# Observation of Two-Atom Correlation of an Ultracold Neon Atomic Beam

Masami Yasuda and Fujio Shimizu

*Department of Applied Physics, University of Tokyo, Bunkyo-ku, Tokyo 113, Japan*

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The intensity correlation spectrum of an ultracold $^{20}$Ne atomic beam in the $1s_3[3s : {}^1P_0]$ state is experimentally studied. The spectrum shows a peak around the origin with the width corresponding to the kinetic energy spread of atoms in the beam source. [S0031-9007(96)01330-0]

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Various interferometric effects of neutral atomic beams have been demonstrated in recent years [1–9]. However, those experiments deal with the wave nature of a single atom. This is in sharp contrast to the case of optical beams, in which interesting results on many-photon correlation effects have been studied. This is partly due to the difference in the technical level of preparing samples. The invention of lasers and following development in nonlinear optics enabled us to work with optical beams with various statistical characteristics, whereas for particles with mass the only sample available for us was a beam of uncorrelated particles. For random particles the first order correlation is constant in time, and a nontrivial spectrum can be observed only in higher order correlations. Furthermore, to observe a many-particle correlation effect, at least two particles have to be found in a single external quantum state, which was prohibitively small with a conventional particle beam. This situation has changed considerably for a neutral atomic beam owing to the laser cooling technique. In a Bose-Einstein condensate of alkali gases, which has been reported recently by several groups [10–12], atoms are in a highly degenerate state. Even with commonly used laser-cooling techniques it is possible to achieve a density in which the probability of finding two atoms in the same mode is in an experimentally detectable range.

We report in this Letter the first observation [13] of the second order correlation of a laser-cooled atomic beam, which is the atomic analogy of the Hambury Brown and Twiss experiment on an optical source [14]. An ultracold metastable $^{20}$Ne atomic beam in the $1s_3[3s : {}^3P_0]$ state was generated by releasing atoms from a Ne trap in the $1s_5[3s : {}^3P_2]$ state by optical pumping [15]. We restricted the area of the detector to cover only the diffraction limited portion of the atomic beam source and measured the time-interval distribution between two atoms that successively hit the detector. The temporal correlation showed a peak around the origin that corresponded to the energy distribution of the atomic beam.

The joint probability $P(r_1, t; r_2, t + \tau)$ of finding an atom at $t$ and $r_1$ and then an another atom at a later time $t + \tau$ and $r_2$ is

$$P(r_1, t; r_2, t + \tau) = \langle \Psi | \delta^\dagger(r_1, t) \delta^\dagger(r_2, t + \tau) \times \delta(r_2, t + \tau) \delta(r_1, t) | \Psi \rangle ,$$

where $\delta^\dagger(r, t)$ and $\delta(r, t)$ are the operators to create and annihilate the atom at $r$ and $t$, respectively. The probability $P(\tau)$ of detecting two atoms separated in time by $\tau$ is obtained by averaging the above expression on $r_1$ and $r_2$ over the detector surface and on $t$. In our experimental setup the evaluation of $P(\tau)$ is not difficult, if the atomic beam is diffraction limited, and the surface of the detector coincides with the wave front of the atomic beam. When the atoms are not correlated and the velocity distribution at the source has a Gaussian form, the result is the same as the intensity correlation of a chaotic classical wave and is given by

$$P(\tau) = N^2 \left\{ 1 + \frac{\beta}{\sqrt{1 + (\Delta\omega\tau)^2}} \right\}, \qquad (1)$$

where $N$ is the count rate of the atom detector and $\Delta\omega = m v_s^2/(2\hbar)$. The constant $\beta$ is 1 for bosonlike atoms and $-1$ for fermionlike atoms. The quantity that we measured in the present work was the time interval distribution and was not equal to $P(\tau)$. However, the difference between the two quantities was negligibly small in the temporal range of our interest, $|\tau| \leq 1\mu$s, because the average atom count $N$ was in the order of $10^2$ s$^{-1}$, and the probability of detecting an atom within 1 $\mu$s was far less than 1. It should be noted that, when $N/\Delta\omega \ll 1$, quantum efficiency of the detection system does not affect the spectral shape of Eq. (1). In the experiment described below, various procedures that reduce the effective detection efficiency are used; they do not change the spectral shape as long as the reduction of the efficiency is $\tau$ independent. However, degradation of spatial coherence of the atomic beam hitting the detector does reduce the height of the peak around $\tau = 0$ relative to the background signal. An excessively large acceptance angle of the beam and wave-front mismatch with the detector surface are such examples; they increase also the width of the peak, because the spatial coherence depends on $v_s$ and slower atoms are less affected. In the analysis of the following experiment, we use $\beta$ as a fitting parameter.

The real experimental procedure was somewhat complicated due to technical reasons. Atoms moved very slowly compared to photons, and the longitudinal coherence length was extremely short. It was necessary to provide an atom detector whose surface matched the wave

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front of the atomic de Broglie wave within 1 $\mu$m. Because of weak intensity of our atomic beam, careful elimination of the transient response of the detector was necessary to obtain a real correlation signal. We used four detectors, and only the atoms that were detected by two different detectors were used for analysis. In addition, the experiment was repeated with two configurations in which the spectral shape was expected to be distinctively different.

The schematics of the experimental setup is shown in Fig. 1. We focused a 598 nm laser beam into the magneto-optical trap of metastable neon atoms in the $1s_5$ state. The atoms were pumped to a higher $2p_5[3p : {}^3S_1]$ state. Half of the atoms in the $2p_5$ decayed to the ground state. The remaining atoms decayed to the $1s_3$ metastable state. Both atoms were freed from the trapping force and fell nearly vertically pulled by gravity. We ignored the ground state atoms, because they were insensitive to the detector. By restricting the view angle of the atomic beam the spatially coherent portion of the $1s_3$ atoms was detected at 82 cm below the trap. The vertical velocity distribution of the $1s_3$ neon atomic source had a Gaussian shape with the $1/e$ velocity $v_s = 28$ cm/s. At the detector atoms were accelerated to 4 m/s and the velocity spread was reduced to 0.5 cm/s. The diameter $d_s$ of the $1s_3$ atomic source was estimated from an independent experiment on the double-slit interference and was 60 to 100 $\mu$m. The coherent angle at the atomic source $\theta_{\rm coh} \approx 2h/(mv_s d_s)$ was, therefore, $1.8 \times 10^{-3}$ to $3 \times 10^{-3}$. This means that the diameter of the diffraction limited atomic beam at the detector was 0.16 to 0.26 mm [16].

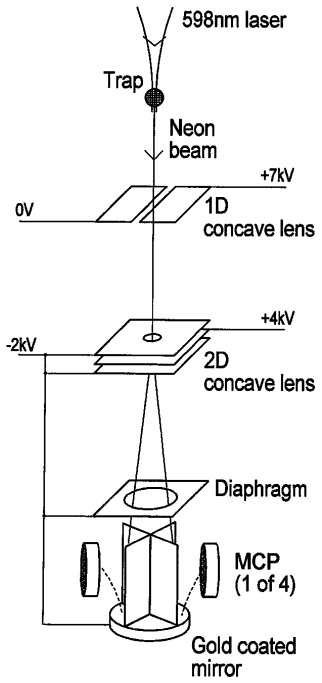


FIG. 1. The experimental configuration. The figure shows the configuration of the first experiment. In the second experiment two lenses were replaced with a single two-dimensional defocusing lens composed of four spheres. The radius of the curvature of the gold-coated mirror was also changed from 500 to 600 mm.

The detector consisted of a gold-coated concave mirror with the diameter of 12 mm and four microchannel plate detectors (MCPs) that detected Penning electrons ejected from the mirror surface. The surface of the mirror was divided into four quadrants by walls of 0.1 mm thick aluminum sheets. Electrons ejected from each quadrant were received by a separate MCP. The curvature of the mirror was adjusted to coincide with the calculated wave front of the atomic beam within $10^2$ nm. Vertical alignment of the mirror and the detector was done by using the 598 nm pumping laser. First, the gold-coated mirror was removed, and the direction of the vacuum chamber was adjusted so that the laser beam reflected from a liquid surface returned the same path. Then the mirror was installed, and its direction was adjusted. The deviation of the laser beam from the perpendicular direction was estimated to be less than $3 \times 10^{-4}$ rad.

Electron pulses from each MCP were amplified and pulse shaped by a discriminator. The signal was then fed into the second-pulse suppressor that killed pulses that were detected within 6 $\mu$s after the first pulse from the same MCP. The device contained a monostable vibrator that was triggered by the first pulse and produced an inhibiting pulse. This pulse stopped the second pulse within 6 $\mu$s coming from the same MCP. The output pulses with a width of 25 ns from four channels were summed together and then fed into an interval counter that started counting by the first pulse and stopped by the second pulse with a resolution of 16.67 ns. The counter was designed to stop and clear the content whenever the second pulse was not detected within 4 $\mu$s. When two pulses were detected within 4 $\mu$s, the event was recorded on a desktop computer as a near-coincident event. The record carried the time interval, the position of the activated detectors, the time of the event, and the information specifying the operating condition. The average pulse count was typically 100 to 200 $s^{-1}$. Therefore the probability of having two pulses within 4 $\mu$s was less than $10^{-3}$. The data collection continued for 68.3 s and then was interrupted for 0.8 s. During this interruption, we measured the velocity distribution of the atomic source by a time-of-flight technique [15]. In addition, the shape and intensity of the trapped atoms were always monitored using two charge coupled device cameras and were recorded by a videorecorder. The data were accumulated continuously for 20 to 50 h.

In the first experiment we used two configurations that differed in the degree of spatial coherence of the atomic beam. The spatial coherence was controlled by defocusing lenses and a diaphragm placed between the source and the mirror as shown in Fig. 1. The radius of the curvature of the detector mirror was 500 mm. The effective diameter of the atomic beam that hit the mirror was controlled by an electrostatic defocusing lens. The lens was placed 33.6 cm above the mirror

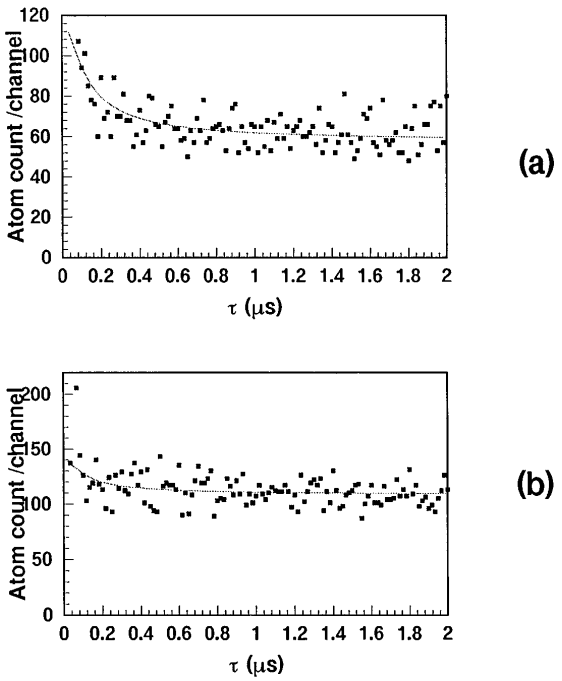


FIG. 2. The second order correlation spectrum: (a) with a coherent atomic beam, in which the beam with the diameter of 0.3 mm at the defocuser was expanded to cover the gold-coated mirror of 12 mm in diameter, and (b) with an incoherent beam, in which the beam of 2.3 mm in diameter hit the mirror without deflection.

and consisted of three aluminum disks with a hole 2.3 mm in diameter. The three disks were separated by 2.3 mm. The lens expanded the divergence of the atomic beam by approximately 40 times when a potential of +6 kV was applied to the middle disk. The effective diameter of the diaphragm at the lens was then reduced to 0.3 mm, so the atomic beam hitting the detector was nearly coherent. When the electric potential was not applied, all atoms that passed through the 2.3 mm hole hit the mirror. Since this diameter was an order of magnitude larger than the diameter of the diffraction limited beam, the atomic beam was expected to be incoherent. To equalize the counting rate between the two configurations, a one-dimensional defocuser that consisted of two parallel aluminum plates separated by 5 mm was placed approximately 15 cm below the atomic source. It expanded the beam divergence along the direction perpendicular to the slit while giving no effect along the parallel direction. A potential difference of 7 kV was applied when the voltage on the two-dimensional defocuser was switched off. To reduce the effect arising from electronic noise the following events were removed from the analysis: the events that were detected within 100 atom counts from the preceding or following event and all events that contained more than three short ($\tau <$ 66 ns) coincidences in the successive 10 events.

Figure 2 shows the observed correlation spectrum. Figure 2(a) was the spectrum when a voltage of 6 kV was applied on the defocusing lens, while in Fig. 2(b) the voltage was switched off. Each point shows the total number of events during the window time of $\Delta\tau =$ 16.67 ns. The data collection time was 47 h for 2(a) and 43 h for 2(b). The count of the first point was identically zero because the input pulse width was longer than the channel width of the interval counter. The peak around $\tau = 0$ is clearly seen in Fig. 2(a), while in Fig. 2(b) it is almost absent. In spite of the above effort to eliminate spurious pulses, the data near the origin $\tau = 0$ showed irregularly high values. To obtain quantitative evaluation, we fitted the $\beta$ in Eq. (1) from the data points between the fifth and 100th points from $\tau = 0$ by using the average velocity $v_0 = 28$ cm/s, which was obtained from the time-of-flight measurement. The least-squares fitting of $\beta$ gives $1.00 \pm 0.30$ for the coherent case, and for the incoherent case $0.19 \pm 0.15$, where the error indicates the $3\sigma$ value. This means that the separation between the coherent and incoherent configurations is larger than $5\sigma$. The inclusion of the second to fourth data points gives an unrealistic value of $\beta$ ($> 1$) for the coherent case. However, the separation between two configurations remains larger than $5\sigma$. If we increase the number of points excluded from the analysis, the $\beta$ slightly decreases and stabilizes at around 0.8 for the coherent case and 0.15 for the incoherent case. As the number of exclusions is increased, the error bar for the coherent configuration gradually increases, which is expected because the existence of the peak relied on the data $\tau < 0.5$ $\mu$s. The separation between two configurations in terms of confidence level remains better than $3\sigma$ up to the exclusion of the 12th point. This difference of the correlation spectrum between the two configurations is a convincing evidence that the observed peak in Fig. 2(a) results from the second order correlation of the atomic beam. In the incoherent configuration the atomic beam diameter was at least 6 times larger than that of a diffraction limited beam with the average atomic velocity. If the residual peak in Fig. 2(b) is caused by slower atoms that have a larger diffraction angle, the height should not exceed 3% of the background count. Therefore the observed value of $\beta = 0.19$ shows that the effect from the electronic transient response was not completely eliminated. For the same reason the observed $\beta$ of the coherent configuration is larger than the value that would be obtained without a transient response.

In the above experiment the trajectory of atoms between the lens and mirror was altered when the configuration was switched. We repeated the experiment using another set of configurations in which the trajectory of atoms was identical. In one case the mirror surface was adjusted to match the wave front of the atomic beam, while in the other case the axis of the mirror was tilted by $10^{-2}$ rad causing the average arrival-time variation of $\tau_a = 15$ $\mu$s over the mirror surface. To coherently illuminate the entire mirror surface we used a defocusing lens that consisted of four metal spheres with a diameter of 0.8 mm. The

spheres were located on the apexes of a 1.26 mm square and were placed approximately 48 cm above the mirror. A static potential of 1800 V was applied between two diagonal pairs of the spheres. The effective diameter of the beam at the lens was 0.25 mm. The radius of curvature of the mirror was 600 mm. In a typical run the data were continuously collected for 24 h, and the configuration was switched every 6 h. The result of a 70 h accumulation is shown in Fig. 3. The data were analyzed by the same way as in the first experiment. The dotted line in Fig. 3(a) was the fitting by Eq. (1) with $v_0 = 28$ cm/s, and the most probable value of $\beta$ was 0.68. The error at $3\sigma$ was $\pm 0.29$. When the mirror was tilted, the height difference of the mirror surface caused the shift of the time origin. As a result, the spectral width was expected to increase approximately by a factor $\Delta\omega\tau_a$ and the peak height reduced approximately by the same factor. The simplest way to approximate this effect is to replace $\Delta\omega$ in Eq. (1) with $1/\tau_a$. Using $\Delta\omega\tau_a = 10$ we obtained $\beta = 0.20$, which was shown in Fig. 3(b) by a dotted line. The error of the $\beta$ at $3\sigma$ was $\pm 0.19$. The confidence level of separation in two configurations was, therefore, approximately $3\sigma$.

In conclusion, we have shown for the first time a quantum statistical two-atom correlation effect by using a beam of $1s_3$ metastable $^{20}$Ne atoms. The shape of the spectrum should change depending on the kinetic energy distribution of atoms. If the distribution has a double peak, the spectrum will show beating with a frequency corresponding to the energy difference of two peaks. The beating is also expected if two independent atomic beams are coherently combined on the detector. When the particles obey fermion statistics, the spectrum is expected to have the same shape with opposite sign. This can be tested by an experiment with odd isotope $^{21}$Ne atoms. A recent report on the Bose-Einstein condensation of atomic gas provides an interesting sample, which is not in the chaotic state. The study by correlation measurement will be a valuable technique to investigate quantum statistical nature of correlated samples.

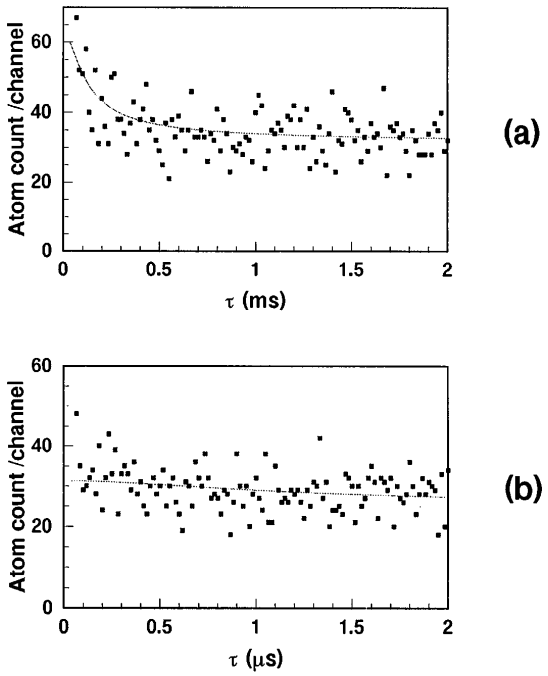


FIG. 3. The second order correlation spectrum: (a) when the mirror was aligned properly to match the wave front of the atomic beam, and (b) when the mirror was tilted approximately by $10^{-2}$ rad.

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[16] The angle $\theta_{\rm coh}$ is the diffraction angle of an atom having the average velocity $|v_s|$.