

Electron Density Distribution in Organometallic Materials

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Abstract: The electron density distribution is a fundamental property that provides information on the way in which atoms are held together to form molecules, polymers or supramolecular aggregates. Particular attention should be dedicated to the investigation of inorganic or organometallic materials, for their application in several fields. The goal of the research in this area is to find the inherent relationship between the actual electron density distribution of a molecule or a solid and its properties, including reactivity. This review summarizes the most recent results of electron density analysis and gives some personal perspective on future developments, focusing on applications in material science.

Keywords: Electron density · Molecular orbital · Quantum chemistry · X-ray diffraction



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1. Introduction: Why Electron Density?

Knowing the electron density distribution $\rho(\mathbf{r})$ is fundamental for all chemistry.

It was Schrödinger who first pointed out that the electronic charge and current densities are the two most important quantities to understand the magnetic and electric properties of matter.^[1] Indeed, 80 years of research since that statement have proven that chemical reactions, behavior of molecules, as well as supramolecular assemblies and material properties all depend on the distribution and movement of the electrons in a compound.

In everyday life, a chemist frequently uses the electron density to explain chemical bonding mechanisms, to predict molecular geometries (for example, using the valence shell electron pair repulsion theory)^[2] or chemical reactions (for example, in terms of electrophilic or nucleophilic additions). Aggregations of molecules at supramolecular level are also understood in terms of simplified electrostatic models to explain the formation of an adduct or the behavior of a material (for example, host-guest systems used to store or separate gas molecules).

The electron density basically represents a bridge between physics and chemistry. The laws of quantum mechanics predict the average distribution and movement of the electrons. On the other hand, chemistry needs more generalized and simplified understanding of the molecular electronic structure in order to handle problems of larger size.

In the past 40 years, the Quantum Theory of Atoms in Molecules (QTAIM),^[3] introduced by Bader and applied by theoretical chemists and later on by experimental crystallographers, has often allowed chem-

ical information to be extracted from the quantum mechanical description of electrons. Despite some criticisms,^[4] QTAIM has slowly become the paradigm for the interpretation of electron density distribution. This is certainly because it mainly rests on the three-dimensional scalar function $\rho(\mathbf{r})$,^[5] however determined, and it gives a visual representation of many chemical concepts. Moreover, QTAIM analysis allows easy comparisons between theory and experiment or between different theoretical approaches.

The principles of QTAIM are well described in specialized textbooks.^[3,6] Here, only a few concepts will be briefly described. An atom is defined in real space by boundaries constructed from the gradient field of the electron density, $\nabla\rho(\mathbf{r})$. In particular, it is possible to define a volume, called the *atomic basin*, which contains the electron density associated with a given nucleus (a maximum of the electron density and an attractor of $\nabla\rho(\mathbf{r})$ vectors). In a molecule, atomic basins are separated by uniquely determined (interatomic) surfaces. All density gradient vectors at a given point on a surface S are perpendicular to the normal vector $\mathbf{n}(\mathbf{r})$ of the surface. In other words,

$$\nabla\rho(\mathbf{r}) \cdot \mathbf{n}(\mathbf{r}) = 0, \forall \mathbf{r} \in S \quad (1)$$

The electron density, or any other property, integrated within the *atomic basin* constitutes the atomic contribution to that molecular property. This partitioning is unique and exact.

One of the most attractive feature of QTAIM is the possibility to ‘visualize’ chemical bonds by means of lines of maximum electron density (called *bond paths*) that connect two nuclei. A collection of bond paths defines the *molecular graph*.

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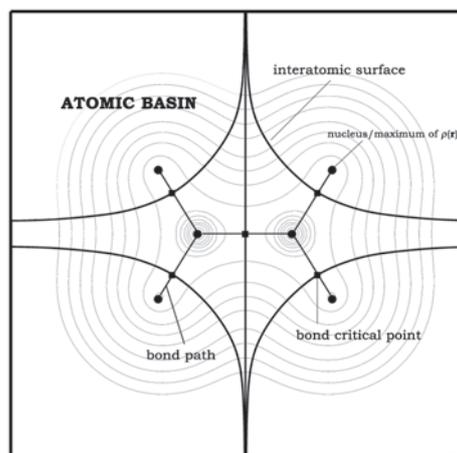


Fig. 1. Schematic representation of the principal topological feature of the electron density distribution of C_2H_4

In Fig. 1, the main topological features of a molecular electron density for C_2H_4 are shown.

The meaning of *bond path* and its chemical and physical interpretation generated considerable debate in the scientific community. Bader stressed on the homeomorphism between the distribution of electron density and that of potential energy density $V(\mathbf{r})$ (both computed at the equilibrium geometry).^[7] In the field of $V(\mathbf{r})$, a bond path indicates a lowering of energy, thus assuring the presence of (chemical) bonding. It should be noted, however, that the homeomorphism between $V(\mathbf{r})$ and $\rho(\mathbf{r})$ is only 'visually assigned' and cannot be generalized. Many authors have strongly criticized the interpretation of *bond paths* in chemical terms.^[8] In fact, beside its undisputed simplicity, a *bond path* is sometime found between atoms that chemists would hardly consider linked by a chemical bonding. On the other hand, the recent interpretation by Martín Pendás and coworkers^[9] is probably the most illuminating: they demonstrated that bond paths give evidence of preferred or privileged exchange channels in a molecule, *i.e.* "real-space carriers of quantum-mechanical exchange".^[9]

In many occasions, the chemical bond is better revealed by a substantial delocalization of electron pairs through two or more *atomic basins*, even if not directly linked through a *bond path*. For this reason, the *electron delocalization indicator* δ (measuring the number of electron pairs shared by two *atomic basins*)^[10] is extremely efficient and informative, especially where a direct, localized two-center bonding does not occur. This is frequent in organometallic molecules, where a metal may be linked to a multi-haptic ligand or *vice versa* a ligand could bridge two or more metals. Interesting, in this respect, is the apparently strange occurrence in $Fe(\eta^4-C\{CH_2\}_3)(CO)_3$, which was brilliantly illustrated,

experimentally and theoretically, by Farrugia and coworkers.^[11] The peculiarity of this compound is the presence of only one *bond path* connecting the Fe atom and the central carbon of the $C(CH_2)_3$ ligand, despite the idealized hapticity of 4 (Fig. 2). At the same time, more substantial electron sharing is found between the metal and the three methylene carbons than between Fe and the central (methane) carbon. Farrugia spoke of "chemical bonds without chemical bonding",^[10] a situation more common than expected if strong electron delocalization is present in the molecule. A similar example will be illustrated in Section 3.1 for metal–metal bonded systems.

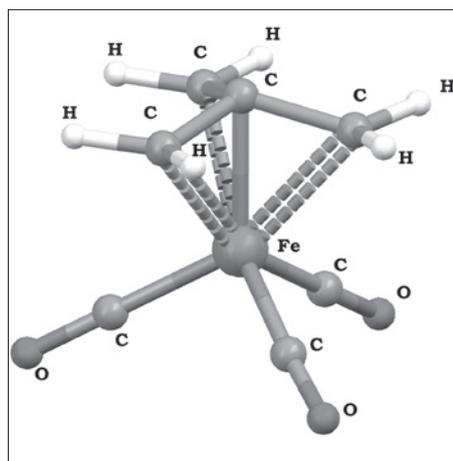


Fig. 2. Molecular geometry of $Fe(\eta^4-C(CH_2)_3)(CO)_3$. Note that despite that a single bond path is found connecting Fe and the central C of the trimethylenemethane ligand, more substantial electron sharing is found between Fe and each methylene carbon (dashed bonds in the picture).

The drawback of δ is that the pair density is necessary, not just the one electron density. This could be problematic from the experimental point of view.^[12] In this sense, the experimental electron density analysis might be somewhat limited, but research in the last few years has shown that chemical bonding features are retrieved from the simple analysis of the electron density, as we will see in Section 3. An alternative is represented by the possibility to calculate a molecular orbital wave function (at Hartree Fock, DFT or post Hartree Fock level) constrained to reproduce, at a given agreement level, the measured X-ray scattering intensities.^[13] This 'experimental' wave function offers the advantage of combining observations and theory (making available all density matrices), but it suffers of ambiguity when 'weighting' the measured intensity and for the high computational costs.

To overcome the problem of relying on the pair density, Gatti and coworkers proposed the use of the so-called *source*

function,^[14] *i.e.* a Green function of the electron density, computed only from its second derivatives:

$$G(\mathbf{r}, \mathbf{r}') = \nabla^2 \rho(\mathbf{r}') / |\mathbf{r} - \mathbf{r}'| \text{ and} \\ \rho(\mathbf{r}) = (1/4\pi) \int G(\mathbf{r}, \mathbf{r}') d^3 \mathbf{r}' \quad (2)$$

All points in the real space determine the electron density at a given point \mathbf{r} .

Integration of $G(\mathbf{r}, \mathbf{r}')$ within an *atomic basin*, gives the atomic contribution to the point \mathbf{r} (which is not necessarily positive). $G(\mathbf{r}, \mathbf{r}')$ provides some information about bond localization or delocalization, although it is important to stress that there is no physical link between the source function and the electron sharing among *atomic basins*.^[15]

Recently, much progress has been made to use $\rho(\mathbf{r})$ for more precise evaluations of electrostatic properties (such as intermolecular interaction energies, molecular and atomic electric moments, electric potential, fields and field gradients *etc.*).^[16] The groups of Becker^[17] and Espinosa^[18] investigated the role of electric field (*i.e.* the gradient of the electrostatic potential, $\phi(\mathbf{r})$)^[19] and derived a theory of atoms in molecules based on $\phi(\mathbf{r})$ instead of $\rho(\mathbf{r})$. Useful applications of this analysis were anticipated by Pathak and Gadre in a series of studies of the molecular electrostatic potential maps.^[20] The definition of electrophilic or nucleophilic sites in a molecule becomes more rigorous after the analysis of $\phi(\mathbf{r})$, which allows several applications, especially in biomolecular chemistry because of the well-recognized role of electrostatic forces between molecules in the process of protein folding and binding.^[21] This review is more oriented toward inorganic supramolecular chemistry, therefore we will not go into further details.

All the arguments presented in this paragraph clearly show that $\rho(\mathbf{r})$ contains enormous information to better understand the chemical bonding, and more generally the static (and dynamic) properties of a chemical system (a molecule, a polymer or a three-dimensional solid). Some examples concerning the chemistry of organometallic molecules will be given in Section 3 and some perspectives on future applications in Section 4. In Section 2, we will briefly summarize the requirements for an accurate electron density mapping

2. Background: How is the Electron Density Obtained?

The determination and analysis of the $\rho(\mathbf{r})$ in molecules and solids has grown as a major research area since the first experiments and theoretical predictions, which date back to the 1960s.^[22] Interestingly, the possibility to obtain the electronic

structures of atoms and molecules from X-ray diffraction on crystals was envisaged by Debye^[23] in the early days of crystallography, a time when measurements were not accurate enough to precisely detail the electron density distribution. Nowadays, instead, we can take advantage of automatic, fast and very sensitive diffractometers, equipped with devices that allow stable data collections down to very low temperatures (even below 10 K). Moreover, X-ray sources range from standard sealed tube (connected to high voltage generators) to modern synchrotron radiation sources, available at accelerator facilities, reaching enormous brilliances.

The best way to obtain experimentally an electron density map is to refine a parameterized model against X-ray diffraction intensities.^[24] Many models can be adopted, but the most popular one is by far the multipolar model, in particular within the notation introduced by Hansen and Coppens.^[25] The electron density of the crystal is expanded in contributions from each atom. An atom is expanded in terms of its electronic structure, for simplicity reduced to the core and valence electron densities.

$$\rho(\mathbf{r}) = \sum_{\text{atoms}} \rho_i(\mathbf{r}-\mathbf{r}_i) \quad (3)$$

$$\rho_i(\mathbf{r}) = P_{i,\text{core}} \rho_{i,\text{core}}(\mathbf{r}) + \kappa^3 P_{i,\text{valence}} \rho_{i,\text{valence}}(\kappa\mathbf{r}) + \sum_{l=0,lm\max} [\kappa^{l+3} R_l(\kappa\mathbf{r}) \sum_{m=0,l} P_{lm\pm} y_{lm\pm}(\mathbf{r}/r)] \quad (4)$$

The atomic shells are allowed to contract or expand and to assume aspherical forms (as it is conceivable when atomic densities are deformed by the chemical bonding). This is possible by refining κ radial scaling parameters and population coefficients $P_{lm\pm}$ of the multipolar expansion for each atomic valence shell (spherical harmonics $y_{lm\pm}$ are used to describe the asphericity).

Several software packages^[26] are available for multipolar refinement of the electron density and some of them^[26a,26c,27] also compute properties from the refined multipolar coefficients.

Obviously, $\rho(\mathbf{r})$ can be obtained also from theoretical methods, once a molecular wave function has been calculated. The most widely adopted approach is certainly the molecular orbital wave function method. It is quite important to mention the differences between software packages using Gaussian type functions as basis sets^[28] and those using Slater type orbitals (STO),^[29] which more accurately describe the core electron density. The code

ADF^[29] strongly pursued the application of relativistic corrections, very important for heavier elements, that also find correspondence in the theoretical scattering factors and functions (corrected for relativistic contractions)^[30] used in the multipolar model approach.

3. Applications: What Do We Expect from Electron Density Studies on Organometallic Materials?

3.1 Chemical Bonding in Organometallic Molecules

Bonding to a transition metal has many peculiarities that mainly depend on the small concentration of electron density in the bonding, which determines a lower covalency and a larger degree of delocalization.^[31] Nevertheless, it was well demonstrated that electron density analysis is able to reveal even the subtleties of these bonds and provide information for theoretical studies of organometallic compounds, catalysts or materials.

The small concentration of electrons in the bonds involving a metal is demonstrated by the usually positive Laplacian of the density, $\nabla^2\rho(\mathbf{r})$, in the region between a metal and a coordinated ligand (or between two metals). $\nabla^2\rho(\mathbf{r}) > 0$ mathematically indicates a local depletion of the electron density.^[3] Although some scientists interpreted this as a clear sign of ionicity,^[32,33] Macchi and Sironi have often stressed the misinterpretation of those observations.^[34] Indeed, a scarce concentration of electrons simply means a small degree of bond localization, but it does not have direct implications on the amount of covalency. It is certainly true that a strong covalent bond produces a large amount of locally concentrated electron density in the interatomic region. However, weaker interactions (as those involving transition metals) may

show a less predictable behavior.

Bearing this in mind, it became obvious that the analysis of chemical bonding in organometallic molecules requires the pair density distribution $\Pi(\mathbf{r}_1, \mathbf{r}_2)$,^[35] not just the one electron density. Electron delocalization indexes δ (obtained from $\Pi(\mathbf{r}_1, \mathbf{r}_2)$) proved to be very informative, reproducing some expectations of the ‘chemical common sense’, however giving also some unexpected findings. The most interesting example is the metal–metal bonding in metal carbonyl clusters.

On one hand, the simple electron counting rules predict two-center two-electron metal–metal bonds in these molecules (formally, up to four metal clusters),^[36] see some examples in Fig. 3. On the other hand, experiments and calculations evidenced small amounts of electron density in the M–M region (not significantly different from the pure superposition of isolated, unperturbed, atoms),^[37] which led some authors to speak of non-covalent interactions.^[32] This apparent contradiction was also associated with an older controversy between the presence of a direct M–M interaction or an electrostatic attraction between one metal and the ligand groups of the other.^[38] An accurate analysis of the electron density^[39] showed that whereas small and not locally concentrated, $\rho(\mathbf{r})$ in a M–M interaction is associated with a dominant potential energy density (typical of covalency),^[40] however the ligands coordinated to any of the two metals are significantly affected by the M–M bond, as visualized through the Laplacian map and the bond paths (Fig. 4). This suggests that a view in terms of localized two-center M–M bonding is too approximated and a delocalized mechanism should be considered.

Macchi and Sironi analyzed the pair density of various $M_2(\text{CO})_n$ systems^[39] (reported in Fig. 3), comparing the theoretical results with the experimental observations and drew the following conclusions:

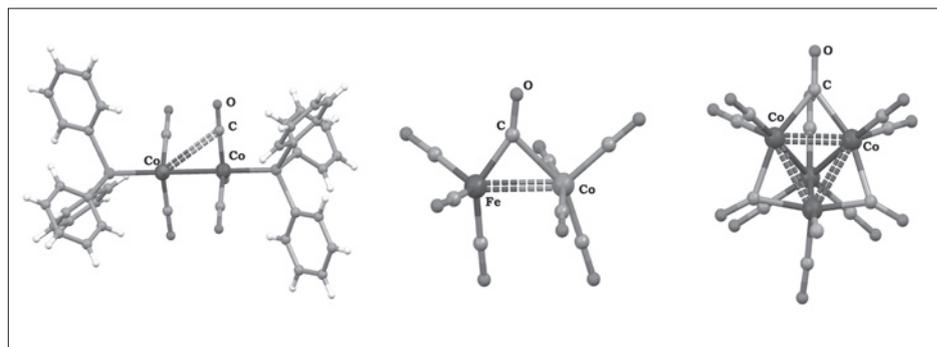


Fig. 3. Molecular geometries of the three metal carbonyl complexes used for studying the M–(CO)–M system in different conformations. On the left, $\text{Co}_2(\text{CO})_6(\text{AsPh}_3)_2$ with terminal carbonyls; in the center $[\text{FeCo}(\text{CO})_6]^-$ with semibridging carbonyl; on the right, $\text{Co}_4(\text{CO})_{11}(\text{PPh}_3)$ (phenyl rings omitted for clarity) with symmetrically bridging carbonyls. Bond paths in the electron density topology are represented with stick bonds, substantial electron sharing (in the absence of a direct bond path) by dashed lines.

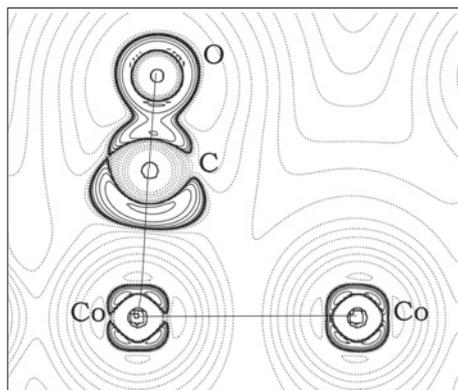


Fig. 4. $\nabla^2\rho(r)$ map for $\text{Co}_2(\text{CO})_6(\text{AsPh}_3)_2$ from experimental multipolar model (negative contours are solid lines, positive contours are dotted lines). Note the perturbation of the carbonyl electron density in proximity of the Co–Co bond. Note that no 1,3 Co---C bond path can be located on the electron density map, but that substantial electron sharing is computed between these atoms (and all the other equivalent contacts).

- i) Electron counting rules are misleading because there is no simple two-center-two-electron bonding in M–M systems, especially in the presence of π -acidic ligands coordinated to one or both the metals. The actual electron sharing between two metals is always partial (ca. 50% of an electron pair for a formally single M–M bond of metal carbonyl complexes). Nevertheless, the covalent nature of the interaction is evident.
- ii) The ligands do indeed take part in the bonding. However, their participation is not a mere electrostatic perturbation, but an actual electronic contribution. If the ligands are strongly π -acidic (carbonyls for example) they subtract substantial electron density (thus electron sharing) from the M–M bond.

Other theoretical works later confirmed those findings using the domain-averaged Fermi Hole approach.^[41]

The electron density analysis has also been used to characterize other chemical bonds of many intriguing organometallic systems. Among the most relevant results, we find the estimation of ligand field effects,^[42] a new interpretation of *agostic* interactions,^[43] the rationalization of the coordination of olefins^[44] and epoxides^[45] to transition metals, the investigation of organolithium chemistry,^[46] and the study of magnetic coordination complexes and polymers.^[47] In all these examples, the traditional bonding schemes based on molecular orbitals have been complemented or even substantially revised, as in the seminal work by Scherer and McGrady on *agostic* interactions.^[43]

3.2 Intermolecular Interactions, Supramolecular Chemistry

In the last two decades, chemical research has moved toward supramolecular

chemistry, at a very impressive rate. The number of materials produced by aggregation of molecules or ions is countless and the field of crystal engineering has emerged as a major science. For this reason the study of supramolecular interactions, through various kinds of structural analysis and theoretical interpretations, is nowadays very important. Many scientists have also used electron density analysis to investigate the various forms of hydrogen bonding^[48] especially because of its relevance in biochemistry.

On the other hand, less attention has been paid to metal-organic coordination polymers or in general modern inorganic materials. These species are very interesting because they produce multidimensional infinite networks able to host, select and organize guest molecules carrying some specific properties. The accurate analysis of the electron density distribution could be fundamental to understand the interaction between the framework and the guest (therefore predicting the most efficient supramolecular organization) or to estimate the actual properties of the material. Section 4.1 will be dedicated to illustrate some potential applications in this area, largely unexplored. Here we will focus on a few examples that have recently appeared.

Macchi and Tiana^[49] analyzed theoretically the perturbation of ionic metal–carbonyl complexes, in order to shed light on the changes occurring to these molecules due to the strong electric field they are subject to, in the solid state forms. The analysis focused on the anion $[\text{Co}(\text{CO})_4]^-$, known in several salts of many different counterions (ranging from highly polarizing alkali metals to much softer alkyl ammonium derivatives). Analysis of the electron density in the isolated ion shows that the negative charge modifies the bonding in the Co–C bonds with respect to neutral molecules, reinforcing metal-to-ligand back donation

at the expense of ligand-to-metal donation. This in turn weakens the C–O bond. However, the cationic field in crystals of $\text{M}[\text{Co}(\text{CO})_4]^-$ species may substantially alter this picture, especially if M is an alkaline metal. The Co–C bonds might be reinforced or weakened depending on the pattern of cations around the anion. Two mechanisms play a fundamental role: the electron density polarization (induced by the positive charges surrounding the anionic complex) and the anion-to-cation partial charge transfer (observable at least for smaller and more closely coordinated alkali metals, like Li^+). In Fig. 5, the different packing of Li^+ and Cs^+ salts is illustrated by the corresponding Hirshfeld surfaces^[50] drawn for the anion in the two salts. In the two different supramolecular structures, the cations produce a strong polarization of the C–O bond (Li^+) or of the Co atom directly (Cs^+). Interestingly, the deformation induced by the cation field is comparable in magnitude to that of the anionic charge itself.

Iversen and coworkers^[47] have pioneered the study of magnetic metal organic frameworks, mainly using synchrotron X-ray radiation, in order to maximize the accuracy of the experimental electron density determinations. The analysis of electron populations at the metal atom sites has enabled insights to be obtained on the origin of magnetism and super-exchange mechanism in these species.

4. Perspectives: Where are Electron Density Studies Going?

As mentioned above, the field of electron density determination and analysis is experiencing a very exciting period thanks to the progress in many technical areas that allows experiments at the highest accuracy level and developments of computational

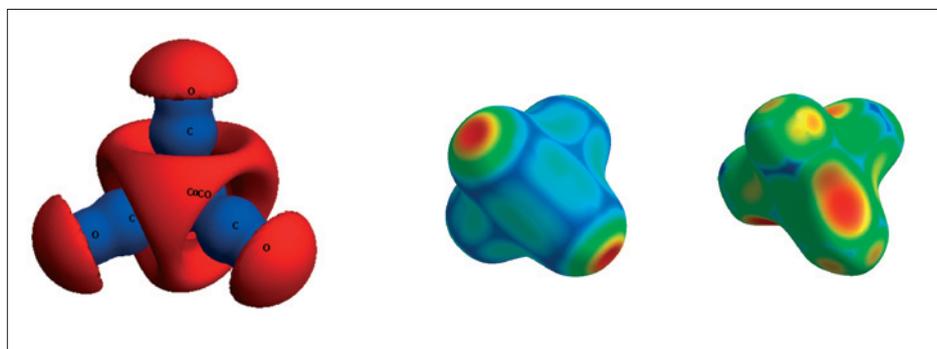


Fig. 5. $[\text{Co}(\text{CO})_4]^-$ Electrostatic potential (left) and Hirshfeld surfaces in Li (center) and Cs (right) salts. Positive electrostatic potential is in blue, whereas negative is in red. The color plotted on the Hirshfeld surface indicate distance of nearby cations from the anion surfaces (shortest distances are in red, longest in blue). Note that the two packing are extremely different as in Li salt, the cation is ‘bound’ through the carbonyl oxygens, in Cs salt is opposed to it. This is due to the dual nature of the electrostatic potential of the anion, having lobes of most negative regions in both regions. The polarization onto the electron density of the cobaltate anion is however very different in one case or the other.

chemistry methods. This leads to increased expectations of new results, especially for the implications in chemistry, biochemistry and material science. In the author's opinion, the most appealing fields of research where electron density analysis will play a very important role are those listed in the following.

4.1 Multifunctional Hybrid Materials

"Organometallic crystal engineering is the modeling, synthesis, characterization and evaluation of crystalline materials constituted by organometallic molecules and ions".^[51] In particular, multifunctional porous materials obtained from the combination of organic ligands and metallic centers have attracted enormous attention for the diversity of their potential applications. In fact, they can combine the versatile behavior of organic molecules and the bulk properties of inorganic solids. These hybrid metal-organic materials are quite different from organic polymers, activated carbons or inorganic solids. Much advantage is taken from the robustness afforded by the *linkers* (organic ligands) and variable spin and charge states of the *connectors* (metal atoms). These characteristics are exploited to produce materials with predefined physical properties and/or able to generate host-guest systems. The guest molecules can be absorbed, desorbed, selected, reacted or otherwise arranged in order to create specific material functionality arising from their electronic structure. Moreover, combination of different functionalities between host (metal-organic) frameworks and guest (very often organic) molecules has created a variety of poly-functional materials.^[52]

Good control in the preparation and functionalization of a target material is in general claimed. However, this is typically obtained only by empirical rationalization and simple, rigid modeling of the frameworks. Instead, more control of the distinct structural and functional aspects is needed. Surprisingly, however, the number of accurate theoretical investigations is small compared to the reports on preparation and structural characterization.

Applications of charge density analysis in the field of functional materials are rather few but much development can be anticipated. In particular, the usage of electron density analysis for calculation of material properties is as yet an unexplored area. Indeed, a combined molecular mechanics and electron density approach could result in accurate evaluation of intermolecular interactions coupled to parameterized treatment of the molecular flexibility. Some work in this direction has been anticipated especially for mineral phases by Gale and

Rohl,^[53] using a simplified treatment of the electrostatic interactions respect to the more modern exact potential approach by Volkov and Coppens.^[16d]

Equally important is the possibility to analyze a molecule embedded in the solid state and monitor the changes to its behavior (for optoelectronic applications). The X-ray constrained wave functions allow calculations of a molecular wave function, though including effects of the solid state packing and recent progresses by Spackman and Jayatilaka made possible the calculations of molecular polarizabilities directly from X-ray diffraction data.^[54]

All these works suggest that electron density analysis could be useful for the crystal engineering process. Spackman and coworkers^[55] have shown that even the simple analysis of the promolecule electron density (*i.e.* the electron density of a molecule constituted of spherical unperturbed atomic densities) can be informative to understand leading motifs of crystal packing. The Hirshfeld surfaces^[50] can be useful to map different kinds of weak or strong intermolecular interactions and they offer an intuitive way to idealize supramolecular aggregates. Spackman and coworkers^[55] analyzed the distribution of internal (d_i) and external (d_e) distances from the molecular surface; an approach particularly useful to emphasize the diversities between polymorphs or the similarities between isomorphs.

It certainly emerges from all these works that electron density analysis can offer crystal engineering what is exactly needed to improve the design of new materials: i) a simple modelling of building blocks to allow the supramolecular structure to be predicted with 'paper and pencil'; ii) a more accurate evaluation of interactions between molecules to eventually simulate the actual stability of the material or its behavior.

4.2 Dynamic Electron Density and the Development of Reactivity Indexes

The examination of electron density is currently moving toward 'dynamical' aspects. It is noteworthy that the subtitle 'density and dynamics' was added to the most recent Gordon Research Conference on this subject, traditionally called 'Electron density distribution and chemical bonding'.^[56] *Dynamic* here means studying properties that do not depend only on the ground state electron density distribution or on the ground state equilibrium geometry. For example, many studies on excited states have been reported, thanks to progress in time-resolved crystallography.^[57] No accurate electron density mapping is currently possible because only a small fraction of the sample is actually converted

during laser excitation and the experimental measurements are therefore extremely sophisticated. So far, researchers could map the molecular geometry changes, using a sort of deformation density map. Nevertheless, the complement of theoretical calculations has also allowed full analysis of the electron density, *e.g.* for the Pt-Pt bond in $[\text{Pt}_2(\text{H}_2\text{P}_2\text{O}_3)_4]^{4-}$.^[58]

The prediction of chemical reactivity from accurate mapping of the electron density distribution remains a major goal. Some recent work by Stalke and coworkers^[59] on organo-lithium complexes demonstrates the possibility to use electron density analysis also to anticipate chemical reactivity (and stereochemical control) rather than using simple point charge distributions.

4.3 Materials under Extreme Conditions

Structural studies of materials under external stimuli have become very popular and have often provided new information compared to corresponding studies without perturbation. There are many examples that have direct implications on the study of the chemical bonding or materials properties.

For example, crystallographic studies under electric field may give enormous information on the material properties as well as on the chemical bonding. Recent works on this subject has shown the large potentiality of this method. The experimental electron density is certainly highly approximated^[60] but the results are still noteworthy.

Another interesting field is that of high-pressure crystallography. This technique has been widely adopted by mineralogists who are interested in mimicking the effects of the earth mantle and simulate minerals under extreme conditions. More recently, however, many chemical applications have appeared. Noteworthy is the discovery of a covalent solid of nitrogen after transformation of the triply bonded molecules into a polymer of single-bonded N atoms.^[61] Because of the very complicated experimental techniques, the accuracy of data is not enough, at the moment, to extract electron density maps. However, new high pressure equipment could provide the opportunity to obtain higher resolution data (especially when using synchrotron radiation sources and short wave lengths) with higher accuracy. In addition, theoretical calculations in the solid state have made enormous progress^[28c] and simulations at high pressure are now very reliable and accurate.^[62]

5. Conclusions

This paper has briefly reviewed the progress in electron density analysis with

special focus on metal–organic compounds. The results obtained by experimental and theoretical approaches demonstrate that the chemical information contained in $\rho(\mathbf{r})$ can be in fact extracted and used to improve the understanding of chemical bonding mechanisms. However this research field is now progressively moving toward ‘dynamic’ applications, meaning that information on the molecule behavior (reactivity, response to external stimuli, etc.) can and should be investigated. It is expected that these studies will impact especially on materials science.

Received: January 9, 2009

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