Crossover from weak to strong pairing in unconventional superconductors

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Superconductors are classified by their pairing mechanism and the coupling strength, measured as the ratio of the energy gap, 2Δ, to the critical temperature, T_c. We present an extensive comparison of the $2\Delta/k_BT_c$ ratios among many single- and multiband superconductors from simple metals to high-T_c cuprates and iron pnictides. Contrary to the recently suggested universality of this ratio in Fe-based superconductors, we find that the coupling in pnictides ranges from weak, near the BCS limit, to strong, as in cuprates, bridging the gap between these two extremes. Moreover, for Fe- and Cu-based materials, our analysis reveals a universal correlation between the gap ratio and T_c, which is not found in conventional superconductors and therefore supports a common unconventional pairing mechanism in both families. An important consequence of this result for ferropnictides is that the separation in energy between the excitonic spin-resonance mode and the particle-hole continuum, which determines the resonance damping, no longer appears independent of T_c.

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I. INTRODUCTION

At present, results of the few existing systematic experimental studies of the pairing strength in iron-arsenide superconductors remain at odds with each other. Some report a more or less universal value of $2\Delta/k_BT_c$, either below[1] or well above[2,3] the weak-coupling limit of 3.53 predicted by the Bardeen-Cooper-Schrieffer (BCS) theory, whereas others present evidence for a strongly doping-dependent coupling.[4] The reported values of $2\Delta/k_BT_c$ scatter from as low as ∼3, below the weak-coupling limit,[4–8] to 10 and above,[9] as summarized in Table I in the Appendix. Hence should one classify Fe-based superconductors as weakly or strongly coupled? Can they be at all considered as a single family?

To address these questions, we have analyzed all the available energy-gap reports in various Fe-based superconductors and their kin. We put these results into a broader context by comparing them to single- and multiband conventional superconductors, high-T_c cuprates, as well as heavy-fermion compounds and a few other superconducting (SC) materials. More than a hundred of such measurements are listed in Tables I– III (see Appendix).

II. GAP RATIOS

Fe-based superconductors are multiband metals, whose conduction bands are formed almost exclusively by the Fe 3*d* electrons.[10,11] Because in the SC state they typically exhibit energy gaps of two sizes,[2,12–17] it is illustrative to compare them to other multigap superconductors, such as MgB_2,[18–26] as well as to the high-T_c materials with a single gap. In Fig. 1, the gap ratios, $2\Delta/k_BT_c$, are plotted vs T_c. For multigap superconductors, we differentiate between the small ($\Delta_<$) and large ($\Delta_>$) energy gaps, which lie below and above the weak-coupling limit, respectively.[27]

First of all, we note that the majority of low-T_c superconductors, including heavy-fermion compounds, such as $CeCoIn_5$, $CeCu_2Si_2$, or UPd_2Al_3, exhibit relatively low gap ratios within ∼30% of the BCS limit, according to the latest reports.[28,29] In conventional superconductors, the gap ratios remain in this narrow range (semielliptical shaded region in Fig. 1) even at higher T_c, as best illustrated by $Ba_{1-x}K_xBiO_3$ (T_c = 30 K),[30–32] Rb_2CsC_{60} (T_c = 33 K),[33] or MgB_2 (T_c = 39 K) with its chemically substituted derivatives.[19,26,34,35] This behavior is in stark contrast to that of unconventional superconductors, such as Fe-based compounds or over- and optimally doped copper oxides. There, the $2\Delta_>/k_BT_c$ ratios exhibit a statistically significant positive correlation with T_c and for the majority of materials cluster along the $4.0 + 0.06\ K^{-1}\ T_c$ line, in both families. This universal behavior could result from a common pairing mechanism in these two families that clearly differentiates them from phonon-mediated superconductors. Underdoped cuprates, however, do not conform to this scaling and exhibit even higher $2\Delta/k_BT_c$ ratios (hatched region in Fig. 1) due to the influence of the pseudogap and proximity to the Mott-insulating state. Therefore we have restricted our collection of cuprates to over- and optimally doped compounds, where superconductivity is not impaired by any competing phases.

A closer look at the Fe-based superconductors reveals a wide spread of gap ratios, from weak BCS-like values in nonmagnetic LiFeAs[37–42] to twice larger values in high-T_c ferropnictides with strong antiferromagnetic (AFM) correlations, such as optimally doped $Ba_{1-x}K_xFe_2As_2$ (BKFA)[15–17,43–48] or various 1111-compounds.[14,49–54] We would like to emphasize that despite all the uncertainties in the published values, these differences are established beyond any doubt, as they have been confirmed by many complementary experiments, at least for several most studied materials (Table I). Therefore in contrast to the high-T_c cuprates, which can be generally classified as strong-coupling superconductors, Fe-based systems show a larger variability and fill in the wide gap between conventional and cupratelike pairing strengths. The overall trend confirms that the superlinear increase of $\Delta_>$ with T_c,

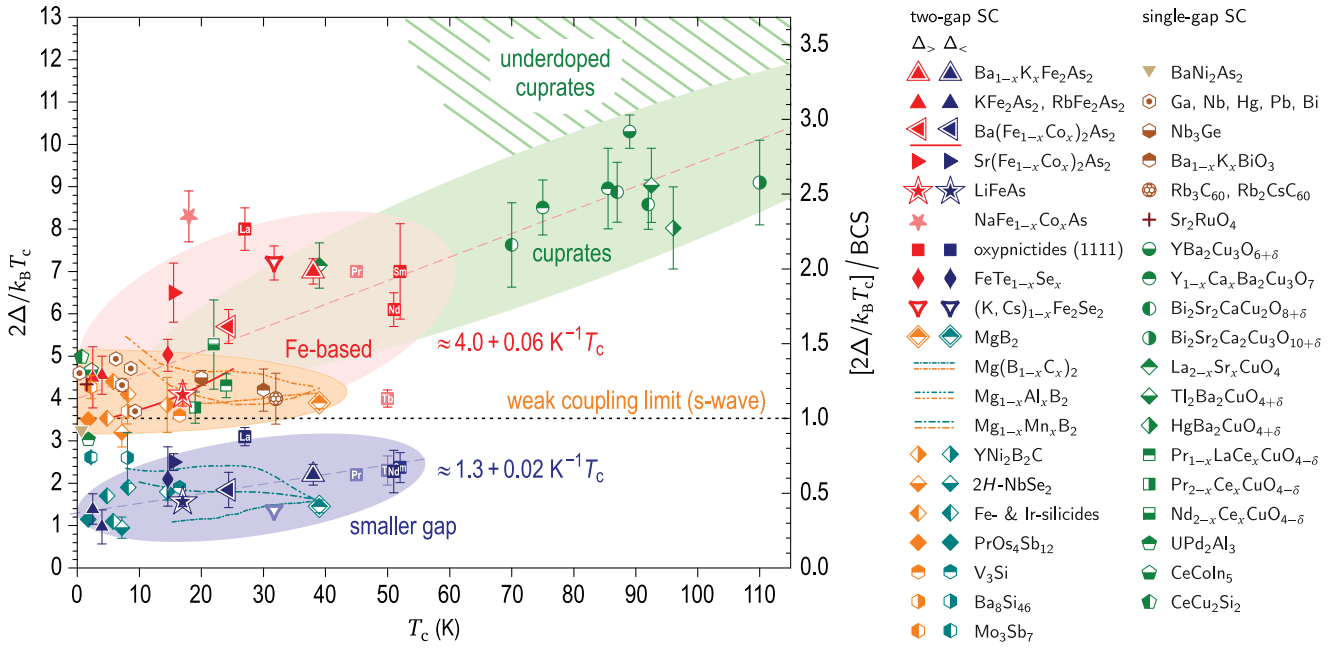

FIG. 1. (Color online) The gap ratios, $2\Delta/k_BT_c$, for different families of single- and two-gap superconductors vs their critical temperatures at ambient pressure, T_c. The data points summarize most of the recent energy-gap measurements in ferropnictides, high-T_c cuprates,[36] and some conventional superconductors. Each data point is an average of all the available measurements of the corresponding compound by various complementary techniques (see Tables I–III). The error bars represent one standard deviation of this average for repeatedly measured compounds or the experimental errors of single measurements, whenever averaging could not be performed. Such unconfirmed points are shown in lighter colors. Points confirmed in a considerable number of complementary measurements are additionally outlined. The weak-coupling limit, predicted for *s*-wave superconductors by the BCS theory, is shown by the dotted line. For weakly coupled *d*-wave superconductors, a slightly higher value of 4.12 is expected (not shown).

suggested in Ref. 4, remains qualitatively valid for all Fe-based compounds in general. However, the absolute values of the gap ratios for $Ba(Fe_{1-x}Co_x)_2As_2$ (BFCA), extracted from heat-capacity measurements in Ref. 4 (solid line in Fig. 1), appear to be somewhat underestimated in comparison to other reports.

Next, we consider the smaller gap, which is found in many multiband superconductors below the BCS limit. For all studied superconductors (both conventional and unconventional), we find somewhat smaller variability of the $2\Delta_</k_BT_c$ values, which tend to accumulate close to the $1.3 + 0.02\ \mathrm{K}^{-1}T_c$ line. The fact that its slope has the same sign as that for the larger gap is consistent with predictions of the Eliashberg theory for interband pairing,[12,27] suggesting a similar scaling of both gaps with the effective coupling (λ_{eff} in Ref. 27), in contrast to the BCS formalism.

Let us now discuss several particular test cases for the above-mentioned trends. The first example comes from the juxtaposition of the stoichiometric conventional superconductor MgB_2 ($T_c = 39$ K)[18–26] and the optimally hole-doped BKFA ($T_{c,\,\mathrm{max}} = 38.5$ K).[15–17,43–48,55] Both are multiband superconductors with almost identical critical temperatures, and their two well-separated SC gaps have been extensively measured by various experimental methods, such as angle-resolved photoemission (ARPES),[16,17,43,44,56] scanning tunneling spectroscopy (STS),[57–59] point-contact Andreev reflection (PCAR) spectroscopy,[45,46] muon-spin rotation (μSR),[47,48] calorimetry,[15] and others (see Table I). By averaging these results, the gap ratios can be determined with a very small uncertainty. The larger gap in MgB_2 yields an average $2\Delta_>/k_BT_c$ ratio of 3.9 ± 0.13, only 10% above the weak-coupling limit.[19,26,34,35] The corresponding ratio for BKFA, however, is 7.0 ± 0.3, almost twice the BCS value. For the smaller gap, we find a qualitatively similar difference.

It is tempting to ascribe this difference to the stronger coupling in ferropnictides in general, but such a scenario is disproved by our second test case, where we compare differently doped Ba-122 materials. Superconductivity in the Ba-122 family can be induced either by a partial substitution of Ba with K or Rb that leads to hole doping of the FeAs layers, or by replacing Fe atoms with Co or Ni within the layers. The end points of both series, corresponding to 100% substitution, are stoichiometric low-T_c superconductors KFe_2As_2 ($T_c = 4$ K), $RbFe_2As_2$ ($T_c = 2.5$ K), and $BaNi_2As_2$ ($T_c = 0.68$ K), all characterized by weak coupling.[5,60,61] Moreover, $BaNi_2As_2$ appears to be a conventional phonon-mediated superconductor.[5,62] This implies that the $2\Delta_>/k_BT_c$ ratio must vary continuously with doping within the Ba-122 family—an effect that so far has been directly observed only in the Co-doped series.[4] Figure 1 suggests this variation to be even stronger (almost twofold) in BKFA, where higher values of T_c can be reached. Indeed, the extensively studied optimally doped BFCA ($T_c = 25$ K) has an average gap ratio of only 5.4 ± 0.4, in the middle between those of optimally doped BKFA and weakly coupled superconductors.[63–65]

To complete our chain of comparisons, we now focus on the high-T_c part of the plot that contains oxypnictides and most of the copper oxides. With the exception of a single, so far unconfirmed, PCAR measurement on Tb-1111,[66] most other works report high values of the gap ratios in La-, Pr-, Nd-, and Sm-based 1111 compounds,[14,49–54] with an average around 7 ± 1. In high-T_c copper oxides with similar or slightly higher critical temperatures, such as $Bi_2Sr_2CaCu_2O_{8+\delta}$ (Bi-2212), comparable ratios around 8.5 ± 0.5 have been reported[67–69] (see Table III). A further increase of the $2\Delta/k_BT_c$ ratio toward $\sim$10, close to the strong-coupling limit of the Eliashberg theory,[70] is observed in Hg-1223 ($T_c = 130$ K) and Hg-1201 ($T_c = 96$ K) cuprates,[36] suggesting that the positive correlation between this ratio and T_c, similar to the one we found for Fe-based compounds, could be universal for all unconventional superconductors, including cuprates.[71] Gap ratios in the most recently discovered iron-selenide superconductors[72–74] ($T_{c,\,max} \approx 33$ K) also conform to this general trend[75–80] and are similar to those of optimally doped BKFA.

However, we cannot fail to mention some deviations from this trend that are best demonstrated by LiFeAs, the bearer of the highest known $T_c = 18$ K among stoichiometric Fe-based materials, together with its close relative NaFeAs. Despite its relatively high T_c, LiFeAs is characterized by weak coupling barely above the BCS limit,[37–42,81,82] possibly related to the absence of notable Fermi surface nesting in its band structure[37] or even a different pairing mechanism.[83,84] In NaFeAs, on the contrary, superconductivity with $T_c \approx 10$ K coexists with antiferromagnetism.[85] Upon electron doping, the AFM order is destroyed and critical temperatures up to 20 K can be reached, resulting in a phase diagram[85] similar to those of 122-ferropnictides, in which the SC dome envelops an AFM quantum critical point. The SC gap in slightly overdoped $NaFe_{0.95}Co_{0.05}As$ ($T_c = 18$ K, i.e., coinciding with that of LiFeAs) was recently measured by ARPES,[86] resulting in $2\Delta/k_BT_c = 8.3 \pm 0.6$, which is much higher than in LiFeAs. This example illustrates that despite the above-mentioned correlation between the gap ratio and T_c, identical critical temperatures even among Fe-based superconductors can still correspond to $2\Delta/k_BT_c$ values as different as those of MgB_2 and optimally doped BKFA that we compared earlier. The relative role of magnetic correlations, doping-induced inhomogeneities, exotic pairing mechanisms, and other factors possibly leading to this exceptional behavior still remains to be investigated.

III. HEAT-CAPACITY JUMP

Energy-gap measurements are not the only way to quantify the deviation of a superconductor from the weak-coupling limit. Calorimetry provides direct access to the magnitude of the jump, ΔC, in the electronic specific heat at T_c (for a review in iron pnictides, see Ref. 87). In the framework of the BCS theory, it is related to the normal-state Sommerfeld coefficient, γ_n, by $\Delta C/\gamma_n T_c = 1.43$, whereas in conventional superconductors with stronger coupling this ratio was shown to increase monotonically with $2\Delta/k_BT_c$.[88] In Fig. 2, we compare the specific-heat-jump ratio reported in some Fe-based

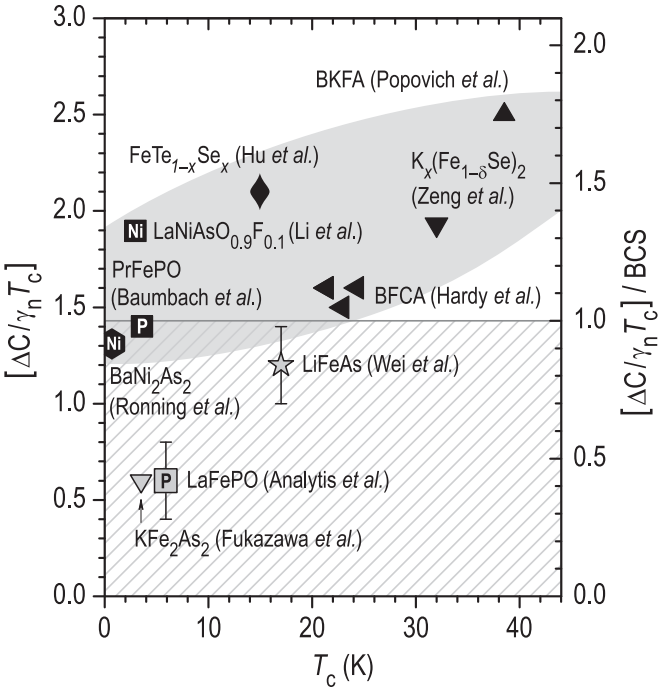

FIG. 2. Heat-capacity measurements of the $\Delta C/\gamma_n T_c$ ratio for various Fe-based superconductors (see Table IV), as compared to the BCS prediction of 1.43. Points that were reported below this weak-coupling limit (hatched area) are shown in gray color.

superconductors.[4,15,41,42,89–95] For optimally doped BKFA with a relatively high value of T_c, the $\Delta C/\gamma_n T_c$ ratio lies 75% above the BCS limit.[15] It exceeds all other values reported for pnictides with lower critical temperatures, confirming the increased deviation from the BCS prediction as T_c increases.

IV. SPIN-RESONANCE MODE: SCALING RELATIONSHIPS

It is remarkable that the largest deviations from the BCS limit are found in those compounds that possess an intense spectrum of spin fluctuations, which are believed to be important for the SC pairing. In contrast to the phonon spectrum, which is to a good approximation insensitive to the SC transition, magnetic excitations originate within the electronic subsystem and may experience drastic changes below T_c, manifest in the spectral weight redistribution and the formation of a spin-resonance mode both in high-T_c cuprates[36,96–98] and in ferropnictides.[99–116] Such changes could offer a positive feedback effect, stabilizing the SC state and contributing to the excessively large gap amplitudes.

Conversely, the proximity of the spin-excitonic resonance to 2Δ determines its damping by particle-hole scattering,[117] hence the behavior of the energy gap discussed above has important consequences for the SC resonant mode. In 122-compounds, its energy ω_{res} varies with the out-of-plane component of the momentum q_z so that its minimum, reached

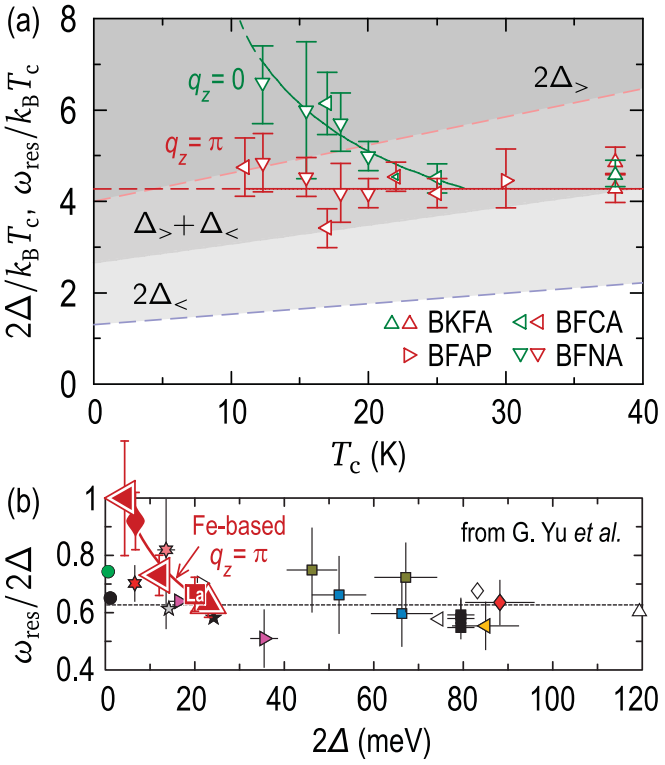

FIG. 3. (Color online) (a) Normalized spin-resonance energy, ω_{res}/k_BT_c, in the Ba-122 iron arsenides for $q_z = \pi$ and $q_z = 0$ (Refs. 99–103), plotted vs T_c (see Table V). The gray shading shows the particle-hole continuum with a three-step onset at $2\Delta_<$, $\Delta_< + \Delta_>$, and $2\Delta_>$. (b) Ratios of the spin-resonance energy at $q_z = \pi$ to the SC gap, $\omega_{res}/2\Delta$, in Fe-based superconductors (large symbols) in comparison to the universal ratio of 0.64 proposed for other unconventional superconductors.[36] The meaning of the symbols is retained from Fig. 1 and Ref. 36, respectively.

at $q_z = \pi$, scales linearly with T_c, whereas the maximal value at $q_z = 0$ always stays above 4 meV, if extrapolated down to $T_c \to 0$.[99–103] This results in ω_{res}/k_BT_c ratios that are plotted in Fig. 3(a). The ratio stays constant for $q_z = \pi$, but diverges for $q_z = 0$ as $T_c \to 0$. Because $2\Delta/k_BT_c$ remains finite at all temperatures, such a behavior must increasingly suppress the resonance intensity for $q_z = 0$ as its energy enters the particle-hole continuum [shaded regions in Fig. 3(a)] with decreasing T_c. So far, direct experimental evidence for such a suppression[106] remains scarce. A systematic investigation of the resonant peak's intensity and shape for doping levels with $T_c < 11$ K is therefore warranted.

For $q_z = \pi$, the situation with the resonance damping is more speculative, as it depends on the detailed q_z dispersion of the continuum and the exact T_c dependence of the gap ratios. Generally for a two-gap superconductor, the particle-hole continuum has a three-step onset at $2\Delta_<$, $\Delta_< + \Delta_>$ and $2\Delta_>$. In 122-superconductors, however, the smaller gap typically resides only on one of the Γ-centered holelike bands,[16,17,43,44] rendering $2\Delta_<$ onset irrelevant for interband scattering close to the nesting vector. In electron-doped 122-compounds with optimal T_c, the resonance mode appears below $2\Delta_>$, but has a significant overlap with $\Delta_< + \Delta_>$, which possibly contributes to its unusually large energy width.[99–103] This situation would not change with doping under the assumption of constant $2\Delta_>/k_BT_c$ ratios. However, if one assumes them to follow the average linear trends implied by Fig. 1 (dashed lines), the resonance would approach $2\Delta_>$ even at $q_z = \pi$, leading to its further broadening and suppression. This possibility is consistent with the fact that resonant modes have not so far been reported in either under- or overdoped samples with $T_c < 11$ K.

The described behavior of the gap implies that Fe-based superconductors violate the universality of the $\omega_{res}/2\Delta$ ratio proposed in Ref. 36. Indeed, according to gap values in Fig. 1 and the proportionality $\omega_{res} \approx (4.6 \pm 0.4)\, k_BT_c$, established in Refs. 99–103, this ratio continuously increases from ~0.65 in the optimally doped BKFA to ~0.8 in the optimally doped BFCA. Then it approaches unity in compounds with even lower T_c, such as underdoped BFCA or the 11-family, as illustrated by the large symbols in Fig. 3(b). The universal ratio of $\omega_{res}/2\Delta = 0.64$ has been interpreted as the result of a fundamental spin-mediated pairing mechanism in unconventional superconductors.[36] Therefore its breakdown in Fe-based systems, which becomes increasingly pronounced for low-T_c compounds (Table V), might be indicative of a variation in the role played by spin fluctuations. Supposedly, they become increasingly less important to the SC pairing as T_c decreases (e.g., due to an interplay with conventional phononic pairing), which can explain the simultaneous increase in $\omega_{res}/2\Delta$ and the reduction of the gap ratio.

Recently we became aware of a new inelastic-neutron-scattering (INS) study[118] performed on several overdoped samples of polycrystalline BKFA. The results of this work indicate that the deviation of the $\omega_{res}/2\Delta$ ratio from the "universal" value[36] and the suppression of the resonant-mode spectral weight with decreasing T_c, discussed above, also hold on the overdoped side of the phase diagram.

Another recent work[119] has lately revealed an enhancement of the antiferromagnetic INS signal in LiFeAs below T_c, resembling an overdamped spin-resonance mode. It is strongly broadened in energy and appears centered around ~8 meV, i.e., above $2\Delta \approx 6.1 \pm 0.5$ meV (see Table V). This implies a considerable overlap of the resonance peak with the particle-hole continuum (as in under- or overdoped 122-systems) and a large $\omega_{res}/2\Delta$ ratio of 1.3 ± 0.4, far above the universal value of 0.64. The results are consistent with the weak-coupling behavior suggested earlier by the small gap ratios observed in this compound.[37–42]

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APPENDIX: TABLES

TABLE I. Summary of the energy gap measurements in Fe-based superconductors. The gap values are obtained from the published results of point-contact Andreev-reflection (PCAR) or tunneling spectroscopy, scanning tunneling spectroscopy (STS), angle-resolved photoelectron spectroscopy (ARPES), and optical spectroscopy measurements that directly probe the electronic density of states, as well as indirectly from the calorimetric measurements of the electronic specific heat, magnetization measurements of the lower critical field (H_{c1}), muon-spin-rotation (μSR), small-angle neutron scattering (SANS), microwave surface-impedance (MSI), tunnel-diode resonator (TDR), or magnetic force microscopy (MFM) measurements of the London penetration depth, from the nuclear-magnetic-resonance (NMR) or nuclear-quadrupolar-resonance (NQR) measurements of the spin-lattice relaxation rate, and from the time-resolved femtosecond spectroscopy (FTS) via the temperature dependence of the photoinduced reflectivity. The error values marked by an asterisk represent the spread of the gap values measured in different points on the sample or using different junctions. They can be therefore larger than the uncertainty of the average.

Doping level		Sample	T_c (K)	$\Delta_<$ (meV)	$2\Delta_</k_BT_c$	$\Delta_>$ (meV)	$2\Delta_>/k_BT_c$	Experiment	Method or comment	Reference
122-family of ferropnictides										
$Ba_{1-x}K_xFe_2As_2$, hole-doped (BKFA)										
$x = 25\%$	(UD)	FeAs-flux	26	4.0 ± 0.8	3.6 ± 0.7	7.8 ± 0.9	7.0 ± 0.8	ARPES	symmetrization	Nakayama *et al.*[3]
$x = 40\%$	(OP)	»	37	5.8 ± 0.8	3.6 ± 0.5	12.3 ± 0.8	7.7 ± 0.5	»	»	»
$x = 70\%$	(OD)	»	22	4.4 ± 0.8	4.6 ± 0.9	7.9 ± 0.8	8.3 ± 0.9	»	»	»
$x = 29\%$	(UD)	Sn-flux	28	$3.7 \pm 0.5^*$	$3.1 \pm 0.4^*$			PCAR	*c*-axis Au junction	Zhang *et al.*[1]
$x = 28\%$	»	»	31.5	2.3	1.7	9.8	7.2	^{75}As-NMR	spin-lattice relax. rate	Matano *et al.*[120]
$x = 32\%$	(OP)	FeAs-flux	38.5	3.5	2.2	11	6.6	calorimetry	electronic specific heat	Popovich *et al.*[15]
$x = 40\%$	»	»	38	3.6 ± 0.5	2.2 ± 0.3	8.2 ± 0.9	5.1 ± 0.5	STS	peak-to-peak distance	Shan *et al.*[58]
»	»	»	37	3.5 ± 0.5	2.3 ± 0.3			PCAR	single-gap BTK fit	Lu *et al.*[45]
»	»	»	»	$3.3 \pm 1.1^*$	$2.1 \pm 0.7^*$	$7.6 \pm 0.9^*$	$4.8 \pm 0.6^*$	STS	two-band model	Shan *et al.*[57]
»	»	»	»	6.4 ± 0.5	4.0 ± 0.3	11.3 ± 1.0	7.0 ± 0.6	ARPES	k_z-resolved, symmetrization	Xu *et al.*[44]
»	»	»	»	6.0 ± 1.0	3.7 ± 0.6	12.0 ± 1.0	7.5 ± 0.6	ARPES	symmetrization	Ding *et al.*[16]
»	»	»	»	6.0 ± 1.5	3.7 ± 1.0	13 ± 2	8.1 ± 1.2	ARPES + STS	»	Wray *et al.*[59]
»	»	»	»	5.8 ± 0.8	3.6 ± 0.5	12.0 ± 0.8	7.5 ± 0.4	ARPES	»	Nakayama *et al.*[43]
»	»	»	»			12.5 ± 2.0	7.8 ± 1.2	optics	reflectance	Li *et al.*[121]
»	»	»	36.2	2.0 ± 0.3	1.3 ± 0.2	8.9 ± 0.4	5.7 ± 0.3	magnetization	lower critical field	Ren *et al.*[122]
»	»	»	35	7.5 ± 1.5	5.0 ± 1.0	11 ± 1.5	7.3 ± 1.0	ARPES	symmetrization	Zhao *et al.*[56]
»	»	Sn-flux	32	< 4	< 3	9.2 ± 1.0	6.7 ± 0.7	»	Dynes-function fit	Evtushinsky *et al.*[17]
»	»	»	»	1.5 ± 1.0	1.1 ± 0.7	9.1 ± 1.0	6.6 ± 0.7	ARPES + μSR	penetration depth	Khasanov *et al.*[48]
»	»	Bridgman	36	3.5	2.3	12	7.7	optics	optical conductivity	Kwon *et al.*[123]
»	»	polycryst.	38	6.8 ± 0.3	4.1 ± 0.2	12	7.3	μSR	penetration depth	Hiraishi *et al.*[47]
$x = 45\%$	(OD)	Sn-flux	27	$2.7 \pm 0.7^*$	$2.3 \pm 0.6^*$	$9.2 \pm 0.5^*$	$7.9 \pm 0.4^*$	PCAR	*ab*-plane junction average	Szabó *et al.*[46]
$x = 49\%$	»	»	25.5	$3.1 \pm 0.7^*$	$2.8 \pm 0.6^*$			»	*c*-axis Pb junction	Zhang *et al.*[1]
$x = 55\%$	»	FeAs-flux	32.7	3.3	2.3	6.8	4.8	MSI	penetration depth	Hashimoto *et al.*[124]
$x = 77\%$	»	Sn-flux	21	$2.7 \pm 0.3^*$	$3.0 \pm 0.4^*$			PCAR	*c*-axis Pb junction	Zhang *et al.*[1]
KFe_2As_2, 100% hole-doped (K-122 or KFA)										
N/A		FeAs-flux	4.0			0.93 ± 0.12	5.4 ± 0.7	TDR	nodal-gap model	Hashimoto *et al.*[125]
		»	3.6	0.23 ± 0.03	1.5 ± 0.2	0.55 ± 0.02	3.55 ± 0.13	SANS	three-gap model	Kawano-Furukawa *et al.*[61]
		polycryst.	3.5	0.07	0.46	0.73	4.84	^{75}As-NQR	fully gapped $s^{\pm}$	Fukazawa *et al.*[89]
$RbFe_2As_2$, 100% hole-doped (Rb-122)										
N/A		polycryst.	2.5	0.15 ± 0.02	1.4 ± 0.2	0.49 ± 0.04	4.5 ± 0.4	μSR	penetration depth	Shermadini *et al.*[60]
$Ba(Fe_{1-x}Co_x)_2As_2$, electron-doped (BFCA)										
$x = 7.0\%$	(OP)	FeAs-flux	22			$7.0 \pm 2.4^*$	$7.4 \pm 2.5^*$	STS	peak-to-peak distance	Massee *et al.*[126]
»	»	»	23			$5.5 \pm 0.5^*$	$5.5 \pm 0.5^*$	PCAR	*c*-axis Pt junction	Samuely *et al.*[63]
»	»	»	24.5			7.3	6.9	STS	peak-to-peak distance	Nishizaki *et al.*[127]
$x = 7.5\%$	»	»	25.5	4.5 ± 1.0	4.1 ± 0.9	6.7 ± 1.0	6.1 ± 0.9	ARPES	symmetrization	Terashima *et al.*[64]
»	»	»	25	3.1 ± 0.2	2.9 ± 0.2	7.4 ± 0.3	6.9 ± 0.3	optics	optical conductivity	Tu *et al.*[128]
$x = 10\%$	»	»	24.5	4.4 ± 0.6	4.2 ± 0.6	9.9 ± 1.2	9.4 ± 1.1	PCAR	*ab*-plane, BTK fit	Tortello *et al.*[129]
»	»	»	25.3			$6.3 \pm 1.7^*$	$5.8 \pm 1.6^*$	STS	peak-to-peak distance	Yin *et al.*[65]
$x = 7.4\%$	(OD)	»	22.5	1.5	1.6	3.7	3.8	μSR	penetration depth	Williams *et al.*[130]
$x = 7.5\%$	»	»	21.4	1.75	1.9	4.1	4.4	calorimetry	electronic specific heat	Hardy *et al.*[90]
$x = 4.0\%$	(UD)	»	5.8	0.38	1.5	0.86	3.4	»	»	Hardy *et al.*[4]
$x = 4.5\%$	»	»	13.3	0.89	1.5	2.2	3.8	»	»	»
$x = 5.0\%$	»	»	19.5	1.36	1.6	3.5	4.2	»	»	»
$x = 5.5\%$	»	»	21.5	1.84	2.0	4.4	4.7	»	»	»
$x = 5.7\%$	(OP)	»	24.4	1.94	1.9	5.2	5.0	»	»	»
$x = 6.0\%$	»	»	24.2	1.94	1.8	5.0	4.8	»	»	»
$x = 6.5\%$	(OD)	»	23.8	1.78	1.7	4.6	4.5	»	»	»
$x = 7.5\%$	»	»	22.9	1.81	1.8	4.4	4.5	»	»	»
$x = 7.6\%$	»	»	21.5	1.84	2.0	3.9	4.2	»	»	»
$x = 9.0\%$	»	»	20.7	1.62	1.8	3.8	4.3	»	»	»
$x = 11.0\%$	»	»	13.0	0.89	1.6	2.0	3.6	»	»	»
$x = 11.3\%$	»	»	11.0	0.83	1.7	1.75	3.7	»	»	»
$x = 11.6\%$	»	»	9.4	0.54	1.3	1.27	3.1	»	»	»
$x = 12.0\%$	»	»	5.1	0.25	1.1	0.67	3.1	»	»	»
$x = 6.0\%$	(UD)	»	14	$4 \pm 2^*$	$7 \pm 3^*$	$8 \pm 2^*$	$13 \pm 3^*$	STS	Dynes-function fit	Teague *et al.*[9]
$x = 12.0\%$	(OD)	»	20	$5 \pm 2^*$	$6 \pm 3^*$	$10 \pm 2^*$	$11 \pm 3^*$	»	»	»
$x = 10\%$	»	thin film	»	1.85 ± 0.15	2.1 ± 0.2	$\geqslant 3.5$	$\geqslant 4.0$	optics	optical conductivity	Maksimov *et al.*[131]
$x = 6.5\%$	(OP)	FeAs-flux	24.5	3.3	3.1	5.0	4.7	»	»	Kim *et al.*[132]
$x = 4.9\%$	(UD)	»	15.8	0.8	1.2	3.0	4.4	MFM	penetration depth	Luan *et al.*[133]
$x = 5.1\%$	»	»	18.6	1.1	1.4	3.7	4.6	»	»	»

TABLE I. (*Continued.*)

Doping level		Sample	T_c (K)	$\Delta_<$ (meV)	$2\Delta_</k_BT_c$	$\Delta_>$ (meV)	$2\Delta_>/k_BT_c$	Experiment	Method or comment	Reference
$x = 7.0\%$	(OP)	»	22.4	2.5	2.6	6.4	6.6	»	»	»
$x = 8.5\%$	(OD)	»	19.6	1.0	1.2	3.2	3.8	»	»	»
$x = 11\%$	»	»	13.5	0.7	1.2	2.0	3.4	»	»	»
$EuFe_2(As_{1-x}P_x)_2$, isovalently substituted (EFAP)										
$x = 18\%$	(OP)	Bridgman	28			4.7	3.8	optics	optical conductivity	Wu *et al.*[134]
$Sr(Fe_{1-x}Co_x)_2As_2$, electron-doped (SFCA)										
$x = 7.5\%$	(OP)	Sn-flux	19.5	1.4	1.7	8.6	10.2	STS	peak-to-peak distance	Park *et al.*[135]
$x = 12.5\%$	(OD)	FeAs-flux	13.3	1.3 ± 0.3	2.3 ± 0.5	3.7 ± 0.4	6.5 ± 0.7	μSR	penetration depth	Khasanov *et al.*[136]
$x = 13\%$	»	»	15.5	$1.8 \pm 0.3^*$	$2.7 \pm 0.5^*$			PCAR	c-axis Pb & Au junctions	Zhang *et al.*[1]
$BaNi_2As_2$, 100% electron-doped (BNA)										
N/A		Pb-flux	0.68			0.095	3.24	calorimetry	electronic specific heat	Kurita *et al.*[5]
1111-family of ferropnictides										
$LaFeAsO_{1-x}F_x$, electron-doped (La-1111)										
$x = 8\%$	(UD)	polycryst.	23	3.0	3.0	7.5	7.5	^{75}As-NQR	spin-lattice relax. rate	Kawasaki *et al.*[49]
$x = 10\%$	(OP)	»	26	3.9 ± 0.7	3.5 ± 0.6			PCAR	BTK-fit	Shan *et al.*[137]
»	»	»	»	3.4 ± 0.5	3.0 ± 0.5			calorimetry	electronic specific heat	Mu *et al.*[138]
»	»	»	»	4.0 ± 0.6	3.6 ± 0.5			magnetization	lower critical field, d-wave fit	Ren *et al.*[139]
»	»	»	27	3.8 ± 0.4	3.3 ± 0.3	10.0 ± 0.6	8.5 ± 0.5	PCAR	generalized BTK fit	Gonnelli *et al.*[50]
$PrFeAsO_{1-x}F_x$, electron-doped (Pr-1111)										
$x = 11\%$	(UD)	polycryst.	45	4.3	2.2	13.7	7.1	^{75}As -& ^{19}F-NMR		Matano *et al.*[14]
$NdFeAsO_{1-x}F_x$, electron-doped (Nd-1111)										
$x = 10\%$	(OP)	polycryst.	51	$5.1 \pm 0.2^*$	$2.6 \pm 0.1^*$	$11.7 \pm 1.2^*$	$5.7 \pm 0.5^*$	PCAR	Pt junctions	Samuely *et al.*[53]
»	»	sol.-state	53			15 ± 1.5	6.6 ± 0.7	ARPES	symmetrization	Kondo *et al.*[52]
$SmFeAsO_{1-x}F_x$, electron-doped (Sm-1111)										
$x = 20\%$	(OP)	monocryst.	51.2	6.45 ± 0.25	3.0 ± 0.2	16.6 ± 1.6	7.7 ± 0.9	PCAR	Au contact, BTK fit	Karpinski *et al.*[140]
»	»	»	49.5	8.0		3.7		TRS	photoinduced reflectivity	Mertelj *et al.*[141]
$x = 10\%$	»	polycryst.	51.5	3.7 ± 0.4	1.7 ± 0.2	10.5 ± 0.5	4.7 ± 0.2	PCAR	Pt/Ir or Au junctions	Wang *et al.*[142]
$x = 20\%$	»	»	52	6.15 ± 0.45	2.7 ± 0.2	18 ± 3	8.0 ± 1.3	»	Ag-paste contact	Daghero *et al.*[51]
$x = 9\%$	(UD)	»	42	4.9 ± 0.5	2.7 ± 0.3	15 ± 1	8.3 ± 0.6	»	»	»
$x = 15\%$	»	»	»	6.7 ± 0.15	3.7 ± 0.1			»	Au junctions	Chen *et al.*[143]
$SmFeAsO_{1-x}$, oxygen-deficient (Sm-1111)										
$x = 15\%$	(OP)	polycryst.	52	8.25 ± 0.25	3.7 ± 0.1			STS	d-wave model	Millo *et al.*[144]
$TbFeAsO_{1-x}F_x$, electron-doped (Tb-1111)										
$x = 10\%$	(UD)	polycryst.	50	5.0 ± 0.8	2.3 ± 0.4	8.8 ± 0.5	4.1 ± 0.2	PCAR	Au junctions	Yates *et al.*[66]
111-family of ferropnictides										
$Li_{1+\delta}FeAs$, undoped (Li-111 or LFA)										
N/A		self-flux	18	1.0 ± 0.5	1.3 ± 0.6	3.2	4.1	ARPES	Dynes-function fit	Borisenko *et al.*[37]
		»	17			3.0 ± 0.2	4.1 ± 0.3	SANS + ARPES	penetration depth	Inosov *et al.*[38]
		»	16.9	1.2	1.6	2.6	3.6	calorimetry	electronic specific heat	Stockert *et al.*[42]
		»	16			~ 2.5	3.6	STS	preliminary result	Hanaguri *et al.*[81]
		»	17	1.4 ± 0.4	1.9 ± 0.6	2.96 ± 0.05	4.0 ± 0.1	MSI	penetration depth	Imai *et al.*[7]
		Bridgman	17.5	1.4 ± 0.1	1.9 ± 0.13	2.9 ± 0.2	3.8 ± 0.3	magnetization	lower critical field, $\mathbf{H} \parallel c$	Song *et al.*[40]
		»	»	1.2 ± 0.1	1.6 ± 0.13	2.9 ± 0.2	3.8 ± 0.3	»	lower critical field, $\mathbf{H} \parallel ab$	»
		»	»	1.7	2.22	2.8	3.77	TDR	penetration depth	Kim *et al.*[8]
		polycryst.	17	1.9	2.6	4.4	6.0	^{75}As-NQR	spin-lattice relax. rate	Li *et al.*[6,82]
		»	15	0.7	1.2	2.3	3.5	calorimetry	electronic specific heat	Wei *et al.*[41]
		grains	»	0.6 ± 0.13	1.0 ± 0.4	3.3 ± 1.0	5.4 ± 1.6	magnetization	lower critical field	Sasmal *et al.*[39]
$NaFe_{1-x}Co_xAs$, electron-doped (Na-111)										
$x = 5\%$	(OD)	self-flux	18			6.5 ± 0.5	8.3 ± 0.6	ARPES	symmetrization	Liu *et al.*[86]
Arsenic-free Fe-based superconductors										
$FeSe_{1-x}$, chemically deficient										
$x = 15\%$	(OD)	polycryst.	8.3	0.38 ± 0.01	1.1 ± 0.02	1.60 ± 0.02	4.45 ± 0.06	μSR	penetration depth	Khasanov *et al.*[145]
$FeTe_{1-x}Se_x$, isovalently substituted										
$x = 50\%$	(OP)	Bridgman	14.6	0.51 ± 0.03	0.8 ± 0.05	2.61 ± 0.09	4.15 ± 0.14	μSR	penetration depth	Bendele *et al.*[146]
»	»	polycryst.	14.4	0.87 ± 0.06	1.4 ± 0.1	2.6 ± 0.1	4.2 ± 0.2	»	»	Biswas *et al.*[147]
»	»	self-flux	13.9			2.2	3.7	calorimetry	electronic specific heat	Günther *et al.*[148]
$x = 45\%$	»	unidirect.	14	2.5	4.1	5.1	8.5	optics	optical conductivity	Homes *et al.*[149]
»	»	solidificat.	14.2			3.8	6.2	PCAR	c-axis Au junctions	Park *et al.*[150]
$x = 43\%$	»	self-flux	14.7	2.5	3.92	3.7	5.84	calorimetry	electronic specific heat	Hu *et al.*[151]
$x = 15\%$	»	»	14			2.3	3.8	STS	Dynes-function fit	Kato *et al.*[152]
$Fe_{1-x}Mn_xTe_{0.5}Se_{0.5}$										
$x = 2\%$	(OP)	self-flux	14.4			2.7	4.4	calorimetry	electronic specific heat	Günther *et al.*[148]
$A_x(Fe_{1-\delta}Se)_2$ (A = K, Rb, Cs), heavily electron-doped (highest T_c among arsenic-free Fe-based superconductors)										
K, $x = 0.7$	(UD)	Bridgman	28	1.5	1.3			optics	optical conductivity	Yuan *et al.*[75]
$Tl_{0.63}K_{0.37}$	»	»	29			8.5 ± 1.0	6.8 ± 0.8	ARPES	symmetrization	Wang *et al.*[76]
$Tl_{0.45}K_{0.34}$	»	»	28			8.0	6.6	»	»	Zhao *et al.*[77]
K, $x = 0.7$	(OP)	»	32			9.0	6.5	»	»	»
$Tl_{0.58}Rb_{0.42}$	»	»	»			12.5 ± 2.5	9.1 ± 1.8	»	»	Mou *et al.*[78]
K, $x = 0.8$	»	self-flux	31.7			10.3 ± 2	7.5 ± 1.5	»	»	Zhang *et al.*[79]
»	»	»	»	30		10.8 ± 2	7.6 ± 1.0	^{77}Se NMR	spin-lattice relax. rate	Ma *et al.*[80]
»	»	»	»	»		10.3 ± 2	7.9 ± 1.5	»	»	

TABLE II. Selected reports of the energy-gap measurements in multiband superconductors known before the discovery of high-T_c superconductivity in ferropnictides, as well as in several single-band superconductors. For high-T_c cuprates, see the next table.

Compound	Sample	T_c (K)	$\Delta_<$(meV)	$2\Delta_</k_BT_c$	$\Delta_>$(meV)	$2\Delta_>/k_BT_c$	Experiment	Method or comment	References
Multiband superconductors									
MgB_2									
	polycryst.	39.3	2.8 ± 0.2	1.7 ± 0.2	7 ± 0.5	4.1 ± 0.3	PCAR	Cu junction	Szab *et al.*[18]
	monocryst.	38.2	2.9 ± 0.3	1.8 ± 0.2	7.1 ± 0.5	4.3 ± 0.3	»	Ag paint or In junctions	Gonnelli *et al.*[19]
	polycryst.	38.7	3.5 ± 0.4	2.1 ± 0.3	7.5 ± 0.5	4.5 ± 0.3	STS	Dynes-function fit	Giubileo *et al.*[20]
	thin films	40	2.3	1.3	7.1	4.1	»	peak-to-peak distance	Iavarone *et al.*[21]
	polycryst.	38.8	2.7	1.6	6.2	3.7	Raman	2-gap fit	Chen *et al.*[22]
	»	36.5	1.7 ± 0.2	1.1 ± 0.2	5.6 ± 0.2	3.5 ± 0.2	PES	Dynes-function fit	Tsuda *et al.*[23]
	monocryst.	36	2.3 ± 0.4	1.5 ± 0.3	5.5 ± 0.4	3.5 ± 0.3	ARPES	BCS-function fit	Tsuda *et al.*[24]
	»	38	1.5 ± 0.5	0.9 ± 0.3	6.5 ± 0.5	3.9 ± 0.3	»	»	Souma *et al.*[25]
neutron-irradiated		7–38	2.0 ± 0.3			3.5 ± 0.3	specific heat, transport and PCAR (review)		Xi[26]
$Mg(B_{1-x}C_x)_2$, $Mg_{1-x}Al_xB_2$ or $Mg_{1-x}Mn_xB_2$ (chemically substituted MgB_2)									
C-substituted			1.5 ± 0.5			4.0 ± 0.3	PCAR	review	Gonnelli *et al.*[35]
Al-substituted				2.1 ± 0.5		4.2 ± 0.3	»	»	»
Mn-substituted				1.9 ± 0.2		3.7 ± 0.5	»	»	»
$2H$-$NbSe_2$									
	monocryst.	7.2	0.2 ± 0.2	0.7 ± 0.7	1.2 ± 0.1	3.8 ± 0.3	ARPES	BCS-function fit	Yokoya *et al.*[153]
	»	»			0.8 ± 0.4	2.6 ± 1.3	»	leading edge	Borisenko *et al.*[154]
	»	7.1	0.4 ± 0.1	1.2 ± 0.2	1.0 ± 0.2	3.2 ± 0.6	TDR	penetration depth	Fletcher *et al.*[155]
YNi_2B_2C									
	monocryst.	13.77	1.19	2.0	2.67	4.5	calorimetry	electronic specific heat	Huang *et al.*[156]
	»	14.5	$0.31 \pm 0.06^*$	$1.6 \pm 0.3^*$	$2.0 \pm 0.2^*$	$3.2 \pm 0.3^*$	PCAR		Mukhopadhyay *et al.*[157]
	»	15.2	1.6	2.4	2.8	4.3	INS	phonon line shapes	Weber *et al.*[158]
$R_2Fe_3Si_5$ (R = Lu,Sc) or $Sc_5Ir_4Si_{10}$									
$Lu_2Fe_3Si_5$	monocryst.	5.8	0.3	1.1	1.1	4.4	calorimetry	electronic specific heat	Nakajima *et al.*[159]
$Sc_2Fe_3Si_5$	»	4.8	0.35	1.7	0.74	3.53	»	»	Tamegai *et al.*[160]
$Sc_5Ir_4Si_{10}$	»	8.2	0.7	1.9	1.45	4.1	»	»	»
V_3Si									
	monocryst.	16.5	1.36	1.9	2.6	3.6	MSI	penetration depth	Nefyodov *et al.*[161]
Ba_8Si_{46}									
	polycryst.	8.1	0.9 ± 0.2	2.6 ± 0.6	1.3 ± 0.1	3.7 ± 0.3	tunneling	BCS-function fit	Noat *et al.*[162]
Mo_3Sb_7									
	polycryst.	2.2	0.24	2.5	0.38	4.0	calorimetry	electronic specific heat	Tran *et al.*[163]
	»	»	0.26	2.73	0.43	4.54	μSR	penetration depth	Tran *et al.*[164]
$PrOs_4Sb_{12}$ (heavy-fermion superconductor)									
	monocryst.	1.75	0.09	1.15	0.27	3.5	calorimetry	thermal conductivity	Seyfarth *et al.*[165]
Single-band superconductors									
Nb (highest T_c among elemental superconductors)									
	polycryst.	9.26			1.5	3.7	PES	Dynes-function fit	Chainani *et al.*[166]
Pb									
	monocryst.	7.2			1.35 ± 0.06	4.3 ± 0.2	neutron spin-echo phonon lifetimes		Aynajian *et al.*[167]
$Ba_{1-x}K_xBiO_3$									
$x = 40\%$	(OP)	thin films	19		3.0 ± 0.2	3.7 ± 0.5	PCAR	Au junction	Sato *et al.*[30]
»	»	monocryst.	30.8		5.6 ± 0.7	4.2 ± 0.5	optics	reflectivity	Puchkov *et al.*[31]
»	»	»	30		6.0	4.6	»	infrared conductivity	Marsiglio *et al.*[32]
$CeCoIn_5$ (highest T_c among heavy-fermion superconductors)									
	monocryst.	2.3			0.46	4.6	PCAR	Au junctions	Park *et al.*[168]
UPd_2Al_3 (heavy-fermion superconductor)									
	thin film	1.8			0.24	3.0	tunneling	Dynes-function fit	Jourdan *et al.*[169]
Sr_2RuO_4 (presumably a spin-triplet superconductor)									
	monocryst.	1.5			0.28	4.3	tunneling	BCS-function fit	Suderow *et al.*[170]

TABLE III. Summary of the energy-gap measurements in copper-oxide-based superconductors.

Compound		Sample	T_c (K)	Δ (meV)	$2\Delta/k_BT_c$	Experiment	Method or comment	Reference
Hole-doped cuprates								
$Bi_2Sr_2CaCu_2O_{8+\delta}$ (Bi-2212 or BSCCO)								
	(OD)		70	23 ± 3	7.6 ± 1.0	STM + tunneling	review	Yu *et al.*[36]
	»		87	33.5 ± 3.5	8.9 ± 1.0	»	»	»
	»		86	33 ± 4	8.8 ± 1.0	ARPES	symmetrization + fit	Lee *et al.*[69]
	(OP)		92	36 ± 2	9.0 ± 0.5	»	»	»
	»	float. zone	91	32 ± 3	8.1 ± 0.8	»	empirical fit	Fedorov *et al.*[67]
Pb-BSCCO	(UD)	annealed	77	28	8.4	»	leading edge	Borisenko *et al.*[68]
$Bi_2Sr_2Ca_2Cu_3O_{10+\delta}$ (Bi-2223)								
	(OD)		110	43 ± 5	9.1 ± 1.0	ARPES	backfolded dispersion	Ideta *et al.*[171]
$La_{2-x}Sr_xCuO_4$ (LSCO)								
	(OD)	float.-zone	26	8.0 ± 1.0	7.1 ± 0.9		review	Yu *et al.*[36]
	»	»	31	10.5	7.8	optics	»	»
$x = 0.15$	(OP)	»	39	17.5 ± 1.5	10.3 ± 0.9	ARPES	leading edge	Yoshida *et al.*[172]
$YBa_2Cu_3O_{6+\delta}$ (YBCO)								
$\delta = 0.6$	(UD)		63	39.5 ± 1.5	14.4 ± 0.6		review	Yu *et al.*[36]
$\delta = 0.7$	»		67	39.5 ± 1.5	13.6 ± 0.5		»	»
$\delta = 0.85$	»		89	39.5 ± 1.5	10.2 ± 0.4		»	»
$Y_{1-x}Ca_xBa_2Cu_3O_7$ (Ca-YBCO)								
$x = 0.10$	(OD)		85.5	33 ± 4	8.9 ± 1.1		review	Yu *et al.*[36]
$x = 0.15$	»		75	26 ± 3	7.0 ± 0.8		»	»
»	»	flux method	77	29 ± 3	8.7 ± 1.0	ARPES	peak position	Zabolotnyy *et al.*[173]
$HgBa_2Ca_2Cu_3O_{8+\delta}$ (Hg-1223)								
	(OP)		130	60	10.6	optics	review	Yu *et al.*[36]
$HgBa_2CuO_{4+\delta}$ (Hg-1201)								
	(OP)		96	44 ± 4	10.6 ± 1.0		review	Yu *et al.*[36]
	(UD)		90	22.4	5.8 ± 1.0	optics		Yang *et al.*[174]
UD 78 K – OD 42 K			42–95		6.4 ± 1.0	Raman		Guyard *et al.*[175]
$Tl_2Ba_2CuO_{6+\delta}$ (Tl-2201)								
	(OP)		92.5	43 ± 4	10.7 ± 1.0		review	Yu *et al.*[36]
	(OD)		90	37	9.5	optics	»	»
	»		»	28	7.2	»	»	Schachinger *et al.*[176]
Electron-doped cuprates								
$Nd_{2-x}Ce_xCuO_{4-\delta}$ (NCCO)								
$x = 0.15$	(OP)	float.-zone	22	5.0 ± 1.0	5.2 ± 1.1	ARPES	leading edge	Sato *et al.*[177]
$Pr_{2-x}Ce_xCuO_{4-\delta}$ (PCCO)								
$x = 0.13$	(UD)		17	2.5 ± 0.4	3.5 ± 0.5	tunneling	Pb/I/PCCO junctions	Dagan *et al.*[178]
$x = 0.15$	(OP)		19	3.3 ± 0.3	4.0 ± 0.4	»	»	»
$x = 0.16$	(OD)		16	2.6 ± 0.4	3.8 ± 0.5	»	»	»
$Pr_{1-x}LaCe_xCuO_{4-\delta}$ (PLCCO)								
$x = 0.11$	(OP)	float.-zone	26	2.5 ± 0.2	2.2 ± 0.2	ARPES	leading edge	Matsui *et al.*[179]
$x = 0.12$	»	»	25	3.6 ± 0.2	3.5 ± 0.2	tunneling	Pt/Ir junctions	Giubileo *et al.*[180]
»	»	»	24	7.2 ± 1.2	6.9 ± 1.2	STS		Niestemski *et al.*[181]
$x = 0.12, 0.15$	»	13–24			3.6 ± 0.2	PCAR	BTK fit	Shan *et al.*[182]
Ruthenocuprates								
$RuSr_2GdCu_2O_8$ (Ru-1212)								
Ru-1212		polycryst.	30	2.8 ± 0.2	2.2 ± 0.2	PCAR	Pt/Ir junctions	Piano *et al.*[183]
»		»	27	6.0 ± 0.5	5.1 ± 0.4	»	»	Calzolari *et al.*[184]

TABLE IV. Heat-capacity measurements of the specific-heat-jump ratio, $\Delta C/\gamma_n T_c$, in iron arsenide superconductors (also see Fig. 2).

Compound		Sample	T_c (K)	$\Delta C/\gamma_n T_c$	Reference
$Ba_{1-x}K_xFe_2As_2$, hole-doped (BKFA)					
$x = 32\%$	(OP)	FeAs-flux	38.5	2.5	Popovich *et al.*[15]
KFe_2As_2, 100% hole-doped (K-122 or KFA)					
N/A		polycryst.	3.5	0.6	Fukazawa *et al.*[89]
$Ba(Fe_{1-x}Co_x)_2As_2$, electron-doped (BFCA)					
$x = 7.5\%$	(OD)	FeAs-flux	21.4	1.6	Hardy *et al.*[90]
$x = 5.75\%$	(OP)	»	24.3	1.6	Hardy *et al.*[4]
$x = 5.5\%$	(UD)	»	22.9	1.5	»
$BaNi_2As_2$, 100% electron-doped (BNA)					
N/A		Pb-flux	0.68	1.31	Ronning *et al.*[91]
PrFePO					
N/A		O_2-annealed	3.6	1.4	Baumbach *et al.*[92]
LaFePO					
N/A		Sn-flux	5.9	0.6 ± 0.2	Analytis *et al.*[93]
$LaNiAsO_{1-x}F_x$					
$x = 5.5\%$	(OP)	polycryst.	3.8	1.9	Li *et al.*[94]
$Li_{1+\delta}FeAs$, undoped (Li-111 or LFA)					
N/A		grains	17	1.2 ± 0.2	Wei *et al.*[41]
N/A		self-flux	16.9	1.24	Stockert *et al.*[42]
$FeTe_{1-x}Se_x$					
$x = 43\%$	(OP)	self-flux	14.7	2.11	Hu *et al.*[151]
$K_x(Fe_{1-\delta}Se)_2$ (KFS)					
$x = 0.8$		Bridgman	32	1.93	Zeng *et al.*[95]

TABLE V. Summary of the spin resonance energies (ω_{res}), corresponding onset energies of the particle-hole continuum ($2\Delta_>$), normalized resonance energies ($\omega_{res}/k_B T_c$), and the $\omega_{res}/2\Delta_>$ ratios in Fe-based superconductors.

Compound		Sample	T_c (K)	ω_{res} (meV)		$\omega_{res}/k_B T_c$		$2\Delta_>$ (meV)	$\omega_{res}/2\Delta_>$		Reference
				$q_z = 0$	$q_z = \pi$	$q_z = 0$	$q_z = \pi$		$q_z = 0$	$q_z = \pi$	
$Ba_{1-x}K_xFe_2As_2$, hole-doped (BKFA)											
$x = 40\%$	(OP)	polycryst.	38		14.0 ± 1.0		4.3 ± 0.3	22.9 ± 1.0		0.61 ± 0.05	Christianson *et al.*[104]
$x = 33\%$	»	self-flux	»	15.0 ± 1.0	16.0 ± 1.0	4.6 ± 0.3	4.9 ± 0.3	22.9 ± 1.0	0.66 ± 0.05	0.70 ± 0.05	Zhang *et al.*[103]
$Ba(Fe_{1-x}Co_x)_2As_2$, electron-doped (BFCA)											
$x = 4\%$	(UD)	self-flux	11		4.5 ± 0.5		4.7 ± 0.5	4.4 ± 0.9		1.0 ± 0.2	Christianson *et al.*[105]
$x = 4.7\%$	»	»	17	9.0 ± 1.0	5.0 ± 0.5	6.1 ± 0.7	3.4 ± 0.4	4.7 ± 1.3	1.9 ± 0.6	1.1 ± 0.3	Pratt *et al.*[106]
$x = 7.5\%$	(OP)	»	25	9.7 ± 0.5	9.0 ± 0.5	4.5 ± 0.3	4.2 ± 0.3	12.3 ± 0.9	0.79 ± 0.07	0.73 ± 0.07	Inosov *et al.*[99]
$x = 8\%$	(OD)	»	22	8.6 ± 0.5	8.6 ± 0.5	4.5 ± 0.3	4.5 ± 0.3	10.8 ± 0.8	0.80 ± 0.07	0.70 ± 0.05	Lumsden *et al.*[107]
$Ba(Fe_{1-x}Ni_x)_2As_2$, electron-doped (BFNA)											
$x = 3.7\%$	(UD)	self-flux	12.2	7.0 ± 0.8	5.0 ± 0.5	6.7 ± 0.8	4.8 ± 0.5	unknown (no direct measurements)			Wang *et al.*[100]
$x = 4.5\%$	»	»	18	8.9 ± 0.8	6.5 ± 1.0	5.7 ± 0.5	4.2 ± 0.6		»		Park *et al.*[101]
$x = 5\%$	(OP)	»	20	9.1 ± 0.4	7.2 ± 0.5	5.3 ± 0.3	4.2 ± 0.3		»		Chi *et al.*[108]
»	»	»	»	8.7 ± 0.4	7.2 ± 0.7	5.1 ± 0.3	4.2 ± 0.4		»		Li *et al.*[109]
»	»	»	»	8.0 ± 0.5		4.6 ± 0.3			»		Zhao *et al.*[110]
$x = 7.5\%$	(OD)	»	15.5	8.0 ± 2.0	6.0 ± 0.5	6.0 ± 1.5	4.5 ± 0.4		»		Wang *et al.*[100]
$BaFe_2(As_{1-x}P_x)_2$, isovalently substituted (BFAP)											
$x = 35\%$	(OP)	polycryst.	30		11.5 ± 1.5		4.5 ± 0.6	unknown (no direct measurements)			Ishikado *et al.*[111]
$LaFeAsO_{1-x}F_x$, electron-doped (La-1111)											
$x = 8\%$	(OP)	polycryst.	29		13.0 ± 1.0		5.2 ± 0.4	20.0 ± 1.2		0.65 ± 0.06	Shamoto *et al.*[102]
$Li_{1+\delta}FeAs$, undoped (Li-111 or LFA)											
N/A		polycryst.	17		8.0 ± 2.0		5.5 ± 1.4	6.1 ± 0.5		1.3 ± 0.4	Taylor *et al.*[119]
$FeTe_{1-x}Se_x$, isovalently substituted (11-family)											
$x = 0.4$	(OP)	self-flux	14		6.5 ± 0.5		5.3 ± 0.4	6.9 ± 1.2		0.94 ± 0.18	Qiu *et al.*[112]
»	»	»	»	6.0 ± 0.5		5.0 ± 0.4		»	0.87 ± 0.17		Argyriou *et al.*[113]
$x = 0.5$	»	unidirect. solidif.	»	6.2 ± 0.5		5.1 ± 0.4		»	0.90 ± 0.17		Wen *et al.*[114]
»	»	Bridgman	»	6.5 ± 0.5		5.3 ± 0.4		»	0.94 ± 0.18		Mook *et al.*[115,116]

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