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Author

Brewer, Leo.

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Energies of the Electronic Configurations of the Lanthanide
and Actinide Neutral Atoms

Leo Brewer

Inorganic Materials Research Division,
Lawrence Radiation Laboratory
and Department of Chemistry,
University of California,
Berkeley, California 94720

ABSTRACT

The thermodynamic data for the lanthanide and actinide metals have been combined with spectroscopic data to develop a method of estimating the energies of the electronic configurations of the neutral gaseous atoms. Term values are tabulated for the lowest spectroscopic states of each configuration. Many of the odd terms of LaI have been reclassified.

INTRODUCTION

The energies of the various electronic configurations of the gaseous atoms provide important information that can be used to fix the crystal structures and thermodynamic data for the elements and their compounds.^{1,2,3} Conversely, thermodynamic data can be used to fix the energies of electronic configurations. In particular, the relationships between lattice

constants, melting points, and enthalpies of sublimation and the cohesive energies of the metals can be used to predict some of the missing energies of electronic configurations of the gaseous lanthanide and actinide atoms.

I had been thwarted from working with the lanthanides and actinides earlier because of the belief that virtually no spectroscopic data were available. However, in response to the challenge⁴ to apply to the actinides the methods successful for predicting the behavior of transition metals, I discovered that sufficient spectroscopic information had been added during the last decade to allow detailed predictions of the metallurgical chemistry of the lanthanides and actinides.

Comparison of Melting and Boiling Points of the Lanthanides

The use of spectroscopic data to interpret thermodynamic data is illustrated by the dilemma posed by Figure 1 which contrasts the variation of melting point of the lanthanide metals with the variation of enthalpy of sublimation, which is closely proportional to the boiling point. The relationship between lattice constant and number of electrons used in bonding^{5,6} establishes that the lanthanide metals use essentially only three valence electrons for bonding except for Eu and Yb which use only two bonding electrons. When bonding is similar in the solid and liquid phases, the melting point is expected to increase with increase of the strength of bonding or the cohesive energy. Thus the low melting points of Eu and Yb are clearly related to their bivalent bonding character. For the trivalent metals, the general increase in melting point with increase of nuclear charge and corresponding decrease in atomic radius is attributed to increasing cohesive energy. However, the enthalpies of sublimation show a steady decrease from La to Sm in contrast to the

increase in melting points. Then there is an abrupt increase in enthalpy of sublimation for Gd followed again by a decrease in enthalpies of sublimation running contrary to the increasing melting points.

The contradiction between the trends in melting and boiling points is resolved by examining Figure 2 which shows the energies of the lowest electronic states of some of the configurations of the lanthanides. As the 4f electrons do not contribute significantly to bonding, the divalent or trivalent character of a given configuration is determined by the number of non-f electrons. In contrast to the trivalent character of the lanthanide metals other than Eu and Yb, the ground electronic states of almost all of the gaseous lanthanides are divalent. As one goes from La to Eu, the energy of the divalent ground state drops steadily relative to the trivalent electronic configurations. There is a sudden jump in energy of the divalent state of Gd followed by a drop for the heavier lanthanides. It is clear that the abnormality of the trend in boiling points is not to be attributed to the metallic phase, but is due to abnormality of the gas. The vapor consists predominately of atoms of different valence character than in the metal. The correct measure of the cohesive energy is the enthalpy of sublimation to a gaseous atom with the same electronic configuration as in the metal. Figure 3 shows melting point trend again compared now with the cohesive energy or the enthalpy of sublimation of the trivalent metals to the gaseous atom in a trivalent electronic state. For Eu and Yb, a divalent valence state was used. The cohesive energies as measured by the energy required to pull apart the atoms without change in electronic configuration are seen to show the same trend as the melting points with the exception of Ce

which is complicated by contributions from several electronic configurations in the liquid state.

Calculation of Energy Differences of Divalent and Trivalent States

In those instances where the metal is trivalent and the ground state of the gas is divalent, one can use the enthalpies of sublimation determined from vapor pressure measurements to calculate the energy difference between the lowest spectroscopic state of the trivalent bonding configuration and the divalent ground state for the gaseous atom. For example, when the electronic configuration in the metal can be fixed as $f^{n-3}d_{sp}$ on the basis of the crystal structure of the metal^{1,2,3} and the ground state of the gaseous atom corresponds to the $f^{n-2}s^2$ configuration, the energy difference between the lowest spectroscopic states of the $f^{n-3}d_{sp}$ and $f^{n-2}s^2$ configurations is given by the difference between the valence state enthalpy of sublimation or bonding enthalpy, shown in Figure 4, and the experimental enthalpy of sublimation. The method will be illustrated by the example of holmium. The variation of bonding enthalpy with atomic number is smooth enough and slow enough so that one can reliably interpolate between the known points of Figure 4 for Dy and Er to obtain a value of 137.5 kcal/gram atom evolved when Ho in the $f^{10}d_{sp} \ ^8M_{25/2}^o$ gaseous atomic state condenses to metallic Ho with hexagonal crystal structure. The calculation of the known points of Figure 4 can be illustrated for Er. The ground electronic state of gaseous Er is $f^{12}s^2 \ ^3H_6$ and from Figure 2 we see that the $f^{11}d_{sp} \ ^7M_{12}$ state of gaseous Er is $22\ 900\text{ cm}^{-1}$ or 65.7 kcal higher in energy. The enthalpy of sublimation of hexagonal Er at 298°K to the $\ ^3H_6$ ground state of the gaseous atom has been determined as 75.8 kcal/gram atom.⁷ The bonding enthalpy of $f^{11}d_{sp}$

$7M_{12}$ atoms to form hexagonal metallic Er is then $75.8 + 65.7 = 141.5$ kcal/gram atom. The corresponding bonding enthalpy of hexagonal Dy is 133.5 kcal/gram atom. A linear interpolation yields the 137.5 kcal value for Ho. The experimental enthalpy of sublimation of hexagonal Ho metal to the $f^{11}s^2 4f_{15/2}^0$ gaseous ground state is 71.9 kcal/gram atom.⁷ Thus one obtains $137.5 - 71.9 = 65.6$ kcal or $22\,900\text{ cm}^{-1}$ as the energy of the $f^{10}d_{25/2}^0$ state of Ho above the ground state. As one can fix the energy of the $f^{10}d_{25/2}^0$ at $15\,200\text{ cm}^{-1}$ above the energy of the $f^{10}d_{17/2}^2 6f_{17/2}^0$ state, the lowest trivalent level, by methods to be described below, the difference in energy between the lowest divalent and trivalent states of $f^{11}s^2$ and $f^{10}d_{25/2}^0$, respectively, is $7\,700\text{ cm}^{-1}$.

Similar calculations can be carried out for most of the other lanthanides and actinides. However, for Eu, Yb, Md, and No, which are bivalent, for La, Gd, Lu, Ac, Cm, and Lr, which are trivalent, and for Th, which is tetravalent, for both the metal and the ground state of the gas, no information can be obtained from the heat of sublimation concerning the energy difference between electronic states of different valency. For Ce, the gas and most of its metallic forms are trivalent, but to the extent that the dense face-centered cubic form of Ce can be considered tetravalent, information concerning the energy difference between tri- and tetra-valent states of Ce can be estimated. For all other lanthanides and actinides, excepting Pa, U, and Np, the heats of sublimation are directly related to the promotion energy required to raise the ground divalent electronic state to a trivalent state. The ground states of Pa and U are trivalent and the ground state of Np is divalent, but the metallic states use valencies of four and higher and the heats of

sublimation will be related to the relative energies of several valence levels. For those metals with different valencies in the metal and gas, the promotion energy between the gaseous states of different valency is given by the equation: Promotion Energy = Bonding Energy minus Energy of Sublimation. Where the sublimation energy is not known, but the promotion energy is known, the sublimation energy can be predicted by the reverse calculation.

Prediction of Energies of Electronic Configurations

The problem of estimating the energies of the various electronic configurations of the gaseous atoms can be divided into two parts. The first is the determination of the relative energies of states of a given atom of different valency or with different numbers of f electrons. The second is the determination of the energy differences between different electronic configurations with the same valency or with the same number of f electrons. Racah⁸ had suggested methods of estimating energy differences between states of different valency and Camus⁹ and Fred¹⁰ have presented plots which could be interpolated or extrapolated to obtain estimates. I have combined these methods with values obtained through use of heats of sublimation as described above to obtain the values of Figure 5 for the energies of the lowest electronic state of the $f^{n-2}s^2$ configuration compared to the lowest electronic state of the $f^{n-3}ds^2$ configuration for all of the lanthanides and actinides. In addition the energies of the lowest electronic state of the $f^{n-4}d^2s^2$ configuration are given for the actinides Th to Pu. The only lanthanide for which a tetravalent value can be given is cerium for which the $d^2s^2 3F_2$ state is estimated to lie $36\,000\text{ cm}^{-1}$ above the ground $fd^2 1G_4^o$ state.

The second part of the problem of the energies of different configurations of the same valency depends upon considering the variations of the relative energies as a function of atomic number in terms of the relative nuclear shielding by f electrons of the $s, p,$ and d electrons. Camus⁹, Nir¹¹, and other authors have noted that there were indications of smooth variation of relative energies of different configurations with atomic number. Enough data are now available to demonstrate that quite accurate predictions can be made for many configurations and the ability to predict is rapidly increasing as more data become available.

To check on the accuracy of my methods of prediction, I prepared tables indicating the estimated values for the various configurations along with limits of uncertainty. The table for a given element was distributed among the spectroscopists who had published recently on that element. Altogether I received thirty eight newly determined experimental values. Of these only thirty one were checks of my estimates; the other seven values that I had listed were based on approximate values reported in the literature that must have been based on preliminary measurements as they were very close to the accurate experimental values.

Virtually every new result was within the limits of uncertainty that I had listed. Of the nine checks of my estimates of $f^{n-2}sp$ or $f^{n-3}dsp$ energies relative to $f^{n-2}s^2$ and $f^{n-3}ds^2$, respectively, the differences between the experimental and estimated energies varied from less than 100 to 900 cm^{-1} with an average deviation of 350 cm^{-1} . For the $f^{n-2}ds$, $f^{n-3}d^2s$, and $f^{n-4}d^3s$ configurations relative to the corresponding s^2 configurations, the average deviation was 750 cm^{-1} . For the configurations p^2 , dp , d^2p , and s^2p relative to s^2 and ds^2 , respectively, the average deviation was 3000 cm^{-1} . The average deviation for the d^3 configurations was 2600 cm^{-1} . The average deviation of the energy difference

between divalent and trivalent states was 1600 cm^{-1} and, with one exception, the average deviation for estimates of the energy difference between trivalent and tetravalent states was 2500 cm^{-1} . With the inclusion of these new data, the uncertainty of the remaining estimates has been considerably reduced.

The one serious discrepancy in the estimation of the energy of the tetravalent states of Pu has important consequences in regard to interpretation of the bonding of plutonium metal and will be discussed in more detail in a forthcoming paper, but a brief discussion is appropriate here. The energy of the $f^4 d^2 s^2 7M_6$ state of Pu has been recently fixed²⁵ at $36\,051 \text{ cm}^{-1}$ from which the $f^4 d^3 s^2 9M_5$ state can be fixed at $42\,500 \text{ cm}^{-1}$. I had first estimated⁴ the energy of the $f^4 d^3 s$ state as $\gg 21\,000 \text{ cm}^{-1}$ from which I drew the conclusion that plutonium metal can not be using more than three non-f electrons in bonding. This conclusion is now firmly fixed by the spectroscopic data. However, the use of only three non-f electrons led to difficulties in regard to the role of 5f electrons in bonding as the internuclear distance and heat of sublimation of Pu indicated more than three bonding electrons. On the other hand, one can account for the internuclear distances and heats of sublimation of the lanthanides and heavier actinides without any substantial contribution of f electrons to the bonding. The decisive argument against use of f electrons in bonding was the heat of sublimation of Pa which was smaller than one would expect with use of the fd^3s configuration assuming no contribution to the f electron. On this basis I revised my estimate of the tetravalent states of Np and Pu downwards. It now appears that the heat of sublimation of Pa is in error to the extent of at least

five kilocalories per mole and one must allow for significant contribution of 5f electron bonding for the metals Pa, U, Np, and Pu. I have also increased my estimates of the tetravalent states of Np and Am to be consistent with the new Pu data.

All of the newly determined data have been incorporated in Figures 6 and 7 which present the energies of the lowest spectroscopic states of the divalent configurations of the lanthanides and actinides, respectively, relative to a reference zero for the lowest state of the $f^{n-2}s^2$ configuration and in Figures 8 and 9 which present the corresponding values for the trivalent configurations relative to a reference zero for the lowest state of the $f^{n-3}ds^2$ configuration.

The energy required to promote an s electron to a p state can be examined in terms of the $sp-s^2$, $dsp-ds^2$, $dp-ds$, and d^2p-d^2s energy differences. The first two promotions involve low levels which are less mixed with other configurations and show a very simple behavior. The two $sp-s^2$ curves for the lanthanides and actinides and the two $dsp-ds^2$ curves all fall almost one on another with only slightly greater (5-20%) promotion energies for the actinides than for the lanthanides. There is a slow linear increase of promotion energy with atomic number until the f shell is half-filled and a faster rate of increase for the second half of the f shell; for example, 260 cm^{-1} per ΔZ for $sp-s^2$ up to Eu and 460 cm^{-1} per ΔZ beyond Eu compared to 100 cm^{-1} per ΔZ for $dsp-ds^2$ up to Gd and 480 cm^{-1} per ΔZ beyond Gd. The rate of increase of promotion energy with Z is 2.3 to 2.7 times faster for the actinides than for the lanthanides. All of these results are those to be expected on the basis of the p electron being better shielded from the nucleus by

the f electrons than are the s electrons. The $dp-ds$ and d^2p-d^2s promotion energies vary in a similar but less regular way as these more excited states interact more with other configurations.

It might have been expected that the curves of Figures 6-9 would be much less regular and therefore less useful for making accurate predicting of missing values because of configuration interactions. The procedure used here takes advantage of the fact that these interactions can be expected to vary reasonably smoothly from element to element. The lowest state of each configuration is used rather than the center of gravity because the energy of the lowest state is more useful for predicting thermodynamic properties of metals. It is also often the least perturbed state, at least for low lying configurations.

The promotion of an s or p electron to a d electron shows a more complex behavior. As Z is increased, the d electron first drops in energy as in the transition metal series and then starts to rise as the f electrons become more effective shielders of the nuclear charge. The initial drop and the subsequent increase is more rapid for the actinides than for the lanthanides. By consideration of these various shielding effects, it is possible to fill in the missing points between the experimental values which are shown as circles in Figures 6-9, and to extrapolate beyond the experimental points as indicated by dashed extensions of the curves. Interpolated points of well behaved curves such as the sp or dsp curves could be fixed within an uncertainty of 100 to 300 cm^{-1} . The values from the extrapolated curves obviously become less certain the greater the extrapolation. A similar set of more poorly defined curves was also prepared for the tetravalent states of the actinides.

The relative energies of the various configurations of a given valence can then be combined with the energy differences given in Figure 5 between levels of different valence to obtain the spectroscopic term values. The most striking feature of Figure 5 is the more rapid stabilization of the divalent state relative to the trivalent state for the first half of the lanthanides than for the first half of the actinides due to the slower stabilization of the f electrons for the actinides and the reverse behavior after the f subshell has been half-filled. This variation accounts for the greater volatility of the lighter lanthanides compared to the lighter actinides and predicts that the second half of the actinides will be more volatile than the corresponding lanthanides. The contrast in volatility between the first half of the lanthanides with the corresponding actinides is enhanced by the use of tetravalent and higher valences by the actinides from Th. to Np. A paper to be submitted to a metallurgical journal will detail the many metallurgical applications of spectroscopic data.

Tabulation of Term Values

Tables I-XXX present the term values of the lowest spectroscopic state of each electron configuration listed for all of the lanthanides and actinides. Although the coupling cases vary greatly among the electronic configurations of the lanthanides and actinides, most publications have used LS nomenclature for purposes of identifying the levels and this practice has been followed here. In some instances the published work does not give LS identifications for the reported level. In those instances the actual coupling is tabulated along with a corresponding LS symbol.

In many instances it is found that the lowest state is the state predicted by Hund's rule even when LS coupling does not hold. When the analyses are incomplete, it is not always clear that the lowest reported state is the lowest energy state of the configuration. If the lowest observed state was in agreement with Hund's Rule, it was accepted as the lowest state. Otherwise an attempt was made to predict the position of the Hund's Rule lowest state to determine if a lower state had been missed or whether Hund's Rule was not obeyed. When the lowest state does not correspond to Hund's Rule, the symbol is followed by an asterisk. In general the asterisk means that the indicated state is accepted as the lowest state; in a few instances of very incomplete data, there may be yet lower states of the configuration. When the lowest state has not been established experimentally or by theoretical calculations, the state symbol is given in parentheses and is usually the lowest state according to Hund's Rule, whether Hund's Rule is expected to hold or not. When Hund's Rule is found not to work, the estimates of the energies are not to be changed; the state designations are to be changed as the thermodynamic data for the metal will give the energy of the lowest state using the procedures described above.

The energies are given in thousands of wavenumbers. Since the uncertainty of the thermodynamic data for the metals is on the order of $0.3 \times 10^3 \text{ cm}^{-1}$ or larger, none of the estimated values are given to closer than a tenth of a unit (100 cm^{-1}). Unless indicated otherwise, the uncertainty of estimates should be below 1000 cm^{-1} . Values obtained from long extrapolations have larger uncertainties which are listed.

Moore's bibliography¹² was indispensable for a review of the literature and the experimental values given in the tables came from the references

given by Moore plus a few recent references. Moore's bibliography will not be duplicated here and the numbers in parentheses after each table heading refer only to the recent references and to those older references from which tabulated values were actually obtained.

The values given in Tables I-XXX are restricted to those involving 4f, 5d, 6s and 6p electrons for the lanthanides and 5f, 6d, 7s and 7p electrons for the actinides. All divalent configurations involving these electrons have been tabulated. Values are given for all trivalent configurations except for $f^{n-3}p^3$ and $f^{n-3}dp^2$, which should lie well above $30\,000\text{ cm}^{-1}$ for all lanthanides and actinides, and only a few estimates are given for $f^{n-3}sp^2$. It is unfortunate that among the transition metals and the lanthanides and actinides, values for the sp^2 configuration are known only for Y, Gd, and Lu as this configuration is expected to be of metallurgical importance. With only these three data, it is difficult to make predictions for the remaining elements. It is hoped that the availability of the predicted values for yet unassigned configurations will be of aid to spectroscopists in interpreting and assigning the spectral lines which are only 10% assigned for some of the lanthanides and actinides.

Assignment of LaI Levels

As an illustration of the use of Tables I-XXX in assigning of levels, the odd terms of LaI will be considered. From Table I, we predict that all levels below about $38\,000\text{ cm}^{-1}$ must belong to the five configurations dsp (nine states), s^2p (one state), fs^2 (one state), d^2p (nineteen states), and fds (fifteen states). The nine possible states of the dsp configuration

have been found between 13 260 and 25 950 cm^{-1} and eighteen states of the d^2p configuration have been assigned in the range 17 947 to 33 204 cm^{-1} with only 2P missing. Of the two states s^2p^2P and fs^2^2F expected around 15 000 cm^{-1} , only one state with sublevels at 15 220 and 16 280 cm^{-1} which is attributed to 2P has been reported. Many other odd levels are listed¹³ between 23 221 and 32 518 cm^{-1} that either are not assigned or are assigned to the fd^2 configuration for which we predict no states below about 38 000 cm^{-1} . Two unassigned levels at 36 722 and 37 732 cm^{-1} are within the uncertainty of the 38 000 cm^{-1} limit and could belong to fd^2 . One can reassign the states below 32 600 cm^{-1} to the fds configuration as shown in Table XXXI.

The only levels which have not been located are the $^2H^o_{9/2-11/2}$ state which should be around 23 000 to 30 000 cm^{-1} , a $^2P^o_{1/2}$ level around 27 000 cm^{-1} , the $^4H^o_{7/2-13/2}$ state which should be around 30 000 cm^{-1} and $^4P^o_{1/2}$ which should also be around 30 000 cm^{-1} , and $^2G_{7/2-9/2}$ which should be around 28 000 to 30 000 cm^{-1} . Four odd levels remain unassigned below 36 700 cm^{-1} . They are the $v' ^2F^o$? state, $J = 5/2$ at 24 507.89 with $g = 1.159$ and $J = 7/2$ at 25 378.46 with $g = 1.13$, and the $4f r ^2F^o$ state, $J = 5/2$ at 31 477.16 with $g = 0.92$ and $J = 7/2$ at 32 140.60 cm^{-1} with $g = 1.16$. Since the two possible $^2F^o$ states of the fds configuration have been assigned, the $v' ^2F^o$ and $4f ^2F^o$ states have no assignment to a configuration with an f electron unless some of the levels assigned to the d^2p configuration are misassigned and there should be some interchange between the levels assigned to the d^2p and dsf configurations. Since the configurations cover the ranges 17 947 to 33 204 and 23 221 to 32 500 cm^{-1} respectively and since four pairs of states (2P , two 2D , and 2F) lie

within 1000 cm^{-1} of one another, there must be considerable configuration interaction and some states must be assigned at least in part to both configurations. In addition, between two to four J values must have been misassigned to accommodate the four unassigned levels. Around 160 lines of the LaI spectrum are unclassified and additional study should locate the three missing $^2\text{H}^{\circ}$, $^4\text{H}^{\circ}$, and $^2\text{G}^{\circ}$ fds states and the missing $d^2p \ ^2\text{P}^{\circ}$ state plus the three missing $J = 1/2$ levels of both configurations.

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Table I. $\text{La} \text{I}, 10^3 \text{cm}^{-1}$

| Odd Terms | | | Even Terms | | |
|------------------|--------------------------|----------|------------------|------------------------|---------|
| dsp | ${}^4\text{F}_{3/2}^0$ | 13.260 | ds ² | ${}^2\text{D}_{3/2}$ | 0.000 |
| s ² p | ${}^2\text{P}_{1/2}^0$? | 15.220 | d ² s | ${}^4\text{F}_{3/2}$ | 2.668 |
| fs ² | $({}^2\text{F}_{5/2}^0)$ | (≥15.1) | d ³ | ${}^4\text{F}_{3/2}$ | 12.430 |
| d ² p | ${}^4\text{G}_{5/2}^0$ | 17.947 | fsp | $({}^4\text{G}_{5/2})$ | (≥27.8) |
| fds | ${}^2\text{G}_{7/2}^0$ * | 23.221 | fdp | $({}^4\text{I}_{9/2})$ | (≥37.6) |
| fd ² | $({}^4\text{I}_{9/2}^0)$ | (≥38.0) | | | |
| fp ² | $({}^4\text{G}_{5/2}^0)$ | (≥49. .) | | | |

Table II. Ce I, 10^3cm^{-1}

| Odd Terms | | | Even Terms | | |
|-----------|---------------|-----------------|------------|---------------|-----------------|
| fds^2 | ${}^1G_4^0 *$ | 0.000 | f^2s^2 | 3H_4 | 4.762 |
| fd^2s | ${}^5H_3^0 *$ | 2.369 | f^2ds | ${}^5I_4 *$ | 12.114 |
| fd^3 | ${}^5I_4^0$ | 12.35 | $fdsp$ | $({}^5I_4)$ | 13.4 |
| f^2sp | $({}^5I_4^0)$ | (17.9) | fs^2p | $({}^3F_3)^*$ | (15.6) |
| f^2dp | $({}^5L_6^0)$ | (28.) | fd^2p | $({}^5K_5)$ | (17.9) |
| fsp^2 | $({}^5G_2^0)$ | (30.) ± 10 | f^2d^2 | $({}^5L_6)$ | (27.) |
| ds^2p | $({}^3F_2^0)$ | (48.) ± 5 | d^2s^2 | $({}^3F_2)$ | (36.) ± 5 |
| d^2sp | $({}^5G_2^0)$ | (50.) ± 5 | f^2p^2 | $({}^5I_4)$ | (39.) ± 9 |
| d^3p | $({}^5G_2^0)$ | (58.) ± 5 | d^3s | $({}^5F_1)$ | (42.) ± 5 |
| | | | dsp^2 | $({}^5F_1)$ | (51.) ± 10 |

Table III. $\text{Pr}^{\text{I}}, 10^3 \text{cm}^{-1}$

| Odd Terms | | | Even Terms | | |
|-------------|-----------------|-----------|-------------|----------------|-------------|
| $f^3 s^2$ | $4I_9^0/2$ | 0.0 | $f^2 ds^2$ | $(4K_{11}/2)$ | (3.)± 1.5 |
| $f^3 ds$ | $(6L_{11}^0/2)$ | (8.0) | $f^2 d^2 s$ | $(6L_{11}/2)$ | (5.2)± 2 |
| $f^2 dsp$ | $(6L_{11}^0/2)$ | (16.4)± 2 | $f^3 sp$ | $(6K_9/2)$ | (13.4) |
| $f^2 s^2 p$ | $(4I_9^0/2)$ | (19.)± 2 | $f^2 d^3$ | $(6L_{11}/2)$ | (15.)± 2 |
| $f^2 d^2 p$ | $(6M_{13}^0/2)$ | (21.)± 2 | $f^3 dp$ | $(6M_{13}/2)$ | (23.3) |
| $f^3 d^2$ | $(6M_{13}^0/2)$ | (22.2) | $fd^2 s^2$ | $(4H_7^0/2) *$ | (51.)± 5 |
| $f^3 p^2$ | $(6K_9^0/2)$ | (34.)± 1 | | | |

Table IV. $\text{Nd}_{\frac{1}{2}^+}$, 10^3cm^{-1} (17, 18, 19, 20, 21)

| Odd Terms | | | Even Terms | | |
|-------------|-------------|----------------|---------------|-----------|----------------|
| $f^3 ds^2$ | $^5L_6^0$ | 6.764 | $f^4 s^2$ | 5I_4 | 0.000 |
| $f^3 d^2 s$ | $^7M_6^0$ | 8.800 | $f^4 ds$ | 7L_5 | 8.475 |
| $f^4 sp$ | $^7K_4^0$ | 13.673 | $f^3 dsp$ | 7M_6 | 20.272 |
| $f^3 d^3$ | $(^7M_6^0)$ | $(19.) \pm 1$ | $f^3 s^2 p$ | $(^5K_5)$ | (23.2) |
| $f^4 dp$ | $^7M_6^0$ | 23.554 | $f^4 d^2$ | 7M_6 | 21.890 |
| | | | $f^3 d^2 p$ | 7N_7 | 24.856 |
| | | | $f^4 p^2$ | $(^7K_4)$ | $(34.) \pm 1$ |
| | | | $f^2 d^2 s^2$ | $(^7L_5)$ | $(65.) \pm 5$ |

Table V. $\text{Pm} \left| \frac{I}{\hbar} \right|, 10^3 \text{cm}^{-1}$

| Odd Terms | | | Even Terms | | |
|-----------|---------------------------|----------------|------------|-------------------------|----------------|
| f^5s^2 | ${}^6\text{H}_{5/2}^0$ | 0.0 | f^4ds^2 | $({}^6\text{L}_{11/2})$ | (11.) |
| f^5ds | $({}^8\text{K}_{7/2}^0)$ | (9.6) | f^4d^2s | $({}^8\text{M}_{11/2})$ | (13.8) |
| f^5d^2 | $({}^8\text{L}_{9/2}^0)$ | (21.5) \pm 2 | f^5sp | $({}^8\text{I}_{5/2})$ | (13.8) |
| f^4dsp | $({}^8\text{M}_{11/2}^0)$ | (24.6) | f^4d^3 | $({}^8\text{M}_{11/2})$ | (23.) \pm 1 |
| f^4s^2p | $({}^6\text{K}_{9/2}^0)$ | (26.7) | f^5dp | $({}^8\text{L}_{9/2})$ | (24.) |
| f^4d^2p | $({}^8\text{N}_{13/2}^0)$ | (31.) \pm 1 | | | |
| f^5p^2 | $({}^8\text{I}_{5/2}^0)$ | (34.) \pm 1 | | | |

Table VI. $\text{Sm}^{\text{I}}, 10^3 \text{cm}^{-1}$ (21, 22, 23)

| Odd Terms | | | Even Terms | | |
|---------------------------|----------------------|----------------|---------------------------|--------------------|----------------|
| $f^6 \text{sp}$ | ${}^9\text{G}_0^0$ | 13.796 | $f^6 \text{s}^2$ | ${}^7\text{F}_0$ | 0.000 |
| $f^5 \text{ds}^2$ | ${}^7\text{K}_4^0$ | 15.5 | $f^6 \text{ds}$ | ${}^9\text{H}_1$ | 10.801 |
| $f^5 \text{d}^2 \text{s}$ | $({}^9\text{I}_4^0)$ | (19.3) | $f^6 \text{d}^2$ | $({}^9\text{I}_2)$ | (26.) \pm 2 |
| $f^6 \text{dp}$ | ${}^9\text{I}_2^0$ | 22.844 | $f^5 \text{dsp}$ | $({}^9\text{L}_4)$ | (29.2) |
| $f^7 \text{s}$ | ${}^9\text{S}_4^0$ | 25. | $f^5 \text{s}^2 \text{p}$ | $({}^7\text{I}_3)$ | (30.4) |
| $f^5 \text{d}^3$ | $({}^9\text{L}_4^0)$ | (28.) \pm 1 | $f^6 \text{p}^2$ | $({}^9\text{G}_0)$ | (35.) \pm 1 |
| $f^7 \text{d}$ | $({}^9\text{D}_2^0)$ | (33.) \pm 3 | $f^5 \text{d}^2 \text{p}$ | $({}^9\text{M}_5)$ | (37.) \pm 1 |

Table VII. Eu^{II} , 10^3cm^{-1} (24, 25, 26)

| Odd Terms | | | Even Terms | | |
|-------------|---------------------|----------------|-------------|-------------------|----------------|
| $f^7 s^2$ | $^8 S^0_{7/2}$ | 0.000 | $f^7 sp$ | $^{10} P_{7/2}$ | 14.068 |
| $f^7 ds$ | $^{10} D^0_{5/2}$ | 12.924 | $f^6 ds^2$ | $^8 H_{3/2}$ | 25.1 |
| $f^7 d^2$ | $(^{10} F^0_{3/2})$ | $(30.5) \pm 1$ | $f^7 dp$ | $^{10} F_{3/2}$ | 28.520 |
| $f^7 p^2$ | $(^{10} P^0_{7/2})$ | $(36.) \pm 1$ | $f^6 d^2 s$ | $(^{10} I_{3/2})$ | $(30.)$ |
| $f^6 s^2 p$ | $(^8 G^0_{1/2})$ | $(39.)$ | $f^6 d^3$ | $(^{10} I_{3/2})$ | $(43.) \pm 1$ |
| $f^6 dsp$ | $(^{10} I^0_{3/2})$ | $(39.)$ | | | |
| $f^6 d^2 p$ | $(^{10} K^0_{5/2})$ | $(49.) \pm 1$ | | | |

Table VIII. Gd_{II} , $10^3 cm^{-1}$ (27, 28, 29, 30, 31, 32)

| Odd Terms | | | Even Terms | | |
|-------------|------------------|------------|-------------|----------------|------------|
| $f^7 ds^2$ | ${}^9D_2^0$ | 0.000 | $f^8 s^2$ | 7F_6 | 10.947 |
| $f^7 d^2 s$ | ${}^{11}F_2^0$ | 6.378 | $f^7 s^2 p$ | 9P_3 | 13.434 |
| $f^7 d^3$ | ${}^{11}F_2^0$ | 22.432 | $f^7 dsp$ | ${}^{11}F_2$ | 14.036 |
| $f^8 sp$ | ${}^9F_6^*$ | 25.658 | $f^8 ds$ | ${}^9G_7^*$ | 24.255 |
| $f^7 sp^2$ | ${}^{11}P_4^0$ | 35.561 | $f^7 d^2 p$ | ${}^{11}G_1$ | 25.069 |
| $f^8 dp$ | $({}^9I_{10}^0)$ | (41.) ± 1 | $f^8 d^2$ | $({}^9I_{10})$ | (46.) ± 2 |
| | | | $f^8 p^2$ | $({}^9G_8)$ | (48.) ± 1 |

Table IX. $Tb|I, 10^3 \text{cm}^{-1}$ (33, 34)

| Odd Terms | | | Even Terms | | |
|-------------|-----------------------|----------------|-------------|---------------------|----------------|
| $f^9 s^2$ | ${}^6H_{15/2}^0$ | 0.000 | $f^8 ds^2$ | ${}^8G_{13/2}^*$ | 0.286 |
| $f^8 s^2 p$ | $({}^8G_{11/2}^0)^*$ | (12.7) | $f^8 d^2 s$ | ${}^{10}G_{15/2}^*$ | 8.191 |
| $f^8 dsp$ | $({}^{10}I_{21/2}^0)$ | (14.7) | $f^9 sp$ | ${}^8I_{19/2}$ | (14.6) |
| $f^9 ds$ | $({}^8K_{21/2}^0)$ | (15.) | $f^8 d^3$ | ${}^{10}I_{21/2}$ | (27.) ± 1 |
| $f^8 d^2 p$ | $({}^{10}K_{23/2}^0)$ | (27.3) ± 1 | $f^9 dp$ | ${}^8L_{23/2}$ | (32.) ± 1 |
| $f^9 d^2$ | $({}^8L_{23/2}^0)$ | (38.) ± 3 | $f^8 sp^2$ | $({}^{10}G_{17/2})$ | (35.4) |
| $f^9 p^2$ | $({}^8I_{19/2}^0)$ | (38.) ± 1 | | | |

Table X. Dy I, 10^3cm^{-1} (37, 35, 34, 37, 29)

| Odd Terms | | | Even Terms | | |
|-------------|------------------|----------------|-------------|----------------|----------------|
| f^{9ds^2} | ${}^7H_8^0 *$ | 7.565 | f^{10s^2} | 5I_8 | 0.000 |
| f^{10sp} | ${}^7I_9^0 *$ | 14.512 | f^{10ds} | $({}^7L_{11})$ | (16.2) |
| f^{9d^2s} | $({}^9L_{12}^0)$ | (17.1) | f^{9s^2p} | $({}^7I_9)$ | (19.) |
| f^{10dp} | $({}^7M_{12}^0)$ | (34.) \pm 2 | f^{9dsp} | $({}^9L_{12})$ | (22.4) |
| f^{9d^3} | $({}^9L_{12}^0)$ | (40.) \pm 2 | f^{9d^2p} | $({}^9M_{13})$ | (37.) \pm 2 |
| f^{9sp^2} | $({}^9I_{10}^0)$ | (42.) \pm 1 | f^{10p^2} | $({}^7K_{10})$ | (39.) \pm 1 |
| | | | f^{10d^2} | $({}^7M_{12})$ | (41.) \pm 4 |

Table XI. Ho I, 10^3cm^{-1}

| Odd Terms | | | Even Terms | | |
|--------------|----------------------|---------------|--------------|--------------------|---------------|
| $f^{11}s^2$ | ${}^4I_{15/2}^0$ | 0.000 | $f^{10}ds^2$ | $({}^6I_{17/2})^*$ | (7.7) |
| $f^{11}ds$ | $({}^6L_{21/2}^0)$ | (17.6) | $f^{11}sp$ | $({}^6K_{19/2})$ | (15.4) |
| $f^{10}s^2p$ | $({}^6K_{17/2}^0)^*$ | (18.1) | $f^{10}d^2s$ | $({}^8M_{25/2})$ | (18.8) |
| $f^{10}dsp$ | $({}^8M_{25/2}^0)$ | (22.9) | $f^{11}dp$ | $({}^6M_{23/2})$ | (35.) ± 2 |
| $f^{10}d^2p$ | $({}^8N_{27/2}^0)$ | (39.) ± 3 | $f^{10}sp^2$ | $({}^8K_{21/2})$ | (42.) ± 2 |
| $f^{11}p^2$ | $({}^6K_{19/2}^0)$ | (40.) | $f^{10}d^3$ | $({}^8M_{25/2})$ | (45.) ± 3 |
| $f^{11}d^2$ | $({}^6M_{23/2}^0)$ | (45.) ± 5 | | | |

Table XII. Er I, 10^3cm^{-1} (32, 13, 41, 43, 45)

| Odd Terms | | | Even Terms | | |
|------------------------------------|----------------|-------------|--------------|--------------|------------|
| $f^{11}ds^2$, $^4I_{15/2}d_{3/2}$ | $^5L_6^0$ * | 7.177 | $f^{12}s^2$ | 3H_6 | 0.000 |
| $f^{12}sp$, $^3H_6^3P_0$ | $^5I_6^0$ * | 16.321 | $f^{11}s^2p$ | $(^5K_7)$ * | 16.465 |
| $f^{11}d^2s$ | $(^7M_{12}^0)$ | (20.0) | $f^{12}ds$ | $(^5K_5)$ * | (19.0) |
| $f^{12}dp$ | $(^5L_{10}^0)$ | (37.) ± 1 | $f^{11}dsp$ | $(^7M_{12})$ | (22.9) |
| $f^{11}sp^2$ | $(^7K_{10}^0)$ | (41.) ± 2. | $f^{12}p^2$ | $(^5I_8)$ | (41.) |
| $f^{11}d^3$ | $(^7M_{12}^0)$ | (49.) ± 4 | $f^{11}d^2p$ | $(^7N_{13})$ | (41.) ± 4 |
| | | | $f^{12}d^2$ | $(^5L_{10})$ | (49.) ± 6 |

Table XIII. Tm^I , $10^3 cm^{-1}$ (9, 44, 45, 46, 47)

| Odd Terms | | | Even Terms | | |
|--|--------------------|-------------|-----------------------------------|------------------|------------|
| coupling | | | | | |
| $f^{13}s^2$ | ${}^2F_{7/2}^0$ | 0.000 | $f^{12}ds^2, {}^3H_6 \frac{3}{2}$ | ${}^4I_{9/2}$ | * 13.119 |
| $f^{13}ds, \left[\frac{7}{2}, {}^3\left(\frac{3}{2}\right) \right]$ | ${}^4G_{5/2}^0$ | ** 20.406 | $f^{13}sp, \frac{7}{2} {}^3P_0$ | ${}^4G_{7/2}$ | * 16.742 |
| $f^{12}s^2p, {}^3H_6 \frac{1}{2}$ | ${}^4I_{11/2}^0$ | * 22.468 | $f^{12}d^2s$ | $({}^6L_{7/2})$ | * (27.6) |
| $f^{12}dsp, {}^3H_6 {}^4F_{3/2}$ | ${}^6K_{9/2}^0$ | * 29.308 | $f^{14}s$ | $({}^2S_{1/2})$ | (30.) ± 10 |
| $f^{13}p^2, \frac{7}{2} {}^3P_0$ | ${}^4G_{7/2}^0$ | * 41.841 | $f^{13}dp, \frac{7}{2} {}^3F_2$ | $({}^4F_{3/2})$ | * 38.3 |
| $f^{12}d^2p$ | $({}^6M_{23/2}^0)$ | (49.) ± 5 | $f^{12}sp^2$ | $({}^6I_{17/2})$ | (47.) ± 2 |
| $f^{13}d^2$ | $({}^4G_{5/2}^0)$ | * (53.) ± 7 | $f^{12}d^3$ | $({}^6L_{21/2})$ | (60.) ± 5 |

Table XIV. Yb I, 10^3cm^{-1} (1, 4, 19)

| Odd Terms | | | Even Terms | | |
|--------------|-------------|----------------|--------------|-------------|----------------|
| $f^{14}sp$ | $^3P_0^0$ | 17.288 | $f^{14}s^2$ | 1S_0 | 0.000 |
| $f^{13}ds^2$ | $^3F_2^0 *$ | 23.188 | $f^{14}ds$ | 3D_1 | 24.489 |
| $f^{13}d^2s$ | $(^5I_8^0)$ | (40.) | $f^{13}s^2p$ | $(^3G_3) *$ | (30.) |
| $f^{14}dp$ | $(^3F_2^0)$ | (42.) ± 2 | $f^{13}dsp$ | $(^5I_8)$ | (40.0) |
| $f^{13}sp^2$ | $(^5G_6^0)$ | (57.) ± 2 | $f^{14}p^2$ | $(^3P_0)$ | (43.) |
| $f^{13}d^3$ | $(^5I_8^0)$ | (77.) ± 6 | $f^{14}d^2$ | $(^3F_2)$ | (57.) ± 8 |
| | | | $f^{13}d^2p$ | $(^5K_9)$ | (62.) ± 6 |

Table XV. Lu I, 10^3cm^{-1}

| Odd Terms | | | Even Terms | | |
|--------------|-----------------|----------------|--------------|---------------|----------------|
| $f^{14}s^2p$ | $^2P^0_{1/2}$ | 4.136 | $f^{14}ds^2$ | $^2D_{3/2}$ | 0.000 |
| $f^{14}dsp$ | $^4F^0_{3/2}$ | 17.427 | $f^{14}d^2s$ | $^4F_{3/2}$ | 18.851 |
| $f^{14}d^2p$ | $(^4G^0_{5/2})$ | (41.) \pm 7 | $f^{14}sp^2$ | $^4P_{1/2}$ | 32.986 |
| | | | $f^{14}d^3$ | $(^4F_{3/2})$ | (61.) \pm 7 |

Table XVIII. Pa I, 10^3cm^{-1} (6.4, 11)

| Odd Terms | | | Even Terms | | |
|-----------|--------------------|------------|------------|------------------|------------|
| fd^2s^2 | ${}^4H_{7/2}^0$ * | 1.978 | f^2ds^2 | ${}^4K_{11/2}$ | 0.000 |
| fd^3s | $({}^6I_{7/2}^0)$ | (7.) | f^2d^2s | $({}^6L_{11/2})$ | 7.000 |
| f^3s^2 | ${}^4I_{9/2}^0$ | 11.445 | fds^2p | $({}^4I_{9/2})$ | (14.) |
| f^2s^2p | ${}^4I_{9/2}^0$ | 13.019 | fd^2sp | $({}^6K_{9/2})$ | (16.) |
| f^2dsp | ${}^6L_{11/2}^0$ | 14.393 | f^2d^3 | $({}^6L_{11/2})$ | (18.) ± 3 |
| f^3ds | $({}^6L_{11/2}^0)$ | (22.5) | d^4s | $({}^6D_{1/2})$ | (19.5) ± 4 |
| d^3sp | $({}^6G_{3/2}^0)$ | (24.) ± 5 | fd^3p | $({}^6K_{9/2})$ | (22.) ± 1 |
| f^2d^2p | $({}^6M_{13/2}^0)$ | (30.5) | f^3sp | $({}^6K_{9/2})$ | (25.6) |
| f^3d^2 | $({}^6M_{13/2}^0)$ | (39.) ± 2 | f^3dp | $({}^6M_{13/2})$ | (37.5) |
| f^3p^2 | $({}^6K_{9/2}^0)$ | (44.5) ± 1 | | | |

Table XVI. Ac I, 10^3cm^{-1} (13)

| Odd Terms | | | Even Terms | | |
|-----------|-------------------|---------------|------------|---------------|----------------|
| s^2p | $(^2P_{1/2}^0)$ | $(9.5) \pm 1$ | ds^2 | $^2D_{3/2}$ | 0.000 |
| dsp | $^4F_{3/2}^0$ | 13.713 | d^2s | $^4F_{3/2}$ | 9.217 |
| fs^2 | $(^2F_{5/2}^0)$ | $(30.) \pm 5$ | d^3 | $(^4F_{3/2})$ | $(20.) \pm 3$ |
| d^2p | $^4G_{5/2}^0$ | 31.495 | fsp | $(^4G_{5/2})$ | $(43.) \pm 5$ |
| fds | $(^2G_{7/2}^0) *$ | $(42.) \pm 5$ | fdp | $(^4I_{9/2})$ | $(57.) \pm 5$ |
| fd^2 | $(^4I_{3/2}^0)$ | $(59.) \pm 7$ | f^2s | $(^4H_{7/2})$ | $(60.) \pm 10$ |
| fp^2 | $(^4G_{5/2}^0)$ | $(61.) \pm 5$ | | | |

Table XVII. $\text{Th}^{\text{I}}, 10^3 \text{cm}^{-1}$ (52,53,54)

| Odd Terms | | | Even Terms | | |
|-----------------------|--------------------|----------------|------------------------|------------------|----------------|
| fds^2 | $^3\text{H}_4^0$ | 7.795 | d^2s^2 | $^3\text{F}_2$ | 0.000 |
| ds^2p | $^3\text{F}_2^0$ | 10.783 | d^3s | $^5\text{F}_1$ | 5.563 |
| d^2sp | $^5\text{G}_2^0$ | 14.465 | fs^2p | $^3\text{F}_3$ * | 18.432 |
| fd^2s | $^5\text{H}_3^0$ * | 15.619 | dsp^2 | $(^5\text{F}_1)$ | $(20) \pm 10$ |
| d^3p | $^5\text{G}_2^0$ | 21.738 | fdsp | $^5\text{I}_4$ | 22.098 |
| fsp^2 | $(^5\text{G}_2^0)$ | $(23.) \pm 6$ | f^2s^2 | $(^3\text{H}_4)$ | $(28.) \pm 3$ |
| fd^3 | $(^5\text{I}_4^0)$ | $(27) \pm 3$ | fd^2p | $(^5\text{K}_5)$ | $(39.)$ |
| f^2sp | $(^5\text{I}_4^0)$ | $(42.) \pm 3$ | f^2ds | $(^5\text{K}_5)$ | $(39.) \pm 3$ |
| f^2dp | $(^5\text{L}_6^0)$ | $(55.) \pm 3$ | f^2d^2 | $(^5\text{L}_6)$ | $(57) \pm 4$ |
| | | | f^2p^2 | $(^5\text{I}_4)$ | $(60) \pm 5$ |

Table XIX. $U^I, 10^3 \text{cm}^{-1}$

| Odd Terms | | | Even Terms | | |
|--------------|-------------|----------------|---------------|-----------|----------------|
| $f^3 ds^2$ | $^5L_6^0$ | 0.000 | $f^4 s^2$ | 5I_4 | (6.) |
| $f^3 d^2 s$ | $^7M_6^0$ | 6.249 | $f^2 d^2 s^2$ | 5L_6 | 11.503 |
| $f^3 d^3$ | $(^7M_6^0)$ | (17.) \pm 4 | $f^3 s^2 p$ | 5K_5 | 13.463 |
| $f^4 sp$ | $(^7K_4^0)$ | (21.) \pm 1 | $f^3 dsp$ | 7M_6 | 14.644 |
| $fd^4 s$ | $(^7H_2^0)$ | (22.) \pm 5 | $f^2 d^3 s$ | 7L_5 | 15.721 |
| $f^2 ds^2 p$ | $(^5L_6^0)$ | (24.) \pm 1 | $f^4 ds$ | $(^7L_5)$ | (17.5) \pm 1 |
| $f^2 d^2 sp$ | $(^7M_6^0)$ | (25.) \pm 1 | $d^5 s$ | $(^7S_3)$ | (28.) \pm 8 |
| $f^4 dp$ | $(^7M_6^0)$ | (31.) \pm 2 | $f^3 d^2 p$ | $(^7N_7)$ | (30.5) |
| $f^2 d^3 p$ | $(^7M_6^0)$ | (31.5) \pm 2 | $f^4 d^2$ | $(^7M_6)$ | (33.) \pm 3 |
| | | | $f^4 p^2$ | $(^7K_4)$ | (40.) \pm 2 |

Table XX. Np I, 10^3cm^{-1}

| Odd Terms | | | Even Terms | | |
|-------------|------------------|------------|------------|----------------|------------|
| f^5s^2 | $(^6H_{5/2}^O)$ | (0.0) ± 1 | f^4ds^2 | $^6L_{11/2}$ | 0.000 |
| f^5ds | $(^8K_{7/2}^O)$ | (12.) ± 2 | f^4d^2s | $(^8M_{11/2})$ | (7.5) |
| f^4s^2p | $(^6K_{9/2}^O)$ | (12.5) | f^5sp | $(^8I_{5/2})$ | (15.) ± 1 |
| f^4dsp | $(^8M_{11/2}^O)$ | (14.6) | f^4d^3 | $(^8M_{11/2})$ | (16.) ± 4 |
| $f^3d^2s^2$ | $(^6M_{13/2}^O)$ | (19.5) ± 2 | f^5dp | $(^8L_{9/2})$ | (24.5) ± 2 |
| f^3d^3s | $(^8M_{11/2}^O)$ | (24.5) ± 2 | f^3ds^2p | $^6M_{13/2}$ | (31.) ± 2 |
| f^5d^2 | $(^8L_{9/2}^O)$ | (26.) ± 4 | f^3d^2sp | $(^8N_{13/2})$ | (33.5) ± 1 |
| f^4d^2p | $(^8N_{13/2}^O)$ | (30.) ± 1 | f^2d^4s | $(^8K_{7/2})$ | (35.) ± 3 |
| f^5p^2 | $(^8I_{5/2}^O)$ | (35.) ± 2 | f^3d^3p | $(^8N_{13/2})$ | (41.) ± 3 |
| f^2d^3sp | $(^8M_{11/2}^O)$ | (44.) ± 6 | | | |

Table XXI. Pu^{I} , 10^3cm^{-1} (11180, 59)

| Odd Terms | | | Even Terms | | |
|--------------|---------------|----------------|---------------|-------------|----------------|
| $f^5 ds^2$ | ${}^7K_4^0$ | 6.314 | $f^6 s^2$ | 7F_0 | 0.000 |
| $f^5 d^2 s$ | ${}^9L_4^0$ | 14.912 | $f^6 ds$ | 9H_1 | 13.528 |
| $f^6 sp$ | ${}^9G_0^0$ | 15.449 | $f^5 s^2 p$ | ${}^7H_2^*$ | 17.776 |
| $f^5 d^3$ | $({}^9L_4^0)$ | (23.) \pm 5 | $f^5 dsp$ | 9L_4 | 20.828 |
| $f^6 dp$ | ${}^9I_2^0$ | 23.896 | $f^6 d^2$ | $({}^9I_2)$ | (31.) \pm 5 |
| $f^5 sp^2$ | $({}^9I_2^0)$ | (30.) \pm 5 | $f^6 p^2$ | $({}^9G_0)$ | (36.) \pm 2 |
| $f^4 ds^2 p$ | $({}^7M_6^0)$ | (47.) \pm 2 | $f^4 d^2 s^2$ | 7M_6 | 36.051 |
| $f^4 d^2 sp$ | $({}^9N_6^0)$ | (51.) \pm 1 | $f^5 d^2 p$ | $({}^9M_5)$ | (38.) \pm 2 |
| $f^4 d^3 p$ | $({}^9N_6^0)$ | (58.) \pm 3 | $f^4 d^3 s$ | $({}^9M_5)$ | (42.5) \pm 1 |

Table XXII. Am I, 10^3 cm^{-1}

| Odd Terms | | | Even Terms | | |
|---------------|-----------------------|----------------|-------------|---------------------|----------------|
| $f^7 s^2$ | ${}^8 S_{7/2}^0$ | 0.000 | $f^6 ds^2$ | $({}^8 H_{3/2})$ | $(15.5) \pm 3$ |
| $f^7 ds$ | $({}^{10} D_{5/2}^0)$ | $(14.5) \pm 1$ | $f^7 sp$ | $({}^{10} P_{7/2})$ | (15.8) |
| $f^6 s^2 p$ | $({}^8 G_{1/2}^0)$ | $(26.) \pm 3$ | $f^6 d^2 s$ | $({}^{10} I_{3/2})$ | $(25.) \pm 3$ |
| $f^6 dsp$ | $({}^{10} I_{3/2}^0)$ | $(31.) \pm 3$ | $f^7 dp$ | $({}^{10} F_{3/2})$ | $(28.) \pm 3$ |
| $f^7 d^2$ | $({}^{10} F_{3/2}^0)$ | $(36.) \pm 6$ | $f^6 d^3$ | $({}^{10} I_{3/2})$ | $(35.) \pm 6$ |
| $f^7 p^2$ | $({}^{10} P_{7/2}^0)$ | $(37.) \pm 3$ | | | |
| $f^6 d^2 p$ | $({}^{10} K_{5/2}^0)$ | $(50.) \pm 3$ | | | |
| $f^5 d^2 s^2$ | $({}^8 L_{9/2}^0)$ | $(56.) \pm 5$ | | | |

Table XXIII. Cm I, 10^3cm^{-1} (39)

| Odd Terms | | | Even Terms | | |
|-------------|------------------|----------------|-------------|----------------|----------------|
| $f^7 ds^2$ | ${}^9D_2^0$ | 0.000 | $f^8 s^2$ | 7F_6 | 1.214 |
| $f^7 d^2 s$ | ${}^{11}F_2^0$ | 10.145 | $f^7 s^2 p$ | 9P_3 | 9.263 |
| $f^8 sp$ | $({}^9F_6^0) *$ | (17.7) | $f^7 dsp$ | ${}^{11}F_2$ | 15.252 |
| $f^7 d^3$ | $({}^{11}F_2^0)$ | (21.) \pm 6 | $f^8 ds$ | $({}^9H_9)$ | (18.) |
| $f^8 dp$ | $({}^9I_{10}^0)$ | (32.) \pm 4 | $f^7 d^2 p$ | $({}^{11}G_1)$ | (36.) \pm 4 |
| | | | $f^8 p^2$ | $({}^9G_8)$ | (39.) \pm 3 |
| | | | $f^8 d^2$ | $({}^9I_{10})$ | (41.) \pm 7 |

Table XXIV. Bk I, 10^3cm^{-1} (27)

| Odd Terms | | | Even Terms | | |
|-------------|------------------------------|------------|-------------|------------------------------|------------|
| $f^9 s^2$ | ${}^6\text{H}_{15/2}^0$ | 0.000 | $f^8 ds^2$ | ${}^8\text{G}_{11/2}$ * | 7.4 |
| $f^8 s^2 p$ | $({}^8\text{G}_{11/2}^0)$ * | (14.7) | $f^9 sp$ | $({}^8\text{I}_{19/2})$ | (17.2) |
| $f^9 ds$ | $({}^8\text{K}_{21/2}^0)$ | (19.) | $f^8 d^2 s$ | $({}^{10}\text{G}_{15/2})$ * | (20.) |
| $f^8 dsp$ | $({}^{10}\text{I}_{21/2}^0)$ | (23.) | $f^9 dp$ | $({}^8\text{L}_{23/2})$ | (34.) ± 5 |
| $f^9 p^2$ | $({}^8\text{I}_{19/2}^0)$ | (39.) ± 3 | $f^8 d^3$ | $({}^{10}\text{I}_{21/2})$ | (35.) ± 7 |
| $f^9 d^2$ | $({}^8\text{L}_{23/2}^0)$ | (45.) ± 8 | | | |
| $f^8 d^2 p$ | $({}^{10}\text{K}_{21/2}^0)$ | (46.) ± 5 | | | |

Table XXV. Cf I, 10^3cm^{-1} (10)

| Odd Terms | | | Even Terms | | |
|-------------|----------------|------------|--------------|--------------|------------|
| $f^9 ds^2$ | $(^7H_8^0) *$ | (12.) | $f^{10} s^2$ | 5I_8 | 0.000 |
| $f^{10} sp$ | $(^7I_9^0) *$ | (19.) | $f^9 s^2 p$ | $(^7I_9)$ | (17.) |
| $f^9 d^2 s$ | $(^9L_{12}^0)$ | (26.5) | $f^{10} ds$ | $(^7L_{11})$ | (21.) |
| $f^{10} dp$ | $(^7M_{12}^0)$ | (43.) ± 6 | $f^9 dsp$ | $(^9L_{12})$ | (28.) |
| $f^9 d^3$ | $(^9L_{12}^0)$ | (46.) ± 8 | $f^{10} p^2$ | $(^7K_{10})$ | (40.) ± 4 |
| | | | $f^{10} d^2$ | $(^7M_{12})$ | (50.) ± 9 |
| | | | $f^9 d^2 p$ | $(^9M_{13})$ | (53.) ± 5 |

Table XXVI. Es I, 10^5cm^{-1}

| Odd Terms | | | Even Terms | | |
|--------------|------------------|-----------------|--------------|------------------|------------------|
| $f^{11}s^2$ | ${}^4I_{15/2}^0$ | 0.0 | $f^{10}ds^2$ | $({}^6I_{17/2})$ | $* (13.) \pm 2$ |
| $f^{10}s^2p$ | $({}^6K_{19/2})$ | $(16.) \pm 2$ | $f^{11}sp$ | $({}^6K_{19/2})$ | $(19.)$ |
| $f^{11}ds$ | $({}^6L_{21/2})$ | $(23.)$ | $f^{10}d^2s$ | $({}^8M_{25/2})$ | $(30.) \pm 2$ |
| $f^{10}dsp$ | $({}^8M_{25/2})$ | $(30.) \pm 2$ | $f^{11}dp$ | $({}^6M_{23/2})$ | $(40.) \pm 7$ |
| $f^{11}p^2$ | $({}^6K_{19/2})$ | $(41.) \pm 4$ | $f^{10}d^3$ | $({}^8M_{25/2})$ | $(53.) \pm 9$ |
| $f^{11}d^2$ | $({}^6M_{23/2})$ | $(54.) \pm 10$ | | | |
| $f^{10}d^2p$ | $({}^8N_{27/2})$ | $(57.) \pm 8$ | | | |

Table XXVII. $\text{Fm}^{\text{I}}, 10^3 \text{cm}^{-1}$

| Odd Terms | | | Even Terms | | |
|------------------------------|---------------------|-----------------|------------------------------|---------------------|-----------------|
| $f^{11} \text{ds}^2$ | $(^5\text{L}_6)^*$ | $(15.) \pm 3$ | $f^{12} \text{s}^2$ | $(^3\text{H}_6)$ | 0.0 |
| $f^{12} \text{sp}$ | $(^5\text{I}_6)^*$ | $(19.5) \pm 2$ | $f^{11} \text{s}^2 \text{p}$ | $(^5\text{K}_5)^*$ | $(16.) \pm 3$ |
| $f^{11} \text{d}^2 \text{s}$ | $(^7\text{M}_{12})$ | $(34.) \pm 3$ | $f^{12} \text{ds}$ | $(^5\text{K}_5)^*$ | $(26.) \pm 3$ |
| $f^{12} \text{dp}$ | $(^5\text{L}_{10})$ | $(43.) \pm 8$ | $f^{11} \text{dsp}$ | $(^7\text{M}_{12})$ | $(32.5) \pm 3$ |
| $f^{11} \text{d}^3$ | $(^7\text{M}_{12})$ | $(61.) \pm 11$ | $f^{12} \text{p}^2$ | $(^5\text{I}_8)$ | $(42.) \pm 5$ |
| | | | $f^{12} \text{d}^2$ | $(^5\text{L}_{10})$ | $(58.) \pm 11$ |
| | | | $f^{11} \text{d}^2 \text{p}$ | $(^7\text{N}_{13})$ | $(61.) \pm 9$ |

Table XXVIII. Md I, 10^3cm^{-1}

| Odd Terms | | | Even Terms | | |
|--------------|--------------------|-----------------|--------------|-----------------|-----------------|
| $f^{13}s^2$ | $(^2F_{7/2}^0)$ | 0.0 | $f^{13}sp$ | $(^4G_{7/2})^*$ | (20.) \pm 2 |
| $f^{12}s^2p$ | $(^4I_{11/2}^0)^*$ | (23.) \pm 5 | $f^{12}ds^2$ | $(^4K_9/2)^*$ | (25.) \pm 4 |
| $f^{13}ds$ | $(^4G_{5/2}^0)^*$ | (28.) \pm 3 | $f^{12}d^2s$ | $(^6L_{7/2})^*$ | (46.) \pm 5 |
| $f^{12}dsp$ | $(^6K_{9/2}^0)^*$ | (43.) \pm 5 | $f^{13}dp$ | $(^4F_{3/2})^*$ | (46.) \pm 9 |
| $f^{13}p^2$ | $(^4G_{7/2}^0)^*$ | (43.) \pm 5 | $f^{12}d^3$ | $(^6L_{21/2})$ | (79.) \pm 13 |
| $f^{13}d^2$ | $(^4I_{15/2}^0)$ | (62.) \pm 12 | | | |
| $f^{12}d^2p$ | $(^6M_{23/2}^0)$ | (74) \pm 12 | | | |

Table XXIX. No I, 10^3cm^{-1}

| Odd Terms | | | Even Terms | | |
|------------------------------|----------------------|-----------------|------------------------------|--------------------|-----------------|
| $f^{14} \text{sp}$ | $(^3\text{P}_0^0)$ | (21.) \pm 2 | $f^{14} \text{s}^2$ | $(^1\text{S}_0)$ | 0.000 |
| $f^{13} \text{ds}^2$ | $(^3\text{F}_2^0) *$ | (32.) \pm 6 | $f^{13} \text{s}^2 \text{p}$ | $(^3\text{G}_3) *$ | (27.) \pm 6 |
| $f^{14} \text{dp}$ | $(^3\text{F}_2^0)$ | (49.) \pm 10 | $f^{14} \text{ds}$ | $(^3\text{D}_1)$ | (30.) \pm 4 |
| $f^{13} \text{d}^2 \text{s}$ | $(^5\text{I}_8^0)$ | (56.) \pm 6 | $f^{14} \text{p}^2$ | $(^3\text{P}_0)$ | (44.) \pm 6 |
| $f^{13} \text{d}^3$ | $(^5\text{I}_8^0)$ | (94.) \pm 17 | $f^{13} \text{dsp}$ | $(^5\text{I}_8)$ | (51.) \pm 6 |
| | | | $f^{14} \text{d}^2$ | $(^3\text{F}_2)$ | (66.) \pm 13 |
| | | | $f^{13} \text{d}^2 \text{p}$ | $(^5\text{K}_9)$ | (85.) \pm 15 |

Table XXX. Lr I, 10^3cm^{-1}

| Odd Terms | | | Even Terms | | |
|--------------|-----------------|-----------|--------------|---------------|-----------|
| $f^{14}s^2p$ | $(^2P_{1/2}^0)$ | (0.0) | $f^{14}ds^2$ | $(^2D_{3/2})$ | (8.0)± 2 |
| $f^{14}dsp$ | $(^4F_{3/2}^0)$ | (27.5)± 2 | $f^{14}sp^2$ | $(^4P_{1/2})$ | (29.)±10 |
| $f^{14}d^2p$ | $(^4G_{5/2}^0)$ | (64.)±11 | $f^{14}d^2s$ | $(^4F_{3/2})$ | (34.)± 2 |
| | | | $f^{14}d^3$ | $(^4F_{3/2})$ | (78.)±13 |

Table XXXI. Assignment of Ia I Odd Levels to the fds Configuration

| <u>Previous Assignment</u> | <u>New Assignment</u> | <u>J</u> | <u>Energy cm⁻¹</u> | <u>Interval</u> | <u>Obs. g</u> | <u>LS g</u> |
|--|-----------------------------------|----------|-----------------------------------|-----------------|-------------------|-----------------|
| 1 ^o | fds ² G ^o | 7/2 | 23 221.16 | | 1.078 | 0.889 |
| 2 ^o | | 9/2 | 23 466.85 | 245.7 | 1.12 | 1.11 |
| fds w ² F ^o | fds w ² F ^o | 5/2 | 23 875.00 | | 0.957 | 0.857 |
| | | 7/2 | 24 409.70 | 534.7 | 1.17 | 1.143 |
| 4 ^o | fds ² D ^o | 3/2 | 24 173.86 | | 0.72 | 0.80 |
| 3 ^o | | 5/2 | 23 549.42 | -624.4 | 1.16 | 1.20 |
| 5 ^o | fds ² P ^o | 3/2 | 27 749.05 | | | |
| d ² f y ⁴ G ^o | fds y ⁴ G ^o | 5/2 | 27 022.60 | | 0.571 | 0.571 |
| | | 7/2 | 27 455.34 | 432.7 | 0.976 | 0.984 |
| | | 9/2 | 28 089.18 | 633.8 | 1.159 | 1.172 |
| | | 11/2 | 28 743.21 | 654.0 | 1.28 | 1.273 |
| d ² f x ⁴ F ^o | fds x ⁴ F ^o | 3/2 | 24 910.39 | | 0.724 | 0.400 |
| | | 5/2 | 24 984.33 | 73.9 | 1.063 | 1.029 |
| | | 7/2 | 25 380.33 | 396.0 | 1.228 | 1.238 |
| | | 9/2 | 25 997.27 | 616.9 | 1.319 | 1.333 |
| d ² f w ⁴ D ^o | fds w ⁴ D ^o | 1/2 | 28 893.47 | | 0.00 | 0.000 |
| | | 3/2 | 29 199.53 | 306.1 | 1.15 | 1.200 |
| | | 5/2 | 29 502.17 | 302.6 | 1.263 | 1.371 |
| | | 7/2 | 29 894.91 | 392.7 | 1.352 | 1.429 |
| 8 ^o | fds ⁴ P ^o | 3/2 | 30 417.47 | | 1.533 | 1.733 |
| 9 ^o | | 5/2 | 30 896.88 | 479.41 | 1.424 | 1.600 |

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(Table XXXI continued)

| <u>Previous Assignment</u> | <u>New Assignment</u> | <u>J</u> | <u>Energy cm⁻¹</u> | <u>Interval</u> | <u>Obs. g</u> | <u>IS g</u> |
|--|-----------------------------------|----------|-----------------------------------|-----------------|-------------------|-----------------|
| d ² f y ² H ⁰ (See note below table) | fds y ² H ⁰ | 9/2 | 32 415.73 | 102.39 | 0.92 | 0.909 |
| | | 11/2 | 32 518.12 | | 1.11 | 1.091 |
| 4f t ² F ⁰ | fds t ² F ⁰ | 5/2 | 27 699.38 | 873.7 | 0.87 | 0.857 |
| | | 7/2 | 28 543.10 | | 1.00 | 1.143 |
| 4f v ² D ⁰ | fds v ² D ⁰ | 3/2 | 28 971.82 | 803.75 | 0.71 | 0.80 |
| | | 5/2 | 29 775.57 | | 1.253 | 1.20 |
| 6 ⁰ | fds ² P ⁰ | 1/2 | 29 564.92 | 371.81 | | |
| 7 ⁰ | | 3/2 | 29 936.73 | | 1.492 | 1.333 |

Note: Stein¹⁴ reports correction of energy of y ²H_{9/2}⁰ level from 32 410.76 to 32 415.73 and Giacchetti¹⁷ reports that he cannot confirm the 32 518 level.

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TECHNICAL INFORMATION DIVISION
LAWRENCE RADIATION LABORATORY
UNIVERSITY OF CALIFORNIA
BERKELEY, CALIFORNIA 94720