Direct Numerical Simulations for Non-equilibrium Superconducting Dynamics at the Transition Edge: Simulation for MgB$_2$ Neutron Detectors

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Abstract We perform large-scale numerical simulations on the non-equilibrium superconducting dynamics after a neutron capture at the superconducting transition edge in MgB$_2$ by solving the time-dependent Ginzburg-Landau equation coupled with the Maxwell and the heat diffusion equations. The simulations are carried out under the current-biased condition in order to explain experimental results made in the JAEA reactor JRR-3, and the time scale of the obtained voltage signal is found to be almost consistent with the experiments. Moreover, the time evolution of the voltage signal is connected with that of the spatial profile of the superconducting order parameter.

Keywords Superconducting neutron detector · MgB$_2$

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1 Introduction

After the discovery of an alloy superconductor MgB$_2$ [1], a large amount of experimental study has been made in order to clarify fundamental aspects of MgB$_2$. As a
result, several novel features have been clarified, and many applications taking advantage of MgB$_2$ have been proposed. Among these ideas, an application suggested by Ishida et al. is quite attractive for atomic energy science \cite{2} and detector physics. The idea is as follows. When a neutron hits a MgB$_2$ sample, a nuclear reaction occurs between a neutron and an isotope of boron, i.e., $^{10}$B with a high probability. Then, a constant nuclear energy is released, and the energy transforms into heat, which leads to an instantaneous destruction of the superconducting state if MgB$_2$ is set in the superconducting state. Thus, an event of the nuclear reaction is expected to be observable as an electrical signal \cite{2}, since the destruction of superconductivity nucleates a normal hot spot along which electrical resistance is generated as the electrical current flows. This idea is principally equivalent to the detection mechanism of the superconducting transition edge sensor (TES) for X-rays and others. However, the real experiment is not so easy since one needs nuclear reactors. Thus, we construct a simulation framework to provide helpful information on making a neutron detecting device. Especially, one of the strong motivations comes from the prediction of the time scale of the electrical signal prior to the experiment since a guideline on the setup of the measurement tools is crucial for success within a limited number of experiments. We believe that the simulation enables to avoid wasteful trial experiments.

Motivated by the projective reason described above, we develop a direct computer simulation framework \cite{3–5}. The employed equation is the time-dependent Ginzburg-Landau (TDGL) equation with superconducting fluctuations, the Maxwell equation with gauge field fluctuations, and the heat diffusion equation \cite{3–5}. The TDGL equation is grounded on the BCS theory, which well describes conventional metallic superconductors, and its time-dependent dynamics provide a theoretically valid picture only close to the superconducting transition. In addition, the TDGL framework is numerically convenient because the main issue is to directly solve the partial differential equations without regard for quantization effects.

In this paper, we present the simulation framework and its simulation results for the time evolution of the electrical signal and the superconducting electron density, which is characterized by the “superconducting order parameter”. Moreover, we compare the simulation results with experimental ones. The most dramatic point is the comparison of the time scale of the signal. The simulation predicts that the time response is of orders of $10^{-8}$ s, which is almost consistent with that of the experimental results.

The theoretical framework for the TDGL equation with superconducting fluctuations and the numerical simulation method are given in Sect. 2. The simulation results for the time evolution of the voltage signal and the order parameter profile are presented, and the comparison with experimental results are discussed in Sect. 3.

### 2 Theoretical Framework and Simulation Method

The time-dependent Ginzburg-Landau theory has variations in their validity regimes. Among them, we focus on the most typical one, whose valid area is only close to the superconducting transition, i.e., the upper critical field line $H_{c2}(T)$. The time-dependent Ginzburg-Landau equation has a simple damped feature, which is characterized by the relaxation time. Thus, the formalism is very convenient for direct