Observation of $1/k^4$-tails in the asymptotic momentum distribution of Bose polarons

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We measure the asymptotic momentum density in a Bose-Einstein condensate with dilute spin impurities, after an expansion in the presence of interactions. In the absence of impurities, we confirm the theoretical scenario of C. Qu et al. [Phys. Rev. A 94, 063635 (2016)] according to which signatures of the quantum depletion at large momenta vanish during an expansion of an interacting Bose-Einstein condensate. When impurities are present, we observe tails decaying as $1/k^4$ at large momentum $k$ in the condensate and in the impurity cloud. These results highlight the key role played by impurities when present, a possibility that had not been considered in our previous work R. Chang et al. [Phys. Rev. Lett. 117, 235303 (2016)]. We show that the algebraic tails originate from the impurity-BEC interaction, but that their amplitudes greatly exceed those expected for the in-trap contact of weakly-interacting Bose polarons. This discrepancy may be due to the non-trivial dynamics of the expansion in the presence of bath-impurity interactions.

Impurities strongly affect the properties of low-temperature ensembles of particles. Well-known examples range from the Kondo effect [1–4], to quantum localization [5–7] and polar crystals [8, 9]. Similarly, the transport of massive impurities strongly depends on the medium in which they propagate and scatter, as illustrated in experiments conducted with gaseous Bose-Einstein condensates (BECs) as a bath [10–16]. Impurities can also serve as accurate probes for equilibrium and out-of-equilibrium properties of their many-body environment [17–21]

Theoretical approaches introduce a quasi-particle, the polaron, which describes the dressing of the impurity by the collective excitations of the bath [22, 23]. In quantum gas experiments, such descriptions were validated both in ensembles of bosons [24] and of fermions [25]. Furthermore, the capability to tune interaction strengths in atomic gases permitted detailed studies beyond the weakly-interacting regime [26–28] and tests of theories in the unitary regime [29]. However, recent theoretical work [30–32] illustrated the need for a precise knowledge of the impurity-bath interaction to accurately describe Bose polarons and quantities such as their energy. Tan’s contact predicted for Bose polarons [24]. This suggests that the expansion dynamics of the bath-impurity system play a central role in our observation.

Our experiment also addresses a previous observation of $1/k^4$-tails in an expanding BEC [34]. That experiment was conducted under identical conditions as the present work: the same impurities were very likely present but we did not attempt to detect them. In this work, we show that the tails disappear when the impurities are removed from the BEC, and therefore we experimentally confirm the prediction of [35] which states that the $1/k^4$-tails adiabatically vanish in an expanding, pure BEC. Our results are to be contrasted with a recent study [36] which observed $1/k^4$-tails after an expansion in an interacting, pure BEC.

In our experiment the bath is a BEC of metastable Helium-4 ($^4{\text{He}}^*$) atoms in the $m_J = +1$ sub-level and the impurity gas is composed of a small number of $^4{\text{He}}^*$ atoms in the $m_J = 0$ sub-level (see below). The impurity-bath scattering length $a_{1B} \approx 142 \ a_0$ is equal to the scattering length within the BEC, $a_{BB} \approx 142 \ a_0$ [37], with $a_0$ the Bohr radius. Our experiment starts with the production of a degenerate Bose gas of $^4{\text{He}}^*$ atoms in a crossed optical dipole trap [38]. The evaporation to BEC is performed with (most of) the $^4{\text{He}}^*$ atoms polarised in the $m_J = +1$ magnetic sub-level to avoid the large inelastic collisions present in non-polarised $^4{\text{He}}^*$ gases [37]. The polarisation of the atoms is maintained in the optical trap with a magnetic bias field of $\sim 4 \ G$. 

The ODT frequencies at the end of the evaporation are $\omega_x/2\pi = 110$ Hz, $\omega_y/2\pi = 400$ Hz and $\omega_z/2\pi = 420$ Hz. This procedure does not ensure a full spin-polarisation of the gas. Indeed, we recently discovered that a small fraction ($f_I \lesssim 1\%$) of spin impurities ($m_J = 0$ atoms) is present in the trap. These impurities originate from spin flips occurring during the loading of the optical trap from a magnetic quadrupole trap [38]. This unanticipated experimental situation is an opportunity to study the properties of Bose polaron. Because $a_{BB}$ and $a_{1B}$ are equal, the mean-field interaction of impurities with the BEC exactly cancels the effect of the trap. As a consequence, spin impurities are trapped in a flat-bottom potential in the region where the BEC is present. Note that spin impurities in the $m_J = -1$ magnetic sub-level, if present after the optical trap loading, are rapidly lost in the presence of a BEC and expected to play no role in our observations. These rapid losses are due to the large rate of Penning collisions between $m_J = -1$ and $m_J = +1$ atoms, which exceeds by four orders of magnitude that between $m_J = 0$ and $m_J = +1$ atoms [37].

In the following, we concentrate on the tails of the asymptotic momentum density at large momenta, exploiting our ability to record extremely dilute gases of $^4\text{He}$*. Our investigation builds upon (i) tuning the number of impurities and the atom number in the BEC independently, and (ii) detecting selectively the spin sub-levels. We vary the BEC atom number $N_{\text{BEC}}$ from $1 \times 10^4$ to $1 \times 10^6$ by modifying the shape of the optical trap during the evaporation process [39]. The impurity fraction $f_I$ is varied between 0.05% and 1% using optical pumping and varying holding times in the trap [39]. Once we have prepared the trapped gas in the conditions we are interested in, we switch off the trap and let the gas expand in free-fall for a long time-of-flight (TOF) $t_{\text{TOF}} = 298$ ms. Exploiting the different magnetic properties of $m_J = +1$ and $m_J = 0$ atoms, we selectively detect the two spin sub-levels. More precisely, we can choose to detect the atoms initially trapped in the $m_J = 0$ state by pulsing a magnetic gradient during the expansion to push the $m_J = +1$ atoms away from the detector (see Fig. 1a). Alternatively, we apply a radio-frequency pulse (of duration 30 $\mu$s) after 1 ms of expansion, to transfer a known fraction of $m_J = +1$ atoms into the $m_J = 0$ state before adding the magnetic pulse. The use of the rf pulse results in the detection of both initially trapped $m_J = +1$ and $m_J = 0$ atoms (see Fig. 1b). In the following, we discuss the measurements that exploit these two possibilities.

In a first set of experiments, we concentrate on measuring the asymptotic momentum density $\rho_I(k)$ of the impurity atoms plotted as a function of $k$. In the presence of a spin-polarised BEC in $m_J = +1$ (green dots) $\rho_I$ exhibits algebraically decaying tails, compatible with $1/k^4$ (dashed-dotted black line). The red dashed line is a fit with a Gaussian function. Inset: in the absence of a spin-polarised BEC in $m_J = +1$ (black dots), $\rho_I$ is well-fitted by a Gaussian function corresponding to the momentum density of an ideal Bose gas at $T \simeq 200$ nK (red dashed line).

FIG. 1. (a) To detect only spin impurities ($m_J = 0$), a magnetic gradient is applied during the expansion to push the BEC atoms ($m_J = +1$) away from the detector. (b) To probe simultaneously BEC atoms and impurities, a radio-frequency (RF) pulse couples the atomic states independently, and number of impurities and the atom number in the BEC between $m$ atoms, which exceeds by four orders of magnitude that $m$ of Penning collisions between observations. These rapid losses are due to the large rate the presence of a BEC and expected to play no role in our observations. Note spin impurities in the $m_J$ potential in the region where the BEC is present. As a consequence, spin impurities are trapped in a flat-bottom sequence, spin impurities are trapped in a flat-bottom potential

FIG. 2. Asymptotic momentum density $\rho_I$ of the impurity atoms plotted as a function of $k$. In the presence of a spin-polarised BEC in $m_J = +1$ (green dots) $\rho_I$ exhibits algebraically decaying tails, compatible with $1/k^4$ (dashed-dotted black line). The red dashed line is a fit with a Gaussian function. Inset: in the absence of a spin-polarised BEC in $m_J = +1$ (black dots), $\rho_I$ is well-fitted by a Gaussian function corresponding to the momentum density of an ideal Bose gas at $T \simeq 200$ nK (red dashed line).
ratio in \( \rho_t \) by taking a spherical average. The dataset in the main panel of Fig. 2 is recorded with a number of atoms in the BEC \( N_{\text{BEC}} = 4 \times 10^5 \), and a fraction of impurities \( f_I \approx 0.5 \% \). The asymptotic momentum density \( \rho_t \) exhibits algebraic tails decaying as \( 1/k^4 \). By contrast, the inset shows the same quantity measured in the absence of a BEC, so that only the impurity cloud is present in the trap. To eliminate the BEC from the trap, we added a magnetic gradient strong enough to expel the sub-level \( m_J = +1 \), while keeping the atoms in \( m_J = 0 \) optically trapped. As shown in the inset of Fig. 2, the density \( \rho_t \) without the BEC does not exhibit algebraic tails, and it is well fitted by a Gaussian function modeling a thermal gas at \( T = 200 \) nK. This indicates that algebraic tails are observed in \( \rho_t \) only in the presence of a BEC.

In a second set of experiments, we measure the asymptotic momentum density of a cloud in which a known fraction of the trapped \( m_J = +1 \) BEC atoms is transferred to the He\(^*\) detector (see Fig. 1b). We repeat the experiment and analysis performed in [34] but in a regime where the fraction of spin impurities in the BEC is lowered to our smallest possible value \( f_I \approx 0.05 \% \). For a direct comparison with [34], we introduce the “apparent contact” \( C = (2\pi)^3 A \) from the measured amplitude \( A = k^4 \times \rho(k) \) of the tails (fitted over the momentum range \( 2 \mu m^{-1} - 6 \mu m^{-1} \)), and in Fig. 3 we plot \( C \) divided by the BEC atom number \( N_{\text{BEC}} \). We stress that the apparent contact \( C \) is obtained from analyzing the atomic densities measured after an expansion in the presence of interactions. Therefore, the apparent contact will generally differ from Tan’s contact at equilibrium in the trap.

The values \( C/N_{\text{BEC}} \) measured at small impurity fraction \( f_I \) lie much lower than those found previously [34] and are consistent with zero (see Fig. 3). This highlights the central role played by the impurities in the findings we previously reported in [34]. In particular, this rules out the hypothesis that the tails are a direct signature of the quantum depletion of the spin-polarized BEC. Indeed, the resulting fitted amplitudes are much smaller than Tan’s contact \( C_{\text{Bogo}}^{B} \), associated to the quantum depletion of a trapped spin-polarized BEC [34],

\[
C_{\text{Bogo}}^{BB} = (64/7) \pi^2 a_B^2 n_{\text{BCE}} N_{\text{BEC}},
\]

where \( n_{\text{BEC}} \) indicates the BEC density at the trap center. Eq. (1) is obtained starting from Tan’s contact for a homogeneous BEC, \( C_0 = 16 \pi^2 a_B^2 n_{\text{BCE}} N_{\text{BEC}} \), and using a local density approximation (LDA) in the trap [34]. The validity of the LDA is ensured by \( \xi \lesssim 0.4 \mu m \ll R_x \approx 15 \mu m \), where \( \xi \) is the BEC healing length and \( R_x \) the smallest in-trap BEC radius. Our observations confirm the scenario predicted theoretically in [35] where the amplitude of the \( 1/k^4 \)-tails associated with the quantum depletion of a spin-polarized BEC adiabatically decreases during an expansion in the presence of interactions. The measurements and conclusions discussed here therefore differ from those presented in a recent work [36], which studied magnetically-trapped \(^4\text{He}\) atoms. So far, unambiguous signals of the quantum depletion in time-of-flight experiments have been found only when interactions do not affect the expansion [40, 41].

Having shown that the \( 1/k^4 \)-tails result from the bath-impurity interaction, we investigate the dependence of their amplitude \( A \) on both the number \( N_I \) of impurities and the BEC atom number \( N_{\text{BEC}} \). The values of \( A \) are obtained from fitting the plateau found in the function \( k^4 \times \rho(k) \) in the range \( 2 \mu m^{-1} - 6 \mu m^{-1} \). We have recorded data sets where only impurities are detected (no RF transfer) and where both impurities and the majority (BEC) atoms are detected (with RF transfer). We combine the analysis of these measurements [42] to extract the apparent contact for the majority (resp. impurity) atoms as \( C_{\text{BEC}} = (2\pi)^3 A_{\text{BEC}} \) (resp. \( C_I = (2\pi)^3 A_I \)). The observed variations of these apparent contacts are compared with those of Tan’s contact expected in the trap in Figs. 4 and 5.

In the weakly-interacting majority (BEC) atoms, one expects contributions to the Tan’s contact from, (i) the bath-bath interactions and (ii) the bath-impurity interactions. The bath-bath contact \( C_{\text{Bogo}}^{BB} \) of Eq. (1) was derived in the LDA approximation. For the bath-impurity contact \( C_{\text{Bogo}}^{BI} \) we also use the LDA approximation, assuming that the dilute impurities do not affect the density profile of the BEC. Since the impurities are trapped

![FIG. 3. Amplitude C of the 1/k^4-tails (normalised to the BEC atom number N_{BEC}) plotted as a function of the BEC density, for two fraction of impurities f_I = 1 % (blue squares) and f_I = 0.05 % (red dots). The dashed-line is the (normalised) in-trap contact C_{Bogo}^{BB}/N_{BEC} of a spin-polarised BEC predicted by the Bogoliubov theory (see Eq. 1 of the main text).]
in a flat-bottom potential, we find

\[ C_{\text{Bogo}}^{BI} = (32/5)\pi^2 a_{BI}^2 n_{\text{BEC}} N_I. \]  

(2)

In the impurity cloud, the interaction between impurities is negligible due to their very small concentration, and only \( C_{\text{Bogo}}^{BI} \) is expected to play a significant role in determining the asymptotic amplitude of their momentum tails.

In Fig. 4(a), we plot the apparent contact \( C_I \) of the impurities as a function of impurity number \( N_I \). The BEC atom number is fixed to \( N_{\text{BEC}} = 5.5 \times 10^5 \). (b) Apparent contact \( C_I \) of the impurities as a function of the BEC density \( n_{\text{BEC}} \). The impurity number is fixed to \( N_I = 770 \). In both panels, the green dashed line is equal to \( 280 \times C_{\text{Bogo}}^{BI} \).

In conclusion, we have studied the asymptotic momentum densities of weakly-interacting Bose polarons formed when dilute spin impurities are immersed in a Bose-Einstein condensate. Our experiments showed that: (i) the presence of impurities is necessary for the survival of the \( 1/k^4 \)-tails in the BEC after the expansion dynamics; (ii) the apparent contact \( C_{\text{BEC}} \) increases linearly with the number of impurities \( N_I \). We find that the increase in \( C_{\text{BEC}} \) is consistent with the linear scaling expected for the in-trap bath-impurity contact \( C_{\text{Bogo}}^{BI} \). Once more, the amplitude of the apparent contact is orders of magnitude (\( \sim 2000 \times \)) larger than the in-trap prediction of Eq. (2). Interestingly, the apparent contact of the majority atoms is found to rapidly vary with \( n_{\text{BEC}} \) at a fixed number of impurities (see Fig. 5(b)), with a scaling compatible with that of the bath-bath in-trap contact \( C_{\text{Bogo}}^{BB} \propto n_{\text{BEC}}^{7/2} \). Our measurements thus suggest that the apparent contact \( C_{\text{BEC}} \) of the majority atoms varies as \( C_{\text{BEC}} \propto N_I \times n_{\text{BEC}}^{7/2} \).

FIG. 4. (a) Apparent contact \( C_I \) of the impurities as a function of impurity number \( N_I \). The BEC atom number is fixed to \( N_{\text{BEC}} = 5.5 \times 10^5 \). (b) Apparent contact \( C_I \) as a function of the BEC density \( n_{\text{BEC}} \). The impurity number is fixed to \( N_I = 770 \). In both panels, the green dashed line is equal to \( 280 \times C_{\text{Bogo}}^{BI} \).

FIG. 5. (a) Apparent contact \( C_{\text{BEC}} \) for the majority atoms as a function of \( N_I \). The red dot corresponds to the data set with \( f_1 \sim 0.05\% \) shown in Fig. 3. The blue dashed line corresponds to \( 2000 \times C_{\text{Bogo}}^{BI} \). (b) \( C_{\text{BEC}} \) as a function of \( N_{\text{BEC}} \) for a fixed number of impurities \( N_I = 300 \). Inset: \( C_{\text{BEC}} \) plotted as a function of the BEC density \( n_{\text{BEC}} \). In the main panel and the inset, the dashed black line is proportional to \( n_{\text{BEC}}^{7/2} \).
improvement $N_t$, suggesting that impurities also enhance $C_{\text{BEC}}$: (iii) the scaling $C_{\text{BEC}} \propto n_{\text{BEC}}^{7/2}$ has the same functional dependence of Tan’s contact $C_{\text{Bogo}}$, indicating that the impurities may enhance the in-trap contact $C_{\text{Bogo}}$ of the BEC. In addition, we are unable to identify algebraic tails in the asymptotic densities when the bath is a non-degenerate (classical) gas, instead of a BEC.

All these observations are consistent with a scenario in which the impurities strongly enhance the amplitude of the $1/k^4$-tails during the expansion with respect to the in-trap expectation. A detailed analysis of the complete expansion dynamics seems therefore crucial to understand our puzzling observations.

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