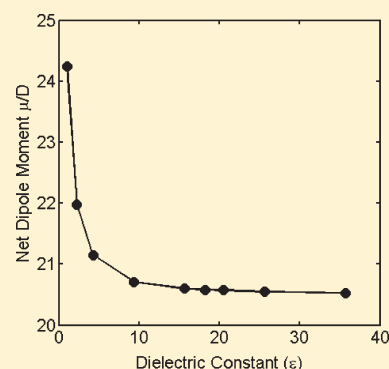


Solvents Level Dipole Moments

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ABSTRACT: The dipole moments of highly polar molecules measured in solution are usually smaller than the molecular dipole moments that are calculated with reaction field methods, whereas vacuum values are routinely calculated in good agreement with available vapor phase data. Whether from Onsager's theory (or variations thereof) or from quantum mechanical methods, the calculated molecular dipoles in solution are found to be larger than those measured. The reason, of course, is that experiments measure the net dipole moment of solute together with the polarized (perturbed) solvent "cloud" surrounding it. Here we show that the reaction field charges that are generated in the quantum mechanical self-consistent reaction field (SCRF) method give a good estimate of the net dipole moment of the solute molecule together with the moment arising from the reaction field charges. This net dipole is a better description of experimental data than the vacuum dipole moment and certainly better than the bare dipole moment of the polarized solute molecule.



INTRODUCTION

The evaluation of the dipole moments of highly polar molecules is of great importance in understanding the electrostatic interactions between these molecules in condensed phases. In particular, the organic electro-optic molecules (OEO) under development in these laboratories typically have dipole moments that are calculated to be 20–30 D in vacuo with quantum mechanical methods¹ and to have even larger dipole moments when analyzed with one or another of the techniques available for estimating the increment to the dipole moment arising from polarization of the molecule in response to the solvent reaction field. However, the limited measurements available, many of which are unpublished, do not find "apparent" dipole moments in solution greater than about 15 D. This glaring discrepancy has created a confusing picture as to how the electrostatic interactions in these systems should be modeled with molecular dynamics (MD), Monte Carlo (MC), or other techniques.

The influence of solvent on the apparent dipole moment of a solute was first comprehended by Onsager.² In this insightful work, Onsager showed that the polarization of a dielectric solvent that is induced by a given (solute) molecule generates a reaction field that acts back on the solute and further enhances its dipole moment by a reciprocal polarization. In this calculation, the solvent is treated as a dielectric continuum and the solute as a polarizable point dipole in a spherical cavity. Kirkwood³ weighed in on this problem by considering the related problem of computing the dipolar contribution to the dielectric constant of a fluid consisting of discrete orientable but unpolarizable dipoles. His treatment emphasized the fact that the orientations of neighboring molecular dipoles are correlated and that the bulk dielectric constant does not give any insight into these correlations. In neither these theories nor their successors has there been any suggestion that the static susceptibility of solvent in the vicinity of a solute molecule may have a different value from the bulk.⁴ However, dipolar saturation has long been recognized as

contributing to the properties of ionic systems.⁵ Simulations of electrostatic interactions in proteins are now being done by assigning different dielectric constants to different regions, with dielectric constants of 4 or 20 being rationalized by different ordering of polar groups.⁶ Here we demonstrate that this multiple dielectric phenomenon is also seen in typical organic solutions.

The discrepancy between measured and calculated dipole moments suggests that there is a leveling effect of solvent on the measured dipole moment of polar solutes that was not considered by Onsager or Kirkwood. Figure 1 illustrates the physics behind this effect. The polarization of the solvent creates a field that polarizes the solute in the direction to enhance its dipole moment. However, the reaction field can be understood to consist of *effective* charges which themselves have a dipole moment, and this moment is directed oppositely to that of the solute.⁷ The crucial issue is that the charge distribution that is set up in the solvent shell surrounding a solute molecule is not the same as the charge distribution in the bulk solvent. This simple argument suggests that solvent molecules surrounding a strongly polar solute molecule may have dielectric properties different from the bulk solvent, the upshot of which is that the bare dipole moment of the solute is not what is measured. The interpretation of experimental data designed to determine the dipole moments of solutes generally relies on there being a single dielectric constant for the solvent, constant everywhere, and that this dielectric constant is that of the reference unperturbed solvent. We suggest that this assumption is rarely valid.

The general rules of solubility coincide with the observation that highly dipolar molecules are only soluble in fairly polar solvents. Typical OEO molecules will dissolve, at least sparingly,

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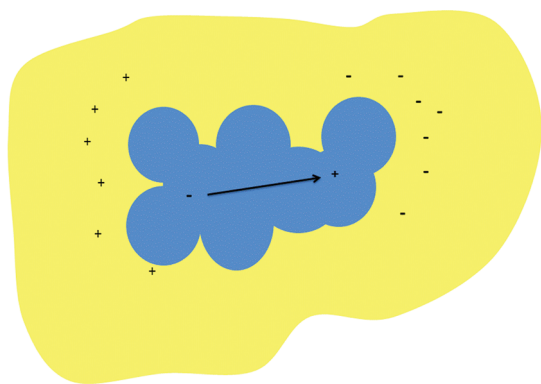


Figure 1. Illustration of the solvent reaction field. A mock molecule is shown in blue with its dipole vector. The surrounding yellow solvent shell is polarized such that its induced charge distribution creates a dipole in opposition to the molecular dipole. Inside the yellow shell the solvent molecules are oriented and polarized by the solute, while outside this shell the solvent retains its bulk dielectric properties. The solvent structure gradually relaxes from highly perturbed orientations adjacent to the solute toward the bulk behavior over a range of distances. The sharp boundary terminating the yellow domain is for illustrative purposes only.

in chloroform (dielectric constant $\epsilon = 4.7$) but not in benzene ($\epsilon = 2.3$). The latter solvent is much favored for the solution measurement of the dipole moments of nonvolatile molecules, as a scan of the extensive compilation by McClellan⁸ shows. In fact, this critical work does not include nonionic molecules with dipole moments larger than about 10 D, owing to the recognized difficulty in estimating the influence of solvent polarization on the measurements of these highly dipolar systems, nor does it typically include examples of dipolar solvents. (In the sequel, the adjective “dipolar” will be dropped in favor of “polar”. This is standard vernacular chemistry usage.)

A solution to understanding the polarization effects that operate in polar solutions can be found in a MD calculation with a highly accurate polarizable force field.⁹ A strongly polar molecule, when placed in a polar solvent, will be polarized by the solvent reaction field. Solvent dipoles are oriented by the polar solute and are further polarized by it. These two contributions to the charge distribution in the solvent generate the reaction field, which is properly understood to be the sum of dipolar fields. (In continuum theories of the solvent response, the permanent and induced dipole contributions to the reaction field are subsumed into the low-frequency dielectric constant of the solvent.) At large distances from the solute (at infinite dilution), the solvent assumes its bulk orientational statistics and hence its bulk dielectric properties.¹⁰ The remote bulk dielectric provides a boundary condition on the electric field as has been carefully discussed by Kirkwood.³ Appropriate statistical mechanical averaging of this system, when equilibrated self-consistently, would yield the charge distributions required to evaluate the “apparent solute dipole moment”. This procedure, attractive as it is, requires a higher level of force field and MD simulation than is commonly practiced, and which will take considerable effort to develop. Regardless of how one might obtain the charge distribution, the dipole moment of the solute plus its perturbed solvent cloud (see Figure 1) is the appropriate entity to compare with experiment. Empirical methods have attempted to deal with the solvent effect by means of a composition-dependent

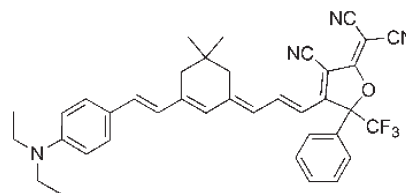


Figure 2. Molecular structure of YLD124: 4-((1*E*,2*E*)-3-(3-(4-(diethylamino)styryl)-5,5-dimethylcyclohex-2-enylidene)prop-1-enyl)-2-(dicyanomethylene)-5-(trifluoromethyl)-2,5-dihydro-5-phenylfuran-3-carbonitrile. This push–pull organic nonlinear optical molecule has an isophorone ring in the conjugated bridge and trifluoromethyl and phenyl groups on the tricyanofuran acceptor ring.

contribution to the solute susceptibility,¹¹ but a simple model to be discussed will show that these have not captured the essence of the problem.

An interim solution to the problem of understanding the dipolar discrepancy is provided by the quantum mechanical self-consistent reaction field model (SCRf).¹² The charges that are generated by the several different algorithms that have been devised to approximate the solvent reaction field can be extracted from the data files and used to compute the *effective* solvent dipole moment. The dipole created by the reaction field charges (RFC), when added to the calculated dipole moment of the subject molecule, provides an approximation to the solvent leveling effect. Since the SCRf methods replace the distributed solvent charge cloud that is discussed in the preceding paragraph by a shell of charges, often distributed at the solvent-accessible surface surrounding the subject molecule, it is expected that this charge localization introduces an approximation of uncertain magnitude. However, we will show that inclusion of these charges in the calculation of the apparent solute dipole moment provides a first approximation to the solvent leveling effect that we are discussing.

COMPUTATIONAL

All calculations were performed with the Gaussian09¹³ quantum mechanical package. Since our purpose is not ultimate accuracy, we opted to use the DFT functional B3LYP with 6-31G* basis set for all calculations on a highly polar chromophore. To explore the influence of the method (HF and MP2) and basis sets (cc-pVDZ and 6-311G), additional calculations on *p*-nitroaniline were performed with the same package. The SCRf-PCM and SCRf-CPCM¹⁴ methods with default parameters were used to evaluate the solvent reaction field and its effect on the molecular dipole moment. In all cases, the molecular geometries were optimized with the specified method, basis set, and solvent field; small differences from the vacuum geometries were observed in all cases. Parameters for the solvents used are those incorporated in the Gaussian09 package; default values of the dielectric constants (ϵ) taken from the Gaussian09 documentation are provided in the Results section. The SCRf charges and their coordinates were obtained from fully converged SCRf calculations, and the effective dipole moments of the reaction field charges were calculated in the usual way.

RESULTS

Two molecules were selected for this work: *p*-nitroaniline (pNA) and YLD124.¹⁵ The structure of YLD124 is shown in Figure 2. This molecule is typical of the OEO chromophores with

Table 1. Calculated (B3LYP/6-31G*) and Experimental Dipole Moments of *p*-Nitroaniline (pNA)

solvent	ϵ	μ/D (pNA)	μ/D (rx) ^a	μ/D (net) ^b	μ/D (exp) ^c
vacuum	1.00	7.1215	0.00	7.12	NA
1,4-dioxane	2.210	8.2832	2.1932	6.09	6.82 ± 0.07
benzene	2.271	8.3104	2.2542	6.06	6.22 ± 0.11

^a Magnitude of the dipole moment of the reaction field charges (RFC).^b Magnitude of the vector sum of the molecular dipole and RFC dipole.^c Ref 5: averages and standard deviations calculated from data at $25 \pm 5^\circ$.**Table 2.** Calculated SCRF-PCM Dipole Moment of YLD124 with Reaction Field Dipole

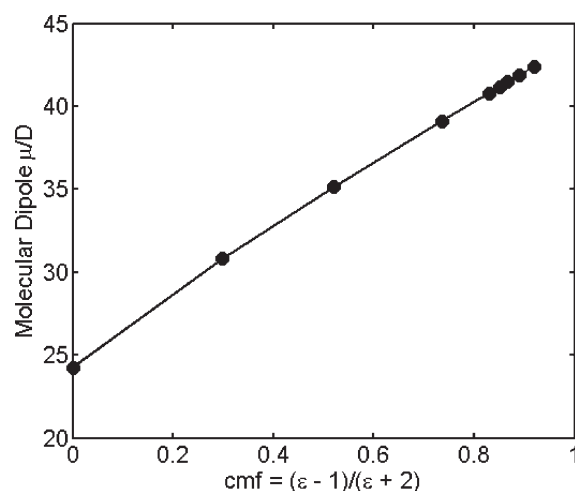
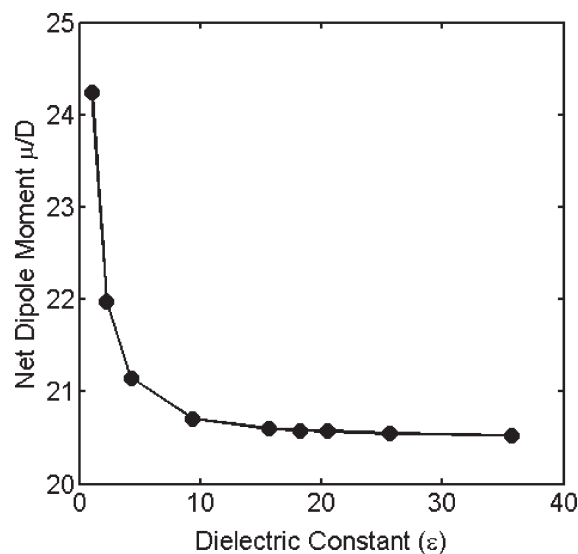
solvent	ϵ	$(\epsilon - 1)/(\epsilon + 2)$	μ/D (YLD124)	μ/D (rx)	μ/D (net)
vacuum	1.000	0.000	24.2378	0.0000	24.24
benzene	2.271	0.298	30.7923	8.8096	21.98
bromoform	4.2488	0.520	35.1256	13.9782	21.15
2-brpropane ^a	9.3610	0.736	39.1036	18.3955	20.71
cyclohexanone	15.619	0.830	40.7889	20.1910	20.60
butanone	18.246	0.852	41.1849	20.6064	20.58
acetone	20.493	0.867	41.4498	20.8832	20.57
benzonitrile	25.592	0.891	41.8907	21.3416	20.55
acetonitrile	35.688	0.920	42.4077	21.8775	20.53

^a 2-Bromopropane.

large hyperpolarizabilities that are under development in these laboratories. The small pNA molecule was chosen because it was one of the first OEO molecules studied and because experimental dipole data are available in the McClellan⁸ compilation. The experimental data are compared with calculations done with B3LYP and the 6-31G* basis set in Table 1; calculated dipole moments, reaction field dipole moments, and net dipole moments are provided.

The vacuum dipole moment of pNA calculated with MP2/cc-pVDZ is 5.69 D, much smaller than the value 6.94 D calculated with B3LYP/cc-pVDZ or with MP2/6-311G (6.59 D in vacuo). The relatively small differences [relative to the magnitude of the reaction field charge (RFC) dipole] between vacuum dipoles calculated with B3LYP with small basis sets and MP2 with a large basis set suggests that the differences between net and experimental dipole moments in Table 1 cannot be explained by deficiencies in method or basis set but are the result of the calculated RFC overestimating the solvent dipole contribution. The fact that MP2 with a high basis set for the vacuum pNA structure gives a dipole moment close to that measured in solution has been, and might continue to be, a confusing issue. We consider this coincidence to be fortuitous only. It should be noted that the calculated net dipole in Table 1 for pNA in benzene is reasonably close to the measured value, but this is not the case for 1,4-dioxane.

Calculated results for YLD124 are given in Table 2. Figure 3 displays a plot of the molecular dipole moment against the Clausius–Mossotti function,¹⁶ $\text{cmf} = (\epsilon - 1)/(\epsilon + 2)$. In previous work, we have found that quantum mechanically calculated dipole moments and hyperpolarizabilities are nearly linear functions of cmf or its modifications,^{1,17} and this behavior is confirmed here. Just as interesting from the experimental point of view is a plot of “net dipole moment” against solvent dielectric

**Figure 3.** Dependence of the molecular dipole moment of YLD124 on the Clausius–Mossotti function (cmf). The data are taken from Table 2.**Figure 4.** Dependence of net dipole moment of the YLD124 chromophore with its solvent shell as a function of solvent dielectric constant. Data for this plot are given in Table 2.

constant in Figure 4. The leveling effect of solvent is clearly demonstrated in this plot.

DISCUSSION

It may be useful to present a simple model to aid in the understanding of the coupling between solute dipole and solvent organization. As Liu et al.¹⁸ correctly state, the polarization of a liquid mixture is a volume fraction average of the component contributions. Consider a binary mixture of two components, solvent with a nominal volume fraction ϕ_1 and solute with volume fraction $\phi_2 = 1 - \phi_1$. Our simple model is this: Figure 1 suggests that a sufficiently dilute mixture consists of three species, unperturbed solvent characterized by the bulk susceptibility χ_1 with an actual or effective volume fraction θ_1 , the solute with its molecular susceptibility χ_2 at volume fraction $\theta_2 = \phi_2$, and the

solvent associated to the solute molecules with an effective volume fraction $\theta_3 = \varphi_1 - \theta_1$ and having a susceptibility $\chi_3 = \chi_1 - \delta\chi$ different from the bulk by the amount $\delta\chi$. This differs from the usual assumption in the analysis of experimental data, in which the solvent is assumed to have its bulk susceptibility everywhere, even when in contact with the solute. It follows from additivity principles that

$$\chi = \theta_1\chi_1 + \theta_2\chi_2 + \theta_3\chi_3 \quad (1)$$

The assumption is made that the solution is sufficiently dilute so that the solvent shells surrounding each solute molecule are separated from one another, and this allows us to write $\theta_3 = \theta_2 V_{\text{sh}}/V_2 = \varphi_2 r$, where $V_{\text{sh}}/V_2 = r$ is the volume of the perturbed solvent shell surrounding each solute relative to the volume of the solute molecule. Using these definitions, eq 1 reduces to

$$\chi = \varphi_1\chi_1 + \varphi_2(\chi_2 - r\delta\chi) \quad (2)$$

That is, the apparent susceptibility increment due to the solute is not that of the bare *polarized* solute but is reduced by the amount $r\delta\chi$ arising from the polarized solvent shell surrounding the solute molecules. A perturbed solvent shell accompanies each solute molecule down to infinite dilution. Attempting to correct for this effect by adding a term of the form $\varphi_2(d\chi_1/d\varphi_2)$ will not capture the effect, as this vanishes at infinite dilution. Given that the net dipole moments calculated with the SCRF method are smaller than the vacuum dipoles, we may infer that the sign of $\delta\chi$ is positive for the systems presented here. This is consistent with the 1930s data of Müller.¹⁹

Inspection of Table 16.1 of Smyth's monograph⁴ or the compilation of McClellan⁸ suggests that the positive sign for $\delta\chi$ is true most of the time. Notable exceptions are ethyl acetate and diethyl ether, for which measurements in benzene appear to give larger dipole moments than the gas-phase values; Smyth's entries for acetaldehyde appear to be transposed in comparison with McClellan. Note that ethyl acetate and diethyl ether have nontrivial torsional degrees of freedom about C–O bonds; the conformations in vacuo and in solution might be different. In any event, this discussion illustrates that critical evaluation of experimental data would take us far afield of the present purpose.

The magnitude of the solvent reorganization term, $r\delta\chi$, in eq 2 is calculated to be larger than the incremental dipole moment of the solute induced by the reaction field. This is consistent with experimental data presented in Table 1, although the magnitudes are not in perfect agreement. In our simple picture, much of the magnitude of the experimental term arises from the ratio of volumes of the solvent shell to the solute molecule. Typical MD simulations show that correlations extend over several molecular diameters. If we take just one layer of spherical molecules around a given spherical molecule of the same radius, the ratio $r \sim O(10)$, the actual value might be several times larger. The susceptibility increment per solvent molecule is not required to be very large for the experiments to be comprehensible. Polar solvent molecules organize themselves around a highly polar solute molecule in response to molecular electrostatic fields that are orders of magnitude larger than the external fields imposed on samples during measurement of dielectric susceptibilities. It should not be surprising that molecules in these solvent shells do not respond to external fields in the measurement of the dielectric constant in the same way as molecules in the bulk solvent.

The comparison of the computations for pNA with experimental data suggests that the PCM method or its variant, the

Table 3. Calculated Dipole Moments of *p*-Nitroaniline in Benzene Using Various Methods and Basis Sets

method	basis set	μ/D (pNA)	μ/D (rx)	μ/D (net)
B3LYP-PCM	cc-pVDZ	8.2212	2.2303	5.99
B3LYP-PCM	6-31G*	8.3104	2.2542	6.06
B3LYP-CPCM	6-31G*	8.4039	2.5000	5.90
HF-PCM	6-31G*	7.7882	2.1074	5.68
MP2-PCM	6-31G*	6.9151	2.1249	4.79
MP2-PCM	6-311G	7.5098	2.4310	5.08

screened conductor model, C-PCM,¹⁴ overestimates the dipole moment of the RFC by about 10–20%. The magnitudes of the net dipole moments calculated with a variety of methods and basis sets consistently yield smaller apparent dipole moments than those measured. Inspection of Table 3 shows that this is not a fault of basis set or method—the net dipole moments calculated with all methods and basis sets are smaller than the experimental values in benzene. As stated in the Introduction, we had no expectation that the SCRF methods would give a quantitative account of the polarized solvent's dipolar field. The actual molecular fields that generate a solvent reaction field are dipolar fields, those resulting primarily from the additive effects of static and induced dipoles in the organized solvent shell, and secondarily from the uniform field induced in the distant continuum dielectric. The moments that are induced in solvent-shell molecules are given by the product of their anisotropic polarizability tensors with the local fields. This is apt to be a far more complex field structure than can be captured with a distribution of surface charges. However, given the picture that the susceptibilities are different from the bulk in the vicinal solvent, we suggest that quantitative improvements in the SCRF models might be had by simply adjusting the solvent dielectric that is used in the theories.

In the Introduction, we offered the opinion that measured dipole moments of very strongly polar molecules are never larger than about 15 D. The calculations on the OEO chromophore, YLD124, asymptote to an apparent dipole moment of about 20.5 D, which is significantly larger than the ca. 15 D that was conjectured in the Introduction to be observed as the upper limit of measured solution dipole moments. The calculations on pNA, on the contrary, result in apparent dipole moments that are too small. There is no obvious explanation for the RFC being too large for smaller molecular dipoles and too small for larger molecular dipoles. Clearly it would be advantageous to obtain a comprehensive data set to know whether our conjecture or the calculations are more nearly correct for OEO molecules.

CONCLUSION

The self-consistent reaction field (SCRF) method was designed to estimate the enhancement to molecular dipole moments arising from solvent reaction fields. However, the charges that the method generates also provide a means to calculate the effective dipole moment of the polarized solvent that surrounds a solute molecule. The net dipole moment that is calculated by summing the molecular dipole and the moment of the SCRF charges provides an estimate of the dipole moment assigned to solute molecules, which is what is measured in experiments. We have shown that solvents exert a leveling effect on these net or *apparent* solute dipole moments. The apparent dipole moments

calculated with the SCRF method for the two solutes investigated here, in solution with solvents of any dielectric constant (but non-hydrogen bonding), are smaller than the vacuum dipole moments. The charges that are developed in the solvent by virtue of its polarization by the solute generate a dipole moment that is larger than the incremental dipole that is induced in the solute molecule by the reaction field. The standard interpretation of experimental data apparently assumes that the bulk susceptibility of the solvent applies up to near-neighbor distances with dissolved solute. For the rigid, non-hydrogen-bonding systems that have been presented, we have shown that a more consistent interpretation of data is achieved if the solvent surrounding a solute is assumed to be perturbed and to have an effective susceptibility that is smaller than the bulk solvent. This is consistent with the theory of Gong et al.⁵ in modifying the Born model of hydration energies in aqueous systems. The distance-dependent dielectric phenomenology that is used in biological settings is echoed here but at lower solvation energy scales.

The combined influences of polarization and screening in condensed phases partially compensate one another, which may be an explanation for the success of force fields in which quantum mechanically computed charges for molecules in vacuo are empirically reduced^{20,21} by about 10% for application to condensed phase simulations. This empirical scaling reduces the strength of the electrostatic nonbonded interactions, making their strength approximately equivalent to a more sophisticated polarizable and screened force field that encompasses the effects that are discussed here. We believe that it would be extremely useful to have high-quality data sets on “apparent solution dipole moments” for a few high polarity molecules in a wide range of solvents that might serve to calibrate theoretical methods, including the parametrization of polarizable force field models.

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