Evidence for coalescence in lightly doped strontium-substituted lanthanum cuprate samples

E. Yu. Beliayev¹, Dianela Osorio²,³ and P. Contreras³

¹ Verkin Institute for Low Temperature Physics and Engineering, National Academy of Sciences of Ukraine, Kharkiv, Ukraine.
² Actually at the University of Pavia, Pavia, Italy.
³ Department of Physics, University of the Andes, Mérida, Venezuela.

Abstract: By comparing the experimental results obtained in the study of the electron transport and magnetic properties of samples of lightly doped strontium-substituted lanthanum cuprates and the results of the theoretical analysis in the reduced elastic scattering space (RPS), we constructed the classical self-consistent strong-binding energy density profile $n(\tilde{\omega})$ in the superconducting mode for La$_{2-x}$Sr$_x$CuO$_4$ HTSC material. It is found that the imaginary part of the RPS can be zero, almost constant, or strongly self-consistent, depending on the Sr impurity concentration $x$. Supposing the Sr impurity concentration is very dilute, a constant imaginary part of the elastic scattering cross-section brings a sub-melted coalescent superconducting metallic state similar to the constant lifetime in the normal state, except for the unitary narrow, sharp peak at zero frequency. A broadening of this peak occurs for optimal concentration of Sr atoms, mixing a more significant amount of nodal fermion quasiparticles with Cooper pairs and making the energy density profile strongly self-consistent.

Keywords: Coalescence, Unitary Limit, Metallic State, HTSC, Light Doping, Reduced Elastic Scattering Phase Space, Line nodes, Lightly-Doped Strontium-Substituted Lanthanum Cuprate.

1. Introduction.

This work is dedicated to understanding at experimental and phenomenological levels some properties in the unusual low-temperature behavior of unconventional, lightly-doped strontium-substituted lanthanum cuprate samples (La$_{2-x}$Sr$_x$CuO$_4$). We compare experimentally obtained evidence for the lightly-doped superconductor with a phenomenological analysis in the reduced elastic scattering phase space (RPS) to understand the relation between classical and quantum physical phenomena in lightly-doped cuprates.

The RPS is a physical self-consistent elastic scattering space based on the imaginary and real parts of the self-consistent elastic scattering cross-
section \((\Re(\tilde{\omega}), \Im(\tilde{\omega}))\), i.e., energy is conserved, while momentum is not. That corresponds to the unitary limit in \(\text{La}_{2-x}\text{Sr}_x\text{CuO}_4\). The RPS resembles the “phase space distribution probability in quantum-mechanics” introduced by Wigner in 1932 [1, 2, 3].

In reference [2], it is pointed out the main feature of this approach: “the method is useful in providing easy reductions from quantum theory to classical physics kinetic regimes under suitable conditions”. Therefore, we use it to compare the interval \((\Re(\tilde{\omega}), \Im(\tilde{\omega}))\) as a function of doping, with previously reported evidence for some low concentration phases in doped strontium-substituted lanthanum cuprate samples on the threshold between the superconducting phase of the lightly-doped \(\text{La}_{2-x}\text{Sr}_x\text{CuO}_4\) compound and antiferromagnetic phase of \(\text{La}_2\text{CuO}_4\). With this, we can physically explain Dalakova and co-workers’ experimental findings [4 - 16].

This work is organized as follows. Section 2 shows the experimental results for low strontium doping in \(\text{La}_{2-x}\text{Sr}_x\text{CuO}_4\) HTSC with some physical insights into what happens. Section 3 analysis the scattering cross-section for \(\Re(\tilde{\omega})\) and \(\Im(\tilde{\omega})\) parts and builds up a phenomenological self-consistent density of energy profile based on the unitary limit of lightly doped \(\text{La}_{2-x}\text{Sr}_x\text{CuO}_4\). Finally, conclusions are elaborated.

2. Experimental low temperatures evidences for coalescence in lightly-dopped \(\text{La}_{2-x}\text{Sr}_x\text{CuO}_4\) samples with strong AFM correlations.

![Fig. 1. Micrographs of thin sections of \(\text{La}_{2-x}\text{Sr}_x\text{CuO}_4\) samples with \(x = 0.001\) (left) and \(x = 0.002\) (right)](image)

Despite all the efforts of the technologists, the samples turned out to be inhomogeneous on a microscopic scale, and microprobe analysis invariably
showed that in the mixture with a strontium concentration of \( x = 0.001 \) after the completion of the solid-state synthesis, there were areas with either a Sr concentration of \( x = 0.002 \) or with a Sr concentration close to zero (Fig. 1). In all other cases, there were no such problems. At Sr concentrations of \( x = 0.005 \) or \( x = 0.01 \), the strontium concentration in any parts of the sample corresponded to the prescribed one. However, at \( x = 0.001 \), the sample was prone to a phase separation into two phases with almost zero strontium content and a strontium concentration close to \( x = 0.002 \).

Also, the Neel temperature \( T_N \), which should increase monotonically with decreasing of strontium concentration [5] at the concentration of \( x = 0.001 \), suddenly dropped sharply (Fig. 2). The free carriers (holes) that appeared upon strontium doping level \( x = 0.001 \) destroyed the strict AFM ordering in La\(_2\)CuO\(_4\) Mott-Hubbard dielectric, leading to a sharp drop in \( T_N \) values and severe deterioration in its antiferromagnetic characteristics.

![Figure 2: Dependency of Neel temperature \( T_N \) in strontium-substituted lanthanum cuprates on strontium concentration.](image)

Using another physical language, it can be explained based on "hot centres" picture [6, 7]. The substitution of a heavy lanthanum atom for lighter strontium led to an increase in the frequency of local vibrations near a single local strontium atom, thus significantly increasing the local temperature of the crystal lattice. Obviously, with an increase in the degree of doping, between such hot impurity centres some beats have inevitably arisen that disrupt the resonance.
For this reason, at a certain concentration, the accumulation of strontium atoms in one place turns out to be energetically favourable since it lowers the local temperature, and this is the physical basis for the coalescence phenomenon when single strontium atoms tend to coalesce into clusters. Having approached close enough distance, the "hot centers" began to interact through harmonics and lowered their energy of resonant vibrations, giving it to the lattice.

3. Numerical self-consistent evidence for coalescence in the unitary scattering limit for La$_{2-x}$Sr$_x$CuO$_4$ samples.

In this section, we build a coalescence self-consistent density function profile of quasiparticles with the help of a phenomenological computational unitary model based on the scattering cross-section analysis for dressed fermion quasiparticle carriers in strontium-substituted lanthanum cuprate [17, 18], aiming at comparing the results from this section with the previous experimental section analysis for the strontium concentration $x$. The reduced scattering phase space (RPS) ($\Re(\omega)$, $\Im(\omega)$) plot is built with three experimental parameters, using the tight-binding anisotropic method [19] for a particular model: the superconducting gap at zero temperature $\Delta_0 = 33.9$ meV, the Fermi energy $\epsilon_F = 0.4$ meV, and the first neighbour hoping $t = 0.2$ meV, accordingly to experimental ARPES data [25], as was studied by us in [17, 18] using the Scalapino linear model [20, 21]. The normal state TB energy is $\xi(k_x, k_y) = \epsilon_F + 2 t \left[ \cos(k_x a) + \cos(k_y a) \right]$ with electron-hole symmetry $\xi(k_x, k_y) = \xi(-k_x, -k_y)$. This is the nearest-neighbour expression for a band centred at the corners ($\pm \pi/a$, $\pm \pi/a$) of the first Brillouin zone.

In references [22, 23] it was theoretically and experimentally found that La$_{2-x}$Sr$_x$CuO$_4$ HTSC is in the unitary strong scattering limit, if the Fermi surface is isotropic. The original idea of parametrizing the scattering self-consistent cross-section based on the strength $c$ and the impurity concentration $\Gamma^+$ for isotropic HTSC with line nodes was proposed in [24].

Therefore, the superconducting gap corresponds to a paired state with a singlet order parameter basis function $\phi(k_x, k_y) = \phi(-k_x, -k_y)$, and $\Delta(k_x, k_y) = \Delta_0 \phi(k_x, k_y) = \Delta_0 \left[ \cos(k_x a) - \cos(k_y a) \right]$. The superconducting gap for this symmetry has lines nodes on the Fermi surface corresponding to the one-dimensional irreducible representation $B_{1g}$ of the tetragonal point symmetry.
group D$_{4h}$. In this model, nonmagnetic disorder due to strontium atoms, strongly quenches superconducting ordering leading to suppression of $T_c$.

Based on Fig. 3, and the theory and calculations elaborated in [17, 18] we write Equation 1, which helps to understand the coalescence region observed by Dalakova and co-workers in a series of experimental works [4-7] introduced in Section 2. Therefore, intuitively, the function which we called here the energy density self-consistent profile function $n(\tilde{\omega})$ (in Planck units, it is given by meV), can separate by means of the following relationship, three different phases based on impurity concentration $x$ in the unitary limit calculation as follows:

$$
\begin{cases}
  n(\tilde{\omega}) \sim \begin{cases}
  \rightarrow 0, & \Gamma^+ = 0.01 \text{ meV (}a\text{-Mott Hubbard dielectric } La_2CuO_4) \\
  \text{constant } + \delta \Im(\tilde{\omega}), & \Gamma^+ = 0.05 \text{ meV (}b\text{-lightly doped coalescent } La_{2-x}Sr_xCuO_4) \\
  \Im(\tilde{\omega}), & \Gamma^+ > 0.05 \text{ meV (}c\text{-strange metal phase } La_{2-x}Sr_xCuO_4)
\end{cases}
\end{cases}
$$

In Equation 1, we can distinguish these phases using the experimental results from Section 2. In order to do so, we construct the following table based on the exact calculation for using the TB modelling parameters, accordingly to Table 1:

| Phases                           | a - Mott-Hubbard dielectric $La_2CuO_4$ | b – Lightly-doped coalescent $La_{2-x}Sr_xCuO_4$ | c - Strange metal phase | idem | idem |
|----------------------------------|----------------------------------------|-----------------------------------------------|------------------------|------|------|
| $\Gamma^+$ (meV)                 | 0.01                                   | 0.05                                          | 0.10                   | 0.15 | 0.20 |
| $x$                              | 0.0003                                 | 0.002                                        | 0.003                  | 0.005 | 0.01 |

Therefore, region (a) shadowed clear blue in the left part of Fig. 2 represents an almost zero imaginary scattering cross-section $\Im(\tilde{\omega}) \sim 1/\tau(\tilde{\omega}) \rightarrow 0$ for most of the entire energy window interval $\omega \in (-40, +40)$ meV. It means there are no dressed by non-magnetic impurity scattering quasiparticles,
except a few at the unitary resonance at zero frequency ($\Gamma^+ = 0.01 \text{ meV} \rightarrow x = 0.0003$).

We attribute this region being very close to the Mott-Hubbard dielectric La$_2$CuO$_4$ antiferromagnetic phase, about which Dalakova and co-workers report in their studies on the results of strontium doping $x$. In the previous publication, we reported this phase as the one where $\tau^{-1}(\tilde{\omega}) \rightarrow \text{const} \ll 1$ [18].

Region (b) in the left part of Fig. 3 is given by the blue line and represents the almost constant imaginary scattering cross-section $\Im(\tilde{\omega}) \sim \tau^{-1}(\tilde{\omega}) \rightarrow \text{constant}$, for most of the entire $\omega$ interval with a small amount of dressed by non-magnetic impurity scattering quasiparticles at the impurity concentration given by $\Gamma^+ = 0.05 \text{ meV}$ except for a small resonance $\delta \Im(\tilde{\omega})$. It corresponds to ($\Gamma^+ = 0.05 \text{ meV} \rightarrow x = 0.002$) or the coalescing phase with a metallic behavior for a lightly doped La$_{2-x}$Sr$_x$CuO$_4$.

In order to explain coalescence when linear momentum is not conserved in the unitary metallic limit, we propose that the dressed quasiparticles momentum $k$ is transferred to strontium atoms in the crystal lattice. Wherein, Sr atoms migrate through the lattice and stick together in a coalescence metallic state, but only for a very small concentrations of non-magnetic Sr atoms, ($\Gamma^+ = 0.05 \text{ meV} \rightarrow x = 0.003$) as was observed experimentally by Dalakova and co-workers. Therefore, near the superconducting-antiferromagnetic transition in lightly-doped strontium-substituted lanthanum cuprate, a robust metallic coalescence phase with an almost constant scattering lifetime can be interpreted theoretically and experimentally.

Region (c) represents the strong self-consistent imaginary part calculation of the scattering cross-section for most of the entire frequency region when $\Im(\tilde{\omega}) \sim \tau^{-1}(\tilde{\omega})$, and $\Gamma^+ > 0.05 \text{ meV} \rightarrow x = 0.001$, up to $\Gamma^+ = 0.20 \text{ meV} \rightarrow x = 0.01$ (shadowed gray). It represents the so-called strange metal phase in cuprates, where self-consistent effects in the RPS, in the imaginary part of the elastic scattering cross-section, mix the nodal Fermi dressed quasiparticles and Cooper pairs, making very difficult the explanation of physical properties inherent to this region, where the self-consistent density profile is strongly frequency-dependent.

From the point of view of the experimentally observed electronic transport properties of lightly-doped lanthanum cuprates, attention may be drawn to Fig. 1. There, one can see a resonance at near-zero $x$ concentration. Thus, hypothesis arises that it is precisely this resonance that can explain the
fact that in a series of articles [4, 5, 6], the team led by Dalakova and co-workers failed to prepare homogeneous samples of strontium-substituted lanthanum cuprate with an ultra-low concentration of Sr atoms ($x = 0.001$).

It also seems that one of the reasons for multiphase behavior in low-doped La$_{2-x}$Sr$_x$CuO$_4$ samples is the different strength of chemical bonds. The bonds between strontium and oxygen are 30 times stronger than those between the rest of the elements. Moreover, the crystal lattice near strontium atoms is in a sub-melted state. Thereby strontium atoms easily migrate and coalesce, much like a drop of water, which has a greater surface tension on the surface of a spilled oil. This work is consistent with the Fermi liquid anisotropic theory for HTSC cuprates proposed by M.B. Walker [26]

**Conclusions.**

In this work, it was found a classical self-consistent density profile $n(\tilde{\omega})$ of fermion dressed quasiparticles using the imaginary and real parts of the elastic scattering cross-section for different values of impurity concentration $x$ in lightly doped strontium-substituted lanthanum cuprate experimental sample based on the Scalapino model for cuprates with linear nodes in the unitary metallic limit. Depending on the impurity atoms
concentration, a phenomenological density profile $n(\tilde{\omega})$ using a plot with axes $(\Re(\tilde{\omega}), \Im(\tilde{\omega}))$ can be determined to be almost constant or not. Based on this inference, three $x$-doping phases are distinguished as experimentally was found by Dalakova and co-workers on lightly doped strontium-substituted lanthanum cuprate samples.

One almost antiferromagnetic phase where $n(\tilde{\omega}) \to 0$, therefore there are no dressed quasiparticles, a coalescent lightly-doped with Sr phase with $n(\tilde{\omega}) \to \text{const}$ with a small amount of non-magnetic impurities concentration and the strange metallic phase in doped HTSC, where $n(\tilde{\omega})$ is very dependent on self-consistency. All three phases belong to the unitary scattering regime where $c = 0$ and the non-magnetic potential of strontium atoms $U_0$ is strong.

Physically, as the antiferromagnetic-superconducting phases approach each other, the substitution of a heavy lanthanum atom for the lighter strontium atom, led to an increase in the frequency of vibrations near a single local Sr atom, thus significantly increasing the local temperature of the crystal lattice, therefore, at a certain concentration the accumulation of strontium atoms in one place is energetically favorable, since it lowers the local temperature, which is the basis of coalescence phenomenon, and single non-magnetic strontium atoms tend to coalesce into metallic clusters.

In addition, since the linear momentum of dressed quasiparticles $p$ is not conserved in the unitary metallic limit (only energy, i.e., elastic scattering), $p$ is transferred to strontium atoms in the crystal lattice, those Sr atoms migrate though the lattice and stick together forming the coalescence metallic cluster, but only for the lowest concentrations of non-magnetic strontium atoms, $(\Gamma^+ = 0.05 \text{ meV (theory)} \equiv x = 0.002(\text{experiment})$.

On the other hand, we recently used the same method and found, three phases in the triplet compound strontium ruthenate based on a similar model, two phases for quasinodal points (one of them very inhomogeneous), and one phase with point nodes and the ground state similar to HTSC with line nodes [27]. Also, in [28] it was found using the same methodology, that superconducting strontium ruthenate is mostly in the unitary limit $c = 0$. Therefore, we may conclude that the analysis of the TB scattering cross-section in the $[\Re(\tilde{\omega}), \Im(\tilde{\omega})]$ RPS seems to be a useful tool in order to understand some aspects of unconventional superconductors such as the different phases dependency on the strength parameter $c$ and non-magnetic disorder concentration $\Gamma^+$. 
Acknowledgments.

The authors did not receive any financial support for research, authorship and/or publication of this article.

References

[1] E. P. Wigner (1932). "On the quantum correction for thermodynamic equilibrium". Phys. Rev. 40 (5): 749–759. doi:10.1103/PhysRev.40.749
[2] P. Carruthers and F. Zachariasen, Quantum collision theory with phase space distributions, Rev. Mod. Phys. 55 (1983) 245, DOI: https://doi.org/10.1103/RevModPhys.55.245
[3] M. Hillery, R.F. O'Connell, M.O. Scully, and E.P. Wigner, 1984, Distribution functions in physics: Fundamentals, Physics Reports, 106(3), 121, DOI: https://doi.org/10.1016/0370-1573(84)90160-1
[4] N. V. Dalakova, B. I. Belevtsev, E. Y. Beliayev, A. S. Panfilov, and N. P. Bobrysheva, “Suppression of antiferromagnetic order in low-doped ceramic samples La$_{2-x}$Sr$_x$CuO$_4$,” Материалы 16-го Международного симпозиума «упорядочение в минералах и сплавах», 12-17 сентября 2013 г., Ростов-на-Дону, Туапсе, Россия., vol. 1, pp. 124 - 127, 2013.
[5] N. V. Dalakova, B. I. Belevtsev, E. Y. Belyaev, A. S. Panfilov, N. P. Bobrysheva, and A. A. Selyutin, “Low-temperature nonlinear effects in the conductivity of lightly doped cuprates La$_{2-x}$Sr$_x$CuO$_4$ in antiferromagnetic state,” Low Temp. Phys., vol. 40, no. 5, pp. 397–407, May 2014, doi: 10.1063/1.4881175.
[6] Н. В. Далакова, Б. И. Белевцев, Е. Ю. Беляев, А. С. Панфилов, and Н. П. Бобрышева, “Подавление антиферромагнитного порядка в слабодопированных керамических образцах La$_{2-x}$Sr$_x$CuO$_4$,” Известия Российской академии наук. Серия физическая, vol. 78, no. 4, pp. 398–402, 2014, doi: 10.7868/S0367676514040115.
[7] B. Keimer et al., “Magnetic excitations in pure, lightly doped, and weakly metallic La$_2$CuO$_4$,” Phys. Rev. B, vol. 46, no. 21, pp. 14034–14053, Dec. 1992, doi: 10.1103/PhysRevB.46.14034.
[8] А. Г. Чирков and В. Г. Чудинов, “Самолокализованные колебания в высокотемпературных сверхпроводниках,” ЖТФ, vol. 71, no. 1, pp. 36–43, 2001.

[9] В. Г. Чудинов, А. Г. Чирков, Е. Б. Долгушенева, and В. М. Дядин, “Влияние ангармонизма на динамику решетки системы La-Sr-Cu-O (метод молекулярной динамики),” Сверхпроводимость: физика, химия, техника, vol. 6, no. 2, pp. 204–209, 1993.

[10] N. V. Dalakova, B. I. Belevtsev, A. S. Panfilov, and E. Y. Beliayev, “Temperature behavior of conductivity in a La$_2$CuO$_{4+\delta}$ single crystal upon the paramagnetic-antiferromagnetic transition,” Bull. Russ. Acad. Sci. Phys., vol. 75, no. 5, pp. 692–694, May 2011, doi: 10.3103/S1062873811050133.

[11] N. V. Dalakova, B. I. Belevtsev, N. P. Bobrysheva, A. S. Panfilov, E. Y. Beliayev, and A. A. Selyutin, “Resistive properties of La$_{2-x}$Sr$_x$CuO$_4$ low-doped cuprates in the antiferromagnetic state at low temperatures,” Bull. Russ. Acad. Sci. Phys., vol. 76, no. 10, pp. 1139–1142, Oct. 2012, doi: 10.3103/S1062873812100036.

[12] B. I. Belevtsev, N. V. Dalakova, A. S. Panfilov, and E. Y. Beliayev, “Anomalies of conductivity behavior near the paramagnetic-antiferromagnetic transition in single-crystals La$_2$CuO$_{4+d}$,” Phys. B Condens. Matter, vol. 405, no. 5, 2010, doi: 10.1016/j.physb.2009.11.074.

[13] Н. В. Далакова, Б. И. Белевцев, Е. Ю. Беляев, and А. С. Панфилов, “Нелинейные эффекты в проводимости слаболегированных купратов La$_2$–xSr$_x$CuO4 в антиферромагнитном состоянии при низких температурах,” Физика низких температур, vol. 40, no. 5, pp. 513 – 526, 2014, [Online]. Available: http://dspace.nbuv.gov.ua/bitstream/handle/123456789/119494/02-Dalakova.pdf?sequence=1.

[14] Н. В. Далакова, Б. И. Белевцев, Е. Ю. Беляев, Ю. А. Колесниченко, А. С. Панфилов, and И. С. Брауде, “Влияние магнитных (фазовых) неоднородностей на поводимость антиферромагнитного монокристалла LaCuO4+d при низких температурах,” Известия РАН, Сер. физич., vol. 72, no. 8, pp. 1215–1218, 2008.

[15] Н. В. Далакова, Е. Ю. Беляев, Ю. А. Савина, О. И. Юзефович, С. В. Бенгус, and Н. П. Бобрышева, “Влияние Композиционного Беспорядка в Системе Сверхпроводящих Гранул на
Сверхпроводящие Свойства Керамических Образцов La2–xSrxCuO4,” Известия РАН, Сер. физич., vol. 82, no. 7, pp. 59–62, 2018, doi: 10.1134/S0367676518070165.

[16] Н. В. Далакова et al., “Сверхпроводимость керамических образцов La 1.85 Sr 0.15 CuO 4,” Известия Российской академии наук. Серия физическая, vol. 78, no. 4, pp. 486–489, 2014, doi: 10.7868/S0367676514040127

[17] P. Contreras and Dianela Osorio, 2021. Scattering Due to Nonmagnetic Disorder in 2D Anisotropic d-wave High Tc, Superconductors. Engineering Physics. Vol. 5, No 1. pp. 1-7. https://doi.org/10.11648/j.ep.20210501.11

[18] P. Contreras, Dianela Osorio, and E Beliayev, Dressed behavior of the quasiparticles lifetime in the unitary limit of two unconventional superconductors, Low Temp. Phys. 48, (2022) 187, https://doi.org/10.1063/10.0009535

[19] W. A. Harrison, Electronic Structure and Properties of Solids (Dover, New York, 1980).

[20] D. Scalapino. 1995. The case for $d_{x^2−y^2}$ pairing in the cuprate superconductors. Physics Reports. 1995. 250(6):329-365 DOI: https://doi.org/10.1016/0370-1573(94)00086-I

[21] C. Tsuei and J. Kirtley. 2000. Pairing symmetry in cuprate superconductors. Reviews of Modern Physics, 72:969 DOI: https://doi.org/10.1103/RevModPhys.72.969

[22] N. Momono and M. Ido. 1996. Evidence for nodes in the superconducting gap of La$_{2-x}$Sr$_x$CuO$_4$. T$^2$ dependence of electronic specific heat and impurity effects. Physica C 264, 311-318. DOI: https://doi.org/10.1016/0921-4534(96)00290-0

[23] Y. Sun and K. Maki. 1995. Transport Properties of D-Wave Superconductors with Impurities. EPL 32(4) pp. 355. DOI: https://doi.org/10.1209/0295-5075/32/4/012

[24] E. Schachinger and J. P. Carbotte. 2003. Residual absorption at zero temperature in d-wave super-conductors Phys. Rev. B 67, 134509. DOI: https://doi.org/10.1103/PhysRevB.67.134509

[25] T. Yoshida et al. 2012. Coexisting pseudo-gap and superconducting gap in the High-Tc superconductor La2-xSrxCuO4. Journal of the Physical Society of Japan, 81:011006, doi:10.1143/JPSJ.81.011006
[26] M. B. Walker. 2001. Fermi-liquid theory for anisotropic superconductors. Phys. Rev. B. 64(13) 134515, DOI: https://link.aps.org/doi/10.1103/PhysRevB.64.134515

[27] P. Contreras, D. Osorio and Shunji. Tsuchiya, Quasi-point versus point nodes in Sr$_2$RuO$_4$, the case of a flat tight binding $\gamma$ sheet. Accepted to be published in Rev. Mex. Fis. March 2022. arXiv:2112.11240v2 [cond-mat.supr-con] hal-03500276v2

[28] P. Contreras, D. Osorio and S. Ramazanov, Non-magnetic tight- binding effects on the $\gamma$ sheet of Sr$_2$RuO$_2$. Rev. Mex. Fis 68(2) (2022) 1, DOI: https://doi.org/10.31349/RevMexFis.68.020502