as a nanoscale reaction vessel in which to produce mineralized nanoparticles that have optical, catalytic or magnetic activity[4], and packing nanoparticles into ordered assemblies leads to the emergence of collective behaviours that have found applications in opto-electronics, medicine and sensing[5]. Zhang and colleagues' findings might therefore provide a useful method for fine-tuning such collective phenomena by enabling controllable and reversible structural ordering in 3D nanoparticle arrays. Success will hinge on the identity and properties of the particles produced in the cavities of ferritin molecules, on the separation distances and ordering that the protein structure and crystal lattice impose on these nanoparticles, and on whether the kinetics of polymer expansion and contraction can be accelerated or otherwise precisely controlled.

Beyond ferritin, the use of other natural protein cages[4] — and, more excitingly, of synthetic protein cages designed from scratch[6,7] — should provide the versatility needed to control nanoparticle separation distances and lattice systems. Furthermore, the development of creative polymer chemistry will aid efforts to modify the kinetics of expansion and contraction. ■

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NANOTECHNOLOGY

Molecular machines swap rings

A chemical system has been made in which two rings on an axle can switch places by allowing a smaller ring to slip through the cavity of a larger one. The advance opens up potential applications in molecular data storage.

STEVE GOLDUP

Many of the synthetic molecular machines[1] that have been developed in the past 40 years are based on rotaxanes: molecules in which a ring-shaped component encircles a linear axle that is terminated with large 'stoppers' to prevent the ring from slipping off. The threading of the axle through the ring limits the motion of the ring to shuttling back and forth along the axle. Such shuttling has been used in a range of molecular machines that includes switches[2], ratchets[3], pumps[4] and small-molecule synthesizers[5]. Rotaxanes in which more than one ring encircles the axle have also been made[6], reminiscent of an abacus, but the rings have been unable to switch places. Writing in *Nature Chemistry*, Zhu *et al.*[7] now report a system in which the rings can slip past one another, opening the way to new types of molecular machine.

To achieve a ring-through-ring shuttling motion, Zhu and colleagues assembled a rotaxane that contains two differently sized rings (Fig. 1). One has a circumference of 24 atoms, which is about as small as a ring can be in a rotaxane, whereas the other is almost twice as large at 42 atoms. Both rings form hydrogen bonds with nitrogen–hydrogen (N–H) units of the axle, and this enabled the authors to probe the rings' movement using nuclear magnetic resonance (NMR) spectroscopy.

At room temperature, the authors observed two distinct N–H signals in the NMR spectrum of the rotaxane, because the signal for an N–H unit that is bonded to the small ring appears at a different frequency from that of an N–H unit bonded to the larger ring. This told Zhu and co-workers that the rings exchange places slowly at this temperature, or not at all. However, as the sample of rotaxane was heated, the signals began to broaden and then merged into a single peak. This finding confirmed that the rings change places quickly at elevated temperatures. The only way that this could have occurred is by the smaller ring passing through the larger one.

Zhu *et al.* determined that, at room temperature, the energy barrier that must be overcome for the rings to change places is about 52 kilojoules per mole of rotaxane, which corresponds to a shuttling rate of about 3,600 times per second. For comparison, in an analogous rotaxane that contains only the smaller ring, the ring hops between the N–H groups approximately 80,000 times per second, or roughly 20 times faster. On the basis of this comparison, the authors estimate that the ring-through-ring movement 'costs' about 12 kilojoules per

50 Years Ago

The British General Post Office is busy organizing a "telephone fortnight" in an attempt to silence the public criticism of its services. So far, the promotion has given everybody a chance to tell their favourite telephone stories, most of them unflattering to the GPO. The GPO's timing was inept; it is only two weeks since it announced increases in postal and telephone charges, and it might have been better to let the hubbub settle down before organizing the campaign … In the next three years, the GPO is intending to spend £1,100 million on investment in telecommunications … In the longer term, the GPO should be wondering how to increase the number of subscribers … Britain still has very few telephones — 183 telephones per 1,000 of population.
From *Nature* 4 May 1968

100 Years Ago

Students of animal behaviour will find some interesting facts on the "drumming" of the ruffed grouse … in *Forest and Stream* for April, illustrated by a series of remarkable photographs, probably the first of the kind which have ever been taken. The author, Mr. F. K. Vreeland, had the good fortune to watch at close range one of these birds while "displaying", and he is convinced that the strange drumming sound then made is produced by the use of the wings alone. This may indeed be the case, but we suspect that later investigations will show that these sounds are at least partly vocal … The author is apparently so much of an "outdoor naturalist" that he has never read any of the voluminous literature on this theme of courtship displays. But in some respects this adds rather than detracts from the value of his observations, since his records are made without bias.
From *Nature* 2 May 1918

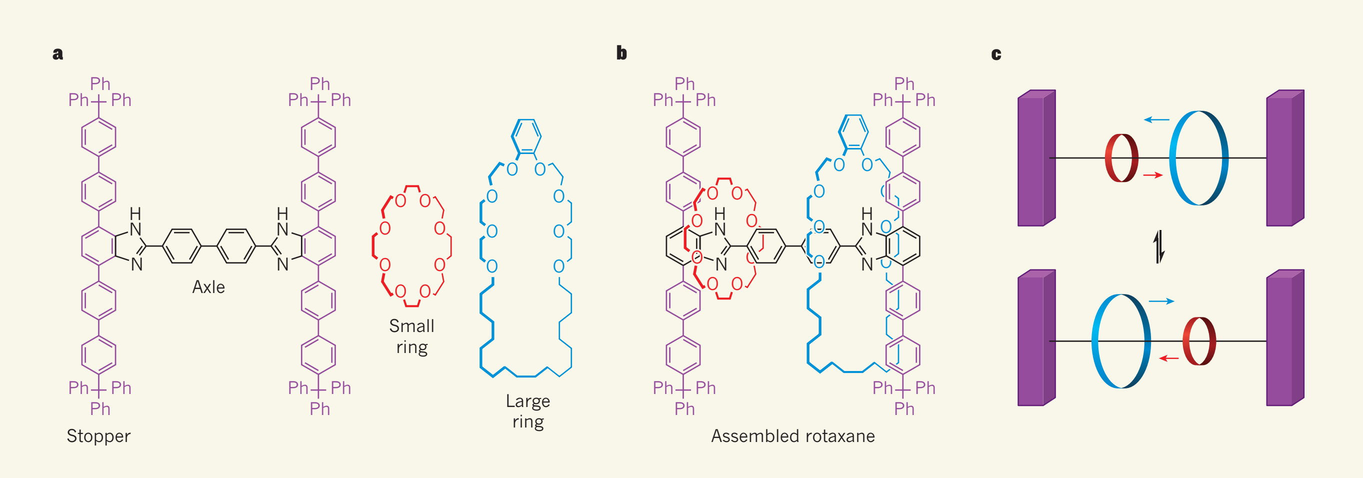

Figure 1 | Ring-through-ring shuttling of a rotaxane. **a**, **b**, Zhu *et al.*[7] report a molecule known as a rotaxane that consists of two rings, one much larger than the other, threaded on to an axle. Large groups, known as stoppers, at the ends of the axle prevent the rings from slipping off (Ph, phenyl group). **c**, The authors find that the rings can slip past each other to exchange their positions on the axle. Shuttling takes place by means of the smaller ring passing through the larger one.

mole — a considerable amount, but not as high as might have been expected.

The two-ringed rotaxane is remarkably simple compared with some of the synthetic molecular machines that have been produced so far. It might therefore seem surprising that this is the first time that a ring-through-ring shuttling process has been observed. However, to achieve their breakthrough, Zhu and colleagues had to bring together several key structural features.

First, the dramatic difference in the size of the rings is important for enabling shuttling to occur. Indeed, the authors produced another rotaxane analogue in which the larger ring was 12 atoms smaller and found that no ring-through-ring shuttling occurs, even at elevated temperatures.

Second, when large rings are used as components of rotaxanes, the stoppers on the ends of the axle must be extremely large to prevent the rings from slipping off. This demand can complicate the synthesis of rotaxanes because larger stoppers often cause problems with solubility, and their use typically adds further steps to an already complex synthetic route. Zhu *et al.* overcame these issues by using simple T-shaped stoppers that they had developed previously to make porous materials (known as metal–organic frameworks) that incorporate rotaxanes[8].

Such structural issues highlight a limitation of the newly identified dynamic process: if rotaxane structures that show ring-through-ring shuttling must be so contrived, will it be possible to use ring-through-ring shuttling to develop molecular machines? It is to be hoped that the answer is 'yes', because ring-through-ring shuttling could bring an extra dimension to rotaxane-based switches. A potential application suggested by the authors is molecular-level weaving, in which ring-through-ring shuttling controls the entanglement of molecular threads — essentially, a small ring is used to pull a molecular chain through a larger ring, akin to threading a macroscopic needle.

Multi-ring rotaxanes could potentially also be used for information storage, in which data are encoded by the order of the rings on the axle. Before now, there was no major advantage to this approach compared with storing data in simpler molecules, because the ring order was fixed at the time of synthesis[6]. Zhu and colleagues' work opens up the possibility of using external stimuli to order and reorder the rings, and therefore of writing and rewriting any encoded information. ■

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MEDICAL RESEARCH

Life of a liver awaiting transplantation

People waiting for a liver transplant can die before an organ is found, or, if one is available but of poor quality, there is a risk of transplant failure. A machine that preserves livers might offer a way forward. **SEE ARTICLE P.50**

STEFAN SCHNEEBERGER

The standard approach for handling donated livers before transplantation is storing them on ice. On page 50, Nasralla *et al.*[1] report the results of a clinical trial that compared two organ storage methods. More than 200 people who received a liver transplant were randomly allocated either a donor liver that had been stored on ice or one preserved with the aid of a machine that perfuses the organ at body temperature (37 °C) with oxygenated blood containing nutrients (Fig. 1). The latter method is called normothermic machine perfusion (NMP), and this technique enables organ function to be monitored outside the body before transplantation.

The concept of machine perfusion of an organ awaiting transplantation is not new. Indeed, machine-assisted perfusion was in use before cold storage became the method of choice owing to its simplicity and reproducibility[2]. However, interest in revisiting perfusion