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On the electronic quantum structures of conductors

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Abstract. This paper investigates the quantum of kinetic momentum in a two-particle system of correlated electrons. Under these conditions, the minimum possible magnetic flux quantum becomes half of the flux calculated for a single electron, presenting an apparent contradiction. Since magnetic flux is an additive quantity, one might naturally expect an increase, not a decrease, in the flux. This study aims to resolve this contradiction. While pair correlation leads to a halving of the magnetic flux quantum relative to F. London's value, n-fold correlations would theoretically reduce the quantum by a factor of n. This, however, defies conventional explanation. It is unacceptable to attribute the quantum of kinetic momentum to a Cooper pair; rather, a quantum of kinetic momentum must be assigned to an individual particle, not a system of particles. F. London's quantum should, therefore, be regarded solely as a quantum of magnetic flux.

Keywords: quantum structure, correlated electrons, conductor, mean free path, kinetic moment, magnetic flux

Introduction

Two-particle quantum systems of electrons, referred to as Cooper pairs (Daido, Yanase 2024; Sivukhin 2002), emerge in conductors as a result of electron-phonon interactions (Ishida, Matsueda 2021; Wu, Liu 2023).

In these systems, a quantum of kinetic momentum $\hbar$ is ascribed to the correlated electron pair, resulting in a magnetic flux quantum that is half the value calculated for a single electron (Pavlov 2020). This presents a contradiction, as magnetic flux is inherently additive, and one would typically expect an increase in flux rather than a decrease. The objective of this study is to address and resolve this contradiction.

The research adopts a theoretical approach, employing both quantum mechanical and semiclassical considerations (Nesterov et al. 2024; Timchenko et al. 2022).

The exclusivity of two-particle systems in the creation of magnetic flux

Pair correlations occur in conductors with short electron mean free paths, and are absent in those with long mean free paths (Sivukhin 2002). The quantum of magnetic flux from a two-particle system was first measured in 1961 for conductors with short electron mean free paths. However, this does not preclude the possibility of measuring the magnetic flux quantum from a single electron in a conductor with a long mean free path, where pair correlations are absent. Notably, the quantum measured by F. London is twice as large as the value measured in 1961, and advancements in measurement equipment have increased sensitivity.

Consequently, the creation and measurement of magnetic flux by a two-particle system of electrons is not exclusive; a single electron can also generate a magnetic flux.

Magnetic quantization from a conductor with a long electron mean free path

The magnetic flux energy expression is derived as follows:

$$E = \frac{I\Phi}{2}.$$

Current from a single electron:

$$I = \frac{e}{T},$$

where T is the time it takes for an electron to complete one revolution in a circular path.

$$T = \frac{2\pi R}{v}.$$

Here R is the size of the circular contour, v is the linear velocity of the charge.
At the same time,

$$E = \frac{m_e v^2}{2}.$$

Comparison of the given expressions derives

$$\Phi = \frac{2\pi R m_e v}{e} = \frac{2\pi R p}{e},$$

where p is the amount of motion.

Since the electron is not correlated (unique), no dual interpretation of the quantum of its kinetic moment is possible. This leads us to the following:

$$m_e v R = pR = \hbar, \tag{1}$$

and results in:

$$\Phi_L = \frac{2\pi\hbar}{e} = \frac{h}{e}. \tag{2}$$

This represents the well-known F. London's quantum of magnetic flux.

Magnetic quantization from current created by two electrons

The current generated by two moving charges is double that of a single charge, irrespective of whether the charges are correlated.

Consequently, the magnetic flux created by the doubled current is also twice as large. Applying this to the equations above (2), we derive:

$$\Phi_2 = 2\Phi_L = \frac{2h}{e}.$$

The textbook value of the magnetic flux quantum created by a Cooper pair is four times smaller.

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$$\Phi_0 = \frac{h}{2e}. \tag{3}$$

Obtaining value (3) is possible only by adding the values that are inverse to (2)

$$\frac{1}{\Phi} = \frac{1}{\Phi_L} + \frac{1}{\Phi_L} = \frac{2}{\Phi_L} = \frac{2e}{h}. \tag{4}$$

There is no reasonable explanation for this.

Pairwise correlations are not the limit

The textbook calculation of the magnetic flux quantum accounts only for Cooper pairs of electrons, thus assuming pairwise correlations. At the same time, correlations of more than two electrons are possible, and, in some cases, multi-particle correlations could even be less pronounced.

Just as pair correlations result in a halving of the magnetic flux quantum compared to F. London's value, *n*-particle correlations would theoretically reduce the quantum by a factor of *n*:

$$\Phi_0 = \frac{h}{ne}. \tag{5}$$

There is no rational explanation for this, just like (3) and (4).

Magnetic quantization from a conductor with a short electron mean free path

If we accept the expression for the Cooper pair (Equation 3), it follows that one electron generates half the magnetic flux of the Cooper pair:

$$\Phi_0 = \frac{1}{2}\frac{h}{2e} = \frac{h}{4e}.$$

In the case of n-particle correlations, the magnetic flux quantum would further decrease:

$$\Phi_0 = \frac{1}{n}\frac{h}{ne} = \frac{h}{n^2 e}.$$

This phenomenon is conceptually unacceptable (Popov 2024b).

On double standards

In a poor conductor, two correlated electrons are assigned a quantum of kinetic momentum ħ on the basis of their being part of a quantum system. This would have to be agreed with if this approach were extended to other similar quantum systems, such as two electrons in helium, where the role of phonons (in conductors) is analogous to the attractive force of the atomic nucleus in helium (Popov 2024a). Let this be so. In other words:

$$2m_e v r_{\text{He}} = \hbar. \tag{6}$$

There are three forces applied to an electron: attraction to the nucleus, repulsion from another electron, and centrifugal force.

$$\frac{2e^2}{4\pi\varepsilon_0 r_{\text{He}}^2} - \frac{e^2}{4\pi\varepsilon_0 (2r_{\text{He}})^2} = \frac{m_e v^2}{r_{\text{He}}},$$

$$1.75\frac{e^2}{4\pi\varepsilon_0 r_{\text{He}}^2} = \frac{m_e v^2}{r_{\text{He}}}. \tag{7}$$

Expression (6) squared

$$4m_e^2v^2r_{\mathrm{He}}^2=\hbar^2,$$

$$r_{\mathrm{He}}^3=\frac{\hbar^2}{4m_e^2v^2}.$$

Thет relation (7) takes the form:

$$1.75\frac{e^2}{4\pi\varepsilon_0}\frac{4m_e^2v^2}{\hbar^2}=\frac{m_ev^2}{r_{\mathrm{He}}},$$

$$r_{\mathrm{He}}=\frac{m_ev^2\,4\pi\varepsilon_0\hbar^2}{1.75e^2\,4m_e^2v^2}=\frac{4\pi\varepsilon_0\hbar^2}{1.75e^2\,4m_e}=\frac{a_0}{7}.$$

In quantitative terms it results in:

$$r_{\mathrm{He}}=\frac{a_0}{7}=\frac{5.2917721092\cdot10^{-11}}{7}\approx7.56\cdot10^{-12}(m).$$

The result differs from the table value by almost four times.

At the same time, if not the pair, but each electron is attributed a quantum of kinetic momentum $\hbar$, the resulting calculations will be correct.

There are two possible ways out of this situation.

First. The pair of helium electrons should not be assigned a quantum of kinetic momentum $\hbar$. Therefore, in order to avoid double standards, other multi-particle systems, including the Cooper pair of electrons, should not be assigned it either.

Second. Multi-particle quantum systems should be assigned a quantum of kinetic momentum $\hbar$, including the pair of helium electrons. But then we will have to admit that the radius of the helium atom is four times smaller than is commonly believed.

The first option seems more preferable.

Conclusion

Kinetic momentum is an additive quantity. The contributions of each element of a multi-particle system must be summed. If the kinetic momentum of a multi-particle system is equal to the quantum ħ, it implies that each particle (electron) has a kinetic moment equal to a fractional part of the quantum. This, however, undermines the very concept of a quantum.

Therefore, attributing the quantum $\hbar$ of kinetic moment to the Cooper pair is fundamentally incorrect.

On the other hand, if the value of the magnetic flux quantum for the Cooper pair measured in 1961 is reliable, then the radius of the helium atom must be four times smaller than currently assumed.

Alternatively, the quantum of kinetic momentum ħ should be attributed to individual particles, not systems of correlated particles. F. London's quantum should, therefore, be regarded solely as a quantum of magnetic flux.

Conflict of Interest

The author declares that there is no conflict of interest, either existing or potential.

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