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# A SUMMARY OF RUBY R-LINE MEASUREMENTS UNDER SHOCK LOADING

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The purpose of this report is to summarize the ruby-emission results obtained by Paul Horn, Jim Burt and Xiao-An Shen under shock wave uniaxial strain loading, below the HEL. The experimental conditions under which these measurements were carried out have been discussed in detail elsewhere.[1–4] Here we simply list the values of the parameters obtained from each experiment in Tables I and II, and briefly describe how these parameters were determined.

1. Initial temperatures

   Our measurements were carried out at either room or liquid nitrogen temperature. In the latter case, a K-type thermocouple was used to monitor the sample temperature.

2. Impact velocity, $v$

   This parameter was measured directly using velocity pins.[5]

3. Particle velocity, $u$

   Because of the symmetric impact (sapphire on sapphire) used in the ruby-emission experiments, the particle velocities in the states of peak compression and tension are merely equal to half the impact velocity.[1–4] In the states of partial unloading from the sapphire-fused silica interface, the particle velocity was calculated using the $\sigma-u$ relations for sapphire and fused silica obtained by Barker and Hollenbach,[6] i.e. $\sigma = \rho_o(11.19+u)u$ and $\sigma = 131.7u-73.61u^2+99.47u^3-41.63u^4$ kbar, respectively.

4. Density compression, $\mu = \rho/\rho_o-1$

   The values for the states of compression were obtained by employing the Rankine-Hugoniot jump condition, $\rho/\rho_o = D/(D-u)$ with $\rho_o = 3.985 g/cm^3$ and $D = 11.19+u$ mm/$\mu$s for sapphire, while those for the states of tension were calculated using a stepwise approximation,[7] i.e., $\Delta u = \sqrt{(\Delta\sigma\Delta\rho)}/\rho$. In the latter case, a table of $u$ and $\sigma$ (longitudinal and lateral stresses) as a function of $\rho$ was generated using the nonlinear elastic relations[1] with the nonlinear elastic constants of Hankey and Schuele (see Table III),[8] and the density compression was obtained from this table by finding $\rho$ whose $u$ was equal to half the impact velocity, i.e. $v/2$.

5. Longitudinal stress

   Two longitudinal stress values were obtained for each compression state, one from the Rankine-Hugoniot jump conditions (see Items 3 and 4) and the other from the nonlinear elastic relations.[1] Since the jump conditions are not applicable in the case of tension loading, only one value was listed in Tables I and II, which was obtained from the $u-\sigma-\rho$ table discussed above.

6. Lateral stresses

   The compression data were calculated using the nonlinear elastic relations[1] with the density compressions determined from the jump conditions, while the tension results were obtained from the $u-\sigma-\rho$ table.

7. Measured wavelength shifts

   The average shifts for each stress state was listed. No temperature corrections were made to these values.

8. Temperature rise

The shock-induced temperature rise was estimated for each experiment using the isentropic compression model

$$\Delta T = T_o(e^{(\gamma/V)\Delta V}-1) \text{ with } \gamma = 1.27 \text{ and } V_o = 0.251\ cm^3/g \text{ (see Ref. 1).}$$

9. Corrected wavelength shifts

Temperature corrections were made to only the room temperature data using the relation $\Delta\lambda_{cor} = \Delta\lambda_{mea} - 0.06\,\Delta T$,[9] since the peak positions of the R lines are independent of temperature below 100 K.

For the purpose of theoretical analysis, we fitted the R-line shifts (corrected, in wavenumber) to a quadratic model, $\Delta\nu = a_o + a\mu + b\mu^2$, and the parameters $a_o$, $a$ and $b$ obtained from the fitting were listed in Table IV. Here $a_o$ reflected mainly the precision of our measurements. Because of the asymmetric response of the R-lines to uniaxial strain along the a-axis,[4] the compression and tension data along this axis were fitted separately, and, the fits were constrained to pass the origin, i.e. $a_o = 0$.

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**TABLE I: Compilation of ruby c-axis data.**

| Experiment (shot) number[a] | Initial temperature (K) | Impact velocity (km/sec) | Particle velocity[b] (km/sec) | Density compression[c] | Longitudinal stress $\sigma_{33}^{c}$ (kbar) | $\sigma_{33}^{d}$ (kbar) | Lateral stress $\sigma_{11}=\sigma_{22}$ (kbar) | $\Delta\lambda_{R_1}$ (measured) (Å) | $\Delta\lambda_{R_2}$ (measured) (Å) | $\Delta T$ (K) | $\Delta\lambda_{R_1}$ (corrected) (Å) | $\Delta\lambda_{R_2}$ (corrected) (Å) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | | 0.222 | 0.111 | 0.0099 | 50.0 | 49.7 | 11.4 | 7.4 | 9.1 | 3.5 | 7.2 | 8.9 |
| (86552) | 300 | | | | | | | | | | | |
| $1_r$ | | | 0.175 | 0.0042 | 21.0 | 21.0 | 4.7 | 2.9 | 4.1 | 1.5 | 2.8 | 4.0 |
| 2 | | | 0.166 | 0.0148 | 75.1 | 74.5 | 17.3 | 12.3 | 14.2 | 5.4 | 12.0 | 13.9 |
| (86536) | 300 | 0.332 | | | | | | | | | | |
| $2_r$ | | | 0.263 | 0.0062 | 31.0 | 31.0 | 7.0 | 4.5 | 5.8 | 2.3 | 4.4 | 5.7 |
| 3 ( ? ) | 300 | 0.440 | 0.220 | 0.0197 | 100.0 | 99.5 | 23.4 | 17.2 | 20.0 | 7.2 | 16.8 | 19.6 |
| 4 (86510) | 300 | 0.444 | 0.222 | 0.0198 | 101.0 | 100.0 | 23.5 | 16.7 | 19.3 | 7.4 | 16.3 | 18.9 |
| 5 | | | 0.272 | 0.0243 | 124.2 | 123.0 | 29.2 | 22.3 | 25.3 | 9.0 | 21.8 | 24.8 |
| (86521) | 300 | 0.544 | | | | | | | | | | |
| $5_r$ | | | 0.433 | 0.0099 | 50.0 | 49.7 | 11.4 | 7.8 | 9.2 | 3.7 | 7.6 | 9.0 |
| 6 | | | 0.180 | 0.0161 | 81.6 | 81.1 | 18.9 | 13.5 | 15.6 | 1.6 | 13.5 | 15.6 |
| (87527) | 77 | 0.360 | | | | | | | | | | |
| $6_r$ | | | 0.075 | 0.0067 | 33.8 | 33.6 | 7.6 | 4.9 | 5.8 | 0.7 | 4.9 | 5.8 |
| 7 | | | 0.216 | 0.0193 | 98.3 | 97.4 | 22.9 | 17.0 | 19.1 | 1.9 | 17.0 | 19.1 |
| (87520) | 77 | 0.432 | | | | | | | | | | |
| $7_r$ | | | 0.089 | 0.0080 | 40.2 | 40.1 | 9.1 | 6.9 | 7.6 | 0.8 | 6.9 | 7.6 |
| 8 | | | 0.221 | 0.0198 | 100.6 | 100.0 | 23.5 | 17.4 | 19.6 | 1.9 | 17.4 | 19.6 |
| (87533) | 77 | 0.442 | | | | | | | | | | |
| $8_r$ | | | 0.091 | 0.0082 | 41.1 | 41.1 | 9.4 | 6.5 | 7.3 | 0.8 | 6.5 | 7.3 |
| 9 | | | 0.264 | 0.0236 | 120.4 | 119.4 | 28.3 | 21.5 | 24.3 | 2.3 | 21.5 | 24.3 |
| (87538) | 77 | 0.528 | | | | | | | | | | |
| $9_r$ | | | 0.108 | 0.0097 | 48.7 | 48.7 | 11.1 | 7.8 | 8.9 | 0.9 | 7.8 | 8.9 |
| 10 | | | 0.114 | 0.0102 | 51.4 | 51.2 | 11.7 | 7.2 | --- | 1.0 | 7.2 | --- |
| (88504) | 77 | 0.228 | | | | | | | | | | |
| $10_t$ | | | 0.114 | -0.0102 | --- | -50.3 | -10.9 | -6.9 | -7.6 | -1.0 | -6.9 | -7.6 |
| 11 | | | 0.177 | 0.0158 | 79.9 | 79.6 | 18.5 | 13.2 | 14.8 | 1.5 | 13.2 | 14.8 |
| (88506) | 77 | 0.353 | | | | | | | | | | |
| $11_t$ | | | 0.177 | -0.0158 | --- | -77.4 | -16.5 | -9.2 | -10.4 | -1.5 | -9.2 | -10.4 |
| 12 | | | 0.244 | 0.0218 | 110.9 | 110.2 | 26.0 | 19.8 | 22.1 | 2.1 | 19.8 | 22.1 |
| (88509) | 77 | 0.487 | | | | | | | | | | |
| $12_t$ | | | 0.244 | -0.0218 | --- | -106.1 | -22.2 | -12.4 | -14.4 | -2.1 | -12.4 | -14.4 |

[a] Subscripts $r$ and $t$ denote relief and tension data, respectively.

[b] The relief data are calculated using the results of Barker and Hollenbach on z-cut sapphire and fused silica.

[c] Calculated using the data of Barker and Hollenbach on z-cut sapphire, except the tension data which were obtained using the nonlinear elastic constants obtained by Hankey and Schuele.

[d] Calculated using the nonlinear elastic constants given by Hankey and Schuele.

**TABLE II: Compilation of ruby a-axis data.**

| Experiment (shot) number[a] | Initial temperature (K) | Impact velocity (km/sec) | Particle velocity[b] (km/sec) | Density compression[c] | Longitudinal stress $\sigma_{11}^{c}$ (kbar) | $\sigma_{11}^{d}$ (kbar) | Lateral stress $\sigma_{22}$ (kbar) | $\sigma_{33}$ | $\Delta\lambda_{R_1}$ (measured) (Å) | $\Delta\lambda_{R_2}$ | $\Delta T$ (K) | $\Delta\lambda_{R_1}$ (corrected) (Å) | $\Delta\lambda_{R_2}$ |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | | | 0.227 | 0.0203 | 103.4 | 103.3 | 35.1 | 24.2 | 26.8 | 20.6 | 7.7 | 26.4 | 20.2 |
| (88532) | 300 | 0.454 | | | | | | | | | | | |
| $1_r$ | | | 0.361 | 0.0083 | 41.9 | 41.9 | 14.0 | 9.5 | 10.2 | 8.0 | 3.2 | 10.0 | 7.8 |
| 2 | | | 0.275 | 0.0246 | 125.6 | 125.5 | 42.8 | 29.7 | 33.1 | 24.9 | 9.3 | 32.6 | 24.3 |
| (88541) | 300 | 0.550 | | | | | | | | | | | |
| $2_r$ | | | 0.438 | 0.0100 | 50.4 | 50.3 | 16.8 | 11.5 | 12.2 | 9.9 | 3.8 | 12.0 | 9.7 |
| 3 | | | 0.156 | 0.0139 | 70.5 | 70.4 | 23.7 | 16.3 | 17.9 | 14.5 | 1.4 | 17.9 | 14.5 |
| (89503) | 77 | 0.312 | | | | | | | | | | | |
| $3_t$ | | | 0.156 | -0.0140 | --- | -68.1 | -22.0 | -14.7 | -11.5 | -14.9 | -1.4 | -11.5 | -14.9 |
| 4 | | | 0.190 | 0.0169 | 86.0 | 85.9 | 29.0 | 20.0 | 22.0 | 16.0 | 1.5 | 22.0 | 16.0 |
| (89504) | 77 | 0.379 | | | | | | | | | | | |
| $4_t$ | | | 0.190 | -0.0171 | --- | -82.5 | -26.5 | -17.6 | -13.2 | -18.1 | -1.5 | -13.2 | -18.1 |
| 5 | | | 0.049 | 0.0044 | 21.9 | 21.8 | 7.2 | 4.9 | 5.3 | 4.3 | 0.4 | 5.3 | 4.3 |
| (89510) | 77 | 0.098 | | | | | | | | | | | |
| $5_t$ | | | 0.049 | -0.0044 | --- | -21.6 | -7.1 | -4.8 | -3.8 | -3.8 | -0.4 | -3.8 | -3.8 |
| 6 | | | 0.243 | 0.0217 | 110.7 | 110.6 | 37.6 | 26.0 | 29.1 | 21.6 | 2.2 | 29.1 | 21.6 |
| (89511) | 77 | 0.486 | | | | | | | | | | | |
| $6_t$ | | | 0.243 | -0.0219 | --- | -104.9 | -33.5 | -22.2 | -15.5 | -24.2 | -2.2 | -15.5 | -24.2 |

[a] Subscripts *r* and *t* denote relief and tension data, respectively.

[b] The relief data are calculated using the results of Barker and Hollenbach on z-cut sapphire and fused silica.

[c] Calculated using the data of Barker and Hollenbach on z-cut sapphire, except the tension data which were calculated using the nonlinear elastic constants obtained by Hankey and Schuele.

[d] Calculated using the nonlinear elastic constants given by Hankey and Schuele.

**TABLE III: Nonlinear elastic constants of single crystal sapphire.**

| | | | |
|---|---|---|---|
| $C_{33}$ | 4981 | $C_{333}$ | -33400 |
| $C_{13}$ | 1109 | $C_{133}$ | -9220 |
| $C_{23}=C_{13}$ | 1109 | $C_{233}=C_{133}$ | -9220 |
| $C_{11}$ | 4968 | $C_{111}$ | -38700 |
| $C_{21}$ | 1636 | $C_{211}$ | -10900 |
| $C_{31}=C_{13}$ | 1109 | $C_{311}$ | -9630 |

Note: All values are in units of kbar.

**TABLE IV: Parameters $a_o$, a, b.**

| Parameter | c-axis R$_1$ | c-axis R$_2$ | a-axis R$_1$ compression | a-axis R$_1$ tension | a-axis R$_2$ compression | a-axis R$_2$ tension |
|---|---|---|---|---|---|---|
| $a_o$ | 0.52 | -0.31 | --- | --- | --- | --- |
| a | -1493.9 | -1715.6 | -2419.7 | -2042.8 | -2052.3 | -1920.6 |
| b | -16492.5 | -16186.2 | -14091.1 | -25739.6 | --- | -18202.3 |