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The goals of this project involve the use of innovative acoustic techniques to study new materials and new developments in solid state physics, such as effects in mesoscopic electronic systems. Major accomplishments include a) the publication of a number of major papers, b) the determination of the anisotropy of an aluminum alloy quasicrystal, c) the completion of ultrasound measurements on ceramic beads with varying heat treatment, d) preparation of a diamond substitute material, TiB_2, for determination of the elastic constants, e) the development of a new transduction method for measuring optical absorption in highly transparent materials, f) the determination of the effects of nonlinearity on Anderson localization, and g) the use of an acoustic analog to explain the discrepancy between theory and experiment for normal electron persistent currents in a mesoscopic system.

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INNOVATIVE TECHNIQUES FOR STUDYING NEW MATERIALS AND NEW DEVELOPMENTS IN SOLID STATE PHYSICS

This report summarizes the goals and accomplishments for ONR grant N00014 -92-J-1186,"Innovative Acoustic Techniques for Studying New Materials and New Developments in Solid State Physics". The goals of the project are a) to use resonant ultrasound spectroscopy to study new materials, such as small ceramic spheres which are used in oil extraction and solar energy collectors, open-cell ceramics which are used in high strength, low weight structural applications, and diamond substitute materials such as TiB_2, b) to use a resonant photoacoustic technique to measure optical absorption in highly transparent materials which are used in infrared fiber optics, c) the use of acoustic analogs to study effects in mesoscopic electronic systems, and d) the development of a new technique for studying fracture in brittle materials. In appendices we present a list of our publications, presentations, etc., and a preprint of a paper describing the use of an acoustic analog to explain the discrepancy between theory and experiment for normal electron persistent currents in a mesoscopic electronic system.

Published papers, submitted papers, talks, etc.

A complete list of publications, talks, etc. is presented in Appendix I. To summarize, there were three invited review papers on our research with acoustic holography and acoustic analogs of mesoscopic systems, and five papers accepted for publication in refereed journals, including one in the prestigious Physical Review Letters and two in the proceedings of a conference; two additional papers were submitted to Physical Review Letters. A number of invited talks describing our research were given: there were two lectures at universities, four invited lectures national meetings, and a tutorial lecture at the 1992 Physical Acoustics Summer School; there were also six contributed papers at national meetings.

A new graduate student, Jun Wang, has joined our research group; he will be working on the acoustic analogs of mesoscopic electronic systems.

In the sections which follow, a brief summary of the research accomplishments will be presented. In some cases, details may be found in the published papers or in the preprints.

Measurement of the elastic anisotropy of a high quality quasicrystal

Since the discovery of quasicrystalline symmetry in solids, there has been considerable interest in determining the consequences of the new symmetry and verifying that actual materials have the properties unique to true quasicrystals. A crucial measurement is the determination of the elastic tensor and the attenuation of the associated sound modes. Theory predicts that a true quasicrystal would be elastically isotropic and have only two independent elastic constants, but the attenuation and third order elastic constants would be anisotropic. There has a controversy as to whether the actual aluminum alloy materials such as AlCuLi are true quasicrystals, or are cubic crystals with large five-fold-symmetric unit cells. Since a cubic material would have three independent elastic constants (apart from an unlikely special case), a vital clue as to the true nature of an actual material would be the measurement of the anisotropy represented by $\epsilon = | 1 - 2C_{44}/(C_{11} - C_{12}) |$. Previous measurements of transverse and longitudinal bulk sound velocity by Reynolds, et al., and of Rayleigh wave velocity by Sathish, et al., have shown that AlCuLi is isotropic to within the accuracy of the measurements, which were 0.02 and 0.01 respectively. Unfortunately, this is inconclusive since α-tungsten, which is cubic, has an anisotropy of only 0.009. Recently we have used resonant ultrasound to determine the elastic tensor of a very small, high quality sample of AlCuLi, and have found $\epsilon = 0.0020$, which differs from zero by more than the precision of the measurement, which was $\pm$ 0.0004. A paper detailing these results is in preparation.

Studies of ceramic spheres with varying heat treatment

The small sample resonant ultrasound technique was used to measure the elastic constants and acoustic attenuation of ceramic spheres which are used in oil recovery and in solar energy collection and transfer. Their utility is degraded when, at a certain temperature, they undergo a phase transition and subsequent microcracking. Because the presence of microcracks increases the acoustic attenuation, the effect could be measured with the widths of the peaks in the resonant ultrasound spectrum. Our measurements showed that microcracks did appear at the expected temperature, but at higher temperatures the cracks healed, returning the ceramic spheres to a useful state. At the present time we are awaiting a contribution from our collaborator, John Hellmann of the Department of Material Science, for the completion of a manuscript describing this research.

Measurement of the elastic properties of the diamond substitute TiB_2

We have obtained samples of titanium di-boride (TiB_2), whose hardness is second only to that of diamond, from David Green of the Department of Material Science, and are preparing them (orienting and polishing) for measurement with resonant ultrasound. Measurements of thin (~10 μ m) plates will be compared to those of thick samples to search for any systematic problems in measuring very thin samples. This information will be used for measurement of high quality samples of the high temperature superconductor La_2CuO_4, which are available in thicknesses of ~20 μm.

Measurement of the effects of nonlinearity on Anderson localization

While there has been considerable theoretical and experimental research with quantum and classical wave propagation in linear systems, involving effects of Anderson localization, etc. as found in mesoscopic electronic systems, there has been considerably less research with nonlinear media. A fundamental question is whether or not nonlinear effects weaken Anderson localization. There are about eight theoretical papers which treat this question, and half predict that localization is destroyed, and half predict that it is not. We have performed an experiment involving nonlinear acoustic wave propagation in a disordered potential field, and have obtained an unambiguous result. Details of this research may be found in the publication Phys. Rev. Lett. **69**, 1807 (1992). We have also made measurements of nonlinear wave propagation in a periodic field, and in addition to the expected effects of canting and hysteresis, other novel effects are observed. Analysis of these results is underway.

The use of acoustic analogs to explain the normal electron persistent current discrepancy

Currently one of the most exciting areas of condensed matter physics is the study of mesoscopic electronic systems. Such systems consist of metal or semiconductor elements which are sufficiently small and at sufficiently low temperature that inelastic electron-phonon scattering is reduced, and the electron propagates as a phase coherent wave throughout the entire sample. The behavior of electron waves in disordered solid samples, or samples with inelastic scattering limited to boundary elements (contact "pads"), etc. has become understood only through recent discoveries, such as the notion of Anderson localization. A manifestation of the enigmatic nature of these systems is the discrepancy between the theoretically predicted and experimentally measured amplitudes of persistent currents in mesoscopic normal metal rings. Recently we have studied an acoustic wave analog of the persistent current experiment which suggests a possible explanation for the discrepancy. Details may be found in Appendix II.

The development of a resonant photoacoustic technique for infrared absorption

A new graduate student, Wei-li Lin, has taken over this project from Chang Yu, who received his Ph.D. degree. Lin has reproduced Yu's results, and has begun tests of a new transduction method intended to increase the sensitivity of the technique. The new technique involves the use of piezoelectric film rather than the capacitive devices used previously. While the piezoelectric film is much more sensitive, it requires clever mounting so that it does not reduce the Q of the sample resonance.

Developments in the study of fracture

In order to learn the latest developments in the field of fracture from the point of view of condensed matter physics, graduate student Wei-li Lin was sent to the University of California Summer School on Nonlinear Science, "Slips, Cracks, and Tears". He is currently reviewing the material for the physics department in a series of weekly seminars.

Current and Other Funding

It is anticipated that there will be no remaining funds at the end of the contract period.

Other research grants include NSF Division of Materials Research, Low Temperature Physics Program, DMR 9000549, which includes 2 man-months of the principal investigators time.

APPENDIX I. PUBLICATIONS, PRESENTATIONS, ETC.

PAPERS SUBMITTED TO REFEREED JOURNALS
(Not yet published)

1. M. J. McKenna, T. P. Brosius, and J. D. Maynard, "Observation of two-stage layering transitions for solid 4He on graphite" submitted to Phys. Rev. Lett.

2. M. J. McKenna, P. S. Shaw, and J. D. Maynard, "A possible explanation of the normal electron persistent current discrepancy", submitted to Phys. Rev. Lett.

3. P. S. Spoor, M. J. McKenna, and J. D. Maynard, "Using acoustic resonators to study superfluid-filled silica aerogel, high Tc superconductors, and quasicrystals", to be published in J. Low Temp. Phys.

4. J. D. Maynard, "A possible explanation of the discrepancy in electron persistent current amplitudes: A superfluid persistent current analog", to be published in J. Low Temp. Phys.

PAPERS PUBLISHED IN REFEREED JOURNALS

1. J. D. Maynard, "Using Piezoelectric Film and Acoustic Resonance to Determine the Complete Elastic Tensor in One Measurement", J. Acoust. Soc. Am. **91**, 1754-1762 (1992)

2. C. Yu, M. J. McKenna, J. D. White, and J. D. Maynard, "A new resonant photoacoustic technique for measuring very low optical absorption in crystals and glassses", J. Acoust. Soc. Am. **91**, 868-877 (1992)

3. M. J. McKenna, R. L. Stanley, and J. D. Maynard, "Effects of nonlinearity on Anderson localization", Phys. Rev. Lett. **69**, 1807 (1992)

BOOKS (AND SECTIONS THEREOF) PUBLISHED

1. J. D. Maynard, "Acoustical Holography", in the *McGraw-Hill Encylclopedia of Science and Technology,* 7th edition, ed. S. Parker (McGraw-Hill, New York, 1992) p. 86

TECHNICAL REPORTS AND THESES PUBLISHED

1. Final Report for ONR N00014-85-K-0701, 1988-1991, "Acoustic studies of new materials: Quasicrystals, low loss glasses, and high Tc superconductors"

BOOKS (AND SECTIONS THEREOF) SUBMITTED FOR PUBLICATIONS

1. J. D. Maynard, "Tuning up a quasicrystal", in *Proceeding of the Bolef Symposium in Physical Acoustics* , ed R. K. Sundfors, to be published

2. J. D. Maynard, "Learning about phonons with frequencies below one KHz", in *Seventh International Conference on Phonon Scattering in Condensed Matter* , ed R. O. Pohl, (Springer-Verlag, Berlin, 1993), to be published

INVITED PRESENTATION AT TOPICAL OR SCIENTIFIC/TECHNICAL SOCIETY CONFERENCES

1. Colloquium, Department of Physics, University of Pittsburgh, April 13, 1992, "Nonlinearity and Disorder"

2. Invited Lecture, Society of Engineering Science 28th Annual Technical Meeting, University of Florida, Gainsville, November, 1991 "Using Piezoelectric Film and Ultrasound Resonance to Determine the Elastic Tensor of Small Fragile Samples"

3. Invited Lecture, Bolef Symposium in Physical Acoustics, Lake Buena Vista, Florida, December 1991 "Tuning up a Quasicrystal"

4. Invited Symposium Lecture, 123rd Meeting of the Acoust. Soc. Am., Salt Lake City, May 12, 1992 "Nonlinear Effects in Periodic and Disordered Wave media"

5. Invited Lecture, 1992 Physical Acoustics Summer School, Asilomar Conference Center, Pacific Grove, CA, June, 1992, "Linear and nonlinear wave propagation in periodic, random, and quasiperiodic media"

6. Invited lecture, Seventh International Conference on Phonon Scattering in Condensed Matter, Cornell University, August, 1992, "Learning about phonons with frequencies below one KHz"

7. Seminar, Cornell University, Department of Physics, September 8 1992 "Acoustic analogs of mesoscopic systems", David Lee, host

CONTRIBUTED PRESENTATIONS AT TOPICAL OR SCIENTIFIC/TECHNICAL SOCIETY CONFERENCES

1. J. D. Maynard and M. J. McKenna, "Experimental Studies of Disorder and Nonlinearity", Bull. Am. Phys. Soc. **37**, 294 (1992)

2. M. J. McKenna, P. S. Spoor, and J. D. Maynard, "Determination of the Elastic Constants of a Single Grain Al-Cu-Li Quasicrystal in a Single Measurement", Bull Am. Phys. Soc. **37**, 615 (1992)

3. M. J. McKenna, T. P. Brosius, and J. D. Maynard, "An Analysis, in Terms of Quantum Kinks, for a New Growth Mode for Solid 4He on Grafoil", Bull. Am. Phys. Soc. **37**, 951 (1992)

4. J. D. Maynard, "A Possible Explanation for the Discrepancy in Electron Persistent Current Amplitudes: A Superfluid Acoustic Analog", Bull. Am. Phys. Soc. 37, 969 (1992)

5. J. D. Maynard, "A possible explanation for the discrepancy in electron persistent current amplitudes: A superfluid acoustic analog", Symposium on Quantum Fluids and Solids - 1992, Penn State University, June, 1992

6. V. A. Hopkins, M. J. McKenna, and J. D. Maynard, "A study of two- dimensional Anderson localization as a function of disorder", Symposium on Quantum Fluids and Solids - 1992, Penn State University, June, 1992

7. M. J. McKenna, T. P. Brosius, and J. D. Maynard, "An analysis, in terms of quantum kinks, for a new growth mode for solid 4He on Grafoil", Symposium on Quantum Fluids and Solids - 1992, Penn State University, June, 1992

8. P. S. Spoor, M. J. McKenna, and J. D. Maynard, "Using acoustic resonators to study superfluid-filled silica aerogel, high Tc superconductors, and quasicrystals", Symposium on Quantum Fluids and Solids - 1992, Penn State University, June, 1992

HONORS/AWARDS/PRIZES

None

GRADUATE STUDENTS SUPPORTED UNDER CONTRACT FOR YEAR ENDING 30 SEPTEMBER 1991

1. Philip Spoor (Ph.D. candidate, acoustics) Elastic Constants for Aluminum Alloy Quasicrystals and High Tc Superconductors

2. Vern Hopkins (Ph.D. candidate, physics) NMR measurements for 3He at the 4He quantum solid/liquid interface Began Fall 1990

3. Wei-Li Lin (Ph.D. candidate, physics) Infrared resonant photoacoustics Began Summer 1991

4. Jun Wang (Ph.D. candidate, physics) Soliton propagation through disordered media Began Fall 1992

POSTDOCTORALS SUPPORTED UNDER CONTRACT FOR YEAR ENDING 30 SEPTEMBER 1991

Mark McKenna, Research Associate, began July 1, 1989

MISCELLANEOUS

Meetings attended:

1. Aspen Winter Physics Conference on Condensed Matter Physics, "Future Trends in Low Temperature Physics" January, 1992

2. University of California Summer School on Nonlinear Science, "Slips, cracks, and tears" (attended by student Wei-li Lin)

Undergraduates Involved in Research:

1. Ron Stanley (REU student) Senior

2. Brian Pudliner, BA Spring 1991

3. Chris Koeppen, BA Spring 1992

4. Brian S. Wilson, Junior Jan 1992

5. Justin Keat (REU student, summer 1992)

6. Michael Baloh, Junior 1992

APPENDIX II. A Possible Explanation of the Normal Electron Persistent Current Discrepancy

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ABSTRACT

Recent experiments have shown that normal electrons may maintain their phase coherence around mesoscopic rings, resulting in "persistent currents" and a quantization of the magnetic flux inside a ring in units of h/e. While the current as a function of flux was found to oscillate with the correct period, the magnitude of the oscillations exceeded the theoretical predictions by more than an order of magnitude. In this paper we present a wave mechanical analog of the normal electron persistent current, and some experimental results, which suggest a possible explanation for the discrepancy.

PACS Numbers: 73.20.Dx, 03.40.Kf, 43.20.+g

Currently one of the most exciting areas of condensed matter physics is the study of mesoscopic electronic systems. Such systems consist of metal or semiconductor elements which are sufficiently small and at sufficiently low temperature that inelastic electron-phonon scattering is reduced. and the electron propagates as a phase coherent wave throughout the entire sample. The behavior of electron waves in disordered solid samples, or samples with inelastic scattering limited to boundary elements (contact "pads"), etc. has become understood only through recent discoveries, such as the notion of Anderson localization. A manifestation of the enigmatic nature of these systems is the discrepancy between the theoretically predicted and experimentally measured amplitudes of persistent currents in mesoscopic normal metal rings.[1,2] Currently explanations are being sought in terms of electron-electron scattering, but such effects may be too small to account for the discrepancy.[3] Recently we have studied an acoustic wave analog of the persistent current experiment which suggests a possible explanation for the discrepancy.

The normal electron persistent current experiment, such as that of R. Webb, et al.[1], involves a normal metal ring surrounded by a drive loop and squid pickup loop. The pickup loop monitors the current in the ring, through its mutual inductance, as the magnetic flux Φ in the system is changed with the drive loop. The current in the ring is found to oscillate with a period of $\Phi_0 = h/e$, the normal electron flux quantum, as predicted by theory. However, the magnitude of the current oscillations exceed the theoretically predicted value by more than an order of magnitude.

For an initial model of the ring, we consider an ideal circular waveguide, with circumference L and eigenstates $\psi \propto \exp(\pm i 2\pi x/\lambda)$, where λ is the wavelength and x is a coordinate which follows the waveguide. A current associated with the eigenstate is given by

$$I = ne\frac{i\hbar}{2m}\left(\psi^{*}\nabla\psi - \psi\nabla\psi^{*}\right) = neh/m\lambda \qquad (1)$$

where m and e are the electron mass and charge, and n is the number of electrons per unit length in the ring. The quantization condition is that an integral number of wavelengths must fit in the circumference L, so that $L = N\lambda$, and $I = N\,(neh/mL)$. Since N is an integer, I is quantized in units of

$$\Delta I = \frac{neh}{mL} = \frac{ev_F}{L} \tag{2}$$

where $v_F = nh/m$ is the Fermi velocity. As will be shown subsequently, current oscillations of magnitude ΔI in the ideal ring correspond to changes in magnetic flux through the ring of magnitude Φ_0.

An actual normal metal ring is not a perfect waveguide, but will contain defects which elastically scatter the wave. We consider a large section of the waveguide as containing all of the defects. At one end of the scattering section we write the eigenfunction as a combination of two linearly independent solutions:

$$\psi = Ae^{i2\pi\Phi/\Phi_0}e^{i2\pi x/\lambda} + Be^{i2\pi\Phi/\Phi_0}e^{-i2\pi x/\lambda}$$

The factor $\exp\,(i2\pi\Phi/\Phi_0)$ arises from the vector potential term in the Schrodinger equation. For the other end of the scattering section we assume a similar form for the eigenfunction, but use coefficients A' and B'. From general scattering theory we have

$$A = (1/T)\,A' + (R/T)^*\,B' \tag{4}$$

$$B = (R/T)\,A' + (1/T)^*\,B' \tag{5}$$

where R and T are the complex reflection and transmission coefficients for the scattering section. From conservation of flux, $\mid R \mid^2 + \mid T \mid^2 = 1$. We require periodic boundary conditions, so that ψ and its derivative must match at $x = 0$ and $x = L$. With Eqs. 4 and 5, we now have four equations for A, B, A', and B'.

For nonzero solutions, the determinent of the coefficients must vanish, yielding the eigenvalue condition

$$2\pi L/\lambda = N2\pi - \tan^{-1}\left[Im(T)/Re(T)\right] \pm \cos^{-1}\left[\mid T \mid \cos(2\pi\Phi/\Phi_0)\right] \qquad (6)$$

Note that if there were no scatterers, then $\mid T \mid = 1$, and changes of one quantum in the eigenvalue (or changes of $\Delta I = ev_F/L$) correspond to changes of Φ_0 in Φ. Most significantly, if there are scatterers, then $\mid T \mid < 1$, and while the period of the oscillations in Φ remains Φ_0, the magnitude of the oscillations in ΔI is reduced. If one assumes that $\mid T \mid^2 \simeq L_e/L << 1$, where L_e is the mean free path for the elastic scattering, then one has

$$\Delta I \simeq \frac{ev_F}{L}\frac{L_e}{L} \qquad (7)$$

A simple way of formulating Eq. 7 is to note that as a consequence of the elastic scattering, the electron must follow a tortuous path around the ring, so that the effective length of the waveguide is $L' \simeq L(L/L_e)$. Eq. 7 becomes

$$\Delta I = \frac{ev_F}{L'} = \frac{ev_F(L/L')}{L} \qquad (8)$$

In the normal electron persistent current experiments, L/L' is determined with a transport (quantum conductivity) measurement. When this value (typically 0.01 to 0.1) is used in Eq. 8, one obtains values of ΔI which are more than an order of magnitude smaller than the values of ΔI found in the actual experimental persistent current measurement.

The difference between Eq. 2 and Eq. 8, i.e. replacing v_F by $v_F(L/L')$, is analogous to the "acoustic scattering correction" used for sound waves undergoing multiple scattering in a disordered array of scatterers. A model used to study

the acoustic scattering correction can now be used to gain insight into the normal electron persistent current discrepancy.

In the acoustic scattering model, one first imagines a "black box" of length L, containing a straight waveguide, also of length L. One sends in a wave $\exp(i\omega x/v_0)$ $\exp(-i\omega t)$ and measures the total phase shift θ_0 accross the box. Since $\theta_0 = \omega L/v_0$, one could determine the speed of the wave with $v_0 = \omega L/\theta_0$. One next considers a box of length L containing a meandering waveguide (with a "square wave" shape) with a total length $L' > L$. The phase shift accross this box would be $\theta = \omega L'/v_0 =$ $\theta_0 (L'/L)$, and not knowing what was inside the box, one would calculate a wave speed $v = \omega L/\theta = v_0 (L/L')$. This is analogous to the effective velocity $v_F (L/L')$ in Eq. 8.

For the normal electron persistent current experiment, one imagines the "square wave" waveguide (of length L') bent into a ring of circumference L, as shown in Fig. 1. If a drive transducer (a point source) were placed at one point on the waveguide, and a receive transducer were placed diametrically opposite, then a wave could be sent around the ring, as shown in Fig. 1a. The phase advance at the received transducer could be used to determine the wave velocity, and one would calculate a velocity $v = v_0 (L/L')$, as before. However, such a measurement would correspond to a transport measurement; the important point which we shall make is that a persistent current measurement is fundamentally different from a transport measurement.

In the persistent current measurement, the state of the system is probed with an AC axial magnetic field. The axial magnetic field produces a field at the ring which is uniform and purely azimuthal; there is no radial component. In the acoustic system, the analog of the axial magnetic field would be a rotation of the acoustic fluid; the analog of the AC axial magnetic field would an oscillation of the "square wave" waveguide about its axis, producing a purely azimuthal excitation. The results of this type of excitation of the waveguide are quite different from those of the point source, as can be seen in Fig. 1b. The axial oscillation would produce an advance of the phase along the azimuthal parts of the waveguide, but not along the radial parts. The fluid in the radial parts of the waveguide would be driven back and forth between the sides of the waveguide, corresponding to a waveguide mode which has infinite phase velocity along its length; i.e. there is no phase advance along this part of the waveguide. The result is that the phase advance around the waveguide involves L rather than L', and the velocity determined from the phase would be v_0 rather than $v_0 (L/L')$. In the persistent current experiment, the correct expression for ΔI would be ev_F/L, and this would give good agreement with the experimental results, removing the discrepancy.

This explanation of the discrepancy between theory and experiment for normal electron persistent currents is based on the observation that the linear response of a system depends not only on the eigenvalues of the system, but also on the nature of the driving excitation field. The response of a normal electron mesoscopic system in a transport measurement, involving one particular type of excitation, may be fundamentally different from that in a persistent current measurement, which involves another particular type of excitation.

That the response of a system may depend on the nature of the excitation field may be elaborated as follows. The response of a linear system may be written as a sum over normal modes, with each term having a numerator and a denominator. The denominator involves the difference between the driving frequency and the natural frequency of the normal mode, with a damping term which prevents the denominator from vanishing. The numerator involves an inner product between the driving excitation field and the normal mode eigenfunction. In a transport measurement, the excitation field is a point (or slightly extended) source, so that the numerator has the same nominal value for all the (normalized) normal modes, and the reponse of the system has resonances when the denominator is minimized at the natural frequencies. For the analog of a persistent current measurement, imagine a one-dimensional acoustic waveguide with point scatterers; a flow of the fluid giving a Doppler shift of the sound wave provides the analog of the vector potential field. Between the point scatterers, the wave field may be written as a traveling wave in one direction, Doppler shifted up, and a traveling wave in the opposite direction, Doppler shifted down. Now imagine that the walls of the waveguide are lined with drive transducers whose phase may be independently controlled. These transducers may be phased so as to follow a traveling wave progressing, and Doppler shifted, in one direction only. The response of the system in this case will be dominated not by minima in the denominator, but instead by maxima in the numerator. If the fluid flow is increased so that the Doppler shift is increased, then the change in frequency of the drive required to follow the maximum in the response will be determined by the full Doppler shift, and will be unaffected by the effect of the scatterers. The effects of the change in the natural frequencies resulting from the change in the Doppler shift (rendered small by the scatterers as in Eq. 6) in the denominator will be of less importance. In effect, the phased driving excitation projects out the unreflected part of the wave field.

It should be noted that the argument involving the nature of the excitation field is valid for a strictly one-dimensional system of scatterers. This is not really necessary since the actual persistent current experiment is two-dimensional, in the sense that the conductor comprising the ring has a finite width. This makes it easier to explain the discrepancy, since in two-dimensions the effects of elastic scattering are much less dramatic than in one-dimension. As illustrated with the "square wave" waveguide, scattering in the transverse (radial) direction contributes to the tortuosity correction for a transport measurement, but not for a persistent current measurement.

It should also be noted that in an actual "square wave" circular waveguide, the presence of phase-advancing waves in the azimuthal parts will excite some phase-advancing waves in the radial parts, even though these are not sustained by the azimuthal driving force. However, it should be true that in the presence of some damping (residual inelastic scattering) the azimuthal excitation strongly favors modes with a purely azimuthal phase advance. We have tested this theory using a waveguide with the shape of an "L", which is the simplest element of a "square wave" waveguide. One end of the "L" has a receive transducer, and the modes of the waveguide are excited in two different ways. One method of excitation uses a point source at the end of the waveguide opposite the receiver, which should excite modes which correspond to fitting an integral number of half-wavelengths within the total length of the "L" waveguide (with a length L'). The second method of excitation is to drive the entire waveguide back and forth with a motion parallel to one arm of the "L" (with a length L). The second method should favor those modes which correspond to fitting an integral number of half-wavelengths along the parallel arm of the "L", and which have no phase shift along the perpendicular arm of the "L". The results of the experiment are shown in Fig. 2; Fig. 2a shows the response as a function of drive frequency for the point source excitation, and Fig. 2b shows the results for the uniform one-dimensional excitation. The peaks in the spectra are labeled with an L or L' with a subscript which is the number of half-wavelengths which fit into the length L or L' respectively; the label W indicates waveguide modes of the perpendicular arm of the "L", with the first subscript indicating the number of half-wavelengths accross the waveguide, and the second subscript indicating the number of half-wavelengths along the waveguide. The presence of the enhanced peaks if Fig. 2b confirm the predictions; the uniform one-dimensional drive does favor the modes with no phase advance along the perpendicular arm of the waveguide. A detailed account of this experiment will be published in a longer paper.[4]

We would like to acknowledge crucial discussions with R. A. Webb, A. J. Leggett, B. L. Altschuler, and R. M. Herman. This research was supported by NSF Grant DMR 9000549 and the Office of Naval Research.

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2. L. P. Levy, G. Dolan, J. Dunsmuir, and H. Bouchiat, Phys. Rev. Lett. **64**, 2074 (1990)

3. B. L. Altschuler, private communication.

4. M. J. McKenna and J. D. Maynard, to be submitted.

Figure Captions

Fig. 1. Different methods of exciting a circular, meandering waveguide. a) A simple source and detector at diametrically opposite points are analogous to a transport measurement and involve the length L'. b) An AC azimuthal excitation field is analogous to a persistent current measurement and invloves the length L.

Fig. 2. Response spectra of an "L" shaped waveguide (the simplest element of a "square wave" meandering waveguide) for two different types of excitation. a) Simple source excitation, showing nominal excitation of all modes. b) Uniform one-dimensional excitation of the entire waveguide, showing preferential excitation of modes involving only the length L.

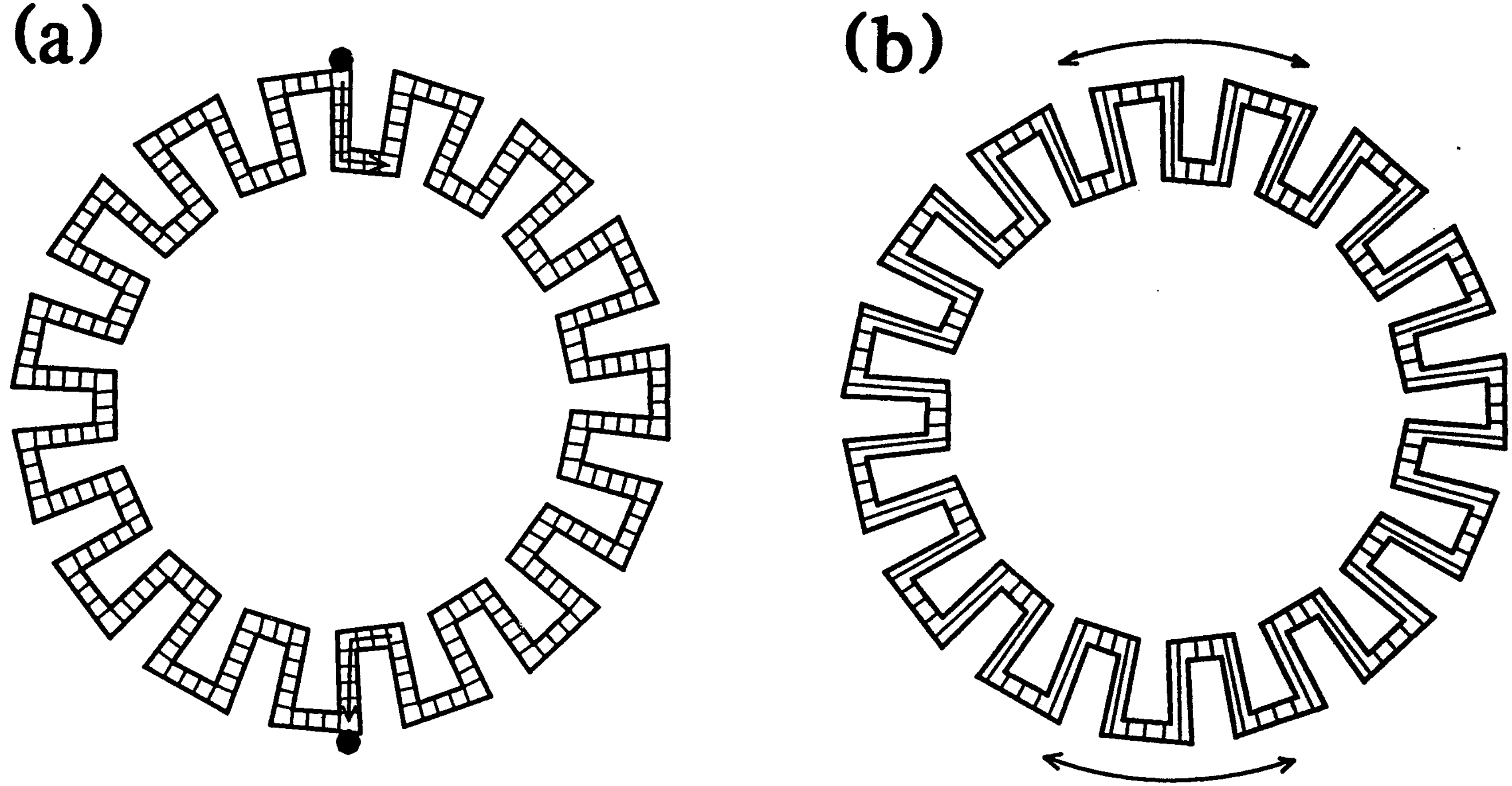
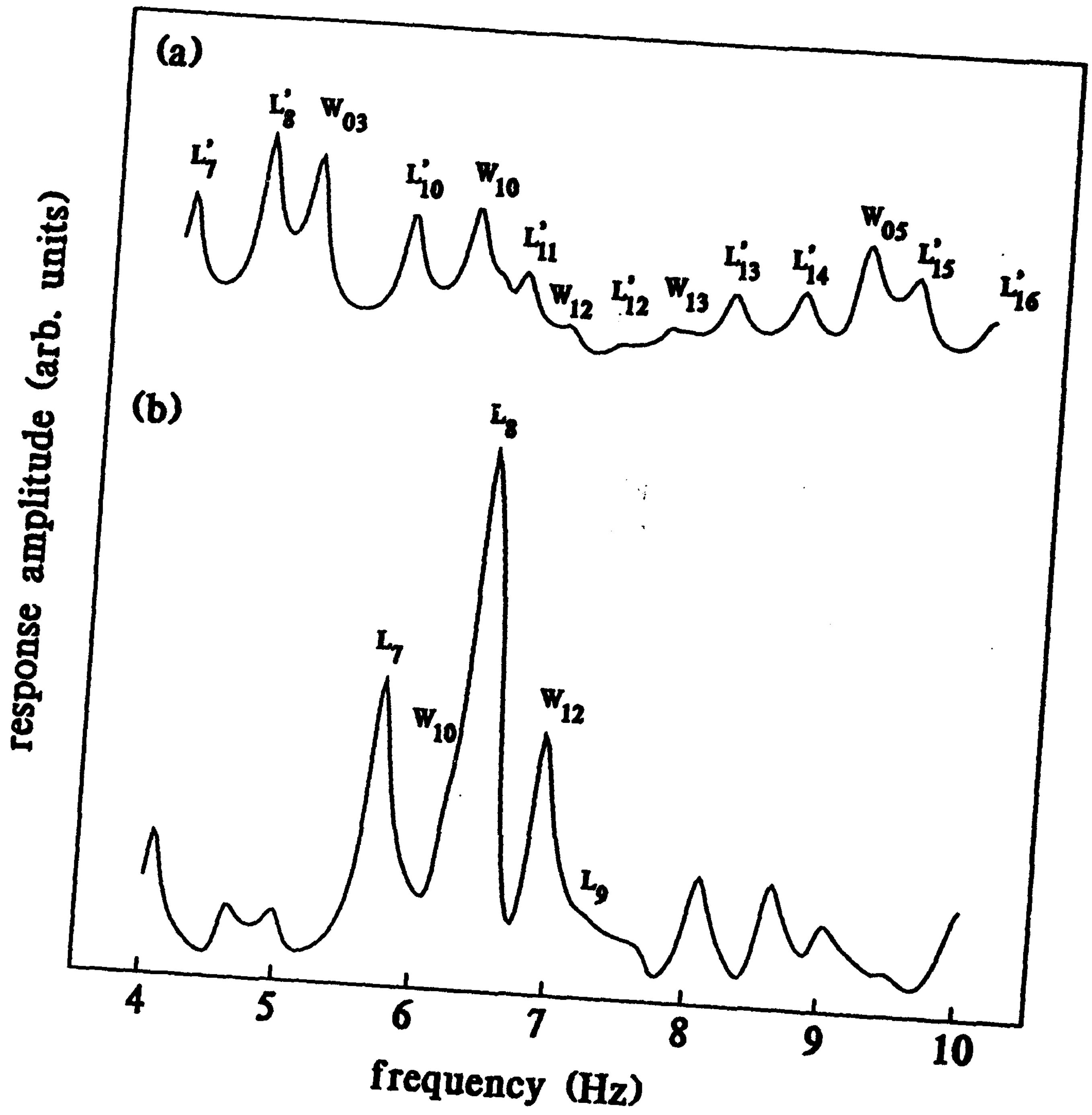


Fig. 1



(a)
L'7
L'8
W03
L'10
W10
L'11
W12
L'12
W13
L'13
L'14
W05
L'15
L'16
(b)
L7
W10
L8
W12
L9
response amplitude (arb. units)
4
5
6
7
8
9
10
frequency (Hz)

Fig. 2