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Mixed QM/MM Calculations in Biological Systems

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The computational study of a variety of important processes, such as processes involving bond breaking and forming and electron reorganization, requires the application of quantum mechanical methods. In biological systems, this situation is further complicated because the influence of the environment must be taken into account. In these situations, hybrid quantum mechanics / molecular mechanics methods can be used. We describe here two new QM/MM implementations based on the Amber Molecular Dynamics packages that make it possible to use of a variety of quantum mechanical methods with any of the techniques available in Amber. Results are provided for the application of these implementations to two different systems.

1 Introduction

Due to the large system size, computational studies of biologically relevant systems such as proteins, nucleic acids and carbohydrates need to resort to approximated Molecular Mechanics (MM) methods which apply parameterized force fields to describe molecular properties such as bond lengths, angles, dihedrals, electrostatic and van der Waals forces. The use of such parameterized methods greatly reduces the computational complexity, allowing the study of processes including ligand binding, enzyme reaction mechanisms, protein folding, refolding, and denaturation, providing invaluable help in the analysis of complex experimental data and structures.

Despite continuous efforts to develop more reliable force fields for use in MM calculations, including the use of QM calculations and genetic algorithms in the parameterization of the force field, classical mechanics methods lack the ability to treat fundamentally quantum processes, such as bond breaking and forming and charge fluctuations as a function of geometry, or to describe parts of the potential energy surface far from equilibrium. In some cases, although computationally expensive, it is possible to treat a model system purely by QM methods, but the effect of the environment must be either neglected or simulated by a continuum dielectric approximation. An alternative that allows the explicit inclusion of environment effects while treating the most relevant part of the system with full quantum mechanics was first explored by Warshel and Levitt as early as 1976,¹ and is the use of hybrid quantum mechanics / molecular mechanics (QM/MM) calculations whereby a subsection of the system is treated by QM methods, the remainder (environment) is treated by standard molecular mechanics (MM) methods, and a coupling potential is used to connect the two regions.

Recent work in our group has focused in the implementation and application of hybrid QM/MM techniques for the study of biologically relevant systems. In particular, discussed here are two recently developed interfaces: the new native, (semi-empirical) QM/MM support available in Amber 9,² and the integration of the Amber MD program with a QM program through the PUPIL interface. These interfaces offer the advantage of blending seamlessly with the Amber program, allowing the application of any of the advanced sampling methods available in Amber to QM/MM problems.

2 QM/MM

In a hybrid QM/MM calculation, the system is partitioned into two regions: A QM region, typically consisting of a relatively small number of atoms relevant for the specific process being studied, and a MM region with all the remaining atoms. The total Hamiltonian (\hat{H}) for such a system is written as:

$$\hat{H} = \hat{H}^{QM} + \hat{H}^{MM} + \hat{H}^{QM/MM}, \quad (1)$$

where \hat{H}^{QM} and \hat{H}^{MM} are the Hamiltonians for the QM and MM parts of the system, and are calculated using either the QM method chosen or the usual force field equations, respectively. The remaining term, $\hat{H}^{QM/MM}$, describes the interaction between the QM and MM parts and typically contains terms for electrostatic, van der Waals and bonded interactions across the region boundaries:

$$\hat{H}^{QM/MM} = \hat{H}_{vdW}^{QM/MM} + \hat{H}_{elect}^{QM/MM} + \hat{H}_{bonds}^{QM/MM}. \quad (2)$$

In the approach used for both Amber QM/MM interfaces presented here, the van der Waals ($\hat{H}_{vdW}^{QM/MM}$) is treated as usual by the MM program, using the standard 12-6 Lennard-Jones parameters from the force field in use. It has been shown that this choice does not introduce significant errors in the calculation.³ Also, both interfaces described here use a link atom scheme if bonds are broken across the QM–MM boundary. Finally, the remaining term ($\hat{H}_{elect}^{QM/MM}$), describing the electrostatic interaction between the MM and QM zones, depends on the specific interface.

3 Semi-Empirical QM/MM in Amber

One of the most used programs for MD simulations is the *sander* program, part of the Amber suite. The *sander* interface for QM/MM has been recently rewritten, placing strong emphasis on speed and accuracy, allowing the simulation of systems with a reasonably sized quantum mechanical region (around 300 atoms) for long (nanoseconds) timescales. It now natively includes a number of semi-empirical Hamiltonians for QM/MM simulations including MNDO,^{4,5} AM1,⁶ PM3,^{7,8} PDDG/PM3⁹ and SCC-DFTB.¹⁰ Our group has been involved in the implementation of the SCC-DFTB method.

The Self-Consistent-Charge Density-Functional Tight Binding (SCC-DFTB) is an approximate method based on Density Functional Theory (DFT) from a second order expansion of the DFT total energy in the charge density fluctuations, and has been described in detail elsewhere.^{11,10} It has been successfully applied to the study of a variety of systems, and has been shown to yield results comparable in accuracy to *ab-initio* MP2 calculations

with large basis sets.¹² (For a recent review on applications of SCC-DFTB to biological systems, the reader is referred to Ref.[13].)

The integration of SCC-DFTB with Amber 9 has been described recently.¹⁴ In this implementation, the electrostatic interaction energy between the QM and MM regions ($\hat{H}_{elect}^{QM/MM}$ in Equation 2) is calculated as a Coulomb interaction between the atomic Mulliken charges calculated from the SCC-DFTB (q_α) and the classical RESP charges on the MM atoms (Q_A), as in Equation 3.

$$E_{elect}^{QM/MM} = \sum_{\alpha}^{QM} \sum_A^{MM} \frac{Q_A q_\alpha}{r_{\alpha A}}. \quad (3)$$

Showing how the QM/MM implementation can directly tap into the methods in Amber, the free energy surface (FES) for the capped alanine dipeptide (ACE-ALA-NME, AD) in vacuum was generated using Replica Exchange Molecular Dynamics,¹⁵ with the AD treated by SCC-DFTB. 6 replicas were used, at temperatures of 161.2K, 219.9K, 300.0K, 419.3K, 558.4K and 761.8K. Exchanges were attempted 10,000 times, with 0.5ps between attempts, and a time step of 1fs with SHAKE was used. The Langevin thermostat with a

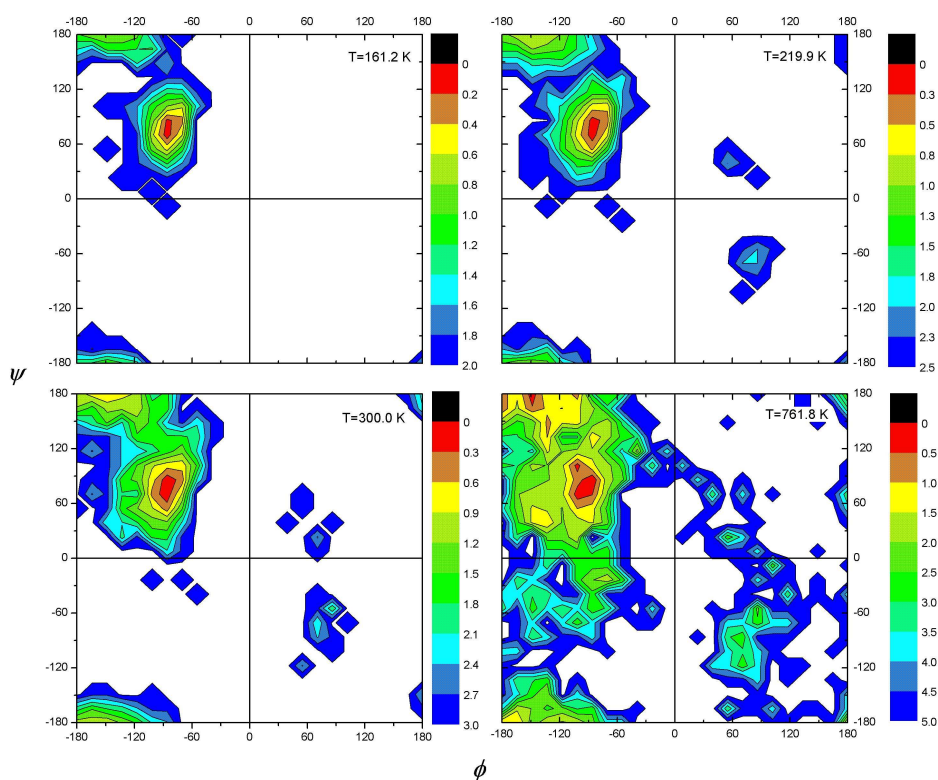


Figure 1. Free Energy Surfaces for alanine dipeptide obtained from the SCC-DFTB/REMD calculation.

collision frequency of 2.0ps^{-1} was used to regulate the temperatures.

Figure 1 shows the FES for four different temperatures, as calculated from $G = -RT \ln(P)$, where G is the Gibbs free energy, R is the gas constant and T is the temperature, and P is the (normalized) probability P of finding the AD in a conformation at a particular region in (ϕ, ψ) -space from the MD trajectories. The surfaces show a clear minimum around ϕ/ψ values of $(-83^\circ, 76^\circ)$, which corresponds to the known $C7_{eq}$ minimum for AD in vacuum, and other structures are populated as temperature increases. The relative energies compare well with calculated *ab-initio* values calculated previously.¹⁶

4 Amber-Gaussian QM/MM Through the PUPIL Interface

The interface described in the previous session has the advantage of being convenient and easy to use, especially for users experienced with the Amber MD program. At the current stage of development, however, the QM region is fixed throughout the calculation, and limited to semi-empirical Hamiltonians.

The PUPIL (Program for User Program Interfacing and Linking) is a free, open source package created to facilitate the interfacing of *arbitrary* MD and QM programs.^{17,18} Currently, interfaces with DLPOLY, MNDO97 and Siesta have been developed. We have

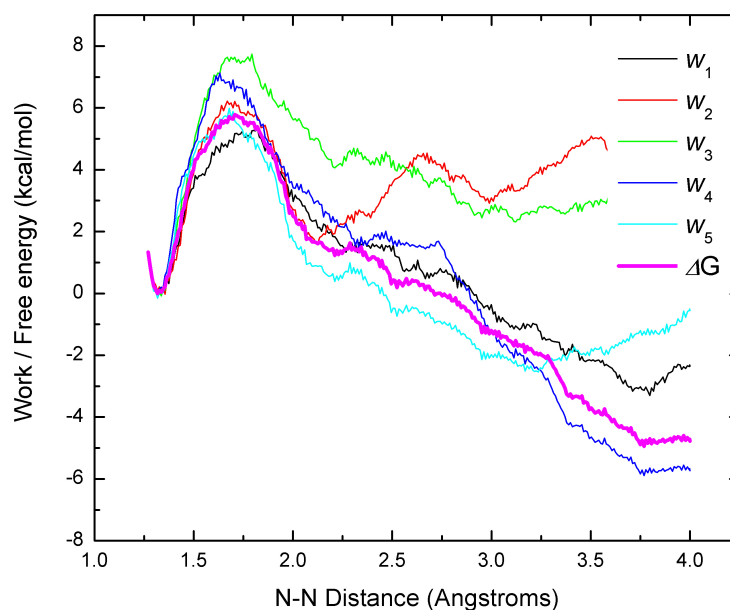


Figure 2. Work of breaking the N-N bond in Angeli's salt for 5 different simulations, and the free energy obtained by the Jarzynsky equation.

recently included interfaces with *sander* and Gaussian03 to the PUPIL system. In PUPIL, the equations of motion are propagated as usually by the MD program and the forces over the QM region are provided by the QM program, while the PUPIL interface manages execution of the two programs, as well as the required information flow. The influence of the MM atoms on the QM zone is taken into account by electronic embedding, where the MM atoms are considered as point charges fixed at the positions of the MM atoms, and with the charge values from the force field parameters in use.

In the Gaussian03 interface, the force contribution from the quantum atoms to the total force acting upon the classical atoms (F_i^{QM}) is obtained by dividing the electronic density into a grid, and calculating the interaction of the MM charge with each point in the grid:

$$F_i^{QM} = \sum_j^{cube} \mathbf{r}_{ij} \frac{q_{PC_i} dq_j}{|r_{ij}|^3}, \quad (4)$$

where

$$dq_j = \rho_j dx dy dz. \quad (5)$$

As an example, the free energy change associated to a specific process can be calculated using the Jarzynski relationship:¹⁹⁻²¹

$$e^{-\beta\Delta G(d)} = \left\langle e^{-\beta W(d)} \right\rangle_{d=d_0}, \quad (6)$$

where the brackets indicate an average taken over a large number of independent realizations of the process (in this case, molecular dynamics trajectories) all starting at different points belonging to the same equilibrated ensemble.

Figure 2 shows work results five trajectories breaking the N-N bond in the monoprotonated Angeli's salt (O2N-NHO⁻) in explicit water, together with the free energy calculated using Equation 6. The Angeli's salt was treated quantum mechanically by Gaussian03 at the UB3LYP/6-311+G(d) level, and put in a large box of TIP3P water molecules. The free energy barrier for breaking the N-N bond is calculated to be 5.84 kcal/mol, which is in good agreement with previous estimations using B3LYP with the same basis set and implicit solvation.²²

5 Conclusions

This communication describes and exemplifies two new QM/MM implementations. Both have the advantage of being based on the Amber molecular dynamics package, allowing their application in tandem with any of the advanced sampling methods available in Amber. Results of calculations using both implementations are provided.

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