Coherence, Correlations, and Collisions: What One Learns about Bose-Einstein Condensates from Their Decay

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We have used three-body recombination rates as a sensitive probe of the statistical correlations between atoms in Bose-Einstein condensates (BEC) and in ultracold noncondensed dilute atomic gases. We infer that density fluctuations are suppressed in the BEC samples. We measured the three-body recombination rate constants for condensates and cold noncondensates from number loss in the $F = 1, m_f = -1$ hyperfine state of ^{87}Rb. The ratio of these is 7.4(2.6) which agrees with the theoretical factor of 3! and demonstrates that condensate atoms are less bunched than noncondensate atoms. [S0031-9007(97)03611-9]

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The onset of Bose-Einstein condensation (BEC) is defined by the sudden accumulation of many bosons in a single quantum state. The symmetry property of bosons is such that if a gas is indeed composed of many identical bosons all occupying the same single-particle state, the gas will exhibit a collection of correlation properties known as coherence. While most early experiments on dilute-gas BEC [1–3] have shown good quantitative agreement with the simple physical model of macroscopic occupation of a single state, no dilute-gas experiment explicitly addressed the issue of coherence in the condensate until the striking observation by Andrews *et al.* [4] of first-order coherence in a sodium condensate. In this paper we describe collision-rate measurements that probe the *higher-order* coherence properties of thermal and Bose-condensed rubidium atoms [5]. In particular, the coherence of the BEC ground state is contrasted with the chaotic fluctuations of the ultracold noncondensed states.

The correlation properties of degenerate samples of ideal bosons have already been extensively studied in the context of quantum optics [6]. In fact, the close analogies between the macroscopically occupied state of a laser beam (characterized as a "coherent state") and that of a Bose condensate have prompted the use of the term "atom laser" to describe some aspects of BEC [7]. Quantum optics teaches that a laser beam is described by a quantum field that exhibits both (i) "first-order coherence," meaning that a measurement of the phase of the field at one point in space and time may be used to predict the phase of the field at some other point [8] and (ii) "higher-order coherences," meaning in essence that the intensity fluctuations in a coherent sample are suppressed relative to those in a thermal sample with the same mean intensity.

The analog of intensity fluctuations in a beam of photons is density fluctuations in a gas of atoms. For example, Fig. 1(a) shows the calculated [9] three-body correlation function for a gas of thermal (i.e., noncondensed) bosons. Note that there is an enhanced probability for finding three bosons close together. The same physics accounts for short-time photon bunching in a thermal light beam (the Hanbury-Brown-Twiss effect [10]), for the two-atom bunching that has been observed in beams of ultracold (but not condensed) atoms [11], and for three-pion correlations in $p\bar{p}$ annihilations [12,13]. To paraphrase Walls and Milburn [14] (who were in fact actually discussing two-photon correlations), the physical origin of such correlations may be understood in terms of a noisy quantum field: There is a high probability that the first boson is found at a high intensity fluctuation, and hence an enhanced probability for finding a second and third atom boson nearby. The correlations in the positions of multiple, identical bosons thus strongly depend on the type of fluctuations that exist in the density. For example, for Gaussian (thermal) fluctuations, the average of the square of the density is a factor of 2 larger than the square of the average density, and this is precisely the factor of 2 observed in two-boson correlation experiments. The atom-bunching effect is expected to vanish in a condensate, precisely as photon bunching does in an ideal laser beam—see Figs. 1(b) and 1(c).

In principle, with sufficiently high spatial and temporal resolution, the density fluctuations in a dilute gas could be imaged directly [15], or detected as coincidence counts in a beam experiment [11]. Kagan and Shlyapnikov [16] have pointed out, however, that an easier experimental approach to probing fluctuations is to take advantage of an observable that is directly sensitive to the probability of finding three atoms near each other, that is, the loss rate of atoms due to three-body recombination. They calculated that three-body recombination in a condensate would be a factor of 3! less rapid than in a thermal cloud at the *same* mean density, and proposed that this change in recombination rate could be a useful signature for detecting the onset of BEC. It is this proposal that motivates our experimental approach, although in the current experiment, the empirical onset of BEC is independently identified by the appearance of a sharp feature in the center of the coordinate and momentum-space atom distribution. We use

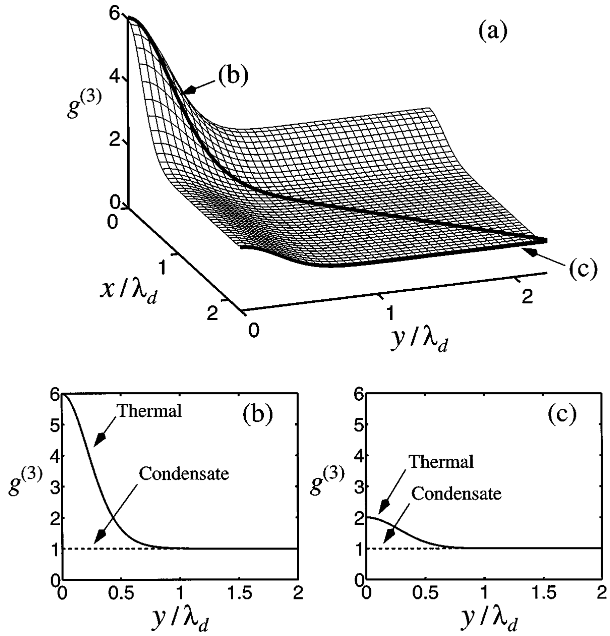

FIG. 1. (a) Calculated third-order correlation function, $g^{(3)}$ [6], for noncondensed ideal bosons. Given a particle at the origin, and a second particle a distance x from the origin, the z axis gives the relative, conditional probability for finding a third particle a distance y from the origin. The de Broglie wavelength is defined by $\lambda_d = h/(2\pi m k_B T)^{1/2}$, where m is the particle's mass and T is temperature. The calculation assumes a cloud in the dilute limit and is not valid for distances x and y less than or equal to the range of two-body interactions. (b) A sample cut through the surface shown in (a), with x set equal to y for ease of display. Note that in a thermal cloud one is 3! times more likely to find three atoms close together than one would naively assume given the mean density. The factor of 3! vanishes for the Bose-condensed atoms. Thus if one has Bose-condensed and non-Bose-condensed samples at similar density, one would expect a factor of 3! less three-body recombination. (c) A cut through the surface shown in (a) with the third particle held well away from the origin ($x/\lambda_d = 2$). Here the surface reduces to a familiar two-boson correlation function, showing the factor of 2 at the origin well known in photon-bunching experiments. Preliminary measurements of the "atom bunching" in a thermal atom beam have been reported by Yasuda [11].

the shape of the mean density distribution to normalize the observed three-body loss rate, and thus extract a rate constant. The central result of this paper is that our comparison of the three-body recombination rate constant in condensed and noncondensed samples provides a quantitative confirmation of the predicted factor of 3! [17], and thus provides very strong evidence for the existence of higher-order coherence in Bose-condensed rubidium.

In this experiment, collisional rate constants were inferred from the loss rate of atoms from the trap. It is known that there are three loss processes for ultracold atoms in a magnetic trap: (1) collisions with background gas, (2) dipolar relaxation, and (3) three-body recombination. However, prior to this work the rate constants for these three processes in very cold rubidium clouds, either condensed or noncondensed, were not accurately known. We use the fact that these loss processes have different density dependencies to distinguish their respective contributions. Measurement of the loss rate of atoms from the trap as a function of density is most easily done by preparing a sequence of identical samples and then measuring the number and density of the sample as a function of time. The density decreases with time because of both the loss of atoms and the rise in the sample temperature due to heating.

The experimental apparatus and techniques used to make and study the cold clouds have been described previously [18]. Using a double magneto-optic trap (MOT) we collect 10^9 atoms. These are optically pumped into the $F = 1, m_f = -1$ state and loaded into a baseball-coil magnetic trap. The bias field is determined by an additional set of Helmholtz coils. The net bias is 1.6 G with a radial field gradient of 300 G/cm and axial curvature 84 G/cm^2. The atoms are then cooled by radio frequency (rf) evaporation. After being evaporatively cooled to the desired temperature, the cloud is held in the magnetic trap for varying intervals of time t. It is then released from the trap and imaged using absorption, or recaptured in a MOT. We find the temperature T of the cloud from the velocity distribution of the noncondensate atoms observed in the absorption image. Although the number of atoms N can also be obtained from this image, we find that we can determine N more precisely by detecting fluorescence on a photodiode from atoms recaptured in a MOT. To study cold noncondensates we evaporatively cool the atoms to a temperature of 800 nK, slightly above the transition temperature of 670 nK. At this point we have 7×10^6 atoms at a peak density of 5×10^{13} cm^{-3}. To study condensates, we cool the atoms to and have 250 nK and have 2×10^6 atoms at a peak density of 5×10^{14} cm^{-3}.

A typical set of data is shown in Fig. 2. It can be seen that at long times, or equivalently, low densities, the loss rate is exponential, indicating that it has no dependence on the density of the sample. The deviation from the exponential line at short times indicates that at higher densities the loss rate is primarily density dependent. To determine the dependence we must determine the density of each sample. We obtain this from the temperature and number of atoms in the sample. We fit the absorption images with a thermal Bose-Einstein distribution to find the sample temperature. To avoid problems with large optical depths we fit the absorption images only in the wings. The number of atoms in the trap is simply found from the photodiode fluorescence signal using the known scattering rate per atom. For noncondensate clouds we calculate the original density in the unreleased trap for each hold time from the measured temperature and number and the known spring constants for the harmonic potential.

We do not measure condensate density directly but instead measure total number N and temperature T and infer density from experimentally well-established properties of alkali condensates. From measured N and T we infer [2] the condensate occupation number N_0. We

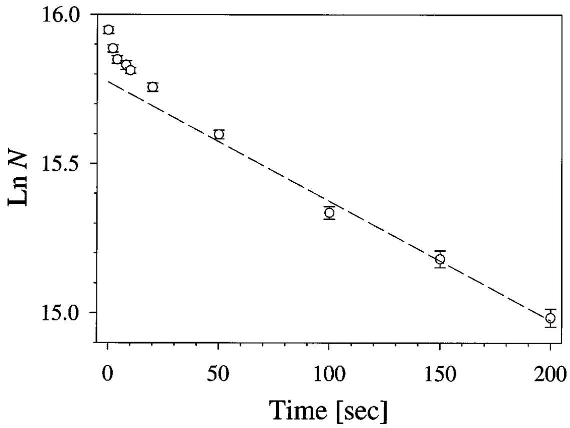

FIG. 2. The natural log of the number of atoms as a function of time in a typical set of data (in this case, for noncondensate atoms). At long times the number loss is due to background collisions and is independent of density. When plotted in this way, the data fall on a straight line with slope equal to the negative inverse of the lifetime, τ, set by background collisions, or about 250 s. The deviation of the data from this straight line at short times is the density-dependent loss.

model the condensate density profile $n(\boldsymbol{x})$ as an inverted parabola proportional to $U_0 - U(\boldsymbol{x})$, where $U(\boldsymbol{x})$ is the trapping potential and U_0 is a function of N_0. The function $U_0(N)$ can be determined from the Thomas-Fermi limit of the Gross-Pitaevski (GP) [19] equation combined with molecular spectroscopy data [20], but we need not assume the validity of the GP equation nor indeed even of quantum mechanics to justify the inverted parabola shape. The shape is due to balance of forces and will be valid as long as the cloud is dilute and kinetic energy (KE) is a small contribution to the condensate energy [21]. We determine the form of $U_0(N)$ (i.e., $U_0 \propto N^{0.4}$) and the prefactor for rubidium from published condensate expansion data [3], again assuming only that KE is small in the condensate, and that the condensate self-interacts in a dilute fashion [21].

This gives the density of the clouds as a function of time. The loss due to three-body recombination is modeled by the rate equations

$$\frac{dN}{dt} = -K_m \int_V n^m(\boldsymbol{x},t)d^3x \qquad (m = 1, 2, \text{ or } 3)\,, \quad (1)$$

or equivalently

$$\ln\frac{N(t)}{N(0)} = -K_m \int_0^t dt' \int_V \frac{n^m(\boldsymbol{x},t')}{N(t')} d^3x \qquad (m = 1, 2, \text{ or } 3)\,. \quad (2)$$

The rate constant for an m-body process, K_m, is determined from a fit to Eq. (2), n is the density, and $N(t)$ is the number after time t. The condensate clouds contain some noncondensate fraction and, in general, the rate constants for the two parts will be different.

We find that all of the density-dependent loss we observe is due to three-body recombination. This can be seen in Fig. 3. Equation (2) shows that when the data are plotted as shown a single three-body loss process appears as a straight line with a slope equal to the negative of the desired rate constant. The different slopes for noncondensate and condensate data give the rate constants, $K_3^{\mathrm{nc}} = 4.3(1.8) \times 10^{-29}$ cm^6/s and $K_3^c = 5.8(1.9) \times 10^{-30}$ cm^6/s, respectively. This value for K_3^{nc} is in good agreement with a calculation by Fedichev *et al.* [23], even though it is not clear that the experimental system satisfies the claimed range of validity for the theory. The ratio of the noncondensate to the condensate rate constants is 7.4(2.6). This is in agreement with the theoretical value of 3! (for noninteracting atoms) and is dramatically different from 1. This proves that, relative to thermal atoms, the density fluctuations are suppressed for condensate atoms ("higher-order coherence") as in a laser or any macroscopically occupied state of ideal bosons.

The rate constants are quite sensitive to uncertainties in the determination of temperature and number. These uncertainties then are the primary cause for the errors in the rate constants. The heating that we observe also has a density dependence, under some conditions, raising concerns that there may be an associated loss that would distort our results. To check that this was not the case, we took data with the rf evaporative field on and set to different frequencies during the hold time. These frequencies are well above that used to determine the initial sample temperature, but have a dramatic effect on the heating rate. As shown in Fig. 3, the loss rates from the samples were the same although the heating rates were very different.

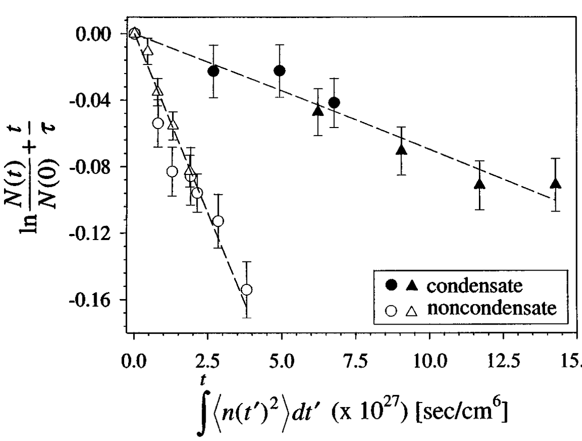

FIG. 3. The natural log of the number of atoms as a function of $\int_0^t \langle n^2(\boldsymbol{x},t')\rangle\, dt'$ [22] where we define $\langle n^2(\boldsymbol{x},t')\rangle = \frac{1}{N(t')}\int_V n^3(\boldsymbol{x},t')\, d^3x$ [see Eq. (2)]. On the vertical axis, t/τ accounts for loss due to background collisions. Circles and triangle refer to separate runs with different heating rates. Closed symbols refer to condensate data and open symbols refer to noncondensate data. When a line is fit to the data, the slope gives the negative of the rate constant. A slight deviation from a straight line in the condensate data is due to terms involving mixtures of condensate and noncondensate atoms. These terms are included in the analysis by which rate constants are determined, but left out here for clarity.

We could see no indication of a loss rate that was linear in density which would be the signature of the two-body process dipolar relaxation. With our statistical uncertainties, we can set an upper bound on the dipolar relaxation loss rate constant for the $F = 1$, $m_f = -1$ state of ^{87}Rb in a 1.6 G field of $K_2^{\rm nc} \leq 1.6 \times 10^{-16}$ cm^3/s. This is consistent with the small values predicted for alkali atoms in the $F = 1$, $m_f = -1$ state [24].

This work represents a quantitative demonstration that BEC atoms have the higher-order coherence characteristic, for instance, of laser photons. We have also shown that the dominant loss process for cold noncondensates and condensates in the $F = 1$ state of ^{87}Rb is three-body recombination. The rate constant that we have determined sets a limit on attainable lifetimes and densities in condensate samples of ^{87}Rb.

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[21] The assumption that KE in a condensate is small is consistent with all empirical observations, including expansion energy measurements. It is amusing to note that the central result of this paper, that fluctuations in density are much smaller in a condensate than in a thermal cloud, does not depend on the small KE assumption: If KE were not negligible, published expansion data would yield only an upper limit on condensate size such that the value we quote for the suppression of three-body correlations, 7.4(2.6), would be only a *lower* limit.

[22] The error bars in Figs. 2 and 3 represent plus or minus one standard error and are derived from the statistics of the data. They do not include systematic errors explicitly, but due to systematic drifts during the experiment some systematic error is implicitly included. Consequently the error bars are larger than they would be if they were purely statistical.

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