In a relativistic treatment of the photoeffect based on the Born approximation and hydrogenic Dirac functions, Sauter[10] derived an angular distribution for K electrons which can be used to replace Eq. (3) and, after performance of the transformation outlined above, gives a REC distribution for highly relativistic collisions,

$$I_{\mathrm{REC,rel}}(\vartheta_{\mathrm{lab}}) \propto \sin^2\vartheta_{\mathrm{lab}}\left[1+\frac{(\gamma-1)(\gamma-2)}{2\gamma(1-\beta\cos\vartheta_{\mathrm{lab}})}\right], \quad (5)$$

where $\gamma=(1-\beta^2)^{-1/2}$. It is interesting to note that $I_{\mathrm{REC,rel}}(\vartheta_{\mathrm{lab}})$ remains quite symmetric with respect to forward-backward intensities even for very high collision velocities. Since deviations from such a symmetry are relatively easy to measure, the possibility may arrive to check relativistic angular distributions for the photoeffect by means of REC measurements.

In conclusion, we have shown that retardation effects are very important in a discussion of REC and can be measured quantitatively. In particular, shifts of the angular distribution due to retardation are offset by the Doppler effect. Among further consequences of the presented results, we point out that retardation effects may become important in connection with the observation of angular distributions of other collision-induced radiation phenomena such as, for example, combined-atom x-ray continua resulting from either REC into molecular orbitals[11] or, perhaps, transitions between quasimolecular orbitals.

We acknowledge discussions with M. Kleber and Č. Zupančič. This work was supported in part by the Bundesministerium für Forschung und Technologie.

[1]H. W. Schnopper, H.-D. Betz, J. P. Delvaille, K. Kalata, A. R. Sohval, K. W. Jones, and H. E. Wagner, Phys. Rev. Lett. 29, 898 (1972).

[2]M. Kleber and D. H. Jakubassa, Nucl. Phys. A252, 152 (1975).

[3]J. S. Briggs and K. Dettmann, J. Phys. B 10, 1113 (1977).

[4]H.-D. Betz, M. Kleber, E. Spindler, F. Bell, H. Panke, and W. Stechling, in *Proceedings of the Ninth International Conference on the Physics of Atomic and Electronic Collisions*, edited by J. S. Risley and R. Geballe (Univ. Washington Press, Seattle, 1975), p. 520.

[5]E. Spindler, H.-D. Betz, and F. Bell, J. Phys. B 10, L561 (1977).

[6]H.-D. Betz, F. Bell, H. Panke, and G. Kalkoffen, in *Proceedings of the Fourth International Conference on Atomic Physics. Abstracts of Contributed Papers, Heidelberg, Germany, 1974*, edited by J. Kowalski and H. G. Weber, (Heidelberg Univ. Press, Heidelberg, Germany, 1974), p. 670.

[7]J. Lindskog, J. Phil, R. Sjödin, A. Marelius, K. Sharma, R. Hallin and P. Lindner, Phys. Scr. 14, 100 (1976).

[8]R. Schulé, H. Schmidt-Böcking, and I. Tserruya, J. Phys. B 10, 889 (1977).

[9]H. A. Bethe and E. E. Salpeter, in *Handbuch der Physik*, edited by S. Flügge (Springer, Berlin, 1957), p. 397.

[10]F. Sauter, Ann. Phys. (Leipzig) 11, 454 (1931), and 9, 217 (1931).

[11]W. Wölfli, Ch. Stoller, G. Bonani, M. Stöckli, M. Suter, and W. Däppen, Z. Phys. A 286, 249 (1978).

Interactions of Blackbody Radiation with Atoms

T. F. Gallagher and W. E. Cooke
Molecular Physics Laboratory, SRI International, Menlo Park, California 94025
(Received 19 December 1978)

Blackbody radiation affects low-frequency ($h\nu \ll kT$) atomic transitions both by inducing transitions and producing ac frequency shifts, important effects that have previously been ignored. Here we report the calculation and experimental observation of a manifestation of the former, the threefold reduction of the Na np radiative lifetimes by 300-K blackbody-radiation–induced stimulated emission and absorption. Estimates of ac frequency shifts for Rydberg and ground-state atoms are given.

In most cases the effects of room-temperature blackbody radiation on atomic systems are ignored, and justifiably so. However, the thermal bath of blackbody photons can be quite important for low-frequency ($h\nu \ll kT$) transitions in an atom because it both induces transitions and produces ac Stark or Zeeman shifts. These effects are most dramatic for atoms in highly excited or Rydberg states because these states have low-frequency transitions with enormous electric di-

pole matrix elements and are thus strongly coupled to the blackbody radiation. In fact, blackbody radiation has very significant effects on several classes of Rydberg-state experiments including lifetime measurements, spectroscopy, and all measurements requiring the maintenance of state-selected populations. Furthermore, we suspect that many peculiarities which have been reported in the study of Rydberg atoms are due to blackbody-radiation–induced transitions. For example, puzzling observations which have been attributed to photoionization,[1,2] field-ionization anomalies,[2] and collisional ionization[3] can be easily explained by blackbody-radiation–induced transitions.[4]

Although the blackbody effects are most dramatic in Rydberg atoms it is important to note that the ac shifts are present even in ground-state systems. For example, we estimate the ac Zeeman shift of the H or Cs hyperfine transition to be one part in 10^{16} of the transition frequency, comparable to the projected stability of atomic frequency standards.[5]

Here we report the observation of the most dramatic manifestation of the blackbody radiation, the reduction of the apparent radiative lifetime of Na np states by a factor of 3 due to 300-K blackbody-radiation–induced stimulated emission and absorption. The measured lifetimes are in good agreement with our calculation of the altered lifetimes. We estimate the ac Stark effects for Rydberg atoms and suggest some of the implications for high-resolution spectroscopy.

The usual expression for the radiative lifetime τ of state n is given by the sum of the spontaneous transition rates[6]

$$\frac{1}{\tau} = \sum_{n'} A_{nn'}, \tag{1}$$

where $A_{nn'}$ is the Einstein A coefficient for the transition from state n to lower state n' of energies E_n and $E_{n'}$, respectively. If $T \neq 0$ K then there are blackbody photons present which contribute to the radiative decay rate both by absorption and stimulated emission. The lifetime τ^* for $T \neq 0$ is given by[7]

$$\frac{1}{\tau^*} = \sum_{n'} A_{nn'}(\bar{n}+1) + \sum_{n''}(g_{n''}/g_n) A_{n''n}(\bar{n}), \tag{2}$$

where $g_{n''}$ and g_n are the degeneracies of states n and n'', and $\bar{n}$, the photon occupation number, is given by $[\exp(h\nu/k_B T) - 1]^{-1}$. States n' lie below n and states n'' lie above n and include implicitly the continuum states. It is convenient to define a generalized A coefficient

$$A_{nn'}^* = A_{nn'} \text{ for } E_n > E_{n'}$$
$$A_{nn'}^* = g_{n'} A_{n'n}/g_n \text{ for } E_n < E_{n'}. \tag{3}$$

Using the definition of Eq. (3) we may write the blackbody addition to the $T = 0$ K decay rate as

$$\frac{1}{\tau^b} = \sum_{n'} A_{nn'}^*(\bar{n}). \tag{4}$$

Thus

$$1/\tau^* = 1/\tau + 1/\tau^b. \tag{5}$$

By far the largest lifetime effect should occur for the high Na np states which have large branching ratios to nearby s and d states even at 0 K. Consequently we chose to measure τ^* for the Na $17p$ and $18p$ states since such measurements are perhaps the most dramatic illustration of the effects of blackbody-radiation–induced stimulated emission and absorption.

The experimental approach and apparatus have been described in detail elsewhere[8] so we shall only outline them here. In the experiment we pass an atomic beam of Na between a plate and a grid 1.12 cm apart where it is crossed by two 5-ns dye-laser pulses which excite, for example, the $3s \rightarrow 3p$ and $3p \rightarrow 18p$ transitions as shown in Fig. 1. To excite the $18p$ state we use a Stark switching technique.[9] A voltage of 60 V is applied

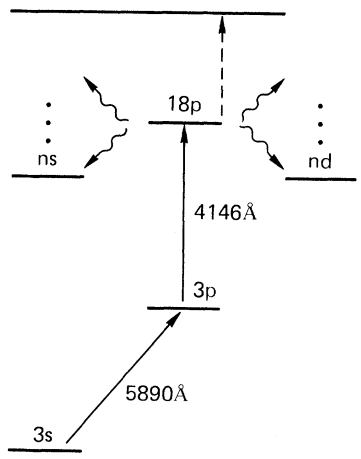

FIG. 1. Relevant energy levels for the experiment with the $18p$ state. The solid vertical arrows indicate the laser excitation, the wavy arrows indicate the blackbody-radiation–induced stimulated emission and absorption, and the broken arrow indicates field ionization (shown for the $18p$ state).

to the plates during the laser excitation which admixes s and d character to the $18p$ state allowing the $3p \rightarrow 18p$ transition. The voltage is turned off 200 ns after the laser pulse in a time of 20 ns, and the atoms pass adiabatically to the zero-field $18p$ state.[10] At a variable time after the laser excitation we apply a positive high-voltage pulse (up to 10 kV) to the plate ionizing the Rydberg atoms and accelerating the ions formed through the grid into a particle multiplier. By varying the amplitude of the ionizing pulse we can selectively ionize specific excited states (field-ionization thresholds for the states of interest are given in Ref. 8). Thus, we are able to determine the time evolution of the population of each state after the laser pulse. In these experiments we populated the Na $17p$ and $18p$ states and observed the decay for 20 μs. Since the stoms travel ~2 cm during this time the collection efficiency along the beam path was a matter of some concern. The aperture of the grid is > 4 cm long and the multiplier face is ~3 cm long so we felt reasonably confident that the collection efficiency would be roughly constant along a 2-cm length of the beam path. To test this we excited long-lived (50–100 μs) l states, $l \sim 14$–17, using Stark switching and observed that the excited-state population did not decay more than 25% in 20 μs (even though these states are connected by $\Delta l = 1$ blackbody-radiation–induced transitions, all the high-l states have long lifetimes and so the highly-excited-state population persists). Thus we are able to conclude that our collection efficiency is reasonable and we can attribute a diffusion rate, Γ_d, of at most 13×10^3 s^{-1} to atoms passing out of the observation region.

We observed the decay of the $17p$ state, for example, by first recording the population of the $17p$ and higher-lying states as a function of time after the laser pulse by setting the ionization pulse amplitude just above the $17p$ threshold. Then we recorded the population in only the states above $17p$ by setting the ionizing pulse just below the $17p$ threshold. The difference gave the time decay of the $17p$ state, which we corrected for the collection efficiency. To check the possibility of collisional effects, measurements were made with the atomic beam density increased by a factor of 4 above the normal value, 10^9 cm^{-3}, and with the background pressure raised from its normal value, 8×10^{-7} Torr, to 10^{-5} Torr of air with no apparent effect on the observed lifetime. In Table I we give the measured values of τ^* with statistical errors and diffusion effects taken into account. The skewed uncertainties stem from the unidirectional allowance for diffusion. Also given are the values of τ obtained by Gounand[11] using the Coulomb approximation and our calculated values of τ^b and τ^*. In Fig. 2 we plot the calculated values of τ and τ^* and the measured values of τ^*. (Again, the uncertainties are skewed about the measured values due to the unidirectional allowance for diffusion.) From Fig. 2 it is apparent that the 300-K lifetimes are in-

TABLE I. Lifetimes of the Na $17p$ and $18p$ states.

State	τ[a] (μs)	τ^b (μs)	τ^* calc (μs)	τ^* obs (μs)
$17p$	48.4	22.7	15.5	$11.4^{+5.0}_{-1.4}$
$18p$	58.4	25.6	17.9	$13.9^{+8.8}_{-2.9}$

[a]See Ref. 11.

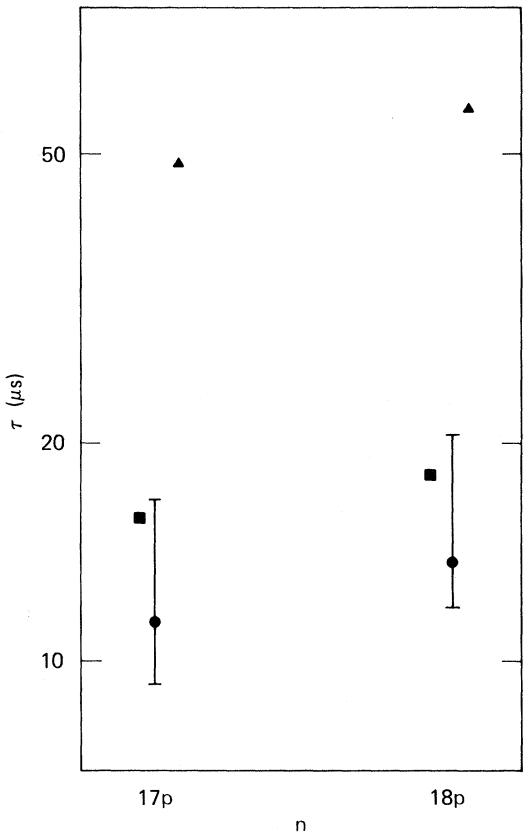

FIG. 2. Na np lifetimes. The plotted points are calculated values for τ (filled triangle), the calculated values for τ^* (filled square), and the measured values of τ^* (filled circle).

deed a factor of 3 shorter than the 0-K lifetimes, in accord with our calculated values.

In fact, less dramatic but noticeable effects are visible in other Rydberg states. For example, the Rb np lifetimes for $n = 12$–22 measured by Gounand *et al.*[12] at 460 K are ~30% below the calculated values. According to our calculations this discrepancy is completely removed by the inclusion of blackbody effects. We have observed similar 20% effects in observations of high Na ns-state lifetimes[4] and this may be the cause of discrepancies noted by Latimer[13] between calculated and observed Xe f lifetimes.

Although the effect of blackbody radiation on the radiative lifetimes can be very dramatic, it is the rapid diffusion of population from an initially excited Rydberg state to other nearby states which is of general importance for experiments with Rydberg atoms. The diffusion of Rydberg population is similar to the effects produced by collisions with rare-gas atoms, and the relative rates provide an illustrative comparison. For example, the thermal bath of photons transfers population from the 18s state to the two neighboring p states at a rate of 4×10^4 s^{-1}; this rate is equivalent to that produced by a background pressure of 10 mTorr of Ar [using an estimated cross section of 20 Å^2 for Na ns-state depopulation by Ar (Ref. 4)]! Thus even under "collision free" conditions blackbody radiation produces rapid redistribution of Rydberg-state populations.

As an example of the redistribution effects of the blackbody radiation, consider the effect on the measurement of threshold fields for pulsed electric field ionization of laser excited atoms. If the ionizing pulse is delayed by ~1 μs from the laser excitation, the blackbody flux drives transitions to higher and lower states leading to spurious thresholds with the result that ~5% of the initial populations is not in the state populated by the laser. The clearest manifestation of this is a small "background" ionization signal at fields below the threshold ionization field for the state excited by the laser.[1,2] Upon closer examination the background is found to have structure,[4] and its magnitude is consistent with blackbody radiation's driving the atoms from the initially populated state to a higher state with a lower ionization threshold field.[4]

Let us now consider the ac Stark shifts produced by the blackbody radiation.

For a Rydberg state most of the energy of the 300-K blackbody radiation is at frequencies far higher than the frequencies of the important transitions, those that comprise the bulk of the oscillator-strength sum. In this case we may ignore the weak, near-resonant parts of the blackbody spectrum since contributions on the high- and low-frequency sides of each transition will cancel to first order. Furthermore, we can express the ac Stark shift ΔW of the Rydberg state as[15]

$$\Delta W = \sum_k \frac{(\mu_k E_{\rm BB})^2 W_k}{(h\nu_{\rm BB})^2} . \quad (6)$$

Here μ_k and W_k are dipole matrix element and energy of the transition to state k. For state k below and above the initial state $W_k < 0$ and $W_k > 0$, respectively. $E_{\rm BB}$ and $h\nu_{\rm BB}$ are the blackbody-radiation electric field and photon energy. The sum k extends over all the allowed, $\Delta l = \pm 1$, transitions. By removing from the summation those factors which do not depend on k we can recast Eq. (6) into factors depending only on the blackbody spectrum and a sum over oscillator strengths, equal to 1. If we then integrate over the blackbody spectral distribution we find (in atomic units)

$$\Delta W = \alpha^3 (k_{\rm B} T)^2/3. \quad (7)$$

Thus all the Rydberg states are shifted up by an equal amount. Physically this is not surprising since, if $W_k \ll h\nu_{\rm BB}$ for the majority of the oscillator-strength sum, the electron is like a free electron and its properties should be independent of n. Evaluating Eq. (7) at $T = 300$ K we find a shift of 2.2 kHz.

Lower-lying states for which $W_k \ll h\nu_{\rm BB}$ is not satisfied will not be shifted. Consequently we expect that the shifts should be most apparent in transitions from the ground state to the Rydberg states, such as those investigated by Lee *et al.*[16]

The blackbody ac shift is by no means restricted to Rydberg atoms but should lead to Stark shifts of 1 Hz in rotational transitions of polar molecules, and analogous Zeeman shifts of ~1 μHz in the Cs atomic hyperfine transition. To date, however, the existence of such ac shifts has not been verified experimentally.

Here we have described in detail a dramatic illustration of the effects of room-temperature blackbody radiation on Rydberg atoms, the reduction of the radiative lifetime by stimulated emission and absorption. This effect and the consequent radiative redistribution of population have previously been ignored and must be considered in any experiments with Rydberg atoms. We would again like to stress that ac frequency

shifts are not peculiar to Rydberg states but that the blackbody fields will affect all low-frequency transitions and may be particularly important for high-resolution measurements.

We would like to acknowledge helpful discussions with D. L. Huestis, P. F. Liao, P. Lambropoulos, D. C. Lorents, and R. E. Olson, and we are grateful to F. Gounand for his calculations of alkali lifetimes. This work was supported by the U. S. Air Force Office of Scientific Research under Contract No. F44620-74-0059.

[1]T. F. Gallagher, W. E. Cooke, and S. A. Edelstein, Phys. Rev. A 17, 904 (1978).
[2]R. F. Stebbings, C. J. Latimer, W. P. West, F. B. Dunning, and T. B. Cook, Phys. Rev. A 12, 1453 (1975).
[3]M. G. Littman, M. L. Zimmerman, and D. Kleppner, Phys. Rev. Lett. 37, 486 (1976).
[4]T. F. Gallagher and W. E. Cooke, to be published.
[5]F. L. Walls, private communication.
[6]H. A. Bethe and E. E. Salpeter, *The Quantum Mechanics of One and Two Electron Atoms* (Academic, New York, 1957).
[7]R. Loudon, *The Quantum Theory of Light* (Oxford Univ. Press, London, 1973).
[8]T. F. Gallagher, L. M. Humphrey, W. E. Cooke, R. M. Hill, and S. A. Edelstein, Phys. Rev. A 16, 1098 (1977).
[9]W. E. Cooke, T. F. Gallagher, S. A. Edelstein, and R. M. Hill, Phys. Rev. Lett. 40, 178 (1978).
[10]R. R. Freeman and D. Kleppner, Phys. Rev. A 14, 1614 (1976).
[11]F. Gounand, to be published.
[12]F. Gounand, P. R. Fournier, J. Cuvellier, and J. Berlande, Phys. Lett. 59A, 23 (1976).
[13]C. J. Latimer, J. Chem. Phys. 69, 1314 (1978).
[14]T. F. Gallagher and W. E. Cooke, to be published.
[15]C. H. Townes and A. L. Schawlow, *Microwave Spectroscopy* (McGraw-Hill, New York, 1955).
[16]S. A. Lee, H. Helmcke, J. L. Hall, and B. P. Stoicheff, Opt. Lett. 3, 141 (1978).

Two-Dimensional Distribution of Self-Generated Magnetic Fields near the Laser-Plasma Resonant-Interaction Region

Y. Sakagami, H. Kawakami, and S. Nagao
Faculty of Engineering, Gifu University, Kakamigahara, Gifu 504, Japan

and

C. Yamanaka
Institute of Laser Engineering, Osaka University, Suita, Osaka 565, Japan

(Received 6 November 1978)

The two-dimensional distribution of self-generated magnetic fields near the laser-plasma interaction region is observed for the first time by the very simple method of laser irradiation of audio magnetic tape. The lobe structure is a maximum at the incident angle of 10° to 15° for p-polarized laser light. The direction of the fields is perpendicular to the density gradient and to the incident p-polarization plane. These observations support resonance absorption as the field-generation mechanism.

Self-generated dc megagauss magnetic fields have recently been observed in laser-plasma interaction experiments.[1] Fields of this magnitude can have a substantial effect both on the absorption[2] and transport properties.[3] The original work on this subject concentrated on thermoelectric sources for the magnetic fields.[1,4] Recently, the dc magnetic fields generated concomitantly with the resonance-absorption process have been studied theoretically.[5,6] The diagnostic tools to observe the magnetic fields have been restricted up to now to magnetic probes,[1] Faraday rotation,[7,8] and current probes.[9] They provided measurements of the magnitude of the fields mainly in the vacuum space, but not the detailed geometry near the source region. Knowledge of the field geometry may lend important insight into the proposed generation mechanism. Experiments to reveal the field geometry have been limited to microwave simulations using a divergent beam.[10]

In the experiments reported here, we show the first observation of the two-dimensional distribution of the self-generated magnetic fields near the resonant region by a very simple method. We also show the field-generation mechanism to

