Collisional Dynamics of Polaronic Clouds Immersed in a Fermi Sea

Hiroyuki Tajima,1,2 Junichi Takahashi,3 Eiji Nakano,1,4 and Kei Iida1

1Department of Mathematics and Physics, Kochi University, Kochi 780-8520, Japan
2Quantum Hadron Physics Laboratory, RIKEN Nishina Center, Wako, Saitama 351-0198, Japan
3Department of Electronic and Physical Systems, Waseda University, Tokyo 169-8555, Japan
4Institut für Theoretische Physik, Goethe Universität Frankfurt, D-60438 Frankfurt am Main, Germany

(Dated: January 1, 2020)

We propose a new protocol to examine polaron properties in a cold atom experiment. Initially, impurity clouds are prepared around the edge of a majority gas cloud. After time evolution, the collision of two impurity gas clouds exhibits several polaron properties. To confirm our scenario, we perform a nonlinear hydrodynamic simulation for collisional dynamics of two Fermi polaronic clouds. We found that the dynamics is governed by the impurity Fermi pressure, polaron energy, and multi-body polaron correlations. The different density dependence among these effects would help to confirm each effect by experiments. Our idea is applicable to other systems such as Bose polarons as well as nuclear systems.

PACS numbers:

Introduction—Ultracold atomic gases provide us with a perfect testing ground for fundamental quantum physics [1, 2]. Recently, this system enables quantum simulation of extreme states of matter such as neutron matter [3–14] and high-Tc superconductors [15–20]. A striking feature of this system is the controllability of physical parameters such as interaction and density. This advantage helps to extensively investigate various properties of the most fundamental quantum impurity system, namely, a polaron [21, 22].

The so-called Fermi (Bose) polaron can be realized by immersing impurity atoms into fermionic (bosonic) gas clouds, which work as a medium for impurity atoms. Since these systems are described by a simple Hamiltonian, various physical properties of the polarons can be investigated experimentally and theoretically as an important benchmark of quantum many-body physics. In particular, the excitation properties of polarons have been precisely determined from the RF spectroscopy [23–28] as well as the spin-dipole oscillation [29, 30]. Furthermore, the induced polaron-polaron interaction in a Fermi sea has been observed in recent experiments [31, 32]. This interaction, which reflects medium properties, has attracted much attention from various research fields such as condensed matter [33] and nuclear physics [34, 35]. For example, light cluster and strange hadronic states in nuclear matter such as deuterons, alpha particles, and hyperons can be regarded as quantum impurities in strongly correlated nuclear media [36].

The energy shift and broadening in Fermi polaron spectra have been discussed in connection with the polaron-polaron interaction [37–39]. In the case of Bose polarons, formation of bipolarons originating from these mediated interactions has been predicted [40, 41]. While these induced interactions are relatively long-ranged, such as Ruderman-Kittel-Kasuya-Yoshida (RKKY) interaction [42–44] in heavy Fermi polarons [45, 46] and Yukawa or Efimov attractions [48, 47] in Bose polarons, such a non-locality of the induced interactions is still under investigation. Although non-trivial pairing states due to the induced interactions have extensively been discussed [48, 43, 51], these states have not yet been observed. The non-locality may also play a crucial role in the spatial structure of impurities and media [52, 56]. In examining how induced interactions depend on the inter-impurity distance, an alternative experiment design associated with the dynamics is promising [57–59].

In this work, we propose a novel scheme to investigate the polaron properties in cold atom experiments, as shown in Fig. 1. First, we prepare two-component gas clouds in such a way that two clouds of minority component (spin down) are separately prepared near the edge of a majority gas cloud (↑) in a harmonic trap. After certain time evolution, these impurity clouds fall into the trap center due to the harmonic trap potential as well as the polaron binding energy.

![FIG. 1: Initial setup for later impurity collision in our protocol. Two minority (↓) clouds are separately prepared near the edge of a majority gas cloud (↑) in a harmonic trap. After certain time evolution, these impurity clouds fall into the trap center due to the harmonic trap potential as well as the polaron binding energy.](attachment:image.png)
ence of dissipation. Since the spin-selective preparation in real space is realizable in ultracold atoms, our idea can be demonstrated in future experiments. We note that a similar protocol has theoretically been proposed to realize a spin-polarized droplet in a unitary superfluid Fermi gas.

To confirm this scenario, we demonstrate the collisional dynamics of impurity clouds by solving non-linear hydrodynamic equations and discuss how the polaronic properties affect the dynamics during the time evolution. We note that the hydrodynamic description works well to reproduce the dynamics of strongly interacting Fermi gases in real experiments. Euler’s equation for this system is given by

\[ \frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{v}) = 0, \]

\[ \frac{\partial \mathbf{v}}{\partial t} + \frac{\nabla P}{\rho} + \mathbf{v} \nabla \cdot \mathbf{v} = -\nabla U - \frac{1}{2} \nabla \sigma + \nabla \cdot \left( \tau \left[ \nabla \mathbf{v} + \mathbf{v} \nabla \right] \right) + \sum_{\sigma} \rho_{\sigma} \mathbf{F}_{\sigma}, \]

where \( \rho \) and \( \mathbf{v} \) are the local density and velocity field of majority (\( \sigma = \uparrow \)) and minority (\( \sigma = \downarrow \)) atomic clouds, \( V_{\text{trap},\sigma}(z) = \frac{m_\sigma^*}{2} \left( \mathbf{v}_{\sigma}^2 - \mathbf{v}_\sigma^2 \right)^2 / \omega_{\sigma}^2 \) with \( \mathbf{v}_\sigma^2 = \mathbf{v}_\sigma^2 - \mathbf{v}_\sigma^2 \), \( \omega_{\sigma}^2 = \gamma_{\sigma} \), \( \mathbf{v}_\sigma \) is the local density and velocity of the Fermi gas \( \rho_{\sigma} \), \( m_\sigma^* \) is the effective mass for \( \sigma \) component. The majority component can approximately be described by an ideal gas; we thus set \( m_\uparrow^* = m_\uparrow \) and \( \gamma_\uparrow \approx 0 \). We employ the energy density \( E \) based on the Landau-Pomeranchuk Hamiltonian as

\[ E = \Xi_p + \Xi_A + \Xi_F + \Xi_G + O(n_\uparrow^4), \]

where \( \Xi_p \) is the pressure term. In the case of Fermi-Fermi mixtures, it is given by

\[ \Xi_p = \frac{3}{5} \eta_\uparrow \varepsilon_{F,\uparrow} + \frac{3}{5} \eta_\downarrow \varepsilon_{F,\downarrow}, \]

where \( \varepsilon_{F,\sigma} = (6\pi^2 n_{\sigma}^2)^{\frac{4}{3}} / (2m_\sigma^{*2}) \). The other terms \( \Xi_A = -\alpha n_{\downarrow}, \Xi_F = \rho \mathbf{F}, \) and \( \Xi_G = \tau n_{\downarrow}^3 \) are associated with the polaron energy, polaron-polaron interaction, and induced three-body force, respectively. From dimensional analysis, one can obtain \( \alpha = \chi \varepsilon_{F,\uparrow}, \chi = \frac{3}{5} \kappa, \) and \( \tau = \frac{3}{5} \chi \varepsilon_{F,\uparrow} / m_\uparrow^*, \)

Before moving to numerical calculations, we clarify how the polaronic properties appear in the collisional dynamics. \( \Xi_p \) induces the repulsive force as

\[ \nabla \left( \frac{\partial \Xi_p}{\partial n_\downarrow} \right) = \frac{(6\pi^2)^{\frac{4}{3}}}{3m_\uparrow^*} \nabla n_\downarrow \frac{n_\downarrow}{n_\uparrow}, \]

which depends only on the impurity density \( n_\downarrow \). On the other hand, an attractive force originating from \( \Xi_A \) as given by

\[ \nabla \left( \frac{\partial \Xi_A}{\partial n_\downarrow} \right) = -\frac{(6\pi^2)^{\frac{4}{3}}}{3m_\uparrow^*} \nabla n_\downarrow \frac{n_\downarrow}{n_\uparrow}, \]

depends only on the majority density \( n_\uparrow \). We assume that the majority cloud is not affected by the impurity dynamics due to the high polarization. Therefore, \( \Xi_A \) works as a potential energy for impurities. Moreover, one can find that the interaction terms \( \Xi_F \) and \( \Xi_G \) depend on both of the majority and impurity densities as

\[ \nabla \left( \frac{\partial \Xi_F}{\partial n_\downarrow} \right) = \frac{(6\pi^2)^{\frac{4}{3}}}{3m_\uparrow n_\uparrow} \left( 3\nabla n_\downarrow - \frac{n_\downarrow}{n_\uparrow} \nabla n_\uparrow \right), \]

\[ \nabla \left( \frac{\partial \Xi_G}{\partial n_\downarrow} \right) = \frac{(6\pi^2)^{\frac{4}{3}}}{3m_\uparrow n_\uparrow} \left[ \frac{n_\downarrow}{n_\uparrow} \nabla n_\downarrow - 2 \left( \frac{n_\downarrow}{n_\uparrow} \right) ^2 \nabla n_\uparrow \right]. \]

From the above, one can find that effects of the induced multi-polaron forces on the dynamics become stronger in a region where the gradient of the majority density profile \( |\nabla n_\uparrow| \) is larger. We emphasize that it is a sharp contrast to the case of \( \Xi_F \) in which the force is not affected by the majority density. Such differences of density dependence among these ingredients enable us to selectively examine each effect during the dynamics in an appropriate setup. This is remarkable since recently a variety of shapes of trap potentials are experimentally realized. If one prepares the majority density profile with a large gradient at thermal equilibrium and locates impurity clouds on such a gradient, only polaronic effects on the driving force would be strongly enhanced.

In this work, we consider Fermi polarons with \( m_\uparrow = m_\downarrow \) that are induced by the \( \uparrow \downarrow \) attraction in the unitary limit. As long as the trap potential is independent of \( \sigma \), i.e., \( V_{\text{trap},\sigma}(z) = V_{\text{trap}}(r_\perp) \equiv V_{\text{trap}}(r_\perp) \equiv \omega_{\perp}^2 \), \( \omega_{\perp} \equiv \omega_{\perp} \equiv \omega_\perp \) quasi-particle properties of this system are relatively well-known theoretically and experimentally. We thus employ \( \chi = 0.6, \kappa = 0.2, \) and \( m_\uparrow^*/m_\downarrow^* = 1.17 \). Particularly, these are close to the FNDMC results \( \chi = 0.59, \kappa = 0.14, \) and \( m_\uparrow^*/m_\downarrow^* = 1.09 \), which essentially involve effects of the polaron formation and the induced interpolaron correlations in a non-perturbative manner. We take \( \lambda = 0 \) since \( \Lambda \) is negligibly small in the mass-balanced Fermi-Fermi mixture; it may play a non-trivial role in Bose polarons as well as in mass-imbalanced mixtures. The majority density is approximated by the Thomas-Fermi density profile of an ideal trapped Fermi gas as \( n_\uparrow = \frac{(2m_\uparrow^*)^{\frac{1}{2}}}{(6N_\uparrow \omega_\perp^2)^{1/3}} |E_{F,0} - V_{\text{trap}}(r_\perp, z)|^{\frac{1}{2}} \), where \( E_{F,0} = (6N_\uparrow \omega_\perp^2)^{1/3} \) is the Fermi energy of majority atoms of total number \( N_\uparrow \). In addition to the above polaron properties in the energy density, the spin relaxation coefficient \( \gamma_\uparrow \) of a Fermi polaron is known to
be proportional to \((T/T_{F,0})^2\) in the low temperature regime \([23, 28, 80]\), where \(T_{F,\sigma}\) is the effective local Fermi temperature of \(\sigma\) component. Note that the bulk viscosity is exactly zero at unitarity limit due to the conformal symmetry \([81]\). The shear viscosity, at least in a population-balanced unitary Fermi gas, is small due to strong correlations \([64, 82, 83]\). Indeed, it is expected to be close to the Kovtun-Son-Starinets (KSS) bound \([84]\). For simplicity, we ignore such transport coefficients in this work.

The purpose of this letter is not to examine the whole precise dynamics during the collision but a transient behavior before the collision in a qualitative way. In this regard, we focus only on the axial motion (along which we take the \(z\)-direction). The hydrodynamic equations relevant for this motion are reduced to the one-dimensional equations,

\[
\frac{\partial v_{z,\sigma}}{\partial t} = -\frac{1}{m_{\sigma}^*} \frac{\partial}{\partial z} \left( \frac{\partial E}{\partial n_{\sigma}} \right) - \gamma_{\sigma} v_{z,\sigma},
\]

\[
-\frac{v_{z,\sigma}}{m_{\sigma}^*} \frac{\partial n_{\sigma}}{\partial z} - \frac{\partial v_{z,\sigma}}{\partial z},
\]

where \(\gamma_{\sigma}\) is the shear viscosity.

Following recent polaron experiments \([28]\), we take \(\omega_{z}/\omega_{\perp} = 20/233\) and \(N_\perp = 1.5 \times 10^5\). We set an initial condition in such a way that the initial impurity density profile \(n_i(z, t = 0)\) has double peaks near the edge of the majority gas cloud as in Fig. 1. The form adopted here is

\[
n_i(z, t = 0) = \frac{Y n_t(0)}{2\sqrt{2\pi\eta^2}} \left[ e^{-\frac{(z_1-0.2)^2}{2\eta^2}} + e^{-\frac{(z_1+0.2)^2}{2\eta^2}} \right].
\]

Here, we set \(z_1 = 0.8R_z\) for instance. Since the impurity concentration \(Y\) is required to be small to keep the stability of the majority cloud during the time evolution, we take \(Y = 0.01\). Finally, the width of impurity clouds is taken as \(\eta = 0.05R_z\). We have confirmed that change in this choice would make no qualitative difference. The nonlinear differential equations \((9)\) and \((10)\) are numerically solved by the fourth-order Runge-Kutta method with the discretization of the space and time as \(\Delta z = 4 \times 10^{-3}R_z\) and \(\Delta t = 1.33 \times 10^{-3}E_{F,0}^{-1}\). These are chosen in such a way as to fulfill \(\Delta z/\Delta t > |v_{z,\perp}|\), which is required to stabilize the numerical simulation as indicated by the Courant-Friedrichs-Lewy condition \([86]\). Furthermore, we take a smearing process along the \(z\) direction as \(f(z) = [f(z_{i-1}) + f(z_{i+1})]/2\) \((f = n_{i,t}, v_{z,i})\) at each step. This procedure is justified when \(\Delta z\) is sufficiently small.

**Numerical results—** Figure 2 (a) exhibits time-dependent axial density profile \(n_i(z)\) of fermionic impurity clouds with \(\gamma_{\perp} = 0\). The collision time \(t_c\) can be estimated as the 1/4 period of dipole oscillations, i.e.,

\[
t_cE_{F,0} = \frac{2\pi}{4\omega_*} \approx 666, \text{ where the renormalized axial trap frequency } \omega_*^2 \text{ involves the effective mass } m_*^\perp \text{ and the attractive polaron energy } \Xi_A \text{ as } \omega_*^2 = \omega_z^2 = \omega_z \sqrt{\frac{m_*^\perp}{m_*^\parallel}} (1 + \chi).
\]

The impurity Fermi pressure (P) and the polaron-polaron interaction (F) induce appreciable broadening of impurity clouds. In particular, the impurity Fermi pressure plays an important role just before the collision because \(\Xi_P\) becomes large when \(n_i\) increases. While a core appears near the trap center \((z = 0)\) at \(t \approx 0.9t_c\), one can find broadened impurity clouds still remain even around \(t = t_c\). It is analogous to the shock wave formation observed in the collision experiment in a unitary Fermi gas \([60]\). Figure 2(b) displays the velocity field profile \(v_{z,\perp}(z)\) in the absence of the spin relaxation. Around \(t = t_c\), \(|v_{z,\perp}(z)|\) is also large in a region near the trap center where the core is seen. In addition, the \(z\)-derivative of \(v_{z,\perp}(z)\) becomes discontinuous around the inner edges of the gas clouds, which is reminiscent of the shock front. Since the shock wave is formed when \(|v_{z,\perp}(z)|\) exceeds the speed of sound given by \(c = \sqrt{\frac{\omega_*^2}{m_*^\perp}}\), the region where \(|v_{z,\perp}(z)|\) is large and \(n_i(z)\) is small is expected to be shock dominated. Indeed, at a typical density \(n_i(z) = 10^{-2}n_t(0)\), we obtain \(c \approx 2 \times 10^{-3}R_zE_{F,0}\). We note that in our calculations \(|v_{z,\perp}(z)|\) is always less than \(\Delta z/\Delta t = 3 \times 10^{-3}R_zE_{F,0}\), as mentioned above \([80]\).

To examine effects of the polaron-polaron interaction \((\Xi_F)\), we demonstrate the collisional dynamics of two impurity clouds in the absence of the impurity Fermi pressure \((\Xi_P)\); the results for the axial density profile \(n_i(z)\)

\[
\text{FIG. 2: The time evolution of fermionic impurity clouds in a Fermi sea before the collision in the presence of the impurity Fermi pressure } \Xi_P \text{ as well as polaronic properties } \Xi_F + \Xi_P. \text{ The panels (a) and (b) show the axial density profile and the velocity field profile } v_{z,\perp}(z) \text{, respectively.}
\]
FIG. 3: Time-dependent axial density profile $n_\perp(z)$ of impurity clouds obtained with different strength of the polaron-polaron interactions in the absence of the impurity Fermi pressure. The cases of (a) $\kappa = 0$, (b) $\kappa = 0.2$, and (c) $\kappa = 1$ are plotted.

with different strength of the polaron-polaron interactions [(a) $\kappa = 0$, (b) 0.2, and (c) 1] are exhibited in Fig. 3. The comparison between (a) and (b) indicates that the polaron-polaron interaction with $\kappa = 0.2$, which is relevant for polarized $^6$Li-$^7$Li mixture, plays a role in broadening impurity gas clouds although it is small compared to the impurity Fermi pressure effect shown in Fig. 2 (a). In addition, the shock wave or ripple behavior (biased peaks) can be found near the inner edge of impurity gas clouds. We note that the shock wave is not formed during the evolution in the absence of $\Xi_F$ and $\Xi_F$ (see Fig. 3 (a)), because $\Xi_A$ does not involve $\nabla n_\perp$, which acts to broaden the impurity clouds. In other words, two impurity clouds in the initial setup have already behaved as shock waves because of $c = 0$ everywhere. In this case, two impurity clouds propagate like solitons and shrink as they fall into the center. To make the effect of $\Xi_F$ more visible, we also perform the simulation with strongly repulsive polaron-polaron interaction ($\kappa = 1$), as shown in Fig. 3 (c). Indeed, one can find the broadening of impurity clouds as well as the appearance of ripples and a core during the evolution. We note that the present case with vanishing impurity Fermi pressure is relevant for bosonic impurities immersed in a Fermi sea. In the latter case, the role of the impurity Fermi pressure may be replaced by the boson-boson repulsion.

Finally, we plot in Fig. 4 the axial impurity density profile $n_\perp(z)$ at intermediate times $t = t_c/4-t_c$. These results clearly reflect specific features of this protocol that we have discussed. While the comparison between the results of $E = \Xi_A$ and $E = \Xi_A + \Xi_F$ at $t = t_c/2-(3/4)t_c$ shows the cloud broadening due to $\Xi_F$, such a difference at $t = t_c$ is negligible because the polaronic properties are important near the edge of the majority cloud rather than the trap center. The biased peaks near the inner edge, which can be seen in the results of $E = \Xi_A + \Xi_F$ and $E = \Xi_A + 5\Xi_F$ at $t = t_c$, clearly indicate the appearance of ripples due to the repulsive forces. From Fig. 4 (d), moreover, one can confirm the shock wave formation at $t = t_c$ in the cases of $E = \Xi_A + \Xi_F + \Xi_F$ and $E = \Xi_A + 5\Xi_F$ where the central core and surrounding parts coexist. These results suggest that since the impurity Fermi pressure can be estimated from the well-known equation of state of an ideal Fermi gas, one could extract information on the polaron-polaron interaction from relevant experiments.

Summary—In this work, we propose a new protocol to examine the polaron properties from collisional dynamics of impurity clouds in cold atom experiments, which begin by preparing the two impurity clouds around the edge of a majority gas cloud. To demonstrate our scenario, we perform the numerical simulation with nonlinear hydrodynamic equations and show how the polaronic effects appear in the non-equilibrium dynamics. In addition, we show that the collision is sensitive to the polaron-polaron
repulsion. In the absence of the impurity Fermi pressure and this repulsion, impurity clouds collapse at the center of the trap. Since these effects exhibit different density and temperature dependence, one can selectively examine each effect by tuning the experimental setup appropriately.

We emphasize that our study could open new directions for further understanding of polarons. Our scenario can immediately be applied to other systems such as Bose polarons. In this work, we confine ourselves to the one-dimensional dynamics before the collision since the cloud motions are governed by the spin-dipole mode. On the other hand, the quadrupole mode can be expected to occur after the collision, especially in the region where the central core is formed. Study of this collective mode would require full treatment of the three-dimensional dynamics, which involves the shear viscosity [67]. In addition, the local density approximation adopted here neglects the long-range nature of the induced polaron-polaron interaction. Effects of the long-range RKKY-type interaction could also manifest themselves in our setup, and we are now in progress along this direction [57].

We would like to thank K. Nishimura, T. Hata, T. Hatsuda, P. Naidon, and H. Togashi for useful discussions. H. T. is supported by a Grant-in-Aid for JSPS fellows (No. 17K05443). Aid for Scientific Research from JSPS (Nos. 17K05445, 18K03501, 18H05406, 18H01211, and 19K14619).

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