Brief Reports

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Isotropic elasticity of the Al-Cu-Li quasicrystal

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The elasticity tensor of a single-grain quasicrystal of composition $Al_{5.1}CuLi_3$ has been determined. The longitudinal and transverse mode velocities have been obtained at ultrasonic frequencies (20 MHz) for several propagation and polarization directions. We find that the quasicrystal is elastically isotropic within the experimental uncertainty of 2%. This finding supports hydrodynamic analyses which predict isotropy. At 300 K, the measurements yield 6.4×10^5 cm s^{-1} and 3.8×10^5 cm s^{-1} for longitudinal and transverse velocities, respectively, and a Debye temperature Θ of 493 K.

Since the discovery of icosahedral symmetry in Al_6Mn,[1] advances in theory very rapidly provided a description of these remarkable incommensurate phases. Moreover, the classes of materials with quasicrystalline structures have been expanded greatly.[2] Of these quasicrystals, the composition $Al_{5.1}CuLi_3$ is remarkable in that it appears to exist as an equilibrium phase.[3] This permits one to grow relatively large single-grain quasicrystals and to perform classes of experiments which were not possible on previously prepared materials. In particular, the elastic properties of quasicrystals have been predicted to be unusual.[4-6] The quasicrystal is believed to be elastically isotropic at long wavelengths. In addition, the coupling of phonons to phasons, diffusive at long wavelengths, may lead to anisotropy in the attenuation of sound.[7] Finally, if the phason can relax during the time of the elasticity measurement, anisotropic elasticity may be observed.

A substance is considered elastically isotropic if its elastic tensor contains two independent components describing the material's response to compressional and shear stresses. Glasses, for example, are elastically isotropic because they are disordered on a microscopic length scale. The origin of the unusual isotropic elasticity of quasicrystals is as follows.[8] The elastic stiffness is described by a fourth-rank tensor C_{ijkl}. Thus any anisotropy must be described by a Y_{4m} spherical harmonic. For icosahedral anisotropy, however, the first relevant spherical harmonics are the Y_{6m}; thus the system is isotropic. The elastic energy of a quasicrystal contains contributions from the phonons, phasons, and a coupled phonon-phason term. The latter term leads to anisotropy in the elasticity provided the quasicrystal can equilibrate during the course of a measurement. Since the relaxation of a phason to an applied stress is likely to be slow since it requires atomic diffusion, the influence of the phonon-phason coupling should not be large under most experimental conditions. We note, however, that enhanced densities of states of atomic tunneling species have been observed in quasicrystals at very low temperatures which have been attributed to defects associated with the phasons.[9]

The present experiment was performed on a single-grain quasicrystal of composition $Al_{5.1}CuLi_3$ grown from the melt[10] at a rate of 2 mm/hr. The quasicrystal was oriented by x-ray diffraction and a sample was cut from the boule by a string saw with faces perpendicular to a twofold and a fivefold axis. Opposite surfaces were polished flat and parallel. The sample thicknesses were 0.39 and 0.26 cm for the twofold and fivefold axes, respectively. The faces were chosen to be as orthogonal as possible in order to minimize acoustic side-wall reflections. Thus, ultrasonic measurements were made along two different axes but on the same sample. Pulsed longitudinal and transverse sound waves were sent through the samples via 20-MHz X-cut and AC-cut quartz tranducers, respectively. Velocity measurements for each mode were taken at 300 K using the transit-time method. Care was taken

TABLE I. Sound velocities V_L and V_T are given in units of 10^5 cm s^{-1}. Elastic constants C_{ij}, bulk modulus B, Young's modulus E, and Lamé constant λ are given in units of 10^{12} dyn cm^{-2}. Poisson's ratio σ is dimensionless.

	V_L	V_T	C_{11}	C_{44}	B	E	λ	σ
twofold	6.4±0.1	3.8±0.1	1.0	0.35	0.53	0.87	0.29	0.23
fivefold	6.5±0.2	3.7±0.2	1.0	0.33	0.58	0.84	0.36	0.26

to affix the transducer firmly to the samples with resin. At least three double-transit reflections were observed for all modes. Additionally, transverse velocities were measured as a function of angle between the sound polarization vector and quasicrystal axes.

Table I shows the values obtained for velocities of the transverse and longitudinal modes. For the transverse modes, velocities were independent of wave polarization for both symmetry axes. The errors arise primarily from non-plane-wave propagation due to internal scattering, diffraction, and perturbations from the transducer. There are three independent indications of elastic isotropy. (1) V_L is the same along the twofold and fivefold axes. (2) V_T is the same along the twofold and fivefold axes. (3) V_T is independent of polarization along a twofold axis. These results are consistent with a medium whose longitudinal wave elastic response can be described by two elastic coefficients, C_{11} and C_{44}, as shown in Table I.

The results discussed above indicate no evidence for elastic anisotropy within the accuracy of the experiments (2%). The most suggestive evidence that the isotropy may be even greater than the stated uncertainty arises from transverse-mode propagation along a twofold axis. Here, the change in velocity was noted on rotating the polarization vector (by rotating the transducer) in 45° increments. No change in transverse velocity was observed to within 0.5%. This measurement eliminates errors from bonding, nonparallelism, side-wall reflections, and scattering since it is essentially differential.

A previous report[11] on the mechanical properties of Al-Cu-Li quasicrystals included an ultrasound measurement on a polygrain multiphase material and obtained $V_L = 6.94\times10^5$ cm s^{-1}. This is about 8% larger than the presently reported value for a single-grain (equilibrium) quasicrystal. We note that the solidification rate in that report was 2 orders of magnitude larger than the present one.

Since, to our knowledge, there are no other reports of the elastic properties of quasicrystals, we look to related properties for comparison. The low-temperature specific heat of the $Mg_3Zn_3Al_2$ system in crystalline, quasicrystalline, and amorphous phases was measured recently.[12] From the T^3 coefficient it is possible to extract a mean sound velocity $\bar{V}$. A value $\bar{V}=2.28\times10^5$ cm s^{-1} was obtained for the quasicrystalline phase of $Mg_3Zn_3Al_2$, appreciably lower than the velocities for the $Al_{5.1}CuLi_3$ quasicrystal for which $\bar{V}=4.21\times10^5$ cm s^{-1}. It was noted[12] also that there is appreciable softening of the quasicrystal relative to the crystal: $\bar{V}$ decreases by 25%.

It is straightforward to calculate the low-temperature phonon specific heat for $Al_{5.1}CuLi_3$. The Debye temperature $\Theta=(h/k_B)(3N/4\pi V)^{1/3}\bar{V}$, where $\bar{V}^{-3}=(2V_T^{-3}+V_L^{-3})/3$ for an isotropic material. Here N is Avogadro's number and V the molar volume. Estimates of the density, 2.464 g cm^{-3}, and V, 9.95 g mol^{-1}, have been obtained from data[13] reported for the 162-atom/cell cubic crystalline phase of Al_5CuLi_3 of lattice parameter 13.914 Å. The specific heat is then given by $C=\beta T^3$ where $\beta=(12\pi^4 N k_B/5\Theta^3)=6.66$ erg g^{-1} K^{-4} and $\Theta=493$ K.

An untested prediction is that the anisotropy of a quasicrystal should be manifested in the acoustic attenuation.[7] We have been unable to observe this feature as a consequence of the high "background" attenuation of the samples, 2 cm^{-1} at 20 MHz. Measurements on larger crystals or at higher frequencies should enable these ideas to be tested.

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