organic compounds

6-Bromoindigo dye

David J. Szalda,[a]* Keith Ramig,[a] Olga Lavinda,[a] Zvi C. Koren[b] and Lou Massa[c]

[a]Department of Natural Sciences, Baruch College, Box A0506, 1 Bernard Baruch Way, New York, NY 10010, USA, [b]The Edelstein Center for the Analysis of Ancient Artifacts, Department of Chemical Engineering, Shenkar College of Engineering and Design, 12 Anna Frank Street, 52526 Ramat-Gan, Israel, and [c]Departments of Chemistry and Physics, Hunter College and the Graduate School, City University of New York, 695 Park Avenue, New York, NY 10065, USA

Correspondence e-mail: dszalda@baruch.cuny.edu

6-Bromoindigo (MBI) [systematic name: 6-bromo-2-(3-oxo-2,3-dihydro-1*H*-indol-2-ylidene)-2,3-dihydro-1*H*-indol-3-one], $C_{16}H_9BrN_2O_2$, crystallizes with one disordered molecule in the asymmetric unit about a pseudo-inversion center, as shown by the Br-atom disorder of 0.682 (3):0.318 (3). The 18 indigo ring atoms occupy two sites which are displaced by 0.34 Å from each other as a result of this packing disorder. This difference in occupancy factors results in each atom in the reported model used to represent the two disordered sites being 0.08 Å from the higher-occupancy site and 0.26 Å from the lower-occupancy site. Thus, as a result of the disorder, the C—Br bond lengths in the disordered components are 0.08 and 0.26 Å shorter than those found in 6,6′-dibromoindigo (DBI) [Süsse & Krampe (1979). *Naturwissenschaften*, **66**, 110], although the distances within the indigo ring are similar to those found in DBI. The crystals are also twinned by merohedry. Stacking interactions and hydrogen bonds are similar to those found in the structures of indigo and DBI. In MBI, an interaction of the type C—Br···C replaces the C—Br···Br interactions found in DBI. The interactions in MBI were calculated quantum mechanically using density functional theory and the quantum theory of atoms in molecules.

Comment

In nature, the violet 6-bromoindigo dye (commonly abbreviated as MBI, monobromoindigo) is an important colorant and one of three indigoids in the purple and violet pigments produced from the *Hexaplex* (= *Murex*) *trunculus* species of the Muricidae family of sea snails (Koren, 2008a). In antiquity, these and related Mediterranean molluscs were used for the production of red–purple or Tyrian Purple woollen dyes, as well as blue–purple dyes, for kings, emperors and high priests. MBI, which can be the major component of a purple molluscan pigment, is a chromatic marker for the *H. trunculus* snail, and thus detecting a significant quantity of it in an

archaeological pigment indicates that the malacological provenance of that pigment is this snail (Koren, 2008a). This colorant has been found, together with others, in pigments and dyes on archaeological artifacts dating back nearly four millennia as, for example, a paint pigment (Karapanagiotis, 2006; Karapanagiotis *et al.*, 2006; Sotiropoulou & Karapanagiotis, 2006; Koren, 2008a), as a residual pigment in a Phoenician dye vat (Koren, 1995) and as a textile dye (Koren, 1997, 2008b). The composition of MBI in the purple pigment, present together with the other two indigoids, *viz.* the blue–violet indigo (IND) and the red–purple 6,6′-dibromoindigo (DBI) dyes, thus affects the final color of the raw pigment and of dyes produced from it.


MBI
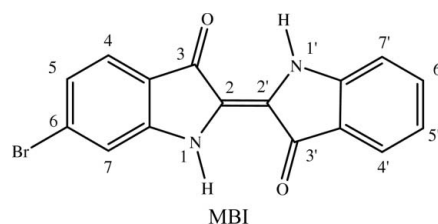
MBI has been studied chromatographically and spectrometrically (Wouters & Verhecken, 1991; Clark & Cooksey, 1999; Cooksey, 2001; Koren, 2006, 2008a,c; Nowik *et al.*, 2011), and colorimetrically (Clark & Cooksey, 1999). However, although the crystal structures of unsubstituted indigo (Reis & Schneider, 1928; von Eller, 1952, 1955; Gribova *et al.* 1956; Süsse & Wolf, 1980; Süsse *et al.*, 1988) and DBI (Süsse & Krampe, 1979; Larsen & Watjen, 1980; Süsse, 1983) have been determined, the exact structure of crystalline MBI has not been established previously. A preliminary study of MBI was reported by Ziderman *et al.* (2004) and the first X-ray structure of MBI (Fig. 1) to be detailed is reported herein.

Within the crystal structure, the MBI molecule is oriented in one direction with an occupancy of 0.682 (3), as depicted in Fig. 1, and in the other direction with an occupancy of 0.318 (3), so that the Br atom would be located near C6B. This is not a simple disordering, but, due to packing forces involving the Br atom, there is a slippage of the indigo ring so that all the atoms occupy two sites, which are displaced by about 0.34 Å between the two orientations. In Fig. 2, the indigo ring-atom disorder [0.682 (3):0.318 (3)] can be observed. The
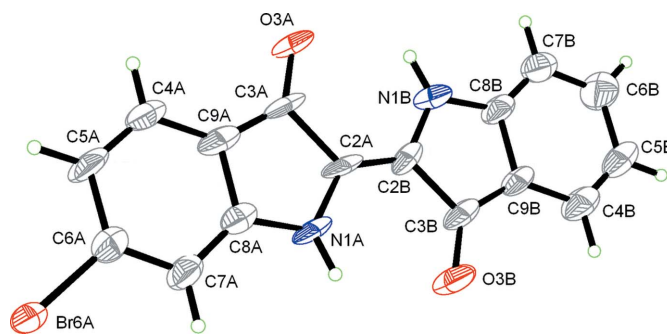
Figure 1
The molecular structure of MBI, showing the atom-numbering scheme. Displacement ellipsoids are drawn at the 50% probability level.
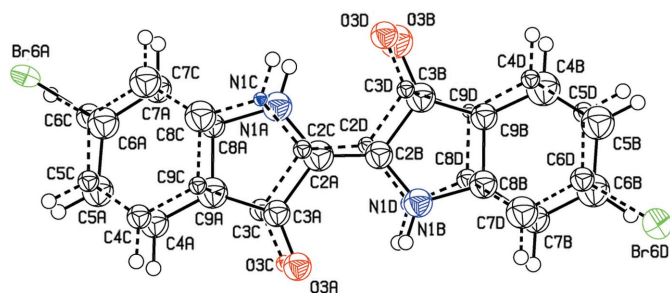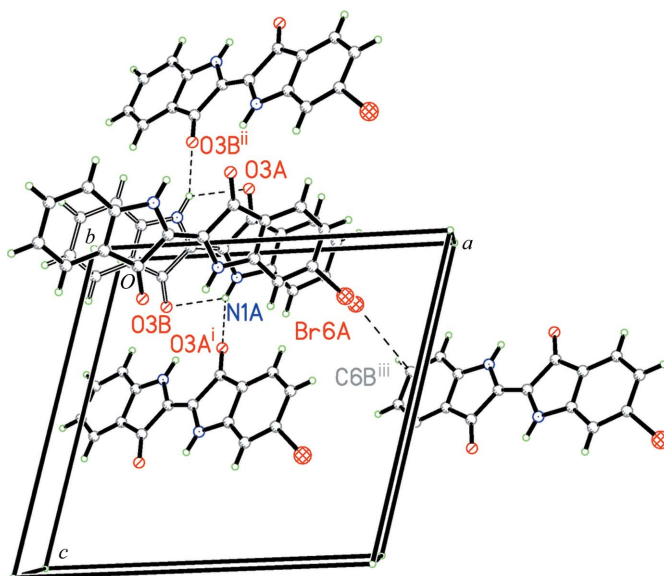
Figure 2
The isotropic refinement results for two disordered indigo rings. The positions of the atoms in the ring differ by 0.34 Å. In the proposed structure, the atoms are the weighted average of these two positions.

Figure 3
The stacking along $(x, y + 1, z)$ of MBI in the unit cell. The interactions between atoms Br6A and C6B[iii] and the N—H···O hydrogen-bonding interactions (details in Table 1) are shown as dashed lines. [Symmetry codes as in Table 1, additionally (iii) $x + 1, -y, z + \frac{1}{2}$.]

positions of the refined atoms in Fig. 1 are the weighted averages of the two positions in Fig. 2. Because all the atoms within the ring are shifted uniformly, the distances within the ring are similar to those found in DBI (Süsse & Krampe, 1979; Larsen & Watjen, 1980; Süsse, 1983), but the C—Br bond lengths are 0.08 and 0.26 Å shorter than those found in DBI. When the Br atom is attached to atom C6A, all the other atoms in the indigo ring are shifted 0.08 Å from the refined position of C6A (away from the Br atom, to the right in Fig. 1), while when the Br atom is attached to atom C6B, all the atoms in the ring are shifted 0.26 Å in the opposite direction (to the left in Fig. 1) from their refined positions. This disorder is too small to resolve but is reflected in the elongated displacement parameters of the atoms in the indigo ring. The Br atom is displaced by 0.28 (2) Å from the 18-atom mean plane [r.m.s. deviation = 0.04 (2) Å]. In DBI, the same 18 atoms are also planar (r.m.s. deviation = 0.04 Å), but the Br atom is only 0.09 Å out of this plane. The out-of-plane distortion of Br6A in MBI results in a decrease in the length of the Br6A···C6B interaction which is described below.

As in the IND and DBI structures, the molecules of MBI exhibit a stacking interaction along the *b* axis at a distance of 3.375 (5) Å between the best-fit planes [closest contacts: C2B···C7B[i] = 3.372 (11) Å and C9B···C6B[i] = 3.384 (12) Å; symmetry code: (i) $x, y - 1, z$], which is similar to the distances found in DBI [3.452 (1) Å; Süsse, 1983] and IND [3.345 (1) (Süsse *et al.*, 1988) and 3.401 (1) Å (Süsse & Wolf, 1980)].

MBI has two intramolecular hydrogen bonds between the imine H atom on one half of the molecule and the carbonyl O atom on the other half (see Table 1 for details). There are also intermolecular hydrogen bonds between the two imine H atoms and two carbonyl O atoms on symmetry-related molecules (Table 1). These hydrogen bonds connect molecules related by the *c*-glide. Each indigo molecule is hydrogen bonded to four others. This is a feature also found in IND and DBI. The major differences among the three structures are in the interactions made by the groups attached to C6A and C6B.

In IND, C5 and C6 have an interaction with an H atom on a symmetry-related molecule, with H···C distances of 2.81 (3) and 2.88 (3) Å, respectively. In DBI, atom Br6 exhibits two close contacts with the Br atoms of neighboring molecules. The Br···Br contact distances are each 3.531 (2) Å and the two C6—Br6···Br angles are 92.6 (1) and 167.6 (1)°, making

both contacts type 2 (Pedireddi *et al.*, 1994). As shown in Fig. 3, in MBI one of these Br···Br contacts is replaced by a Br6A···C6B interaction, with a distance of 3.510 (9) Å, and a Br6A···H6B contact of 3.25 Å replaces the other Br···Br contact. As mentioned previously, atom Br6 is bent out of the plane of the indigo ring towards atom C6B of a symmetry-related molecule at $(x + 1, -y, z + \frac{1}{2})$, which results in a close contact between atoms Br6A and C6B. In DBI, the corresponding distance is 4.083 (4) Å.

The asymmetry of the MBI molecule causes a different crystal packing from IND and DBI. Monomer, dimer and tetramer units were modeled in the gas phase and their wave functions were used to obtain Bader electron atomic charges (Bader & Zou, 1992; Bader & Matta, 2004). In each of these cases, the crystal structure geometry was maintained. Additionally, optimization of a single MBI molecule was performed.

To understand the nature of the short-contact interactions within the MBI crystal structure, we calculated the corresponding bond paths, which are definitive characteristics of all bonding interactions. The quantum theory of atoms in molecules (QTAIM) calculations performed using the *AIMALL* software package (Keith, 2010) reveal the presence of a C6B···Br6A bond path, which indicates attractive forces between atoms Br6A and C6B. Analysis of the electron density $\rho(r)$ contour plot (Fig. 4) shows that the C6B area has low electron density relative to that around atom Br6A. (Note, for example, the relatively greater number of contour lines around Br6A *versus* C6B.) There is less positive charge on C6B compared with neighboring atoms. Fig. 5 presents the calculated magnitude of MBI short-contact interactions as an indication of the stabilization which must occur in the experimental structure. The interaction energy I_1 between two
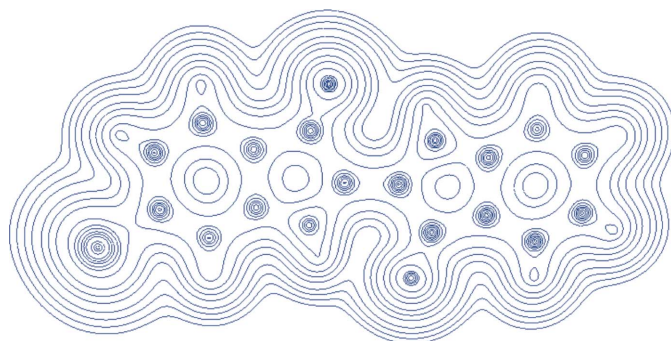
Figure 4
Electron density $\rho(r)$ contour plot calculated using QTAIM.
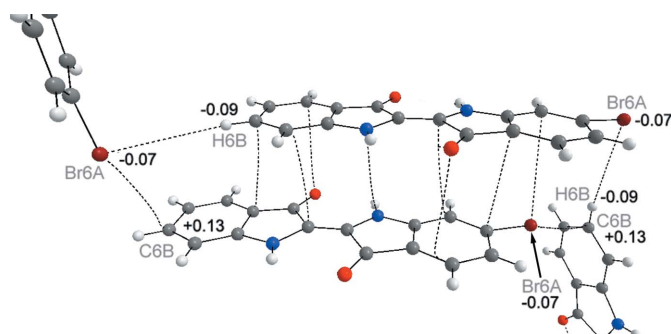
Figure 5
The MBI tetramer, showing bond paths calculated using QTAIM as dashed lines. Atomic charges, q (A), are indicated for selected atoms.

individual monomer units was computed as: $I_1 = E(\text{dimer}) - 2E(\text{monomer})$. The interaction energy I_2 for the C6B···Br6A and H6B···Br6A contacts combined was computed as: $I_2 = E(\text{trimer}) - E(\text{dimer}) - E(\text{monomer})$. These calculations gave $I_1 = -0.92$ kcal mol^{-1} and $I_2 = -0.79$ kcal mol^{-1} (1 kcal mol^{-1} = 4.184 kJ mol^{-1}). Thus, the experimental geometry of the MBI crystal structure results in attractive binding interactions, as expected.

In conclusion, suitable crystals of MBI of sufficient quality for X-ray diffraction have been obtained for the first time. These data complete the structural knowledge of naturally derived molecules with the same framework, namely IND, MBI and DBI. Such structural information opens possibilities for further studies of MBI behavior and its properties as a colorant.

Experimental

The title compound was prepared according to an established procedure (Clark & Cooksey, 1999). Crystals suitable for X-ray analysis were obtained by slow crystallization from boiling ethyl benzoate.

Crystal data

$C_{16}H_9BrN_2O_2$	$V = 641.8$ (3) Å^3
$M_r = 341.16$	$Z = 2$
Monoclinic, Pc	Mo $K\alpha$ radiation
$a = 12.347$ (3) Å	$\mu = 3.21$ mm^{-1}
$b = 4.6558$ (12) Å	$T = 173$ K
$c = 11.607$ (3) Å	$0.25 \times 0.10 \times 0.02$ mm
$\beta = 105.856$ (8)°	

Table 1
Hydrogen-bond geometry (Å, °).

D—H···A	D—H	H···A	D···A	D—H···A
N1A—H1A···O3A^{i}	0.88	2.12	2.916 (8)	150
N1A—H1A···O3B	0.88	2.37	2.895 (8)	119
N1B—H1B···O3B^{ii}	0.88	2.09	2.890 (9)	150
N1B—H1B···O3A	0.88	2.38	2.913 (9)	119

Symmetry codes: (i) $x, -y, z + \frac{1}{2}$; (ii) $x, -y + 1, z - \frac{1}{2}$.

Data collection

Bruker APEXII CCD area-detector diffractometer	4715 measured reflections
Absorption correction: multi-scan (SADABS; Bruker, 2005)	2180 independent reflections
$T_{min} = 0.513$, $T_{max} = 0.745$	1558 reflections with $I > 2\sigma(I)$
	$R_{int} = 0.056$

Refinement

$R[F^2 > 2\sigma(F^2)] = 0.059$	H-atom parameters not refined
$wR(F^2) = 0.141$	$\Delta\rho_{max} = 0.55$ e Å^{-3}
$S = 1.01$	$\Delta\rho_{min} = -0.60$ e Å^{-3}
2180 reflections	Absolute structure: Flack (1983), with 934 Friedel pairs
201 parameters	Flack parameter: 0.42 (2)
23 restraints	

The GAUSSIAN09 (Frisch et al., 2009) package of programs was used for theoretical calculations employing the B3LYP/6-31G(2d,2p) level of theory (Jacquemin, Preat & Perpéte, 2005; Jacquemin, Preat, Wathelet & Perpéte, 2005; Jacquemin et al., 2006). Diffraction data for MBI indicated monoclinic symmetry and systematic absences consistent with the space groups Pc and $P2/c$. Pc was used for the solution and refinement of the structure based on E statistics. No reasonable model could be found in the space group $P2/c$. Systematic absences and E statistics are inconsistent with the space group $P2_1/c$. A molecule of MBI does not have inversion symmetry but disordering results in a pseudo-inversion center in the molecule. Solution and refinement of the structure in the space group $P2_1/c$ resulted in an R factor of 12.97 for the 852 independent reflections. Although the positions of the atoms suggest the space group $P2_1/c$, the site-occupancy factors for the two Br atoms are very different and this factor is large enough to change the space group to Pc. (0.682 of a Br atom corresponds to about 24 electrons, while 0.318 of a Br atom corresponds to about 11 electrons.)

The 18 atoms which form the indigo ring occupy two sites as a result of this packing disorder, ca 0.34 Å apart. Refining a disordered isotropic model, except for the Br atoms which was refined using anisotropic displacement parameters, in which two MBI molecules (one labeled A and B, and the other C and D) were used gave a model as presented in Fig. 2. Refinements were carried out with several different restraints imposed. The one which produced the best results restrained the atoms in the two MBI molecules sharing the same position (for example, N1A and N1C) to be 0.34 (2) Å from each other. Refinement of this disordered model, in which all the atoms except the Br atoms were isotropic, resulted in an R factor of 0.068 for 1558 independent reflections and 181 variables. This model contained very large s.u. values on the bond lengths and angles, especially on the molecule with the smaller occupancy factor and with C6A—Br6A and C6D—Br6D bond lengths of 1.94 (2) and 1.84 (3) Å, respectively, and resulted in many chemically-equivalent bond lengths appearing as long in one ring and short in the other. Due to the difficulty in resolving the disorder using these two sites for each atom in the indigo ring, a model with one atom representing the

two positions was used, and the elongated displacement parameters are a result of this positional disordering. Since the disordering of the molecule is not 0.50:0.50, the position of the one atom representing the two positions 0.34 Å apart is not the average of the two sites but a weighted average: the refined atom position is 0.08 Å from the disordered atom with 0.682 (3) occupancy and 0.26 Å from that with lower occupancy. This explains the shortening of the C6—Br6 bond lengths by 0.08 and 0.26 Å. In the final refinement, the bond lengths of the atoms in each of the two rings of the two halves of the indigo molecule were restrained to be the same length.

H atoms were placed at calculated positions, with C—H = 0.95 Å and N—H = 0.88 Å, and allowed to ride on the atom to which they were attached, with $U_{iso}(H) = 1.2U_{eq}$(parent atom). The crystals were twinned, with the two twin domains related to each other by a center of inversion. The final value of the Flack parameter (Flack, 1983) was 0.42 (2), indicating that the crystal was a inversion twin with approximately equal amounts of each twin component.

Data collection: *APEX2* (Bruker, 2010); cell refinement: *SAINT* (Bruker, 2005); data reduction: *SAINT*; program(s) used to solve structure: *SHELXS97* (Sheldrick, 2008); program(s) used to refine structure: *SHELXL97* (Sheldrick, 2008); molecular graphics: *XP* in *SHELXTL* (Sheldrick, 2008); software used to prepare material for publication: *publCIF* (Westrip, 2010).

Supplementary data for this paper are available from the IUCr electronic archives (Reference: GG3263). Services for accessing these data are described at the back of the journal.

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