

TABLE II. Final values of positional and isotropic thermal parameters.<sup>a</sup>

Atom No.	%S	x	y	z	B (Å <sup>2</sup> )
1	40	0.001	0.121	0.000	5.30
2	67	0.667	0.453	-0.109	5.66
	67	0.597	0.403	-0.026	5.66
	67	0.547	0.333	0.057	5.66
	67	0.528	0.264	0.141	5.66
3	60	0.460	0.780	-0.171	5.59

<sup>a</sup> Atom numbers 1, 2, 3 correspond to molecule numbers I, II, III. For atoms 2: Positions are taken according to the relation given in the text; only the first  $z$  parameter was permitted to vary. The  $z$  of atom 1 was fixed at 0.000. With the stated constraints, the final least-squares calculation gave  $\sigma$ 's of 0.001 for  $x$  and  $y$  parameters, 0.006-0.008 for  $z$  parameters, and 0.2-0.3 Å<sup>2</sup> for  $B$  parameters.

refinement of the trial  $x$  and  $y$  parameters for space group  $P3_1$  without special treatment to account for the  $6/m$  diffraction symmetry. After these calculations had converged, further series of calculations with the full set of data were carried out, first with isotropic thermal parameters and subsequently with anisotropic ones. The least-squares calculations were continued until all parameter changes were negligibly small and the discrepancy factor,  $R = \sum ||F_0| - |F_c|| / \sum |F_0|$ , had decreased to 0.11. However, throughout the calculations, the thermal parameters of molecule II, both when held isotropic and when allowed to be anisotropic, tended to be unreasonably high (of the order of  $B = 9-12$  Å<sup>2</sup>, as compared with  $B = 4-6$  Å<sup>2</sup> for the other molecules), or when the thermal parameters of the three molecules were constrained to be equal, the multiplier for molecule II tended toward a high sulfur content (up to 90% S). Furthermore, the compositions of the three molecules were not satisfactorily consistent with the positional parameters. High correlations<sup>11</sup> between certain pairs of parameters were found throughout the calculations.

Additional least-squares calculations were made with several different trial values for the positional parameters of molecule II. None of these was found to lead to a better result than that obtained originally. However, from a series of least-squares calculations utilizing only the data with  $l=0$  it was found that rotation of molecule II by 30° increments from the original position gave three new nonequivalent positions which were apparently no worse than the original one. Each led to temperature factors of  $B = 9-12$  Å<sup>2</sup> for molecule II. This implied that molecule II might be disordered over at least these four positions. When this disorder was included in the least-squares calculations, without allowing the molecule II positions to vary, the isotropic temperature factor of molecule II refined to an apparently reasonable value only slightly higher than those of the other two molecules.

Further least-squares calculations showed that no further improvement was obtained with molecule II disordered over 16 positions corresponding to 7½° increments of rotation from the original position. On the

other hand, it was found that disorder of the molecule over only two positions, namely, the original one and one rotated 60° from it, leads to results no better than those obtained without disorder. It was concluded that molecule II is probably disordered over four sets of positions. From considerations of the packing it appeared that the  $z$  coordinates of the three new positions are given very nearly by  $z_0 + \frac{1}{12}$ ,  $z_0 + \frac{1}{6}$ , and  $z_0 + \frac{1}{4}$ , respectively, where  $z_0$  is the value for the original position. With these values of  $z$ , least-squares calculations utilizing the full set of data, still without allowing the molecule II positions to vary, also yielded satisfactory isotropic temperature factor values.

After it had been established that the disordered model leads to an apparent improvement in the thermal parameters, the multipliers were readjusted by a trial-and-error method in which several least-squares calculations were made with various combinations of multiplier and thermal parameter values to find those which gave the best over-all and individual agreement between  $|F_0|$  and  $|F_c|$ . Then, a final least-squares calculation, in which all three multipliers and the  $x$  and  $y$  for molecule II were held constant and the  $z$ 's for molecule II were constrained according to the relationship indicated above, was carried out. Because without drastic program changes it was not possible to use a single set of anisotropic thermal parameters for the disordered molecule II, all thermal parameters were kept isotropic. The final calculation yielded (with the constraints described above) the positional and isotropic thermal parameter values shown in Table II. Table III gives a comparison of the  $|F_c|$  with the

TABLE III. Comparison of observed and calculated structure amplitudes. Note  $|F_{hkl}| \equiv (1/\sqrt{2}) (|F_{hkl}|^2 + |F_{\bar{h}\bar{k}l}|^2)^{1/2}$ ,  $-i = h+k$ .

$z = 0$		$z = 0(\text{cont'd})$		$z = 1(\text{cont'd})$		$z = 2(\text{cont'd})$		
hk	$ F_0 $	$ F_c $	hk	$ F_0 $	$ F_c $	hk	$ F_0 $	$ F_c $
10	24	20	36	9	7	35	17	17
20	3	3	17	25	23	45	10	9
30	31	26	27	<4	3	16	<6	5
40	7	11	18	4	5	26	14	12
50	7	7				36	12	10
60	7	10				17	8	9
70	9	11				27	5	6
80	8	7				18	<3	2
90	8	7	hk	$ F_0 $	$ F_c $			
10	11	11	10	20	17			
20	21	20	20	91	89			
30	31	30	30	103	91			
40	41	40	40	60	56	hk	$ F_0 $	$ F_c $
50	51	50	50	35	33	10	58	62
60	61	60	60	35	35	20	69	53
70	71	70	70	8	5	30	97	68
80	81	80	80	<4	3	40	32	34
90	91	90	90	157	50	50	28	27
10	11	11	11	31	60	12	15	60
20	21	20	21	67	70	15	14	70
30	31	30	31	67	67	11	33	38
40	41	40	41	16	19	21	98	84
50	51	50	51	17	18	21	98	84
60	61	60	61	16	16	31	7	8
70	71	70	71	10	13	41	37	41
80	81	80	81	12	16	51	28	26
90	91	90	91	64	64	61	8	9
10	11	10	11	32	12	71	<4	3
20	21	20	21	13	17	12	62	64
30	31	30	31	25	26	22	44	41
40	41	40	41	9	12	32	12	15
50	51	50	51	68	65	42	9	10
60	61	60	61	33	33	52	14	16
70	71	70	71	22	22	62	13	14
80	81	80	81	21	23	72	5	7
90	91	90	91	17	15	13	45	40
10	11	10	11	7	8	23	12	17
20	21	20	21	19	17	33	47	8
30	31	30	31	6	4	43	16	14
40	41	40	41	26	25	53	6	8
50	51	50	51	4	4	64	24	24
60	61	60	61	46	46	6	14	7
70	71	70	71	11	12	24	31	28
80	81	80	81	40	36	34	9	8
90	91	90	91	25	26	44	18	17

<sup>a</sup> Intensities too high to be satisfactorily estimated.

$|F_0|$  calculated from these parameter values. The final value of  $R$  is 0.11.

An alternate solution, namely replacement of molecule II by a pure sulfur helix with 10 atoms per three turns, was explored extensively but was finally rejected. In this model the lattice constant  $c$  is tripled and the symmetry is lowered to that of space group  $P1$ . To account for the  $6/m$  diffraction symmetry, an effectively sextuply twinned crystal must be assumed. This model did not lead to satisfactory agreement between  $|F_0|$  and  $|F_c|$ , especially for many of the unobserved data, including those of intermediate reciprocal lattice levels which should occur when  $c$  is tripled.

### DISCUSSION

The attempt to refine the structure of the pressure-induced phase of  $S_{0.56}Se_{0.44}$  suffered from a number of complications. These were: large correlations between parameters, rotation twinning, positional disorder, and insufficient data for the large number of variable parameters. Further, because of the gradual decomposition of the crystal by the x irradiation,<sup>5</sup> to minimize exposure time, the photographic technique was used. From our experience with the structure of the pressure-induced fibrous sulfur phase, we believe it unlikely that significant improvement could have been attained in this case with counter data and attempts to replace crystals as they became too degraded by the exposure to x rays. Thus, as in the sulfur case,<sup>2</sup> we do not claim to have achieved an ultimately refined structure. We believe, however, that we have made the best of a complicated situation and that the structure proposed for this phase is essentially correct.

It is possible, and perhaps probable, that the disorder is more complicated than as given. One may well question why it is that only one of the three crystallographically nonequivalent molecules may have more than one position in the structure. It could be that other combinations of disorder would give equally good, or perhaps better, agreement between calculated and observed amplitudes and physically reasonable values for the composition and for the positional and thermal parameters. No attempt was made to explore this possibility; the number of possible combinations is very large and we have decided that further effort on this problem is unwarranted.

We were rather surprised to find that the compositions of the three molecules differed. However, forcing the molecules to have the same composition impairs the agreement between calculated and observed amplitudes and gives unreasonable values of thermal parameters. Thus we must conclude that for best packing in the solid state, the compositions of the nonequivalent molecules must be different. This implies that some intermolecular diffusion occurs during the crystallization process.

Interatomic distances and angles were calculated with the ORTEP program.<sup>12</sup> Within each molecule the nearest-neighbor distance is 2.25 Å. The S-S distance in fibrous sulfur is 2.07 Å; in hexagonal Se,<sup>13</sup> the Se-Se distance is

2.32 Å. For a 40% S molecule, the calculated bond distance is 2.21 Å; for a 60% S molecule, it is 2.17, and for a 67% S molecule, it is 2.15 Å. At least the last two are substantially lower than the observed value.

The space group fixes the vertical distance between two nearest atoms in a molecule to  $c/3$  or 1.54 Å (see Ref. 14); thus the variables on which the bond distance depends are  $x$  and  $y$ . In the least-squares calculations while the values of these parameters were fixed for the "disordered" molecule, they were allowed to vary for the two other molecules. Convergence under the imposed constraints led to the observed bond distance and to rather small  $\sigma^2$ s (0.001) in the  $x$  and  $y$  parameters for these two molecules. If the standard errors are meaningful, then the difference between observed and "calculated" bond distance is significant for molecule III.

The helix radii are  $0.95 \pm 0.03$  Å; in hexagonal Se<sup>13</sup> it is 0.95 Å. The interbond angles in all three molecules are  $102^\circ$ ; it is  $105^\circ$  in hexagonal Se,<sup>13</sup>  $102^\circ$ - $109^\circ$  in  $\alpha$ -Se,<sup>15</sup>  $104^\circ$ - $107^\circ$  in  $\beta$ -Se,<sup>16</sup>  $106^\circ$  in pressure-induced fibrous S ( $^{10}S_3$  helix),<sup>2</sup>  $108^\circ$  in orthorhombic<sup>17</sup> S, and  $102^\circ$  in rhombohedral<sup>18</sup> S.

The shortest distance between nonbonded atoms in all three molecules is 3.49 Å. The shortest distance between atoms in different molecules is 3.54 Å; in hexagonal Se, the closest approach between atoms in different chains is 3.46 Å. (The poorer packing efficiency of the pressure-induced  $S_{0.56}Se_{0.44}$  phase than of hexagonal Se had been deduced earlier.<sup>3</sup>)

The dihedral angle formed by a sequence of four consecutive atoms, that is, between the planes of the first three and the last three is  $100^\circ$ . This angle is  $95^\circ$  in fibrous sulfur and  $98^\circ$ - $101^\circ$  in orthorhombic sulfur. (These angles were not calculated in Refs. 13, 15, and 16.)

Projections of the structure down the  $c$  axis are shown in Fig. 1. The different projections show the different possible orientations of molecule II.

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<sup>3</sup> S. Geller and M. D. Lind, *Science* **155**, 79 (1967).

<sup>4</sup> S. Geller, *Science* **161**, 290 (1968).

<sup>5</sup> S. Geller and M. D. Lind, *Trans. Am. Crystallogr. Assoc.* **5**, 81 (1969).

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<sup>9</sup> A. J. Freeman and R. Watson, tabulated in *International Tables for X-Ray Crystallography* (Kynoch Press, Birmingham, England, 1962), Vol. 3, p. 206.

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<sup>13</sup> M. E. Straumanis, *Z. Krist.* **102**, 432 (1940).

<sup>14</sup> In Ref. 2, the pitch was erroneously given as 1.54 Å; this is actually the vertical distance between nearest atoms in the molecule or  $\frac{1}{3}$  of the pitch which is the length of the  $c$  axis, 4.62 Å.

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