

# The van der Waals rovibronic spectrum of *p*-difluorobenzene–Ar up to 125 cm<sup>-1</sup> intermolecular energy: Assignment and character of van der Waals modes

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(Received 20 October 1994; accepted 14 November 1994)

The van der Waals (vdW) vibronic spectrum built on the electronic  $0_0^0, S_1(B_2) \leftarrow S_0(A_1)$  origin of *p*-difluorobenzene–Ar is investigated with rotational resolution ( $\Delta\nu_{UV} = 60$  MHz). For the first time vdW vibronic bands are detected up to a van der Waals energy of 125 cm<sup>-1</sup> and assigned by a rotational analysis of the band structure. The band origin positions of the ten detected bands display a regular behavior with moderate anharmonicities and minor influences due to Fermi resonances. Using the concept of three-dimensional Kraitchman equations and of normalized effective planar moments characteristic data on the nuclear displacements in the two different bending coordinates are deduced from the measured rotational constants. The fundamental vdW vibronic states at low energies can be described in terms of one-dimensional normal modes while vdW states at higher energies display mixed mode character. © 1995 American Institute of Physics.

## I. INTRODUCTION

Two central goals of the spectroscopy of van der Waals (vdW) complexes concern their *structure* and the exploration of their *intermolecular motions*. Accurate information on the structure of the prototype complexes of an aromatic molecule and noble gas atoms has emerged from rotationally resolved investigations in the UV spectral region. First examples were *s*-tetrazine complexed with one and two Ar atoms (Refs. 1 and 2) and benzene–(Ar)<sub>*n*</sub> (*n* = 1, 2) (Refs. 3–5) which proved a central binding position of the Ar atom at a distance of 3.58 Å in the *S*<sub>0</sub> state of benzene–Ar. Measurements have been extended to larger aromatic (two and more rings) substrates complexed by two and more Ar atoms only recently.<sup>6–9</sup> These investigations clearly show that an opposite-sided binding topology with central noble gas atoms is favored and no dropletlike Ar subclusters are likely to be formed on one side of the aromatic substrate.

In contrast to the advanced knowledge of the structures our understanding of the intermolecular motions within the aromatic–noble gas complexes is far from complete. The van der Waals mode structure of the *S*<sub>1</sub> ← *S*<sub>0</sub> transition in aromatic molecule–atom complexes has been studied by vibrationally resolved vibronic spectroscopy providing no rotational resolution. van der Waals vibronic spectra of benzene–Ar (Ref. 10), monosubstituted benzene–Ar complexes (Refs. 11 and 12), *s*-tetrazine–Ar (Refs. 13 and 14), carbazole–Ar (Ref. 15), fluorene–Ar (Ref. 16), and naphthalene–Ar (Ref. 17) have been reported.

First quantum mechanical three-dimensional (3D) calculations of bound vdW rovibrational states in clusters involving *aromatic molecules* have been performed for benzene–Ar and *s*-tetrazine–Ar as early as in 1986.<sup>18</sup> However, it turned out that the expansion of the (empirical) intermolecular potential in spherical harmonics works better for the nonaromatic complex NH<sub>3</sub>–Ar.<sup>19</sup> Very recently the multidimensional intermolecular potential energy surface of NH<sub>3</sub>–Ar has been determined from experimental data.<sup>20</sup> For *aromatic*

molecule–noble gas complexes Brocks and van Koeven derived a vdW vibrational Hamiltonian in the body fixed frame.<sup>21</sup> This approach has been applied using different basis sets for fluorene–Ar (Ref. 21) and benzene–Ar (Refs. 22 and 23). Either empirical potentials or analytic representations of *ab initio* potential surfaces were used in these 3D quantum mechanical calculations. By this means in very recent work vibrationally resolved vdW vibronic spectra of aniline–Ar (Ref. 24), (4 fluoro-)styrene–Ar (Ref. 25), and (2,3 dimethyl-)naphthalene–Ar (Refs. 26 and 27) were interpreted.

For a critical test of theoretical results on the vibrational wave function rotationally resolved experimental spectra of vdW vibronic states are required. Rotational constants obtained in this way are the result of an averaging of the vibrational motion and thus contain information on the average displacements during the intermolecular vibration. Hitherto, only two examples for vdW vibronic spectra with rotational resolution have been reported. In *s*-tetrazine–Ar, Levy and co-workers obtained rotational contours of the origin band and one vdW vibronic band involving the stretching vibration,<sup>28</sup> theoretical work was performed by Tiller and Clary.<sup>29</sup> Champagne *et al.* obtained highly resolved UV spectra of vdW bands in *trans*-stilbene–Ar.<sup>30</sup> For benzene–Ar rotational resolution has been achieved for all three vdW vibronic bands known from low resolution spectroscopy.<sup>5,31</sup> The complete rotational analysis of these vibronic bands will be presented elsewhere<sup>5,31</sup> and compared with the calculations of the rovibrational states.<sup>22,23</sup>

In this work the high resolution spectra of several van der Waals vibronic bands of another model system, *p*-difluorobenzene–Ar (*p*DFB–Ar) are presented leading to a complete analysis of the vdW vibrations. This complex is of particular interest because its reduced symmetry leads to spectra without degenerate modes and the electronic origin becomes electronically allowed. In recent work we found a vdW bond length of 3.55 Å in *p*DFB–Ar in the *S*<sub>0</sub> state,<sup>32</sup>

and presented rotationally resolved spectra of the two lowest energy vdW vibronic bands.<sup>33</sup> We found proof for a Herzberg–Teller activity of the short in-plane vdW bending mode  $b_y$  at  $+34\text{ cm}^{-1}$ . In this work the assignment of eight additional vdW vibronic bands up to a vdW excess energy of  $0_0^0+125\text{ cm}^{-1}$  will be derived from the analysis of their rotational band structure. From the fitted rotational constants information on the typical displacements is derived.

## II. EXPERIMENT

The experimental setup for recording rotationally resolved spectra of *p*DFB–Ar complexes with the technique of mass-selective resonance-enhanced two-photon ionization has been described in detail in our previous work.<sup>32</sup> Briefly, for the first narrow-band excitation step the light of a cw single mode laser (Coherent 699/21) is pulsed amplified in excimer laser-pumped dye cells yielding nearly Fourier transform-limited 1 mJ light pulses with a duration of 20 ns [full width at half maximum (FWHM)] and a frequency width of 60 MHz (FWHM) after frequency doubling. For ionization a broadband excimer-pumped dye laser (Lambda Physik FL 2002) is used with a pulse energy of 1 mJ. The laser light beams were attenuated by a factor of 10–50 to avoid saturation and line broadening. The wavelength of the (second) ionization laser had to be chosen carefully, since the second excitation step to the ionization continuum requires a higher photon energy than the first step and could lead to a one-color signal. *p*-Difluorobenzene at a concentration of 1% is seeded in Ar at a backing pressure of 2 bar and the mixture is expanded through a solenoid valve with a 300  $\mu\text{m}$  orifice into the vacuum chamber. A skimmer of 1.5 mm diameter placed 4 cm downstream reduces the residual Doppler width below the laser linewidth, and the ionized complexes are mass separated in a homemade time of flight mass spectrometer.

## III. THE MODEL SYSTEM *p*DFB–Ar

In the prototype aromatic molecule–noble gas complex, benzene–Ar, only three vdW vibronic bands on the blue side of the  $6_0^1$  transition were found at vdW excess energies of  $+31$ ,  $+40$ , and  $+63\text{ cm}^{-1}$  in spectra with vibrational resolution<sup>10</sup> and rotational resolution.<sup>5,31</sup> Thus, the region of overlap suitable to compare with theoretical vdW rovibrational states calculated from the *ab initio* potential (well

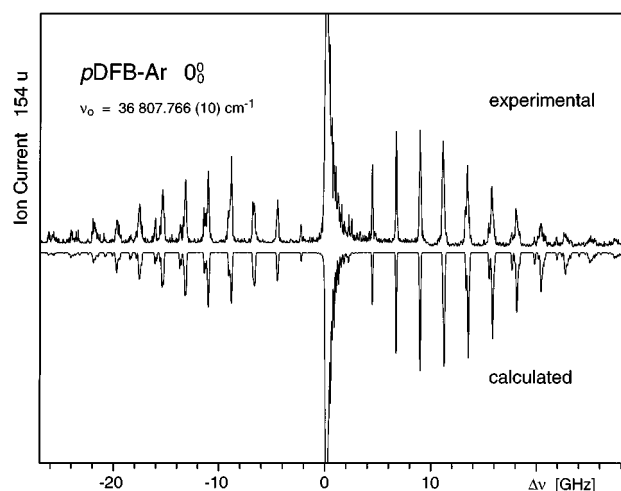


FIG. 1. Upper trace: Rotationally resolved spectrum of the  $0_0^0$  ( $S_1 \leftarrow S_0$ ) transition of the *p*-difluorobenzene–Ar vdW complex obtained by recording the ion current at mass 154 u as a function of the frequency of the laser providing the first photon in the two-photon ionization process. Lower inverted trace: Theoretical *c*-type rotational spectrum of a near oblate asymmetric top calculated with the rotational constants resulting from the best fit to the experimental spectrum (Table I) (taken from Ref. 33).

depth  $429\text{ cm}^{-1}$ ) (Ref. 34) is small. Higher vdW vibronic states are needed for this comparison. In this work we will demonstrate that *p*DFB–Ar is suitable for detection of high lying vdW vibronic bands due to its lower symmetry and the parallel-type rotational structure of most of the bands. The rotational structure of the parallel-type bands with a strong *Q*-branch peak is different from the perpendicular band structure of vdW vibronic bands in benzene–Ar. It will be shown that this leads to an increased sensitivity for the detection of additional quanta of weak vdW transitions.

The one-photon electronic transition  $S_1(^1B_2) \leftarrow S_0(^1A_1)$  in *p*DFB–Ar ( $C_{2v}$ ) is electric dipole allowed with a transition moment directed along the short in-plane  $y(\parallel c)$  axis; i.e., a *c*-type rotational band is observed. The spectrum of the  $0_0^0$  band in *p*DFB–Ar is shown in the upper trace of Fig. 1.<sup>33</sup> Its rotational structure with a strong blue-shaded *Q* branch and well separated *P*- and *R*-branch subgroups in the wings of the band is characteristic of a parallel-type band. The rotational analysis of this spectrum was described in detail in our recent work,<sup>32</sup> and the resulting rotational constants are

TABLE I. Wave numbers of the band origins  $\nu_0$ , vibrational shifts  $\delta\nu$ , asymmetry parameters  $\kappa$ , and rotational constants of *p*-difluorobenzene–Ar in its ground electronic ( $0_0$ ), electronically ( $0^0$ ), and vibrationally ( $30^1$ ) excited states. Indicated errors of the rotational constants reflect the uncertainty of the  $\Delta A = A' - A''$ ,  $\Delta B$ , and  $\Delta C$  values resulting from the fit procedure.

$0_0$ state <sup>a</sup>		$0^0$ state <sup>a</sup>		$30^1$ state	
	$\nu_0$ ( $\text{cm}^{-1}$ )	36 807.766(10)	$\nu_0$ ( $\text{cm}^{-1}$ )	36 927.646(10)	
			$\delta\nu$ ( $\text{cm}^{-1}$ )	+119.880(15)	
$A_0''$ ( $\text{cm}^{-1}$ )	0.038 01	$A_0'$ ( $\text{cm}^{-1}$ )	0.037 65(10)	$A_v'$ ( $\text{cm}^{-1}$ )	0.037 89(10)
$B_0''$ ( $\text{cm}^{-1}$ )	0.036 45	$B_0'$ ( $\text{cm}^{-1}$ )	0.036 90(10)	$B_v'$ ( $\text{cm}^{-1}$ )	0.036 30(10)
$C_0''$ ( $\text{cm}^{-1}$ )	0.023 20	$C_0'$ ( $\text{cm}^{-1}$ )	0.023 55(3)	$C_v'$ ( $\text{cm}^{-1}$ )	0.023 45(5)
$\kappa_0'$	+0.789	$\kappa_0'$	+0.894		

<sup>a</sup>Taken from Ref. 32.

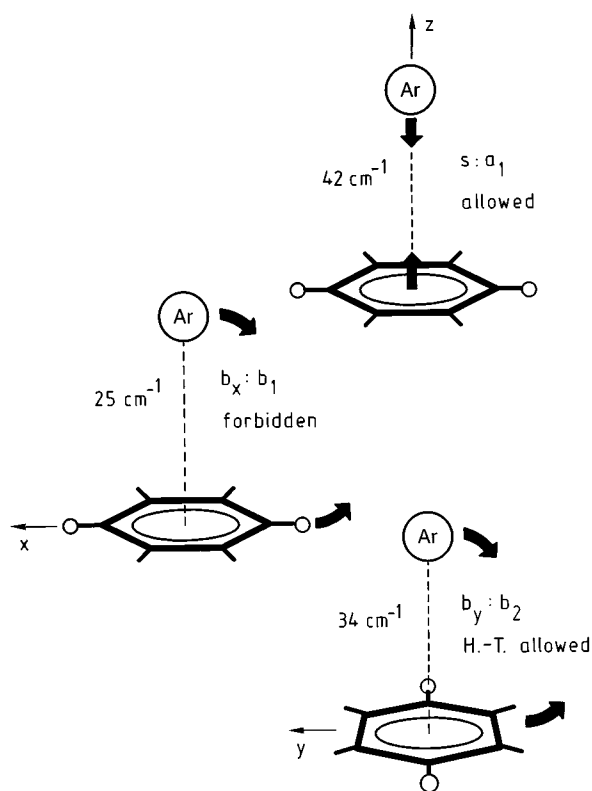


FIG. 2. Structure of the *p*-difluorobenzene–Ar vdW complex of point group  $C_{2v}$  with the axes  $x(\parallel b)$ ,  $y(\parallel c)$ ,  $z(\parallel a)$ . The Ar atom is located on the  $C_2$  axis at an effective vdW distance of 3.55 Å from the molecular plane. The arrows indicate the relative motions of the *p*DFB molecule and the Ar atom when the vdW stretching mode  $s$  ( $a_1$ ), the long in-plane bending mode  $b_x$  ( $b_1$ ), and the short in-plane bend  $b_y$  ( $b_2$ ) are excited. The indicated wave numbers are the vibrational shifts of the vdW vibronic spectra discussed in this work. The possibility of single quantum excitation in the  $S_1$  state is indicated, including Herzberg–Teller coupling by vdW modes (for an explanation, see the text).

presented in Table I. A theoretical stick spectrum convoluted with a 120 MHz (FWHM) Gaussian function was calculated from these rotational constants and for a rotational temperature of 1.5 K. It is shown in the lower inverted trace of Fig. 1 and represents the vibronic  $c$ -type spectrum of a near oblate ( $\kappa'' = +0.789$ ) asymmetric rotor with the electronic transition dipole moment polarized along the short in-plane axis of the *p*DFB molecule (see Fig. 2). The  $c$ -type rotational selection rules are  $(ee) \leftrightarrow (oe)$  and  $(eo) \leftrightarrow (oo)$  for  $(K_{-1}, K_{+1})$ , where  $e, o$  denotes the even and odd parity, respectively. The nuclear spin statistical weights for the structure discussed below are  $g_n = 14$  for  $(K''_{-1}, K''_{+1}) = (ee), (eo)$  and  $g_n = 18$  for  $(K''_{-1}, K''_{+1}) = (oe), (oo)$ . For the wave number of the rotationless origin of the band we found  $\nu_0 = 36\,807.766(10) \text{ cm}^{-1}$ .

The structure of *p*DFB–Ar derived from the rotational spectrum is presented in Fig. 2. In the electronic ground state  $S_0$  the Ar atom is found to be placed on the  $C_2$  axis of the bare molecule at an effective van der Waals distance of  $z''_{\text{eff}} = 3.55(2) \text{ Å}$ .<sup>32</sup> This is reduced by 0.06 Å after electronic excitation to the  $S_1$  state. The decrease of the vdW bond length can be visualized from the blue shading of the  $Q$

TABLE II. Frequency shifts, intensities (very strong, vs; strong,  $s$ ; weak,  $w$ ; very weak, vw) of bands in the rovibronic spectrum of *p*DFB–Ar and their assignment.

Frequency shift ( $\text{cm}^{-1}$ )	Relative intensity	Assignment
0.0 <sup>a</sup>	vs	$0_0^0$
1.860(20)	$w$	
4.140(20) <sup>b</sup>	$w$	$22_1^1$
33.695(15) <sup>a</sup>	$s$	$b_{y0}^1$
41.549(10) <sup>a</sup>	$s$	$s_0^1$
43.425(20)	vw	
45.679(20)	vw	$s_0^1 22_1^1$
50.593(15)	$w$	$b_{x0}^2$
65.876(15) <sup>a</sup>	$s$	$b_{y0}^2$
80.652(10)	$w$	$s_0^2$
89.617(15)	vw	$s_0^1 b_{x0}^2$
95.95(10)	vw	$b_{y0}^3$
99.105(15)	vw	$b_{x0}^4$
117.133(15)	vw	$s_0^3$
119.880(15) <sup>a</sup>	vs	$30_0^1$
124.348(20)	vw	$30_0^1 22_1^1$
125.562(15)	vw	$b_{y0}^4$

<sup>a</sup>Previously these transitions have been also detected in low resolution (Ref. 35).

<sup>b</sup>Previously this transition has been also detected in low resolution in the bare *p*DFB molecule (Ref. 42).

branch, and the peaks in the  $R$  branch which are narrower and higher than in the  $P$  branch.

#### IV. THE vdW ROVIBRONIC SPECTRUM OF *p*DFB–Ar

Three vdW vibronic bands located at +34, +42, and +66  $\text{cm}^{-1}$  to the blue of the electronically allowed origin are known from vibrationally resolved spectroscopy.<sup>35</sup> In the high resolution scan because of the sharp central  $Q$  branch and the regular  $P$ - and  $R$ -branch substructure we found a large number of vibronic bands within 125  $\text{cm}^{-1}$  to the blue of the  $0_0^0$  band, which are weaker by a factor of 10–100 than the  $0_0^0$  band and thus were not detected in earlier low resolution investigations.<sup>35,36</sup> The observed frequency positions are listed in Table II. We found 16 bands in this frequency range. Ten of these are assigned as vdW vibronic transitions. The most prominent of the remaining bands is the  $30_0^1$  band with a  $c$ -type rotational structure at +119.880(15)  $\text{cm}^{-1}$  (Table I).  $\nu_{30}$  is a skeletal  $b_{2g}$  ( $D_{2h}$ ) vibration whose symmetry species is reduced to  $a_1$  in the complex ( $C_{2v}$ ). The  $c$ -type rotational structure observed in this work corroborates the assignment of this band in previous work.<sup>37</sup>

In Fig. 2 the relative motions of the *p*DFB molecule and the Ar atom are shown for the three possible intermolecular modes. These are the totally symmetric stretching mode  $s$  ( $a_1$ ) leading to a displacement perpendicular to the aromatic ring and two bending modes ( $b_{x,y}$ ) with a displacement perpendicular to the vertical rotational axis. While the bending modes  $b_{x,y}$  ( $e_1$ ) are degenerate in benzene–Ar, the degeneracy is lifted in *p*DFB–Ar ( $C_{2v}$ ) leading to a *long* in-plane bend ( $b_1$ ) and a *short* in-plane bending mode ( $b_2$ ), which are different in frequency.

Vibronic transitions leading to  $a_1$  fundamental vibrational states, to combinations and overtones of  $a_1$  vibrations,

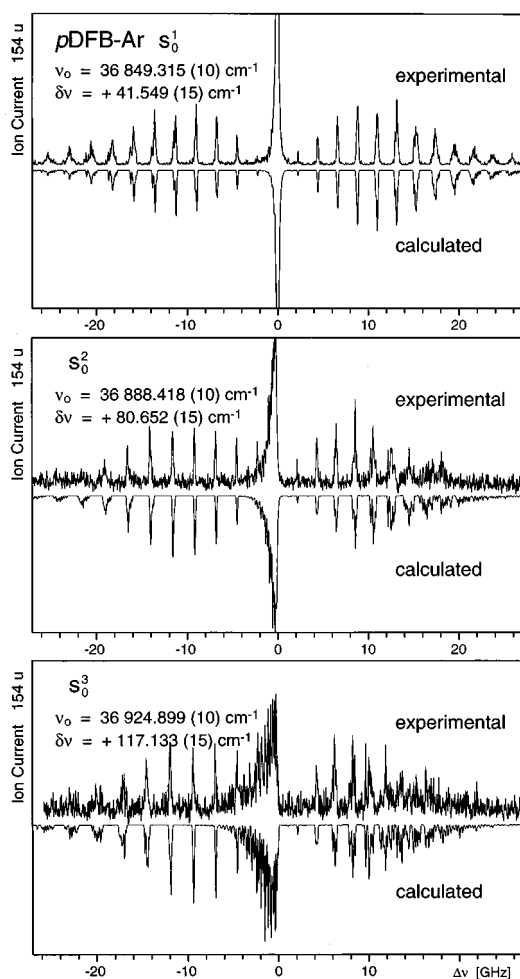


FIG. 3. Rotationally resolved spectra of the  $s_0^1$  (upper),  $s_0^2$  (middle), and  $s_0^3$  (lower) ( $S_1 \leftarrow S_0$ ) transitions leading to excited states of the vdW stretching mode of the *p*-difluorobenzene–Ar vdW complex. Simulations of the experimental spectra by calculated *c*-type rotational spectra of a near oblate asymmetric top are shown in the inverted traces.

or to odd overtones of nontotally symmetric vibrational species are symmetry allowed, can be Franck–Condon active, and display a *c*-type rotational structure.

## A. van der Waals stretching modes

### 1. $s_0^1$ , $s_0^2$ , $s_0^3$ bands

We assign the *c*-type bands with origins at +41.549(15), +80.652(15), and +117.133(15)  $\text{cm}^{-1}$  to the  $s_0^1$ ,  $s_0^2$ , and  $s_0^3$  transitions, respectively. Their rotational structure is shown in Fig. 3. The rotational constants of the final states change in a way that leads to an increasing red-shading of the sharp central  $Q$  branch with increasing stretching quantum number. The fitted best set of rotational constants is used for the theoretical spectra displayed on the inverted lower trace.

The assignment of the  $s_0^1$  band agrees with the result of previous work.<sup>35,36</sup> It is in line with the assignment of  $s_0^1$  bands of benzene–Ar (Refs. 5 and 10) and *s*-tetrazine–Ar (Refs. 13, 14, and 28). Neglecting influences from possible Fermi resonances (see Sec. V), a one-dimensional cubic ex-

TABLE III. Band origins  $\nu_0$ , vibrational shifts  $\delta\nu$ , and rotational constants  $A'_{\text{vdW}}$ ,  $B'_{\text{vdW}}$ ,  $C'_{\text{vdW}}$  of stretching vdW vibronic states.  $\delta A$ : =  $A'_{\text{vdW}} - A_0$ ,  $\delta B'$ , and  $\delta C'$  are the deviations of the rotational constants of the vdW vibronic state from the respective values of the  $0^0$  state. Changes of planar moments  $\delta P_{x,y}^{\text{eff}}$ , effective vdW bond length  $z_{\text{eff}}$ , and change  $\delta z_{\text{eff}}$  of the vdW vibronic states.

	$s^1$ state	$s^2$ state	$s^3$ state
$\nu_0$ ( $\text{cm}^{-1}$ )	36 849.315(10)	36 888.418(10)	36 924.899(10)
$\delta\nu$ ( $\text{cm}^{-1}$ )	+41.549(15)	+80.652(15)	+117.133(15)
Trans. dipole	<i>c</i> -type	<i>c</i> -type	<i>c</i> -type
$A'_{\text{vdW}}$ ( $\text{cm}^{-1}$ )	0.037 70(10)	0.037 65(15)	0.037 40(15)
$\delta A$ ( $\text{cm}^{-1}$ )	+0.000 05(15)	$\pm$ 0.000 00(18)	−0.000 25(18)
$B'_{\text{vdW}}$ ( $\text{cm}^{-1}$ )	0.036 15(10)	0.035 30(15)	0.034 40(15)
$\delta B$ ( $\text{cm}^{-1}$ )	−0.000 75(15)	−0.001 60(18)	−0.002 50(18)
$C'_{\text{vdW}}$ ( $\text{cm}^{-1}$ )	0.023 30(3)	0.022 92(5)	0.022 37(5)
$\delta C$ ( $\text{cm}^{-1}$ )	−0.000 25(5)	−0.000 62(6)	−0.001 18(6)
$\delta P_x^{\text{eff}}$ ( $\text{u}\text{\AA}^2$ )	−1.196	−0.516	+3.775
$\delta P_y^{\text{eff}}$ ( $\text{u}\text{\AA}^2$ )	+0.602	+0.516	−0.783
$z_{\text{eff}}$ ( $\text{\AA}$ )	3.53	3.59	3.65
$\delta z_{\text{eff}}$ ( $\text{\AA}$ )	+0.04	+0.10	+0.16

trapolation of the frequency shifts of the  $s^1$ ,  $s^2$ , and  $s^3$  states (Table III) yields  $D_e(\text{stretch}) \approx 300 \text{ cm}^{-1}$ , with the harmonic frequency  $\omega_e = 42.2 \text{ cm}^{-1}$ , the (diagonal) anharmonicities  $\omega_e x_e = +1.091 \text{ cm}^{-1}$ , and  $\omega_e y_e = -0.029 \text{ cm}^{-1}$ . We deduce further evidence for the validity of this assignment from the rotational constants of these bands.

### 2. $s^n$ rotational constants

Generally, there are three major contributions to the rotational constants which reflect three different kinds of vibration–rotation interaction:<sup>38</sup> (i) harmonic contribution due to “inverse vibrational averaging,” (ii) anharmonicity, or more general, asymmetry of a potential, and (iii) Coriolis coupling.

The experimentally determined rotational constants  $A'_{\text{vdW}}$ ,  $B'_{\text{vdW}}$ ,  $C'_{\text{vdW}}$  (Table III) are plotted as a function of the vdW vibrational stretching quantum number  $\nu_s$  in Fig. 4(a).

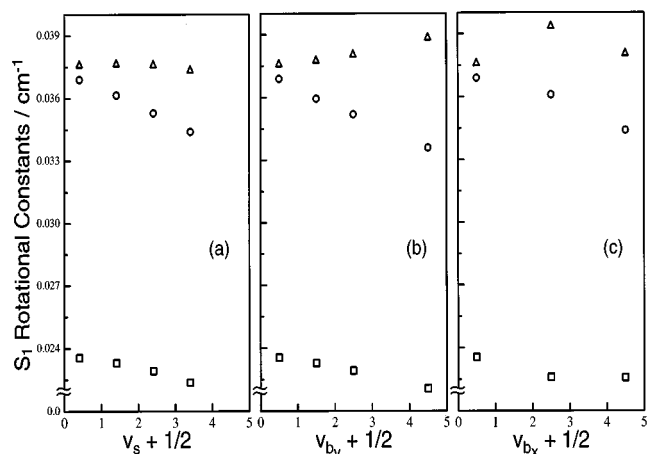


FIG. 4. Evolution of measured  $S_1$  rotational constants,  $A'_{\text{vdW}}$  ( $\Delta$ ),  $B'_{\text{vdW}}$  ( $\circ$ ),  $C'_{\text{vdW}}$  ( $\square$ ) for an increasing number of excited quanta of the vdW stretching modes (a), short in-plane bending modes (b), and long in-plane bending modes (c). For an explanation, see the text.

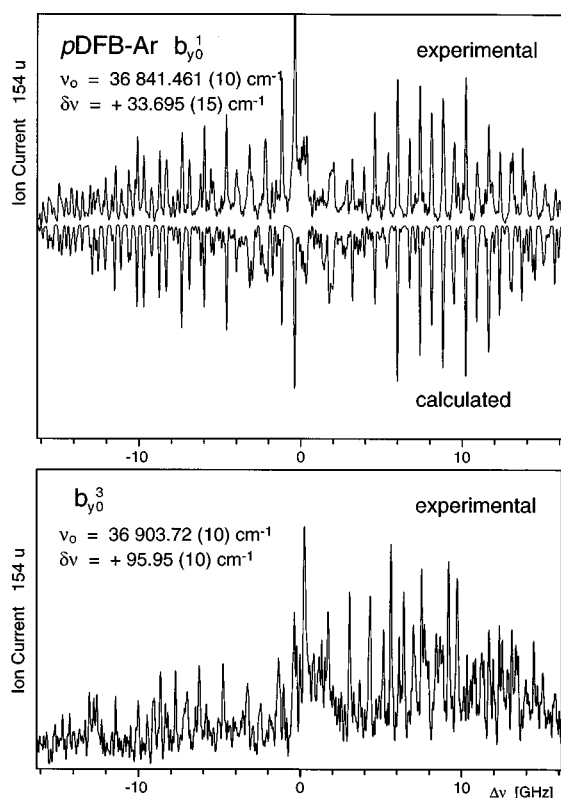


FIG. 5. Rotationally resolved spectra of the  $b_{y_0}^1$  (upper) and  $b_{y_0}^3$  (lower) ( $S_1 \leftarrow S_0$ ) transitions involving odd quanta of the Herzberg–Teller active short in-plane vdW bending mode of the *p*-difluorobenzene–Ar vdW complex. A simulation of the experimental spectrum by a calculated *a*-type rotational spectrum of a near oblate asymmetric top is shown in an inverted trace for the  $b_{y_0}^1$  transition (upper).

Note that we find  $A'_{\text{vdW}} \approx B'_{\text{vdW}}$  for  $v_s=0$  indicating that *p*DFB–Ar is a near oblate ( $\kappa'_0 = +0.894$ ) asymmetric top. This equality is increasingly perturbed by excitation of vdW vibrations. The  $B'_{\text{vdW}}$  and  $C'_{\text{vdW}}$  rotational constants decrease with increasing  $v_s$  due to effective moments of inertia  $I_b^{\text{eff}}$  and  $I_c^{\text{eff}}$  increasing by harmonic and anharmonic vibration–rotation interaction. On the contrary, the  $A'_{\text{vdW}}$  constant remains nearly unchanged (see the small values for  $\delta A: = A'_{\text{vdW}} - A'_0$  in Table III). This is reasonable since the *a* axis is collinear to the vdW stretching coordinate and  $I_a^{\text{eff}}$  is not influenced by intermolecular displacements along this coordinate. The constant  $A'_{\text{vdW}}$  value (up to  $v_s=3$ ) demonstrates that no displacements perpendicular to the *z* coordinate are involved in the excited states and stretch–bend coupling is small. It also corroborates our assignment as  $s_0^1$ ,  $s_0^2$ ,  $s_0^3$  transitions.

## B. Short in-plane bending vibrations: Herzberg–Teller active vdW modes

The bands with origin at +33.695(15) and +95.95(10)  $\text{cm}^{-1}$  shown in Fig. 5 display a rotational structure completely different from the *c*-type found for all other bands in Figs. 1, 3, 6, and 7.

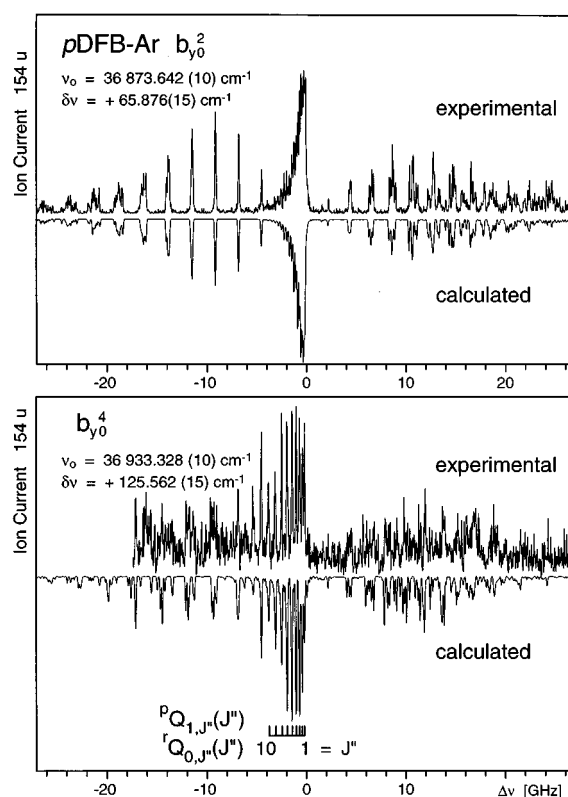


FIG. 6. Rotationally resolved spectra of the  $b_{y_0}^2$  (upper) and  $b_{y_0}^4$  (lower) ( $S_1 \leftarrow S_0$ ) transitions involving even quanta of the short in-plane vdW bending mode of the *p*-difluorobenzene–Ar vdW complex. Simulations of the experimental spectra by calculated *c*-type rotational spectra of a near oblate asymmetric top are shown in the inverted traces. For the  $b_{y_0}^4$  band the *Q* subbranches are indicated.

### 1. $b_{y_0}^1$ band

Recently, we have shown that the band at +33.695(15)  $\text{cm}^{-1}$  can be simulated with *a*-type rotational selection rules (see Fig. 5).<sup>33</sup> This excludes the assignment as a first bending overtone  $b_0^2$  (which should display a *c*-type band structure). Furthermore, from the regular well reproduced rotational structure we can exclude Coriolis coupling to the  $s^1$  state as the origin for the appearance of this band. The unperturbed *a*-type rotational structure is proof for the Herzberg–Teller (HT) induced activity of this band.<sup>33</sup>

### 2. $b_{y_0}^3$ band

The structure of the band at +95.95(10)  $\text{cm}^{-1}$  (lower trace of Fig. 5) is much closer to the *a*-type structure than to a *c*-type structure (see, e.g., the strong peak in the center and the periodic structure on the blue side). For this reason we assign it to the  $b_{y_0}^3$  band.

### 3. $b_{y_0}^2$ , $b_{y_0}^4$ bands

The bands with origin at +65.876(15) and +125.562(15)  $\text{cm}^{-1}$  display a clear *c*-type structure (see Fig. 6). We assign them to the  $b_{y_0}^2$  and the  $b_{y_0}^4$  transition, respectively. The  $b_{y_0}^4$  band with an excess energy of +125.562(15)

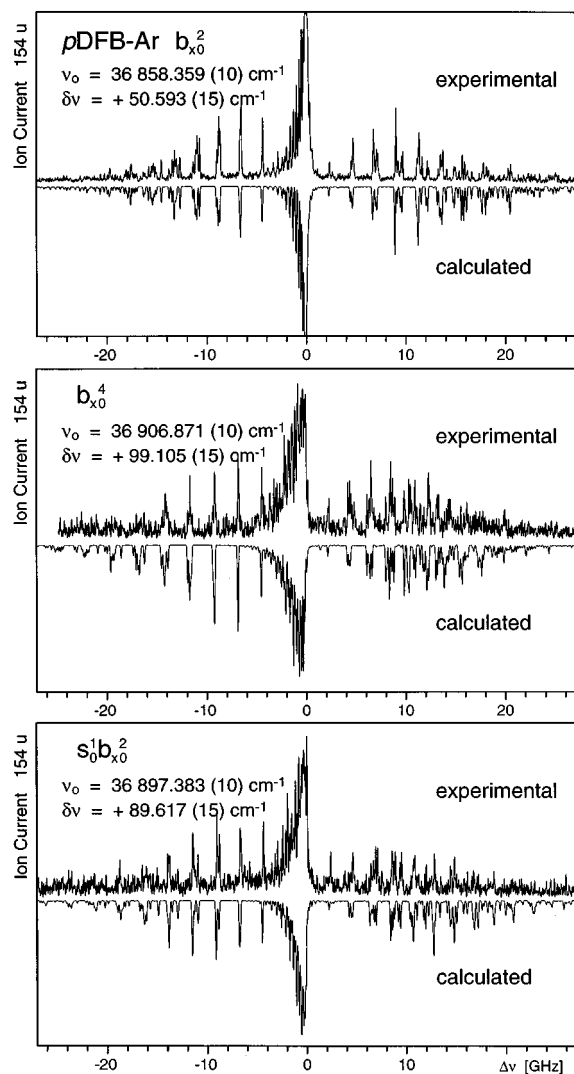


FIG. 7. Rotationally resolved spectra of the  $b_{x0}^2$  (upper) and  $b_{x0}^4$  (middle) ( $S_1 \leftarrow S_0$ ) transitions involving even quanta of the long in-plane vdW bending mode, and the  $s_0^1 b_{x0}^2$  transition (lower) involving the fundamental stretch and long in-plane bending overtone combination mode of the *p*-difluorobenzene–Ar vdW complex. Simulation of the experimental spectra by calculated *c*-type rotational spectra of a near oblate asymmetric top are shown in the inverted traces.

$\text{cm}^{-1}$  is the highest energy vdW vibronic band found in our experiment. Vibration–rotation interaction leads to a strongly red shaded  $Q$  branch so that single  $J''$  values are resolved [the asymmetry splitting between the  ${}^P Q_{1,J''}(J'')$  and  ${}^R Q_{0,J''}(J'')$  subbranches is less than the experimental linewidth]. Congestion in the  $P$  branch of the experimental  $b_{y0}^4$  spectrum is caused by the overlapping  $R$  branch of the  $30_0^1$  band whose origin is only  $5.68(2) \text{ cm}^{-1}$  located to the red (Table I).

#### 4. $b_y^n$ rotational constants

The  $A'_{\text{vdW}}$  constants of the  $b_y^n$  vibronic states (Table IV) display a monotonous increase as a function of vibrational quantum number  $\nu_{b_y}$  [see Fig. 4(b)]. This is different from the behavior of the  $A'_{\text{vdW}}$  constant of the stretching mode and

clearly demonstrates that a librational motion<sup>39</sup> is involved, with a (hindered) rotational motion of the substrate within the complex, thus corroborating the bending assignment of the vibration. The increase of  $A'_{\text{vdW}}$  is *not* caused by anharmonicity, since this could only lead to *decreasing* rotational constants. Thus, harmonic vibrational averaging of the bending wave function is the origin of increasing  $A'_{\text{vdW}}$  constants. On the other hand, the monotonous *decrease* of the  $B'_{\text{vdW}}$  and  $C'_{\text{vdW}}$  constants is due to harmonic and/or anharmonic contributions.

### C. Long in-plane bending vibrations

#### 1. $b_{x0}^2$ and $b_{x0}^4$ bands

The bands with origin at  $+50.593(15)$  and  $+99.105(15) \text{ cm}^{-1}$  (see Fig. 7) are assigned to the  $b_{x0}^2$  and  $b_{x0}^4$  transitions. The forbidden  $b_x$  mode ( $b_1$ ) *cannot* be HT active by symmetry. It can be only excited as even quanta in the  $S_1 \leftarrow S_0$  transition; i.e., the fundamental  $b_{x0}^1$  is missing in our spectrum. Considering the bending modes as *librational* modes, with a large part of mode energy due to (hindered) rotational motion of the substrate within the complex, a significant reduction of the (benzene–Ar) bending frequency is expected, if hydrogen atoms are *p*-disubstituted by fluorine in *p*DFB–Ar. For the bending mode,  $b_x$ , a displacement of the heavy halogen atoms is involved. Thus a lower  $b_x$  frequency than in benzene–Ar is expected in agreement with the experimental  $b_x$  frequency of about  $25 \text{ cm}^{-1}$  significantly below the value of about  $34 \text{ cm}^{-1}$  found for the  $b_y$  fundamental.

#### 2. $s_0^1 b_{x0}^2$ band

At this point there is only one remaining vdW vibronic band to be assigned. This is the *c*-type band with origin at  $+89.617(15) \text{ cm}^{-1}$  (see Fig. 7). Its position agrees quite well with the sum of the frequencies of the  $b_x^2$  and the  $s_0^1$  state and is thus assigned to the  $s_0^1 b_{x0}^2$  combination band.

#### 3. $b_x^n$ rotational constants

As expected for bending vibrations the dependence of rotational constants  $A'_{\text{vdW}}$ ,  $B'_{\text{vdW}}$ ,  $C'_{\text{vdW}}$  (Table V) on excited  $b_x$  quanta [see Fig. 4(c)] shows a similar behavior as found for the  $b_y^n$  states between  $n=0$  and  $n=4$  [see Fig. 4(b)]. However, disagreement is found for the  $A'_{\text{vdW}}$  and  $C'_{\text{vdW}}$  constants of the  $b_x^4$  state [see Fig. 4(c)] showing a nonmonotonous behavior. This can no longer be attributed solely to harmonic and/or anharmonic effects but rather to a selective Coriolis coupling. Considering Jahn's rule,<sup>40</sup>  $\Gamma(b_x^4) \otimes \Gamma(b_y^3) = \Gamma(R_x^4)$ , we find that second order Coriolis coupling to the very weak HT active  $b_y^3$  state only  $3.16(10) \text{ cm}^{-1}$  to the red is possible.

#### D. Mode character

The frequency shifts of all discussed vdW vibronic bands are displayed in Fig. 8 as a function of their vdW vibrational quantum number. The goal of this section is to elucidate the character of these vibrational motions. In particular, the mixing of bending and stretching modes for higher quanta will be discussed.

TABLE IV. Band origins  $\nu_0$ , vibrational shifts  $\delta\nu$ , and rotational constants  $A'_{\text{vdW}}$ ,  $B'_{\text{vdW}}$ ,  $C'_{\text{vdW}}$  of short in-plane bending vdW vibronic states.  $\delta A$ : =  $A'_{\text{vdW}} - A'_0$ ,  $\delta B'$ , and  $\delta C'$  are the deviations of the rotational constants of the vdW vibronic state from the respective values of the  $0^0$  state. Changes of planar moments  $\delta P_{x,y}^{\text{eff}}$ , effective vdW bond length  $z'_{\text{eff}}$ , and change  $\delta z_{\text{eff}}$  of the vdW vibronic states.

	$b_y^1$ state	$b_y^2$ state	$b_y^3$ state	$b_y^4$ state
$\nu_0$ (cm $^{-1}$ )	36 841.461(10)	36 873.642(10)	36 903.72(10)	36 933.328(10)
$\delta\nu$ (cm $^{-1}$ )	+33.695(15)	+65.876(15)	+95.95(10)	+125.562(15)
Trans. dipole	<i>a</i> -type	<i>c</i> -type	<i>a</i> -type	<i>c</i> -type
$A'_{\text{vdW}}$ (cm $^{-1}$ )	0.037 82(10)	0.038 10(10)		0.038 90(10)
$\delta A$ (cm $^{-1}$ )	+0.000 17(15)	+0.000 45(15)		+0.001 25(15)
$B'_{\text{vdW}}$ (cm $^{-1}$ )	0.035 95(10)	0.035 20(10)		0.033 60(10)
$\delta B$ (cm $^{-1}$ )	-0.000 95(15)	-0.001 70(15)		-0.003 30(15)
$C'_{\text{vdW}}$ (cm $^{-1}$ )	0.023 28(5)	0.022 92(3)		0.022 07(3)
$\delta C$ (cm $^{-1}$ )	-0.000 27(7)	-0.000 63(5)		-0.001 48(5)
$\delta P_x^{\text{eff}}$ ( $u\text{\AA}^2$ )	-2.891	-3.838		-5.627
$\delta P_y^{\text{eff}}$ ( $u\text{\AA}^2$ )	+0.879	-1.450		-8.761
$z'_{\text{eff}}$ ( $\text{\AA}$ )	3.54	3.55		3.53
$\delta z_{\text{eff}}$ ( $\text{\AA}$ )	+0.05	+0.06		+0.04

Vibration–rotation interaction results in an increase,  $\delta z_{\text{eff}} = z'_{\text{eff}}(\text{vdW vibronic state}) - z'_{\text{eff}}(0^0)$ , of the effective vdW bond length (along the stretching coordinate) with increasing intermolecular energy for the vdW vibronic states  $s^1$ ,  $s^2$ , and  $s^3$  (Table III). While excitation of the short in-plane bending modes (Fig. 2) does not affect the intermolecular distance (Table IV), the excitation of the long in-plane bending overtone (Fig. 2) results in a large value of  $\delta z_{\text{eff}}$  (Table V). This indicates bend–stretch coupling. The consideration of effective coordinates  $x'_{\text{eff}}$  and  $y'_{\text{eff}}$ , using three-dimensional Kraitchman equations,<sup>38</sup> is not instructive since their calculation partially leads to imaginary values for the higher vibrational states, as found for similar cases. Thus we apply an analysis of planar moments  $P_{x,y,z}^e$ . Planar moments of a rigid nonplanar molecule with moments of inertia  $I_{x,y,z}^e$  are defined as

$$P_x^e = \frac{1}{2}(I_y^e + I_z^e - I_x^e) = \sum_i m_i x_i^2, \quad (1)$$

where  $x_i$  is one Cartesian coordinate of the  $i$ th atom. Expressions for  $P_y^e$  and  $P_z^e$  are obtained by cyclic permutation of the subscripts  $x$ ,  $y$ ,  $z$ . Employing effective moments of inertia,  $I_{x,y,z}^{\text{eff}}$ , the resulting effective planar moments contain contributions from vibration–rotation interactions and Eq. (1) is replaced by

$$2P_x^{\text{eff}} = I_y^{\text{eff}} + I_z^{\text{eff}} - I_x^{\text{eff}} = 2P_x^e - \Delta_x, \quad (2)$$

where  $\Delta_x$  represents the pseudoinertial defect, containing generally harmonic and anharmonic vibrational contributions.<sup>41</sup> Large values of  $\Delta_{x,y,z}$  indicate major effects due to vibration–rotation coupling, i.e., in the absence of Coriolis coupling this means strong harmonic and/or anharmonic vibrational averaging.

TABLE V. Band origins  $\nu_0$ , vibrational shifts  $\delta\nu$ , and rotational constants  $A'_{\text{vdW}}$ ,  $B'_{\text{vdW}}$ ,  $C'_{\text{vdW}}$  of vdW vibronic states involving the long in-plane bend.  $\delta A$ : =  $A'_{\text{vdW}} - A'_0$ ,  $\delta B'$ , and  $\delta C'$  are the deviations of the rotational constants of the vdW vibronic state from the respective values of the  $0^0$  state. Changes of planar moments  $\delta P_{x,y}^{\text{eff}}$ , effective vdW bond length  $z'_{\text{eff}}$ , and change  $\delta z_{\text{eff}}$  of the vdW vibronic states.

	$b_x^2$ state	$b_x^4$ state <sup>a</sup>	$s^1 b_x^2$ state
$\nu_0$ (cm $^{-1}$ )	36 858.359(10)	36 906.871(10)	36 897.383(10)
$\delta\nu$ (cm $^{-1}$ )	+50.593(15)	+99.105(15)	+89.617(15)
Trans. dipole	<i>c</i> -type	<i>c</i> -type	<i>c</i> -type
$A'_{\text{vdW}}$ (cm $^{-1}$ )	0.039 40(10)	0.038 10	0.039 30(10)
$\delta A$ (cm $^{-1}$ )	+0.001 75(15)	+0.000 45	+0.001 65(15)
$B'_{\text{vdW}}$ (cm $^{-1}$ )	0.036 10(10)	0.034 40	0.034 90(10)
$\delta B$ (cm $^{-1}$ )	-0.000 80(15)	-0.002 50	-0.002 00(15)
$C'_{\text{vdW}}$ (cm $^{-1}$ )	0.022 60(3)	0.022 57	0.022 52(3)
$\delta C$ (cm $^{-1}$ )	-0.000 95(5)	-0.000 98	-0.001 03(5)
$\delta P_x^{\text{eff}}$ ( $u\text{\AA}^2$ )	-0.039	-3.704	-6.120
$\delta P_y^{\text{eff}}$ ( $u\text{\AA}^2$ )	-19.926	-1.584	-12.679
$z'_{\text{eff}}$ ( $\text{\AA}$ )	3.22	3.60	3.38
$\delta z_{\text{eff}}$	-0.27	+0.11	-0.11

<sup>a</sup>No errors of rotational constants were derived because the band is perturbed (see the text).

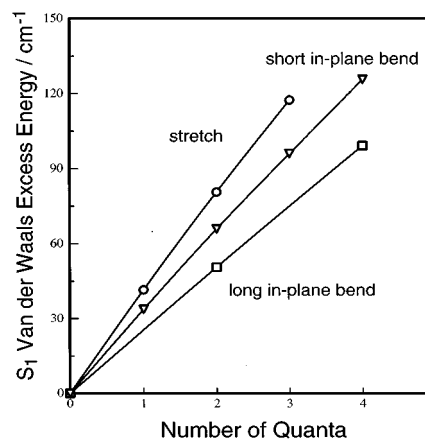


FIG. 8.  $S_1$  vdW excess energy as a function of excited quanta of the vdW stretching modes, the short in-plane bending modes, and the long in-plane bending modes. The solid line represents a spline interpolation of the experimental points.

For molecules with a plane of symmetry and when the only out-of-plane atoms are symmetrically equivalent pairs, harmonic and/or anharmonic contributions to the pseudoinertial defect can be classified<sup>41</sup> as due to (i) *symmetric* or *antisymmetric* vibrations (with respect to the plane of symmetry) of (ii) either *in-plane* or *out-of-plane* atoms. Since in *p*DFB–Ar there exist the *xz* and *yz* planes of symmetry, we can use this concept to characterize the  $b_x$  and  $b_y$  vdW bending modes. It is found that, e.g., a  $b_x$  normal mode can in principle produce harmonic contributions to  $\Delta_x$  via the anti-symmetric (with respect to the *yz* plane) vibrations of both in-plane and out-of-plane atoms involved. Furthermore, it is seen that a  $b_x$  normal mode also affects  $\Delta_y$  via harmonic and anharmonic contributions from the symmetric (with respect to the *xz* plane) vibrations of the out-of-plane atoms involved.

In order to extract information on mode character from experimental data in the electronically excited state, we consider instead of the pseudoinertial defect the quantity  $\delta P_x^{\text{eff}}$ , which we define as

$$\delta P_x^{\text{eff}} := P_x^{\text{eff}}(\text{vdW vibronic state}) - P_x^{\text{eff}}(0^0). \quad (3)$$

The numerical values of  $\delta P_x^{\text{eff}}$  and  $\delta P_y^{\text{eff}}$  evaluated for all vdW vibronic states are listed in Tables III–V. Large values ( $|\delta P^{\text{eff}}| > 1$ ) indicate significant vibrational averaging. Small values of both  $\delta P_x^{\text{eff}}$  and  $\delta P_y^{\text{eff}}$  found for the  $s^1$  and  $s^2$  states (Table III). This means that these states represent nearly genuine stretching normal modes with negligible amplitudes in the (*x*,*y*) coordinates. For the  $b_x^2$  state a large  $\delta P_y^{\text{eff}}$  ( $= -19.926 \text{ u}\text{\AA}^2$ ) and a nearly zero  $\delta P_x^{\text{eff}}$  is found (Table V). Although a genuine  $b_x$  normal mode (with zero *y* amplitude) could, in principle, contribute to both  $\delta P_x^{\text{eff}}$  and  $\delta P_y^{\text{eff}}$  (as discussed for  $\Delta_x$  and  $\Delta_y$ ), in our experiment a measurable effect is seen only for  $\delta P_y^{\text{eff}}$ . We take this as evidence for a genuine  $b_x$  motion in the sense that there is no amplitude in the other bending ( $b_y$ ) direction (however, for  $b_x^2$  there is an effect of bend–stretch coupling seen from  $\delta z_{\text{eff}}$ , see earlier text). The  $s^1$ ,  $s^2$ , and  $b_x^2$  states represent genuine normal modes and can thus be described by accurate vdW vibrational quantum numbers in a one-dimensional approximation (as mentioned earlier, for the  $b_x^2$  state this is only true for the *x* and *y* coordinates). On the other hand, mode mixing is seen to be significant for higher energy vdW vibronic states, e.g., we find large values for  $\delta P_x^{\text{eff}}$  and  $\delta P_y^{\text{eff}}$  for the  $s^1 b_x^2$  (Table V) or  $b_y^4$  (Table IV) states. Therefore the assignments given in this work for these high energy vdW states have to be considered as linear approximation.

## V. CONCLUSIONS

In this work, using sub-Doppler UV techniques with rotational resolution, the vdW vibronic spectrum of *p*DFB–Ar is measured up to an intermolecular excess energy of 125  $\text{cm}^{-1}$ . This represents an expansion of directly excited vdW energy by a factor of 2 compared to previous results from vibrationally resolving techniques. For the assignment of the bands the identification and simulation of their rotational structure was inevitable. The transition frequencies obtained in this way show a regular behavior with moderate anharmo-

nicities and no major perturbations of frequency positions due to anharmonic coupling. The latter mechanism couples the skeletal  $30^1$  state at  $+119.880(15) \text{ cm}^{-1}$  and the  $s^3$  vdW vibronic state at  $+117.133(15) \text{ cm}^{-1}$ , shifting the vdW state towards somewhat lower energies.

A major result of this work is the characterization of the mode character of excited vdW vibronic states. For this we interpreted the influence of vibration–rotation interaction by an analysis of effective planar moments. As a result we conclude that the vibrational motion in the  $s^1$  and  $s^2$  states leads to linear displacements along the *z* axis with negligible components along the *x* and *y* coordinates. Similarly, vibrational amplitude in the  $b_x^2$  state contains no  $b_y$  character (although it contains some stretch displacement pointing to the librational character of the bending mode). Thus, for low energy states a simple one-dimensional harmonic picture seems to be adequate, in line with the small observed anharmonicities.

A different situation is found for higher energetic states, e.g., the  $b_y^4$  state. Here considerable motional amplitude along the *x* and *y* coordinates is observed indicating that the vibrational state can no longer be considered as a pure  $b_y$  vibration in a one-dimensional picture.

In conclusion we have shown that rotationally resolved UV spectroscopy of van der Waals vibronic bands is useful for characterization of the intermolecular vibrational motion and the intermolecular potential. The measured rotational constants of the different vdW vibronic bands can provide a critical test of future results from 3D quantum mechanical bound state calculations based on theoretical model potentials.

## ACKNOWLEDGMENTS

The authors are grateful to Professor E. W. Schlag for his continuous interest in this work. They thank R. Neuhauser for assistance and helpful discussions during the course of the experiments. Financial support from the Deutsche Forschungsgemeinschaft and the Fonds der Chemischen Industrie is gratefully acknowledged.

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