the number of H_3^+ ions that have been produced from the N_ν H_2^+ ions in the vibrational level ν. Defining the relative cross section for this process as

$$\sigma_\nu = N_\nu'/N_\nu, \tag{4}$$

it follows immediately that

$$\sigma_\nu = \alpha_\nu'/\alpha_\nu. \tag{5}$$

The values for σ_ν reported in Table I have been obtained from Eq. (5) and are expressed in terms of the value for $\sigma_{\nu=0}$ which has been set arbitrarily equal to 1.0.

Our interpretation is based on the assumption of identical collection efficiencies for H_2^+ and H_3^+ ions. Evidence for this has been discussed extensively by Reuben and Friedman.[5] Their discussion centers around a conjecture of Polanyi[6] on energy transfer processes in elementary reactions. Polanyi predicts the appearance of heat of reaction as vibrational energy rather than kinetic energy in the secondary ions. Experiments with retarding potentials are presently being attempted in this laboratory to confirm the above assumption. These experiments are complicated by the fact that the retarding potentials interfere with the electron selector.

To our knowledge, cross sections for the reaction (1), with such great detail and such low ionizing electron energies, have not been reported in the literature. However, Gutbier,[7] and Reuben and Friedman[5] have published values for the absolute cross sections corresponding to ionizing electron energies of 75 eV and 50 eV, respectively.

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STIMULATED BRILLOUIN SCATTERING AND COHERENT GENERATION OF INTENSE HYPERSONIC WAVES*

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Stimulated Brillouin scattering of an intense maser beam, involving coherent amplification of a hypersonic lattice vibration and a scattered light wave, has been detected in quartz and sapphire. This process is analogous to Raman maser action, but with molecular vibration replaced by an acoustic wave of frequency near 3×10^{10} cps, and with both the acoustic and scattered light waves being emitted in specific directions.

Either compressional or shear waves can be excited, but for a compressional wave the coupling between acoustic and optical waves is simplest, and describable as electrostriction. Electrostrictive pressure is given by $p=(E^2/8\pi)\rho d\epsilon/d\rho =(E^2B/8\pi)d\epsilon/dp$, where E is the electric field, ρ the density of material, ϵ its dielectric constant, and B the bulk modulus. Thus two optical waves whose frequencies differ by ω_S can drive a pressure wave of this frequency, due to the quadratic dependence of pressure on E and the consequent generation of a beat frequency. Similarly, a pressure wave of frequency ω_S couples to an electromagnetic wave E through the varying induced dipole moment density $(E/4\pi)(d\epsilon/dp)p$.

If one assumes an intense driving wave, as from an optical maser, of form $E_0\cos(\omega_0 t-\vec{k}_0\cdot\vec{r})$, a scattered electromagnetic wave $E_{-1}\cos[(\omega_0-\omega_S)\times t-\vec{k}_{-1}\cdot\vec{r}+\varphi_{-1}]$, and an acoustic wave $p_0\cos(\omega_S t$

$-\vec{k}_S \cdot \vec{r} + \varphi_S)$, the power transfer or amplification may be easily calculated from the above coupling terms following, for example, Garmire, Pandarese, and Townes,[1] or Kroll.[2] Maximum gain occurs when $\vec{k}_0 = \vec{k}_{-1} + \vec{k}_S$, from which may be derived the relation $\omega_S = 2\omega_0(vn/c)\sin\frac{1}{2}\theta$, where v is the velocity of the acoustic wave of frequency ω_S, n the index of refraction (assumed identical for ω_0 and $\omega_0 - \omega_S$), and θ is the angle between incident and scattered electromagnetic radiation. Such an expression was originally given by Brillouin,[3] who discussed the scattering of light by thermally excited acoustic waves. This is the normal Raman process which corresponds to the stimulated emission and amplification discussed here.

The threshold condition for buildup of the acoustic and scattered wave when the radiation is contained in a resonant cavity can be derived from the above as[4]

$$\frac{E_0^2}{8\pi} \geq \frac{2\epsilon B}{(\rho d\epsilon/d\rho)^2 k_S L_S k_{-1} L_{-1}},$$

where L_S and L_{-1} are decay lengths, or inverse effective absorption coefficients, of the sound and light waves, respectively. For $L_S = 10^{-2}$ cm, $L_{-1} = 10^2$ cm, and for normal bulk moduli, the power flow $nE_0^2c/8\pi$ across the cavity to meet the threshold condition for amplification is about 1 MW/cm^2. Kroll[5] has examined the traveling wave case, and in particular the behavior of a backward-scattered light wave. The threshold condition in this traveling wave case is

$$\frac{E_0^2}{8\pi} \geq \frac{2\epsilon B}{(\rho d\epsilon/d\rho)^2 k_S k_{-1}} (L_S^{-1} + L_{-1}^{-1})^2.$$

For the above values of L_S and L_{-1}, this gives a threshold power flow of about 10^4 MW/cm^2. The maximum energy which can be thus fed into acoustic waves due to first-order scattering is the fraction ω_S/ω_0 given by the ratio of phonon-to-photon energies, or the order of 10^{-4} of the input energy. Substantial buildup of the acoustic wave and scattered light during the short pulse of a giant-pulse maser requires, of course, light intensities which are appreciably above threshold, and only under these conditions can the acoustic energy approach this maximum or the scattered wave be easily detected. Some additional theoretical considerations and details are in a forthcoming paper.[4]

The experimental arrangement for the generation and observation of the stimulated Brillouin radiation is shown in Fig. 1. Intense 6940Å radiation from a giant-pulse ruby maser with a power output of ~50 megawatts during 30 nsec was focused inside the sample. At the focus, assuming no optical distortions within the crystal, the power density would be of the order of 10^6 MW/cm^2. The Brillouin radiation scattered in the backward direction was chosen for study; it has the maximum frequency shift and least dependence of frequency on angle, thus leading to better resolution and higher accuracy of measurement of the frequency shift. Furthermore, for

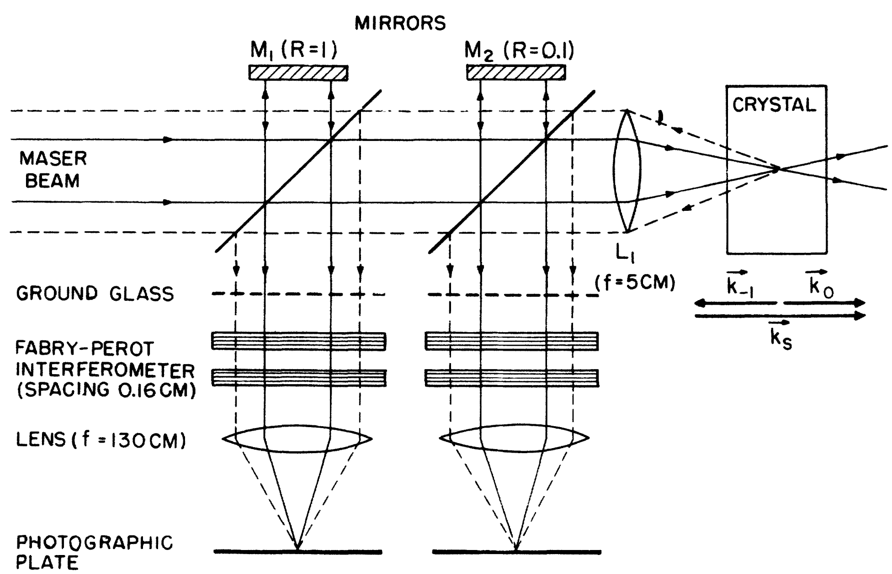

FIG. 1. Schematic of experimental arrangement.

this direction the maximum buildup is expected for the scattered light and the corresponding acoustic wave which, from the wave-vector equation, travels in the direction of the incident light. The back-scattered radiation collected by the lens L_1 in Fig. 1 was detected and resolved with the aid of the two Fabry-Perot interferometers. Maser radiation of different intensities was also sampled by the interferometers using the glass-plate beam splitters and mirrors M_1, M_2 having reflectivities of 1 and 0.1, respectively. Thus a comparison of the two interferograms photographed simultaneously distinguished clearly between radiation coming from the ruby, and that scattered directly backward from the sample.

A comparison of the two interferograms in Fig. 2, taken with a single maser pulse, makes it evident that the inner rings come from radiation scattered directly backward from the quartz sample. The inner ring is hence identified as B for Brillouin scattering in this figure, and the other set of rings as M for the original maser light. It can be seen that the Brillouin scattering is very intense, being comparable in intensity with the incident light, and hence evidently much amplified over the normal intensity of Brillouin scattering. The interorder separation of the interferometers was 3.15 cm^{-1}. It can be seen that the scattered light is shifted by about 1 cm^{-1}, corresponding to an acoustic wave of frequency near 3×10^{10} cps.

The frequency shifts of light scattered by stimulated Brillouin emission from quartz and sapphire are listed in Table I. Frequency shifts listed in the first two lines for light incident along and perpendicular to the C axis in quartz are average values of several measurements on two plates, and are accurate to about 3%. Less intense interferograms of Brillouin scattered radiation in sapphire, and for scattering at 90° in

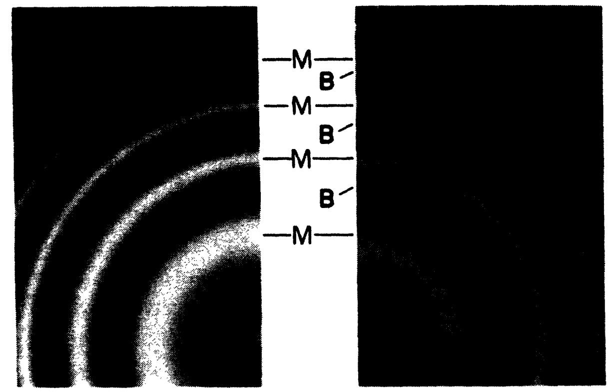

FIG. 2. Fabry-Perot interferograms of the maser radiation (rings labeled M) and of the Brillouin scattered radiation (rings labeled B) from quartz.

quartz, were also obtained. The measured shifts for these, which are also given in Table I, may be somewhat less accurate. The observed shifts are all in good agreement with those calculated from known elastic constants for small strains, which are included in Table I for comparison. They are also consistent with shifts measured by Krishnan[6] from normal Brillouin scattering. Thus there seems to be no doubt that we are observing Brillouin scattering, and the high intensity compared with normal scattering shows marked amplification and buildup of the corresponding acoustic waves.

Each pulse of maser light which was of sufficient intensity to produce this large buildup of Brillouin scattering also caused extensive internal fractures in the crystal. This is to be expected from the high local stresses produced by the intense acoustic wave present, or by the local heating which results from damping of these acoustic waves. The latter type of heating is appreciably larger than that due to normal optical ab-

Table I. Measured frequency shifts of scattered light and comparison with calculated values.

Crystal	Direction of incidence and scattering angle	Observed shift (cm^{-1})	Calculated shift[a] (cm^{-1})
Quartz	∥ to C axis, 180°	0.99	0.97[b]
	⊥ to C axis, 180°	0.85	0.88[c]
	∥ to C axis, 90°	0.73	0.67[d]
Sapphire	∥ to C axis, 180°	2.07	2.01[b]

[a]Calculated from elastic constants [H. B. Huntington, Solid State Phys. 7, 213 (1958)].
[b]Using $\rho v_L^2 = C_{33}$.
[c]Using $\rho v_L^2 = C_{11}$.
[d]Using $\rho v_L^2 = \frac{1}{2}(C_{11}+C_{12}+C_{44})$.

sorption in good optical materials. At low temperatures, acoustic losses can be much less, threshold power densities much lower, and longer pulses of less intense radiation should result in generation of more moderate amounts, and more controlled acoustic waves.

The amplification of hypersonic waves due to stimulated Brillouin scattering may be viewed as phonon maser action, although it may also be called parametric amplification, and the mechanism involved is rather different from phonon masers using paramagnetic materials.[7] Stimulated Brillouin scattering affords a method of generating very intense hypersonic waves (in present cases approximately one kilowatt) at frequencies higher than those previously available (e.g., approximately 60 000 Mc/sec produced here in sapphire). Furthermore, hypersonic waves of very high frequency can be thus generated in most substances rather than only in very limited classes of materials, and their propagation studied. In regions of high anomolous dispersion, coherent oscillations of still much higher frequencies may be induced; these correspond to optical branches of the acoustic spectrum,[8] and in the extreme case to the normal molecular Raman scattering.

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PRODUCTION OF A BEAM OF POLARIZED NEGATIVE HYDROGEN IONS*

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In the study of nuclear scattering and reactions, polarization measurements frequently are essential for a detailed understanding of the processes involved. In the past, most such experiments made use of the double-scattering technique, whereby the first scattering (or reaction) produces the polarized particles. The disadvantages of this method are that the counting rates are low, that the polarized beam from the first target has a large spread in energy and angle, and that the polarization varies with energy. Also, for deuterons, there is no scatterer for which the phase shifts are known well enough to predict the polarization of the outgoing deuterons.

For these reasons, there is considerable interest in methods by which polarized particles can be obtained from accelerators. In practice, this has been accomplished at Harwell[1] and at Minnesota,[2] with linear accelerators, and at Saclay[3] with a cyclotron. Also, at the Department of Terrestrial Magnetism a polarized beam has been injected into an electrostatic accelerator.[4] This was possible only because of the unusually large size of the high-voltage terminal of this machine, and has the disadvantage that the rather complex ion source is inaccessible for repair and must be operated by remote control.

Important advantages can be gained if it is possible to produce negative hydrogen ions with nuclear polarization. Negative ions can be accelerated by a tandem electrostatic accelerator, in which case the ion source is at ground potential. In addition, of course, one gains the advantage of the energy doubling which results when the negative ions are stripped of their electrons in the terminal of the machine and are then accelerated to ground potential.

The negative ions are usually produced by passing an intense beam of positive ions of about 50-

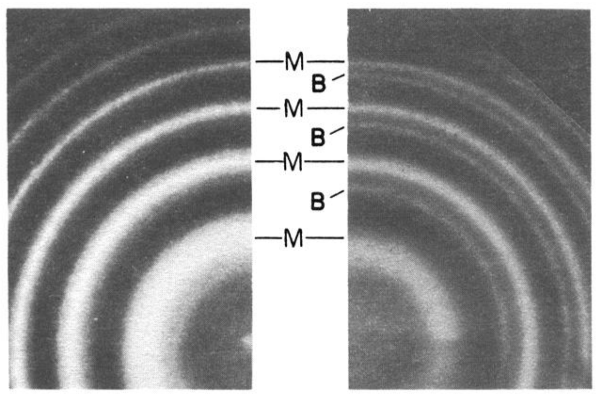

FIG. 2. Fabry-Perot interferograms of the maser radiation (rings labeled M) and of the Brillouin scattered radiation (rings labeled B) from quartz.