

REPORT DOCUMENTATION PAGE			Form Approved OMB No. 0704-0188	
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1. AGENCY USE ONLY (Leave blank)		2. REPORT DATE 28 May 1996	3. REPORT TYPE AND DATES COVERED Summary 01 Jun 95 - 31 May 96	
4. TITLE AND SUBTITLE Innovative Acoustic Techniques for Studying New Materials and New Developments in Solid State Physics (Includes ASSERT)			5. FUNDING NUMBERS PE 61153N G N00014-92-J-1186 G N00014-93-1-0779	
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7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) The Pennsylvania State University Department of Physics 104 Davey Lab University Park, PA 16802			8. PERFORMING ORGANIZATION REPORT NUMBER	
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES) Office of Naval Research ONR 331 800 North Quincy Street Arlington, VA 22217-5660			10. SPONSORING/MONITORING AGENCY REPORT NUMBER	
11. SUPPLEMENTARY NOTES			19960621 069	
12a. DISTRIBUTION/AVAILABILITY STATEMENT Approved for public release: Distribution unlimited			12b. DISTRIBUTION CODE	
13. ABSTRACT (Maximum 200 words) The goals of this project involve the use of innovative acoustic techniques to study new materials and new developments in solid state physics. Major accomplishments include a) the publication of two papers in the prestigious journal Phys. Rev. Lett.: one on the use of resonant ultrasound spectroscopy (RUS) to determine the isotropy of a quasicrystal, and one on the behavior of nonlinear pulses propagating in disordered media, b) the publication of an article on RUS in the magazine Physics Today, c) the study of problems with the RUS analysis technique, d) the verification of the high information content of the data, higher than expected, in the fracture experiment, which led to a significant expansion of the fracture facility, and e) the observation of some exciting results which show that a wide range of fluid parameters, and significantly different acoustic signals, may be obtained in liquid coalescence experiments using normal liquid helium.				
14. SUBJECT TERMS Acoustics, Solid State Physics, Materials, Fracture			15. NUMBER OF PAGES 9	
			16. PRICE CODE	
17. SECURITY CLASSIFICATION OF REPORT UNCLASSIFIED	18. SECURITY CLASSIFICATION OF THIS PAGE UNCLASSIFIED	19. SECURITY CLASSIFICATION OF ABSTRACT UNCLASSIFIED	20. LIMITATION OF ABSTRACT	

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

This annual summary report presents the accomplishments for ONR grant N00014-92-J-1186, "Innovative Acoustic Techniques for Studying New Materials and New Developments in Solid State Physics". Accomplishments include the publications of two papers in the prestigious journal *Phys. Rev. Lett.* and an article in *Physics Today*. Some numerical problems with the data analysis in Resonant Ultrasound Spectroscopy (RUS) were finally resolved. Initial data in the fracture experiment led to a significant improvement in the test facility, and preliminary data in the liquid coalescence experiment seems to be very promising.

Papers, Talks, etc.

Progress with respect to papers, etc. includes the publication of two papers in the prestigious journal *Phys. Rev. Lett.* (presented in the appendix), and an invited publication in the magazine *Physics Today*. One *Phys. Rev. Lett.* presents the first evidence of the elastic isotropy of quasicrystals, and is a landmark in our research with resonant ultrasound spectroscopy (RUS). The second *Phys. Rev. Lett.* presents the first experimental observation of the theoretically predicted behavior for nonlinear pulses in disordered media, and is a part of our ongoing research on Anderson localization. The publication in *Physics Today* is a review of the emerging technology of RUS. [Precise references for the published papers are provided in the appendix.]

Two papers have been submitted for inclusion in the Proceedings of the XXI Conference on Low Temperature Physics; these papers undergo peer review, and if accepted, will be published in *Physica*. A review of wave propagation in periodic, random, and quasicrystalline media, with a tutorial on Anderson localization, has undergone major revision and will be submitted to the *J. Acoust. Soc. Am.* Three contributed papers were presented at meetings, and three invited lectures were given. The Ph.D. dissertation of Wei-li Lin, "Resonant Photoacoustics", was successfully defended; Lin has taken a position with Shure Microphone in Minneapolis, MN.

During the past year the total research group has consisted of four graduate students (some with only partial ONR support) and two postdocs; a number of outstanding undergraduates have made significant contributions to our research. A list of the publications, personnel, etc. is presented in the appendix.

In the sections which follow, a brief summary of the research accomplishments will be presented.

Measuring the Isotropy of a Quasicrystal with Resonant Ultrasound Spectroscopy

One of the fascinating properties of quasicrystals is that, unlike conventional crystals, qua-

single crystals are elastically isotropic. For conventional crystals with high symmetries (e.g. cubic crystals), many physical properties are isotropic, but the property of linear elasticity is fundamentally anisotropic. Thus it is interesting that icosahedral quasicrystals, having long-range order like conventional crystals, must be isotropic in sound propagation. Measuring these properties experimentally has been challenging, because while conventional crystals are fundamentally anisotropic, their elastic constants may be numerically very close to those of an isotropic material, so that it is difficult to distinguish between intrinsically isotropic and anisotropic behavior in a measurement. In our research we used resonant ultrasound spectroscopy to obtain high precision measurements of the elastic constants of both the quasicrystalline and periodic approximant phases of AlCuLi and found, with a significant level of confidence, that the quasicrystalline phase is isotropic (differing from the most nearly isotropic conventional crystal by ten standard deviations), while the periodic approximant is not. This measurement provides an important landmark for the RUS technology, because it represents a measurement for which conventional ultrasonic methods failed; RUS was necessary in order to determine all of the elastic constants self-consistently (without having to remount transducers) and with high precision. Details of this research are presented in the publication listed in the appendix.

In order to obtain the best precision, it was necessary to account for the deviation of the sample from an exactly rectangular parallelepiped. While this could be done with the standard formulation of RUS analysis, it was found that numerical problems appeared. Some problems were solved with subtle program repairs, but others were of a more fundamental nature. Graduate student Phil Spoor reported on these aspects of RUS in an invited talk at the May 1996 meeting of the Acoustical Society of America, and they will form a part of his Ph.D. dissertation, which is now being written.

Acoustic Studies of Brittle Foam Fracture as a Model for Current Theories in Statistical Physics

The objective of our research project in fracture is to improve models which predict fracture in brittle materials with random bond strength distributions, such as concrete, ceramics, etc. Recently, theorists from condensed matter physics have been developing analogies between fracture and contemporary physics problems involving directed polymer growth in a random medium; viscous fingering, diffusion limited aggregation, self-organized criticality, etc. In the theory, the brittle material is modeled as a network of bonds which are distributed randomly in the network with some probability distribution. Fracture is simulated by applying a stress or strain at the boundaries of the bond network; at some value of the boundary load, one of the internal bonds will break, increasing the load on the remaining bonds, and the process continues, ending in a catastrophic avalanche when the sample breaks in two.

In order to provide a test of the theories, it is necessary to have a measurement which can detect individual bonds breaking during the catastrophic avalanche. For the usual materials used in the study of fracture (glasses, resins, etc.), it would be impossible to detect individual atomic bonds breaking. However, it would be possible in a macroscopic

model of a brittle solid. For this purpose we have been studying an open cell carbon foam material consisting of a network of struts with lengths on the order of 1-2 mm. The struts play the role of the random bonds in the statistical physics models. When this material is placed in water, the water completely permeates the sample, and sound from a breaking interior strut easily propagates through the water in the open sample to a transducer outside the sample. With this system, we are able to measure, as a function of time and applied stress, precursors and their distributions in amplitude, space, and time, the statistics of the individual bond breaking events during the cascade at the catastrophic fracture, the fractal nature of the fracture surface, etc.

After fabricating a major facility for the fracture studies, including a large water tank, transducer arrays, data acquisition, etc., a considerable amount of data was taken for samples ranging in size from 3 cm to 10 cm in diameter. These data were analyzed, and the results were very promising, exceeding our expectations in regard to the spatial localization of the breaking bonds. While it was hoped that bond breaking events could be localized by triangularization with several transducers, it was anticipated that multiple scattering of the sound by the disordered strut network would limit the spatial analysis. However, it was found that by performing a wavelet analysis of the received signals, a characteristic high frequency component was found to propagate through the water with negligible scattering by the strut network, and a distinct arrival time could be used to accurately locate the bond breaking event. Furthermore, while the analysis was readily accomplished for precursors, it also worked for the final catastrophe, permitting a visualization of the propagation path of the crack front. Finally, the wavelet analysis also revealed that precursors consisted not only of single bonds breaking, but also several correlated bond breaking events.

The initial data showed that the amplitude of the received signals decreased significantly with the distance from the source to the transducers, and this indicated that more transducers surrounding the sample were necessary. Increasing the number of transducers from three to six would significantly enhance the chance that a transducer would be relatively near the source. While obtaining and mounting more transducers was not a problem, obtaining more preamplifiers and analog-to-digital (A/D) channels would have been expensive. Originally a commercial 50 MHz, low noise preamplifier, with a gain of 100, was used, but this unit cost \$1500. We found that comparable preamplifiers (with gains of 10) were recently available as integrated circuits, costing less than \$10. These integrated circuits and special printed circuit boards were purchased and assembled in pairs (for a gain of 100) to produce six 50 MHz, low noise preamps, comparable to the commercial unit, for minimal cost. For the additional A/D converters, an old four channel 1 MHz digitizer was re-commissioned; some effort was required to interface the old digitizer with the computer, but this was eventually accomplished. The fracture facility now has ten A/D channels available, with eight in use: two at different gain settings (to increase the dynamic range, avoiding saturation by large signals) for one transducer for amplitude and frequency analysis, five for five transducers for precursor and final avalanche amplitude and spatial analysis, and one which monitors the stress applied to the sample.

In addition to the data recorded by stressing the open cell samples, data were also taken by

manually breaking individual bonds inside a sample. The force required to break a bond was recorded along with the acoustic signal generated, and this premitted an absolute determination of the bond strength distribution for typical open cell samples. The acoustic signals recorded for the manually broken bonds provided a calibration for the analysis used in locating the position of bond breaking events, as mentioned earlier.

Studies of Liquid Coalescence

The underwater noise of rain, involving liquid coalescence, is important for environmental and military as well as scientific reasons. Significant theoretical and experimental studies have been done with water, and it would be of interest to extend measurements to a different fluid such as liquid helium. Helium has some interesting features in that the fluid and surface parameters may be varied over a wide range, and the liquid-vapor interface is particularly clean and well documented. We have completed preliminary measurements using a simple system, and have obtained some exciting results which show that changing fluid parameters by changing the temperature of liquid produces significant changes in the acoustic signals produced by liquid droplet impact. Some background for this research is presented below.

Pumphrey, Crum et. al.[1] studied the impact of water droplets on a water surface by using acoustic techniques and high-speed imaging. They showed that only a small range of raindrops (about 0.8 - 1.1 mm in size) forms entrained bubbles in water. The oscillations of these entrained bubbles contribute to the major acoustic power of the underwater noise. The numerical study by Oguz and Prosperetti[2] showed that for small drops, the drop crater is not deep enough to "pinch" an air bubble, while for higher energy drops, the inward lateral velocity is not sufficient to close the cavity before the bottom jet shoots out of it to prevent the bubble formation. They gave an empirical formula for the boundaries of the entrainment region, which depends on the water droplet size and its impact velocity and other physical properties of water. A severe difficulty in experimental studies of instabilities lies in eliminating or determining the effects of impurities or defects on the onset of the instability. An important feature of our experiments using liquid helium is that the fluids and the interfaces are more impurity-free than for any other system.

The preliminary experiment was done in an available commercial cryostat system (capable of 0.3 K operation) with optical access. In order to maintain a quiet liquid-vapor interface, the whole system is mounted on a vibration isolation table. The experimental cell, with superleak-tight quartz windows, contains two needles of 200 μm and 400 μm attached to the top of the cell, and these are used to generate liquid drops.

During the experiments, bulk helium fills the lower half of the cell. Droplets are formed by slightly cooling the top of the cell, so that vapor condenses on the ceiling, and a liquid film runs down the needle, grows into a droplet at the tip, and finally falls off. The impact of the droplet onto the surface of the bulk liquid is detected by an acoustic transducer just below the liquid surface. We used a conventional electret transducer with a high sensitivity, but with a bandwidth limited to approximately 30 kHz.

Signals from impacting droplets were obtained during our preliminary runs. The diameters of the droplets are about twice the size of the needles. The estimated impact velocities of the droplets are about 25 to 45 cm/s. A low noise preamplifier was used to boost the signal, and 100 sample averages were used during the data collection. In Figs. 1 and 2, traces of acoustic signals from the impact of a 400 μm diameter droplet formed from the 200 μm needle at two different temperatures are shown. The temperature is 4.2K for Fig. 1, and about 3.1K for Fig. 2.

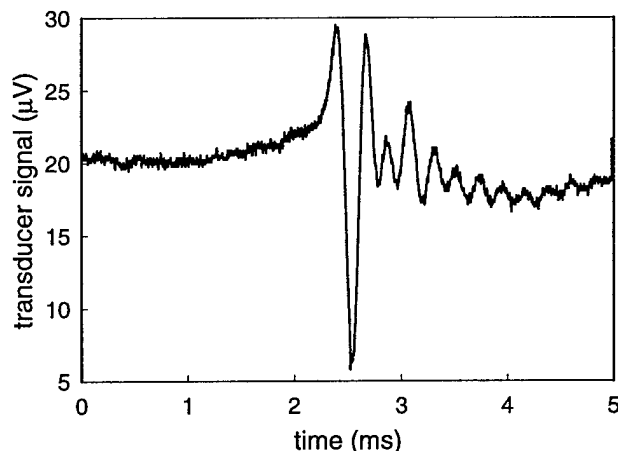


Fig. 1. Acoustic signal generated by the impact of a 400 μm helium droplet at 4.2K.

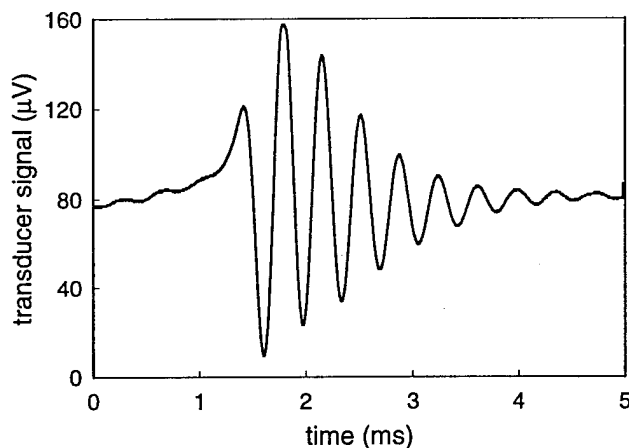


Fig. 2. Acoustic signal generated by the impact of a 400 μm helium droplet at 3.1K.

The oscillatory nature of the trace resembles those acoustic signals generated from entrapped bubbles in the water droplet experiments[1]. However, sizes of the droplets in our experiment are much smaller. Furthermore, the acoustic signals from liquid helium droplets are very temperature dependent. The lower the temperature, the stronger the signal, and the shape of the signal changes significantly. The signal amplitude (before the preamplifier) is about 30 μV at 4.2K and about 150 μV at 3.1K. The frequency of the oscillations also shows strong temperature dependence: about 4 KHz at 4.2K and about 2 KHz at 3.1K.

From the numerical calculation by Oguz and Prosperetti[2], the boundaries of the bubble entrainment region satisfy an empirical formula

$$We = kFr^\alpha \quad (1)$$

where $We = \rho V^2 a / \sigma$ is the Weber number, and $Fr = V^2 / ga$ is the Froude number. Here V is the impact velocity, σ the surface tension, g the gravitational constant, a the diameter of the droplet. The constants k and α are 20.3 and 0.247 for the upper boundary and 18.2 and 0.179 for the lower boundary. Using the constants for liquid helium at 4.2 K, we obtain the range of velocities for a 400 μm droplet to form entrapped bubbles is between 43 to 56 cm/s. This is compared favorably with the estimates of 25 to 45 cm/s in our experiment.

The research was interrupted because the research cryostat developed a leak and had to be returned to the factory for repair. At the present time the cryostat is re-installed, and experiments are underway again.

Current and Other Funding

Other research grants include:

1. NSF Division of Materials Research, Condensed Matter Physics Program, DMR 93-06791, which includes 1 man-month of the principal investigators time.
2. ONR, Physics Division, September 15, 1993 to September 14, 1996, 180,000/3 yr, "Anisotropic heat exchanger/stack configurations for thermoacoustic heat engines"; includes 1 man-month of time for the principle investigator, distributed over 12 months.

References

1. H. C. Pumphrey, L. A. Crum, L. Bjono, J. Acoust. Soc. Am. (1989) Vol. 85, 1518-26; H.C. Pumphrey, L. A. Crum, J. Acoust. Soc. Am. (1990), Vol. 87, 142-48.
2. H. N. Oguz, A. Prosperetti, J. Fluid Mech. (1990), Vol. 219, 143-79; A. Prosperetti, H. N. Oguz, Annu. Rev. Fluid Mech., (1993), Vol. 25, 577-602.

APPENDIX

OFFICE OF NAVAL RESEARCH PUBLICATIONS / PATENTS / PRESENTATIONS / HONORS REPORT for 01 JUNE 1995 through 31 MAY 1996

Contract/Grant Number: N00014-92-J-1186/N00014-93-1-0779/N00014-93-1-1127
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- a. Number of papers submitted to refereed journals but not yet published: 2
- b. Number of papers published in refereed journals: 2
- c. Number of books or chapters submitted but not yet published: 0
- d. Number of books or chapters published: 0
- e. Number of printed technical reports & non-refereed papers: 1
- f. Number of patents filed: 1
- g. Number of patents granted: 0
- h. Number of invited presentations at workshops or prof. soc. meetings: 3
- i. Number of contributed presentations at workshops or prof. soc. meetings: 3
- j. Honors/awards/prizes for contract/grant employees: 1
- k. Number of graduate students supported at least 25% this year: 4
- l. Number of post docs supported at least 25% this year: 2

Grad Students FEMALE:	0	Post-Docs FEMALE:	1
Grad Student MINORITY:	1	Post-Docs MINORITY:	1
Grad Student ASIAN E/N:	1	Post-Docs ASIAN E/N:	1

PUBLICATIONS, PRESENTATIONS, ETC.

PAPERS SUBMITTED TO REFEREED JOURNALS BUT NOT YET PUBLISHED

1. T. Zhang, B. Bennett, V. A. Hopkins, and J. D. Maynard, "Effects of finite amplitude fields on superfluidity", submitted to *Physica*, April, 1996
2. T. Zhang, B. Bennett, V. A. Hopkins, and J. D. Maynard, "Using liquid helium to study fluid interface coalescence effects", submitted to *Physica*, April, 1996

PAPERS PUBLISHED IN REFEREED JOURNALS

1. P. S. Spoor, J. D. Maynard, and A. R. Kortan, "Elastic isotropy and anisotropy in quasicrystalline and cubic AlCuLi", *Phys. Rev. Lett.* **75**, 3462-3465 (1995).
2. V. A. Hopkins, J. Keat, T. Zhang, and J. D. Maynard, "Observation of the predicted behavior of nonlinear pulse propagation in disordered media", *Phys. Rev. Lett.* **76**, 1102-1105 (1996).

PRINTED TECHNICAL REPORTS AND NON-REFEREED PAPERS

Wei-li Lin, Physics Ph.D. Thesis, 1996; *The Measurement of Ultra Low Optical Absorption in Solids in the Near Infrared Using a Resonant Photoacoustic Technique*.

PATENTS/APPLICATIONS

Patent Disclosure, "High Speed Digital Imaging System", September, 1995

INVITED PRESENTATIONS AT TOPICAL OR SCIENTIFIC/TECHNICAL SOCIETY CONFERENCES

1. Dartmouth College, Department of Physics, Hanover, NH, January 12, 1996. Host: Jeff Nunes. "Tuning-up a Quasicrystal".
2. Co-author, Consortium on Resonant Ultrasound Spectroscopy, Santa Fe, NM, August 24-26, 1995. Host: Albert Migliori. "Numerical anomalies in the Rayleigh-Ritz method for calculating the normal mode vibrations of arbitrarily shaped elastic solids".
3. Co-author, 131st Meeting of the Acoustical Society of America, Indianapolis, IN, May 13-17, 1996. Host: Albert Migliori, "An investigation of computational problems associated with resonant ultrasound spectroscopy".

CONTRIBUTED PRESENTATIONS AT TOPICAL OR SCIENTIFIC/TECHNICAL SOCIETY CONFERENCES

1. L. C. Krysac and J. D. Maynard, "Detailed observation of the complete fracture process of brittle carbon foam", J. Acoust. Soc. Amer. **98**, 2875 (1995). St. Louis, MO, November 27-December 1, 1995.
2. L. C. Krysac and J. D. maynard, "The dynamics of brittle fracture", Bull. Am. Phys. Soc. **41**, 314 (1996). St. Louis, MO, March 18-22, 1996.
3. P. S. Spoor and J. D. maynard, "Isotropy and anisotropy in icosahedral and cubic AlCuLi", Bull. Am. Phys. Soc. **41**, 787 (1996). St. Louis, MO, March 18-22, 1996.

HONORS/AWARDS/PRIZES

Invited publication: J. D. Maynard, "Resonant Ultrasound Spectroscopy", Physics Today **49**, 26-31 (1996).

GRADUATE STUDENTS SUPPORTED UNDER CONTRACT FOR YEAR ENDING 31 OCTOBER 1995

1. Philip Spoor (Ph.D. candidate, acoustics) began Fall 1989, Elastic Constant Measurements for Quasicrystals
2. Brian Bennett (Ph.D. Candidate, Acoustics Program) began summer 1994, Fluid coalescence
3. David Chao Zhang (Ph.D. candidate, physics) began summer 1994, Thermoacoustic heat engines
4. Jason White (Ph.D. candidate, physics) began summer 1994, Resonant Ultrasound Spectroscopy

POSTDOCTORALS SUPPORTED UNDER CONTRACT FOR YEAR ENDING 31 OCTOBER 1994

1. Tian-ming Zhang, Postdoctoral Scholar, began June, 1994
2. Cindy Krysac, Postdoctoral Scholar, began July, 1994

MISCELLANEOUS

Undergraduates Involved in Research:

1. Joseph Buck, Senior, 1994-95
2. John Lelii, NSF Research Experience for Undergrad. student 1995
3. Kirk Fisher, Junior, 1994-95
4. Patrick Johnston, 1994-95
5. Mike Marotta, NSF Research Experience for Undergrad. student 1995