Reports

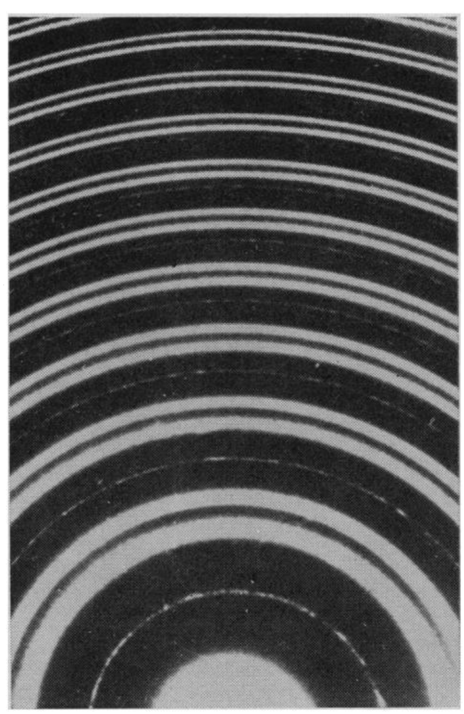
Stimulated Brillouin and Raman Scattering in Quartz at 2.1° to 293°Kelvin

Abstract. *Stimulated Brillouin shifts observed at 2.1°K in quartz are the same as those observed at 293°K. No extreme nonlinear behavior is observed. Recent anomalous results reported by Russian workers are shown to be due to the very strong stimulated Raman scattering that sets in at low temperatures.*

We have studied stimulated Brillouin (*1*) and Raman scattering in single-crystal quartz over a temperature range of 2.1° to 293°K. The velocity of sound was calculated from the Brillouin shifts at various temperatures. Contrary to a recent report by Russian workers (*2*), we found no increase in the Stokes shift at temperatures below 80°K; we did observe strong stimulated Raman radiation which could be misinterpreted as Brillouin radiation. Even at 2.1°K, where Krivokhizha *et al.* observed an anomalous increase of 2.5 times in the Stokes shift for a *z*-directed high-intensity ruby laser beam, we measured the usual Brillouin shift corresponding to the normal velocity of sound. In connection with their results, the Russian workers suggested several possible approaches by way of explanation, such as influence of the intense electric field of the light wave on the index of refraction or on the velocity of sound. Such extreme nonlinear phenomena would be exceedingly interesting and would undoubtedly stimulate much further theoretical and experimental investigation; however, our very similar quartz scattering experiments do not show the existence of such effects.

Most of our experiments were carried out with a focused 250-megawatt ruby laser attenuated to approximately 3 to 10 megawatts in order to avoid or minimize damage to the sample or to optical components in the beam path (*3*). At these power levels, and with the sample immersed in liquid helium at 2.1°K, we usually observe one Brillouin shift in a Fabry-Perot interferometer when the exciting radiation travels along the *x*- or *z*-direction. In either case the shifts are the same, respectively, as those measured at room temperature within the experimental accuracy of about 2 percent. We do, however, observe a weak additional line in radiation scattered out of the *x*-direction; because of its relative displacement (3 percent) with respect to successive interference orders of the etalon, this line is not associated with the Brillouin shifts (Fig. 1). The occurrence of this line is compatible with the 466 cm^{-1} Raman line of quartz.

In scattering along the *z*-axis, we observe a shift (with or without the regular Brillouin shift appearing) which is compatible with the 128 cm^{-1} Raman line of quartz (Fig. 2). Since interferometer measurements cannot uniquely identify widely shifted lines, we simultaneously photographed the scattered radiation on a grating spectrograph. In every case, the suspected Raman lines were observed and showed complete correlation with the unidentified Fabry-Perot etalon lines. For example, the spectrogram taken simultaneously with the interferometer picture of Fig. 2 shows only a strong line at 132 cm^{-1}, and no other lines. Thus the subsidiary line in Fig. 2 is identified as 128 cm^{-1}, stimulated vibration of the classical room temperature Raman spectrum (duly temperature shifted). Thus at 2.1°K, for *z*-directed scattering, the Raman threshold for the 128 cm^{-1} line is lower than the 466 cm^{-1} line; for *x*-directed scattering, both the 466 cm^{-1} and the 128 cm^{-1} line often appear. In all cases, the stimulated Raman radiation is sufficiently intense to pass through the narrow-band ruby-pass filter in front of the etalon. It also appears that there is a tendency for stimulated Brillouin scattering to be suppressed at the expense of stimulated Raman radiation. Such interference between Brillouin



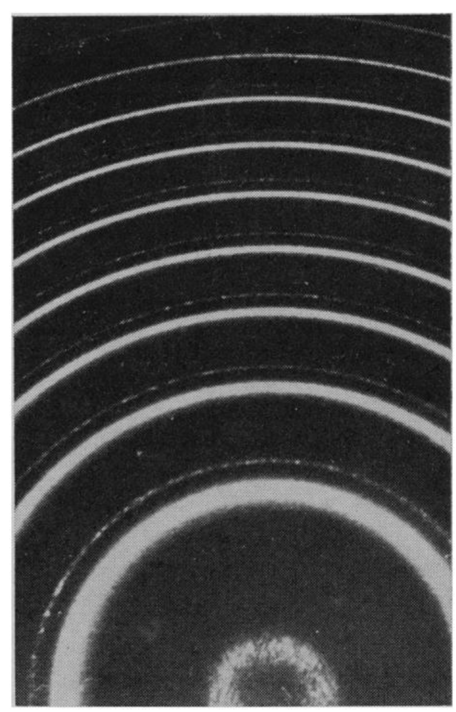


Fig. 1 (left). Fabry-Perot interferometer spectrum of backward Brillouin scattering along *x*-direction in quartz at 2.1°K. Brillouin shift is 0.84 cm^{-1}. The weak line is displaced successively by 0.11 cm^{-1} with respect to each interorder spacing and is identified to be the 468 cm^{-1} Raman line. Fig. 2 (right). Backward Brillouin scattering along *z*-direction in quartz at 2.1°K; no Brillouin shift. The weak line indicates an apparent Brillouin shift of 2.30 cm^{-1}, but is actually the 132 cm^{-1} Raman line.

and Raman processes has been observed previously (*4*).

In order to verify that additional nonlinear effects did not set in at higher powers, we raised the incident power on the dewar in small increments. The measured results continued to be the same up to 100 megawatts, at which point catastrophic failure of the helium dewar occurred.

We believe that the anomalous Brillouin shifts reported by Krivokhizha *et al.* can be attributed to stimulated Raman scattering which becomes quite strong at low temperatures. In fact, simultaneous observation of Raman and Brillouin lines on the same Fabry-Perot interferogram has enabled us to measure Raman shifts and their temperature dependences to an accuracy of 0.1 cm^{-1} (*5*).

P. E. TANNENWALD
J. B. THAXTER
Lincoln Laboratory, Massachusetts Institute of Technology, Lexington

References and Notes

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6. We thank F. H. Perry for his valuable contributions in carrying out the experimental measurements. Operated with support from the U.S. Air Force.

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Possibility of Maser Action in Cosmic Radio Sources

Abstract. *A mechanism is described for maser action in synchrotron sources. The process may contribute to the low-frequency radiation from 3C273B.*

The question raised here is whether a substantial part of the radiation from a cosmic radio source may be due to induced emission rather than spontaneous emission. Such a situation can arise when a population inversion exists in the energy source of the radiation and when the source is optically thick to its own radiation, as is the case with an ordinary maser.

It is widely believed that the radio power emitted from cosmic radio sources is synchrotron radiation—the classical radiation of relativistic electrons gyrating in a magnetic field (*1–5*). Most of the power is radiated by the electrons at high harmonics of their gyrofrequency, which is given by

$$\nu_g = \frac{\nu_0}{\gamma} = \frac{eH}{2\pi mc\gamma} \quad (1)$$

where γ is the Lorentz factor of the electron. Appreciable power is radiated at harmonics up to a critical frequency given by

$$\nu_c = \frac{3}{2}\,\nu_g\,\gamma^3 \quad (2)$$

It is to be expected that inhomogeneities in the magnetic field over the orbit of the electron will cause the line width of a given harmonic to be much larger than the spacing between harmonics. If so, the power spectrum radiated by a given electron will be a continuum, whose shape is given by (*6*)

$$p(\nu,\gamma) = \frac{\sqrt{3}e^3 H}{mc^2}\,\frac{\nu}{\nu_0}\int_{\frac{\nu}{\nu_c}}^{\infty} K_{5/3}(x)\mathrm{d}x \approx$$

$$\frac{\sqrt{3}e^3 H}{mc^2}\begin{cases} 2.15\,(\nu/\nu_c)^{\frac{1}{3}},\ \nu/\nu_c \ll 1 & \text{(a)} \\ 1.25(\nu/\nu_c)^{\frac{1}{2}}\,e^{-\nu/\nu_c},\ \nu/\nu_c \gg 1 & \text{(b)} \end{cases} \quad (3)$$

If a radio source is optically thick to its own synchrotron radiation, one has to calculate the induced emission and absorption of synchrotron radiation as well as the spontaneous emission given by Eq. 3. The rate of induced emission and absorption can be calculated from the rate of spontaneous emission by means of Einstein's relations. Ordinarily, absorption exceeds induced emission, so that a radiator which is optically thick can emit radiation only from a surface layer. But in certain situations, such as a maser, the induced emission can exceed the absorption. In this case, the combination of the two processes is called negative absorption.

Is it possible for a source of synchrotron radiation to display this phenomenon? This question was examined in a very interesting paper by Twiss (*7*), before the advent of quasars. He concluded that if the relativistic electrons have a population inversion, that is, if there are more electrons at higher energies than at lower energies, negative absorption is indeed possible. Unfortunately, as was shown later, Twiss had not included the statistical weights of the electrons correctly. A correct calculation (*8*) showed that under the circumstances described by Twiss, negative absorption is not possible. The conditions necessary for negative absorption have been reviewed in a very lucid fashion by Wild *et al.* (*9*).

I have examined the question of negative absorption again, and have found that it is possible after all. This conclusion differs from previous ones because the effect of an ambient plasma on the synchrotron radiation has been included. In order to describe this effect, I shall proceed from the discussion of Wild *et al.* (*9*). There, one finds the derivation of a formula (Eq. 27 in *9*, p. 348) for the general coefficient of absorption of a radiating system. For the special case of synchrotron radiation, it becomes (*3*)

$$K(\nu) = \frac{1}{4\pi m\nu^2}\int_1^{\infty}\mathrm{d}\gamma\,\frac{N(\gamma)}{\gamma^2}\,\frac{\mathrm{d}}{\mathrm{d}\gamma}\times [\gamma^2 p(\nu,\gamma)]\ \mathrm{cm}^{-1} \quad (4)$$

where $N(\gamma)\mathrm{d}\gamma$ is the number of electrons per unit volume having Lorentz factors between γ and $\gamma + \mathrm{d}\gamma$.

If, as is the usual case, $K(\nu)$ is positive, the radiation from an optically thick body comes mainly from a surface layer of thickness K^{-1} and is less than that due to spontaneous emission alone. But if $K(\nu)$ is negative, the radiation from an optically thick body may exceed the spontaneous radiation by the factor (approximately)

$$\tau(\nu)^{-1}\,e^{\tau(\nu)} \quad (5)$$

where

$$\tau(\nu) = -\int_0^L K(\nu,x)\mathrm{d}x \quad (6)$$

is the integral of the absorption coefficient across the radiating system, whose depth is L.

Equation 4 gives the criterion for negative absorption. The relativistic electron distribution $N(\gamma)$ must be confined primarily to an energy region such that $(\mathrm{d}/\mathrm{d}\gamma)[\gamma^2 p(\nu,\gamma)]$ is negative. But the $p(\nu,\gamma)$ given by Eq. 3 never decreases faster than $\gamma^{-2/3}$ (for fixed ν); therefore, regardless of the electron distribution, negative absorption is not possible for such a system of synchrotron radiators.

Now let us consider how the situation is altered by the presence of an ambient plasma. In this case, the synchrotron power spectrum has a striking difference from that of Eq. 3, known to radio astronomers as the Razin effect (*10–12*). The detailed discussion of this effect is rather involved; for our purposes, a heuristic discussion due to Scheuer (*11*) will suffice.

It is well known that a simple plasma