

Impact of Theory of Substitution on the Solubility of Crown Ethers

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Abstract

Due to the various uses of crown ethers in different fields such as nanotechnology, medicine, agriculture, separation of metals, etc., it is essential to identify and investigate the crown ether structures and substituent effect on their solubility so as to enhance their usage. Therefore, the aim of this study is to investigate the theory of substitution effect on the solubility of crown ethers (12-crown-4) and accordingly select the most appropriate substituents. The first step to accomplishing this goal involved designing the selected molecules followed by the optimization of these molecules using the computational software in the gas phase. Several electron-withdrawing and electron-donating substituents were connected to the molecule and subsequently optimized in the gas and solution phases in the presence of various solvents. This was followed by the computation of energy and dipole moment. A comparison of these values revealed that the bromine substituent possessed the highest energy stability while the chlorine substituent has the highest dipole moment. Moreover, the aqueous solvent has the greatest impact on the ethers' energy and dipole moment.

Keywords: Crown ether, substitution, solubility, dipole moment, optimization

INTRODUCTION

Currently, macromolecular chemistry and its subcategories including the host-guest system are widely used. Crown ethers, which are a type of macromolecules, are used as solvent extraction reagents due to their cation solvation properties [1-5]. The crown ethers can also act as a host and phase-transfer catalyst as they facilitate the migration of a reactant from one phase to another during a reaction.

Apart from their applications in solvent chemistry, crown ethers are of importance in chemistry and biology as well. The capability of these ethers to be combined enables them to be used in a number of ion-selective electrodes [6]. In addition to their use in conventional colored spectroscopic methods, crown ethers have also been widely used to create ionic sensors, which respond to the presence of target ions through fluorescent radiation [7].

Due to the chirality of some crown ether alternatives, scientists have been able to separate a number of optically active compounds from racemic compounds [8, 9]. Moreover, due to the wide application of crown ethers in various fields such as nanotechnology, medicine, agriculture, separation of metals, etc., the identification and investigation of the crown ether structures and the substituent effect on their solubility is highly essential to improve their application. Therefore, this study theoretically and computationally investigates crown ethers and the substituents' impact on their solubility.

METHODOLOGY

Gaussian 09 software (Wallingford, CT) was used to design the desired molecules and perform quantum computing in this project. In this study, the 12-crown-4 crown ethers were selected and designed by replacing the hydrogen atoms with new substituents (Figure 1). Quantum computing was carried out on these ethers to introduce new structures of electron-donating, electron-withdrawing, and solubility of the substituents.

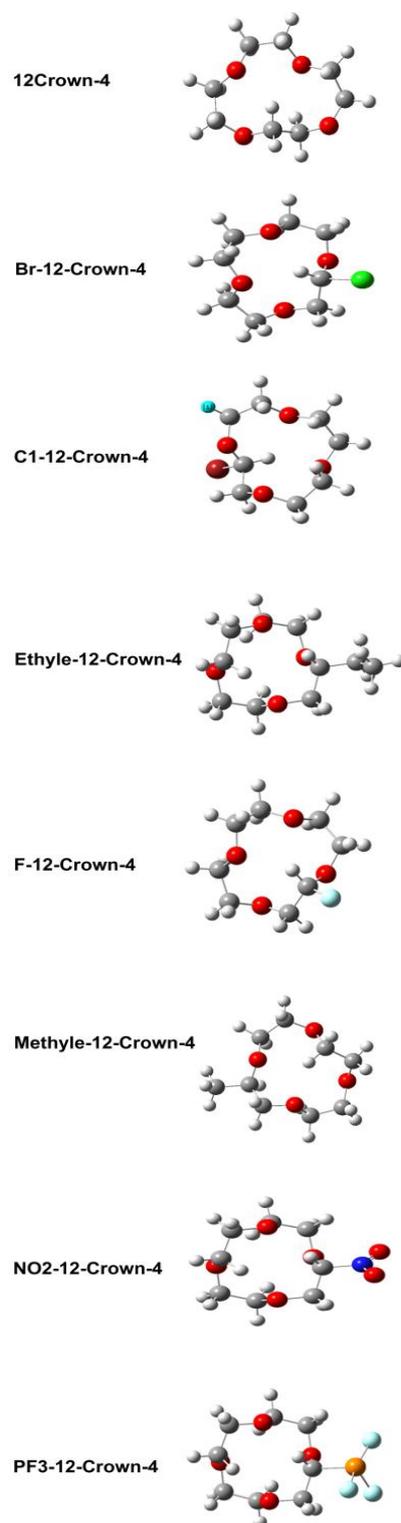


Figure 1: 12-Crown-4 ether and its various substituents

The geometric structures of ethers, which were non-substituted and substituted in the gas phase, were optimized using the B3LYP (Becke, three-parameter, Lee-Yang-Parr) hybrid function and 6-31 + G basis set followed by the evaluation of energy and electronic features of the ethers.

In the solvent phase, computational quantum mechanics, self-consistent reaction field (SCRF) technique, and conductor-like polarizable continuum model (CPCM) were used to carry out the studies on the ethers. Computational quantum chemistry is associated with the numerical computation of molecular electronic structures by ab-initio and semi-empirical techniques. Similarly, the SCRF technique is the Gaussian keyword required for all the implicit solvent models while CPCM is applied for the computation of aqueous solvation free energies for a number of organic molecules. Subsequently, in the final stage of this study, all the ethers were optimized in acetone, dimethyl sulfoxide (DMSO), methanol, tetrahydrofuran (THF), and aqueous solvents, and their energy and electron properties were evaluated.

RESULTS AND DISCUSSION

The chemical structure of the non-substituted and simple 12-crown-4crown ether selected for this study is displayed in Figure 2. One of the hydrogen atoms was removed and replaced by bromine (Br), chlorine (Cl), ethyl, fluorine (F), methyl (—CH₃), nitrogen dioxide (NO₂) and Trifluoro Phosphide (PF₃) substituents, and their electronic properties were evaluated. The obtained results are summarized in Table 1.

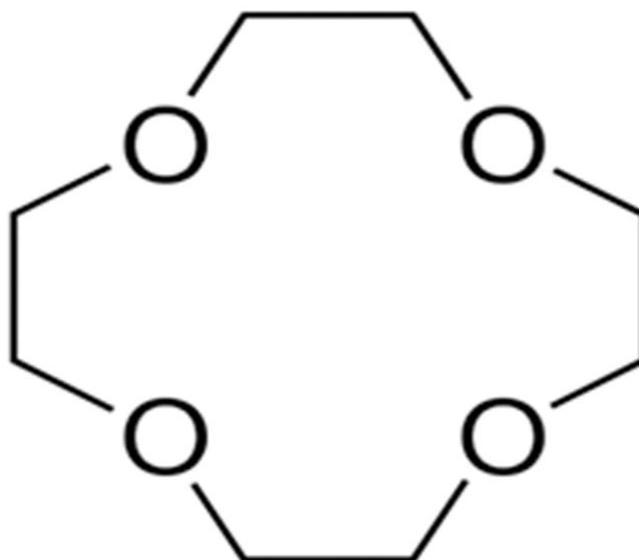
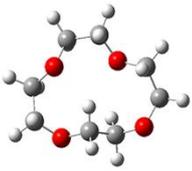
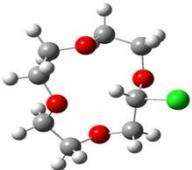
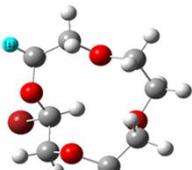
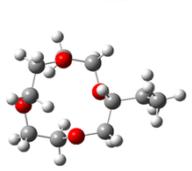
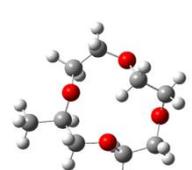
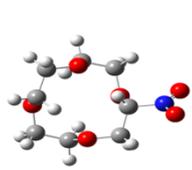
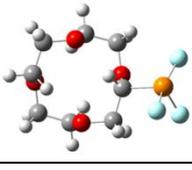


Figure 2. The chemical structure of 12 Crown-4

Table 1: Optimization of various substituents of 12-Crown-4 in the gas phase.

ΔE (Kj)	ΔE (a.u.)	Energy (J)	Energy (a.u.)	Shape	Name
-	-	$-2675/78 \times 10^{-15}$	-615/124		12-Crown-4
-11183/71	-2570/97	$-13859/53 \times 10^{-15}$	-3186/10		Br-12-Crown-4
-1999/17	-459/58	$-4674/98 \times 10^{-15}$	-1074/71		Cl-12-Crown-4
-339/99	-78/16	$-3017/76 \times 10^{-15}$	-693/74		Et-12-Crown-4
-431/60	-99/22	$-3107/37 \times 10^{-15}$	-714/34		F-12-Crown-4
-170/99	-39/31	$-2846/77 \times 10^{-15}$	-654/43		Me-12-Crown-4
-55196/1	-204/43	$-3565/04 \times 10^{-15}$	-819/55		NO2-12-Crown-4
-2784/78	-640/18	$-5460/55 \times 10^{-15}$	-1255/3		PF3-12-Crown-4

The addition of a substituent into the 12-Crown-4 ether resulted in a more negative energy in all substituents than the non-substituted ones. Therefore, it was evident that the addition of a substituent to the 12-Crown-4 ether enhances its stability. The sustainability process of the substituents' energy is as follows:



The energy sustainability process here shows that the electron-withdrawing substituents increase the energy stabilization compared to the electron-donating substituent, as the former attracts the negative charge of the oxygen.

Geometric optimization of various crown ethers in solvent

The substituted and non-substituted crown ethers were designed and then optimized in the aqueous, methanol, DMSO, acetone, and THF solvents. Tables 2-6 represent the energy and sustainable energy of the optimized structure of these ethers.

Table 2: Optimization of various crown ethers in the acetone solvent.

ΔE (a.u.)	Energy (J)	Energy (a.u.)	Shape	Name
	-	$-2675/81 \times 10^{-15}$	-615/13	12-Crown-4
$-11183/80 \times 10^{-15}$	-2570/99	$-13859/62 \times 10^{-15}$	-3186/12	Br-12-Crown-4
$-1999/21 \times 10^{-15}$	-459/59	$-4675/03 \times 10^{-15}$	-1074/72	Cl-12-Crown-4
$-341/99 \times 10^{-15}$	-78/62	$-3017/81 \times 10^{-15}$	-693/75	Et-12-Crown-4
$-431/65 \times 10^{-15}$	-99/23	$-3107/46 \times 10^{-15}$	-714/36	F-12-Crown-4
$-170/99 \times 10^{-15}$	-39/31	$-2846/81 \times 10^{-15}$	-654/44	Me-12-Crown-4
$-889/27 \times 10^{-15}$	-204/43	$-3565/08 \times 10^{-15}$	-819/56	NO ₂ -12-Crown-4
$-2784/78 \times 10^{-15}$	-640/18	$-5460/59 \times 10^{-15}$	-1255/31	PF ₃ -12-Crown-4

Table 3: Optimization of various ethers in the (DMSO) solvent.

ΔE (a.u.)	Energy (J)	Energy (a.u.)	Shape	Name
	-	$-2675/81 \times 10^{-15}$	-615/135	12-Crown-4
$-11183/76 \times 10^{-15}$	-2570/98	$-13859/62 \times 10^{-15}$	-3186/12	Br-12-Crown-4
$-1999/17 \times 10^{-15}$	-459/58	$-4675/03 \times 10^{-15}$	-1074/72	Cl-12-Crown-4
$-341/95 \times 10^{-15}$	-78/61	$-3017/81 \times 10^{-15}$	-693/75	Et-12-Crown-4
$-431/60 \times 10^{-15}$	-99/22	$-3107/46 \times 10^{-15}$	-714/36	F-12-Crown-4
$-170/95 \times 10^{-15}$	-39/30	$-2846/81 \times 10^{-15}$	-654/44	Me-12-Crown-4
$-889/22 \times 10^{-15}$	-204/42	$-3565/08 \times 10^{-15}$	-819/56	NO ₂ -12-Crown-4
$-2784/73 \times 10^{-15}$	-640/17	$-5460/59 \times 10^{-15}$	-1255/31	PF ₃ -12-Crown-4

Table 4: Optimization of various ethers in the methanol solvent.

ΔE (a.u.)	Energy (J)	Energy (a.u.)	Shape	Name
	-	$-2675/81 \times 10^{-15}$	-615/135	12-Crown-4
$-11179/45 \times 10^{-15}$	2569/99	$-13859/62 \times 10^{-15}$	-3186/12	Br-12-Crown-4
$-1999/21 \times 10^{-15}$	-459/59	$-4675/03 \times 10^{-15}$	-1074/72	Cl-12-Crown-4
$-431/99 \times 10^{-15}$	-78/62	$-3017/81 \times 10^{-15}$	-693/75	Et-12-Crown-4
$-2675/81 \times 10^{-15}$	-99/23	$-3107/46 \times 10^{-15}$	-714/36	F-12-Crown-4
$-170/95 \times 10^{-15}$	-39/31	$-2846/81 \times 10^{-15}$	-654/44	Me-12-Crown-4
$-2675/81 \times 10^{-15}$	-204/43	$-3565/08 \times 10^{-15}$	-819/56	NO ₂ -12-Crown-4
$-2675/81 \times 10^{-15}$	-640/18	$-5460/59 \times 10^{-15}$	-1255/31	PF ₃ -12-Crown-4

Table 5: Optimization of various ethers in the THF solvent.

ΔE (a.u.)	Energy (J)	Energy (a.u.)	Shape	Name
-	-	$-2675/81 \times 10^{-15}$	-615/133	12-Crown-4
$-11183/76 \times 10^{-15}$	-2570/98	$-13859/62 \times 10^{-15}$	-3186/12	Br-12-Crown-4
$-1999/17 \times 10^{-15}$	-459/58	$-4675/03 \times 10^{-15}$	-1074/72	Cl-12-Crown-4
$-341/91 \times 10^{-15}$	-78/60	$-3017/81 \times 10^{-15}$	-693/74	Et-12-Crown-4
$-431/60 \times 10^{-15}$	-99/22	$-3107/46 \times 10^{-15}$	-714/36	F-12-Crown-4
$-170/95 \times 10^{-15}$	-39/30	$-2846/81 \times 10^{-15}$	-654/44	Me-12-Crown-4
$-889/22 \times 10^{-15}$	-204/42	$-3565/08 \times 10^{-15}$	-819/56	NO ₂ -12-Crown-4
$-2784/73 \times 10^{-15}$	-640/17	$-5460/59 \times 10^{-15}$	-1255/31	PF ₃ -12-Crown-4

Table 6: Optimization of various substituents in the aqueous solvent.

ΔE (a.u.)	Energy (J)	Energy (a.u.)	Shape	Name
-	-	$-2675/81 \times 10^{-15}$	-615/135	12-Crown-4
$-11183/76 \times 10^{-15}$	-2570/98	$-13859/62 \times 10^{-15}$	-3186/12	Br-12-Crown-4
-1999×10^{-15}	-459/59	$-4675/03 \times 10^{-15}$	-1074/73	Cl-12-Crown-4
$-341/95 \times 10^{-15}$	-78/61	$-3017/81 \times 10^{-15}$	-693/75	Et-12-Crown-4
$-431/60 \times 10^{-15}$	-99/22	$-3107/46 \times 10^{-15}$	-714/36	F-12-Crown-4
$-170/95 \times 10^{-15}$	-39/30	$-2847/77 \times 10^{-15}$	-654/44	Me-12-Crown-4
$-889/22 \times 10^{-15}$	-204/42	$-3565/08 \times 10^{-15}$	-819/56	NO ₂ -12-Crown-4
$-2784/73 \times 10^{-15}$	-640/17	$5460/59 \times 10^{-15}$	-1255/31	PF ₃ -12-Crown-4

This study showed that the various substituent effects on different solvents in ethers' energy are the same as their effects in the gas phase. They are as follows:



Therefore, it was observed that by adding substituents to the 12-Crown-4 ether in various solvents, the energy of all substituents was found to be more negative than the non-substituted ones. This showed that the addition of a substituent to the 12-Crown-4 ether results in the enhancement of its stability.

The results also suggested that the different solvents have insignificant impacts on the stability and sustainable energies of the 12-Crown-4 crown ethers. Therefore, it was evident that the effect of different solvents on various ether energies is negligible.

Dipole moment of the substituted and non-substituted ethers in the various gas and solvent phases

Computing dipole moment

Dipole moment is an important physical quantity for compounds. It is defined in relation to the response of the molecules to an applied electric field. In addition, it is the first derivative of the energy with respect to the applied electric field. It also serves as a measure of the asymmetry in the distribution of the molecule charge and is shown in a three-dimensional vector, which can be obtained from the equation [1-4]:

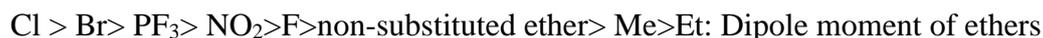
$$\mu = \sqrt{\mu_x^2 + \mu_y^2 + \mu_z^2}$$

Higher order moments are important only when the dipole moment is zero.

Table 7 represents the dipole moment of non-substituted and substituted crown ethers in different solvent and gas phases. The effect of different solvents on the dipole moment of ethers in the gas phase is as follows:

Tetra Hydro Furan <Acetone <Methanol ≡ Dimethyl Sulfoxide <Water: Effect of solvents on dipole moment.

Overall, the results of this study indicate that the polar solvents have greater effects on the dipole moment compared to the nonpolar solvents. The dipole moment of ethers in gas and all the solvent phases are as follows:



The dipole moment here shows that the electron-withdrawing substituents increase the dipole moment more than the electron-donating substituents, resulting in an increased solubility. Therefore, in these compounds, the solubility is higher in the presence of polar solvents and electron-withdrawing substituents.

Table 7: Dipole moment (Debye) of various substituents in different gas and solvent phases.

Aqueous	THF	Methanol	DMSO	Aston	Gas	Name
4/631	4/434	4/601	4/616	4/570	3/607	12-Crown-4
7/74	7/28	7/66	7/7	7/59	5/54	Br-12-Crown-4
8/37	7/81	8/27	8/32	8/19	5/85	Cl-12-Crown-4
0/3403	0/33	0/3384	0/3393	0/3317	0/2813	Et-12-Crown-4
5/93	5/63	5/88	5/91	5/83	4/40	F-12-Crown-4
3/58	3/44	3/56	3/57	3/54	2/79	Me-12-Crown-4
5/77	5/61	5/75	5/76	5/72	4/79	NO ₂ -12-Crown-4
6/6	6/30	6/30	6/58	6/53	4/99	PF ₃ -12-Crown-4

CONCLUSION

In this study, the density functional theory (DFT) method along with B3LYP hybrid function and 6-31 G basic set in two gas and solvent phase were used to perform quantum computing on non-substituted and substituted 12-Crown-4 ether. It was concluded that the electron-withdrawing substituents and polar solvents cause an increase in the solubility of 12-Crown-4 crown ethers. The bromine substitution has the most sustainable energy while the substitution of chlorine has the highest dipole moment with a little difference from the bromine substitution. Moreover, the aqueous solvent has the greatest impact not only on the energy and dipole moment but also on the solubility of the ethers. In general, the ether with bromine substituent in the aqueous solvent has the best solubility.

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BIOGRAPHY

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