

Halogen...halogen *contra* C–H...halogen interactions†

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Cite this: *CrystEngComm*, 2014, 16, 8279

Received 31st January 2014,
Accepted 5th June 2014

DOI: 10.1039/c4ce00241e

www.rsc.org/crystengcomm

Pressure affects the competition between C–H...X hydrogen bonds and X...X halogen...halogen interactions. In bromomethane, CH₃Br, pressure changes the molecular arrangement of the two solid-state phases of this compound: low-pressure phase α is dominated by halogen...halogen interactions, whereas above 1.5 GPa the β phase is governed by C–H...halogen bonds. The CH₃Br phase α is isostructural with solid CH₃I of orthorhombic space group *Pnma*, while CH₃Br phase β is polar, isostructural with CH₃Cl and CH₃CN crystals, of orthorhombic space group *Cmc2*₁. The crystal structures of CH₃Cl (b.p. = 249.1 K) and CH₃Br (b.p. = 276.7 K) have been determined by high pressure single-crystal X-ray diffraction up to 4.38 GPa and 2.85 GPa, respectively. In CH₃Br, pressure of 1.5 GPa enforces the close packing and opposite electrostatic-potential matching between molecular surfaces in contact. The interweaved C–H...X bonded diamondoid networks of β -CH₃X are similar to those of acetonitrile, H₂O ice VII and solidified X₂ halogens. The phase diagrams of CH₃Br and CH₃Cl have been constructed.

Introduction

The molecular arrangement in crystals is most often associated either with Kitaigorodski's close packing rule or with specific intermolecular interactions, such as OH...O hydrogen bonds in H₂O ice. Even weak specific interactions, such as halogen...halogen,^{1,2} halogen...O^{3–5} and CH...O contacts,⁶ can compete between themselves^{7,8} and with the close packing rule.⁹ Members of the group of halomethanes (CH₃X, X = Cl, Br, I) are the simplest organic polar compounds and ideal models for studying weak halogen...halogen and C–H...halogen interactions. In many molecular crystals without strong hydrogen bonds the X...X and C–H...X interactions dominate the molecular arrangement and are the shortest intermolecular contacts in the crystal structure.¹⁰ Pressure can considerably modify the intermolecular interactions in crystals. It was evidenced that weak hydrogen bonds CH...O^{11–13} and CH...N¹⁴ significantly increase their role in high-pressure structures. For example, formamide¹⁵ and (+)-sucrose¹⁶ transform at high pressure as a result of the increased role of CH...O interactions, in sucrose competing with OH...O bonds. The competition between halogen...halogen and C–H...halogen interactions was studied for a series of six dihalomethanes CH₂XY (X, Y = Cl, Br, I). They crystallize in several structural types of space group *Pbcn* (CH₂Cl₂, CH₂BrCl phase II), *C2/c* (CH₂Br₂, CH₂I₂ phase I, CH₂BrCl phase I, CH₂BrI), *Pnma* (CH₂ClI phase III), *Pna2*₁

(CH₂ClI phase IV) and *Fmm2* (CH₂I₂ phase II).^{17–22} In all of these compounds and their polymorphs, halogen...halogen interactions persist despite considerable structural differences. However, the persistence of halogen...halogen contacts in dihalomethanes can be due to the geometric effect of at least two-thirds of the molecular surface (for CH₂Cl₂) belonging to the halogen atoms. In these structures, even if other contacts are preferred and formed, the halogen...halogen contacts would be formed simply for there is no other molecular surface available. In methyl halides, of general formula CH₃X, there is one halogen atom per molecule (hence its molecular surface is smaller than those of CH₂X₂ and CHCl₃) and the competition between C–H...X and X...X interactions is more apparent. Therefore we have studied the structures of methyl halides in order to determine the effect of pressure on X...X and H...X interactions. CH₃Cl and CH₃Br are gases under normal conditions, which required that a special technique be developed and employed for loading these gases into the diamond-anvil cell (DAC).

The low-temperature/ambient-pressure CH₃Br and CH₃I crystals are isostructural, of the orthorhombic space group *Pnma*,^{23,24} while the CH₃Cl crystal has a different structure, of the orthorhombic space group *Cmc2*₁.²⁵ At room temperature the *Pnma*-symmetric CH₃I structure is stable up to at least 2.5 GPa.²⁶ No polymorphs or phase transitions were detected in CH₃Cl and CH₃I at low temperature, while calorimetric measurements indicated that CH₃Br undergoes a first-order phase transition at 173.75 K.²⁷ The Raman and far infrared spectra showed that the deuterated analogue, CD₃Br, transforms at 158 K, about 16 K below the transition of CH₃Br.²⁸ The crystal structures of CD₃Br in both its phases were determined by neutron powder diffraction at 175 K and 146 K.²⁹ We have

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† Electronic supplementary information (ESI) available: Detailed experiment and structure description. CCDC 957707–957715. For ESI and crystallographic data in CIF or other electronic format see DOI: 10.1039/c4ce00241e



presently established that in that study the high- and low-temperature phases were confused. Initially, the sample had been kinetically flash-frozen and cryo-ground in the temperature and atmosphere of liquid nitrogen. In accordance with Ostwald's rule the sample crystallized in the high-temperature phase α and at 146 K it was metastable throughout data collection. This α -phase determined at 146 K was of the orthorhombic space group $Pnma$. Then the sample had transformed to the low-temperature β phase before it was warmed to 175 K, *i.e.* 17 K above the transition temperature of CD_3Br at 158 K. Again, the β phase remained metastable under these conditions for the duration of powder data collection at least. Thus incidentally at higher temperature the crystal structure of low-temperature phase β was determined. This β -phase is of the orthorhombic space group $Cmc2_1$. Consequently, in that previous study the persistence of crystal phases in their metastable regions caused the reversed assignment of high- and low-temperature phases α and β , respectively.²⁹



Fig. 1 Phase diagrams of CH_3Cl (green) and CH_3Br (red) superimposed for convenient comparison (they are shown separately in Fig. S10 of the ESI†). The boiling points at 0.1 MPa (249.1 and 276.7 K; b.p.), melting points at 0.1 MPa (175.5 and 179.5 K; m.p.) and the critical points (c.p. 6.68 MPa/416.3 K and 5.23 MPa/467.2 K) from ref. 27 and 48; the freezing points (f.p.) at 295 K from our DAC experiment; the freezing lines obtained from the m.p. at 0.1 MPa, f.p. at 0.78 GPa/295 K and 0.65 GPa/295 K and from melting points at 1.22 GPa and 1.11 GPa (our optical observations of CH_3Cl and CH_3Br melting in the DAC – spectroscopic pressure calibration and temperature measured by a thermocouple attached to one diamond anvil); diffractometric determinations of CH_3Cl (green circles), CH_3Br phase α (red squares), CH_3Br phase β (red circles), CD_3Br phase α (red square crossed) and CD_3Br phase β (red circle crossed). The red dashed line shows the solid–solid boundary between phases α - CH_3Br and β - CH_3Br . The magnified gas–liquid region is shown in the upper inset: the experimental vapour–pressure data (green and red circles after ref. 27 and 48) and the gas–liquid boundary extrapolation (green and red lines); the enhanced liquid–solid region is shown in the lower inset. Note that the boiling point lines were determined below 0.1 MPa, however, short of reaching the triple points.

The phase diagrams of CH_3Br and CH_3Cl presently outlined in our study are shown in Fig. 1. These phase diagrams of CH_3Cl and CH_3Br have similar melting and boiling boundaries, shifting slightly toward lower temperature and higher pressure for CH_3Cl . In this respect, the transition of CH_3Br between solid phase α , isostructural with the crystal of CH_3I , and phase β , isostructural with CH_3Cl , is particularly intriguing. The crystal structure of perdeuterated methyl fluoride, CD_3F , determined by neutron powder diffraction at 5 K, is of the monoclinic space group $P2_1/n$ and is distinctly different from other methyl halides.³⁰ Presently, we have extended the structural relationship and phase diagrams of CH_3Cl and CH_3Br into the high-pressure region (Fig. 1) and investigated the role of $\text{X}\cdots\text{X}$ and $\text{C-H}\cdots\text{X}$ interactions in the CH_3X structures and CH_3Br transformations.

Experimental

Chloromethane, CH_3Cl (m.p. 175.5 K, b.p. 249.1 K), and bromomethane, CH_3Br (m.p. 179.5 K, b.p. 276.7 K), of 99.5% purity from Sigma-Aldrich were used. For high-pressure studies they were loaded into a modified Merrill–Bassett³¹ diamond-anvil cell (DAC) by combining compression and cryogenic conditions and *in situ* crystallized. At 295 K, CH_3Cl froze at 0.78 GPa and CH_3Br at 0.65 GPa in the form of a polycrystalline mass, filling the whole volume of the high-pressure chamber. The single crystals of CH_3Cl and CH_3Br (Fig. 2) were obtained under isochoric conditions: the DAC with the polycrystalline mass was heated with a hot-air gun till all but one grain melted. Then the DAC was slowly cooled to room temperature and the single crystal grew and eventually filled the entire volume of the chamber. The experimental details and progress of growing the single crystals of CH_3Cl are shown in Fig. S1–S4† and of CH_3Br in S5–S9 in the ESI.†

Diffraction data were collected at 295 K using a KUMA KM4-CCD diffractometer with graphite-monochromated $\text{MoK}\alpha$ radiation.³² The CrysAlisCCD and CrysAlisRED programs³³ were used for the data collection and determination of the *UB* matrix and for the initial data reduction and *Lp* corrections for both compounds. The intensity of reflections has been accounted for by the absorption of X-rays by the DAC, sample shadowing by the gasket, and absorption of the sample crystal itself.^{34,35} The crystal structures of CH_3Cl and CH_3Br were solved by direct methods. H atoms were located from molecular geometry, in α - CH_3Br the disordered model

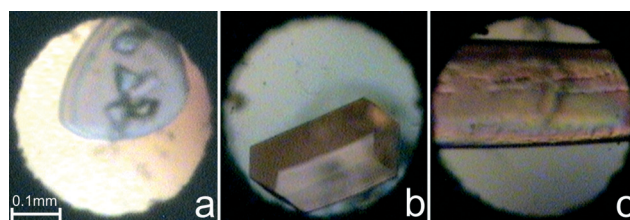


Fig. 2 Single-crystal samples in the diamond-anvil cell: (a) CH_3Cl at 4.38 GPa/483 K; (b) CH_3Br phase α at 1.11 GPa/345 K; and (c) CH_3Br phase β at 1.55 GPa/379 K.



was applied (Shelxl instruction AFIX 137),³⁶ and the structures were refined with anisotropic C and X atoms. Details of the experiments, structure refinements and crystal data are given in the ESI.†

The program GAUSSIAN03³⁷ and a PC were used with the B3LYP/3-21G** level of theory for DFT calculations of the electrostatic potential on the surface of CH₃X molecules. Electrostatic potential was mapped onto the molecular surfaces defined as 0.001 a.u. electron-density envelope.³⁸

Discussion

Isobaric and isothermal freezing of halomethanes CH₃X leads to the same crystalline phases.^{23–25} At 295 K, CH₃Cl and CH₃I crystallize at 0.78 and 0.41 GPa, respectively, in their low-temperature/0.1 MPa phases of CH₃Cl and CH₃I and they are stable within the investigated pressure range. At 295 K, CH₃Br freezes at 0.65 GPa in phase α (space group *Pnma*) and at 1.50 GPa it transforms to phase β (space group *Cmc2*₁). At this transition the unit-cell volume decreases by $-4.7 \text{ \AA}^3$ (-1.9%) (Fig. 3).

Two main molecular-association types conform to the opposite electrostatic-potential matching principle.²² In CH₃X molecules the negative electrostatic potential (Fig. 4) is on the rim about the C–X bond, the more positive potential region is on the “caps” of the X atom at the extension of the C–X bond and the highest potential is around the H-atoms. The electrostatic potential magnitude and the area at the extension of C–X bonds increase from F to I (Fig. 4).



Fig. 3 The molecular volume (unit cell *V*) as a function of pressure of CH₃Cl (green), CH₃Br (red) and CH₃I (purple). Symmetry *Cmc2*₁ is indicated by circles and *Pnma* by squares. The red dashed vertical line marks the transition between CH₃Br phases α and β . Low temperature/0.1 MPa data from ref. 23–25; 295 K/high pressure data of CH₃I from ref. 26. The dashed lines between the low-temperature/0.1 MPa and 295 K/high-pressure points are for guiding the eye only.



Fig. 4 (a) Molecules CH₃F, CH₃Cl, CH₃Br and CH₃I as well as their surfaces with electrostatic potential colour scale, common for all drawings and ranging from -0.015 (red) to 0.015 a.u. (blue); (b) the electrostatic potential magnitude on the surface of the methyl H-atoms and at the polar caps of the halogens plotted against the minimum potential in all CH₃X surfaces located on the rim of halogen atoms. Symbols δ_H^+ and δ_X^+ denote the maximum electrostatic potential magnitudes on the surface of H and X atoms, respectively.

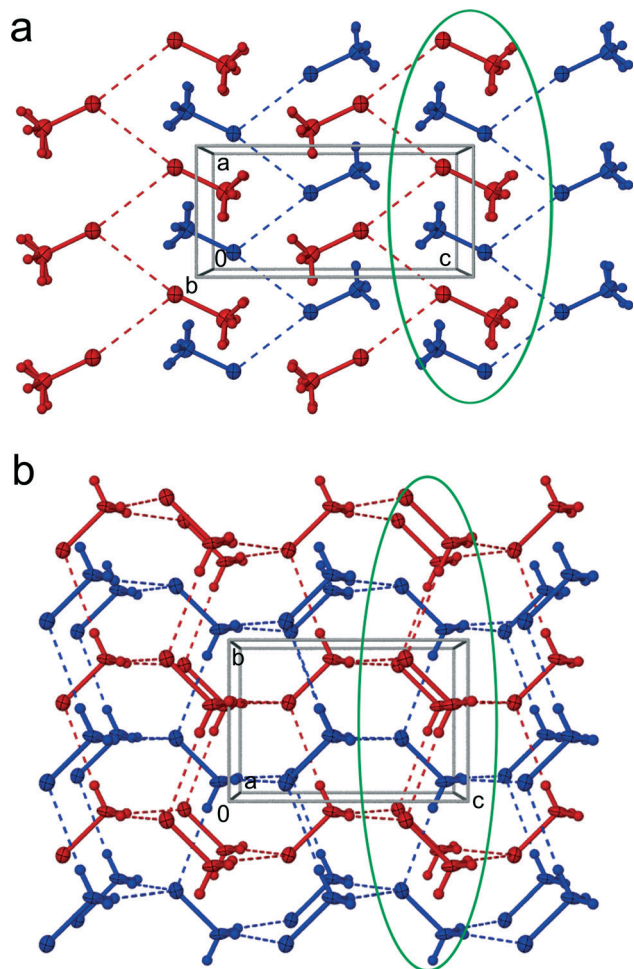
Based on the electrostatic-potential magnitudes (Fig. 4), the halogen...halogen interactions in CH₃I are stronger than those in CH₃Br and those in CH₃Cl are still weaker. Indeed, the CH₃I structure is governed by I...I contacts,²⁶ and no Cl...Cl but C–H...Cl contacts are formed in CH₃Cl.

The positive electrostatic potential on the halogen atom polar region of the molecular surface can act like H-donors in hydrogen bonds. Fig. 4 shows that the magnitude of polar electrostatic potential of the iodine atom is approximately twice as high as that of bromine and that no positive polar potential exists in CH₃Cl. This is consistent with the strongest preference for the X...X bonds in CH₃I and in CH₃Br. The electrostatic potential of the H atoms is higher than that of the I atoms and approximately equal for all CH₃Cl, CH₃Br and CH₃I. A large contribution to the X...X interactions arises

Halomethanes CH_3X crystallize either in space group $Cmc2_1$ or in space group $Pnma$. Although the space-group symmetries are different, the CH_3X structures have much in common (Fig. 5): the unit cells are roughly similar

^a Ref. 26. ^b This work.

In β -CH₃Br the halogen bonds Br $\cdots$ Br are broken and replaced by bonds C-H $\cdots$ Br (Fig. 5b, Table 2). Each CH₃Br molecule forms three C-H $\cdots$ Br bonds on the H-donor side and accepts three C-H $\cdots$ Br bonds around the Br atom. The molecules are arranged head-to-tail into two 3-dimensional interpenetrating (CH $\cdots$ Br)-bonded networks (Fig. 5b). Between these two networks the molecular parts of opposite electrostatic potential are closer than those of the same sign. The difference between phases α and β is most apparent in the ratio of Br $\cdots$ Br contacts contributing 5.5% to the overall Hirshfeld surface at low pressure and this contribution is reduced five-fold at high pressure to about 1%. This rearrangement causes a massive effect for the H $\cdots$ Br Hirshfeld-surface contributions, increasing from 49.6% at 1.11 GPa to 62.1% at 1.55 GPa. These changes in contributing Hirshfeld areas are compensated for in the reduced surface of H $\cdots$ H contacts of 44.9% and 36.9%, respectively.



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Table 2 Selected interatomic distances (Å) and angles (°) of the crystalline CH₃Br phase α and β structure at high pressure compared with those observed at low-temperature. Intermolecular distances shorter than the sum of van der Waals radii⁵² are written in bold

CH ₃ Br at:	Phase α 0.1 MPa/153 K ^a	Phase α 1.11 GPa/295 K ^b	Phase α 1.50 GPa/295 K ^b
Molecular dimensions			
C1–Br1 (Å)	1.863	1.912(10)	1.898(9)
Intermolecular dimensions			
Br1 ⁱ ...Br1 ⁱ (Å)	3.587	3.571(3)	3.546(3)
$\angle$ C1–Br1 ⁱ ...Br1 ⁱ (°)	116.0	118.5(4)	116.5(2)
$\angle$ Br1 ⁱ ...Br1 ⁱ –C1 ⁱ (°)	166.8	166.0(4)	168.2(2)
C1 ^j ...Br1 ^j (Å)	3.882	3.825(8)	3.844(4)
H12 ^k ...Br1 ^k (Å)	3.124	3.242	3.058
H11 ^l ...Br1 ^l (Å)	3.170	3.315	3.084
CH ₃ Br at:	Phase β 1.55 GPa/295 K ^b	Phase β 1.83 GPa/295 K ^b	Phase β 2.85 GPa/295 K ^b
Molecular dimensions			
C1–Br1 (Å)	1.919(16)	1.892(14)	2.024(25)
Intermolecular dimensions			
Br1 ^m ...Br1 ^m (Å)	3.948(3)	3.908(4)	3.878(9)
$\angle$ C1–Br1 ^m ...Br1 ^m (°)	63.9(5)	62.6(5)	62.4(7)
$\angle$ Br1 ^m ...Br1 ^m –C1 ^m (°)	152.9(5)	154.3(5)	152.7(7)
C1 ⁿ ...Br1 ⁿ (Å)	3.501(16)	3.487(15)	3.313(24)
C1 ^o ...Br1 ^o (Å)	3.551(17)	3.471(18)	3.444(24)
C1 ^p ...Br1 ^p (Å)	3.671(9)	3.684(9)	3.599(14)
H1 ^q ...Br1 ^q (Å)	3.073	3.094	2.909
H3 ^r ...Br1 ^r (Å)	3.041	3.009	2.897

^a Ref. 24. ^b This work. Symmetry codes: (i) 0.5 + x, 0.5 – y, 0.5 – z; –0.5 + x, 0.5 – y, 0.5 – z; (j) –x, –0.5 + y, –z; –x, 0.5 + y, –z; (k) 1 – x, 0.5 + y, –z; (l) 1 – x, –0.5 + y, –z; (m) –x, –y, 0.5 + z; –x, –y, –0.5 + z; (n) –x, 1 – y, 0.5 + z; (o) –x, –y, 0.5 + z; (p) –0.5 + x, 0.5 + y, z; 0.5 + x, 0.5 + y, z; (q) x, 1 + y, z; (r) –0.5 – x, 0.5 – y, 0.5 + z; 0.5 – x, 0.5 – y, 0.5 + z.

Isobaric,²⁵ isothermal and isochoric crystallization of CH₃Cl all lead to the same phase isostructural with β -CH₃Br. It is apparent that weaker Cl...Cl interactions are overcome by C–H...Cl bonds (see Table 3) and no *Pnma*-symmetric polymorph is formed. The CH₃Cl structure is consistent with the chlorophobic rule.^{44,45}

It is remarkable that CH₃Br phase β is isostructural with the high-pressure acetonitrile phase β .¹⁴ The CH₃Br and CH₃CN molecules are similar in shape and in the electrostatic

potential distribution on the molecular surface (except the polar Br-atom positive region, which is not involved in the C–H...Br bonds). Also, the favoured directions of C–H...X bonds are similar. Consequently, a similar aggregation of three molecules around each –Br and $\equiv$ N atoms takes place (Fig. 6). The difference, that in acetonitrile the transition is induced by the transformation between 2-fold C–H...N (α -CH₃CN) to 3-fold C–H...N (β -CH₃CN) bonding whereas methyl bromide transforms between 2-fold Br...Br (α -CH₃Br) to 3-fold C–H...Br

Table 3 Selected interatomic distances (Å) and angles (°) of the crystalline CH₃Cl structure at high pressure compared with those observed at low temperature. Intermolecular distances shorter than the sum of van der Waals radii⁵² are distinguished in bold

CH ₃ Cl at:	0.1 MPa/148 K ^a	1.22 GPa/295 K ^b	1.69 GPa/295 K ^b	2.91 GPa/295 K ^b	4.38 GPa/295 K ^b
Molecular dimensions					
C1–Cl1 (Å)	1.805	1.746(7)	1.792(4)	1.750(5)	1.716(7)
Intermolecular dimensions					
Cl1 ⁱ ...Cl1 ⁱ (Å)	4.010	3.906(5)	3.871(8)	3.712(5)	3.670(7)
$\angle$ C1–Cl1 ⁱ ...Cl1 ⁱ (°)	64.4	63.4(3)	61.7(2)	66.3(2)	64.7(3)
$\angle$ Cl1 ⁱ ...Cl1 ⁱ –C1 ⁱ (°)	156.1	156.9(3)	156.5(1)	151.0(2)	151.1(2)
C1 ^j ...Cl1 ^j (Å)	3.507	3.454(8)	3.371(5)	3.316(6)	3.285(8)
C1 ^k ...Cl1 ^k (Å)	3.618	3.493(9)	3.407(5)	3.409(7)	3.322(8)
C1 ^l ...Cl1 ^l (Å)	3.734	3.650(6)	3.582(5)	3.421(3)	3.391(8)
H1 ^m ...Cl1 ^m (Å)	3.138	3.085	2.962	2.788	2.706
H3 ⁿ ...Cl1 ⁿ (Å)	3.125	3.011	2.926	2.855	2.823

^a Ref. 25. ^b This work. Symmetry codes: (i) –x, –y, 0.5 + z; –x, –y, –0.5 + z; (j) –x, 1 – y, 0.5 + z; (k) –x, –y, 0.5 + z; (l) –0.5 + x, 0.5 + y, z; 0.5 + x, 0.5 + y, z; (m) x, 1 + y, z; (n) –0.5 – x, 0.5 – y, 0.5 + z; 0.5 – x, 0.5 – y, 0.5 + z.





Fig. 6 Hirshfeld surfaces^{50,51} of α -CH₃Br, β -CH₃Br and β -CH₃CN¹⁴ viewed along the molecular axis from the Br/N-top of molecules and decorated with colour maps of intermolecular distances relative to the van der Waals radii. Other interacting molecules are shown as stick models. Distances longer than van der Waals radii are shown in shades of navy blue, the equal ones are white and the shorter red. The colour scale ranges from -0.15 to 0.65.

(β -CH₃Br) bonding, is meaningful. It indicates that, apart from other factors, the steric hindrance between large halogen atoms can be disadvantageous for their close association.

Conclusions

Phase α -CH₃Br, isostructural with CH₃I and dominated by halogen...halogen bonds, is destabilized by pressure and transforms into phase β -CH₃Br governed by C-H...halogen interactions. Phase β of CH₃Br and the CH₃Cl crystal are isostructural. It can be envisaged that CH₃I may also transform into a C-H...I bonded phase at pressure considerably higher than 2.5 GPa as obtained in our previous study.²⁶ Due to halogen...halogen and C-H...halogen forces systematically increasing in the CH₃Cl < CH₃Br < CH₃I sequence, only CH₃Cl up to 1.2 GPa and CD₃Br phase β determined at ambient pressure and 175 K²⁹ are the loose crystals.^{46,47} This indicates that CH₃X molecules are more evenly accommodated in space group *Cmc*2₁ and that C-H...X interactions are favoured by the close-packing effect. This effect can significantly contribute to the stability of CH₃X at high pressure. However, detailed measurements of the CH₃Br crystal volume as a function of temperature are still needed to evaluate the contribution of close packing to the C-H...X *versus* X...X competition.

Acknowledgements

This study was supported by the TEAM grant no. 2009-4/6 from the Foundation for Polish Science.

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