Notes on the spectrum of neutral mercury in the natural mixture of isotopes

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1. Introduction

The energy levels and observed spectral lines were recently compiled by Saloman [06SAL] (hereafter referred to as "the original compilation"). This compilation accomplished a formidable task of a critical review of about 170 experimental papers on this spectrum published between 1890 and 2006. Saloman's work started from a solid basis of about 140 energy levels previously compiled by Moore [58MOO], to which he added preliminary values derived from several sources published between 1969 and 2004. Saloman analyzed the measurement uncertainties in the published experimental data and selected the observed lines that matched the previously known energy levels. Then he re-optimized the energy levels and made several new assignments for lines that were unclassified or did not match the new improved set of energy levels.

I was given a task of inserting the energy level and line data in the NIST Atomic Spectra Database (ASD). The task was originally assumed to be a purely technical job consisting of replacing the old data in ASD with the new data tables compiled by Saloman. However, I immediately found that the data in ASD include many energy levels that are missing in the original compilation. The main source of the old levels was the same compilation of Moore [58MOO] revised and extended by Sansonetti and Martin [05SAN]. Since these authors are reputable atomic data compilers, the results of their work should not be simply ignored. The original compilation did not specify the reasons for omission and/or revision of the old values, so I started investigating such cases. It immediately became obvious that many omissions were caused by some technical problems with the approach used in the original compilation to select the data. For example, in many cases an omitted level was determined by a single observed line, and the observed wavelength of this line did not fit the difference of the preliminary upper and lower energy level values. In such cases, the identification was automatically discarded, as well as the upper level. Then a new identification was suggested based on the match with the energy difference between some other known levels. Expected relative intensities of transitions, in general, were not calculated. As a result, many of the 6s6d – 6s*n*f series lines were either omitted or wrongly assigned to transitions having negligibly small predicted intensities.

Another problem with the approach of the original compilation concerns the omission of all forbidden lines. Their presence in the observed Hg I spectrum produced by laboratory discharges was noted by many researchers and should not be left unaccounted for in the list of observed lines. Electric quadrupole (E2) transitions become allowed in the

presence of electric fields. In the laboratory spectra, the lines corresponding to them have intensities comparable to those of allowed (electric dipole) lines. Several tens of such E2 transitions were reported by many authors. While I agree with Saloman's argument that these lines suffer from Stark shifts, I think that they should not be completely ignored. At least those E2 lines that were measured with reasonably good precision, e.g., by Suga et al. [37SUG], Murakawa [35MUR], and Johansson and Svensson [60JOH] should be included in the list. In these experiments, Stark shifts were smaller than the wavelength measurement uncertainties. On the other hand, the extensive list of forbidden lines observed by Fukuda [24FUK] under conditions of very high electric voltages and currents requires separate careful examination and might be of interest to those who are interested in Stark shifts. These shifts were apparently rather large in that experiment.

Another class of forbidden lines observed in Hg I and ignored in the original compilation is due to hyperfine-induced transitions. In particular, the very important $6s^2\ ^1S_0 - 6s6p\ ^3P^\circ_0$ transition at 2655.8 Å, investigated by Mrozowski [38MRO], should be included in the list.

The approach used in the original compilation had one more problem. Namely, there are many cases in which the wavelength value chosen for a particular transition was not the best measurement, but the one that better agreed with preliminary level values. For example, several tens of lines were included from the early measurements of Murakawa [35MUR]. However, those lines were subsequently re-measured with better accuracy by Suga et al. [37SUG] and Kamiyama [43KAM]. These choices affected the optimized level values and increased their uncertainties.

The original compilation stated that the level values for the $6sn\text{f}\ ^1F^\circ_3$ series with $n > 13$ exhibit no-smooth behavior of quantum defects. I found that this was due to incorrect line identifications. The series of $6s6\text{d}\ ^1D_2 - 6sn\text{f}\ ^1F^\circ_3$ transitions can be traced in the line list of Kamiyama [43KAM] up to $n = 21$. Revised level values based on corrected and new line assignments display a smooth behavior of quantum defects along the series.

In my analysis of the Hg I spectrum I used the following tools: 1) parametric fitting with Cowan's codes [81COW], 2) fitting of the polarization formula using the computer code POLAR by Sansonetti [05SANa], 3) fitting of the Ritz quantum-defect formulas using the computer code RITZPL by Sansonetti [05SANb]. In the parametric fitting, I included all known energy levels with the principal quantum numbers $n \leq 18$ of both parities. As a result, I obtained a list of predicted transitions with accurate wavelengths and reasonably well calculated relative intensities (scaled according to Boltzmann population of upper levels). This list served as the basis for verification of line assignments.

After careful examination of 659 line assignments given in the original compilation, I discarded 42 spurious classifications, added 69 forbidden transitions, added about 30 new identifications, and changed the observed wavelengths and intensities for about 50 observed lines (in the latter cases, I took the measured values from sources different from those used in the original compilation). All these changes made it necessary to re-optimize the energy levels.

The new level optimization was made with the computer code LOPT [06KRA] which, unlike the code ELCALC [70RAD] used in the original compilation, allows for inclusion of forbidden transitions in the level optimization procedure. Two highly deviating lines were excluded from the level optimization. These were the lines at 2640.65(5) Å [34WAL] (6s6p $^3P°_2$ – 6s10d $^3D_1$, Ritz wavelength 2640.447 Å) and 2578.912(6) Å [50BUR] (6s6p $^3P°_2$ – 6s12d $^1D_2$, Ritz wavelength 2579.056 Å). The lower level 6s6p $^3P°_2$ common to both these transitions is involved in 79 observed combinations and is determined with a very small uncertainty of ±0.007 cm^{-1}. The upper levels 6s10d $^3D_1$ and 6s12d $^1D_2$ are based on several observed well-measured lines and their optimized values are verified to fit smoothly to the Ritz quantum-defect formulas. Therefore, the large disagreements of the observed wavelengths with the Ritz values definitely indicate some problems with the wavelength measurements in the quoted papers.

As a result of the revision of the line list and the new level optimization, I have added 24 new energy levels to the list of the original compilation and discarded six. The values of 33 levels have been significantly revised (i.e., the new values differ from the old ones by more than one value of uncertainty given in the original compilation). For 32 levels, the uncertainties have been significantly reduced, while for 24 levels the uncertainties of the new values are significantly larger than the old ones. In all the latter cases, the small uncertainties in the original compilation were due to erroneous line assignments based on spurious coincidences.

2. Detailed comments on the line assignments

1. The line at 11976.33 Å was given in the original compilation as the 6s6d $^3D_2$ – 6s6f $^3F_2$ transition. The original classification of this line in Suga et al. [37SUG] was 6s6d $^3D_2$ – 6s6f $^3F_3$. My calculations of relative line intensities based on a parametric fitting confirmed the original assignment. Therefore, I added the level 6s6f $^3F_3$ at 79743.6(3) cm^{-1}, which is based on this line only. Similar misidentifications have been made in the original compilation for the other 6s6d ^{1,3}D – 6s*n*f ^{1,3}F multiplets for n = 8–15. Although all levels of the 6snf configurations are based in Suga et al. [37SUG] on one line each, the configurations are very compact (level spacing less than 3 cm^{-1}), and line intensities, as well as quantum defects, display a regular behavior along the series, which confirms the classifications of Suga et al. [37SUG]. The line intensities are also in reasonably good agreement with my Cowan-code calculations. The levels were discarded in the original compilation because of a small mismatch between the observed wavelength and the Ritz one, which was based on the energy levels from Moore [58MOO]. This reason is insufficient for discarding these levels, so I restored them with the new, corrected values, based on the revised lower level energies from the original compilation.

It should be noted that the line classifications given by Suga et al. [37SUG] are based mainly on the identifications of Murakawa [35MUR], which were supported by Murakawa's observations of the forbidden E2 transitions 6s6p ^{1,3}P – 6snf ^{1,3}F (n = 5–9). These E2 transitions were not included in the original compilation.

2. The line at 11887.66 Å from Volk's thesis [14VOL] was classified in the original compilation as the 6s6d $^1D_2$ – 6s6f $^3F_2$ intercombination transition. This line had a width of 5.5 Å in Volk's spectrum and is in fact a blend of the 11885.20(4) and 11890.55(4) Å lines (6s6d $^1D_2$ – 6s6f $^1F_3$ and 6s6d $^3D_1$ – 6s6f $^3F_2$, Suga et al. [37SUG]). Therefore, I discarded this line.

3. The 6s7f ^{1,3}F levels were based in the original compilation on the following observed lines:

λ_{obs} (Å)	σ_{obs} (cm^{-1})	Intens.	Lower level		Upper level		Ref.
10230.0(5)	9772.5	1d	5d^{10}6s6d	$^1D_2$	5d^{10}6s7f	$^1F°_3$	[35MUR]
10235.01(40)	9767.7	5	5d^{10}6s6d	$^3D_1$	5d^{10}6s7f	$^3F°_2$	[36MUR]
10296.2(5)	9709.7	1d	5d^{10}6s6d	$^3D_2$	5d^{10}6s7f	$^1F°_3$	[35MUR]
10332.34(40)	9675.7	10	5d^{10}6s6d	$^3D_3$	5d^{10}6s7f	$^3F°_4$	[37SUG]
10335.0(6)	9673.2	1	5d^{10}6s6d	$^3D_3$	5d^{10}6s7f	$^3F°_3$	[37WIE]

The line at 10296.2(5) Å from Murakawa [35MUR] was erroneously classified in the original compilation as an intercombination transition. It was later measured by Suga et al. [37SUG] at 10296.75(40) Å and correctly classified as 6s6d $^3D_2$ – 6s7f $^3F_3$ transition. The lines at 10230.0(5) and 10235.01(40) were also re-measured by Suga et al. [37SUG] at 10228.80(40) and 10234.99(40) Å. However, the wavelength 10228.80 Å for the 6s6d $^1D_2$ – $^1F°_3$ transition strongly contradicts with Murakawa's measurement of the 6s6p $^1P°_2$ – 6s6f $^1F°_3$ E2 transition at 3697.79 Å. If the 10228.80 Å wavelength value from Suga et al. 1937 were correct, the calculated (Ritz) wavelength of the E2 transition would be 3697.48 Å. Therefore, I retained the wavelength from another Murakawa paper [36MUR] for the 6s6d $^3D_2$ – 6s7f $^3F_3$ transition, 10229.22(4) Å, which is in a slightly better agreement with the E2 transition wavelength and has an uncertainty similar to that of Suga et al. [37SUG]. In addition, the wavelength of the $^3D_3$-$^3F°_3$ transition from Murakawa [36MUR] is in better agreement with the Ritz value than the wavelength from Wiedmann [37WIE] used in the original compilation. The new line list for the 7f levels is as follows:

λ_{obs} (Å)	σ_{obs} (cm^{-1})	Intens.	Lower level		Upper level		Ref.
10229.22(40)	9773.24	7	5d^{10}6s6d	$^1D_2$	5d^{10}6s7f	$^1F°_3$	[36MUR]
10234.99(40)	9767.72	8	5d^{10}6s6d	$^3D_1$	5d^{10}6s7f	$^3F°_2$	[37SUG]
10296.75(40)	9709.04	10d	5d^{10}6s6d	$^3D_2$	5d^{10}6s7f	$^3F°_3$	[37SUG]
10332.34(40)	9675.70	10	5d^{10}6s6d	$^3D_3$	5d^{10}6s7f	$^3F°_4$	[37SUG]
10334.08(40)	9674.07	1	5d^{10}6s6d	$^3D_3$	5d^{10}6s7f	$^3F°_3$	[36MUR]

4. The line at 9526.21 Å from Suga et al. [37SUG] was wrongly assigned in the original compilation to the 6s6d $^3D_3$ – 6s8f $^1F°_3$ intercombination transition. I restored the original classification from Suga et al. [37SUG], 6s6d $^3D_3$ – 6s8f $^3F°_4$, and added back the 6s8f $^3F°_4$ level derived from this transition. This level was present in the old compilation of Moore [58MOO] but was discarded in the original compilation. The measurement accuracy of Murakawa [36MUR] was approximately the same as that of Suga et al. 1937. However, his observed intensity values are in better agreement with the calculated ones, so, for consistency, I replaced all wavelengths and intensities of the 6s6d ^{1,3}D – 6s8f ^{1,3}F°

transition array with the values from Murakawa [36MUR], and adjusted the level values accordingly.

5. The line at 8988.73 Å from Murakawa [36MUR] was wrongly assigned in the original compilation to a blend of the 6s6d $^1D_2$ – 6s9f $^3F°_{3,2}$ intercombination transitions, which have negligible calculated intensity. I restored the original correct classification 6s6d $^1D_2$ – 6s9f $^1F°_3$ [35MUR, 36MUR] and used the wavelength and intensity from Suga et al. [37SUG], 8988.86(40), I_{obs} = 8 to derive the upper level $^1F°_3$, which was missing in the original compilation.

The line at 9039.97 from Murakawa [36MUR] was doubly classified in the original compilation as a blend of the 6s6d $^3D_2$ – 6s9f $^3F°_{3,2}$ transitions. I discarded the $^3F°_2$ assignment, which has a negligibly small calculated intensity, and used the wavelength and observed intensity from Suga et al. [37SUG], 9039.20(40), I_{obs} = 4d to derive a corrected value for the upper level $^3F°_3$.

The line at vacuum wavelength of 36312.93 Å from Plyler et al. [55PLY], originally classified as the 6s7p $^3P°_2$ – 6s8s $^3S_1$ transition, was given in the original compilation a second classification, 6s8d $^3D_3$ – 6s9f $^3F°_4$. Since there are no indications that such high-energy levels were excited in the experiment of Plyler et al. [55PLY], I discarded this additional assignment.

For consistency, I used the wavelengths and observed intensities from Suga et al. [37SUG] for the 6s6d $^3D_1$ – 6s9f $^3F°_2$ and 6s6d $^3D_3$ – 6s9f $^3F°_4$ transitions instead of the values from Murakawa [36MUR] used in the original compilation, and derived the upper level values from these transitions.

6. The line at 8704.55 Å from Murakawa [35MUR] was wrongly assigned in the original compilation to the 6s6d $^1D_2$ – 6s10f $^3F°_2$ intercombination transition, which has a negligibly small calculated intensity. I restored the original correct assignment, 6s6d $^1D_2$ – 6s10f $^1F°_3$, from Murakawa [35MUR], used the wavelength and observed intensity from Suga et al. [37SUG], 8704.51(40) Å, I_{obs} = 7, and derived the missing 6s10f $^1F°_3$ level from this transition.

The line at 8751.55 Å from Murakawa [35MUR] was doubly classified in the original compilation as a blend of the 6s6d $^3D_2$ – 6s10f $^3F°_{3,2}$ transitions. I discarded the $^3F°_2$ assignment, which has a negligibly small calculated intensity, and used the wavelength and observed intensity from Suga et al. 1937, 8751.91(40), I_{obs} = 7 to derive a corrected value for the upper level $^3F°_3$.

For consistency, I used the wavelengths and observed intensities from Suga et al. [37SUG] for the 6s6d $^3D_1$ – 6s10f $^3F°_2$ and 6s6d $^3D_3$ – 6s10f $^3F°_4$ transitions instead of the values from Murakawa [35MUR] used in the original compilation, and derived the upper level values from these transitions.

7. The line at 8511.82 Å from Murakawa [35MUR] was wrongly assigned in the original compilation to the 6s6d $^1D_2$ – 6s11f $^3F°_2$ intercombination transition, which has a negligibly small calculated intensity. I restored the original correct assignment, 6s6d $^1D_2$ – 6s11f $^1F°_3$ + 6s6d $^3D_1$ – 6s11f $^3F°_2$ [35MUR]. Both these transitions were resolved and re-measured by Kamiyama [43KAM]. I used the wavelengths and observed intensities from the latter paper and derived the missing 6s11f $^1F°_3$ level from the 6s6d $^1D_2$ – 6s11f $^1F°_3$ transition (at 8511.04 Å).

The line at 8557.27 Å from Kamiyama [43KAM] was wrongly assigned in the original compilation to the 6s6d $^3D_2$ – 6s11f $^3F°_2$ transition, which has a negligibly small calculated intensity. I restored Murakawa's correct assignment, 6s6d $^3D_2$ – 6s11f $^3F°_3$ [35MUR] and derived the missing 6s11f $^3F°_3$ level from this transition.

I used the wavelength and observed intensity from Suga et al. [37SUG] for the 6s6d $^3D_3$ – 6s11f $^3F°_4$ transitions instead of the values from Murakawa [35MUR] used in the original compilation, and derived the corrected upper level value from this transition.

8. The line at 8374.04 Å from Kamiyama [43KAM] was wrongly assigned in the original compilation to a blend of the two intercombination transitions 6s6d $^1D_2$ – 6s12f $^3F°_{2,3}$. Both of these transitions have negligibly small calculated intensities. I restored the correct assignment of this line to 6s6d $^1D_2$ – 6s12f $^1F°_3$ [35MUR] and derived the missing 6s12f $^1F°_3$ level from this line.

The line at 8418.61 Å from Kamiyama [43KAM] was doubly classified in the original compilation as a blend of the 6s6d $^3D_2$ – 6s12f $^3F°_{2,3}$ transitions. I discarded the $\Delta J = 0$ assignment, because it has a negligibly small calculated intensity.

9. I added the line at 8272.53 Å, classified by Kamiyama [43KAM] as the 6s6d $^1D_2$ – 6s13f $^1F°_3$ transition and derived the missing 6s13f $^1F°_3$ level from this line.

The line at 8316.43 Å from Kamiyama [43KAM] was doubly classified in the original compilation as a blend of the 6s6d $^3D_2$ – 6s13f $^3F°_{2,3}$ transition. I discarded the $\Delta J = 0$ assignment, because it has a negligibly small calculated intensity.

The line at 8338.36 Å from Murakawa [35MUR] was assigned in the original compilation to the 6s6d $^3D_3$ – 6s13f $^3F°_4$ transition, while the line at 8340.47 Å from Kamiyama [43KAM] was classified as 6s6d $^3D_3$ – 6s13f $^3F°_3$. The latter transition has a negligibly small calculated intensity. The line from Kamiyama is actually the same line as the one observed by Murakawa, measured more accurately by Kamiyama. Therefore, I deleted the line at 8338.36 Å and changed the classification of the 8340.47 Å line to 6s6d $^3D_3$ – 6s13f $^3F°_4$.

10. The line at 8262.19 Å from Kamiyama [43KAM] was wrongly assigned in the original compilation to the 6s6d $^3D_3$ – 6s14f $^3F°_3$ transition. I restored the original classification from Kamiyama [43KAM], 6s6d $^3D_3$ – 6s14f $^3F°_4$.

The line at 8238.35 Å from Kamiyama [43KAM] was doubly classified in the original compilation as a blend of the 6s6d $^3D_2$ – 6s14f $^3F°_{2,3}$ transition. I discarded the $\Delta J = 0$ assignment, because it has a negligibly small calculated intensity.

Since the entire 6s14f configuration, consisting of the $^1F°_3$ and $^3F_{2,3,4}$ levels, has a calculated width of only 1 cm^{-1}, it is easy to calculate the Ritz wavelengths of the 6s6d $^3D_1$ – 6s14f $^3F°_2$ and 6s6d $^1D_2$ – 6s14f $^1F°_3$ transitions. They are 8197.7 and 8195.7 Å, respectively. The line list of Wiedmann [37WIE] contains lines at 8197.4 (I_{obs} = 2) and 8195.5 Å (I_{obs} = 9). The first of these lines was correctly assigned in the original compilation to the 6s6d $^3D_1$ – 6s14f $^3F°_2$ transition. The second line was re-measured by Kamiyama [43KAM] at 8195.72 Å (I_{obs} = 10) and classified as 5d^{9}6s^2($^2D_{5/2}$)6p ^{2}[3/2]° – 6s9d $^3D_3$. The original compilation added a second classification to this line, 6s6d $^1D_2$ – 6s17p $^1P°_1$. This transition has a negligibly small calculated intensity for the conditions of observation of Kamiyama [43KAM], so I replaced this classification with 6s6d $^1D_2$ – 6s14f $^1F°_3$.

The line at 10444.5 Å from Murakawa [36MUR] was assigned in the original compilation to a blend of the 6s8s $^3S_1$ – 6s17p $^1P°_1$ and 6s8s $^3S_1$ – 6s14f $^3F°_2$ transitions. Both of these transitions should be extremely weak under the conditions of observation in that experiment. All other lines observed in that work had lower levels with n = 6 or 7, and upper levels with n < 12. Therefore, I discarded both assignments and dropped this line from the list.

11. The line at 8214.20 Å from Kamiyama [43KAM] was assigned in the original compilation to the 6s7p $^1P°_1$ – 6s17s $^1S_0$ transition. A comparison of observed and calculated intensities along the series shows that this transition could not be observed in Kamiyama's work [43KAM]. Therefore, I restored the original classification given by Kamiyama, 6s6d $^3D_3$ – 6s15f $^3F°_4$, and derived the missing upper level from this transition.

The line at 8177.20 Å from Kamiyama [43KAM] was classified in the original compilation as a blend of the 6s6d $^3D_2$ – 6s18p $^1P°_1$ and 6s6d $^3D_2$ – 6s15f $^3F°_2$ transitions. The second assignment places the 6s15f $^3F°_2$ level at 83621.8(4) cm^{-1}, while the $^3F°_3$ and $^3F°_4$ levels are at 83603.9(6) and 83601.9(4) cm^{-1}. The total width of the 6s15f configuration calculated with Cowan's codes is less than 1 cm^{-1}, so the above value of $^3F°_2$ is unrealistic. I discarded this assignment. The 6s6d $^3D_1$ – 6s15f $^3F°_2$ transition was probably masked in [43KAM, 37SUG, 37WIE] by the much stronger 6s6d $^1D_2$ – 6s15f $^1F°_3$ transition at 8136.30(30) Å [43KAM].

12. By means of fitting the polarization formula to the revised values of the 6snf $^1F°_3$ ($n \leq$ 15) levels, I predicted the higher members of this series with an uncertainty of about ±1 cm^{-1}. Then the transitions 6s6d $^1D_2$ – 6snf $^1F°_3$ for n = 16–21 were easily identified in the line list of Kamiyama [43KAM]. They are at 8090.40(30), 8049.99(30), 8017.88(30), 7990.98(30), 7968.63(30), and 7951.22(30) Å.

13. The line at vacuum wavelength of 45134.34(55) Å from Plyler et al. [55PLY] was assigned in the original compilation to the 6s9d $^1D_2$ – 6s14p $^1P°_1$ transition. Since Plyler et al. did not report any of the lower members of this series, I presume that these highly excited 6s*n*p levels were not observed in their experiment. Therefore, I have discarded the classification given in the original compilation.

14. The lines of mercury in the natural mixture of isotopes are, in general, wide and asymmetric due to the presence of several isotopes and hyperfine structure. Because of that, the measured line centers or maxima of the peaks may deviate significantly from the Ritz values. Therefore, in many cases the relatively large deviations of observed wavelengths from the Ritz values may not necessarily be due to measurement errors. In several papers, e.g. [37SUG], [35MUR], [36MUR], and [43KAM], the measured wavelengths (in angstroms) in the red and infrared regions were given with two figures after the decimal point. However, they deviate from the Ritz values by (0.3–0.6) Å on average. Therefore, in the level optimization procedure these wavelengths have been assigned such increased uncertainties. The uncertainty values I used are generally the same as assessed in the original compilation. It is not clear whether the deviations of the precise values of measured wavelengths from the Ritz values are caused by the measurement errors or by intrinsic properties of those lines. To be on the safer side, I have rounded off the wavelength from the above-mentioned papers to one figure after the decimal point.

15. In the original compilation it was noted that the line at 2699.514 Å from Burns et al. [50BUR] is inconsistent with values quoted for different separated isotopes [52BUR], [52BURb]. Therefore, in the compilation this wavelength was replaced with the value of 2699.36 Å from Walerstein [34WAL]. However, Burns and Adams [52BUR] in the footnotes for their Table I noted that that they made an error in their 1950 measurement of this line and gave a corrected wavelength of 2699.376 Å for it. This new value agrees well with the Ritz value, so I replaced the wavelength from Walerstein with the new value from Burns and Adams [52BUR].

References

[05SAN] J. E. Sansonetti and W. C. Martin, *Handbook of Basic Atomic Spectroscopic Data*, J. Phys. Chem. Ref. Data **34**(4), 1559–2259 (2005).

[05SANa] C. J. Sansonetti, *Computer program POLAR*, private communication (2005).

[05SANb] C. J. Sansonetti, *Computer program RITZPL*, private communication (2005).

[06KRA] A. E. Kramida and G. Nave, Eur. Phys. J. D **37**, 1–21 (2006).

[06SAL] E. B. Saloman, J. Phys. Chem. Ref. Data **35**, 1519 (2006).

[14VOL] Theo Volk, *Wellenlängen-normalen im Ultrarot von Quecksilber, Zink, Cadmium; Ultrarot Berylliumlinien*, Dissertation, Univ. Tübingen, Germany, 18 pp. (1914) (Ger.).

[24FUK] M. Fukuda, Jap. J. Phys. **3**, 139 (1924).

[34WAL] I. Walerstein, Phys. Rev. **46**, 874 (1934).

[50BUR] K. Burns, K. B. Adams, and J. Longwell, J. Opt. Soc. Am. **40**, 339 (1950).
[52BUR] K. Burns and K. B. Adams, J. Opt. Soc. Am. **42**, 56 (1952).
[52BURb] K. Burns and K. B. Adams, J. Opt. Soc. Am. **42**, 716 (1952).
[58MOO] C. E. Moore, *Atomic Energy Levels as Derived from the Analysis of Optical Spectra – Molybdenum through Lanthanum and Hafnium through Actinium*, in *Natl. Stand. Ref. Data 35, Vol III (Reprint of NBS Circ. 467, Vol. III, 1958)*, 245 pp. (Nat. Bur. Stand., U.S., 1971).
[34WAL] I. Walerstein, Phys. Rev. **46**, 874 (1934).
[35MUR] K. Murakawa, Proc. Phys.-Math. Soc. Jpn. **17**, 14–33 (1935).
[36MUR] K. Murakawa, Proc. Phys.-Math. Soc. Jpn. **18**, 345–347 (1936); Erratum: **18**, 564 (1936).
[37SUG] T. Suga, M. Kamiyama, and T. Sugiura, Sci. Pap. Inst. Phys. Chem. Res. (Japan) **34**(741), 32–49 (1937).
[37WIE] G. Wiedmann and W. Schmidt, Z. Phys. **106**, 273–278 (1937) (Ger.).
[38MRO] S. Mrozowski, Z. Phys. 108, 204–211 (1938).
[43KAM] M. Kamiyama, *Arc Spectrum of Mercury (Hg I)*, Bull. Inst. Phys. Chem. Res. (Japan) **22**(10), 877–890 (1943) (Jpn.).
[50BUR] K. Burns, K. B. Adams, and J. Longwell, J. Opt. Soc. Am. **40**, 339 (1950).
[55PLY] E. K. Plyler, L. R. Blaine, and E. D. Tidwell, J. Res. Natl. Bur. Stand. **55**, 279 (1955).
[60JOH] I. Johansson and K. F. Svensson, Ark. Fys. (Stockholm) **16**, 353–360 (1960).
[81COW] R. D. Cowan, *The Theory of Atomic Structure and Spectra*, University of California Press, Berkeley, 1981.
[70RAD] L. J. Radziemski, Jr., K. J. Fisher, and D. W. Steinhaus, *Calculation of Atomic-Energy-Level Values*, Los Alamos Scientific Lab., Univ. California Report LA-4402, 79 pp. (Los Alamos, 1970).