Intermolecular effects on the radiogenic formation of electron-capture phosphorus-centered radicals. A single-crystal ESR study of diastereoisomeric precursors
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Abstract: ESR experiments on X-irradiated single crystals of the 2R,4S,5R and 2S,4S,5R diastereoisomers of 2-chloro-3,4-dimethyl-5-phenyl-1,3,2-oxazaphospholidine 2-sulfide reveal that the yield of radiogenic electron-capture reactions in the solid state strongly depends on intermolecular interactions in the crystal. In the present case a high yield of P-Cl three-electron-bond phosphoranyl radical anions is found in crystals of the 2R,4S,5R isomer, whereas the radical formation can be detected for the 2S,4S,5R isomer. An analysis of nonbonded interactions with neighboring molecules reveals that the geometry relaxation necessary for the radical stabilization is easily accommodated in crystals of the 2R,4S,5R isomer but not in the 2S,4S,5R isomer, explaining the observed difference in electron-capture efficiency. Experiments on radical formation in a MeTHF host matrix give further insight into the importance of the environment on radiogenic radical formation. The possible concurrent effect of the matrix on the electronic configuration and spin density distribution of the resulting phosphoranyl radical is discussed.

The radiogenic formation of phosphorus-centered radicals has been extensively studied over the last decades. The continuing interest in phosphorus-centered radicals originates partly from their possible role in the radiation chemistry of nucleic acids and is partly a consequence of their interesting electronic, structural, and dynamical properties. It has been established that the radical configuration, formed as a result of the electron-addition process, also be decisive for the nature of the observed radiation products.

In particular we reported on the pronounced differences observed in electron capture of 1,2-phenylene phosphoranyl radicals. It was found that other effects, which are not generally taken into account, can strongly depend on the nature of the substituents linked to the phosphorus atom, while the chiral centers on C(4) and C(5) are sufficiently apart. The use of diastereoisomeric matrix by studying radical formation in single crystals of two isomers, (2R,4S,5R) and (2S,4S,5R), has shown, by studying the electron capture of 1,2-phenylene phosphoranyl chloride in the pure compound and in frozen solutions, that the environment of the precursor molecule influences the resulting radical configuration after X-irradiation.

In this paper we examine the influence of the surrounding matrix by studying radical formation in single crystals of two diastereoisomeric compounds, (2R,4S,5R)- and (2S,4S,5R)-2-chloro-3,4-dimethyl-5-phenyl-1,3,2-oxazaphospholidine 2-sulfide (1 and 2).

These two compounds differ by the configuration of the central phosphorus atom, while the chiral centers on C(4) and C(5) are identical. This introduces a difference in the crystal structures, which mimics the effect of a changing matrix. Possible intrinsic different electron-accepting properties are minimized when the chiral centers are sufficiently apart. The use of diastereoisomeric compounds in the study of matrix effects has an important advantage over frozen solutions because, unlike in a randomly oriented glassy matrix, the microenvironment can be accurately accessed via X-ray crystallographic analyses.

It will be shown that 1 and 2 behave very differently toward low-temperature X-irradiation, especially concerning the yield of electron-capture radicals. A detailed analysis of the crystallographic structural data reveals that this difference is a consequence of nonbonded interactions modulating the geometry relaxation that accompanies the stabilization of the initial electron-capture radical product.

Experimental Section

X-irradiation and ESR. Single crystals were mounted on a quartz rod and subsequently sealed in a quartz tube. The quartz tubes containing single crystals, powdered samples, or frozen solutions were X-irradiated in a glass Dewar vessel containing liquid nitrogen (77 K) with unfiltered radiation from a Cu source operating at 40 kV and 20 mA for approximately 6 h. ESR spectra were recorded on a Bruker ER 200D spectrometer, operating with an X-band standard cavity and interfaced with a Bruker Aspect 3000 data system. In a typical run a sweep width of 0.1875 T was sampled with 4K points, resulting in a resolution of 0.045 mT. The single crystals were rotated perpendicular to the magnetic field, in 10° steps, by using a single-axis goniometer. Temperature was controlled with the aid of a Bruker ER 411 variable-temperature unit. Photobleaching experiments were performed using a Philips SF 500 W high-pressure Hg vapor lamp. The beam was focused on the sample in the microwave cavity.

Spectral Analysis. The single-crystal ESR spectra were analyzed by use of a computer program that calculates the spin Hamiltonian parameters from the angular dependence of the resonant fields. For the radicals studied, the spin Hamiltonian consists of Zeeman, hyperfine, and nuclear Zeeman parts of orthorhombic symmetry and nonaxial orientation of g and A. The resonant fields were calculated via an exact diagonalization of the Hamiltonian.

Synthesis. (2R,4S,5R)- and (2S,4S,5R)-2-chloro-3,4-dimethyl-5-phenyl-1,3,2-oxazaphospholidine 2-sulfide (1 and 2) were synthesized according to the method described by Lesiak et al. The pure diastereoisomeric compounds were obtained after chromatography of the crude reaction product on a silica-60 gel column. A mixture of n-hexane and diethyl ether was used as eluent. The compounds 1 (R = 0.20) and 2 (R = 0.15) were obtained as viscous oils. Single crystals were obtained after several recrystallizations from n-hexane at 4 °C.

1: 1H NMR (CDCl3) δ 8.08; 1H NMR (CDCl3) δ 8.08 (3H, d, CCH3), 2.75 (3H, d, NCH3), 1JPhNCH3 = 16.7 Hz, 3.75 (1H, dd, C(4)H, 1JPhNCH3 = 13.1 Hz), 5.60 (1H, d, C(5)H, 1JPhNCH3 = 7.2 Hz), 7.30–7.44 (5H, m, PhH); mp 58 °C. 2: 1H NMR (CDCl3) δ 7.59; 1H NMR (CDCl3) δ 0.88 (3H, d, CCH3), 2.92 (3H, d, NCH3), 1JPhNCH3 = 14.7 Hz, 3.84...
Electron-Capture Phosphorus-Centered Radicals

of the 2R,4S,5R isomer

at 105 K after annealing to 225 K.

(1 H, dd, C(4)H, \( J_{\text{CH}} = 28.9 \text{ Hz} \)), 5.83 (1 H, dd, C(5)H, \( J_{\text{HCH}} = 0.7 \text{ Hz} \)), 7.29–7.48 (5 H, m, PhH); mp 130 °C.

Results

Radical Formation in the Pure Compounds. The ESR spectrum of the 2R,4S,5R isomer (1), recorded at 105 K after X-irradiation at 77 K, is shown in Figure 1a. The spectrum consists of three groups of lines. The low- and high-field absorptions are due to a radical, labeled 1a, exhibiting hyperfine coupling to both a \(^{31}\text{P}\) and \(^{35}\text{Cl}\) or \(^{37}\text{Cl}\) isotope. On the basis of the large \( J_{31\text{P}} \) hyperfine coupling, radical 1a is assigned to an electron-capture phosphoranyl radical. The central absorptions, which also appear in the ESR spectrum (Figure 1a), result from the superimposed spectra of two other radical products, marked 1b and 1c. The individual absorptions of 1b and 1c were readily obtained by selective UV photobleaching and temperature-resolved ESR methods, respectively. First, UV-irradiation of the single crystal, inside the microwave cavity, for 1 min using a high-pressure Hg vapor lamp leads, besides the loss of the lateral signals 1a, to an enhanced resolution of the central hyperfine pattern assigned to 1b as a consequence of the loss of 1c (Figure 1b). Alternatively, in a second experiment, the spectrum of 1c is obtained via slow annealing of the crystal to 225 K, which results in the irreversible loss of both 1a and 1b. Radicals 1b and 1c are assigned to electron loss and aromatic anion centers, respectively.

In sharp contrast to the high yield and corresponding strong ESR absorptions established upon X-irradiation of 1, X-irradiation of a single crystal of the 2S,4S,5R isomer (2) results in a very weak ESR spectrum. The spectrum shown in Figure 2a shows only a single weak central absorption but displays virtually no signals in the lateral regions. Only after X-irradiation of a large powdered sample of 2 can the very weak features of an electron-capture phosphoranyl radical (2) be detected (Figure 2b). The extra couplings discernable on the low- and high-field \(^{31}\text{P}\) manifolds are attributed to \(^{35}\text{Cl}\) and \(^{37}\text{Cl}\) couplings.

It is important to note that the ESR spectra of 1 and 2 shown in Figures 1a and 2a were recorded for single crystals of approximately the same weight and same irradiation time. Hence, Figures 1a and 2a clearly demonstrate the different efficiency of the radiation-induced electron-capture process.

Single-Crystal ESR Analysis. In order to obtain a detailed description of radical 1a, we performed a single-crystal ESR analysis. In this way it is possible to obtain accurate hyperfine coupling tensors that give information on the amount of spin density on the various nuclei. Moreover, since the X-ray crystallographic analysis of 1 has been reported, it is possible to relate the principal directions of the magnetic tensors mutually and to the molecular coordinates.

Compound 1 crystallizes in the orthorhombic space group P2_12_2_ with four molecules in the unit cell at special orientations (x, y, z), (x, y, z), (x, y, z), (x, y, z). X-irradiated single crystals of 1 were rotated in the three perpendicular crystallographic planes with respect to the direction of the magnetic field. The angular variation of the observed ESR transitions is depicted in Figure 3. As a consequence of the internal symmetry of the unit cell and the perpendicular orientation of the magnetic field relative to the rotation axis, the spectra of the four molecules coalesce into two observable sites. For orientations where the magnetic field exactly parallels one of the crystallographic axes, all four sites become magnetically equivalent and the ESR spectrum reduces to a simple eight-line pattern (Figure 1a). The spectra were analyzed by using the following Hamiltonian.\(^{8,9}\)

\[
H = g_S \cdot \text{g} \cdot B - g_B \cdot \text{g} \cdot \text{N} \cdot \text{I}_P \cdot B - g_C \cdot \text{g} \cdot \text{Cl} \cdot \text{I}_C \cdot B + S \cdot \text{A} \cdot \text{I}_P + S \cdot \text{A} \cdot \text{C} \cdot \text{I}_C
\]


(9) In principle there exists an ambiguity in the matching of the curves shown in Figure 3. Therefore it is possible to obtain eight different sets of g and A tensors. The eight sets can easily be separated into two classes of four tensors with mutually equivalent principal values but different direction cosines. Only one of the two sets of four tensors corresponds to the right-handed coordinate system used in the single-crystal ESR analysis. These four remaining tensors correspond to the four differently oriented parent molecules in the unit cell, and hence all ambiguity in the matching of the curves is resolved.
The remaining three orientations are related to Figure 3. The resulting principal values can be derived from the three principal values via the equations* for an exact diagonalization of the Hamiltonian. For the final calculated field values is and the remaining symbols have their usual definition. The were optimized to reproduce the experimental field positions via hampering the analysis in full detail. The magnetic parameters were not always resolved in the spectra, thus satellite resonances were not always resolved in the spectra, (-x, -y, z), and (-x, y, -z).

Table I comprises the tensors of radical la. The isotropic and dipolar components of the hyperfine coupling tensors can be derived from the three principal values via the equations

\[ A_{iso} = \frac{(A_1 + A_2 + A_3)}{3} \]
\[ A_{dip} = \frac{(A_3 - A_{iso})}{2} \]

Table I. Principal Values and Direction Cosines of the A (MHz) and g Tensors of 1a

<table>
<thead>
<tr>
<th></th>
<th>tensor</th>
<th>direction cosines</th>
</tr>
</thead>
<tbody>
<tr>
<td>( ^{31}\text{P} )</td>
<td>( A_1 )</td>
<td>2111</td>
</tr>
<tr>
<td></td>
<td>( A_2 )</td>
<td>2143</td>
</tr>
<tr>
<td></td>
<td>( A_3 )</td>
<td>2575</td>
</tr>
<tr>
<td>( ^{35}\text{Cl} )</td>
<td>( A_1 )</td>
<td>61</td>
</tr>
<tr>
<td></td>
<td>( A_2 )</td>
<td>69</td>
</tr>
<tr>
<td></td>
<td>( A_3 )</td>
<td>157</td>
</tr>
<tr>
<td>( g )</td>
<td>( g_1 )</td>
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<tr>
<td></td>
<td>( g_2 )</td>
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</tr>
<tr>
<td></td>
<td>( g_3 )</td>
<td>2.010</td>
</tr>
</tbody>
</table>

*The direction cosines are listed for one of the four possible sites. The remaining three orientations are related to \((x, y, z)\) by \((-x, -y, z)\), \((-x, -y, z)\), and \((-y, y, z)\).

where \( A_p \) and \( A_C \) describe the \( ^{31}\text{P} \) and \( ^{35}\text{Cl} \) hyperfine interactions and the remaining symbols have their usual definition. The \( ^{35}\text{Cl} \) satellite resonances were not always resolved in the spectra, thus hampering the analysis in full detail. The magnetic parameters were optimized to reproduce the experimental field positions via an exact diagonalization of the Hamiltonian. For the final \( A_p \), \( A_C \), and \( g \) tensors the root mean square error of all observed and calculated field values is 0.25 mT, substantially less than the line width.

Figure 3. Angular variation of the resonant fields in single crystals of the 2R,4S,5R isomer I for radical 1a in the ac, cb, and ba crystallographic planes.

phospholidine moieties of 1 and 2 are enantiomeric and therefore expected to possess identical electron-accepting properties. According to Bartczak et al., the molecular geometry of 1 (2R:4S:5R) resembles rather closely that of its diastereoisomer 2 (2S:4S:5R). Their P-Cl bond lengths are reported to be almost identical (2.047 and 2.049 Å). Furthermore, both P-Cl bonds are in an axial position with respect to the ring defined by the N, P, O, and C(5). The angle of the P-Cl bond with the normal to the plane for 1 (19.1°) is very similar to the corresponding angle for 2 (26.5°). The geometric equivalence of the phospholidine moieties of 1 and 2 leads to the tentative conclusion that the intrinsic molecular properties of 1 and 2 are not likely to cause the pronounced difference in electron-capture yield. We favor an explanation in terms of steric intermolecular interactions, which affect the geometry relaxation accompanying the stabilization of an initially formed P-Cl bond electron adduct. In the present case of molecules 1 and 2, it is expected that the necessary relaxation takes the form of P-Cl bond stretching. We therefore studied the steric molecular interactions that result in the single-crystal matrix upon elongation of the P-Cl bond.

The precursor molecules 1 and 2 in their respective crystal lattice and surrounded by their nearest neighbors are depicted in Figure 4. This figure shows that the steric hindrance encountered upon stretching the P-Cl bond is less for compound 1 than for compound 2. A more quantitative determination of the steric interactions involved in P-Cl bond elongation and distortion was obtained by expanding the crystal lattice, using the reported crystallographic data around a single central molecule. All nearest neighboring molecules (total of 27 cells, 108 molecules) were included and the steric interaction of the chlorine nucleus on a plane perpendicular to the least-squares plane, constituted by N, P, O, and C(5). The angle (2R74S,5R) of the chlorine nucleus with all other nuclei in the crystal.13,14 Figure 6 shows the contour plots of the change in van der Waals energy for 1 and 2 for an elongation from 2.05 to 2.30 Å. The contour lines correspond to orientations for which the shortest steric interaction distance has a constant value. The x and y coordinates in these plots represent the projection of the position of the chlorine nucleus on a plane perpendicular to the original P-Cl bond. Since the shortest steric interaction distance of 1 reaches higher values than its isomer 2, it can be concluded that the space available to 1 is larger than the space available to 2. These plots and similar ones for other stretching distances show that not only the total area embraced by the isosteric curves is larger for 1 than for 2, but also the direction in which the elongation can be accommodated is in favor of 1. For 1 the curves are centered around x = 0 and y = 0, i.e., elongation is possible without the need of a distortion of the tetrahedral geometry. For 2, on the other hand, some distortion is required to reach the region of lesser steric hindrance.

In a second approach we calculated the change in van der Waals energy associated with P-Cl bond length elongation for the chlorine nucleus with all other nuclei in the crystal.15 Figure 6 demonstrates that a change of the Cl-P-S angle (corresponding to the x coordinate in the plot) is a low-energy distortion for 1 but severely hindered in 2. The importance of this distortion appears from previous studies on similar P-Cl σ* phosphoranyl radicals, which have shown that the singly occupied molecular orbital (SOMO) is located in the plane of phosphorus, chlorine, and the doubly bonded substituent, which is the result of some admixture of a trigonal-bipyramidal (TBP) configuration with the unpaired electrons.

<table>
<thead>
<tr>
<th>radical</th>
<th>g_x</th>
<th>g_y</th>
<th>A_{w0} MHz</th>
<th>2A_{dp} MHz</th>
<th>μ_p %</th>
<th>μ_p %</th>
<th>A_{w0} MHz</th>
<th>2A_{dp} MHz</th>
<th>μ_p %</th>
<th>μ_p %</th>
</tr>
</thead>
<tbody>
<tr>
<td>1a</td>
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<td>2.010</td>
<td>2276</td>
<td>299</td>
<td>17.0</td>
<td>40.7</td>
<td>95</td>
<td>62</td>
<td>1.7</td>
<td>17.5</td>
</tr>
<tr>
<td>1d</td>
<td>1.999</td>
<td>2.006</td>
<td>1350</td>
<td>269</td>
<td>10.1</td>
<td>36.6</td>
<td>93</td>
<td>55</td>
<td>1.6</td>
<td>15.7</td>
</tr>
<tr>
<td>2a</td>
<td>1.998</td>
<td>2.014</td>
<td>2336</td>
<td>246</td>
<td>17.5</td>
<td>33.5</td>
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<tr>
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<td>1.999</td>
<td>2.006</td>
<td>1385</td>
<td>247</td>
<td>10.4</td>
<td>33.5</td>
<td>93</td>
<td>55</td>
<td>1.6</td>
<td>15.7</td>
</tr>
</tbody>
</table>

The van der Waals parameters were extracted from the MM3 program: Allinger, N. L.; Yuh, Y. H. QCPE 198. Based on the nonbonded distances in the crystal lattices of 1 and 2 the van der Waals radii of hydrogen and carbon were shortened to 1.20 and 1.85 Å, respectively.
electron in an equatorial position (TBP-e) to the $\sigma^*$ configuration. As a consequence, the geometric and electronic configuration of the phosphoranyl radical is distorted to some extent from an exact $\sigma^*$ toward a TBP-e structure. The single-crystal ESR experiments on 1a demonstrate that the angle of the $^{31}$P-A direction with the original P-Cl bond lies between 12 and 17° (vide supra). Since the $^{31}$P-A direction corresponds to the direction of the phosphorus 3p atomic orbital contributing to the SOMO, the SOMO is distorted by the same amount from the parent P-Cl bond. For $^{35}$Cl, the corresponding angle is even larger (19-33°), but this has a smaller effect because the atomic spin density on chlorine (19.2%) is much less than on phosphorus. The important effect of the distortion of the SOMO from the parent P-Cl bond is in fact 2-fold: first the Cl-P-S angle widens, and second, the electron density in the plane between the two bonds is increased. Both factors require appreciable space in the x direction, which is available in 1 but not in 2. From the analysis presented above it is clear that the P-Cl bond length elongation and distortion is easily accommodated in 1, but inhibited by nonbonded interactions in 2. This explains the observed difference in the yield of electron-capture radicals in the two diastereoisomers.

Radical Formation in a Host Matrix. If the surrounding molecules exert a large effect on the stabilization of phosphoranyl electron-capture radicals, it is to be expected that stabilization can be influenced by changing the microenvironment. This is easily achieved by studying compounds 1 and 2 in a host matrix, e.g., a frozen organic solvent. Equimolar solutions of 1 and 2 in 2-methyltetrahydrofuran (MeTHF) were rapidly frozen to form a glassy sample and subsequently X-irradiated for 6 h at 77 K. Inspection of the resulting spectra at 105 K (Figure 7) reveals that in MeTHF compounds 1 and 2 behave very similarly toward X-irradiation. If we confine to the lateral regions of the spectra, two different radical species can be detected for both 1 and 2. There is no doubt that these are both phosphorus-centered radicals. The outer signals, which are broad transitions without any resolvable hyperfine splitting, correspond to the primary electron-
Capture products of the parent molecules 1a and 2a. The strong features labeled 1d (Figure 7a) and 2b (Figure 7b) are assigned to a thiophosphonyl radical, formed as a result of a dissociation of the P−Cl bond. The hyperfine coupling parameters of 1d and 2b (Table I) are comparable to those of the thiophosphonyl radical \( \Delta A_{153} \text{MHz}, 2 \Delta A_{dd} = 299 \text{MHz} \), formed in single crystals of dipyrrolidinochlorophosphine sulfide after annealing of the primary P−Cl \( \alpha^* \) electron-capture radical product.\(^1\)

This assignment is supported by the increase of the intensity of the signals ascribed to 1d and 2b and the concurrent decay of the electron-capture radicals upon raising the temperature to 115 K. Besides the MeTHF matrix, we also examined radical formation in a frozen solution of diethyl ether. It is found that both 1 and 2 almost exclusively give rise to a dissociative electron-capture reaction, giving the thiophosphonyl species 1d and 2b.

The differences observed between X-irradiation of the pure crystalline compounds and those embedded in a host matrix show unequivocally that the stabilization of radiogenic radical products is controlled by the environment of its precursor.

**Discussion**

The present study demonstrates that the efficiency of the radiogenic formation of electron-capture radical products strongly depends on steric interactions with surrounding molecules. The high yield of phosphoranyl radicals in crystals of 1 is a consequence of the space that is available for the elongation of the P−Cl bond after electron capture. For 2, nonbonded interactions in the crystal matrix prevent the elongation and distortion of the P−Cl bond and hence almost no phosphoranyl radicals are formed. The experiments in a MeTHF and diethyl ether host matrix demonstrate that when both diastereoisomers possess a similar environment, they react in almost the same way.

The strong effect of the matrix on radical stabilization raises the question whether the electronic configuration and especially the spin density distribution are also affected by matrix effects. To address this question we have made a plot (Figure 8) of the isotropic phosphorus hyperfine coupling constant \( A_{iso} \text{MHz} \) vs the sum of the Pauling electronegativities \( \Sigma X_P \) of the four atoms directly linked to phosphorus for a number of P−Cl \( \alpha^* \) phosphoranyl radical configurations known from literature data. (1, 1a; 2, 2a; 3, ref 11; 4, ref 16, 5, ref 4; 6, ref 12; 7, ref 18; 8, ref 19; 9, ref 19; 10, ref 16, 11, ref 17, 12, ref 19).

**Figure 8.** The isotropic \( ^{31}P \) hyperfine coupling constant \( A_{iso} \text{MHz} \) vs the sum of the Pauling electronegativities of the four atoms linked to phosphorus for a number of P−Cl \( \alpha^* \) phosphoranyl radical configurations known from literature data. (1, 1a; 2, 2a; 3, ref 11; 4, ref 16, 5, ref 4; 6, ref 12; 7, ref 18; 8, ref 19; 9, ref 19; 10, ref 16, 11, ref 17, 12, ref 19).

Scheme I
no radical anions will be formed. This probably occurs in the pure 2S,4S,5R compound 2. If, however, the limit lies above \( r_1 \) but below \( r_2 \), an electron-capture radical can be readily formed and will be stable toward dissociation because of the steric interactions encountered at \( r = r_1 \) (radical 1a in the single-crystal matrix). Finally, when there exists no steric hindrance below \( r_2 \), a dissociation can occur provided the intrinsic energy barrier at \( r_2 \) can be reached at the temperature at which the experiment is performed. Since a three-electron P-Cl \( \sigma^* \) bond is expected to be rather weak, the force constant associated with the P-Cl bond vibration is low and the curve of \( M^{-} \) will possess only a shallow minimum. As a consequence it can be expected that all molecular arrangements between \( r_1 \) and \( r_2 \) possess a similar spin density distribution.

In this respect it is important to note that the mode of geometry relaxation, necessary for the stabilization of a particular electron-capture radical, first of all depends on the intrinsic properties of the precursor molecule. In general this relaxation will take the form of bond stretching or bond bending. In special cases, more than one deformation will be possible for stabilization, leading to different radical configurations.20 The actual relaxation process is expected to be an energetically favorable combination of intrinsic stabilization modes and external intermolecular constraints imposed upon the molecule by its environment. This leads to the principle that in general an electron-capture radical product can only be generated when the space offered by the matrix corresponds to a favorable relaxation pathway of a hypothetical isolated molecule. The important result is that the electron-accepting properties of a molecule will only be fully expressed if the matrix easily accommodates the newly formed radical product. Nevertheless, the resulting radical structure corresponds to a low-energy configuration of the isolated molecule.

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