Six states mechanical switching of redox-active molecular tweezers

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Abstract: A six level molecular switch was achieved using terpy(Ni-salphen)$_2$ tweezers addressable by three orthogonal stimuli (metal coordination, redox reaction and guest binding). The redox non-innocent and valence tautomerism properties of Ni-salphen complexes were exploited to add two new dimensions to a mechanical switch. All six states are stable and accessible by the right combination of stimuli and were characterized by NMR, XRD or EPR spectroscopy and DFT calculations.

Molecular machines have recently attracted an increasing interest due to their promising abilities to control matter at the molecular scale.[1] Among the large variety of mechanical machines,[2] molecular switches[3] using mechanical motion in response to external stimuli can be considered as important precursors. Beyond switches based on bi-stable systems, the introduction of multistate systems may be necessary to develop multifunctional devices. For example, molecular computing could in principle exploit ternary or higher-order digit representations, which would permit smaller device components. Despite this obvious interest, molecules that can exist in more than two stable and independently addressable states remain largely unexplored.[4] In particular examples of six-level molecular switches are scarce in the literature and the only examples have been obtained by combining a photochromic unit with redox or pH-sensitive active units. [4a, 4c, 4d] While photo- and electro-induced processes have received much attention as modes of switching, multistate switching by those stimuli is difficult to implement as it requires selective excitation of more than two units, and therefore designing of multiple modules without excitation overlap. In this regard, using a coordination based mechanical switch is an interesting approach since it enables addressability by the design of the coordination sites with total conversion and thermal stability[5] that can be difficult to achieve with photochromic systems.

We are interested in using the mechanical motion of switchable molecular tweezers[6] to control properties at the molecular level. Our system is based on a terpyridine ligand functionalized in 6 and 6" positions by salphen complexes. The open tweezers adopts a 'W' shaped conformation that can be switched to a 'U' one by a coordination stimulus bringing in proximity the two functional salen complexes. By using platinum or copper salen complexes a modulation of the luminescence[7] and magnetic[8] properties respectively was achieved demonstrating the versatility of such mechanical switch. We wished to exploit the modularity of our platform to combine ion triggered mechanical motion with redox activity and substrate binding in order to achieve a multi-state switch. Ni-salphen complexes were thus chosen as functional units since the salphen ligand in such case are known to be non-innocent with reversible oxidation properties.[9] Furthermore upon one electron oxidation a valence tautomerism can be observed between Ni^{II}-salen and Ni^{II}-salen$^+$ species in the presence of pyridine ligands enabling an additional orthogonal stimulus.[10] Herein we describe the synthesis of terpy (Ni-salphen)$_2$ tweezers (Figure 1) and the study of their six-level switch by using three orthogonal stimuli: i) metal coordination of the terpyridine moiety to open/close the tweezers ii) reversible oxidation of the Ni-salphen complexes and iii) guest binding to oxidized Ni-salphen coupled to valence-tautomerism.

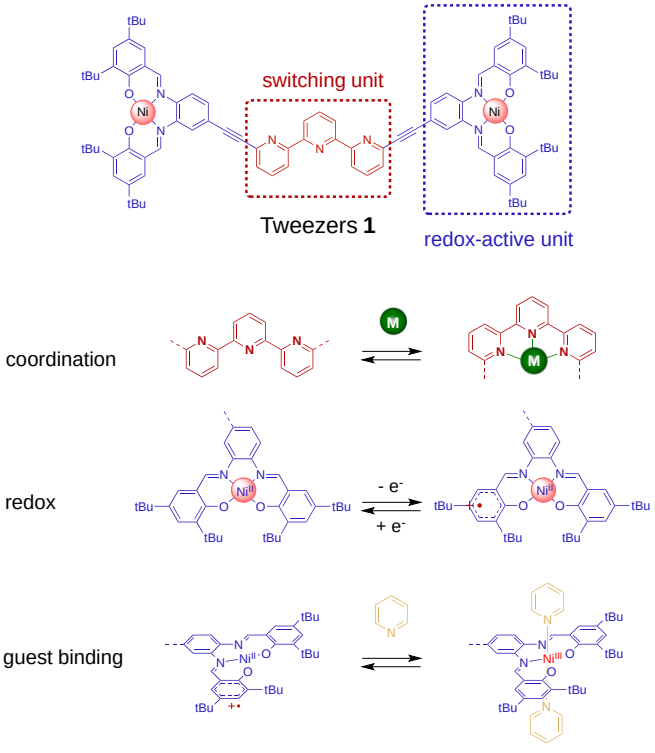

Figure 1. Redox-active molecular tweezers **1** and effect of the 3 orthogonal stimuli (coordination, redox and guest binding).

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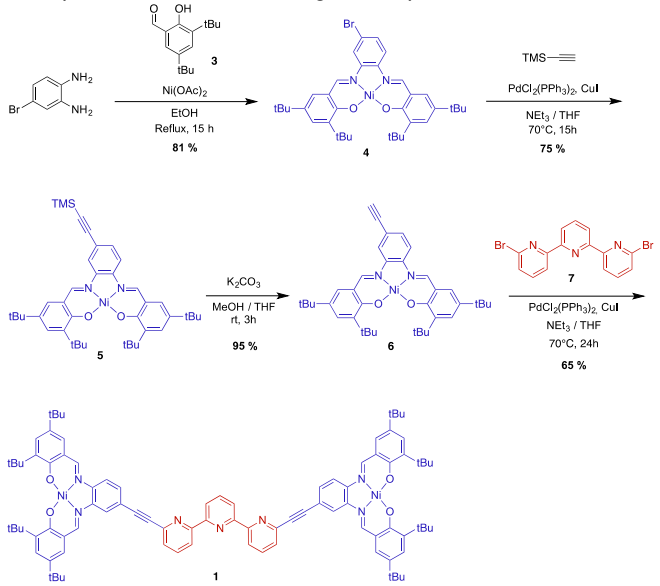
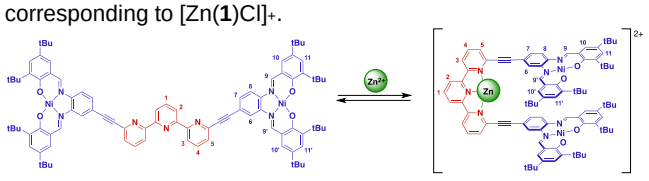
Tweezers **1** were synthetized by a modular approach using a chemistry on complex strategy (Scheme 1) with a double Sonogashira coupling between alkyne Ni-salen complex and 6,6'' dibromo-terpyridine as key step. Ni-salphen complex **4** was first obtained by a one-pot condensation between salicylaldehyde **3** and 4-bromo-1,2-diaminobenzene using Nickel acetate as a template. The aryl bromine was then reacted with TMSA in a Sonogashira coupling reaction to yield after deprotection complex **6**. After a final double coupling with **7**, tweezers **1** were obtained and fully characterized by NMR spectroscopy and mass spectrometry. This modular strategy and the inert nature of the Nickel-salen complexes enabled a perfect control the coordination of the two binding sites (salphen and terpyridine). The absence of correlation in the NOESY spectra between H_2 and H_3 (Figure S2) is in agreement with an *s*-trans 'W' shaped conformation of the terpy in solution due to the repulsion between the nitrogen lone pairs.



Scheme 1: Synthesis of Tweezers 1.

The mechanical switching between the open and closed form of the neutral species (coordination stimulus **a**) was studied by NMR titration. Upon addition of Zn^{2+} the ^{1}H NMR spectra (Figure 2) showed a progressive disappearance of the open tweezers signals and the appearance of a new set of peaks corresponding to the closed conformation. After addition of 1 eq of Zn^{2+} the tweezers are fully closed and the formation of the 1:1 complex was confirmed by 2D NMR with a NOE correlation peak between H_2 and H_3 (Figure S3) and by mass spectrometry (Figure S4) with molecular ion peak at 1568.6 *m/z* corresponding to [Zn(**1**)Cl]$^+$.



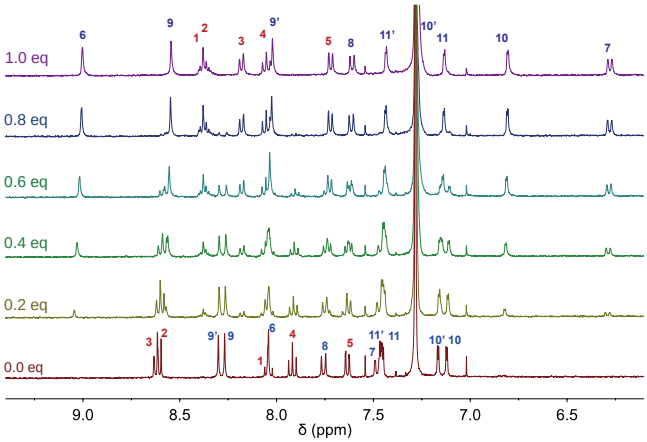


Figure 2: ^{1}H-NMR (400 MHz) titration of Tweezers **1** with $ZnCl_2$ in $CDCl_3$ at 300 K.

Single crystals of closed tweezers [Zn(**1**)]Cl_2 suitable for X-ray diffraction were obtained by slow evaporation (Figure 3). [Zn(**1**)]Cl_2 crystalized in monoclinic space group I2/a, with an unit cell of 20286.8(6) Å^3 (*a* = 35.3839(4), *b* = 11.1376(2), *c* = 51.7427(9) Å, α = γ = 90°, β = 95.8060(10)). Each Ni-salphen unit adopts a square planar geometry with an average Ni-O and Ni-N distances of 1.851 and 1.853 Å respectively characteristic of Ni-salen complexes.[9b] The tweezers present an helicoidally shaped geometry that brings in close proximity the two Ni-salphen units with a Ni-Ni distance of 4.82 Å. The reversibility of the motion was then obtained by adding tris(2-aminoethyl)amine (tren) as a competitive ligand that can selectively remove the zinc without decoordinating the Ni-salphen complexes. The titration was followed by NMR (Figure S5) and showed the disappearance of the closed tweezers protons and the recovery of the open conformation after addition of around 1 eq of tren demonstrating the reversibility of the mechanical switch.

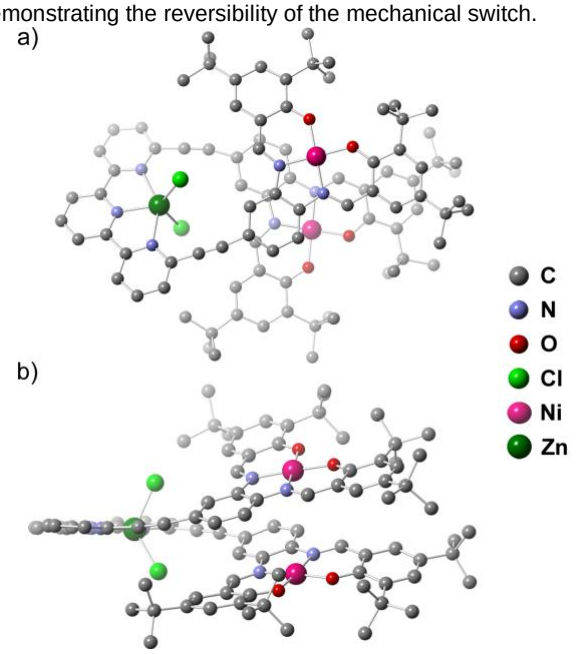


Figure 1: Crystal structure of closed tweezers [Zn(**1**)]Cl_2.

Ni-salen complexes are known to present redox non-innocent properties,[9] ie upon oxidation the complex presents valence tautomerism with a ligand centered oxidation at room temperature that can switch to a metal centered oxidation at very low temperature.[11] More interestingly this tautomerism can be promoted by the coordination of an apical ligand such as pyridine that can result in an exclusive Ni^{III} species.[10] These subtle electronic properties of the Ni-salphen moieties were taken advantage of to add two other dimensions to the switching mechanism of the tweezers.

The electrochemical properties of the tweezers were studied by cyclic voltammetry (CV) and differential pulse voltammetry (DPV) (Figure 4). CV of the open tweezers displays two successive reversible two-electrons redox waves (0.97 and 1.32 V/SCE) corresponding to the formation of $\mathbf{1}^{2+}$ and $\mathbf{1}^{4+}$ species respectively (Edge **b**). The simultaneous oxidation of both Ni-salphen indicates no electronic interaction between the two redox-active moieties in the open conformation, which is expected despite a conjugated pathway from the large distance between them (~20 Å). Upon closing by addition of 1.3 eq of Zn^{2+}, the first oxidation wave is clearly split in two reversible waves at 0.92 and 1.08 V/SCE. The first oxidation potential value is shifted by 50 mV to lower potential compared to the open conformation. This effect can be attributed to the coordination of the terpy by Zn^{2+} that results in back-donation of the zinc to the π system[12] as observed on a model half-tweezers terpy-(Ni-salphen) where zinc coordination has the same effect (Figure S6). However, the splitting can be attributed to the interaction between the two Ni-salphen units that are in close spatial proximity in the closed conformation. To discriminate between electronic coupling or electrostatic effects, spectro-electrochemisty experiments were performed. The monitoring of the UV-Vis and NIR spectra upon electrolysis presented no significant difference in the NIR region between the open and closed conformation with in both cases the appearance of a large intervalence band around 900 nm corresponding to the intra-complex transition usually observed in Ni-salen complexes[9a, 13] (see Figure S7-8). This indicates that the splitting of the first oxidation wave is probably due to an electrostatic effect. The proximity of the positive charge generated upon oxidation of one Ni-salphen renders the oxidation of the second one more difficult (Edge **b'**) as already observed in multi-ferrocenyl systems.[14] Oxidized tweezers $\mathbf{1}^{2+}$ were then generated by bulk electrolysis and could be switched reversibly by successive addition of $Zn(ClO_4)_2$ and excess (10 eq) terpyridine demonstrating the reversible switching along Edge **a'**. Tren ligand could not be used to selectively reopen the oxidized tweezers in this case as it also reduced the tweezers. It can nevertheless be considered as a combined agent that can directly reset the system to the open form **1** (Stimuli **a + b**). Thus two additional states of the molecular switch system are accessible by oxidation.

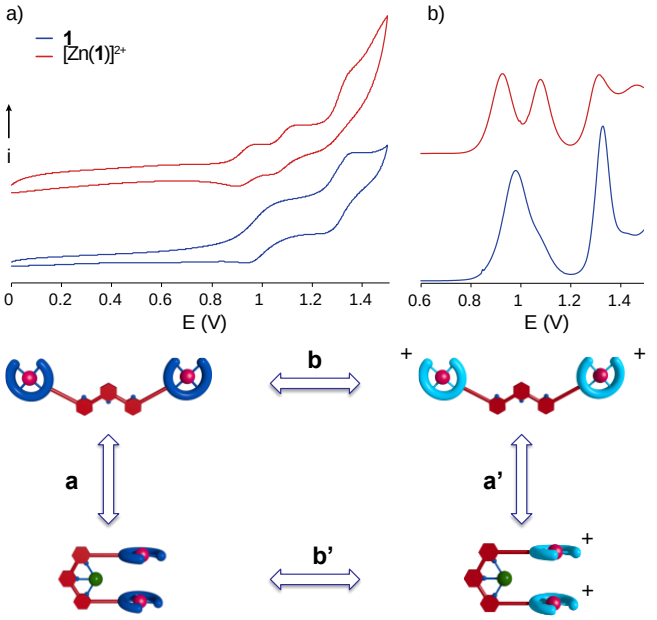


Figure 4: a) CV and b) DPV of open and closed tweezers on Pt working electrode in CH_2Cl_2 (2.0×10^{-4} M) with $TBAPF_6$ (0.1 M). Scan rate: 20 $mV.s^{-1}$, potential are recorded versus SCE.

An additional orthogonal stimulus was then used to add another dimension of switching. Indeed pyridine has been described to promote a geometry change from square planar to octahedral by coordinating Ni in apical position after oxidation of the complex. Thus the effect of pyrazine on $\mathbf{1}^{2+}$ was studied by EPR to provide an accurate insight on the location of the unpaired electrons.

X-band EPR spectrum of open tweezers $\mathbf{1}^{2+}$ (Figure 5a) in frozen CH_2Cl_2 (+ 0.1 M $TBAPF_6$) solution at 20 K displays two rhombic signals at g_{av} values of 2.23 and 2.03 that can be respectively attributed to a ligand radical and low spin Ni^{III} species according to the literature.[9b, 10, 15] The ligand centered radical rhombic signal is characteristic of the presence of excess supporting electrolyte ($TBAPF_6$).[15b] As previously observed,[15b] the signal corresponding to Ni^{III} became less intense at higher temperature (see Figure S9 at 100 K) suggesting a valence tautomerism depending on the temperature. In presence of an excess of pyrazine a characteristic low spin Ni^{III} signal with hyperfine splitting is observed for $\mathbf{1}^{2+}$ (Figure 5b). The presence of a well-resolved quintuplet in the high-field component ($g = 2.03$) is indicative of the existence of an octahedral Ni^{III} complex with two equivalent pyrazine ligands axially bonded (Edge **c**).[10] The spectrum is very similar to isolated Ni-salen$^+$ complexes indicating that the two Ni-salphen moieties in the tweezers are not interacting. The coordination of the pyrazine ligands seems thus unable to trigger a closing of the tweezers by the establishment of a bridging pyrazine between the to Ni centers.

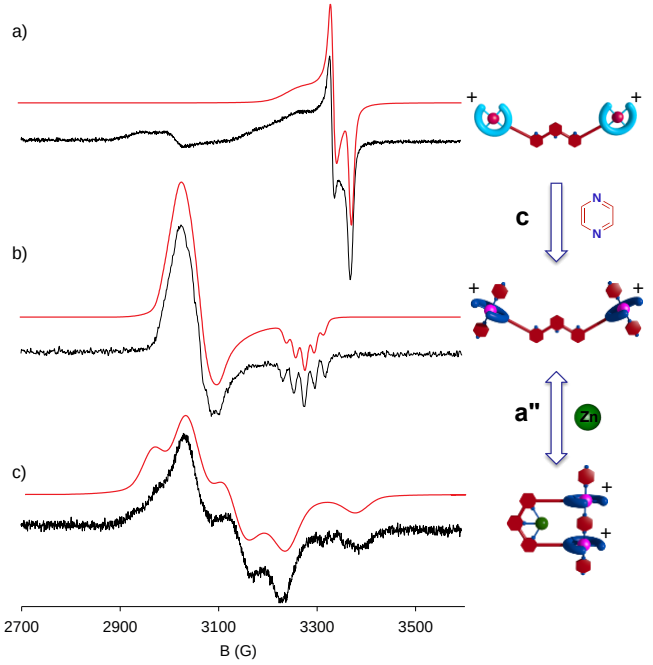


Figure 5: X-band EPR spectrum of oxidized (a) open tweezers $\mathbf{1}^{2+}$ (b) $\mathbf{1}^{2+}$ with 100 eq. of pyrazine and (c) closed tweezers $[Zn(\mathbf{1})]^{4+}$ with 100 eq. of pyrazine in frozen solution of CH_2Cl_2 (1.0×10^{-4} mol.L^{-1} + 0.1 M $TBAPF_6$) at 20 K (black); theoretical fit (red).

However upon addition of zinc(II) a drastic change in the EPR spectra was observed (Figure 5c) (Edge **a''**). The signal was fitted by a S=1 spin system corresponding to the two ½ spins located on the Ni^{III} in exchange and dipolar coupling interactions, yielding to the formation of two new spin state S = 0 and S = 1. The fit gave access to the g values (g_x = 2.230; g_y = 2.160; g_z = 2.027) and to the dipolar zero field splitting parameter (D = 183 MHz). In order to discriminate between through space interaction between the two Ni-salphen moieties and through ligand interaction by a bridging pyrazine a control experiment in presence of pyridine was conducted. The EPR spectra of $[Zn(\mathbf{1})]^{4+}$ in presence of pyridine is very different from the one with pyrazine and is similar to the open tweezers in presence of pyrazine (Figure S9). Since pyridine cannot play the role of bridging ligand and only coordinate the Ni in apical position we can assume that in the closed tweezers one pyrazine ligand bridges the two Ni centers by an allosteric effect, and enables a through ligand exchange interaction (Edge **c'**). As single crystals for diffraction studies could not be obtained, DFT calculations were then performed (FHI-aims code[16] with PBE functional[17] and numerical tight basis set, for more details see Computational details in Supporting Information) to confirm the location of the pyrazine. The accuracy of such methodology has been verified by comparison with the experimental structure of the $[Zn(\mathbf{1})]^{2+}$ complex (Figure SX) An optimized structure was obtained showing the tweezers in a folded geometry similar to the one in the crystal structure but with a larger intramolecular Ni-Ni distance of 7.10 Å (Figure 6). The flexibility of the alkyne spacers allows this distortion and enables the bridging position of one pyrazine.

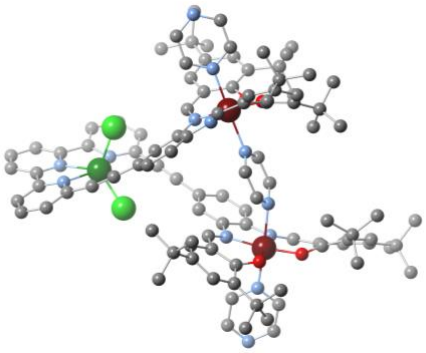


Figure 6: DFT optimized structure of $[Zn(\mathbf{1})pzCl_2]^{2+}$ using the PBE functional with the FHI-aims code.

To have a better insight on ground state spin value in the closed form, the exchange coupling constant was evaluated from the evolution of the intensity of the EPR signal as a function of temperature. The integration curve decreased at low temperature corresponding to an antiferromagnetic coupling between the two spin centers, indicating a S = 0 fundamental state. By fitting with a two-level Boltzmann model (Figure S11) a value of $J = -2.4$ cm^{-1} was obtained. This behavior was corroborated by calculations with the B3LYP functiona[18] using optimized structure shown in Fig. 6 yielding a calculated J value[19,20] of -2.3 cm^{-1} in excellent agreement with the experimental data (see Supporting Information for more details). Thus, the pyrazine stimulus enables two new accessible states that can be monitored by EPR. The coordination of the pyrazine ligand in the oxidized state has a drastic effect on the electronic properties of the system by shifting the radical location from Ni^{II}-phenoxyl to Ni^{III}-phenoxide and enabling a through ligand magnetic coupling in the closed form. The pyrazine can be removed after reduction since no apical binding on the Ni-salphen complex was observed for the neutral tweezers. Thus the redox stimulus acts as a reset of the system enabling the recovery of open tweezers **1**.

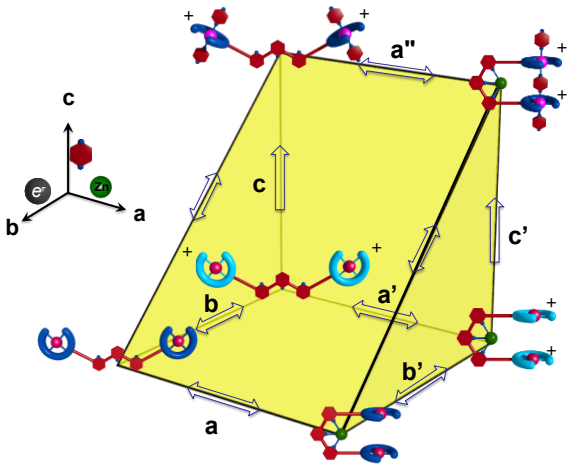


Figure 7: Representation of the six-level switching with 3 orthogonal stimuli (coordination, redox and guest binding).

In summary, by combining three orthogonal stimuli (redox, coordination, guest binding) a remarkable six-states multifunctional switching system was achieved that can be represented in 3D as a truncated cube (Figure 7) with each stimulus along one axis. The metal coordination stimulus (axis **a**) enables a mechanical closing of the neutral and oxidized open states (edges a, a', a"). The switching along theses edges is reversible upon addition of a competitive ligand such as tren or terpyridine. The orthogonal redox stimulus (axis **b**) triggers a reversible oxidation of the open or closed tweezers (axis **b**) adding two new accessible states along edge b and b'. Finally, the orthogonal pyrazine binding stimulus (axis **c**) enable two new states accessible from the oxidized species along edge c and c'. This last stimulus is not directly reversible but a reduction can be used as a reset since pyrazine doesn't bind the neutral tweezers. In conclusion, the supramolecular concepts of mechanical motion and guest binging (molecular recognition) were combined in a molecular tweezers with the fascinating Ni-salen redox features to implement a fully reversible six-state system in which all states are stable and can be accessed and interconverted by the right combination of stimuli.

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Keywords: molecular switch • magnetism • Nickel • salen

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