

# Electrical Resistivity Due to Resonance Scattering in High-Temperature Superconductors

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High-temperature superconductors (HTSCs) exhibit unconventional normal state electrical resistivity, diverging from standard Fermi-liquid behaviour. Resonance scattering is a major contributing factor to this anomalous resistivity, where charge carriers strongly interact with collective excitations like spin fluctuations or impurity-induced localized states. This mechanism is particularly relevant for cuprates, where strong electron correlations and a complex energy landscape result in non-trivial temperature dependence of resistivity. This behaviour often manifests as a linear behaviour over a wide range. We discuss the microscopic origins of resonance scattering, its impact on the transport properties of HTSCs, and its role in understanding the crossover between the normal and superconducting states. We also examine experimental signatures and theoretical models that describe this phenomenon, highlighting.

**Keywords:** HTSC, Resonance scattering, Fermi liquid, Self-energy, BCS

## I. Introduction

High-temperature superconductors (HTSCs), especially those in the cuprate category, have intrigued researchers for decades because of their atypical electrical and magnetic characteristics. In contrast to typical superconductors, which adhere to BCS (Bardeen–Cooper–Schrieffer) theory and display comprehensible Fermi-liquid behaviour in the normal state, high-temperature superconductors (HTSCs) markedly diverge from this paradigm. A distinguishing characteristic of these materials is their unusual normal-state resistivity, typically exhibiting a linear temperature dependency across an extensive range, which contradicts the  $T^2$  behaviour anticipated from standard electron-electron scattering in Fermi liquids<sup>1,2</sup>.

A primary mechanism suggested to elucidate this aberration is resonance scattering, in which charge carriers engage robustly with collective excitations such as antiferromagnetic spin fluctuations or localized states caused by impurities. In cuprate, these interactions are intensified by robust electron correlations and the existence of a pseudo-gap and partial gap in the electronic density of states that arises above the superconducting transition temperature,  $T_c$ . These interactions impede coherent quasi-particle motion, leading to the complex transport behavior observed in experiments. Resonance scattering's significance is further corroborated by inelastic neutron scattering (INS) experiments, which demonstrate a distinct magnetic resonance mode emerging below  $T_c$ , associated with the superconducting energy gap and indicating robust coupling between spin excitations and charge carriers<sup>3,4</sup>.

This magnetic resonance has emerged as a distinctive marker for spin-mediated pairing interactions, connecting the normal and superconducting states and suggesting the fundamental pairing process in high-temperature superconductors. Comprehending the microscopic origins of resonance scattering is essential for elucidating the anomalous normal-state transport and investigating the overarching mechanism of high-temperature superconductivity. Theoretical frameworks, including as the Marginal Fermi liquid (MFL) theory and spin fluctuation-mediated pairing models, have been established to elucidate these phenomena<sup>5,6</sup>. This paper seeks to analyze these concepts and experimental signatures comprehensively, providing insights into the transition from normal to superconducting phases and the persistent pursuit of room-temperature superconductivity.

## Theory

The unusual electrical resistivity seen in high-temperature superconductors, particularly in the cuprates, suggests a failure of traditional quasiparticle theory. In a conventional Fermi liquid, the electrical resistivity is mainly a result of interactions between electrons and phonon scattering, which generally exhibit a temperature dependence characterized by  $\rho(T)$  at low temperatures. HTSCs, especially in their optimally doped and underdoped states, demonstrate a resistivity that shows a linear increase with temperature across a broad spectrum, which is a characteristic that contradicts conventional Fermi-liquid behaviour<sup>6</sup>.

This deviation is frequently linked to resonance scattering, where charge carriers interact with low-energy bosonic excitations, particularly spin fluctuations. The concept suggests that these collective excitations, resulting from robust antiferromagnetic correlations in the  $\text{CuO}_2$  planes, function as a dynamic scattering potential. The alignment of the energy from these fluctuations with that of the charge carriers results in the fulfillment of resonance conditions, which subsequently enhances scattering and diminishes coherent quasi-particle motion.

The spin-fermion model has been formulated in the context of cuprates to elucidate the interplay involved. This model demonstrates a coupling between itinerant electrons and collective spin fluctuations, with the scattering rate being directly associated with the spin susceptibility  $\chi(q, \omega)$ . In proximity to the antiferromagnetic wavevector  $\mathbf{Q} = (\pi, \pi)$ , the susceptibility exhibits a pronounced peak, particularly below  $T_c$ , where neutron scattering experiments indicate a clearly defined magnetic resonance mode. The marginal

Fermi liquid (MFL) phenomenology, introduced by Varma et al., provides an explanation for this non-Fermi-liquid behaviour by suggesting that the electron self-energy exhibits a linear dependence on both energy and temperature. The self-energy is given by

$$\text{Im}[\Sigma(\omega, T)] \propto \lambda_{\text{max}}(|\omega|, T) \quad (1)$$

This observation correlates directly with the linear-in- $T$  resistivity documented in experiments and aligns with angle-resolved photoemission spectroscopy (ARPES) findings, which reveal broad quasiparticle peaks and a notable absence of coherence in the normal state<sup>7,8</sup>.

In the context of transport theory, the resistivity influenced by resonance scattering can be articulated through the Boltzmann transport equation or the Kubo formula, which incorporates a scattering rate that includes contributions from spin fluctuations. The observation of a resonant peak in the spin susceptibility, as indicated by neutron scattering, plays a crucial role in influencing the imaginary component of the electron self-energy, which in turn affects the resistivity<sup>8</sup>.

Additionally, resonance states induced by impurities, frequently observed in scanning tunneling microscopy (STM) investigations, create extra localized modes that may interact with the charge carriers. The contribution of these modes to scattering plays a significant role in suppressing the coherence length of the superconducting state<sup>9,10</sup>.

Theoretical models collectively highlight the significant impact of resonance scattering on the transport properties of HTSCs. Their analysis offers a detailed examination of the crossover behaviour evident in the phase diagram of cuprates, establishing connections between the strange metal phase, pseudo-gap regime, and superconductivity.

### Observational Indicators

Experimental investigations of high-temperature superconductors (HTSCs) have yielded significant evidence that underscores the importance of resonance scattering in their unique normal-state and superconducting characteristics. Methods like inelastic neutron scattering (INS), angle-resolved photoemission spectroscopy (ARPES), and scanning tunneling microscopy (STM) have played a crucial role in investigating the microscopic origins of the phenomena<sup>10-12</sup>.

### Inelastic Neutron Scattering (INS)

INS serves as a highly effective method for investigating magnetic excitations in cuprates. A notable characteristic identified in various high-temperature superconductors, including  $\text{YBa}_2\text{Cu}_3\text{O}_{6+x}$  and  $\text{Bi}_2\text{Sr}_2\text{CaCu}_2\text{O}_{8+\delta}$ , is the neutron resonance mode. This mode manifests as a distinct peak in the spin excitation spectrum, emerging below the superconducting transition temperature,  $T_c$ , and is localized around the antiferromagnetic wavevector ( $Q = \pi, \pi$ ).<sup>12-14</sup> The energy associated with this mode exhibits a scaling behaviour that is roughly proportional to  $T_c$ , indicating a significant relationship between magnetic excitations and superconductivity.

This resonance supports theories suggesting that spin fluctuations play a role in mediating pairing and influencing charge carrier scattering in the normal state. Furthermore, the strength of the mode is linked to the expansion of the superconducting gap, highlighting its significance in relation to the pairing mechanism and transport anomalies.<sup>14-16</sup>

**Angle-Resolved Photoemission Spectroscopy (ARPES)** ARPES investigations provide detailed momentum-resolved insights into the electronic structure. In cuprates, ARPES demonstrates extensive quasiparticle spectra in the normal state, characterized by the absence of distinct peaks, indicative of significant scattering effects. The spectra exhibit increased sharpness in the superconducting state, suggesting a decrease in scattering attributed to the gapping of spin fluctuations<sup>17,18</sup>

Furthermore, ARPES measurements reveal a “kink” in the dispersion close to the Fermi level, generally observed in the range of 50–70 meV. This phenomenon has interpreted as indicative of coupling between electrons and a bosonic mode, presumably the spin resonance identified in INS. This indicates a clear relationship between electronic self-energy effects and collective spin excitations, aligning with the principles of resonance scattering.

### Scanning Tunneling Microscopy (STM)

STM and spectroscopic imaging provide detailed insights into the spatial distribution of the local density of states (LDOS). In cuprates, the presence of impurity atoms, such as Zn, leads to the formation of localized resonance states that exist within the superconducting gap. The presence of zero-bias conductance peaks underscores the sensitivity of high-temperature superconductors to local perturbations, suggesting that even minor disturbances can lead to significant scattering effects<sup>19-21</sup>.

Furthermore, the quasi-particle interference patterns identified through Fourier transformed STM provide additional evidence for significant scattering occurring at specific momentum transfers, frequently aligning with the antiferromagnetic wavevector ( $Q = \pi, \pi$ )<sup>22</sup>. The findings support the notion that impurity effects and spin-driven resonance scattering play a significant role in low-energy excitations.

## Mathematical Framework

### Resonance Scattering and Self-Energy

The electrical resistivity  $\rho(T)$  in HTSCs is often model via the electron self energy  $\chi(k, \omega)$ , where the imaginary part  $Im \Sigma$  determines the scattering rate.

According to the Marginal Fermi Liquid theory (Varma et al.) equation (1). This leads to a linear-in- $T$  resistivity<sup>23,24</sup>

$$\rho(T) \propto T$$

### Spin-Fermion Model

In the spin-fermion model, the scattering rate is determined by interaction between electrons and spin fluctuations, which are described by a dynamic spin susceptibility  $\chi(q, \omega)$ <sup>25,26</sup>

$$\chi(q, \omega) = \frac{\chi_Q}{1 + \xi^2(q-Q)^2 - \frac{i\omega}{\omega_{sf}}} \quad (2)$$

Where:  $\chi_Q$  is the peak susceptibility,  $\xi$  is the correlation length,  $(Q = \pi, \pi)$  is the antiferromagnetic wavevector and  $\omega_{sf}$  is a spin-fluctuation characteristic frequency.

The scattering rate due to spin fluctuations becomes

$$\Gamma(\omega, T) \propto \int d^2q \text{Im}[\chi(q, \omega)] \quad (3)$$

This leads to non-Fermi liquid behaviour, where resistivity scales linearly with  $T$ .

### Electrical Resistivity and Spectral Function

From Kubo's formula, electrical conductivity  $\sigma$  is given by<sup>26-28</sup>

$$\sigma(T) \propto \int d\omega \left( -\frac{\partial f(\omega)}{\partial \omega} \right) \int d^2k A(k, \omega)^2 v_k^2 \quad (4)$$

Where  $f(\omega)$  is the Fermi-Dirac distribution and  $A(k, \omega) = \frac{1}{\pi} \text{Im} \left[ \frac{1}{\omega - \epsilon_k - \Sigma(k, \omega)} \right]$  is the spectral function,  $v_k$  is the quasi-particle velocity.

### Graphical representation

Fig.1. is a graph showing temperature-dependent resistivity  $\rho(T)$  behaviour for Fermi liquid vs. non-Fermi liquid (HTS) cases. Let us consider a model resonance scattering in high-temperature superconductors (HTSCs), particularly due to spin fluctuations, we adopt the spin-fermion model. This framework effectively captures the interaction between itinerant electrons and collective spin excitations observed in cuprates systems. The total Hamiltonian is expressed as<sup>29,30</sup>

$$H = H_{el} + H_{sf} + H_{int} \quad (5)$$

### Electronic Hamiltonian:

$$H_{el} = \sum_{k, \sigma} \epsilon_k c_{k\sigma}^\dagger c_{k\sigma} \quad (6)$$

This term represents the kinetic energy of non-interacting electrons, where  $\epsilon_k$  is the energy dispersion and  $c_{k\sigma}^\dagger c_{k\sigma}$  are the electron creation and annihilation operators with momentum  $k$  and spin  $\sigma$ .<sup>31,32</sup>

### Spin Fluctuation Term:

$$H_{sf} = \sum_{k, \sigma} \omega_q S_q^\dagger S_{qk} \quad (7)$$

This describes collective spin excitations (magnons), where  $\omega_q$  is the energy of spin fluctuations with momentum  $q$ , and  $S_q$  is the spin operator in momentum space.<sup>33,34</sup>

### Interaction Hamiltonian:

$$H_{int} = g \sum_{k, q, \sigma, \sigma'} \sigma_{\sigma\sigma'} \cdot S_q c_{k\sigma'} \quad (8)$$

This term describes the coupling between electrons and spin fluctuations. Here,  $g$  is the coupling strength,  $\sigma$  are the Pauli matrices, and  $S_q$  is the spin operator.<sup>34,35</sup>

To compute the impact of these interactions on electronic properties, we evaluate the electron self-energy  $\Sigma(k, \omega)$  arising from spin fluctuation scattering:

$$\Sigma(k, \omega) = \sum \int d\omega \frac{\chi(q, \omega)}{\omega - \epsilon_{k-q} - \omega + i\delta} \quad (9)$$

The susceptibility is often model as a Gaussian peaked around specific momentum and energy values associated with resonance conditions:

$$\chi(q, \omega) = \exp \left[ -\frac{(q-q_0)^2}{2\gamma_q^2} - \frac{(\omega-\omega_0)^2}{2\gamma_\omega^2} \right] \quad (10)$$

Typical parameter values from experiments are  $q_0 = \pi$ ,  $\omega_0 = 40 \text{ meV}$ ,  $\gamma_q = 0.3$ ,  $\gamma_\omega = 5$ , This form successfully reproduces resonance peaks observed in neutron scattering experiments and supports the hypothesis that spin fluctuations contribute significantly to the observed anomalous transport behaviour in the normal state of HTSCs.<sup>36-40</sup>

| $T \text{ (K)}$ | $\rho_{linear}(T)(\Omega \cdot cm)$ | $\rho_{quadratic}(T)(\Omega \cdot cm)$ |
|-----------------|-------------------------------------|----------------------------------------|
| 0               | 0.0                                 | 0.0                                    |
| 10              | 5.0                                 | 0.2                                    |
| 20              | 10.0                                | 0.8                                    |
| 30              | 15.0                                | 1.8                                    |
| 40              | 20.0                                | 3.2                                    |
| 50              | 25.0                                | 5.0                                    |
| 60              | 30.0                                | 7.2                                    |
| 70              | 35.0                                | 9.8                                    |
| 80              | 40.0                                | 12.8                                   |
| 90              | 45.0                                | 16.2                                   |
| 100             | 50.0                                | 20.0                                   |

Table 1. Temperature dependence of linear and quadratic resistivity

To investigate the temperature dependence of resistivity in high-temperature superconductors, we analyze two commonly used empirical models: the linear and the quadratic resistivity behaviour. The linear temperature dependence of resistivity is often observed (in Table 1) in the normal state of cuprate superconductors and is model as [16]

$$\rho_{linear}(T) = aT$$

In some materials, especially at low temperatures, resistivity follows a quadratic dependence on temperature, characteristic of Fermi-liquid behaviour<sup>39-42</sup>

$$\rho_{quadratic}(T) = bT^2$$

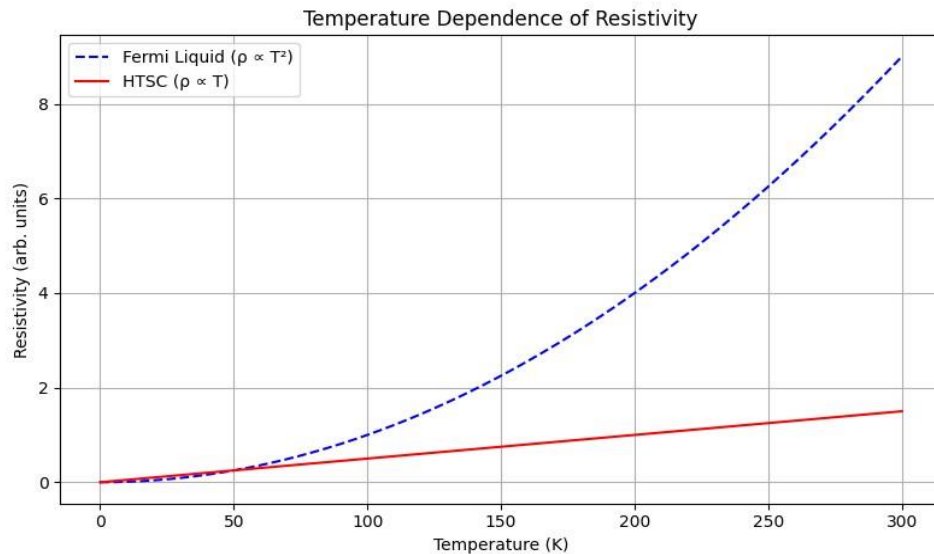


Fig.1. Temperature-dependent resistivity behaviour for Fermi liquid vs. non-Fermi liquid (HTSC) cases.

## II. Summery

The research investigates the atypical electrical resistivity in high-temperature superconductors (HTSCs), specifically cuprates, where traditional Fermi-liquid theory is inadequate to elucidate their peculiar behaviour. These materials frequently exhibit a linear temperature dependency of resistivity, in contrast to the conventional quadratic  $T^2$  behaviour observed in standard metals.

The primary principle is *resonance scattering*, in which charge carriers (electrons or holes) engage intensely with spin fluctuations or localized states generated by impurities. This scattering impedes quasiparticle mobility, resulting in non-Fermi liquid behaviour.

1. Spin fluctuations, along with robust antiferromagnetic interactions, function as a dynamic scattering potential.
2. The Marginal Fermi Liquid theory and Spin-Fermion models elucidate the observed resistivity and spectrum characteristics.
3. Methods such as Inelastic Neutron Scattering (INS), Angle-Resolved Photoemission Spectroscopy (ARPES), and Scanning Tunneling Microscopy (STM) offer empirical validation.
4. Mathematical models illustrate how these interactions alter the electron self energy, affecting resistivity.
5. Graphs and equations contrast linear and quadratic resistivity, illustrating the deviations of high-temperature superconductors from classical standards.

## III. Conclusion

A critical mechanism for comprehending the peculiar metallic behaviour and superconducting transition in HTSCs is resonance scattering. An essential step towards realizing room-temperature superconductivity, it connects magnetic excitations with electrical transport anomalies. This research contributes to the understanding of cuprate physics by combining theoretical models with strong experimental data in support of spin-fluctuation-driven pairing and resonance scattering theories could be extended to iron-based superconductors or twisted bilayer graphene.

## References

1. Bednorz, J. G. & Müller, K. A. Possible high  $T_c$  superconductivity in the Ba-La-Cu-O system. *Zeitschrift für Physik B Condensed Matter* 64, 189–193 (1986).
2. Devitre, A., Fischer, D., Woller, K., ... B. C.-R. of S. & 2024, undefined. A facility for cryogenic ion irradiation and in situ characterization of rare-earth barium copper oxide superconducting tapes. [pubs.aip.org](https://pubs.aip.org).
3. Zaluzhnyy, I. A. et al. Structural Changes in YBa<sub>2</sub>Cu<sub>3</sub>O<sub>7</sub> Thin Films Modified with He<sup>+</sup>-Focused Ion Beam for High-Temperature Superconductive Nanoelectronics. *ACS Appl Nano Mater* 7, 15943–15949 (2024).
4. Zaluzhnyy, I., Goteti, U., B. S.-A. A. N. & 2024, undefined. Structural Changes in YBa<sub>2</sub>Cu<sub>3</sub>O<sub>7</sub> Thin Films Modified with He<sup>+</sup>-Focused Ion Beam for High-Temperature Superconductive Nanoelectronics. *ACS Publications*.
5. Oji, U. et al. Spatial 3D correlation of flux pinning with porosity distribution in YBa<sub>2</sub>Cu<sub>3</sub>O<sub>7-δ</sub> using tensorial neutron tomography. *Elsevier*.
6. Gardew, D. High-Temperature Superconductors. (2024).
7. Zou, C. et al. Evolution from a charge-ordered insulator to a high-temperature superconductor in Bi<sub>2</sub>Sr<sub>2</sub>(Ca,Dy)Cu<sub>2</sub>O<sub>8+δ</sub>. [nature.com](https://www.nature.com).
8. Eisterer, M., Bodenseher, A. & Unterrainer, R. Universal degradation of high-temperature superconductors due to impurity scattering: predicting the performance loss in fusion magnets. (2024).
9. Miyatake, T., Wako, Y., Abe, R., ... S. T.-J. of the P. & 2024, undefined. Neutron Diffraction Study of Layered Nickelates Pr<sub>4</sub>Ni<sub>3-x</sub>CoxO<sub>8</sub> for High-Temperature Superconductor Candidate. [journals.jps.jp](https://journals.jps.jp).
10. Zou, C. et al. Evolution from a charge-ordered insulator to a high-temperature superconductor in Bi<sub>2</sub>Sr<sub>2</sub>(Ca,Dy)Cu<sub>2</sub>O<sub>8+δ</sub>. [nature.com](https://www.nature.com).
11. Ma, M. et al. Ferromagnetic interlayer coupling in superconductors revealed by inelastic neutron scattering. *APS*.
12. Xie, T. et al. Neutron Scattering Studies on the High- Superconductor LaNiO at Ambient Pressure. [arxiv.org](https://arxiv.org).
13. Ma, M. et al. Ferromagnetic inter-layer coupling in FeSe<sub>{1-x}S\_{x}</sub> superconductors revealed by inelastic neutron scattering. (2024) doi:10.1103/PHYSREVB.110.174503.
14. Heier, G. & Savrasov, S. Y. Calculations of Spin Fluctuation Spectral Functions  $\alpha^2F$  in High-Temperature Superconducting Cuprates. (2024).
15. Miyatake, T., Wako, Y., Abe, R., Tsukamoto, S. & Uehara, M. Neutron Diffraction Study of Layered Nickelates Pr<sub>4</sub>Ni<sub>3-x</sub>CoxO<sub>8</sub> for High-Temperature Superconductor Candidate. *J Physical Soc Japan* 93, (2024).
16. Kuzovnikov, M. A. et al. High-pressure synthesis and neutron scattering study of tantalum hydride and a tantalum polymorph with A15-type structure. *Phys Rev B* 110, 184113 (2024).
17. Xie, T. et al. Strong interlayer magnetic exchange coupling in La<sub>3</sub>Ni<sub>2</sub>O<sub>7</sub> revealed by inelastic neutron scattering. (2024).
18. Pantazopoulos, P., Feist, J., ... F. G.-V.-N. & 2024, undefined. Unconventional magnetism mediated by spin-phonon-photon coupling. [nature.com](https://www.nature.com).
19. Merzoni, G., Martinelli, L., Braicovich, L., B, N. B.-P. R. & 2024, undefined. Charge response function probed by resonant inelastic x-ray scattering: Signature of electronic gaps of. *APS*.

20. Merzoni, G. et al. Charge response function probed by resonant inelastic x-ray scattering: Signature of electronic gaps of YBa<sub>2</sub>Cu<sub>3</sub>O<sub>7-δ</sub>. *Phys Rev B* 109, (2024).
21. Ghirri, A., Bonizzoni, C., Maksutoglu, M., Applied, M. A.-P. R. & 2024, undefined. Interplay between magnetism and superconductivity in a hybrid magnon-photon bilayer system. *APS*.
22. Rosa, F., Martinelli, L., Krieger, G., ... L. B. preprint arXiv & 2024, undefined. Spin excitations in Nd<sub>1-x</sub>Sr<sub>x</sub>NiO<sub>2</sub> and YBa<sub>2</sub>Cu<sub>3</sub>O<sub>7-δ</sub>: the influence of Hubbard U. *arxiv.org*.
23. Ghirri, A., Bonizzoni, C., Maksutoglu, M. & Affronte, M. Interplay between magnetism and superconductivity in a hybrid magnon-photon bilayer system. *Phys Rev Appl* 22, (2024).
24. Fan, Y., Li, J., A, Y. W.-P. R. & 2024, undefined. Quantum magnon conversion accompanying magnon antibunching. *APS*.
25. Wang, N., Li, S. Y., Yu, L. & Zhu, A. D. Long-distance entanglement via magnon-induced Brillouin light scattering. *Phys Rev B* 110, (2024).
26. Fan, Y., Li, J. & Wu, Y. Quantum magnon conversion accompanying magnon antibunching. *Phys Rev A (Coll Park)* 110, (2024).
27. Wu, L. et al. Bose-Einstein condensation of a two-magnon bound state in a spin-one triangular lattice. (2024).
28. Gao, Y. et al. Spin Supersolid Phase and Double Magnon-Roton Excitations in a Cobalt-based Triangular Lattice. *arxiv.org*.
29. Klein, M. V. et al. New features of the Mott-Hubbard insulator gap of parent HTS compounds found by resonance Raman scattering and UV-excited ordinary Raman scattering. *Journal of Superconductivity* 7, 429–433 (1994).
30. magnon excitation hamiltonian for HTS - Google Scholar. [https://scholar.google.com/scholar?hl=en&as\\_sdt=0%2C5&q=magnon+excitation+hamiltonian+for+HTS&btnG=](https://scholar.google.com/scholar?hl=en&as_sdt=0%2C5&q=magnon+excitation+hamiltonian+for+HTS&btnG=).
31. Ianovskaia, A. S., Bobkov, A. M. & Bobkova, I. V. Magnon influence on the superconducting density of states in superconductor-ferromagnetic-insulator bilayers. *Phys Rev B* 108, (2023).
32. Walker, C. T. & Pohl, R. O. Phonon Scattering by Point Defects. *Physical Review* 131, 1433 (1963).
33. Pohl, R. O. Thermal Conductivity and Phonon Resonance Scattering. *Phys Rev Lett* 8, 481 (1962).
34. Batignani, G. et al. Temperature dependence of Coherent versus spontaneous Raman Scattering. (2024).
35. Müller, M. et al. Temperature dependence of the magnon-phonon interaction in hybrids of high-overtone bulk acoustic resonators with ferromagnetic thin films. *Phys Rev Appl* 21, 034032 (2024).
36. Lentchner, G. et al. Incorrect Resonance Escape Probability in Monte Carlo Codes due to the Threshold Approximation of Temperature-Dependent Scattering. *Ann Nucl Energy* 207, (2024).
37. Li, G., Zheng, J., Cui, Z. & Guo, R. Unusual temperature dependence of thermal conductivity due to phonon resonance scattering by point defects in cubic BN. *Phys Rev B* 110, L060101 (2024).
38. Troyan, I. A. et al. Progress, problems and prospects of room-temperature superconductivity. *Журнал экспериментальной и теоретической физики* 166, (2024).
39. Hussey, N. E. High-temperature superconductivity and strange metallicity: Simple observations with (possibly) profound implications. *Physica C: Superconductivity and its Applications* 614, 1354362 (2023).
40. Velluire Pellat, Z. et al. Hybrid quantum systems with high-T  $\text{c}$  superconducting resonators. *Scientific Reports* 2023 13:1 13, 1–10 (2023).
41. Zou, C. et al. Evolution from a charge-ordered insulator to a high-temperature superconductor in Bi<sub>2</sub>Sr<sub>2</sub>(Ca,Dy)Cu<sub>2</sub>O<sub>8+δ</sub>. *Nature Communications* 2024 15:1 15, 1–9 (2024).
42. Jois, S., Lado, J. L., Gu, G., Li, Q. & Lee, J. U. Andreev Reflection and Klein Tunneling in High-Temperature Superconductor-Graphene Junctions. *Phys Rev Lett* 130, 156201 (2023).