Casimir phase-shifts and decoherence in atom interferometers

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1 Introduction

Atom interferometry is central in many technological devices. The possibility of a highly accurate measure of the phase difference between the arms of the interferometer enables the construction of amazingly sensitive inertial sensors, to name an example. The presence of a medium close to the interferometer has a strong effect in its behaviour, provoking decoherence[1] and a measurable[2] phase-shift. The medium interacts with the atom mediated by the electromagnetic field, yielding, in general, a problem involving several degrees of freedom, posing a situation difficult to deal theoretically.

We will suppose the atom to be in the ground state with a wave packet which is a superposition of two wave packets strongly localized on the interferometer’s arms. Our system will be composed also by the electromagnetic field $A_p$, and by the material medium (dielectric or metallic), which will be described by a polarization field $P(x)$ coupled to a reservoir $X(x)$ composed by a continuous lattice of fictitious harmonic oscillators. Physically, the reservoir consists on a large number of degrees of freedom which dissipates energy of the rest of the system. Since our major interest is on the atom, we will be concerned only with the mean effect of the medium and the field on the atomic behaviour. In order to do so, we shall trace upon the irrelevant variables. We shall perform the calculations with the aid of the path integral technique, following [3]. In the next section we shall illustrate this method.

2 The influence functional

In the path integral formalism the density matrix element $\rho(X, X'; t)$ may be written as

$$\rho(X, X'; t) = \int \mathcal{D}X' \mathcal{D}X e^{iS[X] - S[X']}$$

with

$$\int \mathcal{D}X' \int \mathcal{D}X' \int \mathcal{D}X' \int \mathcal{D}X' \rho(X_0, X'_0, 0)$$

The reservoir’s mean influence on the matter is contained in the reduced density matrix $\rho_X(P, P')$ obtained from the complete density matrix by tracing upon the reservoir’s variables. Therefore

$$\rho_X(P, P') = \int \mathcal{D}X \rho_X(P, P', X, X'; t)$$

obtained by tracing out, the reservoir, then also the polarization field, the electromagnetic field and finally the internal degree of freedom of the atom. Although the idea is the same for each step, the evaluation is not always so simple as the first, which we discussed in the last section. This is because from the second trace on we don’t have a unitary Hamiltonian any more, due to dissipation. However, all the influence actions appearing after each trace retains the style of eq. (3), i.e., one part will correspond to a susceptibility kernel and the other to a fluctuation kernel[5].

4 Phase-shift and decoherence

After the last trace we are entitled to write

$$\rho(r_1, r'_1; t) = \int \mathcal{D}r_1' \mathcal{D}r_1 e^{iS[r_1] - S[r_1]}$$

Since we are supposing that the wavefunction characterizing the atom is a superposition of two highly localized wave packets, one in each arm of the interferometer, our density matrix may be written as 2x2 matrix.

$$\begin{pmatrix} \rho(r_1, r_1; t) & \rho(r_1, r_2; t) \\ \rho(r_2, r_1; t) & \rho(r_2, r_2; t) \end{pmatrix}$$

The non-diagonal terms of this matrix expose the coherence between the wave packets and are the main actors of this play. Therefore, the influence functional $S_D(r_1, r_2)$ contains both the information about the decoherence and the phase-shift, which are, respectively, the imaginary and the real parts of it. One of the fine advantages of this treatment is the possibility of evaluating at once both effects.

5 Conclusion

Recent calculation was performed using this method for a perfectly conducting plate[6]. Their result contains some interesting features, namely, a non-local phase-shift given by:

$$\phi_{21} = Re \{ S_D[r_1, r_2] \}. \tag{6}$$

This phase depends conjointly on both trajectories and is, as long as the authors know, a new result in the atom-interferometer context. Our objective now is to extend the calculation to a real material. Decoherence might be enhanced in this case since the real material has more channels into which information may leak.

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References