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# Improved General Understanding of the Hydrogen-Bonding Phenomena: A Reply

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We believe that fair-minded readers will recognize that our „anti-electrostatic hydrogen bonding“ (AEHB) article[1] was prepared for a general chemical audience of Angewandte Chemie readers, building on „common parlance“ rather than the imagined technical associations that Frenking and Caramori (FC)[2] wish to assign them (else we would have properly cited such associations). In fact, there is little usage per se of natural bond orbital (NBO) analysis[3–5] or related technical terminology in our work, except to exhibit obvious graphical similarities between NBO interactions in AEHB and conventional hydrogen-bonded species. Nothing approaching full-fledged NBO analysis (i.e., in the sense of chapters 1–6 of „Discovering Chemistry with Natural Bond Orbitals“;[4] see below) was attempted or claimed in our work. Many of FC's strongest remarks (viz., „Coulombic interactions are calculated…using hand-waiving arguments and a wrong equation“, „Pauli repulsion…is completely ignored“, „NBO calculations always suggest orbital interactions for explaining chemical phenomena“, „the NBO method is useless for elucidating the nature of chemical bonding because it affords only information about orbital interactions in a biased way,…“) are unsupported and fallacious, seemingly directed at some imagined parody of NBO analysis rather than what could be fairly inferred from our AEHB paper or the broader literature of NBO methods.[5]

Let us first summarize important points on which there appears to be substantial agreement. FC raise no substantive quibbles concerning our computational AEHB work, nor claim any previous anticipation of the surprising H-bonding in these high-energy complexes between like-charged ions. Furthermore, they express essential agreement with our basic assertion that H-bonding (like ordinary covalent bonding) cannot be reasonably understood in classical electrostatic terms, but instead derives from deeper aspects of Schrödinger's quantum-mechanical wave equation (which different workers may prefer to express in different words). In agreement with our AEHB work and earlier papers on H bonding,[6] FC express skepticism of the simplistic classical point-charge formulas (and presumably the associated „dipole–dipole“ conceptions) that are the basis of most current molecular dynamics simulations and classroom pedagogy of H-bonding. Hence, their sharp criticisms focus essentially on the NBO method itself, and how it differs in terminology and concepts from the particular „energy decomposition analysis“ (EDA) method[7] that the senior author has long advocated.[8]

To clarify the specific verbal associations that FC wish to attribute to „electrostatics“ (or „elstat“) and other components of EDA-based labeling, we start from the basic EDA assumption,[7,9] that the interaction energy ($\Delta E_{\text{int}}$) of species „A“ and „B“ at separation $R$ can be decomposed into simple additive contributions from electrostatic ($\Delta E_{\text{elstat}}$), Pauli exchange repulsion ($\Delta E_{\text{Pauli}}$), and quantum-mechanical „orbital“ interactions ($\Delta E_{\text{orbital}}$), namely Equation (1)[10]

$$\Delta E_{\text{int}} = \Delta E_{\text{elstat}} + \Delta E_{\text{Pauli}} + \Delta E_{\text{orbital}} \quad (1).$$

In this expression (as in the original Kitaura–Morokuma treatment[9]), „the more precise quantum-theoretical approach“ for estimating electrostatics is taken as given in Equation (2),

$$\Delta E_{\text{elstat}} = \int \rho^{\text{A}}(1)\rho^{\text{B}}(2)/r_{12}\,\mathrm{d}\tau \quad (2)$$

where $\rho^{\text{A}}(1)$, $\rho^{\text{B}}(2)$ are respective electron densities for isolated species (calculated at infinite separation) that are placed into overlapping juxtaposition at finite separation $R$ to perform the integral over interelectron $r_{12}$ values. The „$\Delta E_{\text{Pauli}}$“ component (evaluated as a difference between antisymmetrized and non-antisymmetrized orbital products) also harbors significant sensitivity to overlap ambiguities,[11] further clouding EDA physical interpretations compared to the lucid Weisskopf picture[12] that underlies NBO-based steric analysis.[13] The remaining „$\Delta E_{\text{orbital}}$“ term [formally corresponding to the resonance-type donor–acceptor interactions that are independently quantified by a variety of variational, perturbative, and natural resonance theoretic (NRT) techniques in NBO theory[3–5]] is merely defined by energy difference in EDA theory, thereby inheriting composite errors of „$\Delta E_{\text{elstat}}$“, „$\Delta E_{\text{Pauli}}$“ components. This makes

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Equation (1) tautologically true, and thus unfalsifiable to its committed proponents, but raises severe questions (analogous to those for other „bookkeeping“ partitionings of total energy,[14,15]) concerning the predictive or explanatory value of the EDA dissection or its individual components.

It is certainly true that the $\Delta E_{\text{elstat}}$ identification [Eq. (2)] can be justified in the long-range limit $R \rightarrow \infty$ (or practically speaking, for $R$ much greater than the sum of van der Waals radii). However, Equation (2) becomes exponentially questionable as the subsystems penetrate into the sub-van der Waals region of quantum-mechanical exchange interactions, as was implicitly recognized also in the original EDA formulation of Bickelhaupt and Baerends.[16] The conceptual errors resulting from uncritical extension of Equation (2) into the short-range overlap regime were clearly identified in earlier NBO literature,[17] where ambiguous „overlap density“ was shown to lead to gross underestimates of resonance-type charge transfer (FC's „orbital“) effects even in the domain of common H bonds at relatively modest van der Waals penetration distances (ca. 0.5 Å). Frenking's group pioneered much more aggressive EDA applications down to covalent bonding distances (more than 1.5 Å inside van der Waals contact!) where unassigned overlap densities become increasingly problematic and EDA-based electrostatic estimates exhibit inexplicably large variations of magnitude (and sign) that dwarf $\Delta E_{\text{int}}$ itself. (The dotted line of FC's Figure 2 illustrates one example of such variability, depicting an „electrostatic component“ of $H_2$ chemical bonding that defies any common conception of the term and is grossly larger than the binding energy it purports to rationalize.) The severe conceptual errors resulting from the intrinsic overlap dependence of EDA and other „nonorthogonal perturbation theory“ formulations are now rather widely recognized in the analysis of H bonding[18] and related hyperconjugative phenomena.[19]

For completeness, it should be mentioned that the most direct NBO–EDA comparison should properly be made through NBO-based „natural energy decomposition analysis“ (NEDA) method of Glendening et al.[20] NEDA leads similarly to additive „electrical“ (EL), „core“ (CORE), and „charge transfer“ (CT) components that are formal analogs of $\Delta E_{\text{elstat}}$, $\Delta E_{\text{Pauli}}$, and $\Delta E_{\text{orbital}}$, respectively. For the equilibrium $F^{-}\cdots HCO_3^{-}$ under discussion (B3LYP/6-311++ level), NEDA suggests that, relative to their effects in the transition state, EL and CT interactions are stabilizing by 6.75 and 12.26 $\text{kcal mol}^{-1}$, respectively, while CORE repulsions are destabilizing by 18.77 $\text{kcal mol}^{-1}$.[21] NEDA thereby yields a significantly different picture than FC's preferred EDA of the relative importance of charge transfer versus electrical components, while also incorporating their important coupling (with significant portions of the „electrical“ contribution deriving from CT-induced charge shifts, for instance). Individual NEDA components are also perforce consistent with other NBO-based descriptors, such as independently calculated STERIC and NRT keyword evaluations, variational $DEL orbital deletions, NCE (natural Coulomb electrostatics), DIPOLE, and other relevant measures of charge distribution, Pauli exchange repulsions, and resonance-type donor–acceptor interactions.[22] None of these authentic features of comprehensive NBO analysis are mentioned by FC.

Although still further removed from the substance of our AEHB communication, we cannot allow the litany of NBO criticisms gathered in FC's Ref. [12] to pass unchallenged. Their remarks extend to a broad diversity of topics, including: 1) nature of ethane-like rotation barriers, 2) importance of p orbitals in transition metal bonding, or d orbitals in heavy main-group bonding, 3) theoretical origin of the empirical „18-electron rule“, and 4) electronic mechanism of coinage metal ligation with N-heterocyclic carbenes (NHCs). We concur with FC that these NBO versus EDA disagreements are all interwoven at a deep mathematical level, such that success or failure of EDA or NBO rationalizations for one problem implies similar success or failure for the others. In this spirit we can briefly comment on each subsidiary issue (1–4) as follows:

1) For details of the underlying mathematics and conceptual incongruities of older „2e-destabilizing“ rationales of ethane-barrier behavior (as predictably resurrected in overlap-dependent EDA schemes), see Ref. [23,24]. No details of these references have been addressed or refuted by FC or other EDA proponents.

2) FC provide a list of older references that originally raised the issue of possible „bias“ in NAO-based definition of ground-state valence shell, but fail to mention the more recent comprehensive study[25] that thoroughly addresses and resolves such issues. Methodological details and conclusions of this study have not been addressed or refuted by FC or other subsequent authors.

3) A forthcoming article[26] details the simple „3c/4e-hyperbonding saturation limit“ that rationalizes most of the empirical 18e-rule, without invocation of FC's envisioned „p-orbital contribution“ to transition-metal bonding.

4) The NOCV-EDA application[27] described in FC's Ref. [12] inappropriately assumes neutral „prep“ fragments for the metal-NHC complex (as required by EDA methodology for consistency with the neutral long-range dissociation limit), whereas the actual complex is conspicuously ionic (by NPA, QTAIM, Mulliken, or other common population analysis methods) because of electron transfer from the metal to the „non-innocent“ carbine ligand. The claim of significant p-orbital contribution to the ionic $d^{10}$ metal configuration is therefore vastly overstated.[28]

We can conclude that what remains after correcting for misstatements and omissions is FC's ardent advocacy to substitute narrow EDA-based definition of „electrostatics“ in place of common parlance. Such semantic substitution would indeed allow FC's title proposition to become tautologically true, but serves effectively to support superficial „electrostatics“ orthodoxy and quench constructive attempts (i.e., in the spirit of the 2011 IUPAC recommendations[29]) to improve general understanding, pedagogy, and empirical force-field modeling of H-bonding phenomena.

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[16] According to Equation (11) of Ref. [7], the „elstat“ contribution (said to be „a term that can be conceived as the classical electrostatic attraction between unperturbed charge distributions of A and B“) contains three additional terms beyond the expression [Eq. (2)] quoted by FC, but (p. 15) „at large distance (when $\rho^{A}$ and $\rho^{B}$ do not overlap), these terms cancel“. Our concern is precisely with errors that arise at shorter distances when the cancellation is no longer exact.

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