NDnano Summer Undergraduate Research
2022 Project Summary

1. Student name & home university: Maximilian Niebur, Johns Hopkins University

2. ND faculty name & department: Dr. Yi-Ting Hsu, Physics

3. Summer project title: Realization and detection of topological superconductivity

4. Briefly describe new skills you acquired during your summer research:
Learned new mathematical techniques for solving quantum physics problems with the Bogliubov-de Gennes and Schrödinger equations.

5. Briefly share a practical application/end use of your research:
Topological materials have possible future uses in many fields of small-scale electronics including solid-state data storage, quantum computing, more energy efficient circuit components, and as thermoelectric materials.

6. 50- to 75-word abstract of your project:
Topological phases feature physical observables being related to topological invariants. The most prominent example is the Chern number which relates the conductance of the quantum Hall state to the integral of the Berry curvature over the Brillouin zone. There are many other such topological phases, including the newly discovered field of topologic superconductors. I worked to understand theories about the nature of such materials, and how they may be realized.

7. References for papers, posters, or presentations of your research:

Niebur, Maximilian. (2022, July 15). *A Theory of Topologic Materials* [Research Presentation]. NURF presentation session, Notre Dame, IN, United States.

One-page project summary that describes problem, project goal and your activities / results:

Topological materials are most basically identified by materials whose wavefunctions have invariant properties under adiabatic alteration of their Hamiltonian. They were first theorized in the 1980s as an explanation for the plateaued conductance of the quantum Hall state. When a 2D electron gas, is placed in a strong magnetic field, the Hall conductance across the gas was found to be quantized to 1 part in 1 billion in experiment. The conductance was directly proportional to an integer value equal to the integral of a curvature over the closed surface of the insulator in momentum space. The related Gauss-Bonnet Theorem suggests that this value is always quantized, and it follows that it should be an integer from Dirac's quantization of the magnetic monopole. This is the most basic topological insulator, where the quantum Hall effect creates a structure that is insulating in the bulk, but has metallic edge states. Later a new topological phase was found, dubbed the quantum spin Hall insulator. This phase was found in materials where strong spin-orbit coupling leads to inversion of the *s* and *p* like subbands in odd parity systems. It behaves like two opposite copies of the quantum Hall effect, one for spin-up electrons, one for spin-down electrons. Since this new phase was found independent of the strong magnetic field that characterized the quantum Hall effect, it preserved time reversal symmetry. This state was found to have a new binary topological classification, where 1 indicated the topologically non-trivial quantum spin Hall effect, and 0 indicated the trivial insulating phase. Of most interest, insulators based on this topological classification were also found in 3D systems, where the system was insulating in the bulk, but with metallic surfaces.

In 2016, topological superconductors were first found in experiment when a gated insulator was cooled below 500 mK, at which point its resistance in the bulk dropped to 0. This confirmed the presence of previously theorized topological non-trivial superconducting states. The discovery of new topological phases and a prediction of possible topological superconductors led to an eventual classification system for topological materials in 2008. This system classified the two materials by the presence or absence of both time-reversal and particle-hole symmetries, the two key differentiators between topologic phases.

While the topological nature of these phases has been classified, it is still an open question as to how the topological superconductors fit into the larger classification of superconductors, and the mechanism to their superconductivity. The prevailing theory describes the superconductivity using Bogoliubov-deGennes Majorana quasiparticles. These exist as bound Majorana zero modes in the superconducting vortices in the simplest theorized examples, or by Majorana edge or corner states in u higher order topologic phases. The goal was to find possible ways to realize and detect topological superconducting materials with Majorana corner modes.