Relationship Between Nematicity, Antiferromagnetic Fluctuations, and Superconductivity in FeSe$_{1-x}$S$_x$ Revealed by NMR

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The S-substituted FeSe, FeSe$_{1-x}$S$_x$, under pressure ($p$), provides a versatile platform for studying the relationship among nematicity, antiferromagnetism, and superconductivity. Here we present a short review of the recent experimental evidence showing that nematicity has a remarkable impact on the relationship between antiferromagnetic fluctuations and superconductivity. This has been revealed by several $^{77}$Se nuclear magnetic resonance studies that have tracked the variability of antiferromagnetic fluctuations and superconducting transition temperature ($T_c$) as a function of $x$ and $p$. $T_c$ is roughly proportional to antiferromagnetic fluctuations in the presence or absence of nematic order suggesting the importance of antiferromagnetic fluctuations in the Cooper pairing mechanism in FeSe$_{1-x}$S$_x$. However, the antiferromagnetic fluctuations are more effective in enhancing superconductivity in the absence of nematicity as compared to when it is present. These experimental observations give renewed insights into the interrelationships between nematicity, magnetism, and superconductivity in Fe-based superconductors.

Keywords: nematicity, unconventional superconductivity, NMR, magnetic correlations, quantum materials

1 INTRODUCTION

Suppressing the transition temperatures of long-range orders with a tuning parameter has led to the discovery of superconductivity (SC) in the associated quantum phase transition (QPT) regions of several classes of materials such as heavy-Fermion systems [1–3], itinerant ferromagnets [4, 5], high $T_c$ cuprates and Fe-based superconductors [3, 6]. The quantum critical fluctuations of the suppressed long-range order parameter(s) could thus be responsible for the elusive Cooper pairing mechanism in those unconventional superconductors.

In most Fe-based superconductors, SC appears close to the quantum phase transitions of two long-range orders: the nematic order, which is an electronically driven structural transition from high-temperature tetragonal (C4 symmetry) to low-temperature orthorhombic (C2 symmetry), and the antiferromagnetic (AFM) order with spontaneously oriented electronic spins characterized by a wave vector ($\mathbf{q} = (\pi,0)$ or $(0,\pi)$) [3, 7–9]. In those systems, the nematic transition temperature ($T_N$) is at or just above the Néel temperature ($T_N$), and both phases are simultaneously suppressed with carrier doping and/or the application of pressure ($p$), leading to two QPTs originating from the nematic and the AFM states. As SC in these compounds emerges around the two QPTs, AFM and nematic phases are believed to play important roles for the appearance of SC. However, the
The nematic phase in FeSe can be suppressed by pressure application, with FeSe$_{1-x}$S$_x$ nematicity or antiferromagnetism on SC independently [13]. This provides a favorable platform for the study of the role of superconducting transition at $T_c$ [10].

In this sense, the sulfur-substituted FeSe system, FeSe$_{1-x}$S$_x$, provides a favorable platform for the study of the role of nematicity or antiferromagnetism on SC independently [13]. FeSe$_{1-x}$S$_x$ has the simplest of crystal structures among the Fe-based superconductors, with a quasi-two dimensional FeSe(S) layer in the $ab$ plane, stacked along the $c$ axis. At $x = 0$, FeSe undergoes a nematic transition at $T_\text{n} \approx 90$ K followed by a superconducting transition at $T_c \approx 8.5$ K, but it does not show a long range AFM order at ambient $p$ [13–16]. This allows the study of AFM fluctuations inside the nematic order and its relationship with SC [17]. The nematic phase in FeSe can be suppressed by pressure application, with $T_\text{n}$ decreased down to 32 K at $p = 1.5$ GPa [18]. $T_\text{s}$ shows a complex multi-domed structure with $p$, reaching a maximum $T_\text{s} \approx 37$ K at $p \sim 6$ GPa [19–21]. At the same time, an AFM ordered state appears above $p = 0.8$ GPa [22, 23], and $T_\text{N}$ merges with $T_\text{N}$ above $p = 1.7$ GPa [24], limiting the range for studying the effects of nematicity on SC without AFM state.

The nematic phase in FeSe can also be suppressed with the isovalent S substitution for Se in FeSe$_{1-x}$S$_x$ as shown in Figure 1A taken from Ref. [25] based on data from Refs. [26, 27], where $T_s$ decreases to zero at the critical $x$ value, $x_c \sim 0.17$. As no long-range AFM order appears in FeSe$_{1-x}$S$_x$ at ambient $p$, one can study the variability of $T_c$ including a nematic QPT without an AFM order. At $x_c$, diverging nematic fluctuations were reported from elasto-resistivity measurements [28], and a temperature- ($T$) linear behavior of the resistivity was seen under high magnetic fields ($H$) [29]. As shown in Figure 1A, $T_c$ first increases up to 10 K around $x = 0.09$ making a maximum and then decreases gradually at higher $x$ without showing any clear change in $T_c$ around $x_c$ [18, 26, 30]. Nevertheless, the considerable change in the size and anisotropy of the SC gap is observed at the nematic QPT in spectroscopic-imaging scanning tunneling microscopy [26, 30, 31], thermal conductivity [32], and specific heat [33] measurements, implying different SC states inside (SC1) and outside (SC2) nematic states [25]. In addition, signatures of the crossover between Bardeen-Cooper-Schrieffer and Bose-Einstein-Condensate superconductivities at the nematic QPT were recently reported by laser-excited angle-resolved photoemission spectroscopy (ARPES) measurements [34].

The nematic phase in the S-substituted FeSe system is also controlled by pressure application and an AFM state appears at higher $p$ [35–38]. The three-dimensional $T$-$p$-$x$ phase diagram of...
FeSe$_{1-x}$S$_x$ up to $p = 8$ GPa has been reported by Matsuura et al. [35] in which the AFM ordered phase shifts to higher $p$ with increasing $x$. A typical $p$-$T$ phase is shown in Figure 2A for the case of $x = 0.09$ [37]. In this case, with increasing $p$, the nematic phase disappears around $p \sim 0.5$ GPa corresponding to a putative nematic QPT, and the AFM state appears above $p \sim 3.5$ GPa. In addition to the nematic, AFM, and SC states, Fermi liquid behaviors were reported at low temperatures in $x = 0.09$ (see Figure 2A) [37] and $0.11$ [39] after the suppression of the nematic order by applying $p$. The Fermi liquid phase was recently attributed to the presence of a quantum griffiths phase close to the nematic QPT [40]. Similar to the $T$-$x$ phase diagram of FeSe$_{1-x}$S$_x$, SC phase was shown to have two different states (SC1 and SC2) separated by the nematic QPT as shown in Figure 2A. Such two different SC states under $p$ were also reported in $x = 0.11$ [39] and $0.12$ [41], which is more apparent under $H$ [41]. The presence of a series of nematic quantum phase transitions in the $x$-$p$ phase diagram [35] allows the study of the correlation between $T_c$ and AFM fluctuations in the presence and absence of the nematic order [37].

In this mini review, we show the positive correlation between AFM fluctuations and SC and the impact of nematicity on the relationship based on the nuclear magnetic resonance (NMR) studies of the FeSe$_{1-x}$S$_x$ system under $p$. After briefly introducing some basics of NMR which are used in $^{77}$Se NMR studies to characterize the AFM fluctuations, we review the relationship between AFM fluctuations and SC in the presence of nematic order in FeSe under $p$ and in FeSe$_{1-x}$S$_x$ at ambient $p$. Then, we show the studies of FeSe$_{1-x}$S$_x$ system under $p$, where we review the relationship between AFM fluctuations and SC in the absence of nematic order. Finally, we end with a summary including the current research gaps and potential future developments in the field.

2 NUCLEAR MAGNETIC RESONANCE AND ANTIFERROMAGNETIC FLUCTUATIONS

NMR is one of the powerful techniques to study the magnetic and electronic properties of materials from a microscopic point of view and has been utilized to investigate the physical properties of Fe-based superconductors. Nuclei with finite angular momentum undergo Zeeman splitting in the presence of a magnetic field at the nuclear site ($H_{\text{muc}}$). The energy difference between the nearest nuclear spin levels is given as $\Delta E = \gamma_N h H_{\text{muc}}$ where $\gamma_N$ is the nuclear gyromagnetic ratio. In the NMR technique, nuclei are excited from lower energy states to higher ones by applying electromagnetic wave whose energy is equal to $\Delta E$.

The resonance frequency is determined by $H_{\text{muc}}$, which is a sum of the external magnetic field ($H$) and the hyperfine field ($H_{\text{hf}}$) due to the interaction between nuclei and electrons. The shift of the resonance line due to the hyperfine interaction is defined by $K = H_{\text{hf}}/H$ which is the so-called Knight shift in metals. In general, the shift $K$ has the $T$-independent orbital component, $K_{\text{orb}}$, and $T$-dependent spin component, $K_s$, which can be expressed as $K = K_{\text{orb}} + K_s$. $K_s$ is proportional to the static and uniform magnetic

\[ K_s \propto \chi_s \]
the ratio \( \pi \) of relaxation rate (1/\( \tau_1 \)) divided by \( T \), 1/\( T \) is sensitive to the \( q \)-sum of the imaginary part of susceptibility (\( \chi''(q, \omega_N) \)) at the NMR frequency (\( \omega_N \)) [42] and is given as

\[
1/T_1T \sim \gamma_N k_B \sum_q |A(q)|^2 \chi''(q, \omega_N)/\omega_N
\]  

where \( A(q) \) is the \( q \)-dependent hyperfine form factor. 1/\( T_1T \) gives us information about the total magnetic correlations at all \( q \) values. Therefore, one can obtain important insights about \( q \) dependent magnetic correlations by comparing \( K_s \) and 1/\( T_1T \) data.

In simple metals, \( K_s \) is related to the density of states at the Fermi energy [\( N(E_F) \)] where \( K_s = A_h(g_{\parallel} \gamma)^2 N(E_F)/2 \), and 1/\( T_1T \) is proportional to the square of \( N(E_F) \) as 1/\( T_1T = \pi N g_{\parallel}^2 \gamma_N^2 N(E_F) \cdot k_B \) [43]. In a Fermi liquid picture, the ratio \( S = T_1 TK_s^2 \) becomes a constant [42, 44] which is called the Korringa relation. In real materials, an experimentally determined value of \( T_1 TK_s^2 \) may deviate from \( S \) due to electron correlations. Thus, the deviation parameter defined as \( \alpha = S/(T_1 TK_s^2) \) provides information about electron correlations in materials. When AFM fluctuations are present, \( \chi'(q, \omega_N) \) with \( q \neq 0 \) is enhanced with little or no effect on \( K_s \), which probes only the \( q = 0 \) component of \( \chi' \). Therefore, 1/\( T_1T \) is enhanced much higher than \( K_s \) and \( \alpha \) becomes greater than unity. On the other hand, \( \alpha \approx 0 \) is expected for ferromagnetic correlations.

When the Korringa relation does not hold due to strong magnetic fluctuations (non-Fermi liquid picture), the \( T \) dependence of 1/\( T_1T \) could be different from that of \( K_s \). When strong AFM fluctuations exist in systems, the contribution to 1/\( T_1T \) from AFM fluctuations will be the source of the different \( T \) dependence, and the experimentally observed 1/\( T_1T \) is sometimes decomposed as 1/\( T_1T = 1/\( T_1T \)_{\text{AFM}} + 1/\( T_1T \)_{\text{q=0}} \) [18, 45, 46]. Here (1/\( T_1T \)\(_{\text{AFM}} \) denotes the AFM contributions from \( \chi(q \neq 0, \omega_N) \) and (1/\( T_1T \)\(_{\text{q=0}} \) represents the contributions from \( q = 0 \) components. By assuming (1/\( T_1T \)\(_{\text{q=0}} = CK_s^2 \), where \( C \) is the empirically determined proportionality constant, one can extract the AFM contribution to 1/\( T_1T \) by subtracting (1/\( T_1T \)\(_{\text{q=0}} \) from the observed 1/\( T_1T \), providing insights into the magnetic fluctuations.

In the case of Fe-based superconductors, Kitagawa et al. proposed that anisotropy in 1/\( T_1T \) at the chalcogen or pnictogen sites provides more detailed information about AFM fluctuations [47]. According to them, the ratio of 1/\( T_1T \) values measured under \( H \) parallel to \( c \) axis (1/\( T_1T_c \)) and parallel to \( ab \) plane (1/\( T_1T_{ab} \)) \( R = T_{1c}/T_{1ab} \) can determine the dominant \( q \) for AFM fluctuations. In the case of isotropic AFM fluctuations, \( R = 1.5 \) is expected for stripe-type AFM fluctuations with \( q = (\pi, 0) \) or \( (0, \pi) \), whereas when Néel type AFM fluctuations with \( q = (\pi, \pi) \) are present, \( R = 0.5 \). Such analysis has been extensively used in Fe-based superconductors [18, 37, 47–51] and related materials [52, 53] to characterize the AFM fluctuations in those systems.

## 3 ANTIFERROMAGNETIC FLUCTUATIONS AND SUPERCONDUCTIVITY WITH NEMATICITY

Soon after the discovery of the Fe-based superconductors [54, 55], \(^{77}\)Se (1 = 1/2, \( \gamma_N/2\pi = 8.1432 \) MHz) NMR studies on polycrystalline FeSe were carried out [17, 56] and the importance of AFM fluctuations for superconductivity has been pointed out. Figure 1B shows the \( T \) dependence of 1/\( T_1T \) values in FeSe under various pressures reported by Imai et al. [17]. At higher temperatures above \( T \approx 100 \) K, 1/\( T_1T \) at all pressures decreases with decreasing \( T \). This behavior is similar to the \( T \)-dependence of \( K \) shown in Figure 1C where \( K \) shows a monotonic decrease when cooling from 480 to ~ 100 K. The variations in both 1/\( T_1T \) and \( K \) above ~ 100 K were explained in terms of spin gap formation or a peculiar band structure near the Fermi level [57]. However, upon cooling below \( T \approx 100 \) K, the \( T \) dependences of 1/\( T_1T \) and \( K \) show quite different behaviors. Although \( K \) is nearly independent of both \( T \) and \( p \) below 50 K, 1/\( T_1T \) shows strong enhancements at all measured pressures at low temperatures where peaks are observed at the \( p \)-dependent \( T_c \) or \( T_N \). As described above, \( K \) is proportional to \( \chi(0,0) \) and 1/\( T_1T \) reflects the \( T \) dependence of \( q \)-summed \( \chi''(q, \omega_N) \). Therefore, the enhancements of 1/\( T_1T \) at low temperatures unequivocally establish the presence of AFM fluctuations at the \( T \) region, suggesting that the AFM fluctuations are relevant to the SC in FeSe. In fact, a close relationship between the AFM fluctuations and SC has been pointed out from the \( p \) dependences of \( T_c \) and 1/\( T_1T \) data: the maximum of 1/\( T_1T \) increases along with \( T_c \) as shown in Figure 1B where \( T_c \) at different \( p \) are marked by downward arrows [17]. Broad humps in 1/\( T_1T \) observed at temperatures much higher than their respective \( T_c \) values at \( p = 1.4 \) and 2.2 GPa are due to magnetic orderings. It should be noted that, due to the occurrence of the AFM order under high pressures in FeSe, the relationship between \( T_c \) and the maximum of 1/\( T_1T \) can only be compared at low pressures in this system. A later single crystalline \(^{77}\)Se NMR studies under \( H||ab \) and \( H||c \) characterized the AFM order and the AFM fluctuations at higher pressures to be of stripe type [51, 58].

\(^{77}\)Se NMR study of single crystalline FeSe\(_{1-x}S_x\) by Wiecki et al. [18] at ambient \( p \) also provided clear experimental evidence of the close relationship between the AFM fluctuations and SC in this system. Figure 1D shows the \( T \) dependence of 1/\( T_1T \) in FeSe\(_{1-x}S_x\) for \( H||ab \) (upper) and \( H||c \) (lower), respectively, at ambient \( p \) [18], which includes the data from Ref. [58]. As in FeSe, \( K \) for all \( x \) shows monotonic decreases when lowering \( T \) from room \( T \) down to ~ 100 K, before leveling off at constant values [18] for both \( H||ab \) and \( H||c \). Although 1/\( T_1T \) shows a similar \( T \) dependence as \( K \) in all cases above 100 K, 1/\( T_1T \) shows a strong upturn below \( T \approx 100 \) K due to the growth of AFM fluctuations. The AFM fluctuations appear below 100 K for all samples of \( x = 0, 0.09, 0.15, \) and 0.29, however, the enhancement of the AFM fluctuations shows a strong \( x \) dependence. For \( x \) less...
than $x_c \sim 0.17$, $1/T_1T$ increases with decreasing $T$ showing a Curie-Weiss-like behavior expected for two-dimensional AFM fluctuations from the self-consistent renormalization theory [42]. On the other hand, for $x = 0.29$ greater than $x_c$, a subtle upturn on cooling below $T \sim 100$ K is observed, suggesting the tiny growth of the AFM fluctuations, followed by a nearly $T$ independent behavior below $T \sim 25$ K without showing clear Curie-Weiss-like behaviors. At all measured $x$ values, the ratios $R \equiv T_{1x}/T_{1ab}$ are found to be ~ 1.5 below $T \sim 100$ K shown in the inset of the lower panel of Figure 1D, indicating that the AFM fluctuations are characterized to be stripe type and do not change with $x$.

The $x$-$T$ phase diagram (Figure 1A) of FeSe$_{1-x}$S$_x$ at ambient $p$ allowed Wiecki et al. to examine the correlation between AFM fluctuations and $T_c$, and it was shown to persist, despite the presence of a nematic QPT isolated from an AFM order. The maximum values of $1/T_1T$ first increased when $x$ was changed from 0 to 0.09, then decreased for $x = 0.15$ and higher, similar to the $x$ dependence of $T_c$ shown in Figure 1A. Figures 1E,F taken from Ref. [18] are contour plots of the magnitude of AFM fluctuations determined by $1/T_1T$ data in FeSe under $p$ (E) and in FeSe$_{1-x}$S$_x$ at ambient $p$ (F), respectively, along with their respective phase diagrams. It can be seen that $T_c$ is enhanced at the $p$ or $x$ values where AFM fluctuations are stronger. This indicates the correlation between $T_c$ and AFM fluctuations in both cases and also demonstrates the primary importance of AFM fluctuations to SC in FeSe$_{1-x}$S$_x$. It was also pointed out that, although nematic fluctuations are most strongly enhanced near the nematic QCP at $x \sim 0.17$ in the case of FeSe$_{1-x}$S$_x$, no clear correlation with $T_c$ was observed [18].

**4 ANTIFERROMAGNETIC FLUCTUATIONS AND SUPERCONDUCTIVITY WITHOUT NEMATICITY**

With the firm establishment of the correlation between AFM fluctuations and SC in FeSe$_{1-x}$S$_x$, the question then arose about the role of nematicity on the relationship. As described above, FeSe$_{1-x}$S$_x$ provides a suitable platform for the study of the role of nematicity on the relationship by changing samples as reported by Wiecki et al. [18]. The application of pressure on FeSe$_{1-x}$S$_x$ also provides a versatile opportunity to study the effect of nematicity on the relationship. This has an advantage because $p$ is known as one of the clean tuning parameters which control the ground state without changing the composition avoiding any additional effects of $S$ substitutions such as homogeneity by changing $x$. Several $^{77}$Se NMR studies on single crystalline FeSe$_{1-x}$S$_x$ under pressure have been carried out [37, 38, 41, 59]. Here we show the results of NMR measurements under pressure up to 2.1 GPa on $x = 0.09$ whose $p$-$T$ phase diagram is shown in Figure 2A reported in Ref. [37]. With $p$, the nematic phase is suppressed and disappears around the critical pressure $p_c \sim 0.5$ GPa, and an AFM state appears above 3 GPa with a dome-shaped Fermi-liquid phase between nematic and AFM phases. $T_c$ shows a clear $p$ dependence with a double dome structure with and without long-range nematicity, making the system suitable in investigating the role of nematicity on the relationship.

**Figure 2B** shows the $T$ dependence of $1/T_1T$ for $x = 0.09$ under $H_{lab}$ (black) and $H_{c}$ (red) at several pressures, taken from the study by Rana et al [37]. Below $p_c = 0.5$ GPa, with decreasing $T$, $1/T_1T$ increases below ~70 K showing Curie-Weiss-like behavior originating from two dimensional AFM fluctuations and starts to decrease around $T_c$ ($T_c$ for $H_{lab}$ are shown by black arrows in the figures). On the other hand, above 0.5 GPa, $1/T_1T$ exhibits quite different temperature dependences in comparison with those observed at low pressures. Although $1/T_1T$ is slightly enhanced below ~70 K, indicating the existence of the AFM spin fluctuations, $1/T_1T$ is nearly constant exhibiting the so-called Korringa behavior, expected for Fermi-liquid state below the temperature (defined as $T_{FL}$) marked by blue arrows. Thus the results indicate that the nature of AFM fluctuations changes below and above $p_c = 0.5$ GPa in FeSe$_{0.91}$S$_{0.09}$.

Similar $T$ dependences of $1/T_1T$ have also been reported in $^{77}$Se NMR studies of FeSe$_{1-x}$S$_x$ by Kuwayama et al. [38, 41] under $p$ up to 3.9 GPa. The authors pointed out that AFM fluctuations with different $q$ vectors may be responsible for the two distinct SC domes [41]. However, Rana et al. found that the AFM fluctuations are characterized to be stripe type and $p$ independent by showing the fact that the ratios $R$ are close to ~1.5 at low temperatures for all measured $p$ shown in the insets of Figure 2B.

Then what is the difference in the nature of AFM fluctuations in the presence and absence of nematic order? The idea that nematicity changes the relationship between $T_c$ and AFM fluctuations was proposed by Rana et al [37] and can be clearly seen in Figure 2C taken from that study. Here, in the $x$ axis, the maximum values of $1/T_1T$ with $H_{lab}$ were taken as a representative of the magnitude of AFM fluctuations for different values of $x$ and $p$ in FeSe$_{1-x}$S$_x$. The corresponding $p$ and $T_c$ dependent $T_c$ values were plotted in the $y$ axis. The data included for $x = 0, 0.12$ and 0.29 were taken from Refs. [17, 58, 60], Ref. [41] and Ref. [18], respectively, while those for $x = 0.09$ were reported by Ref. [37]. These experimental data were classified into two groups: one that includes the data points where $T_c$ and AFM fluctuations are in the nematic order, and another that includes those measured in the absence of nematic order. The slope for the linear fitting of the data points in the absence of nematicity was higher by a factor of ~5 compared to the slope for the linear fitting of those in the presence of nematicity. The results indicate that, for example, $T_c$ is less sensitive to the strength of spin fluctuations in the tetragonal phase of FeSe$_{1-x}$S$_x$ at ambient pressure for $x < 0.17$ while it is largely enhanced in the orthorhombic phase of FeSe$_{0.91}$S$_{0.09}$ above 0.5 GPa even with a small increase in AFM fluctuations. When nematicity is absent, the AFM fluctuations in this system are present at both the wave vectors $q = (\pi, 0)$ and $q = (0, \pi)$ due to the four-fold rotational symmetry (C4) of the tetragonal state. However, in the presence of nematicity, the rotational symmetry is reduced to two-fold rotational symmetry (C2) and the AFM fluctuations are present at only one of the wave vectors, either vector $q = (\pi, 0)$ or $q = (0, \pi)$ [61, 62]. Based on those results, Rana et al. pointed out that the AFM fluctuations with C4 symmetry are more effective in enhancing $T_c$ for the FeSe$_{1-x}$S$_x$ system.
5 SUMMARY

We presented a brief overview of $^{77}$Se NMR studies in FeSe$_{1-x}$S$_x$ at ambient pressure and under pressure, especially focusing on the role of nematicity on the relationship between superconducting transition temperature $T_c$ and antiferromagnetic (AFM) fluctuations. It was shown that $T_c$ has a positive relationship with AFM fluctuations, suggesting the importance of AFM fluctuations in the pairing mechanism of superconducting electrons in FeSe$_{1-x}$S$_x$. Furthermore, nematicity is found to play a central role on the positive relationship. In the absence of nematic order, $T_c$ can be greatly enhanced by AFM fluctuations. When the nematic order is present, this enhancement decreases by a factor of ~5. The evidence of the various $^{77}$Se NMR studies in the FeSe$_{1-x}$S$_x$ system under pressure.

Although the findings provide a renewed insight on the relationships between nematicity, magnetism, and unconventional superconductivity in Fe-based superconductors, the origin for the strong impact of nematicity on the relationship between $T_c$ and AFM fluctuations is still an open question. Further detailed experimental as well as theoretical investigations of the underlying reason behind the impact of nematicity on the relationships between superconductivity and AFM fluctuations would bring us a step towards understanding the physical mechanism behind unconventional superconductivity.

AUTHOR CONTRIBUTIONS

All authors listed have made a substantial, direct, and intellectual contribution to the work and approved it for publication.

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