near 7.33 MeV should await polarization measurements with better energy resolution. Our assignment of 1^- to the levels at 5.51 and 7.08 MeV agrees with previous assignments for these levels. Our assignment of 1^- to the 7.06-MeV level contradicts a previous widely accepted 1^+ assignment based on ^{208}Pb($p,p'\gamma$) and ^{208}Pb($d,d'\gamma$) measurements.[6] However, the data on which the tentative 1^+ assignment was based do not exclude 1^-. Our 1^- assignment for the 7.33-MeV level is the first parity assignment that has been made for this level.

The apparent pattern of $M1$ strength in ^{208}Pb, which had been used to adjust some parameters in the effective nucleon-nucleon interaction,[4] has now changed drastically. What appeared to be the two levels that contained most of the $M1$ strength are no longer believed to be $M1$; our experiment reassigns the 7.06-MeV level $[B(M1)\uparrow \sim 13\mu_0^2]$, and two recent experiments[10,11] contradict the $M1$ assignment of the 7.99-MeV level $[B(M1)\uparrow \sim 11\mu_0^2]$. At present the only remaining 1^+ strength is believed to be spread over a number of weak levels that have been identifed between 7.4 and 7.8 MeV[8] and perhaps between 8.0 and 9.5 MeV,[7,11] which together exhaust only a relatively small fraction of the expected $M1$ strength. In view of both this observed fragmentation of $M1$ strength and the absence of strong identified 1^+ states, it seems that the pattern of $M1$ strength in ^{208}Pb will remain uncertain until experiments are performed which are sufficiently sensitive to identify weakly excited 1^+ states, perhaps over a much extended range of excitation.

This research, including the development and operation of MUSL-2 and its experimental areas, was supported by the National Science Foundation.

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Direct Measurement of the Effective Initial Tipping Angle in Superfluorescence

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(Received 13 November 1978)

We report the first direct measurement of the effective initial tipping angle θ_0 in superfluorescence. A coherent pulse of small area θ, resonant on the superfluorescence transition, is injected into a completely inverted sample of cesium atoms and the delay of the output pulse is measured as a function of θ. The value of θ_0 obtained agrees in essence with $2/(N)^{1/2}$. The latter value is predicted by recent theories which consider the quantum initiation of superfluorescence and which take propagation effects into account.

In recent years several observations of superfluorescence (SF), the cooperative emission of N initially inverted atoms, have been reported.[1-3] For a rod-shaped sample, of length L and cross-sectional area S and with Fresnel number $F \equiv S/\lambda L$ equal to or larger than 1, the collective radiation time is $\tau_R = (8\pi\tau_n)/(3\lambda^2\rho L)$, where ρ is the atomic density, λ is the wavelength of the emitted radiation, and τ_n is the natural lifetime of the upper level. The origin of the collective motion may be ascribed to quantum fluctuations. In semiclassical calculations, based on the Maxwell-Bloch equations, the role of the fluctuations is often simulated by a coherent pulse of properly chosen area θ_0, which propagates along the axis of the rod and tips the individual Bloch vectors over an angle θ_0.[4,5] However, the value to be given to θ_0 has been under debate, and widely different values have been applied. Rehler and Eberly[6] derived a delay time for the SF pulse which implies $\theta_0^{\rm RE} = 1/(\mu N)^{1/2}$, where the geometrical factor $\mu = 3\lambda^2/(8\pi S)$ for $F = 1$. Bonifacio and Lugiato[7] arrived at $\theta_0^{\rm BL} = (2/N)^{1/2}$. Finally, MacGillivray and Feld[4] have calculated the value $\theta_0^{\rm MF} = [(2\pi)^{1/2} N(\alpha L)^{3/2}]^{-1/2}$, where αL is the amplitude gain of the sample. For the experiment to be described below ($N \simeq 2\times 10^8$, $\tau_R \simeq 0.4$ ns, $\alpha \simeq 12.5$) we calculate the following values: $\theta_0^{\rm RE} = 2.7\times 10^{-2}$, $\theta_0^{\rm BL} = 1.0\times 10^{-4}$, and $\theta_0^{\rm MF} = 6.7\times 10^{-6}$. Clearly, an accurate knowledge of the effective initial tipping angle θ_0 is of major importance for the understanding of SF.

In some recent publications θ_0 has been treated as an adjustable parameter which was chosen so as to give a best fit of the observed delay times to those calculated with Maxwell-Bloch theory. Such a determination of θ_0, however, is inherently inaccurate because the delay time depends linearly on the density and only logarithmically on θ_0. Errors in the measurement of the excited-state density thus cause large errors in θ_0.

In this Letter a direct measurement of the effective initial tipping angle is reported; the measurement does not depend on a particular model for the SF evolution, nor is it affected by experimental errors in the excited-state density.

The experiment is based on the following idea. Immediately after the sample has been completely inverted by a short pump pulse, a small-area pulse at the SF wavelength is injected into the sample. As long as the area θ of that pulse is smaller than θ_0, the delay time of the SF output pulse will not be affected. However, when $\theta > \theta_0$ the delay time will be reduced. Thus by measuring the delay time as a function of the area θ of the injected pulse the magnitude of θ_0 can be found. The experiments have been performed in cesium vapor, which is well suited for the study of SF.[2,3] As in previous work[3] a transverse magnetic field of 0.28 T is applied to select the two-level transition $7P_{3/2}$ ($m_j = -\frac{3}{2}$, $m_I = -\frac{5}{2}$) to $7S_{3/2}$ ($m_j = -\frac{1}{2}$, $m_I = -\frac{5}{2}$), at a wavelength of 2931 nm for the SF. Atoms are excited from the $6S_{1/2}$ ground state to $7P_{3/2}$ by a pump pulse at 455 nm. The experimental setup is presented in Fig. 1. Two cesium cells at a mutual distance D of 50 cm are successively pumped by the same pump laser beam. This beam has a diameter d_1 of 270 μm at the first cell, and a diameter d_2 of 450 μm at the second cell, which corresponds to $F\approx 2$ for cell 1 ($L_1 = 1$ cm), and to $F \approx 1$ for cell 2 ($L_2 = 5$ cm). The pump pulse has a time duration of about 2 ns full width at half maximum, a bandwidth of 400 MHz, and a peak power of 35 W. The vapor density in cell 1 is adjusted so that an SF pulse is emitted with a delay time of about 1.5 ns; its width is found to be nearly 2 ns. This SF pulse is the infrared (ir) injection pulse for cell 2. The spatial coherence of the injection pulse over the cross section of the pumped volume in cell 2 is guaranteed by the geometry, i.e., $d_1 d_2 \ll \lambda D$. Temporal coherence is assumed for the injection pulse; strong evidence for this coherence of SF radiation exists in the observation of "classical" beats in SF on two different uncoupled transitions[2] and in SF from different groups of atoms.[8] From the measured intensity at a certain distance from cell 1 and from the measured divergence d_1/L_1 of the ir beam we find that cell 1 emits roughly a π pulse.

For the measurement of the intensity we have used the nominal sensitivity of the detector (Judson J-12LD, InAs, with nominal quantum efficiency 22%). The area of the injection pulse can be reduced with the aid of calibrated attenuators consisting of Perspex plates of 1-mm thickness. Their transmittance is 0.04 at 2931 nm, whereas they transmit the pump beam fully apart from small reflection losses. The density in cell 2 is adjusted so that without injection the delay time of the SF pulse is approximately 13 ns. For injected areas above 5×10^{-4} the delay time is re-

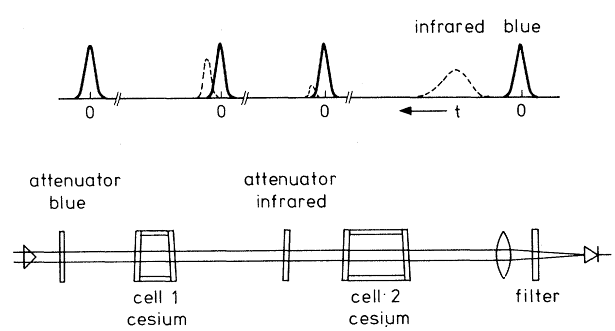

FIG. 1. Sketch of the experimental setup.

duced considerably, as can be seen from Fig. 2, where pulse shapes are given for various values of the injected area, with constant density in both cells and with a constant pump intensity. It must be mentioned that under given experimental conditions there is still a factor of 2 shot-to-shot fluctuation in the delay time of both the injection and the output SF pulse.[9] For presentation in Fig. 2, pulses have been selected that are close to the average ones in delay and in amplitude.

Inspired by the theory of small-area pulse injection of Burnham and Chiao,[10] we have plotted in Fig. 3 the relation between the average delay time τ_D and $[\ln(\theta/2\pi)]^2$ for one particular experiment, i.e., at constant vapor density in both cells and varying attenuation of the injection pulse. As expected[10] for large injection pulses τ_D increases linearly. For small injection pulses initiation of SF is dominated by quantum fluctuations and τ_D is constant. At the crossover $\theta=\theta_0$ by definition. A small correction (dashed line in Fig. 3) must be made for the delay of the injection pulse with respect to the pump pulse. From similar plots for several experiments the most probable value of θ_0 for the experimental conditions described above ($N\simeq 2\times 10^8$) is found to be $\theta_0 = 5\times 10^{-4}$. Taking into account the shot-to-shot fluctuations and the uncertainty connected with the measurement of θ, we estimate $10^{-4}\leqslant \theta_0 \leqslant 2.5\times 10^{-3}$. The values for θ_0 predicted by Rehler and Eberly and by MacGillivray and Feld differ by at least one order of magnitude from the experimental value. The value of Bonifacio and Lugiato is just included in the experimental range.

Recently the quantum initiation of SF has been studied theoretically by Glauber and Haake[11] and by Schuurmans, Polder, and Vrehen.[12] The propagation of the electromagnetic field is fully included in both theories, which arrive at very similar results. Schuurmans, Polder, and Vrehen have calculated an explicit expression for θ_0:

$$\theta_0^{\mathrm{SPV}} = \frac{2}{\sqrt{N}}\,[\ln(2\pi N)^{1/8}]^{1/2}.$$

For the present experiment one finds $\theta_0^{\mathrm{SPV}} = 2.3\times 10^{-4}$, which is in good agreement with the measured value. An injection pulse of area 5×10^{-4} and 2-ns duration carries a total energy of one single photon through the cross section of the SF sample. Loosely speaking it may thus be said that the SF evolution is triggered by the first photon emitted spontaneously along the axis of the sample. Note that the theoretically calculated pulse area of 2.3×10^{-4} corresponds to a single photon for a pulse duration τ_R.

In earlier work[3] the observation of single-pulse SF from cesium atoms has been reported. The possibility has then been entertained that the absence of ringing could at least partly be attributed to a very large value of θ_0 ($\theta_0 \approx 10^{-2}$). That possibility can now be excluded.

The experiment provides an example of coherent pulse propagation in a narrow-band amplifier. In fact, it closely resembles the situation dis-

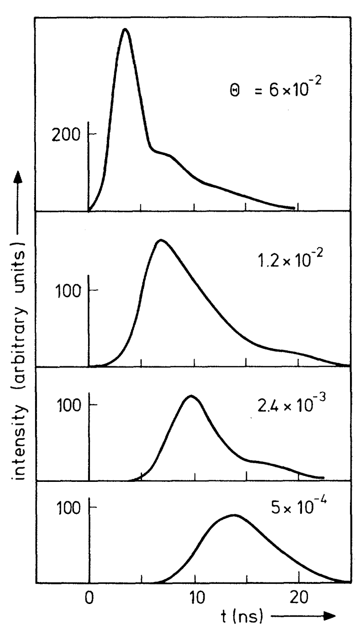

FIG. 2. Output pulse shapes for various values of the area θ of the injection pulse.

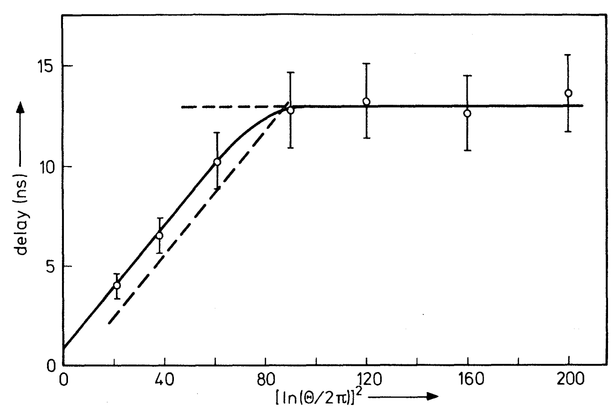

FIG. 3. Delay time τ_D of output pulse vs $[\ln(\theta/2\pi)]^2$. The dashed line is used to correct for the delay of the injection pulse with respect to the pump pulse.

cussed theoretically by Burnham and Chiao[10] using Maxwell-Bloch theory. Complete inversion of a two-level system followed by a rotation of the Bloch-vector over an angle θ, as realized in the experiment, is equivalent to rotation over an angle $\pi - \theta$ from the ground state, as considered by those authors. A detailed comparison of the experiment with the Burnham-Chiao calculations is beyond the scope of this Letter. A few remarks may suffice. The linear increase of τ_D with $[\ln(\theta/2\pi)]^2$ as depicted in Fig. 3 agrees with the Burnham-Chiao calculations for $\tau_R \simeq 0.4$ ns. No effort has been made in the present experiment to measure τ_R carefully. However, we refer to our earlier work (Ref. 3). An intrinsic delay time of 13 ns in the present data corresponds to a delay time of about 10 ns in the data of Ref. 3.[13] From Ref. 3, Fig. 3, one then finds $0.24 \text{ ns} < \tau_R < 0.64$ ns. It follows that the experimental result is consistent with the Burnham-Chiao theory as far as delay times are concerned. The amount of ringing observed is generally much smaller than expected from this theory. This could be due, however, to the finite Doppler dephasing time ($T_2{}^* \simeq 5$ ns) in the experiment.

In summary, we have measured the effective initial tipping angle θ_0 using a direct method which does not depend on a particular model for the SF evolution and which does not require the measurement of the excited-state density. The measured value is of the order of $2/\sqrt{N}$ and agrees well with recent theories on the quantum initiation of SF. The result excludes the possibility that the observation of single-pulse SF can be explained by a very large value of θ_0. The experiment also represents an example of coherent pulse propagation in an amplifier. Measurements of the intrinsic fluctuations in the SF delay times resulting from the stochastic nature of the initiation are now in progress.

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