Quantum Nondemolition Demonstration via Repeated Backaction Evading Measurements

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Repeated backaction evading measurements have been performed for the first time. The first backaction evading device prepares the field state while the second one measures it again. The conditional variance of the signal at the output of the first device given the measurement is 1.8 dB below the shot noise and the signal to noise ratio transfer coefficient is 1.34. The conditional variance of the final signal given the first device measurement is also 1.8 dB below the shot noise and the normalized correlation between the two meter outputs is 0.3. These figures are clearly in the quantum regime, and they constitute a full demonstration of the quantum nondemolition principle.

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The principles of quantum mechanics allow one to measure many times a single observable of a quantum system. However, the first precise measurement, which can ideally be regarded as preparing the system in a well-defined eigenstate of the measured observable, introduces also in the system a "measurement noise," which may eventually come back to the measured quantity, preventing one from retrieving the first result in the subsequent measurements. A scheme where this noise is entirely kept in an observable which is conjugated with the measured quantity is usually called a "backaction evading" (BAE) measurement, while this strategy was termed "quantum nondemolition" (QND) by Braginsky and Vorontsov [1] and Thorne *et al.* [2]. Though proposed *and* initially studied in the context of mechanical oscillators for gravity wave detection [2–4], QND ideas were first implemented in quantum optics [5–12]. In the standard situation encountered with propagating laser beams, where the quantum fluctuations are small compared to the mean intensities, quantitative criteria have been developed for evaluating the efficiency of a given experimental setup as a QND or a BAE measurement device [13,14]. The first quantity to look at is the correlation between the two outputs of the measurement system (signal and meter), which characterizes the device ability for quantum state preparation (QSP). This correlation can be measured through the conditional variance $V_{S/M}$ of the signal output S, given the measurement M. This quantity has a built-in reference to the signal shot-noise level, which is normalized to 1: $V_{S/M} < 1$ indicates nonclassical operation, while the ideal limit of perfect QSP would be $V_{S/M} = 0$. Other important quantities are the transfer coefficients T_S and T_M, which quantify the transfer of the signal to (quantum) noise ratio of the input signal beam towards, respectively, the output signal and meter [14,15]: $T_S + T_M$ larger than 1, up to the maximum of 2, can be obtained using only a phase-sensitive device.

Many experiments have been devoted to the demonstration of BAE measurements. A first idea [16] was to use the optical Kerr effect in order to couple the intensity fluctuations of the signal beam to the phase fluctuations of the meter beam. Using the nonresonant Kerr effect in optical fibers, with either continuous wave (cw) beams [5] or optical pulses in the soliton regime [6], quantum noise correlation was demonstrated, but the performances of these experiments were limited by unwanted phase noise in the meter beam. Better results were obtained using quasiresonant two-photon nonlinearities [7–9]. In particular, complete BAE measurements [9] were demonstrated using two-photon transition in a sodium atomic beam, with $V_{S/M} = 0.85$ and $T_S + T_M = 1.35$, clearly in the quantum domain. Another series of experiments has been initiated in Ref. [10] using pulsed traveling-wave $\chi^{(2)}$ parametric gain. A type-II phase-matched potassium trihydrogen phosphate (KTP) crystal is sandwiched between two half-wave plates, and the signal and the meter are two orthogonally polarized beams copropagating through the device. The signal and meter beams are separated using a polarization beam splitter. For a particular gain-dependent orientation of the half-wave plates, called the "evasion angle," it was demonstrated that the device should operate as a BAE device. Signal-meter correlations were again demonstrated, but performances were limited by losses and low parametric gain. More recently, it was demonstrated [11] that traveling-wave phase-sensitive type-II phase-matched parametric amplification can be combined with twin beam correlation in order to meet all criteria for BAE. This experiment demonstrated good performances for optical tapping and duplication, but the signal output is

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an amplified copy of the signal input and, therefore, does not follow exactly the initial QND idea. Finally, a full BAE experiment was reported in Ref. [12], based essentially on the same principles as Ref. [10], but for cw beams. In that case, the gain of the parametric amplifier was enhanced using a ring optical cavity. The reported results were $V_{S/M} = 0.7$ and $T_S + T_M = 1.2$, both values in the quantum domain.

Though some of these experiments [9,12] have performances that are good enough for QND, a full demonstration of the QND principle through repeated measurements is still missing. Indeed, as expressed by Caves *et al.* [4] and recalled in Ref. [12], "the key feature is repeatability—once is not enough!" In this Letter, we report a repeated BAE experiment that clearly demonstrates all QND features for repeated measurements. An important feature is that each of the two BAE setups, based on pulsed type-II parametric amplifiers, also has performances that are the best achieved so far and, therefore, make this demonstration more convincing.

The diagram for the QND scheme is represented in Fig. 1. The signal under measurement is sent to a first BAE (BAE_1) setup. The output meter beam is detected by a first high efficiency detector while the unperturbed signal goes through a second BAE (BAE_2) setup having two outputs: a second meter output and the signal output, both detected by high quantum efficiency detectors. When the orientation of the half-wave plates for each device is adjusted at the evasion angle $\arccos[(\sqrt{G}+1)/\sqrt{2(G+1)}]$, where G is the phase-sensitive gain, the input-output relation of the quantum fluctuation for the BAE_1 device takes the simple form [10]

$$\begin{aligned} X_{S1}^{\mathrm{out}} &= X_{S1}^{\mathrm{in}}, \quad X_{M1}^{\mathrm{out}} = X_{M1}^{\mathrm{in}} + f_1 X_{S1}^{\mathrm{in}}, \\ Y_{S1}^{\mathrm{out}} &= Y_{S1}^{\mathrm{in}} - f_1 Y_{M1}^{\mathrm{in}}, \quad Y_{M1}^{\mathrm{out}} = Y_{M1}^{\mathrm{in}}, \end{aligned} \tag{1}$$

where X_S (X_M) and Y_S (Y_M) denote the quadrature components for the signal (meter). We will use conventionally X

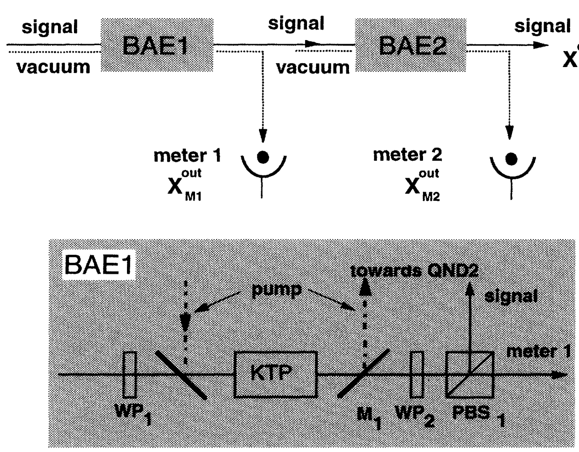

FIG. 1. Simplified diagram of the repeated BAE system (top). Bottom: detail on the first BAE setup. The pump is injected and extracted by dichroic mirrors. WP_i are half-wavelength plates aligned at evasion angle.

for the amplitude quadrature which is directly detected on a photodetector, using the field of the injected (and eventually amplified) signal beam as a local oscillator. We assume that the input meters are in the vacuum state. The parameter f is related to the phase-sensitive gain G by $f = \sqrt{G} - 1/\sqrt{G}$. After BAE_1, the signal goes to BAE_2, where we have

$$\begin{aligned} X_{S2}^{\mathrm{out}} &= X_{S2}^{\mathrm{in}} = X_{S1}^{\mathrm{in}}, \\ X_{M2}^{\mathrm{out}} &= X_{M2}^{\mathrm{in}} + f_2 X_{S2}^{\mathrm{in}} = X_{M2}^{\mathrm{in}} + f_2 X_{S1}^{\mathrm{in}}, \\ Y_{S2}^{\mathrm{out}} &= Y_{S2}^{\mathrm{in}} - f_2 Y_{M2}^{\mathrm{in}} = Y_{S2}^{\mathrm{in}} - f_2 Y_{M1}^{\mathrm{in}}, \\ Y_{M2}^{\mathrm{out}} &= Y_{M2}^{\mathrm{in}} = Y_{M1}^{\mathrm{in}}. \end{aligned} \tag{2}$$

After this second measurement, the signal field amplitude X_{S1}^{in} is still preserved, while the information has been encoded on X_{M1}^{out} in the first measurement and on X_{M2}^{out} in the second one. As said previously, the performances of the BAE_1 device will be characterized by the transfer coefficient for the signal and meter T_{S1} and T_{M1} and the conditional variance between the signal and meter beams $V_{S1/M1}$ [14]. Then the performances of the whole QND system will be characterized by three measurements. First, the conditional variance $V_{S2/M2}$ between the signal and meter beams for BAE_2, with the BAE_1 measurement performed at the same time: this quantifies the ability of the device to operate with an input which has already phase-dependent noise. Second, the conditional variance between the final output signal and the first meter beam $V_{S2/M1}$ will quantify the nondemolition property of BAE_2, since the QSP property of BAE_1 has already been characterized by $V_{S1/M1}$. Third, the correlation between the two meter outputs C_{M1M2} will quantify the degree of correlation [17] of the two successive measurements, i.e., the fact that "the needles move together" since they are measuring the same quantum signal.

Each BAE apparatus (see Fig. 1) is constituted by two type-II KTP crystals sandwiched between half-wavelength plates WP_i aligned at the evasion angle. The crystals are pumped by a frequency-doubled mode-locked and Q-switched YLF laser. The pump beam at 527 nm consists of 35-ps-long pulses with a repetition rate of 76 MHz modulated by a Gaussian train envelope of 400 ns long (FWHM), produced at a repetition rate of 800 Hz. A small part of the fundamental laser beam injected collinearly to the pump constitutes the signal under measurement. It consists of 630-ns-long (FWHM) trains of 50-ps-long pulses, synchronized with the pulses of the pump beam. At the output of BAE_1 the pump beam is separated by a dichroic mirror M_1. After WP_2, a polarizing beam splitter (PBS_1) allows one to separate the meter and the signal. The meter is detected by the photodetector PhD_1 and the signal is recombined with the pump beam by a mirror M_2 after the selection of the evasion angle through WP_3. At the output of BAE_2 the pump is filtered; WP_4 select the evasion angle and a polarizer beam splitter allows the separation of the signal and the meter as in the previous case.

The signal and meter beams are focused (FWHM = 200 μm) in a 500-μm-diameter InGaAs photodetector (Epitaxx ETX-500) with nominal efficiency of about 95% and low dark current. Optical saturation of the photodetector is avoided by limiting the optical gain and by adjusting the incident intensities. In order to reduce the thermal noise, the photodetectors are charged to 500 Ω, and a coil system allows the impedance to be transformed to 50 Ω to be matched to the following electronic elements. The photocurrent is split 90/10. The 10% portion is used for the measurement of the 76 MHz modulation of the mode-locked train and provides a direct intensity reference. This is done by demodulating the photocurrent at 76 MHz using as a local oscillator the second harmonic of the 38 MHz mode-locker RF. A low-pass filter ($F_c = 10.7$ MHz) restores the envelope with a band of 10 MHz. The 90% portion of the photocurrent is used for the measurement of the quantum noise. The noise measurement bandwidth is determined by a bandpass filter that transmits between 12 and 25 MHz and has 90 dB attenuation outside this range, preventing saturation of the subsequent low-noise amplifier (Trontech L20B) by the 76 MHz modulation and its harmonics. This was checked by examining the absence of any distortion in the temporal profile of the amplified pulse. The filtered noise is sent into a square-law amplifier (AD734) then filtered as previously (low-pass filter, $F_c = 10.7$ MHz). Since the gain bandwidth of the traveling-wave parametric amplifier is flat up to hundreds of GHz, the noise at 18 MHz gives a quantitative measure of the noise at the modulation frequency. In order to treat signals more quantitatively, video averaging is provided by two boxcars following each of the measurement channels (intensity and noise); the boxcars are triggered by the Q-switch synchronization from the laser power supply and their gate width is 10 ns. Each measurement involves 1024 Q-switched trains, averaged by a computer that received the data from the boxcars. All measurements are made by registering simultaneously the modulation (at 76 MHz) and the noise (at 18 MHz) for the output beams. The pump beam is dilated to 1.25 times the signal beam and the confocal parameter is 4.3 m for the pump and 1.4 m for the signal. This prevents the geometrical and diffraction effects from degrading the nonclassical performances [18].

In Fig. 2 we present the difference (stars) and the sum (circles) between the signal and the meter quantum noise at the output of QND_1 as a function of the attenuation of the meter photocurrent output. The difference of the quantum noise between two Poissonian beams having the signal and the meter intensity is also presented (squares). The curves are normalized to the signal input quantum noise. When the electronic phases are adjusted to 0° (sum) and 180° (difference), the measured noise powers are

$$V_{\mathrm{meas}} = V_S^{\mathrm{out}}[1 + g_{\mathrm{el}}^2 V_M^{\mathrm{out}}/V_S^{\mathrm{out}} \pm 2g_{\mathrm{el}}|C_{SM}^{\mathrm{out}}|(V_M^{\mathrm{out}}/V_S^{\mathrm{out}})^{1/2}], \quad (3)$$

where V_S^{out} and V_M^{out} are the signal and meter output noise powers, g_{el} is the electronic gain or attenuation of the meter, and C_{SM}^{out} is the normalized correlation [17] between the signal and the meter. The minimum of the "difference" curve as a function of the attenuation of the meter, obtained for $g_{\mathrm{el}} = |C_{SM}^{\mathrm{out}}|(V_S^{\mathrm{out}}/V_M^{\mathrm{out}})^{1/2}$ is $V_{\mathrm{min}} = V_S^{\mathrm{out}}(1 - |C_{SM}^{\mathrm{out}}|^2)$ which is nothing but the conditional variance [14].

The curve of Fig. 2 has been obtained for a gain of the amplifier set to $G_1 = 2$. The first remark is the important correlation between the signal and the meter outputs, as shown by the gap between the "sum" and difference curves. Furthermore, for an attenuation of the order of 7 dB, the difference goes to 1.8 dB below the shot noise demonstrating a conditional variance $V_{S1/M1} = 0.66$ or 1.8 dB below shot noise. For high enough attenuation both curves go close to 0 dB, showing that QND_1 adds no noise to the signal. The transfer coefficient for the signal and the meter measured in a separated way gives $T_{S1} = 0.94$ and $T_{M1} = 0.4$, or $T_{S1} + T_{M1} = 1.34$, which is clearly in the nonclassical domain ($T_{S1} + T_{M1} > 1$). The measured values for the conditional variance $V_{S1/M1}$ and the transfer coefficients T_{S1} and T_{M1} are in good agreement

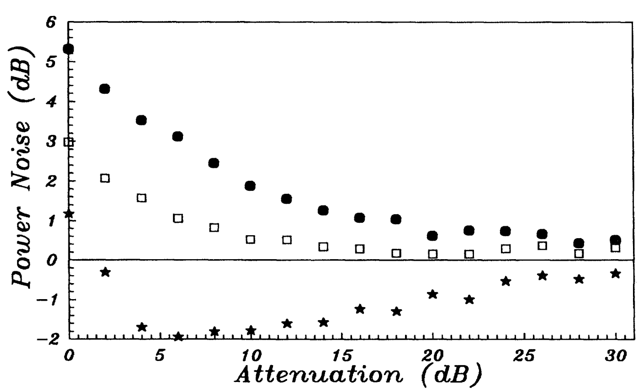

FIG. 2. Power noise of the difference (stars) and the sum (circles) of the meter (M_1) and signal (S_1) photocurrents as a function of the electronic attenuation of the meter photocurrent. In squares the difference for two Poissonian beams having the signal and the meter intensities.

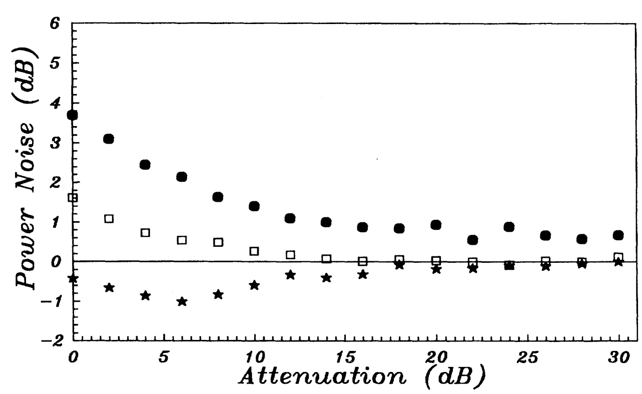

FIG. 3. Same as Fig. 2, but with M_2 as the meter and S_2 as the signal.

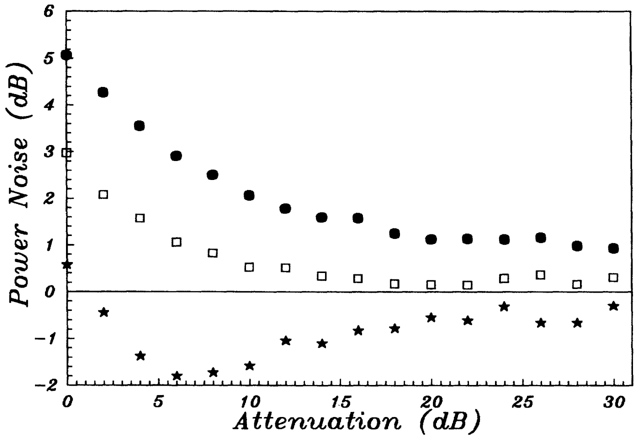

FIG. 4. Same as Fig. 2, but with M_1 as the meter and S_2 as the signal.

with the theoretical predictions ($V_{S1/M1} = 0.65$, $T_{S1} = 0.95$, $T_{M1} = 0.34$) for meter and signal propagation efficiencies $\eta_M^{\text{prop}} = \eta_S^{\text{prop}} = 0.95$.

The output signal is sent to QND_2 whose amplifier gain is $G_2 = 1.9$. We present in Fig. 3 the difference (stars) and the sum (circles) of the signal and the meter outputs of QND_2, together with the difference for Poissonian beams of equivalent intensities (squares). The general behavior is similar to that of Fig. 2. The inferred conditional variance $V_{S2/M2} = 0.8$ or 1.0 dB below shot noise is less than that obtained for QND_1 but still clearly in the nonclassical domain. This degradation of the performances of QND_2 could be attributed to its lower gain and to some residual depolarization effects. Figure 4 represents the equivalent curves for the signal at the output of QND_2, given the first meter measurement. This shows again a conditional variance $V_{S2/M1} = 0.66$ or 1.8 dB below shot noise, demonstrating that the final signal output is still strongly correlated with the first meter. Furthermore, the measured correlation between the two meter outputs is $C_{M1M2} = 0.3$, demonstrating that the successive measurements are also strongly correlated. This value is in good agreement with the measured correlations between $S1$ and $M1$, between $S2$ and $M2$, and the transfer coefficients

$$C_{M1M2} = C_{S1M1}C_{S2M2}/\sqrt{T_{S1}T_{S2}} = 0.29\,. \tag{4}$$

This completes the demonstration of the QND principle.

The aim of the QND measurement is to monitor a single observable, keeping it unspoiled by the fluctuations due to the coupling between the system and the measurement apparatus. An irrefutable test of the QND principle is given by the ability of the system to provide identical results in repeated measurements beyond the standard quantum limit. We have developed two BAE setups having equivalent performances. When operated in series, the final output S_2 is strongly quantum correlated with both measurement channels (M_1 and M_2), which are also correlated between themselves. This experiment clearly demonstrates the QND principle and opens also interesting perspectives for quantum processing of information insensitive to losses.

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