Eur. Phys. J. D **12**, 124 (2000)

THE EUROPEAN
PHYSICAL JOURNAL D
EDP Sciences

## *Reply to the comment on*

# Quantum backaction of optical observations on Bose-Einstein condensates

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Eur. Phys. J. D **7**, 413 (1999)

Received 11 July 2000

**PACS.** 03.75.Fi Phase coherent atomic ensembles; quantum condensation phenomena – 03.65.Bz Foundations, theory of measurement, miscellaneous theories (including Aharonov Bohm effect, Bell inequalities, Berry's phase) – 42.50.Dv Nonclassical field states; squeezed, antibunched, and sub-Poissonian states; operational definitions of the phase of the field; phase measurements

How is a Bose-Einstein condensate perturbed by dispersive imaging [1]? Suppose that dispersive imaging is absorptionless, what is the quantum backaction?

In our paper [2] we have only addressed the second question. We found that two processes contribute to the backaction, phase diffusion and condensate depletion. The pioneering paper [1] referred only to phase diffusion as the quantum backaction and made no estimation of the diffusion rate. According to our calculation [2], depletion turned out to dominate the quantum backaction. Since the depletion rate agreed with the experimental facts [1] within the available accuracy, we conjectured that the quantum backaction might indeed explain the observed perturbation. However, in our analysis we have entirely ignored the residual absorption of dispersive imaging, in order to determine the backaction *per se*. The Comment [3] stresses the fact that absorption is still stronger than the quantum backaction. This is correct, as can be seen from the following calculation.

The depletion rate due to backaction is, according to equation (62) of reference [2],

$$\gamma_{\mathrm{L}} = (\pi^2/4)(\chi_0^2/\hbar c) I \lambda^{-3}, \tag{1}$$

where $\lambda$ denotes the wave length of light, $I$ is the intensity and $\chi_0$ is the susceptibility per atom-wave density. We assume the individual atoms as two-level systems with detuning $\varDelta$ and Rabi frequency

$$\omega_{\mathrm{R}} = (d/\hbar) E^{(+)}, \tag{2}$$

where $d$ is the dipole moment and $E^{(+)}$ is the positive frequency part of the electric field strength. Our goal is to compare $\gamma_{\mathrm{L}}$ with the spontaneous emission rate [4]

$$\varGamma = \frac{1}{4\pi\epsilon_0}\frac{4d^2}{3\hbar}\left(\frac{2\pi}{\lambda}\right)^3 = \frac{1}{4\pi\epsilon_0}\frac{4d^2\hbar\,|\omega_{\mathrm{R}}|^2}{3\,|E^{(+)}|^2}\left(\frac{2\pi}{\lambda}\right)^3 . \tag{3}$$

First, we express $\chi_0$ in terms of the detuning and of the Rabi frequency, utilizing the fact that the light-matter interaction energy in the Lagrangian (1) of reference [2] is equal to the optical potential,

$$\frac{\epsilon_0\chi_0}{2}E^2 = \epsilon_0\chi_0|E^{(+)}|^2 = -\hbar\,\frac{|\omega_{\mathrm{R}}|^2}{2\varDelta} \cdot \tag{4}$$

According to equations (16, 36) of reference [2] the light intensity is

$$I = 2\epsilon_0 c\,|E^{(+)}|^2. \tag{5}$$

Consequently, we obtain

$$\gamma_{\mathrm{L}} = \frac{3}{16}\,\varGamma\,\left|\frac{\omega_{\mathrm{R}}}{2\varDelta}\right|^2 . \tag{6}$$

The upper-state excitation of a far-detuned two-level atom is $|\omega_{\mathrm{R}}/(2\varDelta)|^2$. The incident light excites the atoms, and the subsequent spontaneous decay gives rise to Rayleigh scattering, being the principal absorption mechanism. Therefore, the calculated backaction rate is 3/16 of the absorption rate.

Even in the limit of extremely far detuning, absorption is still stronger than the quantum backaction, as can be seen from the comparison of the two different rates. Consequently, residual absorption sets indeed the limit of dispersive imaging [3].

## References

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