Spin gap in heavy fermion compound UBe\textsubscript{13}

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Keywords: heavy fermion, spin gap, spin polaron

Abstract
Heavy fermion (HF) compounds are well known for their unique properties, such as narrow bandwidths, loss of coherence in a metal, non-Fermi-liquid behaviour, unconventional superconductivity, huge magnetoresistance etc. While these materials have been known since the 1970s, there is still considerable uncertainty regarding the fundamental mechanisms responsible for some of these features. Here we report transverse-field muon spin rotation (\(\mu^+\)SR) experiments on the canonical HF compound UBe\textsubscript{13}, in the temperature range from 0.025 to 300 K and in magnetic fields up to 7 T. The \(\mu^+\)SR spectra exhibit a sharp anomaly at 180 K. We present a simple explanation of the experimental findings identifying this anomaly with a gap in the spin excitation spectrum of \(f\)-electrons opening near 180 K. It is consistent with anomalies discovered in heat capacity, NMR and optical conductivity measurements of UBe\textsubscript{13}, as well as with the new resistivity data presented here. The proposed physical picture may explain several long-standing mysteries of UBe\textsubscript{13} (as well as other HF systems).

1. Introduction

In strongly correlated metallic materials, the interplay between local spins and itinerant electrons determines the spin fluctuation spectrum. In a 3\textit{d}-electron system, such a spectrum emerges as a result of strong dominance of the Fermi energy over the magnetic energy [1]. By contrast, in \(f\)-electron itinerant systems the Fermi energy is heavily renormalized down to the scale of the magnetic energy [2], resulting in a strong influence of the spin dynamics and spectral weight of spin fluctuations on transport, magnetic and thermodynamic properties. A depletion of spectral weight upon cooling may indicate the opening of a gap (or pseudogap) in the spectrum of spin fluctuations.

The concept of a pseudogap has recently become essential for understanding strongly correlated electron systems [3]. The pseudogap, a state characterized by a partial gap and loss of coherence in the electronic excitations, has been associated with many physical phenomena in a variety of materials ranging from cold atoms to colossal magnetoresistive manganites to copper oxide superconductors etc. Particularly interesting is the opening of a gap in a system of \(f\)-electron spin excitations [4, 5]. At low temperature, such systems display a continuous transition from an array of uncorrelated local magnetic moments to a Fermi-liquid (FL) phase in which \(f\)-electrons are strongly hybridized with conduction band electrons [6]. As a result, \(f\)-electrons not only create a sharp resonance at the Fermi level, giving rise to a large effective mass \(m^*\) of quasiparticles, but also transfer their magnetic entropy to the Fermi surface [6]. In this case, a gap may open up as found in URu\textsubscript{2}Si\textsubscript{2} at \(T = 17.5\) K [5]. In this article, we discuss a spin gap opening in the canonical heavy fermion (HF) compound UBe\textsubscript{13}. 

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UBe$_{13}$ crystallizes in the cubic NaZn$_{13}$ structure with a lattice constant $a = 1.025$ nm. The U atoms form a simple cubic sublattice with a rather large U–U spacing, suggesting strong hybridization with the itinerant carriers [4]. Unlike in other uranium-based HF compounds, there is no evidence for static magnetic order in UBe$_{13}$, although finite-range antiferromagnetic (AFM) correlations have been reported [7]. In UBe$_{13}$, superconductivity (SC) arises from a paramagnetic (PM) metallic phase as a cooperative phenomenon involving heavy quasiparticles that form pairs [3, 8]. The susceptibility $\chi$ exhibits typical Curie–Weiss behaviour at high temperature with $\mu_{\text{eff}} \approx 3.36 \mu_B$ but deviates from this law below 200 K and then levels off at 20 K [9].

Interest in UBe$_{13}$ is reinforced by various observations of a non-Fermi-liquid (NFL) behaviour [4, 9–12], often explained by the proximity to the quantum critical point [10, 11, 13], which challenges the validity of the quasiparticle concept. However, various experiments indicate a dominant role of quasiparticles, although the specific quantum states that might replace the Fermi liquid remain unclear [13]. Quite remarkably, the FL behaviour in UBe$_{13}$ (as in some other HF systems) is restored by application of a strong magnetic field [11]. Another remarkable feature which requires further explanation is that while UBe$_{13}$ displays coherent quasiparticle behaviour at low temperature, at higher temperature it exhibits an incoherent metallic state dominated by spin-flip scattering [11, 14].

The unconventional SC of UBe$_{13}$ suggests the opening of a spin gap, as it protects paired electrons from spin exchange with the environment, which is detrimental to SC. The robustness of the superconducting state with respect to magnetic fields indicates that the characteristic temperature of the onset of the spin gap is not low. Surprisingly, despite a wealth of experimental data the opening of a spin gap in UBe$_{13}$ has not been detected. It well may be caused not by a lack of data but by the absence of a consistent theory explaining the entire set of experiments. It is well known that neither NFL nor loss of coherence phenomena can be explained by the quadrupolar Kondo effect [10]. Furthermore, band energy calculations produce an $m^*$ value that is at least an order of magnitude too low [15]. Moreover, band theory fails to explain the loss of coherence.

In order to identify the fundamental electronic state that is consistent with the crucial experimental results, various polaron models have been proposed among others [15, 16]. Although electronic and magnetic polaron models face their own difficulties, they both may account for the NFL behaviour and loss of coherence, and produce a correct $m^*$ [15]. The electronic polaron model fails to explain the strong influence of magnetic field. By contrast, the spin polaron (SP) model [16] offers an electronic state that may help to reconcile theory with experiment. In particular, the SP model [17, 18] offers a straightforward explanation of a major puzzle in UBe$_{13}$—a remarkable magnetoresistivity (MR) [9]. Both MR and magnetostriction indicate that the carrier number is a strong function of magnetic field, as if ‘the carrier is released by $B$’ [12]. The remarkable sensitivity of the electron transport to magnetization (an order of magnitude stronger than in hole-doped manganites) may be explained by carrier localization into SP and their release by magnetic field. Recent observation of SP in magnetoresistive Lu$_2$V$_2$O$_7$ [19] supports this model.

Below we present a combination of new muon spin rotation and resistivity measurements exhibiting a distinct anomaly at about 180 K. We also provide a set of arguments in support of the spin gap opening at this temperature.

2. Experimental section

Standard measurements to characterize lattice constants, resistivity behaviour, $T_c$ and effective magnetic moments are performed and show that the properties of our single crystal samples are consistent with the literature data. Magnetization measurements in magnetic fields up to 7 T are carried out using SQUID Quantum Design. Standard 4-point DC resistivity measurements are carried out using ohmic contacts based on Ga–Sn eutectic system.

Time-differential $\mu^+\text{SR}$ experiments are carried out in the temperature range from 0.025 to 300 K, with magnetic fields $B$ up to 7 T, on the M15 surface muon channel at TRIUMF using the HiTime and DR spectrometers.

Muon spin rotation utilizes positively charged, 100% spin polarized muons implanted into a sample where an external magnetic field is applied either transverse (TF or $T_2$ measurements) or parallel (LF or $T_1$ measurements) to the initial spin polarization direction. The time evolution of the $\mu^+$ spin polarization, $P_\mu(t)$, is measured by monitoring positrons emitted preferentially along the $\mu^+$ spin direction, at the time of decay. The raw experimental measure is a positron count, binned by time of decay, that is then used to determine $P_\mu(t)$. A detailed outline of the $\mu^+$ SR technique is given in [20–22].

A typical TF spin polarization function can be modeled in the form

$$P_\mu(t) = \sum_n A_n G_n(t) \cos(2\pi\nu_n t + \phi_n),$$

(1)
where the $\mu^+$ in site (or state) $n$ precesses at the Larmor frequency $\nu_n$. The amplitude $A_n$ is a measure of signal intensity, which directly correlates to the probability of a $\mu^+$ persisting in state $n$. The relaxation function $G_n(t)$ characterizes the way in which the measured time evolution of the precessing signal is damped, which relates to the distribution of local fields and their dynamics. The initial phase $\phi$ accounts for any apparent shift of the beginning of $\mu^+$ precession. Typically, $G_n(t)$ is assumed to have the exponential form $G_n(t) \sim \exp(-t/T_n)$ for TF experiments. In LF studies, the non-oscillatory signal decays as $G_n(t) \sim \exp(-t/T_f)$.

### 3. Results

#### 3.1. Muon spin rotation studies

We carried out two sets of time-differential $\mu^+$ SR experiments [20–22]. One is based on implanting muons into single crystal samples. The other set of measurements is performed with a mosaic of crystals oriented randomly with respect to the direction of the external magnetic field. At high temperature, Fourier transforms of the $\mu^+$ SR time spectra exhibit a single line at the 'bare' muon frequency, $\nu_n = \gamma_B B/2\pi$ (where $\gamma_B = 2\pi \times 135.538 \, 79 \, \text{MHz} \, \text{T}^{-1}$ is the muon magnetogyric ratio), which coincides with that detected in a CaCO$_3$ reference sample used for independent measurements of $B$. However, below $T^* \approx 180 \, \text{K}$ such simple spectra change abruptly to reveal a characteristic doublet (figure 1) which persists down to the lowest temperature (figure 2).

Previous observations of such two-line spectra [23, 24] prompted a suggestion of two inequivalent (in magnetic field) sites (halfway between neighbouring U atoms) occupied by positive muons in UBe$_{13}$. The interpretation is based on the physical picture of the muon staying 'bare' and acting as a local magnetometer. This is a conventional and well-respected method of analysis of $\mu^+$ SR spectra leading to excellent results for numerous systems. However, this two-site assignment model, when applied to UBe$_{13}$ implies well-defined dipolar contributions, which can be verified. Unexpectedly, the splitting of the lines turned out to be about 1.5 times smaller than predicted [23] while the ratio of dipolar contributions for the two signals (obtained from fits of experimental data) was only $-0.66$ (see equation (2) of [23]), to be compared with the theoretical value of $-2$ — a qualitatively incorrect prediction.

Previous $\mu^+$ SR studies were carried out at low temperature only. In the present work we extended the experiments to higher temperature and magnetic field. However, instead of reconciling theory and experiment, our attempts to employ the standard interpretation model [23, 24] face additional difficulties, which are not limited by the anomaly at 180 K. The two-site assignment suggests a temperature independent strict 1:2 muon site occupation ratio [23, 24] while the experiment shows a slightly temperature dependent amplitude ratio of $0.40 \pm 0.05$. Furthermore, the frequencies of both lines do not follow the temperature dependence of the magnetization (figure 3). Specifically, the lower frequency signal does not follow the reversed magnetization which would be the case if the hyperfine coupling of the 'bare' muon with the environment is negative. One expects significant magnetic anisotropy on the order of 2% [25] in the position and splitting of the two lines when the magnetic field is applied along different crystalline axes. The results of our experiments with a piled up
mosaic of randomly oriented small crystals match those coming from oriented single crystal. Even by attributing the entire linewidth to the anisotropy, it does not exceed 0.2%.

In short, we are not able to construct a coherent explanation of the entire set of experiments within the framework of the standard interpretation scheme. Inevitably, it impels us to look for alternative models. After all, it should not be surprising that interpretation of experiments on unconventional compounds may require unconventional physical models.

The doublet in figures 1 and 2 may originate from a coupled $\mu^+e^-$ spin system in high transverse magnetic field [19, 20, 22, 26–31]: the two lines correspond to two muon spin-flip transitions between states with the electron spin orientation fixed, the splitting between them being determined by the muon-electron hyperfine interaction $A$ [26, 27]. The temperature behaviour of lines with one line going up in frequency and the other going down as temperature decreases is often a signature of a muon-electron bound state [20, 22].

In a metallic magnetic system, the itinerant electron’s energy depends strongly on the magnetization, with the minimum energy being achieved by ferromagnetic (FM) ordering [32]. Then the strong $s\leftrightarrow f (d)$ exchange interaction between a carrier and local $f (d)$-moments can cause electron localization into an FM ‘droplet’ in a PM (or AFM) sea—a SP [32–34]. In the process of electron localization into SP in a metal, the exchange energy gain upon transition from the PM to the FM state is opposed by an increase of the electron kinetic energy (the entropy term due to ordering within SP becomes significant only at very high $T$) [26, 27, 29, 30]. Application of magnetic field releases the carrier from SP into the conduction band—a process which offers not only an explanation of the huge negative MR but also reveals the reason why the carrier number is a strong function of...
magnetic field in UBe$_{13}$. This effect may be relevant to earlier studies on suppression of HFs by high magnetic fields of a few dozen tesla [35–37]. Such SP states have been previously invoked to explain $\mu$ SR spectra in strongly correlated insulators [28, 38], semiconductors [26, 27, 31] and metals [29, 30]. The latter reference initiated a debate on SP formation in MnSi [39, 40]. In metals, $\mu + e$ SP hyperfine splitting is revealed through the frequency splitting $\Delta \nu$ between the two SP lines (figure 4). In UBe$_{13}$, $\Delta \nu$ is proportional to the external field for the entire temperature and field range because the Curie–Weiss constant $\Theta$ is large and negative (around $-100$ K, see [9]) and the argument of the Brillouin function [26, 27, 29, 30] is always small. The absence of saturation does not allow for determination of the spin $S$. We can only determine that $A (S + 1)$ is about 425 MHz. Nevertheless, by assuming the polaron state to be of the $1s$-type and expressing both $A$ ($A \propto R^{-3}$) and $S$ as functions of the SP size $R$, one can find a self-consistent solution: $A \approx 45$ MHz, $S \approx 8.5$, $R \approx 0.25$ nm. It corresponds to an electron wavefunction overlapping $f$-orbitals of the two neighbouring U ions—each having a magnetic moment $\mu_{U} = g\mu_{B}(S + 1/2)/2 = 3.6 \mu_{B}$, which is close to the $\mu_{eff}$ found from the susceptibility measurements.

In a PM, strong spin exchange with the environment [20, 22] would result in rapid spin fluctuations of the SP electron, averaging the hyperfine interaction to zero, thereby resulting in a collapse of the doublet into a single line at $\nu_{0}$ (see [26, 41, 42] for details) unless the SP spin is decoupled from the local spins [26, 27, 29, 42]. Such decoupling is possible in high $B$ when the Zeeman energy of $S$ exceeds an exchange interaction $J$ between local spins—this is the case in magnetic insulators where the SP doublet is detected up to very high temperature [19, 26–28]. In metals, RKKY interactions make $J$ much stronger, so that decoupling requires $B$ strengths that are inaccessible in the current experiment. In UBe$_{13}$, in a magnetic field $H = 1$ T the Zeeman energy associated with SP ($S \approx 8.5$, see above) amounts to about 5 K. This energy scale should be set against the characteristic exchange coupling $J$ in UBe$_{13}$, for which the PM Curie–Weiss constant $\Theta \sim 100$ K [9] (see also our measurements: inset in figure 6) makes a good estimate. Thus the magnetic field required for the Zeeman energy to overcome $J$ exceeds 20 T, rendering a magnetic field decoupling regime inaccessible in the current experiment. This explains the single line above 180 K, which by no means indicates the absence of the SP above 180 K—just active spin exchange with the environment [26, 27, 29, 42]. Within the SP physical model the abrupt appearance of the doublet at 180 K (figures 3 and 4) is naturally interpreted as the opening of a spin gap that eliminates low-lying spin excitations, thereby making spin exchange of $S$ with its environment ineffective.

This interpretation has to be set against another possibility—fast muon diffusion above 180 K, which may lead to collapse of the doublet into a single line. However, this diffusion (if any) takes place on a background of very fast spin fluctuations of the host U spins. Within the thermally activated muon diffusion model, the muon hop rate is expressed as $\tau_{\text{diff}}^{-1} = \tau_{\text{ph}} \exp(-E/T)$, where $\tau_{\text{ph}} \sim 10^{3}$ s$^{-1}$ is the characteristic phonon frequency and $E$ is the activation energy. Typical activation energies for muon diffusion in crystals amount to $10^{3} - 10^{4}$ K. Then $\tau_{\text{diff}}^{-1}$ in UBe$_{13}$ at about 200 K can be estimated as $\sim 10^{9}$ s$^{-1}$. As the frequency $\tau_{\text{diff}}^{-1}$ of the spin fluctuations of U spins is at least an order of magnitude higher than $\tau_{\text{diff}}^{-1}$, the muon spin relaxation $T_{2}^{-1}$ due to spin fluctuation greatly exceeds that due to muon diffusion. Thus the influence of muon diffusion in UBe$_{13}$ is

![Figure 4](image-url)
dwarfed by the U spin dynamics and can hardly influence the muon spin relaxation over the entire measured temperature range.

The above discussion does not apply for the very specific case of the muon local diffusion between the two meta-stable sites. In transverse magnetic field, if the muon precession frequency becomes much smaller than its hop rate between these sites at 180 K, the doublet would collapse into a single line. However, anomalies discovered at 180 K by several different techniques which do not involve the muon—specific heat [43], NMR [44] or optical conductivity [14]—do imply that these anomalies relate to UBe$_{13}$ system itself rather than the muon local diffusion.

The explanation which invokes spin gap opening at 180 K is consistent with anomalies in specific heat [43], NMR [44] and optical conductivity [14], which are discussed in terms of crystal field splitting of the $5f^3$ U ion with characteristic energy $\sim$180 K. Below we provide additional arguments in favour of the spin gap opening.

### 3.2. Muon spin relaxation

Time-domain fits of $\mu^+\text{SR}$ spectra consisting of two oscillating components also show an anomaly consistent with a gap opening at $T_{sg} = 180$ K (figure 5) in terms of spin fluctuations. The muon spin relaxation rate in transverse magnetic field, $T_2^{-1}$, provides a measure of the magnetic field inhomogeneity at the muon site(s) and gives information on the rate of U spin fluctuations, $\tau_\text{fl}^{-1}$. Specifically, in the static limit (slow spin fluctuation limit), $T_2^{-1} = \delta$, while in the fast spin fluctuation limit $T_2^{-1} \sim \delta^2 \tau_\text{fl}^{-1}$, where $\delta = \gamma_\mu B$ [20, 22] ($\Delta B \sim B_{loc}$) gives the width of the distribution of local magnetic field $B_{loc}$ experienced by the muon ensemble in a fluctuating spin environment. A simple estimate of the dipolar magnetic field at the muon site in the static limit [23] due to U magnetic moments of $3.36$ $\mu_B$ yields $B_{loc} \sim 0.7$ T, giving $\delta \sim 10^8$ s$^{-1}$. As the spin fluctuation rate $\tau_\text{fl}^{-1}$ of a disordered paramagnet amounts to about $10^{10}$–$10^{12}$ s$^{-1}$, UBe$_{13}$ is in the fast fluctuation limit $\tau_\text{fl} \ll 1$ over the entire measured temperature range (consistent with the absence of magnetic ordering in UBe$_{13}$). In the fast fluctuation limit, $T_2^{-1} = T_t^{-1}$, where $T_t^{-1}$ is the muon relaxation rate in longitudinal magnetic field. This is consistent with earlier studies [45] which exhibited $T_1^{-1}(T)$ very close to our $T_2^{-1}(T)$ as well as our $T_t^{-1}(T)$ measurements (inset in figure 5). Very similar arguments and formalism are presented in diffusion studies based on $T_1^{-1}(T)$ and $T_2^{-1}(T)$ measurements [46, 47]. The advantage of $T_2^{-1}$ studies is that one can follow the behaviour of every single line, corresponding to every single transition, whereas $T_1^{-1}$ measurements reveal only a complicated average relaxation.

As the temperature decreases, spin fluctuations slow down until they disappear abruptly at 180 K. It can be naturally associated with elimination of low-lying spin excitations at the gap opening, which manifests itself as a sharp anomaly in the muon $T_2^{-1}$ (figure 5). As a crude estimate, the width of the spin gap $\Delta_{\text{spin}} \sim T_{sg}$ is surmised to be 180 K. Experimental measurements of both the spin gap and the temperature dependence of the relaxation rate in other materials [48] show that such estimates are quite accurate. Remarkably, in the vicinity of the transition at $T_{sg}$, where $\Delta_{\text{spin}}$ has only started to open, the relaxation rates of the two lines differ significantly. The probable explanation is based on Zeeman splitting of the SP species (parallel and antiparallel to the magnetic field), which amounts to a good portion of $\Delta_{\text{spin}}$ due to the high value of the SP spin $S$. Specifically, since the
muon spin relaxation rate can be approximated as $T_2^{-1} \sim \exp(-\Delta_{\text{spin}}/T)$ within the SP model, the relaxation rate of the low-frequency line ($S$ antiparallel to $\vec{B}$) should be significantly higher than that of the high-frequency line ($S$ parallel to $\vec{B}$) because $\Delta_{\text{spin}}$ is reduced by the Zeeman splitting for the former and increased accordingly for the latter. By contrast, in the bare muon model both relaxation rates should be the same, because the Zeeman splitting is very small due to the small muon magnetic moment. Accordingly, in the bare muon model it is the low-frequency line which corresponds to lower $B_{\text{loc}}$ and therefore should have lower $T_2^{-1}$—i.e. there is a qualitative discrepancy between this model and the experiment. We view these data as an additional argument in favour of the SP model revealing a spin gap opening at 180 K.

3.3. Resistivity measurements

Our measurements of the electric resistivity $\rho$ in the same single crystals (figure 6) are consistent with the opening of a spin gap in UBe$_{13}$ near 180 K. The basic behaviour of $\rho$ in UBe$_{13}$ involves carrier scattering in metals with local spins [49–51]: below 300 K, $\rho$ is dominated by such scattering [52]; at high temperature, $\rho$ consists of a temperature-independent local scattering term and a $1/T$ term due to scattering on paramagnons [49–51]. At still lower temperature, Kondo scattering takes over. A crossover from $\rho(T) = A/T + C$ to $\rho(T) = D \ln(E/T)$ at about 180 K signifies a characteristic change in the spin fluctuation spectrum of the system. Fits to the data yield the following values: $A = 8.5 \times 10^{-3}$ Ohm cm K, $C = 94 \times 10^{-6}$ Ohm cm, $D = 47.4 \times 10^{-6}$ Ohm cm and $E = 3500$ K. At high temperature, the largest contribution to $\rho$ comes from carriers with small momentum $q \sim 0$ [49–51] scattered by low-lying excitations. As the spin gap opens up, eliminating such excitations, both $1/T$ and $C$ contributions are dwarfed. On the other hand, opening of the spin gap promotes resonant Kondo scattering effective at significant $q$ and energy [53]. Moreover, disappearance of the low-lying spin excitations causes strong suppression of long-wavelength magnetic fluctuations accompanied by deviation of $\chi$ from the Curie–Weiss law at 180 K, observed in the $\Theta(T)$ dependence (inset in figure 6). Local values of the Curie–Weiss constant $\Theta(T)$ are extracted approximating the measured magnetic susceptibility to a Curie–Weiss law $[\text{const}/(T-\Theta(T))]$ for 10 K intervals in the temperature range from 5 K to 285 K. A similar procedure is implemented in [9]. Opening of the spin gap might be explained by the position of an $f$-level lying 180 K below the Fermi surface.

4. Discussion

It is important to add some remarks on the plausibility of the physical picture of SP in UBe$_{13}$. There are no smoking-gun experiments detecting SP in HF systems. At the moment, the concept is speculative. It should also be noted that the SP model has a qualitative character and further work is necessary to make it quantitative. A standard approach to HF behaviour considers, as a starting point, a set of strongly localized $f$-electrons; the appearance of a new energy scale results from hybridization of conduction electrons with local $f$-moments so that heavy quasiparticles appear on the Fermi surface. An alternative approach [54] starts from a delocalized band carrier whose transport depends on the strength of its coupling with excitations of the medium: in the limit of strong coupling, an electron accompanied by lattice or spin excitations forms a quasiparticle—a polaron. As is
the case for the well-known lattice polaron, formation of SP may profoundly renormalize the bare electron band (bandwidth $\Delta_0 \sim 1$ eV) into an extremely narrow ($\Delta_{SP} \sim 10^{-4} \sim 10^{-3}$ eV) SP band [32]. At low temperature, such an SP band supports coherent SP dynamics [31]. As SP have spin higher than 1/2, they do not need to follow a FL state—hence NFL behaviour is possible. At still lower temperature, formation of spin bipolarons might cause SC [29, 55]. In that case the opening of a spin gap is a ‘must have’ ingredient, as it protects paired electrons from spin exchange with the environment, which otherwise destroys pairs. At higher $T$, however, the SP dynamics occurs against a background of strong coupling to spin fluctuations, which destroys coherence. A dramatic renormalization of the SP band is expected to go hand-in-hand with a significant increase of the electron effective mass, which may allow for an application of general concepts developed for coherent-to-incoherent crossover of the tunnelling dynamics of heavy particles: suppression of coherence in the metal is expected at $T \sim \Delta_{SP}$ [47]. As a result, at high temperature SP are characterized by incoherent hopping transport and the band picture breaks down. However, at low temperature the band picture manifests itself in a coherent transport of heavy quasiparticles—SP. Thus, such an SP description allows us to arrive at results qualitatively similar to the standard approach to HF, albeit without involvement of the Kondo screening. A noteworthy advantage of such an approach is that it naturally accounts for the loss of coherence at higher temperature. At the moment, however, it is difficult to capture the low-temperature physics of HF compounds with a single concept of SPs. The situation is not very much different for other models which face their own problems. For example, the two-fluid Kondo lattice model captures many aspects of HF behaviour and can be used to quantitatively fit the so-called Knight shift anomaly in $\mu^+\text{SR}$ spectra of UBe$_{13}$ [56], but it does not include interactions that would lead to low temperature broken symmetries [57]. The calorimetric data [43] suggest that as long as UBe$_{13}$ belongs to the universal class of Kondo systems it should exhibit a narrow quasielastic scattering peak with a width of about 8 K. This peak has not been detected. Notice that such a peak is not expected when the SP model is adopted. Also, the spin gap opening at about 180 K explains both the Schottky anomaly [43] and the wide Lorentzian peak of magnetic fluctuations [58] by magnetic excitations over the gap. We see that no model is universal; SP is not an exception. The latter is worthy to join the fray since it well describes the high-temperature $\mu^+\text{SR}$ data and may be useful in explaining other properties of UBe$_{13}$ such as the huge magnetoresistive effect.

5. Conclusions

In summary, we carried out a set of muon spin resonance measurements on single crystalline HF compound UBe$_{13}$. To explain the observed behaviour, we considered two physical models of the muon in metal: conventional ‘bare muon’ model and SP model. Both models have advantages and drawbacks but the latter seems to provide a coherent picture, especially taking into account the reported transport and magnetization measurements. Undoubtedly the models require additional experimental and theoretical studies, and we hope that our work will stimulate further research. Adoption of the SP interpretation model leads to immediate realization that the anomaly at 180 K is due to opening of a spin gap in UBe$_{13}$. A crucial advantage of the reasoning based on SP is that it connects our results with other puzzling properties of UBe$_{13}$ such as NFL behaviour, loss of coherence, and huge magnetoresistance. Our recent studies show that the emergence of SP might be a general phenomenon in HF systems, in which SP behaves as a HF, as we have found characteristic doublets in several other HF systems, utilizing the same $\mu^+\text{SR}$ measurement technique.

Acknowledgments

This work was partially supported by the Kurchatov Institute, NSERC of Canada, the US DOE, Basic Energy Sciences (grant DE-SC0001769), Russian Foundation for Basic Research (grants 16-07-00204 and 16-29-03027) and Russian Science Foundation (grant 14-19-00662).

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