

chromatography (silica gel, CH<sub>2</sub>Cl<sub>2</sub>-THF 85:15) separated pure **15** from its *exo*-hydroxyethyl epimer. Removal of the chiral auxiliary was accomplished using Red-Al in toluene (-60 to -20 °C) followed by heating the crude tricyclic amination **17** with ethanolic Bu<sub>4</sub>NH<sub>2</sub>PO<sub>4</sub> for 20 h. In this manner the bicyclic ketone **18** was isolated, after flash chromatography (ether, silica in 94.7% yield from **15**). Furthermore, treatment of **18** with 8.0 equiv of Et<sub>3</sub>N, 4.0 equiv of acetic anhydride in THF, and heating for 4 days gave (*R*)-(-)-4-methyl-4-(acetoxymethyl)-2-cyclohexanone (**19**), [ $\alpha$ ]<sub>D</sub><sup>25</sup> -28.42°, in 75% yield. The absolute configuration was derived from the X-ray structure of **16**.

The above demonstrates the utility of these bicyclic lactams (**4**, **5**, **10**, **14**) as chiral precursors to various 4-substituted cyclopentenones and cyclohexenones in high enantiomeric purity. Additional aspects of this class of compounds are under investigation and will be reported in the near future.

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**Supplementary Material Available:** Physical data for all compounds, 270-MHz spectra for (+)- and ( $\pm$ )-mesembrine and X-ray structure of **16** (7 pages). Ordering information is given on any current masthead page.

### Time Reversal of the Evolution under Scalar Spin-Spin Interactions in NMR. Application for $\omega_1$ Decoupling in Two-Dimensional NOE Spectroscopy

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It is known that two-dimensional (2D) NMR<sup>1</sup> is accessible to numerous manipulations which can significantly enhance its power for the analysis of complex molecules. In this context, it is frequently desirable to simplify 2D spectra by eliminating the effects of scalar spin-spin couplings during the evolution period in order to achieve homonuclear decoupling in the  $\omega_1$  frequency dimension. The only technique so far available for this purpose, the constant-time experiment proposed by Bax and Freeman,<sup>2,3</sup> suffers from a strong dependence of the signal intensities on relaxation times and *J* coupling constants.

In this paper we introduce a new concept which allows time reversal (TR) of the evolution under scalar spin-spin interactions leading to homonuclear decoupling without the disadvantages of constant-time experiments. The basic principle relies on the different dependencies of the various coherence transfer pathways on the rotation angle  $\beta$  of a TR rotation introduced at a suitable place. The TR element effects a unique selection of those pathways that involve time reversal of the *J* evolution.

The condition for time reversal can easily be formulated in terms of spin multiplet components expressed by product operators. In the case of a three-spin system we encounter for example the operator  $I_1^+ I_2^\alpha I_3^\beta$ , signifying a single-quantum coherence of spin  $I_1$  with the coupling partners  $I_2$  and  $I_3$  in their  $\alpha$  and  $\beta$  states,

respectively. Time reversal of the *J* evolution is achieved if the TR element inverts all passive spins ( $I_2, I_3$ ) while leaving the active spin ( $I_1$ ) unaffected:  $I_1^+ I_2^\alpha I_3^\beta \rightarrow I_1^+ I_2^\beta I_3^\alpha$ . No single nonselective rotation exists that fulfills this requirement. However, the desired effect can be achieved by combining experiments obtained with a pulse of variable rotation angle  $\beta$  selecting the proper dependence on  $\beta$  which is given by  $\cos^2(\beta/2) \sin^4(\beta/2)$  in the above case. The basic principles are closely related to those of the recently introduced E.COSY technique.<sup>4,5</sup>

In the following, we insert the TR element in the middle of the evolution period  $t_1$  of the pulse sequence for 2D NOE spectroscopy (NOESY).<sup>6-9</sup> The single TR pulse with flip angle  $\beta$  and phase  $\phi$  is replaced for experimental convenience by an equivalent pair of 90° pulses, 90°( $\beta + \phi$ )-90°( $\pi + \phi$ ). The entire pulse sequence for the NOESY TR experiment is then

$$90^\circ(\beta + \Psi_1) - \frac{1}{2}t_1 - \{90^\circ(\beta + \phi) - 90^\circ(\pi + \phi)\} - \frac{1}{2}t_1 - 90^\circ(0) - \tau_m - 90^\circ(\Psi_2) - \text{acq}(\Psi_1 + \Psi_2)$$

The phase cycle for  $\beta$  is determined by the maximum number  $N - 1$  of coupling partners of any relevant spin in the sample. The phase  $\beta$  should be cycled in increments of  $\pi/N$ ,  $\beta_j = j\pi/N$  ( $j = 0, 1, \dots, N - 1, N + 1, \dots, 2N - 1$ ) with the following weight factors<sup>10</sup> for the individual experiments:<sup>11</sup>  $W_j = (N/8)(-1)^{j+N} \{\cos(\frac{1}{2}\beta_j)\}^{-2}$ .

The 90°( $\beta + \phi$ )-90°( $\pi + \phi$ ) pulse pair may also be regarded as a multiple quantum filter.<sup>12,13</sup> The described phase cycle is then equivalent to a combination of *p*-quantum-filtered spectra with the weights  $(-1)^p/12(3p^2 - N^2 - 1/2)$  for  $0 \leq p \leq N$ .

The above phase cycle for  $\beta$  selects the coherence transfer pathways<sup>14</sup> with  $\Delta p$  even of which only  $\Delta p = 0$  leads to refocusing of the scalar interactions. It is therefore essential to select  $\Delta p = 0$  by an additional phase cycle of the entire TR element. This is achieved by the three-step cycle  $\phi = 0, 2\pi/3, 4\pi/3$ .

The phases  $\Psi_1$  and  $\Psi_2$  are cycled to suppress axial peaks ( $\Psi_1 = 0, \pi$ ) and single-quantum coherence during  $\tau_m$  ( $\Psi_2 = 0, \pi$ ), respectively. Zero-quantum suppression, a well-known problem in conventional NOESY,<sup>15</sup> is superfluous using NOESY TR due to the refocusing of the *J* interactions. The TPPI method<sup>14,16</sup> can be applied to the first pulse as usual for separating positive and negative frequencies and for obtaining pure 2D absorption line shapes.

Two potential drawbacks of the NOESY TR experiment should be mentioned. (1) In comparison to conventional NOESY, a sensitivity loss of about a factor 2.5 (depending on *N*) has to be taken into account, comparing the intensity of the singlet in the  $\omega_1$  dimension of the NOESY TR spectrum with the intensity of a non-degenerate multiplet component in the corresponding conventional NOESY spectrum. (2) Additional, undesired cross peaks centered at the positions  $(\omega_1, \omega_2) = (\frac{1}{2}[\Omega_k + \Omega_j], \Omega_m)$  can occur in systems of coupled spins. Spin  $I_m$  can either belong to the same spin system as  $I_k$  and  $I_l$  or may show cross relaxation to  $I_k$  or  $I_l$ . These peaks are, however, easily distinguished from the desired  $\omega_1$ -decoupled peaks because they exhibit an antiphase

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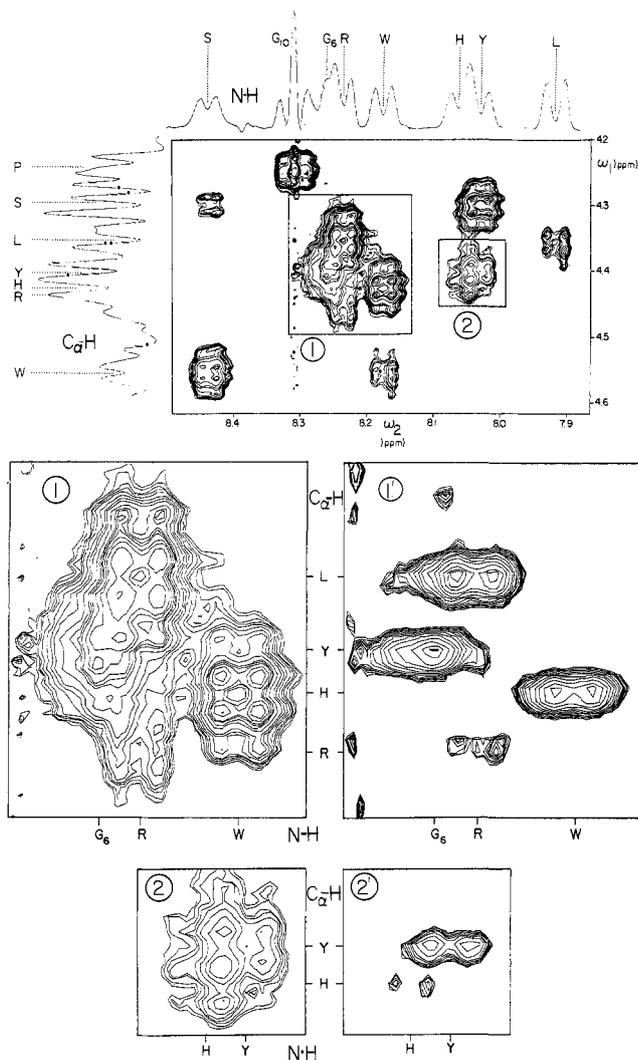
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**Figure 1.** Part of the NH-C $\alpha$ H region of the 300-MHz NOESY spectrum (2K  $\times$  2K data matrix) of the decapeptide LHRH. The two framed regions 1 and 2 showing severe overlaps are also plotted on expanded scales. The corresponding regions from the NOESY TR spectrum (700  $t_1$  samples zero filled to 2K  $\times$  2K) exhibiting homonuclear decoupling in the  $\omega_1$  dimension are shown in the frames 1' and 2'. No undesired cross peaks (see text) appeared in the NH-C $\alpha$ H region so suppression<sup>10</sup> was unnecessary.  $N = 4$  (see text) was sufficient in this experiment since the C $\alpha$  protons can have at maximum three coupling partners, leading to the seven-step cycle  $[\beta_j; W_j]$ :  $[0^\circ; 0.500]$ ,  $[45^\circ; -0.586]$ ,  $[90^\circ; 1.000]$ ,  $[135^\circ; -3.414]$ ,  $[225^\circ; -3.414]$ ,  $[270^\circ; 1.000]$ ,  $[315^\circ; -0.586]$ .

multiplet structure in  $\omega_1$ . If necessary, the undesired peaks can also be suppressed<sup>10</sup> in a way similar to the suppression of zero-quantum coherence in NOESY.<sup>15</sup>

An application of NOESY to the decapeptide LHRH (p-Glu-His-Trp-Ser-Tyr-Gly<sup>6</sup>-Leu-Arg-Pro-Gly<sup>10</sup>-NH<sub>2</sub>) is demonstrated in Figure 1. Severe overlaps of the cross peaks in the two framed regions 1 and 2 impede assignments and render impossible quantitative NOE measurements. The problems can be resolved by decoupling in the  $\omega_1$  dimension by the application of NOESY TR. A comparison of the blowups 1, 2 and 1', 2' obtained with conventional NOESY and NOESY TR, respectively, clearly demonstrates the advantages of  $\omega_1$ -decoupling obtained with the proposed technique.

In conclusion, we have shown that it is indeed possible to reverse the  $J$  coupling evolution and demonstrated the utility in combination with 2D NOE spectroscopy. The technique is easy to implement on modern spectrometers, and the resulting spectra can enjoy considerable simplification compared to conventional spectra. The TR element can be inserted to achieve  $\omega_1$  decoupling in all homo- or heteronuclear 2D experiments where the components in phase with respect to the homonuclear couplings are

selected at the end of the evolution period.

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### Lanthanum Complexes of Spheroidal Carbon Shells

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In a recent letter<sup>1</sup> laser vaporization of graphite in a high-pressure supersonic nozzle was demonstrated to produce a remarkably stable C<sub>60</sub> molecule in high yield. It was suggested that the stability of this new species arises from its unique ability to close into a highly aromatic, spheroidal shell: a truncated icosahedron where all carbons occupy equivalent sites at the juncture of (two) six-membered and (one) five-membered rings. This "soccerball" structure contains a central cavity which should be an exceptionally strong binding site for a wide range of even quite large atoms. In accord with this notion, we now present evidence for the formation of a stable C<sub>60</sub>La complex. Also formed are a variety of less symmetrical C<sub>n</sub>La complexes, all of which are much more stable than the corresponding bare C<sub>n</sub> cluster. None of the complexes shows any tendency to pick up an additional La atom. In all cases the complexes are thought to have the single La atom either wholly or partially surrounded by an aromatic shell of carbons arranged in networks of five- and six-membered rings.

The carbon source for this experiment was a low-density graphite disk<sup>2</sup> impregnated with lanthanum by exposure to a boiling, saturated solution of LaCl<sub>3</sub> in water. After rinsing and drying, this disk was mounted in a rotation/translation device on the side of a pulsed supersonic nozzle.<sup>3</sup> Vaporization was performed by 5 ns, 35-mJ pulses of a Nd:YAG laser at 532 nm, focused to a 1-mm diameter spot on the graphite disk. The helium carrier (roughly 1 atm pressure) present in the pulsed nozzle at the time of laser vaporization thermalized the carbon fragments ejected from the graphite surface and provided a buffer gas to stabilize the La-C<sub>n</sub> reaction products. Expansion of this cluster-laden gas then produced a supersonic beam which was probed 1.2-m downstream by a time-of-flight (TOF) mass spectrometer. Ionization of the carbon clusters and reaction products was produced by ArF excimer laser radiation at 6.4 eV. Details of this apparatus have appeared elsewhere.<sup>4</sup>

Figure 1 displays the TOF mass spectrum of this carbon + lanthanum cluster beam at two widely differing fluences for the ionizing laser pulse. The vertical scale has been deliberately expanded as the dominant peak remains C<sub>60</sub> as in our previous results<sup>1</sup> with pure graphite disks. The expanded scale shows many carbon clusters<sup>5</sup> in the form C<sub>n</sub>La where  $n$  is an even number

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