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PHOTOINDUCED HYDROGEN ISOTOPE EXCHANGE IN ANISOLE AND TOLUENE

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Abstract—Photochemical electrophilic aromatic substitution processes in deuterated and tritiated anisoles and toluenes have been examined. Valence isomerization did not occur in anisole on irradiation. The relative reactivities of the ortho, meta and para positions in toluene are 2 : 1 : 1·4 respectively, differing from those in the ground state. Up to 51% exchange has been observed for o-D-toluene and up to 30% exchange for o-D-anisole after 8 h irradiation. Extensive photodecomposition occurs under all conditions with anisole but is slower with toluene. Comparison of the observed substitution pattern of toluene with excited state electron distributions points to the involvement of the second excited singlet and first excited triplet states in the photochemical hydrogen exchange process.

There has been considerable interest in the study of heterolytic photosubstitution reactions in aromatic systems $ArX \xrightarrow{h\nu} ArY$.[1] Interest in such processes has been generated by the observations that there is a pronounced enhancement of reaction rates; some of the reactions occur almost quantitatively and many thus have synthetic utility[2] and there are alterations or reversals in the positional reactivities in some molecules.

In recent years the special case of photoinduced hydrogen isotope exchange, viz. protodedeuteration (detritiation) or deutero (tritio) deprotonation has been examined by many groups.[3-9] Photoinduced hydrogen isotope exchange in acid media is an ideal way to study photochemical electrophilic aromatic substitution because of the similarity of the substituting and leaving groups and the fact that a judicious choice of the acid medium can inhibit or eliminate competing thermal (dark) reactions. Since the basicities of excited states are much greater than those of the corresponding ground states, protonation of the excited molecule can be achieved in very much weaker acid. The use of specifically deuterated molecules also offers a method of examining the reactivities of different positions within the same molecule.

In the present study, conditions were sought for the photochemical hydrogen isotope exchange of anisole and toluene. Under all conditions extensive photolysis of anisole occurs and this process competes with hydrogen exchange. However, using a gas chromatography/mass spectrometer link-up as little as 8 per cent of the original anisole concentration could be analysed. With toluene, photolysis is of lesser importance. Probably due to varying lamp intensity the reproducibility of the hydrogen exchange experiments is at best about ±7%.

DISCUSSION

The purpose of the present work was to build up a picture of the relative reactivities of the ortho, meta and para positions in anisole and toluene in electronically excited states. Theoretical calculations of the excited state localization energies for electrophilic attack and for excited state charge distributions in simple monosubstituted benzenes indicated that the positional reactivities in the excited state would be different to those in the ground state.[1,9] In support of these calculations experimental results showed that the rate of hydrogen isotope exchange was greater in the excited state[3,4,9] and that positional reactivities were altered in monosubstituted benzenes.[9] The results obtained for monosubstituted benzenes[9] have been criticised[5] and they have recently been corrected[7] while this work was in progress. The relative reactivities of the positions are however quite different from the relative reactivities displayed in the ground state. Photoinduced hydrogen–deuterium exchange has also been observed in α- and β-D-naphthalenes in moderately concentrated sulphuric acid. The reactivity of the β-position excees that of the α by about 15% in marked contrast to the results for thermal hydrogen isotope exchange where the reactivity of the α-isomer is about 10 times that of the β.[8] However, in trifluoroacetic acid and n-hexane, photodedeuteration of α- and β-D-naphthalenes indicated that the α-compound exchanged 3·5 times more rapidly than the β-compound.[9]

Acetic acid was used as medium for the irradiation in this work because neither anisole nor toluene underwent thermal (dark) exchange in this solvent at 25°. The possibility of photochemical valence isomerization was checked for anisole using tritiated materials. About 15 to 20% isomerization of tritium had been shown to occur in o-T-anisole on irradiation in n-hexane.[10]

A different detection method to that used in the previous report[10] was employed and no migration of label could be detected on irradiation of ortho, meta or

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para-T-anisoles in acetic acid. Apart from the difference in media, a possible explanation for this difference in results could be that a medium pressure Hg arc was employed in this work, whereas a high pressure arc was used in the earlier experiment.

The rates of photodetritiation of the three isomeric anisoles were surprisingly almost the same. However, it was found that the rate of loss by photolysis of anisole from the acetic acid system was of the same order as the detritiation rates. It seemed therefore that the rate of loss of tritium was due not to tritium hydrogen exchange (photodetritiation) but to loss of anisole. If hydrogen isotope exchange was also occurring it must lie within the experimental error and could not therefore be detected.

The occurrence of a major photolytic reaction in acetic acid was unexpected and it was not investigated further since the reaction products of this photolysis have recently been identified by Havinga's group.[9] Because of this photolysis reaction deuterated anisoles were used instead of tritiated anisoles. The former compound can be analysed by GC/MS, determining the peaks at 108, 109 and 110. This method allows hydrogen isotope exchange to be observed independently of the competing photolysis reaction. Less than 10 per cent of the original concentration of anisole remained after 8 h irradiation, but after extraction into n-pentane and concentration of the pentane extracts this was sufficient to allow monitoring of the molecular ions. Since hydrogen isotope exchange was not observed the photochemical apparatus was altered so as to allow the solution to receive a greater amount of light. The rate of anisole loss was unchanged, but extensive D–H exchange was observed in the three anisoles, particularly in o-D-anisole. The latter compound gave, on average, 30 per cent exchange. Havinga obtained 25·1 per cent exchange for the same compound.[9] Considering the difficulty experienced in obtaining reproducible results and remembering that in this work irradiation was carried out for 8 h in acetic acid, while Havinga irradiated for a shorter period (6 h) in trifluoroacetic acid and n-hexane, agreement is good.

We had less difficulty in obtaining reproducible results with the deuterated toluenes (Table 1) possible because of the fact that competing photolytic reactions appear to be of lesser importance than with anisole as substrate. The results in Table 1 indicate that the ratio of excited state reactivities is approximately 2 : 1 : 1·4 for the ortho, meta and para positions respectively. This result is in sharp contrast to the relative reactivities of the positions towards thermal (dark) hydrogen isotope exchange in acetic acid—sulphuric acid, when the ratio of the reactivities is essentially 1 : 0 : 1.[11] For anisole Havinga has found that the relative reactivities are 6 : 1 : 2 for the excited state,[9] compared to 1 : 0 : 1 for the ground state dark reactions. Our results for the excited state orientation pattern in toluene complement Havinga's results on anisole, and while there are differences in the relative reactivities for the two compounds the overall picture which emerges is much the same; in particular, there is a dramatic change in the excited state (as compared to the ground state) reactivity of the meta position. The quantum yield for hydrogen isotope exchange in toluene is $\phi = 1{\cdot}3 \times 10^{-2}$ while for anisole, under the same conditions the process is only about half as efficient ($\phi = 6 \times 10^{-3}$).[9] The results presented in this paper are in approximate agreement with this. Thus, the ortho position of toluene underwent about 50 per cent exchange in 8 h and under identical conditions the ortho position of anisole exchanged about 30% hydrogen isotope.

Table 1. Per cent photodedeuteration of toluene in acetic acid at 25°

Toluene	Run A[b]	Run B[b]
o-D-toluene	44[c]	51
m-D-toluene	20	27
p-D-toluene	28	35

[a] None of the deuterated toluenes underwent thermal (dark) exchange in acetic acid at 25° in an 8 h period.

[b] These percentages represent the difference in deuterium content of the standards, prior to and after irradiation.

[c] In another run, Dr Aw Beng Teck, University of Sussex, has obtained a figure of 46 per cent and when nitrogen was *not* bubbled through the solution, but when magnetic stirring was carried out, this figure fell to 41 per cent.

Finally the question of the nature of the excited state(s) has to be considered. The demonstration of quenching of fluorescence by acids suggests that the first excited singlet state is involved in a prototropic equilibrium. Strickler[8] has presented evidence that in naphthalene, fluorescence quenching and excited state exchange proceed via a protonated S_1 state. Also, Kuzmin[4] in naphthalene exchange experiments and Mackor[3] in exchange experiments of the α-protons in 9,10 - dimethylanthracene have obtained support for the involvement of singlets. However, it has not always been possible to demonstrate hydrogen exchange in systems where fluorescence quenching of acids was observed.[5] The electronically excited state for hydrogen exchange in anthracene is thought to be the triplet.[4] The evidence being that since the basicities of the S_1 and T_1 states of anthracene are similar,[12] and the protonation rate constants for these states are also analogous then, the triplet state having the longer lifetime ought to be the one involved in hydrogen exchange. Vesley[6] has considered both triplet and singlet excited states as intermediates in hydrogen/deuterium exchange in p-hydroquinone in aqueous acid, however he favours the former state for p-hydroquinone on the basis of its higher intersystem crossing yield.

Another approach to the identification of the excited state involves the calculation of excited state electron distributions and comparison of these with the experimentally determined substitution patterns. This method has been pioneered by Zimmermann and co-workers,[13] who used LCAO MO methods to calculate excited state electron distributions. Havinga has found that the observed substitution pattern for anisole is not in line with the orientation that would be expected for S_1, S_2, T_1 or T_2 states judging from calculated electron distributions.[7] For toluene the excited state electron distributions have been calculated by Jaffe[14] using Mataga integrals for the singlet calculation and Parasa integrals for the triplets. The electron density differences for excited singlets and triplets from the ground state (S_0) are given in Fig. 1. The substitution pattern revealed by the data in Table 1 is in agreement with the involvement of either an S_2 or a T_1 state in the photochemical exchange. From the S_1 and T_2 state electron distributions one would predict that the para position in toluene would be the most activated to hydrogen exchange and these electron distributions are not therefore in agreement with the observed orientation.

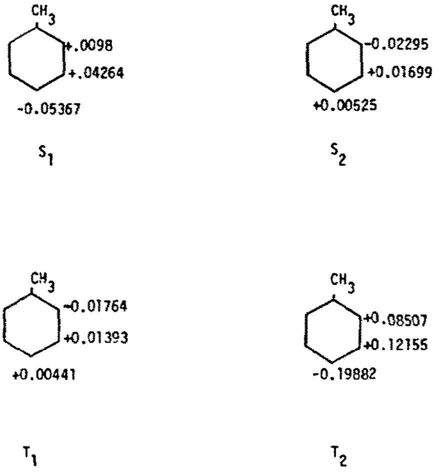

Fig. 1. Electron density differences between singlet excited states and the ground state and between triplet excited states and the ground state.

Triplet sensitization and quenching experiments are indicated in order to ascertain the nature of the excited state. Sensitization experiments were not tried since in view of the high triplet energy of toluene[15] a sensitizer with $E_T > 83$ Kcal/mole would be needed, furthermore it would need to be soluble and stable in acetic acid and have a lower singlet energy than the substrates employed. In one run, nitrogen was omitted and the percentage exchange in o-D-toluene fell slightly to 41%. This experiment does support the possibility of some oxygen quenching of triplets and may indicate a triplet mechanism for excited state hydrogen exchange. It should be noted that in the present experiments rigorous attempts to exclude oxygen and to deoxygenate solutions by degassing were not carried out. Havinga does not appear to have excluded oxygen during anisole or naphthalene photochemical hydrogen exchange experiments.[7] Interestingly, the involvement of triplets in nucleophilic aromatic photosubstitutions is well established,[16] though there are a few cases where a singlet is involved.[17]

EXPERIMENTAL

Tritiated samples were counted on an IDL Tritium Scintillation Counter Type 6012A using a scintillator solution containing 2,5 - di - (5 - tert - butyl - 2 - benzoxazolyl)thiophen (BBOT) in toluene (4 g/l) (BDH Analar). The deuterium content of samples was determined by mass spectrometry and in the case of samples which had been irradiated, the reaction products were injected into a gas chromatograph and the peaks due to the molecular ions were determined in the mass spectrometer.

The isomeric tritiated and deuterated materials were prepared by hydrolysis with tritiated or deuterated water of the appropriate Grignard reagents. The bromo-anisoles and -toluenes were fractionally distilled through Vigreaux columns prior to use in preparation of Grignard reagents. The isomeric purity of the distilled bromocompounds was checked by GLC analysis, typical results being: o-bromoanisole, (contain 2% p-, 0·5% m-, 0·2% unidentified material), m-bromoanisole (contain 2% o-, trace of p-) and p-bromoanisole (contain 5% o-, 2% m-).

Trifluoroacetic acid (Koch-Light) (500 ml) was fractionally distilled first from silver oxide (5 g) and then from concentrated sulphuric acid (50 ml). The purity of the acid was then checked by measuring the rate of detritiation of {10-T-} phenanthrene at 70° dissolved in it. Acetic acid (BDH Analar), n-pentane (BDH) and n-decane (BDH) were used as obtained.

Photochemical apparatus

In an affort to ensure that the intensity of the light emitted by the submersible Hanovia 100 watt medium pressure Hg arc, which was used in this study, remained constant, a mains voltage stabilizer, a variable slide transformer and a voltmeter and ammeter were incorporated in the electrical circuit.[18] After an initial warm-up period of 5 to 10 min the voltage across the arc was adjusted to 130–140 volts and the current set at exactly 0·5 amp. Any current variation during experiments was corrected using the control on the variable transformer.

Photochemical experiments were carried out in two types of reaction flask. One consisted of a cylindrically shaped quartz reaction flask (diam 15 mm, length 70 mm fitted with a B10 ground glass stopper and an inlet through which nitrogen was passed. This flask was strapped to the side of the lamp and aligned with the arc in such a way as to allow as much light as possible to pass into the solution. The flask and lamp were immersed in a constant temperature water bath at 25°, containing a cooling coil through which tap water was circulated. A submersible magnetic stirrer was used to agitate the solution.

In an alternative apparatus a Pyrex cylindrical reaction flask into which the lamp fitted was used. With the lamp in position this apparatus had a capacity of about 130 ml. The greater volume of solution used allowed the substrate concentration to be reduced. Nitrogen gas was bubbled up through the solution. The assembly was submerged in a bath at 25°; the nitrogen bubbling through the solution agitated it sufficiently to minimise any localized irradiation or heating effects due to inadequate circulation.

Preliminary studies

Initial runs showed that both o- and p-T-anisoles had appreciable rates of thermal detritiation in trifluoroacetic acid at 25°. Further when anisole ($3{\cdot}7 \times 10^{-3}$ M) in trifluoroacetic acid was irradiated in the apparatus described first in the preceding section the solution darkened considerably; even after one hour and it was clear that extensive photolysis occurred. These facts led to the exploration of the use of the weaker acid, acetic acid, as medium. Neither o- nor p-T-anisole undergoes detritiation in this medium at 25° over a 21 h period. The method for following the rates of detritiation has been described.[19] In general, aliquots of the reaction mixture were neutralized with base and the substrate was then extracted with toluene containing the scintillator.

Experiments to detect photochemical valence isomerization

o-, m- and p-T-Anisoles were irradiated separately in acetic acid for 4 h. The x-T-anisole recovered from each experiment was purified by GLC. The anisoles recovered from the irradiation of o- and p-T-anisoles were thermally detritiated in trifluoroacetic acid at 70°. The rates obtained were identical with those given by unirradiated samples of o- and p-T-anisole under similar conditions. Further, no residual activity (above background) could be detected. If any isomerization of tritium had occurred (from o- and p- to the m-positions then a small residual activity would have been expected even after ten half-lives of the thermal detritiations. Control runs using a small amount of m-T-anisole added to the o- or p- isomer established that this was a reliable method for detecting isomerization to the m-position.

In the case of the x-T-anisole recovered from the irradiation of m-T-anisole, thermal detritiation at 70° in trifluoroacetic acid, containing 0·1 M lithium bromide, gave a rate constant of $11\cdot37\times10^{-6}\,S^{-1}$, in good agreement with the rate constant obtained for the detritiation of a non-irradiated sample of m-T-anisole ($11\cdot85\times10^{-6}\,S^{-1}$). Also, no thermal detritiation occurred if the recovered x-T-anisole was kept at 70° in pure trifluoroacetic acid for a half-life period of o-/p-T-anisole exchange.

Apparent rates of photodetritiation

o-T-, m-T- and p-T-Anisole in acetic acid ($3\cdot7\times10^{-3}$ M) were irradiated separately in the first-described apparatus and the "rate of photo detritiation" was followed. These rates were all of the same order being o-, $7\cdot4\times10^{-5}\,S^{-1}$, m- $10\cdot0\times10^{-5}\,S^{-1}$ and p- $9\cdot2\times10^{-5}\,S^{-1}$. Rates were accurate to within ±12%.

Rates of loss of anisole and toluene

The rate of anisole loss was determined as $8\cdot0\pm0\cdot78\times10^{-5}\,S^{-1}$ using either apparatus. This rate was followed by neutralizing aliquots of the reaction mixture, extracting the anisole with n-hexane containing n-decane as internal standard and measuring the ratio of the anisole and n-decane peak heights on the GLC (SE-30, 150°). Rate constants obtained in this way were accurate to within ±10%. There was no loss of toluene in acetic acid after 3 h irradiation and after 5 h, only a 13 per cent loss was detected by GLC (Second-described apparatus), n-Octane was used as an internal standard in the runs with toluene.

Photodedeuteration runs

In these runs a concentration of 6×10^{-3} M, the concentration used by Havinga in his original studies on anisole, of anisole and toluene was used. After irradiation for 8 h in the second-described apparatus the samples were neutralised and extracted with n-pentane, which was then concentrated to a small volume. The pentane extracts were injected into the gas chromatograph and all foreign organic material was removed and the abundances of the peaks 108, 109 and 110 of anisole and the peaks 92, 93 and 94 of toluene were determined in the mass spectrometer. The accuracy of the MS analysis was ±2% provided the concentration of the aromatic compound was sufficient to maintain a constant pressure in the ion source of the mass spectrometer.

Reproducibility of runs was poor with the deuterated anisoles despite taking great care to ensure that the voltage difference across the Hg lamp and the current through the system were the same in each run. Presumably the intensity of the light emitted by the arc varied somewhat from run to run. In successive experiments 27% and 33·5% exchange with o-D-anisole was observed and lesser amounts with the other isomers.

Results with the deuterated toluenes were more consistent and two typical sets are given in Table 1.

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