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Time dependent solvation: a new frontier for quantum mechanical continuum models

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Abstract In the last years solvation continuum models have been coupled with modern quantum chemical calculations; this has permitted a detailed description of the electronic structure of a huge variety of solvated species. The aim of this paper is to show that these improved versions of the continuum theories are indeed able to qualitatively monitor the same picture of polar solvent dynamics as do molecular theories. The way towards an accurate and complete theory is still very long but it is important to show that this way exists and, at least partially, it has been already indicated. As an example of a possible strategy, some recent developments in the extension of the Polarizable Continuum Model (PCM) to time dependent solvation are presented and discussed.

1 Introduction

The last two decades have been fundamentally important in the study of chemical dynamics in liquids. During this period, our understanding of solvent effects on chemical processes, on orientational and dielectric relaxations and many other relevant problems increased enormously and several of these areas can now be regarded as mature fields. There are two main reasons for this great advance in our understanding of liquid phase dynamics. First, the rapid development in laser and ultrafast spectroscopic techniques allowed increasingly shorter time resolution [1–3]. Second, theoretical formalism was developed to generally address the ultrafast relaxation of the solvent and the chemical reactions [4–7].

In the progress of theoretical and computational tools, the main role has been played by classical molecular dynamics (MD) simulations. These methods in fact, by explicitly taking into account the microscopic nature of all the molecules forming the liquid or the solution, represent the natural instrument to describe the time evolution of the interactions

and of the overall structure. Classical MD approaches, however, present a serious disadvantage, they do not consider the real electronic structure of the molecules but resort to classical approximations represented by the selected force field. This limit becomes important when one is interested in a detailed study of the charge distribution of a solvated system (for example a biomolecule) and how it is modified by the solvent; for this kind of study, a quantum mechanical (QM) calculation becomes mandatory. At present, this level of description cannot be reached with simulations (at least not in standard liquid simulations even if *ab initio* MD approaches are becoming more and more efficient [8–10]). The obvious reason for such a limitation is that in MD simulations one has to monitor and compute the properties of many molecules, the largest part of which has little influence on the local molecular charge distribution that has to be known with a high degree of accuracy. A possible solution is thus to resort to focussed models, in which attention is centered on a small portion of the liquid, called the main part *M*, while the remainder, called *R*, is treated at a lower level.

Focused models can be considered a straightforward extension of the single-molecule model traditionally used in quantum chemistry, with the addition of a simple potential mimicking the interaction with the solvent. A key point in the formulation of the focussed models is the description of the thermodynamic averages. A second key point is the definition of the interaction potential that must be adapted to the specific characteristics of the desired focussed model. There are at present two options available: the first is to use the same simplified expressions employed in MD simulations (two-body potentials with some corrections, interactions cut at a given limited distance) and making the opportune thermodynamic average of them, the second is to resort to continuous formulations of integral type, valid for all distances and directly giving the thermodynamic average. In these methods the surrounding solvent is treated as a continuous medium bathing the solute.

In addition to the implicit average which allows to avoid the consideration of many different solute–solvent configurations, there are two other important advantages of continuum

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models. The first is a significant reduction in the number of degrees of freedom, while the second is the fact that they provide, and at very low cost, a very accurate way to treat the long-range electrostatic forces and at the same time they can easily include the polarization effects which are often neglected (due to the computational cost) in explicit methods like MD simulations. Continuum models have a long history (going back to Born, Onsager and Kirkwood to quote the authors of the first models [11, 12]), however only recently have they been coupled to QM techniques in order to get an accurate description of the solute structure and charge distribution which can mutually equilibrate with the solvent dielectric polarization (see for example [13, 14] for a review on the subject). Also in this modern definition of continuum models the main physical concept is still that formulated by Onsager, namely the *reaction field*. The reaction field, which is the electric field exerted on the solute by the solvent that has been polarized, is now converted in a proper QM operator to be included in the solute Hamiltonian and, in this way, the solute charge distribution (i.e. its wavefunction) is modified by the solvent. The resulting new (or distorted) solute charge in turn further alters the polarization of the solvent. If these mutual effects are iterated to self-consistency, the method (which is usually indicated as self-consistent reaction field, SCRF) will finally lead to a solute–solvent system in which each component has been modified by the other to give a fully equilibrated description.

In the last years a variety of extensions and generalizations of this basic approach have been proposed. Some of them involve modellistic representations of nonelectrostatic interactions (such as dispersion and repulsion forces between solute and solvent molecules), while others generalize the model to more complex solvents, i.e. no longer homogeneous and isotropic. Thanks to these and many other extensions (see ref. [15] for a very recent review), in the last decade continuum solvation models have become the default approach to study energies/geometries and properties of solvated systems. This enormous diffusion of continuum models, however has not implied a parallel extension to what could appear as a natural field of application, namely the study of solvent relaxation. In this field, in fact, the use of continuum models is still very limited, only few examples of accurate QM continuum models have been proposed [16–18] while often simplified versions are adopted [19]. Due to this limited range of applications and, more important, to the delay in the development of an accurate theory, the common belief still is that continuum models are incapable of adequately treating solvation dynamics. Fifteen years ago Neria and Nitzan, [20] posed some fundamental questions concerning continuum models and solvation dynamics, mainly

1. To what extent can the solvation dynamics be accounted for by the information contained in the long-wavelength dielectric function, $\epsilon(\omega) = \epsilon(k = 0, \omega)$, mainly by its Debye form,

$$\epsilon(\omega) = \epsilon_\infty + \frac{\epsilon_0 - \epsilon_\infty}{1 + i\omega\tau_D} \quad (1)$$

where ϵ_0 and ϵ_∞ are the static and the optical permittivity, respectively and τ_D the relaxation time.

2. How well can the solvation process be described by linear response theory?
3. How does solvent “shell structure” about the solute molecule manifest itself in the solvation process? What is the role of cooperativity in the solvent response?
4. How do different ranges of solute-solvent interaction affect the solvation dynamics, and can they be accounted for by the calculated wavelength dependent dielectric response?

Surprisingly, after 15 years these questions are still open. With this paper, however, we want to show that the main reason for this is that the most recent (and most advanced) continuum models have not been exploited in this field; in fact, improved versions of the continuum theories are able to qualitatively monitor the same picture of polar solvent dynamics as do molecular theories. As a matter of fact, continuum models present important advantages with respect to standard molecular simulations, and this could become decisive in the immediate future. Combined with modern quantum chemical calculations they allow a precise description of the electronic structure of a huge variety of solvated species, whereas almost all the diffused molecular treatments still invoke crude solute models, and, not requiring thermodynamic averages, they can be extended to very complex systems both as regards the nature of the solute and the composition of the environment.

To show that strategies for continuum solvent models to adequately treat solvation dynamics exist, we shall present some very recent developments our group in Pisa has made in this field. The paper is therefore organized as follows: in Sect. 2 a short summary of the basic aspects of continuum models is presented with reference to the Polarizable Continuum Model (PCM) [21–24] we have developed in our group. In Sect. 3 the extension of this model to QM descriptions is summarized as concerns its main aspects. In Sect. 4 a detailed presentation and analysis of the new generalization of the PCM model to time dependent solvation is reported and finally, in Sect. 5, two numerical applications to two typical TD phenomena which are largely affected by solvent relaxation (a ionization process and an electronic transition) are presented. This paper finishes in Sect. 6 with an indication of the main problems we shall have to face but also with some paragraphs on hopes for the future.

2 Continuum models: the PCM approach

Traditionally, the description of the electrostatic interactions has represented the keystone of continuum models. Within continuum electrostatic frameworks the main aspect to consider is thus the definition of the macroscopic characteristics of the dielectric, i.e. the form of the dielectric constant. Following this analysis we can define different systems, but here we shall focus our attention exclusively on the simplest, and

also the most common case (a solute in infinitely dilute solution of a homogeneous isotropic solvent).

For the selected system, i.e. a solute M in a cavity C surrounded by an infinite homogeneous isotropic dielectric with permittivity ϵ , the basic relations to be considered are the Poisson and Laplace equations, with the related boundary conditions; namely:

$$\begin{cases} -\Delta V = 4\pi\rho_M & \text{in } C \\ -\epsilon\Delta V = 0 & \text{outside } C \\ [V] = 0 & \text{on } \Sigma \\ [\partial V] = 0 & \text{on } \Sigma \end{cases} \quad (2)$$

where V is the electrostatic potential due to the presence of the charge distribution ρ_M located inside the cavity and Σ the cavity surface. The jump condition $[V] = 0$, means that the potential V is continuous across the interface Σ , i.e. $V_e - V_i = 0$ on Σ , where the subscripts e and i indicate regions outside and inside the cavity, respectively. The equality $[\partial V] = 0$ is a formal expression of the jump condition of the gradient of the potential; in our limit isotropic system it takes the well-known form:

$$\left(\frac{\partial V}{\partial n}\right)_i - \epsilon \left(\frac{\partial V}{\partial n}\right)_e = 0 \quad (3)$$

where n is the outward pointing unit vector perpendicular to the cavity.

The main approaches used to solve this problem can be divided in different classes; [14] here, we shall focus our attention on the apparent surface charge (ASC) methods particularly on the PCM [21–24].

The first step is the transformation of the first two equations in (2) into integral equations on the surface Σ , that can be easily solved with standard numerical methods. In this framework, the solution of system (2) is given by the sum of two electrostatic potentials, one produced by ρ_M and the other due to a surface charge distribution σ , placed on the interface Σ , which arises from the polarization of the dielectric medium:

$$V(x) = V_M(x) + V_\sigma(x) = \int_{R^3} \frac{\rho_M(y)}{|x-y|} dy + \int_{\Sigma} \frac{\sigma(s)}{|x-s|} ds \quad (4)$$

where the integral on the first term is taken over the entire three-dimensional space.

In the numerical implementation of the method, a partition of the surface into N small elements, called tesserae, of known area a_i , is introduced: on each element a constant charge density is assumed. In this framework, which belongs to the more general technique used in physics and engineering, and known as the Boundary Element Method (BEM), the integral form of $V_\sigma(x)$ in Eq.(4) is reduced to a finite sum running over the point charges representing the surface charge:

$$V_\sigma(x) = \sum_i^N \frac{q_i(s_i)}{|x-s_i|} \iff q_i(s_i) = \sigma(s_i)a_i \quad (5)$$

where vector s_i indicates the position on each tessera i where one has to evaluate the constant value of σ (usually, it identifies the center of the tessera and is called the representative point).

Over the years different strategies have been proposed to define the apparent charges $q_i(s_i)$; these strategies have generated alternative versions of PCM: nowadays three basic approaches remain, namely DPCM [21,22], CPCM [25], and IEFPCM [23,24] (in chronological order). Among these three methods, IEFPCM represents the most general (it includes as subcases the other two) and the most accurate one, and will thus be our focus.

For the scope of the present paper it is not necessary to repeat the whole theory beyond the IEFPCM (the interested reader can find all the details in the references papers), instead it is important to report the basic equation giving the apparent charges q_i , namely:

$$\mathbf{T}(\epsilon)\mathbf{q} = \mathbf{b}(\mathbf{V}) \quad (6)$$

or, in an explicit form,

$$\begin{aligned} \left(\frac{4\pi\epsilon}{\epsilon-1} + z_i [a_j]\right) (S_{ii}q_i + y_i[q_j]) \\ - z_i [a_j (S_{jj}q_j + y_j[q_k])] = b_i \end{aligned} \quad (7)$$

where

$$z_i [x_j] = \sum_{j \neq i} D_{ij}x_j \quad (8)$$

$$y_r [q_s] = \sum_{r \neq s} S_{rs}q_s \quad (9)$$

$$b_i = -2\pi V_i + \sum_j D_{ij}a_j V_j \quad (10)$$

In Eqs. 6–10, V_i are the values of the solute electrostatic potential on the tessera i and S_{rs} and D_{rs} are the electrostatic potential and the perpendicular component of the field at the cavity surface (at position r) produced by a unit charge placed in s : for the exact expressions of the diagonal and off-diagonal elements of these matrices we refer to the reference paper.

In the following it will be much more convenient to introduce an iterative form of expression (7), namely [26]:

$$q_i^{(n)} = S_{ii}^{-1} \left(\frac{4\pi\epsilon}{\epsilon-1}\right)^{-1} [b_i + w_i[q_j^{(n-1)}]] - S_{ii}^{-1} y_i[q_j^{(n-1)}] \quad (11)$$

where

$$\begin{aligned} w_i[q_j^{(n-1)}] = -z_i [a_j] \left(S_{ii}q_i^{(n-1)} + y_i[q_j^{(n-1)}] \right) \\ + z_i [a_j (S_{jj}q_j^{(n-1)} + y_j[q_k^{(n-1)}])] \end{aligned} \quad (12)$$

3 Quantum mechanical theory of solvation

The generalization of the model described in the previous section to QM descriptions of the solute charge implies defining

an Effective Hamiltonian, i.e. a Hamiltonian to which solute-solvent interactions are added in terms of two solvent reaction potentials

$$\hat{H}_{eff} |\Psi\rangle = \left[\hat{H}^0 + \hat{\rho}_r V_r^R + \hat{\rho}_r \mathbf{V}_{rr'}^R \langle \Psi | \hat{\rho}_{r'} | \Psi \rangle \right] |\Psi\rangle = E |\Psi\rangle \quad (13)$$

where \hat{H}^0 is the Hamiltonian describing the isolated molecule, $\hat{\rho}_r$ represents the operator of the solute electronic charge density, V_r^R is the solvent *permanent reaction potential* (i.e. that induced by the solute nuclei), and $\mathbf{V}_{rr'}^R$ describes the solvent *electronic reaction potential* (e.g. the reaction induced by the solute electrons). Here, an extension of the Einstein convention on the sum has been exploited: the space variables r and r' , appearing as repeated subscripts, imply an integration in the three-dimensional space.

The first solvent term in the effective Hamiltonian of Eq. (13), V_r^R , does not lead to any difficulty, either from the theoretical or practical view point. Many examples are known in which an external potential is introduced in the molecular calculations. On the contrary, the treatment of the operator $\hat{\rho}_r \mathbf{V}_{rr'}^R \langle \Psi | \hat{\rho}_{r'} | \Psi \rangle$ is rather delicate, as this term induces a nonlinear character to the solute Schrödinger equation.

Following the standard scheme developed for the self consistent field (SCF) theory in vacuo, we can define the effective Fock (or Kohn-Sham) operator for the solvated system, as a sum of the gas-phase Fock operator plus a specific solvent term F^R . By introducing the common finite-basis approximation and expanding the molecular orbitals (MOs) on a basis set of atomic orbitals (AO), this solvent term becomes:

$$F_{\mu\nu}^R(\mathbf{P}) = -\mathbf{V}_{\mu\nu}^\dagger \cdot [\mathbf{q}^N + \mathbf{q}^e(\mathbf{P})] = -\mathbf{V}_{\mu\nu}^\dagger \cdot \mathbf{q}(N; \mathbf{P}) \quad (14)$$

where we have merged the two solvent terms of Eq. (13) into the single matrix \mathbf{F}^R by simply summing up the nuclear and electron- induced charges into the total apparent charges, \mathbf{q} (we have also left explicit the dependence of this charges on the solute density matrix \mathbf{P} as well as on the nuclear charges N). In Eq. (14) the indices $\mu\nu$ refer to basis set orbitals and $\mathbf{V}_{\mu\nu}$ is the vector collecting the electrostatic potential integrals on the same basis functions computed at the cavity surface positions (the symbol \dagger indicates a transposition of the column vector into a row vector).

The SCF problem determined by the effective Fock operator can be solved with the same iterative procedure of the problem in vacuo; the only difference introduced by the presence of the continuum dielectric is that, at each cycle, one has to simultaneously solve the standard QM problem and the additional problem of the evaluation of the interaction matrices. In this scheme the solvent apparent charges are obtained through a self-consistent technique which is nested to that determining the solute wave function; as a consequence, at the convergency, solute and solvent distribution charges are mutually equilibrated and the final energetic quantity becomes

$$\mathcal{G} = E^0 + \frac{1}{2} \text{tr} \mathbf{P} \mathbf{F}^R(\mathbf{P}) + \frac{1}{2} \mathbf{V}_N^\dagger \cdot \mathbf{q} \quad (15)$$

where E^0 is the energy corresponding to the gas-phase \hat{H}^0 and \mathbf{V}_N is the vector collecting the electrostatic potentials of the solute nuclei on the cavity surface.

This brief analysis on the main quantum mechanical aspects of continuum solvation models has been presented here to show the large potentialities of these models to be extended to many different QM levels including accurate correlated methods. In fact, the simple form of the matrix $\mathbf{F}^R(\mathbf{P})$ allows one to exploit theoretical and computational instruments largely used for isolated systems, without requiring any additional specificity. This is a very important point which makes the modern versions of continuum models the state-of-the-art of theoretical approaches to describe solvent effects not only on the solute energy but also on more complex quantities such as geometries and molecular properties [15, 27].

4 Time dependent solvent polarization

In the modeling of time-dependent (TD) phenomena in solution, one of the open questions is how to take into account the evolution of the solvent polarization and of the related solute-solvent interaction. In fast processes, such as electronic excitations, electron transfers or ionizations, the time-scale of the change in the charge density of the solute is usually much smaller than the time-scale in which a polar solvent fully relaxes to reach a new equilibrium state. During this relaxation, the solvent nuclear and molecular motions act as inertia on the solvation response and a nonequilibrium regime is established. Due to the mutual solute-solvent polarization, the new equilibrium is reached through changes of both solute and solvent, and an accurate description of the reorganization path should consider the evolution of their interaction and, possibly, the solute geometry relaxation.

Here, however, we shall focus exclusively on the evolution of the solvent polarization and we shall neglect effects due changes in the solute geometrical structure. In this approximation, the fundamental process to consider is the effect of an electric field E acting in the dielectric. According to the linear response theory, the resulting polarization $P(t)$ is determined by the field in the medium not only at the time t but also at previous time t' , in a form expressed by the integral

$$P(t) = \int_{-\infty}^t dt' \chi(t-t') E(t') \quad (16)$$

where $\chi(t-t')$ is the solvent response function (or memory kernel) and we have assumed an isotropic and uniform (local) dielectric. The convolution integral (16) can be transformed in the product of its Fourier transform, namely

$$P(\omega) = \frac{\epsilon(\omega) - 1}{4\pi} E(\omega) \quad (17)$$

where $\epsilon(\omega)$ is the complex dielectric constant. The real part of $\epsilon(\omega)$ is the frequency dependent dielectric constant describing the component of the polarization density in phase with

the oscillating field; while the complex part, or loss factor, determines the component of the polarization with a phase difference with respect to the Maxwell field causing the loss of energy of the electric field in the medium [11,12].

In the present paper, the interest is focused on polar solvents, and thus further details about the solvent behavior in an electromagnetic field will be limited to these. In polar solvents, the electric polarization can be split into three part, the orientational, the atomic, and the electronic component, each part corresponding to motions of a different kind of particle (molecules, atoms, electrons, respectively) with different characteristic times. As the frequency increases, nonequilibrium effects will appear in the different contributions of the polarization. In particular, the orientational contribution (characterized by response times larger than 10^{-12} s) will first start to lag behind the variations of the electromagnetic field, followed by the atomic term (with times around 10^{-14} s), and finally, at very high frequencies, by the electronic term (with times around 10^{-16} s).

Within the continuum framework the different response times of the various terms constituting the solvent polarization $P(t)$ can be (and indeed have been) taken into account using two alternative approaches. Either a separation of the solvent response (e.g. the apparent charges in the PCM scheme described in the previous section) into a dynamic contribution, associated with the electronic motion, or an inertial (or orientational) contribution, due to the nuclear and molecular motion is introduced (see for example [28–32] for the general theory, and ref. [35–37] for PCM-nonequilibrium theory) or dynamic and an inertial contributions are implicitly taken into account in a single response function [16,17,38–41]. When the nonequilibrium response is described in terms of two contributions, the dynamic component of the response which is assumed to equilibrate instantaneously to the final state, is calculated in terms of the optical permittivity while the inertial component, which remains in equilibrium with the charge density of the initial state, is obtained as a difference between the total and the dynamic response. By contrast, when a single solvent response is used, a complex dielectric permittivity as a function of the frequency, $\epsilon(\omega)$ is used and a Fourier transform is performed to get a real time-dependent response.

Obviously, the second approach is of more general use as it can be applied to follow the completely evolution of the solvent response whereas the first approach is confined by the limit of $t \rightarrow 0$, i.e. to the very first step of the phenomenon considered; in this case, however, the two approaches perfectly overlap. In the following two subsections these two approaches will be presented and commented on while in Sect. 5 they will be applied to study an ionization process and an electronic excitation for a molecular solute in a polar solvent.

4.1 Nonequilibrium solvation

In we limit ourselves to the initial step of the whole process, i.e. a sudden change in the solute state (a vertical electronic

transition, a charge transfer, etc.), we can safely assume a Franck-Condon like response of the solvent, exactly as for the solute molecule; the nuclear motions inside and among the solvent molecules will not be able to immediately follow the fast changes in the solute electronic charge distribution and thus the corresponding part of the response (also indicated as inertial) will remain frozen in the state immediately previous to the change. The actual polarization will thus be the sum of an inertial (fixed) term and a dynamic (instantaneous) term: this is exactly the approximation also known as Pekar or Marcus partition [15].

In the PCM framework, this will lead to a partition of the apparent charges in two separate sets, [20] one related to the dynamic (or fast) electronic response, \mathbf{q}_{dyn} , and the other to the slower, or inertial, response connected to nuclear and/or molecular motions, \mathbf{q}_{in} . According to what was said before, the dynamic component will depend on the instantaneous charge distribution of the solute and on the optical dielectric constant. The inertial apparent charges, on the contrary, will still depend on the solute charge distribution of the initial state ρ_M^0 and, in the following they will therefore be indicated as \mathbf{q}_{in}^0 .

From a physical point of view, we can always define the equation giving the dynamic surface charges by considering a system of the type (2) in which both the operator and the related boundary conditions are defined in terms of ϵ_∞ . For the dynamic charges, Eq. (6) thus becomes

$$\mathbf{T}(\epsilon_\infty)\mathbf{q}_{\text{dyn}} = \mathbf{b}(\mathbf{V}(\rho_M^{\text{fin}})) \quad (18)$$

where ρ_M^{fin} is the charge distribution of the solute in its final state.

In this nonequilibrium situation, the definition of the electrostatic free energy has to be changed with respect to that reported in Sect. 3. In particular, the contribution of the inertial polarization has to be seen as an external fixed field and not as a field which mutually polarizes with the solute charge; the proper free energy thus becomes:

$$G_{\text{fin}}^{\text{neq}} = G_{\text{fin}}^{\text{dyn}} + \left[\text{tr} \mathbf{P}^{\text{fin}} \mathbf{F}_{\text{in}}^S + \mathbf{V}_N^\dagger \mathbf{q}_{\text{in}}^0 \right] \quad (19)$$

$$[F_{\text{in}}^S]_{\mu\nu} = -\mathbf{V}_{\mu\nu}^\dagger \cdot \mathbf{q}_{\text{in}}^0 \quad (20)$$

where the terms in square parentheses represent the interaction energies of the inertial charges \mathbf{q}_{in}^0 (determined by ρ_M^0) with solute electrons and nuclei. In Eq. (19), $G_{\text{fin}}^{\text{dyn}}$ is the equivalent of Eq. (15) with solvent induced contributions defined in terms of the dynamic charges only, i.e.:

$$G_{\text{fin}}^{\text{dyn}} = E^{\text{fin}} + \frac{1}{2} \text{tr} \mathbf{P}^{\text{fin}} \mathbf{F}_{\text{dyn}}^S(\mathbf{P}^{\text{fin}}) + \frac{1}{2} \mathbf{V}_N^\dagger \cdot \mathbf{q}_{\text{dyn}} \quad (21)$$

We note that by introducing the correct reference states, which in solvation problems are usually defined in terms of a set of noninteracting electrons and nuclei for the solute and an unperturbed pure dielectric at a given T for the solvent, we have to subtract in Eq. (19) a further energy term. In fact, $G_{\text{fin}}^{\text{dyn}}$ has been derived with the inertial part of the solvent polarization already switched on; hence, in order to get a

reliable comparison between equilibrium and nonequilibrium energies, we need to take into account the energy required to create the inertial charge. This term has the form given in Eq. (21) but this time the solute charge distribution refers to the initial full equilibrium state and the dynamic charges are substituted by the inertial ones, namely:

$$G_{\text{ini}}^{\text{in}} = \frac{1}{2} \text{tr} \mathbf{P}^0 \mathbf{F}_{\text{in}}^S + \frac{1}{2} \mathbf{V}_N^\dagger \cdot \mathbf{q}_{\text{in}}^0$$

where \mathbf{P}^0 is the density matrix corresponding to the initial state.

4.2 Solvation dynamics: the TDPCM approach

In the previous section we have considered just the instant immediately after a sudden change in the solute, namely the nonequilibrium solvation. However, such nonequilibrium is just an instantaneous situation that will relax towards a new equilibrium state corresponding to the final solute state. This time-dependent (nonequilibrium) relaxation of the solvent, which is generally indicated as Solvation dynamics, occurs in a timescale and through relaxation modes which are typical of the structure of the solvent molecules and of the solute-solvent intermolecular interactions.

In order to study the effects of solvent relaxation we have to generalize the PCM model described in Sect. 2 for the solute-solvent equilibrium and in Sect. 4.1 for the nonequilibrium to a real time dependence. This generalization has been recently proposed within the original (D)PCM scheme by Caricato et al. [41]; here we present an alternative version of the same model, this time being applied to the IEFPCM, which from now on we shall indicate as TDPCM.

The starting assumption is that the change in the solute molecule occurs instantaneously (at time $t = 0$) and the corresponding variation of the electrostatic potential V_i on a tessera i between the initial (0) and the final (fin) state is a step change:

$$V_i(t) = V_i^0 + \theta(t) \Delta V_i \quad (22)$$

where the function $\theta(t)$ is the step function and

$$(\Delta V)_i = V_i^{\text{fin}} - V_i^0 \quad (23)$$

The time-dependent solvent polarization charges at a generic time t can be written as:

$$\mathbf{q}(t) = \mathbf{q}^0 + \delta \mathbf{q}(\Delta \mathbf{V}, t) \quad (24)$$

with the following boundary conditions:

$$\begin{aligned} \mathbf{q}(t \rightarrow -\infty) &= \mathbf{q}^0 \\ \delta \mathbf{q}(t \rightarrow -\infty) &= 0 \end{aligned} \quad (25)$$

and

$$\mathbf{q}(t \rightarrow \infty) = \mathbf{q}^{\text{fin}} \quad (26)$$

$$\delta \mathbf{q}(t \rightarrow \infty) = \Delta \mathbf{q} = \mathbf{q}^{\text{fin}} - \mathbf{q}^0$$

where \mathbf{q}^0 and \mathbf{q}^{fin} are the polarization charges when the initial and the final solute-solvent equilibrium is valid, respectively.

In relations (24) and (26), the time at which the perturbation starts is $t = 0$. Before the perturbation takes place ($t \rightarrow -\infty$) the term $\delta \mathbf{q}$ is nil since $\Delta \mathbf{V} = 0$.

Considering the solvent as a dielectric material polarized by the presence of an external potential, under the assumption that the coupling between the two is weak, it is possible to apply the results of the linear response theory. This is exactly what done in Eq. 16, where the TD polarization $P(t)$ induced inside the medium at time t is expressed in terms of a convolution integral of the electric field E and a medium response function χ : the physical meaning of this relation is that the polarization at time t is a superposition of delayed effects, and that the response at time t to a unit, δ function-shaped external electric field applied at $t = 0$, is exactly the medium response function χ .

By applying the same assumptions for the variation of the polarization charges $\delta \mathbf{q}$ at time t due to a change in the electrostatic potential at time $t = 0$, we obtain:

$$\delta \mathbf{q}(\Delta \mathbf{V}, t) = \int_{-\infty}^t dt' \mathbf{R}(t-t') \theta(t') \Delta \mathbf{V} \quad (27)$$

This expression is transformed in a numerical procedure by passing from the time domain to the frequency domain. This change is required as the dielectric response of the solvent is described in terms of its complex dielectric permittivity as a function of a frequency ω . The ω dependence of $\hat{\epsilon}$ can either be modeled using pure diffusive expressions (as in the Debye relaxation expression [11,12]), or calculated on the basis of experimental measurements of the absorption. The use of Laplace-transformed equations to pass from the time to the frequency domain has the effect of simplifying the formalism and of allowing the straightforward use of the function $\hat{\epsilon}(\omega)$. Starting from Eq. 27 the variation of the charges becomes:

$$\delta \mathbf{q}(\Delta \mathbf{V}, t) = \delta' \mathbf{q}(\Delta \mathbf{V}, t) + \mathbf{R}_0 \Delta \mathbf{V} \quad (28)$$

$$\delta' \mathbf{q}(\Delta \mathbf{V}, t) = -\frac{2}{\pi} \int_0^\infty \frac{d\omega}{\omega} \text{Im}[\mathbf{R}(\omega)] \cos(\omega t) \Delta \mathbf{V} \quad (29)$$

where \mathbf{R}_0 is the IEF response matrix computed using the static dielectric permittivity ϵ .

In order to find a proper frequency-dependent *response function* $\mathbf{R}(\omega)$ we can resort to the iterative Eq. 11. By considering the first order term and applying it to $\delta' \mathbf{q}(\Delta \mathbf{V}, t)$, we obtain:

$$\delta' q_i^{(0)}(\Delta V, t) = S_{ii}^{-1} g_i(t) b_i[\Delta V] \quad (30)$$

where

$$g_i(t) = \frac{2}{\pi} \int_0^\infty \frac{d\omega}{\omega} \text{Im} \left[\left(\frac{4\pi\epsilon(\omega)}{\epsilon(\omega) - 1} \right)^{-1} \right] \cos(\omega t) \quad (31)$$

By adding the effects of the mutual polarization among charges we finally get

$$\begin{aligned} \delta' q_i^{(n)}(\Delta V, t) &= \delta' q_i^{(0)}(\Delta V, t) - S_{ii}^{-1} g_i(t) w_i \left[\delta' q_j^{(n-1)} \right] \\ &\quad - S_{ii}^{-1} y_i \left[\delta' q_j^{(n-1)} \right] \end{aligned} \quad (32)$$

The integral in Eq. 31 can be solved analytically if we use the Debye expression (1) for $\epsilon(\omega)$; in that case, in fact:

$$g_i^D(t) = \frac{2}{\pi} \frac{A}{\tau} \int_0^\infty d\omega \frac{1}{B^2 + \omega^2} \cos \omega t \quad (33)$$

where the constants A and B are:

$$A = -\frac{(\epsilon - \epsilon_\infty)}{4\pi\epsilon_\infty^2} \quad (34)$$

$$B = \frac{1}{\tau} \frac{\epsilon}{\epsilon_\infty}$$

and the solution is:

$$g_i^D(t) = \frac{A}{B\tau} e^{-Bt} \quad (35)$$

which presents an exponential decay, as expected from the Debye model.

It is important to note that the use of the Debye model leads to an analytical value of the function $g_i(t)$, however its use is not necessary: our approach in fact can be applied to any other functional form for the complex dielectric permittivity $\epsilon(\omega)$ (like for example a multiple Debye, a Davidson–Cole, or a Cole–Cole form [11,12]) as well as to a combined scheme including a fit of experimental data for the high frequency portion of $\epsilon(\omega)$. The only practical difference is that in the latter case, the integral in Eq. 31 is solved numerically but, in principle, the important difference is that a more realistic description of the non-diffusive portion of the solvent response can be achieved. This issue, which is strictly connected to the question (2) reported in the Introduction, will be better analyzed in the following section.

5 Two examples of applications

5.1 Charge transfer and reorganization energies

An important dynamic process involving a fast change in the solute charge distribution followed by a relaxation of the solvent is the transfer of charge (for example an electron) from a donor to an acceptor. This is indeed one of the most fundamental transformations in chemistry and physics. In the condensed phase, the dynamics of charge transfer are strongly shaped by the local environment (see for example, the importance of the solvent's influence on electron transfers as exemplified by Marcus theory [42]). Any charge transfer requires significant rearrangement of the solvent molecules around each of the two reactants and, hence, costs a great deal of solvent polarization free energy. This free energy penalty for disrupting the local solvent structure is known as the solvent reorganization energy.

In this Section we present a selection of results from a study we have recently performed [41] on charging process of solvated *N, N* dimethyl aniline (DMA) (Fig. 1), a popular system in studies of the charge-transfer reaction [43].

Here we report results only for the direct DMA \rightarrow DMA $^+$ process in acetonitrile whereas in the reference paper [41],

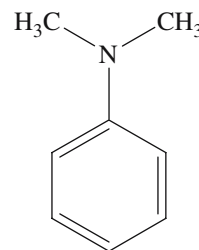


Fig. 1 Graphical representation of *N, N* dimethylaniline (DMA) in its neutral form

parallel studies are reported also for the reverse process and for water as solvent.

By applying the TDPCM solvation model described in Sect. 4.2 we are now able to evaluate the time evolution of the energy necessary for the solvent to reorient according to the new charged solute; this energy which we define here as the nonequilibrium energy $U^{\text{neq}}(t)$ is given by¹

$$U^{\text{neq}}(t) = U_{\text{solv}}(t) - \frac{1}{2} [\mathbf{V}^0]^\dagger \cdot \delta \mathbf{q}'(\Delta V, t) \quad (36)$$

where the symbol 0 on the solute electrostatic potential means that it has been calculated for the neutral DMA in the equilibrated solvent. The time-dependent interaction energy $U_{\text{solv}}(t)$ is defined as:

$$U_{\text{solv}}(t) = \frac{1}{2} \mathbf{V}^\dagger(t) \cdot \mathbf{q}(t). \quad (37)$$

as well as the time dependent charges $\mathbf{q}(t)$ and $\delta \mathbf{q}'(\Delta V, t)$ are given by Eq. 24 and Eq. 29 respectively. A schematic illustration of the process as well as of the energetic quantities involved is reported in Fig. 2.

The electronic wave functions of solvated DMA and DMA $^+$ were computed based on the restricted DFT and the restricted open-shell DFT methods, respectively, with the Dunning/Huzinaga d95v+(*d,p*) basis set using the non-local exchange correlation functional by Becke, Lee, Parr and Yang (B3LYP) [44,45]. The geometry used has been obtained at the same level of calculation in the presence of the solvent (acetonitrile) with the IEFPCM model implemented into GAUSSIAN 03 [46]. The cavity surrounding the solute was the result of the superimposition of interlocking spheres centered on atomic sites or groups of atoms. The radii of the spheres were: $R(\text{C}) = 1.925 \text{ \AA}$, $R(\text{CH}) = 2.125 \text{ \AA}$, $R(\text{CH}_3) = 2.525 \text{ \AA}$, $R(\text{N}) = 1.840 \text{ \AA}$. For the use of the Debye relaxation expression in Eq. 1, we used 3.37 ps for the relaxation time τ_D and 1.807 and 36.74 for the optical and the static dielectric constants, respectively.

In Fig. 3 we report the time evolution of the difference between the TD nonequilibrium interaction energy $U^{\text{neq}}(t)$ and the solvation equilibrium energy $G_{\text{fin}}^{\text{eq}}$ of the charged system.

¹ We note that the time-dependent energy reported in Eq. 36 is different from the one reported in the reference paper [41]; there, in fact the interest was in the comparison with a previous study on the same system performed by Sato et al. [43]. Both functions give the same solvent reorganization energy as limit value but here this limit refers to short times while in the reference paper the limit was reached at infinite time.

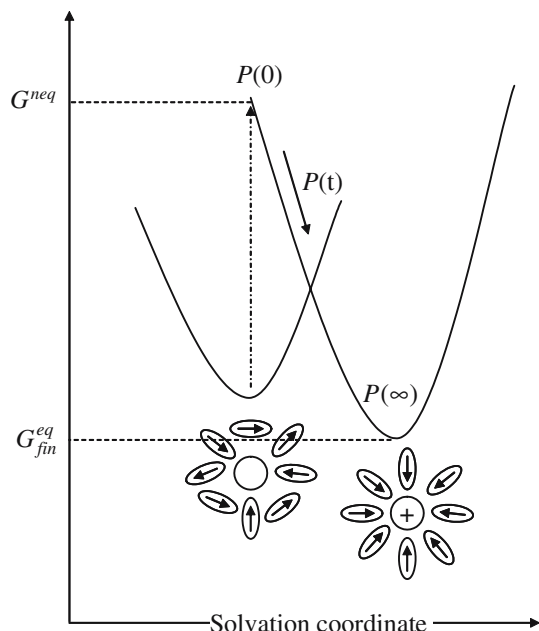


Fig. 2 Schematic illustration of the potential energy surfaces of the neutral and the charged solute with respect to the “solvation coordinate”. The solvent orientational motions along the solvation coordinate together with instantaneous polarization P are shown

As expected by the use of the Debye behavior for the dielectric permittivity, the plot presents an exponential decay; it is, however, to be noted that such decay is faster than that expected by the value of the Debye relaxation time ($\tau_D = 3.37$ ps). This is due to the fact that the solvent dynamics is governed by the so-called longitudinal dielectric relaxation time, τ_L

$$\tau_L = \frac{\epsilon_\infty}{\epsilon_0} \tau_D$$

which for acetonitrile is 0.16 ps. This longitudinal relaxation time is a bulk property of the solvent that microscopically involves the concerted response of many molecules and is much faster than the time scale for reorientation of a single solvent molecule.[47,48]

It is well known that experimental results deviate from this prediction by being both nonexponential and decreasing with different rate than $\exp(-t/\tau_L)$. This important discrepancy between observation and prediction has been one of the main objections to the use of continuum models to treat solvent dynamics; as a matter of fact, this is an easy problem to solve when a proper treatment of the solvent response is introduced as in the TDPCM model described in the previous section. Within this framework, in fact, we can avoid to use the Debye expression (1) (and thus of the following eqs. 33, 34, 35), instead resort to experimental data for the high frequency portion of the complex dielectric permittivity: this approach will be described in the following section.

Here, it is important to make a connection between the plot reported in Fig. 6 and the solvent reorganization energy

λ_s which by definition yields [42, 49]:

$$\lambda_s^d = G_{\text{fin}}^{\text{neq}} - G_{\text{fin}}^{\text{eq}} \quad (38)$$

where $G_{\text{fin}}^{\text{neq}}$ is the nonequilibrium solvation free energy in the final (here charged) state (see Fig. 6). By assuming that the changes in the solute charge density due to the equilibration of the solvent are negligible Eq. 38 exactly coincides with the $t \rightarrow 0$ limit of the curve, and we thus obtain a value of 1.02 eV for λ_s^d . To check the validity of this assumption we have also calculated λ_s^d from Eq. 38 and found small discrepancies in the range of few meV.

We will not stress the quantitative comparison between results from our theory and the experiment, because the latter always involves an electron donor-electron acceptor pair while our calculations misses, for example, contributions from anion species and from the interactions between redox pairs. However, it is worthwhile to make some comparison between the present model and the Marcus picture (λ_s^M), in which the solvent reorganization energies are derived from the Born model

$$\lambda_s^M = \frac{1}{2} \left(\frac{1}{\epsilon_\infty} - \frac{1}{\epsilon_0} \right) \frac{1}{a}$$

where a is the radius of the system when approximated by a sphere. By using the parameters employed in a previous study [43] (namely $a = 3.47$) we obtain $\lambda_s^M = 1.10$ eV which is quite close to what found in this work. This agreement together with a good accord (in the limit that we have just underlined) with the experimental λ_s of 1.39 eV measured for a similar system (DMA with duroquinone in $\text{C}_3\text{H}_7\text{CN}$) gives us confidence in the validity of the model and of its applicability to more complex systems.

5.2 Time dependent Stokes shift

As a second application of the model I present here a study of the time-dependent Stokes shift (TDSS) of the fluorescence spectrum of Coumarin 153 (C153, see Fig. 4) in water.

Time Dependent Stokes Shift is indeed the most largely used spectroscopy to measure polar solvation dynamics [50]. In this experiment, a solute probe inside the polar solution is excited optically to its excited state which is characterized by a different charge distribution, resulting in a different dipole moment of the solute. This change in solute dipole moment happens very fast, leaving the surrounding solvent molecules in the configuration still in equilibrium with the solute ground state charge distribution. Subsequently, the solvent molecules rotate and translate to solvate the new charge distribution, which leads to a lowering of the energy of the solute (which is chosen so to have a long fluorescence lifetime). As the energy of the solute decreases due to stabilization by solvation, the fluorescence from the excited state undergoes a red shift. The physical scenario is illustrated in Fig. 5 where we have chosen a probe molecule that is nonpolar or weakly polar in the ground state but is highly polar in the electronically excited state. As long as the solute probe is in

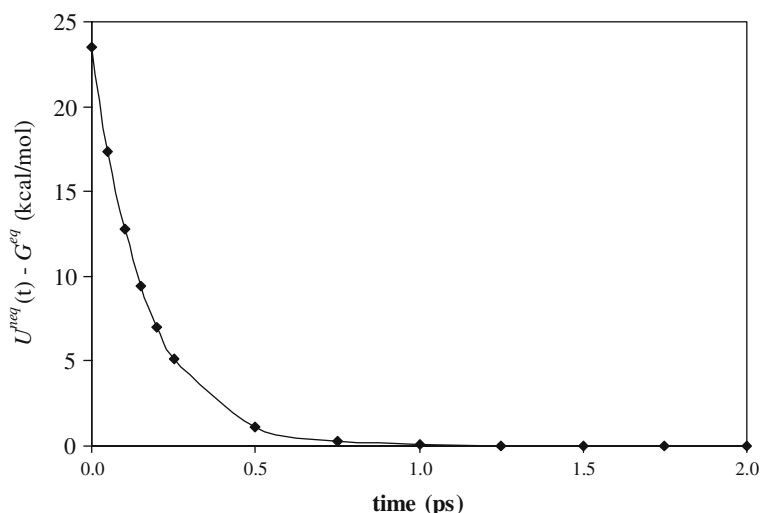


Fig. 3 Time evolution of the TD nonequilibrium interaction energy $U^{neq}(t)$ for the DMA \rightarrow DMA $^+$ process in acetonitrile solution. The energy values (in kcal/mol) are with respect to the solvation equilibrium energy G_{in}^{eq} of the charged system

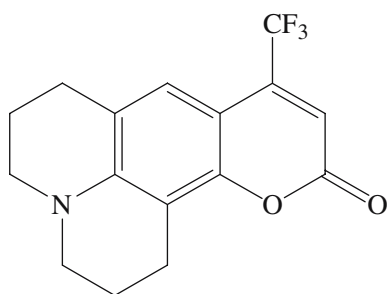


Fig. 4 Graphical representation of Coumarin 153 (C153)

the ground state, the solvent dipoles remain randomly oriented around the solute. When the probe solute is excited by an ultrashort pulse, the solvent dipoles initially (i.e., at $t = 0$) remain randomly oriented about the instantaneously created dipole charge distribution. With an increase in time, the solvent dipoles gradually reorient until final equilibrium when all solvent dipole are correctly oriented around the solute.

The measured quantity in this process is thus:

$$S(t) = \frac{\nu(t) - \nu(\infty)}{\nu(0) - \nu(\infty)}, \quad (39)$$

where $\nu(t)$ indicates the time evolution of the maximum in the fluorescence signal and $\nu(\infty)$ corresponds to the maximum of the steady-state emission spectrum.

Under the approximation that the effects of the solute geometry relaxation after the electronic excitation are negligible, the TDSS may be approximated in terms of the solvation time correlation function (STCF) defined as: [54, 55]

$$S(t) \simeq \frac{\Delta U_{solv}(t) - \Delta U_{solv}(\infty)}{\Delta U_{solv}(0) - \Delta U_{solv}(\infty)}. \quad (40)$$

where $\Delta U_{solv}(t)$ is the time evolution of the difference in the solvation energy between the ground and the excited state of the solute.

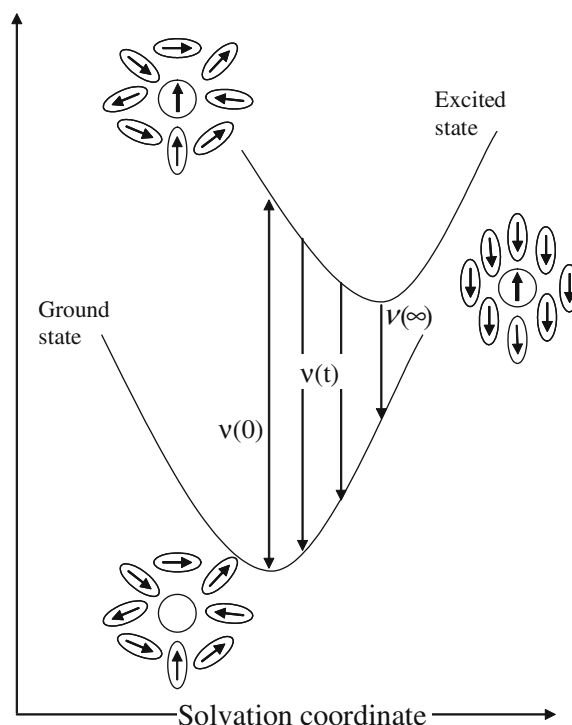


Fig. 5 Schematic diagram of how an electronic transition in a solute can be used to study the dynamics of solvation. Shown here is an illustration of a polar solvent's response to excitation of a solute which has zero dipole moment in its ground state but a large dipole in its excited electronic state. A short laser pulse is used to excite the solute from the ground state to the excited state. Since the electronic transition is rapid compared to nuclear motions of the solvent, the excited state is initially prepared with a solvation environment that is characteristic of equilibrium in the ground state. Over time the solvent reorganizes or progresses along the "solvation coordinate", in order to lower the solvation energy in the excited state. This relaxation can be followed by measuring the emission from the solute as a function of time after excitation. Solvation leads to a time-dependent red shift of the emission spectrum that can be used via Eq. 39 as a direct probe of the solvation dynamics

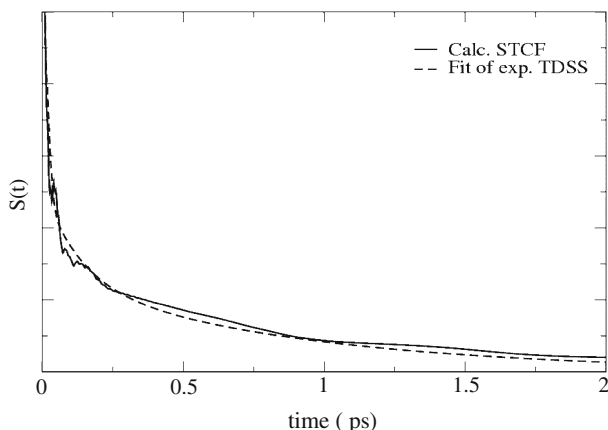


Fig. 6 Comparison of the calculated STCF of C153 in water with the fit of experimental data collected by Jimenez et al. [59]

It is evident that $\Delta U_{\text{solv}}(t)$ can be obtained by applying the TDPCM scheme described in Sect. (4.2), namely

$$\Delta U_{\text{solv}}(t) = \frac{1}{2} (\Delta \mathbf{V})^\dagger \cdot \delta \mathbf{q}(\Delta \mathbf{V}, t). \quad (41)$$

where $\Delta U_{\text{solv}}(0)$ and $\Delta U_{\text{solv}}(\infty)$ are the differences between the interaction energies corresponding to an equilibrated ground state and a vertical excited state, and an equilibrated excited state and a vertical (below) ground state, respectively.

In the assumption that we have made to obtain Eq. 40, only the electronic contribution to the total solvation energy have been considered. Actually, dispersion as well as specific interactions (i.e., hydrogen bond) contribute to the total solvation. It is therefore a critical problem to choose a probe that gives rise predominantly to electrostatic interactions. Coumarins, and in particular C153 (Fig. 6) are the chromophores used most often in fluorescence upconversion studies of solvation dynamics in polar and in supercritical solvents. They have been shown to have almost planar geometry and highly emissive intramolecular charge transfer in polar solvents. In addition, the transition from the ground state to the first excited singlet state in this molecule does not interfere with nearby transitions, giving rise to a charge redistribution which can be considered dipolar. The almost rigid structure of C153, together with the larger masses and moments of inertia with respect to those of the solvent molecules, make it an ideal probe for solvation dynamics, since these characteristics result in a small contribution of solute motion to the solvation response. In C153 the charge transfer occurs between the donor amino-group and the acceptor group- CF_3 .

The study of the STCF of C153 in polar solvents by using a PCM scheme has been originally presented by Ingrosso et al. [40] using a preliminary version of the TDPCM scheme described in Sect. (4.2). These results have been confirmed by the present version of the model and thus we here report just a part of that study concerning the STCF (40) of C153 in water.

As in the previous example on DMA ionization, here also the QM calculations were carried out using the IE-FPCM model implemented into GAUSSIAN 03 [46] and the

same type of cavity resulting from the overlap of spheres centered on atoms, or groups of atoms ($R(\text{C}) = 1.925 \text{ \AA}$, $R(\text{CH}) = 2.125 \text{ \AA}$, $R(\text{CH}_2) = 2.525 \text{ \AA}$, $R(\text{N}) = 1.840 \text{ \AA}$, $R(\text{O}) = 1.824 \text{ \AA}$, and $R(\text{F}) = 1.764 \text{ \AA}$). The calculations of $S(t)$ have been preceded by geometry optimization of C153 in water at the DFT level, using the B3LYP hybrid functional and a 6-311G(d) basis set. The first electronic excited state properties and energies have been obtained at CIS level using the same basis set. The results, obtained by applying eqs. 40–41, but this time using experimental data [56–58] for the $\epsilon(\omega)$ profile, are reported in Fig. 6 where they are also compared with the fit of experimental data collected by Jimenez et al. [59] for a similar system, namely coumarin C343⁻, in water.

Before going into a more detailed analysis, we can observe that the calculated function shows a more complex decay than the experiments: this is not new [19] and it can be explained by recalling that possible oscillations are neglected in the global fit of the experimental data used to get the $S(t)$ reported in Fig. 6 (also if present they would be undetectable with the resolution of the experimental technique). The same oscillatory behavior has been confirmed by molecular dynamics studies which have shown that the first peak is associated to the libration mode of the water molecules whereas the broader peak centered at 0.2 ps has been attributed [19, 60] to the interaction between the libration mode and the O...O stretching in the hydrogen bond network.

If the oscillations are not considered, the concordance of experimental and calculated function is quite good. In both cases, the lower time-scales portion of the function is well represented as a Gaussian function. The Gaussian shape of the solvent response has been attributed [59] to inertial solvation dynamics. This initial fast relaxation (few tens of femtoseconds) constitutes more than 60% of the total solvation and it couples mainly to the hindered rotation (that is, libration) and the hindered translation (that is, the intermolecular vibration), which are the available high-frequency modes of the solvent; neither long-amplitude rotation nor molecular translation is significant here. In the intermediate time, there are contributions from the moderately damped rotational motions of water molecules. In this region the function begins to follow a Debye-like, diffusional behavior with a visible slowing of the decay.

6 Conclusions

The study of time-dependent phenomena in condensed phase is surely a research field in which theory and computation have still to express their real potentialities especially when quantum mechanical descriptions are used. By contrast, from an experimental point of view an enormous progress has been achieved in the last years and now many accurate studies are available on different systems which are comparable to theory. This amount of data should thus represent a strong incentive for all those researchers who want to contribute to a field of fundamental importance in many areas ranging from

biochemistry to physics. In this paper a very limited window has been opened on a correspondingly limited part of the theoretical research, however, the hope is to give a different perspective and some new ideas concerning the role of QM continuum models. It is evident that these ideas represent only a preliminary indication of a possible direction to follow which is surely not the only one or maybe not even the best one, but the good news is that something is moving. We are quite confident that the TDPCM approach we have reviewed here can represent a valid tool to realize a more reliable and more accurate coupling of QM approaches and solvation dynamics but at the same time we have no doubt that most of the work is yet to be done. For example, the fundamental questions presented in the Introduction cannot be answered in terms of the simple examples of applications presented in Sect. 5 but still some hints have come forth and thus it is worth insisting on this direction.

As already noted, continuum models have a long history but their real potentialities have become clear only in the last decades when they have been coupled to QM descriptions for the solute [13–15]. Now it is time for them to take a new important step further and extend their applications to time-dependent phenomena. This extension however should not be done independently of the experience acquired in these years on more standard applications of the models to study energy/geometries and properties of solvated systems. From these studies it appears in fact evident that mere continuum approaches are often too simplistic and their combinations or couplings with discrete approaches are not only beneficial but in some cases compulsory. The recent applications of continuum models to the study of molecular properties (and especially to the very environment sensitive NMR chemical shifts [61–64]) have clearly shown that solvation is a very complex phenomenon in which specific effects (due to solvent molecules in the first solvation shells) synergetically combine with bulk effects. In addition, the different dynamics of the first solvation shell(s) with respect to that of the bulk can lead to effects which can hardly be accounted for with uniform pictures as those generally used in continuum models (see, for example, ref [65] for an interesting discussion on this point).

It is thus necessary to accept from the very beginning that hybrid or combined approaches, mixing not only different level of calculations (like for example in QM/MM or other similar methods nowadays largely diffused) but also different “philosophies” (like for example continuum and discrete descriptions but also electronic calculations and statistical analyses [66]) represent the most promising strategy. In the near future, researchers will thus need a multidisciplinary knowledge and parallelly an open attitude without preconceptions towards new or unusual methodologies.

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