FLUXOID ECHOES

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We wish to report the observation of induced transient radiation from a type-II superconductor, in the form of echoes, similar to spin echoes,[1] and to echoes observed in plasmas.[2] The echoes are observed when the superconductor is placed in a magnetic field and irradiated by two rf pulses separated by a time τ. Echoes are observed at times τ (main echo) and 2τ (secondary echo) after the second rf pulse (see Fig. 1). The echoes have the following properties: (i) The echoes are observed in powdered samples of vanadium-titanium and niobium-zirconium alloys, 400 mesh in size, filed in air, or ground with a boron-nitride tool in air. They are not observed in powders of the same alloys made by dissolving hydrogen in the alloys, crushing the brittle hydride in a mortar, and removing the hydrogen by heating in vacuum; nor are they observed in samples obtained by milling with a tungsten-carbide tool.[3] (ii) The amplitude of the echo at any frequency is proportional to the magnetic field strength (up to 20 kG, which is, however, weak compared with H_{c2}; below 3 kG, no echoes could be observed; see Fig. 2). (iii) The rf phases of the main echo and the secondary echo are, to within the experimental accuracy of ±10°, the same as that of the spin echo of the V^{51} or Nb^{93} nuclei. (iv) The echoes are observed at all frequencies in the range 3-20 MHz. The amplitude is not strongly frequency dependent in the range 3-10 MHz, and falls at higher frequencies (see Fig. 2). (v) As τ is increased, the echo amplitude decays exponentially and the value of T_2 characterizing the decay is field independent, and slightly frequency dependent. For 10 MHz T_2 is approximately 65 μsec at 4.1°K and 45 μsec at 1.3°K for the V-Ti alloy, and 40 μsec at 4.1°K for the Nb-Zr alloy. (vi) The amplitude of the echo increases slightly (by roughly 30-50%) as the temperature is decreased from 4.1 to 1.3°K, in the V-Ti alloy. (No echoes are observed at 11°K, which is above the superconducting transition temperature.) (vii) The echoes are of maximum strength when the rf pulses are approximately equal, and the product of the rf field H_{rf} and the pulse length t_w is of order 200 G μsec. For t_w less than 5 μsec the amplitude of the echo is linearly proportional to $H_{rf}t_w$, when both pulses are identical. For longer pulses the echo amplitude decreases. (viii) A very weak stimulated echo can be observed following a third rf pulse. (ix) After each rf pulse a free decay tail is also observed. (x) The amplitude of the echo is much stronger than the value expected from an NMR signal; up to 20 kG the amplitude, integrated over the magnetic field, is about two orders larger than the signal from the V^{51} or Nb^{93} nuclei.

We believe that these echoes are due to the excitation of fluxoids[4] which behave as anhar-

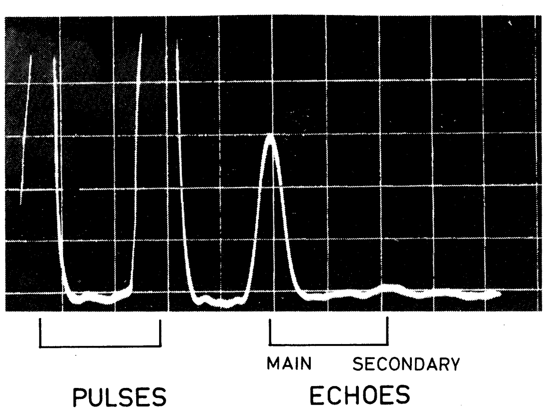

FIG. 1. Oscilloscope photograph of main and secondary echoes in a V-Ti alloy, in frequency of 10 MHz and magnetic field of 19.5 kG. The pulse lengths are 5 μsec. The time scale is 20 μsec/cm.

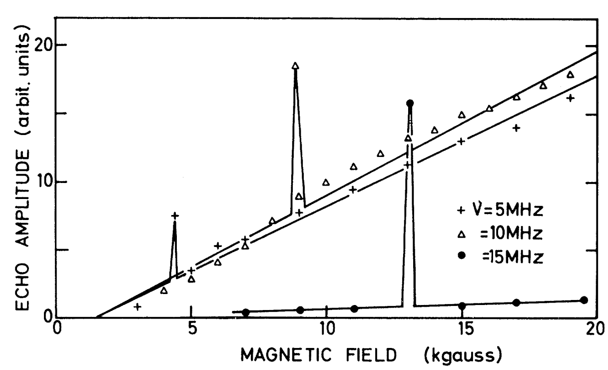

FIG. 2. Field dependence of the main echo amplitude. The amplitudes at different frequencies are normalized so that the strength of the NMR signal is proportional to the Boltzman factor.

monic oscillators.[5,6] The excitation frequency of an individual fluxoid is given by[4] $\omega = (\hbar k^2/4m^*)\ln(\lambda/\xi)$, where k is the wave number, λ the penetration depth, ξ the coherence length, and m^* typically 50 electron masses. Frequencies of order 5 MHz correspond to wavelengths of about 3 μ. This length is about one order smaller than the particle size (~40 μ). It may correspond to sections of fluxoids tied between defects (such as oxygen atoms). Three types of anharmonicity could be operative in this case[5]: (1) a dependence of the resonant frequency on the amplitude of the oscillation; (2) a dependence of dissipation on the amplitude; and (3) a dependence of the response to an external pulse on the phase. Referring to the picture presented by Gould,[6] we can determine the echo formation and the phase relation between the main and the secondary echoes. The relative phase between the main and the secondary echoes is $\pm\frac{1}{2}\pi$ for the first type, π for the second type, and 0 or π for the third type. In the first two types the amplitude of the echo would build up linearly with τ, for small values of τ (since the echo is due to a bunching of phases which takes time to build up from the bunching of frequencies). For the third type the amplitude decays with τ for all values of τ. The recovery time of our receiver is about 20 μsec. No echo buildup was observed for values of τ larger than this. Thus, if the anharmonicity were of the first two types, the spread due to this anharmonicity should be at least 10 kHz in order to account for the echo formation. This spread is comparable with the bandwidth of the echo, which is about 20 kHz (see Fig. 1), and thus too big to be a dominant mechanism. Also, from the phase relationship between the main and the secondary echoes it seems that the anharmonicity is of the third type.

The dependence on the method of sample preparation may be accounted for by assuming that different methods produce different defects in the crystals. The fluxoids are pinned to these defects and their effective length is reduced. We look at them as vibrating strings, the resonant frequency of which is increased as their length is reduced. This view is supported by the fact that the effect is more pronounced at the low range of frequencies investigated. A possible mechanism for the anharmonicity responsible for the echo formation is a dislodging of the pinned fluxoids by the rf pulses. The linear field dependence of the amplitude of the echoes seems to indicate that the signal is proportional to the number of fluxoids; this and the field independence of T_2 seem to indicate that effects of interactions among fluxoids are not predominant, at least for values of H much smaller than H_{c2}. The temperature dependence of T_2 can be accounted for by a larger friction of fluxoid motion as would be expected for thermally activated motion.[7]

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