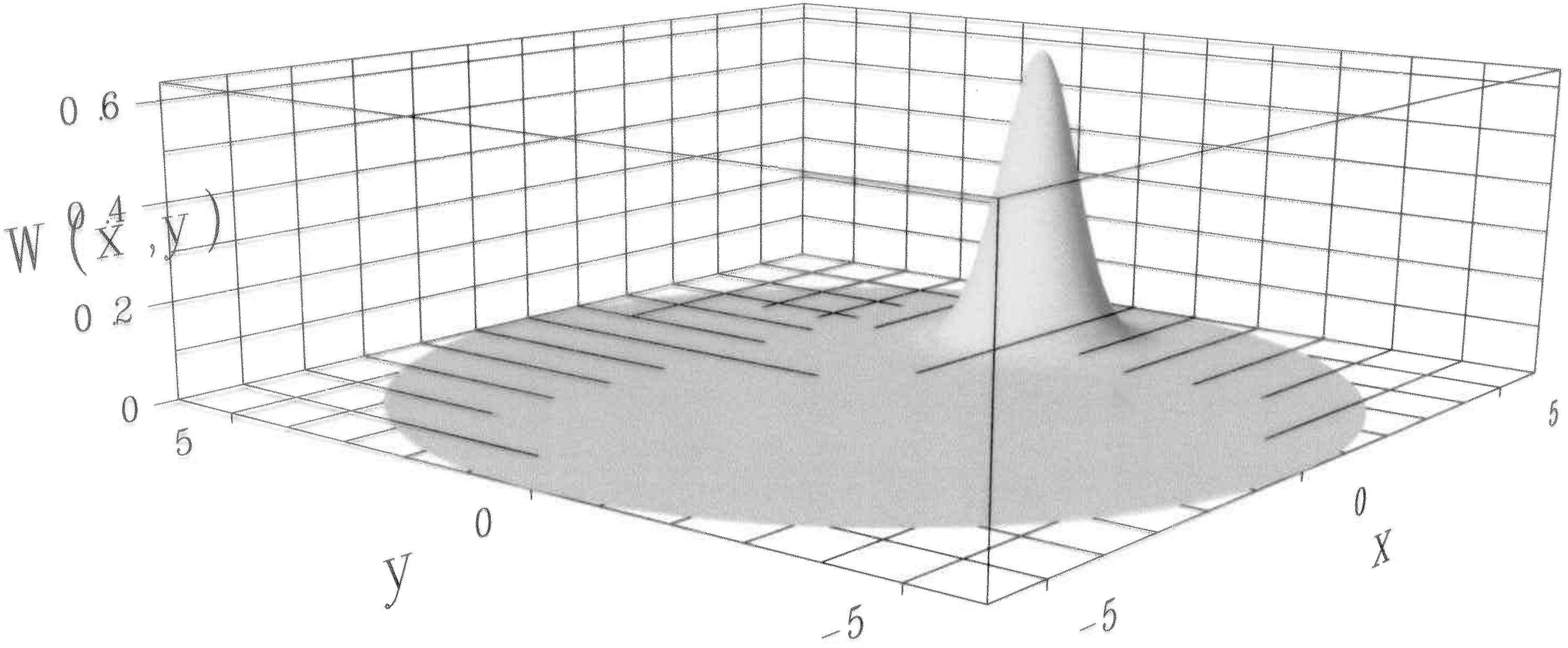
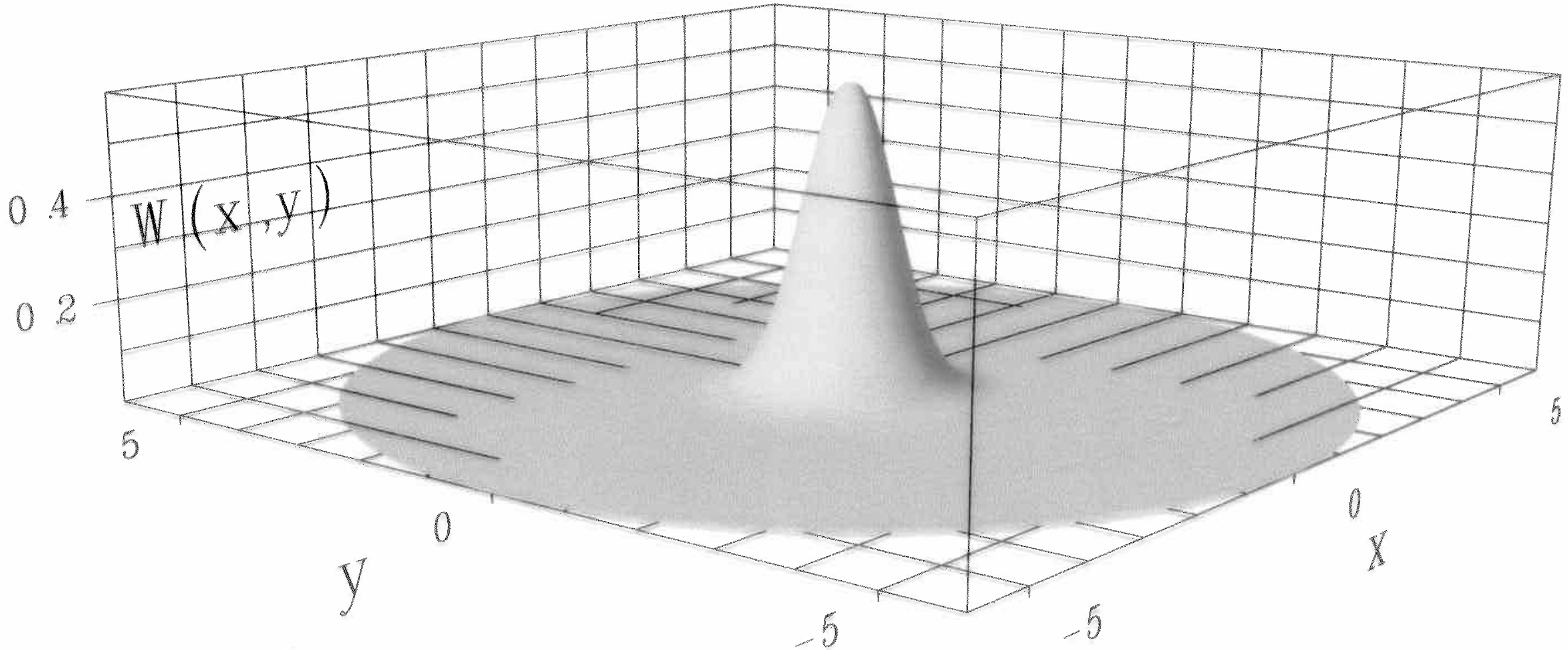
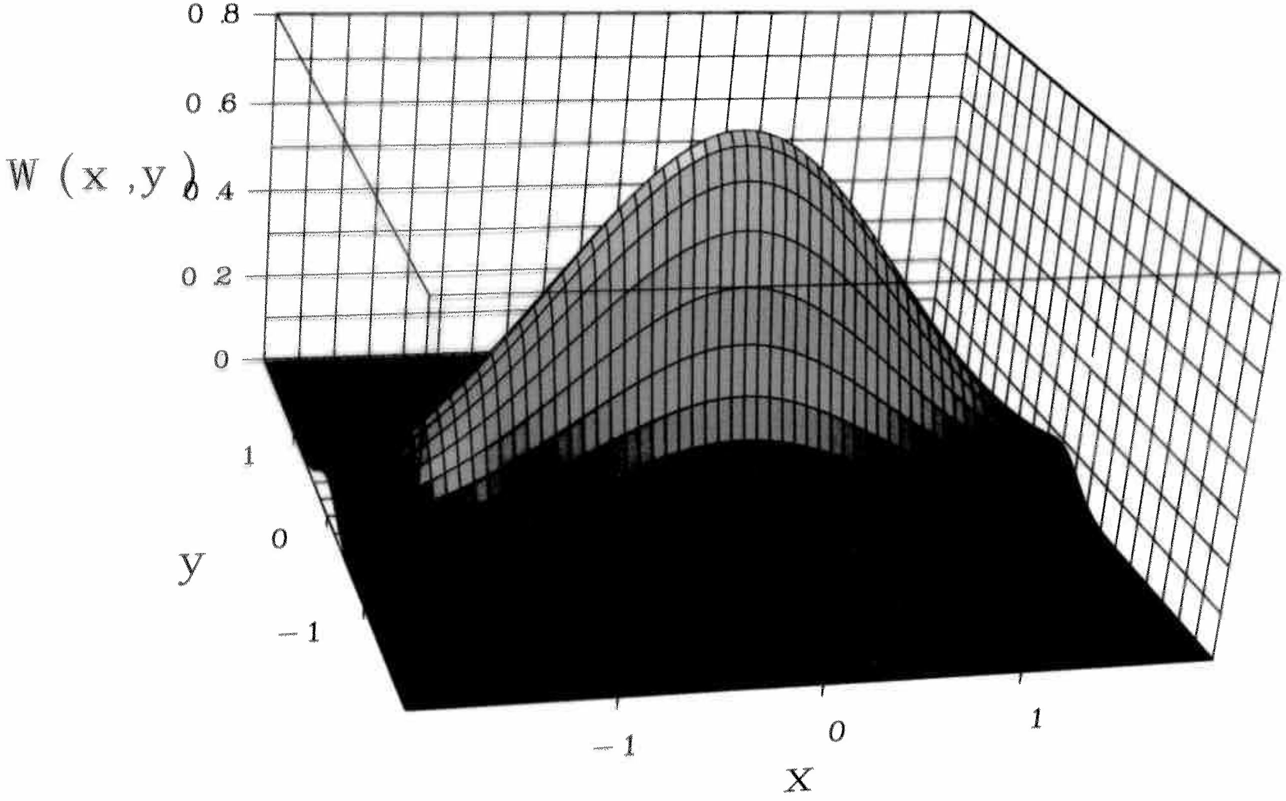


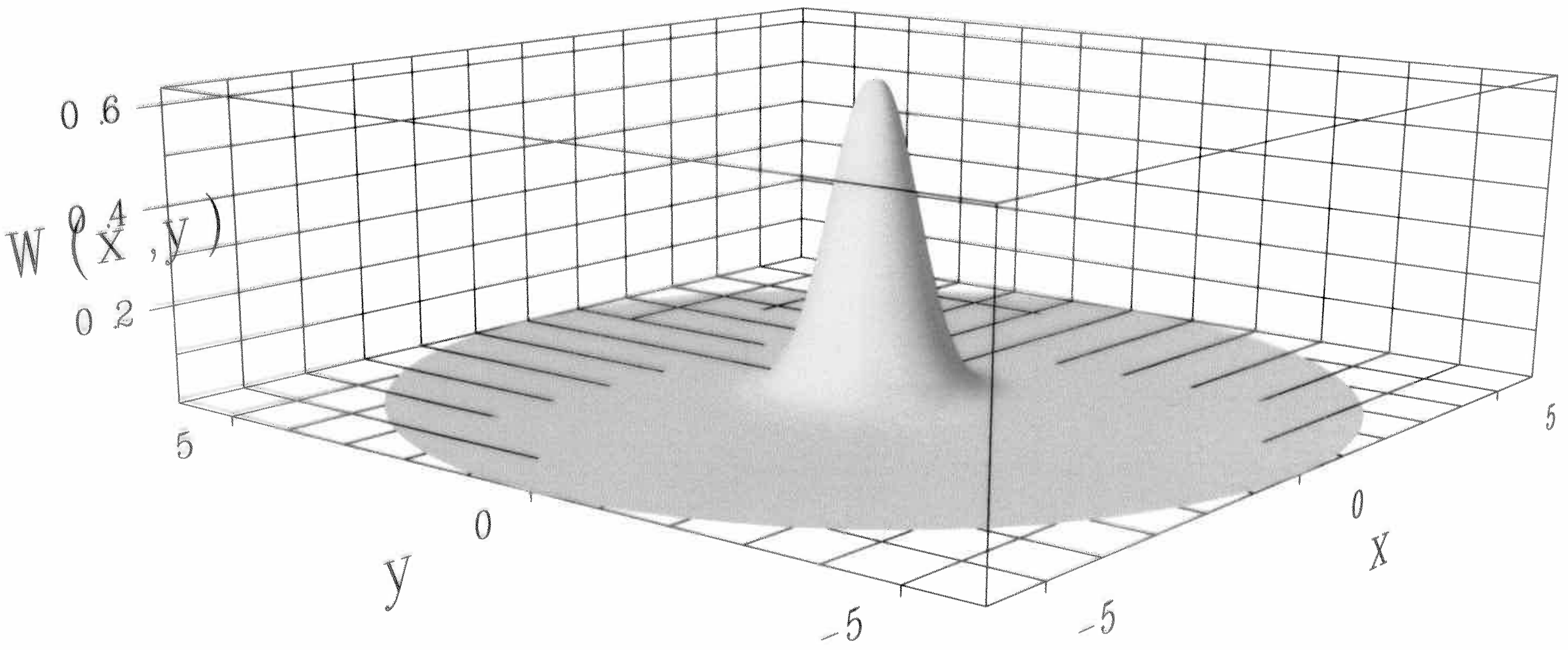
Stato Coerente $|\alpha\rangle$



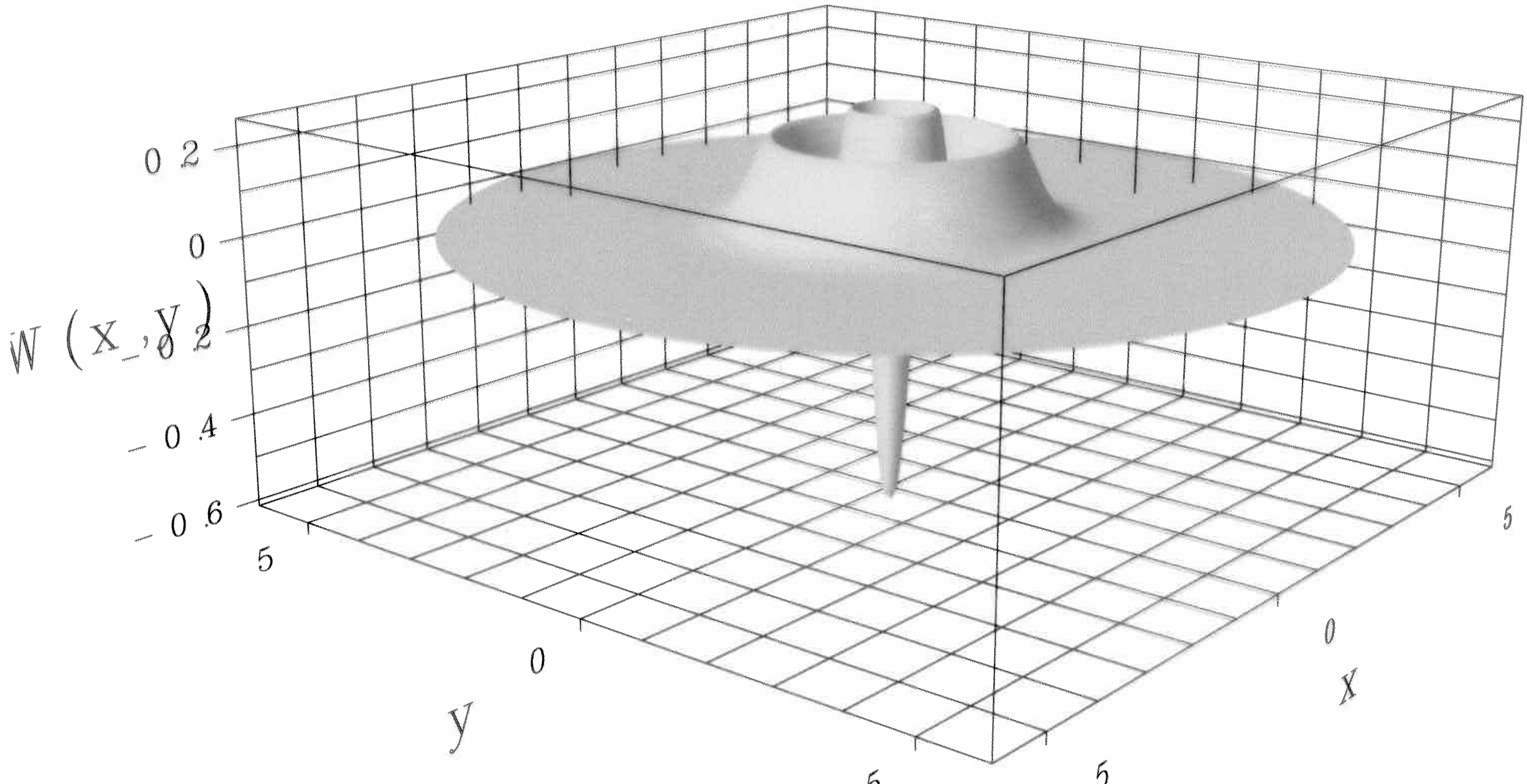
Vuoto $|0\rangle$ (coerente - Fock)



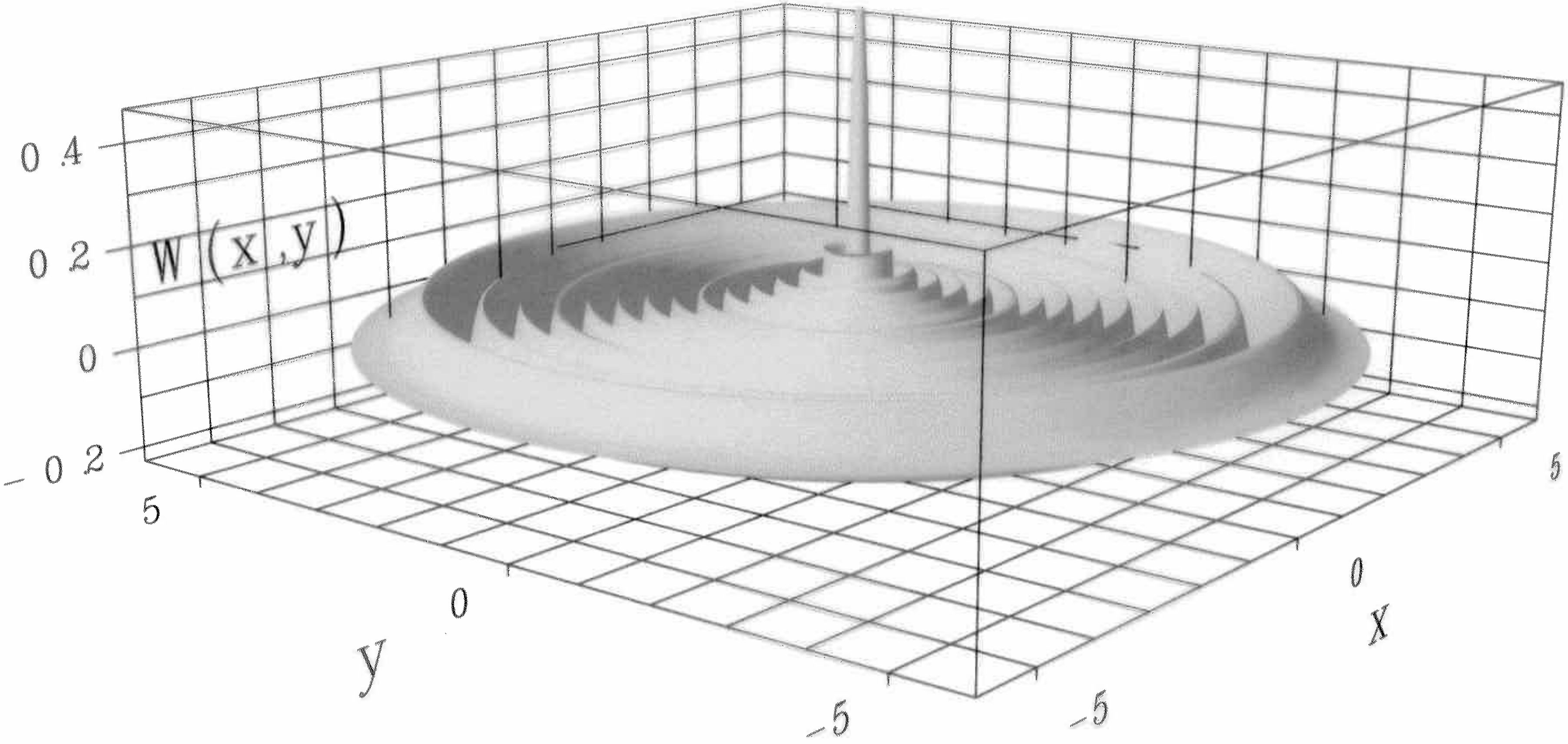
Vuoto squeezed



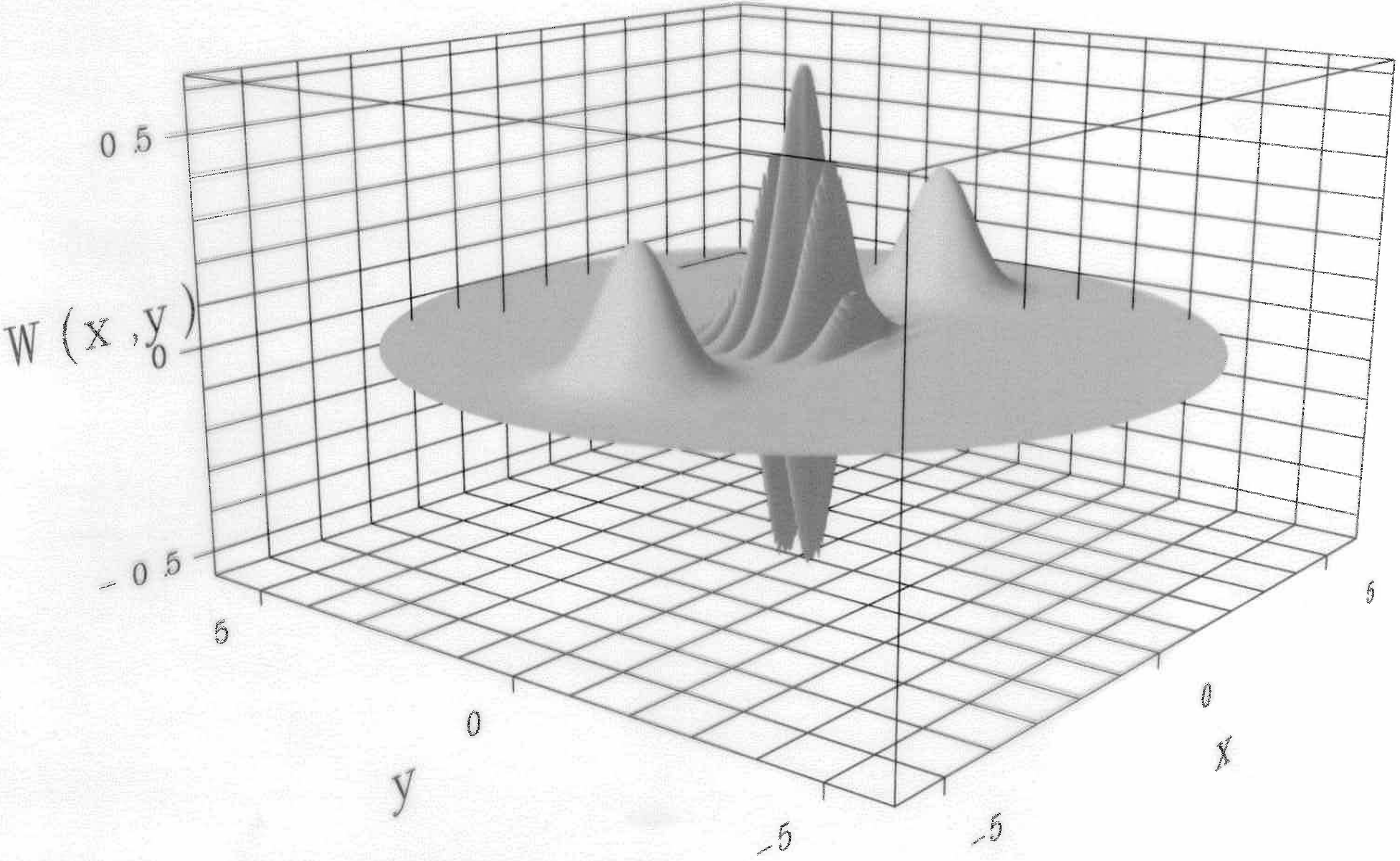
St. termico $\rho = (1 - e^{-\beta}) e^{-\beta a^\dagger a}$, $\beta = \frac{\hbar\omega}{kT}$



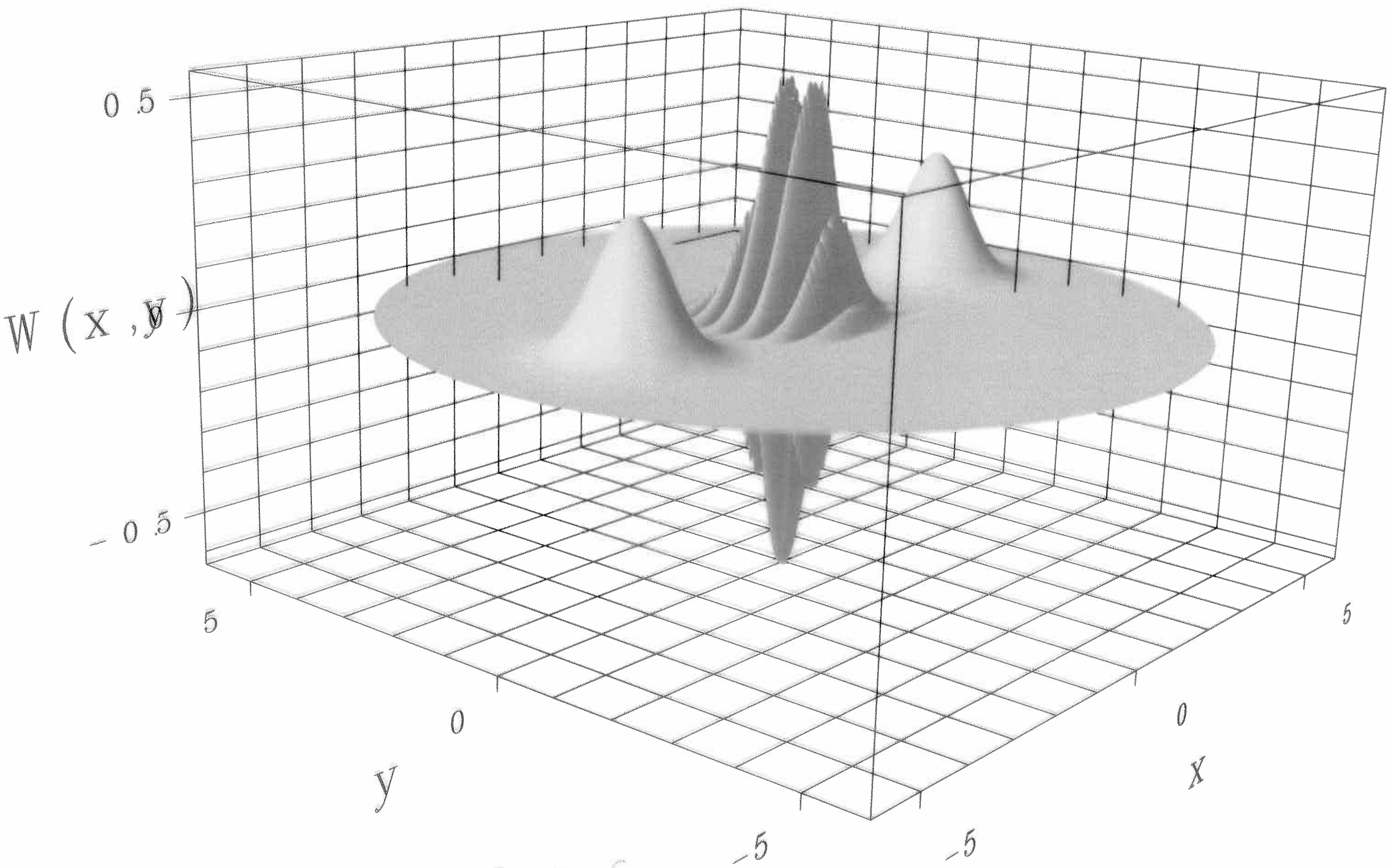
Stato di Fock |3>



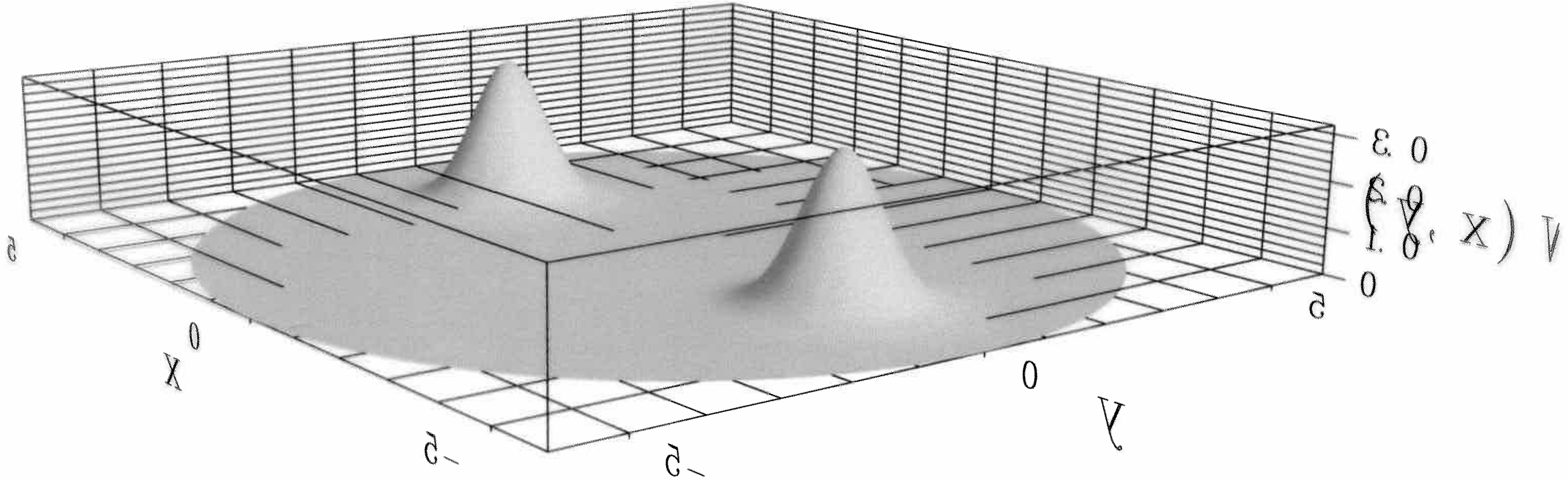
St. Fock $|28\rangle$



Gatto maschio: $|\psi\rangle = \frac{1}{\sqrt{2}}\left(|\alpha\rangle + |-\alpha\rangle\right)$



Gatto femmina: $|\psi\rangle = \frac{1}{\sqrt{2}}(|\alpha\rangle - |-\alpha\rangle)$



Mistura coerenti: $\rho = \frac{1}{2}(|\alpha\rangle\langle\alpha| + |-\alpha\rangle\langle-\alpha|)$

Breitenbach, Schiller, Mlynek, Nature 387, 471 (1997)

Of the various methods that have been proposed to reconstruct the quantum state numerically from the set of measured distributions P_θ, two are employed here. The first method makes use of the fact that the distributions $P_\theta(x_\theta)$ are the marginals of the Wigner function $W(x, y)$ in rotated coordinates;

$$P_\theta(x_\theta) = \int_{-\infty}^{\infty} W(x_\theta \cos\theta - y_\theta \sin\theta, x_\theta \sin\theta + y_\theta \cos\theta)\, \mathrm{d}y_\theta \qquad (1)$$

where $y_\theta = -x\sin\theta + y\cos\theta$. Therefore $W(x, y)$ can be obtained from the set P_θ by back-projection via the inverse Radon transform[2]. The second method furnishes the elements of the density matrix in the Fock basis via integration of the distributions P_θ over a set of pattern functions[3,4]. In contrast to the inverse Radon transform, this procedure does not involve any filtering of the experimental data and also allows an estimation of the propagation of statistical errors.

The experiment

The experimental set-up is shown in Fig. 1. Central to the experiment is a monolithic standing-wave lithium-niobate optical parametric oscillator (OPA)[13,24], pumped by a frequency-doubled continuous-wave Nd:YAG laser (1,064 nm). The infrared laser wave is filtered by a high-finesse mode-cleaning cavity, which transmits 75% of the laser power. Its narrow linewidth of 170 kHz suppresses the high-frequency technical noise of the laser, yielding a shot-noise-limited local oscillator for light powers in the milliwatt range at frequencies $\geq$1 MHz (ref. 13). The pump wave 2ω (power ~20–30 mW) for the OPA is generated by resonant second harmonic generation.

In the past OPAs have been frequently used as sources of non-classical light[10,13,25–28]. Operated below threshold, the OPA is a source of squeezed vacuum. We studied the field's spectral components around a frequency offset by $\Omega/2\pi = 1.5$ or 2.5 MHz from the optical frequency ω, to avoid low-frequency laser excess noise. To generate bright light (that is, with non-vanishing average electric field at the frequencies $\omega \pm \Omega$), we employ the OPA in a dual port configuration[28]. A very weak wave split off the main laser beam is phase-modulated by an electro-optic modulator (EOM) at the frequency Ω (modulation index $\beta \ll 1$) and injected into the

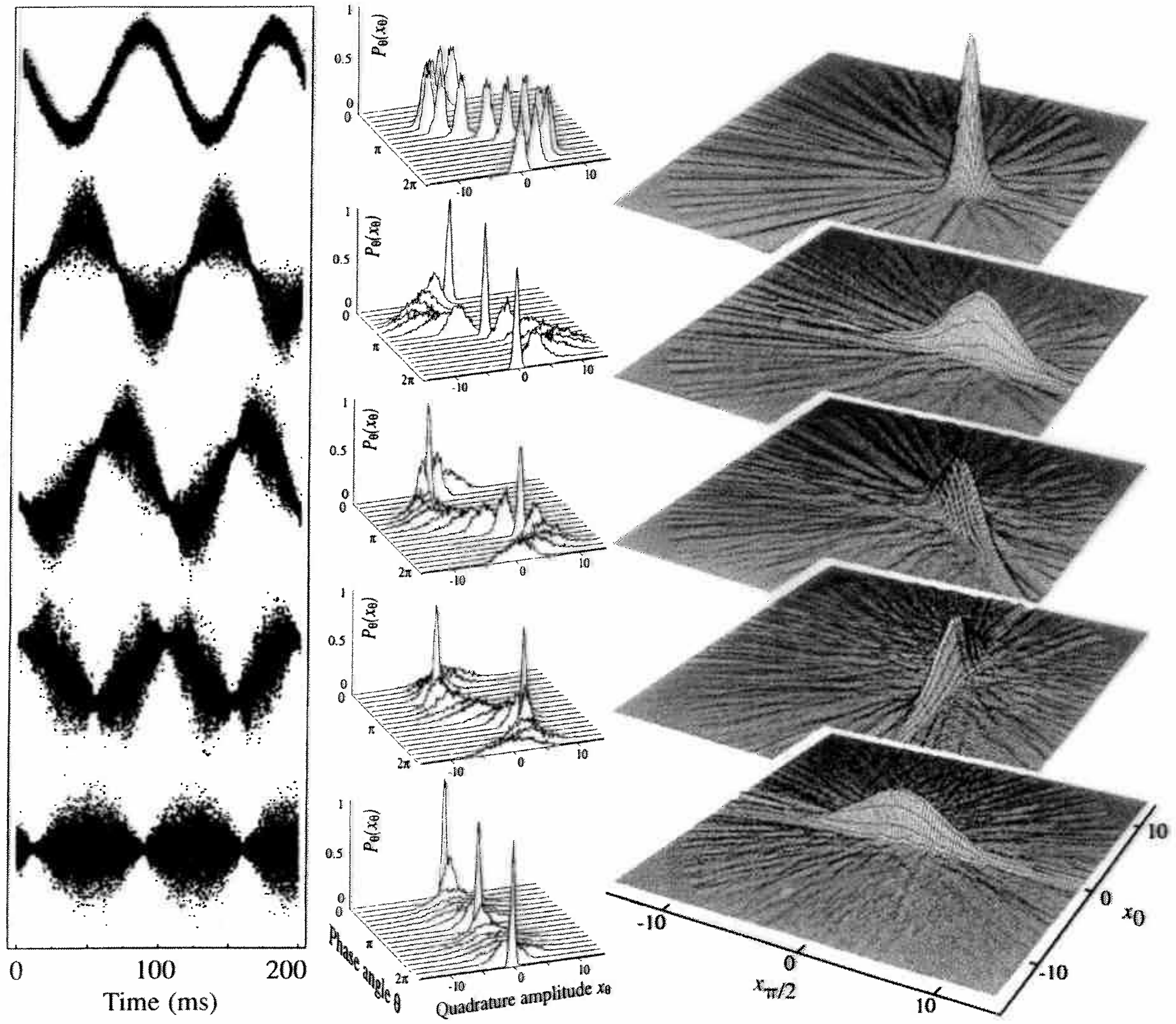


Figure 2 Noise traces in $i_\Omega(t)$ (left), quadrature distributions $P_\theta(x_\theta)$ (centre), and reconstructed Wigner functions (right) of generated quantum states. From the top: Coherent state, phase-squeezed state, state squeezed in the $\phi = 48°$-quadrature, amplitude-squeezed state, squeezed vacuum state. The noise traces as a function of time show the electric fields' oscillation in a 4π interval for the upper four states, whereas for the squeezed vacuum (belonging to a different set of measurements) a 3π interval is shown. The quadrature distributions (centre) can be interpreted as the time evolution of wave packets (position probability densities) during one oscillation period. For the reconstruction of the quantum states a π interval suffices.