A model that can predict the exact quasi-particle properties of heavy Fermi polarons

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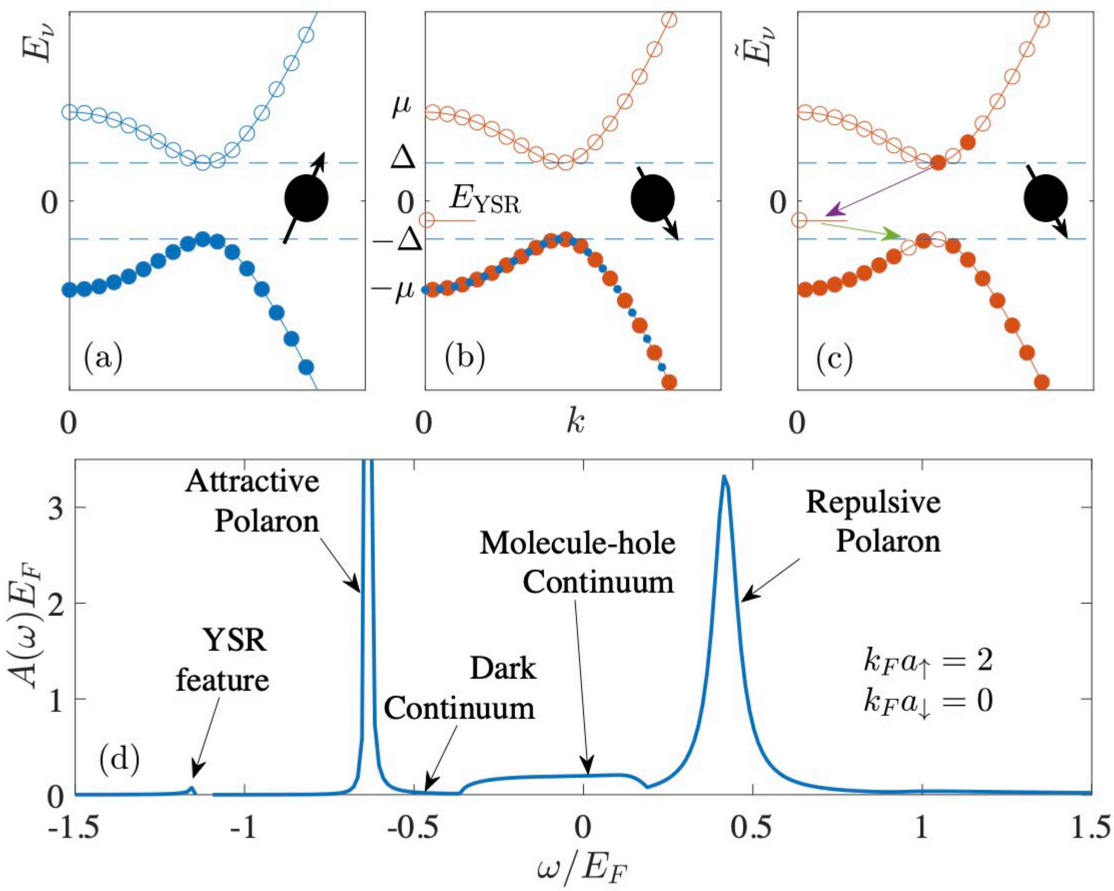


A sketch of the occupation and structure of the single-particle spectrum of a two-component BCS superfluid. (a) shows the spectrum when the impurity is in the non-interacting states (black arrow up). (b) and (c) show the spectrum when the impurity interaction is on (black arrows down) at zero and finite temperature, respectively. The absorption spectrum with parameters $T=0.1E_F$ and $k_Fa=-2$ in (d) shows universal polaron features. In addition, at finite temperature, additional decay channels [green and purple arrows in (c)) exist via the Yu-Shiba-Rusinov within the gap, giving rise to additional resonance peaks (YSR feature). Credit: Wang, Liu & Hu.

Physicists studying quantum many-body physics very rarely reach exact solutions or conclusions, particularly in more than one dimension. This is also true for the Fermi polaron problem, describing instances in which the many-body quantum background is a non-interacting Fermi gas.

The Fermi polaron problem has been studied extensively over the past decade or so. However, predicting the quasi-particle properties of Fermi polarons with high levels of confidence has so far proved to be very challenging.

Researchers at Swinburne University of Technology recently introduced a model that could be used to predict the exact quasi-particle properties of a heavy polaron in Bardeen-Cooper-Schrieffer (BCS) Fermi superfluids. Their paper, published in *Physical Review Letters*, introduces a theoretical, exact solution for a many-body system, which could eventually be tested and realized in experimental settings.

The recent study builds on one of the team's previous papers published in *Physical Review A*. This past work specifically focused on crossover polarons with a mobile impurity.

"Our previous work and many other theoretical studies of polarons using various approximation methods give some universal features (such as the existence of attractive/repulsive polarons and a dark continuum)," Jia Wang, one of the researchers who carried out the study, told Phys.org.

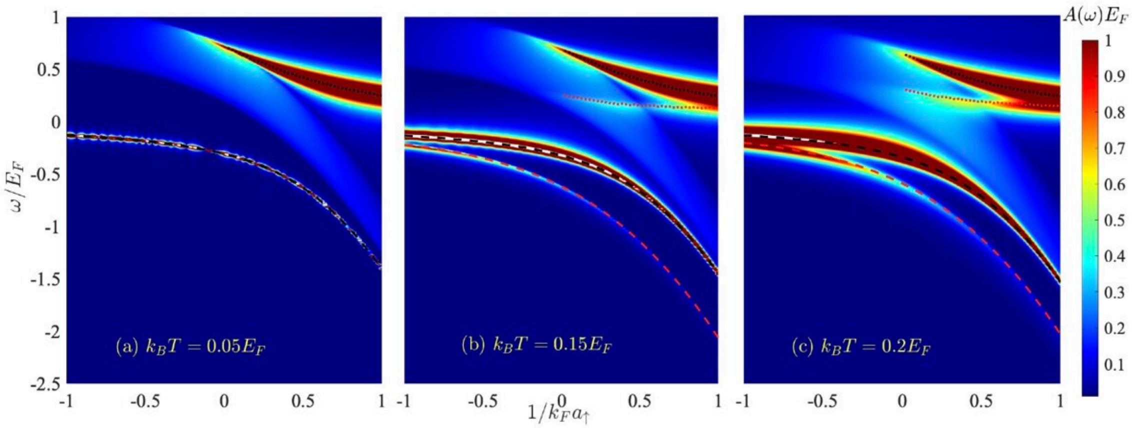
"We believe that the suppression of multiple quasiparticle excitations in the background medium is the mechanism underlying these features."

Wang and his colleagues believe that the mechanism underpinning the universal features of Fermi polarons could either be the recoil energy of a mobile impurity or the existence of an energy gap in a superfluid. For their hypothesis to be verifiable in an experimental setting, however, they first had to represent it theoretically.

"We came across a fascinating paper, which studied immobile impurities in non-interacting Fermi gases," Wang said. "This model is exactly solvable using a 'functional determinant approach (FDA)' method. However, polarons do not exist in such systems due to the famous 'Anderson's orthogonality catastrophe.' Essentially, this is because immobile impurity does not have recoil energy, and the existence of multiple particle-hole excitations destroys the polaron resonance."

In the many-body system described by Wang and his colleagues, the presence of a superfluid gap can suppress the polaron's multiple particle-hole excitations. Therefore, they set out to extend the FDA method, which is typically inapplicable to Fermi polarons, to their BCS superfluid system.

"We also wanted to experimentally investigate Fermi superfluid excitations, which have been a long-standing research topic," Wang explained. "Several experiments have recently realized introducing another species of atoms, which can play the role of impurities, into a BCS superfluid. Our predictions show that in these accessible systems, one can use the polaron spectrum of impurities to measure features of the background superfluid excitation spectrum (such as the superfluid gap and the sub-gap Yu-Shiba-Rusinov state)."



The polaron spectrum as a function of interaction strength (1/a) and frequency. The additional features that show up at finite temperatures are due to the existence of the in-gap Yu-Shiba-Rusinov states. The positions of these new features (red dashed and dotted curves) are quantitatively determined by the polaron energies, superfluid gap, and Yu-Shiba-Rusinov state energies. Credit: Wang, Liu & Hu.

While the calculations carried out by Wang and his colleagues technically assume immobile impurity in a system, they also provide a good approximation of heavy impurities. Alternatively, in experimental settings, physicists should be able to localize impurities using a deep optical lattice.

"Ours was a theoretical study," Wang explained. "Our model considers a system of immobile impurity in a two-component Fermi superfluid. The impurity has two internal states (hyperfine spin states), and we assume that one interacts strongly with the superfluid and the other is non-interacting."

Using their FDA-based theoretical model, the researchers were able to unveil all the universal polaron features, with a simple in-principal exact calculation. This is a remarkable achievement, as previous studies had been unable to rigorously prove all exact and universal quasi-particle properties of Fermi polaron systems.

"Preparing impurity initially at the non-interacting state, we calculated the probability of the impurity absorbing a photon and switching to the strongly interacting state as a function of the photon frequency, which we denote as A(ω)," Wang said. "Suppose this absorption probability shows a sharp peak around some frequency ω, this indicates the existence of a quasiparticle with energy $\hbar$ ω, which we call heavy crossover polaron."

In the future, the theoretical work conducted by this team of researchers could pave the way for laboratory experiments with cold atoms testing their hypothesis. In addition, physicists could also draw inspiration from their paper to conduct slightly different tests known as "Ramsey-interference-type experiments," which involve some of the processes and technical details outlined in their paper.

As the theory presented by Wang and his colleagues is fairly general, it could be applied to several different experimentally realizable systems. For instance, the team suggests an experimental realization of their proposed system using heavy 133Cs impurities in a BCS Fermi superfluid of 6Li atoms, which had already been realized in some previous works.

"The contributions of our work are two-fold," Wang said. "Firstly, we investigated a model that can be solved exactly and gives all universal features of Fermi polarons. These features have only been calculated approximately in various studies before, but our analysis indicates these universal features originate from suppressing multiple particle-hole excitations of the fermionic medium. Secondly, we discover an interesting finite temperature phenomenon for a magnetic impurity (that interacts with the two components of the superfluid with different strengths) in a two-component Fermi superfluid."

When they conducted their calculations, the researchers found that the polaron spectrum exhibited additional enhancement peaks at finite temperature, which corresponded to the subgap Yu-Shiba-Rusinov bound state. Their interesting theoretical predictions could soon be tested in different physics labs worldwide.

"To the best of our knowledge, this is the first study applying polaron -related theory to investigate subgap Yu-Shiba-Rusinov bound states in ultracold gases," Wang added. "In our next studies, we plan to investigate heavy polarons in other superfluid systems, such as topological superfluid. We hope that our method will help us to understand the background medium's topological phase transition via an in-principal exact calculation."

More information: Jia Wang et al, Exact Quasiparticle Properties of a Heavy Polaron in BCS Fermi Superfluids, *Physical Review Letters* (2022). DOI: 10.1103/PhysRevLett.128.175301

Jia Wang et al, Heavy polarons in ultracold atomic Fermi superfluids at the BEC-BCS crossover: Formalism and applications, *Physical Review A* (2022). DOI: 10.1103/PhysRevA.105.043320