Photoionization by blackbody radiation

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We have measured the blackbody photoionization rate from the 17*d* state of sodium as a function of temperature from 90 to 300 K. The experimental rates, which vary by a factor greater than one hundred over this temperature range, are in good agreement with our theoretical values.

I. INTRODUCTION

Blackbody radiation can play an important role in experiments with Rydberg atoms. It is now recognized that blackbody radiation can affect measurements of natural lifetimes[1] and collisional rates,[2] and it can induce radiative transfer between bound levels.[3–5] Photoionization by blackbody radiation can be significant in measurements of all these processes. Furthermore, it can be an important source of noise in Rydberg atom experiments at room temperature.[2] Calculations that we carried out in connection with previous studies of radiative transfer among Rydberg states[6] indicated that blackbody photoionization, particularly its temperature dependence, should be measurable under controlled conditions. We present here the results of such a study.

The surprisingly high photoionization rate for Rydberg atoms in blackbody fields is due to the enormous radii of these atoms and their large dipole matrix elements to the continuum. At a temperature of 300 K, the photoionization rate from the sodium 17*d* state is 10^3 s^{-1}. This amounts to 3% of the total thermal radiative transfer rate from that level. At 1000 K, the photoionization rate is 10% of the total blackbody transfer rate and about one-half the spontaneous decay rate. The effect of blackbody photoionization is even larger for higher-lying levels: at 1000 K, the photoionization rate from the 32*d* state amounts to 25% of the total depopulation rate.

In addition to the desire to confirm our theoretical understanding of blackbody photoionization, this study is motivated by a number of experimental needs. Accurate knowledge of the photoionization rate can be an important aid for calibrating collisional ionization rates from highly excited states. In addition, measurements of these rates in a cooled apparatus provide a valuable check on the temperature of infrared radiation within the apparatus and on our ability to control extraneous sources of noise such as collisional ionization.

II. SYSTEMATICS OF BLACKBODY PHOTOIONIZATION

The photoionization rate in a thermal radiation field is[7]

$$R=\int_0^\infty \frac{c\sigma(\nu)\rho(\nu,T)}{4}d\nu\ , \tag{1}$$

where σ is the average cross section for photoionization and $\rho(\nu,T)$ is the Planck distribution for the electromagnetic energy density at temperature T and frequency ν. σ is given in atomic units by

$$\sigma=\frac{4\pi\alpha\omega}{3}\sum_{l'=l-1}^{l+1}\frac{l_{\max}}{2l'+1}\int_0^\infty P_{\epsilon l'}(r)rR_{nl'}r^2dr\ , \tag{2}$$

where $P_{\epsilon l}(r)$ is the energy-normalized continuum wave function, R_{nl} is the bound-state wave function, and $l_{\max}$ is the larger of l and l'.

We have developed a numerical method to calculate the bound-to-free matrix element in Eq. (2). It is based on the Coulomb approximation as used by Zimmerman *et al.*[8] for calculating bound-to-bound matrix elements. The boundary conditions on both wave functions are fixed at large r; the wave functions are integrated inward and truncated at a small core radius. In the continuum, the asymptotic phase of the wave function must approach that of

hydrogen, but with a phase shift $\pi\delta_l$, where δ_l is the quantum defect extrapolated from the bound states. To execute this numerically, a properly normalized WKB solution is fitted to a hydrogen wave function and then shifted in phase by $\pi\delta_l$. This function is used to start the numerical integration of the desired wave function. For the bound state, the condition that the wave function approach zero as r approaches infinity is approximated by starting the numerical integration far in the classically forbidden region.

To test the accuracy of the matrix elements, photoionization cross sections were calculated for hydrogen and compared with the exact solution.[9] Agreement was better than 1 part in 10^4. In addition, cross sections in sodium were compared with numerical calculations of Aymar[10,11] for $n < 8$. The two methods agreed to within 1% for d-state photoionization cross sections. Based on these comparisons, we believe our theoretical values for the blackbody photoionization rates are reliable within the accuracy of the experiment.

Our numerical calculations have revealed a useful scaling law for behavior of the blackbody photoionization rate as a function of n and T when $kT > W_n$, where W_n is the binding energy:

$$R \sim W_n^2 \left[\exp\left[\frac{W_n}{kT} \right] - 1 \right]^{-1} . \tag{3}$$

This approximation results from the fact that the cross section is largest near the continuum edge and falls off rapidly in frequency in an interval small compared to the width of the blackbody distribution. [The data presented here lie in the region $kT < 0.5 W_n$ where Eq. (3) is not applicable.]

III. EXPERIMENT

The experiment involved measuring the total number of ions created when a beam of excited sodium Rydberg atoms interacted with ambient blackbody radiation for a fixed time. Repeated measurements were taken as the temperature was decreased from 300 to 90 K.

Measurements were performed in an effusive beam of sodium atoms which passed through a thermally controlled interaction region. Details of this apparatus and a description of the radiation distribution within the interaction region are given in Refs. 6 and 12. The atoms were excited to the $17d$ state by two pulsed dye lasers. The laser beams were colinear with the atom beam and excitation took place between two field plates in a cryogenic chamber. After a delay of 500 ns, a small electric field of 8 V/cm was applied to steer the photoions through small holes in the lower field plate to an electron multiplier. The 500-ns interval is sufficiently short to insure that blackbody-radiation-induced transfer of population from the $17d$ level to adjacent p and f levels did not affect the measurements.

The temperature was varied by pouring measured amounts of liquid nitrogen into the cryostat and allowing the nitrogen to boil off. Although the cryostat rapidly equilibrated to a new temperature, thermal drift limited useful observation time to about 15 min for each data point. Since the laser ran at 10 pps, and each photoionization data "pulse" was accompanied by a field-ionization pulse and two background measurements, we were limited to about 1800 data pulses at each temperature. The statistical error was largest at the lowest temperature, 90 K, where we detected less than 1 photoion in 20 laser pulses. However, it was less than other sources of error.

The density of excited atoms was about 10^5 cm^{-3} in the interaction region, low enough to avoid effects of Rydberg-Rydberg collisions and superradiant transfer between levels. In addition, the background pressure within the apparatus was less than 10^{-7} torr, sufficiently small to avoid Rydberg atom-background gas collisions. Experimentally, there was no evidence of collisions.

Repeated runs were made as the temperature of the shields surrounding the interaction region was lowered from 300 to 90 K. Below 90 K, the photoion count rate was too low to obtain useful data.

Because of uncertainties in the geometry and collection efficiency, we were unable to measure absolute cross sections. The data were normalized to theory at high temperature, where the statistical and systematic errors are least important.

IV. RESULTS

The experimental results are displayed in Fig. 1, together with the calculated photoionization rate curve.

There are three sources of error whose relative contributions to the uncertainty vary over the temperature range. The first is counting statistics; the second is laser intensity fluctuation, accounting for an error of approximately 2–3% on each point; the last is a background drift, essentially a baseline error, which was estimated to be about ± 5 s^{-1} for each data point. The uncertainty at low tempera-

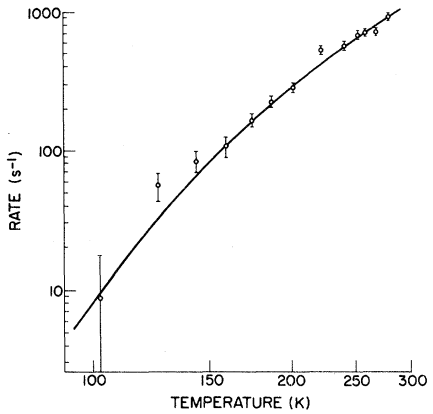

FIG. 1. Blackbody-induced photoionization rate vs temperature for the 17*d* state in Na. Scales are logarithmic. Solid line represents our calculated values. Experimental points were normalized to the calculated value at 300 K.

tures arises largely from background drift. At higher temperatures, the error arises from counting statistics and effects due to shot to shot fluctuations in the laser intensity.

In addition to these sources of error, a systematic shift due to the 8 V/cm steering field was considered. This field, which serves to collect the photoions, also ionizes all levels with $n > 80$. Thus, radiative or collisional transfer to these high-lying levels is detected along with the photoions. To investigate this, we repeated the experiment with a collection voltage of several hundred V/cm, sufficient to ionize levels with $n > 30$. An increase in the signal was observed; it was consistent with the rate of blackbody-induced transfer expected to occur to levels with $n > 30$. The rate of radiative transfer to levels with $n > 80$ was calculated to be so small it could safely be ignored as a source of error.

Because photoionization by blackbody radiation involves shorter wavelength photons than those which induce transfer to adjacent levels, this measurement of the photoionization rate provides a much stricter test of the effective radiation temperature within the cooled interaction region than our previous study of blackbody-induced transfer.[6] In that study, long-wavelength radiation was blocked from the excitation region by a fine mesh grid over the apertures. Short-wavelength photons are not blocked by the grids and one must rely entirely on the surface of the thermally controlled interaction region to absorb any radiation from the 300-K external region. The effect of such radiation would be to elevate the photoionization-rate curve at low temperature. For instance, at 100 K, photoionization due to (a) 1% contribution of a 300-K distribution would have been observable. Based on the apparatus aperture sizes and the emissivity of the materials in our interaction region, we estimate that less than 0.4% of a 300-K blackbody distribution exists within the interaction region.[6] This is consistent with our data.

The photoionization rate varied by a factor greater than 100 over the temperature range studied. The good agreement between theory and experiment indicates that there are no gross theoretical errors. An experiment was also run on the 16*d* state of Na, with similar good agreement. This agreement provides evidence that one can achieve close to the idealized experimental situation where the radiation field is characterized by the ambient temperature, and there are no extraneous noise sources.

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