Non-equilibrium Superconducting Dynamics after Neutron Capture in MgB$_2$ and Novel Superconductivity Confined inside Nano-scale Domains

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We perform large-scale numerical simulations on non-equilibrium superconducting dynamics after a neutron capture in MgB$_2$ by solving the time-dependent Ginzburg-Landau equation coupled with the Maxwell and the heat diffusion equations. The simulation results reveal that an electrical response accompanied by the non-equilibrium superconducting dynamics is sufficiently rapid to detect each neutron individually even in a large neutron flux yielding 10$^5$ counts per sec. On the other hand, we investigate a possibility of superconductivity confined in nano-scale domains by using exact diagonalization method. It is found that if the confined potential is strong enough to make an electron cluster inside a nano-scale region around a potential center and the Coulomb repulsion exceeds a critical value, then a Cooper pairing correlation develops around the electron cluster. This superfluidity can be easily confirmed in an atomic Fermi gas loaded on an optical lattice created by two laser beam interference.

Keywords: Nano-scale Superconductor, Non-equilibrium Superconductivity, Neutron Detection, Superconductivity Mechanism, MgB$_2$

1. Introduction

After the discovery of an alloy superconductor MgB$_2$ [1], a unique application using MgB$_2$ has been suggested by Ishida et al. [2]. The idea is as follows. A nuclear reaction between a neutron and $^{10}$B releases a fixed energy. The energy transforms into a heat which leads to an instantaneous destruction of the superconducting state. Then, the moment is observable as the electrical signal [2] since the electrical resistance arises with the destruction of superconductivity. This is principally the same as the detection mechanism of the superconducting transition edge sensor (TES) for X-ray [3].

In this paper, we investigate how the superconductivity destructive region created by the nuclear reaction expands and shrinks inside the superconductor and estimate a time-resolution of MgB$_2$ strip geometry as a neutron detector by performing direct numerical simulations [4] of the time-dependent Ginzburg-Landau (TDGL) equation coupled with the Maxwell and the heat diffusion equations [5].

The nuclear reaction between the neutron and $^{10}$B emits $^\alpha$ particle with an energy of 1.47MeV. Then, the initial speed of the $^\alpha$ particle is 2.7 × 10$^6$ m/sec, and the speed is lost by the interaction with electrons and lattice ions inside MgB$_2$. In the atomic energy research, the traveling range of $^\alpha$ particle inside solid state matters have been intensively investigated. According to their results [6, 7], we can assume it to be 3 $\mu$m and therefore, the time of flight to be 1.0 × 10$^{-12}$ sec. Based on this assumption, we make a simple model in which the energy is lost with the same rate per second and calculate a time period from the initial nuclear-energy release to the recovery of superconductivity by installing the model onto the TDGL simulation code [5]. As a result, we find that the time period is short enough to individually detect each neutron even in 10$^9$ neutron flux per second which corresponds to the high-intensity neutron flux emitted from the pulse neutron source in J-PARC [8].

The superconductivity mechanism of High-T$_c$, cuprate
superconductors is now still elusive [9] although a tremendous of theoretical and experimental investigations have been made. This is because the superconductivity emerges on experimentally unexplored and theoretically difficult electronic states, i.e., strongly-correlated electronic states.

The Hubbard model [10] has been regarded as a typical model showing strongly-correlated behaviors like the metal-insulator transition. Since the discovery of High-Tc superconductors, the model has been intensively investigated in order to clarify whether or not the model describes high temperature superconductivity exceeding 100K. However, the issue has been not resolved yet. This is because it is quite difficult to solve theoretically and numerically Hubbard model (≥2D) in thermo-dynamical limit.

On the other hand, we point out that the superconductivity still exists even if it is confined inside nano-scale domains. In fact, in atomic gas systems, the experimental success of Bose-Einstein condensation is performed on trapped finite systems. Recently, the experimental development in atomic physics is so rapid that superfluidity even in atomic Fermi gases has been confirmed [11]. Furthermore, we note that the interference of two lasers creates an optical lattice [12] which enables to experimentally study the Hubbard model. Although there has been still no experiment on the atomic Fermi gas loaded on an optical lattice, the theme is a quite big challenge inspiring all fundamental physicists. In this paper, in order to study superconductivity in confined systems, we numerically study the Hubbard model with a trap potential and explore a possibility of superfluidity [13].

The contents of this paper are as follows. In Section II, a model of the thermal-heat release with the motion of α particle after the neutron capture is given, and results of large-scale simulations incorporating the model are shown. In Section III, we examine a possibility of superconductivity in electron systems confined inside a nano-scale range and discuss physical significance of numerical results.

2. Non-equilibrium Superconducting Dynamics after the Neutron Capture in MgB₂

The boron B in MgB₂ has two isotopes, i.e., 10B and 11B, and 10B has a quite large nuclear reaction cross-section for thermal neutrons. The nuclear reaction is described as follows,

\[ ^{10}\text{B} + n \rightarrow ^{7}\text{Li} + ^{4}\text{He} (\alpha), \]

where, both 7Li and 4He are charged particles which strongly interact with the electron and lattice systems inside MgB₂ superconductor. In the nuclear reaction, 7Li and \(\alpha\) particles initially receive 0.84MeV and 1.47MeV, respectively. In this paper, we focus on the heat energy released by only the motion of \(\alpha\) particle for simplicity. We note that the energy release process by 7Li particle is principally equivalent with that of \(\alpha\) particle and the inclusion of all the processes is easy.
3. Exact Diagonalization for Fermion-Hubbard Model with Confined Potential

The Hubbard model [10] is one of the most intensively studied models by computers because it owns very rich physics although the model expression is quite simple. The Hamiltonian of the Hubbard model with a trap potential is given as [13]

\[
H = -t \sum_{\langle i,j \rangle} (\alpha_i^{+} \alpha_j + \text{H.C.}) + \sum_i n_i \left( \frac{\alpha_i^{+} \alpha_i}{N} \right)^{3} V \sum_{\langle i,j \rangle} n_{i\sigma} \left( i - \frac{N}{2} \right)^{2}
\]

where \( t, U, \) and \( V \) are the hopping parameter from \( i \)-th to \( j \)-th sites (normally \( j \) is the nearest neighbor site of \( i \)), the repulsive energy for the on-site double occupation of two fermions, and the parameter characterizing the strength of the trapping potential, respectively, as schematically shown in Fig. 1.

We diagonalize the Hubbard Hamiltonian \( H \) and calculate an binding energy which is a probe for superfluidity by varying \( U > 0 \) and \( V \).[13]. We discuss a condition in which Cooper pair develops based on the binding energy given by \( E_b = E_g (n+1 \uparrow, n+1 \downarrow) + E_g (n \uparrow, n \downarrow) - 2E_g (n \uparrow, n+1 \downarrow) \) where \( E_g (n \uparrow, n \downarrow) \) is the ground state energy for \( n \) up-spin and \( n \) down-spin fermions. If \( E_b \) is negative, then an attractive interaction works between two fermions, which leads to an instability of cooper pair formation. Figure 4 shows \( E_b \) vs \( U/t \) for three cases in which the total number of fermions varies from \( N_F = 6 (3 \uparrow, 3 \downarrow) \) to \( 10 (5 \uparrow, 5 \downarrow) \) and \( V/t \) is fixed to be 29.7 in all cases. From Fig. 4 it is found that \( E_b \) goes to negative above a critical \( U_c \) (~8) and the negative amplitude increases with increasing \( N_F \). We confirm that \( U/t \) dependence of \( E_b \) almost converges at \( N_F = 10 \) although results of \( N_F > 10 \) are not shown here. These results mean that a large \( U/t \) (>\( U_c \)) leads to a superfluidity associated with attractive interaction between two particles under sufficient particles.

Next, let us focus on a change of the particle distributions around \( U_c \). Figure 5(a) and (b) show those as \( U < U_c \) and \( U > U_c \), respectively. When \( U < U_c \), the distribution is like a dome-shape. This means that particles concentrate in the central area since \( V \) is dominant over \( U \). When \( U > U_c \) the shape changes into a flat mountain like mesa[13]. This means that the Mott state (1 fermion per site) emerges reflecting a strong correlation effect due to large \( U \). In addition, we find that particle fluctuations occur only around the Mott cluster, i.e., particles clings to the wing of the Mott cluster and the attractive interaction works between their particles. This remote pairing via the Mott cluster is intrinsic to confined systems which is the first observation in a history of superfluid and superconductivity [13].
4. Summary and Conclusion

We performed two kinds of large scale simulations related to superconductivity. The first one is to examine the non-equilibrium superconducting dynamics after the neutron capture in MgB₂, and the second one is the exploration of superconductivity confined inside the nano-domains. As a result of the use of the Earth Simulator, we succeeded in roughly estimating a time resolution of the MgB₂ neutron detector and finding a new type of superconductivity peculiar to the confined systems.

References


MgB$_2$超伝導体の中性子捕獲後の非平衡ダイナミクスと
ナノスケールに閉じ込められた系での新しい超伝導

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1. プロジェクトの概要
最近発達してきた超伝導ナノファブリケーションのテクニックにより全く新しいタイプの超伝導デバイス開発の可能性が開かれてきた。これを受けて本プロジェクトでは、以下の3つの新しい超伝導デバイス開発に関連したシミュレーション研究を行った。
1) 中性子発来の時系列を検出する超伝導デバイス開発のための研究。
2) 1)のテーマを基礎からサポートし、かつ新しいナノスケールでの新奇超伝導物理現象を探索するための研究。
3) 高温超伝導体と金属超伝導体とをモザイク状に配置するなど、ナノ量子ドットデバイスのシミュレーション研究。

2. 得られた成果（2004年度）の概要
今年度得られた最も大きな成果はテーマ1に関連して行った超伝導体MgB$_2$の中性子捕獲後の超伝導非平衡ダイナミクスのシミュレーションによる中性子検出の時間分解能の見積もりとテーマ2に関連するナノスケールに閉じ込められた強相間電子系が示す新しいタイプの超伝導状態の発見である。以下に具体的な成果の概要を記す。

1) 超伝導体MgB$_2$に中性子が照射されるとB（ポロン）の同位体$^{10}$Bは核反応を起こし、一定の運動エネルギーを持ったα粒子が発射される。この際、α粒子の物質の飛距離は3μm程度と見積もられることから、飛行時間と運動エネルギーから熱エネルギーへの変換過程のモデル化が可能となる[1]。本年度はこのモデルを、超伝導の非平衡ダイナミクスを記述する時間依存のギンブ耳-ランダウ方程式のシミュレーションに組み込むことで、捕獲後の時間変化を詳細にシミュレーションし、その結果、中性子検出の時間分解能が極めて高いことを見出した。

2) 一般に酸化物高温超伝導体に代表されるような電子相間の極めて強い系の代表的理論的モデルとしてハーバードモデルがあるが、当プロジェクトではこのモデルを有限に閉じ込めることで超伝導性子間のポテンシャルを付加し、ポテンシャルが超伝導にどのような影響を与えるかを超大規模行列（最大で千数億次元に達する）の対角化を行うことで調べることとした。その結果、閉じ込めポテンシャルが効果に働き、ポテンシャル中心にモット相と呼ばれる、高粒子密度のフェルミ粒子の状態を介して互いに隔てられた局所相で階層のペアリング相関が発達するという全く新しいタイプの超伝導状態を発見することに成功した。この超伝導は、固体で実現することは現状では難しいが、トラップされたフェルミ原子ガスにおいては近い将来実現可能である[2]。

＜引用文献＞

キーワード: ナノ超伝導体, 非平衡超伝導, 中性子検出, 超伝導発現機構, MgB$_2$