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京 都 大 学 大 学 院 理 学 研 究 科

Ｄ Ｃ ３ 回 生 研 究 発 表 会
要旨集

２０２２年１１月２２日（火）

物 理 学 第 一 分 野

物理学第一分野ＤＣ３回生研究発表会

場所：理学研究科５号館　５階・第４講義室（５２５号室）+Zoom
発表：２０分（別に質問１０分程度）

２０２２年１１月２２日（火）９：００～　開始

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Superconducting diode effect in disordered systems

Condensed Matter Theory Group　　Yuhei Ikeda

Abstract The recent discovery of the superconducting diode effect (SDE) has attracted much attention owing to its intriguing phenomenon. In this work, we describe the intrinsic mechanism of SDE in disordered systems.

The acquisition of new functionalities in superconductors is essential not only for engineering development, such as the creation of more energy-saving devices but also for the development of the basic science of superconductivity. In recent years, nonreciprocal transport phenomena have attracted much attention as a new functionality of matter. In the field of superconductivity, the superconducting diode effect (SDE) has been observed in [Ni/V/Ta] artificial superlattice superconductors with inversion symmetry breaking [1]. The SDE refers to a current flow with zero electrical resistance in one direction and a finite resistance in the opposite direction. A theoretical explanation for the SDE was given in terms of the deparing current [2-5], i.e., SDE by intrinsic mechanism. Moreover, the theory shows an interesting result suggesting that the sign change of SDE is closely related to the helical superconductivity [2], in which Cooper pairs are stabilized with a finite center-of-mass momentum. On the other hand, the time-reversal symmetry breaking by an applied magnetic field violates the assumption of Anderson's theorem, and it is widely known that impurities have a significant effect on the physical properties of superconductivity [5, 6]. The evaluation of the effect of impurities on the SDE is interesting not only for the performance evaluation of superconducting diodes but also for the development of the fundamental theory of noncentrosymmetric superconductors.

In this work, we investigate the impurity effect on the SDE using a microscopic analysis based on the Rashba-Zeeman model and a self-consistent Born approximation. Our results show that the sign change of the SDE disappeared by applying the disorder (see Fig.1). Furthermore, the similarity of the behavior with respect to impurity concentration supports the existence of a correspondence between the SDE and helical crossover.

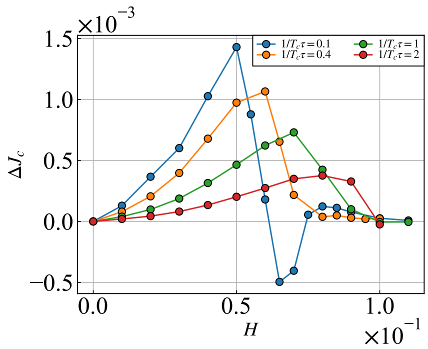

Fig. 1. Magnetic field dependence of the SDE for various impurity concentration.

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Eigenvalue analysis of amorphous solids consisting of frictional grains under athermal quasistatic shear

Physics of Matter and Statistical Dynamics Group　Daisuke Ishima

Abstract We study the two-dimensional amorphous solids consisting of frictional grains under athermal quasistatic shear. Then, we propose a framework to determine the rigidity by the eigenvalue analysis of the dynamical matrix. We have confirmed that the rigidity and stress-strain curve by the eigenvalue analysis agree with the results of simulations.

Since amorphous materials consisting of dispersed grains such as powders, colloids, bubbles, and emulsions are ubiquitous in nature, to understand their property is important for our daily life. It is known that amorphous materials behave as fragile solids above a critical density.

The rigidity of amorphous solids is determined with the aid of eigenvalue analysis of Hessian which is obtained from the configuration of grains if mutual friction between grain is negligible [1]. In general, however, we cannot neglect the friction between grains. Moreover, we realized that the scaling law of the rigidity with respect to pressure and strain only for frictional grains [2]. Thus, mutual friction between grains is important, but no one has obtained the rigidity from the eigenvalue analysis of frictional grains so far.

We have determined the rigidity by the eigenvalue analysis for frictional grains with infinitesimal strain with the aid of the Jacobian matrix [3]. Moreover, if we restrict our interest to harmonic systems, we succeed to extend the eigenvalue analysis even for finite strain. We have confirmed that the stress-strain curve obtained by the eigenvalue analysis almost perfectly agree with that by the simulation except for the yielding point (see Fig. 1) [4].

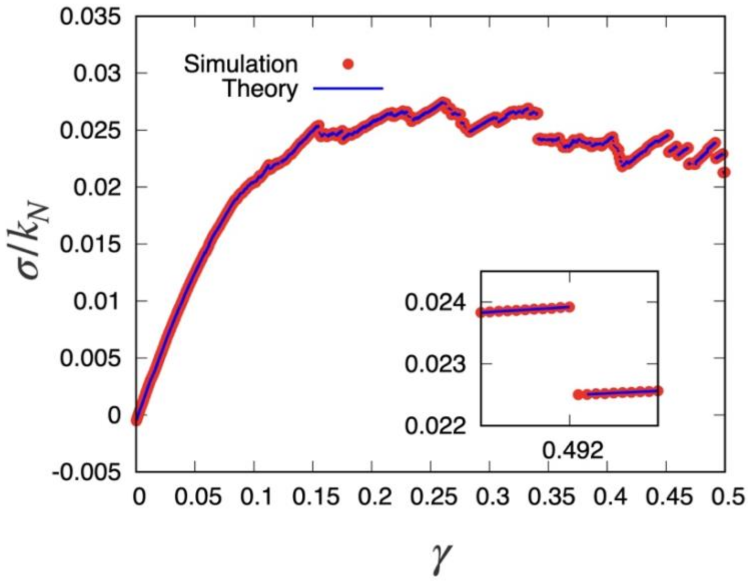

Fig. 1. Plots of the stress-strain curve for $0 \leq \gamma \leq 0.5$ for one sample of collection of grains, which includes the results by the eigenvalue analysis (line) and simulation results (filled symbols). The inset is a close-up of the stress-strain curve in the vicinity of a stress-drop event.

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Generalization of Jordan-Wigner Transformations and Junction Models

YITP, Solid State Physics, Masahiro Ogura

Abstract In this presentation we discuss our new geometric method for generalized Jordan-Wigner transformations (JWTs). This method includes ordinary JWT for the transverse field Ising model and the redundant Majorana representation for the Kitaev honeycomb lattice model. We also explain some examples including junction models.

Exactly solvable models have played important roles to understand strongly correlated systems. In particular, the Jordan-Wigner transformations (JWTs) and their variants (e.g., the redundant Majorana representations) are well-known and useful methods for solving the 2D classical Ising model, the transverse field Ising model, and the Kitaev honeycomb lattice model [1,2]. These examples have unveiled many important phenomena like phase transitions [3].

In this presentation we describe a new method to construct the generalized JWTs [4]. This method is based on algebras, graph theory and simplicial homology theory. From a given lattice spin Hamiltonian, we can construct a graph which reflects its algebraic property. (This graph is called the commutativity graph). If this commutativity graph corresponds to some proper simplicial complex, the given Hamiltonian can be transformed into a Majorana quadratic form, from which the spectrum of the system is calculated.

This method is the visually simple procedure to transform given Hamiltonians into Majorana quadratic forms. Moreover, it includes the ordinary JWT for the transverse field Ising model and the redundant Majorana representations for the Kitaev honeycomb lattice model. We also present 1D junction models and calculate their Majorana zero modes [5].

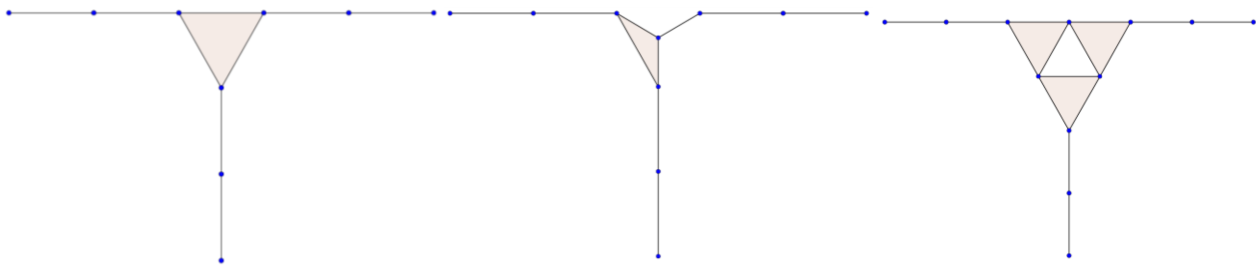

Fig. 1. Tri-junction models which can be converted into Majorana quadratic forms.

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Spin-triplet multiple superconducting phases in UTe_2 induced by magnetic field and pressure

Quantum Materials Lab. Katsuki KINJO

Abstract The outstanding feature of superconducting (SC) UTe_2 is the multiple SC phases by the magnetic field (H) and pressure (P). To investigate the SC properties in these phases, we performed ^{125}Te-NMR measurements. Our measurements revealed that the spin-triplet state in the P and H-induced superconductivity is different from that in P = 0.

In superconductivity, two electrons form a pair called the Cooper pair. Hence, superconductivity is classified into two categories: spin-singlet or spin-triplet superconductivity. In spin-triplet superconductors, the total spin angular momentum $\boldsymbol{S}$ is 1, resulting in the spin and orbital degrees of freedom. Due to these degrees of freedom, unusual behaviors such as multiple superconducting (SC) phases and magnetic field (H) boosted superconductivity are expected. However, there are few candidates for spin-triplet superconductors, and thus, spin-triplet multiple SC phases have not been intensively investigated so far.

In 2018, S. Ran *et al*. discovered the superconductivity in uranium ditelluride (UTe_2) with its superconducting critical temperature T_c ~ 1.6 K[1]. UTe_2 is a leading candidate for the spin-triplet superconductor because the physical properties are very similar to those in the U-based ferromagnetic superconductors: magnetic properties and the anisotropy of the upper critical field (H_{c2}) of superconductivity, especially H-boosted superconductivity under the b-axis field, and the extremely large upper critical field (H_{c2})[1]. Furthermore, recent nuclear magnetic resonance (NMR) measurements revealed the tiny change or absence of the change in the spin susceptibility, supporting the spin-triplet scenario[2-4].

In UTe_2, multiple SC phases induced by the b-axis high magnetic field above 16 T (HFSC) or pressure above 0.3 GPa (SC2) are observed as shown in Fig. 1. To investigate the SC properties, especially the spin state in these phases, we performed the ^{125}Te-NMR measurements under a high magnetic field[5] and high pressure[6]. For high-field measurement, above 20 T, the change in the NMR Knight shift (ΔK) below $T_c(H)$, which is proportional to the change in the spin susceptibility in the SC state, becomes zero, evidencing the SC spin rotation induced by the high magnetic field.

Under high pressure, the new SC phases are observed above 0.3 GPa (SC2, SC3 in Fig. 1), and superconductivity suddenly disappears above 1.6 GPa. Our NMR results under pressure above T_c revealed that the electronic state dramatically changes above 1.6 GPa, and that superconductivity occurs in the heavy-fermion state. [6].

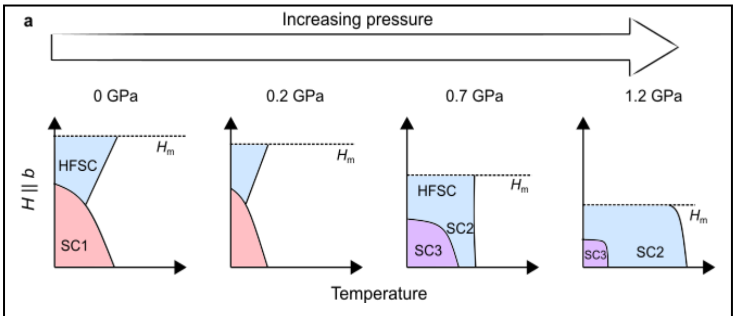

Fig. 1 Schematic image of multiple SC phases in UTe_2.

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Information flow in turbulence

Nonlinear Dynamics Group　Tomohiro Tanogami

Abstract We investigate the nature of information flow in turbulence from an information-thermodynamic viewpoint. We show that information of large-scale turbulent fluctuations is transferred to small scales along with energy cascade. Furthermore, we show that information-thermodynamic efficiency is extremely low compared to other information processing systems such as Maxwell's demon.

Various phenomena observed in complicated systems such as the earth system and chemical reaction networks can be regarded as nonequilibrium cooperative phenomena that emerge from many-body interactions. To elucidate and control the dynamics behind such phenomena, it is pertinent to focus on information transfer between components constituting the system. Particularly in mesoscopic systems affected by thermal fluctuations, the nature of such information transfer can be described by information thermodynamics. Information thermodynamics is essentially stochastic thermodynamics for subsystems and provides constraints that are consistent with thermodynamics on the exchange of heat and information between subsystems [1]. Recently, it has been applied to information processing at the cellular level in biological systems and even to deterministic chemical reaction networks.

Turbulent cascade can be regarded as a nonequilibrium cooperative phenomenon that emerges from extremely complicated interactions, where energy is transferred conservatively from large to small scales. This phenomenon can be described intuitively as the successive generation of smaller vortices by the stretching of larger vortices. Along with the energy cascade, fluctuations of small-scale quantities follow those of large-scale quantities with a time delay τ_L, which corresponds to the characteristic time scale for the largest eddies to be stretched into smaller eddies. This phenomenon suggests that information on turbulent fluctuations is also transferred from large to small scales. While turbulence has been studied in various contexts from such an information-theoretic viewpoint over recent decades, the nature of the information flow associated with turbulent cascade has not yet been elucidated. In particular, no previous studies have considered the effects of the thermal fluctuations that are inherent in fluids on information transfer, even though the thermal fluctuations can affect the turbulence dynamics significantly [2].

Here, we aim to elucidate the nature of information flow in turbulence from an information-thermodynamic viewpoint [3]. To this end, we employ the framework of fluctuating hydrodynamics to explicitly take thermal fluctuations into account. Specifically, we use the shell model with thermal noise, which is a simplified caricature of the fluctuating Navier-Stokes equations. This approach not only enables us to obtain fundamental constraints on information flow, but also allows comparative studies with other information processing systems.

We show that information of large-scale eddies is transferred to small scales along with the energy cascade (Fig. 1). The information transfer rate is characterized by τ_L. Furthermore, we numerically show that the information-thermodynamic efficiency is extremely low compared to other information processing systems such as Maxwell's demon. This result implies that transferring information from large to small scales involves enormous thermodynamic costs, indicating the poor performance of turbulence as an information processing system.

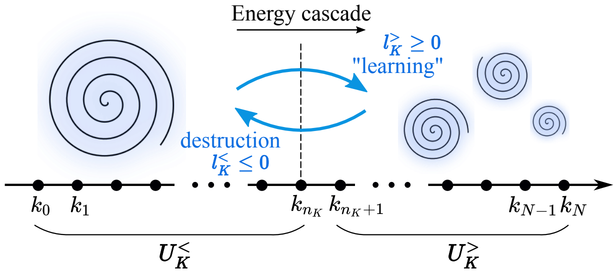

Fig. 1. Schematic of information flow in turbulence.

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Anomalous electron hydrodynamics in noncentrosymmetric materials

Condensed Matter Theory Group, Riki Toshio

Abstract We formulate electron hydrodynamic theory for noncentrosymmetric materials and propose several unconventional transport phenomena, such as asymmetric Poiseuille flow. Furthermore, we investigate the interplay quantum geometry and surface plasmons on periodic grating nanostructures, thereby providing a promising route toward a novel type of highly sensitive, broadband terahertz photodetectors.

At low temperatures, in some ultraclean metals, the electron mean free path of collisions with impurities and phonons becomes much larger than that of electron-electron scatterings and the sample size. Under this condition, electron-electron scattering becomes the most dominant process governing electron transport, giving rise to the formation of a viscous flow of an electron fluid [1]. This regime is called “hydrodynamic regime” where the electron dynamics is described by an emergent hydrodynamic theory. Recently, such hydrodynamic behaviors have already been reported through several DC transport experiments in clean metals, such as graphene [2], GaAs quantum wells [3], and Weyl semimetal WP2 [4]. Interestingly, in the past few years, symmetry of crystals and quantum geometry gives a new twist to the concept of electron hydrodynamics, leading to rich and novel hydrodynamic phenomena such as anisotropic or Hall viscosity effects [5-7].

In this presentation, we firstly develop an electron hydrodynamic theory for noncentrosymmetric metals, where a novel class of electron fluids is realized by lowering crystal symmetries and resulting geometrical effects [8,9]. The obtained hydrodynamic theory suggests an interesting analogy between electron fluids in noncentrosymmetric metals and chiral fluids in vacuum, and predicts novel hydrodynamic phenomena, that is, *asymmetric Poiseuille flow* and *anomalous edge current*.

Next, we investigate an interplay between quantum geometrical effects and surface plasmons through surface plasmonic structures, based on the obtained theory [10]. We demonstrate that the quantum nonlinear Hall effect can be dramatically enhanced over a very broad range of frequency by utilizing plasmonic resonances and near-field effects of grating gates. Furthermore, we clarify a universal relation between the photocurrent induced by the Berry curvature dipole and the optical absorption, which is essential for computational material design of long-wavelength photodetectors. We also discuss a novel mechanism of geometrical photocurrent, which originates from an anomalous force induced by oscillating magnetic fields and is described by the dipole moment of orbital magnetic moments of Bloch electrons in the momentum space. Our theory is relevant to 2D quantum materials such as layered WTe2 and twisted bilayer graphene, thereby providing a promising route toward a novel type of highly sensitive, broadband terahertz photodetectors.

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High-harmonics generation in $Pr_{0.6}Ca_{0.4}MnO_3$

Solid state spectroscopy group　Aiko Nakano

Abstract Investigating which degrees of freedom is crucial in nonlinear optical process for strongly-correlated materials is attractive. Here, we show the enhancement of the high-harmonics intensity with an increasing charge-ordering gap energy in $Pr_{0.6}Ca_{0.4}MnO_3$. Our results suggest the significance of the correlation between different degrees of freedom in nonlinear optical process.

In strongly correlated materials, a single electron picture is not good approximation due to strong correlation among multiple degrees of freedom, which induces various intriguing states. High-harmonics generation (HHG) gives an experimental platform to find out a novel nonlinear optical process and understand the role of strong correlation effect beyond the mean field theory [1].

Manganese oxides are typical strongly-correlated materials which exhibit various phase related to spin, charge, and orbital degrees of freedom by tuning physical parameters such as temperature and chemical substitution. For example, $Pr_{0.6}Ca_{0.4}MnO_3$ presents the charge-orbital ordered (CO-OO) state below 240K, and the *CE-type* antiferromagnetic (AFM) spin ordered state below 50K [2]. Such a characteristic of manganese oxides enables us to investigate the relation between multiple degrees of freedom and nonlinear optical properties comprehensively.

Here, we measured the high harmonic signals from $Pr_{0.6}Ca_{0.4}MnO_3$ in a temperature range across the critical temperatures of the CO-OO and the AFM transitions. Figure 1 shows high harmonic spectra at 294K (dotted black line) and 7K (solid blue line). The intensities of HHG are suppressed at high temperature above transition temperatures. The inset of Fig. 2 shows third order harmonic signal as a function of temperature. Third harmonic signal shows a gradual decrease below T_{CO} and has a kink just above T_{CO}. We found the increase of the third harmonic intensity is proportional to the square of the gap energy [3] as shown in Fig. 2. The enhancement of the HHG intensity with gap opening was also reported for Mott-insulating state in Ca_2RuO_4 previously [1]. In the presentation, we will discuss the role of strong correlations in the nonlinear optical process.

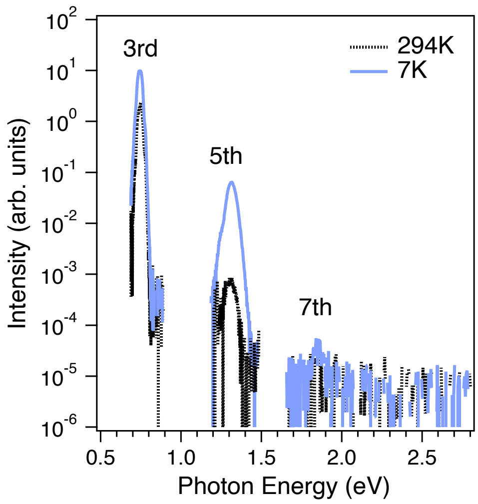

Fig. 1. High harmonic spectra in the single crystal of $Pr_{0.6}Ca_{0.4}MnO_3$ at 294K (dotted black line) and 7K (solid blue line.) The driving photon energy is 0.26eV and the intensity at the focus point is around 0.3TW/cm^2.

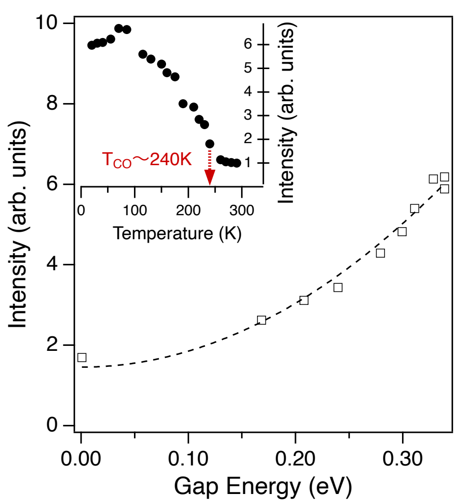

Fig.2. The correlation between the third harmonics intensity and the gap energy [3]. The inset shows the temperature dependence of the third harmonics intensity in a range from 7K to 295K.

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Theoretical study on dissipative quantum many-body phenomena in ultracold atoms

Kazuki Yamamoto, Condensed Matter Theory Group

Abstract Recent progress in ultracold atoms has enabled control of dissipation as well as flexible tuning of physical parameters. Motivated by such backgrounds, we investigate several representative quantum many-body phenomena in ultracold atoms with dissipation, focusing on Fermi-Hubbard models, fermionic tight-binding chains, and quantum spin systems.

In recent years, open quantum systems have been actively studied both experimentally and theoretically. In many cases, coupling to the environment causes decoherence of quantum states and it is often detrimental to their control. Remarkably, dissipation can also be instrumental in the preparation of novel states in open quantum systems. To date, a lot of studies have been done by using dissipation such as particle loss, dephasing, and measurement backaction, and it is reported both theoretically and experimentally that dissipation can realize unique nonequilibrium phenomena. On the other hand, many-body effects, which are known to bring about rich phenomena induced by correlation, have not been fully understood yet in nonequilibrium quantum systems subject to dissipation.

In our study, we have explored the following three topics by introducing dissipation, which is relevant to cold-atom experiments:

(a) Non-Hermitian (NH) fermionic superfluidity and nonequilibrium dynamics of dissipative fermionic superfluids induced by two-body loss of Cooper pairs [1, 2],

(b) Rectification physics in nonequilibrium steady states induced by dissipation [3],

(c) Universal properties of dissipative Tomonaga-Luttinger (TL) liquids [4].

First, on topic (a), we have analyzed a NH BCS Hamiltonian and developed a NH BCS theory to obtain a NH gap equation for order parameters, which induces unconventional reentrant phase transitions unique to NH systems. Then, we have analyzed loss-induced dynamics of dissipative fermionic superfluids by studying the Lindblad master equation. We have demonstrated that when dissipation is introduced to one of the two superfluids coupled via a Josephson junction, it gives rise to a nonequilibrium dynamical phase transition characterized by the vanishing dc Josephson current. Then, on topic (b), we have shown that unidirectional particle transport can in general occur when a Lindblad operator is reciprocal provided that the inversion symmetry and the time-reversal symmetry of the microscopic Hamiltonian are broken. Finally, on topic (c), we have uncovered that NH XXZ spin chain in the massless regime with weak dissipation belongs to the universality class characterized by the complex-valued TL parameter, which is related to the complex generalization of the $c = 1$ conformal field theory.

In this presentation, we first introduce the overview and advancement of ultracold atoms with dissipation, and then explain our results concentrating on topic (a).

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