TYPE Correction
PUBLISHED 14 November 2022
DOI 10.3389/fphy.2022.1026111

Check for updates

OPEN ACCESS

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SPECIALTY SECTION
This article was submitted to Interdisciplinary Physics, a section of the journal Frontiers in Physics

RECEIVED 23 August 2022
ACCEPTED 14 September 2022
PUBLISHED 14 November 2022

CITATION
Lokare Y (2022), Corrigendum: Stern-Gerlach interferometry for tests of quantum gravity and general applications.
Front. Phys. 10:1026111.
doi: 10.3389/fphy.2022.1026111

Corrigendum: Stern-Gerlach interferometry for tests of quantum gravity and general applications

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KEYWORDS

Stern-Gerlach interferometry, matter-wave interferometers, entanglement entropy, density matrix, interference signal, precision sensing, quantum metrology

A Corrigendum on
Stern-Gerlach interferometry for tests of quantum gravity and general applications

by Lokare Y (2022). Front. Phys. 10:785125. doi: 10.3389/fphy.2022.785125

In the original article, two references were not cited. These are as follows:

20. Marshman RJ, Mazumdar A, Bose S. Locality and entanglement in table-top testing of the quantum nature of linearized gravity. Phys Rev A (Coll Park) (2020) 101: 052110. doi:10.1103/physreva.101.052110

21. Bose S, Mazumdar A, Schut M, Toros M. Mechanism for the quantum natured gravitons to entangle masses. Phys Rev D (2022) 105:106028. doi:10.1103/ physrevd.105.106028

The citations appearing as Ref. [20] and Ref. [21] in the reference list, respectively) have now been inserted in **Section 4: Entanglement dynamics in the density matrix formalism**.

Additionally, there was a mistake in the original article relating to a reference (i.e., Ref. [18] in the original article) which has now been withdrawn from arXiv. Previously this was listed as:

18. Lokare Y. A complete analysis of spin coherence in the full-loop stern-gerlach interferometer using non-squeezed and squeezed coherent states of the quantum harmonic oscillator (2021).

The original article referenced and discussed results appearing in Ref. [18]. **Section 5**, Paragraphs 1-6 and equations 22-26 have now been removed and the section rewritten. This section now reads:

"In principle, it is possible to realize full-loop Stern-Gerlach interferometers using pure Bose-Einstein condensates (BECs). A possible arrangement is to have a BEC initially confined within a harmonic trap, which is then released and probed in a Stern-Gerlach interferometric setup. To this end, we consider one such case, as proposed and/or analyzed in Ref. [22]. We work under the crude assumption that interactions between atoms in the BEC are effectively negligible, in light of which the analysis will simply reduce to the single-particle limit. Note here that a rapid free expansion of the BEC post-release is being assumed. The wave-packet of a BEC satisfies the Gross-Pitaevskii equation, as follows

$$i\hbar\frac{\partial\psi(t)}{\partial t} = H_{\mathrm{MF}}(t)\psi(t), \tag{23}$$

where the Hamiltonian $\boldsymbol{H_{\mathrm{MF}}(t)}$ in the mean-field approximation assumes the form $H_{\mathrm{MF}}(t) = -\frac{\hbar^2}{2m}\nabla^2 + U(r,t) + g|\psi|^2$. Here, note that $\boldsymbol{U(r,t)}$ denotes the time-dependent potential that arises from external effects such as gravity, etc. (g here denotes the mean-field coupling parameter which is characterized in terms of the s-wave scattering length (denoted as a) of the BEC in question, as $\boldsymbol{g = 4\pi\hbar^2 a/m}$). Given **Eq. 23**, it is possible to derive a closed-form expression for the evolution of a BEC wave-packet in the center-of-mass frame [22]. This can be done so as long as the time-dependent potential $\boldsymbol{U(r,t)}$ assumes a quadratic profile around the BEC center-of-mass. The scaling ansatz (see Ref. [22]) is shown to be exact if one approximates the wave function at the time of release by a Gaussian wave-packet that evolves in this quadratic potential (interatomic interactions have been ignored). Thus, we consider the form of the wave function before release from the harmonic trap (approximated by a Gaussian and assumed to be stationary initially) as follows

$$\psi_i(z,\quad t=0) = (2\pi)^{-1/4}(\delta z)^{-1/2}\exp\left(-\frac{z^2}{4(\delta z)^2}\right), \tag{24}$$

where $\boldsymbol{\delta z}$ denotes the width of the initially prepared Gaussian wave-packet. The one-dimensional scaling factor assumes the form $\gamma \equiv \sqrt{1+\omega^2 t^2}$ and the scaled spatial and momentum splitting between the wave-packets is given as [22]

$$\Delta\bar{z}(t) = \Delta z(t)\big/\gamma, \tag{25}$$

and

$$\Delta\bar{p}_z(t) = \gamma\Delta p_z(t) - m\frac{d\gamma}{dt}\Delta z(t), \tag{26}$$

where m is the mass of the atoms in the BEC, $\Delta\bar{z}(t)$ is the macroscopic splitting between the wave-packets in position space, and $\Delta\bar{p}_z(t)$ denotes the macroscopic splitting between the wave-packets in momentum space. From **Eq. 11** and **Eq. 24**, we get for the interference signal strength $\boldsymbol{\phi_{\mathrm{BEC}}}$ [computed over the total time-of-flight $\boldsymbol{\tau}$]

$$\phi_{\mathrm{BEC}} = \frac{1}{\sqrt{2\pi}}\frac{1}{\delta z}\int_{-\infty}^{\infty}\exp\left(-\left(\frac{z-\Delta\bar{z}(t)}{2\delta z}\right)^2 - \left(\frac{z+\Delta\bar{z}(t)}{2\delta z}\right)^2\right) \times \exp\left(-2i\frac{\Delta\bar{p}_z(t)}{\hbar}z\right)dz. \tag{27}$$

The integral in Eq. 27 is a standard Gaussian integral, simplifying which we get

$$\phi_{\mathrm{BEC}} = \exp\left(-\frac{1}{2}\left(\left(\frac{\Delta\bar{z}(\tau)}{\delta z}\right)^2 + \left(\frac{\Delta\bar{p}_z(\tau)}{\delta p_z}\right)^2\right)\right), \tag{28}$$

where $\boldsymbol{\delta p_z}$ denotes the initial momentum uncertainty in the initially prepared BEC wave-packet (*note*: the Gaussian wave-packet is a minimum uncertainty state that saturates the uncertainty principle, for which $\boldsymbol{\delta z\ \delta p_z = \hbar/2}$). From **Eqs 25, 26, 28**, one can deduce an approximate closed-form expression for $\boldsymbol{\phi_{\mathrm{BEC}}}$.

To maximize the Stern-Gerlach interference signal strength, Eq. 28 suggests that the following conditions must hold[1]

$$\Delta\bar{z}(\tau) \ll \delta z, \tag{29}$$

and

$$\Delta\bar{p}_z(\tau) \ll \delta p_z. \tag{30}$$

A more robust analysis is however in order, for the following reasons. In an experimental setup, it is quite possible that the initial BEC wave-packet might not assume a Gaussian profile, in light of which Eqs. 27, 28 would not be sufficient to quantify the interference signal strength. Moreover, analyzing the model in the single-particle limit yields only approximate results[1]. It is in fact, necessary to consider a full quantum many-body treatment of a trapped impure BEC (i.e., by incorporating finite-temperature effects), which from an experimental point of view, seems more reasonable. Experimental realizations of the kind described here have already been reported in the literature. Ref. [23] for instance, reports the realization of a high stability Stern-Gerlach spatial fringe interferometer with pure BECs.

Using heavy neutral test masses instead of atomic clouds is another viable, yet formidable approach[1]. It is worth bearing in mind however that such an experiment would demand a delicate balance between several experimental parameters. A more realistic implementation of such a setup (more specifically, the quantification of the Stern-Gerlach interference signal strength) will have to take into account the effects of the field gradient present in the $\boldsymbol{x-y}$ plane (per Maxwell's equations), in addition to the one applied along $\boldsymbol{z}$[1]. This warrants a 2D analysis of such a setup [14]. In recent years, there have been attempts to address some of these issues. Marshman *et al.* not long ago analyzed a numerical model of a slightly modified version of an SG interferometric setup [24] by including the effects of the field gradient in the $\boldsymbol{x-y}$ plane (in addition to the one already existing along the $\boldsymbol{z}$ direction). Furthermore, they consider field gradients of intermediate strengths and the effect of the diamagnetic properties of the test mass in their analysis. Their results demonstrate that the introduction of a gradient-free region (see Ref. [24] for more details) along the wave-packet trajectories can facilitate the acceleration of micron-sized test masses in the interferometric setup, which in turn can help one

1 Bose S, Mazumdar A. Private Communication. (2021).

realize more efficient splitting between the individual wave-packets.

Considering the above correction, **Eq. 33** appearing in **Section 6** of the original article is re-labelled to **Eq. 31**.

In addition, Refs. [20] and [97] appearing in the original article have now been published in peer-reviewed journals. Therefore, their journal references have been added and now read as follows:

20. Japha Y. Unified model of matter-wave-packet evolution and application to spatial coherence of atom interferometers. Phys Rev A (Coll Park) (2021) 104:053310. doi:10.1103/physreva.104.053310

24. Marshman RJ, Mazumdar A, Folman R, Bose S. Constructing nano-object quantum superpositions with a Stern-Gerlach interferometer. Phys Rev Res (2022) 4:023087. doi:10.1103/physrevresearch.4.023087

Finally, the **Acknowledgments** have been modified to better reflect the contributions of Prof. A. Mazumdar and Prof. S. Bose. The updated statement reads:

"The author YL would like to express his gratitude to his former mentors, A. Mazumdar and S. Bose, with whom he has had several useful and/or insightful discussions on matter-wave interferometry and related areas (in particular, realizing quantum gravity tests using Stern-Gerlach interferometry)."

The author apologizes for this error and states that this does not change the scientific conclusions of the article in any way. The original article has been updated.

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