Singly and Doubly Interlocked [2]-Catenanes: Influence of the Degree of Entanglement on Chemical Stability as Estimated by Fast Atom Bombardment (FAB) and Electrospray Ionization (ESI) Mass Spectrometries (MS)

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A doubly interlocked [2]-catenane and its topological stereoisomer are studied by FAB- and ESI-MS; whereas the behaviour of both compounds is identical under very mild conditions (ESI-MS at low extraction cone voltage), they show marked differences in more forcing conditions (FAB-MS and ESI-MS at high extraction cone voltage).

Topology[1,2] is attracting great interest in mathematics, chemistry and biology. Catenanes[3–5] and knots[6] are fascinating molecular objects, whose synthesis at a preparative scale remains a challenge.

Recent developments in MS,[7–13] are of increasing utility. For example, FAB-MS and ESI-MS have allowed the unambiguous characterization of multi-ring interlocked systems coordinated to several copper(I) centres.[14,15]

The template effect of transition metals has been used in the synthesis of various catenanes and knots[4,6] Recently it allowed the preparation, in a poor yield, of the first 4-crossing [2]-catenane **1** and its topological stereoisomer **2** containing the same rings, but only singly interlocked to one another (Fig. 1).[16]

We now report that MS can be extremely powerful in elucidating subtle structural differences. It can, in particular, indicate which compound is the more robust: **1** or **2** and thus demonstrate which catenane is doubly interlocked. In fact, both molecules being topological stereoisomers, identical MS data were expected. However, the doubly interlocked catenane, whose structure is more constrained than the singly interlocked catenane, cannot readily accommodate an excess of energy during the ionization process and was found to break more easily.

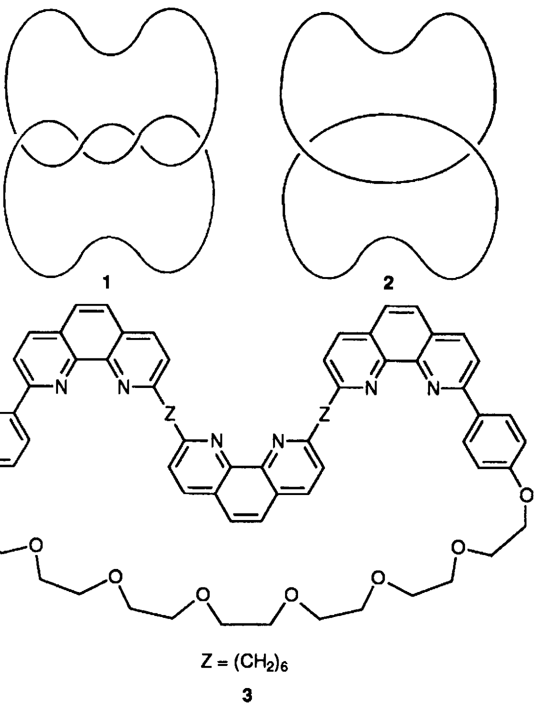

Fig. 1 Each constituent ring of catenanes **1** and **2** corresponds to the macrocycle **3**

The FAB-MS† of **1** and **2** show that both compounds are catenanes since the classical pattern of interlocking rings is obtained.[17] The spectra of **1** and **2** look similar. They are characterized by two peaks: (i) *m*/*z* = 2359, corresponding to the ion $[\mathbf{1} + \mathrm{H}]^+$ or $[\mathbf{2} + \mathrm{H}]^+$, and (ii) *m*/*z* = 1180, corresponding to the ion $[\mathbf{3} + \mathrm{H}]^+$ and originating from the cleavage of one ring followed by fast unthreading of the linear fragment produced. The comparison of the relative intensities of the peak at *m*/*z* = 2359 and of the peak at *m*/*z* = 1180 for **1** and **2** is a clear indication that **1** is more easily cleaved than **2**. Whereas the FAB-MS of **1** shows a *m*/*z* = 1180 peak four times more intense than the *m*/*z* = 2359 peak, both peaks observed in the FAB-MS of **2** have almost the same intensity.

This trend was confirmed by ESI-MS,‡ which uses a very soft ionization technique, and (i) *in mild conditions* (at *V*c = 60 V; *V*c is the extracting cone voltage) ESI-MS of **1** and **2** are very similar (see Fig. 2) and show no fragmentation. Both [2]-catenanes are characterized by three pseudomolecular peaks: the mono-charged peaks at *m*/*z* = 2360.3 ($[\mathbf{1} + \mathrm{H}]^+$)

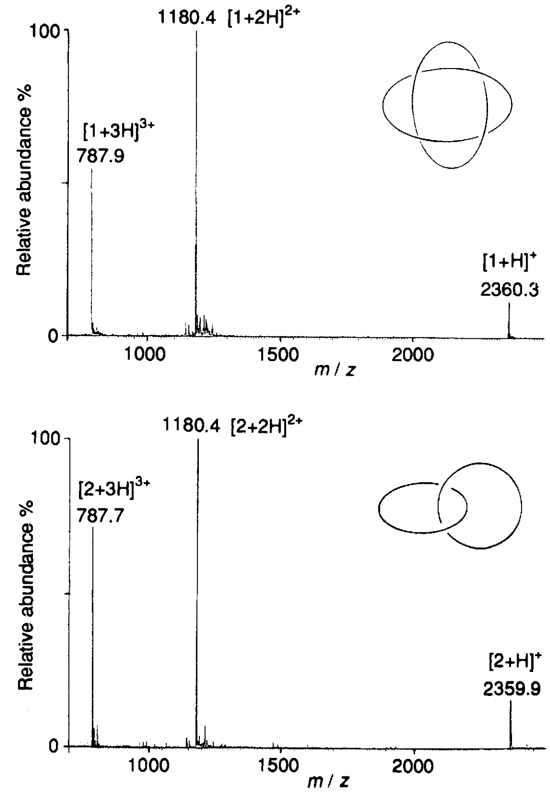

Fig. 2 ESI mass spectra of **1** and **2**, recorded in mild conditions at *V*c = 60 V. Both spectra are practically identical and, contrary to the FAB-MS experiments, no fragmentation occurs both for **1** and **2**.

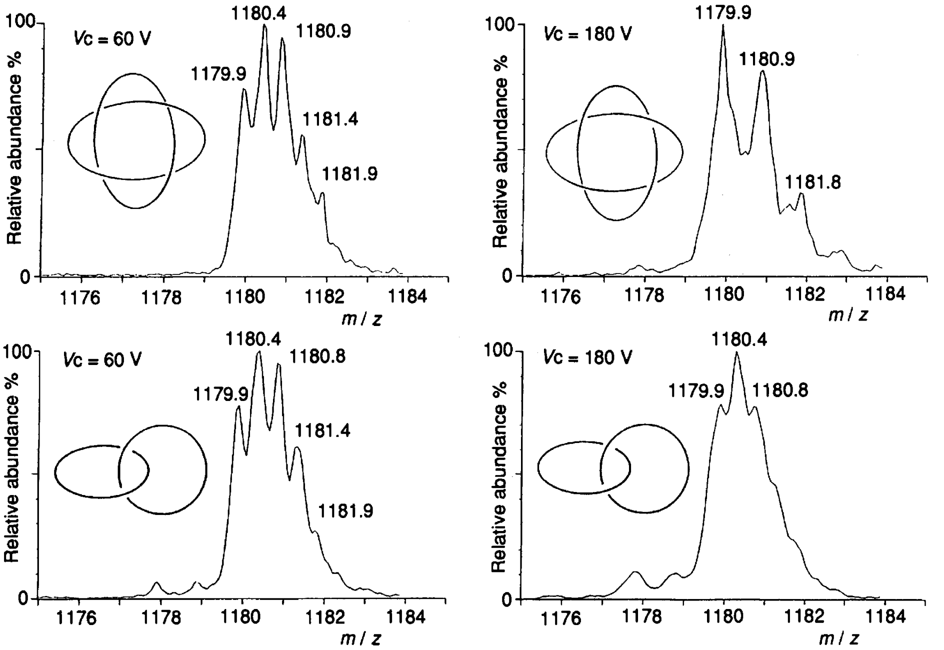

Fig. 3 Display from m/z = 1175 to m/z = 1185 of the ESI mass spectra of **1** and **2** at Vc = 60 V and Vc = 180 V

and at m/z = 2359.9 ($[\mathbf{2} + \mathrm{H}]^+$), the doubly charged peaks at m/z = 1180.4 ($[\mathbf{1} + 2\mathrm{H}]^{2+}$) and at m/z = 1180.4 ($[\mathbf{2} + 2\mathrm{H}]^{2+}$), the triply charged peaks at m/z = 787.9 ($[\mathbf{1} + 3\mathrm{H}]^{3+}$) and at m/z = 787.7 ($[\mathbf{2} + 3\mathrm{H}]^{3+}$). (ii) *in more brutal conditions* (at Vc = 180 V), isotopical patterns of the ion m/z = 1180 indicate that **1** and **2** have very different behaviours (Fig. 3). **1** is cleaved in a large proportion, leading to the major ion $[\mathbf{3} + \mathrm{H}]^+$. In contrast to **1**, **2** remains almost intact, still affording the ion $[\mathbf{2} + 2\mathrm{H}]^{2+}$ as the major component. It is interesting to point out that **3** is the only fragment observed.

Both FAB-MS and ESI-MS techniques are in perfect accordance and point to a significantly greater stability of the singly interlocked [2]-catenane **2** as compared with **1**. These different behaviours correspond to what is intuitively expected on the basis of steric congestion. The more entangled and thus the more strained the compound is, the easier it is to break one of the cyclic components.

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Footnotes

† Positive FAB-MS is carried out on a ZAB-HF double focusing mass spectrometer (mass to charge, m/z, range of 3200 at 8 keV ion kinetic energy) with a resolution of 2500 (resolution 5% valley). Desorption of the sample is performed with a Xe atom beam (8 keV). The solid catenanes are dissolved in dichloromethane at a concentration of 5 μg μl^{-1}. The matrix is *meta*-nitrobenzylalcohol. Typically, 1 μl of matrix is deposited on a stainless steel target and 1 μl of catenane solution is added.

‡ ESI-MS are obtained on a VG BioQ triple quadrupole with a mass to charge (m/z) range of 4000 (VG BioTech, Ltd, Altrincham, UK). Vc[18] varies from 40 V to 200 V. The source temperature is at 30 °C. The resolution is enough to separate the peak at m/z = 1179.5 from the peak at m/z = 1180.0 with a valley of 60%. The catenanes are dissolved in dichloromethane at a concentration of approximately 50 pmol μl^{-1}.

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