# Final Report - DOE Grant No. DE-FG02-07ER46424


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## Abstract


We present a final report on the activities undertaken under DOE Grant No. DE-FG02-07ER46424, entitled "Interaction effects in quasi one-dimensional electronic systems," originally under the direction of Prof. Julia Meyer. The report includes an overview of the grant and the personnel involved, a list of publications acknowledging the grant, and a summary of the results and conclusions drawn from research supported by the grant.

## I. OVERVIEW AND SUMMARY OF PERSONNEL INVOLVED IN THE GRANT

DOE Grant No. DE-FG02-07ER46424, entitled "Interaction effects in quasi one-dimensional electronic systems," began in 2007 and ran until 2010, with a three-year no-cost extension till 2013. The original Principal Investigator was Prof. Julia Meyer of Ohio State University. Part way through the first thee-year term, Prof. Meyer left Ohio State to take up a position at CEA Grenoble, in France. For a while, she continued to supervise her Ph. D. student, Mehul Dixit, from a distance, but when this became impractical, she transferred this supervision, first, to Prof. Nandini Trivedi at Ohio State, and then to me. I became PI of the grant around 2010. The grant still had enough funding for Mehul Dixit for about a year, after which he was partly supported by a teaching assistantship at Ohio State. He obtained his Ph. D. in 2012, and then took up a postdoc at the University of Missouri.

The personnel involved in the grant, besides Julia Meyer, are mostly included in the publications acknowledging support from the grant. They are David Stroud (Prof. of Physics, Ohio State University - emeritus since 2011), Mehul Dixit (graduate student in physics at Ohio State, supported by the grant), Alexios Klironomos (postdoc at Ohio State, supported by the grant, and now an associate editor at Physical Review B), Kwangmoo Kim (former graduate student of David Stroud at Ohio State, now a postdoc at the Korea Institute for Advanced Study in Seoul), Konstantin Matveev (staff physicist at Argonne National Lab), and Tobias Meng and Markus Garst at the University of Cologne, Germany. Prof. Trivedi supervised Dr. Dixit for several months but they completed no grant-supported research during that time.

## II. PUBLICATIONS ACKNOWLEDGING SUPPORT FROM THE GRANT

1. "Wigner crystal physics in quantum wires," Julia S. Meyer and K. A. Matveev, Journal of Physics-Condensed Matter, Vol. **21**, Article No. 023203 (2009).

2. "Quantum phase transition in quantum wires controlled by an external gate," Tobias Meng, Mehul Dixit, Markus Garst, and Julia S. Meyer, Journal of Physics-Condensed Matter, Vol. **21**, Article No. 126323 (2011).

3. "Formation of defects in multirow Wigner crystals," A. D. Klironomos and Julia S.

Meyer, Phys. Rev. B **83**, Article No. 024117 (2011).

4. "Photonic band structures of periodic arrays of pores in a metallic host: tight-binding beyond the quasistatic approximation," Kwangmoo Kim and D. Stroud, Optics Express Vol. **21**, pp. 19834-19849 (2013).

5. "Realization of one-way electromagnetic modes at the interface between two dissimilar states," Mehul Dixit and David Stroud, Appl. Phys. Lett. Vol. **104**, Article No. 061604 (2014).

## III. SUMMARY OF CONCLUSIONS DRAWN FROM THE RESEARCH SUPPORTED BY THE GRANT

1. The physics of interacting quantum wires has attracted a lot of attention recently. When the density of electrons in the wire is very low, the strong repulsion between the wires leads to the formation of a Wigner crystal. In the paper, "Wigner crystal physics in quantum wires," Meyer and Matveev reviewed the rich spin and orbital properties of the Wigner crystal in both the one-dimensional and the quasi-one-dimensional regimes. In the one-dimensional Wigner crystal, the electron spins form an antiferromagnetic Heisenberg chain with exponentially small exchange coupling. In the presence of leads, the resulting inhomogeneity of the electron density causes a violation of spin-charge separation. As a consequence, the spin degrees of freedom affect the conductance of the wire. Upon increasing the electron density, the Wigner crystal starts deviating from the strictly one-dimensional geometry, forming a zigzag structure instead. Spin interactions in this regime are dominated by ring exchanges, and the phase diagram of the resulting zigzag spin chain has a number of unpolarized phases as well as regions of complete and partial spin polarization. Finally, the authors addressed the orbital properties in the vicinity of the transition from a one-dimensional to a quasi-one-dimensional state. Due to the locking between chains in the zigzag Wigner crystal, only one gapless mode exists. Manifestations of Wigner crystal physics at weak interactions are explored by studying the fate of the additional gapped low-energy mode as a function of interaction strength.

2. In the paper, "Quantum phase transition in quantum wires controlled by an external

gate," Meng, Dixit, Garst, and Meyer considered electrons in a quantum wire interacting va a long-range Coulomb potential screened by a nearby gate. They focused on the quantum phase transition from a strictly one-dimensional to a quasi-one-dimensional electron liquid that is controlled by the dimensionless parameter $nx(0)$, where $n$ is the electron density and $x(0)$ is the characteristic length of the transverse confining potential. If this transition occurs in the low-density limit, it can be understood as the deformation of the one-dimensional Wigner crystal to a zigzag arrangement of the electrons described by an Ising order parameter. The critical properties are governed by the charge degrees of freedom and the spin sector remains essentially decoupled. At large densities, on the other hand, the transition is triggered by the filling of a second one-dimensional subband of transverse quantization. Electrons at the bottom of the second subband interact strongly due to the diverging density of states and become impenetrable. The authors argue that this stabilizes the electron liquid as it suppresses pair-tunneling processes between the subbands that would otherwise lead to an instability. However, the impenetrable electrons in the second band are screened by the excitations of the first subband, so that the transition is identified as a Lifshitz transition of impenetrable polarons. The authors discuss the resulting phase diagram as a function of $nx(0)$.

3. In the paper, "Formation of defects in multirow Wigner crystals," Klironomos and Meyer studied the structural properties of the ground state of a quasi-one-dimensional classical Wigner crystal confined in the transverse direction by a parabolic potential. With increasing density, the one-dimensional crystal first splits into a zigzag crystal before progressively more rows appear. While for up to four rows the ground state possesses a regular structure, five-row crystals exhibit defects in a certain density regime. The authors dentify two phases with different types of defects. Furthermore, using a simplified model, they show that beyond nine rows no stable regular structures exist. Manifestations of Wigner crystal physics at weak interactions are explored.

4. In the paper, "Photonic band structures of periodic arrays of pores in a metallic host: tight-binding beyond the quasistatic approximation," Kim and Stroud have calculated the photonic band structures of metallic inverse opals and of periodic linear chains of spherical pores in a metallic host below the plasma frequency $\omega_p$. In both cases,

the authors use a tight-binding approximation, assuming a Drude dielectric function for the metallic component but without making the quasistatic approximation. The tight-binding modes are linear combinations of the single-cavity transverse magnetic (TM) modes. For the inverse-opal structures, the lowest modes are analogous to those constructed from the three degenerate atomic p-states in fcc crystals. For the linear chains, in the limit of spheres which have radius small compared to a wavelength, the results bear some qualitative resemblance to the dispersion relations for metal spheres in an insulating host, as calculated by Brongersma *et al.* [Phys. Rev. B **62**, R16356 (2000)]. Because the electromagnetic fields of these modes decay exponentially in the metal, there are no radiative losses, in contrast to the case of arrays of metallic spheres in air. The authors suggest that this tight-binding approach to photonic band structures of such metallic inverse materials may be a useful approach for studying photonic crystals containing metallic components, even beyond the quasistatic approximation.

5. In the paper entitled "Realization of one-way electromagnetic modes at the interface between two dissimilar metals," Dixit and Stroud calculated the dispersion relations for electromagnetic waves propagating at the interface between two dissimilar Drude metals in an external magnetic field **B** parallel to the interface. The propagating modes are found to be bound to the interface and to travel perpendicular to **B**. In certain frequency ranges, the waves can propagate in one direction only. The frequency range for these one-way modes increases with increasing magnitude B. One group of modes occurs at moderate frequencies, between the lower and upper plasma frequencies of the two metals. The other occurs at much lower frequencies, between the lower and upper cyclotron frequencies. The authors discuss possible ways to realize such modes in real materials, including dissimilar superconductors with different superconducting gaps.

6. Finally, in a preprint not yet submitted for publication, Mehul Dixit and David Stroud have developed a simple formalism to calculate the effective magnetoelectric tensor of a composite material. A magnetoelectric material is a material in which an electric field can induce a magnetization, and conversely an applied magnetic field can induce an electric polarization. Such a response usually occurs in inhomogeneous materials, such as composite materials. In this preprint, tentatively entitled "Effective magneto-

electric tensor of a composite material," the authors have developed a way to calculate this tensor for a composite, given the magnetoelectric tensors of the constituents. The problem is solved by a decoupling transformation that exactly reduces the problem to that of finding the coefficients ($\epsilon$ or $\mu$) of a conventional composite with two independent curl-free fields. Tjhe magnetoelectric coefficients of the composite are obtained entirely in terms of the coefficients of the individual components. The decoupling transformation is idential to that first used in the solution of the analogous problem in composite thermoelectrics. This paper will be submitted for publication as soon as the authors develop a simple example of real materials - they plan to do this in the next several months. It will acknowledge the DOE grant.