Stability and production of positron-diatomic molecule complexes

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Abstract

The energies at geometries close to the equilibrium for the $e^+\text{BeO}$ and $e^+\text{LiF}$ ground states were computed by means of diffusion Monte Carlo simulations. These results allow us to predict the equilibrium geometries and the vibrational frequencies for these exotic systems, and to discuss their stability with respect to the various dissociation channels. Since the adiabatic positron affinities were found to be smaller than the dissociation energies for both complexes, we propose these two molecules as possible candidates in the challenge to produce and detect stable positron-molecule systems.

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Despite the wide diffusion of positron and positronium (Ps) based analytical techniques to study solids [1], polymers [2], solutions [3], and organic molecules in the gas phase [4, 5], a direct observation of the compounds between the positron and an atom or a molecule is still lacking. In fact, $\Gamma_2$, annihilation rate from positron annihilation lifetime spectroscopy and angular correlation annihilation radiation are the only standard measurements carried out during the interaction positron-matter. The prediction of these observables is required to infer the formation of the positronic compounds, a task that appears complex, especially for heavy atoms and ions or large molecules, due to the high accuracy that is needed for the wave function that describes the complexes.

The theoretical work on positron containing systems is scarce, and in our opinion this is due to the difficulty in describing accurately the electron-positron correlation using standard quantum chemistry methods like Self Consistent Field (SCF), Configuration Interaction, and Coupled Cluster methods [6].

Two more approaches have been pursued during the last years, namely Density Functional Theory (DFT) [7] and variational calculations based on Explicitly Correlated Gaussian (ECG) trial wave functions [8, 9]; they also suffer from practical drawbacks. Although DFT methods have a convenient scaling of the computational cost versus the system complexity, the exact exchange-correlation potential between electrons and the correlation potential between electrons and positron are only approximately known. As far as ECG wave functions are concerned, two groups [8, 9] showed that accurate results can be obtained even for positron containing systems. Unfortunately, the ECG wave functions suffer from the fast increase of the computational cost with the number of particles, therefore preventing their use for medium and large systems. Nevertheless, accurate results can be obtained employing the frozen-core approximation for atoms and molecules [8].

In our ongoing project to study positronic compounds as a way to understand matter-antimatter interactions and to predict the existence of a bound state for positron-atom or positron-molecule complexes [10-15], we employ the fixed node diffusion Monte Carlo (FN-DMC) method [16]. This technique is known to be able to recover most of the correlation energy between electrons and between electrons and a positron [10-15,17-19]. Although FN-DMC is a powerful technique, it is not easy to reduce the nodal error introduced by the fixed node approximation. This result might be achieved in principle by employing more accurate trial wave functions or resorting to the nodal release technique, but both approaches do not easily apply to large systems, i.e. more than ten electrons, due to their computational cost. Nevertheless, the FN-DMC method has given accurate positron affinities, as well as electron affinities [20], for systems up to twelve electrons, both atoms and molecules, exploiting the cancellation of nodal errors [12].

In the quest for stable positronic complexes, we studied the potential surface for $e^+LiH$ by FN-DMC calculations [21] and found that the equilibrium distance and the vibrational transitions are different from those of LiH, opening the possibility for a spectroscopic detection of this compound. However, the LiH adiabatic positron affinity (APA) is larger than the dissociation energy (DE), and a third body would be required to dissipate the excess energy. We suggested to start from a van der Waals complex of LiH with a rare gas, and to attach the positron to this so that the rare gas should dissipate the excess energy. Similar consideration can be extracted from the work by Mitroy and Ryzhikh [22], where they employed a full non-adiabatic approach and ECG functions to establish the stability of $e^+LiH$.

To avoid this complex mechanism, in this Letter we investigate other systems to see if we can find a molecule whose APA is smaller than the DE, allowing the positron to be attached and to form the complex without the intervention of a third body. If the spectroscopic properties of this compound differ from those of the parent molecule, it could be a good candidate for experimental observation.

We have performed accurate calculations of the total energy for $e^+BeO$ and $e^+LiF$ systems at various internuclear distances by means of FN-DMC. These results allow us to obtain the equilibrium distances for both molecules and to compute the vibrational frequencies.

In the FN-DMC algorithm we sample a distribution of configurations in $3N$ dimensional space that represents $\Psi_0\Psi_T$, where $\Psi_0$ is the ground state wave function having the same nodal surfaces
of the trial wave function $\Psi_T$. Using this distribution we obtain a MC estimate of the fixed node energy $E_0$ using the mixed estimator

$$E_0 = \frac{1}{N} \sum_{i=1}^{N} E_{\text{loc}}(\mathbf{R}_i) = \frac{1}{N} \sum_{i=1}^{N} \frac{H\Psi_T(\mathbf{R}_i)}{\Psi_T(\mathbf{R}_i)}$$

(1)

In our calculations the trial wave function $\Psi_T$ is

$$\Psi_T = \det |\phi_\alpha| \det |\phi_\beta| e^{U(\mathbf{r}_{\mu\nu})} \Omega(\mathbf{r}_p, \mathbf{r}_{p\nu})$$

(2)

$\phi_{\alpha,\beta}$ are orbitals and $e^{U(\mathbf{r}_{\mu\nu})}$ is the electronic correlation factor used by Schmidt and Moskowitz in their works on atoms and ions \cite{23, 24}. In Eq. \ref{eq:2}

$$\Omega(\mathbf{r}_p, \mathbf{r}_{p\nu}) = \sum_{i=1}^{N_{\text{terms}}} c_i \Phi_i(\mathbf{r}_p, \mathbf{r}_{p\nu})$$

(3)

where \cite{25, 26}

$$\Phi_i(\mathbf{r}_p, \mathbf{r}_{p\nu}) = f_i(\mathbf{r}_p) \exp \left[ k_{i,1} \sum_{\nu=1}^{N_{\nu}} r_{\nu} - \sum_{n=1}^{N_{\text{nuc}}} k_{i,n+1} r_{p,n} \right]$$

(4)

In this equation $f_i(\mathbf{r}_a)$ is a function that contains explicitly the dependence on the spatial coordinates of the positron and $k_i$ is a vector of parameters for the $i$-th term of the linear expansion.

While the $\phi_{\alpha,\beta}$ orbitals were obtained by means of standard SCF calculations on the parent neutral molecule, the other parameters of $\Psi_T$ were optimized minimizing the variance of the local energy using a fixed sample of configurations. Although this method produces wave functions whose properties are generally less accurate than those obtained by minimizing the energy \cite{27}, it is much faster. Moreover, the FN-DMC energy value depends only on the location of the nodal surfaces of the electronic part of the wave function, so that it is not extremely important to have the best possible description of its positronic part. Nevertheless, if one is interested in properties different from the energy, whose accuracy is strongly dependent on the quality of the trial wave function (for example the $\delta(\mathbf{r}_{+\mathbf{r}})$), a re-optimization of all the wave function parameters is needed \cite{14}.

All the FN-DMC simulations were carried out using a target population of 5000 configurations and a time step of 0.001 hartree$^{-1}$. Few more simulations employing a time step of 0.0005 hartree$^{-1}$ were run to check for the absence of the time step bias in the mean energy values. The FN-DMC energy results for various internuclear distances of $e^+\text{LiF}$ and $e^+\text{BeO}$ are shown in Table 1.

We fitted these energy values by means of a second order polynomial and computed equilibrium geometrical parameters and the fundamental vibrational wavenumber $\omega_e$ for the two complexes $e^+\text{Li}^{19}\text{F}$ and $e^+\text{Be}^{16}\text{O}$. All the results are collected in Table 2.

Comparing the results in Table 2 with the experimental values \cite{28} for $^7\text{Li}^{19}\text{F}$ ($R_e = 2.955$ bohr, $\omega_e = 910.34$ cm$^{-1}$) and $^9\text{Be}^{16}\text{O}$ ($R_e = 2.515$ bohr, $\omega_e = 1487.32$ cm$^{-1}$), we note that after the addition of the positron both molecules have larger equilibrium distances and vibrational frequencies. While the increase of $R_e$ is similar to the one we found for $e^+\text{LiH}$ \cite{21} and can be rationalized invoking the repulsive interaction of the positron with the nuclei, the increase of stiffness of the two bonds is an unexpected result. However, it must be pointed out that the computed frequencies have an estimated statistical accuracy of the order of 10%, and this means that care must be taken in discussing the change of this property.

In a previous work \cite{12} we computed the total energies for LiF (-107.4069(9) hartree) and BeO (-89.7854(13) hartree) at their equilibrium distances by means of FN-DMC. Together with the $E_{\text{min}}$ values shown in Table 3, these energies allow us to compute the adiabatic positron affinity (APA) for these two systems, namely 0.022(1) hartree for $e^+\text{LiF}$, and 0.025(2) hartree for $e^+\text{BeO}$. These two values are smaller than the APA for the $e^+\text{LiH}$ (0.0366(1) hartree). This result was already
observed for the vertical PA \[12\], and is in contrast with the fact that the dipole moment of LiF ($\mu = 6.33$ Debye) and BeO ($\mu = 6.26$ Debye) are larger than the one of LiH ($\mu = 5.88$ Debye) \[29\]. This indicates that the dipole moment is not sufficient to predict a qualitative trend in the PA, and that this value strongly depends on the specific features of each molecule.

As far as the dissociation of these complexes is concerned, care must be taken in choosing balanced values for the energies of the fragments for the possible dissociation channels. For a positron-diatomic molecule complex e$^+$MX, where M = Li or Be and X = O or F, the possible fragmentations are e$^+$M + X, M$^+$ + PsX, M + e$^+$X, and PsM + X$^+$. Although not all the energy values of the fragments are known, one can safely assume that the PsM + X$^+$ dissociation pattern has the highest energy with respect to the other possibilities. This is due firstly to the large ionization potential of X (0.5005 hartree for O, and 0.6403 hartree for F) \[30\], at least twice as large as the positronium (Ps) ground state energy (-0.25 hartree); secondly, to the usually small binding energy of Ps to metal atoms (for instance, the binding energy of Ps to Li in the PsLi complex is just 0.01158 hartree \[8\]). Moreover, we believe it is reasonable to discard also the M + e$^+$X channel, since the possibility of obtaining binding between e$^+$ and X is hindered by the small polarizability of X. To support this conclusion, we stress that even for HF and H$_2$O, that are both polar molecules, DMC did not show binding with the positron \[12\]. Although this is not a proof, it strongly suggests that e$^+$O and e$^+$F probably are not bound. Accepting these possibilities, we are left only with e$^+$M + X and M$^+$ + PsX as possible fragmentations. To compute the total energy for both channels we use the ECG results for e$^+$Li (-7.53233 hartree), e$^+$Be (-14.669042 hartree), Li$^+$ (-7.279913 hartree), and Be (-14.667355 hartree) \[3\], and the FN-DMC results for O (-75.0518(4) hartree), F (-99.7176(3) hartree) \[31\], PsO (-75.3177(5) hartree), and PsF (-100.0719(8) hartree) \[1\]. Moreover, we estimate the Be$^+$ energy (-14.3248 hartree) subtracting the ionization potential (0.3426 hartree) \[30\] to the total energy of Be. Using these results, we end up with an energy of -107.2499(3) hartree for e$^+$Li and F, and an energy of -107.3518(8) hartree for Li$^+$ and PsF. This fragmentation, similar to the one found for e$^+$LiH (i.e. Li$^+$ and PsH), is primarily driven by the small value of the Li ionization potential. Differently, for e$^+$BeO we obtain -89.6642(5) hartree for Be$^+$ and PsO, and -89.7208(4) hartree for e$^+$Be and O, so that the most stable dissociation fragments present a positron-atom bound state. Using the lowest energy dissociation threshold for the two systems one gets a DE of 0.080(1) hartree for e$^+$LiF, and 0.090(2) hartree for e$^+$BeO. Both these values are larger than the APA, and this fact means that the two positron-molecule complexes do not dissociate after positron addition to the parent molecules. This outcome is different from what we found for the addition of e$^+$ to LiH, where the e$^+$LiH complex breaks up due to the excess of the APA with respect to the DE \[21\]. Therefore, it does not appear necessary for LiF and BeO to use a third body, and a simple positron addition will give birth to stable complexes in rotovibrational excited states. As previously stated, the possibility to produce these stable species could give the chance to experimentally detect stable positron complexes. Roughly speaking, a mean lifetime on the order of 10$^{-9}$ seconds is expected for these systems, and this may be large enough to allow a spectroscopical analysis in the reaction chamber by means of Fourier Transform Infrared Spectroscopy if a sufficient concentration of e$^+$MX can be produced, and if the frequency shift after positron attachment is large enough that the vibrational spectrum of the complex does not overlap with the neutral molecule one. Unfortunately the large uncertainty in $\omega_\gamma$ does not allow a quantitative prediction of this frequency shift. Moreover, positrons having kinetic energy larger than the difference DE-APA can open the various fragmentation channels depending on the excess of their relative energies. For instance, the collision between positron and BeO can produce e$^+$Be and O as fragments, so that the annihilation of e$^+$ with the electronic cloud of Be can be directly recorded from the 2 $\gamma$ photons. Moreover, it might be possible to detect the stable state of PsF, a system that, differently from PsCl and PsBr, has not been prepared in solution \[3\].

In conclusion, we have presented accurate APA and DE for e$^+$LiF and e$^+$BeO systems computed by means of FN-DMC. These results allow us to discuss possible mechanisms of formation for positron-molecule complexes by direct attachment of e$^+$ to the molecules, and the possibility to produce e$^+$M and PsX systems. It should be now interesting to compute the $\Gamma_{2\gamma}$ annihilation rate
for these complexes, in order to predict their mean lifetime after e\(^+\) addition. Unfortunately, more technical work on the method appears to be necessary before these calculations can be carried out for these large systems.

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| R   | (E)          |
|-----|-------------|
| e^+LiF | 2.955  -107.4243(8) |
|       | 3.200  -107.4291(8) |
|       | 3.400  -107.4249(10) |
|       | 3.500  -107.4176(8) |
| e^+BeO | 2.30   -89.7975(13)  |
|       | 2.40   -89.8089(15)  |
|       | 2.51   -89.8108(18)  |
|       | 2.75   -89.7998(14)  |

Table 1: Total energy at various internuclear distances. All values are in atomic units.
|                  | $e^{+7}\text{Li}^{19}\text{F}$ | $e^{+9}\text{Be}^{16}\text{O}$ |
|-----------------|-------------------------------|-------------------------------|
| $E_{\text{min}}$ (hartree) | -107.429(1)                  | -89.8108(16)                 |
| $R_e$ (bohr)    | 3.18                         | 2.53                         |
| $\omega_e$ (cm$^{-1}$) | 1073                         | 1537                         |
| $R_0$ (bohr)    | 3.20                         | 2.55                         |

Table 2: Equilibrium properties for $e^{+7}\text{Li}^{19}\text{F}$ and $e^{+9}\text{Be}^{16}\text{O}$