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Zwitterion Radicals and Anion Radicals from Electron Transfer and Solvent Condensation with the Fingerprint Developing Agent Ninhydrin

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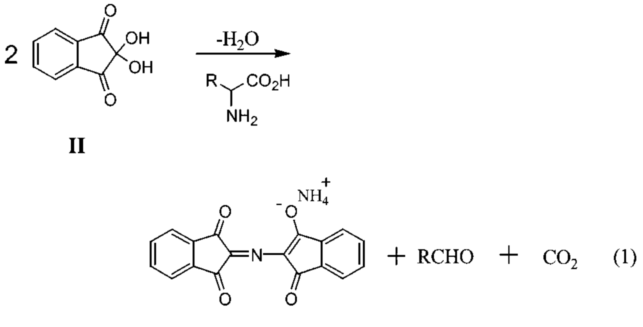
Ninhydrin (the fingerprint developing agent) spontaneously dehydrates in liquid ammonia and in hexamethylphosphoramide (HMPA) to form indantrione, which has a sufficiently large solution electron affinity to extract an electron from the solvent (HMPA) to produce the indantrione anion radical. In liquid NH_3, the presence of trace amounts of amide ion causes the spontaneous formation of an anion radical condensation product, wherein the no. 2 carbon (originally a carbonyl carbon) becomes substituted with $-NH_2$ and $-OH$ groups. In HMPA, the indantrione anion radical spontaneously forms condensation products with the HMPA to produce a variety of zwitterionic radicals, wherein the no. 2 carbon becomes directly attached to a nitrogen of the HMPA. The mechanisms for the formation of the zwitterionic paramagnetic condensation products are analogous to that observed in the reaction of ninhydrin with amino acids to yield Ruhemann's Purple, the contrast product in fingerprint development. The formation of anion and zwitterionic radical condensation products from ninhydrin and nitrogen-containing solvents may represent an example of a host of analogous polyketone−solvent reactions.

Indantrione (**I**) and ninhydrin (**II**) are well-known compounds due to their use in forensics as latent fingerprint developing agents and as bioanalytical reagents.[1−7] The reaction between certain amino acids and ninhydrin results in a brightly colored compound called Ruhemann's Purple (**III** in reaction 1), named after its discoverer, Siegfried Ruhemann.[1]

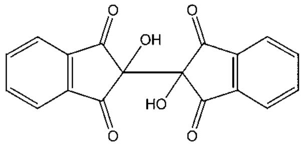


II

III

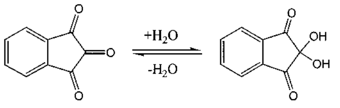
(1)

The formation and chemistry of **III**, also known as diketohydrindylidene−diketohydrindamine, were studied in detail by Ruhemann himself[1−6] and several other researchers[7] and more recently by Jouillié and coworkers.[8] The mechanistic details of the formation of **III** have been debated, but it is agreed that the formation of hydrindantin (**IV**) is an important side reaction, which results from the reaction of ninhydrin with amino acids.



IV

In the presence of water, indantrione exists in equilibrium with **II**, reaction 2, and the initial attack can be thought of as a Schiff base type condensation reaction on the trione or a simple S_N2 reaction that results in the displacement of hydroxide. The condensation with an amine function is critical to the formation of **III**, reaction 1, since the nitrogen certainly has to come from the amine or amino acid. The intermediates proposed in the formation of **III** have been disputed, but certain compounds are prominent in the discussion. The first of these are



I **II**

(2)

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[1] Ruhemann, S. *Trans. Chem. Soc.* **1910**, *97*, 1438.
[2] Ruhemann, S. *Trans. Chem. Soc.* **1910**, *97*, 2025.
[3] Ruhemann, S. *Trans. Chem. Soc.* **1911**, *99*, 1306.
[4] Ruhemann, S. *Trans. Chem. Soc.* **1911**, *99*, 792.
[5] Ruhemann, S. *Trans. Chem. Soc.* **1911**, *97*, 1486.
[6] Ruhemann, S. *Trans. Chem. Soc.* **1910**, *101*, 780.
[7] (a) Harding, V. J.; Warneford, F. H. S. *J. Biol. Chem.* **1916**, *24*, 319. (b) Harding, V. J.; Warneford, F. H. S. *J. Biol. Chem.* **1916**, *24*, 337. (c) Schonberg, A.; Moubasher, R. *Chem. Rev.* **1952**, *50*, 261. (d) Moubasher, R.; Ibrahim, M. J. *Chem. Soc.* **1948**, 702. (e) McCaldin, D. J. *Chem. Rev.* **1960**, *60*, 39. (f) Johnson, A. W.; McCaldin, D. J. *J. Chem. Soc.* **1958**, 817. (g) MacFadyen, D. A.; Fowler, N. *J. Biol. Chem.* **1950**, 186, 13.
[8] Joullié, M. M.; Thompson, T. R. *Tetrahedron* **1991**, *47*, 8791.

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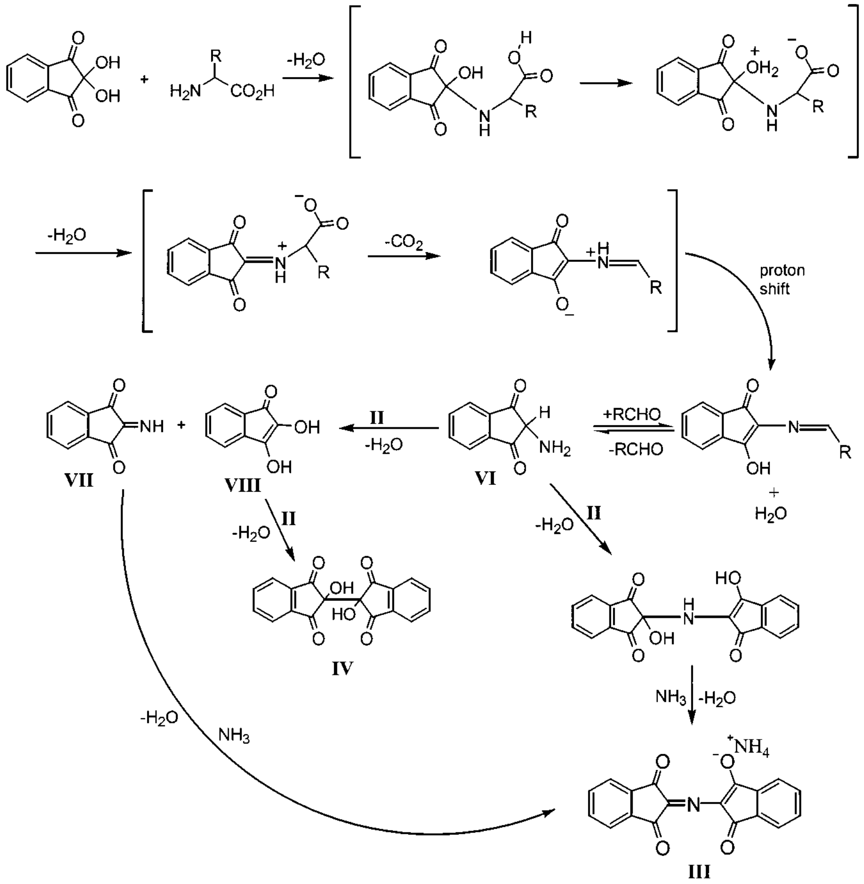
Scheme 1

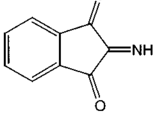


2-amino-1,3-indandione (**VI**), reaction 3, and the oxidized form of **VI**, 2-imino-1,3-indandione (**VII**). The amino

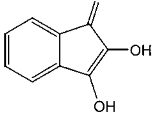
(3)

V **VI**

compound ultimately results from an initial attack at the C2-position of the ninhydrin. The imino compound (**VII**) forms under certain conditions from the oxidation of **VI**. The oxidative formation of the imine is in agreement with the observations of McCormick and Lamothe.[9] Their studies suggested that **V**, which is in dynamic equilibrium with **VI**, is unstable and susceptible to hydrolysis by ninhydrin in solution to yield the imine and the enediol (**VIII**). The imine (**VII**) can then be reacted with ninhydrin to yield the Ruhemann's purple (**III**).



VII



VIII

McCaldin and Johnson, in 1950, proposed a scheme[7f] that was an expansion on the Strecker degradation[10] proposed by Moubasher and Schönberg.[7c] In their scheme, they introduced an amino intermediate (**VI**), which is common to both the formation of Ruhemann's purple and of the hydrindantin (**IV**). The existence of the amino intermediate was further supported by the resulting product ratios caused by an excess of ninhydrin in solution. The introduction of excess ninhydrin would force the reaction conditions to favor the formation of Ruhemann's purple, and indeed, this was found to be true.[7f] They also postulated that **VII** is actually formed from intermediate **VI** (Scheme 1).[7e,f]

MacFadyen and Fowler presented evidence in contrast to the scheme proposed by McCaldin and Johnson.[7g] They suggested that hydrindantin (**IV**) is a critical intermediate in the formation of Ruhemann's purple, since the red color due to **IV** was lost at a rate equal to that for the formation of **III**. This is in contrast to the formation of hydrindantin as a side reaction. The formation of hydrindantin is only a side reaction in Scheme 1. They also proposed that the strong reducing agent, enediol **VIII**, was actually formed from the hydrindantin. The logic for this assumption resulted from the fact that one molecule of product **III** was formed from one molecule of **VII**. This mechanism is not in disagreement with that proposed by Wittmann, which includes reaction 4.[11]

Perhaps the most significant scheme for the formation of Ruhemann's purple is that proposed by Friedman and Williams (Scheme 2).[12] It is regarded in a review by

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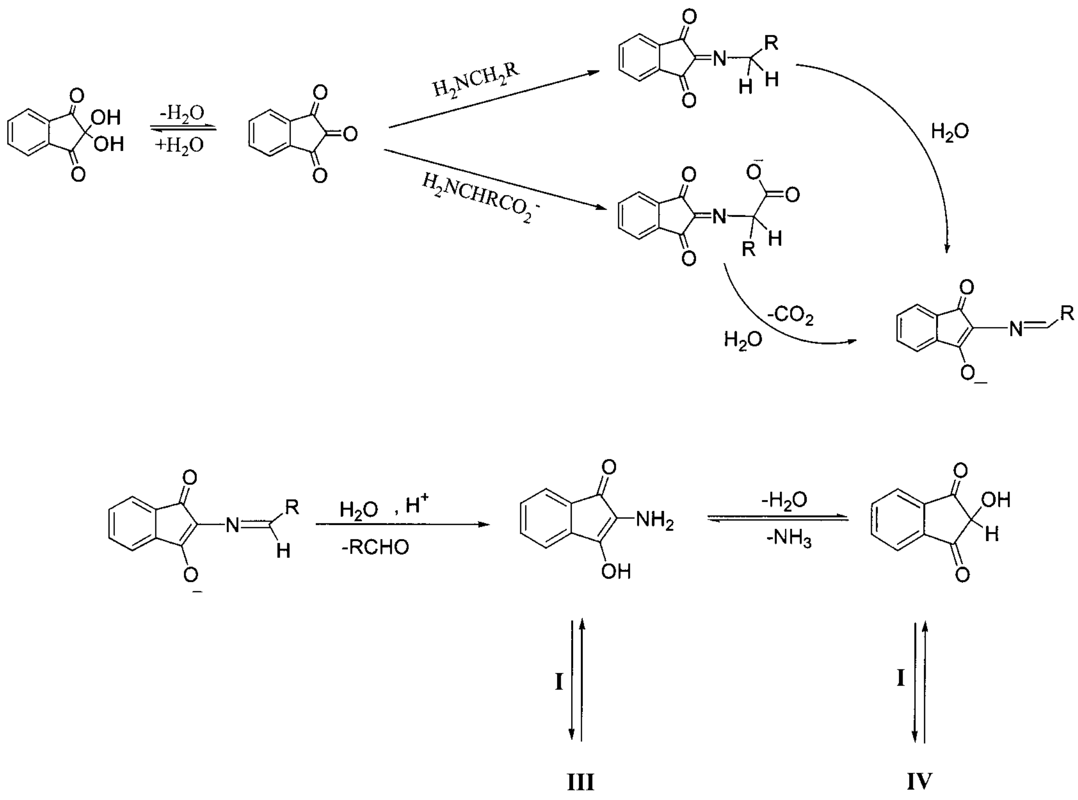
[9] Lamothe, P. J.; McCormick, P. G. *Anal. Chem.* **1973**, *45*, 1906.

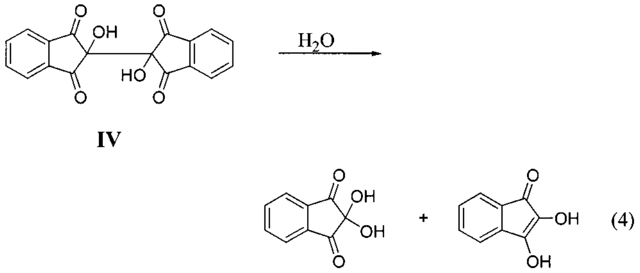
[10] (a) Strecker, *A. Ann.* **1862**, *123*, 363. (b) Schonberg et al. *J. Chem. Soc.* **1948**, 176.

[11] Wittmann, H.; Muller, A. K.; Ziegler, E. *Monatsh. Chem.* **1969**, *100*, 497.

[12] Friedman, M.; Williams, L. D. *Bioorg. Chem.* **1974**, *3*, 267.

Scheme 2





(4)

Bottom[13] as that most consistent with regard to the experimental studies of ninhydrin. They also view the initial attack as nucleophilic, rather than a S_N2 displacement type reaction, to yield a Schiff base.[12] Although the reaction mechanism proposed by Friedman and Williams is similar to those proposed by Lamothe and McCormick[9] and Johnson and McCaldin[7f] (Scheme 1), they omit the reaction between the imine and the enediol. The entire formation of the product is viewed as the reaction between the amine and the indantrione itself.

Lamothe and McCormick's studies of the mechanistic details of the formation of Ruhemann's purple involved careful voltammetric techniques.[9] They observed that the enolic form of the amino compound (**V**), is unstable in a solution with ninhydrin present. Hence, the keto form (**VI**) would be the reactive intermediate in the overall mechanism rather than that postulated by Friedman and Williams[12] and others.

The intense mechanistic studies regarding Ruhemann's purple demonstrate the difficulty in determining what intermediates exist in solutions containing ninhydrin. The general mechanism for the formation of **III** and the important intermediates involved along with their functions have been elucidated, and there is tentative agreement with respect to these issues. Here, we report that the solution electron affinity of indantrione is sufficiently high to cause electron transfer from a common nonaqueous solvent system (hexamethylphosphoramide) to yield the anion radical of **I**. Further, the chemistry involving this anion radical system is as rich as that for the neutral ninhydrin. Specifically, the radical anion of **I** reacts with the solvent systems in a manner that is analogous to the reactions shown in Schemes 1 and 2 yielding a series of unique paramagnetic zwitterionic condensation products. When liquid ammonia serves as the solvent, the radical anion of **I** reacts with the solvent to yield a paramagnetic anionic condensation product.

Results and Discussion

Dissolution of indantrione or ninhydrin in liquid ammonia produces, as expected, a clear diamagnetic solution. Portions of such diamagnetic solutions, under high vacuum, were poured into EPR tube sidearms, which were subsequently sealed with a hand torch. Surprisingly, when the clear solution comes into contact with any of the glass near the seal point a brick red solution results that, upon EPR analysis, yields a strong well-resolved EPR spectrum, Figure 1. This spectrum does not resemble that for the indantrione anion radical, which exhibits splittings from two sets of two equivalent protons.[14,15a] Computer simulation of the new spectrum

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[13] (13) Bottom, C. B.; Hanna, S. S.; Siehr, D. *J. Biochem. Ed.* **1978**, *6*, 4.

[14] (14) (a) For an excellent discussion, see: Russell, G. A. Semidione Radical Anions. In *Radical Ions*; Kaiser, E. T., Kevan, L., Eds.; Interscience Publishers: John Wiley & Sons: New York, 1968. (b) Russell, G. A.; Young, M. C. *J. Am. Chem. Soc.* **1966**, *88*, 2007.

[15] (15) (a) Reiter, R. C.; Stevenson, C. D.; Wang, Z. Y. *J. Phys. Chem.* **1990**, *94*, 5717. (b) Stevenson, C. D.; Alegria, A. E. *J. Phys. Chem.* **1975**, *79*, 361.

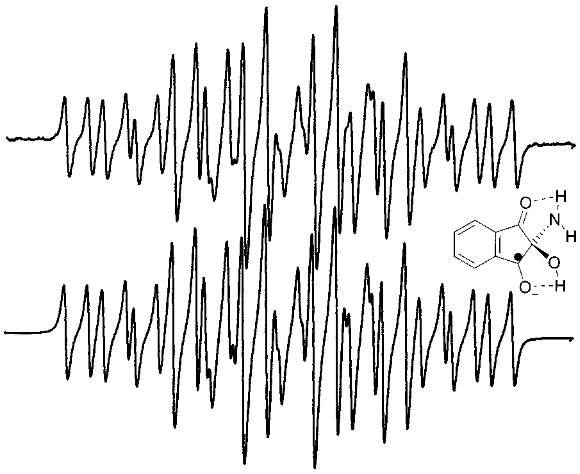


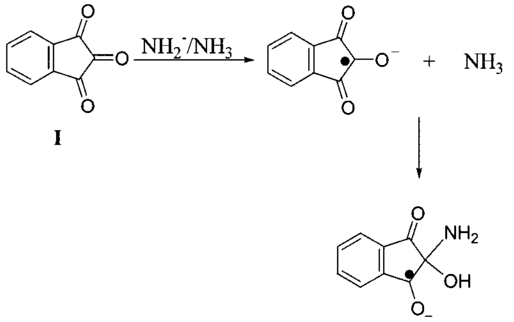
Figure 1. (Upper) 10 G scan of an x-band EPR spectrum of the anion radical formed after a liquid ammonia solution of indantrione comes into contact with glass that had been heated to the softening point. (Lower) computer simulation generated using the coupling constants: ($a_N = 1.215$, $a_{H's} = 1.885$, 0.4043, 0.6658, 2.47 G) and a peak-to-peak line width (Δw_{pp}) of 0.085 G.

(Figure 1) reveals the presence of a nitrogen nucleus and four nonequivalent spin-$^1/_2$ nuclei interacting with the unpaired electron ($a_N = 1.215$, $a_{H's} = 1.885$, 0.4043, 0.6658, 2.47 G). The only nitrogen present is that contained in solvent molecules. Therefore, the solvent (NH_3) must be forming a paramagnetic condensation product with indantrione.

Clearly something is produced on the glass surface (probably NH_2^-) during the sealing procedure that results in the formation of the radical species. Amide is known to form from the interaction of NH_3 with hot glass and other oxide surfaces.[16] The nonequivalency of the hyperfine interactions for any of the four benzenoid ring protons indicates the symmetry of the indantrione molecule has been lost upon the formation of the radical.

This new species could be either a radical ion or a neutral radical. The addition of $KClO_4$ to solutions of this new radical results in modification of the coupling constants. Since a K^+ interaction with the π-system is very unlikely in a polar solvent like liquid ammonia, this is clearly due to ion association with the K^+ ion.[15b] Hence, the paramagnetic product is an anion radical. Further, a radical yielding nearly identical coupling constants can be generated when methylamine is used in lieu of the ammonia, indicating that the protons observed in the EPR experiment are on the ninhydrin and not part of the amine component.

In summary, the results suggest the following: (1) the initial electron-transfer comes from NH_2^-; (2) the radical is a condensation product of indantrione and ammonia; (3) the radical is anionic; (4) the degeneracy of the equivalent ring protons is broken; and (5) the unpaired electron does not interact with the protons attached to the nitrogen. It seems probable that this adduct is structurally similar to the amino intermediates prominent in the formation of Ruhemann's purple. Attack on the central carbonyl carbon of the semi-trione by NH_3 (directed via H-bonding between the oxygen and a hydrogen on the ammonia) coupled with intramolecular proton transfer from the nitrogen to the oxygen would produce the 2-amino-2-hydroxyindandione anion radical, reaction 5.

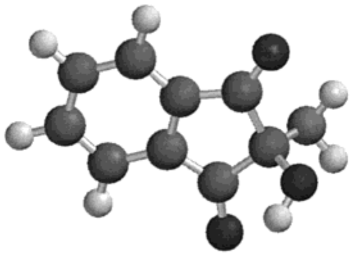


I

(5)

IX

On first thought, this product does not seem to satisfy criterion 4. However, a B3LYP/6-31G* geometry optimization shows that the hydroxyl proton is directed toward one of the carbonyl oxygens, breaking the symmetry of the molecule, structure **IX**. Even though the hydrogen bond between an NH proton and an oxygen on one side of the molecule can rapidly switch to the other side, the EPR time scale is very fast (nanoseconds). On the EPR time scale motions of this type appear frozen.[14] We must also keep in mind that the calculation represents a prediction for a gas phase isolated molecule, and it may not be meaningful to apply it to a system in a protic solvent like NH_3.



IX

Reaction (with ammonia) at C1 or C3 would be inconsistent with all previous indantrione studies.[1-14] While the reaction of a nucleophile with an anion radical is somewhat unusual, Russell and co-workers observed an analogous reaction between indansemitrione and the hydroxide ion.[14]

The spin densities were calculated from a single-point PM3 calculation using the B3LYP-predicted geometry in a manner that is analogous to the B3LYP/6-31G*//AM1 procedure reported by Houk and co-workers.[17] These calculated spin densities do predict four nonequivalent ring protons and negligible splittings from the NH and OH protons, in agreement with experiment.

At first, the existence of an anion radical containing an −OH group seems improbable. However, the indantrione anion radical does persist in the presence of water.[18] Further, Russell and co-workers noted that the reduction

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[16] (a) Peri, J. B. *J. Phys. Chem.* **1965**, *69*, 231. (b) Kim, J. Y.; Sriram, M. A.; McMichael, P. H. Kumta, P. N.; Phillips, B. L.; Subhash H.; Risbud, S. H. *J. Phys. Chem.* **1997**, *101*, 4689.

[17] Houk, K. N.; Gescheidt, G.; Batra, R.; Bernd, G.; Spichty, M. *J. Phys. Chem.* **1996**, *100*, 18371.

[18] Stevenson, C. D.; Alegria, A. E.; Fontanez, F. *J. Phys. Chem.* **1976**, *80*, 1113.

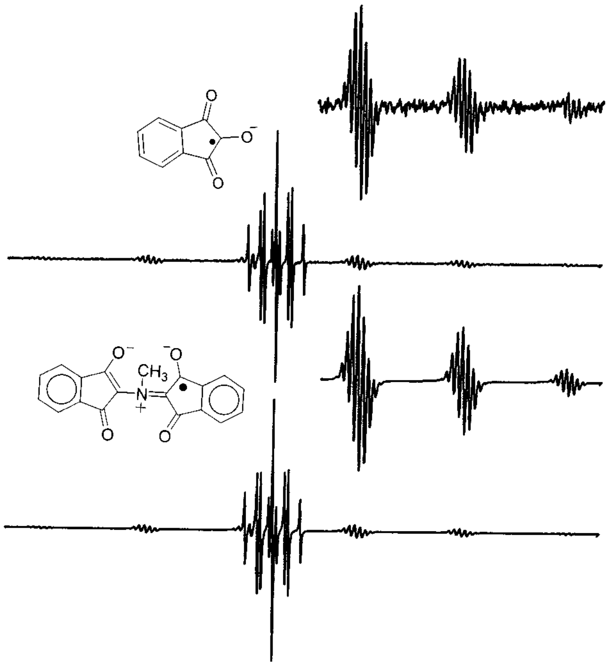
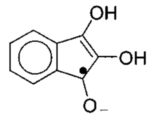


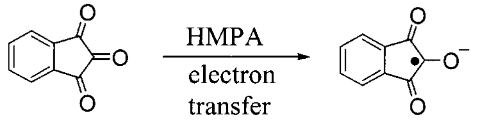
Figure 2. (Upper) full (47 G scan) EPR spectrum of a solution of ninhydrin in HMPA. The large central nine-line feature is due to the indantrione anion radical. The species producing the (superimposed) hextet of nonets is present in the same concentration. (Lower) computer simulation using $a_{\mathrm{H's}}$ of 1.235 G (2Hs) and 0.94 G (2H's) for $\mathbf{I}^{\cdot-}$ ($\Delta w_{\mathrm{pp}} = 0.075$ G) and $a_{\mathrm{H's}}$ of 8.3 G for one nitrogen, 8.3 G for three Hs, and 0.42 G for eight H's ($\Delta w_{\mathrm{pp}} = 0.18$ G). The insets represent expanded views of the last three of the hextet bundles. The hextet of nonets is shifted upfield by 2.4 G and is due to **XI**.

of ninhydrin in a strongly basic solution yields an anion radical that has −OH groups (**X**).[14]



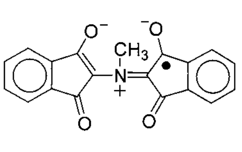
X

The results of the reaction of indansemitrione with the ammonia solvent were sufficiently intriguing (Figure 1) to motivate us to investigate similar reductive reactions in other nitrogen-containing solvents in hope of gaining further insight into the reactivity of the indantrione anion radical. The only other common solvent capable of supporting the solvated electron is HMPA. Dissolution of indantrione in dry HMPA under high vacuum yields a paramagnetic solution. Initially, the EPR active species exhibits the intense nine-line pattern expected for the indantrione anion radical, which demonstrates, unequivocally, that an electron transfer takes place from the HMPA to the indantrione to produce the semitrione, reaction 6.

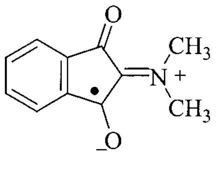


(6)

After a period of 3−4 h, a new radical is clearly observed in the EPR spectrum, Figure 2. The spectrum for the new radical consists of a hextet with a large coupling constant of 8.30 G, which is further split into a nonet with a coupling constant of 0.42 G. A computer simulation of this spectrum reveals that the new radical is present in a concentration equal to that of the indantrione anion radical, Figure 2. The computer simulation shows that the relative intensities of the six nonets do not agree with binomial expansion coefficients. In fact, the intensity pattern clearly shows that this hextet is due to a nitrogen and three protons (presumably a methyl group) sharing the same coupling constant ($a_{\mathrm{N}} = a_{\mathrm{H}} =$ 8.30 G). The nonets proved to be due to eight equivalent protons with a coupling constant of 0.42 G. This value is a little less than half of the small coupling constant displayed in the indantrione anion radical. Since the indantrione anion radical has four ring protons, the eight protons with equivalent a_{H}'s must originate from two indantrione moieties as in structure **XI**. indansemitrione reacts with HMPA to produce radical **XI**. Hence, the spectrum for $\mathbf{I}^{\cdot-}$ is replaced by that of **XI**. Radical **XI** is similar to Ruhemann's purple (**III** in Scheme 1) except that it is an anion radical (best drawn as an intramolecular salt bridge system). The presence of the methyl group on the nitrogen renders it quaternary.



XI



XII

Several hours after the spectrum for **XI** is fully developed, three new radicals exhibit themselves in the EPR spectrum. The spectrum due to **XI** and the unassociated indantrione decays within a day to leave three final radicals. These new radicals yield the spectrum shown in Figure 3; note the large nonet. The EPR patterns for two of these species are very similar. Both paramagnetic compounds exhibit a coupling constant of 9.59 G for a nitrogen nucleus. They both also exhibit splittings from two sets of equivalent protons with coupling constants of $a_{\mathrm{H}} = 0.72$ G (2H's) and $a_{\mathrm{H}} = 0.49$ G (2H's). The two species differ in that for one of them the large nonet results from the six equivalent protons (two methyl groups) and a nitrogen with identical coupling constants of 9.59 G. The other (nearly superimposed) nonet results from three protons (a single methyl group) with a coupling constant of 9.59 G and an $I = {}^{1}/_{2}$ nucleus with a very large coupling constant of 28.77 G. The third species exhibits two sets of two protons and a single nitrogen. This is consistent with the imine radical of **VII**; see Figure 3.[19]

The species exhibiting coupling from the identical pair of methyl groups and the single nitrogen has been previously observed, by Orr, in a reaction mixture of dimethylamine and indantrione, and it is the zwitterionic free radical **XII**.[19] The remaining species obviously has an analogous structure. However, one of the methyl groups is replaced by a spin = ${}^{1}/_{2}$ nucleus. The magnitude of this coupling constant suggests that there is a very large interaction of the unpaired electron with a nucleus with a large gyromagnetic ratio. The only available single

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[19] Orr, J. C. *Nature* **1965**, *205*, 1008.

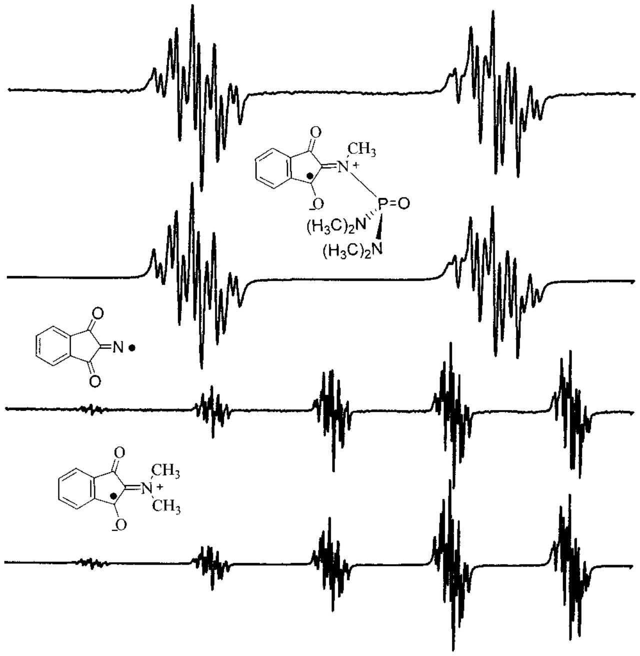
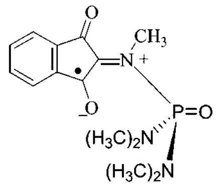


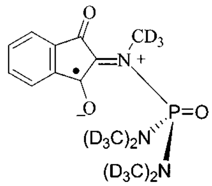
Figure 3. (Lower) 50 G scan encompassing the first five of the nine bundles of the EPR spectrum of the same solution as described in Figure 2, but recorded 48 h later. Just below it is a computer-generated simulation produced by mixing three radicals (**XII**, **XIII**, and an imine radical) in a ratio of 1.1:0.9: 0.6. **XIII** is shifted by 0.2 G upfield of **XI** and has coupling constants of: $a_H = 0.72$ G (2H's), 0.49 (2H's), and 9.59 (3H's); $a_N = 9.59$ G (1N); and $a_P = 28.77$ (1P). **XII** is described by: $a_H = 0.72$ (2H's), 0.49 (2H's), and 9.59 (6H's); and $a_N = 9.59$ (1N). The imine radial is simply a proposed structure, and it is shifted 0.16 G downfield and exhibits splittings of $a_H = 0.72$ G (2H's) and 0.49 G (2Hs); and $a_N = 9.21$ G (1N). The top two spectra are expanded views (20 G scans) of bundles four and five of the real spectrum and the computer simulation just below it.

nucleus with such a large gyromagnetic ratio is the phosphorus in the HMPA.

There is precedence for the hyperfine interaction of the phosphorus nucleus ($a_P = 0.07$ G) from HMPA solvent in the EPR spectra of anion radicals through an ion-induced dipole interaction.[20,21] This could not be the case for our system, due to the extremely large interaction of the phosphorus nucleus with the unpaired electron. Clearly, the phosphorus is covalently bonded to the anion radical. Hence, we propose **XIII** is responsible for this EPR spectrum.



XIII



XIV

To confirm that a solvent fragment had indeed attached in such a manner as to give radical species **XIII**, the experiment was repeated with a mixture of HMPA

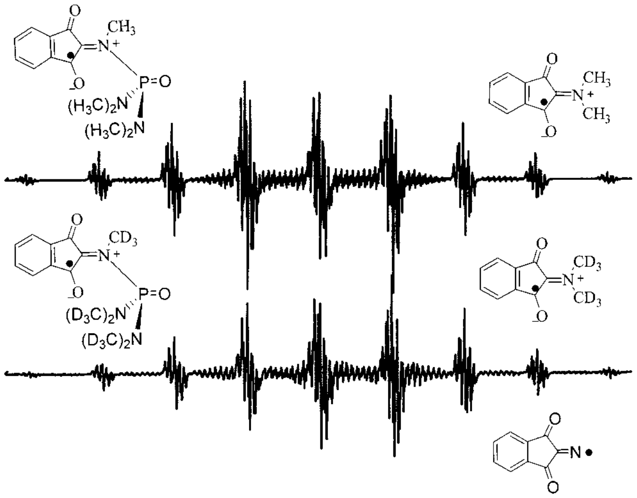


Figure 4. (Upper) full (82.5 G scan) EPR spectrum of a solution of ninhydrin in a mixture of HMPA and HMPA-d_{18} recorded 48 h later. This is the same experiment described in Figure 3, but with perdeuterated HMPA added to the solution. Note the presence of **XIV** and in **XII**-d_3, which exhibit $a_D = 1.473$ G for six and three deuteriums, respectively. (Lower) computer simulation generated exactly as described in Figure 3 but including an approximate 33% contribution from deuterated species. The upfield intensity differences between the real and computer simulated spectra are due to g-tensor anisotropy effects in the zwitterion radicals. This effect proves the presence of a large nitrogen splitting.

and perdeuterated HMPA (ca. 2:1, respectively) serving as the solvent. Indeed, deuterium splittings are equal to the product of the methyl group proton couplings in **XIII** and the ratio of the gyromagnetic ratios (γ_D/γ_H). A computer simulation of the resulting spectrum (Figure 4) reveals a mixture of **XIII** and **XIV**. A B3LYP/6-31+G*// PM3 calculation was carried out on **XIII** in the manner of Houk and co-workers.[17] While the calculated coupling constants do not quantitatively agree with the experiment, they predict that the spin-density on the two dimethylamino functionalities is very small. The calculation also predicts a large coupling constant for the phosphorus, nitrogen, and the methyl group on the nitrogen.

Orr noted that the reaction of ninhydrin with amino acids yields EPR active species under basic conditions.[19,22] The reaction of ninhydrin with glycine or aqueous base yields the EPR spectrum corresponding to the anion radical of ninhydrin.[19] The ability of amino acids to transfer an electron to ninhydrin motivated Orr to react ninhydrin with several amines to yield various paramagnetic products.[19] The reactions of ninhydrin with methylamine, ethylamine, *n*-butylamine, and diethylamine all produce the indantrione anion radical. More notable was the reaction of ninhydrin with dimethylamine.

Upon heating a methanol solution containing equimolar amounts of ninhydrin and dimethylamine, the formation of a different radical species occurs. EPR analysis of this species gave a spectrum with a spectral width of 70 G. His reported EPR spectrum is nearly identical to the spectrum for the dimethylaminoindandione zwitterion radical (**XII**). The most obvious difference is the change in the large coupling constant (8.8 G vs our 9.59

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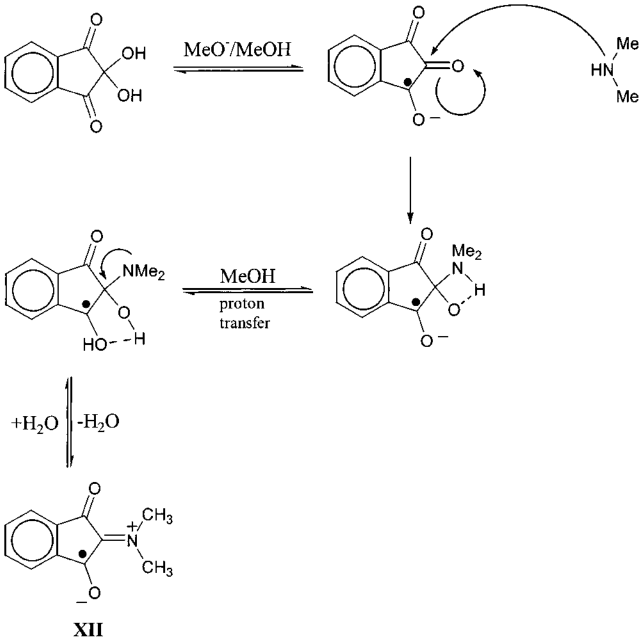
[20] Stasko, A.; Tkác, A.; Malík, L. *J. Magn. Reson.* **1978**, *31*, 161.

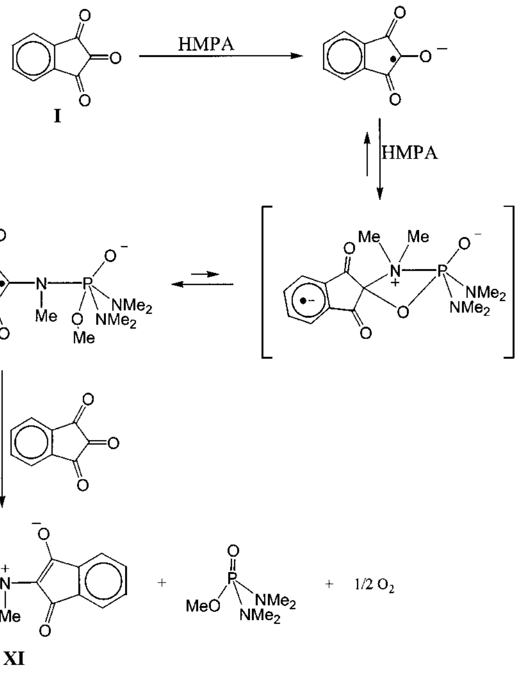
[21] The coupling constant reported by Stasko et al. is 0.07G (0.007 mT). This is 4 orders of magnitude smaller than the coupling constant for the indantrione system ($a_p = 28.77$ G).

[22] The earliest known example appears to be: Lagercrantz, C.; Yhland, M. *Acta Chem. Scand.* **1963**, *17*, 1677.

Scheme 3



Scheme 4

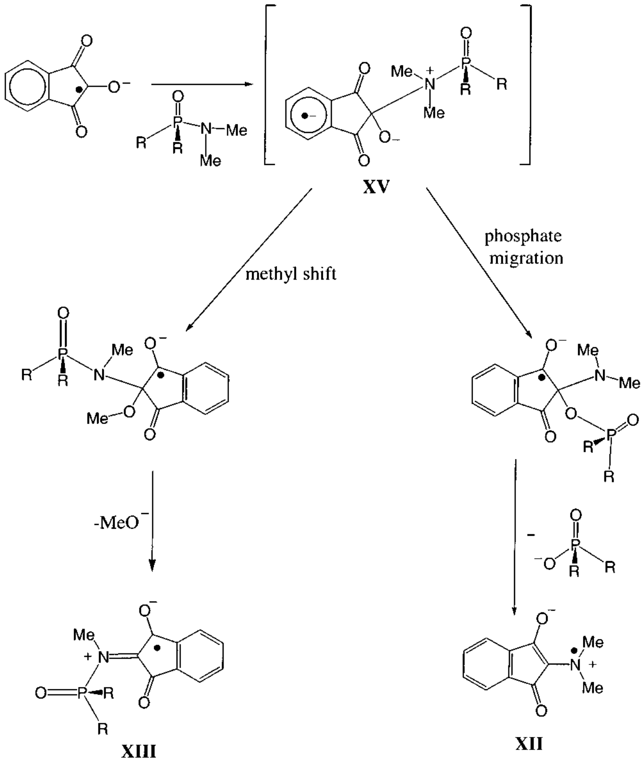


G). This is to be expected, since methanol can form hydrogen bonds, and as noted earlier, H-bonding affects the coupling constants of indantrione systems.[15a] Orr did not propose a mechanism for the formation of **XII**, but Scheme 3 is consistent with his and our data.

The kinetically preferred paramagnetic indantrione-solvent condensation product is **XI**. This material is probably formed via a nucleophilic displacement of the oxygen at the C2-position of the semitrione by a nitrogen atom of the solvent (HMPA). A proposed mechanism is shown in Scheme 4. In the final step, $(NCH_3)_2(OCH_3)PO_2^{\bullet-}$ is proposed to serve as a leaving group, which rearranges to tetramethylphosphoricdiamidemethyl ester and oxygen, to give the observed zwitterionic anion radical **XI**.

The first step in this scheme is analogous to that shown in Scheme 2 (the attack of the C2 carbon by a nitrogen).

Scheme 5



The analogy holds throughout the reaction scheme. **XI** is formed via the attack on the ninhydrin C2 position by the nitrogen on the HMPA–ninhydrin anion radical complex. This is analogous to the attack of the nitrogen in dimethylamine on C2 of the ninhydrin anion radical (see Scheme 3). **XI** does not persist, however, as the EPR signal for **XI** gradually fades and is replaced by that for the thermodynamically preferred zwitterion radical products **XII** and **XIII**. The signal for **XI** is lost due to probable cleavage and electron transfer to form diamagnetic products. Both zwitterion radicals **XII** and **XIII** can be formed in a manner somewhat analogous to that for the formation of Ruhemann's Purple. That is, a nitrogen in the solvent molecule can attack the carbonyl carbon. This leads to the reactive intermediate **XV** (Scheme 5 where R represents a dimethylamino group). There are two possibilities for the breakup of **XV**: (a) a shift of the methyl group from the nitrogen to the negatively charged oxygen to give the methyl ether or (b) a shift of the tetramethylphosphoramide group to give the phosphate ester. These anion radical intermediates subsequently undergo sigma bond cleavage as described by Savéant and co-workers,[23] to yield the thermodynamically stable zwitterion radicals **XII** and **XIII**.

Experimental Section

Zwitterion radical and anion radical solutions were generated by adding ~6 mg of ninhydrin or indantrione to a capillary break seal tube. The break seal tube was sealed with a hand torch and placed into an apparatus that consisted of a test tube fitted with a ground glass joint and a 3 mm sidearm, which served as an EPR sample tube. Either HMPA or ammonia, dried over potassium metal, was distilled under high vacuum directly into the apparatus to give a volume of 2–3 mL. The apparatus was subsequently sealed from the vacuum

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[23] Laurence, P.; Robert, M.; Savéant, J. M. *J. Am. Chem. Soc.* **1999**, *121*, 7158.

system with a hand torch. In the case of ammonia, the temperature of the solvent was maintained at dry ice/acetone temperature (−78 °C). Subsequently, the substrate was exposed to the solvent by rupturing the break seal. The resulting solutions were poured into the EPR sample tubes. The EPR sample tube was sealed with a hand torch and maintained at room temperature until EPR analysis. The samples were monitored via EPR over time.

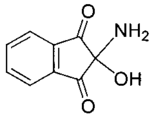
All EPR spectra were recorded on a Bruker EMX 9.5 GHz (X-Band) Spectrometer. Computer simulations of the experimental EPR spectra were carried out using EWSim by Scientific Software Services.[24]

Molecular orbital calculations and molecular modeling were carried out using the Titan program by Schrödinger and Wavefunction.[25]

Conclusions

Zwitterions are replete in the literature and are used in a variety of practical applications, such as the production of drugs, enzyme inhibitors, and synthetic starting materials.[26] There is also a host of literature concerning the radical ions.[14a] However, zwitterion radicals are rare. The fingerprint developing agent (ninhydrin) spontaneously dehydrates in HMPA, and the resulting indantrione undergoes electron transfer from the solvent to produce the indantrione anion radical. This anion radical cleaves the HMPA and forms zwitterion radical indantrione-HMPA condensation products. The structures of these products and the mechanisms for their formation resemble those involved in the fingerprint development process.

The assertion is made that the ninhydrin semitrione reacts with nucleophiles as opposed to the trione reacting with the nucleophile followed by reduction. This follows from the fact that the semitrione is the first species observed upon mixing the trione and HMPA, and since there is a large excess of HMPA (it being the solvent) there should be no neutral trione in solution when the zwitterionic materials begin to appear. Also, the structures of the condensation products and of the trione would indicate that the trione has a less negative reduction potential; e.g. it is easier to reduce **I** than **XVI** (the unreduced form of **IX** in reaction 5). Further, Russell has previously noted ninhydrin semitrione reactions with nucleophiles.[14]



XVI

The importance of single electron transfer, triggering the breaking of a chemical bond, has recently been pointed out.[27] In contrast, this work describes a single electron transfer from the solvent (HMPA) to indantrione, which triggers the formation of new chemical bonds and consequent zwitterion radical formation. We anticipate the observation of a host of analogous polyone-solvent reaction systems soon.

Acknowledgment. We thank the National Science Foundation (Grant CHE-9617066) for support of this work.

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(24) Morse, P. D.; Reiter, R. C. *EWSim User Manual*; Scientific Software Services: Bloomington, Il., 1990.

(25) TITAN version 1 program from Wavefunction, Inc. and Schrodinger, Inc.

(26) Broadus, K. M.; Kass, S. R. *J. Am. Chem. Soc.* **2000**, *122*, 9014.

(27) Pause, L.; Robert, M.; Savéant, J. *J. Am. Chem. Soc.* **2000**, *122*, 9829.