


## Magnonic spin-current shot noise in an itinerant Fermi gas

Tingyu Zhang,<sup>1,2</sup> Hiroyuki Tajima<sup>1,\*</sup> and Haozhao Liang<sup>1,2</sup>

<sup>1</sup>*Department of Physics, School of Science, The University of Tokyo, Tokyo 113-0033, Japan*

<sup>2</sup>*Interdisciplinary Theoretical and Mathematical Sciences Program (iTHEMS), RIKEN, Wako, Saitama 351-0198, Japan*

 (Received 20 November 2023; revised 19 January 2024; accepted 6 February 2024; published 1 March 2024)

Spin transport phenomena at strongly correlated interfaces play central roles in fundamental physics as well as spintronic applications. To anatomize spin-transport carriers, we propose the detection of the spin-current noise in interacting itinerant fermions. The Fano factor given by the ratio between the spin current and its noise reflects elementary carriers of spin transport at the interface of spin-polarized Fermi gases realized in ultracold atoms. The change of the Fano factor microscopically evinces a crossover from quasiparticle transport to magnon transport in itinerant fermionic systems.

DOI: [10.1103/PhysRevApplied.21.L031001](https://doi.org/10.1103/PhysRevApplied.21.L031001)

*a. Introduction.* Quantum transport phenomena have significantly advanced modern physics, contributing to notable discoveries such as superconductivity, superfluidity, the Josephson effect, and the quantum Hall effect [1–3]. Recently, they have been extensively studied in cold atomic systems due to their high controllability and cleanliness. By utilizing Feshbach resonances [4], we are able to scan systems from weakly interacting to strongly interacting regimes in both attractive and repulsive branches, enabling the study of transport phenomena over a wide range of interaction strengths [5,6]. State-of-the-art experimental techniques allow us to examine various transport phenomena, such as multiple Andreev reflections [7] and the Josephson effect [8–11] in ultracold atomic systems.

Spin transport, among these phenomena, has garnered attention in various systems [12–18]. The spin-tunneling process at an interface has been investigated in the field of spintronics through the spin Seebeck effect [19–23] and microwave-irradiation-caused spin-pumping effect [12,24–26]. Moreover, spin transport has been studied in ultracold Fermi gases [27–29], offering a controllable interaction strength unlike solid-state systems. The spin current can be directly induced and measured with a spin bias that can be tuned through an external magnetic field [30,31], facilitating the study of spin-tunneling phenomena between Fermi gases with a simple two-terminal setup [32,33].

On the other hand, a key mechanism of spin transport, i.e., the spin-flip tunneling process at interfaces, remains elusive in ultracold Fermi gases. In this regard, tunneling spin transport has been studied based on the conventional quasiparticle tunneling process, unlike ferromagnetic or

antiferromagnetic insulators where quasiparticle tunneling is absent and the spin-flip tunneling process is definitely important [22,34]. It is thus much required to distinguish elementary spin-transport carriers for the identification of the spin-flip process in ultracold Fermi gases. One notable feature of spin-flip tunneling is magnon tunneling transport, linked to ferromagnetic phase transitions in repulsive Fermi gases [35]. Recently, it is reported that the spin-flip current exhibits a predominantly cubic dependence on the polarization bias due to the magnon mode [36]. A nonlinear conductance associated with the magnon mode has also been observed in magnetic tunneling junctions [37–39]. While the ferromagnetic phase in the so-called excited branch is metastable and thus exhibits a short lifetime [40], the spin tunneling transport of the gapped magnon mode still plays a crucial role even in the normal phase. In particular, a physical observable characterizing a crossover from quasiparticle to magnon tunneling transport would aid in understanding spin transport in itinerant fermionic systems comprehensively, potentially connecting itinerant and insulating systems in terms of spin transport.

The shot noise [41] arising from the discrete nature of current carriers is expected to be crucial for studying this issue. Proportional to both the effective charge and the average current, the Fano factor, defined as the noise-to-current ratio, serves as a powerful tool to probe current carriers. It has been used to detect the effective charge through a normal metal-superconductor junction [42,43] and to determine the fractional charges in the fractional quantum Hall regime [44,45]. The Fano factor has also been applied to assess the effective spin carried by a magnon in the spin Seebeck effect and spin-pumping-induced spin transport [46]. The spin-current noise has been measured at a ferromagnet-metal interface in an electric charge channel via the inverse spin Hall effect [47], while it is recently

\*htajima@g.ecc.u-tokyo.ac.jp

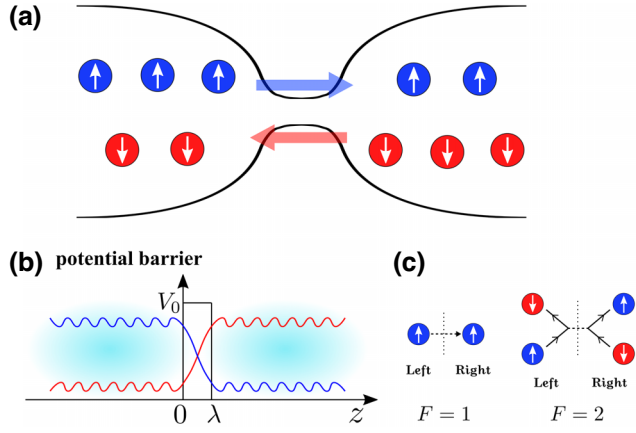


FIG. 1. (a) Schematic view of the two-terminal system considered in this work. Spin currents are induced through the potential barrier due to the spin imbalance between two reservoirs. (b) Rectangular potential barrier with height  $V_0$  and width  $\lambda$  applied to the junction. The blue (red) wavy lines denote the wave functions of particles in the left (right) reservoir. (c) Quasiparticle tunneling and spin-flip tunneling. At large polarization bias, the Fano factors for these two processes read 1 and 2, respectively.

proposed that the Fano factor for tunneling in strongly correlated Fermi gases changes from 1 to 2 as the interaction strengthens, indicating a crossover from quasiparticle tunneling to pair tunneling dominance [48]. While the magnon-mediated spin-current shot noise is found to be small in recent experiments for solid-state systems such as a ferromagnet-metal junction [49], it can be enhanced by tuning the interaction strength or the tunneling barrier in cold atomic systems. These findings motivate us to investigate the Fano factor for spin tunneling in spin-polarized Fermi gases.

In this work, to tackle the spin transport at strongly correlated interfaces of itinerant systems, we propose a two-terminal junction inducing the spin tunneling through a rectangular potential barrier between two polarized Fermi gases with a repulsive interaction as shown in Figs. 1(a) and 1(b). Using the Schwinger-Keldysh approach [50,51], we analyze the spin current and corresponding shot noise. In the large bias limit, the Fano factor  $F$  can be regarded as a probe of spin carriers at large polarization bias [Fig. 1(c)]. We show the interaction and barrier-shape dependencies of  $F$ , which reveal how the tunneling channel changes from quasiparticle-dominant to magnon-dominant process. Once the spin shot noise is measured in itinerant Fermi gases, the existence of spin-flip tunneling can be clearly revealed and an analog quantum simulation of spintronics devices can be feasible in systematic ways.

*b. Model.* Throughout the paper, we take  $\hbar = k_B = 1$  and the volumes for both reservoirs to be unity. We consider a two-terminal model for two-component Fermi gases with a contact-type repulsive interaction. Despite the potential

barrier in the center of the junction, we assume homogeneous gases in the reservoirs far from the barrier. The total Hamiltonian is given by  $H = H_L + H_R + H_t$ , where the reservoir Hamiltonian reads

$$H_{i=L,R} = \sum_{p,\sigma} \varepsilon_{p,\sigma,i} c_{p,\sigma,i}^\dagger c_{p,\sigma,i} + g \sum_{p,p',P} c_{p+\frac{p}{2},\uparrow,i}^\dagger c_{-p+\frac{p}{2},\downarrow,i}^\dagger c_{-p'+\frac{p}{2},\downarrow,i} c_{p'+\frac{p}{2},\uparrow,i}. \quad (1)$$

Here,  $\varepsilon_{p,\sigma,i} = \varepsilon_p - \mu_{\sigma,i} = p^2/(2m) - \mu_{\sigma,i}$  is the single-particle energy in the reservoir  $i = L, R$  with reservoir chemical potential  $\mu_{\sigma,i}$ ,  $g$  is the interaction strength, and  $c_{p,\sigma,i}^\dagger$  ( $c_{p,\sigma,i}$ ) denotes the single-particle creation (annihilation) operator in the reservoir  $i$ . For the tunneling Hamiltonian  $H_t$ , we propose an effective Hamiltonian where the pair tunneling is omitted, as we consider zero chemical bias and thus mass tunneling does not arise. Accordingly,  $H_t$  includes only the quasiparticle and spin-flip tunneling terms, respectively given by

$$H_{1t} = \sum_{p,q,\sigma} \mathcal{T}_{1,p,q} c_{p,\sigma,R}^\dagger c_{q,\sigma,L} + \text{H.c.}, \quad (2)$$

$$H_{2t} = \sum_{p,q} \mathcal{T}_{2,p,q} (S_{p,L}^+ S_{q,R}^- + S_{q,R}^+ S_{p,L}^-), \quad (3)$$

with the spin ladder operators  $S_{p,i}^+ = c_{p,\uparrow,i}^\dagger c_{p,\downarrow,i}$  and  $S_{p,i}^- = c_{p,\downarrow,i}^\dagger c_{p,\uparrow,i}$ . Here,  $\mathcal{T}_{1,p,q}$  and  $\mathcal{T}_{2,p,q}$ , respectively, represent the tunneling strengths of one-body and spin-flip tunnelings, which depend on the single-particle transmission coefficient [52] and hence can be tuned via the potential barrier.

In this study, we introduce a rectangular barrier with width  $\lambda$  and height  $V_0$ :  $V(z) = 0$  for  $z < 0$  and  $z > \lambda$ , and  $V(z) = V_0$  for  $0 \leq z \leq \lambda$ , as shown in Fig. 1(b). Assuming momentum conservation during the tunneling process ( $\mathbf{k} - \mathbf{k}' \rightarrow 0$ ), the tunneling strengths can be obtained from the derivation of the tunneling Hamiltonian [52] as  $\mathcal{T}_{1,k,k'} \equiv \mathcal{T}_{1,k} \delta_{kk'} = [C_{k,\sigma} \varepsilon_k + V_0 \mathcal{B}_{k_z}] \delta_{kk'}$  and  $\mathcal{T}_{2,k,k'} \equiv \mathcal{T}_{2,k} \delta_{kk'} = 2g \text{Re}[C_{k,\uparrow}^* C_{k,\downarrow}] \delta_{kk'}$ , where  $C_{k,\sigma}$  is the transmission coefficient for a single particle tunneling through the barrier with momentum  $\mathbf{k}$  and spin  $\sigma$  and  $\mathcal{B}_{k_z}$  is an overlap integral for wave functions within the potential barrier (see the Supplemental Material [53]). Notice that we can apply such a momentum-conservation approximation since the contribution of momentum-unconserved tunneling to the total current can be much less than the momentum-conserved one.

With calculations detailed in the Supplemental Material [53], the momentum dependence of the tunneling strengths is depicted in Figs. 2(a) and 2(b), where different features

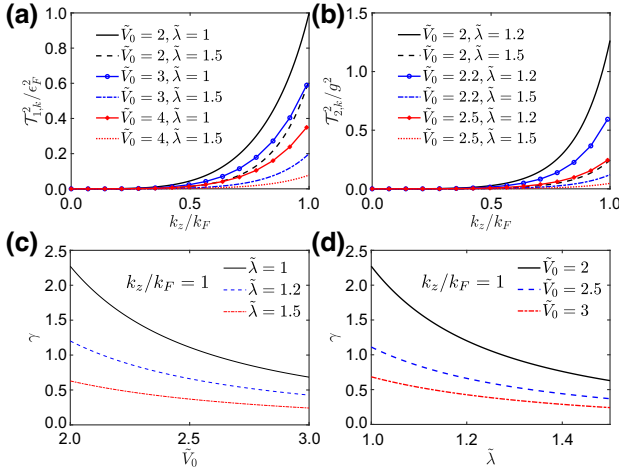


FIG. 2. Momentum dependence of (a) module squared quasi-particle tunneling strength and (b) module squared spin-flip tunneling strength. The ratio  $\gamma$  as a function of (c) the height and (d) the width of the potential barrier. Here,  $\tilde{V}_0 = V_0/\epsilon_F$ ,  $\tilde{\lambda} = \lambda k_F$ , and  $k_z$  denotes the momentum vector parallel to the axis of the potential barrier.

of potential barriers are considered. The tunneling of particles near the Fermi surface with large momentum  $k_z$  plays a dominant role in the total tunneling process, making it reasonable to approximately regard the tunneling strength as constants  $T_1 \equiv T_{1,k_z=k_F}$  and  $T_2 = T_{2,k_z=k_F}$ . In addition,  $T_{2,k}$  is shown to be more sensitive than  $T_{1,k}$  to the potential barrier, enabling adjustment of the ratio of the two tunneling strengths by barrier tuning. In this case, we can set  $|2\epsilon_F \text{Re}[C_{k,\uparrow}^* C_{k,\downarrow}]|/|C_k \epsilon_F + V_0 \mathcal{B}_{kz}| = \gamma$ . Figures 2(c) and 2(d) present how this ratio is affected by the height and width of the potential barrier, respectively.

*c. Spin current and noise.* To calculate the tunneling currents, we apply the mean-field approximation, which yields a reservoir Hamiltonian as  $H_i \simeq \sum_{p,\sigma} \xi_{p,i}^\sigma c_{p,\sigma,i}^\dagger c_{p,\sigma,i} - g n_{\uparrow,i} n_{\downarrow,i}$ , where we introduce  $\xi_{p,i}^\sigma = \mathbf{p}^2/2m - \mu'_{\sigma,i}$  with an effective chemical potential  $\mu'_{\sigma,i} = \mu_{\sigma,i} - g n_{\bar{\sigma},i}$ , while  $n_{\sigma,i} = \sum_{\mathbf{p}} \langle c_{p,\sigma,i}^\dagger c_{p,\sigma,i} \rangle$  denotes the particle number density for each component.

The spin-current operator is defined as  $\hat{I}_s = i[N_{\uparrow,L}, H_L] - i[N_{\downarrow,L}, H_L]$ , where  $N_{\sigma,i} = \sum_{\mathbf{p}} c_{p,\sigma,i}^\dagger c_{p,\sigma,i}$  denotes the particle number of  $\sigma$ -spin component in reservoir  $i$ . Assuming a nonequilibrium steady state where local equilibrium is permitted in each reservoir, and employing the Schwinger-Keldysh approach with the lowest-order perturbation of  $H_i$ , the expectation value of spin current is obtained as  $I_s = I_{1s} + I_{2s}$ . The one-body tunneling contribution reads

$$I_{1s} = 4T_1^2 \sum_{p,q,\sigma} \int \frac{d\omega}{2\pi} \beta_\sigma [\text{Im} G_{q,\sigma,L}^{\text{ret}}(\omega - \Delta\mu'_\sigma) \times \text{Im} G_{p,\sigma,R}^{\text{ret}}(\omega)] [f(\omega - \Delta\mu'_\sigma) - f(\omega)], \quad (4)$$

with the factor  $\beta_\uparrow = 1$ ,  $\beta_\downarrow = -1$  and  $\Delta\mu'_\sigma = \mu'_{\sigma,L} - \mu'_{\sigma,R}$ .  $G_{p,\sigma,i}^{\text{ret}}(\omega)$  is the retarded single-particle Green's function in frequency representation and  $f(\omega) = 1/(e^{\omega/T} + 1)$  is the Fermi distribution function. Introducing a fictitious magnetic field  $h_i = \mu_{\uparrow,i} - \mu_{\downarrow,i}$  in each reservoir, we obtain the spin-flip tunneling current as

$$I_{2s} = 8T_2^2 \sum_{p,q} \int \frac{d\omega}{2\pi} \text{Im} \chi_{p,L}^{\text{ret}}(\omega) \text{Im} \chi_{q,R}^{\text{ret}}(\omega - 2\Delta h) \times [b(\omega - 2\Delta h) - b(\omega)], \quad (5)$$

where the polarization bias reads  $\Delta h = h_L - h_R$ ,  $\chi_{p,i}^{\text{ret}}(\omega)$  is the dynamical spin-flip susceptibility, and  $b(\omega) = 1/(e^{\omega/T} - 1)$  is the Bose distribution function. In linear response theory, the spin-flip susceptibility is given as a retarded correlation function:  $\chi_{p,i}^{\text{ret}}(t, t') = -i\theta(t - t') \langle [S_{p,i}^+(t), S_{p,i}^-(t')] \rangle$ , where the quantum average  $\langle \dots \rangle$  represents the expectation value with respect to the unperturbed state of the system and  $[S_{p,i}^+(t), S_{p,i}^-(t')] = S_{p,i}^+(t) S_{p,i}^-(t') - S_{p,i}^-(t') S_{p,i}^+(t)$ . By applying the random phase approximation [54,55], the Fourier transform of the spin-flip susceptibility is expressed as  $\chi_{p,i}^{\text{ret}}(\omega) = \Pi_{p,i}(\omega)/(1 + g\Pi_{p,i}(\omega))$ , where  $\Pi_{p,i}(\omega)$  is the Lindhard function [56].

We are now ready to analyze the spin-current shot noise  $\mathcal{S}$  defined as  $\mathcal{S}(t_1, t_2) = \frac{1}{2} \langle \{\hat{I}(t_1) \hat{I}(t_2)\} \rangle$  [41,57,58], where  $\{\hat{I}(t_1) \hat{I}(t_2)\} = \hat{I}(t_1) \hat{I}(t_2) + \hat{I}(t_2) \hat{I}(t_1)$ . We apply the direct-current limit for the shot noise  $\mathcal{S} := \mathcal{S}(\omega \rightarrow 0)$ , where  $\mathcal{S}(\omega)$  is the Fourier transform of  $\mathcal{S}(t_1, t_2)$ :

$$\mathcal{S}(\omega) = \frac{1}{\tau} \int_0^\tau dt_1 \int_0^\tau dt_2 e^{i\omega(t_1-t_2)} \mathcal{S}(t_1, t_2). \quad (6)$$

We introduce the typical time interval for the noise measurement,  $\tau$ , which ought to be sufficiently larger than the transport time scale [59] and can thus be taken as  $\tau \rightarrow \infty$ . Keeping the result up to leading order, we obtain the spin shot noise as a sum of one-body (quasiparticle) and spin-flip (magnon) contributions  $\mathcal{S} = \mathcal{S}_{1s} + \mathcal{S}_{2s}$ , where each term reads

$$\mathcal{S}_{1s} = 4T_1^2 \sum_{p,q,\sigma} \int_{-\infty}^{\infty} \frac{d\omega}{2\pi} \text{Im} G_{p,\sigma,L}^{\text{ret}}(\omega - \Delta\mu'_\sigma) \text{Im} G_{q,\sigma,R}^{\text{ret}}(\omega) \times [f(\omega - \Delta\mu'_\sigma)(1 - f(\omega)) + (1 - f(\omega - \Delta\mu'_\sigma))f(\omega)], \quad (7)$$

$$\mathcal{S}_{2s} = 16T_2^2 \sum_{p,q} \int_{-\infty}^{\infty} \frac{d\omega}{2\pi} \text{Im} \chi_{p,L}^{\text{ret}}(\omega) \text{Im} \chi_{q,R}^{\text{ret}}(\omega - 2\Delta h) \times [b(\omega)(1 + b(\omega - 2\Delta h)) + (1 + b(\omega))b(\omega - 2\Delta h)]. \quad (8)$$

We note that the current shot noise is proportional to the effective spin charge of the current carrier, and one can

easily prove that at large polarization bias  $\mathcal{S}_{1s}/I_{1s} = 1$  and  $\mathcal{S}_{2s}/I_{2s} = 2$ . This indicates that the Fano factor  $F = (\mathcal{S}_{1s} + \mathcal{S}_{2s})/(I_{1s} + I_{2s})$  changes from 1 to 2 as the tunneling channel changes from quasiparticle-dominated to magnon-dominated transport as shown in Fig. 1(c).

*d. Fano factor for spin transport.* To investigate the spin tunneling current and the Fano factor, we introduce the dimensionless interaction strength  $g^* = g\mathcal{N}/\epsilon_F = 8k_F a/3\pi$  with the scattering length  $a$ , Fermi momentum  $k_F$ , Fermi energy  $\epsilon_F$ , and  $\mathcal{N} = k_F^3/3\pi^2$ . Here,  $k_F$  in both reservoirs are set to be equal for inducing pure spin current. By fixing the left reservoir to be fully polarized and varying the polarization of the right side, we numerically analyze the  $F$ - $\Delta h$  characteristics as shown in Fig. 3, where the largest bias ( $\Delta h/\epsilon_F = 2$ ) corresponds to the case of two reservoirs with full but opposite polarization. This  $F$ - $\Delta h$  feature indicates that the large-bias limit is valid when  $\Delta h$  exceeds approximately  $1.5\epsilon_F$ . In addition, a divergence is found at  $\Delta h \rightarrow 0$  due to zero current but finite noise. Noticing  $\Delta\mu'_\uparrow = \Delta h$  and  $\Delta\mu'_\downarrow = -\Delta h$  in Eqs. (4) and (7), as well as the identities  $f(\omega)[1 - f(\omega)] = -T\partial f(\omega)/\partial\omega$ ,  $b(\omega)[1 + b(\omega)] = -T\partial b(\omega)/\partial\omega$ , one can get the Onsager relation near  $\Delta h = 0$ , which yields  $F^{-1} = \Delta h/2T$  and is shown in the inset of Fig. 3.

Figure 4 demonstrates how  $F$  varies with the interaction, where the polarization bias is set as  $\Delta h/\epsilon_F = 2$  to ensure the large-bias limit. We should note that the repulsive Fermi gas considered here is intrinsically unstable against ground-state pair formation [60], leading to particle loss via three-body recombination. To avoid this, the results in Fig. 4 are calculated up to  $g^* = 1$ , which is close to the largest interaction strength reported by experiments [40] for maintaining stability. At weak coupling ( $g^* < 0.2$ ),  $F$  remains close to 1, indicating a dominance of quasiparticle

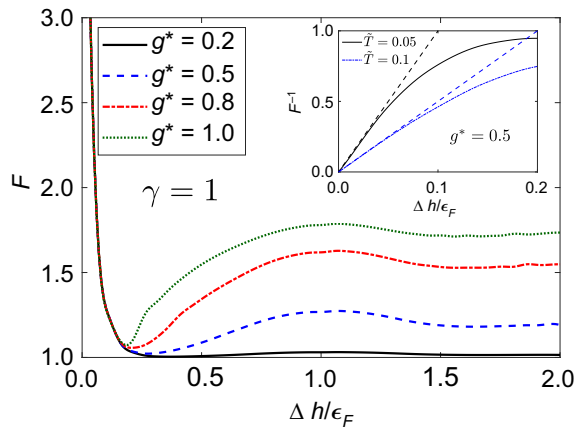


FIG. 3. Bias dependence of the Fano factor for spin tunneling with different interaction strengths. The dimensionless interaction strength is defined as  $g^* = 8k_F a/3\pi$ . The value of  $\gamma$  is set to be 1 and temperature is taken as  $\bar{T} = T/T_F = 0.05$ . The inset shows the Onsager relation  $F^{-1}(\Delta h \rightarrow 0) = \Delta h/2T$ .

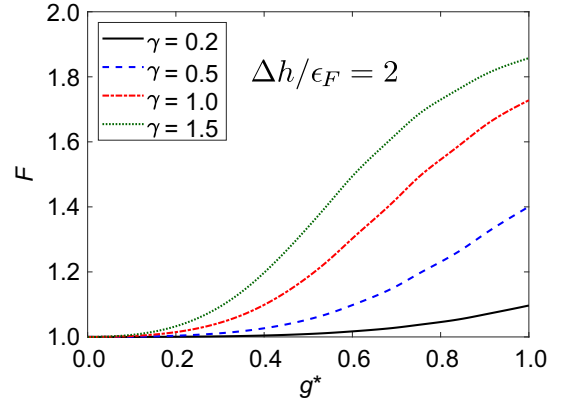


FIG. 4. Interaction dependence of the Fano factor for spin tunneling with different values of  $\gamma$ . The Fermi energies of both sides are set to be equal. The polarization bias is taken as  $\Delta h/\epsilon_F = 2$  to maintain the large-bias condition and the temperature is set to be  $\bar{T} = 0.05$ .

spin tunneling. Beyond that,  $F$  increases as the interaction becomes stronger, suggesting an enhanced spin-flip tunneling. For  $\gamma = 1.5$ , the Fano factor reaches a value  $F \simeq 1.85$ , signifying magnon-dominated transport for the tunneling processes. While the pair-dominant regime is realized in attractively interacting Fermi gases even in the normal phase due to the preformed pair formation [48], the dominance of spin-flip tunneling in the present system originates from the stimulation of magnon modes with the strong repulsion [61].

While the spin current has been experimentally measured in cold atomic systems using a quantum point contact [30,31], noise detection experiments have not yet been conducted. However, a theoretical proposal for mass current noise measurement exists [62]. In this setup, a single-sided optical cavity overlaps with one reservoir of a two-terminal system, and an incident probe beam monitors the atom number in the reservoir. The current noise can be measured through the phase of the probe. Even in the presence of particle losses, the current noise contains components proportional to the particle loss rate and can thus be experimentally measured [63]. We anticipate that our theoretical study will spark experimental interest, potentially catalyzing the initiation of noise measurement experiments.

*e. Conclusion.* In this work, we theoretically investigate the spin-tunneling current and the associated shot noise induced by a magnetization bias between two repulsively interacting itinerant Fermi gases. We demonstrate that the noise-to-current ratio, known as the Fano factor, can serve as a probe of the current carrier in the spin-tunneling process. The Fano factor increases with a stronger repulsive interaction or appropriately tuned potential barrier, indicating a crossover from quasiparticle tunneling to magnon tunneling in itinerant fermions near



the ferromagnetic transition. Detecting magnonic transport through the Fano factor and controlling it via engineered potential barriers could significantly advance spin transport development. Our results illustrate magnetic properties in itinerant fermions relevant to repulsive Fermi gases and metals, emphasizing the importance of noise measurement for understanding multiparticle tunneling at strongly correlated interfaces.

*Acknowledgments.* The authors thank D. Oue, M. Matsuo, T. Kato, and the members in RIKEN iTHEMS NEW working group for useful discussions. T.Z. is supported by the RIKEN Junior Research Associate Program. H.T. is supported by JSPS Grants-in-Aid for Scientific Research under Grants No. 18H05406, No. 22H01158, and No. 22K13981. H.L. is supported by JSPS Grants-in-Aid for Scientific Research under Grant No. 20H05648 and the RIKEN Pioneering Project: Evolution of Matter in the Universe.

- 
- [1] Y. Tanaka and S. Kashiwaya, Theory of Josephson effects in anisotropic superconductors, *Phys. Rev. B* **56**, 892 (1997).
- [2] K. Sukhatme, Y. Mukharsky, T. Chui, and D. Pearson, Observation of the ideal Josephson effect in superfluid  $^4\text{He}$ , *Nature* **411**, 280 (2001).
- [3] M. E. Cage, K. Klitzing, A. M. Chang, F. Duncan, M. Haldane, R. B. Laughlin, A. M. M. Pruisken, and D. J. Thouless, *The Quantum Hall Effect* (Springer New York, NY, 2012).
- [4] C. Chin, R. Grimm, P. Julienne, and E. Tiesinga, Feshbach resonances in ultracold gases, *Rev. Mod. Phys.* **82**, 1225 (2010).
- [5] C. A. Regal, M. Greiner, and D. S. Jin, Observation of resonance condensation of fermionic atom pairs, *Phys. Rev. Lett.* **92**, 040403 (2004).
- [6] M. Bartenstein, A. Altmeyer, S. Riedl, S. Jochim, C. Chin, J. H. Denschlag, and R. Grimm, Crossover from a molecular Bose–Einstein condensate to a degenerate Fermi gas, *Phys. Rev. Lett.* **92**, 120401 (2004).
- [7] D. Husmann, S. Uchino, S. Krinner, M. Lebrat, T. Giamarchi, T. Esslinger, and J.-P. Brantut, Connecting strongly correlated superfluids by a quantum point contact, *Science* **350**, 1498 (2015).
- [8] G. Valtolina, A. Burchianti, A. Amico, E. Neri, K. Khani, J. A. Seman, A. Trombettoni, A. Smerzi, M. Zaccanti, M. Inguscio, and G. Roati, Josephson effect in fermionic superfluids across the BEC-BCS crossover, *Science* **350**, 1505 (2015).
- [9] S. Krinner, T. Esslinger, and J.-P. Brantut, Two-terminal transport measurements with cold atoms, *J. Phys.: Condens. Matter* **29**, 343003 (2017).
- [10] T. Enss and J. H. Thywissen, Universal spin transport and quantum bounds for unitary fermions, *Ann. Rev. Condens. Matter Phys.* **10**, 85 (2019).
- [11] W. J. Kwon, G. D. Pace, R. Panza, M. Inguscio, W. Zwerger, M. Zaccanti, F. Scazza, and G. Roati, Strongly correlated superfluid order parameters from dc Josephson supercurrents, *Science* **369**, 84 (2020).
- [12] J. König and J. Martinek, Interaction-driven spin precession in quantum-dot spin valves, *Phys. Rev. Lett.* **90**, 166602 (2003).
- [13] J. Linder and J. W. Robinson, Superconducting spintronics, *Nat. Phys.* **11**, 307 (2015).
- [14] Y. Ohnuma, M. Matsuo, and S. Maekawa, Theory of the spin Peltier effect, *Phys. Rev. B* **96**, 134412 (2017).
- [15] T. Kato, Y. Ohnuma, M. Matsuo, J. Rech, T. Jonckheere, and T. Martin, Microscopic theory of spin transport at the interface between a superconductor and a ferromagnetic insulator, *Phys. Rev. B* **99**, 144411 (2019).
- [16] P. N. Jepsen, J. Amato-Grill, I. Dimitrova, W. W. Ho, E. Demler, and W. Ketterle, Spin transport in a tunable Heisenberg model realized with ultracold atoms, *Nature* **588**, 403 (2020).
- [17] W. Han, S. Maekawa, and X.-C. Xie, Spin current as a probe of quantum materials, *Nat. Mater.* **19**, 139 (2020).
- [18] M. A. Silaev, Finite-frequency spin susceptibility and spin pumping in superconductors with spin-orbit relaxation, *Phys. Rev. B* **102**, 144521 (2020).
- [19] K. Uchida, S. Takahashi, K. Harii, J. Ieda, W. Koshibae, K. Ando, S. Maekawa, and E. Saitoh, Observation of the spin Seebeck effect, *Nature* **455**, 778 (2008).
- [20] K.-i. Uchida, J. Xiao, H. Adachi, J.-i. Ohe, S. Takahashi, J. Ieda, T. Ota, Y. Kajiwara, H. Umezawa, H. Kawai, *et al.*, Spin Seebeck insulator, *Nat. Mater.* **9**, 894 (2010).
- [21] J. Xiao, G. E. W. Bauer, K.-c. Uchida, E. Saitoh, and S. Maekawa, Theory of magnon-driven spin Seebeck effect, *Phys. Rev. B* **81**, 214418 (2010).
- [22] H. Adachi, J.-i. Ohe, S. Takahashi, and S. Maekawa, Linear-response theory of spin Seebeck effect in ferromagnetic insulators, *Phys. Rev. B* **83**, 094410 (2011).
- [23] H. Adachi, K.-i. Uchida, E. Saitoh, and S. Maekawa, Theory of the spin Seebeck effect, *Rep. Prog. Phys.* **76**, 036501 (2013).
- [24] Y. Tserkovnyak, A. Brataas, and G. E. W. Bauer, Enhanced Gilbert damping in thin ferromagnetic films, *Phys. Rev. Lett.* **88**, 117601 (2002).
- [25] Y. Kajiwara, K. Harii, S. Takahashi, J.-i. Ohe, K. Uchida, M. Mizuguchi, H. Umezawa, H. Kawai, K. Ando, K. Takanashi, *et al.*, Transmission of electrical signals by spin-wave interconversion in a magnetic insulator, *Nature* **464**, 262 (2010).
- [26] Y. Ohnuma, H. Adachi, E. Saitoh, and S. Maekawa, Enhanced dc spin pumping into a fluctuating ferromagnet near  $T_C$ , *Phys. Rev. B* **89**, 174417 (2014).
- [27] G. M. Bruun, Spin diffusion in Fermi gases, *New J. Phys.* **13**, 035005 (2011).
- [28] T. Enss, Transverse spin diffusion in strongly interacting Fermi gases, *Phys. Rev. A* **88**, 033630 (2013).
- [29] A. B. Bardou, S. Beattie, C. Luciuk, W. Cairncross, D. Fine, N. S. Cheng, G. J. A. Edge, E. Taylor, S. Zhang, S. Trotzky, and J. H. Thywissen, Transverse demagnetization dynamics of a unitary Fermi gas, *Science* **344**, 722 (2014).
- [30] A. Sommer, M. Ku, G. Roati, and M. W. Zwierlein, Universal spin transport in a strongly interacting Fermi gas, *Nature* **472**, 201 (2011).

- [31] S. Krinner, M. Lebrat, D. Husmann, C. Grenier, J.-P. Brantut, and T. Esslinger, Mapping out spin and particle conductances in a quantum point contact, *Proc. Natl. Acad. Sci. USA* **113**, 8144 (2016).
- [32] S. Uchino and M. Ueda, Anomalous transport in the superfluid fluctuation regime, *Phys. Rev. Lett.* **118**, 105303 (2017).
- [33] Y. Sekino, H. Tajima, and S. Uchino, Mesoscopic spin transport between strongly interacting Fermi gases, *Phys. Rev. Res.* **2**, 023152 (2020).
- [34] Z. Qiu, J. Li, D. Hou, E. Arenholz, A. T. N'Diaye, A. Tan, K.-i. Uchida, K. Sato, S. Okamoto, Y. Tserkovnyak, *et al.*, Spin-current probe for phase transition in an insulator, *Nat. Commun.* **7**, 12670 (2016).
- [35] M. Sandri, A. Minguzzi, and F. Toigo, Dynamical spin-flip susceptibility for a strongly interacting ultracold Fermi gas, *Europhys. Lett.* **96**, 66004 (2011).
- [36] T. Zhang, D. Oue, H. Tajima, M. Matsuo, and H. Liang, Spin transport between polarized Fermi gases near the ferromagnetic phase transition, *Phys. Rev. B* **108**, 155303 (2023).
- [37] V. Drewello, J. Schmalhorst, A. Thomas, and G. Reiss, Evidence for strong magnon contribution to the TMR temperature dependence in MgO based tunnel junctions, *Phys. Rev. B* **77**, 014440 (2008).
- [38] S. Iwakiri, S. Sugimoto, Y. Niimi, Y. Kozuka, Y. K. Takahashi, S. Kasai, and K. Kobayashi, Negative correlation between the linear and the nonlinear conductance in magnetic tunnel junctions, *Phys. Rev. B* **103**, 245427 (2021).
- [39] M. Shinozaki, J. Igarashi, S. Iwakiri, T. Kitada, K. Hayakawa, B. Jinnai, T. Otsuka, S. Fukami, K. Kobayashi, and H. Ohno, Nonlinear conductance in nanoscale CoFeB/MgO magnetic tunnel junctions with perpendicular easy axis, *Phys. Rev. B* **107**, 094436 (2023).
- [40] Y. Ji, G. L. Schumacher, G. G. T. Assumpção, J. Chen, J. T. Mäkinen, F. J. Vivanco, and N. Navon, Stability of the repulsive Fermi gas with contact interactions, *Phys. Rev. Lett.* **129**, 203402 (2022).
- [41] Y. Blanter and M. Büttiker, Shot noise in mesoscopic conductors, *Phys. Rep.* **336**, 1 (2000).
- [42] X. Jehl, M. Sanquer, R. Calemczuk, and D. Mailly, Detection of doubled shot noise in short normal-metal/superconductor junctions, *Nature* **405**, 50 (2000).
- [43] A. A. Kozhevnikov, R. J. Schoelkopf, and D. E. Prober, Observation of photon-assisted noise in a diffusive normal metal–superconductor junction, *Phys. Rev. Lett.* **84**, 3398 (2000).
- [44] R. De-Picciotto, M. Reznikov, M. Heiblum, V. Umansky, G. Bunin, and D. Mahalu, Direct observation of a fractional charge, *Physica B* **249**, 395 (1998).
- [45] L. Saminadayar, D. C. Glatli, Y. Jin, and B. Etienne, Observation of the  $e/3$  fractionally charged Laughlin quasiparticle, *Phys. Rev. Lett.* **79**, 2526 (1997).
- [46] M. Matsuo, Y. Ohnuma, T. Kato, and S. Maekawa, Spin current noise of the spin Seebeck effect and spin pumping, *Phys. Rev. Lett.* **120**, 037201 (2018).
- [47] B. F. Miao, S. Y. Huang, D. Qu, and C. L. Chien, Inverse spin Hall effect in a ferromagnetic metal, *Phys. Rev. Lett.* **111**, 066602 (2013).
- [48] H. Tajima, D. Oue, M. Matsuo, and T. Kato, Nonequilibrium noise as a probe of pair-tunneling transport in the BCS–BEC crossover, *PNAS Nexus* **2**, pgad045 (2023).
- [49] L. Siegl, M. Lammel, A. Kamra, H. Huebl, W. Belzig, and S. T. B. Goennenwein, Electrical detectability of magnon-mediated spin current shot noise, *Phys. Rev. B* **108**, 144420 (2023).
- [50] J. Schwinger, Brownian motion of a quantum oscillator, *J. Math. Phys.* **2**, 407 (1961).
- [51] L. V. Keldysh, Diagram technique for nonequilibrium processes, *Zh. Eksp. Teor. Fiz.* **47**, 1515 (1964).
- [52] H. Tajima, D. Oue, and M. Matsuo, Multiparticle tunneling transport at strongly correlated interfaces, *Phys. Rev. A* **106**, 033310 (2022).
- [53] See Supplemental Material at <http://link.aps.org/supplemental/10.1103/PhysRevApplied.21.L031001> which contains the derivation of tunneling coupling strengths.
- [54] T. Izuyama, D.-J. Kim, and R. Kubo, Band theoretical interpretation of neutron diffraction phenomena in ferromagnetic metals, *J. Phys. Soc. Japan* **18**, 1025 (1963).
- [55] F. Englert and M. Antonoff, Band theory of ferromagnetism: Qualitative aspects, *Physica* **30**, 429 (1964).
- [56] J. Lindhard, On the properties of a gas of charged particles, *Kgl. Danske Videnskab. Selskab Mat.-Fys. Medd.* **28**, 8 (1954).
- [57] M. Büttiker, Scattering theory of current and intensity noise correlations in conductors and wave guides, *Phys. Rev. B* **46**, 12485 (1992).
- [58] O. S. Lumbroso, L. Simine, A. Nitzan, D. Segal, and O. Tal, Electronic noise due to temperature differences in atomic-scale junctions, *Nature* **562**, 240 (2018).
- [59] J.-P. Brantut, C. Grenier, J. Meineke, D. Stadler, S. Krinner, C. Kollath, T. Esslinger, and A. Georges, A thermoelectric heat engine with ultracold atoms, *Science* **342**, 713 (2013).
- [60] G. Valtolina, F. Scazza, A. Amico, A. Burchianti, A. Recati, T. Enss, M. Inguscio, M. Zaccanti, and G. Roati, Exploring the ferromagnetic behaviour of a repulsive Fermi gas through spin dynamics, *Nat. Phys.* **13**, 704 (2017).
- [61] G. Vignale and K. S. Singwi, Spin-flip electron-energy-loss spectroscopy in itinerant-electron ferromagnets: Collective modes versus stoner excitations, *Phys. Rev. B* **32**, 2824 (1985).
- [62] S. Uchino, M. Ueda, and J.-P. Brantut, Universal noise in continuous transport measurements of interacting fermions, *Phys. Rev. A* **98**, 063619 (2018).
- [63] S. Uchino, Particle current, noise, and counting statistics of quantum transport in the presence of a single-particle loss, [arXiv:2307.03020 \[cond-mat.quant-gas\]](https://arxiv.org/abs/2307.03020) (2023).