Brillouin scattering from the icosahedral quasicrystal $Al_{63.5}Cu_{24.5}Fe_{12}$

J.J. Vanderwal, P. Zhao, and D. Walton
Department of Physics and Astronomy, McMaster University, Hamilton, Ontario, Canada L8S 4M1
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Acoustic surface waves in the quasicrystal $Al_{63.5}Cu_{24.5}Fe_{12}$ have been studied by Brillouin spectroscopy. Both surface and bulk velocities of sound were determined. From these c_{11} was found to be 2.3×10^{12} dyn/cm^2, and c_{12} is 1.0×10^{12} dyn/cm^2. The attenuation of the Rayleigh wave was also measured.

A stable icosahedral phase is readily formed in the Al-Cu-Fe alloy.[1] We present here Brillouin spectra for this quasicrystal.

The penetration of light into an opaque material is determined by the conductivity of the material. In metals, where large numbers of conduction electrons shield the metallic interior, it is impossible to detect bulk phonon modes.[2] The conductivity of the Al-Cu-Fe quasicrystal[3] in the visible regime is comparable to that of a metal. It is, in fact, larger than the conductivity of either aluminum or copper at 19436 cm^{-1} (5145 Å). Thus only surface phonons will be observed in our experiment. Nevertheless it is possible to deduce the bulk elastic constants from the surface waves: Loudon[4] has shown that the scattering from metal surfaces is due to reflection from surface ripples. The spectrum consists of a sharp peak at the frequency of the Rayleigh wave, followed by a shoulder extending to higher frequencies where bulk waves are allowed. There is a minimum in the shoulder at the frequency of the longitudinal bulk phonon, which yields the bulk longitudinal velocity. In essence, a continuum of coupled shear vertical and longitudinal bulk acoustic phonons, commonly called Lamb waves,[5] modulate the sample surface, causing scattering.

The incident wave vector, k_i, can be resolved into components perpendicular and parallel to the sample surface. For a beam incident at an angle θ to the sample normal, the surface wave vector, k_R, equals $2k_i \sin\theta$. At frequencies below $k_R v_T$, where v_T is the bulk transverse velocity, the model equation[4] has a singularity at the frequency $k_R v_R$, where v_R is the Rayleigh surface wave velocity. Thus a peak, having zero width, is predicted at this frequency. At frequencies between $k_R v_T$ and $k_R v_L$, where v_L is the bulk longitudinal acoustic wave velocity, the theory predicts a broad nonzero profile with zero intensity at both ends of the frequency range. v_L can be obtained from the high frequency minimum, and there is a relationship between v_R, v_L, and v_T from which v_T may be calculated: for an isotropic substrate,[6]

$$[2-(v_R/v_T)^2]^4 = 16[1-(v_R/v_L)^2][1-(v_R/v_T)^2]. \quad (1)$$

The isotropic elastic constants can then be deduced from the velocities and the density. The density of Al-Cu-Fe quasicrystals has been measured, and is 4.5 g/cm^3.[7]

A polycrystalline sample of the $Al_{63.5}Cu_{24.5}Fe_{12}$ quasicrystal was used in this experiment. The sample, whose size was approximately $3\times2\times0.5$ mm^3, was mechanically polished to reduce its diffuse scattering intensity.

An argon-ion laser operating at 5145 Å, with incident polarization in the scattering plane, provided the excitation source. Backscattering geometry was employed, with the sample normal at 75° to the incident beam direction. In this way the Brillouin signal could be optimized.[8] A tandem Fabry-Pérot interferometer controlled by a microcomputer was used in a five-pass configuration along with standard optics, and a photomultiplier detector.

Since the major constituent of the quasicrystal is aluminum, a polycrystalline sample of Al was also examined for comparison. Spectra for both samples were acquired at two free spectral ranges (FSR): at 60 GHz to more clearly observe broad spectral features and at 30 GHz to more accurately measure phonon frequencies and linewidths. Runs at higher FSR were also done but yielded no new information. Figure 1 shows room-temperature spectra acquired at 60 GHz FSR, looking at the anti-Stokes side. The elastic peaks at 0 frequency are of the order of 10^9 counts, and have been scaled to

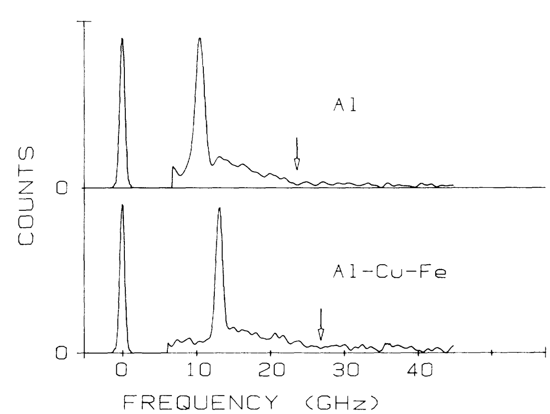

FIG. 1. Sample Brillouin spectra of polycrystalline aluminum (top) and the polycrystalline icosahedral quasicrystal $Al_{63.5}Cu_{24.5}Fe_{12}$ (bottom) at room temperature. The common free spectral range was 60 GHz. Arrows in both spectra indicate the estimated position of $k_R v_L$.

TABLE I. Velocities of sound of the surface (v_R), bulk longitudinal (v_L), and bulk transverse (v_T) phonons are given for aluminum and the quasicrystal $Al_{63.5}Cu_{24.5}Fe_{12}$. Comparison with other sources is made.

	$v_R(m/s)$	$v_L(m/s)$	$v_T(m/s)$	
Al	2845	6420	3040	Ultrasonic
	2829	6393	3022	Brillouin
Al-Cu-Fe		7480	3424	Neutron
	3529	7191	3809	Brillouin

the level of the Rayleigh surface mode phonon ($\sim 10^2$ counts).

In both spectra a prominent Rayleigh surface phonon is evident and a broad shoulder on the high-frequency side of the surface mode can be observed. The bulk longitudinal acoustic wave velocity can be determined from the minimum in the high frequency shoulder, as described above. Using Eq. (1) the bulk transverse wave velocity can be calculated.

For aluminum, the Rayleigh frequency is 10.62 GHz, with a full width at half maximum (FWHM) of about 188 MHz, while $k_R\ v_L/2\pi$ is approximately 24 GHz. For the Al-Cu-Fe sample, the Rayleigh frequency is higher at 13.25 GHz, and with a narrower width of 93 MHz. The value of $k_R\ v_L/2\pi$ is about 27 GHz. The resultant velocities are given in Table I, and compared to available values. The values for the velocities from the neutron data[9] were obtained by scaling the slopes of the neutron dispersion curves to the known velocities for pure Al.

The elastic constants of $Al_{63.5}Cu_{24.5}Fe_{12}$ may be calculated from the velocities, and are $c_{11} = 2.3 \times 10^{12}$ dyn/cm^2 and $c_{12} = 1.0 \times 10^{12}$ dyn/cm^2. These values are approximately twice those of the corresponding constants of aluminum.

While the attenuation of bulk phonons at room temperature is primarily due to interaction with other phonons, it is believed that in most instances, surface defects play a dominant role in the scattering of surface waves. This effect has been ascribed either to the presence of point defects[10,11] or, more realistically, in terms of surface roughness.[12] In the latter case, the inverse mean-free path of the Rayleigh phonon is expressed as a function of wave vector k_R and two parameters in a Gaussian model of surface roughness:

$$< f(0)f(x_\parallel) >= \delta^2 \exp(-x_\parallel^2/a^2), \tag{2}$$

where $f(x_\parallel)$ is the displacement normal to the surface at a distance $x_\parallel$ from the origin, and a and δ are roughness parameters.

Maradudin and Mills[12] then deduce the following expression for the inverse mean-free path of a phonon whose wave vector is k_R:

$$l_R^{-1} = [(a\delta)^2/\pi]k_R^5 F(ak_R), \tag{3}$$

where F is also a function of v_R, v_T, and v_L. In the long-wavelength limit, $ak_R \ll 1$, F has almost the same value for Al and Al-Cu-Fe, leaving only $a\delta$ as a variable. Thus the difference in attenuation of the Rayleigh phonon in aluminum and Al-Cu-Fe can be plausibly explained by a difference in surface roughness.

Finally, Raman spectra of the Al-Cu-Fe quasicrystal were taken at low and intermediate frequencies; however, no Raman peaks were observed. This is not surprising in view of the high conductivity of the quasicrystal at optical frequencies.

In conclusion, surface-wave velocities have been measured in back reflection for the quasicrystal $Al_{63.5}Cu_{24.5}Fe_{12}$. Assuming elastic isotropy, values of $c_{11} = 2.3 \times 10^{12}$ dyn/cm^2 and $c_{12} = 1.0 \times 10^{12}$ dyn/cm^2 were obtained for the bulk elastic constants. It would appear that this quasicrystal behaves very much like any other metal from the standpoint of surface Brillouin scattering.

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