Orbital-Free Quantum Crystallographic View on Noncovalent Bonding: Insights into Hydrogen Bonds, $\pi\cdots\pi$ and Reverse Electron Lone Pairs $\cdots\pi$ Interactions

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ABSTRACT: A detailed analysis of a complete set of the local potentials that appear in the Euler equation for electron density is carried out for noncovalent interactions in the uracil derivative using experimental X-ray charge density. The interplay between the quantum theory of atoms in molecules and crystals and the local potentials and corresponding inner-crystal electronic forces of electrostatic and kinetic origin is explored. Novel physically grounded bonding descriptors derived within the orbital-free quantum crystallography provided the detailed examination of π -stacking and intricate C=O $\cdots\pi$ interactions and nonclassical hydrogen bonds. The donor-acceptor character of these interactions is revealed by analysis of Pauli and von Weizsäcker potentials together with well-known functions.

Partitioning of crystal space into atomic-like potential basins led us to the definite description of the charge transfer. In this way, our analysis throws light on aspects of these closed-shell interactions hitherto hidden from the description.

KEYWORDS: bond theory, charge transfer, donor-acceptor systems, electronic structure, pi interactions.

INTRODUCTION

Electron density $\rho(\mathbf{r})$ (ED) is a fundamental experimentally measurable function, which is derived from both accurate quantum-chemical calculations and a precise single-crystal diffraction experiment using the Hansen–Coppens multipole formalism.¹ For the past decades, the charge density analysis^{2–5} has proved to be immensely relevant in the fields of crystal engineering,⁶ material sciences,^{7–10} biological and medicinal chemistry,¹¹ and others. While the simple tools of analysis, such as deformation electron density $\delta\rho(\mathbf{r})$ and electrostatic potential (ESP) $\varphi_{es}(\mathbf{r})$ are still useful, more detailed information on the bonding nature is provided by the quantum theory of atoms in molecules.^{12–14} Its further application to crystal ED leads to the quantum theory of atoms in molecules and crystals (QTAIMC).^{15–17} Arguably the important advantage of QTAIMC is the chemically reasonable definition of free and bounded atoms¹⁸ and interactions between them^{19,20} through the topology of three-dimensional ED, which yields the physical ground for many classical chemical concepts.^{21–23} In particular, the idea of Lewis electron pairs found its reflection in the topology of Laplacian of ED $\nabla^2\rho(\mathbf{r})$.^{24–26} Also, the intuitive concepts of covalent chemical bonds and weak noncovalent intra- and intermolecular interactions were given the solid physical evidence in the form of a saddle critical point (CP) $(3, -1)$ in $\rho(\mathbf{r})$ called a bond critical point (BCP) and corresponding pairs of gradient lines originated at these points and terminated at two nuclei of neighboring atoms.^{19,20} These lines define a bond path linking the bonded atoms.

Quantum crystallography is a somewhat broader name that now denotes the field of study including both the ordinary charge-density methods and many novel techniques adopted from quantum chemistry and density functional theory (DFT).^{27,28} The modern comprehensive analysis of chemical bonding for both experimental and theoretical ED employs the various position-space bonding descriptors. Within the orbital-free DFT,^{29,30} they can be derived from ED and its derivatives using various approximations, for instance, for the kinetic energy density of the noninteracting electrons $g(\mathbf{r})$ (KED).^{31,32} This leads to getting the bonding descriptors immediately from experimental ED without the wave function calculation. KED-dependent descriptors, such as electron localization function $\eta(\mathbf{r})$ (ELF),^{33–35} local electron temperature $t(\mathbf{r})$,³⁶ phase-space-defined Fisher information density,³⁷ electronic pressure,³⁸ and others^{39,40} are suited for revealing the electron pair localization and the distribution of the inner-crystal electronic energy. Furthermore, quantum crystallography often operates with forces responsible for chemical interactions in a system, which is a more comprehensive approach.⁴¹ They are the Ehrenfest and Hellmann–Feynman forces acting on electrons and nuclei, respectively. Actual ED distribution within a molecule and a crystal is a direct physical manifestation of these forces.

In DFT, the total energy functional is conventionally composed of the noninteracting kinetic $E_k[\rho]$, electrostatic $E_{es}[\rho]$, exchange $E_x[\rho]$, and correlation $E_c[\rho]$ terms.⁴² In turn, $E_k[\rho]$ for noninteracting electrons can be split into a sum of Pauli $E_P[\rho]$ and von Weizsäcker $E_W[\rho]$ components.⁴³ Recently, Tsirelson and Stash (T&S) suggested to use the corresponding local potential scheme,⁴⁴ which includes the electrostatic $\varphi_{es}(\mathbf{r})$, exchange $\varphi_x(\mathbf{r})$, correlation $\varphi_c(\mathbf{r})$, von Weizsäcker $\varphi_W(\mathbf{r})$,^{45–48} and Pauli $\varphi_P(\mathbf{r})$ ^{49–52} potentials. Starting from the Euler equation for $\rho(\mathbf{r})$, T&S arrived at the following equation:

$$\mu(\mathbf{r}) = -\varphi_{es}(\mathbf{r}) + \varphi_x(\mathbf{r}) + \varphi_c(\mathbf{r}) + \varphi_P(\mathbf{r}) + \varphi_W(\mathbf{r}).$$

Here, $\mu(\mathbf{r})$ is the local one-electron chemical potential. The first three terms constitute the potential acting on any one electron in a molecule $\varphi_{em}(\mathbf{r})$ (PAEM),^{53,54} while the last two give the kinetic potential $\varphi_k(\mathbf{r})$.⁴³ Then the previous equation can be rewritten in terms of one-electron effective forces:

$$\mathbf{F}(\mathbf{r}) = -\nabla\mu(\mathbf{r}) = -\nabla\varphi_k(\mathbf{r}) - \nabla\varphi_{em}(\mathbf{r}) = \mathbf{F}_k(\mathbf{r}) + \mathcal{F}(\mathbf{r}),$$

where net local force $\mathbf{F}(\mathbf{r}) = 0$ due to fact that vector $\nabla\mu(\mathbf{r}) = 0$ everywhere for a many-nuclear many-electron system in equilibrium. Hence, the action of both forces in such a system is balanced, i.e., $\mathbf{F}_k(\mathbf{r}) = -\mathcal{F}(\mathbf{r})$. Taking into account the fact that effective force acting on an electron in a molecule $\mathcal{F}(\mathbf{r})$ is isomorphic to the Ehrenfest force, T&S⁴⁴ suggested using the approximate one-electron image of many-electron inner-crystal force field. Force $\mathcal{F}(\mathbf{r})$ being homotropic pushes electrons to the atomic nuclei and favors homogeneous disorganization (disorder) in a system. At the same time, the heterotropic kinetic force $\mathbf{F}_k(\mathbf{r})$ of quantum nature prevents the complete compensation of electric charges, as it would be if only force $\mathcal{F}(\mathbf{r})$ existed. It pulls electrons from nuclei, thus providing inhomogeneous three-dimensional distribution of electrons. Both forces are responsible for the self-organization of electrons in the field of nuclei, each playing its own role. Indeed, only potential fields $\varphi_{es}(\mathbf{r})$ and $\varphi_k(\mathbf{r})$ satisfy the zero-flux condition and allow for construction of corresponding atomic basins around the nuclei similar to those found in $\rho(\mathbf{r})$.^{44,55} It is important, that all one-electron potential and forces can be obtained from the experimental ED through the use of reliable physically grounded approximations.^{44,56} Therefore, it is now the time to apply the described novel technique of bonding analysis and to place them in the realm of more common methods to gain a thorough description of the noncovalent interactions and elucidate their nature and role in crystal space organization.

Despite their relative weakness compared to covalent bonds, noncovalent interactions often govern the structural organization of crystal and other supramolecular systems. The strong classical hydrogen bonds, e.g., O–H $\cdots$ O and N–H $\cdots$ O, are well studied and their role as primary crystal-forming interactions is undisputable. However, much less is known about the weak contacts, which play a special role in the forming of a crystal structure. This statement can be substantiated by the fact that the destruction of a crystal upon melting or dissolution can often be ascribed to the breaking of weaker contacts, whereas H-bonded assemblies with the structure inherited from crystals one can be found in melts and solutions.

Electrostatic consideration of hydrogen bonds is insufficient. The dispersion and exchange effects, which represent the Coulomb electron correlation and same spin electron-electron interaction owing to Pauli exclusion principle, respectively, as well as atomic polarization and charge redistribution within and between the interacting molecules, i.e., charge transfer, need to be also taken into account.⁵⁷ More commonly, hydrogen bonds are described as an interaction of an electron lone pair (LP) of a heteroatom (H-bond acceptor) and an electron deficiency region near the hydrogen atom, which can be ascribed to a donor-acceptor mechanism of formation.⁵⁸ This provides the directionality of bonding,^{59,60} which is however not a strict condition for a nonclassical H-bond.

The bonding of planar π -conjugated systems, which are closely arranged in parallel, is known as $\pi\cdots\pi$ interaction or π -stacking.⁶¹ Hunter and Sanders⁶² emphasized the electrostatics and dispersion (van der Waals) contributions to $\pi\cdots\pi$ interaction, while the charge transfer was reported to have minimal stabilization effects. Interaction of aromatic fragments has been shown^{63–66} to play an important role in chemical and biological recognition,⁶⁷ the structure of proteins,⁶⁸ and molecular self-assembly.⁶⁹

The interaction between the lone electron pair of a heteroatom and a π -system, in short $LP\cdots\pi$ or $n\rightarrow\pi^*$, has caught the attention in the supramolecular chemistry,⁷⁰ biochemical systems,⁷¹ and catalyst design.⁷² The nature of this interaction was thought to be mainly electrostatic with the effective negative charge concentration region of an LP oriented toward the effective positive “hole” in the center of the electron-deficient π -system.^{73–75} However, recent works^{76–79} criticized this approach and noted the contribution of dispersion effects to the formation of $LP\cdots\pi$ interactions as well as charge transfer from the heteroatom to the π -system.

Many other noncovalent interactions contribute to the formation of solids.⁸⁰ Examples include C–H $\cdots\pi$, cation $\cdots\pi$, and anion $\cdots\pi$ interactions,⁷² halogen bonds,⁸¹ and contacts involving carbonyl groups.^{82,83}

Scheme 1. Structural formula for 1,6-dimethyl-3-propargyl-2,4-pyrimidinedione and partial numbering scheme adopted in this article

To the best of our knowledge, no prior studies incorporating the $\mathcal{F}(\mathbf{r})$ and $F_k(\mathbf{r})$ force description for molecular noncovalent interactions in crystals were made. Moreover, Pauli potential $\varphi_P(\mathbf{r})$ and corresponding force $F_P(\mathbf{r})$ has not yet been studied for closed-shell bonding as well. Herein we attempted to fill that gap and take the orbital-free quantum crystallographic approach to describe the noncovalent interactions in the crystalline state by considering the local potentials and corresponding forces. Comparison with the more common bonding descriptors enhanced the understanding of both the nature of donor-acceptor bonding and the behavior of advanced physical quantities used. We have recently performed a high-resolution X-ray diffraction experiment on 1,6-dimethyl-3-(prop-2-yn-1-yl)pyrimidine-2,4(1*H*,3*H*)-dione (DMPU)⁸⁴, a derivative of 6-methyluracil, which presented itself as an attractive research object due to the rather diverse set of noncovalent interactions, such as nonclassical hydrogen bonds essential for organic crystals as well as more rare but not less important π -stacking interactions. The structural formula and atom labels for DMPU are shown in Scheme 1. A more interesting feature of the crystal structure is an intriguing short intermolecular contact $[\text{C}=\text{O} \cdots \text{N}(\text{sp}^2)]$, which is surprisingly strong – among the strongest in the crystal. Mention should be made to a few examples of other experimental charge density studies of the uracil derivatives.^{85–87}

EXPERIMENTAL SECTION

General. The synthesis DMPU, molecular structure determination, and refinement within the Hansen–Coppens multipole model were performed in our previous work.⁸⁴ DMPU crystallizes in the monoclinic space group $P2_1/c$ with one molecule in the asymmetric cell. The experiment was performed on an Agilent Xcalibur E diffractometer using Mo $K\alpha$ radiation at 100.0(5) K. The data ($R_{int} = 0.0287$ and $R_\sigma = 0.0089$) were collected up to resolution $\sin(\theta)/\lambda$ of 1.160 $\text{\AA}^{-1}$ with the final disagreement factors $R(F) = 0.0243$ and $wR(F) = 0.0229$. ORTEP picture for the DMPU showing anisotropic displacement ellipsoids at the 80 % probability is shown in Figure S1.

Experimental electron density analysis. Analysis of experimental ED was performed using the *WinXPRO* v3.4.31, *3DPlot* v2.5.18, and *TrajPlot* v.1.4.0.2 software^{88–90}. The many-configuration wave function bank of Su and Coppens,⁹¹ the same as for the multipole refinement, was used. Atomic coordinates and numerical multipole parameters were adopted from our previous paper.⁸⁴ If not stated otherwise, the spherical cluster with a radius of 15 $\text{\AA}$ around atom N3 with 1466 atoms in total was used for all calculations.

The CP search in the scalar fields $\rho(\mathbf{r})$, $-v(\mathbf{r})$, $\varphi_{es}(\mathbf{r})$, $\varphi_{em}(\mathbf{r})$, and $\varphi_k(\mathbf{r})$ was performed. The maximal distance of 4.5 $\text{\AA}$ for the “atom-atom” search was chosen. For the calculation of energy densities at bond CPs, kinetic energy density $g(\mathbf{r})$ was approximated according to Kirzhnits.³¹ In some figures below, bond CPs are visually represented by ellipsoids⁹² with the principal semiaxes directly proportional to the value of ρ_b and inversely proportional to the eigenvalues of the Hessian matrix $\lambda_{1,2,3}$ [$\text{e \AA}^{-5}$]. BCPs on noncovalent interaction lines tend to have the curvatures $\lambda_{1,2}$ close to zero ($|\lambda_3| \gg |\lambda_{1,2}|$), which results in the discoid shape of CP-ellipsoids, with the largest λ_3 value aligned with a bond path. Various properties along bond paths were calculated using the grid step length of 0.01 $\text{\AA}$ or less.

Atomic ρ -basins and atomic-like φ_{es} - and φ_k -basins were defined with tolerance on an interatomic surface radius of $5 \cdot 10^{-5}$ $\text{\AA}$. Angular parameters $n\theta$ and $n\varphi$ defining the number of grid points inside a β -sphere were set to 96 and 120, respectively. An increment factor for the bond CP search was equal to

0.1 Å. Bader charges were calculated by integrating $\rho(\mathbf{r})$ over the volume of an atomic ρ -basin and subtracting the result from the nuclei charge value.

Gradient trajectories of $\rho(\mathbf{r})$, $\varphi_{es}(\mathbf{r})$, and $\varphi_k(\mathbf{r})$ were calculated with the following parameters: a step along the gradient path of 0.005 Å, an out-of-plane distance up to 0.5 Å, and a cut-off value for gradient path termination $|\nabla f(\mathbf{r})|$ of $0.1 \cdot 10^{-5}$.

Two- and three-dimensional distributions of various functions were calculated with a step size of 0.05 Å or smaller according to the orbital-free formulae presented in the SI. Von Weizsäcker potential $\varphi_w(\mathbf{r})$ was calculated using the exact expression.⁴⁷ ESP was computed within the finite electroneutral cluster.^{93,94} It should be noted that the obtained values of $\varphi_{es}(\mathbf{r})$ and related functions, such as $\varphi_p(\mathbf{r})$ and $\varphi_{em}(\mathbf{r})$, are strongly affected by its size, location of point $\mathbf{r}$ relative to the cluster center, and charge asymmetry. Therefore, the largest possible spherical cluster was constructed to simulate the crystalline environment. The difference between properties $\varphi_{es}(\mathbf{r})$, $\varphi_{em}(\mathbf{r})$, and $\varphi_p(\mathbf{r})$ calculated along the bond paths for the symmetry-related pairs of intermolecular contacts of the central molecule was less than 0.01 a.u. The Pauli potential $\varphi_p(\mathbf{r})$ was computed according to Tsirelson and Liu et al.⁵² with chemical potential $\mu(\mathbf{r}) = \text{const}$ set to zero.⁹⁵ For local exchange $\varphi_x(\mathbf{r})$ and correlation $\varphi_c(\mathbf{r})$ potentials, orbital-free local density approximations from von Barth–Hedin⁹⁶ and Chachiyo–Karasiev^{97,98}, respectively, were used. The KED-dependent functions, such as ELF³⁵ and local temperature $t(\mathbf{r})$,³⁶ were computed using recently developed semi-local orbital-free approximation for $g(\mathbf{r})$ by Tsirelson et al.,³² it is notated as AST throughout the paper. The exchange-correlation term was expressed using van Leeuwen–Baerends exchange potential⁹⁹ with correct asymptotic long-range behavior. Three-dimensional distribution of reduced density gradient $\sigma(\mathbf{r})$ ^{100,101} was computed for the isolated molecular dimer, while isosurfaces for exchange $\varepsilon_x(\mathbf{r})$ and correlation $\varepsilon_c(\mathbf{r})$ energy densities per particle were calculated for the trimer using Becke¹⁰² and Lee–Yang–Parr¹⁰³ approximations, respectively. The source function for experimental ED was evaluated according to the standard procedure.¹⁰⁴

Calculated electron density analysis. The optimized crystal geometry and periodic wavefunction for further analysis were obtained in our previous work⁸⁴ using *CRYSTAL17* 1.0.2 at the ω B97X/pob-TZVP-rev2 level of approximation. The total energy convergence tolerance of 10^{-10} was chosen. The values of the truncation criteria for bielectronic integrals were the following: overlap threshold for Coulomb integrals and Hartree-Fock exchange integrals is equal to 10^{-8} a.u., penetration threshold for Coulomb integrals is 10^{-8} a.u., and the first and second criteria for pseudo-overlap are set to 10^{-8} and 10^{-24} a.u. The shrinking factor of 8 for the Pack–Monkhorst net was used. The computed vibrational frequencies at the Γ -point were positive.

The topological analysis of periodic ED was performed with the *TOPOND2014* software.^{15,105} For the search of bond CPs in $\rho(\mathbf{r})$, the fully automated chain-like strategy in the TRHO module was chosen. The maximum number of EF steps and an NNB variable were set to 40 and 30, respectively. The maximum radius of atomic clusters was set to 10 Å via an RMAX variable. Determination of atomic ρ -basins and integration of selected properties over them were performed in the ATBP module of *TOPOND*. The three-dimensional ELF distributions were calculated with the step size of 0.05 Å using the PL3D module of *TOPOND*.

To preserve the mutual orientation of molecules in the crystalline state, wave function single point calculation of the isolated DMPU dimer or molecule extracted from a crystal was carried out in *Gaussian* 16 (ω B97X-D/aug-cc-pVTZ level of approximation). NBO analysis for the calculated dimer with the search for 3-center bonds and delocalized structures was performed in the *NBO* 3.1 program.¹⁰⁶

RESULTS AND DISCUSSION

Molecular Structure: Electron Distribution and Charge Concentration. Figure 1a shows the deformation electron density map in the plane of the heterocyclic fragment, which reveals the regions of local ED accumulation and reduction, as compared with the spherical atom superposition. The electron delocalization intrinsic to amide and enone conjugated systems is somewhat reflected in the ED

accumulation on the C–C and C–N covalent bonds within the planar heterocycle. As expected, both carbonyl groups feature the characteristic deformation density. Each oxygen atom is characterized by two positive peaks of $\delta\rho(\mathbf{r})$ almost in the plane of heterocycle related to the excessive ED in the nonbonding region and one negative density peak located on the C=O double bond closely to the oxygen nucleus.

Figure 1. Contour maps of deformation density $\delta\rho(\mathbf{r})$ in steps of $0.1 \text{ e } \text{\AA}^{-3}$ (a), the Weizsäcker potential $\varphi_W(\mathbf{r})$ in steps of 0.4 a.u. (b), and approximate electron localization function $\eta_{AST}(\mathbf{r})$ with contour interval at 0.05 (c) plotted in the DMPU heterocyclic plane. Hereinafter, positive, zero, and negative contours are given in blue, green, and red, respectively; the intervals between the major sticks on the axes are set to $1 \text{ \AA}$; for ELF, contours within the intervals $[0, 0.5)$ and $(0.5, 1]$ are shown by dotted and solid lines, respectively, while the contour of 0.5 is dashed.

The regions of positive $\delta\rho(\mathbf{r})$ close to O nuclei coincide with the ones of negative $\nabla^2\rho(\mathbf{r})$ (Figure S2a). They indicate the positions of the nonbonding valence shell charge concentrations (VSCCs), which are usually linked with LPs, and positive regions of von Weizsäcker potential $\varphi_W(\mathbf{r})$ (Figure 1b). Note that the Laplacian of ED shows the curvature of ED and thus only has a topological meaning, while the quantum-mechanical interpretation of a VSCC can be based on the Hunter work.⁴⁶ In the von Weizsäcker

potential $\varphi_W(\mathbf{r}) = \frac{1}{8} \frac{|\nabla\rho(\mathbf{r})|^2}{\rho^2(\mathbf{r})} - \frac{1}{4} \frac{\nabla^2\rho(\mathbf{r})}{\rho(\mathbf{r})}$, the first term is always positive, while the second one takes the same sign as $-\nabla^2\rho(\mathbf{r})$ (see Eq. S10). In regions of space where $\varphi_W(\mathbf{r}) > 0$, an electron motion is classically allowed. Conversely, $\varphi_W(\mathbf{r}) < 0$ denotes the classically forbidden regions where the electron kinetic energy may be negative. In the other words, the regions of $\varphi_W(\mathbf{r}) > 0$ correspond to the negative values of $\nabla^2\rho(\mathbf{r})$ and, therefore, to the local electron space concentration, and vice versa. The behavior of $\varphi_W(\mathbf{r})$ is extensively studied now for crystals.^{48,107,108}

A widely used chemical descriptor for the localization of electron pairs is ELF,^{33,34} a dimensionless scalar function, which measures the local excess of Pauli kinetic energy density $g_P(\mathbf{r})$ relative to the uniform electron gas. In the given interpretation, the regions with $\eta(\mathbf{r}) > 0.5$ correspond to electron pair localization, making them “visible” in the position-space. In the experimental implementation,³⁵ approximate ELF depends on $\rho(\mathbf{r})$, $|\nabla\rho(\mathbf{r})|$, and $g_P(\mathbf{r})$ (Eq. S2). The Kirzhnits³¹ (Eq. S3) and AST³² (Eq. S4) approximations are used to describe KED. The former approximation shows a distinct “double-humped” peak of ELF on covalent bonds³⁵ (Figure S2b), which seems like an inheritance of Laplacian and contradicts the exact theoretical ELF.⁸⁴ AST-approximated ELF (Figure 1c) exhibits single peaks on covalent bonds and a more uniform distribution in the regions of ED accumulation and VSCC near the carbonyl oxygen atoms. Notably, the important difference between the AST-based ELF and wavefunction-derived one is the more expanded character of the latter (vide infra).

Crystal Structure and Intermolecular Interaction. We start by discussing the distribution of molecular ESP mapped on the isodensity surface of the free DMPU molecule (Figure S3). The ESP at any point in three-dimensional space reflects the work that needs to be done to move the test positive charge from infinity to that point. As expected, the negatively charged oxygen atoms O2 and O4 are characterized by the identical uniform distribution of negative $\varphi_{es}(\mathbf{r})$ with no signs of σ -hole on either of them. Carbon and hydrogen atoms, on the other hand, show close to zero or positive potential values,

respectively. Nitrogen atom N1 features a region of locally increased $\varphi_{es}(\mathbf{r})$ on the van der Waals surface, which may be interpreted as a manifestation of a π -hole.¹⁰⁹

To go over to the consideration of inner-crystal ESP distribution, a suitable molecular boundary needs to be defined. The partitioning of three-dimensional space can be done using the atomic ρ -basins, which are defined within QTAIMC as a portion of space enclosed by the surface $S(\mathbf{r})$, at every point of which the flux of gradient vector field $\nabla\rho(\mathbf{r})$ vanishes: $\nabla\rho(\mathbf{r}) \cdot \mathbf{n}(\mathbf{r}) = 0$ for $\forall \mathbf{r} \in S(\mathbf{r})$. Another way to define the molecular boundary is to construct the van der Waals surface of the DMPU molecule.

Figure 2 presents the mapping of $\varphi_{es}(\mathbf{r})$ on the atomic ρ -basins calculated considering the molecular environment and the isodensity van der Waals surface of 0.001 a.u. ($6.7483 \cdot 10^{-3} \text{ e A}^{-3}$) for the molecule “extracted from the crystal”. After switching on the crystalline environment, ESP becomes positive everywhere on the surfaces, reflecting the influence of intermolecular interactions. The effect of neighboring molecules is particularly apparent in the case of O2, which is characterized by the presence of three spherical zones of increased ESP both on the atomic ρ -basin surface and ρ -isosurface (Figure 2b, d). Since we are not able to locate these features for the free molecule, they were interpreted as a consequence of in-crystal intermolecular contacts. In particular, regions of increased $\varphi_{es}(\mathbf{r})$ near O2 are caused primarily by the proximity of the H9, H7a, and H11c nuclei, with $\varphi_{es}(\mathbf{r})$ values in the region of the contact decreasing together with an increase in $\text{O} \cdots \text{H}$ distances (Table 1). Notably, the basin of the O2 atom has the distinct shape of a three-sided pyramid, with each side facing one of the three mentioned hydrogen atoms.

Figure 2. Inner-crystal electrostatic potential $\varphi_{es}(\mathbf{r})$ [$\text{e } \text{\AA}^{-1}$] mapped on ρ -basins (a, b) and ρ -isosurfaces of 0.001 a.u. for the DMPU molecule “extracted from the crystal” (c, d).

Considering the interpenetration of contact atomic spheres (Figure S4), one can notice that the atom O4 is in close contact with atoms N1, C2, and C6 of the neighboring molecule. Corresponding interatomic distances are 0.22, 0.04, and 0.15 Å shorter than the sum of the atomic van der Waals radii, respectively. With that, we assume the existence of the interaction between the oxygen atom and the part of the π -system. The potentially nucleophilic atom O4 approaches the atom N1 in the direction of the abovementioned π -hole, resulting in the “compensation” of ESP on the molecular surfaces in the crystal (Figure 2a, c) with a small positive $\varphi_{es}(\mathbf{r})$ values expanded to C2 and C6 atoms. A region of locally increased $\varphi_{es}(\mathbf{r})$ near the N1 and O4 atoms (small green region) located on the ρ -isosurface can be interpreted as a trace of the π -hole of the N1 atom. At the same time, this feature is not observed on the atomic ρ -basins due to the different volume occupied by the two surfaces, which is clearly represented by their superposition in Figure S5.

To identify the bonding intermolecular contacts, the BCPs and corresponding bond paths are found. The complete list of BCPs and their topological characteristics is presented in Tables S1 and S2. All the non-covalent intermolecular interactions are characterized by $\rho_b < 0.1 \text{ e } \text{\AA}^{-3}$, $\nabla^2\rho_b > 0$, and a ratio

$|v_b|/g_b < 1$; they belong to the closed-shell type.^{110,111} The experimental topological characteristics for the BCPs are generally in good agreement with theoretical ones calculated for the optimized crystal geometry. The biggest difference is observed for the three nonclassical hydrogen bonds, for which the theoretical values of ρ_b are systematically higher (Table 1). Notably, the Kirzhnits KED-expression provides a good agreement of experimental energy densities at the non-covalent BCPs with the ones derived from the wave function. The virial of the Ehrenfest force exerted on the electron density at a point by the nuclei and by the average distribution of other electrons and defines the electronic potential energy density $v(\mathbf{r})$.²⁰ Since the ED distribution is structurally homeomorphic to the inversed potential energy density $-v(\mathbf{r})$, saddle CPs (3, -1) and associated virial paths were found in $-v(\mathbf{r})$ ¹¹² for all present noncovalent interaction.

Table 1 lists the selected interactions responsible for crystal structure formation, which are classified as nonclassical hydrogen bonds, an interaction of carbonyl's oxygen atom with π -system, and $\pi \cdots \pi$ stacking of neighboring uracil heterocycles. The C-H $\cdots$ O and [C=]O $\cdots\pi$ contacts are represented by a single bond path, while the $\pi \cdots \pi$ interaction is characterized by a total of four bond paths, two of which are symmetrically independent. Interactions energies were estimated via correlations based on the link between the interaction energy E and the potential v_b or kinetic g_b energy densities at a BCP.^{113,114} The interaction energy of the hydrogen bond gradually decreases with the increase in O $\cdots$ H distance and reduction of s-character of the hybrid orbitals of corresponding carbon atom: $sp > sp^2 > sp^3$, or in other words, with a decrease of electronegativity of the carbon atom. Even though the bond distance between the O4 and N1 atoms is distinctly larger than for H-bonds, the topological characteristics at the BCPs suggest that this interaction is of similar strength with the strongest O2 $\cdots$ H9 hydrogen bond: $E_v = 2.23$ kcal $\cdot$ mol $^{-1}$ and $E_g = 2.61$ kcal $\cdot$ mol $^{-1}$ for the O2 $\cdots$ H9 contact versus $E_v = 2.43$ kcal $\cdot$ mol $^{-1}$ and $E_g = 2.60$ kcal $\cdot$ mol $^{-1}$ for the O4 $\cdots$ N1 contact. To our surprise, the energy of O4 $\cdots$ N1 contact turned out to be

comparable and even higher than those reported for the analogous interactions between an oxygen atom and a π -system, namely $E_v = 1.2$ (ref.¹¹⁵) and 2.05 (ref.¹¹⁶) kcal·mol⁻¹.

Table 1. Experimental and Theoretical Topological Properties for the Selected Intermolecular Interactions in DMPU Crystals ^a

Contact ^b	d	d_1	d_2	ρ_b	$\nabla^2 \rho_b$	λ_{1b}	λ_{2b}	λ_{3b}	$g_b \cdot 10^3$	$v_b \cdot 10^3$	$h_b \cdot 10^3$
Nonclassical Hydrogen Bonds ^c											
O2...H9 ⁽ⁱ⁾	2.21(12)	1.394	0.841	0.065	1.222	-0.251	-0.198	1.670	9.695	-6.713	2.982
	2.20579	1.379	0.848	0.090	1.414	-0.349	-0.346	2.108	11.571	-8.477	3.094
O2...H7a ⁽ⁱⁱ⁾	2.4108(2)	1.462	0.966	0.044	0.847	-0.159	-0.145	1.150	6.524	-4.257	2.267
	2.41745	1.463	0.972	0.061	0.853	-0.198	-0.187	1.238	6.779	-4.707	2.072
O2...H11c ⁽ⁱⁱⁱ⁾	2.66(16)	1.538	1.158	0.033	0.521	-0.101	-0.096	0.721	4.013	-2.619	1.394
	2.60681	1.534	1.102	0.045	0.568	-0.128	-0.120	0.816	4.659	-3.422	1.237
[C=]O... π Interaction ^d											
O4...N1 ^(iv)	2.8502(3)	1.371	1.479	0.077	1.158	-0.207	-0.193	1.557	9.671	-7.327	2.344
	2.84572	1.377	1.472	0.077	1.162	-0.223	-0.175	1.560	10.371	-8.690	1.681
π ... π Stacking ^e											
N1...C5 ^(v)	3.3678(3)	1.675	1.695	0.039	0.460	-0.082	-0.039	0.581	3.727	-2.677	1.050
	3.38473	1.672	1.723	0.042	0.481	-0.103	-0.048	0.631	4.204	-3.421	0.783
N3...C6 ^(v)	3.4618(3)	1.761	1.746	0.029	0.346	-0.058	-0.007	0.410	2.712	-1.839	0.873
	3.48375	1.753	1.865	0.032	0.403	-0.059	-0.020	0.482	3.302	-2.425	0.877

^a Units of measurement are as follows: interatomic d and atom-BCP $d_{1,2}$ distances [Å]; electron density ρ_b [e Å⁻³]; the Laplacian of ED $\nabla^2 \rho_b$ and the eigenvalues $\lambda_{1,2,3}$ of the Hessian matrix of ED [e Å⁻⁵]; kinetic g_b , potential v_b , and electronic h_b energy densities [a.u.]. Subscript b indicates that the property was calculated at the BCP. Upper rows for each bond contain the experimental data obtained from the multipole model, while the data for the second ones were calculated based on the periodic wave function obtained from the optimized crystal structure. Experimental energy densities were estimated within the Kirzhnits approximation. ^b Symmetry codes are as follows: (i) 2-x, y-0.5, 0.5-z; (ii) 2-x, 1-y, 1-z; (iii) 1+x, y, z; (iv) x, 1.5-y, 0.5+z; (v) 1-x, 1-y, 1-z; (vi) 1-x, 1-y, -z. ^c Some additional parameters for H-bonds: $d(\text{O2} \cdots \text{C9}) = 3.23418(38)$ Å, $\angle(\text{O2 H9 C9}) = 158.5(46)^\circ$, $\angle(\text{C2 O2 H9}) = 137.39(19)^\circ$, $n_{\text{topo}} = 0.027(\text{exp.})/0.036(\text{calc.})$; $d(\text{O2} \cdots \text{C7}) = 3.42336(31)$ Å, $\angle(\text{O2 H7a C7}) = 153.53(1)^\circ$, $\angle(\text{C2 O2 H7a}) = 127.848(15)^\circ$, $n_{\text{topo}} = 0.018/0.020$; $d(\text{O2} \cdots \text{C11c}) = 3.48235(32)$ Å, $\angle(\text{O2 H11c C11c}) = 132.0(88)^\circ$, $\angle(\text{C2 O2 H11c}) = 139.3(9)^\circ$, $n_{\text{topo}} = 0.016/0.018$. ^d $d(\text{O4} \cdots \text{C2}) = 3.1819(3)$ Å, $d(\text{O4} \cdots \text{C6}) = 3.0667(3)$ Å, $\angle(\text{C4 O4 N1}) = 166.88(2)^\circ$. ^e Centroid-to-centroid distance of 3.4362(2) Å, plane-to-centroid distance of 3.3371(2) Å, plane-to-plane shift of 0.8194(4) Å.

Concerning uracil-uracil interaction, two bond paths for N1...C5 and N3...C6 contacts are present. They are characterized by the lowest values of ρ_b among the selected contacts. To determine whether the appearance of these BCPs can be considered as an actual feature of ED, we followed the procedure presented in ref.¹¹⁷ and analyzed the ED in intermolecular regions in terms of information theory. The Shannon information entropy density $s(\mathbf{r}) = -\rho(\mathbf{r})/N \cdot \ln(\rho(\mathbf{r})/N)$ was utilized, where N is the number of electrons in the unit cell. This descriptor provides the means for a statistical evaluation of structural order within a system by comparing it with a uniform electron distribution, for which $s(\mathbf{r})$ is also distributed uniformly.⁹⁰ Conversely, in the regions of ED concentration the electron-electron repulsion increases, which leads to a lack of information about their spatial position and a corresponding increase of $s(\mathbf{r})$. By comparing the Shannon information entropy density s_b calculated for the experimental ρ_b and $s_n(\mathbf{r})$, which is the entropy density of a uniform electron distribution (a model for experimental noise), one can determine whether the ED under consideration carries the information about bonding at a particular BCP. For the two BCPs corresponding to the $\pi \cdots \pi$ interaction, the values of s_b are equal to $1.70 \cdot 10^{-4}$ and $1.30 \cdot 10^{-3}$ a.u. The noise level in the intermolecular region of π -stacking was obtained using the sample standard deviation procedure,¹¹⁸ the value was safely estimated to be less than $1.5 \cdot 10^{-4}$ a.u., which results in $s_n(\mathbf{r})$ for noise less than $5.81 \cdot 10^{-6}$ a.u. From these results we can conclude that the ED in the region of $\pi \cdots \pi$ stack is informationally meaningful. Consequently, the found BCPs for the N1...C5 and N3...C6 contacts contain the structural information and can be used to identify the bonding interaction.

Intermolecular contacts discussed above participate in the formation of DMPU crystal structure in the following way. One can identify the one-dimensional hydrogen-bonded zig-zag chains along the longest axis $0b$ of the unit cell, formed by the shortest O2...H9 hydrogen-bonds. These chains are sewed together in the direction of the $0c$ axis by the N1...O4 contacts, which play the role of a secondary cross-linker and build the two-dimensional layers. Within these layers, $\pi \cdots \pi$ interactions between the uracil

moieties are formed by the inversion centers. Eventually, the weak intermolecular contacts, such as the O2...H11c hydrogen bonds, form a three-dimensional structure with a packing index of 73.0 %, which is quite dense.

Figure 3. Fragments of DMPU molecules packing in the crystal according to XRD: views along the 0a (a) and 0c (b) axes. Inversion centers, glide planes, and two-fold rotation axes are marked by yellow spheres and purple and green symbols, respectively. The selected H-bonded chain is highlighted in magenta. Noncovalent bonds [C=]O4...N1 and [C(sp)-]H9...O2 are shown by blue and green dashed lines.

Hydrogen bonds. Let us discuss the nature of found noncovalent contacts in more detail. Figure 4a features the three-dimensional distribution of $\delta\rho(\mathbf{r})$ in the region where the three main hydrogen bonds

in the DMPU crystal are observed. For each of them, the BCP ellipsoid takes the shape of a rather compact, non-elongated discoid, which demonstrates rather pronounced curvatures of ED $|\lambda_{1,2}|$ at this CP.

We can distinguish three different contributions to the formation of a hydrogen bond. Firstly, the electrostatic contribution can be discussed in terms of Bader charges and internuclear distance for a pair of considered atoms. The atom O2 is characterized by the negative charge of -1.022 e, while the interacting hydrogen atoms carry relatively small positive charges: $+0.219$ e (H9), $+0.128$ e (H7a), and $+0.176$ e (H11c). The strongest H-bond $\text{O2}\cdots\text{H9}$ has the shortest donor-acceptor distance of $2.21(12)$ Å and the highest difference in charges between the oxygen and the hydrogen atoms, which results in the greatest electrostatic contribution compared to the other two H-bonds $\text{O2}\cdots\text{H7a}$ ($2.4108(2)$ Å) and $\text{O2}\cdots\text{H11c}$ ($2.66(16)$ Å). Theoretical Bader charges of the H-atoms are still positive, but are closer to zero, while the oxygen atom O2 appears slightly more negative (Table S3).

The second contributing factor is the atomic charge transfer and polarization. To estimate this effect, we utilized the method of superimposing the gradient fields of $\rho(\mathbf{r})$ and $\varphi_{es}(\mathbf{r})$, first introduced in ref.⁵⁵ and successfully applied in several studies.^{107,117,119–123} Analogously to $\rho(\mathbf{r})$, there exists a vector electric field $\nabla\varphi_{es}(\mathbf{r})$, within which the atoms are separated by the surfaces S_{es} , satisfying the zero-flux condition: $\nabla\varphi_{es}(\mathbf{r}) \cdot \mathbf{n}(\mathbf{r}) = 0$, $\forall \mathbf{r} \in S_{es}(\mathbf{r})$. As it was indicated earlier,⁵⁵ the surfaces S_{es} define the atomic φ_{es} -basins, where the nuclear charges are completely screened by the corresponding electronic charge. Therefore, the volumes enclosed by S_{es} surfaces are viewed as electrically neutral bonded pseudoatoms. ED at any point $\mathbf{r}$ within each atomic basin is attracted only to the corresponding nucleus. Based on that definition, if a ρ -basin of one atom penetrates into a φ_{es} -basin of another one, the part of ED gathered within the basins overlap is captured by the former one. So, the atom with the expanded φ_{es} -basin gotten through the ρ -boundary acts as an ED *contributor*, while the atom which has the boundary of its ρ -basin expanded to the φ_{es} -basin of the second atom plays the roles of an ED *occupier*.

In other words, electrons in the overlap region between the φ_{es} - and ρ -basins of two neighboring atoms belong to the QTAIMC-defined chemical atom but attracted by the electronic inner-crystal electrostatic force $\mathbf{F}_{es}(\mathbf{r}) = \nabla\varphi_{es}(\mathbf{r})$ acting toward the nucleus of neighboring electrically neutral bonded pseudoatom.

Figure 4. Deformation density isosurfaces $\delta\rho(\mathbf{r}) = \pm 0.18 \text{ e } \text{\AA}^{-3}$ in the region of atom O2 (a), deformation density contour map (contour step is $0.05 \text{ e } \text{\AA}^{-3}$) in the plane of two hydrogen bonds (b), and the electrostatic force field $\mathbf{F}_{es}(\mathbf{r})$ in the same plane (c). For figure (a), BCPs are presented by ellipsoids. For (b) and (c), the superposition of boundaries of $\nabla\rho(\mathbf{r})$ (black) and $\nabla\varphi_{es}(\mathbf{r})$ (blue) is shown. Hereinafter, bond paths on isosurface representations or maps are colored according to the element types or given by red solid lines, respectively; BCPs are presented in magenta; CPs (3, -1) of $\varphi_{es}(\mathbf{r})$ and φ_{es} -paths are shown for H-bonds as violet rhombuses and lines.

In the DMPU crystal, the φ_{es} -basins of both oxygen atoms O2 and O4 are far smaller than the corresponding ρ -basins and have a more spherical shape compared to other elements. For instance, the ρ -basin of the O2 atom has a volume of $18.15 \text{ \AA}^3$, while its φ_{es} -basin is only $6.09 \text{ \AA}^3$. Most of the difference was acquired from the adjacent hydrogen atoms H7a, H9, and H11c. Detailed experimental and theoretical data on atomic basins and selected integrated properties are presented in Table S3. As

can be seen from Figure 4b and c, φ_{es} -basins of the neighboring atoms overlap with the ρ -basin of O2, suggesting an appreciable amount of captured ED by the oxygen atom from the environment. Within the areas of basins' overlap marked by green and yellow sections in Figure 4c the electrostatic force $\mathbf{F}_{es}(\mathbf{r})$ acts toward the nuclei of hydrogen atoms H9 and H11c. Thus, the charge transfer visualized through the overlap between φ_{es} -basins of H-atoms and ρ -basin of O2 atom occurs from the hydrogen atoms toward the oxygen atom.

A single line, formed by a pair of gradient lines originating from a saddle CP (3, -1) in $\varphi_{es}(\mathbf{r})$ and terminating at nuclei of neighboring atoms is called a φ_{es} -path. For the three main H-bonds in the DMPU crystal, the saddle CPs (3, -1) in $\varphi_{es}(\mathbf{r})$ as well as the corresponding φ_{es} -paths were successfully found. Notably, for the O2...H9 hydrogen bond, the trajectories of the φ_{es} - and bond paths almost coincide, while in the case of O2...H11c they are highly divergent. Figure 4b shows that the bond path closely follows the shortest route between the two atoms, whereas the φ_{es} -path crosses the regions of positive and negative $\delta\rho(\mathbf{r})$ near the O2 and H11c atoms, respectively.

As are classical hydrogen bonds, nonclassical ones possess the property of directionality, which is reflected in a bond path trajectory and the mutual orientation of positive and negative $\delta\rho(\mathbf{r})$ regions, corresponding to electron lone pairs and ED deficient regions, respectively. In turn, the covalency of interaction can be described with the donor-acceptor type of ED sharing.⁵⁸ In the case of the strongest hydrogen bond O2...H9, the region of $\delta\rho(\mathbf{r})$ at the atom O2 (LP) is oriented exactly at the region of negative $\delta\rho(\mathbf{r})$ near the H9 atom (vacancy). In contrast, the two hydrogen atoms H7a and H11c share the other LP (Figure 4b), which becomes evident from the bond path trajectories in Figure 4a. As was previously mentioned, the basin of the O2 atom is shaped like a three-sided pyramid, where one side is occupied by a single LP, while the other one is located near the edge of a pyramid, facing two hydrogen atoms H7a and H11c at once. A clear representation of this can be found in Figure S6a, where the zero-flux surfaces (ZFSs) constructed for the three hydrogen bonds are shown. These ZFSs indicate where

the interatomic electron sharing occurs. The specific values of total electronic energy density, $h(\mathbf{r})$ integrated over the areas of ZFSs follow the trend of the estimated strength of the hydrogen bonds, although the areas themselves are quite similar, ranging between 4.01 Å² for O2···H11c and 5.62 Å² for O2···H7a. Namely, O2···H9 hydrogen bond has the highest value of specific integrated total energy of $1.14 \cdot 10^{-3}$ a.u., while the O2···H7a and O···H11c bonds are characterized by values of $8.25 \cdot 10^{-4}$ and $7.12 \cdot 10^{-4}$ a.u., respectively.

In summary, we can distinguish two different cases of hydrogen bond formation. In one, one LP of the single oxygen atom is donated wholly to the hydrogen atom H9, while in the other case LP is bifurcated between the two H-atoms, forming two hydrogen bonds simultaneously. Loss in directionality⁶⁰ in the case of O2···H7a and O···H11c hydrogen bonds leads to their significant weakening. What is more important, is that the direction of LP donation is reversed relative to the charge transfer discussed earlier. Namely, the atom O2 plays the role of an LP donor and an ED occupier, while the hydrogen atoms act as an LP acceptor and an ED contributor.

$\pi \cdots \pi$ Interaction between the Uracil Moieties. For both symmetrically independent intermolecular contacts N1···C5 and N3···C6 constituting the $\pi \cdots \pi$ interaction, absolute values of the first and second eigenvalues $\lambda_{1,2}$ of the Hesse matrix of ED are much lower than λ_3 . It indicates the lower ED curvature in the plane of the BCPs.

As opposed to individual atom-atom contacts identified by the presence of a BCP, the interaction of two uracil π -systems can be recognized with the decrease in local electronic temperature $t(\mathbf{r})$ in the intermolecular region, which locally measures the kinetic energy per electron at an external temperature equal to zero.³⁶ Figure 5 depicts the $t(\mathbf{r})$ distribution mapped on the continuous isosurface of reduced ED gradient.^{100,101} The areas of $t(\mathbf{r})$ lowering crossed by the bond paths of individual interatomic contacts denote the decreased electron velocity and coincide with the bonding areas of $\text{sign}[\lambda_2(\mathbf{r})] \cdot \rho(\mathbf{r}) < 0$ (Figure S7), but feature a noticeably more gradual character. Conversely, the “nonbonding”

areas of $\text{sign}[\lambda_2(\mathbf{r})] \cdot \rho(\mathbf{r}) > 0$ could be assigned to the relative increase in local electronic temperature. The interaction of π -systems is centrosymmetric, therefore $t(\mathbf{r})$ distribution is inversed on the opposite side of reduced gradient isosurface. Notably, the decrease of $t(\mathbf{r})$ is more pronounced from the side of carbon atoms C5 and C6, closer to the position of the bond CPs. In summary, we suggest the local electron temperature $t(\mathbf{r})$ as a useful bonding descriptor, which can be applied in conjunction with the reduced density gradient for studying the chemical bonding, in particular in π -stacking systems. It is important to note that $t(\mathbf{r})$ is a DFT-based orbital-free bonding descriptor, while the widely used characteristic $\text{sign}[\lambda_2(\mathbf{r})] \cdot \rho(\mathbf{r})$ is a topological descriptor.

Figure 5. Distribution of approximate local electronic temperature $t(\mathbf{r})$ [a.u.] mapped on the isosurfaces of reduced electron density gradient ($\sigma(\mathbf{r}) = 0.55$) in the region of $\pi \cdots \pi$ stacking.

The exchange $E_x[\rho]$ and correlation $E_c[\rho]$ energies describe the change in the total energy of a system due to the same-spin and spin-independent electron-electron interactions, respectively. Isosurfaces of Becke exchange $\varepsilon_x(\mathbf{r})$ and Lee–Yang–Parr gradient-corrected correlation $\varepsilon_c(\mathbf{r})$ energy densities per electron representing corresponding local energies are shown in Figure 6. The former reveals the areas of potential energy lowering due to the exchange quantum mechanical effect. The negative $E_x[\rho]$ is concentrated close to the molecular framework, where ED is high, and thus governs the shape of molecules in the crystal. Three molecular isosurfaces do not penetrate each other at the

chosen isovalue. On the other hand, the behavior of the $E_c[\rho]$ functional is more complicated. The surface of $\varepsilon_c(\mathbf{r})$ was constructed so that the volume of occupied space approximately coincides with that of $\varepsilon_x(\mathbf{r})$. This reveals the $\varepsilon_c(\mathbf{r})$ channels or bridges along the bond paths, e.g., N1 $\cdots$ C5, corresponding to the local decrease in Coulomb correlation energy. These bridges reflect the directionality and contribution of Coulomb correlation (quantum) effects to the formation of noncovalent bonds, such as $\pi\cdots\pi$ interaction. Analogous bridges were previously found for intermolecular O $\cdots$ O contacts in the α -polymorph of N₂O₄.¹²¹ Further, these constructions allow distinguishing between the two intermolecular contacts N1 $\cdots$ C5 ($\varepsilon_{cb} = -2.13 \cdot 10^{-4}$ a.u., $\varepsilon_{xb} = -0.133$ a.u.) and N3 $\cdots$ C6 ($\varepsilon_{cb} = -1.51 \cdot 10^{-4}$ a.u., $\varepsilon_{xb} = -0.120$ a.u.). Both exchange and correlation energy densities at the BCPs for the former contact are noticeably lower than for the latter one.

Figure 6. Isosurfaces of Becke exchange [$\varepsilon_x(\mathbf{r}) = -0.21$ a.u.] (a) and Lee–Yang–Parr gradient-corrected correlation [$\varepsilon_c(\mathbf{r}) = -2 \cdot 10^{-4}$ a.u.] (b) energy densities per electron calculated for the trimer extracted from the crystal environment.

The ELF $\eta(\mathbf{r})$ helps to establish the mechanism of noncovalent interactions. Figure 7 features the approximate and wave function derived ELF distributions in the planes of two contacts N1 $\cdots$ C5 and

N3 $\cdots$ C6. The approximate ELF distribution is in general agreement with the exact one. For both mentioned interatomic contacts regions of increased ELF and electron concentration at the nitrogen atoms N1 and N3 associated with π -density are facing the ELF holes and electron depletion near the carbon atoms C5 and C6. This serves as clear evidence of a donor-acceptor character^{35,124} of the heteroatomic $\pi\cdots\pi$ interaction.

Figure 7. Contour maps of experimental (a, d) and theoretical (b, e) electron localization functions $\eta_{AST}(\mathbf{r})$ and $\eta_{wf}(\mathbf{r})$ in the planes of paired N1 $\cdots$ C5 (a, b) and N3 $\cdots$ C6 (d, e) bond paths. The contour step is set to 0.05. Spatial orientations of the cross-sections within the $\pi\cdots\pi$ stack are shown in (c, f).

Despite the presence of BCPs for individual N1 $\cdots$ C5 and N3 $\cdots$ C6 contacts, no saddle CPs (3, -1) in $\varphi_{es}(\mathbf{r})$ were found in the region of $\pi\cdots\pi$ interaction. Both N atoms carry the negative Bader charges of ca. -1 e each, while the C5 and C6 atoms have slightly positive charges of +0.274 and +0.054 e., respectively. As can be seen from Figure 8, the atomic ρ -basins of the nitrogen atoms overlap with φ_{es} -basins of the carbon atoms yielding information on the charge transfer. The atoms N1 and N3 play the

role of ED occupiers along the corresponding bond paths. Similar to hydrogen bonds, where LP donation and charge transfer happen in opposite directions, within the $\pi \cdots \pi$ interaction N atoms simultaneously serve as π -density donors and ED occupiers (Figure 7). Additionally, we note that the charge transfer defined in terms of basin superposition may also occur between the atoms of two molecules within π -dimer not linked by the bond path, in particular between the carbon atoms (see Figure S8). In this way, the analysis of superposition of ρ - and φ_{es} -basins can serve as a useful tool for revealing and estimating charge transfer between the individual atoms linked or not by a bond path and regardless of whether interactions are of the shared- or closed-shell type, practical application for which can be found in charge-transfer complexes.

Figure 8. Superposition of gradient fields of the experimental electron density $\nabla\rho(\mathbf{r})$ (grey) and electrostatic potential $\nabla\varphi_{es}(\mathbf{r})$ (blue) associated with the partial charge transfer along the bond paths belonging to the LPs $\cdots\pi$ and $\pi\cdots\pi$ intermolecular interactions, which is showed by the expansion and

contraction of atomic basins' boundaries. CPs (3, -1) of $\varphi_{es}(\mathbf{r})$ between covalently-bonded atoms are omitted.

Lone Pairs' Bifurcation $\cdots\pi$ Interaction Involving the Carbonyl Group and the Uracil Moiety.

Figure 9 illustrates the O4 $\cdots$ N1 contact between the carbonyl oxygen atom and the sp² hybridized nitrogen atom of uracil heterocycle. Similar to hydrogen bonds discussed earlier, the discoid-shaped BCP ellipsoid points to the relatively high principal ED curvatures orthogonal to the direction of the bond path. The ZFS between the two bonded atoms (Figure S6b), unlike the ZFSs for hydrogen bonds, takes a convex shape with an area of 3.74 Å². A specific value of integrated total energy density over the area of the ZFS is equal to 1.51·10⁻³ a.u., which is higher than for hydrogen bonds and fits the regularity of the estimated interaction energies. Despite the relatively high energy of O4 $\cdots$ N1 contact in the crystal, “gas-phase” dimer structure optimization leads to significant geometry changes and the formation of a weak hydrogen bond instead (Figure S9).

As shown in Figure 6b, the bond path for O4 $\cdots$ N1 contact ($\varepsilon_{cb} = -5.09 \cdot 10^{-4}$ a.u.) passes through a wider bridge of negative correlation density $\varepsilon_c(\mathbf{r})$ as compared with N1 $\cdots$ C5. This indicates a significant contribution of electron correlation effects to the formation of the [C=]O $\cdots$ N(sp²) contact. In contrast to the $\pi \cdots \pi$ interaction, for which the BCPs are located in the region of relatively low ED, the BCP for O4 $\cdots$ N1 is characterized by a high value of ρ_b , and, consequently, a considerable contribution of exchange effects ($\varepsilon_{xb} = -0.166$ a.u.).

Figure 9 depicts two interacting molecules, which are mutually oriented so that the two regions of ED accumulation at the oxygen atom are located right above the corresponding regions of positive $\delta\rho(\mathbf{r})$ on the N1–C2 and N1–C6 covalent bonds of the conjugated system. Hence, the studied interaction can be considered as “two LPs $\cdots\pi$ ”. At the same, the bond path follows the shortest trajectory between the two atoms but does not cross any of the oxygen atom's LPs.

Figure 9. Regions of accumulation (blue) and reduction (red) of experimental electron density ($\delta\rho(\mathbf{r}) = \pm 0.18 \text{ e } \text{\AA}^{-3}$) within the LPs $\cdots\pi$ dimer formed by single intermolecular $[\text{C=}] \text{O4} \cdots \text{N1}$ contact. The BCP is shown by an ellipsoid.

Figure 10. Approximate (a, d) and theoretical (b, e) electron localization functions $\eta_{AST}(\mathbf{r})$ and $\eta_{wf}(\mathbf{r})$ in two mutually orthogonal planes containing $\text{O4} \cdots \text{N1}$ bond path. The latter was calculated directly from the periodic wave function obtained after crystal geometry optimization. The contour level is 0.05. Molecular orientations relative to the map planes are shown in (c) and (f) [colored from red ($\eta_{wf}(\mathbf{r}) = 0$) to blue ($\eta_{wf}(\mathbf{r}) = 1$)].

An analogous picture is observed in the ELF distribution shown in two different planes in Figure 10. The wavefunction-derived ELF is generally more expanded compared to the AST-approximate one, which in turn has a smoother character, e.g., less distinct maxima near the N atoms and not so pronounced maxima at the location of LPs of the O atom. As we described previously,⁸⁴ the theoretical ELF shows two distinct maxima at each nitrogen atom N1 and N3 above and below the molecular plane, which is additionally supported by the found Laplacian minima. Localization of π -density at nitrogen atom N1 from the side of LPs $\cdots\pi$ interaction is less pronounced than that from the N1 $\cdots$ C5 contact (Figure S10). Although the numeric values of ELF peaks are very close inside the valence shells of the O4 and N1 atoms, the former shows a slight ELF contraction in the outer region of its valence shell on the bond path, while the latter has a more pronounced maximum further toward the BCP. Hence, both theoretical and experimental data show that the π -density at the nitrogen atom in the form of ELF peak follows the direction of the bond path toward the two LPs' bifurcation. For the sake of comparison, the maps of phase-space-defined Fisher information density and Kirzhnits-approximated ELF are shown in Figure S11 and S12, respectively, which exhibit the analogous features at both interacting atoms.

Both O4 and N1 atoms appear to be almost equally negatively charged (Table S3). No CP (3, -1) in $\varphi_{es}(\mathbf{r})$ and φ_{es} -path was found between O4 and N1. The analysis of $\nabla\rho(\mathbf{r})$ and $\nabla\varphi_{es}$ gradient fields superposition in Figure 8a suggests that in the case of the O4 $\cdots$ N1 contact the oxygen atom plays the role of ED occupier, capturing the electrons from the φ_{es} -basin of the nitrogen atom. Thus, the direction of charge transfer defined in terms of basins' overlap coincides with the direction of the π -density donation from the nitrogen atom.

On the Electronic Potentials and Forces. We are now in a position to consider the interplay between the QTAIMC and the local potentials and corresponding electronic inner-crystal forces in the nonclassical H-bond [C(sp)-]H9 $\cdots$ O2, the strongest one in DMPU crystal, and in the intermolecular contacts N1 $\cdots$ O4[=C] and N1 $\cdots$ C5/N3 $\cdots$ C6 belonging to the LPs $\cdots\pi$ and $\pi\cdots\pi$ interactions,

respectively. Let us first look on the behavior of reverse electrostatic potential $-\varphi_{es}(\mathbf{r})$ and PAEM $\varphi_{em}(\mathbf{r})$ along the intermolecular bond paths and compare these functions for the same interatomic contacts. ESP is generated by classic Coulomb interactions of electrons and nuclei and is measured by the test positive unit charge external to a system. On the other hand, PAEM $\varphi_{em}(\mathbf{r})$ is interaction energy of any one electron at point $\mathbf{r}$ belonging to a system with the rest of the electrons and the nuclei;¹²⁵ it includes the inversed ESP, exchange, and correlation terms.⁵³ The gap between the values of ESP and PAEM at the BCP characterizes the contribution of the exchange-correlation potential $\varphi_{xc}(\mathbf{r})$ to the PAEM and serves as an estimate of the degree of covalency for a given chemical bond.^{126,127} The lower the PAEM-barrier, i.e., the more negative the value of $\varphi_{em}(\mathbf{r})$ at BCP is, the easier neighboring atoms share electrons. More negative values of PAEM corresponds to regions that are more preferable to electrons. It needs to be reiterated here that the results of calculations of both ESP and PAEM depend on an atomic cluster involved in calculations. Therefore, only relative values obtained with the same cluster will be analyzed.

As can be seen in Figure 11, the distribution of $-\varphi_{es}(\mathbf{r})$ along the bond path takes a “bell” shape with a tilted top and has its maximum shifted away from the BCP toward the atom with more “captured” electrons. The asymmetry of ESP can also be noted: $-\varphi_{es}(\mathbf{r})$ displays the flatter increase from the side of the atom less shielded by electrons, which has already been discussed above in terms of a superposition of gradient fields $\nabla\rho(\mathbf{r})$ and $\nabla\varphi_{es}(\mathbf{r})$ (see Figures 4c and 8). Conversely, the PAEM is shaped closer to a symmetrical bell and, being the sum of $-\varphi_{es}(\mathbf{r})$ and $\varphi_{xc}(\mathbf{r}) < 0$ attains the lower values than $-\varphi_{es}(\mathbf{r})$ over the whole range of $\mathbf{r}$.

For the interaction of π -systems consisting of two symmetrically independent contacts N1...C5 and N3...C6, the PAEM-barrier is equal to -0.31 a.u., which results in the gap between $-\varphi_{es}(\mathbf{r})$ and $\varphi_{em}(\mathbf{r})$ at the BCPs of about 0.2 a.u. Hydrogen bond O2...H9 has a much lower PAEM-barrier of -0.44 a.u. and displays a larger gap at the BCPs of ca. 0.25 a.u., which suggests a more significant contribution of

$\varphi_{xc}(\mathbf{r})$ to PAEM and consequently leads to a more significant degree of covalency for the hydrogen bond. Intermolecular contact N1 $\cdots$ O4 is characterized by the least negative value of $-\varphi_{es}(\mathbf{r})$ at the BCP of -0.05 a.u. and a PAEM-barrier of -0.30 a.u., which again gives the gap of 0.25 a.u., similar to the discussed hydrogen bond. We can speculate that since the value of $-\varphi_{es}(\mathbf{r})$ at the BCP is smaller for the mentioned contact as compared to the H-bond, the exchange-correlation potential plays a dominant role in the formation of LPs $\cdots\pi$ interaction. For the H-bond O2 $\cdots$ H9, the contributions of $-\varphi_{es}(\mathbf{r})$ and $\varphi_{xc}(\mathbf{r})$ potentials to PAEM are comparable. Moreover, it is easily noticeable from the asymmetry of $-\varphi_{es}(\mathbf{r})$ that the behavior of $\varphi_{xc}(\mathbf{r})$ is different on the left and right sides of graphs. In general, the relative contribution of $\varphi_{xc}(\mathbf{r})$ to PAEM compared to $-\varphi_{es}(\mathbf{r})$ is bigger from the side of an atom, which captured more electrons.

Figure 11. Reverse electrostatic potential $-\varphi_{es}(\mathbf{r})$ (solid lines) [a.u.] and potential acting on an electron in a molecule $\varphi_{em}(\mathbf{r})$ (dashed lines) [a.u.] along the bond paths of listed interatomic bonding contacts. Zero on the abscissa axis corresponds to the position of BCPs.

The maxima of $\varphi_{em}(\mathbf{r})$ along the bond paths are also slightly shifted from the position of bond CPs toward the more negatively charged atom but to a lesser degree than in ESP. This shift is especially

evident in the case of the O2...H9 bond, where the homotropic force acting on an electron in a molecule, FAEM, $\mathcal{F}(\mathbf{r}) = -\nabla\varphi_{em}(\mathbf{r})$ (vide infra) appreciably “presses” on the ZFS of the more positively charged atom (H9) toward its nucleus. From Figure 11, it is evident that both $\mathbf{F}_{es}(\mathbf{r})$ and $\mathcal{F}(\mathbf{r})$, following the decrease of potentials $-\varphi_{es}(\mathbf{r})$ and $\varphi_{em}(\mathbf{r})$, act along both bond and virial paths toward two neighboring atomic nuclei.

Now let us consider the picture of $\varphi_{em}(\mathbf{r})$ mapped on the surfaces of ρ -basins of atoms involved in noncovalent bonding, as shown in Figure 12. Red or orange concentric regions around the BCPs correspond to the traces of interatomic interactions. Within these regions, a radial $\varphi_{em}(\mathbf{r})$ distribution can be observed, where the potential gradually decreases toward the BCP. On the surfaces of atomic ρ -basins (perpendicular to the bond paths) the force $\mathcal{F}(\mathbf{r})$ is directed toward the minima of PAEM. Together with the graphs in Figure 11, this behavior is consistent with the potential existence of ring CPs (3, +1) in $\varphi_{em}(\mathbf{r})$, i.e., the maxima in one and minima in two other principal directions. Looking ahead, ring CPs (3, +1) in $\varphi_{em}(\mathbf{r})$ correspond to saddle CPs (3, -1) in $\varphi_k(\mathbf{r})$, which will be discussed further.

Figure 12. Atomic ρ -basins of DMPU with $\varphi_{em}(\mathbf{r})$ [a.u.] mapped on them. Two different orientations are shown with selected surrounding molecules.

One can observe a different subset of noncovalent contacts characterized by the irregularly shaped regions of moderately decreased $\varphi_{em}(\mathbf{r})$ around some BCPs. For example, the interaction of π -systems

in Figure 12a, despite being constituted by several bond paths, presents itself only as a diffuse trace of decreased potential. At the same time, the moderate hydrogen bonds $O2 \cdots H11c$, $O2 \cdots H7a$, and $O2 \cdots H9$ feature three concentric regions of varying negativity on faceted atomic ρ -basin of the atom O2. The region of LPs $\cdots\pi$ interaction (Figure 12b) is of special interest to us. Remarkably, despite it being one of the strongest contacts in the DMPU crystal and the presence of the ring CP (3, +1) in $\varphi_{em}(\mathbf{r})$ between the interacting atoms, the contact lacks a descriptive concentric region close to the BCP. Instead, a larger smeared region of moderately negative PAEM can be found on the atomic ρ -basins of N1 and O4. We assume that this feature of PAEM can be thought of as if the LPs $\cdots\pi$ interaction is not spatially limited to the region around the bond path, but presents itself as an extensive intermolecular interaction between the oxygen atom O4 and the π -system of the heterocycle, in particular with the atoms N1, C2, and C6.

Figure 13. Plots of Pauli $\varphi_P(\mathbf{r})$ (blue), von Weizsäcker $\varphi_W(\mathbf{r})$ (red), and kinetic $\varphi_k(\mathbf{r})$ (magenta) potentials [a.u.] along the bond paths of N1 $\cdots$ O4 contact (a) and N3–C2 covalent bond (b). The behavior of the potentials in conjunction with dimensionless approximate ELF $\eta_{AST}(\mathbf{r})$ (green), the values of which were multiplied by the factor of 25 (a) and 20 (b) to fit the ordinate axis. Zero on the abscissa axis corresponds to the position of BCPs.

The von Weizsäcker $\varphi_W(\mathbf{r})$ and Pauli $\varphi_P(\mathbf{r})$ potentials along interatomic lines of closed- and shared-shell contacts are depicted in Figure 13. The intermolecular non-covalent contact $\text{N1}\cdots\text{O4}[\text{=C}]$ and the polar covalent bond $\text{N3}\text{--}\text{C2}$ are chosen as contrasting examples. Alternating series of positive and negative regions of $\varphi_W(\mathbf{r})$ is observed between the nucleus and the outermost electron shell of each bonded atom. The region of moderately positive $\varphi_W(\mathbf{r})$ corresponds to the atomic valence electron shell and is noticeably contracted comparing to the corresponding peak of ELF. In the case of $\text{N1}\cdots\text{O4}$ contact, a negative local minimum of $\varphi_W(\mathbf{r})$ emerges closer to the BCP due to the charge depletion, which is consistent with the abovementioned observation of the closed-shell nature of this contact. This can be interpreted as a barrier that electrons need to overcome to form a sharing interaction.¹⁰⁸ The corresponding force $\mathbf{F}_W(\mathbf{r}) = -\nabla\varphi_W(\mathbf{r})$ is directed toward the decrease of potential. At the same time, for a covalent bond, e.g., $\text{N3}\text{--}\text{C2}$, an analogous minimum of $\varphi_W(\mathbf{r})$ can also be revealed (see Figure 13b), however in this case the value of $\varphi_W(\mathbf{r})$ at that point is positive. Thus, this picture corresponds to a merger and a redistribution of outer electron shells of two bonding atoms. As before, this is also consistent with the definition of shared-shell interaction, where a local electron concentration and the ELF peak is observed around the BCP.

The Pauli potential $\varphi_P(\mathbf{r})$ for polar and nonpolar covalent bonds in crystals computed from experimental (multipole) electron density was studied previously.⁵² Continuing this line, we see in Figure 13 that in noncovalent contacts and covalent bonds the maxima and minima of always positive¹²⁸ Pauli potential $\varphi_P(\mathbf{r})$ correspond to minima and maxima of sign-alternating potential $\varphi_W(\mathbf{r})$. Recall that von Weizsäcker potential $\varphi_W(\mathbf{r})$ describes the electrons in the hypothetical boson-like state,⁴⁷ and ignores the effect of the Pauli exclusion principle. The Pauli potential $\varphi_P(\mathbf{r})$ corrects the kinetic potential for electron exchange at any position point. A region of high $\varphi_P(\mathbf{r})$ separates the atomic core electron density from the valence shell density. The essential difference between the noncovalent contact $\text{N1}\cdots\text{O4}[\text{=C}]$ and the polar covalent bond $\text{N3}\text{--}\text{C2}$ consists of the presence of a distinct local maximum

of $\varphi_P(\mathbf{r})$ near the BCP in the former case. A similar maximum was found in ref.⁵² for an electron-deficient covalent bond B–B in the crystal of MgB_2 .¹²⁹

In general, for the pairs of closed-shell interacting atoms, a significant local increase of $\varphi_P(\mathbf{r})$ is observed in the region of mutual penetration of the valence shells, and coincides with the classically forbidden area of $\varphi_W(\mathbf{r}) < 0$. This local increase in $\varphi_P(\mathbf{r})$ in the interatomic region represents the increase of kinetic energy due to the Pauli exclusion principle. Notably, the appearance of an analogous peak in a Pauli potential profile is observed for a pair of non-bonded atoms as well, which can be interpreted as a Pauli potential barrier. Consequently, in both cases the Pauli force $\mathbf{F}_P(\mathbf{r}) = -\nabla\varphi_P(\mathbf{r})$ pushes electrons from an interatomic border toward atomic ρ -basins. At the same time, for the shared-shell interaction, such as the N3–C2 covalent bond, the reduction of $\varphi_P(\mathbf{r})$ is observed in the extended region near the BCP. The corresponding force $\mathbf{F}_P(\mathbf{r})$ acts on electrons in the direction of the minimum of $\varphi_P(\mathbf{r})$, i.e., to the interatomic region, promoting the formation of a shared-shell chemical bond. These findings are also supported by the distribution of approximate ELF $\eta_{AST}(\mathbf{r})$ along the bond paths of N1...O4 contact and N3–C2 covalent bond in Figure 13, demonstrating the growth with the $\varphi_P(\mathbf{r})$ decrease, and vice versa. We stress that Pauli energy density enters the ELF expression (see Eq. S2) and thus the ELF picture and local potential/force description of bonding are tightly connected. It should be noted that kinetic potential $\varphi_k(\mathbf{r})$ is equal to $-\varphi_{em}(\mathbf{r})$ when chemical potential $\mu(\mathbf{r})$ is set to zero for convenience, which ties the graphs in Figures 11 and 13.

As the net force acting on an electron in a crystal $\mathbf{F}(\mathbf{r}) = \mathbf{F}_k(\mathbf{r}) + \mathcal{F}(\mathbf{r})$ is zero everywhere, the two mutually opposite forces can be distinguished, as expressed by T&S:⁴⁴ the homotropic FAEM $\mathcal{F}(\mathbf{r})$ and the heterotropic kinetic force $\mathbf{F}_k(\mathbf{r})$, which is the sum of Pauli $\mathbf{F}_P(\mathbf{r})$ and von Weizsäcker $\mathbf{F}_W(\mathbf{r})$ forces and governs the kinetic energy components. The forces $\mathcal{F}(\mathbf{r})$ and $\mathbf{F}_k(\mathbf{r})$ are directed at any point in space toward and away from the nuclei, respectively. Only in the Lagrange points in the field of $\varphi_k(\mathbf{r})$ both forces are separately equal to zero. The homotropic FAEM $\mathcal{F}(\mathbf{r})$ and its components $\mathbf{F}_{es}(\mathbf{r})$, $\mathbf{F}_x(\mathbf{r})$,

and $\mathbf{F}_c(\mathbf{r})$ show their respective field sinks at the positions of the atomic nuclei (Figure S13a-d). Since $\mathcal{F}(\mathbf{r}) = -\mathbf{F}_k(\mathbf{r})$ at any $\mathbf{r}$ for a stable system, only one of them may be examined. Throughout this work, we will analyze the performance of the heterotropic kinetic force $\mathbf{F}_k(\mathbf{r})$ as well as its components $\mathbf{F}_p(\mathbf{r})$ and $\mathbf{F}_w(\mathbf{r})$, which show a more intricate and complex behavior (Figure S13e, f).

Figure 14. Isosurfaces of Pauli potential $\varphi_P(\mathbf{r})$ at 0.775 a.u. around the atoms O4 and N1 related to the LPs $\cdots\pi$ intermolecular interaction.

Exploration of three-dimensional behavior of Pauli $\varphi_P(\mathbf{r})$ and von Weizsäcker $\varphi_W(\mathbf{r})$ potentials and corresponding forces $\mathbf{F}_P(\mathbf{r})$ and $\mathbf{F}_W(\mathbf{r})$ certainly contributes to understanding the interactions between the π -system and LP(s) or another π -system. The isosurface of $\varphi_P(\mathbf{r})$ around the carbonyl atom O4 in Figure 14 at the isovalue of 0.775 a.u. takes the shape of a torus of decreased potential with a hole of increased potential in the center. Simultaneously, the atom N1 demonstrates two unified regions of decreased $\varphi_P(\mathbf{r})$ above and below the molecular plane at the same isovalue. The corresponding force $\mathbf{F}_P(\mathbf{r})$ is directed inside the volume of the mentioned torus for the O4 atom (Figure S14) and in the center of decreased potential regions near the N1 atom, pushing electrons into the region of lower Pauli kinetic energy density. However, within the toroidal region of decreased potential force $\mathbf{F}_P(\mathbf{r})$ is directed toward the two distinguishable minima, representing the LP density concentrations, while in the ρ -basin

of N1 it acts only toward the single center. Figure 15a reveals that one of the φ_P -surfaces near N1 is directed toward the hole in the above-mentioned φ_P -torus, while the corresponding bond path between the two atoms goes through the surface and strings the torus. Looking ahead, the φ_K -path follows the same trajectory.

Turning to the consideration of N1...C5 and N3...C6 contacts, one can acknowledge that the interacting atoms feature separate regions of decreased $\varphi_P(\mathbf{r})$ potential expanded within the atomic ρ -basins, which are associated with π -density above and below the uracil plane. Similar to the O4...N1 contact, the regions of decreased $\varphi_P(\mathbf{r})$ near the N1 and N3 atoms are uniformly negative. Both carbon atoms C5 and C6 feature a slightly more complicated distribution of $\varphi_P(\mathbf{r})$, with a local minimum shifted away from the interatomic line. The bond paths for the two mentioned contacts go through the more unified local minima of $\varphi_P(\mathbf{r})$ near the N1 and N3 atoms, which act as ED donors, toward the narrowed region of decreased potential near the C5 and C6 atoms, respectively, as shown in Figure 15b, c. We stress that the behavior of $\varphi_P(\mathbf{r})$ in the region of $\pi\cdots\pi$ and C=O... π interactions is quite similar to the ELF picture in Figures 7 and 10.

Figure 15. Pauli $\varphi_P(\mathbf{r})$ (a-c) and von Weizsäcker $\varphi_W(\mathbf{r})$ (d-f) potentials related to the LPs $\cdots\pi$ (O4 $\cdots$ N1: a, d) and $\pi\cdots\pi$ (N1 $\cdots$ C5: b, e and N3 $\cdots$ C6: c, f) intermolecular interactions. For all maps, the step size is 0.1 a.u. and increases to 0.2 a.u. for $\varphi_W(\mathbf{r})$ after 1 a.u. contour. The maps are superimposed with the corresponding force fields $\mathbf{F}_P(\mathbf{r})$ and $\mathbf{F}_W(\mathbf{r})$, which are shown as arrows. The map planes are the same as in Figures 7 and 10c.

As shown in Figures 15d-f, the regions of positive $\varphi_W(\mathbf{r})$ near the N1 and N3 atoms are oriented toward the regions of reduced potential at the corresponding C5 and C6 atoms, respectively, in the case of $\pi\cdots\pi$ interaction and the electron lone pairs bifurcation of the oxygen atom in the case of O4 $\cdots$ N1 contact. Unlike $\mathbf{F}_P(\mathbf{r})$, the force $\mathbf{F}_W(\mathbf{r})$ pushes electrons to the interatomic border, consequently

contributing to the heterotropic nature of the kinetic force $\mathbf{F}_k(\mathbf{r})$ (Figure S18). The general behavior of $\varphi_P(\mathbf{r})$ and $\varphi_W(\mathbf{r})$ potentials and corresponding forces for the hydrogen bonds is similar to previously discussed $\pi\cdots\pi$ and LPs $\cdots\pi$ interactions (Figure S19). It is worth noting that in our case the compact, artificial zones of negative $\varphi_P(\mathbf{r})$ were found at the hydrogen nuclei.

In summary, the distributions of the Pauli and Weizsäcker potentials and corresponding forces yield a rich bonding picture and can be recommended as a tool for the extraction of physically grounded information about noncovalent chemical bonding and the nature of studied interactions.

The topological features of $\varphi_{em}(\mathbf{r})$ and $\varphi_k(\mathbf{r})$ fields are mutually related.⁴⁴ One can define the so-called φ_k -basins, the volumes of space enclosed by three-dimensional surfaces $S_k(\mathbf{r})$, which satisfy the *kinetic equilibrium* condition $\nabla\varphi_k(\mathbf{r}) \cdot \mathbf{n}(\mathbf{r}) = 0$ for every point $\mathbf{r}$ on $S_k(\mathbf{r})$. Quantum kinetic electron density fluctuations break the statistical equilibrium of the atomic basins and the local forces push or pull electrons across the surface $S_k(\mathbf{r})$ holding the atoms together. Also, the electrons in adjoined basins can exchange their positions keeping the macroscopic state of a system unchanged. Each volume inside the enclosed surface contains the single φ_k -attractor, i.e., maximum CP (3, -3). Special points in space where $\mathbf{F}_k(\mathbf{r}) = \mathcal{F}(\mathbf{r}) = 0$ are linked by two gradient lines forming the so-called φ_k -path, the line of maximally positive kinetic potential with respect to other gradient lines, which connects the two nuclear positions. The saddle CPs (3, -1) in $\varphi_k(\mathbf{r})$ appear at the same positions of space as ring CPs (3, +1) in $\varphi_{em}(\mathbf{r})$ (vide supra). So, given the topological nature of these saddle points, the heterotropic force $\mathbf{F}_k(\mathbf{r})$ acts away from a CP (3, -1) in $\varphi_k(\mathbf{r})$ in the plane perpendicular to it and toward a CP in the direction of a φ_k -path, while the homotropic force $\mathcal{F}(\mathbf{r})$ is directed oppositely.

With a few exceptions, for the studied noncovalent contacts the saddle CPs (3, -1) in $\varphi_k(\mathbf{r})$ and, therefore, ring CPs (3, +1) in $\varphi_{em}(\mathbf{r})$ were found. Table S4 presents the list of all saddle CPs (3, -1) in $\varphi_k(\mathbf{r})$ as well as their topological characteristics. As a rule, these CPs are located very closely to saddle CPs (3, -1) in $\rho(\mathbf{r})$ and $-v(\mathbf{r})$ fields. Figure 16 shows the gradient field $\nabla\varphi_k(\mathbf{r})$ imposed on the gradient

field $\nabla\rho(\mathbf{r})$. The pairs of neighboring atoms forming the O4 $\cdots$ N1 contact (Figure 16a) and two hydrogen bonds (Figure 16b) are connected by the bond- and φ_k -paths in corresponding fields. One can take note of the fact that the saddle CPs (3, -1) in $\varphi_k(\mathbf{r})$ are shifted away from the BCPs toward the atom with more captured electrons, which is the case for both covalent and noncovalent bonds. However, for hydrogen bonds (Figure 16b) this effect is significantly more pronounced than for less directional interactions such as LPs $\cdots\pi$ and $\pi\cdots\pi$ (Figure 16a).

Figure 16. Superposition of gradient fields of the experimental electron density $\nabla\rho(\mathbf{r})$ (grey), kinetic $\nabla\varphi_k(\mathbf{r})$ (orange), and electrostatic $\nabla\varphi_{es}(\mathbf{r})$ (blue) potentials associated with mutual penetration of the corresponding atomic-like potential basins with the complementary ρ -basins along the bond paths belonging to LPs $\cdots\pi$ and $\pi\cdots\pi$ interactions (a) and H-bonds (b). CPs (3, -1) in $\rho(\mathbf{r})$, $\varphi_k(\mathbf{r})$, and $\varphi_{es}(\mathbf{r})$

are shown by magenta, green, and violet rhombuses, respectively. Gradient paths connecting the field attractors are shown by red, green, and violet lines.

Figure 16 shows that for the hydrogen bond O2...H9 and non-covalent contact O4...N1 the trajectories of bond- and φ_k -paths coincide, while for the longer hydrogen bond O2...H11c these trajectories are highly divergent. The difference in orientation of LPs of the O2 atom toward the corresponding charge-deficient areas at H-atoms (as shown in Figure 4b) results in the fact that for the stronger H-bond O2...H9 atomic ZFSs are arranged in parallel. It indicates a more even action of force $\mathbf{F}_k(\mathbf{r})$ along the zero-flux surface, while for the weaker contact O2...H11c basin borders are skewed toward each other. The superposition of gradient fields $\nabla\rho(\mathbf{r})$ and $\nabla\varphi_{es}(\mathbf{r})$ shown in Figure 16 demonstrates that the φ_k -path for the O2...H11c bond is very close to a straight line and lies between the ρ - and φ_{esp} -paths.

Extra information can be obtained from the analysis of the eigenvalues $\Lambda_1 \leq \Lambda_2 \leq \Lambda_3$ of the Hesse matrix of $\varphi_k(\mathbf{r})$ at saddle CPs (3, -1), which show the negative and the positive curvatures of the function in three perpendicular directions analogously to the eigenvalues of Hessian of ED λ_i at BCPs. For a typical covalent bond, the ratios $\Lambda_3/|\Lambda_1|$ and $\Lambda_3/|\Lambda_2|$ are very close pairwise and appear to be in the range between 3 and 4, showing the difference in curvature of the $\varphi_k(\mathbf{r})$ potential in the directions along the φ_k -path and perpendicular to it. For instance, CP (3, -1) in $\varphi_k(\mathbf{r})$ on the N3-C2 covalent bond is characterized by the eigenvalues $\Lambda_1 = -4.12$, $\Lambda_2 = -3.77$, and $\Lambda_3 = 15.61$ a.u. For noncovalent interactions, the eigenvalues Λ_1 and Λ_2 are considerably closer to zero, while the Λ_3 become significantly smaller, which indicates the lesser curvature in all three principal directions compared to a covalent bond. In general, the ratios $|\Lambda_3|/\Lambda_{1,2}$ increase up to ca. 4-40 depending on the directionality of a contact, with the smaller ratios corresponding to more directional contacts (Table S4). Further, the two ratios $\Lambda_3/|\Lambda_1|$ and $\Lambda_3/|\Lambda_2|$ are not always similar pairwise and the difference between them appears to become higher for less directional contacts. This can be illustrated by comparing the eigenvalues: Λ_1

and Λ_2 for the same bonding contact, for instance through the analog of ellipticity $\varepsilon = \frac{\Lambda_1}{\Lambda_2} - 1$, a dimensional quantity. For example, the eigenvalues at CP (3, -1) in $\varphi_k(\mathbf{r})$ for the O2...H9 hydrogen bond are as follows: $\Lambda_1 = -0.30$, $\Lambda_2 = -0.28$, and $\Lambda_3 = 1.33$ a.u., which gives an ellipticity of 0.07, while for O4...N1 contact they are equal to -0.08 , -0.05 , and 1.01 a.u, respectively, which suggests a rather small curvature of $\varphi_k(\mathbf{r})$ at the CPs and results in the ellipticity of 0.6 at saddle CP (3, -1) in $\varphi_k(\mathbf{r})$. This ties well with the PAEM distribution mapped on atomic ρ -basins surfaces shown in Figure 12, where, as was mentioned above, less directional contacts, such as O4...N1, are characterized by the more smeared zones of moderately decreased PAEM.

Earlier, the lack of a PAEM ring CP (3, +1) and, consequently, saddle CP (3, -1) in $\varphi_k(\mathbf{r})$ for some weak bonding contacts was noticed, although a corresponding BCP was still present.⁴⁴ We have also observed that for several bonding contacts in the DMPU crystal, namely N1...C5 and N3...C6, for which we did not find the expected CPs (3, -1) in $\varphi_k(\mathbf{r})$ between the atoms. Nevertheless, the behavior of $\varphi_k(\mathbf{r})$ and the corresponding force $\mathbf{F}_k(\mathbf{r})$ around a BCP and along a bond path suggest that the extremum conditions, necessary for the presence of a Lagrange point, where $\mathcal{F}(\mathbf{r}) = \mathbf{F}_k(\mathbf{r}) = 0$, are met in some directions. On the contrary, we noticed the presence of a couple of saddle CPs (3, -1) in $\varphi_k(\mathbf{r})$ not accompanied by BCPs for several weak intermolecular contacts with hydrogen atoms, for instance O4...H10B^(iv) ($\Lambda_1 = -0.12$, $\Lambda_2 = -0.08$, and $\Lambda_3 = 0.85$) and H10B...H10C^(vi) ($\Lambda_1 = -0.12$, $\Lambda_2 = -0.09$, and $\Lambda_3 = 0.83$). The absence and presence of CPs (3, -1) in $\varphi_k(\mathbf{r})$ is also reproduced in the multipole model refined against theoretical structure factors calculated for optimized crystal geometry. We can speculate that this behavior of the Lagrange points results from the specificity of the atomic structure of DMPU, which dictates the quantum space restrictions imposed by the de Broglie hypothesis and by the Heisenberg uncertainty principle.

We found that for more electronegative atoms in DMPU crystal, such as oxygen and nitrogen, the volumes of φ_k -basins are smaller than corresponding ρ -basins, while for hydrogen atoms this picture is

reversed. The carbon atoms demonstrate similar volumes of ρ - and φ_k -basins (Table S3). At the same time, the shapes of atomic φ_k -basins resemble the ρ -basins. For instance, the φ_k -basin of the O2 atom replicates the characteristic pyramid-like shape, while its φ_{es} -basin has a simplified spherical shape (Figure 17b). The φ_k -basins of the hydrogen atoms H7a, H9, and H11c penetrate the ρ -basin of the atom O2. Kinetic force $\mathbf{F}_k(\mathbf{r})$, originating from the φ_k -basin of the hydrogen atoms, pushes the electrons located inside the overlap toward the atom O2 and is compensated by the FAEM. This is not the case for O4...N1 contact, for which the ZFSs of φ_k - and ρ -basins almost coincide (Figure 17a).

Figure 17. Atomic ρ -, φ_k -, and φ_{es} -basins of the atom O2 in the DMPU crystal as grey, orange, and blue surfaces.

Therefore, the difference in the volume of φ_k -basin ($13.43 \text{ \AA}^3$) of the O4 atom compared to its ρ -basin ($18.13 \text{ \AA}^3$) is mostly realized along the C4–O4 covalent bond, while in the case of the O2 atom (13.870 vs. $18.154 \text{ \AA}^3$) the ρ -basin is expanded mostly toward the hydrogen bonds. The fraction of electrons of ca. 0.65 e , which belongs to the oxygen atoms and is contained within the overlap of its ρ - and φ_k -basins' (Figures 16 and 17a) is in fact affected by the kinetic force $\mathbf{F}_k(\mathbf{r})$ directed from the nuclei of neighboring interacting atoms. Within this region, $\mathbf{F}_k(\mathbf{r})$ pushes the electrons toward the border of oxygen atoms' φ_k -basin. Similarly, the fraction of electrons of ca. 0.34 e enclosed in the sector between the φ_k - and φ_{es} -basins of O2 and O4 (Figures 16b and 17b) could be considered as a portion

of electrons formally affected by exchange-correlation force $\mathbf{F}_{xc}(\mathbf{r})$ acting toward the oxygen nuclei and by the electrostatic force $\mathbf{F}_{es}(\mathbf{r})$ from the surrounding hydrogen atoms.

Conjecture on the Nature of Lone Pairs $\cdots\pi$ Interaction. Now let us speculate on the nature of $[\text{C=}] \text{O} \cdots \text{N}(\text{sp}^2)$ interaction. Electron sharing within the noncovalent heteroatomic interaction could be described via the donor-acceptor mechanism. This is the case for the hydrogen bonds and the described $\pi \cdots \pi$ interaction. Classical $\text{LP} \rightarrow \pi$ mechanism also implies the donor-acceptor character of this interaction,¹¹⁵ where usually one electron lone pair of a donor atom (O) is directed toward the charge depletion at the acceptor (C or N). Applying this idea to our $[\text{C=}] \text{O} \cdots \text{N}(\text{sp}^2)$ contact, which incorporates both lone pairs of the oxygen atom and a localized π -density at the nitrogen atom, we arrived at rather an unusual description.

The source function (Eqs. S18 and S19) enables one to evaluate the distinct contributions from the atomic basins to determination of $\rho(\mathbf{r})$.^{104,130} For the BCP of $\text{O4} \cdots \text{N1}$ contact, two bonded atoms act as ED sinks, with their respective percentage contributions equal to -22.5% and -106.6% . Other nonhydrogen atoms of the “carbonyl-contributing” molecule have small but positive contributions to the BCP, with the largest ones from O2 and C4 of 8.3% and 22.9% , respectively. On the contrary, the atoms of the second, “ π -contributing” molecule yield varying contributions to the BCP: the most negative from C6 and C2 of ca. -10% , and the most positive from C5 (14.2%), O4 (20.4%), and O2 (34.5%). The analysis of the source function supports our claim that the first molecule is indeed a carbonyl group contributor, while in the second molecule the whole π -system is engaged in the interaction.

To provide further evidence we analyzed the second-order perturbative estimates of bond $\rightarrow$ antibond interactions in the NBO model.¹³¹ Although with a small energy ($E^{(2)} = 0.06 \text{ kcal mol}^{-1}$), a direct channel donation from the electron lone pair NBO of N1 (π -density in previous terms) to the antibonding π^* -orbital of $\text{C4}=\text{O4}$ (Figure 18a) is observed with an orbital energy difference of 0.37 a.u. This lone pair

NBO of the N1 atom has an almost pure p_x character with an occupancy of 1.630 e. The back channel is realized through electron density donation from LP NBOs localized on the carbonyl atom O4 into the two-center antibonds of the heterocycle of the second molecule accompanied by moderate stabilization energies $E^{(2)}$ associated with delocalization: LP1(O2)→ $\pi^*(C5=C6)$, $E^{(2)} = 0.45 \text{ kcal mol}^{-1}$; LP2(O2)→ $\pi^*(C5=C6)$, $E^{(2)} = 0.29 \text{ kcal mol}^{-1}$; LP1(O2)→ $\pi^*(O2-C2)$, $E^{(2)} = 0.18 \text{ kcal mol}^{-1}$; LP1(O2)→ $\sigma^*(N1-C6)$, $E^{(2)} = 0.14 \text{ kcal mol}^{-1}$; LP2(O2)→ $\pi^*(O2-C2)$, $E^{(2)} = 0.11 \text{ kcal mol}^{-1}$; LP1(O2)→ $\sigma^*(N1-C10)$, $E^{(2)} = 0.09 \text{ kcal mol}^{-1}$. The energy gap of 0.91 a.u. between $\pi^*(C5=C6)$ orbital and LP1(O2) with an occupancy of 1.978 e and a $sp_x^{0.62}$ composition is greater than the gap of 0.44 a.u. between the $\pi^*(C5=C6)$ and LP2(O2), which has a pure p_y character with an occupancy of 1.875 e. Their mutual orientation is presented in Figure 18 b and c.

Figure 18. Selected natural bond orbitals contributing to LPs $\cdots\pi$ interaction for the direct LP(N1) $\rightarrow\pi^*(\text{C2}=\text{O2})$ (a) and back LP1(O2) $\rightarrow\pi^*(\text{C5}=\text{C6})$ (b) LP2(O2) $\rightarrow\pi^*(\text{C5}=\text{C6})$ (c) donation channels; mesh isosurfaces at 0.022 a.u. Carbonyl-contributing and π -contributing molecules are shown on the right and left, respectively.

In summary, based on traditional tools for revealing electron localization, like ELF and Laplacian of ED, and the novel fundamental notions of orbital-free DFT, such as potentials and local kinetical and PAEM forces, we found that the O4...N1 interaction can be described with the *reverse* LP... π mechanism. Analogously to the Dewar–Chatt–Duncanson model^{132,133} used in coordination structural chemistry^{134–139}, we distinguish two channels of electron sharing: the *direct* one, where, somewhat surprisingly, the nitrogen atom is mostly responsible for the donation of electrons to the oxygen atom along the bond and virial paths, and the *back channel*, where the electron lone pair density from the oxygen atom is shared with the π -system of heterocycle beyond the interatomic line. Some examples of “interaction without bond paths” were reported before.^{140–142} Sound evidence for the described mechanism is presented in the form of the Pauli potential, where the direct channel of ED donation is carried out by the contracted region of decreased $\varphi_P(\mathbf{r})$ at N1 directed inside the hole of enhanced potential at O2 (Figure 14). Considering the same picture from the opposite point of view, the back-donation channel is realized beyond the bond path from the toroidal region of reduced $\varphi_P(\mathbf{r})$ at O2 to the area of increased potential around N1 and near the conjugated heterocycle. The analogous picture is observed in distributions of exact and approximate ELFs (Figure 10) and von Weizsäcker potential (Figure 15d), although in this case instead of a continuous toroidal region two clearly localized LPs are distinguished. The general idea of back-channel donation is also evident from the deformation density, where, as was already stated above, lone pair ED accumulations at the oxygen atom are situated exactly above the corresponding π -density accumulations of heterocyclic π -system (Figure 9). Summarizing, we consider this interaction to have a bilateral mechanism of formation, where two complementary channels of donation are realized from the two opposite sides. Since the direct donation along the bond path happens from the nitrogen atom toward the oxygen, we justifiably call this interaction a *reverse* LPs $\leftarrow\pi$, unlike the classical LP $\rightarrow\pi$.

CONCLUSIONS

Crystal structure of 1,6-dimethyl-3-(prop-2-yn-1-yl)pyrimidine-2,4(1*H*,3*H*)-dione presented itself as an attractive research object due to the rather diverse set of noncovalent interactions. Individual interatomic closed-shell contacts, ranging from widely encountered nonclassical hydrogen bonds and $\pi\cdots\pi$ interactions to a rather unusual interaction between the carbonyl group and heterocyclic π -system were studied by combining the methods of QTAIMC and modern quantum crystallography. Among them, the superpositions of the gradient fields of $\rho(\mathbf{r})$ with electrostatic $\varphi_{es}(\mathbf{r})$ or kinetic $\varphi_k(\mathbf{r})$ potentials allow the partition of the crystal space into the atomic and atomic-like potential basins. These φ_{es} - and φ_k -basins represent the regions of space, inside which electrons are affected by electronic inner-crystal electrostatic $\mathbf{F}_{es}(\mathbf{r})$ and kinetic $\mathbf{F}_k(\mathbf{r})$ forces directed to and away from the nuclei, respectively. Hence, charge transfer is described by the overlap of ρ -basin of ED occupier and the φ_{es} -basin of ED contributor. The use of the kinetic potential $\varphi_k(\mathbf{r})$ instead of electrostatic $\varphi_{es}(\mathbf{r})$ gives the overlap regions, where electrons from the ρ -basin of one atom are pushed by the kinetic force $\mathbf{F}_k(\mathbf{r})$ from the other one toward the border of its φ_k -basin. Quantum kinetic electron density fluctuations break the statistical equilibrium of the atomic basins and the local forces push or pull electrons across the interatomic surface holding the atoms together. Also, the electrons in adjoined basins can exchange their positions keeping the macroscopic state of a system unchanged.

Despite some covalent admixture to non-covalent interactions, the exchange contribution may be more important in some cases. The contribution of the exchange-correlation effect on the formation of bond paths was demonstrated for $\pi\cdots\pi$ and lone pairs $\cdots\pi$ interactions. On one hand, the value of PAEM at a BCP gives the height of a PAEM barrier, which is a potential barrier that electrons need to overcome to form a sharing interaction. On the other hand, a gap between the maxima of PAEM and ESP along the same bond path gives the value of exchange-correlation potential $\varphi_{xc}(\mathbf{r})$, which is tied with the covalency of a bond in question.

Less explored functions, such as Pauli $\varphi_P(\mathbf{r})$ and von Weizsäcker $\varphi_W(\mathbf{r})$ potentials and corresponding forces were utilized for the descriptions of noncovalent interactions. The important finding is that the Pauli potential and the corresponding force reveal the donor-acceptor mechanism of noncovalent interactions. We found that for the pair of closed-shell interacting or even noninteracting atoms a slight increase of $\varphi_P(\mathbf{r})$ (Pauli potential barrier) can be found close to interatomic boundary, which coincides with the minimum of ELF along the interatomic line. The joined analysis of the various potentials and the corresponding forces allowed the extraction of physically grounded chemical information about noncovalent bonding from the experimentally available data.

As expected, nonclassical hydrogen bonds in the DMPU crystal are characterized by the donor-acceptor character. Two ways of hydrogen bond formation may be distinguished: in the first case, the single lone pair is directed exactly toward the vacancy at the hydrogen atom and is fully engaged in a donor-acceptor relationship, while in the second case two hydrogen atoms simultaneously share the other electron lone pair, which results in lower strength of the hydrogen bonds due to the loss of directionality. All nonclassical hydrogen bonds are characterized by the opposite directions of lone pair donation and charge transfer, namely, the oxygen atom plays the role of electron density occupier, while donating its lone pair toward the vacancy at the hydrogen atoms.

The proximity of two planar uracil moieties leads to the decrease of approximate local electronic temperature $t(\mathbf{r})$ in the intermolecular region, which is made particularly evident by mapping $t(\mathbf{r})$ on the isosurface of the reduced ED gradient. Within QTAIME the mentioned $\pi\cdots\pi$ interaction consists of four weak heteroatomic C $\cdots$ N contacts, which demonstrate donor-acceptor character with nitrogen atoms donating the π -density.

An intricate reverse LPs $\cdots\pi$ interaction between the carbonyl group, i.e., two lone pairs of the oxygen atom, and the uracil π -system is reported and described for the first time. In the classical case, LPs $\cdots\pi$ interaction involves the ED donation from one of the lone pairs of donor atom toward the π -

system. Although the only bond path $[C=]O\cdots N(sp^2)$ was found, based on the data gathered with orbital-free DFT bonding descriptors and natural bond orbitals analysis we hypothesized the existence of two channels of electron density donation. The direct channel involves the donation of π -density from the nitrogen atom toward the lone pairs' bifurcation at the oxygen atom along the bond path. The second, back channel, is defined as sharing of the lone pair density from the oxygen atom with the π -system of heterocycle beyond the interatomic line. The existence of the back channel was also supported by the analysis of source function and natural bond orbitals.

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ABBREVIATIONS

a.u., Hartree atomic units; BCP, bond critical point; CP, critical point; DFT, density functional theory; DMPU, 1,6-dimethyl-3-propargyl-2,4-pyrimidinedione; ED, electron density; ELF, electron localization function; ESP, electrostatic potential; FAEM, force acting on an electron in a molecule; KED, kinetic energy density; LP, lone pair; NBO, natural bond orbital; PAEM, potential acting on an electron in a molecule; QTAIMC, quantum theory of atoms in molecules and crystals; VSCC, valence shell charge concentration; ZFS, zero-flux surface.

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Supporting Information

Theoretical background

Deformation electron density ($\delta\rho(\mathbf{r})$, DED) is defined as the difference between the electron density of real system $\rho(\mathbf{r})$ and the independent atom model $\rho_{IAM}(\mathbf{r})$:

$$\delta\rho(\mathbf{r}) = \rho(\mathbf{r}) - \rho_{IAM}(\mathbf{r}) \quad (\text{S1}),$$

where $\rho_{IAM}(\mathbf{r})$ is the density of a set of spherical atoms placed in real atomic positions.¹ The regions of positive and negative $\delta\rho(\mathbf{r})$ correspond to the accumulation and reduction of $\rho(\mathbf{r})$ due to the formation of chemical bonds.

Electron localization function (ELF)² $\eta(\mathbf{r})$ is a local scalar function, which measures the excess of local Pauli kinetic energy compared to the uniform electron gas with the same local value of $\rho(\mathbf{r})$. The value of $\eta(\mathbf{r}) = 1$ corresponds to perfect electron localization, while $\eta(\mathbf{r}) = 0.5$ denotes electron-gas-like delocalization. The experimental ELF implementation for closed-shell systems is based on the following equation:³

$$\eta(\mathbf{r}) = \left[1 + \left(\frac{g_P(\mathbf{r})}{g_{TF}(\mathbf{r})} \right)^2 \right]^{-1} \quad (\text{S2}),$$

where $g_P(\mathbf{r}) = g(\mathbf{r}) - \frac{1}{8} \frac{|\nabla\rho(\mathbf{r})|^2}{\rho(\mathbf{r})}$ is the Pauli electronic kinetic energy density and $g_{TF}(\mathbf{r}) = \frac{3}{10} (3\pi^2)^{\frac{2}{3}} \rho(\mathbf{r})^{\frac{5}{3}}$ is the kinetic energy density (KED) of a homogenous electron gas with the local density equal to the $\rho(\mathbf{r})$. KED $g(\mathbf{r})$ is approximated according to Kirzhnits:⁴

$$g_K(\mathbf{r}) = \frac{3}{10} (3\pi^2)^{\frac{2}{3}} \rho(\mathbf{r})^{\frac{5}{3}} + \frac{1}{72} \frac{|\nabla\rho(\mathbf{r})|^2}{\rho(\mathbf{r})} + \frac{1}{6} \nabla^2 \rho(\mathbf{r}) \quad (\text{S3}),$$

or by purposely developed expression of Tsirelson et al.⁵ (AST approximation):

$$g_{AST}(\mathbf{r}) = g_W(\mathbf{r}) - \rho(\mathbf{r})[\varphi_{es}(\mathbf{r}) + \varphi_{xc}(\mathbf{r}) + \varphi_W(\mathbf{r})] - \frac{1}{5} (3\pi^2)^{\frac{2}{3}} \rho(\mathbf{r})^{\frac{5}{3}} + 0.015 \frac{|\nabla\rho(\mathbf{r})|^2}{\rho(\mathbf{r})} - 0.140 \nabla^2 \rho(\mathbf{r}) \quad (\text{S4}).$$

Reduced density gradient $\sigma(\mathbf{r})$,⁶⁻⁸ reads as:

$$\sigma(\mathbf{r}) = \frac{|\nabla\rho(\mathbf{r})|}{2(3\pi^2)^{1/3} \rho(\mathbf{r})^{4/3}} \quad (\text{S5}).$$

and describes the local deviation of the electron density from homogeneous electron gas.

The local internal temperature of an electron gas $t(\mathbf{r})$,⁹ which measures the kinetic electron energy per particle at an external temperature equal to 0 K, was computed using the AST approximation for $g(\mathbf{r})$ as follows:

$$t(\mathbf{r}) = \frac{2}{3k_B} \frac{g_{AST}(\mathbf{r})}{\rho(\mathbf{r})} \quad (\text{S6}).$$

The total energy DFT functional¹⁰ $E_t[\rho]$ is composed of the noninteracting kinetic $E_k[\rho]$, electrostatic $E_{es}[\rho]$, exchange $E_x[\rho]$, and correlation $E_c[\rho]$ energies:

$$E_t[\rho] = E_k[\rho] + E_{es}[\rho] + E_x[\rho] + E_c[\rho] \quad (\text{S7}).$$

For $E_k[\rho]$, $E_x[\rho]$, and $E_c[\rho]$ the approximations depend on ED and its derivatives, which allows for the direct implementation of proper functionals without the need for wave function calculation.

$E_k[\rho]$ can be defined as a sum of Pauli $E_P[\rho]$ and von Weizsäcker $E_W[\rho]$ kinetic energies:

$$E_k[\rho] = E_W[\rho] + E_P[\rho] \quad (\text{S8}).$$

The functional derivative gives a kinetic potential $\frac{\delta E_k[\rho]}{\delta \rho} = \varphi_k(\mathbf{r})$. The latter is the sum of von Weizsäcker $\varphi_W(\mathbf{r})$ and Pauli potentials $\varphi_P(\mathbf{r})$:^{11–13}

$$\varphi_k(\mathbf{r}) = \varphi_W(\mathbf{r}) + \varphi_P(\mathbf{r}) \quad (\text{S9}).$$

The former is expressed by the following equation:¹⁴

$$\varphi_W(\mathbf{r}) = \frac{\delta E_W[\rho]}{\delta \rho} = \frac{1}{8} \frac{|\nabla \rho(\mathbf{r})|^2}{\rho^2(\mathbf{r})} - \frac{1}{4} \frac{\nabla^2 \rho(\mathbf{r})}{\rho(\mathbf{r})} \quad (\text{S10}).$$

For the latter, $\varphi_P(\mathbf{r})$, which is one of the less-studied functions, describing the bonding features, the exact formula is unknown; however, it can be expressed as:

$$\varphi_P(\mathbf{r}) = \frac{\delta E_k[\rho]}{\delta \rho} - \frac{\delta E_W[\rho]}{\delta \rho} = \varphi_k(\mathbf{r}) - \varphi_W(\mathbf{r}) \quad (\text{S11}).$$

With the exact expression for $\varphi_W(\mathbf{r})$ (Eq. S10), the definition of kinetic potential $\varphi_k(\mathbf{r})$ via experimentally measurable functions is not straightforward. Tsirelson and Liu with coworkers¹⁵ showed that one way to solve this problem is to use the standard form of the Euler equation:

$$\frac{\delta E_k[\rho]}{\delta \rho} = \mu(\mathbf{r}) - \varphi_{KS}(\mathbf{r}) \quad (\text{S12}),$$

where $\mu(\mathbf{r})$ is the electronic chemical potential and $\varphi_{KS}(\mathbf{r})$ is the effective Kohn–Sham potential,¹⁰ which is in turn a sum of electrostatic $\varphi_{es}(\mathbf{r})$, exchange $\varphi_x(\mathbf{r})$, and correlation $\varphi_c(\mathbf{r})$ potentials. The effective potential $\varphi_{KS}(\mathbf{r})$ is defined up to an arbitrary constant and $\mu(\mathbf{r}) = \text{const}$ for a stable equilibrium system; it is therefore convenient to set $\mu(\mathbf{r}) = 0$. Then, Eq. S11 and Eq. S12 can be transformed to the following expression:

$$\varphi_P(\mathbf{r}) = -\varphi_{es}(\mathbf{r}) - \varphi_x(\mathbf{r}) - \varphi_c(\mathbf{r}) - \varphi_W(\mathbf{r}) \quad (\text{S13}).$$

The Pauli potential $\varphi_P(\mathbf{r})$ computed in this way does not favorably depend on approximate KED but instead uses the approximate forms for the exchange and correlation potentials.

Electrostatic potential (ESP, $\varphi_{es}(\mathbf{r})$) was computed according to the known formula:^{16,17}

$$\varphi_{es}(\mathbf{r}) = \sum_a Z_a / (|\mathbf{r} - \mathbf{R}_a|) - \int \frac{\rho(\mathbf{r}_1)}{|\mathbf{r} - \mathbf{r}_1|} d\mathbf{r}_1 \quad (\text{S14}).$$

ESP is generated by classic Coulomb interactions of electrons and nuclei and is measured by the external to a system unit test positive charge. In contrast, PAEM $\varphi_{em}(\mathbf{r})$ is an interaction energy of any one internal electron with the rest of the electrons and the nuclei¹⁸ and includes an exchange-correlation term:¹⁹

$$\varphi_{em}(\mathbf{r}) = -\varphi_{es}(\mathbf{r}) + \varphi_x(\mathbf{r}) + \varphi_c(\mathbf{r}) \quad (\text{S15}).$$

Tsirelson and Stash²⁰ combined all the potentials into the local one-electron potential $\mu(\mathbf{r})$:

$$\mu(\mathbf{r}) = \varphi_k(\mathbf{r}) + \varphi_{em}(\mathbf{r}) = \varphi_P(\mathbf{r}) + \varphi_W(\mathbf{r}) - \varphi_{es}(\mathbf{r}) + \varphi_x(\mathbf{r}) + \varphi_c(\mathbf{r}) \quad (\text{S16}),$$

Since a force is directed towards decreasing of a corresponding potential $\Phi(\mathbf{r}) = -\nabla \varphi(\mathbf{r})$, the last equation yields the respective forces:

$$\mathbf{F}(\mathbf{r}) = -\nabla\mu(\mathbf{r}) = -\nabla\varphi_k(\mathbf{r}) - \nabla\varphi_{em}(\mathbf{r}) = \mathbf{F}_k(\mathbf{r}) + \mathcal{F}(\mathbf{r}) = 0 \quad (\text{S17}),$$

$\nabla\mu(\mathbf{r})$ vanishes everywhere under equilibrium conditions, hence $\mathbf{F}_k(\mathbf{r}) = -\mathcal{F}(\mathbf{r})$. At that, effective force $\mathcal{F}(\mathbf{r})$, being homotropic, attracts electrons to the atomic nuclei and favors homogeneous disorganization, while the heterotropic kinetic force $\mathbf{F}_k(\mathbf{r})$ pulls electrons from the nuclei and keeps structural organization. Notably, vector fields $\nabla\rho(\mathbf{r})$, $\nabla\varphi_{es}(\mathbf{r})$, and $\nabla\varphi_k(\mathbf{r})$ satisfy the zero-flux condition, therefore allowing for the construction of closed basins around the appropriate field attractors.

As shown by Bader and Gatti,²¹ the ED at a given point can be expressed as a sum of the contributions of all the other atoms in a molecule. Local source $LS(\mathbf{r}, \mathbf{r}')$ at the point $\mathbf{r}$ from the other point $\mathbf{r}'$ is defined as follows:

$$LS(\mathbf{r}, \mathbf{r}') = -\left(\frac{1}{4\pi}\right) \frac{\nabla^2 \rho(\mathbf{r}')}{|\mathbf{r} - \mathbf{r}'|}. \quad (\text{S18}),$$

By integrating the local source within an atomic basin Ω , one can express density at any given point as a sum of the SF contributions of each atom $S(\mathbf{r}, \Omega)$ by the following equation:

$$\rho(\mathbf{r}) = \sum_{\Omega} \int_{\Omega} LS(\mathbf{r}, \mathbf{r}') d\mathbf{r}' \equiv \sum_{\Omega} S(\mathbf{r}, \Omega). \quad (\text{S19}).$$

Figure S1. ORTEP for the DMPU molecule showing anisotropic displacement ellipsoids at the 80 % probability according to single-crystal XRD.

Figure S2. Contour maps of Laplacian of electron density $\nabla^2\rho(\mathbf{r})$ (a), electron localization function (Kirsch approximation) $\eta_K(\mathbf{r})$ (b), phase-space-defined Fisher information density (AST approximation) $i_F(\mathbf{r})$ (c) and deformation quantum pressure (AST approximation) $\delta p(\mathbf{r})$ (d) constructed in the plane of DMPU molecule. The step between contour levels was set to 0.05 a.u. for (b). For (a) and

(c), a logarithmic scale in the form of $\pm 2, 4, 8 \cdot 10^n$ was adopted, where $n = -4, -3, -2, -1, 0, 1, 2, 3, 4$ for (a) and $n = -2, -1, 0$ for (c). For (d), a slightly different logarithmic scale was chosen: $\pm 1, 2, 4, 8 \cdot 10^n$, ($n = -2, -1$). For every map, positive, zero, and negative contours are presented by blue, green, and red lines, respectively.

Figure S3. Computed (ω B97X-D/aug-cc-pVTZ) molecular electrostatic potential $\varphi_{es}(\mathbf{r})$ from -0.0662 a.u. (red) through -0.0072 a.u. (green) to 0.0518 a.u. (blue) mapped on ρ -isosurfaces of 0.001 a.u. ($6.7483 \cdot 10^{-3} \text{ e A}^{-3}$) for free “gas-phase” DMPU molecule.

Figure S4. Van der Waals representation of mutual penetration of oxygen atom O4 with nitrogen atom N1 and neighboring carbon atoms C2 and C6. Interacting atoms are highlighted by yellow mesh.

Figure S5. Superposition of atomic ρ -basins (mesh) and ρ -isosurfaces of $6.7483 \cdot 10^{-3} \text{ e } \text{\AA}^{-3}$ or 0.001 a.u. (purple) for the DMPU molecule in the crystal in two different orientations.

Figure S6. Zero-flux surfaces for pairs of atoms participating in H-bonds (a) and LPs $\cdots\pi$ interaction (b) shown as grey mesh. Bond paths are colored according to the element types; BCPs are given as magenta spheres.

Figure S7. Distributions of $\text{sign}[\lambda_2(\mathbf{r})] \cdot \rho(\mathbf{r})$ [$\text{e } \text{\AA}^{-3}$] (a) and approximate local temperature $t(\mathbf{r})$ [a.u.] (b) mapped on the isosurfaces of reduced electron density gradient ($\sigma(\mathbf{r}) = 0.55$) considered in the region of $\pi \cdots \pi$ stacking.

Figure S8. Superposition of gradient fields of the electron density $\nabla\rho(\mathbf{r})$ (grey) and electrostatic potential $\varphi_{es}(\mathbf{r})$ (blue) in the plane of the labeled atoms.

Figure S9. Molecular DMPU dimer extracted from experimental X-ray structure exhibiting the presence of O4 $\cdots$ N1 contact (a) and after the optimization steps at DFT level of ω B97X-D/aug-cc-pVTZ showing the absence of the mentioned non-covalent bond (b).

Figure S10. Isosurfaces of electron localization function ($\eta_{wf}(\mathbf{r}) = 0.84$) shown for labeled atoms calculated from the periodic wave function for the optimized crystal geometry. Bond paths and critical points were taken from the multipole model refined against theoretical structure factors.

Figure S11. Phase-space-defined Fisher information density $i_F(\mathbf{r})$ calculated using AST kinetic energy approximation in the region of O4 $\cdots$ N1 interaction. The planes are the same as in Figures 10 c and f. The common color scale and step lengths for various function ranges are given on the right.

Figure S12. Approximate electron localization function $\eta_K(\mathbf{r})$ calculated using Kirzhnits kinetic energy approximation in two mutually orthogonal planes containing O4 $\cdots$ N1 bond path. The contour level is set to 0.05. The planes are the same as in Figures 10 c and f.

corresponding force fields shown by arrows in the plane of the DMPU molecule. For maps (a-e), a linear scale with the step sizes equal to 0.1, 0.005, 0.4, 0.4, and 0.2 a.u., respectively, is adopted. For (f), a logarithmic scale in the form of $\pm 2, 4, 8 \cdot 10^n$ ($n = -2, -1, 0, 1$) is used.

Figure S14. The force generated by the Pauli potential $F_p(\mathbf{r})$ shown by the arrows colored according to the magnitude of the force and calculated within the interatomic region of O4...N1 contact. Isosurfaces of $\varphi_p(\mathbf{r})$ at 0.775 a.u. and zero-flux surface in $\rho(\mathbf{r})$ between the pair of the atoms are shown by light blue and bright red.

Figure S15. The force generated by the von Weizsäcker potential $F_W(\mathbf{r})$ shown by the arrows colored according to the magnitude of the force and calculated within the interatomic region of O4...N1 contact. Isosurfaces of $\varphi_W(\mathbf{r})$ at 0.3 a.u. and zero-flux surface in $\rho(\mathbf{r})$ between the pair of the atoms are shown by light blue and bright red.

Figure S16. The force generated by the kinetic potential $F_k(\mathbf{r})$ shown by the arrows colored according to the magnitude of the force and calculated within the interatomic region of O4...N1 contact. Isosurfaces of $\varphi_k(\mathbf{r})$ at 1.1 a.u. and zero-flux surface in $\rho(\mathbf{r})$ between the pair of the atoms are shown by light blue and bright red.

Figure S17. The same as in Figure S16. Two additional view points along the bond paths from the atomic positions are given.

Figure S18. Pauli $\varphi_P(\mathbf{r})$ (a-c), von Weizsäcker $\varphi_W(\mathbf{r})$ (d-f), and kinetic $\varphi_k(\mathbf{r})$ (g-i) potentials related to the LPS $\cdots\pi$ (O4 $\cdots$ N1: a, d, g) and $\pi\cdots\pi$ (N1 $\cdots$ C5: b, e, h and N3 $\cdots$ C6: c, f, i) intermolecular interactions. For all maps the step size was chosen to be 0.1 a.u., but it was increased to 0.2 and 0.4 a.u. for $\varphi_W(\mathbf{r})$ and $\varphi_k(\mathbf{r})$ after a 1 a.u.-contour, respectively. The maps are superimposed with the

corresponding force fields $\mathbf{F}_P(\mathbf{r})$, $\mathbf{F}_W(\mathbf{r})$, and $\mathbf{F}_k(\mathbf{r})$, which are shown by arrows. The map planes are chosen to be similar to Figures 7 and 10c of the article.

Figure S19. Pauli $\varphi_P(\mathbf{r})$ (a), von Weizsäcker $\varphi_W(\mathbf{r})$ (b), and kinetic $\varphi_k(\mathbf{r})$ (c) potentials superimposed with the corresponding force fields, which are shown by arrows in the plane of two hydrogen bonds $\text{O2}\cdots\text{H9}$ and $\text{O2}\cdots\text{H11c}$. Quite pronounced regions of reduced Pauli potential taking the dumbbell-like form can be found near the nuclei of hydrogen atoms H9 and H11c. The regions of unphysical negative $\varphi_P(\mathbf{r})$ can be observed on the hydrogen nuclei. The map plane is chosen to be similar to Figure 4b of the article.

Figure S20. Superposition of gradient fields of the electron density $\nabla\rho(\mathbf{r})$ (grey), electrostatic potential $\varphi_{es}(\mathbf{r})$ (blue), and kinetic potential $\nabla\varphi_k(\mathbf{r})$ (orange) for three selected planes.

Figure S21. Scatter plot of experimental reduced electron density gradient $\sigma(\mathbf{r})$ against $[\text{sign}[\lambda_2(\mathbf{r})] \rho(\mathbf{r})] [\text{e } \text{\AA}^{-3}]$. For both atoms, calculations were performed within the constrained multipole model in the cubic region around each atom with the side length equal to 3.2 $\text{\AA}$ and 2.8 $\text{\AA}$ for O2 (blue) and O4 (red), respectively.

Table S1. Experimental and Theoretical Quantum-Topological Characteristics of the Covalent Bonds in DMPU Crystals ^a

Bond	d	d_1	d_2	ρ_b	$\nabla^2 \rho_b$	λ_1	λ_2	λ_3	n_{topo}^b	g_b^c	v_b^c	h_b^c
O2–C2	1.2253(2)	0.790	0.435	2.769	−26.05	−23.667	−21.964	19.583	1.536	0.470	−1.211	−0.741
	1.23209	0.808	0.425	2.667	−12.79	−23.241	−21.320	31.772	1.539	0.542	−1.217	−0.675
O4–C4	1.2245(3)	0.784	0.440	2.797	−27.73	−24.178	−22.034	18.479	1.566	0.470	−1.227	−0.758
	1.23443	0.811	0.424	2.632	−10.95	−22.522	−21.473	33.047	1.560	0.546	−1.205	−0.659
N1–C2	1.3795(3)	0.793	0.586	2.088	−16.23	−16.115	−13.570	13.452	1.041	0.294	−0.757	−0.463
	1.37681	0.838	0.539	2.123	−22.74	−16.970	−14.458	8.689	1.023	0.164	−0.564	−0.400
N1–C6	1.3777(3)	0.807	0.573	2.146	−20.70	−17.045	−15.322	11.666	1.018	0.282	−0.779	−0.497
	1.38183	0.874	0.508	2.011	−19.44	−13.855	−13.601	8.019	0.964	0.204	−0.609	−0.406
N1–C10	1.4633(4)	0.833	0.631	1.787	−9.75	−12.560	−12.042	14.850	0.822	0.246	−0.593	−0.347
	1.46459	0.920	0.545	1.654	−12.75	−10.056	−9.687	6.994	0.720	0.149	−0.431	−0.282
N3–C2	1.3816(3)	0.816	0.566	2.208	−19.71	−17.715	−14.896	12.905	1.101	0.310	−0.824	−0.514
	1.38387	0.844	0.540	2.075	−21.73	−16.319	−14.145	8.731	1.052	0.161	−0.547	−0.386
N3–C4	1.4029(3)	0.805	0.598	1.947	−13.42	−15.112	−12.806	14.493	0.923	0.269	−0.677	−0.408
	1.40090	0.869	0.532	1.961	−19.08	−14.272	−13.385	8.576	0.943	0.169	−0.536	−0.367
N3–C7	1.4693(3)	0.831	0.639	1.649	−4.29	−11.488	−11.011	18.207	0.740	0.245	−0.534	−0.289
	1.46908	0.908	0.562	1.663	−13.15	−10.454	−10.152	7.457	0.662	0.133	−0.403	−0.270
C4–C5	1.4340(3)	0.748	0.686	1.978	−16.10	−14.587	−12.216	10.705	1.287	0.260	−0.687	−0.427
	1.43229	0.761	0.671	2.004	−20.78	−14.894	−12.901	7.016	1.299	0.086	−0.388	−0.302
C5–C6	1.3571(4)	0.555	0.803	2.459	−27.46	−19.156	−15.103	6.801	1.564	0.344	−0.973	−0.629
	1.34879	0.625	0.724	2.278	−23.99	−17.341	−13.042	6.392	1.582	0.136	−0.521	−0.385
C6–C11	1.4920(4)	0.803	0.689	1.719	−12.46	−11.249	−10.953	9.746	1.128	0.208	−0.545	−0.337
	1.49208	0.802	0.691	1.775	−17.13	−12.203	−11.836	6.906	1.151	0.067	−0.312	−0.245
C7–C8	1.4627(3)	0.714	0.749	1.789	−9.57	−12.466	−11.847	14.744	1.194	0.248	−0.595	−0.347
	1.46477	0.681	0.785	1.819	−18.11	−12.808	−12.044	6.745	1.192	0.071	−0.329	−0.259
C8–C9	1.2063(4)	0.572	0.635	2.822	−23.50	−18.011	−16.939	11.452	2.553	0.509	−1.261	−0.753
	1.19921	0.612	0.588	2.755	−27.00	−15.465	−15.263	3.728	2.689	0.292	−0.864	−0.572
C5–H5	1.08(15)	0.706	0.376	1.806	−16.92	−16.686	−15.645	15.409	1.000	0.202	−0.580	−0.378
	1.08249	0.701	0.367	1.885	−23.12	−17.943	−17.302	12.127	1.022	0.037	−0.315	−0.277

C7–H7a	1.0923(3)	0.714	0.378	1.835	−15.32	−17.611	−17.129	19.421	1.017	0.222	−0.603	−0.381
	1.09227	0.719	0.359	1.906	−23.92	−18.650	−18.149	12.876	1.001	0.033	−0.314	−0.281

Continuation of **Table S1**

C7–H7b	1.0915(3)	0.719	0.373	1.868	−15.60	−18.108	−17.380	19.891	1.035	0.230	−0.621	−0.392
	1.09152	0.719	0.357	1.910	−24.03	−18.727	−18.257	12.954	1.011	0.033	−0.316	−0.283
C9–H9	1.07(18)	0.711	0.363	1.864	−17.53	−18.269	−17.980	18.720	0.976	0.215	−0.612	−0.397
	1.07316	0.724	0.332	1.903	−25.29	−19.274	−19.201	13.184	0.958	0.027	−0.316	−0.289
C10–H10a	1.09(19)	0.726	0.365	1.770	−15.89	−16.705	−15.715	16.529	0.975	0.199	−0.562	−0.363
	1.09064	0.706	0.369	1.896	−23.41	−18.190	−17.600	12.379	1.008	0.036	−0.315	−0.279
C10–H10b	1.09(15)	0.726	0.368	1.745	−15.76	−16.546	−15.457	16.240	0.957	0.192	−0.548	−0.356
	1.09296	0.706	0.373	1.881	−23.04	−17.930	−17.326	12.219	1.021	0.036	−0.312	−0.276
C10–H10c	1.09(15)	0.713	0.373	1.740	−15.13	−16.214	−14.655	15.734	0.987	0.195	−0.548	−0.352
	1.09147	0.700	0.371	1.912	−23.68	−18.258	−17.656	12.238	1.008	0.038	−0.321	−0.283
C11–H11a	1.10(19)	0.726	0.369	1.763	−15.53	−16.110	−15.551	16.127	0.990	0.199	−0.559	−0.360
	1.09505	0.703	0.378	1.831	−21.73	−16.802	−16.569	11.637	1.005	0.040	−0.306	−0.266
C11–H11b	1.09(23)	0.720	0.374	1.773	−15.77	−16.245	−15.416	15.896	0.998	0.201	−0.565	−0.364
	1.09324	0.699	0.380	1.839	−21.82	−16.830	−16.580	11.592	1.034	0.042	−0.310	−0.268
C11–H11c	1.09(13)	0.713	0.378	1.732	−15.18	−15.339	−15.279	15.431	0.982	0.193	−0.543	−0.350
	1.09147	0.705	0.371	1.867	−22.65	−17.432	−17.202	11.982	1.037	0.038	−0.311	−0.273

^a Units of measurement are as follows: interatomic d and atom–BCP d_1 , d_2 distances [Å]; electron density ρ_b [$\text{e} \text{Å}^{-3}$]; Laplacian of ED $\nabla^2 \rho_b$ and eigenvalues of Hessian matrix of ED at the BCP λ_1 , λ_2 , and λ_3 [$\text{e} \text{Å}^{-5}$]; kinetic g_b , potential v_b , and electronic h_b energy densities [a.u.]; bond order n_{topo} , dimensionless. Subscript b indicates that the property was calculated at the BCP. Upper rows for each bond contain the experimental data obtained from the constrained multipole model, while the data for the second rows were obtained by the topological analysis of ED based on the periodic wave function after geometry optimization. ^b Values of theoretical n_{topo} in each second row are related to the multipole model refined against calculated structure factors. ^c Experimental energy densities were calculated within the Kirzhnits kinetic energy approximation.

Table S2. Critical points and their topological characteristics for the intermolecular interactions involving atoms of DMPU molecules ^a

Interaction	R_{ij}	d_1	d_2	ρ_b	$\nabla^2\rho_b$	λ_1	λ_2	λ_3	g_b	v_b	h_b	E_v	E_g
O4...N1	2.850	1.371	1.479	0.077	1.158	-0.207	-0.193	1.557	9.671	-7.327	2.344	2.30	2.60
	2.849	1.377	1.472	0.077	1.162	-0.223	-0.175	1.560	10.371	-8.690	1.682	2.73	2.79
O2...H9	2.212	1.394	0.841	0.065	1.222	-0.251	-0.198	1.670	9.695	-6.713	2.982	2.11	2.61
	2.228	1.380	0.848	0.090	1.414	-0.349	-0.346	2.108	11.571	-8.477	3.094	2.66	3.11
O2...H7A	2.411	1.462	0.966	0.044	0.847	-0.159	-0.145	1.150	6.524	-4.257	2.267	1.34	1.76
	2.435	1.463	0.972	0.061	0.853	-0.198	-0.187	1.238	6.779	-4.707	2.072	1.48	1.82
C9...H11B	2.742	1.612	1.177	0.043	0.542	-0.125	-0.075	0.742	4.375	-3.126	1.249	0.98	1.18
	2.740	1.586	1.154	0.051	0.499	-0.128	-0.088	0.715	4.525	-3.874	0.651	1.22	1.22
N1...C5	3.368	1.675	1.695	0.039	0.460	-0.082	-0.039	0.581	3.727	-2.677	1.050	0.84	1.00
	3.395	1.672	1.723	0.042	0.481	-0.103	-0.048	0.631	4.204	-3.421	0.783	1.07	1.13
H9...C10	2.947	1.217	1.791	0.039	0.482	-0.099	-0.055	0.636	3.874	-2.750	1.124	0.86	1.04
	3.263	1.225	2.038	0.042	0.536	-0.064	-0.040	0.640	4.586	-3.614	0.971	1.13	1.23
C5...H10A	2.886	1.647	1.268	0.035	0.443	-0.082	-0.043	0.569	3.512	-2.427	1.085	0.76	0.95
	2.986	1.730	1.256	0.039	0.374	-0.088	-0.077	0.539	3.433	-2.986	0.448	0.94	0.92
O2...H11C	2.656	1.498	1.158	0.033	0.521	-0.101	-0.096	0.721	4.013	-2.619	1.394	0.82	1.08
	2.636	1.534	1.102	0.045	0.568	-0.128	-0.120	0.816	4.659	-3.422	1.236	1.07	1.25
C7...H11B ^b	2.859	1.692	1.175	0.033	0.483	-0.051	-0.043	0.578	3.734	-2.458	1.276	0.77	1.01
	2.800	1.594	1.206	0.034	0.396	-0.080	-0.057	0.533	3.400	-2.690	0.710	0.84	0.92
N3...H11B	2.968	1.701	1.281	0.031	0.429	-0.065	-0.022	0.516	3.339	-2.226	1.113	0.70	0.90
	3.220	1.721	1.499	0.029	0.429	-0.055	-0.011	0.495	3.522	-2.599	0.924	0.82	0.95
N3...C6	3.462	1.761	1.746	0.029	0.346	-0.058	-0.007	0.410	2.712	-1.839	0.873	0.58	0.73
	3.618	1.753	1.865	0.032	0.403	-0.059	-0.020	0.482	3.302	-2.425	0.877	0.76	0.89
O4...C10 ^b	3.450	1.636	1.829	0.029	0.412	-0.058	-0.051	0.523	3.173	-2.069	1.104	0.65	0.85
	3.233	1.673	1.560	0.029	0.364	-0.067	-0.046	0.477	3.083	-2.387	0.697	0.75	0.83
C10...C10	3.875	1.937	1.937	0.028	0.344	-0.080	-0.024	0.448	2.692	-1.812	0.880	0.57	0.72
	n/a												
C9...H7B	2.880	1.693	1.214	0.028	0.370	-0.072	-0.048	0.489	2.859	-1.877	0.982	0.59	0.77
	3.016	1.800	1.216	0.034	0.322	-0.081	-0.062	0.466	2.832	-2.319	0.513	0.73	0.76
C9...H11A	3.081	1.858	1.314	0.021	0.263	-0.053	-0.036	0.352	2.006	-1.287	0.719	0.40	0.54
	3.232	1.968	1.264	0.029	0.279	-0.070	-0.056	0.405	2.416	-1.935	0.481	0.61	0.65
C9...H5 ^b	2.909	1.801	1.143	0.017	0.355	-0.048	-0.029	0.434	2.589	-1.498	1.091	0.47	0.70
	3.558	2.428	1.130	0.035	0.337	-0.089	-0.075	0.501	2.827	-2.157	0.671	0.68	0.76
C9...C9	3.752	1.876	1.876	0.015	0.187	-0.029	-0.007	0.222	1.398	-0.857	0.541	0.27	0.38
	3.628	1.814	1.814	0.023	0.241	-0.053	-0.023	0.324	2.135	-1.707	0.428	0.54	0.57

C9...H11C ^b	3.263	2.027	1.253	0.013	0.200	-0.027	-0.019	0.246	1.468	-0.863	0.605	0.27	0.40
	3.541	2.241	1.300	0.020	0.208	-0.039	-0.029	0.277	1.701	-1.241	0.460	0.39	0.46
H10B...H10C ^c	n/a												
	2.723	1.325	1.398	0.029	0.320	-0.082	-0.047	0.449	2.764	-2.205	0.559	0.69	0.74

Continuation of **Table S2**

H10B...H11A ^c	n/a												
	2.876	1.439	1.437	0.0161	0.1755	-0.04	-0.011	0.226	1.463	-1.105	0.358	0.3467	0.3938
C11...H10C ^c	n/a												
	2.519	1.446	1.073	0.1021	1.4363	-0.217	-0.089	1.7425	12.740	-10.580	2.160	3.3195	3.4296
Sum												15.27	19.21
												22.76	24.85

^a For reduced version with only the selected contacts see Table 1 in the article. The units of measurement are as follows: total length of the bond path between the interacting atoms R_{ij} , the length of the bond paths from BCP to the i^{th} or j^{th} atom d_1 and d_2 [Å], electron density at BCP ρ_b [$e \text{ Å}^{-3}$], Laplacian of electron density $\nabla^2 \rho_b$ and the eigenvalues of the Hessian matrix λ_1 , λ_2 , and λ_3 at BCP [$e \text{ Å}^{-5}$], kinetic, potential, and total energy densities at BCP g_b , v_b , and h_b [a.u.], interaction energies estimated from v_b and g_b using EML correlation E_v and E_b [kcal mol⁻¹]. ^b For the following intermolecular interactions differing BCPs were found from the optimized wave function and in the experimental ED distribution. Although these BCPs are located roughly in the same place, they connect different pairs of atoms due to the geometry changes as a result of structure optimization: H7B...H11B instead of C7...H11B, O4...H10A instead of O4...C10, C8...H5 instead of C9...H5, and C8...H11C instead of C9...H11C. ^c These BCPs were only found from the theoretical periodic wave function, the data for their experimental analogs are not available. On the contrary, C10...C10 contact only the experimental BCPs were found.

Table S3. Atomic ρ -, φ_{es} - and φ_k -basins (Ω) along with values of integrated $\rho(\mathbf{r})$ over them calculated for selected atoms ^a

Atom	$V(\Omega_\rho)$	$\rho(\Omega_\rho)$	$V(\Omega_{es})$	$\rho(\Omega_{es})$	$V(\Omega_k)$	$\rho(\Omega_k)$
O2	18.154	9.022	6.090	7.999	13.870	8.348
	17.653	9.011	6.202	7.999	13.495	8.336
	18.840	9.188	—	—	—	—
O4	18.126	9.040	6.015	7.998	13.426	8.355
	17.894	9.016	6.012	7.998	13.371	8.355
	19.032	9.183	—	—	—	—
N1	10.311	8.048	5.806	6.999	7.581	7.215
	10.125	7.885	6.196	6.999	7.799	7.189
	11.352	8.116	—	—	—	—
N3	11.399	8.000	5.669	6.997	8.254	7.216
	11.401	7.830	6.459	6.996	8.809	7.182
	10.241	8.130	—	—	—	—
C5	10.366	5.726	9.256	5.994	10.472	6.027
	11.113	6.018	8.466	5.996	10.250	6.057
	11.287	5.947	—	—	—	—
C6	8.608	5.946	9.911	5.999	8.983	5.896
	8.004	5.679	10.451	6.000	9.232	5.874
	7.980	5.615	—	—	—	—
H7a	6.219	0.872	8.226	1.000	7.044	0.929
	6.386	0.869	8.792	1.000	7.212	0.933
	6.337	0.942	—	—	—	—
H9	5.792	0.781	10.228	0.998	7.520	0.890
	6.018	0.838	8.606	1.000	7.075	0.926
	5.482	0.871	—	—	—	—
H11c	6.948	0.824	12.717	0.998	8.555	0.902
	7.703	0.945	8.792	0.999	8.030	0.969
	7.595	0.976	—	—	—	—

^a Units of measurement are as follows: volume of atomic basin $V(\Omega)$ [$\text{\AA}^3$], values of integrated ED over the atomic basins $\rho(\Omega)$ [e]. For each atom, the first row corresponds to the experimental data, the second

row contains data is obtained from the model refined against theoretical structure factors for the optimized crystal structure, and the data in the last row is calculated directly from the periodic wavefunction for the optimized crystal structure.

Table S4. Critical points (3, −1) in kinetic potential $\varphi_k(\mathbf{r})$ and their topological characteristics for covalent and noncovalent bonds in DMPU crystal ^a

CP (3, −1)	φ_{k_b}	$\nabla^2\varphi_{k_b}$	R_{ij}	d_1	d_2	Λ_1^b	Λ_2^b	Λ_3^b	ε
Covalent bonds									
O2–C2	2.069	9.740	1.23	0.618	0.607	−7.370	−7.09	24.20	0.04
O4–C4	2.162	9.970	1.23	0.617	0.608	−7.160	−7.12	24.24	0.01
N1–C2	1.776	7.070	1.38	0.689	0.691	−4.370	−4.18	15.62	0.05
N1–C6	1.759	7.450	1.38	0.689	0.689	−4.270	−4.18	15.90	0.02
N1–C2	1.596	7.100	1.38	0.689	0.691	−4.360	−4.17	15.63	0.05
N1–C10	1.52	6.110	1.46	0.729	0.735	−3.430	−3.24	12.78	0.06
N1–C10	1.385	6.340	1.46	0.729	0.734	−3.320	−3.14	12.81	0.06
N3–C4	1.652	6.680	1.40	0.698	0.705	−4.100	−3.89	14.66	0.05
N3–C4	1.632	6.750	1.40	0.698	0.705	−4.030	−3.89	14.67	0.04
N3–C2	1.526	7.730	1.38	0.687	0.695	−4.120	−3.77	15.61	0.09
N3–C7	1.419	5.840	1.47	0.734	0.735	−3.290	−3.17	12.30	0.04
C7–C8	1.51	5.680	1.46	0.732	0.731	−3.160	−3.11	11.95	0.02
C8–C9	2.177	9.010	1.21	0.603	0.603	−6.830	−6.74	22.58	0.01
C9–H9	1.575	5.600	1.07	0.680	0.394	−6.110	−5.99	17.70	0.02
C10–H10C	1.631	5.140	1.09	0.688	0.397	−6.000	−5.88	17.03	0.02
C10–H10B	1.623	5.130	1.09	0.694	0.399	−5.840	−5.75	16.72	0.02
C10–H10A	1.618	5.200	1.09	0.693	0.398	−5.870	−5.77	16.84	0.02
C11–H11C	1.677	5.060	1.09	0.692	0.399	−5.850	−5.76	16.67	0.02
C11–H11B	1.641	5.180	1.09	0.694	0.399	−5.800	−5.72	16.70	0.01
C11–H11A	1.626	5.120	1.10	0.696	0.400	−5.820	−5.69	16.63	0.02
Noncovalent bonds									
O2···H9	0.305	0.750	2.21	1.253	0.959	−0.300	−0.28	1.33	0.05
O2···H7A	0.249	0.690	2.41	1.370	1.043	−0.190	−0.19	1.07	0.01
O2···H7B	0.265	0.310	3.38	1.446	1.944	−0.040	−0.03	0.38	0.22
O2···H11C	0.206	0.560	2.66	1.449	1.208	−0.120	−0.11	0.80	0.11
O4···N1	0.26	0.890	2.85	1.352	1.500	−0.080	−0.05	1.02	0.49
O4···H10B	0.271	0.620	2.65	1.425	1.233	−0.120	−0.09	0.83	0.32
O4···H10A	0.137	0.500	2.97	1.427	1.661	−0.040	−0.03	0.57	0.49
O4···H11A	0.236	0.440	3.00	1.603	1.423	−0.060	−0.03	0.53	1.03
C2···C5	0.204	0.460	3.45	1.722	1.724	−0.060	−0.03	0.55	0.70
C4···N1	0.258	0.490	3.40	1.743	1.678	−0.060	−0.01	0.56	3.11
C5···H10A	0.246	0.480	2.89	1.698	1.252	−0.110	−0.07	0.66	0.47
C8···H11C	0.18	0.360	3.12	1.867	1.332	−0.060	−0.03	0.46	0.89
C9···H5	0.268	0.520	2.91	1.151	1.780	−0.120	−0.09	0.73	0.33

C9...H7B	0.354	0.470	2.88	1.223	1.661	−0.110	−0.09	0.67	0.14
C9...H11B	0.203	0.580	2.74	1.574	1.189	−0.130	−0.09	0.80	0.56
C9...H11A	0.183	0.380	3.08	1.791	1.316	−0.080	−0.05	0.51	0.47
C9...C9	0.087	0.350	3.75	1.869	1.900	−0.030	−0.02	0.40	0.58

Continuation of **Table S4**.

C10...H9	0.353	0.530	2.95	1.745	1.229	−0.120	−0.03	0.68	3.32
C11...H10C	0.446	0.970	2.37	1.398	0.989	−0.230	−0.10	1.29	1.34
H5...H11A	0.188	0.380	2.93	1.478	1.456	−0.070	−0.06	0.50	0.25
H7B...H11B	0.375	0.540	2.44	1.298	1.175	−0.130	−0.09	0.76	0.44
H9...H10A	0.205	0.540	2.55	1.250	1.336	−0.110	−0.04	0.69	2.24
H10B...H10C	0.302	0.420	2.63	1.286	1.358	−0.120	−0.09	0.62	0.30
H10B...H11A	0.28	0.360	2.85	1.428	1.422	−0.090	−0.04	0.49	1.40

^a Units of measurement are as follows: length of the bond path between the interacting atoms R_{ij} and the lengths of the gradient lines from the BCP to the i^{th} and j^{th} atom d_1 and d_2 , respectively, [Å]; Ellipticity $\varepsilon = \frac{\Lambda_1}{\Lambda_2} - 1$ is dimensionless; everything else is presented in atomic units [a.u.].

^b The Greek letters Λ_i denote the eigenvalues of the Hessian matrix of kinetic potential $\varphi_k(\mathbf{r})$.

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