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# OBSERVATION OF A PHOTON ECHO*

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An experiment has been performed in which a ruby crystal has been made to emit spontaneously a short, intense burst of radiation, which we will call a photon echo, after being excited by two short, intense light pulses at 6935 Å from a $Q$-switched ruby laser.[1] In Fig. 1, oscilloscope photographs show the output of a photomultiplier which monitors the radiation from the ruby-crystal sample. In the three cases shown, for excitation pulse separations of 80, 110, and 140 nsec, the time between the echo and the previous excitation pulse is very nearly equal to the time separation of the excitation pulses. This behavior is similar to that observed in nuclear magnetic spin echo experiments.[2]

The purpose of the first excitation pulse is to create a superradiant state[3] which, because of its large oscillating macroscopic electric dipole moment, radiates strongly until it either decays to the ground state or loses phase coherence. In this experiment the dephasing process is dominant and is caused primarily by inhomogeneous crystal strains. After the dipole moment has dephased, a second excitation pulse is applied which essentially performs a time-reversal operation so that the system now starts rephasing. At a time after the second excitation pulse equal to the time separation of the pulses, the rephasing process is complete and the system again exhibits a macroscopic electric dipole moment resulting in a burst of coherent radiation.

A schematic outline of the experimental setup

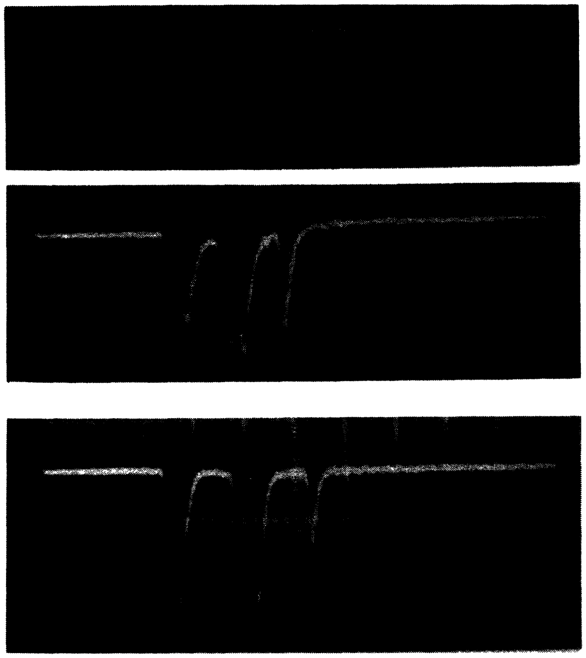

FIG. 1. Oscilloscope photographs of the output from a photomultiplier which monitors the radiation from the ruby sample. The horizontal time scale is 100 nsec/div, and time increases to the right. The excitation pulses appear broadened due to detector saturation. The positions of the echoes imply that these pulses occur ≈15 nsec later than indicated above. This is due to an observed build-up time of ≈10 nsec for the overall giant pulse, with an additional 5 nsec delay likely for the particular modes responsible for the photon echo.

is given in Fig. 2. The $Q$-switched ruby laser is triggered to produce an intense light pulse of approximately 10 nsec duration. This pulse (~200 kW) is split by a beam splitter so that one part is focused directly onto an area of $\approx 0.05$ cm$^2$ of a 1-mm thick ruby crystal (0.005% Cr), while the other part of the beam is directed into an optical delay line[4] to obtain the second pulse. The various mirrors and lenses are adjusted so that both pulses are focused at the same area of the ruby crystal, but it is important that the paths of the two pulses make some small but nonzero angle, $\varphi$, with respect to each other. In this case, it can be shown that the angle (see Fig. 2) at which the excited crystal will radiate its echo is $\approx 2\varphi$ (in the plane defined by the excitation pulses), thereby allowing an aperture to pass the echo but preventing the large initial pulses from overloading the photomultiplier. The angle $\varphi$ was $\approx 3°$ in this experiment. The echo leaves the ruby crystal along the dashed line and enters the lens which images the sample crystal on the face of the phototube. A Kerr-cell shutter is placed before the phototube to reduce the amount of scattered light from the excitation pulses. It is activated by a 100-nsec pulse to permit observation of the echo. Not shown in Fig. 2 are a pair of coils, which can provide a magnetic field of 250 gauss along the direction of the incident excitation pulses, and Dewars for keeping the ruby sample at liquid He temperature and the ruby laser crystal at liquid $N_2$ temperature. Cooling the ruby sample to liquid He temperature is necessary in order to obtain relaxation times[5] which are not short compared to the excitation pulse separation, while the laser crystal need only be cooled to the point where the $R_1$ lines in the sample and the laser crystal overlap.[6]

Several experiments were performed in order to ascertain that the observed echo was originating from the sample crystal and was not the result of a spurious reflection going back through the delay line and onto the detector. (1) The paths of the two excitation pulses were lengthened at $a$-$a$ (Fig. 2) by 2 m with no increase in the delay of the echo. (2) If a magnetic field greater than $\approx 50$ gauss (of either sign) is applied to the ruby sample along the optic axis and parallel to the incident light direction an echo is obtained, while no echo is obtained in zero magnetic field. (3) No echo is observed when the optic axis of the ruby sample is rotated by as little as 3° (or as much as 30°) with respect to the incident light direction unless the magnetic field is rotated parallel to the optic axis. The maximum rotation allowed by our experimental setup is 30°. The optic axis in the sample crystal is $\approx 15°$ to the normal of the surface of the crystal. (4) The crystal was warmed slowly by allowing the He to boil off, and it was found that a few minutes later the echo was lost. To check the possibility of the echo being an ion pulse in the photomultiplier caused by the intense excitation pulses (the results of Fig. 1 argue against this possibility), the $B-$ applied to the photomultiplier was varied between 1500 and 2000 volts with no apparent effect on the position or shape of the echo. Other experiments have been performed which also show that the observation of the echo is a genuine physical effect and will be reported in a later paper.

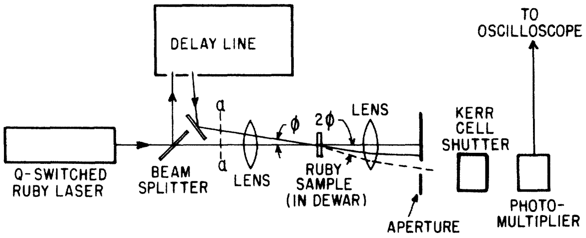

FIG. 2. Schematic experimental arrangement.

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[†] In partial fulfillment of the requirements for the Ph.D. in physics at Columbia University.

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[1] See, for example, F. J. McClung and R. W. Hellwarth, J. Appl. Phys. **33**, 838 (1962).

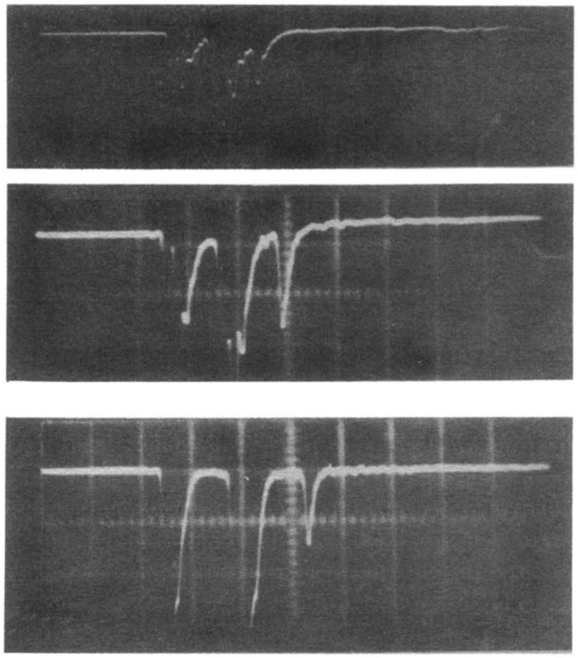
[2] E. L. Hahn, Phys. Rev. **80**, 580 (1950).

[3] R. H. Dicke, Phys. Rev. **93**, 99 (1954).

[4] Based on a mirror design by J. U. White, J. Opt. Soc. Am. **32**, 285 (1942).

[5] The relaxation time of the echo is determined principally by relaxation in the excited $^2E(\bar{E})$ state and has been studied theoretically by D. E. McCumber and M. D. Sturge, J. Appl. Phys. **34**, 1682 (1963).

[6] Absorption experiments performed in this laboratory have shown a sizeable overlap of the $R_1$ lines in ruby crystals at liquid $N_2$ and He temperatures. See also A. L. Schawlow, in Advances in Quantum Electronics, edited by J. Singer (Columbia University Press, New York, 1961), 2nd ed., p. 50.



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