Exploration of chemical bonds in real-space

Chemical bonds not only function as glues that connect atoms but also play a crucial role in providing functionality to molecules. With the recent advancements in organic synthesis techniques, a wide variety of functional molecules have been developed, and unique chemical bonds that cannot be explained by the conventional simplified concept of hybrid orbitals have been proposed. In this context, the experimental elucidation of the electronic states of chemical bonds has become increasingly important.

X-ray structural analysis and nuclear magnetic resonance (NMR) are commonly used to investigate the structure and arrangement of molecules. Spectroscopic methods are used to obtain experimental insights into the electronic states of molecules and molecular orbitals in momentum space. On the other hand, information about the spatial distribution of bonding electrons and molecular orbitals is mostly derived from quantum chemical calculations, such as density functional theory (DFT). As an experimental approach, methods for deriving the real-space distribution of molecular orbitals from spectroscopic data are also being actively developed; however, it is also necessary to discuss the validity of the theoretical model assumed in the analysis.

Here, we focused on the core differential Fourier synthesis (CDFS) method, which enables direct observation of valence electron density (VED) distributions from single-crystal X-ray diffraction data using synchrotron radiation without assuming theoretical models of electronic states [1,2]. In this study, we aimed to elucidate the detailed real-space distribution of bonding electrons by observing high-precision, high-resolution VED distributions using two typical molecular crystals (Glycine and Cytidine) [3]. Single-crystal X-ray diffraction experiments were conducted at SPring-8 **BL02B1** using a four-circle diffractometer (Rigaku Co., Japan). Long scans for VED observation were performed at 45 K for Glycine and 35 K for Cytidine. When applying the CDFS method, [He] type electronic configurations were assumed as the core electrons for C, N, and O atoms.

Figure 1 shows the VED distribution of the Glycine molecule. Unlike the typical recognition of smoothly distributed electron density across the entire molecule, the VED obtained by the CDFS method reveals fine structures. To interpret these fine structures, we consider 2*s* and 2*p* orbitals on a carbon atom. The carbon-carbon bond within the Glycine molecule is conventionally understood as a bonding orbital formed between sp^2 hybrid orbitals on each carbon atom. Here, since the 2*s* orbital contains nodes, the electron density distribution around the carbon atoms exhibits nodal structures. Thus, the experimentally observed nodal structures reflect the nodal plane of 2*s* orbital. By experimentally discerning such structural features in the VED distribution, it becomes possible to know how wavefunctions contribute to bond formation.

In recent years, these types of molecular orbitals are commonly obtained through quantum chemical calculations. However, due to the lack of clear guidelines on the reliability of these calculations, it has been difficult to determine whether various corrections are appropriate. Therefore, we compared the experimentally observed VED distribution with one of the most reliable calculation methods, long-range-corrected density functional theory (LC-DFT) (Fig. 1(d)). As a result, our experimentally observed and theoretically calculated VED are in good agreement, including nodal structures. This fact enables the complementary use of experimental VED and theoretical VED.

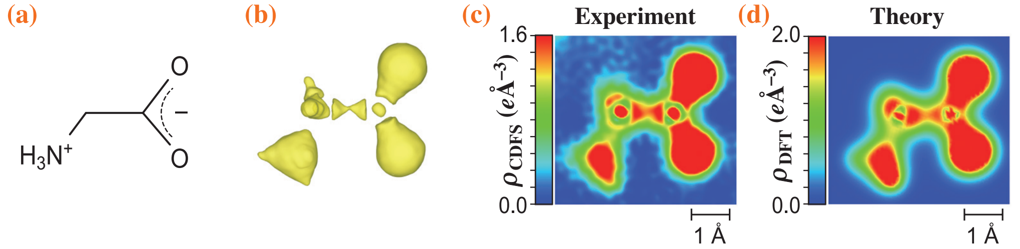

Fig. 1. **(a)** Molecular structure and **(b)** three-dimensional (3D) experimental VED of Glycine. Isosurface level is 1.4 e/Å^3. 2D contour plots of **(c)** experimental and **(d)** theoretical VED.

Subsequently, we explored the possibility of visualizing π-bonds. Figure 2 presents the structure of the Cytidine molecule, consisting of a six-membered ring and a five-membered ring, and its experimental VED. The C2–C1 bond in six-membered ring, where π-bond contributions are expected, exhibits a higher electron density compared to the C3–C4 bond in the five-membered ring. As shown in Fig. 3(a), the cross-section of the C4–C5 bond in the experimental VED exhibits isotropic characteristics, consistent with the features of a σ-bond. However, when examining the cross-section of the C2–C1 bond, an isotropic distribution was also observed (Fig. 3(a)). This can be attributed to the spatial coexistence of σ- and π-bonds, which makes it challenging to observe the anisotropy of the π-bond. To address this, the σ-bond component calculated using DFT was subtracted from the total experimental VED distribution (Fig. 3(b)). As a result, the anisotropic characteristics of π-bonds—nodes in the molecular plane and extensions perpendicular to it—was successfully observed (Fig. 3(a)). Focusing on the energy decomposition of molecular orbitals and complementarily utilizing high-precision DFT calculations is crucial for a comprehensive understanding of specific molecular orbitals. Experimentally visualizing the electronic distribution in molecules is expected to contribute to various research fields where π–π interactions influence functions and structural stability, such as organic semiconductors and DNA double helix.

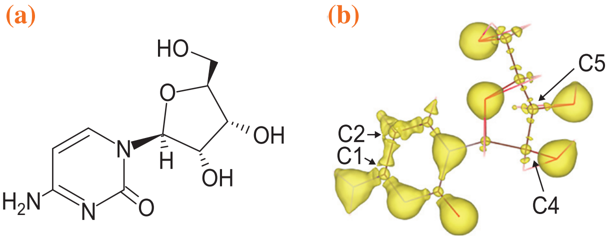

Fig. 2. **(a)** Molecular structure and **(b)** 3D surface plot of experimental VED of Cytidine molecule at an isosurface level of 1.7 e/Å^3.

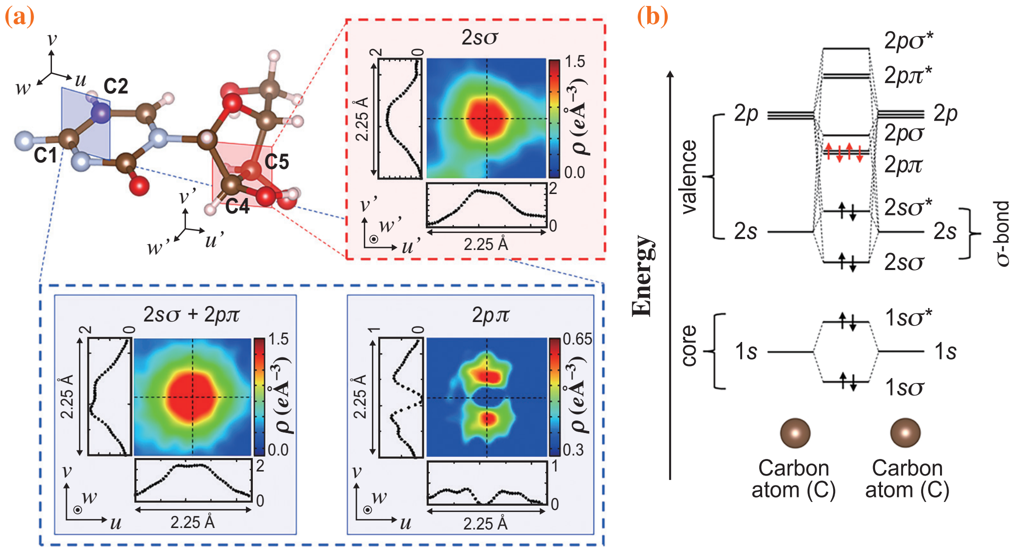

Fig. 3. **(a)** Cross section of the C4–C5 bond in experimental VED $\rho_{\mathrm{CDFS}}(r)$ is shown within the red dashed frame, and the cross sections of the C2–C1 bond in $\rho_{\mathrm{CDFS}}(r)$ (left side) and $\rho_{\mathrm{CDFS}}(r) - \rho_{\mathrm{DFT},2\sigma}(r)$ (right side) are shown in the blue dashed frame. Here, $\rho_{\mathrm{DFT},2\sigma}(r)$ is the theoretically calculated VED corresponding to the 2σ bond between C4–C5. **(b)** Energy level representation for a C=C double bond.

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References

[1] S. Kitou *et al*.: Phys. Rev. Lett. **119** (2017) 065701.
[2] S. Kitou *et al*.: Phys. Rev. Res. **2** (2020) 033503.
[3] *T. Hara, M. Hasebe, T. Tsuneda, T. Naito, Y. Nakamura, N. Katayama, T. Taketsugu, and H. Sawa: J. Am. Chem. Soc.* ***146*** *(2024) 23825.*