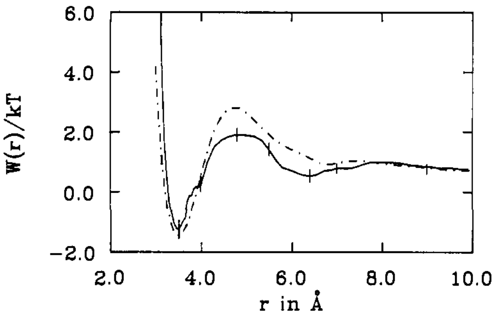

Figure 1. Potential of mean force of Cl^-–Cl^- ion pair in water at 300 K. Solid line is obtained from eq 4; dot-dash line is from ref 1. Error bars were obtained by averaging over the first and last half of the data for each simulation window.

where r is the distance between the two chloride ions, x,y,z are the cartesian coordinates, and x_0 is the center of the window on the x axis. Thus the ions are constrained along the longest axis and near to the center of the box. The force constant k_{yz} is selected to confine the ion to the x axis and k_x and x_0 were chosen so that successive simulation windows overlapped. For a given window, the unbiased estimates of the probability $P(r)$ can be obtained by[4]

$$\langle P(r)\rangle = \langle P(r)e^{\beta U_B(r)}\rangle / \langle e^{\beta U_B(r)}\rangle \qquad (2)$$

A radial distribution function $g(r)$ can be obtained from $P(r)$ as follows

$$g(r) = \frac{\langle P(r)\rangle}{V(r)} \qquad (3)$$

where $V(r) = \pi\Delta r\rho^2$ is the volume of a disk, centered on the x axis, and ρ is the distance from the circumference of a disk to the x axis. The interionic potential of mean force $W(r)$ is then given by

$$W(r) = -kT \ln [g(r)] + C \qquad (4)$$

The entire $W(r)$ from different simulations was combined by a standard matching procedure.[8]

The resultant Cl^-–Cl^- PMF at 300 K was obtained by eq 4 over the range of $3 < r < 10$ Å. A total of 15 windows were used, and each window was sampled for 24 ps following 2 ps of equilibration. In Figure 1 the resulting PMF is shown and compared to the result from previous integral equation studies.[1] By performing sampling at distances large enough to approach the continuum limit we fix the absolute energy of the simulated results (see eq 4). Both estimates of the PMF display a clear minimum in the ion-contact region near 3.5 Å and a very shallow minimum near 6.5 Å.

The computer simulation yields a barrier height to dissociation from the contact well of 3.3 kT, only slightly smaller than the integral equation result of 4.2 kT. The difference is similar to the difference in the hydration energy of −190 kcal/mol computed by integral equations[1] as compared to −143 kcal/mol from MC calculations by J. Chandrasekhar et al.[9]

The umbrella sampling technique in this work has been used to obtain an independent estimate of the PMF of chloride ion pair in water. These results quantify the qualitative free energy surface of like anion pairing predicted by approximate integral equation methods.[1] When like ions approach each other, water molecules form bridging hydrogen bonds with sufficient probability to account for the predicted contact stabilization. Anomalous NMR relaxation rates in dilute alkali–halide aqueous solutions have been interpreted as due to anionic associations,[10] the strongest being in alkali fluoride solutions. In agreement with this integral equations have predicted an even deeper contact stabilization for F^- pairs compared to Cl^- pairs in water.[1] It is clearly of interest to use the same method as described above to obtain the PMF between cations as well, in particular, the sodium ion pair in water. Because there is no highly directional hydrogen bond between water and sodium ions, integral equation techniques have predicted there is no substantial sodium–sodium ion-contact pair minimum in water.

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Double Quantum Based $^6Li,^{13}C$ NMR Correlation Spectroscopy

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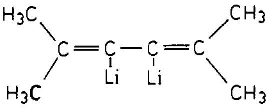
Among the various two-dimensional NMR pulse methods[1] those used for scalar chemical shift correlations are of particular importance for the unequivocal assignment of resonance frequencies. While the existence of a scalar spin–spin coupling is a necessary requirement for these techniques to be applicable, the assignment or even the observation of line splittings in the one-dimensional spectrum is not essential. This feature is of great value in cases where scalar couplings are not resolved due to line-broadening effects[2] or where complex multiplet structures prevent an unequivocal analysis.

With respect to scalar interactions the NMR spectroscopy of lithium–organic compounds profits from the use of the isotope lithium-6 with spin $I = 1$ and a small quadrupolar moment.[3] Line splittings due to ^{13}C, ^6Li spin–spin coupling are thus usually well resolved in the ^{13}C NMR spectra of lithium-6 enriched systems, and their analysis allows the recognition of lithiated carbon atoms in a particular structure.[3] However, two-dimensional scalar $^6Li,^{13}C$ chemical shift correlations become desirable if several lithiated centers exist, leading to a number of ^{13}C multiplets, or in situations where the ^{13}C multiplet structure is not easily deciphered.

We met such a case with 3,4-dilithio-2,5-dimethyl-2,4-hexadiene (**1**), a compound recently synthesized by addition of lithium to tetramethylbutatriene.[4] X-ray results[5] have shown that **1** has a crystal structure which is characterized by a Li_8 cluster with four "inner" and four "outer" lithium atoms surrounded by two "inner" and two "outer" ligands (Figure 1a).



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In a recent NMR investigation[6] a $^6Li,^6Li$ COSY experiment provided evidence that the same structure also exists in THF

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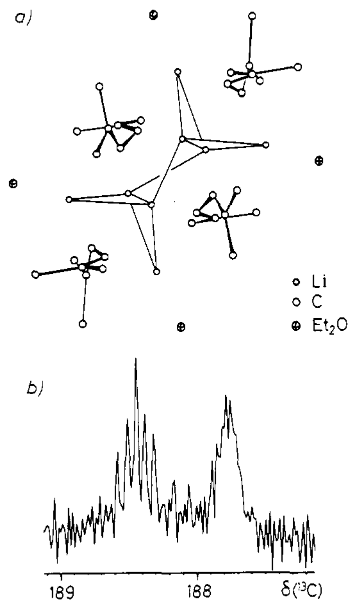


Figure 1. (a) Crystal structure of 3,4-dilithio-2,5-dimethyl-2,4-hexadiene (1)[5] and (b) ^{13}C resonances of the lithiated carbons of **1** (100.16 MHz, −80 °C in THF-d$_8$, referenced to TMS).

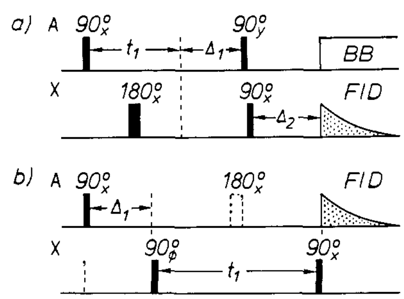


Figure 2. NMR pulse sequences for two-dimensional heteronuclear chemical shift correlations based on magnetization transfer[7] (a) and heteronuclear double quantum coherence[8] (b); $\Delta_1 = 1/2J(\mathrm{A,X})$ for spin $-^1/_2$ nuclei, Δ_2 refocussing delay that depends on the number of X-nuclei. The 180° pulse in sequence (b) is optional. If used, it eliminates the A frequency information from F$_1$.

solution. Accordingly, the ^{13}C NMR spectrum of **1** shows, at −80 °C where exchange is slow, two sets of signals, one for the "inner" and one for the "outer" ligands. In particular, the lithiated carbons yield a quintuplet (J = 6.7 Hz) and a less well-resolved multiplet at 188.45 and 187.77 ppm, respectively (Figure 1b).

For the complete NMR analysis of **1** it was now of interest to correlate the individual ^{13}C signals with ^{1}H as well as ^{6}Li signals and assign them to the inner and outer ligands of structure **1**. It was with this goal in mind that we investigated possible pulse sequences for heteronuclear ^{6}Li,^{13}C shift correlations.

In principle, there are two basic approaches available today to realize such experiments: (1) magnetization transfer[7] and (2) heteronuclear double-quantum spectroscopy[8] (Figure 2). A decision as to which of these alternatives should be applied is dictated in the first place by the experimental setup available. In our case the probehead designed for various pulse experiments on deuteriated compounds[9] proved of value. It can be used for ^{2}H or ^{13}C observation and has ^{1}H decoupling as well as ^{19}F lock facilities. Since the ^{6}Li resonance frequency is close to that of

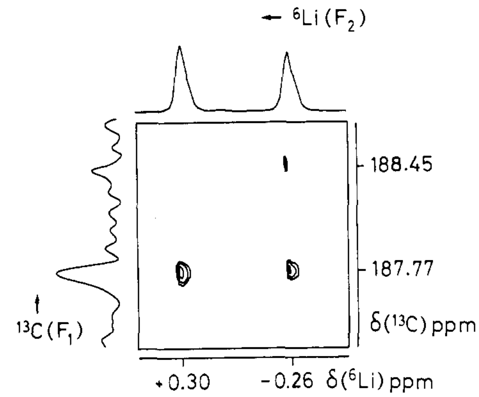
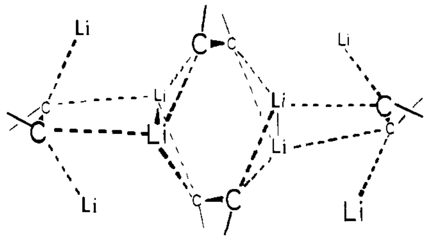


Figure 3. Two-dimensional ^{6}Li,^{13}C shift correlation for **1** (THF-d_8) based on pulse sequence shown in Figure 2b (including the 180° A pulse) with projections of the ^{6}Li and ^{13}C spectrum; δ values refer to TMS (^{13}C, 100.16 MHz) and an external reference of 1 M LiBr in THF-d_8 (^{6}Li, 58.86 MHz); note that the ^{13}C satellites in the ^{6}Li spectrum were detected. Experimental parameters (Bruker WH-400 FT NMR spectrometer equipped with ASPECT 2000 computer) were as follows: 64 t_1 increments of 1.25 ms; sweep widths 300 Hz (F$_2$) and 400 Hz (F$_1$) 96 scans per F$_1$ experiment; relaxation delay 4 s, Δ_1 100 ms, total measuring time 9.3 h. The digital resolution after zero-filling was 1.56 and 1.17 Hz in F$_1$ and F$_2$, respectively; the power spectrum is shown. Window functions were sin^2, t_{90}(^{6}Li) = 77.5 μs, t_{90}(^{13}C) = 55 μs, temperature = 180 K.

deuterium (58.86 vs. 61.40 MHz at 9.4 T), the ^{2}H coil could be tuned to ^{6}Li excitation and detection, while the ^{13}C channel provided the possibility of 90° phase shifts;[10] protons were decoupled as usual, and an external ^{19}F lock was used. As is seen from Figure 2, two alternative experiments are then possible: (1) the conventional shift correlation experiment based on ^{13}C,^{6}Li magnetization transfer (pulse sequence Figure 2a, A = ^{13}C, X = ^{6}Li, $\Delta_1 = 1/4J(\mathrm{A,X})$) and (2) the correlation based on heteronuclear ^{6}Li,^{13}C double quantum coherence (pulse sequence Figure 2b, A = ^{6}Li, X = ^{13}C, Δ_1, $1/2J(\mathrm{A,X})$).

While the first of these alternatives failed to give conclusive results—presumably because of fast transverse ^{13}C relaxation and difficulties in the proper choice of the mixing period due to complex line splittings in the ^{13}C spectrum—the second alternative yielded the two-dimensional spectrum shown in Figure 3. The cross peaks caused by ^1J(^{13}C,^{6}Li) scalar coupling establish the connectivity of the high field ^{6}Li signal with the low field ^{13}C quintuplet as well as that between the low field ^{6}Li signal with the high field ^{13}C signal. More important, however, is the observation of an additional cross peak between the high field ^{6}Li and the high field ^{13}C signal. This explains why the corresponding ^{13}C multiplet is less well resolved (Figure 1b). It contains a further coupling to the second lithium site which leads to line broadening but allows at the same time an unequivocal assignment of the ^{6}Li and ^{13}C resonances. As can be seen from the X-ray structure (Figure 1a), the ligands have virtually orthogonal π-bonds, and only the carbanion carbons of the "outer" ligands can couple to the "inner" as well as to the "outer" lithium sites, while those of the "inner" ligands interact only with the "inner" ^{6}Li nuclei as shown in **2**.



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From the two ^{13}C resonances observed (Figure 1b) that at 187.77

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[10] The synthesizer used for the generation of the ^{6}Li frequency did not allow 90° phase shifts.

ppm must therefore belong to the lithiated carbons of the "outer" ligands, while that at 188.45 corresponds to these carbons in the "inner" ligand. On the other hand, from the two ^{6}Li signals, the high field one belongs to the "inner" and the low field one to the "outer" lithium site. Each C,Li contact is thus formally a three-center two-electron bond.

The new experiment described here further supports our conclusions drawn from the results of the homonuclear ^{6}Li,^{6}Li COSY experiment[6] since it shows independently that the two lithium NMR signals of **1** belong to different lithium sites in the *same* cluster. ^{6}Li,^{13}C shift correlations of the type presented here are thus a valuable addition to the arsenal of NMR techniques used for structure elucidations of lithium–organic compounds in solution.

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Stereocontrol by Energy Transfer: Photoisomerization of α-Arylalkyl Spiro[cyclopropane-1,9′-fluorene]-2-carboxylate

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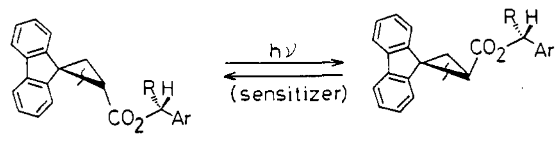
Stereocontrol by selective energy transfer is an attractive subject in photochemistry. Hammond and Cole reported asymmetric induction in the cis-to-trans isomerization of 1,2-diphenylcyclopropane with use of a chiral sensitizer.[1] The reaction was also investigated by Ouannès[2] and more recently by Horner.[3] The origin of the stereodifferentiation must be directly related to the conformational factors in the exciplex or the encounter complex involved in the energy transfer step. However, such factors have been little considered because of conformational freedom of the complex and the poor optical yields obtained (less than 10%). Highly diastereoselective photoreactions controlled by selective energy transfer in models with reasonable conformational flexibility have not yet been reported.

We have recently reported an asymmetric transformation of *N*-(*R*)-(+)-α-arylethyl spiro[cyclopropane-1,9′-fluorene]-2-carboxamide derivatives,[4,5] in which the key step of the diastereodifferentiation is deduced to be in the energy-transfer step. We now wish to report, with clear-cut evidence, highly diastereoselective isomerization controlled by the rate of energy transfer by using intramolecular sensitization of α-phenanthrylalkyl spiro[cyclopropane-1,9′-fluorene]-2-carboxylate (**4Aa–c** ⇄ **4Ba–c**).

As previously reported, the photoracemization of methyl spiro[cyclopropane-1,9′-fluorene]-2-carboxylate (**1**) proceeds via triplet sensitization with high quantum yield (0.88 for acetophenone sensitization).[4] Transformation of diasteromeric esters having an α-arylethyl group, **2A**(**B**) or **3A**(**B**), is also sensitized by various sensitizers. Diastereomeric ratios at the photostationary state are as follows:[6] (**2A**:**2B**, 52:48 for acetophenone; **3A**:**3B**, 81:19 for acetophenone (E_T 73.7 kcal/mol); 82:18 for *p*-methoxyacetophenone (E_T 71.8); 83:17 for triphenylene (E_T 66.5); 92:8 for phenanthrene (E_T 61.9); 93:7 for *p*-phenylacetophenone (E_T 61.1). These can be summarized as follows: (1) Moderate-to-high selectivity for **3A**(**B**) and poor selectivity for **2A**(**B**) are observed. (2) The selectivity becomes higher when the triplet energy of sensitizers becomes lower. These results are best explained by a consecutive energy-transfer mechanism involving an intramolecular process (sensitizer → naphthyl → fluorenyl) (Scheme I).

Scheme I



2A,3A,4Aa~c   2B,3B,4Ba~c

2A(**B**); R = Me, Ar = Ph
3A(**B**); R = Me, Ar = 1-naphthyl
4A(**B**)**a**; R = Me, Ar = 9-phenanthryl
4A(**B**)**b**; R = Et, Ar = 9-phenanthryl
4A(**B**)**c**; R = *i*-Pr, Ar = 9-phenanthryl

Table I. Photoisomerization of **4A**(**B**)**a–c** and the Kinetic Parameters[a]

compd	isomer ratio[b]	quantum yield[c]	$k_1 \times 10^{-4}$ (s^{-1})
4Aa	92:8	0.17 (**4Aa** → **4Ba**)	2.9 ± 0.2
4Ba		0.40 (**4Aa** ← **4Ba**)	77 ± 4
4Ab	94:6	0.094 (**4Ab** → **4Bb**)	1.9 ± 0.1
4Bb		0.40 (**4Ab** ← **4Bb**)	88 ± 5
4Ac	97:3	0.086 (**4Ac** → **4Bc**)	0.92 ± 0.05
4Bc		0.40 (**4Ac** ← **4Bc**)	73 ± 4

[a] At room temperature in benzene under argon atmosphere (>310 nm for flash photolysis, 355 nm for laser photolysis). [b] **4Aa–c**:**4Ba–c** at [**4Aa–c** plus **4Ba–c**] = 1.2 × 10^{-3} M, determined by HPLC. [c] At 334-nm excitation using potassium ferrioxalate actinometer.

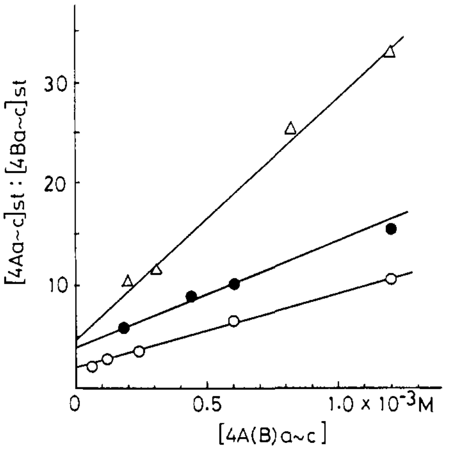


Figure 1. Concentration effect on the photoisomerization of **4Aa–c** ⇄ **4Ba–c** at room temperature in benzene under argon atmosphere [(○) for **4A**(**B**)**a**; (●) for **4A**(**B**)**b**; (△) for **4A**(**B**)**c**].

To demonstrate selective intramolecular energy transfer mechanism, we have investigated the isomerization of **4Aa–c** ⇄ **4Ba–c** in which the substrates have a 9-phenanthryl group on the asymmetric carbon in the ester group. Selective excitation (>310 nm) of the phenanthryl group, without added sensitizer, leads to the photostationary state. Table I shows the diastereoisomer ratios at the photostationary state as well as the quantum yields.[6] The same ratio was obtained whether one starts from pure diastereomer or from the mixture of **4Aa–c** and **4Ba–c**. The observed high diastereoselectivity (84% de for **4A**(**B**)**a**; 88% de for **4A**(**B**)**b**; 94% de for **4A**(**B**)**c**) is in accordance with the fact that the intramolecular sensitization is a key step in the isomerizations.

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(6) Stereochemistries of the diastereomers are determined as depicted in the text; see ref 5.

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