SPECTROSCOPIC DATA FOR THE $6s6p^3P_1$ LEVEL OF LU$^+$ FOR THE DETERMINATION OF THE SOLAR LUTETIUM ABUNDANCE

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Abstract. We report spectroscopic measurements on the $6s6p^3P_1$ level of Lu$^+$ at 28503.16 cm$^{-1}$. The radiative lifetime of this level was measured to be 37.4 ± 1.9 ns using time-resolved laser-induced fluorescence of a slow ion beam. Branching fractions were determined from Lu spectra recorded using the 1.0 m Fourier transform spectrometer at the National Solar Observatory. The log($g$/$f$) values determined by combining the radiative lifetime and branching fractions for the $\lambda$3507.39, $\lambda$5983.90, and $\lambda$6221.87 (air wavelengths) lines are $-1.16 \pm 0.03$, $-1.16 \pm 0.06$, and $-0.76 \pm 0.04$, respectively. The $\lambda$6221.87 line has been identified by Bord, Cowley, and Mirijanian (1997) as the best candidate for the determination of the solar lutetium abundance because it is only slightly blended in the solar spectrum. The present $\lambda$6221.87 transition probability measurement brings their solar lutetium abundance into good agreement with the CI chondrite abundance.

1. Introduction

The abundances of most nonvolatile chemical elements in the solar photosphere are in good agreement with those in CI chondrites (Grevesse, Noels, and Sauval, 1996, henceforth GNS). Lutetium is one of the few elements that deviates significantly from this pattern, with the apparent solar abundance exceeding the CI value by a factor of 4. Moore, Minnaert, and Houtgast (1966) used the line at $\lambda_{3397.062}$ in the solar spectrum, which they attributed solely to Lu II, for the determination of the solar Lu abundance. Bord, Cowley, and Mirijanian (1997, henceforth BCM) show that the $\lambda_{3397.062}$ line is in fact due primarily to NH absorption and is not suitable for a Lu abundance determination. They have identified an alternative, the weak Lu II line at $\lambda$6221.87, which is only slightly blended and measurable on the low noise Jungfraujoch spectra. The programs developed by Cowley (1996), based on LTE, were used by BCM to compute a synthetic solar spectrum. A model atmosphere was constructed using the temperature distribution from Holweger and Müller (1974). Using their theoretical calculation of log($g$/$f$) = −0.604 for the $\lambda$6221.87 line, BCM determine a solar lutetium abundance to be log(Lu$^+$) = −0.10 (on the scale log($H^+$) = 12.0) compared to the CI abundance of log(Lu$^+_{\text{CI}}$) = +0.13 ± 0.02 of GNS.

In the present study we report the radiative lifetime of the 28503.16 cm$^{-1}$ level and the transition probabilities of its three main branches. The transition probability of the $\lambda$6221.87 line is used by BCM to calculate a more accurate value for the solar Lu abundance of log(Lu$^+$) = +0.06, which now is in good agreement (within 0.07 dex) with the CI chondrite abundance. In addition we report the hyperfine A and B constants for the 28503.16 cm$^{-1}$ and 11796.24 cm levels of Lu$^+$. 

2. Radiative Lifetime Measurement

The radiative lifetime of the $6s6p \ ^3P_1$ level of Lu$^+$ was measured using time-resolved laser-induced fluorescence (LIF) on a slow atomic/ionic beam. This technique has many advantages which make it an accurate method for determining radiative lifetimes. The laser provides selective excitation, eliminating error due to cascade repopulation of the level of interest. The atomic beam is optically thin and virtually collision free, so that errors due to radiation trapping and collisional quenching are avoided. Uncertainties of 5% are routine for lifetime measurements using this method.

The apparatus used in this experiment is described in detail by O’Brian et al. (1991), and only a brief description will be given here. The atomic/ionic beam is produced using a hollow cathode discharge sputter source. The hollow cathode is lined with a lutetium foil, and is sealed at one end except for a 1 mm hole through which a weakly collimated beam of atoms and ions exits. The atomic beam is crossed orthogonally by a laser beam which is used to selectively excite the Lu$^+$ level of interest.

The laser beam is produced by a nitrogen laser pumped dye laser, which has a 3 ns pulse duration, 0.2 cm$^{-1}$ bandwidth and is tunable over the range 205 nm–720 nm with the use of frequency doubling crystals. The laser is tuned to either the $\lambda 3507.39$ or the $\lambda 6221.87$ transition of Lu$\ II$, populating the $6s6p \ ^3P_1$ fine-structure level at 28503.16 cm$^{-1}$. Fluorescence is collected in a direction mutually orthogonal to the laser and atomic/ionic beams by a pair of lenses comprising an $f/1$ system. These lenses focus the beam overlap region 1:1 onto the photocathode of a 1P28A photomultiplier tube (PMT).

The transitions used for laser excitation are correctly identified by first setting the laser wavelength to within $\pm 0.1$ nm of the line by angle tuning the grating of the dye laser, and then recording a LIF spectrum over a 0.5–1.0 nm range containing the transition. The wavelength separation between the transition to be studied and any nearby lines can be determined from this spectrum with great precision and accuracy and compared to the list of Lu$\ II$ wavelengths of Meggers, Corliss, and Scribner (1975). Further verification that the line is identified correctly comes from the excellent agreement between lifetime measurements made using two different excitation wavelengths.

The PMT signal is recorded using a Tektronix SCD 1000 transient waveform digitizer which has an analog bandwidth of 1 GHz and a sampling rate as high as 200 GHz. Digitization begins well after the laser pulse has terminated, eliminating the need to deconvolute the laser and fluorescence signals. A fluorescence decay is recorded by taking an average of 640 traces with the laser tuned on the transition and subtracting an average of 640 traces with the laser tuned off the transition. This decay is then least-squares fit to a single exponential and a lifetime extracted. Five fluorescence decay curves are recorded for each set of measurement conditions. The standard deviation for each set of five decays is typically 1–2%.