Transition Probabilities for Neutral Cerium from Boltzmann Analysis of Fourier Transform Spectra[1]

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Abstract. We have measured radiative transition probabilities for 5029 emission lines of neutral cerium within the wavelength range 417 nm to 1110 nm. These results are obtained from Boltzmann analysis of two high resolution Fourier transform emission spectra used in previous studies of cerium, downloaded from the digital archives of the National Solar Observatory at Kitt Peak. The transition probabilities upon which the Boltzmann analyses are based are from the extensive set published by Lawler et al. (J. Phys. B: At. Mol. Opt. Phys. **43**, 085701 (2010)). Comparisons of branching ratios and transition probabilities for lines common to the two spectra provide useful tests for possible systematic effects. Estimated 1σ uncertainties for our transition probability results range from 10% to 18%. Transition probabilities for only 4% of these lines have been previously measured.

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Boltzmann Analysis Method. For an excited atomic state U in an optically thin discharge, the rate of photon emission I_{UL} to a lower state L from an observed volume of the discharge is given by

$$I_{UL} = N_U \cdot g_U \cdot A_{UL}$$

where N_U is the equilibrium population of the upper level, g_U is its degeneracy, and A_{UL} is the absolute transition probability.

Therefore, a plot of (I_{UL} / g_U A_{UL}) vs. upper level energy E_U for emission lines whose transition probabilities are known ("reference lines") reveals how the equilibrium populations vary with excited state energy. If these populations show an exponential decrease over some range of excited state energies, then fitting the data to a Boltzmann distribution becomes the basis for determining transition probabilities for lines from *other* levels in that range using

$$A_{UL} = \frac{I_{UL}}{\left(\beta \cdot g_U \cdot e^{\frac{-E_U}{k_B \cdot T}}\right)} \qquad \text{(Eq. 1)}$$

where I_{UL} is a radiometrically-calibrated intensity in units proportional to photons per second and β and T are the Boltzmann fit parameters.

Ce I Reference Data Set. J. E. Lawler *et al.* [2] measured branching fractions for 136 levels of Ce I, combining these with previously-published lifetimes [3] to yield 2874 absolute transition probabilities.

We measured radiometrically-calibrated intensities for as many of these reference lines as possible in two Ce spectra obtained from the archives of the 1 m FTS at Kitt Peak, one which used an electrodeless discharge lamp (EDL) source and the other a low-current sealed hollow cathode lamp (HCL). Both spectra are among the set of 14 spectra analyzed by Lawler *et al.* in their branching fraction study. Figure 1 at right is a screen shot of the interactive computer program used to search the spectra and integrate line profiles.

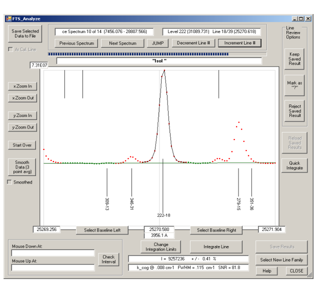
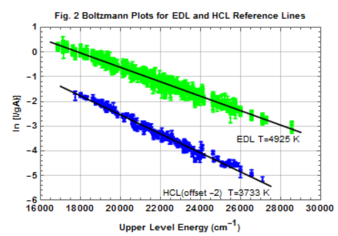


Figure 1

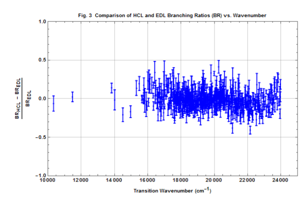
Boltzmann Plots. Figure 2 shows plots of ln(I_{UL}/$g_U A_{UL}$) vs. E_U for EDL and HCL reference lines (2444 lines from 135 upper levels and 348 lines from 129 upper levels, respectively). Both sets of data exhibit linear dependence, yielding effective temperatures of 4925 $\pm$ 14 K (EDL) and 3733 $\pm$ 33 (HCL) for levels in the energy range explored. EDL lines above a certain intensity threshold showed moderate self-absorption and these were excluded from the Boltzmann analysis. This intensity threshold was used as an upper limit for new lines to include in our study.



New Ce I transition probabilities. We carried out intensity measurements and determined transition probabilities using Equation 1 for 5,029 lines not in the reference data set from 408 upper levels in the EDL spectrum and for 906 lines from 233 levels in the HCL spectrum. All of the observed HCL lines are common to both spectra, generally corresponding to the stronger lines of a given level. Due to the lower signal-to-noise ratio of the HCL lines, averaging transition probability results common to the two spectra did not significantly improve the accuracy in those cases. However, the HCL lines were very useful for carrying out self-consistency checks (see next column). A downloadable table of our results listing transition probabilities, *gA* values and log(gf) values for 5029 lines of Ce I is available with the online publication of our paper [1]. 1σ uncertainties for these results range from approximately 10% to 18%, reflecting the random uncertainties for each line from intensity measurements and the Boltzmann fit parameters and an estimated $\pm$10% contribution for deviation of EDL source populations from the Boltzmann model, combined in quadrature.

References:
[1] D. E. Nitz, J. J. Curry, M. Buuck, A. DeMann, N. Mitchell and W. Shull, *J. Phys. B: Atomic, Molecular & Optical Physics* **51**, 045007 (2018).
[2] J. E. Lawler, J. Chisholm, D. E. Nitz, M. P. Wood, J. Sobeck and E. A. Den Hartog, *J. Phys. B: Atomic, Molecular & Optical Physics* **43**, 085701 (2010).
[3] E. A. Den Hartog, K. P. Buettner, and J. E. Lawler, *J. Phys. B: At. Mol. Opt. Phys.* **42** 085006 (2009).

Cross Checks. Data for the new lines common to the two independently-analyzed spectra can be examined to look for evidence of systematic effects associated with the radiometric calibrations, self-absorption of strong lines, and the Boltzmann Analysis assumptions. Figures 3 and 4 compare branch ratios vs. wavenumber and vs. comparison branch line strength for cases in which two or more lines for a given upper level were observed in both spectra. The agreement evident in the graphs, coupled with the knowledge that the HCL spectrum is optically thin [2], indicates that line intensities were reliably measured and that the results are free of self-absorption effects. Note that these results are based solely on intensity comparisons and do not involve the Boltzmann fits.



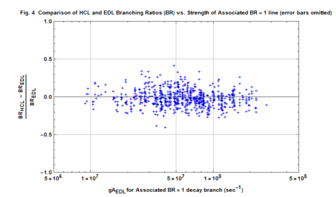
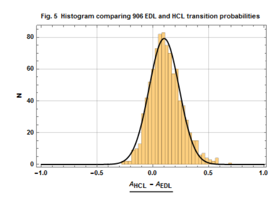


Figure 5 compares transition probabilities derived from the EDL and HCL Boltzmann analyses for the 906 lines common to the two data sets. The HCL transition probabilities are on average about 10% higher than the EDL results and the standard deviation of the distribution is 14%. We have found empirically that the 10% offset is consistent with the mutual uncertainties of the Boltzmann fits, which are dominated by the HCL uncertainties.



Conclusion. We have measured transition probabilities for 5029 lines of neutral cerium between 417 nm and 1110 nm from a Boltzmann analysis which includes comparisons of branching ratios and transition probabilities in two independently-analyzed high resolution Fourier Transform spectra. 4816 of these are first-time measurements. Our results are most useful for modeling applications where reasonably accurate transition probabilities are needed for large numbers of lines, as opposed to situations requiring highly accurate values for a small set of specific lines. A downloadable table of results is available with reference [1].