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Metal ion directed template synthesis using 2-acetyl-1,3-indandione and ethylenediamine: steric and electronic restrictions

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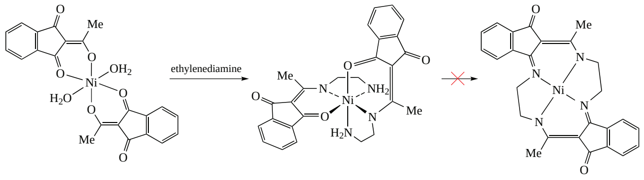
A Ni^{II}-directed template synthesis using 2-acetyl-1,3-indandione and ethylenediamine results in formation of octahedral Ni^{II} complex, whose crystal structure has been resolved using single crystal X-ray diffraction. The structure indicates that only exocyclic enolic oxygen atom of the triketone takes part in the condensation with ethylenediamine. Quantum chemical calculations reveal insights into the observed reactivity of an initial Ni^{II} complex of 2-acetyl-1,3-indandione with ethylenediamine and point out steric effects as the main restriction for a complete cyclization into a tetraaza macrocycle.

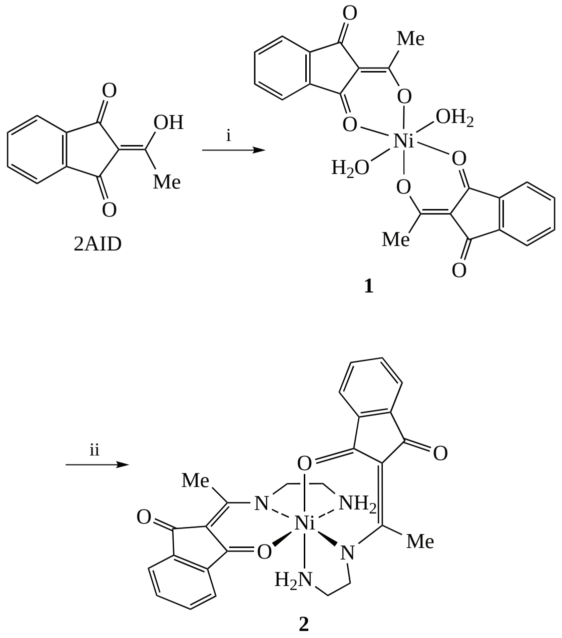


Keywords: template synthesis, Ni^{II} complex, crystal structure, indan-1,3-dione, β-triketones, quantum chemical calculations.

2-Acyl-1,3-indandiones as cyclic β-triketones represent well-known ligands for stable complexes with a wide range of metal ions.[1–7] Besides, an unexpected regioselectivity of 2-acetyl-1,3-indandione (2AID) and its analogs in condensations with hydrazides,[8] thiosemicarbazide,[9] amines[10,11] and amino-aldehydes[12] as well as in acetylation and methylation reactions[13] has been observed. Reactions of 2-acyl-1,3-indanones with *o*-phenylenediamines were found to proceed with formation of three different types of products depending on the molar ratio of reagents and the type of side chain of the acyl group.[14] However, this remarkable reactivity has been poorly explored. There are only a few reports on attempts to involve β-di- and triketones into reactions of macrocyclic template synthesis mediated by metal ions, for example using alkaline earth metal templates[15] or Ni^{II} complexes of cyclic β-polyketones derived from cyclohexanone.[16]

Herein, we describe a metal ion directed template synthesis involving Ni^{II} complex of 2AID and ethylenediamine (Scheme 1) in an attempt to generate cyclam-like macrocycle conjugated with the 1,3-indandione moiety. Direct interaction of 2AID, ethylenediamine and Ni^{II} salt resulted in formation of stable $[Ni(ethylenediamine)_3]^{2+}$ complex, therefore we turned to employ as a starting compound Ni^{II} complex of 2AID.

The syntheses[†] of the Ni^{II} complex of 2AID **1** and the product of its condensation with ethylenediamine **2** were carried out in



Scheme 1 *Reagents and conditions*: i, $Ni(OAc)_2 \cdot 4H_2O$, ethanol, reflux, 3 h; ii, ethylenediamine, ethanol, reflux, 6 h.

[†] *Synthesis of complex* **1**. A solution of 2AID (190.5 mg, 1.01 mmol) in ethanol (10 ml) was mixed with a solution of $Ni(OAc)_2 \cdot 4H_2O$ (130.4 mg, 0.52 mmol) in ethanol (30 ml). The mixture was refluxed for 3 h, then the precipitate formed was filtered off, washed with small portions of ethanol and dried over P_2O_5 for 2 weeks. Yield 95%. Found (%): C, 56.08; H, 3.82. Calc. for $NiC_{22}H_{14}O_6 \cdot 2H_2O$ (%): C, 56.33; H, 3.87.

Synthesis of complex **2**. A solution of complex **1** (93.9 mg, 0.2 mmol) in ethanol (10 ml) was mixed with ethylenediamine (0.4 ml, 2 mmol). The mixture was refluxed for 6 h, then the precipitate formed was filtered off, washed with small portions of ethanol and dried over P_2O_5 for 1 week. Yield 64.5%. Found (%): C, 60.65; H, 5.79; N, 10.81. Calc. for $C_{26}H_{26}N_4NiO_4 \cdot (C_2H_5OH)_{0.33}$ (%): C, 60.14; H, 5.30; N, 10.52. Single crystals were obtained from ethanol solution as orange prisms, *ca*. 0.36×0.30×0.20 mm.

Table 1 Selected experimental and calculated [UB3LYP/6-31G(d,p)] bond lengths and IR frequencies of complexes **1** and **2**. Atoms numbering of compound **2** corresponds to Figure 1, for that of compound **1** see Figure S2 in Online Supplementary Materials. Calculated IR frequencies are scaled with a factor of 0.9614 (s, vs, m and br indicate strong, very strong, medium and broad bands, respectively).

Complex **1**		Complex **2**	
Bond lengths/Å			
Bond	Calculated value	Bond	Calculated (experimental) values
Ni–O(3)	2.1237	Ni(1)–O(1)	2.031 [2.059(3)]
Ni–O(4)	2.1237	Ni(1)–O(4)	2.031 [2.075(2)]
Ni–O(5)	2.0085	Ni(1)–N(1)	2.065 [2.092(3)]
Ni–O(6)	2.0035	Ni(1)–N(4)	2.065 [2.090(3)]
Ni–O(7)	2.0082	Ni(1)–N(3)	2.170 [2.109(3)]
Ni–O(8)	2.0033	Ni(1)–N(2)	2.170 [2.105(3)]
IR frequencies/$\mathrm{cm^{-1}}$ (assignment)			
Experimental	Calculated	Experimental	Calculated
228 s ($\nu_{\mathrm{Ni–O}}$)	228.0	202 s ($\nu_{\mathrm{Ni–O}}$)	208.5
248 m ($\nu_{\mathrm{Ni–O}}$)	243.7	303 m ($\nu_{\mathrm{Ni–N}}$)	343.8; 413.3
437 m	427.5	533 m	522.3
536 m	509.2; 523.0	1345 s ($\nu_{\mathrm{C=C}}$)	1330.3
		1419 s ($\nu_{\mathrm{C=C}}$)	1403.5
1369 m ($\nu_{\mathrm{C=C}}$)	1347.8; 1351.4	1458 s ($\nu_{\mathrm{N–C=}}$; $\nu_{\mathrm{C=C\ in\ Ar}}$)	1455.0
1454 s ($\nu_{\mathrm{N–C=}}$; $\nu_{\mathrm{C=C\ in\ Ar}}$)	1405.9; 1454.4	1540 vs ($\nu_{\mathrm{C–N=}}$)	1507.0; 1513.1
1527 m ($\nu_{\mathrm{C=N–}}$; $\nu_{\mathrm{C=C\ in\ Ar}}$)	1496.9	1573 vs ($\nu_{\mathrm{C=C–O}}$)	1569.4; 1578.2
1583 vs ($\nu_{\mathrm{C=C–O}}$)	1574.9	1613 s ($\nu_{\mathrm{C=O\ coord.}}$)	1603.5
1618 vs ($\nu_{\mathrm{C=O\ coord.}}$)	1607.4	1658 m ($\nu_{\mathrm{C=O\ non\text{-}coord.}}$)	1686.4
1667 m ($\nu_{\mathrm{C=O\ non\text{-}coord.}}$)	1707.8	2875 s ($\nu_{\mathrm{CH_2–}}$)	2843.7
2980 s (ν_{Me})	2932.7	2929 s ($\nu_{\mathrm{CH_2–}}$)	2975.4–2917.3
3400 br ($\nu_{\mathrm{OH\ solv.}}$)	3725.8	3337 br (ν_{OH}; $\nu_{\mathrm{NH_2\ solv.}}$)	3356.0–3437.2

ethanol and the resulting complexes were isolated as solids. Product **2** was characterized by single crystal X-ray diffraction, which evidenced the formation of an octahedral $\mathrm{Ni^{II}}$ complex by condensation of ethylenediamine only with the exocyclic enolic oxygen atom of 2AID. The IR spectra of complexes **1** and **2** in KBr confirmed the coordination of one carbonyl and the deprotonated enolic group of 2AID by a clear downshift of $\nu_{\mathrm{C=O}}$ and $\nu_{\mathrm{C=C–OH}}$ vibrations from 1653 and 1592 $\mathrm{cm^{-1}}$ for 2AID[6] to 1618 and 1583 $\mathrm{cm^{-1}}$ for compound **1** as well as to 1613 and 1573 $\mathrm{cm^{-1}}$ for product **2** (Table 1 and Online Supplementary Materials). Partial condensation of ethylenediamine and its coordination to the $\mathrm{Ni^{II}}$ ion was supported by the additional IR vibrations at 1540 and 1419 $\mathrm{cm^{-1}}$ in complex **2** as well as by the shift of the vibrations at 1454 and 1369 $\mathrm{cm^{-1}}$ for compound **1** to 1458 and 1345 $\mathrm{cm^{-1}}$ after its conversion into compound **2**, these vibrations could be assigned to the coordinated secondary amine groups and corresponding C–N–C bonds. Moreover, vibrations for the ethylene moiety and coordinated amine groups are clearly seen in the IR spectrum of complex **2** at 2929–2875 $\mathrm{cm^{-1}}$ and at 3337–3264 $\mathrm{cm^{-1}}$, respectively. Comparison of the far IR spectra for compounds **1** and **2** recorded in CsI revealed the formation of a Ni–N coordination bond in complex **2** by the emergence of a new band at 303 $\mathrm{cm^{-1}}$.

According to the X-ray data‡ of complex **2**, $\mathrm{Ni^{II}}$ ion has an octahedral geometry where the oxygen atoms from the coordinated carbonyl groups of the two 2AID ligands are in *cis*-position, and most of bond angles deviate from the 90 and 180° values (see Figure 1 and Online Supplementary Materials).

While our synthetic efforts to obtain the $\mathrm{Ni^{II}}$ complex of the unsaturated cyclam-like macrocycle are still in progress, the theoretical calculations suggest that the complex is sterically hindered. In the attempted synthetic route (see Scheme 1) different solvents were used to attain various reflux temperatures. Continuous reflux of complex **2** in ethanol or Cellosolve for 24–120 h with or without ethylenediamine and/or strong base resulted in formation of a complicated mixture of paramagnetic species as evidenced by ^{1}H NMR investigation.

Quantum chemical calculations were carried out for complexes **1** and **2** using the DFT methods UB3LYP/6-31G(d,p) and UB3LYP/6-311G(d,p)[21,22] implemented in a Gaussian 2003 software suite.[23] In addition, we modeled the structure of the anticipated fully cyclized 2AID-conjugated unsaturated cyclam-like tetraaza macrocycle as well as its $\mathrm{Ni^{II}}$ complex (see Online Supplementary Materials). The geometry optimizations for compounds **1** and **2** assuming total spin $S = 1$ for an octahedral d^8 ion converge to experimentally relevant structures. For

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‡ *Crystal data for* **2**. $\mathrm{C_{26}H_{26}N_4NiO_4}$ ($M = 517.22$), monoclinic, space group $P2_1/n$, $a = 14.9563(16)$, $b = 10.9514(12)$ and $c = 17.6484(15)$ Å, $\beta = 103.484(3)°$, $V = 2811.0(5)$ Å^3, $Z = 4$, $d_{\mathrm{calc}} = 1.222$ g cm^{-3}, $\mu = 0.725$ mm^{-1}, $T = 300(2)$ K. The analysis was carried out using a Bruker SMART X2S benchtop diffractometer with doubly-curved silicon crystal monochromated MoKα radiation ($\lambda = 0.71073$ Å). The diffraction data were corrected for absorption effects by multi-scan method. Unit cell parameters were calculated and refined from the full data set. Total 3519 reflections were collected, from which 2884 unique reflections ($R_{\mathrm{int}} = 0.0401$) were used for refinement, the completeness to θ was 99.7%. The structure was solved by full-matrix least squares procedure based on F^2 using a SHELX Version 2014 program package[17] implemented in OLEX[18] and WinGX[19] software suites. All non-hydrogen atoms were refined anisotropically, the hydrogen atoms positions were calculated using a riding model in isotropic approximation. Disordered molecule of ethanol was removed from the final solution using a SQUEEZE tool of the PLATON program.[20] GOF = 1.066 at F^2; final R values [$I > 2\sigma(I)$]: $R_1 = 0.0409$, $wR_2 = 0.0971$; R values (all reflections): $R_1 = 0.0532$, $wR_2 = 0.1037$; largest diff. peak/hole 0.39/–0.35 e Å^{-3}.

CCDC 1993691 contains the supplementary crystallographic data for this paper. These data can be obtained free of charge from The Cambridge Crystallographic Data Centre *via* http://www.ccdc.cam.ac.uk.

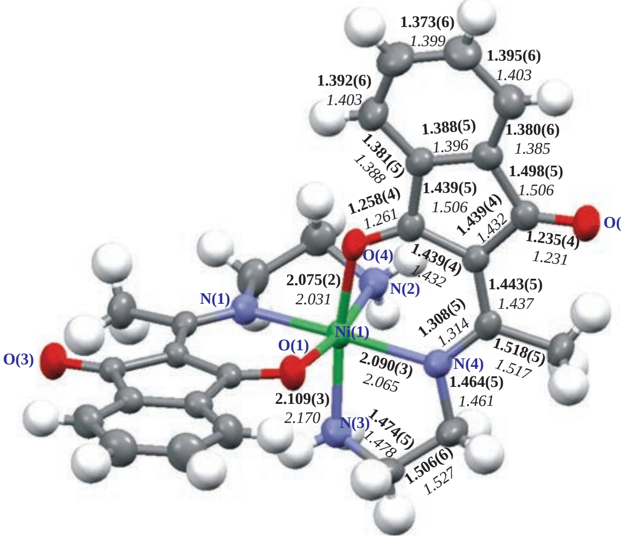

Figure 1 Molecular structure of complex **2**. Selected bond length (Å) from the X-ray data analysis are indicated in the image in bold and the ones from DFT optimization with UB3LYP/6-31G(d,p) (total spin *S* = 1) are indicated in italics. Selected bond angles (°) from the X-ray data: O(1)–Ni(1)–O(4) 88.3(1), O(1)–Ni(1)–N(1) 89.7(1), O(1)–Ni(1)–N(4) 97.5(1), O(1)–Ni(1)–N(3) 87.7(1), O(1)–Ni(1)–N(2) 170.5(1), O(4)–Ni(1)–N(1) 96.8(1), O(4)–Ni(1)–N(4) 89.6(1), O(4)–Ni(1)–N(3) 169.8(1), O(4)–Ni(1)–N(2) 87.6(1), N(1)–Ni(1)–N(4) 170.5(1), N(1)–Ni(1)–N(3) 92.5(1), N(1)–Ni(1)–N(2) 82.3(1), N(4)–Ni(1)–N(3) 81.7(1), N(4)–Ni(1)–N(2) 91.0(1), N(3)–Ni(1)–N(2) 97.7(1).

complex **2** a very good agreement has been obtained between the calculated data using UB3LYP/6-31G(d,p) and the X-ray results (see Figure 1). The same holds for the calculated and experimental IR frequencies for compounds **1** and **2**. Selected bond lengths and vibrational frequencies for both complexes are given for comparison in Table 1. Whereas the models for the high spin octahedral Ni^{II} complex of 2AID and its ethylenediamine conjugate, namely complexes **1** and **2**, reveal structural parameters very close to the experimental data, the calculations for a four-coordinated low-spin Ni^{II} complex of anticipated 2AID–ethylenediamine tetraaza macrocycle result in too short Ni–N bond lengths and short N···N distances (Table S8, Online Supplementary Materials). In fact, the RB3LYP/6-31G(d,p)-optimized Ni–N bond lengths are in the range 1.873–1.870 Å, whereas the experimentally reported ones for four-coordinated Ni^{II} complexes of tetraaza macrocycles are well above 1.94 Å.[24] Moreover, we examined the Mulliken charges at the carbon and oxygen (or nitrogen) atoms in complexes **1** and **2**, and they also indicated that the coordinated carbonyl groups of 2AID in the complexes were less prone to nucleophilic attack and condensation with ethylenediamine compared with the enolic carbon atoms (Table S11, Online Supplementary Materials). The calculated Mulliken charges at the carbonyl carbon atoms of 2AID in complex **1** are 0.373, whereas those at the enolic carbon atoms are 0.407. After formation of complex **2**, the Mulliken charges at the carbonyl carbon atoms decrease to 0.368, which makes them even less suitable for nucleophilic attack by the second amine group of ethylenediamine.

These experimental results agree well with the previously reported regioselectivity of 2-acyl-1,3-indandiones,[10–12] indicating that only the exocyclic enolic carbon atom participates in condensation reactions with amines. Our attempts to complete the cyclization involved reflux of complex **2** with ethylenediamine in Cellosolve at 135 °C for 3–5 days with and without NaOH, and under these conditions full cyclization did not occur. However, a photochemical activation could possibly induce alternative pathways for this reaction.

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Online Supplementary Materials

Supplementary data associated with this article can be found in the online version at doi: 10.1016/j.mencom.2020.07.039.

References

1 K. K. Palkina and A. N. Kochetov, *Russ. J. Inorg. Chem.*, 2011, **56**, 875 (*Zh. Neorg. Khim.*, 2011, **56**, 933).
2 K. K. Palkina and A. N. Kochetov, *Russ. J. Inorg. Chem.*, 2010, **55**, 889 (*Zh. Neorg. Khim.*, 2010, **55**, 953).
3 A. N. Kochetov and L. G. Kuz’mina, *Russ. J. Inorg. Chem.*, 2009, **54**, 248 (*Zh. Neorg. Khim.*, 2009, **54**, 283).
4 A. Ahmedova, P. Marinova, S. Ciattini, N. Stoyanov, M. Springborg and M. Mitewa, *Struct. Chem.*, 2009, **20**, 101.
5 A. Ahmedova, O. Cador, L. Sorace, S. Ciattini, D. Gatteschi and M. Mitewa, *J. Coord. Chem.*, 2008, **61**, 3879.
6 V. Enchev, A. Ahmedova, G. Ivanova, I. Wawer, N. Stoyanov and M. Mitewa, *J. Mol. Struct*., 2001, **595**, 67.
7 K. K. Palkina, A. N. Kochetov, E. V. Savinkina and L. Yu. Alikberova, *Russ. J. Inorg. Chem.*, 2006, **51**, 1743 (*Zh. Neorg. Khim.*, 2006, **51**, 1852).
8 W. A. Mosher and I. S. Bechara, *J. Heterocycl. Chem.*, 1970, **7**, 843.
9 T. L. Lemke and G. R. Parker, *J. Heterocycl. Chem.*, 1980, **17**, 1519.
10 V. Enchev, G. Ivanova, G. Pavlović, M. Rogojerov, A. Ahmedova and M. Mitewa, *J. Mol. Struct.*, 2003, **654**, 11.
11 A. Ahmedova, B. Aleksiev, E. Stanoeva, N. Stoyanov and M. Mitewa, *J. Univ. Chem. Technol. Metall*., 2005, **40**, 265.
12 A. Ahmedova, N. Burdzhiev, S. Ciattini, E. Stanoeva and M. Mitewa, *C. R. Chim.*, 2010, **13**, 1269.
13 Y.-S. Chen, P.-Y. Kuo, T.-L. Shie and D.-Y. Yang, *Tetrahedron*, 2006, **62**, 9410.
14 W. A. Mosher and S. Piesch, *J. Org. Chem*., 1970, **35,** 2109.
15 R. N. Prasad and N. Sharma, *J. Indian Chem. Soc.*, 2012, **89**, 29.
16 P. Bamfield, *J. Chem. Soc. A*, 1969, 2021.
17 G. M. Sheldrick, *Acta Crystallogr., Sect. C: Struct. Chem.*, 2015, **71**, 3.
18 O. V. Dolomanov, L. J. Bourhis, R. J. Gildea, J. A. K. Howard and H. Puschmann, *J. Appl. Crystallogr.*, 2009, **42**, 339.
19 L. J. Farrugia, *J. Appl. Crystallogr*., 2012, **45**, 849.
20 A. L. Spek, *Acta Crystallogr. Sect. C: Struct. Chem.*, 2015, **71**, 9.
21 A. D. Becke, *J. Chem. Phys.*, 1993, **98**, 5648.
22 C. Lee, W. Yang and R. G. Parr, *Phys. Rev. B*, 1988, **37**, 785.
23 M. J. Frisch, G. W. Trucks, H. B. Schlegel, G. E. Scuseria, M. A. Robb, J. R. Cheeseman, J. A. Montgomery, Jr., T. Vreven, K. N. Kudin, J. C. Burant, J. M. Millam, S. S. Iyengar, J. Tomasi, V. Barone, B. Mennucci, M. Cossi, G. Scalmani, N. Rega, G. A. Petersson, H. Nakatsuji, M. Hada, M. Ehara, K. Toyota, R. Fukuda, J. Hasegawa, M. Ishida, T. Nakajima, Y. Honda, O. Kitao, H. Nakai, M. Klene, X. Li, J. E. Knox, H. P. Hratchian, J. B. Cross, V. Bakken, C. Adamo, J. Jaramillo, R. Gomperts, R. E. Stratmann, O. Yazyev, A. J. Austin, R. Cammi, C. Pomelli, J. W. Ochterski, P. Y. Ayala, K. Morokuma, G. A. Voth, P. Salvador, J. J. Dannenberg, V. G. Zakrzewski, S. Dapprich, A. D. Daniels, M. C. Strain, O. Farkas, D. K. Malick, A. D. Rabuck, K. Raghavachari, J. B. Foresman, J. V. Ortiz, Q. Cui, A. G. Baboul, S. Clifford, J. Cioslowski, B. B. Stefanov, G. Liu, A. Liashenko, P. Piskorz, I. Komaromi, R. L. Martin, D. J. Fox, T. Keith, M. A. Al-Laham, C. Y. Peng, A. Nanayakkara, M. Challacombe, P. M. W. Gill, B. Johnson, W. Chen, M. W. Wong, C. Gonzalez and J. A. Pople, *Gaussian 03, Revision D.01*, Gaussian, Inc., Wallingford CT, 2004.
24 T.-H. Lu, C.-S. Chung and T. Ashida, *J. Chin. Chem. Soc.*, 1991, **38**, 147.

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