LASER-BEAM-INDUCED BREAKDOWN AND STIMULATED MANDEL'SHTAM–BRILLOUIN SCATTERING IN LIQUID He^4

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Threshold parameters were determined for the breakdown of liquid and gaseous helium by a ruby laser beam. The low-temperature method for investigating optical breakdown made it possible to find the cause of the appearance of the first "priming" electrons. The removal of a fine suspension from liquid helium showed that, at the beam intensities at which laser-beam induced sparks were usually observed, the breakdown was initiated by thermionic or photoelectric emission of electrons from the finest dust particles. Two consecutive components of the stimulated Mandel'shtam–Brillouin scattering were observed in liquid helium when the laser beam power was $I \approx 10^{10}$ W/cm^2. The shifts of the Mandel'shtam–Brillouin components corresponded to the temperature dependence of the velocity of the first sound in liquid helium in the temperature range 4.2–1.8

1. A low-temperature method for measuring the threshold parameters of the breakdown of helium by a ruby laser beam is described in [1, 2]. The threshold beam intensity is governed by the helium gas density and it should be independent of the gas temperature. This makes it possible to use a dense gas at low temperatures instead of employing high pressures at room temperature. The breakdown is indicated by the appearance of a spark at the focal point of a lens. This focal point is located either in the liquid helium or above it, where the density depends on the height above the liquid level in a Dewar flask. In measurements of the breakdown threshold of liquid helium, boiling is prevented by increasing the pressure in the flask slightly above the equilibrium value. The spark is photographed through a window in the cap of the Dewar-flask. The structure and the shape of the spark is the same in liquid and gaseous helium. The dependence of the threshold parameters on the density can be plotted on the same graph for liquid (density $\rho = 0.145–0.08$ g/cm^3) and gaseous (density $\rho = 0.04–0.004$ g/cm^3) helium. The experimental points fit satisfactorily the single smooth curve given in our earlier paper.[2] The nature of this dependence is the same at room temperature and high pressures.[3, 4] Thus, the breakdown in liquid helium simulates the breakdown in gaseous helium of the same density (helium gas at a pressure of $\sim 10^3$ atm at room temperature). The breakdown in liquid helium is accompanied by boiling, which can be seen clearly if the focal point region is illuminated by a second light source. Boiling is not observed in the light of the spark itself. However, the exact moment of the beginning of boiling cannot be determined in such experiments and it is possible that the breakdown processes develop in very fine bubbles which are formed at the focus of the laser beam.

This low-temperature method should make it possible to investigate a pure dense medium since all impurities should be frozen out and precipitated. Therefore, it would be interesting to use this method in an investigation of the origin of the first "priming" electrons which initiate an avalanche-like ionization in a dense medium illuminated with a laser beam. The low-temperature breakdown in helium may be initiated only by two processes: 1) a 14-quantum photoionization of the helium atoms; 2) thermionic or photoelectric emission of electrons from solid submicroscopic particles which may be suspended in the helium.

An analysis of a large number of experiments[2] showed that the development of an avalanche required a much lower light intensity than the formation of first electrons and that the onset of the ionization should be attributed to the presence of a fine suspension in helium. In some experiments, an easily reproducible sharp threshold was obtained for a given helium density and the dependence of the threshold parameters on the density was in the form of a smooth curve. In other experiments, the breakdown began at quite different light intensities although the density of helium was kept constant. In the case of He II, in which a fine suspension was known to coagulate and precipitate rapidly, the breakdown was frequently not observed even at laser powers which were ten times greater than the power sufficient to cause breakdown in ordinary helium of the same density. The origin of the "priming" electrons initiating an avalanche was determined in experiments in which a mixture of hydrogen and helium was drawn into a Dewar flask containing liquid helium, in such a way that the resultant concentration of H_2 was only $\sim 10^{-7}–10^{-9}$. It was found that the addition of hydrogen always reduced the breakdown threshold of liquid helium to a very small value corresponding to that found in experiments in which the dependence of the breakdown threshold on the density of the medium could be represented by a smooth curve.

The conclusion on the source of the first electrons was later confirmed very clearly by experiments in which liquid helium was purified with electrified aerosol filters (Petryanov filters).[5]

A plug consisting of several filter layers was placed at the bottom of a Dewar flask. This plug could be lifted by a rod which passed through a gland in the cap of the Dewar flask. Before illumination, the plug was raised very slowly so that the lower part of the flask was occupied by helium which had been "strained" by passing through the filters. An exceptionally pure nonboiling helium collected below the plug. No breakdown was observed in such filter helium even at the maximum laser powers (using a light flux $I \approx 6 \times 10^{10}$ W/cm^2, instead of $I \approx 2 \times 10^9$ W/cm^2 which was sufficient to cause breakdown in helium from which dust had not been removed).

It is usual to assume that the first electrons originate from impurity atoms although the ionization potential for all gases is much lower than the photon energy, which is 1.78 eV. We are of the opinion that the results of measurements on cold helium should be taken into account in investigations of laser breakdown in dense gases which may also contain dust particles. (A strong laser pulse heats the windows of a chamber containing a dense gas and this generates a sound wave which shakes loose the dust particles adhering to the walls.) There are also some suggestions[6] that the first electrons are due to thermionic emission from laser-beam-heated dust particles.

2. A strong scattering of light at an angle of 180° to the direction of propagation of the laser beam was observed in liquid helium purified by the method described in the preceding section. It was concluded that this was due to the stimulated Mandel'shtam–Brillouin scattering.[2] Stimulated scattering in liquid He^4 was reported earlier in [7].

The apparatus shown schematically in Fig. 1 was used to investigate the stimulated scattering in liquid helium in the temperature range 4.2–1.8°K. A ruby laser produced 20 MW pulses of 20 nsec duration. The laser beam was focused in the helium by a lens whose focal length was 4.5 cm. The divergence of the beam was about 2×10^{-3} rad. A spectroscopic investigation of the stimulated radiation was carried out using a Fabry–Perot etalon; the dispersion of the etalon was 0.05 cm^{-1}. Interferograms were obtained using Infra-760 photographic plates. The focal length of the lens (L_2) used in focusing the image on the plates was 2 m. The interferograms were interpreted by analyzing the noncentral bands.

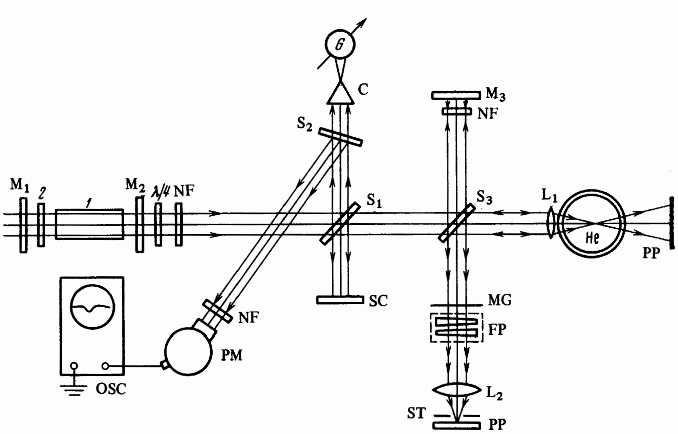

FIG. 1. Schematic representation of the apparatus. 1) Ruby crystal; 2) cuvette containing a solution of vanadium phthalocyanine in nitrobenzene; M_1 and M_3 are dielectric mirrors with a reflection coefficient R = 99.5%; M_2 is a plane-parallel plate; λ/4 is a quarter-wave plate for a radiation of λ = 6943 Å; NF are neutral filters; S_1, S_2, and S_3 are glass-plate beam splitters; C is a calorimeter; MG is matt glass; ST is a stop; PP are photographic plates; SC is a screen; PM is a photomultiplier FÉU-28; OSC is an oscillograph of the S1-11 type; L_1, L_2 are lenses.

The spectral width of the laser radiation line was $\Delta\nu_L$ = 0.025–0.03 cm^{-1}. This width of the laser line made it very difficult to determine the spectral shift of the scattered component relative to the exciting line. The spectrum of the back-scattered radiation, obtained at the highest laser power, always consisted of two consecutive components and the spectral width of the scattered radiation was less than the width of the exciting radiation. We assumed that, at laser beam intensities slightly higher than the stimulated scattering threshold, the shifts of the consecutive components were practically the same[8] and we measured the interval $\Delta\nu$ between the scattered radiation components. Figure 2 shows the interferograms obtained when the mirror M_3 was covered. Table I gives the experimentally determined shifts of the components of the scattered light and the velocities of hypersound in liquid helium, calculated from these shifts. The shifts $\Delta\nu$ given in Table I were obtained by averaging the results obtained from several interference patterns. The error in the measurement of the shift was ±0.002 cm^{-1}. The last column of Table I gives the values of the velocity of the first sound (1.3 MHz) in liquid helium at the corresponding temperatures; these values were taken from [9]. It is evident from Table I that the observed scattering is due to the Mandel'shtam–Brillouin mechanism associated with the propagation of the first sound in He I and He II. The frequency of the hypersound in helium, in the Mandel'shtam–Brillouin scattering, was ~650 MHz. No appreciable dispersion of the velocity of sound was observed. In all the scattering experiments, no breakdown of helium was observed so that no plasma was generated in the focal region. Possible heating of helium in the region where the Mandel'shtam–Brillouin scattering was observed did not affect the value of the shift $\Delta\nu$ of the components of the scattered light because they followed satisfactorily the temperature dependence of the velocity of the first sound in liquid helium. It was likely that such heating occurred somewhat later. Table I also shows that the shifts $\Delta\nu$ were not affected by "pulling" into the nearest laser modes: the dependence of the shift on the temperature of helium always obeyed a definite law.

In the presence of feedback between the laser and the scattering medium, the laser line and the two Mandel'shtam–Brillouin components were poorly resolved in the photographs obtained using a laser line $\Delta\nu$ = 0.025–0.03 cm^{-1} wide and a Fabry–Perot etalon with 0.05 cm^{-1} dispersion.

The photographs in Fig. 2 could not be regarded as

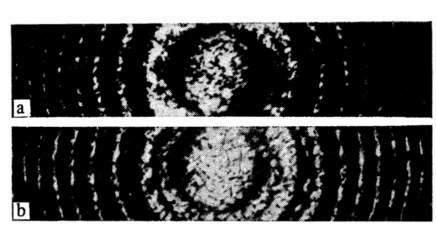

FIG. 2. Spectrograms of two consecutive Stokes components of the stimulated Mandel'shtam-Brillouin scattering in liquid He^4 obtained at the following temperatures of helium: a) 4.2°K; b) 1.8°K.

Table I.

Temperature of liquid helium T, °K	Shift of MB components Δv, cm⁻¹	Velocity of sound v, m/sec (deduced from shift)	Velocity of sound v, m/sec (taken from [9])
4.2	0.017	177	180
2.9	0.021	219	220
2.7	0.021	219	222
2.1	0.021	219	223
1.8	0.022	229	230

showing definitely that the two components were due to consecutive Mandel'shtam–Brillouin scattering and not due to the presence of two simultaneously excited types of stimulated scattering. Thus, the outer component could be due to stimulated thermal (entropy) scattering,[10] because—in the case of liquid helium—it practically coincided with the exciting laser line. This was checked by suppressing feedback between the laser and the scattering medium by means of a $\lambda/4$-plate. When such "decoupling" was employed, only one component was observed in all the photographs (at the same maximum power of the exciting radiation). When the mirror M_3 was not covered but the laser was "decoupled" from the scattering medium, this component did not coincide with the laser line but it was the Stokes satellite of this line, shifted by $\Delta\nu \approx 0.02\ \mathrm{cm}^{-1}$.

Thus, the strong back-scattered radiation contained only the stimulated Mandel'shtam–Brillouin components corresponding to the velocity of propagation of the first sound in liquid helium. In superfluid helium, the thermal scattering should not be observed because $c_p/c_V \approx 1$ (c_p and c_V are the specific heats at constant pressure and volume) and the central component in the thermal scattering should be much weaker than the Mandel'shtam–Brillouin doublet.[11] Moreover, there were no grounds for assuming that the temperature dependence of the polarizability of helium atoms was strong.

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[1] I. I. Abrikosova and M. B. Shcherbina-Samoĭlova, ZhETF Pis. Red. 7, 305 (1968) [JETP Lett. 7, 238 (1968)].

[2] I. I. Abrikosova and O. M. Bochkova, ZhETF Pis. Red. 9, 285 (1969) [JETP Lett. 9, 167 (1969)].

[3] R. G. Meyerand Jr., and A. F. Haught, Phys. Rev. Lett. 11, 401 (1963).

[4] D. H. Gill and A. A. Dougal, Phys. Rev. Lett. 15, 845 (1965).

[5] I. I. Abrikosova and A. I. Shal'nikov, Prib. Tekh. Eksp. No. 2, 242 (1970).

[6] A. Gold and H. B. Bebb, Phys. Rev. Lett. 14, 60 (1965).

[7] G. Winterling, G. Walda, and W. Heinicke, Phys. Lett. 26A, 301 (1968).

[8] D. I. Mash, V. V. Morozov, V. S. Starunov, and I. L. Fabelinskiĭ, Zh. Eksp. Teor. Fiz. 55, 2053 (1968) [Sov. Phys.-JETP 28, 1085 (1969)].

[9] J. C. Findlay, A. Pitt, H. Grayson Smith, and J. O. Wilhelm, Phys. Rev. 54, 506 (1938); 56, 122 (1939).

[10] G. I. Zaĭtsev, Yu. I. Kyzylasov, V. S. Starunov, and I. L. Fabelinskiĭ, ZhETF Pis. Red. 6, 802 (1967) [JETP Lett. 6, 255 (1967)].

[11] V. L. Ginzburg, Zh. Eksp. Teor. Fiz. 13, 243 (1943).

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