Wavelengths and isotope shifts for lines of astrophysical interest in the spectrum of doubly ionized mercury (Hg III)

Craig J. Sansonetti and Joseph Reader
National Institute of Standards and Technology, Gaithersburg, Maryland 20899
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Wavelengths and isotope shifts have been measured for the 1738.4-, 1738.5-, 1740.2-, and 2354.2-Å lines of Hg III with an uncertainty of 0.002 Å. The lines were excited in a pulsed radio-frequency discharge and observed with a 10.7-m normal-incidence vacuum spectrograph. Observations were made with lamps containing natural Hg, ^{198}Hg, and ^{204}Hg. By using well-established relative isotope shifts, wavelengths of these four lines for ^{196}Hg, ^{200}Hg, ^{202}Hg, and the centers of gravity for ^{199}Hg and ^{201}Hg were also determined. The results provide important data for determining elemental and isotopic abundances of Hg from spectra of Hg-rich chemically peculiar stars.

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INTRODUCTION

There is currently significant interest in observing spectral lines of the first three ionization stages of mercury in the spectra of Hg-rich chemically peculiar stars. That Hg was significantly overabundant in such stars was first suggested by Bidelman [1] on the basis of a stellar line at 3984 Å that coincided with one of the strongest lines of Hg II. The wavelength of this line was seen to vary slightly from star to star, and Bidelman suggested that the variations were the result of differing isotopic compositions. By systematically studying the wavelength and profile of the 3984-Å line in 30 Hg-rich stars White, Vaughan, Preston, and Swings [2] confirmed that the distribution of Hg isotopes in these stars deviates greatly from the terrestrial distribution. The deviations are correlated with the temperature of the stars, with cooler stars being relatively more deficient in lighter Hg isotopes. They found that the most extreme isotope anomaly occurs in the star chi Lupi, where, as Bidelman had suggested [1], the emission is apparently due to nearly pure ^{204}Hg. The enhanced abundance of Hg in chi Lupi was definitively confirmed by Leckrone [3] from observations of two additional lines, the 1650- and 1942-Å resonance lines of Hg II acquired by the International Ultraviolet Explorer satellite.

Michaud, Reeves, and Charland [4] have proposed a diffusion model to explain both the enhanced abundance of Hg and the isotope anomalies observed in Hg-rich stars. In this model the balance between radiation pressure and gravity causes heavy Hg isotopes to concentrate in a thin layer of the stellar atmosphere as neutral and singly ionized Hg, while the lighter isotopes exist preferentially at higher altitudes as doubly ionized Hg or are driven away from the star entirely by the radiation pressure. To test this model it is necessary to determine elemental and isotopic abundances for Hg by using lines of different stages of ionization.

Using the Goddard high resolution spectrograph (GHRS) on the Hubble Space Telescope, Leckrone and co-workers have undertaken a systematic study of Hg lines in the spectrum of chi Lupi. Results for the 1942-Å line of Hg II have been reported recently [5]. They confirm that Hg as Hg II is overabundant relative to the solar abundance by a factor of 10^5 and that the observed emission corresponds to essentially pure ^{204}Hg.

GHRS observations have also been obtained for the Hg III lines at 1738.4, 1738.5, 1740.2, and 2354.2 Å. To derive abundances from these data, accurate wavelengths and isotope shifts are needed. The best available wavelength data, due to Johns [6] and Foster [7], are not adequate for the analysis. In the investigations of Johns and Foster the spectra were observed by using natural Hg, most wavelengths were reported only to the nearest 0.01 Å, and only a single, doubly classified line was reported at 1738 Å. Although Foster [8] in a subsequent paper reported isotope shifts for 21 Hg III levels, no data were given that apply to the lines observed with GHRS.

Our present work was undertaken to provide more accurate wavelengths and isotope shifts for these lines of Hg III to permit reliable interpretation of the spectrum of chi Lupi.

EXPERIMENT

The spectrum of doubly ionized Hg was excited in sealed electrodeless-discharge lamps by using a pulsed radio-frequency (rf) oscillator. Four lamps of identical

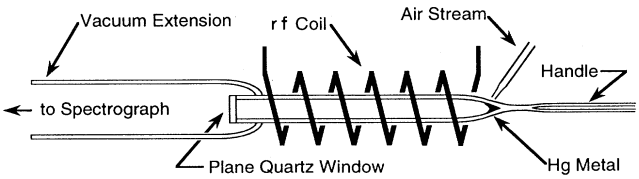

FIG. 1. Schematic representation of the lamps used to observe Hg III with pulsed-rf excitation. The body of the lamp had an outside diameter of 14 mm. The vacuum connection between the lamp and spectrograph was made by a 25.4-mm O-ring quick disconnect.

TABLE I. ^{198}Hg III wavelengths and isotope shifts. Wavelengths shorter than 2000 Å are in vacuum.

Wavelength (Å)	Wave number (cm^{-1})	^{204}Hg–^{198}Hg shift[a] (Å)	(cm^{-1})	Natural Hg–^{198}Hg shift[b] (Å)	(cm^{-1})
1738.4560(20)	57 522.31(7)	0.0218(20)	−0.72(7)	0.0091(20)	−0.30(7)
1738.5207(20)	57 520.17(7)	0.0190(20)	−0.63(7)	0.0078(20)	−0.26(7)
1740.2556(20)	57 462.82(7)	0.0221(20)	−0.73(7)	0.0093(20)	−0.31(7)
2354.2160(20)	42 463.99(4)	0.0398(20)	−0.72(4)	0.0201(30)	−0.36(5)

[a]The wavelength for ^{204}Hg is longer than for ^{198}Hg.
[b]The wavelength for natural Hg is longer than for ^{198}Hg.

dimensions were used: two containing ^{198}Hg and one each containing natural Hg and ^{204}Hg. Each lamp was filled under high vacuum with a few milligrams of Hg and no carrier gas. The lamp design is shown schematically in Fig. 1.

rf power at a frequency of 13.5 MHz was coupled into the Hg discharge by a resonant circuit consisting of a variable capacitor and a free-standing copper coil surrounding the body of the lamp. The capacitor was tuned to maximize the transfer of power to the discharge. Excitation of the Hg III spectrum was optimized by adjusting the duration of the rf pulses, their repetition rate, and the anode voltage of the final amplifier stage of the pulsed-rf supply. These adjustments were facilitated by monitoring selected lines of Hg I, II, and III from the side of the lamp with a 0.5-m monochromator. For best excitation of Hg III the lamp was operated at an anode voltage of about 10 kV, pulse duration of 230 μs, and repetition rate of 110 pulses/s. The metallic Hg was kept concentrated at the rear of the lamp by a gentle stream of air. The entire body of the lamp was cooled by diffuse air from a small fan. We estimate that the Hg vapor pressure in the lamp was about 2.7 Pa (20 mTorr). Under these conditions the lamp operated stably and emitted a strong Hg III spectrum with sharp unperturbed lines.

The spectrum was photographed with the 10.7-m normal-incidence vacuum spectrograph at the National Institute of Standards and Technology. The grating was blazed at 3000 Å and ruled with 1200 lines/mm, providing a plate factor of 0.78 Å/mm. Spectra of Pt I and II emitted by a Pt-Ne hollow cathode lamp were used as wavelength standards. For some exposures of the 2354-Å line the spectrum of Ar II excited by the pulsed-rf oscillator was also used for standards. The lamp for the Ar spectra was similar to that shown in Fig. 1, except that it had no window and was used with flowing gas. Wavelengths for the Pt-Ne lamp spectra were taken from Sansonetti *et al.* [9]; wavelengths for Ar II were taken from Norlén [10]. Exposure times were 5–15 s for the Hg lamps, 2 min for the Ar lamp, and 15 min for the Pt-Ne lamp.

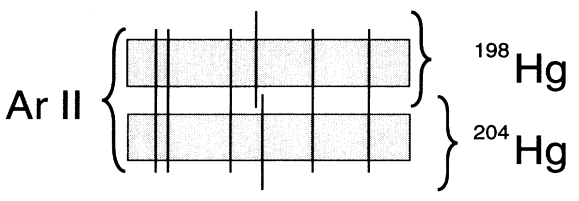

FIG. 2. Schematic representation of the arrangement of the spectra on the photographic plates taken to measure isotope shifts in Hg III. The shaded areas show the two parallel tracks defined by the comparator masks that were used for measurements as described in the text.

The above observations were used to determine wavelengths of the four lines of ^{198}Hg III, given in Table I. Small shifts between the Hg spectrum and the Pt and Ar reference spectra due to slightly different grating illumination were removed by using accurate values for several ^{198}Hg II lines given by Reader and Sansonetti [11]. The final uncertainty in our Hg wavelengths is attributable approximately equally to the uncertainty in the general calibration based on the reference spectra and to the uncertainty in determining the shift between the Hg and reference spectra.

Special exposures were made to measure the isotope shifts between lines of the 204 and 198 isotopes. For these exposures spectra from the ^{198}Hg, ^{204}Hg, and Ar lamps were photographed sequentially. By means of adjustable masks in front of the plate holder, the spectra were arranged to appear as indicated in Fig. 2. The lines of the two Hg isotopes were vertically displaced and slightly overlapping, while the Ar lines were about twice as long as the Hg lines, spanning nearly their combined length. The position of the plate in the spectrograph was not disturbed between exposures.

To minimize possible shifts due to different illumina-

TABLE II. Relative isotope shifts for stable Hg isotopes and natural Hg. Results are given as a fraction of the 202–200 shift.

Species	Relative isotope shift
^{196}Hg	−1.689(5)[a]
^{198}Hg	−0.906(1)[b]
^{199}Hg	−0.786(1)[b]
^{200}Hg	0.000[b]
natural Hg	0.249(2)[c]
^{201}Hg	0.302(1)[b]
^{202}Hg	1.000(1)[b]
^{204}Hg	1.984(1)[b]

[a]Gerstenkorn, Labarthe, and Vergès (Ref. [14]).
[b]Gerstenkorn and Vergès (Ref. [13]).
[c]Calculated using isotopic abundances from Ref. [16] and the relative isotope shifts in this table.

TABLE III. Isotope shifts (Å) from ^{198}Hg. All values, except those for ^{204}Hg, are calculated using the relative isotope shifts in Table II. The values for ^{204}Hg are the experimental values from Table I.

	^{198}Hg III line			
Species	1738.4560	1738.5207	1740.2556	2354.2215
^{196}Hg	−0.0059(5)	−0.0051(5)	−0.0060(5)	−0.0108(5)
^{198}Hg	0.00000	0.00000	0.00000	0.00000
^{199}Hg	0.00091(8)	0.00079(8)	0.00092(8)	0.00165(8)
^{200}Hg	0.0068(6)	0.0060(6)	0.0069(6)	0.0125(6)
natural Hg	0.0087(8)	0.0076(8)	0.0088(8)	0.0159(8)
^{201}Hg	0.0091(8)	0.0079(8)	0.0092(8)	0.0166(8)
^{202}Hg	0.0144(13)	0.0125(13)	0.0146(13)	0.0262(13)
^{204}Hg	0.0218(20)	0.0190(20)	0.0221(20)	0.0398(20)

tion of the grating by the two different Hg sources, the Hg lamps were constructed with identical dimensions and plane quartz windows. An alignment telescope was used to carefully center each lamp on the optical axis of the spectrograph, and the rf exciting coil was not disturbed between exposures. The excitation of Hg III was monitored with the monochromator, and the exposure times were adjusted to obtain equal exposures from the two Hg lamps.

The isotope shifts were determined by measuring two parallel tracks on the photographic plate as shown in Fig. 2. These tracks were defined by masks in the optical system of the comparator so that the position of a line could be measured in either track without moving the comparator cross feed. The plate and comparator were adjusted so that the measured positions of the Ar lines were the same in both tracks. The Ar lines served as a reference to define zero isotope shift.

Measurements were limited to narrow regions around the Hg lines of interest. Each Hg and Ar line was measured in both the upper and lower tracks before proceeding to the next line. This ensured that the isotope shifts would not be affected by possible long term drifts in the comparator.

For each Hg line, the displacement between the two isotopes was found as the difference of the positions measured in the upper and lower tracks. The result was corrected slightly by subtracting the average displacement between the upper and lower track positions of the Ar lines, which was not exactly zero for all lines. The corrected displacement was multiplied by the plate factor to obtain the isotope shift. The measured $^{204-198}$Hg isotope shifts are given in Table I.

To investigate the possibility of a shift between the spectra emitted by the two Hg lamps due to different illumination of the grating, we made two exposures in which we measured the shift between ^{198}Hg and itself following the same procedure used to compare different isotopes. In the first exposure a single lamp was removed and replaced on the spectrograph; in the second two different ^{198}Hg lamps were used. Measurements were made for 12 Hg lines on each exposure. For the first exposure the average shift for the 12 lines was −0.0008(7) Å; for the second exposure the average shift was +0.0015(12) Å. As this constitutes the main source of possible error for the isotope shifts, we estimate the uncertainty of the shifts to be ±0.002 Å.

Shifts between natural Hg and ^{198}Hg were determined by the same technique described above. The results are given in Table I. As the profile of the 2354-Å line of natural Hg was broadened and slightly asymmetric, the uncertainty of its shift was increased to ±0.003 Å.

SHIFTS FOR OTHER Hg ISOTOPES

For heavy elements, where mass-dependent effects are negligible, the relative shifts between isotopic components of a spectral line depend only on the size and shape of the nucleus [12] and therefore are independent of the combining energy levels and the stage of ionization. By using relative isotope shifts derived from lines of Hg I together with our measurements of the $^{204-198}$Hg

TABLE IV. Wavelengths (Å) for natural Hg and the stable isotopes of Hg. The results for the odd isotopes represent the center of gravity of the magnetic hyperfine structure. For each species, the integer part of the wavelength is given in the column heading while the fractional part and the uncertainty are given in the body of the table.

	Hg III line			
Species	1738	1738	1740	2354
^{196}Hg	.4501(21)	.5156(21)	.2496(21)	.2052(21)
^{198}Hg	.4560(20)	.5207(20)	.2556(20)	.2160(20)
^{199}Hg	.4569(20)	.5215(20)	.2565(20)	.2177(20)
^{200}Hg	.4628(21)	.5267(21)	.2625(21)	.2285(21)
natural Hg	.4647(22)	.5283(22)	.2644(22)	.2319(22)
^{201}Hg	.4651(22)	.5286(22)	.2648(22)	.2326(22)
^{202}Hg	.4704(24)	.5332(24)	.2702(24)	.2422(24)
^{204}Hg	.4778(28)	.5397(28)	.2777(28)	.2558(28)

TABLE V. Correlation of isotope shift with level of the $5d^96s$ configuration.

^{198}Hg wavelength (Å)	Even level[a] $5d^96s$	Odd level[a] $5d^96p$	$^{204-198}$Hg shift (cm^{-1})
1738.4560(20)	5_2 $(^2D_{3/2},1/2)_2$	4_1° $(^2D_{3/2},1/2)_1$	−0.72(7)
1740.2556(20)	5_2 $(^2D_{3/2},1/2)_2$	3_2° $(^2D_{3/2},1/2)_2$	−0.73(7)
2354.2160(20)	5_2 $(^2D_{3/2},1/2)_2$	1_2° $(^2D_{5/2},1/2)_2$	−0.72(4)
1738.5207(20)	3_2 $(^2D_{5/2},1/2)_2$	1_2° $(^2D_{5/2},1/2)_2$	−0.63(7)

[a]Both the numerical label used by Johns [6] and the level designation in J_cj coupling as given by Foster [7,8] are indicated. The designation of 3_2° is that of Foster [8], which revised that of Foster [7].

shifts, we are able to calculate shifts for the remaining stable isotopes.

In Table II we list relative isotope shifts for the stable Hg isotopes and natural Hg. Results for the stable isotopes are taken from Gerstenkorn *et al.* [13,14]. They are averages of the relative shifts for lines at 15 295.7 and 19 699.8 Å measured by means of Fourier-transform spectroscopy with an electrodeless discharge lamp and the line at 2536.7 Å measured by Schweitzer [15] by means of Fabry-Pérot interferometry with an atomic-beam light source. The positions for the odd isotopes 199 and 201 represent the centers of gravity of their hyperfine patterns. The relative shifts are in good agreement with much less precise values determined from Hg III lines by Foster [8]. We have calculated the shift for natural Hg from the isotopic shifts by using the known abundances [16] for the stable isotopes.

By using the measured $^{204-198}$Hg shifts in Table I together with the relative shifts in Table II, we determine shifts relative to ^{198}Hg as given in Table III. The shifts for natural Hg differ slightly from our measured values given in Table I. This is probably due to the fact that the position of the center of gravity of the lines of natural Hg on the photograph plates is shifted from the true center of gravity as a result of the nonlinear response of the photographic emulsion.

In Table IV we summarize the wavelengths obtained from the measured and calculated shifts. The wavelengths for natural Hg in this table are those given by the calculated shifts in Table III, which we consider to be the more reliable values.

LEVEL SHIFTS

Hg III has as its ground state $5d^{10}\,{}^1S_0$. All four of the lines we studied are transitions between levels of the $5d^96p$ and $5d^96s$ configurations, and three of them have as their lower level $5d^96s(^2D_{3/2},1/2)_2$. In Table V we show the correlation between measured isotope shift and level of the $5d^96s$ configuration. As expected, the shifts depend almost entirely on the $5d^96s$ levels and only slightly on the $5d^96p$ levels.

The contribution of the $5d^96p$ levels to the observed shifts can be estimated from the results of Foster [8] and the relative isotope shifts in Table II. We obtain $5d^96p$ level shifts of 0.061 cm^{-1} for level 4_1°, 0.055 cm^{-1} for level 3_2°, and 0.046 cm^{-1} for level 1_2°, with uncertainties smaller than 0.005 cm^{-1}. The $^{204-198}$Hg level isotope shifts for the $5d^96s$ levels are thus +0.78(4) cm^{-1} for $5d^96s(^2D_{3/2},1/2)_2$ and +0.68(7) cm^{-1} for $5d^96s(^2D_{5/2},1/2)_2$. (The levels of ^{204}Hg are less tightly bound than those of ^{198}Hg.) Shifts for these levels in the other stable isotopes can be derived from the relative shifts in Table II.

ASTROPHYSICAL IMPLICATIONS

Based on our present measurements, Leckrone *et al.* [17] have analyzed the two lines of Hg III at 1738 Å in the GHRS spectra of chi Lupi. Their analysis shows the same isotope anomaly that was previously found with the lines of Hg II; that is the spectrum is consistent with pure ^{204}Hg. They conclude that this result, which disagrees with some predictions of the diffusion model [4], reveals a need for a new or refined model to explain the elemental and isotope abundance anomalies for Hg in chemically peculiar stars.

ACKNOWLEDGMENT

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