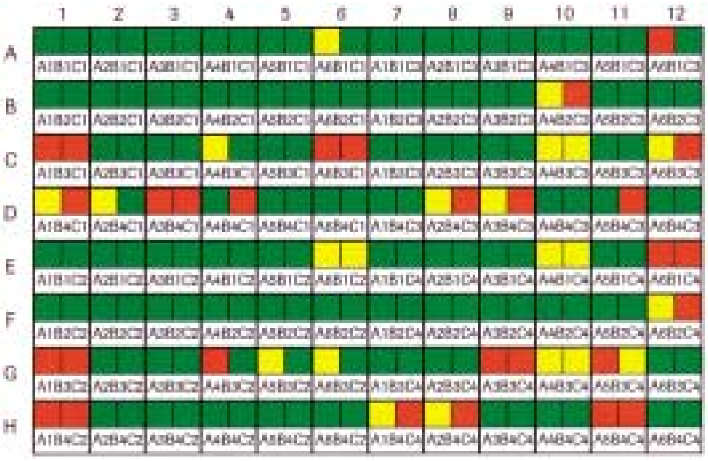

Figure 3. Combined results of the automated NMR and ESIMS analysis are summarized. Each cell contains the expected structure code and the data for NMR (top left), ESIMS (top right). Green means that the proposed structure is true in NMR spectroscopy and gives the expected molecular ion in ESIMS. Yellow indicates unclear results in both NMR spectroscopy and ESIMS. Red means that the proposed structure is false by NMR spectroscopy or does not give a diagnostic molecular ion in ESIMS.

current LC-MS methods. An automated qualitative and relative quantitative analysis of the compounds by using AutoDROP would be possible if the exact amount of sample were known. AutoDROP can be used in combination with ESIMS to analyze compound arrays from combinatorial chemistry and automated synthesis programs, and a wide application of this method is expected.

Experimental Section

The samples (from <1 to 5 mg) were dissolved in [D$_6$]DMSO (600 μL). NMR spectra were acquired in standard NMR tubes (5 mm) on a 400 MHz Bruker DRX 400 spectrometer equipped with a 120-sample changer. Tetramethylsilane was used as internal standard. For ^{1}H NMR 16 experiments were performed; two scans per increment and 128 experiments were performed for 2D HSQC. Cycle time to acquire ^{1}H and 2D HSQC NMR spectra and change the sample was 10 min per sample. AutoDROP is implemented in AMIX software (Bruker) and can be applied to 1D or 2D NMR spectra. ESIMS spectra were acquired on a PE Sciex API 300. Gradient of acetonitrile and H_2O/0.05 % trifluoroacetic acid were used for HPLC. Analytical HPLC was performed on an YMC Pack Pro C_{18} column (5 μm, 75 × 4.6 mm), flow rate 2.5 mL min^{-1}, detection at 254 nm.

Library **1**[4] was synthesized by a multicomponent reaction[5]. A 0.5 M stock solution of all reagents was prepared in ethanol. A solution of a phenol (400 μL, 0.2 mmol) was added to the reactor, and a solution of the corresponding unsaturated aldehyde (400 μL, 0.2 mmol) followed by a solution of the appropriate secondary amine (400 μL, 0.2 mmol) were dispensed. The reactors were closed and heated to 70 °C for 3 h. After cooling to room temperature, twenty-four compounds were collected by decantation, and the remaining seventy-two compounds were purified by preparative HPLC on a YMC Pack Pro C_{18} column (5 μm, 120 Å, 50 × 20 mm).

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Molecular Topology: Easy Self-Assembly of an Organometallic Doubly Braided [2]Catenane**

Christopher P. McArdle, Jagadese J. Vittal, and Richard J. Puddephatt*

Molecular topology[1–5] is in a period of remarkable growth as the advent of new synthetic strategies, based on ideas such as metal-ion templating[6–8] and self-assembly through noncovalent interactions,[9–15] has allowed the design and isolation of supermolecules such as catenanes, rotaxanes, and knots.[16–18] Today, with the synthesis of increasingly intricate molecular topologies,[19–22] these supermolecules attract continued attention for their potential application in the development of molecular devices.[23] In this context, we report the discovery of an elegant example of molecular self-assembly which has led to the isolation and first structural characterization of a doubly braided [2]catenane. This complex organometallic structure, assembled in one step from eight components, exhibits evidence of a fast "rocking" motion of the two 50-membered rings. Fine tuning the organic backbone results in the formation of topologically distinct complexes; a simple ring and a single braid [2]catenane.

In a system comprising two rings, the formation of mechanical bonds (nonbonded interconnections) can lead to topologically isomeric molecules (Figure 1). While simple rings (**A**) and [2]catenanes (**B**) are both well recognized at the molecular level, the doubly braided [2]catenane (**C**) has

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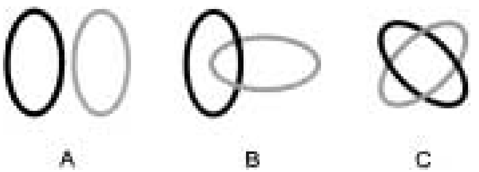
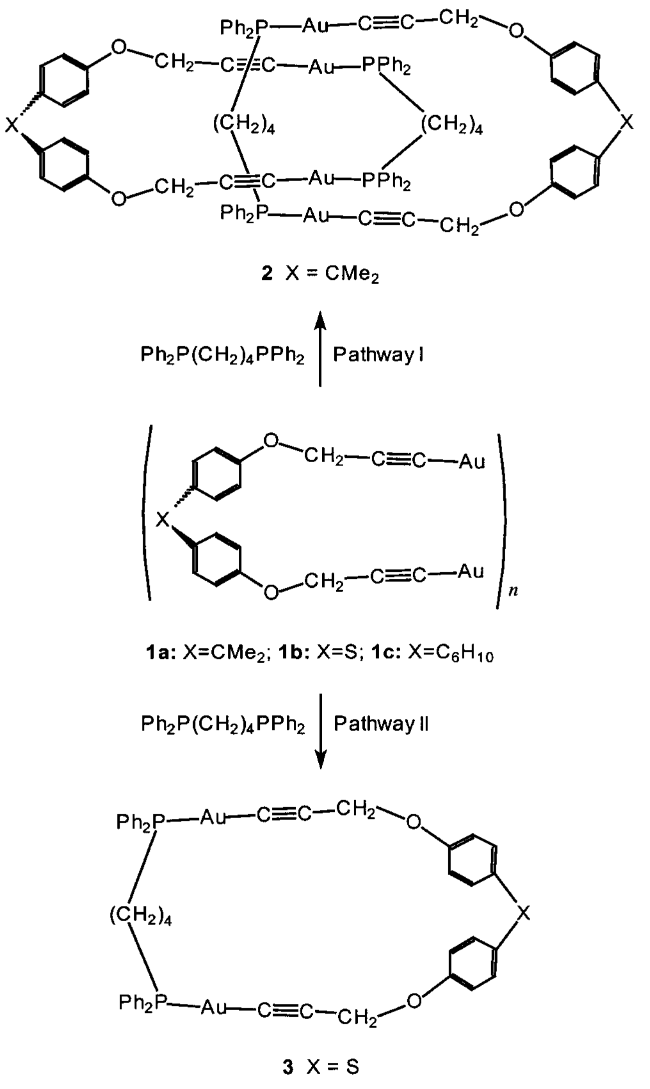


Figure 1. Schematic representation of topological isomers.

remained a serious synthetic challenge, since it requires two rings to be interlocked not once but twice. The doubly braided catenanes **C** have been synthesized by metal-templating strategies,[24, 25] but no X-ray structural characterization has been reported.

Scheme 1 shows how large organogold rings can be formed by self-assembly on reaction of a complex digold(I) diacetylide with a diphosphane ligand, $Ph_2P(CH_2)_4PPh_2$ (dppb). The singly braided [2]catenane **2** was reported to be formed by combination of four components (2+2) when X = CMe_2 (pathway I).[26] The following question naturally arises: can different forms of self-assembly be induced by subtle molecular tailoring, such as changing the "hinge" group X? The answer is a dramatic yes, as shown below.



Scheme 1. Formation of the [2]catenane complex **2** (pathway I) and the simple ring complex **3** (pathway II).

Scheme 1 shows that when the hinge group X is a sulfur atom (X = S), the reaction of **1b** with dppb gave only the simple 25-membered ring (complex **3**) by pathway II, in a reaction which involves the simplest possible combination of two components (1+1). Compound **3** was characterized by both NMR spectroscopy (^1H, ^{31}P, ^{13}C, and 2D experiments) and by X-ray structure determination. The cavity sizes of individual 25-membered rings in **2** and **3** are similar, but the minor conformational changes induced by the different hinge groups clearly affect the secondary aryl–aryl attractive forces that control catenation.[27]

The most exciting development occurred in the case with the hinge group X = cyclohexylidene, C_6H_{10}. The reaction of **1c** with dppb led to the self-assembly of the doubly braided [2]catenane **4** (Figure 2), isolated in pure form in 72% yield. X-ray structure determination (Figure 2b) showed that **4** contains two 50-membered rings, and the cavity formed by each giant ring is large enough to allow the double braid to form. Figure 2c shows the complete structure, illustrating the exquisite way in which the double braiding occurs. The structure contains multiple aryl–aryl secondary bonds (four phenyl–phenyl and four phenyl–aryl) as well as two strong inter-ring aurophilic attractions.[27, 28] Figure 2d shows in a space-filling representation of how the phenyl substituents (along with two solvent dichloromethane molecules that are not shown) pack the remaining cavity. It is truly remarkable that such a complex structure, requiring self-assembly of eight components (4+4), could occur so easily and selectively to give an octagold complex with molecular weight of 4651. This first X-ray structure of any doubly braided catenane (Figure 2) illustrates the inherent chiral nature of such compounds arising from clockwise or anticlockwise braiding.

How rigid is the doubly braided catenane **4**? This is an important question if catenanes are to act as molecular devices. The structure shown in Figure 2, contains no crystallographically imposed symmetry but there are two chemically distinct environments for the phosphorus atoms which may be bound to gold atoms that are or are not engaged in close inter-ring aurophilic attractions. The ^{31}P NMR spectrum (Figure 3) recorded at −90 °C contained two resonances, as expected for the structure shown in Figure 2, but at room temperature only one resonance was observed, indicating that rapid exchange between the two environments is possible. The activation energy at the coalescence temperature of −70 °C was $\Delta G^{\neq} = 41(\pm 1)\,kJ\,mol^{-1}$. Similar coalescence of inequivalent resonances occurred for the phenol group resonances in the ^1H NMR spectra (Figure 3). The least motion that can cause such coalescence is a back-and-forth rocking motion, indicated schematically in Figure 3, that is well suited to molecular switching. More extensive snaking of the two rings[24] is likely to be prevented by eclipsing of bulky diphenylphosphanyl substituents.

In conclusion, all possible combinations of the simple ring, singly, and doubly braided [2]catenanes of Figure 1 can be synthesized easily by judicious choice of the hinge group X in the precursor molecules **1**. The first structure of a doubly braided catenane is reported and it is shown that it undergoes

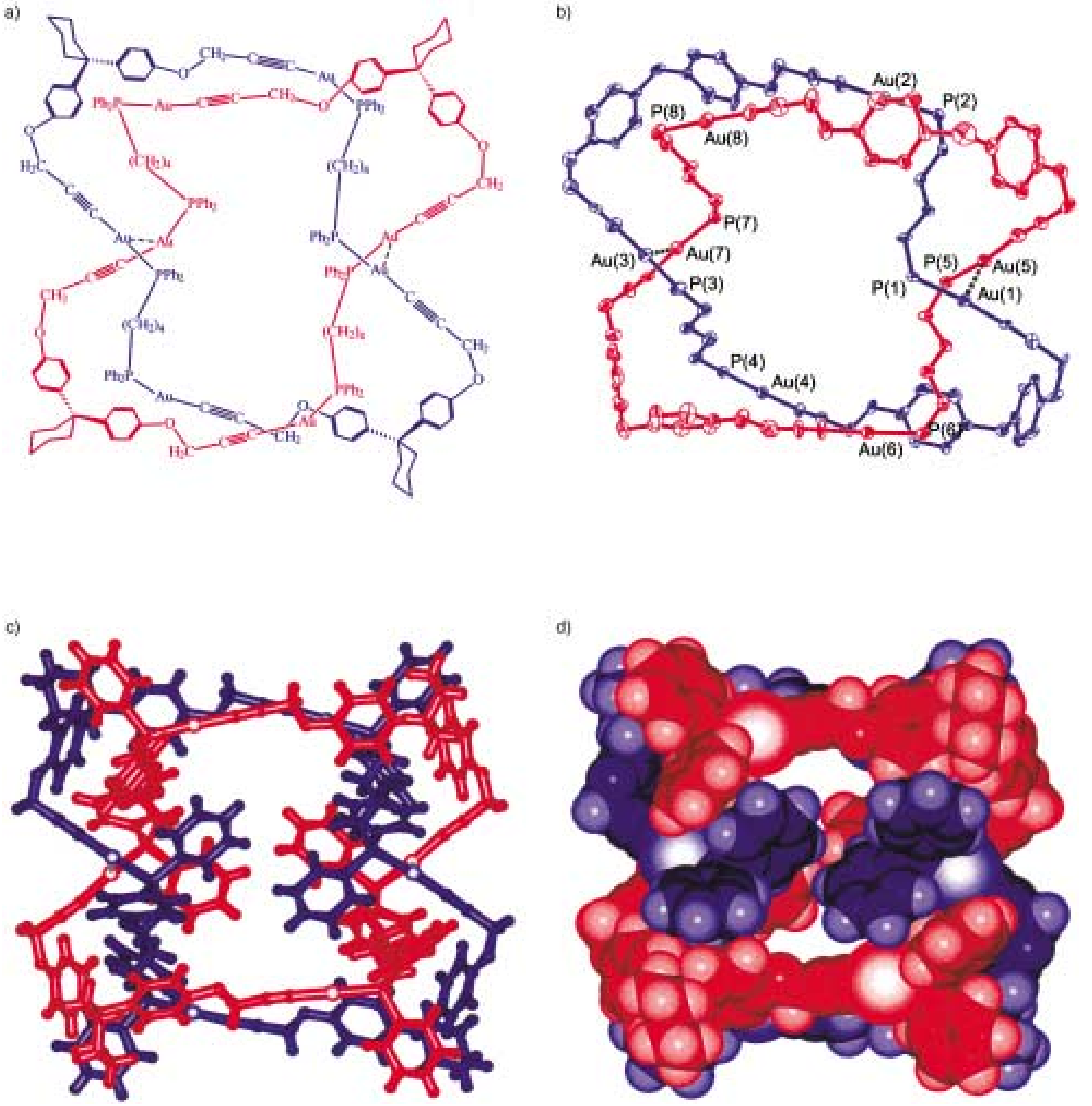


Figure 2. Structure of the doubly braided [2]catenane, complex **4**. a) Structural formula. b) X-ray structure showing core ring atoms only. c) Ball-and-stick representation of the complete structure. d) Space-filling representation of the X-ray structure.

an easy molecular switching motion. Simple extensions to yield yet more intricate molecular topologies are readily envisioned.

Experimental Section

3: A mixture of **1b** (0.100 g, 0.146 mmol) and $Ph_2P(CH_2)_4PPh_2$ (0.056 g, 0.131 mmol) in CH_2Cl_2 (50 mL) was stirred for 3 h at room temperature. Activated charcoal was added to the solution, which was stirred for a further 0.5 h then filtered. The filtrate was concentrated (ca. 1–2 mL) and addition of pentane (100 mL) precipitated **3** as a white solid. The powder was collected by filtration, washed with diethyl ether and pentane, and dried. Yield 0.087 g, 60%. IR (CH_2Cl_2): $\tilde{\nu} = 2135$ (w, C≡C) cm^{-1}; ^1H NMR (CD_2Cl_2, 25 °C): $\delta = 1.73$ (m, 4H; CH_2), 2.34 (m, 4H; CH_2), 4.78 (s, 4H; OCH_2), 7.04 (m, 4H; C_6H_4), 7.35 (m, 4H; C_6H_4), 7.41–7.64 (m, 20H; Ph); ^{31}P NMR (CD_2Cl_2, 25 °C): $\delta = 38.89$; ^{13}C NMR (CD_2Cl_2, 25 °C): $\delta = 27.7$ (CH_2), 28.0 (CH_2), 56.9 (OCH_2), 97.0 (d, $^3J_{P,C} = 26$ Hz; C≡C), 116.2 (C_6H_4), 127.6 (Ph), 129.3 (C_6H_4), 129.4 (Ph), 130.4 (d, $^2J_{P,C} = 54$ Hz; C≡C), 131.8 (Ph), 133.3 (C_6H_4), 133.4, 133.5 (both Ph), 157.8 (C_6H_4); elemental analysis calcd for $C_{46}H_{40}Au_2P_2O_2S$ (%): C 49.65, H 3.62; found: C 49.96, H 3.66. X-ray quality crystals were grown from Et_2O/CH_2Cl_2 solution at 0 °C.

4: This was prepared similarly from **1c** (0.100 g, 0.136 mmol) and $Ph_2P(CH_2)_4PPh_2$ (0.052 g, 0.122 mmol) in CH_2Cl_2 (50 mL), and isolated as a white solid. Yield 0.103 g, 72%. IR (CH_2Cl_2): $\tilde{\nu} = 2134$ (w, C≡C) cm^{-1}; ^1H NMR (CD_2Cl_2, 25 °C): $\delta = 1.51$ (m, 24H; C_6H_{10}), 1.73 (m, 16H; CH_2), 2.23 (m, 16H; C_6H_{10}), 2.34 (m, 16H; CH_2), 4.76 (s, 16H; 2 OCH_2), 6.99 (m,

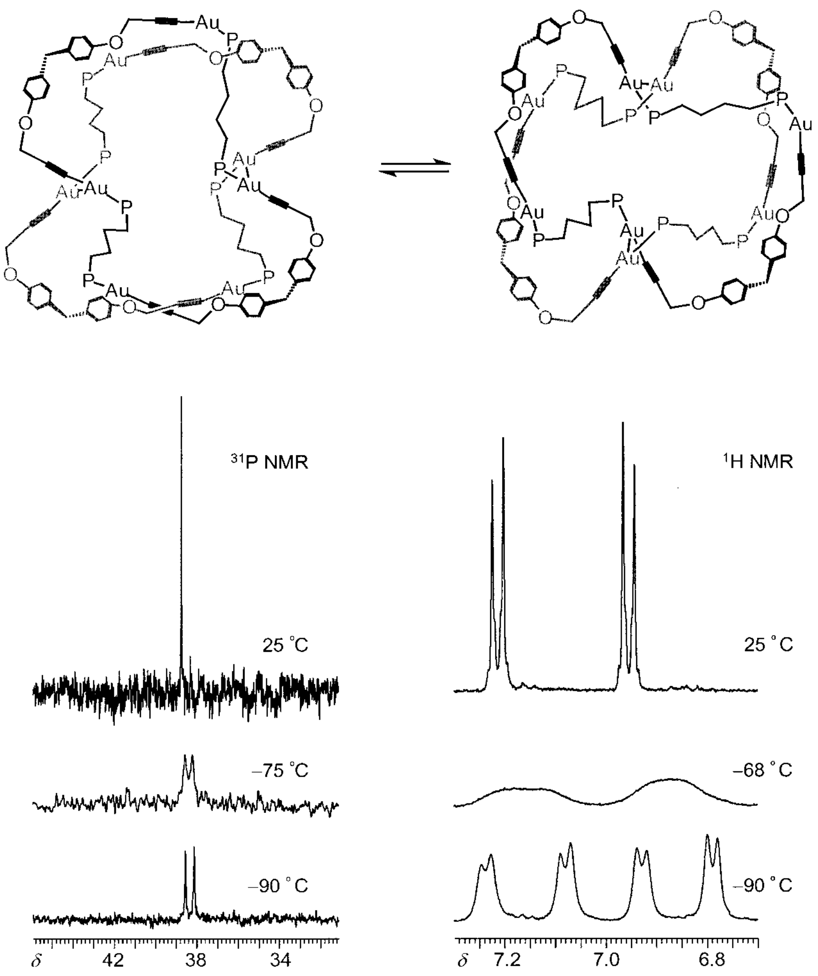


Figure 3. Variable-temperature NMR observations of complex **4**, and the proposed molecular switching motion (cyclohexylidene and phenyl groups are omitted for clarity).

16H; C_6H_4), 7.25 (m, 16H; C_6H_4), 7.43–7.63 (m, 80H; Ph); ^{31}P NMR (CD_2Cl_2, 25°C): $\delta = 38.75$; ^{13}C NMR (CD_2Cl_2, 25°C): $\delta = 23.1$ (C_6H_{10}), 27.8 (CH_2), 28.1 (CH_2), 37.6 (C_6H_{10}), 44.8 (C_6H_{10}), 56.4 (OCH_2), 97.5 (d, $^3J_{P,C} = 26$ Hz; C≡C), 114.7, 128.0 (both C_6H_4), 129.3, 129.4 (both Ph), 130.5 (d, $^2J_{P,C} = 54$ Hz; C≡C), 131.7 (C_6H_4), 133.4, 133.5 (both Ph), 155.7 (C_6H_4); elemental analysis calcd for $C_{208}H_{200}Au_8P_8O_8$ (%): C 53.71, H 4.33; found: C 53.59, H 4.38.

Crystallographic study of complex **4**: X-ray quality crystals were grown by slow diffusion of Et_2O into a CH_2Cl_2 solution of complex **4**, at 0°C. A crystal was sealed in a glass capillary and data were collected at 20°C. Crystal data: monoclinic, $P2_1/n$; $a = 27.1682(3)$, $b = 27.9905(4)$, $c = 31.9272$ Å, $\beta = 91.280(1)^\circ$, $V = 24273(1)$ Å^3, $Z = 4$, $\lambda = 0.71073$ Å, $R1 = 0.1295$, $wR2 = 0.2643$ for 19347 reflections with $F_o > 4\sigma(F_o)$. In this refinement, disordered CH_2Cl_2 molecules were located in seven places in the asymmetric unit and totalled three molecules, and partial occupation by water molecules of solvation was also indicated. The agreement factor is poor as a result of the crystal quality, by the presence of large cavities in the lattice occupied by disordered solvents, and by disorder in some cyclohexyl and phenyl substituents. However, all heavy atoms were clearly identified, and the connectivity of the organometallic rings is proved beyond any doubt. Crystallographic data (excluding structure factors) for the structure reported in this paper have been deposited with the Cambridge Crystallographic Data Centre as supplementary publication no. CCDC-145603. Copies of the data can be obtained free of charge on application to CCDC, 12 Union Road, Cambridge CB21EZ, UK (fax: (+44)1223-336-033; e-mail: deposit@ccdc.cam.ac.uk).

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