

# Calibration of a Raman Spectrometer Using the $\text{Kr}^+$ Laser Plasma Lines

C. Julien and C. Hirlimann

Laboratoire de Physique des Solides, associé au CNRS, Université Pierre et Marie Curie, 4 Place Jussieu, 75230 Paris Cédex 05, France

**We show that the plasma lines of a  $\text{Kr}^+$  laser can be used for the calibration of a Raman spectrometer. We have tabulated the absolute values of the plasma lines as well as the shift of these lines relative to the laser lines.**

## INTRODUCTION

Since the first experiment of Porto and Wood<sup>1</sup> in 1962, lasers have become the preferential exciting sources used in Raman spectroscopy. This is due to the fact that lasers are coherent, monochromatic sources of light providing intense radiation. They are therefore perfectly adequate for use in Raman spectroscopy where the light-scattering efficiency is very low.

In recent years, powerful, fully ionized krypton lasers have been developed which are becoming the most commonly used sources, due to the wide range of discrete lines which extend from near-IR to near-UV. Moreover, the high value of the power available on these lines allows the excitation of a large variety of dyes and leads to a wide range of CW tunable lasers all over the visible region.

## STANDARD CALIBRATION

Spectrometers are commonly calibrated using the emission lines of neon. Neon sources have a very large emission spectrum covering the whole visible region used in Raman spectroscopy (from 400 to 900 nm) with a line separation which is less than 3 nm. In this wavelength range the corresponding gas lasers are helium-neon, ionized argon and ionized krypton, whose lines are shown in Table 1. Spectrometer calibrations using the helium-neon and ionized argon laser lines have been proposed by Loader<sup>2</sup> and Kagel.<sup>3</sup>

## USE OF A $\text{Kr}^+$ LASER

Having a great number of lines ranging from the red to the blue, the  $\text{Kr}^+$  gas laser is highly suitable for spectrometer calibration. The Raman scattering process has a very low efficiency. In the case of a reflective geometry, in opaque materials, even when interferometric filters are used, it is difficult to avoid the observation of plasma lines of the laser. This emphasizes the need for both the absolute position and relative position of the plasma line compared to the different laser line of the  $\text{Kr}^+$  laser.

The  $\text{Kr}^+$  laser lines have recently been tabulated by Beck *et al.*<sup>4</sup> and the plasma lines have been measured by Saidel *et al.*<sup>5</sup> in standard air using an interferometric method. The observed values of the frequencies are corrected for vacuum, taking into account the air index values given by Edlen.<sup>6</sup>

## RESULTS

The plasma lines of a Spectra-Physics 164-11  $\text{Kr}^+$  laser have been recorded through a JT600 triple monochromator.<sup>7</sup> This Raman spectrometer has a 625 mm focal length and it is equipped with three gratings of  $1200 \text{ g mm}^{-1}$ . The very intense plasma lines are attenuated by mean of neutral filters of optical density 1 or 2. During the experiment the laser is misaligned so that there is no laser line and the plasma light beam is sent directly into the spectrometer.

All the data we obtained are shown in Table 2 together with the relative frequencies of each line for the range 405–850 nm.

**Table 1. Major wavelengths at which  $\text{Kr}^+$  lasers can be operated**

| Wavelength in standard air (nm) | Wavenumber in air ( $\text{cm}^{-1}$ ) | Wavenumber in vacuo ( $\text{cm}^{-1}$ ) | Energy (eV) |
|---------------------------------|----------------------------------------|------------------------------------------|-------------|
| 406.7                           | 24 586                                 | 24 579                                   | 3.048       |
| 413.1                           | 24 203                                 | 24 196                                   | 3.000       |
| 415.4                           | 24 070                                 | 24 063                                   | 2.984       |
| 461.9                           | 21 649                                 | 21 643                                   | 2.684       |
| 468.0                           | 21 366                                 | 21 360                                   | 2.649       |
| 476.2                           | 20 997                                 | 20 991                                   | 2.603       |
| 482.5                           | 20 724                                 | 20 718                                   | 2.569       |
| 501.6                           | 19 934                                 | 19 929                                   | 2.471       |
| 520.2                           | 19 200                                 | 19 195                                   | 2.383       |
| 530.9                           | 18 837                                 | 18 832                                   | 2.336       |
| 568.2                           | 17 600                                 | 17 595                                   | 2.182       |
| 647.1                           | 15 454                                 | 15 451                                   | 1.916       |
| 676.4                           | 14 784                                 | 14 779                                   | 1.833       |
| 687.1                           | 14 554                                 | 14 550                                   | 1.804       |
| 752.4                           | 13 290                                 | 13 286                                   | 1.647       |
| 799.3                           | 12 511                                 | 12 507                                   | 1.551       |

Table 2. Possible spurious lines due to emission from the laser plasma when a krypton ion laser is used as the Raman exciting source

| Line | Frequency of<br>emission line<br>in vacuo<br>( $\text{cm}^{-1}$ ) | Wavelength in<br>standard air<br>(nm) | Peak | Apparent Raman displacement of the<br>emission lines in $\text{cm}^{-1}$ from the laser lines |          |          |          |
|------|-------------------------------------------------------------------|---------------------------------------|------|-----------------------------------------------------------------------------------------------|----------|----------|----------|
|      |                                                                   |                                       |      | 406.7 nm                                                                                      | 413.1 nm | 415.4 nm | 461.9 nm |
| 1    | 24 682                                                            | 405.04                                | 50   |                                                                                               |          |          |          |
| 2    | 24 642                                                            | 405.70                                | 300  |                                                                                               |          |          |          |
| 3    | 24 593                                                            | 406.51                                | 300  |                                                                                               |          |          |          |
| 4    | 24 579                                                            | 406.74                                | 1000 | 0                                                                                             |          |          |          |
| 5    | 24 453                                                            | 408.83                                | 500  | 126                                                                                           |          |          |          |
| 6    | 24 391                                                            | 409.87                                | 250  | 188                                                                                           |          |          |          |
| 7    | 24 329                                                            | 410.92                                | 100  | 250                                                                                           |          |          |          |
| 8    | 24 199                                                            | 413.13                                | 1000 | 380                                                                                           | 0        |          |          |
| 9    | 24 153                                                            | 413.91                                | 100  | 426                                                                                           | 46       |          |          |
| 10   | 24 118                                                            | 414.51                                | 250  | 461                                                                                           | 81       |          |          |
| 11   | 24 064                                                            | 415.45                                | 800  | 515                                                                                           | 135      | 0        |          |
| 12   | 23 964                                                            | 417.18                                | 950  | 615                                                                                           | 235      | 100      |          |
| 13   | 23 888                                                            | 418.51                                | 50   | 691                                                                                           | 311      | 176      |          |
| 14   | 23 653                                                            | 422.65                                | 700  | 926                                                                                           | 546      | 411      |          |
| 15   | 23 597                                                            | 423.66                                | 100  | 982                                                                                           | 602      | 467      |          |
| 16   | 23 520                                                            | 425.06                                | 150  | 1059                                                                                          | 679      | 544      |          |
| 17   | 23 508                                                            | 425.27                                | 50   | 1071                                                                                          | 691      | 556      |          |
| 18   | 23 496                                                            | 425.48                                | 100  | 1083                                                                                          | 703      | 568      |          |
| 19   | 23 471                                                            | 425.94                                | 80   | 1108                                                                                          | 728      | 593      |          |
| 20   | 23 420                                                            | 426.86                                | 60   | 1159                                                                                          | 779      | 644      |          |
| 21   | 23 288                                                            | 429.29                                | 600  | 1291                                                                                          | 911      | 776      |          |
| 22   | 23 247                                                            | 430.05                                | 200  | 1332                                                                                          | 952      | 817      |          |
| 23   | 23 153                                                            | 431.78                                | 500  | 1426                                                                                          | 1046     | 911      |          |
| 24   | 23 126                                                            | 432.30                                | 150  | 1453                                                                                          | 1073     | 938      |          |
| 25   | 23 082                                                            | 433.12                                | 80   | 1497                                                                                          | 1117     | 982      |          |
| 26   | 23 071                                                            | 433.33                                | 50   | 1508                                                                                          | 1128     | 993      |          |
| 27   | 22 953                                                            | 435.55                                | 3000 | 1626                                                                                          | 1246     | 1111     |          |
| 28   | 22 878                                                            | 436.97                                | 200  | 1701                                                                                          | 1321     | 1186     |          |
| 29   | 22 817                                                            | 438.15                                | 100  | 1762                                                                                          | 1382     | 1247     |          |
| 30   | 22 791                                                            | 438.65                                | 300  | 1788                                                                                          | 1408     | 1273     |          |
| 31   | 22 716                                                            | 440.09                                | 100  | 1863                                                                                          | 1483     | 1348     |          |
| 32   | 22 604                                                            | 442.27                                | 100  | 1975                                                                                          | 1595     | 1460     |          |
| 33   | 22 558                                                            | 443.17                                | 500  | 2021                                                                                          | 1641     | 1506     |          |
| 34   | 22 533                                                            | 443.68                                | 600  | 2046                                                                                          | 1666     | 1531     |          |
| 35   | 22 499                                                            | 444.33                                | 850  | 2080                                                                                          | 1700     | 1565     |          |
| 36   | 22 450                                                            | 445.32                                | 50   | 2129                                                                                          | 1749     | 1614     |          |
| 37   | 22 397                                                            | 446.37                                | 750  | 2182                                                                                          | 1802     | 1667     |          |
| 38   | 22 340                                                            | 447.50                                | 800  | 2239                                                                                          | 1859     | 1724     |          |
| 39   | 22 306                                                            | 448.18                                | 50   | 2273                                                                                          | 1893     | 1758     |          |
| 40   | 22 266                                                            | 448.99                                | 400  | 2313                                                                                          | 1933     | 1798     |          |
| 41   | 22 103                                                            | 452.31                                | 400  | 2476                                                                                          | 2096     | 1961     |          |
| 42   | 21 940                                                            | 455.66                                | 200  | 2639                                                                                          | 2259     | 2124     |          |
| 43   | 21 840                                                            | 457.72                                | 100  | 2739                                                                                          | 2359     | 2224     |          |
| 48   | 21 661                                                            | 461.53                                | 500  | 2918                                                                                          | 2538     | 2403     |          |
| 49   | 21 643                                                            | 461.92                                | 1000 | 2936                                                                                          | 2556     | 2421     | 0        |
| 50   | 21 574                                                            | 463.39                                | 800  | 3005                                                                                          | 2625     | 2490     | 69       |
| 51   | 21 498                                                            | 465.02                                | 40   | 3081                                                                                          | 2701     | 2566     | 145      |

| Line | Frequency of<br>emission line<br>in vacuo<br>( $\text{cm}^{-1}$ ) | Wavelength in<br>standard air<br>(nm) | Peak | Apparent Raman displacement of the<br>emission lines in $\text{cm}^{-1}$ from the laser lines |          |          |          |          |          |          |
|------|-------------------------------------------------------------------|---------------------------------------|------|-----------------------------------------------------------------------------------------------|----------|----------|----------|----------|----------|----------|
|      |                                                                   |                                       |      | 461.9 nm                                                                                      | 468.0 nm | 476.2 nm | 482.5 nm | 501.6 nm | 502.2 nm | 530.9 nm |
| 49   | 21 643                                                            | 461.92                                | 1000 | 0                                                                                             |          |          |          |          |          |          |
| 50   | 21 574                                                            | 463.39                                | 800  | 69                                                                                            |          |          |          |          |          |          |
| 51   | 21 498                                                            | 465.02                                | 40   | 145                                                                                           |          |          |          |          |          |          |
| 52   | 21 458                                                            | 465.89                                | 850  | 185                                                                                           |          |          |          |          |          |          |
| 53   | 21 360                                                            | 468.04                                | 600  | 283                                                                                           | 0        |          |          |          |          |          |
| 54   | 21 310                                                            | 469.13                                | 270  | 333                                                                                           | 50       |          |          |          |          |          |
| 55   | 21 296                                                            | 469.44                                | 380  | 347                                                                                           | 64       |          |          |          |          |          |
| 56   | 21 095                                                            | 473.90                                | 2300 | 548                                                                                           | 265      |          |          |          |          |          |
| 57   | 21 038                                                            | 474.20                                | 90   | 605                                                                                           | 322      |          |          |          |          |          |

Table 2—continued

| Line | Frequency of<br>emission line<br>in vacuo<br>(cm <sup>-1</sup> ) | Wavelength in<br>standard air<br>(nm) | Peak | Apparent Raman displacement of the<br>emission lines in cm <sup>-1</sup> from the laser lines |          |          |          |          |          |          |
|------|------------------------------------------------------------------|---------------------------------------|------|-----------------------------------------------------------------------------------------------|----------|----------|----------|----------|----------|----------|
|      |                                                                  |                                       |      | 461.9 nm                                                                                      | 468.0 nm | 476.2 nm | 482.5 nm | 501.6 nm | 502.2 nm | 530.9 nm |
| 58   | 20 991                                                           | 476.57                                | 1320 | 652                                                                                           | 369      | 0        |          |          |          |          |
| 59   | 20 977                                                           | 476.57                                | 3500 | 666                                                                                           | 383      | 14       |          |          |          |          |
| 60   | 20 843                                                           | 479.63                                | 70   | 800                                                                                           | 517      | 134      |          |          |          |          |
| 61   | 20 799                                                           | 480.60                                | 150  | 844                                                                                           | 561      | 178      |          |          |          |          |
| 62   | 20 776                                                           | 481.18                                | 800  | 867                                                                                           | 584      | 201      |          |          |          |          |
| 63   | 20 718                                                           | 482.52                                | 950  | 925                                                                                           | 642      | 259      | 0        |          |          |          |
| 64   | 20 689                                                           | 483.21                                | 2000 | 954                                                                                           | 671      | 288      | 29       |          |          |          |
| 65   | 20 659                                                           | 483.66                                | 80   | 984                                                                                           | 701      | 318      | 59       |          |          |          |
| 66   | 20 627                                                           | 484.66                                | 2400 | 1016                                                                                          | 733      | 364      | 91       |          |          |          |
| 67   | 20 582                                                           | 485.72                                | 600  | 1061                                                                                          | 778      | 409      | 136      |          |          |          |
| 68   | 20 484                                                           | 488.04                                | 80   | 1159                                                                                          | 876      | 507      | 234      |          |          |          |
| 69   | 20 336                                                           | 491.59                                | 120  | 1307                                                                                          | 1024     | 655      | 382      |          |          |          |
| 70   | 20 215                                                           | 494.56                                | 500  | 1428                                                                                          | 1145     | 776      | 503      |          |          |          |
| 71   | 20 203                                                           | 494.85                                | 80   | 1440                                                                                          | 1157     | 788      | 515      |          |          |          |
| 72   | 20 155                                                           | 496.03                                | 140  | 1488                                                                                          | 1205     | 836      | 563      |          |          |          |
| 73   | 20 079                                                           | 497.89                                | 130  | 1564                                                                                          | 1281     | 912      | 639      |          |          |          |
| 74   | 20 062                                                           | 498.28                                | 100  | 1581                                                                                          | 1298     | 929      | 656      |          |          |          |
| 75   | 19 957                                                           | 500.90                                | 80   | 1686                                                                                          | 1403     | 1034     | 761      |          |          |          |
| 76   | 19 942                                                           | 501.33                                | 600  | 1701                                                                                          | 1418     | 1049     | 776      |          |          |          |
| 77   | 19 929                                                           | 501.65                                | 100  | 1714                                                                                          | 1431     | 1062     | 789      | 0        |          |          |
| 78   | 19 906                                                           | 502.24                                | 2000 | 1737                                                                                          | 1454     | 1085     | 812      | 23       |          |          |
| 79   | 19 882                                                           | 502.84                                | 70   | 1761                                                                                          | 1478     | 1109     | 836      | 47       |          |          |
| 80   | 19 860                                                           | 503.38                                | 200  | 1783                                                                                          | 1500     | 1131     | 858      | 69       |          |          |
| 81   | 19 811                                                           | 504.63                                | 130  | 1832                                                                                          | 1549     | 1180     | 907      | 118      |          |          |
| 82   | 19 779                                                           | 505.45                                | 100  | 1864                                                                                          | 1581     | 1212     | 939      | 150      |          |          |
| 83   | 19 709                                                           | 507.25                                | 230  | 1934                                                                                          | 1651     | 1282     | 1009     | 220      |          |          |
| 84   | 19 691                                                           | 507.72                                | 250  | 1952                                                                                          | 1669     | 1300     | 1027     | 238      |          |          |
| 85   | 19 655                                                           | 508.65                                | 470  | 1988                                                                                          | 1705     | 1336     | 1063     | 274      |          |          |
| 86   | 19 504                                                           | 512.57                                | 800  | 2139                                                                                          | 1856     | 1487     | 1214     | 425      |          |          |
| 87   | 19 439                                                           | 514.30                                | 140  | 2204                                                                                          | 1921     | 1552     | 1279     | 490      |          |          |
| 88   | 19 351                                                           | 516.68                                | 670  | 2292                                                                                          | 2009     | 1640     | 1367     | 578      |          |          |
| 89   | 19 345                                                           | 516.80                                | 180  | 2298                                                                                          | 2015     | 1646     | 1373     | 584      |          |          |
| 90   | 19 274                                                           | 518.70                                | 320  | 2369                                                                                          | 2086     | 1717     | 1444     | 655      |          |          |
| 91   | 19 225                                                           | 520.02                                | 400  | 2418                                                                                          | 2135     | 1766     | 1493     | 704      |          |          |
| 92   | 19 195                                                           | 520.83                                | 2500 | 2448                                                                                          | 2165     | 1796     | 1523     | 734      | 0        |          |
| 93   | 19 165                                                           | 521.60                                | 350  | 2478                                                                                          | 2195     | 1826     | 1553     | 764      | 30       |          |
| 94   | 19 134                                                           | 522.49                                | 20   | 2507                                                                                          | 2224     | 1855     | 1582     | 793      | 59       |          |
| 95   | 19 117                                                           | 522.95                                | 600  | 2526                                                                                          | 2243     | 1874     | 1601     | 812      | 78       |          |
| 96   | 18 947                                                           | 527.65                                | 220  | 2696                                                                                          | 2413     | 2044     | 1771     | 982      | 248      |          |
| 97   | 18 832                                                           | 530.87                                | 2300 | 2811                                                                                          | 2528     | 2159     | 1886     | 1097     | 363      | 0        |
| 98   | 18 782                                                           | 532.28                                | 200  | 2861                                                                                          | 2578     | 2209     | 1936     | 1147     | 413      | 50       |
| 99   | 18 744                                                           | 533.34                                | 2000 | 2899                                                                                          | 2616     | 2247     | 1974     | 1185     | 451      | 88       |
| 100  | 18 698                                                           | 534.68                                | 300  | 2945                                                                                          | 2662     | 2293     | 2020     | 1231     | 497      | 134      |
| 101  | 18 667                                                           | 535.55                                | 80   | 2976                                                                                          | 2693     | 2324     | 2051     | 1262     | 528      | 165      |
| 102  | 18 450                                                           | 541.84                                | 200  | 3193                                                                                          | 2910     | 2541     | 2268     | 1479     | 745      | 382      |
| 103  | 18 382                                                           | 543.86                                | 400  | 3261                                                                                          | 2978     | 2607     | 2336     | 1547     | 813      | 450      |
| 104  | 18 356                                                           | 544.63                                | 900  | 3287                                                                                          | 3004     | 2633     | 2362     | 1573     | 839      | 476      |
| 105  | 18 282                                                           | 546.82                                | 1100 | 3363                                                                                          | 3080     | 2709     | 2438     | 1647     | 913      | 550      |
| 106  | 18 178                                                           | 549.95                                | 450  | 3467                                                                                          | 3184     | 2813     | 2542     | 1751     | 1017     | 654      |

| Line | Frequency of<br>emission line<br>in vacuo<br>(cm <sup>-1</sup> ) | Wavelength in<br>standard air<br>(nm) | Peak | Apparent Raman displacement of the<br>emission lines in cm <sup>-1</sup> from the laser lines |          |          |          |
|------|------------------------------------------------------------------|---------------------------------------|------|-----------------------------------------------------------------------------------------------|----------|----------|----------|
|      |                                                                  |                                       |      | 501.6 nm                                                                                      | 520.2 nm | 530.8 nm | 568.2 nm |
| 107  | 18 101                                                           | 552.29                                | 1050 | 1828                                                                                          | 1094     | 731      |          |
| 108  | 18 003                                                           | 555.30                                | 400  | 1926                                                                                          | 1192     | 829      |          |
| 109  | 17 973                                                           | 556.22                                | 200  | 1956                                                                                          | 1222     | 859      |          |
| 110  | 17 953                                                           | 556.86                                | 1000 | 1976                                                                                          | 1242     | 879      |          |
| 111  | 17 947                                                           | 557.03                                | 550  | 1982                                                                                          | 1248     | 885      |          |
| 112  | 17 741                                                           | 563.50                                | 1400 | 2188                                                                                          | 1454     | 1091     |          |
| 113  | 17 693                                                           | 565.04                                | 250  | 2236                                                                                          | 1502     | 1139     |          |

Table 2—continued

| Line | Frequency of<br>emission line<br>in vacuo<br>(cm <sup>-1</sup> ) | Wavelength in<br>standard air<br>(nm) | Peak | Apparent Raman displacement of the<br>emission lines in cm <sup>-1</sup> from the laser lines |          |          |          |
|------|------------------------------------------------------------------|---------------------------------------|------|-----------------------------------------------------------------------------------------------|----------|----------|----------|
|      |                                                                  |                                       |      | 501.6 nm                                                                                      | 520.2 nm | 530.8 nm | 568.2 nm |
| 114  | 17 632                                                           | 566.99                                | 300  | 2297                                                                                          | 1563     | 1200     |          |
| 115  | 17 623                                                           | 567.28                                | 570  | 2306                                                                                          | 1572     | 1209     |          |
| 116  | 17 618                                                           | 567.45                                | 400  | 2311                                                                                          | 1577     | 1214     |          |
| 117  | 17 595                                                           | 568.19                                | 3500 | 2334                                                                                          | 1600     | 1237     | 0        |
| 118  | 17 569                                                           | 569.03                                | 2000 | 2360                                                                                          | 1626     | 1263     | 26       |
| 119  | 17 557                                                           | 569.41                                | 400  | 2372                                                                                          | 1638     | 1275     | 38       |
| 120  | 17 539                                                           | 569.98                                | 400  | 2390                                                                                          | 1656     | 1293     | 56       |
| 121  | 17 486                                                           | 571.72                                | 180  | 2443                                                                                          | 1709     | 1346     | 109      |
| 122  | 17 377                                                           | 575.30                                | 1000 | 2552                                                                                          | 1818     | 1455     | 218      |
| 123  | 17 322                                                           | 577.14                                | 1700 | 2607                                                                                          | 1873     | 1510     | 273      |
| 124  | 17 302                                                           | 577.80                                | 400  | 2727                                                                                          | 1893     | 1530     | 293      |
| 125  | 17 059                                                           | 586.07                                | 270  | 2870                                                                                          | 2136     | 1773     | 536      |
| 126  | 17 028                                                           | 587.09                                | 750  | 2901                                                                                          | 2167     | 1804     | 567      |
| 127  | 16 911                                                           | 591.17                                | 110  | 3018                                                                                          | 2284     | 1921     | 684      |
| 128  | 16 753                                                           | 596.75                                | 100  | 3176                                                                                          | 2442     | 2079     | 842      |
| 129  | 16 684                                                           | 599.22                                | 1000 | 3245                                                                                          | 2511     | 2148     | 911      |
| 130  | 16 634                                                           | 601.00                                | 90   | 3295                                                                                          | 2561     | 2198     | 961      |
| 131  | 16 600                                                           | 602.24                                | 200  | 3329                                                                                          | 2595     | 2232     | 995      |
| 132  | 16 560                                                           | 603.72                                | 10   | 3489                                                                                          | 3755     | 2392     | 1155     |
| 133  | 16 404                                                           | 609.45                                | 50   | 3525                                                                                          | 2791     | 2428     | 1191     |
| 134  | 16 337                                                           | 611.96                                | 70   | 3592                                                                                          | 2858     | 2495     | 1258     |
| 135  | 16 207                                                           | 616.88                                | 160  | 3722                                                                                          | 2988     | 2625     | 1388     |
| 136  | 15 860                                                           | 630.37                                | 160  | 4069                                                                                          | 3335     | 2972     | 1735     |
| 137  | 15 837                                                           | 631.28                                | 10   | 4092                                                                                          | 3358     | 2995     | 1758     |
| 138  | 15 642                                                           | 639.11                                | 100  | 4287                                                                                          | 3553     | 3190     | 1953     |
| 139  | 15 597                                                           | 640.98                                | 70   | 4332                                                                                          | 3598     | 3235     | 1998     |
| 140  | 15 581                                                           | 641.66                                | 150  | 4348                                                                                          | 3614     | 3251     | 2014     |
| 141  | 15 572                                                           | 624.02                                | 700  | 4357                                                                                          | 3623     | 3260     | 2023     |
| 142  | 15 451                                                           | 647.09                                | 250  | 4478                                                                                          | 3744     | 3381     | 2144     |

| Line | Frequency of<br>emission line<br>in vacuo<br>(cm <sup>-1</sup> ) | Wavelength in<br>standard air<br>(nm) | Peak | Apparent Raman displacement of the<br>emission lines in cm <sup>-1</sup> from the laser lines |          |          |          |          |
|------|------------------------------------------------------------------|---------------------------------------|------|-----------------------------------------------------------------------------------------------|----------|----------|----------|----------|
|      |                                                                  |                                       |      | 647.1 nm                                                                                      | 676.4 nm | 687.1 nm | 752.4 nm | 799.3 nm |
| 142  | 15 451                                                           | 647.09                                | 250  | 0                                                                                             |          |          |          |          |
| 143  | 15 354                                                           | 651.09                                | 430  | 97                                                                                            |          |          |          |          |
| 144  | 15 214                                                           | 657.01                                | 1000 | 236                                                                                           |          |          |          |          |
| 145  | 15 141                                                           | 660.30                                | 160  | 310                                                                                           |          |          |          |          |
| 146  | 15 090                                                           | 662.50                                | 30   | 360                                                                                           |          |          |          |          |
| 147  | 15 082                                                           | 662.86                                | 160  | 368                                                                                           |          |          |          |          |
| 148  | 15 067                                                           | 623.50                                | 110  | 383                                                                                           |          |          |          |          |
| 149  | 15 046                                                           | 664.45                                | 100  | 405                                                                                           |          |          |          |          |
| 150  | 15 028                                                           | 665.25                                | 100  | 423                                                                                           |          |          |          |          |
| 151  | 14 995                                                           | 668.40                                | 60   | 495                                                                                           |          |          |          |          |
| 152  | 14 779                                                           | 676.44                                | 330  | 671                                                                                           | 0        |          |          |          |
| 153  | 14 764                                                           | 677.12                                | 100  | 686                                                                                           | 15       |          |          |          |
| 154  | 14 550                                                           | 687.08                                | 110  | 906                                                                                           | 229      | 0        |          |          |
| 155  | 14 397                                                           | 694.41                                | 30   | 1053                                                                                          | 382      | 153      |          |          |
| 156  | 14 132                                                           | 707.40                                | 100  | 1318                                                                                          | 647      | 418      |          |          |
| 157  | 14 002                                                           | 713.40                                | 170  | 1448                                                                                          | 777      | 548      |          |          |
| 158  | 13 859                                                           | 721.31                                | 600  | 1590                                                                                          | 919      | 690      |          |          |
| 159  | 13 714                                                           | 728.98                                | 900  | 1736                                                                                          | 1065     | 836      |          |          |
| 160  | 13 679                                                           | 731.05                                | 80   | 1771                                                                                          | 1100     | 871      |          |          |
| 161  | 13 624                                                           | 733.78                                | 60   | 1827                                                                                          | 1156     | 927      |          |          |
| 162  | 13 580                                                           | 736.16                                | 90   | 1871                                                                                          | 1200     | 971      |          |          |
| 163  | 13 559                                                           | 737.30                                | 60   | 1894                                                                                          | 1223     | 994      |          |          |
| 164  | 13 497                                                           | 740.70                                | 800  | 1953                                                                                          | 1282     | 1053     |          |          |
| 165  | 13 444                                                           | 743.58                                | 400  | 2006                                                                                          | 1335     | 1106     |          |          |
| 166  | 13 430                                                           | 744.38                                | 150  | 2020                                                                                          | 1349     | 1120     |          |          |
| 167  | 13 353                                                           | 748.68                                | 280  | 2097                                                                                          | 1426     | 1197     |          |          |
| 168  | 13 341                                                           | 749.36                                | 180  | 2109                                                                                          | 1438     | 1209     |          |          |
| 169  | 13 307                                                           | 751.26                                | 400  | 2144                                                                                          | 1473     | 1244     |          |          |

Table 2—continued

| Line | Frequency of<br>emission line<br>in vacuo<br>(cm <sup>-1</sup> ) | Wavelength in<br>standard air<br>(nm) | Peak | Apparent Raman displacement of the<br>emission lines in cm <sup>-1</sup> from the laser lines |          |          |          |          |
|------|------------------------------------------------------------------|---------------------------------------|------|-----------------------------------------------------------------------------------------------|----------|----------|----------|----------|
|      |                                                                  |                                       |      | 647.1 nm                                                                                      | 676.4 nm | 687.1 nm | 752.4 nm | 799.3 nm |
| 170  | 13 286                                                           | 752.45                                | 600  | 2164                                                                                          | 1493     | 1264     | 0        |          |
| 171  | 13 231                                                           | 755.57                                | 180  | 2220                                                                                          | 1549     | 1320     | 56       |          |
| 172  | 13 214                                                           | 756.54                                | 250  | 2237                                                                                          | 1566     | 1337     | 73       |          |
| 173  | 13 175                                                           | 758.74                                | 550  | 2274                                                                                          | 1603     | 1374     | 110      |          |
| 174  | 13 151                                                           | 760.15                                | 600  | 2299                                                                                          | 1628     | 1399     | 135      |          |
| 175  | 13 008                                                           | 768.52                                | 400  | 2442                                                                                          | 1771     | 1542     | 278      |          |
| 176  | 12 992                                                           | 769.45                                | 250  | 2458                                                                                          | 1787     | 1558     | 294      |          |
| 177  | 12 923                                                           | 773.57                                | 200  | 2528                                                                                          | 1857     | 1628     | 364      |          |
| 178  | 12 898                                                           | 775.07                                | 200  | 2553                                                                                          | 1882     | 1653     | 389      |          |
| 179  | 12 834                                                           | 778.94                                | 130  | 2617                                                                                          | 1946     | 1717     | 453      |          |
| 180  | 12 796                                                           | 781.25                                | 250  | 2655                                                                                          | 1984     | 1755     | 491      |          |
| 181  | 12 774                                                           | 782.60                                | 450  | 2677                                                                                          | 2006     | 1777     | 513      |          |
| 182  | 12 758                                                           | 783.58                                | 190  | 2693                                                                                          | 2022     | 1793     | 529      |          |
| 183  | 12 750                                                           | 784.07                                | 520  | 2701                                                                                          | 2030     | 1801     | 537      |          |
| 184  | 12 727                                                           | 785.48                                | 500  | 2724                                                                                          | 2053     | 1824     | 560      |          |
| 185  | 12 644                                                           | 790.76                                | 120  | 2807                                                                                          | 2136     | 1907     | 643      |          |
| 186  | 12 636                                                           | 791.01                                | 190  | 2813                                                                                          | 2142     | 1913     | 649      |          |
| 187  | 12 631                                                           | 791.45                                | 70   | 2820                                                                                          | 2149     | 1920     | 656      |          |
| 188  | 12 604                                                           | 793.14                                | 130  | 2847                                                                                          | 2176     | 1947     | 683      |          |
| 189  | 12 537                                                           | 797.36                                | 100  | 2914                                                                                          | 2243     | 2014     | 750      |          |
| 190  | 12 507                                                           | 799.32                                | 700  | 2944                                                                                          | 2273     | 2044     | 780      | 0        |
| 191  | 12 499                                                           | 799.80                                | 300  | 2952                                                                                          | 2281     | 2050     | 788      | 8        |
| 192  | 12 467                                                           | 801.86                                | 110  | 2984                                                                                          | 2313     | 2084     | 820      | 40       |
| 193  | 12 404                                                           | 805.95                                | 600  | 3047                                                                                          | 2376     | 2147     | 883      | 103      |
| 194  | 12 379                                                           | 807.50                                | 100  | 3072                                                                                          | 2401     | 2172     | 908      | 128      |
| 195  | 12 359                                                           | 808.80                                | 550  | 3092                                                                                          | 2421     | 2192     | 928      | 148      |
| 196  | 12 335                                                           | 810.44                                | 700  | 3116                                                                                          | 2445     | 2216     | 952      | 172      |
| 197  | 12 322                                                           | 811.29                                | 1500 | 3129                                                                                          | 2468     | 2229     | 965      | 185      |
| 198  | 12 296                                                           | 813.00                                | 700  | 3155                                                                                          | 2484     | 2255     | 991      | 211      |
| 199  | 12 289                                                           | 813.40                                | 200  | 3162                                                                                          | 2491     | 2262     | 998      | 218      |
| 200  | 12 282                                                           | 813.90                                | 100  | 3169                                                                                          | 2498     | 2269     | 1005     | 225      |
| 201  | 12 273                                                           | 814.51                                | 300  | 3178                                                                                          | 2507     | 2278     | 1014     | 234      |
| 202  | 12 225                                                           | 817.70                                | 700  | 3226                                                                                          | 2555     | 2326     | 1062     | 282      |
| 203  | 12 206                                                           | 819.00                                | 600  | 3245                                                                                          | 2574     | 2345     | 1081     | 301      |
| 204  | 12 187                                                           | 820.27                                | 600  | 3264                                                                                          | 2593     | 2364     | 1100     | 320      |
| 205  | 12 179                                                           | 820.80                                | 550  | 3272                                                                                          | 2601     | 2372     | 1108     | 328      |
| 206  | 12 156                                                           | 822.90                                | 500  | 3295                                                                                          | 2624     | 2395     | 1131     | 351      |
| 207  | 12 098                                                           | 826.32                                | 700  | 3353                                                                                          | 2682     | 2453     | 1189     | 409      |
| 208  | 12 072                                                           | 828.10                                | 600  | 3379                                                                                          | 2708     | 2479     | 1215     | 435      |
| 209  | 12 059                                                           | 828.90                                | 600  | 3392                                                                                          | 2721     | 2492     | 1228     | 448      |
| 210  | 12 047                                                           | 829.81                                | 600  | 3404                                                                                          | 2733     | 2504     | 1240     | 460      |
| 211  | 11 945                                                           | 836.90                                | 200  | 3506                                                                                          | 2835     | 2606     | 1342     | 562      |
| 212  | 11 883                                                           | 841.25                                | 50   | 3568                                                                                          | 2897     | 2668     | 1404     | 624      |
| 213  | 11 848                                                           | 843.80                                | 80   | 3603                                                                                          | 2932     | 2703     | 1439     | 659      |
| 214  | 11 799                                                           | 847.33                                | 200  | 3652                                                                                          | 2981     | 2752     | 1488     | 708      |
| 215  | 11 759                                                           | 850.20                                | 400  | 3692                                                                                          | 3021     | 2792     | 1528     | 748      |
| 216  | 11 749                                                           | 850.89                                | 450  | 3702                                                                                          | 3031     | 2802     | 1538     | 758      |
| 217  | 11 736                                                           | 851.86                                | 85   | 3715                                                                                          | 3044     | 2815     | 1551     | 771      |
| 218  | 11 711                                                           | 853.68                                | 180  | 3740                                                                                          | 3069     | 2840     | 1576     | 796      |

## REFERENCES

1. S. P. S. Porto and D. L. Wood, *J. Opt. Soc. Am.* **52**, 251 (1962).
2. J. Loader, *Basic Laser Raman Spectroscopy*. Heyden, London (1970).
3. R. O. Kagel, in *Handbook of Spectroscopy*, Vol. 2, p. 107. Robinson, Cleveland, Ohio (1974).
4. R. Beck, W. Englisch and K. Gürs, *Table of Laser Lines in Gases and Vapors*. Springer-Verlag, Berlin (1978).
5. A. N. Saidel, W. Prokofjen and S. M. Raiski, *Tables of the Spectral Lines*, VEB-Verlag, Berlin (1961).
6. B. Edlen, *J. Opt. Soc. Am.* **43**, 339 (1953).
7. C. Julien, Thesis, Paris (1979).

Received 8 June 1979

© Heyden &amp; Son Ltd, 1980