

Crystal Structures and Molecular Conformations of L-Methionine and L-Norleucine

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The crystal structures of L-methionine and L-norleucine have been determined by X-ray diffraction methods. L-Methionine crystallizes in the space group $P2_1$, $Z=4$, with lattice constants $a=9.498$, $b=5.189$, $c=15.318$, $\beta=97.69^\circ$ and L-norleucine in $C2$, $Z=4$, $a=9.550$, $b=5.260$, $c=15.377$, $\beta=95.60^\circ$. Intensities were measured on a four-circle diffractometer. The full-matrix least-squares refinement of the structure yielded the final R values 0.09 and 0.06 for L-methionine and L-norleucine respectively. The crystal of L-methionine contains two crystallographically independent molecules A and B having different conformations; side-chain conformations at α - β , β - γ and γ - δ bonds are all *trans* in A while they are *trans* (to the amino group), *gauche*, *gauche* in B . The crystal of L-norleucine, on the other hand, contains the molecules having one and the same kind of conformation which corresponds to that of the A molecule in L-methionine. In both crystals, the molecules are held together mainly by hydrogen bonds to form a double-layer structure. The side chains in L-norleucine crystal are packed together in a manner resembling that of the $T\parallel$ packing type in long chain hydrocarbons, while in L-methionine crystal a tendency to pack in the $O\perp$ type is clearly shown.

Introduction

In our preceding papers (Torii & Iitaka, 1970; Torii & Iitaka, 1971) we showed that the crystal structures of L- α -amino acids having hydrocarbon side chains are characterized by hydrogen-bonded double layers of molecules stacked in such a way that their terminal groups of the side chains face each other. Crystal data for L-methionine and L-norleucine indicated that these crystals also contain hydrogen-bonded double layers. However, the space group of L-norleucine is different from that of L-methionine and it was expected that the side chains of the L-methionine molecules are packed in a manner resembling the $O\perp$ packing of the long chain hydrocarbons while those of the L-norleucine molecules are packed in a $T\parallel$ type. We therefore undertook the crystal structure analyses of both crystals to see how the side chains are folded and accommodated in the particular packing of the crystal.

Experimental

The crystals of L-methionine, in the form of thin elongated plates, were obtained by evaporation of ethanol-water solutions at room temperature. L-Norleucine was crystallized as thin elongated plates from a warm saturated aqueous solution by slow cooling. The space groups were determined by the precession photographs and the densities of the crystals were measured by the flotation method using benzene-carbon tetrachloride mixture. The crystal data are listed in Table 1.

The crystal of methionine used for collecting the intensity data was about $0.15 \times 0.60 \times 0.04$ mm in size and that of norleucine was about $0.20 \times 0.50 \times 0.03$ mm. The lattice constants and the intensity data were measured on a Rigaku four-circle diffractometer using Ni-filtered Cu $K\alpha$ radiation. The intensities were measured

Table 1. Crystal data

	L-Methionine	L-Norleucine
	$C_5H_{11}NO_2S$	$C_6H_{13}NO_2$
M.W.	149.2	131.2
a (Å)	9.498 (5)	9.550 (5)
b	5.189 (5)	5.260 (5)
c	15.318 (5)	15.377 (5)
β ($^\circ$)	97.69 (10)	95.60 (5)
Space group	$P2_1$	$C2$
Z	4	4
D_x (g cm $^{-3}$)	1.325	1.134
D_m	1.316	1.136

by an ω - 2θ scan method; a scan speed of $4^\circ 2\theta$ per min was chosen for methionine and $2^\circ 2\theta$ per min for norleucine. The intensities were corrected for Lorentz and polarization factors and each intensity set was placed on an approximately absolute scale by Wilson's method. The total numbers of the observed structure factors above 3σ level were 1010 out of 1441 possible reflexions ($\theta \leq 65^\circ$) for L-methionine and 581 out of 776 possible reflexions for L-norleucine.

Determination and refinement of the structures

The structure of L-methionine was determined on the basis of that of L-isoleucine (Torii & Iitaka, 1971). Both of L-methionine and L-isoleucine belong to the same space group and have similar lattice constants. Therefore the fractional coordinates of all atoms except γ , ϵ carbon and δ sulphur of the two crystallographically independent L-methionine molecules were assumed to be the same as those in L-isoleucine. Calculated structure factors for these trial coordinates gave an R value of 0.40. A subsequent three-dimensional Fourier synthesis phased by the trial model revealed the positions of the remaining four carbon and two sulphur atoms of the two molecules,

Table 2. Final atomic parameters and their e.s.d.'s for L-methionine

For L-molecules the coordinates refer to the right-handed system.
Temperature factors are in the form: $T = \exp[-(\beta_{11}h^2 + \beta_{22}k^2 + \beta_{33}l^2 + 2\beta_{12}hk + 2\beta_{13}hl + 2\beta_{23}kl)]$.

	x	y	z	β_{11}	β_{22}	β_{33}	β_{12}	β_{13}	β_{23}
O(1) _A	0.1076 (6)	-0.0167 (0)	0.4234 (5)	0.0035 (7)	0.0331 (33)	0.0049 (4)	-0.0011 (13)	0.0022 (4)	0.0007 (11)
O(2) _A	0.1746 (7)	0.3481 (22)	0.3674 (6)	0.0064 (8)	0.0197 (33)	0.0068 (5)	0.0040 (14)	0.0021 (5)	-0.0009 (11)
N(1) _A	0.3587 (8)	-0.2395 (24)	0.4305 (6)	0.0056 (9)	0.0173 (33)	0.0054 (5)	0.0029 (14)	0.0004 (6)	-0.0003 (12)
C(1) _A	0.1943 (11)	0.1230 (27)	0.3905 (7)	0.0077 (12)	0.0174 (43)	0.0028 (4)	0.0027 (20)	-0.0003 (6)	-0.0003 (13)
C(2) _A	0.3372 (10)	-0.0021 (26)	0.3765 (7)	0.0049 (10)	0.0187 (39)	0.0043 (6)	-0.0007 (18)	0.0007 (6)	-0.0006 (14)
C(3) _A	0.3453 (11)	-0.0604 (29)	0.2799 (7)	0.0100 (13)	0.0224 (44)	0.0043 (6)	0.0028 (21)	0.0023 (7)	-0.0018 (14)
C(4) _A	0.3597 (17)	0.1842 (34)	0.2286 (9)	0.0217 (23)	0.0458 (73)	0.0039 (6)	0.0030 (35)	0.0046 (10)	0.0025 (18)
S(1) _A	0.3872 (7)	0.0906 (19)	0.1170 (3)	0.0416 (12)	0.0548 (22)	0.0068 (2)	0.0054 (16)	0.0106 (5)	0.0010 (8)
C(5) _A	0.4003 (27)	0.4049 (50)	0.0686 (13)	0.0374 (44)	0.0669 (113)	0.0083 (12)	-0.0007 (65)	0.0076 (20)	0.0035 (33)
O(1) _B	0.6244 (7)	0.5756 (23)	0.4173 (5)	0.0051 (7)	0.0214 (29)	0.0069 (5)	0.0041 (13)	0.0033 (5)	0.0039 (11)
O(2) _B	0.6871 (8)	0.9719 (23)	0.3840 (7)	0.0088 (10)	0.0180 (33)	0.0107 (7)	0.0025 (16)	0.0031 (7)	0.0008 (13)
N(1) _B	0.8845 (9)	0.3892 (26)	0.3975 (7)	0.0066 (9)	0.0376 (49)	0.0051 (5)	0.0101 (19)	0.0020 (6)	0.0008 (14)
C(1) _B	0.7076 (10)	0.7352 (27)	0.3884 (8)	0.0040 (10)	0.0274 (50)	0.0049 (6)	0.0038 (20)	0.0006 (7)	-0.0014 (15)
C(2) _B	0.8342 (16)	0.6231 (28)	0.3496 (8)	0.0058 (11)	0.0253 (44)	0.0071 (8)	0.0030 (20)	0.0039 (8)	0.0007 (17)
C(3) _B	0.7916 (16)	0.5481 (37)	0.2532 (9)	0.0184 (22)	0.0529 (81)	0.0049 (7)	0.0035 (37)	0.0034 (10)	0.0003 (22)
C(4) _B	0.7695 (22)	0.7616 (62)	0.1860 (17)	0.0201 (29)	0.0985 (148)	0.0126 (17)	0.0105 (62)	0.0035 (18)	0.0050 (48)
S(1) _B	0.9317 (8)	0.9068 (21)	0.1635 (5)	0.0325 (10)	0.0723 (32)	0.0116 (4)	-0.0119 (16)	0.0073 (5)	0.0038 (10)
C(5) _B	0.9995 (35)	0.6727 (54)	0.1020 (18)	0.0522 (67)	0.0687 (142)	0.0118 (17)	0.0136 (79)	0.0120 (28)	-0.0009 (39)

Table 2 (cont.)

	x	y	z	B	Bonded to
H(1) _A	0.340 (10)	-0.201 (22)	0.490 (6)	4 (2)	N(1) _A
H(2) _A	0.426 (10)	-0.278 (20)	0.429 (6)	2 (2)	N(1) _A
H(3) _A	0.306 (10)	-0.332 (19)	0.406 (6)	2 (2)	N(1) _A
H(4) _A	0.422 (14)	0.104 (34)	0.393 (8)	7 (4)	C(2) _A
H(5) _A	0.438 (11)	-0.161 (24)	0.286 (7)	6 (3)	C(3) _A
H(6) _A	0.251 (13)	-0.163 (30)	0.266 (8)	8 (3)	C(3) _A
H(7) _A	0.424 (17)	0.216 (34)	0.238 (9)	16 (4)	C(4) _A
H(8) _A	0.304 (16)	0.362 (32)	0.223 (9)	10 (4)	C(4) _A
H(9) _B	0.893 (10)	0.395 (24)	0.462 (7)	6 (2)	N(1) _B
H(10) _B	0.968 (15)	0.389 (32)	0.387 (9)	12 (4)	N(1) _B
H(11) _B	0.805 (13)	0.272 (28)	0.392 (8)	7 (3)	N(1) _B
H(12) _B	0.907 (10)	0.788 (21)	0.362 (6)	3 (2)	C(2) _B
H(13) _B	0.708 (11)	0.433 (27)	0.258 (7)	7 (3)	C(3) _B
H(14) _B	0.886 (12)	0.408 (26)	0.230 (7)	8 (3)	C(3) _B

The atomic coordinates and thermal parameters for all atoms were refined by full-matrix least-squares calculations including anisotropic thermal parameters. The following weighting scheme was adopted;

$$\begin{aligned} \sqrt{w} &= F_o / (1.3 \times 15.0) && \text{when } F_o \leq 15.0 \\ \sqrt{w} &= 1/1.3 && \text{when } 15.0 < F_o \leq 26.0 \\ \sqrt{w} &= 1/[1.3 + 0.0351(F_o - 26.0)] && \text{when } 26.0 < F_o \end{aligned}$$

At this stage a difference Fourier map was calculated using these refined parameters, which revealed the positions of 14 hydrogen atoms out of 22 in all. The positional parameters and isotropic temperature factors for the hydrogen atoms were refined by the full-matrix least-squares calculations (ORFLS program, Busing, Martin & Levy, 1962). The *R* value was reduced to 0.089 for observed structure factors. The final atomic parameters are listed in Table 2 along with their estimated standard deviations. The observed and calculated structure factors are compared in Table 3.

Table 3. Observed and calculated structure factors of L-methionine

h	k	l	Observed	Calculated
0	0	0	10000	10000
0	0	1	10000	10000
0	0	2	10000	10000
0	0	3	10000	10000
0	0	4	10000	10000
0	0	5	10000	10000
0	0	6	10000	10000
0	0	7	10000	10000
0	0	8	10000	10000
0	0	9	10000	10000
0	0	10	10000	10000
0	0	11	10000	10000
0	0	12	10000	10000
0	0	13	10000	10000
0	0	14	10000	10000
0	0	15	10000	10000
0	0	16	10000	10000
0	0	17	10000	10000
0	0	18	10000	10000
0	0	19	10000	10000
0	0	20	10000	10000
0	0	21	10000	10000
0	0	22	10000	10000
0	1	0	10000	10000
0	1	1	10000	10000
0	1	2	10000	10000
0	1	3	10000	10000
0	1	4	10000	10000
0	1	5	10000	10000
0	1	6	10000	10000
0	1	7	10000	10000
0	1	8	10000	10000
0	1	9	10000	10000
0	1	10	10000	10000
0	1	11	10000	10000
0	1	12	10000	10000
0	1	13	10000	10000
0	1	14	10000	10000
0	1	15	10000	10000
0	1	16	10000	10000
0	1	17	10000	10000
0	1	18	10000	10000
0	1	19	10000	10000
0	1	20	10000	10000
0	1	21	10000	10000
0	1	22	10000	10000
0	2	0	10000	10000
0	2	1	10000	10000
0	2	2	10000	10000
0	2	3	10000	10000
0	2	4	10000	10000
0	2	5	10000	10000
0	2	6	10000	10000
0	2	7	10000	10000
0	2	8	10000	10000
0	2	9	10000	10000
0	2	10	10000	10000
0	2	11	10000	10000
0	2	12	10000	10000
0	2	13	10000	10000
0	2	14	10000	10000
0	2	15	10000	10000
0	2	16	10000	10000
0	2	17	10000	10000
0	2	18	10000	10000
0	2	19	10000	10000
0	2	20	10000	10000
0	2	21	10000	10000
0	2	22	10000	10000
0	3	0	10000	10000
0	3	1	10000	10000
0	3	2	10000	10000
0	3	3	10000	10000
0	3	4	10000	10000
0	3	5	10000	10000
0	3	6	10000	10000
0	3	7	10000	10000
0	3	8	10000	10000
0	3	9	10000	10000
0	3	10	10000	10000
0	3	11	10000	10000
0	3	12	10000	10000
0	3	13	10000	10000
0	3	14	10000	10000
0	3	15	10000	10000
0	3	16	10000	10000
0	3	17	10000	10000
0	3	18	10000	10000
0	3	19	10000	10000
0	3	20	10000	10000
0	3	21	10000	10000
0	3	22	10000	10000
0	4	0	10000	10000
0	4	1	10000	10000
0	4	2	10000	10000
0	4	3	10000	10000
0	4	4	10000	10000
0	4	5	10000	10000
0	4	6	10000	10000
0	4	7	10000	10000
0	4	8	10000	10000
0	4	9	10000	10000
0	4	10	10000	10000
0	4	11	10000	10000
0	4	12	10000	10000
0	4	13	10000	10000
0	4	14	10000	10000
0	4	15	10000	10000
0	4	16	10000	10000
0	4	17	10000	10000
0	4	18	10000	10000
0	4	19	10000	10000
0	4	20	10000	10000
0	4	21	10000	10000
0	4	22	10000	10000
0	5	0	10000	10000
0	5	1	10000	10000
0	5	2	10000	10000
0	5	3	10000	10000
0	5	4	10000	10000
0	5	5	10000	10000
0	5	6	10000	10000
0	5	7	10000	10000
0	5	8	10000	10000
0	5	9	10000	10000
0	5	10	10000	10000
0	5	11	10000	10000
0	5	12	10000	10000
0	5	13	10000	10000
0	5	14	10000	10000
0	5	15	10000	10000
0	5	16	10000	10000
0	5	17	10000	10000
0	5	18	10000	10000
0	5	19	10000	10000
0	5	20	10000	10000
0	5	21	10000	10000
0	5	22	10000	10000
0	6	0	10000	10000
0	6	1	10000	10000
0	6	2	10000	10000
0	6	3	10000	10000
0	6	4	10000	10000
0	6	5	10000	10000
0	6	6	10000	10000
0	6	7	10000	10000
0	6	8	10000	10000
0	6	9	10000	10000
0	6	10	10000	10000
0	6	11	10000	10000
0	6	12	10000	10000
0	6	13	10000	10000
0	6	14	10000	10000
0	6	15	10000	10000
0	6	16	10000	10000
0	6	17	10000	10000
0	6	18	10000	10000
0	6	19	10000	10000
0	6	20	10000	10000
0	6	21	10000	10000
0	6	22	10000	10000
0	7	0	10000	10000
0	7	1	10000	10000
0	7	2	10000	10000
0	7	3	10000	10000
0	7	4	10000	10000
0	7	5	10000	10000
0	7	6	10000	10000
0	7	7	10000	10000
0	7	8	10000	10000
0	7	9	10000	10000
0	7	10	10000	10000
0	7	11	10000	10000
0	7	12	10000	10000
0	7	13	10000	10000
0	7	14	10000	10000
0	7	15	10000	10000
0	7			

Table 4. Final atomic parameters and their e.s.d.'s for L-norleucine

For L-molecules the coordinates refer to the right-handed system.
Temperature factors are in the form: $T = \exp [-(\beta_{11}h^2 + \beta_{22}k^2 + \beta_{33}l^2 + 2\beta_{12}hk + 2\beta_{13}hl + 2\beta_{23}kl)]$.

	x	y	z	β_{11}	β_{22}	β_{33}	β_{12}	β_{13}	β_{23}
O(1) _N	0.3749 (3)	-0.0167 (0)	0.4140 (2)	0.0059 (3)	0.0319 (12)	0.0069 (2)	0.0022 (6)	0.0024 (2)	0.0009 (5)
O(2) _N	0.4488 (4)	0.3611 (9)	0.3760 (3)	0.0098 (5)	0.0277 (15)	0.0111 (3)	0.0019 (6)	0.0022 (3)	0.0015 (6)
N(1) _N	0.6280 (4)	-0.2276 (10)	0.4195 (3)	0.0061 (4)	0.0298 (16)	0.0064 (2)	0.0049 (7)	0.0012 (2)	0.0019 (5)
C(1) _N	0.4654 (4)	0.1299 (11)	0.3890 (3)	0.0063 (4)	0.0263 (18)	0.0063 (3)	0.0015 (7)	0.0009 (3)	0.0004 (6)
C(2) _N	0.6055 (4)	0.0097 (11)	0.3681 (3)	0.0064 (4)	0.0344 (20)	0.0066 (3)	0.0013 (9)	0.0016 (3)	0.0007 (7)
C(3) _N	0.6099 (8)	-0.0435 (16)	0.2734 (5)	0.0156 (8)	0.0603 (32)	0.0071 (4)	0.0083 (16)	0.0035 (4)	0.0001 (9)
C(4) _N	0.6239 (13)	0.2022 (23)	0.2197 (6)	0.0398 (22)	0.0919 (63)	0.0083 (5)	0.0104 (31)	0.0074 (8)	0.0066 (14)
C(5) _N	0.6603 (19)	0.1579 (30)	0.1332 (9)	0.0642 (42)	0.1028 (89)	0.0143 (10)	0.0159 (54)	0.0176 (16)	0.0110 (26)
C(6) _N	0.6940 (23)	0.4141 (41)	0.0897 (9)	0.0809 (57)	0.1222 (89)	0.0137 (10)	-0.0039 (63)	0.0181 (18)	0.0124 (24)

Table 4 (cont.)

	x	y	z	B	Bonded to
H(1) _N	0.621 (5)	-0.195 (10)	0.487 (3)	4 (1)	N(1) _N
H(2) _N	0.719 (8)	-0.307 (16)	0.410 (4)	8 (2)	N(1) _N
H(3) _N	0.580 (7)	-0.347 (16)	0.389 (4)	6 (2)	N(1) _N
H(4) _N	0.687 (7)	0.117 (14)	0.388 (4)	4 (1)	C(2) _N
H(5) _N	0.680 (12)	-0.155 (26)	0.256 (7)	13 (3)	C(3) _N
H(6) _N	0.532 (6)	-0.143 (11)	0.250 (4)	4 (1)	C(3) _N

Crystal data of L-norleucine show that there is only one molecule per asymmetric unit. In L-methionine the two crystallographically independent molecules would form a pseudo-C-centered lattice if the side chains were disregarded. It was therefore assumed that the crystal structure of L-norleucine is such that the *B* or *A* molecules in L-methionine crystal are replaced by the *A* or *B* molecules. On the basis of the atomic parameters given in L-methionine, we obtained the trial coordinates of all atoms except γ , δ and ϵ carbon atoms. A three-dimensional electron density map, based on these trial coordinates, revealed three carbon atoms at γ , δ and ϵ positions.

Refinement of the atomic parameters was carried out by the full-matrix least-squares method, including anisotropic thermal parameters. The following weighting scheme was adopted;

$$\begin{aligned} w &= 1/2.7 && \text{when } F_o \leq 40.0 \\ w &= 1/[2.7 + 0.080(F_o - 40.0)] && \text{when } 40.0 < F_o. \end{aligned}$$

A difference Fourier map showed the positions of six hydrogen atoms out of thirteen in all. The positional parameters and isotropic temperature factors for the hydrogen atoms were refined by the full-matrix least-squares calculations. The *R* value was reduced to 0.057. The final atomic parameters and standard deviations are shown in Table 4, and observed and calculated structure factors are given in Table 5. Atomic scattering factors used in the present analysis were those given by Berghuis, Haanappel, Potters, Loopstra, MacGillavry & Veenendaal (1955).

Discussion of the structures

Molecular structures

Figs. 1 and 2 show the conformations of the L-methionine and L-norleucine molecules respectively. These and Figs. 5 and 6 were drawn by the plotter program ORTEP (Johnson, 1965). The bond lengths and angles of the methionine and norleucine molecules are listed in Tables 6 and 7 respectively. In these Tables the corrected bond lengths for thermal motion by the program ORFFE (Busing, Martin & Levy, 1964) are also given. The methionine crystal involves two independent molecules, *A* and *B*. Except for the $C^\gamma-S^\delta$ and $S^\delta-C^\epsilon$ bonds, differences of the corresponding bond lengths in *A* and *B* are smaller than $0.86\sigma_{\text{diff}}$. ($p=0.39$), where σ_{diff} is the sum of the squares of the standard deviations of the corresponding bond lengths in *A* and *B*. It seems that they are not significant. In the cases of

Table 5. Observed and calculated structure factors of L-norleucine

Observed	Calculated
1.247 (5)	1.247 (5)
1.240 (7)	1.240 (7)
1.541 (7)	1.541 (7)
1.487 (9)	1.487 (9)
1.546 (14)	1.546 (14)
1.426 (18)	1.426 (18)
1.552 (26)	1.552 (26)
1.481 (8)	1.481 (8)
125.0 (0.5)	125.0 (0.5)
116.9 (0.4)	116.9 (0.4)
118.0 (0.5)	118.0 (0.5)
108.6 (0.4)	108.6 (0.4)
112.8 (0.5)	112.8 (0.5)
110.4 (0.5)	110.4 (0.5)
112.2 (0.7)	112.2 (0.7)
113.8 (1.0)	113.8 (1.0)
109.9 (1.3)	109.9 (1.3)

Table 7. Bond lengths and angles in norleucine molecules*

	L-Norleucine	corr.†	DL-Norleucine
O(1)-C(1)	1.247 (5) Å		1.20 (4) Å
O(2)-C(1)	1.240 (7)		1.26
C(1)-C(2)	1.541 (7)		1.49
C(2)-C(3)	1.487 (9)	1.513 Å	1.58
C(3)-C(4)	1.546 (14)	1.596	1.51
C(4)-C(5)	1.426 (18)	1.479	1.57
C(5)-C(6)	1.552 (26)	1.584	1.48
C(2)-N(1)	1.481 (8)		1.50
O(1)-C(1)-O(2)	125.0 (0.5)°		122 (5)°
O(1)-C(1)-C(2)	116.9 (0.4)		118
O(2)-C(1)-C(2)	118.0 (0.5)		120
C(1)-C(2)-N(1)	108.6 (0.4)		109
C(1)-C(2)-C(3)	112.8 (0.5)		112
N(1)-C(2)-C(3)	110.4 (0.5)		110
C(2)-C(3)-C(4)	112.2 (0.7)		114
C(3)-C(4)-C(5)	113.8 (1.0)		110
C(4)-C(5)-C(6)	109.9 (1.3)		120

State of rotation

	C(4) is trans to:	N(1)	C(1)
about C(2)-C(3)		trans	trans
about C(3)-C(4)		trans	trans
about C(4)-C(5)		trans	trans

Reference

(1) (2)

* Standard deviations are shown in parentheses denoting the least significant digits of the corresponding values.

† The corrected bond length for thermal motion by the program ORFFE (Busing, Martin & Levy, 1964), postulating that C(i+1) 'rides' upon C(i) (i = 1, 2, 3, 4).

References: (1) Present work. (2) Mathieson (1953).

C^γ-S^δ and S^δ-C^ε bonds, the difference is nearly equal to 2σ_{diff.}. The reason for the difference is not clear but it seems that this is partly due to the large anisotropic thermal vibrations of the terminal atoms. The average values of the other bond lengths are 1.526, 1.476 and 1.250 Å for the C-C, C-N and C-O bonds respectively, and they agree with those derived from a weighted average of amino acid structures (Marsh & Donohue, 1967) within experimental error. In the bond lengths in norleucine, C^γ-C^δ (corrected for thermal motion) is a little shorter than the expected length of C-C single

Table 6. Bond lengths (Å) and angles (°) in methionine molecules*

	L-Methionine		corr.†	DL-Methionine		Dichloro-DL-methionine-palladium
	(A)	(B)		(α)	(β)	
O(1)-C(1)	1.254 (13)	1.268 (16)		1.21 (4)	1.21 (4)	1.205 (21)
O(2)-C(1)	1.230 (18)	1.246 (18)		1.28	1.27	1.295 (23)
C(1)-C(2)	1.547 (15)	1.528 (16)		1.47	1.52	1.536 (22)
C(2)-C(3)	1.525 (17)	1.531 (19)	1.561	1.55	1.58	1.506 (23)
C(3)-C(4)	1.511 (22)	1.511 (34)	1.546	1.51	1.54	1.493 (22)
C(4)-S(1)	1.832 (15)	1.863	1.798	1.79	1.80	1.827 (16)
S(1)-C(5)	1.805 (27)	1.810	1.758	1.77	1.78	1.800 (21)
C(2)-N(1)	1.485 (18)	1.467 (19)		1.52	1.50	1.472 (23)
O(1)-C(1)-O(2)	125.7 (1.1)	124.3 (1.2)		121	122	123.77 (1.69)
O(1)-C(1)-C(2)	116.7 (1.0)	116.7 (1.1)		119	120	113.22 (1.52)
O(2)-C(1)-C(2)	117.6 (1.0)	118.8 (1.1)		120	118	123.00 (1.74)
C(1)-C(2)-N(1)	109.3 (0.9)	110.0 (1.0)		112	110	107.96 (1.35)
C(1)-C(2)-C(3)	112.3 (1.0)	110.7 (1.1)		111	108	107.89 (1.30)
N(1)-C(2)-C(3)	110.8 (1.0)	107.4 (1.1)		110	109	111.94 (1.48)
C(2)-C(3)-C(4)	111.1 (1.1)	117.8 (1.5)		111	113	113.68 (1.38)
C(3)-C(4)-S(1)	107.3 (1.0)	113.4 (1.7)		111	109	117.04 (1.25)
C(4)-S(1)-C(5)	99.8 (1.0)	101.8 (1.4)		100	100	100.14 (0.94)
State of rotation						
about C(2)-C(3)	C(4) is trans to:		N(1)	N(1)	C(1)	C(1)
about C(3)-C(4)			trans	gauche	trans	trans
about C(4)-S(1)			trans	gauche	gauche	gauche
Reference						
	(1)	(1)	(1)	(2)	(2)	(3)

* Standard deviations are shown in parentheses denoting the least significant digits of the corresponding values.

† See footnote in Table 7.

References:

- (1) Present work.
- (2) Mathieson (1952).
- (3) Warren, McConnell & Stephenson (1970).

bonds. Tables 6 and 7 also show the comparison of the values found in the methionine and norleucine molecules in various compounds. It is considered that both methionine and norleucine molecules in the present crystals take the form of a zwitterion.

The deviations of atoms from the least-squares planes are listed in Table 8. As usually found, the carboxyl groups in these two compounds are planar with the C^α atoms while the nitrogen atom deviates slightly from the plane.

In molecule *A* of methionine and norleucine, β , γ , δ and ϵ side chain atoms are extended in a *trans* planar form from the α carbon atoms. However, as shown in Table 8, the α carbon atom $C(2)_N$ is not strictly on the plane.

The various internal rotation angles defining the conformation of the molecules are listed in Table 9. The largest difference between molecules *A* and *B* of

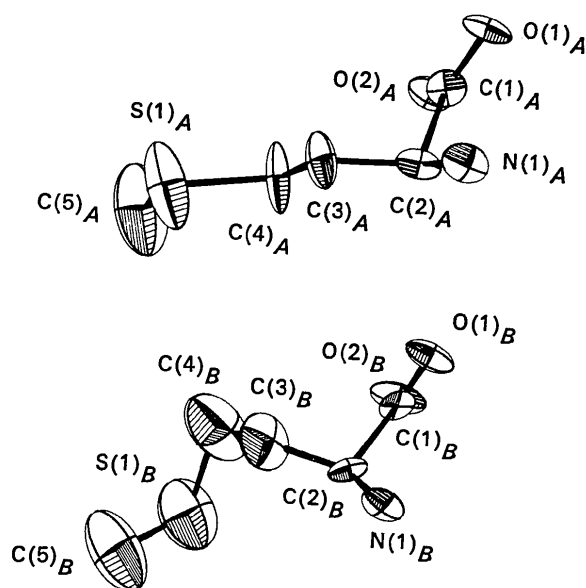


Fig. 1. An ORTEP plot of L-methionine viewed along the *b* axis. The atoms are represented by 50% probability ellipsoids.

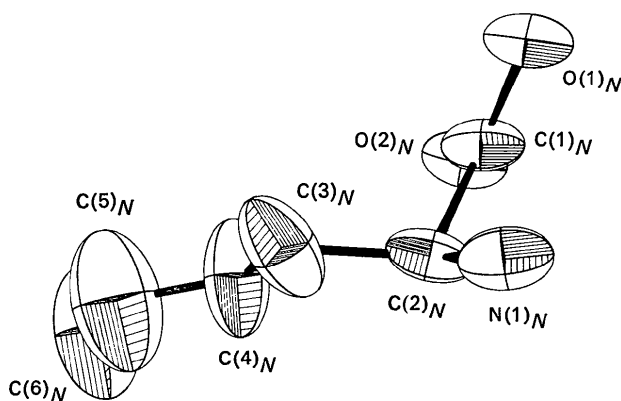


Fig. 2. An ORTEP plot of L-norleucine viewed along the *b* axis.

Table 8. Perpendicular distances of the atoms from the least-squares plane

L-Methionine			
	(I)	(II)	(III)
O(1) _A	-0.002 Å	C(2) _A 0.045 Å	O(1) _B -0.009 Å
O(2) _A	-0.002	C(3) _A -0.039	O(2) _B -0.010
C(1) _A	0.006	C(4) _A -0.043	C(1) _B 0.026
C(2) _A	-0.002	S(1) _A 0.031	C(2) _B -0.007
N(1) _A	0.404	C(5) _A 0.007	N(1) _B 0.709
L-Norleucine			
	(IV)	(V)	
O(1) _N	-0.006 Å	C(3) _N 0.054 Å	
O(2) _N	-0.006	C(4) _N -0.059	
C(1) _N	0.016	C(5) _N -0.048	
C(2) _N	-0.004	C(6) _N 0.052	
N(1) _N	0.569	C(2) _N 0.361	

* Omitted from least-squares plane calculation. Planes are of the form $AX + BY + CZ = D$, where X , Y , Z and D are in Å units relative to the axes a , b and c^* .

(I)	0.3955	$X + 0.3003$	$Y + 0.8680$	$Z = 5.8962$
(II)	0.9927	$X - 0.0360$	$Y + 0.1152$	$Z = 3.7270$
(III)	0.5428	$X + 0.0841$	$Y + 0.8357$	$Z = 8.1419$
(IV)	0.3730	$X + 0.1679$	$Y + 0.9125$	$Z = 6.8135$
(V)	0.9691	$X - 0.0296$	$Y + 0.2431$	$Z = 6.4564$

methionine is found in the conformations around $C^\beta-C^\gamma$ bonds, the internal rotation angle around this bond (χ_2) being 174.2° in *A* and 73.6° in *B*. In the cases of L-cysteine, L-valine and L-isoleucine, it is in the conformations around $C^\alpha-C^\beta$ that the largest differences between the two crystallographically independent molecules are found. In the present structures, however, all the molecules in L-methionine and in L-norleucine take the amino-*trans* conformation and no significant difference is found regarding χ_1 .

Table 9. Internal rotation angles of methionine and norleucine

	ψ_2	χ_1	χ_2	χ_3	Reference*
L-Methionine					
molecule <i>A</i>	-17.5°	194.0°	174.2°	179.7°	(1)
molecule <i>B</i>	-34.3	194.4	73.6	73.6	(1)
α -DL-Methionine	-33.7	299.9	176.9	80.5	(2)
β -DL-Methionine	-29.4	299.0	183.6	190.4	(2)
L-Norleucine	-25.9	194.2	166.5	188.6	(1)
DL-Norleucine	-35.3	303.1	182.2	195.2	(3)

In the cases of crystalline L-methionine or L-norleucine, the conformational angles, ψ_2 , χ_1 , χ_2 and χ_3 defined by Lakshminarayanan, Sasisekharan & Ramachandran (1967), are equivalent to the following internal rotation angles:

$$\begin{aligned} \psi_2 &= \tau[\text{O}(1)-\text{C}(1)-\text{C}(2)-\text{N}(1)] \\ \chi_1 &= \tau[\text{N}(1)-\text{C}(2)-\text{C}(3)-\text{C}(4)] \\ \chi_2 &= \tau[\text{C}(2)-\text{C}(3)-\text{C}(4)-\text{S}(1)] \quad \text{or} \quad \tau[\text{C}(2)-\text{C}(3)-\text{C}(4)-\text{C}(5)] \\ \chi_3 &= \tau[\text{C}(3)-\text{C}(4)-\text{S}(1)-\text{C}(5)] \quad \text{or} \quad \tau[\text{C}(3)-\text{C}(4)-\text{C}(5)-\text{C}(6)] \end{aligned}$$

where $\tau[A-B-C-D]$ is defined as the angles formed by the projection of the $A-B$ bond with that of $C-D$ when the projection is taken along the $B-C$ bond. The positive direction of the angle is taken coincident with that of the right-handed screw advancing along the $B-C$ bond.

* (1) Present work. (2) Mathieson (1952). (3) Mathieson (1953).

In molecule *A* of methionine, the conformations about the $C^\alpha-C^\beta$, $C^\beta-C^\gamma$ and $C^\gamma-S^\delta$ bonds are all *trans* and the side chain fully extends along the *c* axis. In molecule *B*, the corresponding conformations are *trans*, *gauche* and *gauche*, and the side chain is strongly folded. This may be due to the packing effect of the side chains. It can actually be shown that if the side chains of *B* took the *trans* planar conformation and the rotation of the bonds took place only at the $C^\alpha-C^\beta$

bond, very short contacts of about 3.2 Å would be observed between the carbon and sulphur atoms of neighbouring side chains as far as the shape and dimensions of the lattice are not changed.

The conformation of L-norleucine is very similar to that of molecule *A* of methionine.

Hydrogen bonds

Table 10 shows the values of short intermolecular

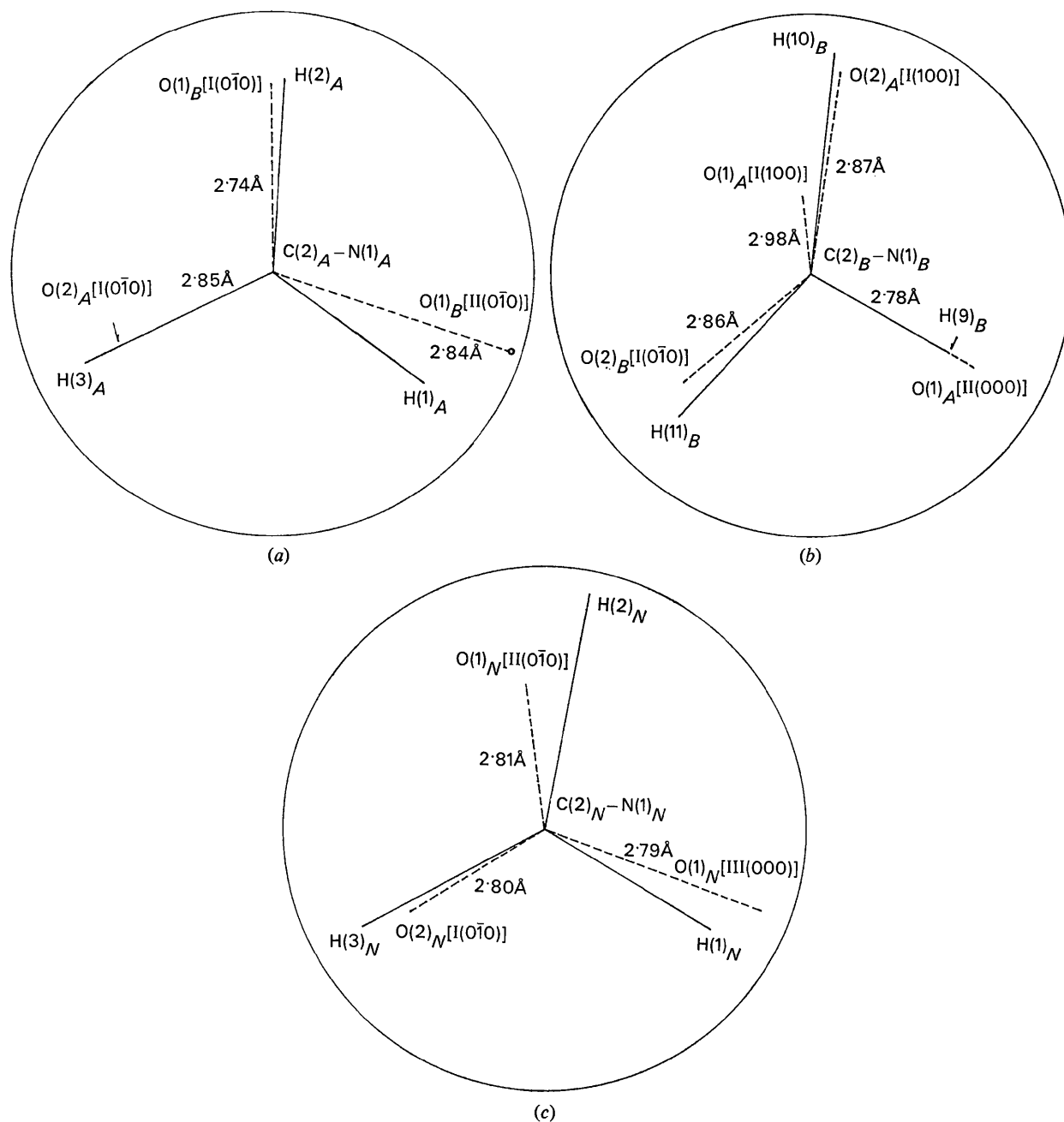


Fig. 3. Stereographic projection showing the arrangement of oxygen and hydrogen atoms around the nitrogen atom. Notation of the symmetry operations is shown in Table 10. Direction of the C-N bond is taken as the polar axis.

N...O distances and C-N...O angles. The arrangements of oxygen atoms around the amino nitrogen atoms are shown in Fig. 3 by stereographic projections, in which the N-H directions are also indicated. Hydrogen bonds form single layers and join adjacent layers to form double layers. In molecule *A* of methionine, the amino nitrogens are surrounded by three oxygen atoms nearly in tetrahedral directions. Molecule *B*, on the other hand, has four oxygen atoms at short distances. Considering its deviation from the N-H direction, O(1)_A[I(100)] seems to be linked mainly by electrostatic forces to the NH₃⁺ group. A similar arrangement has been found in L-valine. The arrangement of oxygen atoms around the amino nitrogen in norleucine seems to be intermediate between those in molecules *A* and *B* of methionine, but N(1)_N...O(2)_N[II(0 $\bar{1}$ 0)], which corresponds to one of the main hydrogen bonds in molecule *B* of methionine, is considerably long as in the case of molecule *A* of methionine, and it does not seem to participate in hydrogen bonding. In Fig. 4 is shown the network of hydrogen bonds in L-methionine superposed on that found in L-norleucine. It is seen that the slight shift of molecule *B* in the $-y$ direction allows the N(1) atom to come closer to O(1) rather than O(2) and the network structure of L-methionine will change to that of L-norleucine.

Crystal structures

A pronounced feature of the crystal structures is the stacking of the hydrogen-bonded double layers of molecules extending parallel to (001), which is quite similar to those found in L-cysteine, L-valine and L-isoleucine. Figs. 5 and 6 are the views of the structures of the single layers along the c^* direction. Thermal motions

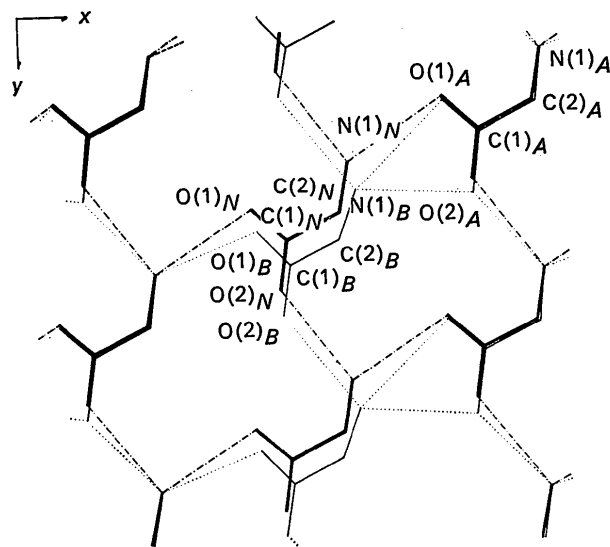


Fig. 4. Comparison of the networks of hydrogen bonds in L-methionine and L-norleucine as viewed along the c^* axis. The network in L-methionine (thin lines) is superposed on that in L-norleucine (thick lines).

Table 10. Intermolecular short N...O distances and C-N...O angles

	N...O	\angle C-N...O
L-Methionine		
N(1) _A -O(1) _B [II(0 $\bar{1}$ 0)]	2.839 (14) Å	88.2 (7)°
N(1) _A -O(2) _A [I(0 $\bar{1}$ 0)]	2.854 (14)	113.7 (7)
N(1) _A -O(1) _B [I(0 $\bar{1}$ 0)]	2.737 (11)	108.1 (7)
N(1) _A -O(2) _B [II(0 $\bar{2}$ 0)]	3.298 (15)	146.6 (7)
N(1) _B -O(1) _A [II(000)]	2.782 (13)	108.3 (7)
N(1) _B -O(2) _B [I(0 $\bar{1}$ 0)]	2.859 (16)	115.1 (8)
N(1) _B -O(2) _A [I(100)]	2.867 (11)	103.8 (7)
N(1) _B -O(1) _A [I(100)]	2.981 (12)	146.3 (8)

Roman numerals I and II denote the operations:

$$\begin{array}{cccc} \text{I} & & x & y \\ \text{II} & 1-x & \frac{1}{2}+y & 1-z \end{array}$$

where the values of x , y and z are given in Table 2.

L-Norleucine

N(1) _N -O(1) _N [III(000)]	2.792 (6) Å	98.1 (3)°
N(1) _N -O(2) _N [I(0 $\bar{1}$ 0)]	2.799 (6)	118.0 (3)
N(1) _N -O(1) _N [II(0 $\bar{1}$ 0)]	2.813 (5)	121.2 (3)
N(1) _N -O(2) _N [II(0 $\bar{1}$ 0)]	3.231 (5)	81.9 (3)

Roman numerals I, II, III and IV denote the operations:

$$\begin{array}{cccc} \text{I} & & x & y \\ \text{II} & \frac{1}{2}+x & \frac{1}{2}+y & z \\ \text{III} & 1-x & y & 1-z \\ \text{IV} & 1\frac{1}{2}-x & \frac{1}{2}+y & 1-z \end{array}$$

where the values of x , y and z are given in Table 4.

of each atom can be seen in Figs. 1 and 2. The orientation of each principal axis of thermal ellipsoid and the root-mean-square (r.m.s.) displacement along each axis are given in Table 12. Within the hydrogen-bonded layers, the amplitude of each atom in the direction normal to the layer is larger than those in other direc-

Table 11. Intermolecular short contacts less than 4.2 Å between side-chain carbon atoms

L-Methionine		
Within single layer:		
C(5) _A -C(4) _B [I(000)]	4.16 (3) Å	
C(4) _A -C(3) _A [I(010)]	4.01 (2)	
C(5) _A -S(1) _A [I(010)]	3.65 (3)	
C(4) _B -S(1) _A [I(010)]	4.03 (2)	
S(1) _B -C(3) _B [I(010)]	3.91 (2)	
S(1) _B -C(5) _B [I(010)]	4.16 (3)	
C(5) _B -C(5) _A [I(100)]	4.16 (4)	
S(1) _B -C(3) _A [I(110)]	4.10 (1)	
Between double layers:		
C(5) _A -C(5) _A [II(00 $\bar{1}$)]	3.98 (4)	
C(5) _A -S(1) _A [II(00 $\bar{1}$)]	3.83 (3)	
C(4) _B -C(5) _A [II(00 $\bar{1}$)]	4.09 (3)	
C(5) _B -C(5) _B [II(10 $\bar{1}$)]	4.07 (4)	
L-Norleucine		
Within single layer:		
C(4) _N -C(3) _N [I(010)]	4.06 (2)	
C(6) _N -C(3) _N [I(010)]	4.15 (2)	
C(6) _N -C(5) _N [I(010)]	3.99 (2)	
Between double layers:		
C(6) _N -C(5) _N [IV(00 $\bar{1}$)]	4.03 (2)	
C(6) _N -C(6) _N [IV(00 $\bar{1}$)]	4.03 (3)	

For symmetry-operation notation see Table 10.

tions. In the side-chain region, the long axes of thermal ellipsoids are perpendicular to the chain and almost parallel to the *a* direction.

Table 12. *R.m.s. displacement and directions of principal axes of thermal vibration*

Principal axes (<i>j</i>)		$U(j) \times 10^2$	$\cos \alpha_{1j}$	$\cos \alpha_{2j}$	$\cos \alpha_{3j}$
L-Methionine					
O(1) _A	1	11	0.982	0.032	-0.187
	2	20	-0.040	0.998	-0.040
	3	27	0.185	0.047	0.982
O(2) _A	1	13	0.842	-0.521	-0.140
	2	20	-0.472	-0.837	0.277
	3	25	0.261	0.167	0.951
N(1) _A	1	14	-0.432	0.829	-0.354
	2	18	-0.893	-0.340	0.294
	3	24	-0.124	-0.443	-0.888
C(1) _A	1	9	0.466	-0.885	0.023
	2	19	-0.843	-0.451	-0.294
	3	21	0.270	0.117	-0.956
C(2) _A	1	13	-0.030	0.991	-0.132
	2	15	0.999	0.025	-0.039
	3	24	0.035	0.133	0.990
C(3) _A	1	12	-0.310	0.582	0.751
	2	21	-0.246	-0.813	0.528
	3	29	0.918	-0.021	0.395
C(4) _A	1	12	0.241	0.174	-0.955
	2	18	0.117	-0.982	-0.149
	3	37	-0.963	-0.076	-0.257
S(1) _A	1	21	0.444	0.028	-0.896
	2	26	0.088	-0.996	0.012
	3	46	-0.892	-0.084	-0.445
C(5) _A	1	21	-0.298	-0.554	0.777
	2	36	-0.196	0.832	0.519
	3	52	0.934	-0.002	0.356
O(1) _B	1	13	0.876	-0.453	-0.165
	2	17	-0.407	-0.878	0.252
	3	29	0.259	0.153	0.954
O(2) _B	1	14	0.549	-0.835	0.024
	2	17	0.831	0.543	-0.125
	3	34	0.091	0.089	0.992
N(1) _B	1	9	-0.731	0.681	0.050
	2	21	0.567	0.647	-0.510
	3	24	-0.379	-0.344	0.859
C(1) _B	1	2	0.737	-0.570	0.363
	2	21	-0.185	0.347	0.919
	3	24	0.650	0.745	-0.150
C(2) _B	1	12	-0.864	0.168	-0.475
	2	19 Å	-0.267	-0.952	0.150
	3	23	0.427	-0.256	-0.867
C(3) _B	1	16	-0.220	-0.669	0.709
	2	30	0.932	-0.360	-0.050
	3	34	0.289	0.650	0.703

Table 12 (cont.)

Principal axes (<i>j</i>)		$U(j) \times 10^2$	$\cos \alpha_{1j}$	$\cos \alpha_{2j}$	$\cos \alpha_{3j}$
C(4) _B	1	28 Å	0.830	-0.308	-0.464
	2	38	-0.023	0.814	-0.580
	3	45	-0.557	-0.492	-0.669
C(5) _B	1	26	-0.437	0.764	0.476
	2	31	-0.561	-0.645	0.520
	3	49	0.704	-0.040	0.710
S(1) _B	1	26	0.512	0.653	-0.558
	2	36	0.368	-0.754	-0.544
	3	43	-0.776	0.074	-0.626
L-Norleucine					
O(1) _N	1	15	-0.969	0.199	0.145
	2	21	-0.178	-0.973	0.147
	3	29	0.170	0.117	0.978
O(2) _N	1	19	-0.499	0.866	-0.038
	2	21	-0.866	-0.496	0.070
	3	36	0.042	0.068	0.997
N(1) _N	1	14	0.849	-0.520	-0.093
	2	22	-0.528	-0.825	-0.201
	3	28	0.028	0.220	-0.975
C(1) _N	1	16	0.928	-0.372	0.003
	2	20	-0.371	-0.927	-0.050
	3	27	0.019	0.042	-0.999
C(2) _N	1	16	0.978	-0.184	-0.094
	2	22	-0.192	-0.979	-0.072
	3	28	-0.079	0.089	-0.993
C(3) _N	1	22	-0.806	0.458	0.374
	2	29	-0.007	-0.640	0.768
	3	32	0.592	0.617	0.519
C(4) _N	1	27	0.337	0.287	-0.897
	2	35	-0.469	0.877	0.105
	3	46	0.816	0.386	0.430
C(5) _N	1	30	-0.431	-0.384	0.817
	2	37	-0.409	0.890	0.202
	3	60	-0.804	-0.247	-0.540
C(6) _N	1	28	0.371	0.482	-0.794
	2	45	-0.244	0.875	0.418
	3	64	0.896	0.039	0.442

The r.m.s. displacement $U(j)$ is directed along the *j*th axes of the ellipsoid where α_{1j} , α_{2j} and α_{3j} are the angles between *j*th axis and the *a*, *b* and *c** axes respectively.

Intermolecular short contacts of the side-chain atoms less than 4.2 Å are listed in Table 11. Within the single layer, there are three short contacts in norleucine, while there are eight in methionine. The packing of the side chains in norleucine is very loose as evidenced by the crystal densities. Close approaches of the side-chain atoms in methionine are nearly of the same order of magnitude as those found in usual hydrocarbon chain packings, except for C(5)_A-S(1)_A[I(010)],

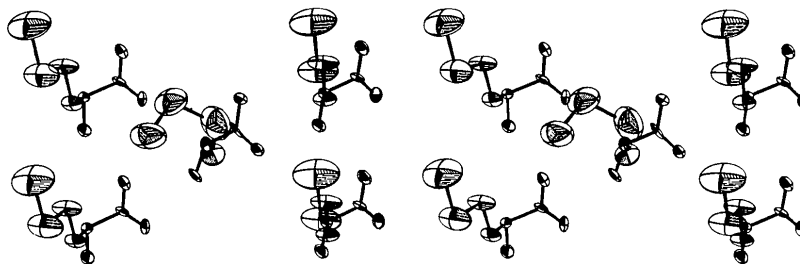


Fig. 5. Stereoscopic drawing of the crystal structure of L-methionine viewed along the *c** axis. The atoms are represented by 50% probability ellipsoids.

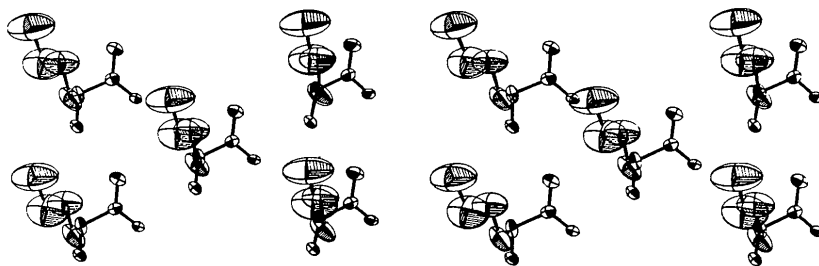


Fig. 6. Stereoscopic drawing of the crystal structure of L-norleucine similar to Fig. 5.

which is a little shorter than the C-S van der Waals contact.

The side chains of norleucine are packed together to form a $T\parallel$ packing of the long chain hydrocarbons (Bunn, 1939), which is known to be one of the stable forms of carbon-chain packing. The subcell dimensions are $a_s = 5.45$, $b_s = 5.26$, $c_s = 2.47$ Å, $\alpha_s = 64.0$, $\beta_s = 118.0$, $\gamma_s = 118.0^\circ$, and the volume per CH_2 -group is 26.4 Å³. The values of b_s , c_s and γ_s agree well with the mean values in the $T\parallel$ subcell, but a_s and β_s are a little larger and α_s is smaller.

L-Methionine molecules are packed in a manner somewhat like the $O\perp$ packing of the long-chain hydrocarbons. However, the side chain of molecule *B* is folded and does not form a plane. Consequently, this packing form is not $O\perp$ in a strict sense. As clearly seen in Fig. 5, the $\text{C}^\beta\text{-C}^\gamma$ bond of molecule *B* is not parallel to that of molecule *A*.

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