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Ferromagnetic Superconductivity And Its Interplay With Spin-Orbit Coupling And Topological Effects

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Abstract: The coexistence of ferromagnetism and superconductivity (FMS) has been a fascinating area of condensed matter physics, providing insight into unconventional superconducting pairings, spin-triplet interactions, and topologically protected surface states. This paper provides a review of recent theoretical and experimental advances in the study of FMS, with an emphasis on tunneling spectroscopy, spin-orbit coupling, and the role of topological materials. We discuss the interaction between spin-polarized currents, superconducting gaps, and ferromagnetic order, alongside the challenges of identifying and manipulating these phenomena in novel materials, including topological insulators and graphene. A particular focus is given to the use of tunneling spectroscopy as a tool to probe pairing symmetries, and the influence of external magnetic fields and spin-orbit coupling on these systems.

Index Terms- ferromagnetism, superconductivity, spectroscopy and spin-polarized currents.

1. Introduction:-

Ferromagnetic superconductivity (FMS) refers to the remarkable coexistence of ferromagnetism and superconductivity in materials, where the macroscopic magnetic ordering competes with or enhances the superconducting phase. In recent years, the discovery of various FMS materials such as UCoGe and URhGe has spurred significant interest due to the possibility of spin-triplet superconductivity, nontrivial superconducting gaps, and the coupling of superconducting states with ferromagnetic order. This field is deeply intertwined with the study of topological materials, non-centrosymmetric superconductors, and spin-orbit coupled systems.

FMS materials challenge conventional understanding, as ferromagnetic order tends to suppress singlet-pairing superconductivity. Instead, these materials often favor triplet-pairing states, leading to unconventional phenomena. Recent advancements in tunneling spectroscopy have enabled detailed investigations into the pairing symmetries of these materials, providing valuable insights into their unconventional superconducting behavior.

This review explores the theoretical models and experimental findings that describe the interplay between ferromagnetism, superconductivity, and spin-orbit interactions in FMS materials. We also highlight the role of tunneling spectroscopy, a critical tool for investigating superconducting gaps and pairing symmetries.

2. Theoretical Models and Frameworks

2.1. BCS Theory and Generalization to FMS:

The foundation of understanding superconductivity in conventional materials lies in the Bardeen-Cooper-Schrieffer (BCS) theory, which describes the formation of Cooper pairs mediated by phonon interactions in conventional superconductors. However, ferromagnetic superconductors introduce a challenge to this theory, as the exchange interaction in ferromagnetic systems typically acts to break Cooper pairs.

Several theoretical models have been developed to describe FMS, primarily extending the BCS theory to incorporate spin-triplet pairings. Spin-triplet pairing is energetically favored in ferromagnetic systems because the ferromagnetic exchange interaction aligns spins in a parallel configuration, stabilizing triplet states. For example, the model described by **Yokoyama and Tanaka (2007**) focuses on the tunneling conductance of normal metal/insulator/ferromagnetic superconductor junctions, predicting distinctive spectral features depending on the pairing symmetry. These predictions offer a valuable framework for interpreting experimental tunneling spectra in FMS materials.

2.2. Spin-Orbit Coupling and Non-Centrosymmetric Superconductors:

Spin-orbit coupling plays a crucial role in non-centrosymmetric superconductors, where the lack of inversion symmetry can induce mixed singlet-triplet pairing states. **Linder and Sudbo** (2008) developed a Hamiltonian that describes the coexistence of itinerant ferromagnetism, spin-orbit coupling, and mixed singlet-triplet superconducting pairing. Their model predicts that tunneling spectra in these systems will exhibit peaks corresponding to the sum and difference of the singlet and triplet gaps, offering a distinct signature for the identification of mixed superconducting states.

Additionally, the interplay between spin-orbit coupling and ferromagnetism in systems like graphene has been explored. **Hsu and Guo** (2018) studied tunneling conductance in graphene ferromagnet-insulator-superconductor junctions, demonstrating that exchange splitting in the graphene Dirac bands leads to novel conductance oscillations. This study highlights the potential for graphene-based materials to exhibit strong coupling between spin and superconductivity, further expanding the field of FMS.

2.3. Topological Effects in Ferromagnetic Superconductor:

Topological insulators (TIs) offer another unique perspective on FMS, as they naturally support robust surface states that are immune to scattering by nonmagnetic impurities. The combination of ferromagnetic order, superconductivity, and spin-orbit coupling on the surface of a TI can lead to the formation of Majorana fermions, which are non-Abelian quasiparticles that could have applications in topological quantum computation. **Linder et al. (2021)** explored the transport properties of superconducting-ferromagnetic junctions on TIs, finding that these systems could host gapless excitations and Majorana states under certain conditions, thus opening the door to new forms of topologically protected superconductivity.

3. Experimental Advances in FMS:

3.1. Tunneling Spectroscopy

Tunneling spectroscopy has proven to be an invaluable tool in studying FMS, as it can directly probe the superconducting gap and reveal the symmetry of the pairing state. In particular, **Yokoyama and Tanaka (2007)** demonstrated that tunneling conductance in normal metal/ferromagnetic superconductor junctions displays distinct features for different pairing symmetries. For example:

- Spin-singlet s-wave pairing results in a gap structure in the tunneling spectrum.
- Spin-triplet opposite-spin pairing yields a double peak structure.
- Spin-triplet equal-spin pairing produces a zero-bias peak (ZBP).

These features provide a direct way to distinguish between different superconducting pairings, crucial for understanding FMS in materials like UCoGe and URhGe.

3.2. Ferromagnetic Superconductors and Critical Temperature Enhancement-

Recent experimental studies on materials like UCoGe have revealed that applying an external magnetic field can significantly enhance superconductivity. This phenomenon, known as reentrant superconductivity, occurs when the ferromagnetic transition is suppressed, leading to an increase in the superconducting transition temperature. The thermoelectric measurements by **Malone et al. (2012**) on UCoGe further support this, showing a strong sensitivity of thermopower to the Fermi surface modifications near critical points.

These findings highlight the complex interplay between superconductivity and ferromagnetism in FMS materials, where external conditions such as pressure and magnetic field can tune the competition between these two phases.

4. Challenges and Future Directions:

4.1. Identifying the Pairing Symmetry-

One of the ongoing challenges in the study of FMS is the accurate identification of the pairing symmetry. Despite the progress made with tunneling spectroscopy and other experimental techniques, distinguishing between spin-triplet and spin-singlet pairings in FMS remains a difficult task. The development of more advanced spectroscopic methods, such as angle-resolved photoemission spectroscopy (ARPES), could provide deeper insights into the electronic structure and pairing symmetries in these systems.

4.2. Unconventional Superconductivity and Topological Materials-

As FMS materials become more closely intertwined with topological systems, there is a growing need for experimental platforms that can probe the effects of both ferromagnetism and superconductivity in topologically nontrivial environments. The realization of Majorana fermions in FMS materials, especially on topological insulators, could offer a breakthrough in quantum computing. Further research into the coupling between ferromagnetic magnons and superconducting qubits, as demonstrated by **Tabuchi et al. (2014),** could provide the next steps toward building hybrid quantum systems.

4.3. Quantum Phase Transitions and Non-Equilibrium States-

Finally, the study of quantum phase transitions and non-equilibrium states in FMS is an emerging area. The use of lattice gauge theory (LGT) to simulate the phase diagrams of FMS systems, as outlined by **Ichinose and Matsui** (2014), is an exciting development. These models help capture the nonperturbative aspects of the FMS phase transitions and could lead to new insights into the behavior of FMS materials at extreme conditions, such as at high magnetic fields or near quantum critical points.

5. Conclusion:

Ferromagnetic superconductivity remains a rich and evolving field at the intersection of condensed matter physics, topological materials, and quantum information science. The theoretical models developed over the years, combined with advanced experimental techniques such as tunneling spectroscopy and thermoelectric measurements, have provided significant insights into the pairing symmetries and the interplay between ferromagnetism and superconductivity. As new materials and experimental platforms emerge, the study of FMS promises to uncover new phenomena that could lead to novel quantum technologies and deepen our understanding of quantum matter.

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