actic nucleosynthesis is necessary.

We thank Mr. J. Brown for his competent and meticulous work in obtaining the whitlockite separate and in sample preparation. Frequent discussions with W. A. Fowler have been both stimulating and thought provoking. This experiment was conceived when the authors became aware of the high density of tracks and uranium found in whitlockite by Paul Pellas.[21] We thank O. Eugster for useful comments on the manuscript.

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EXPERIMENTAL OBSERVATION OF SOMMERFELD AND BRILLOUIN PRECURSORS IN THE MICROWAVE DOMAIN*†

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An experimental investigation of transient electromagnetic wave propagation in the microwave frequency range related to the theoretical investigation of Sommerfeld and Brillouin is reported. Both the Sommerfeld and Brillouin precursors are shown experimentally.

In 1914, Sommerfeld and Brillouin calculated the propagation of a transient signal (specifically a sine wave starting at $t=0$ and terminating at $t=T$) through a dispersive medium. The dispersion relation (Fig. 1) of the medium which they considered was given by $k=(\omega/c)[1+a^2/\omega_0^2-\omega^2)]^{1/2}$ where ω_0 is the characteristic frequency of the electron and a is related to the charge, the mass, and the number of electrons in a unit volume. The response to the above mentioned excitation was calculated in a series of now classic papers which are summarized in a book by Brillouin.[1]

The interesting results of their calculations can be summarized in modern terms as follows: At a given observation point z the main contribution at any time t results from those points on the dispersive curve (see Fig. 1) whose tangent is parallel to z/t. For $\omega \rightarrow \infty$ the tangent of the dispersion curve is c (velocity of light in free space) and is the steepest tangent in the dispersion characteristic. Hence at a given z, no response is observed for $z/t > c$. At a time $t_S = z/c$ the response starts. This is the star of Sommerfeld precursor. In the limit, the contributing frequency approaches infinity at this point in time. As time progresses, the point which gives the main contribution moves along the upper branch of the dispersion curve towards points of smaller abscissa and smaller ordinate; the frequency decreases. At a time given by $z/t_B = c/(1+a^2\omega_0^{-2})^{1/2}$ the first contribution from the lower branch of the dispersion curve (from the point of $\omega = 0$ ordinate) is obtained. This point gives rise to the Brillouin precursor whose first half-cycle is described by an Airy function. As time progresses beyond t_B, contribution to the response from increasing frequencies is obtained from points on the lower branch of the dispersion curve.

The essential features of the propagation of transients in dispersive media were well understood by Sommerfeld and Brillouin. At that time, however, when the asymptotic (stationary-phase, saddle-point) calculations were made, the experimental facilities in the microwave and optic range were inadequate to observe transients. To our best knowledge neither microwave nor optic experiments have been performed hitherto in order to demonstrate precursors.

The microwave experiments presented here are believed to be new and are related to the problem considered by Sommerfeld and Brillouin. In all, three experiments were performed on guiding structures which have dispersion characteristics similar to that of the unbounded dielectric medium.

The first experiment was performed with a ferrimagnetically filled coaxial line. The fundamental mode of this guiding structure has two propagation branches as in Fig. 1, where the characteristic frequencies ω_0 and $(a^2+\omega_0^2)^{1/2}$ are both dependent on the externally applied magnetic field. Here the slope for very high frequencies approaches $c(\epsilon_r)^{-1/2}$. A pulsed sine wave was applied to this structure with a carrier frequency of 0.625 GHz and a rise time of approximately 1 nsec. The response is shown in Fig. 2. With zero applied field, the sine wave is propagated without much distortion. As the field strength is increased to 20 G, the carrier frequency, still above the value of ω_0 but already below $(a^2+\omega_0^2)^{1/2}$, does not propagate, but the precursors propagate and the high-frequency (Sommerfeld-type precursor) and low-frequency (Brillouin precursor)

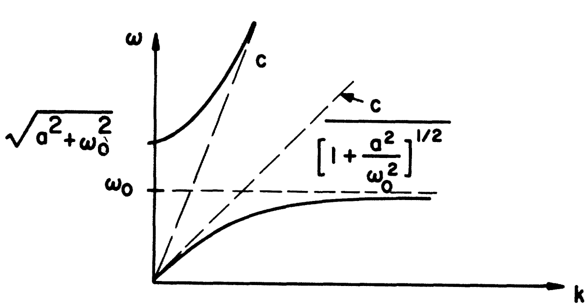

FIG. 1. Unbounded dielectric dispersion characteristic.

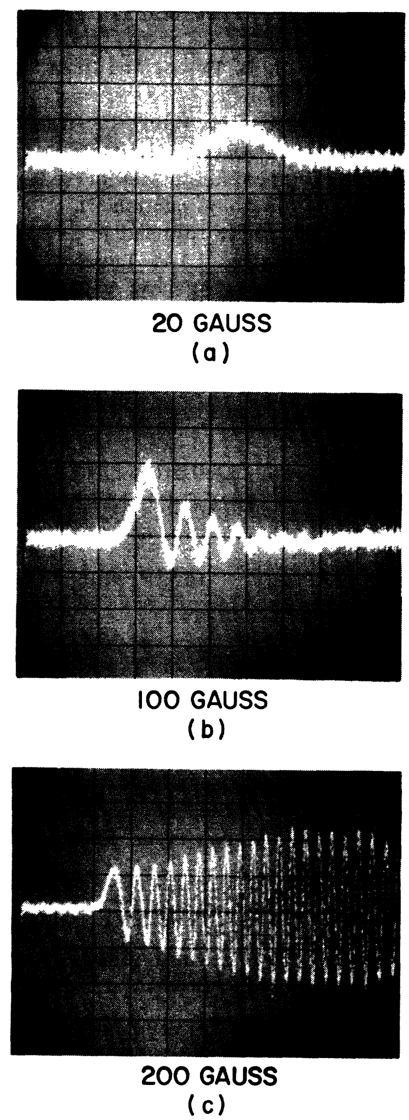

FIG. 2. Pulsed sine-wave response (5 nsec/div).

components of the pulse are clearly visible. As the field strength is increased to 100 G, the Sommerfeld-type precursor is no longer visible (being masked by noise), the Brillouin precursor is visible, but the main signal does not propagate. At 200 G, the relative situation of the frequencies ω_0, $(a^2+\omega_0^2)^{1/2}$, and the carrier is approximately that of the case considered by Sommerfeld and Brillouin, and it is clearly seen that, as predicted by them, the Sommerfeld-type precursor is not visible (due to oscilloscope noise), but that the Brillouin precursor is visible and is followed by the main signal.

To investigate the transient characteristics of these branches separately, we chose two different guiding structures which have transient characteristics similar to these two branches discussed previously. The optic mode of an infinite plasma or an air-filled rectangular waveguide in the TE_{10} mode has a dispersion characteristic which displays the Sommerfeld precursor. We chose the air-filled guide for experiments. The Harms-Goubau line (a surface-wave line) propagates a quasi-TEM mode which for early parts of the transient response is similar to the lower (dielectric) branch.

For the air-filled waveguide experiment, we chose C-band waveguide with a cutoff frequency of 4.29 GHz. To obtain good spectral separation of the frequency components on a time basis and be as close to the source as possible (because of amplitude considerations) we chose a 6-ft length of waveguide (1.83 m). Our source of excitation was a fast rise-time pulse generator (HP1105A, 1106A combination), which yields a 30-psec risetime. We viewed our response on a Hewlett Packard 12.4-GHz sampling oscilloscope. The input reference and response wave forms are shown in Figs. 3(a) and 3(b). The input reference was obtained by using the output of the two coaxial-to-waveguide adapters connected back to back as the reference signal. To measure the delay to any point on the response wave form, we positioned the expander dot on a point on the response wave form and measured the delay to that point on the oscilloscope display. To measure the frequency at that point we set the scope display on the expanded scale and assumed that the wave form corresponding to the position of the dot was in the center of the scope display. Since the accuracy of such a procedure is in question, we plotted the frequency as a function of normalized delay for quite a wide range of frequencies in the response and compared it with the group-delay

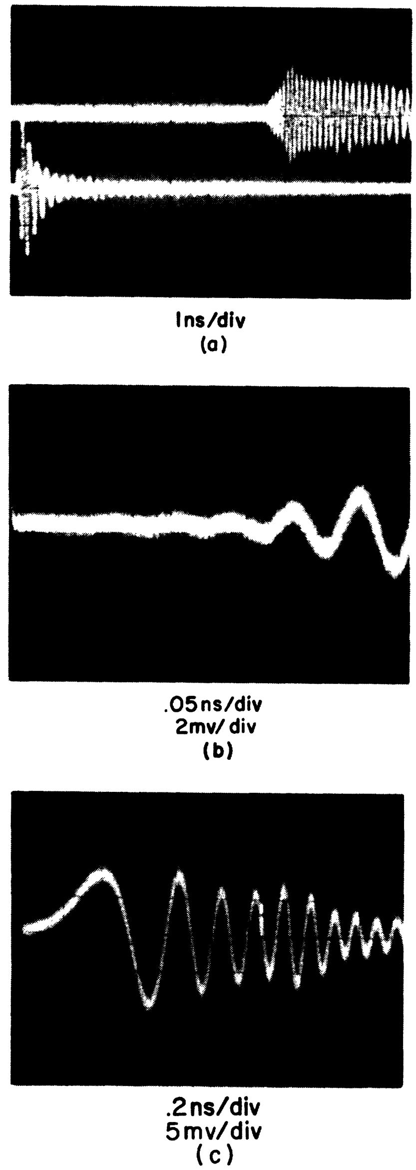

FIG. 3. Precusor wave forms.

characteristic. In all cases, our measured delay was longer than the calculated group delay. At the center of the photograph in Fig. 3(b), the wave form has a frequency 3.6 times the cutoff frequency and arrives with a normalized delay of 1.05. A response, however, can be discerned approximately 3 divisions earlier, which corresponds to a normalized delay of 1.02, or (pessimistically) 2% slower than the speed of light traveling in vacuum. This is quite close to the start of the Sommerfeld precursor and well within the precursor region.

For the Harms-Goubau line experiment, we chose RG8/U coaxial line and took off the outer conductor (ground braid). We used a 6.5-ft length of line for this experiment. As an excitation we used a shorted transmission line on the output of the step generator described previously to obtain a 50-mV, 100-psec–basewidth pulse. This type of excitation has large amplitudes at low frequencies, where the interesting characteristics occur. Because of the finite size of the launching horns (10 in. long and 6.5 in. diam), however, the low frequencies are attenuated by the launching device. The response wave form obtained is shown in Fig. 3(c). The first half-cycle of the transient response is described by an Airy function. A comparison of the wave form obtained by us experimentally and the shape of the Airy function shows remarkable qualitative agreement. This is the function obtained by Brillouin in describing his second precursor.

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STUDY OF $D^0 \to \pi^\pm\delta^\mp$ AND $\delta^\mp \to \pi^\mp\eta$ IN THE REACTION $\pi^+d \to p_S pD^0$ AT 2.7 GeV/c *

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In π^+d interactions at 2.7 GeV/c we have observed the D^0 meson with mass 1.27 ±0.01 GeV/c^2 and width 30 ±15 MeV/c^2 to decay into the $\delta^\pm$ meson with mass 0.98 ±0.01 GeV/c^2 and width 40 ±15 MeV/c^2. The $\delta^\pm$ meson is further observed to decay into $\pi^\pm\eta$ with both neutral and charged decays of the η.

In this paper we report on a study of the following reaction at 2.7 GeV/c:

$$\pi^+d \to p_S p\pi^+\pi^-\eta, \quad (1)$$

where p_S is the proton spectator. In Reaction (1) we have observed the production of the D meson[1,2] and its subsequent decay into $\pi + \delta(980)$ with the δ decaying into $\pi+\eta$; both charged and neutral decays of the η are observed. Our results are similar to those reported on the production of the D and δ in $\bar{p}p$ interactions[3] and production of the δ^- in K^--nucleon interactions.[4,5] It is not clear if the δ observed is the same as that seen in the missing-mass spectrometer experiment.[6]

The events kinematically fitting Reaction (1) came from the following sample of events:

$$\pi^+d \to p_S p2\pi^+2\pi^-\pi^0, \quad 1112 \text{ events}; \quad (2)$$

$$\pi^+d \to p_S p\pi^+\pi^-(\text{MM}), \quad 1698 \text{ events}, \quad (3)$$

where (MM) denotes missing neutrals.[7] The data were obtained from an exposure of 80 000 pictures taken at the Lawrence Radiation Laboratory in the 72-in. deuterium bubble chamber. 716 events in Reaction (2) have a nonvisible spectator while the remainder of events in Reaction (2) and all of those in Reaction (3) have visible spectators. To ensure predominantly π^+-neutron interactions events having spectator proton momentum greater than 250 MeV/c were not used in this analysis.[8] Kinematically fitting Reaction (1) are 412 events from Reaction (2) and 401 events from Reaction (3).

Figure 1(a) shows the $\pi^+\pi^-\pi^0$ mass distribution for events from Reaction (2). The smooth curve is a result of a fit including η and ω production plus phase space. The fit requires that 235 ± 45 η events are produced.[9]

Enhancements corresponding to the $D^0(1280)$ and the $\eta'(960)$ are visible in Fig. 1(b) which shows the $\eta\pi^+\pi^-$ effective-mass distribution. Furthermore, a shoulder corresponding to the $\delta^\pm(980)$ can be observed in the $\eta\pi^\pm$ effective-mass distribution presented in Fig. 1(c). The distributions in Figs. 1(b) and 1(c) are for events in Reaction (2) which fit Reaction (1), that is, events which have an η decaying to $\pi^+\pi^-\pi^0$.

Further evidence for the δ can be seen in Fig. 2(a) which is a Dalitz plot with $M(\eta\pi^+\pi^-)$ constrained to be in the D region. If the D decays into $\delta\pi$ and the decay is invariant under charge symmetry, the number of decays into $\delta^+\pi^-$ must equal the number of decays into $\delta^-\pi^+$; our data

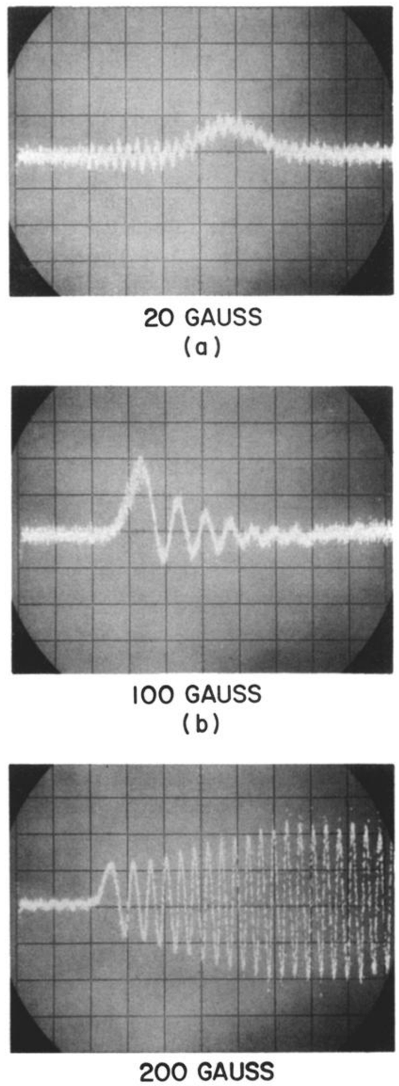

FIG. 2. Pulsed sine-wave response (5 nsec/div).

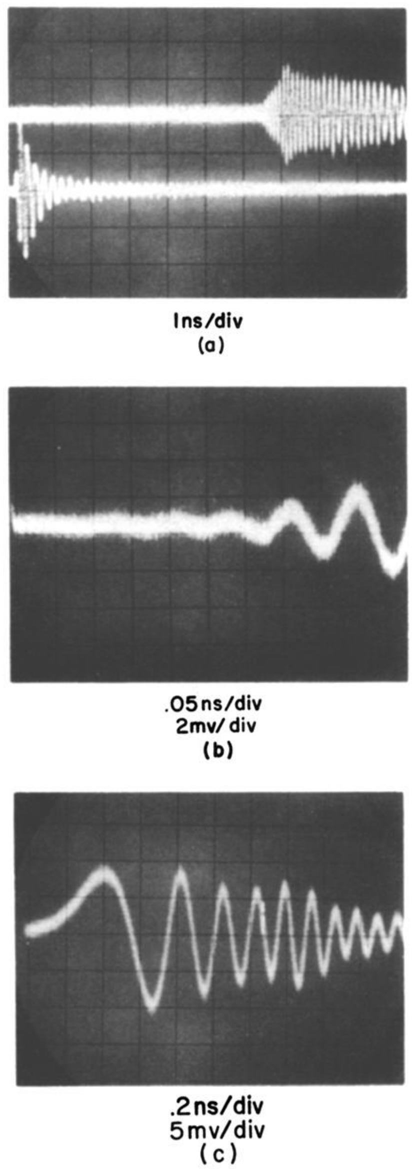

FIG. 3. Precusor wave forms.