s-Indacene-1,3,5,7(2H,6H)-tetraone ('Janus dione') and 1,3-Dioxo-5,6-indanedicarboxylic Acid: Old and New 1,3-Indandione Derivatives

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Abstract: Efficient syntheses, X-ray structures and spectroscopic properties of s-indacene-1,3,5,7(2H,6H)-tetraone (**1**) and 1,3-dioxo-5,6-indanedicarboxylic acid (**2**), their precursors and derivatives, are described for the first time.

**Key words:** arenes, s-indacene, ketones, indandiones, hydrolyses

Recently we demonstrated that the condensation products of s-indacene-1,3,5,7(2H,6H)-tetraone (**1**) with p-dialkyl-amino derivatives of benzaldehyde and cinnamaldehyde possess large two-photon absorption (TPA) cross-section coefficient and high quantum yields of fluorescence, which makes them attractive chromophores for two-photon fluorescent imaging.[1] The TPA behaviour of these chromophores was attributed, in particular, to the unusual orbital structure of 2,6-diylidene substituted derivatives. The above finding and high potential of **1** as a precursor for other s-indacene derivatives was the driving force for studying its chemistry in more detail. However, the literature search showed that the synthesis of **1**, which we propose to name as 'Janus dione', is still a challenge.

Thus, the first attempts to synthesize **1** by mineral acid catalyzed hydrolysis of the 2,6-diethoxycarbonyl derivative and subsequent decarboxylation in analogy to the well known procedure for 1,3-indandione, afforded only a black insoluble polymer as a result of self-condensation.[2] Back in 1963, one of us found that **1** formed grey leaflets in low yields, when the hydrolysis was performed in HOAc.[3] Unfortunately, to the best of our knowledge, this is the only method known to date. The practical yields of **1** never exceeded 10% of the theoretical values. Moreover, the reaction often fails completely giving a polymer as the only product.

We investigated the condensation reaction of pyromellitic anhydride with ethyl acetoacetate in the presence of Et_3N in acetic anhydride and report here on efficient high yield synthesis of **1** and previously unknown 1,3-dioxo-5,6-indanedicarboxylic acid (**2**) (Scheme 1). We found that whereas the above modification afforded good yields of the salt **3**, it was always contaminated with the mono-con-

densation product **4**, which can easily be determined by ^{1}H NMR spectrum of the crude reaction mixture. All previous syntheses of **5** (or the dimethoxycarbonyl derivative) employed condensation of pyromellitic acid tetraester with ethyl (or methyl) acetate in the presence of sodium alcoholates.[2,3] The purity of poorly soluble disodium salt of **5** cannot be effectively controlled. Neutral diester **5** also possesses a very low solubility, is unstable at elevated temperatures and cannot be purified either by crystallization or chromatography. When this compound, prepared by the acidification of **3**, was contaminated with **6**, it afforded only or mostly the polymer even in HOAc. Therefore, the purity of **3** is crucial.

The optimized procedures for synthesis of **3** and **4**, afforded the clean compounds in 60% and 50% yields, respectively. The structure of both compounds was determined by X-ray diffraction analyses (Figures 1 and 2).
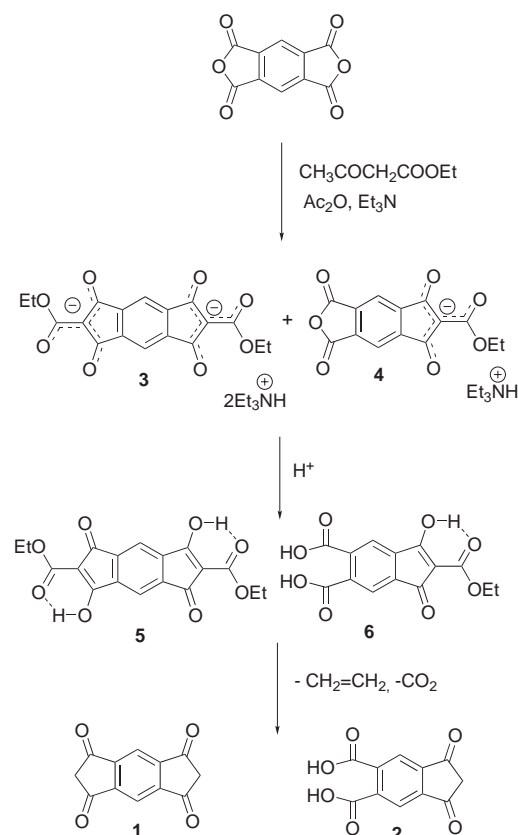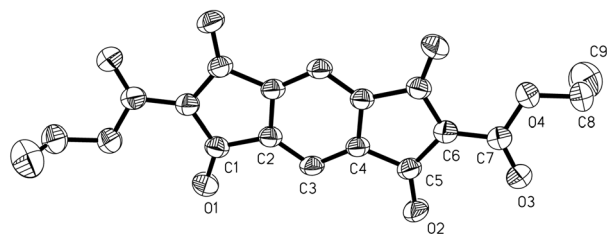

Scheme 1

Figure 1 ORTEP of **3** at 50% probability level for non-hydrogen atoms. The triethylammonium cations and hydrogen atoms are omitted for clarity. Selected distances: C1-O1, 1.231 (2); C1-C2, 1.505 (2); C5-O2, 1.240 (2); C5-C6, 1.432 (2); C1-C6 (–x + 1, –y, –z), 1.437 (2).
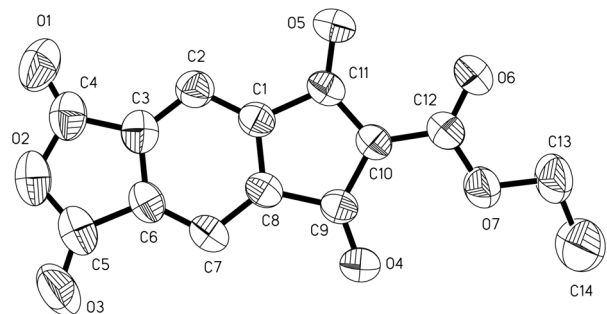

Figure 2 ORTEP of one of two crystallographically independent molecules of **4** at 50% probability level. The triethylammonium cation and hydrogen atoms are omitted for clarity. Selected distances: C4-O1, 1.177 (5); C4-O2, 1.403 (5); C3-C4, 1.472 (5); C5-O3, 1.210 (5); C5-O2, 1.369 (5); C5-C6, 1.471 (5).

Neutral ester derivatives **5** and **6** decomposed on crystallization attempts. However, we found that refluxing both derivatives in anhydrous polar solvents afforded pure **1** or **2** in almost quantitative yields. The purity and the yields of the products depended on the presence of water; using thoroughly dried **5** and **6** in absolute MeCN gave the best results. This surprising finding led us to believe that both **5** and **6**, being very strong O-H acids, are capable of self-protonation and decarboxylation occurs after elimination of ethylene. The reaction indeed did not occur with the corresponding methyl esters.

'*Janus* dione' forms colourless leaflets when it precipitates from the MeCN reaction mixtures and sublimes above 277 °C, forming colourless plates poorly soluble in most common organic solvents. Crystals suitable for X-ray analysis were obtained from an MeCN solution of a freshly sublimed sample (Figure 3). '*Janus* dione' undergoes fast polymerization in the presence of acids, but forms stable dianion in the presence of bases. The UV–Vis spectrum of the dianion solution features a broad structured band around 500 nm (ε = 2,600) (Figure 4). The chemical properties of **1** resemble that of 1,3-indandione in many aspects and will be reported elsewhere.

1,3-Dioxo-5,6-indanedicarboxylic acid (1,3-indandione-5,6-dicarboxylic acid) (**2**) is hitherto unknown. It precipitates from the MeCN reaction mixture as colourless needles and sublimes under elimination of water above 224
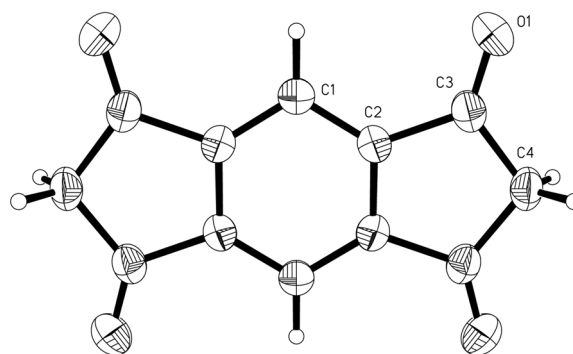
Figure 3 ORTEP of **1** at 50% probability level. Selected distances: C2-C3, 1.496 (2); C3-O1, 1.203 (2); C3-C4, 1.512 (2).
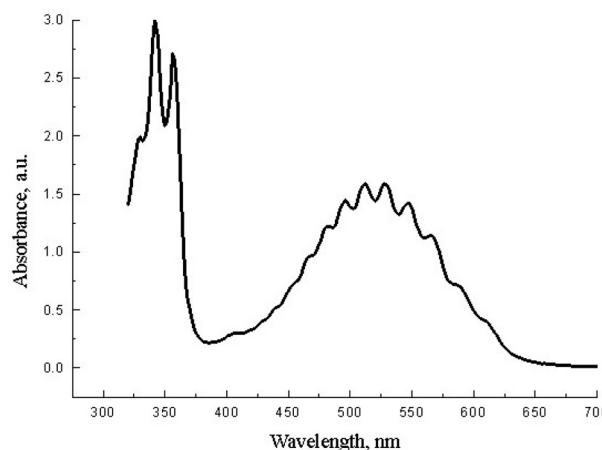

Figure 4 Absorption spectrum of a mixture of **1** and two equivalents of DBU in DMSO.

°C. The X-ray quality crystals were obtained from MeCN (Figure 5). Even clean samples of **2** are unstable and decompose slowly within a few weeks, forming a complicated mixture of self-condensation products.

Heating of **2** in a mixture of toluene and acetic anhydride afforded 1,3,7-trioxo-3,7-dihydro-1*H*-indeno[5,6-c]furan-5-yl acetate (**7**), which is stable in the absence of moisture. In the presence of basic or acidic catalysts, this derivative can be used as a relatively stable synthetic equivalent of **2**. The reactivity of **2** is similar to that of 1,3-indandione. In particular, it reacts smoothly with *p*-diethylamino derivatives of benzaldehyde and cinnamaldehyde in the presence of mineral acids affording the corresponding donor/acceptor substituted alkene derivatives **8** and **9** (Figure 6). The long wave absorption band of derivative **8** is red-shifted by about 30 nm compared to its 5,6-unsubstituted analog 2-*p*-diethylaminobenzylidene-1,3-indandione[4] [λ_{max} (CH$_2$Cl$_2$) = 488 nm, ε = 77,000].

Upon heating derivatives **8** and **9** in acetic anhydride the corresponding cyclic anhydrides are formed easily. Albeit poorly soluble, both anhydrides are highly reactive and rapidly form mono-esters and cyclic imides in reactions with alcohols and primary amines, respectively. Since the 2-ylidene-1,3-indandione-5,6-dicarboxylic acid moiety is
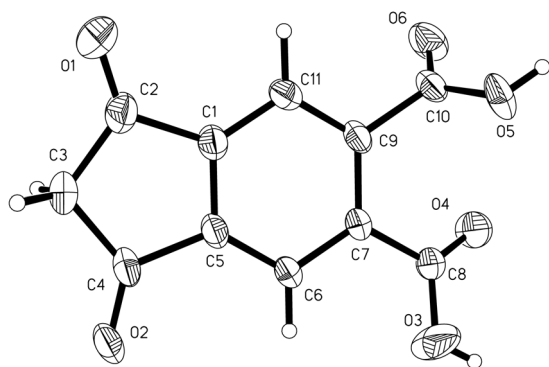
Figure 5 ORTEP of **2** at 50% probability level. Selected distances C2-O1: 1.204 (2); C1-C2: 1.499(2); C2-C3: 1.518 (2); C4-O2: 1.219 (2); C4-C5: 1.482 (2); C3-C4: 1.503 (2).

a stronger acceptor than 2-ylidene-1,3-indandione moiety, these derivatives are expected to be more effective second harmonic generation (SHG) chromophores than the corresponding derivatives of 1,3-indandione.[5] In addition, the presence of two *o*-carboxylic groups offers wide opportunities for further structural modifications and, owing to their hydrophilic properties, allows studies of such chromophores using the Langmuir technique and fabrication of SHG capable LB films. These studies are currently under way in our research labs.
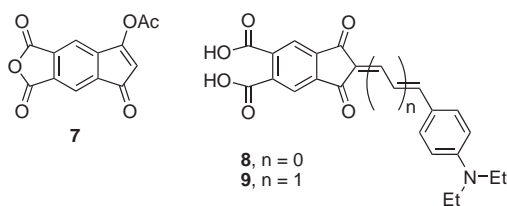

Figure 6

In summary, we elaborated reproducible synthetic procedures and for the first time characterized two simple 1,3-indandione derivatives: *s*-indacene-1,3,5,7(2*H*,6*H*)-tetraone (**1**) and 1,3-dioxo-5,6-indanedicarboxylic acid (**2**). Both compounds can serve as valuable precursors for molecular and polymeric advanced materials.

IR spectra were recorded by Nicolet 5ZDX instrument and UV–Vis spectra by Jasco 2500 spectrophotometer. NMR spectra were recorded on a Bruker DMX 500 MHz instrument.

3,7-Dioxy-1,5-dioxo-1,5-dihydro-*s*-indacene-2,6-dicarboxylic Acid Diethyl Ester Bis(triethylammonium) Salt (3); Typical Procedure
Heating a mixture of pyromellitic anhydride (1 equiv), ethyl acetoacetate (3 equiv), Et$_3$N in (12 equiv) acetic anhydride (16 mL per 1 g of pyromellitic anhydride) at 100 °C for 1.5 h and leaving the mixture overnight at 0–5 °C afforded a precipitate of clean **3** in 60% yield, which was washed with acetic anhydride and Et$_2$O. Orange large crystals become brown at 120 °C and decomposed at 140 °C.

^{1}H NMR (CDCl$_3$): δ = 1.26 (t, 18 H, CH$_3$), 1.30 (t, 6 H, CH$_3$), 3.22 (m, 12 H, CH$_2$N), 4.18 (q, 4 H, CH$_2$O), 7.61 (s, 2 H, CH).

HRMS: *m/z* [M – 2 Et$_3$N] calcd for C$_{18}$H$_{15}$O$_8$: 359.0767; found: 359.0700.

7-Oxy-1,3,5-trioxo-3,5-dihydro-1*H*-2-oxa-*s*-indacene-6-carboxylic Acid Ethyl Ester Triethylammonium Salt (4); Typical Procedure
A mixture of pyromellitic anhydride and ethyl acetoacetate (1:1 equiv) with Et$_3$N (6 equiv) in acetic anhydride (16 mL per 1 g of pyromellitic anhydride) was heated at 70 °C for 15 min following overnight cooling at 0–5 °C afforded a precipitate of clean **4** in 54% yield, which was washed with acetic anhydride and Et$_2$O. Yellow-orange large crystals become green at 120 °C and decomposed at 140 °C.

^{1}H NMR (CDCl$_3$): δ = 1.33 (t, 9 H, CH$_3$), 1.35 (t, 3 H, CH$_3$), 1.68 (br s, 1 H, NH), 3.30 (m, 6 H, CH$_2$N), 4.23 (q, 2 H, CH$_2$O), 8.01 (s, 2 H, CH).

HRMS: *m/z* [M – Et$_3$N] calcd for C$_{14}$H$_9$O$_7$: 289.0348; found: 289.0344.

_s_-Indacene-1,3,5,7(2*H*,6*H*)-tetraone (1); Typical Procedure
Concentrated H$_2$SO$_4$ acid (1 mL) was added to a solution of **3** (1 g, 1.78 mmol) in water (100 mL) at 0 °C. The orange precipitate was filtered off, washed with EtOH (25 mL) and thoroughly dried at r.t. to give **5** (0.6 g, 94%). A suspension of **5** (1 g, 2.79 mmol) and anhyd MeCN (100 mL) was heated under reflux for 2 h. After cooling to r.t. the colourless precipitate was filtered off and dried to give **1** (0.54 g, 90%). The compound was crystallized from MeCN as colourless leaflets. It sublimes above 277 °C.

IR (KBr): 2962, 2925, 1757, 1724, 1714, 1693, 1385, 1362, 1350, 1225, 874, 733 cm^{-1}.

^{1}H NMR (CD$_2$Cl$_2$): δ = 3.39 (s, 4 H, CH$_2$), 8.44 (s, 2 H, CH).

1,3-Indandione-5,6-dicarboxylic Acid (2); Typical Procedure
Concentrated H$_2$SO$_4$ acid (4 mL) was added to a solution of **4** (1 g, 2.57 mmol) in water (50 mL) at 0 °C. The yellow precipitate was filtered, washed with EtOH (5 mL) and thoroughly dried at r.t. to give **6** (0.75 g, 95%). A suspension of **6** (1 g, 3.26 mmol) and anhyd MeCN (100 mL) was heated under reflux for 30 min. The solvent was removed under reduced pressure to give **2** (0.8 g, 95%). Pure product (0.75 g, 90%) was obtained by crystallization from MeCN as colourless needles. It sublimes above 224 °C under elimination of water.

IR (KBr): 3356 (br), 3099, 3050, 2918, 1736, 1693, 1252, 1232, 1196, 1128, 895, 783, 768 cm^{-1}.

^{1}H NMR (acetone-*d*$_6$): δ = 8.20 (s, 2 H, CH), 3.41 (s, 2 H, CH$_2$).

1,3,7-Trioxo-3,7-dihydro-1*H*-indeno[5,6-c]furan-5-yl Acetate (7); Typical Procedure
A mixture of **2** (0.2 g, 0.85 mmol), freshly distilled acetic anhydride (5 mL) and toluene (5 mL) was heated at 90 °C for 1 h. The orange precipitate was filtered off, washed with toluene (20 mL) to give **7** (0.14 g, 63%). Crystallization of pure **7** from toluene afforded yellow needles; mp 174 °C. Yellow crystals; mp 174 °C. X-Ray structure of **7** was determined and will be reported elsewhere.

IR (KBr): 2930, 1849, 1797, 1771, 1709, 1565, 1454, 1376, 1273, 1153, 904, 833, 781, 742 cm^{-1}.

^{1}H NMR (CDCl$_3$): δ = 2.48 (s, 3 H, CH$_3$CO), 6.45 (s, 1 H, CH), 7.84 (s, 1 H, CH), 8.03 (s, 1 H, CH).

Anal. Calcd for C$_{13}$H$_6$O$_6$: C, 60.48; H, 2.34. Found: C, 60.53; H, 2.29.

X-ray Crystal Structure Determinations
Intensity data for X-ray structure determination were collected with Bruker diffractometer, 6K CCD detector [λ(MoK$_α$) = 0.711069A,

graphite monochromator, 1800 frames with a scan width of 0.3° in ω for full sphere coverage of reciprocal space and 50 frames for decay correction, and exposure time of 10 s/frame, detector-crystal distance 4.95 cm] and integrated with Bruker Saint software package using a wide-frame integration algorithm. All structures were solved by direct methods and refined by least squares in full-matrix anisotropic approximation for all non-hydrogen atoms. The hydrogen atoms were included with geometrically calculated positions and refined using 'riding model'. Bruker SHELX software package was used for all calculations and drawings.

A yellow block ($0.5 \times 0.4 \times 0.4$ mm) of **3** is monoclinic, $C_{18}H_{12}O_8 \times 2$ (Et$_3$NH), space group P2$_1$/n, at 298 K, $a = 10.687(1)$, $b = 13.365(2)$, $c = 11.701(2)$ Å, $\beta = 112.202(3)°$, V = 1547.5 (3) Å^3, Z = 2, F(000) = 604. 12867 reflections were collected ($2\theta < 56.58°$), of which 3850 reflections were independent ($R_{int} = 0.0358$ and 1806 with $F_o > 4\sigma(F_o)$): 189 parameters. Structure was refined to $R1 = 0.0463$, $wR2 = 0.1210$, GOF = 0.974. An orange prism ($0.7 \times 0.4 \times 0.3$ mm) of **4** is monoclinic, $C_{14}H_7O_7 \times$ Et$_3$NH, space group $P1$, at 298 K, $a = 10.440(1)$, $b = 13.998(2)$, $c = 15.088(2)$ Å, $\alpha = 69.824(3)°$, $\beta = 73.989(3)°$, $\gamma = 88.154(3)°$, V = 1984.5 (4) Å^3, Z = 4, F(000) = 824. A total of 17816 reflections were collected ($2\theta < 49.42°$), of which 6761 reflections were independent ($R_{int} = 0.0471$) and 4365 with $F_o > 4\sigma$ (F_o): 521 parameters. Structure was refined to $R1 = 0.0831$, $wR2 = 0.256$, GOF = 1.005. A colourless plate ($0.2 \times 0.2 \times 0.05$ mm) of **1** is orthorhombic, $C_{12}H_6O_4$, space group Cmca, at 293 K, $a = 18.962(2)$, $b = 5.782(2)$, $c = 8.353(2)$ Å, V = 915.9 (1) Å^3, Z = 4, F(000) = 440. 5149 reflections were collected ($2\theta < 56.58°$), of which 587 reflections were independent ($R_{int} = 0.0291$) and 495 with $F_o > 4\sigma(F_o)$: 47 parameters. Structure was refined to $R1 = 0.0405$, $wR2 = 0.1072$, GOF = 1.06. A colourless prism ($0.4 \times 0.4 \times 0.2$ mm) of **2** is monoclinic, $C_{11}H_6O_6$, space group P2$_1$/c, at 293 K, $a = 7.662(1)$, $b = 9.814(1)$, $c = 13.458(1)$ Å, $\beta = 106.128(2)°$, V = 972.2 (2) Å^3, Z = 4, F(000) = 8201 reflections were collected ($2\theta < 56.56°$), of which 2410 reflections were independent

($R_{int} = 0.0243$) and 2041 with $F_o > 4\sigma(F_o)$.: 179 parameters. Structure was refined to $R1 = 0.0463$, $wR2 = 0.1298$, GOF = 1.059.

The crystallographic data for structures **1**–**4** have been deposited with the Cambridge Crystallographic data Centre: CCDC 172783–172786.

Acknowledgment

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