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Magdalena Malecka, Swastik Mondal, Sander van Smaalen and Carsten Paulmann

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Charge density distribution of 3-(1-aminoethyldene)-2-methoxy-2-oxo-2,3-dihydro-2 λ^5 -benzo[e][1,2]oxaphosphinin-4-oneMagdalena Małecka,^{a*} Swastik Mondal,^b Sander van Smaalen^b and Carsten Paulmann^{c,d}^aDepartment of Crystallography and Crystal Chemistry, University of Łódź, Pomorska 163/165, 90-236 Łódź, Poland, ^bLehrstuhl für Kristallographie, Universität Bayreuth, D-95440 Bayreuth, Germany, ^cc/o DESY/HASYLAB, Notkestrasse 85, D-22603 Hamburg, Germany, and ^dMineralogisch-Petrographisches Institut, Universität Hamburg, Grindelallee 48, D-20146 Hamburg, Germany

Correspondence e-mail: malecka@uni.lodz.pl

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A combined experimental and theoretical study of one oxaphosphinane derivative was made on the basis of a topological analysis of its electron density distributions. The electron density was determined from a high-resolution X-ray diffraction data set measured with synchrotron radiation at 100 K, whereas theoretical calculations were performed using density functional theory (DFT) methods at the B3LYP/6-311++G(3df,3pd) level of approximation. The charge-density distribution and analysis of topological properties revealed that the P—O bond is of the transit closed-shell type. The crystal structure possesses one intra- and several intermolecular hydrogen bonds. They were characterized quantitatively by topological properties using Bader's Atoms in Molecules theory. All hydrogen bonds were classified as weak. Further analysis of the experimental electron density by the source function allowed the intramolecular hydrogen bond to be characterized as an isolated hydrogen bond, in contrast to the resonance-assisted hydrogen bond in related molecules, such as chromone derivatives.

1. Introduction

Phosphonic analogues of chromone and coumarin derivatives represent a group of compounds possessing remarkable alkylating behaviour and anticancer activity against selected tumour cell lines. The best known phosphoro-organic alkylating drugs are cyclophosphamide and thiotepa. However, they are cytotoxic and possess immunosuppressive properties (Borch & Canute, 1991). Therefore, much effort has been devoted to designing new drugs containing phosphorus that avoid unwanted side effects (Kukhar & Hudson, 2000). Simultaneously, the alkylating properties of phosphonic esters and acids have been confirmed in many studies (Gray & Smith, 1980; Troev & Borisov, 1987). Various biological functions have been described, including the regulation of growth and the inhibition of metabolic processes as well as their role as pesticides (Kafarski & Lejczak, 1991; Mucha *et al.*, 2011) or drugs (Hildebrandt, 1983) including antibiotics (Goding, 1986; Park *et al.*, 1976). Recently, a new family of [1,2]oxaphosphinane derivatives was designed and synthesized, and a novel activity spectrum in the human cell line panel of the National Cancer Institute (NCI) has been discovered (Clarion *et al.*, 2012).

Recent research in Łódź has given extensive attention to oxaphosphinane derivatives as compounds with promising biological and pharmacological properties (Budzisz *et al.*, 2001, 2002, 2003). We have carried out systematic synthetic and structural studies to analyse structure–activity relationships for systems containing phosphorous (Małecka & Budzisz, 2001, 2006). Here we describe the experimental

electron-density distribution of 3-(1-aminoethylidene)-2-methoxy-2-oxo-2,3-dihydro-2 λ^5 -benzo[e][1,2]oxaphosphinin-4-one (I), as determined from multipole refinements against single-crystal X-ray diffraction data collected at 100 K. The experimental results are complemented by theoretical computations of isolated molecules in the gas phase. The results of the electron density distribution were interpreted according to Bader's 'Quantum Theory of Atoms in Molecules' (QTAIM; Bader, 1990), which provides information about the bonding features within a molecule.

Firstly, we have focused on the intramolecular hydrogen bond, which is a characteristic feature for the crystal structure of oxaphosphinane and chromone derivatives (Małacka, 2007). The intramolecular hydrogen bond is undoubtedly a very important interaction in biological chemistry. Several publications have presented the beneficial effects of this type of interaction on ligand–receptor binding. It is associated with conformational restrictions in which the small molecule substituents are favourably aligned in the protein pockets (Nomura *et al.*, 1999; Harter *et al.*, 2004; van Zandt *et al.*, 2004). Mostly, intramolecular hydrogen bonds are part of planar six-membered rings, and are stabilized by a π -conjugated system within the $\text{O}=\text{C}-\text{C}=\text{C}-\text{N}-\text{H}$ motif. They have been classified as resonance-assisted hydrogen bonds (Gilli *et al.*, 1989). The literature contains examples in which the propensity to form resonance-assisted hydrogen bonds was used in the design of new kinase inhibitors (Furet *et al.*, 2008). Therefore, a detailed analysis of the role of the intramolecular hydrogen bond in the investigated compound in promising biological activity is desirable.

One of the unsolved questions of (I) is whether or not the $\text{N}-\text{H}\cdots\text{O}$ intramolecular hydrogen bond can be classified as a resonance-assisted hydrogen bond (Małacka, 2007). This cannot be unambiguously determined from geometrical parameters. Therefore, additional evidence for the nature of this intramolecular hydrogen bond was gained by performing an analysis of the experimental electron density with the Source Function (Gatti *et al.*, 2003). The individual percentage source contributions from three atoms: hydrogen, donor and acceptor [% $S(\text{H})$; % $S(\text{D})$; % $S(\text{A})$] change in a concerted manner so that hydrogen bonds can be defined according to the interpretation of Gilli & Gilli (2000).

What is more, analysis of the electron density $\rho(\text{BCP})$ at bond critical points (BCPs) of hydrogen bonds and their Laplacian $\nabla^2\rho(\text{BCP})$ together with energetic parameters [kinetic energy densities – $G(\text{BCP})$, potential energy density –

Table 1

Crystal data, data collection, spherical and multipole refinement of (I).

Crystal data	
Chemical formula	$\text{C}_{11}\text{H}_{12}\text{NO}_4\text{P}$
M_r	253.19
Crystal system, space group	Orthorhombic, $P2_12_12_1$
Temperature (K)	100
a, b, c (Å)	9.2532 (10), 10.1555 (16), 12.6610 (12)
V (Å ³)	1189.8 (3)
Z	4
D_x (Mg m ^{−3})	1.413
Radiation type	Synchrotron, $\lambda = 0.60000$ Å
μ (mm ^{−1})	0.23
Crystal size (mm)	0.45 × 0.3 × 0.18
Data collection	
Diffractometer	Huber
Scan method	φ scan
Absorption correction	None
No. of measured, independent and observed [$I > 2\sigma(I)$] reflections	98 994, 17 584, 16 534
R_{int}	0.035
$(\sin \theta/\lambda)_{\text{max}}$ (Å ^{−1}), d_{min} (Å)	1.250, 0.4
Overall completeness (%)	94.2
Redundancy	5.8
Spherical atom refinement	
Refinement on	F^2
All data	17 584
R, wR [$I > 2\sigma(I)$]	0.0232, 0.0575
R, wR (all data)	0.0250, 0.0596
S	1.047
No. of parameters	190
$\Delta\rho_{\text{max}}, \Delta\rho_{\text{min}}$ (e Å ^{−3})	0.345, −0.263
Multipole refinement	
Refinement on	F
All data	17 584
Data included in refinement	14 864
(N_{ref})	
$R(F), R_{\text{all}}(F), R_w(F)$	0.015, 0.018, 0.017
$R(F^2), R_{\text{all}}(F^2), R_w(F^2)$	0.023, 0.023, 0.034
S	1.372
No. of parameters	534
N_{ref}/N_v	27.8
$\Delta\rho_{\text{max}}, \Delta\rho_{\text{min}}$ (e Å ^{−3})	0.13/−0.298

$V(\text{BCP})$, total electron energy density – $H(\text{BCP})$] allows for detailed characterization of intermolecular interactions.

Finally, our interest concerns the ionicity and covalency of chemical bonds involving the P atom. The nature of the valency and bonds formed by the P atom has attracted a lot of attention for many years. The concept of the involvement of d orbitals in the bonds formed by phosphorus was initially introduced by Mitchell (1996). However, further computational studies proved that the empty d orbitals have higher energies than s and p orbitals, and therefore could not form effective hybrids (Magnusson, 1990). Nowadays, theoretical studies on the P bond model have (Gilheany, 1994; Denehy *et al.*, 2007):

- (i) one σ bond and three π back-bonds;
- (ii) one σ bond and two π back-bonds;
- (iii) three bent Ω bonds (banana bonds).

One goal of this work is, therefore, to establish the nature of bonds around the P atom where the P atom has four different connections.

2. Experimental

2.1. Data collection and structure refinement details

A transparent bar-shaped crystal ($0.45 \times 0.3 \times 0.18$) was used for data collection at 100 K on a Huber four-circle diffractometer equipped with a MAR165 CCD detector at beamline F1 in HASYLAB/DESY, Hamburg, employing radiation with a wavelength of $0.6000 \text{ \AA}$. A total of 1113 diffraction images were collected in 5 runs with different diffractometer angle settings chosen to obtain the high redundancy required for charge density analysis. Diffraction data up to $\sin(\theta/\lambda) = 1.25 \text{ \AA}^{-1}$ were collected using φ scans with a rotation of $\Delta\varphi = 1^\circ$. Different exposure times were chosen for different 2θ settings of the detector, with 5 and 10 s for $2\theta = 0^\circ$, and 90 s for $2\theta = -45$ and -55° .

Data reduction was performed with the program *EVAL15* (Schreurs *et al.*, 2010) and absorption correction was applied with *SADABS* (Sheldrick, 2008b). The structure was solved by direct methods using *SHELXS97* (Sheldrick, 2008a) and initially refined in the spherical atom approximation (based on F^2) by *SHELXL97* (Sheldrick, 2008a) using the *WinGX* package (Farrugia, 1999). Details of the crystal structure and the refinement are listed in Table 1.

2.2. Multipole refinement

The structure was initially modeled using the initial model of the independent atom model (IAM). For multipole refinements, atomic scattering factors were taken from Su & Coppens (1998). The positional coordinates and anisotropic displacement parameters of the non-H atoms were re-refined against the high-order reflections [$\sin(\theta/\lambda) \geq 1 \text{ \AA}^{-1}$; Jelsch *et al.*, 2005; Hoser *et al.*, 2009; Domagała *et al.*, 2012]. The aspherical multipolar refinement based on F was carried out using *XD2006* (Volkov *et al.*, 2006), employing the Hansen–Coppens formalism (Hansen & Coppens, 1978). The scale factor, atomic positions (xyz coordinates), and atomic displacement parameters (ADPs) were refined with the weighting scheme $w_H = 1/\sigma^2(F_{\text{obs}})$. Multipolar refinement was

performed with the full-matrix least-squares method using the XDLSM module in *XD2006*. The C–H and N–H bonds were set to standard values from neutron diffraction (Allen *et al.*, 2006). For non-H atoms, the valence and multipole populations and κ were allowed to be refined. The multipole expansion was truncated at the hexadecapole level for non-H atoms and the bond-directed dipole level for H atoms. In the next step anisotropic ADPs of the H atoms were generated using the *SHADE* program (Madsen, 2006), which has been recently shown to provide accurate parameter estimates (Munshi *et al.*, 2008). Finally, all the multipole parameters were refined with fixed ADPs for the H atoms. The final multipole model is consistent with rigid-body Hirshfeld criteria. DMSDA (differences of mean-squares displacement

Figure 1

View of molecular structure with atom-numbering scheme and hydrogen bonds. The symmetry codes are: (i) $1-x, -\frac{1}{2}+y, \frac{1}{2}-z$; (ii) $\frac{1}{2}+x, \frac{1}{2}-y, -z$; (iii) $\frac{1}{2}+x, \frac{3}{2}-y, -z$; (iv) $-\frac{1}{2}+x, \frac{1}{2}-y, -z$.

Figure 2

Residual density maps in (a) the C5–C10 plane and (b) the O21–P2–O22 plane. Black solid lines: positive contours; red dotted lines: negative contours; blue dashed lines: zero contours – drawn with intervals of $0.05 \text{ e \AA}^{-3}$.

Table 2

Geometrical and topological parameters of covalent bonds.

Density: $\rho(\text{BCP})$ ($\text{e } \text{\AA}^{-3}$); its Laplacian: $\nabla^2\rho(\text{BCP})$ ($\text{e } \text{\AA}^{-5}$); eigenvalues of Hessian matrix: $\lambda_1, \lambda_2, \lambda_3$ ($\text{e } \text{\AA}^{-5}$); the ellipticity: ϵ (dimensionless); bond degree: BD.

	d	$\rho(\text{BCP})$	$\nabla^2\rho(\text{BCP})$	λ_1	λ_2	λ_3	ϵ	BD
P2—O1	1.6085 (2)	1.282	−0.032	−9.22	−8.81	18.00	0.05	−0.95
P2—O21	1.4743 (2)	1.695	9.888	−12.53	−11.49	33.90	0.09	−1.01
P2—O22	1.5779 (2)	1.546	−4.655	−12.91	−11.69	19.95	0.11	−1.15
P2—C3	1.7519 (2)	1.339	−9.735	−8.02	−7.23	5.51	0.11	−1.15
O1—C9	1.3874 (3)	1.949	−16.625	−16.32	−15.55	15.25	0.05	−1.45
O4—C4	1.2476 (3)	2.774	−32.982	−24.6	−23.3	14.92	0.06	−1.86
O22—C23	1.4480 (2)	1.657	−11.426	−13.85	−11.86	14.28	0.17	−1.29
N1—C31	1.3218 (3)	2.424	−25.844	−20.92	−17.6	12.69	0.19	−1.70
C3—C4	1.4497 (3)	1.905	−16.667	−15.2	−12.53	11.07	0.21	−1.44
C3—C31	1.4155 (3)	1.999	−16.886	−15.34	−12.9	11.36	0.19	−1.47
C4—C10	1.4986 (3)	1.734	−10.023	−11.9	−10.9	12.78	0.09	−1.30
C5—C6	1.3918 (3)	2.135	−16.998	−15.49	−13.73	12.22	0.13	−1.52
C5—C10	1.4048 (3)	2.037	−17.100	−15.77	−12.97	11.65	0.22	−1.49
C6—C7	1.4012 (4)	2.142	−21.060	−18.12	−13.51	10.57	0.34	−1.57
C7—C8	1.3959 (4)	2.037	−17.218	−15.43	−12.52	10.74	0.23	−1.49
C8—C9	1.3934 (3)	2.116	−17.415	−16.28	−12.76	11.84	0.28	−1.51
C9—C10	1.3993 (3)	2.098	−16.525	−16.26	−12.66	12.40	0.28	−1.50
C31—C311	1.5040 (3)	1.772	−15.262	−13.4	−12.66	10.79	0.06	−1.38

amplitudes) values are less than $0.0008 \text{ \AA}^2$. Details of the multipole refinement are listed in Table 1.

2.3. Theoretical calculation

The molecular geometry from the multipole model was taken for a single-point (*SP*) calculation with the DFT method (B3LYP/6-311++G**). Additionally, the gas-phase geometry optimization calculation was performed (*OPT* model). All computations were done using *GAUSSIAN03* (Frisch *et al.*, 2003). The theoretical electron densities were evaluated with the program *AIM2000* (Biegler-König & Schönbohm, 2002) in order to obtain the topological parameters.

3. Results and discussion

3.1. Crystal structure

The crystal structure of compound (I) is in agreement with the previously published IAM (Budzisz *et al.*, 2005; Fig. 1). Bond lengths and bond angles from the multipole model (MP) do not differ significantly from those of the IAM. The residual density maps of the multipole refinement are featureless with values rarely exceeding $0.10 \text{ e } \text{\AA}^{-3}$ in the region of the whole molecule with the exception of the area around the P atom (see Fig. 2) [where the highest peak ($0.20 \text{ e } \text{\AA}^{-3}$) and deepest hole ($0.29 \text{ e } \text{\AA}^{-3}$) are located $0.52 \text{ \AA}$ from P2]. Attempts to model this density by anharmonic ADPs for the P atom failed. The essential geometrical and topological parameters of charge distribution for the multipole refinement are summarized in Table 2.

3.2. Topological analysis of the electron-density distribution in hydrogen-bond regions

The QTAIM of Bader (1990) plays a central role in the understanding of hydrogen bonds. Koch & Popelier (1995) have outlined a set of eight criteria to define the existence and

type of hydrogen bond on the basis of the charge density distribution. Since the intra- and intermolecular hydrogen bonds (both $\text{N—H} \cdots \text{O}$ and $\text{C—H} \cdots \text{O}$) were observed in the crystal lattice of the analyzed structure, a full experimental electron density study was undertaken to examine all interactions in more detail using the QTAIM. A more qualitative approach was used to study hydrogen bonds in detail following the work of Abramov (1997) on the energetic organization of atomic interactions. The kinetic energy densities at the bond critical points (BCPs) $G(r)$ were calculated using the functional

$$G(\text{BCP}) = \frac{3}{10} (3\pi^2)^{2/3} \rho^{5/3}(\text{BCP}) + \frac{1}{6} \nabla^2 \rho(\text{BCP}), \quad (1)$$

while the corresponding potential energy density at the BCPs, $V(\text{BCP})$, was obtained from the relationship shown by Bader (1990)

$$V(\text{BCP}) = \frac{1}{4} \nabla^2(\text{BCP}) - 2G(\text{BCP}). \quad (2)$$

The hydrogen-bond energy was calculated by the distance-dependent relation of Espinosa *et al.* (1998): $E = 25.3 \times 10^3 \text{ e}^{-3.6(\text{H} \cdots \text{A})}$ or was estimated according to the equation

$$E_{\text{HB}} = \frac{1}{2} V(\text{BCP}) \quad (3)$$

(Espinosa *et al.*, 1998, 2002), while the total electron energy density was obtained from $H(\text{BCP}) = G(\text{BCP}) + V(\text{BCP})$. All these parameters provide good descriptors for the determination of the nature of the hydrogen bonds. According to the approach of Rozas *et al.* (2000), the character of hydrogen bonds is defined as being covalent, partially covalent or electrostatic in relation to the strength of the hydrogen bond: strong hydrogen bonds of covalent character [$\nabla^2\rho(\text{BCP}) < 0$ and $H(\text{BCP}) < 0$], medium-strength hydrogen bonds of partially covalent character [$\nabla^2\rho(\text{BCP}) > 0$ and $H(\text{BCP}) < 0$],

Table 3Hydrogen-bonding geometries ($\text{\AA}$, $^\circ$), topological parameters at the hydrogen $\cdots$ acceptor BCP.

Electron density: $\rho(\text{BCP})$ ($\text{e \AA}^{-3}$); its Laplacian: $\nabla^2\rho(\text{BCP})$ ($\text{e \AA}^{-5}$); local energy densities (kJ mol^{-1}): $G(\text{BCP})$; kinetic energy density at the BCP; $V(\text{BCP})$; potential energy density at the BCP; $H(\text{BCP})$: total energy density at the BCP; energies (kJ mol^{-1}) and E_{HB} : estimated energy from the relation $E_{\text{HB}} = \frac{1}{2}V(\text{BCP})$; $|V/G|$: ratio of the potential and kinetic energy density at the BCP (Espinosa *et al.*, 2002); E_{HBgeom} : estimated energy from the distance-dependent relation (Espinosa *et al.*, 1998); bond degree defined as $\text{BD} = H(\text{BCP})/\rho(\text{BCP})$.

	$D-H$	$H\cdots A$	$D\cdots A$	$D-H\cdots A$	$\rho(\text{BCP})$	$\nabla^2\rho(\text{BCP})$	λ_1	λ_2	λ_3	$G(\text{BCP})$	$V(\text{BCP})$	$H(\text{BCP})$	$ V(\text{BCP}) /G(\text{BCP})$	E_{HB}	E_{HBgeom}	BD
N1—H1 $\cdots$ O4	1.01	1.84	2.628 (1)	133	0.234	3.208	−1.10	−1.00	5.30	86.04	−84.71	1.33	0.98	−42.35	−33.60	0.014
N1—H2 $\cdots$ O21 ⁱ	1.01	1.83	2.833 (1)	170	0.177	3.354	−0.86	−0.79	5.00	78.36	−65.36	12.99	0.83	−32.68	−34.83	0.188
C5—H5 $\cdots$ O22 ⁱⁱ	1.08	2.40	3.274 (1)	137	0.06	0.981	−0.25	−0.22	1.44	20.68	−14.66	6.03	0.70	−7.33	−4.47	0.258
C8—H8 $\cdots$ O21 ⁱⁱⁱ	1.08	2.54	3.492 (1)	146	0.045	0.695	−0.16	0.15	1.00	14.40	−9.87	4.53	0.68	−4.93	−2.70	0.258
C23—H23A $\cdots$ O4 ^{iv}	1.06	2.47	3.238 (1)	128	0.05	0.786	−0.16	−0.16	1.10	16.39	−11.38	5.01	0.69	−5.69	−3.48	0.257
C311—H31C $\cdots$ O21	1.06	2.45	3.065 (1)	116	0.083	1.082	−0.18	−0.07	1.33	24.59	−19.70	4.88	0.80	−9.85	−3.74	0.151

Symmetry codes: (i) $1-x, -\frac{1}{2}+y, \frac{1}{2}-z$; (ii) $\frac{1}{2}+x, \frac{1}{2}-y, -z$; (iii) $\frac{1}{2}+x, \frac{3}{2}-y, -z$; (iv) $-\frac{1}{2}+x, \frac{1}{2}-y, -z$.

and weak hydrogen bonds of mainly electrostatic character [$\nabla^2\rho(\text{BCP}) > 0$ and $H(\text{BCP}) > 0$].

The intra- and intermolecular hydrogen interactions in (I) have been characterized through the topological properties of their electron densities (Table 3). Analysis of the multipole electron densities according to the QTAIM theory indicates the existence of two N—H $\cdots$ O and four C—H $\cdots$ O hydrogen bonds in the asymmetric unit (Fig. 1), two more than previously derived from IAM density (Budzisz *et al.*, 2005). No critical point was found for the hydrogen bond C311—H31A $\cdots$ O21 ($1-x, -\frac{1}{2}+y, \frac{1}{2}-z$), mentioned by Budzisz *et al.* (2005). These are shown in Fig. 1 and the geometrical and topological properties at BCPs for these interactions are given in Table 3. In terms of the classification of Rozas *et al.* (2000) these interactions are weak and have mainly electrostatic character. The interactions are characterized by very small values of $\rho(\text{BCP})$ (0.045–0.234 $\text{e \AA}^{-3}$), small positive values of $\nabla^2\rho(\text{BCP})$ (0.695–3.208 $\text{e \AA}^{-5}$), a relatively high value of λ_3 (1.0–5.3) in comparison to $\lambda_{1,2}$ (−0.07 to −1.10), values of $|V(\text{BCP})|/G(\text{BCP}) < 1$ and nearly zero values of $H(\text{BCP})$ (0.0005–0.0049). However, the analysis of energy (E_{HB} , E_{HBgeom}) clearly shows that two hydrogen bonds of N—H $\cdots$ O type are stronger than C—H $\cdots$ O ones. It is worth noticing that observed interactions overlap between the type of closed-shell region and the type of transit shell region (Espinosa *et al.*, 2002).

The energy of the intramolecular N—H $\cdots$ O hydrogen bond has been found to be −42.35 kJ mol^{-1} , which is much smaller than in our previous investigations of chromone derivatives (−56.53 to −77.93 kJ mol^{-1}). Additionally, the total electron energy density $H(\text{BCP})$ has been found to be positive which indicates that the hydrogen bond is weak with mainly electrostatic character. This is in contrast to medium strength hydrogen bonds with partially covalent character in related molecules like chromone derivatives (Małacka *et al.*, 2010, 2012).

3.3. N—H $\cdots$ O intramolecular hydrogen-bond system

To understand whether the intramolecular N—H $\cdots$ O bond system is resonance-assisted or not, the topological properties

of experimental electron density maps are analysed including the source function. Experimental electron densities at the intramolecular hydrogen bond are illustrated qualitatively in the static deformation density maps presented in Fig. S1 of the supplementary material.¹ The electron density of the formally single bond (C3—C4) and that of the formally double bond (C3—C31) do not differ significantly; $\rho(\text{BCP})$ amounts to 1.91 (1) and 2.00 (1) $\text{e \AA}^{-3}$ (see Table 2). Delocalization of these bonds can be seen by comparing the electron density of the C31—C311 pure single bond, which amounts to 1.77 (1) $\text{e \AA}^{-3}$, and the average $\rho(\text{BCP})$ of aromatic bonds ($C_{\text{ar}}-C_{\text{ar}}$) in the benzene ring of 2.09 (1) $\text{e \AA}^{-3}$. Inspection of the bond ellipticity ϵ shows that ellipticities of the C3—C31 and C3—C4 bonds are close to the reference ellipticities of double bonds. Pure single, double and triple C—C bonds have ϵ equal to 0.014, 0.298 and 0.000 in butane, ethene and ethyne, respectively (Popelier, 2000). These values might imply that there is π -electron delocalization within a hydrogen bonded six-membered ring. However, π -electron delocalization within a ring containing conjugated systems of single and double bonds should strengthen the intramolecular N—H $\cdots$ O hydrogen bond. Since this is not the case, examination of the energetic parameters has not confirmed this presumption (§3.2).

Gatti *et al.* (2003) and Gatti & Macchi (2012) examined hydrogen-bonded systems and associated the characteristic source contributions of donor (D), hydrogen (H) and acceptor (A) atoms to the five classes of hydrogen bonds defined by Gilli & Gilli (2000). The contribution of the local sources to the electron density at the bond critical point of the hydrogen bond is described by the source function (SF; Bader & Gatti, 1998). The results are in the range between the typical values for polarization-assisted hydrogen bonds (PAHB) and isolated hydrogen bonds (IHB), but closer to the latter. Contributions from H , D and A atoms are: −17.6, 38.4 and 14.8%. However, the reference values are based on prototypical homonuclear systems. The percentage contribution from D is decreased

¹ Supplementary data for this paper are available from the IUCr electronic archives (Reference: GW5021). Services for accessing these data are described at the back of the journal.

compared with O—H...O isolated hydrogen bonds (-17.6% versus -70% for prototypical IHB), because the N—H bond turns out to be less polarized than the O—H bond. The contribution from the triad $S(H + D + A)$ is 36.1% and indicates the electrostatic nature of the hydrogen bond. This tendency is also reflected in the energy density parameters and the estimated energy, as was pointed out above. It is worth noting that other investigations have also shown that N—H...O hydrogen bonds are the weakest interactions among other chromone and oxaphosphinane derivatives (Małecka, 2007). A different conclusion was drawn for chromone derivatives with a similar intramolecular N—H...O hydrogen-bond system. These hydrogen bonds are known as bonds of rather moderate strength and as resonance-assisted hydrogen bonds with a small positive $S(H)$ contribution (Małecka *et al.*, 2010, 2012).

3.4. Topological analysis of the charge density around the P atom

The P atom adopts distorted tetrahedral geometry with three P—O bonds and one elongated apical P—C bond. Abbreviations used in the text are as follows: P2—O22: P—O_{Me}; P2—O1: P—O_{ring}; P2—O21: P—O; P2—C3: P—C_{ring}.

The values of the electron density at BCPs for the P—O bonds are: $\rho(\text{BCP}) = 1.546 \text{ e } \text{\AA}^{-3}$ for P—O_{Me} and $1.695 \text{ e } \text{\AA}^{-3}$ for P—O (Table 2). These data are comparable with those reported earlier (Slouf *et al.*, 2002; Espinosa *et al.*, 1996; Rodrigues *et al.*, 2001), where $\rho(\text{BCP})$ values for P—O bonds are in the range $1.49\text{--}1.81 \text{ e } \text{\AA}^{-3}$ with an average value of $1.634 \text{ e } \text{\AA}^{-3}$. In the case of the P—O_{ring} bond $\rho(\text{BCP})$ is smaller than the value for the P—O bond and amounts to $1.282 \text{ e } \text{\AA}^{-3}$. The value of the electron density for the P—C_{ring} bond is $1.334 \text{ e } \text{\AA}^{-3}$, which is similar to that found by Kocher *et al.* (2004), $1.336 \text{ e } \text{\AA}^{-3}$, but larger compared with other P—C_{aliphatic} bonds mentioned in the literature, whose average

value is $\rho(\text{BCP}) = 1.183 \text{ e } \text{\AA}^{-3}$ (Slouf *et al.*, 2002; Rodrigues *et al.*, 2001; Mermer & Starynowicz, 2011).

The Laplacian distribution along P2—X bonds [$X = \text{O}, \text{O}_{\text{Me}}, \text{O}_{\text{ring}}, \text{C}_{\text{ring}}$] is presented in Fig. 3. The Laplacian at the BCP of P—O is positive [$\nabla^2\rho(\text{BCP}) = 9.89 \text{ e } \text{\AA}^{-5}$] and the valence-shell charge concentration (VSCC) is exclusively concentrated on the oxygen basin, which is also characteristic for the other P—O_{Me} and P—O_{ring} bonds. However, the values of their Laplacians are: $\nabla^2\rho(\text{BCP}) = -4.66$ and $-0.03 \text{ e } \text{\AA}^{-5}$ for P—O_{Me}, P—O_{ring}, respectively, and $\nabla^2\rho = -9.74 \text{ e } \text{\AA}^{-5}$ for P—C_{ring}. The values of the Laplacians for the P—O bonds are comparable with those published for phosphonate (Slouf *et al.*, 2002), aminophosphonic acid (Janicki & Starynowicz, 2010) and calcium and lithium phosphonates (Mermer & Starynowicz, 2011), where the corresponding Laplacians are positive. Rather high (positive) values and slightly negative values of Laplacians suggest significant ionicity of those bonds, which is greater in the case of the nonprotonated O atom (O21).

As shown by Espinosa *et al.* (2002), analysis of the Laplacian combined with the bond-degree parameter $\text{BD} = H(\text{BCP})/\rho(\text{BCP})$ can be used to classify the bonds into:

- (i) shared-shell, $\nabla^2\rho(\text{BCP}) < 0$ and $\text{BD} < 0$,
- (ii) closed-shell, $\nabla^2\rho(\text{BCP}) > 0$ and $\text{BD} > 0$
- (iii) transit closed-shell $\nabla^2\rho(\text{BCP}) > 0$ and $\text{BD} < 0$ classes of interactions.

Recently, Mermer & Starynowicz (2011, 2012) have applied this approach to analyse bonding in compounds containing P atoms. Following this approach, C—C, C—N and C—O bonds are found to be covalent in the present study (Table 2). However, the P2—O21 bond is located in the transit closed-shell region with a positive value of the Laplacian and a negative value of BD. This is in agreement with the finding that the P2—O21 bond is partially ionic, as discussed earlier. However, the above characterization is not sufficient to define which model of the P—O bond exists in the investigated structure. Therefore, we analysed the spatial arrangement of the atomic valence-shell charge concentrations (Fig. 4) as the imprint of chemical bonding is well manifested in the VSCC. Critical points in the negative Laplacian are indicative of local charge density concentrations (VSCCs). The atomic graphical representation of the VSCC around the P atom and corresponding isosurface plot of $\nabla^2\rho$ are presented in Fig. 4. Around the P atom were found five (3, -3) critical points, three of them are associated with P2—O1, P2—O22 and P2—C3 bonds, and two with P2—O21 bonds. It has been found, however, that one critical point of VSCC (v_5) has a small value of $-0.41 \text{ e } \text{\AA}^{-5}$. The maxima v_1 , v_2 and v_3 lie respectively on the P2—O1, P2—O22 and P2—C3 bonds, while v_4 and v_5 , are shifted by approximately $0.2 \text{ \AA}$ on opposite sides of the P2—O21 bond. The lack of a critical point on the P2—O21 bond path suggests that there is no σ bond between P2 and O21. Additionally, considering the angle between the critical points v_4 and v_5 (120°), the formation of the P2—O21 bond could be interpreted as banana bonds. It is also interesting to note that the value of the ellipticity of the P2—O21 bond is 0.09 , which corresponds well with recent results (Mermer & Starynowicz,

Figure 3

Laplacians along the bond path of P2—O22: P—O_{Me}; P2—O1: P—O_{ring}; P2—O21: P—O and P2—C3: P—C_{ring} bonds. The horizontal axis measures the distance to the BCPs.

2012). Finally it should be noted that the absence of the critical point (v_6) is associated with connections to the P atom that are not chemically equivalent (different environment/ substituents around the P atom).

The experimental electron density results were compared with theoretical ones (*OPT_model*). Some important features can be pointed out:

(i) All values of the experimental and theoretical electron density $\rho(\text{BCP})$ are in good agreement; values of the experimental $\rho(\text{BCP})$ are slightly larger than theoretical ones in the region of the P atom, while for the remaining atoms they are similar.

(ii) Significant differences are found for $\nabla^2\rho(\text{BCP})$ in the phosphorus region. The experimental $\nabla^2\rho(\text{BCP})$ values are -4.65 , -0.03 and $9.88 \text{ e } \text{\AA}^{-5}$, while the theoretical values are -15.70 , 14.23 and $34.82 \text{ e } \text{\AA}^{-5}$ for $\text{P}-\text{O}_{\text{ring}}$, $\text{P}-\text{O}_{\text{Me}}$ and $\text{P}-\text{O}$ bonds, respectively. However, positive Laplacians are reproducible for the experiment, as mentioned above. On the other hand, many examples exist of theoretical values of Laplacians which are comparable to those we have found here (Lopez *et al.*, 1996; Mõ & Yáñez, 1996; Boily, 2002). A thorough investigation of $\nabla^2\rho(\text{BCP})$ values of oxaphosphinane derivatives optimized previously has revealed comparable values.

(iii) Large discrepancies are also observed for the $\text{C4}=\text{O4}$ bond, where the Laplacian obtained experimentally amounts

to $\nabla^2\rho(\text{BCP}) = -32.982 \text{ e } \text{\AA}^{-5}$, whereas that obtained theoretically is $\nabla^2\rho(\text{BCP}) = -6.861 \text{ e } \text{\AA}^{-5}$. The same trend has already been observed in the previous study and has been explained in the literature as being a consequence of the limited flexibility of radial functions used in the multipole model (Volkov *et al.*, 2000, 2001; Volkov & Coppens, 2001; Bach *et al.*, 2001; Zhurova *et al.*, 2006; Gatti & Macchi, 2012). Furthermore, a $\text{C}=\text{O}$ is involved in intermolecular interactions present in the crystal lattice.

4. Conclusions

The experimental charge density of 3-(1-aminoethylidene)-2-methoxy-2-oxo-2,3-dihydro-2 λ^5 -benzo[*e*][1,2]oxaphosphinin-4-one is analysed and has been obtained by multipole refinement of high-resolution single-crystal X-ray diffraction data measured at a temperature of 100 K. Our charge density analysis has focused on the classification of hydrogen bonds in the crystal lattice, with special attention being paid to the intramolecular hydrogen bond and to the nature of the bonds around the P atom.

A topological analysis of the hydrogen bonds including Rozas's approach revealed that both intra- and intermolecular interactions of $\text{N}-\text{H}\cdots\text{O}$ and $\text{C}-\text{H}\cdots\text{O}$ hydrogen bonds are weak with an electrostatic character. This situation is different in the hydrogen bonds found in other chromone derivatives, where $\text{N}-\text{H}\cdots\text{O}$ hydrogen bonds were characterized as being of medium strength (Małecka, 2010). This difference is also reflected in the hydrogen-bond energy estimated according to Espinosa's equation.

The contributions of donor (*D*), hydrogen (*H*) and acceptor (*A*) atoms to the electron density at the BCP of the intramolecular $\text{N}-\text{H}\cdots\text{O}$ hydrogen bond indicated that this is a case of an isolated hydrogen bond. This is not in agreement with our expectation that this intramolecular hydrogen bond was not a resonance-assisted hydrogen bond (RAHB), but an isolated hydrogen bond (IHB).

The topological analysis revealed that one $\text{P}-\text{O}$ bond has significant ionic character, with a positive value of the Laplacian at the BCP. The spatial arrangement of the VSCC together with the ellipticity value indicates that there is an absence of σ -bonds between P2 and O21 atoms, and there is the possibility of the formation of banana or bent bonds. The values of the Laplacian at the BCP for the remaining $\text{P}-\text{O}$ bonds [$\text{P}-\text{O}_{\text{Me}}$, $\text{P}-\text{O}_{\text{ring}}$] suggest a slight ionic character of the $\text{P}-\text{O}$ bonds.

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Figure 4
(a) Graphical representation of the VSCCs around the P atom with numbering scheme. The values of $\nabla^2\rho$ are: $v_1 = -14.04$, $v_2 = -8.30$, $v_3 = -3.32$, $v_4 = -1.12$, $v_5 = -0.41 \text{ e } \text{\AA}^{-5}$; (b) isosurface of negative Laplacian in VSCC of the P atom at $-0.5 \text{ e } \text{\AA}^{-5}$ isolevel; program used for visualization is *Moliso* (Hübschle & Luger, 2006).

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