}$ = 0 should be dominant in the ground state. It translates into severe limits for the "rotor-like" terms in the Hamiltonian, and guarantees that the whole band structure is preserved.

3. The Hamiltonian

The Hamiltonian has a *principal* part H_0:

$$
H_0 \quad = \quad \sum_{\alpha=\pi,\nu} \{H_{sp,\alpha} - G_\alpha\, H_{pair,\alpha}\} - \frac{1}{2}\,\chi\,\tilde{Q}\cdot\tilde{Q}\,. \qquad (3)
$$

which contains spherical Nilsson single-particle terms for protons and neutrons ($H_{sp,\pi[\nu]}$), quadrupole-quadrupole ($\tilde{Q}\cdot\tilde{Q}$) and pairing ($H_{pair,\pi[\nu]}$) interactions. Added to these are five 'rotor-like' terms that are diagonal in the SU(3) basis:

$$
H = H_0 + aJ^2 + bK_J^2 + a_3C_3 + a_{sym}C_2 + dS^2. \qquad (4)
$$

A detailed analysis of each term of this Hamiltonian and its parameterization can be found in [20]. The different terms in H_0 have been widely studied in the nuclear physics literature, allowing their respective strengths to be fixed by systematics [20, 24, 25]. The configuration mixing is due to the SU(3) symmetry-breaking Nilsson single-particle and pairing terms.

The single-particle terms ($H_{sp,\alpha}$) have the form:

$$
H_{sp,\alpha} = \sum_{i_\alpha} \left(C_\alpha \mathbf{l}_{i_\alpha}\cdot\mathbf{s}_{i_\alpha} + D_\alpha \mathbf{l}_{i_\alpha}^2\right), \qquad \alpha = \pi,\nu, \qquad (5)
$$

where C_α and D_α are fixed following the usual prescriptions [24]. In the pseudospin basis the spin-orbit and orbit-orbit contributions are small, but they still generate most of the mixing between pseudo SU(3) irreps.

The 'rotor-like' terms in Hamiltonian (4) are used to fine tune the calculated spectra. The five parameters a, b, a_3, a_{sym}, d were fixed following the prescriptions given in Ref. 18 and 20. The K_J^2 breaks the SU(3) degeneracy of the different K bands, the J^2 term provides small corrections to the moment of inertia. These two terms help to fit the energy of the γ band and the moment of inertia of the ground band, respectively. It is worth keeping in mind that these two terms only modify the wave function slightly, their main effects is on the energies.

The parameters of a_{sym} and a_3 in the $\tilde{C}_2$ and $\tilde{C}_3$ terms must be strongly restricted to avoid drastic changes in the wave functions. The theory is most sensitive to the parameter $\tilde{C}_3$, because when large values for c are employed, the ground state becomes a pure pseudospin 1 state. It can also induce an artificially triaxial ground state in a well deformed nuclei.

4. Results

With all the fitting parameters set to zero in the Hamiltonian, we have poor agreement with the energies of the observed 0+ states, but we do get all 13 0+ states. Also, the 1+ state is calculated at 620 keV when it is observed at 1.84 MeV. In this case the first two excited 0^+ states are lower in energy than their experimental counterparts. The first excited 0^+ state changes very little with a_{sym} parameter for a fixed value of the a_3. By increasing the a_3 parameter we fit the energy of the first excited 0_+ state. By increasing the a_{sym} parameter, many states are being pushed higher in energy, including the excited 0^+ states. By varying the coefficient in front of K_J^2, the energy value of the $K = 2^+$ state can be fit.

With the set of parameters we determined, we were able to identify the low energy spectra and compare it with the experimental one in Fig. 2.

As can be seen, the rotor-like terms in the Hamiltonian allowed for the adjustment of the moment of inertia of the ground-state band, and the energies of the 2_γ^+, 0_2 and 1_1^+ states. It is clear, however, that the predicted third and fourth 0^+ states have higher energies than their experimental counterparts, and that there are only 4 0^+ states below 3 MeV.

Using the enlarged basis listed in Table III we obtained the low energy spectra shown in Fig. 3, which is also compared with the experimental levels.

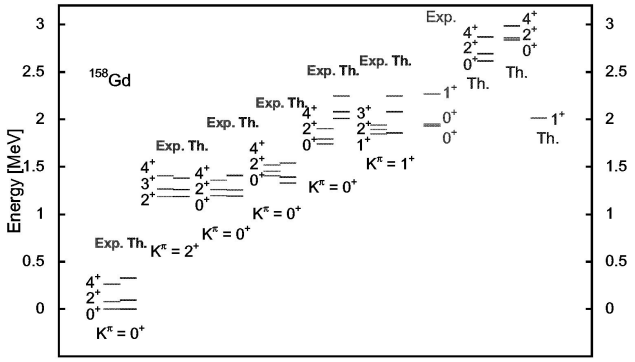

FIGURE 2. Case 1: Low energy spectra of ^{158}Gd obtained with the restricted configuration space. The experimental values are shown on the left-hand side of each band (red lines), and the calculated ones on the right-hand side (blue lines).

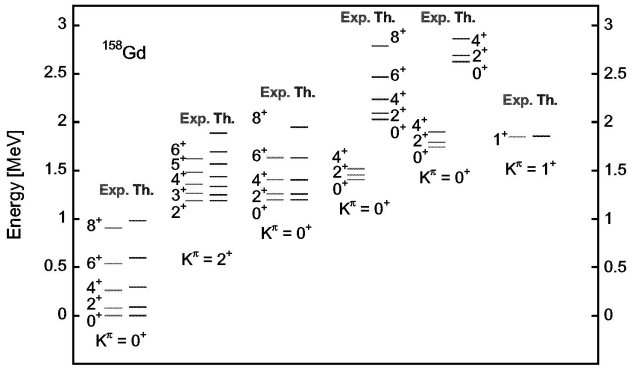

FIGURE 3. Case 2: Low energy spectra of ^{158}Gd obtained with an enlarged configuration space. Conventions as in Fig. 2.

The positive effects of enlarging the basis are clearly seen in this figure. With the same number of parameters, there are now 7 0^+ states below 3 MeV, whose energies are mostly close to the measured ones. This results is not suprising, because both in the IBM and in the PSM the use of enlarged basis allowed for the description of many 0^+ states at low excitation energy.

A detailed analysis of the excited 0^+ states wave functions, and their inter-band B(E2) transition strengths will be reported elsewhere [26]. In the present contribution we restrict the discussion to the B(E2) transition strengths between the excited 0^+ states and the 2_1^+ state belonging to the ground state band, and the 2_γ^+ state, the γ-bandhead. These B(E2) transition strengths are listed in Table **??** for the small basis, case 1, and in Table IV for the large basis, case 2. In both tables the excitation energy of the 0_i state is given in the first column, the calculated $B(E2; 0_i \rightarrow 2_1)$ in the second column, and the calculated $B(E2; 0_i \rightarrow 2_\gamma)$ in the third column.

In both cases the transition strengths to the ground state band are two or more orders of magnitude smaller than the experimental ones. There are, however, three or four B(E2) values to the γ- bandhead larger than 1 W.u. This suggests

TABLE IV. Case 1: The energy value of each excited 0^+ states is given in the first column. The corresponding transition values $B(E2; 0_i- > 2_1)$ are given in the second column, and the $B(E2; 0_i- > 2_\gamma)$ in the third column.

Energy	$B(E2; 0_i \rightarrow 2_1)$	$B(E2; 0_i \rightarrow 2_\gamma)$
(MeV)	(W.u.)	(W.u.)
1.19	0.08	1.22
2.03	0.0004	7.97
2.62	0.001	2.58
3.59	0.01	0.27

TABLE V. Case 2: The energy value of each excited 0^+ states is given in the first column. The corresponding transition values $B(E2; 0_i- > 2_1)$ are given in the second column, and the $B(E2; 0_i- > 2_\gamma)$ in the third column.

Energy	$B(E2; 0_i \rightarrow 2_1)$	$B(E2; 0_i \rightarrow 2_\gamma)$
of $0_i[MeV]$	[W.u.]	[W.u.]
1.19	0.06	7.79
1.33	0.0002	$< 1.0E^{-6}$
2.01	0.001	9.74
2.61	0.0002	3.02
2.83	$< 1.0E^{-6}$	$< 1.0E^{-6}$
3.56	0.01	0.26
3.68	$< 1.0E^{-6}$	$< 1.0E^{-6}$
3.77	$< 1.0E^{-6}$	$< 1.0E^{-6}$

that, while many 0^+ states are described in the pseudo SU(3) model at the right excitation energy, their wave functions are missing some important elements. The mixing of different occupancies in the normal parity sector, induced by the pairing interactions [27], could correct for these deficiencies.

5. Conclusions

The excitation energies of many 0^+ states in ^{158}Gd can be properly described using the pseudo SU(3) model including states with pseudo-spin 0, 1 and 2. While the calculated B(E2) transition strengths to the g.s. band are smaller than the observed ones, those to the gamma band are of the same order, measured in W.u.. Calculations in ^{156}Gd suggest that configuration mixing (different normal and intruder occupations mixed by pairing) could allow stronger transitions to the g.s. band.

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