that electric fields operating on the H(2S) atoms do produce partially polarized quench radiation.

The dilemma presented by these results is now understood thanks to Fano,[5] who pointed out that Lichten was in error in assuming that because the $2^2P_{3/2}$ state is about ten times as far removed in energy from the 2S metastable state as is the $2^2P_{1/2}$ state, its effects could be neglected in the weak-field, Stark-mixing problem. Although the $2^2P_{3/2}$ admixture is only about 10% of that of the $2^2P_{1/2}$ state, both states should be retained in a time-independent perturbation expansion. The dipole matrix element for radiation to the ground state then consists of two terms, one involving the $^2P_{1/2}$ state and the other the $^2P_{3/2}$ state. Upon squaring to find the radiation intensity, a cross product between these terms results which would be of the order of 20% of that from the $^2P_{1/2}$ state alone.[6]

We have worked through the details of this elementary calculation, neglecting hyperfine effects, and find that a polarization of -32.9% is predicted. Whether the slight discrepancy between the preliminary experimental value of -30% and the theoretical value -32.9% has any significance is not known at present.

This newer value of the polarization affects the cross sections for excitation to the 2S state obtained from the data of Ref. 2, by increasing the values approximately 10% above those given in Ref. 3. Based on those data, the maximum in the cross section at approximately 12 eV would be about $0.18\pi a_0^2$, which is only about 20% less than the recent calculated value of Burke, Taylor, and Ormonde[6] using close coupling with correlation terms.

We are deeply indebted to Professor U. Fano for pointing out the correct theoretical arguments, thereby making unnecessary a major effort to prove even more conclusively on experimental grounds that the apparatus was functioning properly, and to Professor E. Gerjuoy for his interest in and discussion of this and other experiments involving hydrogen atoms.

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[1]W. Lichten, Phys. Rev. Letters 6, 12 (1961).

[2]R. F. Stebbings, W. L. Fite, D. G. Hummer, and R. T. Brackmann, Phys. Rev. 119, 1939 (1960).

[3]R. F. Stebbings, W. L. Fite, D. G. Hummer and R. T. Brackmann, Phys. Rev. 124, 2051(E) (1961).

[4]W. R. Ott, W. E. Kauppila, and W. L. Fite, Phys. Rev. Letters 19, 1361 (1967).

[5]U. Fano, private communication.

[6]Note: Interference terms arising from cross products in squares of sums in cases similar to this have been noted by others. See, for example, G. Breit, Rev. Mod. Phys. 5, 91 (1933), and F. D. Colegrove, P. A. Franken, R. R. Lewis, and R. H. Sands, Phys. Rev. Letters 3, 420 (1959).

[7]P. G. Burke, A. J. Taylor, and S. Ormonde, Proc. Phys. Soc. (London) 92, 336 (1967).

OBSERVATION OF THE EFFECT OF FREQUENCY CORRELATIONS ON A CASCADE TRANSITION

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The purpose of this Letter is to report the observation of an effect caused by the frequency correlation of photons emitted in a cascade transition.[1] The experiment consists of measuring the frequency profile of the 0.6096-μm radiation (neon $2p_4 \rightarrow 1s_4$) spontaneously emitted along the axis of a 1.15-μm (neon $2s_2 \rightarrow 2p_4$) He-Ne laser. Since the laser radiation can stimulate emission only in those atoms with a narrow range of axial velocity, there is an excess number of atoms with certain axial velocities in the $2p_4$ state. This velocity selection causes bumps to appear on the Doppler-broadened 0.6096-μm line at frequencies given by $\omega_L' = \omega_{bc} + (\omega_{bc}/\omega_{ab})(\Omega - \omega_{ab})$ and $\omega_L' = \omega_{bc} - (\omega_{bc}/\omega_{ab})(\Omega - \omega_{ab})$. ω_L' is the frequency of the 0.6096-μm radiation in the laboratory; a, b, and c are the $2s_2$, $2p_4$, and $1s_4$ states, respectively; $\hbar\omega_{ab}$ is the $2s_2$–$2p_4$ energy difference; $\hbar\omega_{bc}$ is the $2p_4$–$1s_4$ energy difference; and the laser is tuned to frequency Ω. The widths of the bumps are[1] $\gamma_1 = (\omega_{bc}/\omega_{ab})(\gamma_a + \gamma_b) + \gamma_b + \gamma_c$ and $\gamma_2 = (\omega_{bc}/\omega_{ab})(\gamma_a + \gamma_b) - \gamma_b + \gamma_c$, where the higher frequency bump is the broader when $\Omega > \omega_{ab}$, and the lower frequency bump is the broader when $\Omega < \omega_{ab}$. Since the areas of the bumps are equal, there is also a difference in the heights. The difference in the widths and heights is caused by the correlation between the frequencies of the $2s_2 \rightarrow 2p_4$ radiation and the $2p_4 \rightarrow 1s_4$ radiation.[1]

The presence of the bumps has been reported by other workers,[2-4] but the widths were thought to be equal, and the signal-to-noise ratios were too low to be able to distinguish an unambiguous difference in widths of heights. The purpose of the present experiment was to search for a difference in the bump widths and heights; the presence of a difference constitutes a direct confirmation of the Weisskopf-Wigner[5] and Heitler[6] theories of the spontaneous emission process.

The apparatus used in this work is almost the same as that described in Ref. 4, except a different laser is used, and a chopper and phase-sensitive detector have been added. The principal elements are a laser, a Fabry-Perot interferometer, a monochromator, and a phototube. These elements, in that order, with collimating lenses between them, are placed on a line defined by the 1.15-μm laser beam. A chopper between the laser mirrors serves to turn the laser beam on and off without disturbing the discharge. The chopper is necessary because the bumps are superimposed on a large background, due to emission from atoms which reach the $2p_4$ state by means other than stimulated emission from the $2s_2$ state, e.g., electron bombardment. Under the conditions reported here, the bumps are only a few percent of the background. A 31-cm-long hemisphere laser is used at a pressure of 0.1 Torr neon, 0.5 Torr helium.

The accuracy of the measurement is limited by shot noise, by drifting of the laser frequency, and by the resolution of the Fabry-Perot interferometer. The strength of the signal is limited by the fact that the laser has to be operated near threshold to avoid multimoding, and by the necessarily small angle of acceptance of 0.6096-μm radiation about the laser axis. (The half-angle of acceptance used in this work, 0.025 rad, causes an addition to the bump widths of 17 ± 4 Mc/sec.) Because the laser must be tuned to one side of the "Lamb dip"[7] to obtain a separation of the bumps, it is not stabilized; drifts in the laser frequency put a lower limit on the speed of the Fabry-Perot scan. The scanning rate is about 6 min per order. For the data used in the analysis, the laser frequency changed by less than 5 Mc/sec over one order. Such a change in Ω causes a change in the bump separation of about 20 Mc/sec over an entire order, or about 8 Mc/sec over the portion of the bumps used in the analysis. The instrumental width due to the interferometer and monochromator system, 95 ± 10 Mc/sec, was measured with a commercial 6328-Å laser. A fairly short interferometer spacer is used (6.6 cm) in order to obtain a large enough spectral range (2275 Mc/sec) to include a complete picture of the separated bumps.

Typical recorder tracings of the bumps are shown in Fig. 1. ω_L' increases to the right. Several interferometer orders are shown to demonstrate the fact that the difference in heights is not caused by drifting of the laser power. Figure 1(a) corresponds to $\Omega-\omega_{ab} = +160$ Mc/sec, and Fig. 1(b) is for $\Omega-\omega_{ab} = -170$ Mc/sec. (The values of $\Omega-\omega_{ab}$ are obtained from a knowledge of where the laser is tuned on the "Lamb dip"; the bump separations correspond to the measured values of $\Omega-\omega_{ab}$.) The difference in the bump heights is evident. Additionally, it is seen that the order of the bump heights depends in the predicted way on the sign of $\Omega-\omega_{ab}$. To within the errors, the bumps can be fitted with Lorentzian line shapes.[8] Since both the shot noise and the instrumental width are rather large, this does not constitute a very stringent test of the bump shapes.

Table I gives the mean fractional difference in bump heights and the mean fractional difference in widths obtained from 14 pairs of bumps. The difference in the measured bump heights is 14 ± 2 %, and the difference in the measured widths is 15 ± 4 %. The errors quoted are statistical and comprise two standard deviations of the mean. The systemic errors are estimated to be within the statistical errors. The width

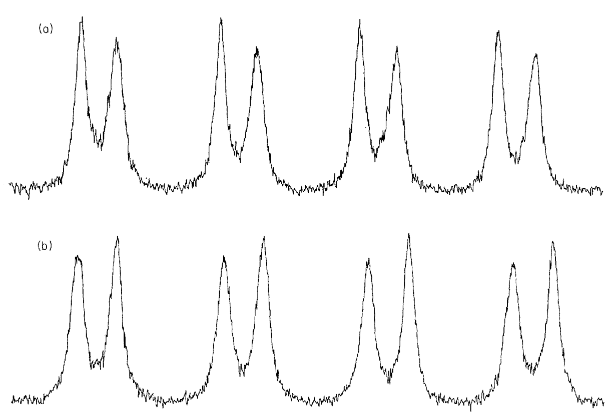

FIG. 1. (a) Four interferometer orders showing the bumps with $\Omega > \omega_{ab}$. (b) Four interferometer orders showing the bumps with $\Omega < \omega_{ab}$.

Table I. Bump parameters.

(Difference in heights)/(Average height)	0.14 ± 0.02
(Difference in widths)/(Average widths)	0.15 ± 0.04
Measured widths	225 ± 8 and 262 ± 8 Mc/sec
Difference in measured widths	37 ± 11 Mc/sec
γ_b'	18 ± 6 Mc/sec
Instrumental width	112 ± 12 Mc/sec
Average bump width minus instrumental width $\equiv \bar{\gamma}$	132 ± 14 Mc/sec
(Difference in measured widths)/$\bar{\gamma}$	0.28 ± 0.09
$(\gamma_a' + \gamma_b')/2Ku$ from "Lamb dip"	0.07 ± 0.01
Ku	550 ± 30 Mc/sec
$\gamma_a' + \gamma_b'$	77 ± 12 Mc/sec
γ_a'	59 ± 14 Mc/sec
γ_c'	-13 ± 27 Mc/sec

measurement is less accurate than the height measurement because the widths are affected more by small changes in the bump separation.

The values obtained for other quantities of interest are also shown in Table I. If there were no collisions, the difference in the measured bump widths would be $2\gamma_b$, and the average of the larger and smaller widths, $\bar{\gamma}$, would be $(\omega_{bc}/\omega_{ab})(\gamma_a + \gamma_b) + \gamma_c$. Since $\gamma_a + \gamma_b$ can be deduced from the shape of the "Lamb dip," values for all three widths could be obtained separately. The effect of collisions is to increase the widths and possibly to destroy the frequency correlation and alter the atomic velocities. If an atom in state b has its velocity changed by a large amount in a collision, it does not contribute to the bump intensity; small changes in velocity would tend to increase $\bar{\gamma}$. If it is assumed that the only effect of the collisions is to increase the widths to the collision-broadened widths γ_a', γ_b', and γ_c', then it is possible to make comparisons among quantities obtained from the bumps and those gotten from the shape of the "Lamb dip." Such a comparison was made but, of course, should not be taken too seriously, pending a further investigation of pressure effects.

The difference in measured widths gives a value for γ_b' of 18 ± 6 Mc/sec. The average bump width minus the instrumental width is 132 ± 14 Mc/sec; this is equated to $(\omega_{bc}/\omega_{ab}) \times (\gamma_a' + \gamma_b') + \gamma_c'$. The quantity $(\gamma_a' + \gamma_b')/2Ku$, where $2(\ln 2)^{1/2}Ku$ is the Doppler width of the 1.15-μm line, was deduced from the shape of the "Lamb dip" at low power levels. The temperature of the atoms, and hence Ku, was found by measuring the Doppler width of the 0.6328-μm line. The value of $\gamma_a' + \gamma_b'$ from the "Lamb dip" was then combined with the values of γ_b' and $\bar{\gamma}$ to obtain $\gamma_a' = 59 \pm 14$ Mc/sec and $\gamma_c' = -13 \pm 27$ Mc/sec. Because of the pressure effects mentioned above, the quoted value of γ_b' is probably smaller than the true value, and the quoted value of γ_a' is probably too large.

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[1]H. K. Holt, Phys. Rev. Letters 19, 1275 (1967).

[2]R. H. Cordover, P. A. Bonczyk, and A. Javan, Phys. Rev. Letters 18, 730 (1967).

[3]R. H. Cordover, P. A. Bonczyk, and A. Javan, Phys. Rev. Letters 18, 1104 (1967).

[4]W. G. Schweitzer, Jr., M. M. Birky, and J. A. White, J. Opt. Soc. 57, 1226 (1967).

[5]V. Weisskopf and E. Wigner, Z. Physik 63, 54 (1930).

[6]W. Heitler, The Quantum Theory of Radiation (Oxford University Press, London, England, 1954), 3rd ed.

[7]W. E. Lamb, Jr., Phys. Rev. 134, A1429 (1964).

[8]The instrumental profile is Lorentzian to well within the errors. If the true bump profile is also Lorentzian, as is expected, the measured bump will be a Lorentzian with a width equal to the sum of the true width and the instrumental width.