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INTERACTION BETWEEN ELECTROMAGNETIC AND ELASTIC WAVES IN A BOROSILICATE GLASS AT LOW TEMPERATURES

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Résumé. — L'influence mutuelle d'ondes électromagnétique et élastique à 9 GHz dans un verre est mise en évidence à 1,5 K. Ces expériences prouvent que des systèmes à deux niveaux possèdent une double nature, ce dont une explication est proposée. La saturation électromagnétique des systèmes à deux niveaux est obtenue à partir d'un champ critique $\mathcal{E}_c = 10^3 \text{ V m}^{-1}$.

Abstract. — Evidence has been obtained of the mutual interaction of 9 GHz electromagnetic and elastic waves in a glass at 1.5 K. These experiments prove that some two-level systems (T.L.S.) have a double nature, an explanation of which is proposed. It has been found that the T.L.S. are electromagnetically saturated by a field higher than $\mathcal{E}_c = 10^3 \text{ V m}^{-1}$.

1. Introduction. — The unusual low-temperature properties of amorphous dielectrics are properly described by a model assuming the existence of two-level systems (T.L.S.) with a broad energy spectrum [1, 2]. The T.L.S. are often mathematically represented by fictitious spin operators S ($S = \frac{1}{2}$) thus enabling the formalism of magnetism to be used.

The strong coupling of the finite T.L.S. population with phonons explains why ultrasonic propagation is so peculiar in these systems [3, 4]. Recently, dielectric constant measurements on glasses at low temperatures [5, 6] have drawn attention to their dielectric behaviour, and have shown that there are similarities between the dielectric and elastic properties. Thus an important question must be raised about the still unknown nature of the T.L.S.: are the same T.L.S. responsible for both electric and elastic properties? A recent experiment [7], performed at 1 GHz and at 0.5 K, has given a first positive answer, namely that the ultrasonic propagation in a glass is modified by an electromagnetic irradiation at a neighbouring frequency.

In this paper we present a short account of two different experiments in a borosilicate glass (BK 7) at 9 GHz and 1.5 K. These experiments show the coupling of the *same* T.L.S. with an elastic wave and an electromagnetic wave. In our first experiment the propagation of an ultrasonic pulse is detected by the

change induced in the electric impedance of a resonant cavity containing the sample. This experiment is analogous, in its principle, to those used to obtain the first evidence for acoustic nuclear resonance [8] and acoustic paramagnetic resonance [9] (with an oscillating electric field here in place of the magnetic field). This new method for studying the acoustic propagation in glasses appears to be much more sensitive than previous methods, which required a transducer to transform the acoustic signal into an electromagnetic signal, thereby introducing an electromechanical conversion coefficient with a loss of 30 or 40 dB.

In the second experiment we measure the decrease in the ultrasonic attenuation when the glass sample is irradiated with an electromagnetic wave at a neighbouring frequency. This experiment is similar to an experiment reported in [7], but our higher frequency provides us with a stronger effect (less than 1 dB at 1 GHz but larger than 10 dB at 9 GHz) and therefore the measurements are easier to perform. In the discussion we propose a tentative explanation of the apparent double nature of the T.L.S., taking into account the effect of polar impurities revealed by a recent experiment [6].

2. Experiments. — Both experiments were performed with two re-entrant cavities A and B. In cavity A, longitudinal ultrasonic waves were generated at frequency ν_{us} using an X-cut quartz transducer to which the BK 7 sample was bonded. The sample

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itself was placed in cavity B, where an electric field at frequency ν_E was produced. The cavity set-up was the same for both experiments, the only difference being the way in which the reciprocal influence of ultrasonic and electromagnetic waves in the glass was detected : the effect was observed with the electromagnetic wave in the first experiment but with the acoustic wave in the second.

2.1 EXPERIMENT N° 1. — Cavity B is a part of a reflection spectrometer. A weak continuous electromagnetic wave is divided in two parts. One part acts as a probe for the T.L.S. population. It is cancelled by interference with the other part. However, every time an ultrasonic pulse reaches the irradiated part of the sample, the spectrometer detects an electric signal because the interference is no longer completely destructive : in other words, a change in the reflection coefficient (or impedance) is observed. The method is very sensitive : we have detected several ultrasonic round-trips, which were not observed with the usual transducer method. In figure 1 the recordings of the

FIG. 1. — ● Lower trace : ultrasonic echoes detected by the superheterodyne receiver. ● Upper trace : electromagnetic intensity detected by the spectrometer with superheterodyne receiver. A spurious electronic signal partly hides the first echo. $T = 1.5$ K, $\nu_{us} = 8\,830$ MHz, $\nu_E = 8\,875$ MHz. Quartz length : 24 mm, BK 7 length : 10 mm. The different echoes are labeled as in figure 2.

ultrasonic echoes (bottom) and of the spectrometer response (top) are given as functions of time. The relative positions of the echoes show that the strongest effect occurs when the ultrasonic pulse excites mainly those T.L.S. which are in the part of the specimen (1-2 mm in length), closest to the tuning piston of the cavity (see Fig. 2). The reason for this is that the most efficient part of the cavity for detection is the region where the electric field is strongest. The rapid decrease of the detected pulses, after the ultrasonic pulse has passed, indicates a short relaxation time T_1 ($\lesssim 10^{-6}$ - 10^{-7} s) at 9 GHz and 1.5 K.

The signal increases with ultrasonic power and is independent of the ultrasonic pulse width. It is also

FIG. 2. — Representation in a x - t diagram of the path of the ultrasonic wave. $Q_1, G_{11}, \dots$ label the ultrasonic echoes in quartz and glass respectively. $E_{11}, \dots$ label the electric pulses detected via the spectrometer. The dashed part represents the spatial region where the efficiency of the detection is a maximum (see text).

larger when the frequencies ν_E and ν_{us} are closer, as a consequence of the linewidth produced by interaction between the T.L.S. By studying the electromagnetic signal intensity as a function of the electric power, we can measure the critical electric power P_c which saturates the T.L.S. population.

When the electric power P is much larger than P_c , we have found that the signal intensity decreases as P^{-1} , which is expected since we observe directly the local T.L.S. population at the irradiated end of the sample. In contrast the ultrasonic attenuation is known to obey a $P^{-1/2}$ law [3] because it is due to the absorption by the T.L.S. along the entire path of the wave.

We obtain $P_c \simeq 50$ μ W in the cavity. For the cavity B, using a value of 7 for the relative dielectric constant in BK 7, this value corresponds to a critical electric field in the glass $\mathcal{E}_c = 10^3$ V m $^{-1}$ within a factor of 2. In analogy with critical elastic strain [10], we assume a coupling Hamiltonian $\mathcal{H}_c = m_x S_x \mathcal{E}$ between the T.L.S. and the electric field in place of $\mathcal{H}_c = G_x S_x \mathcal{E}$ between the T.L.S. and the elastic strain. From our Hamiltonian, when T_1 and T_2 are shorter than the pulse duration (continuous wave regime), we obtain

$$\frac{m_x^2 \mathcal{E}_c^2}{4 \hbar^2} T_1 T_2 = 1$$

where T_1 and T_2 are respectively the longitudinal and transverse relaxation times. With

$$T_1 T_2 = 4 \times 10^{-16} \text{ s}^2 \quad [11]$$

we find that $m_x = 3$ D. Since $m_x = 2 \mu'$, this value is in good agreement with previous estimates of $\mu' = 0.66$ D. [5] and $\mu' = 2$ D. [7]. It is worth emphasizing that our value for $\mathcal{E}_c$ is intrinsic because in our frequency range the conditions for the c.w. regime are fulfilled.

2.2 EXPERIMENT N° 2. — In the second experiment the ultrasonic wave is the probe and the electric pulse is used to partly saturate the T.L.S. population. As a result, there is a decrease in the ultrasonic attenuation. In figure 3 we have plotted the ultrasonic attenuation change as a function of the applied electric power when the two frequencies are close. The effect is stronger when the two frequencies ν_{us} and ν_E are closer and when the ultrasonic power lower. It exists only if the field is applied when the ultrasonic wave is present in the glass ; this confirms that the relaxation time T_1 is short. We have carefully checked that the observed effect is not due to heating (which is actually seen at higher powers but is not plotted in Fig. 3) : the ultrasonic flux is chosen in such a way that the attenuation $I^{-1}(T)$ is an increasing function of temperature (the contribution of the

resonant attenuation $I_R^{-1}(T) \sim T^{-1}$ is not observable). Therefore the attenuation decrease can be explained only by population pumping.

3. Discussion. — The experiments we have reported give the following results :

1) The absorption of electromagnetic energy by the T.L.S. can be saturated in the same way as the ultrasonic absorption. This fact, taken in conjunction with the results of the dielectric constant measurements [5, 6] (which exhibit a $\log T$ variation at low temperature), shows that some T.L.S. have an electric behaviour similar to the elastic behaviour of (possibly) other T.L.S.

2) The cross-experiment (with an ultrasonic wave and an electromagnetic wave) proves that T.L.S. exist which have both elastic and electric properties.

One can give a very simple qualitative explanation for the double nature of the T.L.S. If the T.L.S. are atoms which can tunnel between two positions, they are coupled to an elastic strain because it implies a movement of atoms. Then if dipolar impurities are present, an indirect coupling between the T.L.S. and an electric field can occur : the electric field displaces each impurity, inducing around it a strain which acts on the T.L.S. The resulting coupling between the electric field and the T.L.S. must depend on the impurity concentration ; this is actually observed [6]. This description is analogous to that of the coupling of true spins with phonons : the latter is also indirect and occurs through the spin-orbit interaction [12] (the orbital momentum L takes the part of the electric dipole moment m).

Indeed, further experiments are needed to completely clarify the problem of the double nature of the T.L.S.

FIG. 3. — Ultrasonic attenuation change versus the electromagnetic power which irradiates the BK 7 sample (1 W corresponds to $\mathcal{E} = 1.4 \times 10^5$ V/m in the glass). The ultrasonic flux in the glass sample is about 10^{-3} W/cm².

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