Optical Studies of Triphenylene Anion

M. R. Arick, J. A. M. van Broekhoven, F. W. Pijpers, and E. de Boer*

Contribution from the Department of Physical Chemistry, University of Nijmegen, Nijmegen, The Netherlands.
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Abstract: The optical absorption spectra have been measured of alkali metal reduced solutions of triphenylene in 2-methyltetrahydrofuran from $-155$ to $+75^\circ$. Several ion pairs have been observed. A linear correlation between frequency of absorption and reciprocal of cation radius has been demonstrated for both solvated and contact ion pairs. The low-temperature spectra show a clear equilibrium between two types of ion pairs at high radical concentrations. Its thermodynamic parameters have been measured for sodium, potassium, and rubidium triphenylene solutions. At low-radical concentration dissociation occurs into free ions. The dissociation enthalpy and entropy have been determined. The high-temperature spectra show a gradual increase in frequency as the temperature is increased. This shift has been interpreted as due to an equilibrium between solvated and contact ion pairs. For potassium, rubidium, and cesium triphenylene solutions the thermodynamic constants characterizing the latter equilibrium have been calculated.

In recent years interest in ion pairing has produced several outstanding studies using electron spin resonance (esr) and optical spectroscopy. In these studies it was demonstrated that both temperature and cation changes introduced large effects on both types of spectra. These effects were rationalized in terms of several types of ion pairs.

In this paper we will discuss the ion pairs derived from triphenylene (Tp). The mononegative ion of Tp is orbitally degenerate in its ground state. Anions with degenerate ground state are of special interest because small changes in their surroundings can cause relatively large perturbation in their energy levels. Both counterions and solvent molecules can cause these changes. van Willigen, van Broekhoven, and de Boer (hereafter referred to as I) studied the various species of Tp anion in solution by means of esr. However, with esr information obtained in certain aspects limited, because one is confined to studying low concentrations of radicals over a limited temperature range. In this paper we would like to show that with optical spectroscopy more detailed information is obtained about the Tp species in solution. The combined results of both studies provide a complete picture of the various ion-pair equilibria.

The optical absorption spectra of Tp anions dissolved in 2-methyltetrahydrofuran (MTHF), with Na, K, and Rb as counterion, pointed to the existence of at least three different species. With Cs as counterion only two species were found and with Li only one. We propose that the concentrations of these species are interrelated by several equilibria and that at least four different species are needed to explain all the effects observed with variations in temperature and concentration. The temperature-dependent changes in the optical spectra were used to calculate the thermodynamic quantities in these equilibria. All equilibria showed a marked dependence on the counterion.

Experimental Section

Commercially available Tp (mp 199°) was recrystallized from cyclohexane and sometimes sublimed before use. The solvent MTHF was stored over Na–K alloy and distilled into the glass apparatus just prior to use. The alkali metals (except Li) were sublimed at least twice to obtain a good mirror. Fresh pieces of Li were washed with ether and used as such. The preparation of alkali metal reduced solutions followed the usual procedures described elsewhere (see I). The entire glass apparatus was rinsed with a solution of Tp anion after which this solution was discarded and a fresh one was made for the optical absorption measurements.

The optical spectra were measured with a Cary 14 spectrophotometer equipped with a variable-temperature dewar. A Cryoson temperature controller monitored the flow of cold nitrogen into the dewar and heated it when necessary. The temperature in the dewar was measured by a copper-constantin thermocouple. The temperature was stable at the lower temperatures (below $-50^\circ$) within $1^\circ$ ($\pm 0.5^\circ$) but at higher temperatures the stability was somewhat less ($\pm 1^\circ$). Partially reduced solutions of Tp were used, to avoid the formation of the dinegative ion.

For spectra where isosbestic points were observed (see Results), the concentrations of the species present were calculated using optical densities measured at the characteristic frequencies of each species (see Table I). The extinction coefficients were calculated based on $A_{100} = 5550$ measured for Tp monoanion in tetrahydrofuran at $25^\circ$. The temperature-dependent change in the extinction coefficients for the range where isosbestic points were observed was no more than $15\%$ and had negligible effect on the calculation of the equilibrium constant $K_i$, because $K_i$ is equal to the ratio of two concentrations, which are calculated from the equally temperature affected extinction coefficients.

Furthermore the occurrence of isosbestic points (see Figures 1 and 2) and the fact that superposition spectra could be simulated perfectly from the spectra of the two components demonstrate the correctness of our approach.

Results

The optical spectra of Tp anion dissolved in MTHF were measured from $-155$ to $+75^\circ$. From the measurements the following observations can be made.

Li Reduced Solutions. No shifts in the spectra were found over the whole temperature range for Tp anion concentrations from $1 \times 10^{-4}$ to $8 \times 10^{-4} M$.

Na Reduced Solutions. Between $-110$ and $-70^\circ$ the spectra changed quite dramatically. The spectrum observed at $-110^\circ$ was replaced at higher temperatures by a similar spectrum shifted to higher frequencies. Several spectra measured between $-120$ and $-70^\circ$ for a $6 \times 10^{-4} M$ Tp anion solution are shown in Figure 1. The presence of several isosbestic points indicates that one species is converting into another. If the concentration of Tp anion is below ca. $5 \times 10^{-4} M$, the same pattern of spectra is observed but at a particul-
Table I. $\gamma_{\text{max}}$ Measured at Various Temperatures for the Three Main Absorption Bands in the Optical Spectra of Triphenylene Monoanion in MTHF with Different Counterions (Frequencies in 1000 cm$^{-1}$)

<table>
<thead>
<tr>
<th>Counter-ion</th>
<th>$T_1$, °C</th>
<th>Band 1</th>
<th>Band 2</th>
<th>Band 3</th>
<th>$T_2$, °C</th>
<th>Band 1</th>
<th>Band 2</th>
<th>Band 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Li</td>
<td>-108</td>
<td>13.12</td>
<td>14.56</td>
<td>18.35</td>
<td>-70</td>
<td>13.66</td>
<td>15.04</td>
<td>19.31</td>
</tr>
<tr>
<td>K</td>
<td>-142</td>
<td>13.14</td>
<td>14.60</td>
<td>18.35</td>
<td>-130</td>
<td>13.44</td>
<td>14.84</td>
<td>18.94</td>
</tr>
<tr>
<td>Rb</td>
<td>-155</td>
<td>(13.25)$^a$</td>
<td>(14.71)$^a$</td>
<td></td>
<td>-130</td>
<td>13.44</td>
<td>14.84</td>
<td>18.94</td>
</tr>
</tbody>
</table>

$^a$ Lowest values measured, probably not indicative for the type 1 spectra.

![Figure 1. Several spectra measured for a $6 \times 10^{-4}$ M NaTp solution at $-130$ (---), $-121$ (---), $-112$ (---), $-102$ (---), $-96$ (---), $-89$ (---), $-81$ (---), $-74$ (---), and $-66$° (---). The three prominent bands starting at the highest wavelength are designated 1, 2, and 3.](image1)

![Figure 2. Several spectra measured for a $5 \times 10^{-4}$ M KTp solution at $-139$ (---), $-133$ (---), $-127$ (---), $-121$ (---), $-112$ (---), and $-103$° (---).](image2)

At low concentrations the shape of the spectrum depends on the total radical concentration.

The latter phenomenon was not observed when the concentration of radical anion was much higher. Between $-70$ and $+30$° the spectra continue to shift to higher frequencies but the change is much slower and neither concentration effect nor isosbestic points were observed. Further, the absorption peaks broaden and the extinction coefficients appear to decrease. Several concentrations of Tp anion were investigated ranging from $2 \times 10^{-4}$ to $1 \times 10^{-3}$ M.

**K Reduced Solutions.** The same pattern outlined for NaTp solutions was found for KTp solutions except that the temperatures at which these effects were observed were lower. Thus, between $-139$ and $-90$° the spectra change drastically, with the spectrum at $-139$° replaced at higher temperatures by a similar one shifted to higher frequencies. Several spectra observed between $-139$ and $-90$° are shown in Figure 2. Various isosbestic points are clearly present. Further, the same concentration effect was observed as for NaTp solutions when the concentration was below ca. $4 \times 10^{-4}$ M. Above $-90$° the spectra continue to shift to higher frequencies, but above $+60$° no further shift was seen. Several concentrations of Tp anion were investigated ranging from $2 \times 10^{-4}$ to $1 \times 10^{-3}$ M.

**Rb Reduced Solutions.** The same pattern occurs for RbTp solutions as was found for solutions of NaTp and KTp, but at still lower temperatures. Between $-155$ and $-130$° the spectrum changes rapidly and isosbestic points are present; above $-130$° the shift in frequency is slow. No concentration effects were observed in the anion concentration range from $1 \times 10^{-4}$ to $5 \times 10^{-4}$ M.

**Cs Reduced Solutions.** Between $-150$ and $+30$° the spectrum slowly shifts to higher frequencies. In contrast to the previously discussed studies of NaTp, KTp, and RbTp solutions, no temperature range was found where rapid changes in the optical spectra occurred.

From the outline of the temperature-dependent changes in the optical spectra of the alkali metal reduced solutions of Tp it is clear that three different types of spectra need to be examined: those spectra observed at the lowest temperatures measured (type 1), the spectra that replace these type 1 spectra upon raising the temperature (type 2), and the spectra observed at the highest temperatures (type 3). The numbering of the three types of spectra is the same as the numbering used for the three different esr spectra observed for NaTp solutions and which have been previously reported in I. The positions of the three prominent absorption maxima of these types of spectra are listed in Table I. When the frequencies of the absorption maxima of type 2 and type 3 spectra are plotted vs. the inverse of the cation radius, linear plots are obtained. In Figure 3 such a plot is given for the second absorption band. As expected, these correlation plots predict frequencies for infinite cation radius which appear to be nearly identical with the frequencies measured for LiTp solutions and for NaTp and KTp solutions at low temperatures (type 1).
Discussion

Type 1 and Type 2 Spectra. As established previously, the formation of "free" ions is favored by small cation radius, low temperatures, and low concentrations. These conditions are probably best fulfilled for Li reduced solutions of Tp where only one species is observed. Since in Na and K reduced solutions of Tp at sufficiently low temperatures spectra are measured which are identical with the spectra found in solutions of LiTp (see Table I, column 1), these too should be ascribed to the "free" ion. Thus the observed spectral changes could be attributed to the following equilibrium

$$\text{Tp}^-/\text{Me}^+ \xleftrightarrow{K_1} \text{Tp}^- + \text{Me}^+$$

where Tp^-/Me^+ is a solvent-separated ion pair and Tp- the free ion. This equilibrium will be concentration dependent. As noted earlier, concentration dependence was observed for NaTp and KTp solutions with concentrations below ca. $5 \times 10^{-4} \text{ M}$ but not at radical concentrations much larger. To explain the concentration independency at high radical concentration, we propose that more than one equilibrium is involved. If the existence of a second solvent-separated ion pair is assumed, denoted by Tp^-/S/Me^+, then the following set of equilibria can be written.

$$\text{Tp}^-/\text{Me}^+ \xleftrightarrow{K_1} \text{Tp}^-/\text{S}/\text{Me}^+ \xleftrightarrow{K_{1m}} \text{Tp}^- + \text{Me}^+$$

Clearly only the dissociation is concentration dependent and can be neglected at high radical concentrations. The measured optical superposition spectra in this concentration range can then be explained by means of equilibrium 1, which can be considered as a solvent isomerization reaction. Calculating the ratio of the ion-pair concentrations from the spectra, we can determine $K_1$ as a function of the temperature. The results of this analysis for NaTp, KTp, and RbTp can be found in Figure 4, where ln $K_1$ has been plotted as the absolute value of the temperature. The thermodynamic values obtained from these plots are summarized in Table II.

Table II. Thermodynamic Parameters for the Equilibria Involving Triphenylene Anion and Its Ion Pairs with Alkali Ions in MTHF

<table>
<thead>
<tr>
<th>Counterion</th>
<th>$\Delta H_i$ kcal mol$^{-1}$</th>
<th>$\Delta S_i$ eu</th>
<th>$\Delta H_u$ kcal mol$^{-1}$</th>
<th>$\Delta S_u$ eu</th>
</tr>
</thead>
<tbody>
<tr>
<td>Na</td>
<td>$-8 \pm 1$</td>
<td>$-19 \pm 4$</td>
<td>$-8.8 \pm 0.5$</td>
<td>$-49 \pm 3$</td>
</tr>
<tr>
<td>K</td>
<td>$-4.8 \pm 1$</td>
<td>$-18 \pm 3$</td>
<td>$-6.1 \pm 0.3$</td>
<td>$-44 \pm 3$</td>
</tr>
<tr>
<td>Rb</td>
<td>$-3.2 \pm 1$</td>
<td>$-13 \pm 3$</td>
<td>$-4.0 \pm 0.5$</td>
<td>$-33 \pm 5$</td>
</tr>
<tr>
<td>Cs</td>
<td>$-3.0 \pm 1$</td>
<td>$-12 \pm 4$</td>
<td>$-3.8 \pm 0.5$</td>
<td>$-30 \pm 5$</td>
</tr>
</tbody>
</table>

* Taken from ref 3 (see text).

Table column 3. Both $\Delta H$ and $\Delta S$ appear to become less negative when the radius of the cations increases. The larger the cation radius, the less entropy and enthalphy are involved in the transformation of the ion pairs.

There is much evidence that the species giving rise to spectrum of type 2 is a solvent-separated ion pair, which we formulated as Tp^-//Me^+. First, in the optical absorption spectra a shift in the absorption maxima to higher frequencey is observed when the temperature is increased. This can be explained by a mutual interaction between the two partners in the ion pair. The existence of an ion pair is substantiated by the observed dependence of the absorption maxima on the cation radius (Figure 3). Second, the esr experiments on NaTp in MTHF show that between $-120$ and $-70^\circ$ superposition spectra are measured of esr spectra 1 and 2 (see I). Figure 5a shows such a spectrum at $-87^\circ$; the computer simulation for which the input data are

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in its esr spectrum an alkali hyperfine splitting. The found evidence for the presence of this species. In our and not to a solvated contact ion pair, which may be the esr spectrum 2 does not contain an alkali hyperfine splitting; therefore, we attributed this spectrum and the asymmetrical shape of the spectrum is due to the difference in \( g \) values. The asymmetrical shape of the spectrum is due to the difference in \( g \) values, which corresponds to 0.16 Oe. The esr spectrum 2 does not contain an alkali hyperfine splitting; therefore, we attributed this spectrum and the optical spectrum of type 2 to a solvent-separated ion pair and not to a solvated contact ion pair, which may be denoted as \( \text{Tp}^-/\text{Me}^+ \). Other investigators have found evidence for the presence of this species. In our case it can be discarded, since such a species should have in its esr spectrum an alkali hyperfine splitting. The same reasoning was followed by Höfelmann, et al., in studying the ion pairs of the negative ion of naphthalene. Esr studies by the authors revealed two different ion pairs, one with a large alkali hyperfine splitting constant denoted as a contact ion pair and one with a small alkali hyperfine splitting constant (decreasing to zero at lower temperatures) denoted by them as a solvent-separated ion pair. The latter ion pair corresponds to our species \( \text{Tp}^-/\text{Me}^+ \), the former to the species \( \text{Tp}^-\cdot\text{Me}^+ \) (vide infra, type 3 spectra).

Figures 1 and 2 illustrated that the species giving rise to spectrum of type 2 is converted upon lowering of the temperature into another species giving rise to spectrum of type 1. We attribute the latter spectrum to a free ion (\( \text{Tp}^- \)) and/or a second solvent-separated ion pair, symbolized by \( \text{Tp}^-/\text{S}/\text{Me}^+ \). With the symbol \( S \) we try to indicate that so many solvent molecules are situated between the anion and the cation that the anion is only weakly perturbed by the cation. The perturbation of the cation must be so small that the optical spectra of species \( \text{Tp}^- \) and \( \text{Tp}^-/\text{S}/\text{Me}^+ \) are indistinguishable in shape. This implies that also the esr spectra of \( \text{Tp}^- \) and \( \text{Tp}^-/\text{S}/\text{Me}^+ \) will be identical (see I, esr spectrum of type 1).

It may be remarked that Höfelmann, et al., also found evidence for the presence of two solvent-separated ion pairs in the system Na–naphthalene–tetraglyme. These two species showed quite different electron-exchange rates with neutral naphthalene. This was attributed to a difference in solvation spheres around the cations. The differences in the physical properties of the two solvent-separated ion pairs proposed by us must also arise from a difference in solvation spheres around the cations. The close similarity between the properties of \( \text{Tp}^- \) and \( \text{Tp}^-/\text{S}/\text{Me}^+ \) suggests that the cation in \( \text{Tp}^-/\text{S}/\text{Me}^+ \) is symmetrically encircled by solvent molecules. The solvation of the species \( \text{Tp}^-/\text{Me}^+ \) is less and probably more on the outside, resulting in a smaller cation–anion distance and to changes in the optical spectrum and in the esr spectrum (proton splitting constants become different; see I, spectra 1 and 2). Hence, the conversion of \( \text{Tp}^-/\text{Me}^+ \) into \( \text{Tp}^-/\text{S}/\text{Me}^+ \) should be exothermic and accompanied by a loss of entropy.

It is now possible to analyze the measurements carried out at low radical concentrations, where the dissociation plays a role. For the analysis we made the reasonable assumption that both \( \text{Tp}^- \) and \( \text{Tp}^-/\text{S}/\text{Me}^+ \) have the same extinction coefficients. This assumption is supported by the coincidence of the spectra for NaTp and KTp solution at low temperatures with that of the LiTp solution. Moreover, changing the concentration of Tp from \( 4 \times 10^{-4} \) to \( 1 \times 10^{-4} \) \( M \) and thus changing the ratio of free ions to solvent-separated ion pair by a factor of more than 2 did not alter the calculated total extinction coefficient for the species giving rise to type 1 spectra.

Using this assumption, all concentrations required to calculate \( K_{\text{diss}} \) can be determined. The concentration of \( \text{Tp}^-/\text{Me}^+ \) is measured directly from the optical densities of its absorption maxima. Using values of \( K_t \) measured at higher concentrations (see Figure 4), the concentration of \( \text{Tp}^-/\text{S}/\text{Me}^+ \) can be deduced. The total concentrations of \( \text{Tp}^-/\text{S}/\text{Me}^+ \) and \( \text{Tp}^- \) can be calculated from the optical densities of the absorption spectra. Then the concentration of free Tp ions can be

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**Figure 5.** (a, upper) Superposition esr spectrum of NaTp in MTHF at \(-87^\circ\). (b, lower) Computer simulation (see text).

**Table III.** Input Data for the Computer Simulation Shown in Figure 5b

<table>
<thead>
<tr>
<th>Spectrum 1</th>
<th>Spectrum 2</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>( \text{Tp}^- ) or ( \text{Tp}^-/\text{S}/\text{Me}^+ )</td>
</tr>
<tr>
<td>Splitting constants</td>
<td>1.10 Oe</td>
</tr>
<tr>
<td>Derivative</td>
<td>1.61 Oe</td>
</tr>
<tr>
<td>Weight</td>
<td>80%</td>
</tr>
<tr>
<td>( g ) value</td>
<td>2.002839 ± 7 ( \times 10^{-4} )</td>
</tr>
</tbody>
</table>
A is almost zero. A zero where the absorption frequency maxima are reached by Hirota and Kreilick. These authors assumed that explaining the experimental results has been introduced with temperature (static model). An alternative way of
Figure 3).

as has been demonstrated before these limiting frequencies depend linearly on the cation radius (see Figure 3).

The gradual shift in the absorption maxima on in­
creasing the temperature can be described in terms of a
static ion pair, which changes its structure gradually into each other (dynamic model). An alternative way of
explaining the experimental results has been introduced
by Hirota and Kreilick. These authors assumed that two distinct ion pairs exist in the solution, intercon­
verting rapidly into each other (dynamic model). Especially when line width alternation effects are observed
on the alkali hyperfine lines in the esr spectra, this dynamic model accounts for the experimental facts

arrived at by substracting [Tp⁻/S/Me⁺] from the total concentration of Tp⁻/S/Me⁺ and Tp⁻.

A plot of ln K₉ vs. the reciprocal of the absolute temperature for KTp is shown in Figure 6. From the
position of the various points it is clear that ∆H₉ is almost zero. A zero ∆H₉ was also found for NaTp
by van Broekhoven. It is interesting to remark that the conductance studies of Chang, Slates, and Szware on NaTp in tetrahydrofuran also indicated a zero enthalpy difference for the ion-pair dissociation at low
temperature. Our measurements seem to confirm this.

If the measured points are linearly correlated by a least-squares fit, it is found that ∆H₉ = — 2 ± 1 kcal mol⁻¹
and ∆S = — 25 ± 5 eu. The small ∆H means that the electronic energy levels of Tp anion are only weakly
perturbed by the counterion in the solvent-separated ion pair; the large ∆S reflects the difference in solvation
spheres around the free ion and its association form.

Type 3 Spectra. As has been stated before, the frequencies of the three absorption maxima of spectra
of type 3 increase slowly as the temperature is raised. Limiting values were obtained for KTp, RbTp, and
CsTp solution but not for a solution of NaTp. For the latter solution the limiting value is expected at a
temperature higher than +60 °, the temperature where the absorption frequency maxima are reached
for the KTp solution. Measurements above +60 °
are hampered by the low boiling point of MTHF.

In Table I the limiting frequency values are listed,
together with the value observed for NaTp at +20 °. As has been demonstrated before these limiting fre­
frequencies depend linearly on the cation radius (see
Figure 3).

The optical spectra of NaTp in diethyl ether and
MTHF are identical. In view of the esr results obtained
in these two solvents one might also endeavour to in­
terpret the reversible changes in the optical absorption
spectra observed at higher temperatures in terms of two
distinct ion pairs. In contrast to the averaged spectra
observed with esr the optical spectra should correspond
to superposition spectra due to the quite different time
scale of the optical technique. Since the difference
between the optical spectra of type 2 and 3 is small (see
Table I), no isosbestic points are observed in the relevant
temperature range but only a shift of the absorption
bands. In the cases where limiting frequency values
were reached, i.e., for solutions of KTp, RbTp, and Cs­
Tp, we have calculated from the positions of the absorp­
tion maxima the ratio of contact to solvent-separated
ion pairs for various temperatures, analogous to the
analysis of the esr spectra of type 3 observed for NaTp
in MTHF. As an example, in Figure 7 a plot of ln K₉ vs. the reciprocal of the absolute temperature is shown for KTp. The thermodynamic constants cal­
culated from these linear plots are listed in Table II.

The values for NaTp included in Table II are taken
from I and are derived from esr spectra of type 3. The
thermodynamic parameters thus determined appear to
be reasonable and are comparable with those obtained
by Hirota and Kreilick for sodium anthracene ion

in a natural way. Line width alternation effects on Na
hyperfine lines have indeed been observed for NaTp in
diethyl ether (see I) but not for NaTp in MTHF. However,
the dynamic model proved to be applicable also to the latter case. It was shown in I that the experi­
mental spectra measured for NaTp in MTHF at

Figure 7. Plots of ln Kₙ vs. the reciprocal of the absolute temperature for KTp.

where Tp⁻-Me⁺ represents a contact ion pair showing
an alkali hyperfine splitting in its esr spectrum. The
observed esr spectra were weighted averages of the esr
spectra of these two ion pairs.

The optical spectra of NaTp in diethyl ether and
MTHF are identical. In view of the esr results obtained
in these two solvents one might also endeavour to in­
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by Hirota and Kreilick for sodium anthracene ion

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(1966).
pairs in MTHF. As was observed for the previously discussed equilibria, both $\Delta H$ and $\Delta S$ become less negative as the cation radius increases. It is also gratifying that the results for NaTp and KTp, arrived at via different techniques, are so similar.

Finally, using the equilibrium constant $K_2 t + 20^\circ$ given in I, we have calculated the limiting frequency maximum for NaTp in MTHF. Figure 3 shows that this calculated frequency maximum satisfies rather well the linear relation of frequency vs. the cation radius, indicating the overall consistency of our treatment.

Conclusion
From examination of the absorption spectra of alkali metal reduced solutions of Tp at various temperatures, we have been able to demonstrate the existence of four different species, the free ion and three ion pairs. Further we have measured the equilibria that connect one with the other. For two species the dependence of both the absorption spectra and the equilibria on the cation radius was clearly shown. From the temperature dependence of the equilibria we have calculated the thermodynamic constants for these processes. The values show that all solvation processes studied are accompanied by both a loss of enthalphy and entropy, the effect being strongest for the smallest cation.

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