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Multigap superconductivity in iron-free pnictide $BaPd_2As_2$ revealed by local magnetization and SNS-Andreev spectroscopy

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We present experimental study of the iron-free palladium based analogue of the 122 iron arsenide. Single crystals of $BaPd_2As_2$ with sharp superconducting transition were studied by two distinct techniques: local magnetization and Break–Junction. Local magnetization was used to obtain temperature dependence of the first critical field (H_{c1}) from T_c down to 10 mK. Extracted data was fitted with various models to obtain order parameter value and draw a conclusion about its potential symmetry. The $H_{c1}(T)$ data fitting with theoretical models suggested either a single s-wave gap with high anisotropy factor or two s-wave gaps. Multiple Andreev Reflections spectroscopy was used to determine the quantity of condensates and their order parameter amplitudes. The experimental results of Multiple Andreev Reflections showed the presence of two gap-like features. Studying Andreev spectra temperature evolution from 1.6 K up to T_c we've extracted the gap temperature dependencies. Further fitting proved the presence of two superconducting condensates. The obtained evidence for two gap superconductivity in iron-free analogue of 122 iron arsenide family is reported for the first time. Despite the two gap superconducting state, the characteristic ratio of the large gap value is almost equal to that typical for Bardeen–Cooper–Schrieffer theory; this result shows that $BaPd_2As_2$ is a conventional superconductor unlike $BaFe_2As_2$.

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Introduction. Iron-based superconductors (IBSCs), particularly the 122-family (AFe_2As_2, A – alkaine earth or rare-earth), remain intensely studied [1] due to their high T_c, H_{c2} and complex physics [2–4]. A key question is their pairing mechanism, as electron-phonon coupling seems insufficient, suggesting a role for spin fluctuations.

To isolate the mechanism, scientists study iron-free analogues like $BaPd_2As_2$, where replacing magnetic iron with palladium rules out spin-fluctuation pairing. These compounds are typically considered as conventional, single-gap superconductors. However, their complex Fermi surface suggests a potential for multigap superconductivity, which, if driven by electron-phonon coupling, would be a significant discovery – currently, MgB_2 is the only confirmed example.

This study addresses the unresolved nature of the order parameter in $BaPd_2As_2$. Using two complementary techniques – low-temperature lower critical field (H_{c1}) measurements and Multiple Andreev Reflections (MAR) spectroscopy – we provide evidence that $BaPd_2As_2$ is a two-gap superconductor.

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Experimental results.

Lower critical field (H_{c1}). The temperature dependence of the lower critical field, H_{c1}, was measured down to 10 mK, and the experimental data was approximated by several theoretical models (see Fig. 1a). The single gap models with either d-wave or isotropic s-wave symmetry were unable to properly describe our data. The results were best explained by a two-gap s-wave model, yielding a large gap $\Delta_L = 0.58$ meV and a small gap $\Delta_S = 0.19$ meV. And while anisotropic s-wave model also properly fitted the data, such high anisotropy is improbable.

MAR spectroscopy. Spectroscopic measurements on multiple contacts consistently revealed two distinct features in the conductance spectra. These reproducible features correspond to two superconducting gaps with values of $\Delta_L = 0.51$ meV and $\Delta_S = 0.14$ meV at 1.6 K. Temperature dependencies of both gaps were obtained from the positions of the dips; the extracted gap values are shown in Fig. 1b by circles The large gap follows BCS (Bardeen–Cooper–Schrieffer)-like temperature dependence, while the small gap shows an unusual decay, vanishing well below T_c. This behavior is successfully modeled by a two-band electron-phonon coupling model

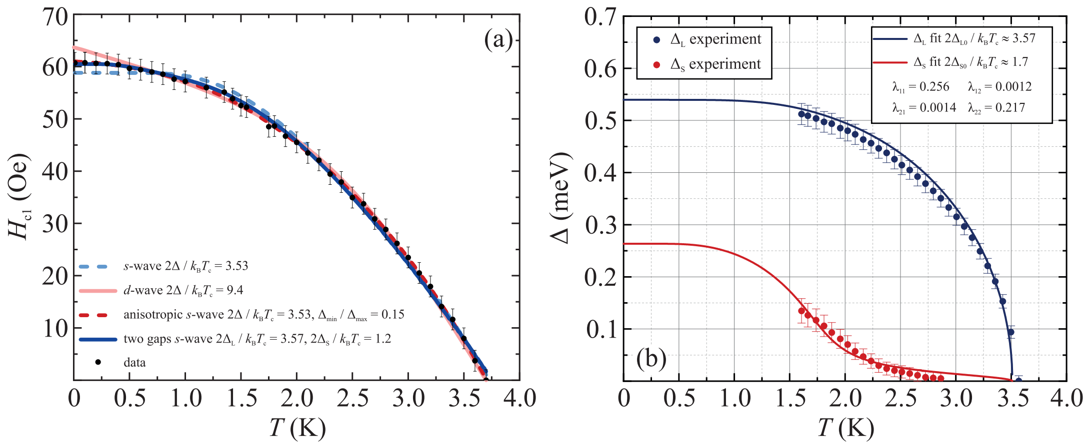

Fig. 1. (Color online) (a) – The lower critical field of the $BaPd_2As_2$ single crystal for the field applied perpendicular to *ab* plane (black circles). The blue dashed line corresponds to the single *s*-wave curve with $2\Delta/k_B T_c = 3.53$. The pink solid line is a d-wave fitting curve with $2\Delta/k_B T_c = 9.4$. The red dashed line represents anisotropic *s*-wave fit with $2\Delta/k_B T_c = 3.53$ and $\Delta_{min}/\Delta_{max} \approx 0.15$. The dark-blue line is the two-gap *s*-wave model fitting curve with $2\Delta_L/k_B T_c = 3.57$ and $2\Delta_S/k_B T_c = 1.2$. (b) – Temperature dependences for the energy gaps (circles) and corresponding fits (solid lines)

with weak interband scattering, further confirming the presence of two distinct superconducting condensates.

Discussion. Most prior studies on similar iron-free superconductors report single-gap behavior. This could be because multiple gaps have the same magnitude, or because the small gap is below the resolution of common techniques like STM or ARPES.

Our low-temperature H_{c1} measurements were crucial, as they allowed us to rule out *d*-wave symmetry. While our H_{c1} data can be fitted with an anisotropic single-gap model, we argue this is less likely than the two-gap explanation, taking into consideration MAR experiments.

Therefore, we conclude that $BaPd_2As_2$ is a multigap superconductor, a property likely shared by other iron-free pnictides that could be confirmed by future studies on materials with higher T_c.

Conclusions. Temperature dependences of both superconducting gaps can be explained by two gap model with electron–phonon pairing mechanism and weak interband scattering. Characteristic ratio for the large gap is very close to that for conventional BCS-superconductors. However, the presence of the second gap makes $BaPd_2As_2$ a pretty unusual superconducting compound raising question about the number of gaps and about the role of the electron-phonon pairing for the whole family of iron-free analogues of 122 IBSC.

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Conflict of interest. The authors of this work declare that they have no conflicts of interest.

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