Doublet structure of the negative-parity states in ^{195}Pt supported by particle-rotor calculations

P. Petkov,[1,2] P. von Brentano,[1] J. Jolie,[1] and R. V. Jolos[1,3]
[1]*Institut für Kernphysik der Universität zu Köln, D-50937 Köln, Germany*
[2]*Institute for Nuclear Research and Nuclear Energy, Bulgarian Academy of Sciences, BG-1784 Sofia, Bulgaria*
[3]*Joint Institute for Nuclear Research, 141980 Dubna, Russia*
(Received 26 May 2007; published 23 October 2007)

It is shown that particle-triaxial-rotor calculations with a Woods-Saxon potential for ^{195}Pt reproduce the experimentally observed doublet structure of the excitation spectrum below 700 keV. The observed strong $B(E2)$ transition strengths are also well reproduced. The structure of every doublet is dominated by one out of two single-particle orbitals. The absolute values of the $E2$ transition probabilities obtained in the particle-rotor model are in overall agreement with the predictions made by assuming a U(6/12) supersymmetry. The ratios of $B(E2)$ values between the states of two doublets agree well with those obtained by assuming a pseudospin symmetry only. This supports the idea of a pseudospin nature of the doublet structure although no a priori assumptions are made concerning a pseudospin symmetry of the Hamiltonian.

DOI: 10.1103/PhysRevC.76.044318 PACS number(s): 21.60.−n, 23.20.Lv, 27.80.+w

I. INTRODUCTION

The nucleus ^{195}Pt, being very well investigated experimentally (cf. Refs. [1–4] and references therein), has for many years attracted considerable attention as an object for theoretical studies mainly from the group theoretical point of view (e.g., Refs. [5–9]). The properties of the low-lying levels of ^{195}Pt have been interpreted as a realization of supersymmetry [10–12], which in the case of the U(6/12) supersymmetry is based on the pseudospin concept (see also Ref. [13]). The grouping of the negative-parity levels below 700 keV in doublets supports the conclusions made on the basis of the supersymmetry and pseudospin scheme.

Another class of theoretical approaches, namely, particle-core coupling models, has also been applied frequently to describe the odd nuclei removed from the closed shells. In the case of ^{195}Pt, the most detailed studies of that type in the past were performed in Refs. [14,15]. Recently, such an approach based on a contemporary particle-rotor model was applied for a description of the low-lying states in ^{195}Pt [16]. It was assumed in these calculations that the core has a triaxial deformation with $\gamma \approx \pi/6$, which is consistent with the expected mean value of this quantity in the framework of the O(6) limit of the IBA (Interacting Boson Approximation) [17]. A reasonable description of the level energies below 700 keV and of the corresponding $E2$ and $M1$ reduced transition probabilities was obtained. The remarkable fact is the reproduction of the doublet structure of the spectrum, although the existence of any symmetry was not assumed in the formulation of this approach.

One of the aims of the present work is to investigate the stability of the solution obtained by the particle-rotor model by applying a more realistic deformed potential, namely a Woods-Saxon (WS) one, instead of the modified harmonic oscillator (MHO) employed in Ref. [16]. In this sense, it is interesting to investigate whether the calculated energy differences between the doublet levels can be minimized by the WS potential and become comparable with the experimental ones. Another aim is to show that the appearance of a doublet structure of the spectrum in the particle-rotor-model calculations for ^{195}Pt is related to the existence of an approximate pseudospin symmetry in the model. The third aim is to compare the particle-triaxial-rotor-model results with both experiment and U(6/12) predictions.

II. THE PARTICLE-TRIAXIAL-ROTOR MODEL, RESULTS OF CALCULATIONS, AND THEIR COMPARISON WITH EXPERIMENT AND U(6/12)

In the present study, we used the particle plus triaxial rotor model (PTRM) of Ref. [18]. Here, we describe only its main features and refer the reader for further details to that paper. As a first step, the single-particle energies and wave functions corresponding to the Woods-Saxon potential with the parametrization of Rost [19] are calculated for fixed core deformation $(\beta_2, \gamma, \beta_4)$. From the generated Nilsson states [20] in the cylindrical basis $\Omega[Nn_z\Lambda]$, one selects a set that is used to construct the particle plus rotor strong coupling basis states. Single-particle matrix elements necessary for the particle plus rotor Hamiltonian and the calculation of transition strengths are computed within this set. The effect of the residual pairing interaction is treated within the BCS approximation and a Fermi level λ, pairing gap Δ, and quasiparticle energies are derived. Further, the particle plus triaxial rotor Hamiltonian matrix is constructed and diagonalized in the one-quasiparticle strong coupling basis for a range of values of the total spin J. The core energy spectrum is taken into account by specifying the hydrodynamic moments of inertia of the triaxial rotor. At the end, electromagnetic matrix elements, both diagonal and off-diagonal, are calculated with the wave functions obtained.

For the PTRM calculations, we used the computer codes SWGAMMA, WSDCUP, ASYRWS, and PROBWS presented in Ref. [21]. In the deformed $N = 82$–126 shell, we included only the six negative-parity single-neutron orbitals from $p_{3/2}$, $f_{5/2}$, and $p_{1/2}$ parentage. They are the ones that lie in the vicinity of the Fermi level and also those used in the U(6/12) approach of Refs. [4,8]. The moments of inertia, which depend on the deformation according to the irrotational formulas, were

adjusted by varying the energy $E_{2_1^+}$ of the 2_1^+ level of the effective even-even core. The attenuation ζ of the Coriolis interaction was also treated as an adjustable parameter. An overall description of the spectrum of the excited states and of the transition strengths was obtained with the parameters $\beta_2 = 0.13$, $\gamma = 30^\circ$, $\beta_4 = -0.04$, $E_{2_1^+} = 290$ keV, and $\zeta = 0.7$. These values are close to the parameters employed in our previous work [16] on ^{195}Pt, where however a MHO potential was used instead of the WS potential.

The experimental excitation spectrum is compared to the calculated ones in the framework of the PTRM and U(6/12) in Fig. 1. The grouping of the doublets in both cases was performed by using the criterion of the existence of only one singlet state in the energy range considered and using the criterion of the minimization of the energy splitting in the doublets. These criteria lead to a unique grouping. It should be mentioned that the calculated energy differences between the doublet levels do not exceed 67 keV. Experimentally, the largest energy difference is 61 keV. This result indicates a better description of the doublet structure in the present work, where a WS potential was employed, compared to the description given in Ref. [16] (see also Fig. 2 in that paper) by using the MHO potential. Additionally, we applied some tests to confirm the doublet structure. Thus, it was noticed that one and the same quasineutron orbital dominates the structure of every doublet. So, there is no doublet of levels (E_x^1, E_x^2) where the dominant components differ (i.e., it is always orbital 31 or orbital 32 that dominates). Already in Ref. [16] it was established that the negative-parity orbitals with numbers 31 and 32 at the quadrupole deformation considered dominate the structure of the low-lying states (cf. also Fig. 1 in Ref. [16] and the following). The use of a WS potential, even after the inclusion of a hexadecapole deformation, does not change this picture. It was also established that the $B(E2)$ strengths between some doublet members are enhanced. This feature is observed both in experiment and theory, as can be seen in Fig. 2. Namely, the transition from the level with higher (lower) spin of the upper doublet to the level with higher (lower) spin of the lower doublet is always strong for particular pairs of doublets. For instance, this is very well illustrated by the transitions between the doublet levels shown on the left of Figs. 2(a) and 2(b). Namely, the cascades $9/2 \rightarrow 5/2 \rightarrow 1/2$ and $7/2 \rightarrow 3/2 \rightarrow 1/2$ are characterized by large $B(E2)$ values. It should be mentioned that the description of the strong $E2$ transitions in the present work is superior to that given in Ref. [16]. However, the description of the weaker transitions is of about the same quality. The description of the $B(E2)$ values in the case of the U(6/12) approach [Fig. 2(c)] is somewhat better than that given by the particle-rotor model. This can be seen in more details in Table I,

TABLE I. Absolute $B(E2)$ values in ^{195}Pt. The first four columns define the initial and final states with the experimental energies and spins. The experimental $B(E2)$ values are taken from Refs. [1,8] and the calculated ones in the framework of the PTRM are from the present work. The theoretical values in the SO(6) limit of U(6/12) are calculated according to Ref. [8].

E_i (keV)	$J_i(\hbar)$	E_f (keV)	$J_f(\hbar)$	$B(E2)$ (e^2 b^2)		
				Experiment	Triaxial rotor	U(6/12)
99	3/2	0	1/2	0.067(9)	0.055	0.035
130	5/2	99	3/2	0.030(13)	<0.0001	0
		0	1/2	0.064(9)	0.001	0.035
200	3/2	99	3/2	≤0.044	0.144	0.082
		0	1/2	0.029(9)	0.001	0
211	3/2	0	1/2	0.194(47)	0.164	0.179
239	5/2	99	3/2	0.054(27)	0.023	0
		0	1/2	0.235(34)	0.230	0.179
389	5/2	130	5/2	0.0002(1)	0.028	0.055
		99	3/2	0.248(134)	0.101	0.219
		0	1/2	0.009(6)	0.001	0
420	3/2	222	1/2	<0.235	0.031	0
		99	3/2	0.0005(4)	0.018	0.177
		0	1/2	0.0015(5)	0.020	0
455	5/2	0	1/2	≤0.04	0.005	0
508	7/2	389	5/2	<26	0.041	0.002
		211	3/2	0.047(20)	0.0003	0.020
		99	3/2	0.194(67)	0.210	0.228
563	9/2	239	5/2	0.091(22)	0.003	0.022
		130	5/2	0.235(54)	0.314	0.253
613	7/2	239	5/2	<1.407	0.020	0
		211	3/2	0.168(107)	0.294	0.215
		99	3/2	0.005(3)	0.002	0.009
667	9/2	239	5/2	0.200(50)	0.334	0.239
		130	5/2	0.012(4)	0.003	0.010

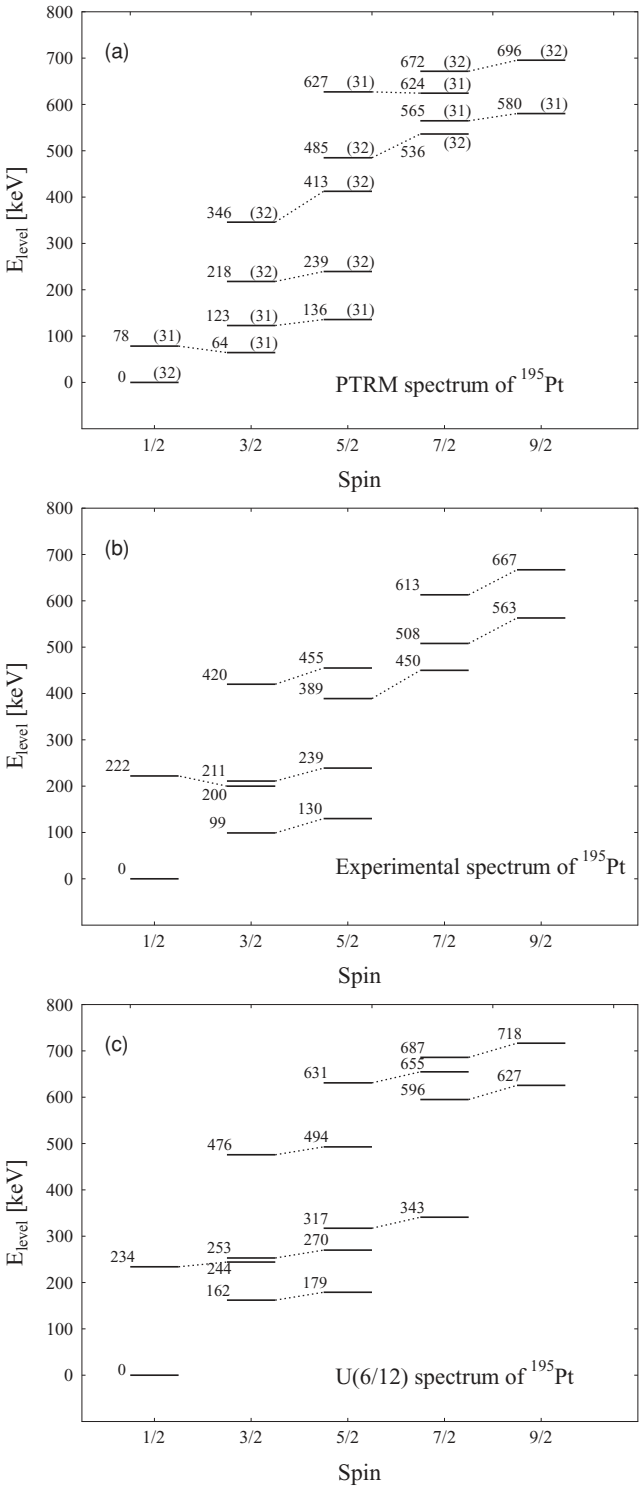

FIG. 1. (a), (c) Calculated and (b) experimental spectra of the excited states in ^{195}Pt below 700 keV. The doublet levels are connected with a dotted line. The criterion for the assignment of doublets is discussed in the middle of Sec. II. In the case of the PTRM spectrum, the number (31,32) of the quasineutron orbital dominating the wave function is also given in brackets.

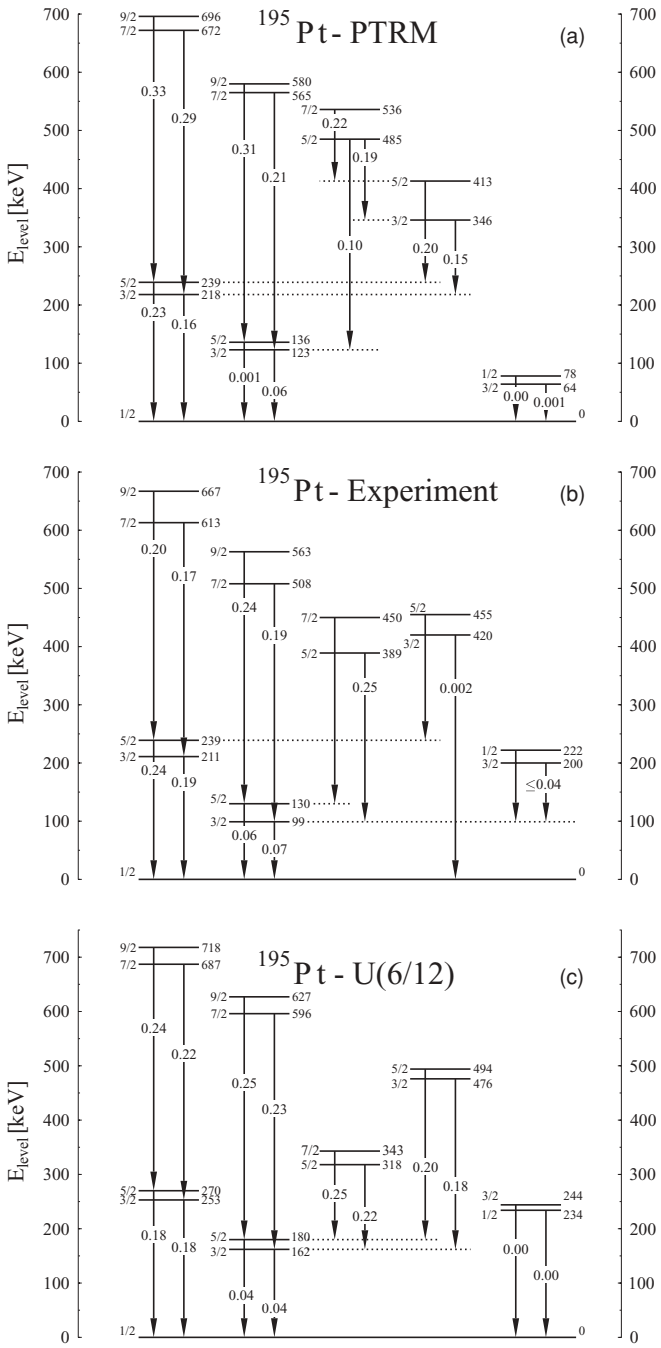

FIG. 2. Band structure assigned from strong $B(E2)$ transition strengths in e^2 b^2 between the doublet levels. Shown are the results of (a) the PTRM, (b) experiment, and (c) U(6/12). The energies (c) are taken from Ref. [4] and the $B(E2)$ values (c) are taken from Ref. [8].

where the experimental $B(E2)$ values of transitions between the lowest states in ^{195}Pt are compared to the theoretical predictions. The biggest discrepancy in the case of the PTRM is the description of the transitions depopulating the $5/2^-$ level at 130 keV, which are theoretically too weak. With the exception of some weak transitions, the rest of the $B(E2)$ strengths are reasonably reproduced. The same holds for the description in the framework of U(6/12). Here, the biggest discrepancy is the strong predicted $B(E2)$ value of $0.177e^2$ b^2 from the $3/2^-$ level at 420 keV to the $3/2^-$ level at 99 keV,

TABLE II. Ratios R of $B(E2)$ reduced transition probabilities between doublet levels in ^{195}Pt. The first column defines the ratio R with the experimental spins and excitation energies of the initial and final levels. In the second column, the absolute values of the $B(E2)$'s obtained in the PTRM calculations are shown to give an idea on the values of the quantities involved in the ratios. The next four columns display the ratios R derived in the PTRM, the pseudospin theory [Eq. (1)], U(6/12) [8], and the experiment [1], where available. The "x" marks in the U(6/12) case correspond to forbidden transitions, which make the ratios undefined. Note also that in pseudospin theory they might be undefined because of a division of zero by zero.

Ratio R	$B(E2)$ values in (e^2 b^2) in the triaxial rotor	R			
		Triaxial rotor	Pseudospin theory	U(6/12)	Experiment
$\frac{B(E2,9/2(667)\to5/2(239))}{B(E2,7/2(613)\to5/2(239))}$	$\frac{0.334}{0.020}$	16.7	10	10	>0.14
$\frac{B(E2,9/2(667)\to5/2(239))}{B(E2,7/2(613)\to3/2(211))}$	$\frac{0.334}{0.294}$	1.14	1.11	1.11	1.19(81)
$\frac{B(E2,9/2(563)\to5/2(130))}{B(E2,7/2(508)\to5/2(130))}$	$\frac{0.314}{0.064}$	4.9	10	10	
$\frac{B(E2,9/2(563)\to5/2(130))}{B(E2,7/2(508)\to3/2(99))}$	$\frac{0.314}{0.210}$	1.50	1.11	1.11	1.21(50)
$\frac{B(E2,9/2(563)\to7/2(695))}{B(E2,9/2(563)\to5/2(678))}$	$\frac{0.126}{0.009}$	14.0	16.5	x	
$\frac{B(E2,9/2(563)\to5/2(678))}{B(E2,7/2(508)\to5/2(678))}$	$\frac{0.009}{0.111}$	0.081	0.064	x	
$\frac{B(E2,7/2(450)\to5/2(455))}{B(E2,7/2(450)\to3/2(420))}$	$\frac{0.223}{0.013}$	17.2	9	x	
$\frac{B(E2,5/2(389)\to5/2(455))}{B(E2,5/2(389)\to3/2(420))}$	$\frac{0.073}{0.188}$	0.39	0.25	x	
$\frac{B(E2,7/2(450)\to5/2(455))}{B(E2,5/2(389)\to5/2(455))}$	$\frac{0.223}{0.073}$	3.05	4.5	x	
$\frac{B(E2,7/2(450)\to3/2(420))}{B(E2,5/2(389)\to3/2(420))}$	$\frac{0.013}{0.188}$	0.069	0.125	x	
$\frac{B(E2,5/2(239)\to1/2(0))}{B(E2,3/2(211)\to1/2(0))}$	$\frac{0.230}{0.164}$	1.40	1	1	1.21(34)

which is experimentally quite weak [0.0005(4) e^2 b^2]. Our conclusion is that both PTRM and U(6/12) can reproduce the gross features of the $B(E2)$ transition strengths in ^{195}Pt.

The appearance of doublets in the PTRM calculations is a remarkable fact because the presence of multiplets is related usually to the existence of some symmetry. However, there are no assumptions about any symmetry in the formulation of the PTRM. The appearance of a doublet structure is natural in the spectra calculated in the U(6/12) dynamical symmetry approach. The results presented in Fig. 1 show that the quality of the description of the energies of the doublets in the PTRM and in the model based on U(6/12) is comparable.

III. PSEUDOSPIN SYMMETRY AS A POSSIBLE EXPLANATION OF THE APPEARANCE OF A DOUBLET STRUCTURE

The calculated spectrum of the low-lying states of ^{195}Pt is shown in Fig. 1(a), where the single-particle structure of the states is also indicated. We see that the excited states forming doublets are based on the same single-particle states although there is some mixing of the single-particle levels. Only two single-particle states dominate the structure of the low-lying levels below 700 keV, which are enumerated in Fig. 1 as (31) and (32). The appearance of a doublet structure in the excitation spectrum can be considered as an indication of some approximate symmetry presented in the Hamiltonian.

We can assume that this is a pseudospin symmetry that was used very intensively in the framework of Interacting Boson Fermion Model (IBFM), including for the interpretation of the experimental data on ^{195}Pt. However, in contrast to IBFM where this symmetry is introduced in the Hamiltonian from the beginning, the PTRM Hamiltonian is formulated without any assumption about pseudospin symmetry.

Thus, we assume that the appearance of a doublet structure in the spectrum resulting from particle-rotor-type calculations performed in Ref. [16] and the present work is related to the pseudospin as it is in the considerations based on the group theoretical arguments. If our assumption is correct then the members of a doublet are characterized by the same value of the total pseudo-orbital momentum $\tilde{L}$ and have the same intrinsic structure. In Fig. 2(a), some of the states are combined in bands. The first band contains the ground state, which is a pseudospin singlet with $\tilde{L}=0$ and doublets with $\tilde{L}=2$ and 4. The second band consists of two doublets with $\tilde{L}=2$ and 4. The first band is based on the single-particle state (32) and the second one on (31). This classification coincides with that in the U(6/12)approach [Fig. 2(c)].

Besides the energies we can also consider the $B(E2)$'s. On the basis of the assumption about pseudospin symmetry the following expression can be derived for the ratios of $B(E2)$'s (see also Ref. [22]):

$$\frac{B(E2;J_1'\alpha'\tilde{L}'\to J_1\alpha\tilde{L})}{B(E2;J_2'\alpha'\tilde{L}'\to J_2\alpha\tilde{L})}=\frac{(2J_1+1)\begin{Bmatrix}\tilde{L} & 1/2 & J_1\\ J_1' & 2 & \tilde{L}'\end{Bmatrix}^2}{(2J_2+1)\begin{Bmatrix}\tilde{L} & 1/2 & J_2\\ J_2' & 2 & \tilde{L}'\end{Bmatrix}^2}. \quad (1)$$

We consider in the following only sufficiently strong $E2$ transitions between doublets based on the same single-particle states. The results of calculations with the help of Eq. (1) are compared in Table II with the results of the particle-rotor-model calculations from the present work. It is seen from this comparison that the overall agreement between the two sets of calculated results is good. The deviations of the calculated ratios from each other do not exceed the factor 1.5–2.0, although the absolute values of the ratios are changed by two orders of magnitude. Thus, these results support the idea of the pseudospin nature of the doublet structure obtained in the particle-rotor-model calculations.

Now we can add some comments on the results obtained. It is known [23,24] that although the splitting of the pseudospin doublets in the Nilsson scheme increases when γ increases from 0 to $\pi/6$, the pseudospin symmetry remains an important physical concept. In our calculations the two intrinsic single-particle levels dominating the structure of the low-lying states correspond at $\gamma = 0^\circ$ to the orbitals 3/2[512] and 3/2[501] (cf. also Fig. 1 in Ref. [16]). At $\gamma = 0^\circ$ these two orbitals are members of two different pseudospin doublets, namely (3/2[512], 1/2[510]) and (5/2[503], 3/2[501]), characterized by projections of the single-particle pseudo-orbital momentum $\tilde{\Lambda}$ equal to 1 and 2, correspondingly. A pseudospin singlet state 1/2[501] is located not far from the second doublet ($\tilde{\Lambda} = 0$). This is in a correspondence with U(6/12), where only spherical single-particle states with $\tilde{L} = 0$ and 2 are considered. Owing to the γ-deformation, which corresponds in our case to the maximum triaxiality ($\gamma \approx 30^\circ$), the members of the single-particle pseudospin doublets and the pseudospin singlet are mixed. In this way both the single-particle states (31) and (32) are formed. Because of the mixing between the pseudospin partners, they have components characterized by different orientations of the pseudospin and therefore being coupled to the same core state they can form doublets having the same pseudo-orbital structure but total angular momenta differing by one unit. In other nuclei from the $A = 190$ mass region, similar doublet structures have been observed and interpreted in the pseudospin scheme. In ^{187}Os, for instance, the energy differences between the low-lying doublet levels do not exceed 10 keV [25,26].

IV. SUMMARY

It is shown that the calculations performed in a framework of the particle-rotor model for ^{195}Pt reproduce the experimentally observed doublet structure of the excitation spectrum below 700 keV. The use of a Woods-Saxon potential for the description of the single-particle levels and wave functions yields smaller energy differences between the doublet members compared to the modified harmonic oscillator potential. The strong $B(E2)$ transition strengths observed experimentally in ^{195}Pt are also reasonably well reproduced. The structure of every doublet is dominated by one out of two single-particle orbitals, namely those with either numbers (31) or (32). The absolute values of the $E2$ transition probabilities obtained in the particle-rotor model are in overall agreement with the predictions made by assuming a U(6/12) supersymmetry. The ratios of $B(E2)$ values between the states of two doublets agree well with those obtained by assuming pseudospin symmetry only. This supports the idea of a pseudospin nature of the doublet structure although no a priori assumptions are made concerning a pseudospin symmetry of the Hamiltonian.

ACKNOWLEDGMENTS

The authors are grateful to A. Dewald and A. Gelberg for useful discussions. P.P. and R.V.J. would like to thank their colleagues from the University of Cologne for their kind hospitality. This work was supported by the DFG (Germany) under Contract Nos. Br 799/12-1 and Jo 391/2-3 as well as by the DFG East-European-Germany Collaboration program. P.P. is indebted to the National Science Fund at the Bulgarian Ministry of Education and Science for financial support.

[1] Z. Chounmei, Nucl. Data Sheets **86**, 645 (1999).
[2] http://www.nndc.bnl.gov/ensdf.
[3] A. Metz, J. Jolie, G. Graw, R. Hertenberger, J. Gröger, C. Günther, N. Warr, and Y. Eisermann, Phys. Rev. Lett. **83**, 1542 (1999).
[4] A. Metz, Y. Eisermann, A. Gollwitzer, R. Hertenberger, B. D. Valnion, G. Graw, and J. Jolie, Phys. Rev. C **61**, 064313 (2000).
[5] A. B. Balantekin, I. Bars, R. Bijker, and F. Iachello, Phys. Rev. C **27**, 1761 (1983).
[6] D. D. Warner, R. F. Casten, M. L. Stelts, H. G. Börner, and G. Barreau, Phys. Rev. C **26**, 1921 (1982).
[7] M. Vergnes, G. Berrier-Ronsin, and R. Bijker, Phys. Rev. C **28**, 360 (1983).
[8] A. Mauthofer, K. Stelzer, J. Gerl, Th. W. Elze, Th. Happ, G. Eckert, T. Faestermann, A. Frank, and P. Van Isacker, Phys. Rev. C **34**, 1958 (1986).
[9] J. Jolie, S. Heinze, P. Van Isacker, and R. F. Casten, Phys. Rev. C **70**, 011305(R) (2004).
[10] F. Iachello, Phys. Rev. Lett. **44**, 772 (1980).
[11] F. Iachello and P. Van Isacker, *The Interacting Boson-Fermion Model* (Cambridge University Press, Cambridge, 1991).
[12] A. Frank and P. Van Isacker, *Algebraic Methods in Molecular and Nuclear Physics* (Wiley, New York, 1994).
[13] P. von Brentano, Int. J. Mod. Phys. E **14**, 121 (2005).
[14] K. T. Hecht and G. R. Satchler, Nucl. Phys. **32**, 286 (1962).
[15] Y. Yamazaki and R. K. Sheline, Phys. Rev. C **14**, 531 (1976).
[16] P. Petkov, P. von Brentano, and J. Jolie, Eur. Phys. J. A **27**, 53 (2006).
[17] A. Arima and F. Iachello, Ann. Phys. (NY) **99**, 253 (1976).
[18] S. E. Larsson, G. Leander, and I. Ragnarsson, Nucl. Phys. **A307**, 189 (1978).
[19] E. Rost, Phys. Lett. **B26**, 184 (1968).
[20] S. G. Nilsson, Kgl. Dan. Vidensk. Selsk. Mat. Fys. Medd. **29**, Nr. 16 (1955).

[21] P. B. Semmes and I. Ragnarsson, Computer manual, presented at Nuclear Structure Theory Workshop, Oak Ridge, TN (August 5–16, 1991).
[22] D. D. Warner and P. Van Isacker, Phys. Lett. **B247**, 1 (1990).
[23] A. L. Blokhin, T. Beuschel, J. P. Draayer, and C. Bahri, Nucl. Phys. **A612**, 163 (1997).
[24] T. Beuschel, A. L. Blokhin, and J. P. Draayer, Nucl. Phys. **A619**, 119 (1997).
[25] A. M. Bruce, C. Thwaites, W. Gelletly, D. D. Warner, S. Albers, M. Eschenauer, M. Schimmer, and P. von Brentano, Phys. Rev. C **56**, 1438 (1997).
[26] J. N. Ginocchio, Phys. Rep. **414**, 165 (2005).