Exploiting antiferromagnetic magnons for strong coupling and condensation phenomena

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Néel ordered state is not the “true ground state” of an antiferromagnet!

“Classical” antiferromagnets exhibit various exchange-enhancement effects!

Antiferromagnetic quantum fluctuations may underlie superconductivity!
Superconductivity

\[ k_B T_c = \hbar \omega_c \exp \left( -\frac{1}{\lambda} \right) \]
Magnon-mediated Superconductivity

\[ k_B T_c = \hbar \omega_c \exp \left( -\frac{1}{\lambda} \right) \]

Kargarian et al., PRL 117, 076806 (2016).
Rohling et al., PRB 97, 115401 (2018).
Hugdal et al., PRB 97, 195438 (2018).
...
Superconductivity in Magnet/Metal Bilayers

Superconductivity in Magnet/Metal Bilayers

Outline

- Brief introduction
- Magnons in ferromagnets
- Antiferromagnetic magnons
- Exploiting squeezing-mediated quantum fluctuations
- Superconductivity enhancement due to squeezing
- Magnon-mediated indirect exciton condensation
Ferromagnet
Ferromagnet Ground State

Ferromagnet Excited State

Ferromagnet Excited State

Ground State

Magnon

Magnon

\[ + \]

Delocalized \(-\hbar\)

Considering only exchange interaction and Zeeman energy!

Wavefunctions Notation

Fully Ordered State

1 Magnon

2 Magnons
Ferromagnet Ground State

\[ \uparrow \uparrow \uparrow \uparrow \uparrow \uparrow \uparrow \uparrow \uparrow \]

\[ \hat{\mathcal{Z}} \]

\[ | \rangle \langle | \]

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Ferromagnet Ground State
Ferromagnet Ground State
Ferromagnet Ground State

\[ H = K_x S_x^2 + K_y S_y^2 + \cdots \]

\[ \left| \uparrow \uparrow \uparrow \uparrow \right\rangle + \left| \downarrow \downarrow \downarrow \downarrow \right\rangle + \cdots = S(r) \left| \upaarrow \right\rangle \]
Squeezed Optical Vacuum

Nonequilibrium state!
Not an eigenstate!

Chapter 7: Nonclassical light
Ferromagnetic Eigenmodes

Ground State

\[ | \uparrow \rangle + | \downarrow \downarrow \rangle + | \downarrow \downarrow \downarrow \downarrow \downarrow \rangle + \ldots = S(r) | \rangle \]

Excitation

\[ | \downarrow \rangle + | \downarrow \downarrow \downarrow \rangle + | \downarrow \downarrow \downarrow \downarrow \downarrow \rangle + \ldots = S(r) | \downarrow \rangle \]
Ferromagnet Summary

- Magnon-squeezing mediated by “weak” spin-nonconserving interactions such as anisotropy
- Net effect of the order of unity
- Bogoliubov transform causes squeezing


\[
\text{Squeezed magnon} \quad \left| \downarrow \right\rangle + \left| \downarrow \downarrow \downarrow \downarrow \downarrow \right\rangle + \left| \downarrow \downarrow \downarrow \downarrow \downarrow \downarrow \right\rangle + ... = S(r) \left| \downarrow \right\rangle
\]
Ferromagnet Summary

- Magnon-squeezing mediated by “weak” spin-nonconserving interactions such as anisotropy
- Net effect of the order of unity
- Bogoliubov transform causes squeezing

\[
\text{Squeezed magnon} \quad \begin{array}{c}
\downarrow \\
+ \\
\downarrow \downarrow \\
+ \\
\downarrow \downarrow \downarrow \\
+ \\
\text{...} \\
= S(r) \downarrow \\
\end{array}
\]

Antiferromagnet
Two Interpenetrating Sublattices

\[ -\hbar + \hbar \]

\[ \hat{Z} \]
Néel Ordered State
Néel Ordered State
Néel Ordered State

\[ H = J \vec{S}_A \cdot \vec{S}_B + \cdots \]
Antiferromagnetic Ground State

\[ H = J \hat{\mathbf{S}}_A \cdot \hat{\mathbf{S}}_B + \cdots \]

Quantum correlated fluctuations
Antiferromagnetic Eigenmodes

Ground State
\[ |\rangle + |\downarrow\rangle + \ldots + |\ldots \downarrow\rangle + \ldots = S_2^2(r) |\rangle \]

Spin-up Excitation
\[ |\uparrow\rangle + |\uparrow\rangle + \ldots + |\ldots \uparrow\rangle + \ldots = S_2(r) |\uparrow\rangle \]
Antiferromagnetic Eigenmodes

\[ \sinh^2 r \]

\[ |0\rangle_{sq} = \sum_n P_n |n, n\rangle_{sub} \]

\[ \sinh^2 r + \cosh^2 r \]

\[ |\uparrow\rangle_{sq} = \sum_n Q_n |n + 1, n\rangle_{sub} \]

\[ r = 3 \]

\[ |P_n|^2 \]

\[ r = 1 \]

\[ |Q_n|^2 \]
Degree of Squeezing

\[ \tilde{H}_{\text{uni}} = \frac{J}{\hbar^2} \sum_{i,\delta} \tilde{S}_A(\mathbf{r}_i) \cdot \tilde{S}_B(\mathbf{r}_i + \delta) - \frac{K}{\hbar^2} \sum_i \left[ \tilde{S}_{Az}(\mathbf{r}_i) \right]^2 - \frac{K}{\hbar^2} \sum_j \left[ \tilde{S}_{Bz}(\mathbf{r}_j) \right]^2 \]

\[ \cosh^2 r \sim \sqrt{\frac{J}{K}} \]

\[ \frac{J}{K} = 10^4 \quad \Rightarrow \quad \cosh^2 r \approx 100 \quad \text{and} \quad r \approx 3 \]

Most squeezed state of light achieved thus far corresponds to \( r \approx 1.7 \)!
Antiferromagnet Summary

- Classical: Néel ordered ground state and sublattice-magnon
- Quantum (Actual): Squeezed vacuum and magnons
- Squeezing caused by exchange
- Large net effect (~ 100 for typical AFM)
- Bogoliubov transform causes squeezing


Antiferromagnet Summary

Ground State
\[ |\downarrow\rangle + |\uparrow\rangle + \ldots + |\ldots\downarrow\rangle + \ldots \]

Spin-up Excitation
\[ |\uparrow\rangle + |\downarrow\rangle + \ldots + |\ldots\uparrow\rangle + \ldots \]

Exploiting Magnon-Squeezing
Coupling Amplification

Coupling Amplification

Coupling Amplification

Amplification of sublattice-spin mediated interactions!


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Enhancement in Spin Pumping Current

Enhancing Cavity Quantum Electrodynamics via Antisqueezing: Synthetic Ultrastrong Coupling

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Experiments @ ~ 280 K
Sublattice-spin-mediated Coupling

- Theoretical proposal
- Nonequilibrium effect
- Best case enhancement ~ 10

- Experimental realization
- Eigenmode property
- Observed enhancement ~ 100

Superconductivity Enhancement
Magnon-mediated Superconductivity

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Squeezed-magnon-mediated Superconductivity

\[ k_B T_c = \hbar \omega_c \exp \left( -\frac{1}{\lambda} \right) \]
Squeezed-magnon-mediated Superconductivity

Squeezed-magnon-mediated Superconductivity

Magnon-mediated Exciton Condensation
Electron-Electron Attraction
Electron-Electron Attraction

Strong interaction

Squeezed magnon = Weak interaction

AFM | N
Electron-Electron Repulsion = Electron-Hole Attraction!
Magnon-mediated Exciton Condensation

Collaborators

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- Arne Brataas
- Asle Sudbø

Konstanz
- Gianluca Rastelli
- Wolfgang Belzig

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- Hannes Maier-Flaig
- Stephan Gepraege
- Andreas Erb
- Rudolf Gross
- Hans Huebl
- Mathias Weiler

Dresden
- Sebastian Goennenwein
Squeezing, Strong Coupling and Superconductivity!

\[ |\uparrow\rangle + |\downarrow\rangle + \ldots + |\uparrow\ldots\uparrow\rangle + \ldots \]