

Ghosh Dastidar, Madhura; Das, Subrata; Mukherjee, Koushik; Majumder, Sonjoy
Pattern formation and evidence of quantum turbulence in binary Bose-Einstein condensates interacting with a pair of Laguerre-Gaussian laser beams. (English) [Zbl 07427915](#)
Phys. Lett., A 421, Article ID 127776, 12 p. (2022)

Summary: We theoretically investigate the out-of-equilibrium dynamics in binary Bose-Einstein condensate confined within two-dimensional box potentials. One species of the condensate interacts with a pair of oppositely wound, but otherwise identical Laguerre-Gaussian laser pulses, while the other species is influenced only via the interspecies interaction. Depending on the number of helical windings (or the magnitude of topological charge), the species directly participating in the interaction with lasers is dynamically segmented into distinct parts that collide together as the pulses gradually diminish. This collision event generates nonlinear structures in the related species, coupled with the complementary structures produced in the other species, due to the interspecies interaction. The long-time dynamics of the optically perturbed species is found to develop the Kolmogorov-Saffman scaling law in the incompressible kinetic energy spectrum, a characteristic feature of quantum turbulence. This study warrants the usage of Laguerre-Gaussian beams for future experiments on quantum turbulence in Bose-Einstein condensates.

MSC:

- [82C26](#) Dynamic and nonequilibrium phase transitions (general) in statistical mechanics
- [81V73](#) Bosonic systems in quantum theory
- [78A60](#) Lasers, masers, optical bistability, nonlinear optics

Keywords:

[Bose-Einstein condensate](#); [Laguerre-Gaussian beam](#); [quantum turbulence](#)

Software:

[Gross-Pitaevskii](#)

Full Text: [DOI](#) [arXiv](#)

References:

- [1] Chu, S., *Rev. Mod. Phys.*, 70, 685 (1998)
- [2] Cohen-Tannoudji, C. N., *Rev. Mod. Phys.*, 70, 707 (1998)
- [3] Phillips, W. D., *Rev. Mod. Phys.*, 70, 721 (1998)
- [4] Ritsch, H.; Domokos, P.; Brennecke, F.; Esslinger, T., *Rev. Mod. Phys.*, 85, 553 (2013)
- [5] Slama, S.; Bux, S.; Krenz, G.; Zimmermann, C.; Courteille, P. W., *Phys. Rev. Lett.*, 98, Article 053603 pp. (2007)
- [6] Walther, H.; Varcoe, B. T.H.; Englert, B.-G.; Becker, T., *Rep. Prog. Phys.*, 69, 1325 (2006)
- [7] Caballero-Benitez, S. F.; Mekhov, I. B., *Phys. Rev. Lett.*, 115, Article 243604 pp. (2015)
- [8] Dutra, S. M., *Cavity Quantum Electrodynamics: The Strange Theory of Light in a Box* (2005), John Wiley & Sons
- [9] Cooper, N. R.; Dalibard, J.; Spielman, I. B., *Rev. Mod. Phys.*, 91, Article 015005 pp. (2019)
- [10] Mivehvar, F.; Piazza, F.; Donner, T.; Ritsch, H., *Cavity qed with quantum gases: new paradigms in many-body physics* (2021)
- [11] Grimm, R.; Weidemüller, M.; Ovchinnikov, Y., *Adv. At. Mol. Opt. Phys.*, 42, 95 (2000)
- [12] Garraway, B. M.; Minogin, V. G., *Phys. Rev. A*, 62, Article 043406 pp. (2000)
- [13] Frese, D.; Ueberholz, B.; Kuhr, S.; Alt, W.; Schrader, D.; Gomer, V.; Meschede, D., *Phys. Rev. Lett.*, 85, 3777 (2000)
- [14] Cornell, E. A.; Wieman, C. E., *Rev. Mod. Phys.*, 74, 875 (2002)
- [15] Ketterle, W., *Rev. Mod. Phys.*, 74, 1131 (2002)
- [16] Bloch, I.; Dalibard, J.; Zwinger, W., *Rev. Mod. Phys.*, 80, 885 (2008)
- [17] Giorgini, S.; Pitaevskii, L. P.; Stringari, S., *Rev. Mod. Phys.*, 80, 1215 (2008)
- [18] Gordon, J. P.; Ashkin, A., *Phys. Rev. A*, 21, 1606 (1980)
- [19] Allen, L.; Beijersbergen, M. W.; Spreeuw, R. J.C.; Woerdman, J. P., *Phys. Rev. A*, 45, 8185 (1992)

- [20] Yao, A. M.; Padgett, M. J., *Adv. Opt. Photonics*, 3, 161 (2011)
- [21] Padgett, M. J., *Opt. Express*, 25, Article 11265 pp. (2017)
- [22] Dennis, M. R.; O'Holleran, K.; Padgett, M. J., *Prog. Opt.*, 53, 293 (2009)
- [23] Ren, Y.-X.; Li, M.; Huang, K.; Wu, J.-G.; Gao, H.-F.; Wang, Z.-Q.; Li, Y.-M., *Appl. Opt.*, 49, 1838 (2010)
- [24] Ruffato, G.; Massari, M.; Romanato, F., *Opt. Lett.*, 39, 5094 (2014)
- [25] Sueda, K.; Miyaji, G.; Miyanaga, N.; Nakatsuka, M., *Opt. Express*, 12, 3548 (2004)
- [26] Beijersbergen, M.; Allen, L.; van der Veen, H.; Woerdman, J., *Opt. Commun.*, 96, 123 (1993)
- [27] Beijersbergen, M.; Coerwinkel, R.; Kristensen, M.; Woerdman, J., *Opt. Commun.*, 112, 321 (1994)
- [28] Heckenberg, N. R.; McDuff, R.; Smith, C. P.; White, A. G., *Opt. Lett.*, 17, 221 (1992)
- [29] Mair, A.; Vaziri, A.; Weihs, G.; Zeilinger, A., *Nature*, 412, 313 (2001)
- [30] Allen, L.; Padgett, M.; Babiker, M., *Prog. Opt.*, 39, 291 (1999)
- [31] Franke-Arnold, S.; Allen, L.; Padgett, M., *Laser Photonics Rev.*, 2, 299 (2008)
- [32] Shen, Y.; Wang, X.; Xie, Z.; Min, C.; Fu, X.; Liu, Q.; Gong, M.; Yuan, X., *Light Sci. Appl.*, 8, 90 (2019)
- [33] Allen, L.; Babiker, M.; Lai, W. K.; Lembessis, V. E., *Phys. Rev. A*, 54, 4259 (1996)
- [34] Babiker, M.; Bennett, C. R.; Andrews, D. L.; Dávila Romero, L. C., *Phys. Rev. Lett.*, 89, Article 143601 pp. (2002)
- [35] Lloyd, S.; Babiker, M.; Yuan, J., *Phys. Rev. Lett.*, 108, Article 074802 pp. (2012)
- [36] Power, W. L.; Allen, L.; Babiker, M.; Lembessis, V. E., *Phys. Rev. A*, 52, 479 (1995)
- [37] Araoka, F.; Verbiest, T.; Clays, K.; Persoons, A., *Phys. Rev. A*, 71, Article 055401 pp. (2005)
- [38] Bougouffa, S.; Babiker, M., *Phys. Rev. A*, 102, Article 063706 pp. (2020)
- [39] Mashhadi, L., *J. Phys. B, At. Mol. Opt. Phys.*, 50, Article 245201 pp. (2017)
- [40] Quinteiro, G. F.; Reiter, D. E.; Kuhn, T., *Phys. Rev. A*, 95, Article 012106 pp. (2017)
- [41] Mukherjee, K.; Majumder, S.; Mondal, P. K.; Deb, B., *J. Phys. B, At. Mol. Opt. Phys.*, 51, Article 015004 pp. (2017)
- [42] Andersen, M. F.; Ryu, C.; Cladé, P.; Natarajan, V.; Vaziri, A.; Helmerson, K.; Phillips, W. D., *Phys. Rev. Lett.*, 97, Article 170406 pp. (2006)
- [43] Mondal, P. K.; Deb, B.; Majumder, S., *Phys. Rev. A*, 89, Article 063418 pp. (2014)
- [44] Mondal, P. K.; Deb, B.; Majumder, S., *Phys. Rev. A*, 92, Article 043603 pp. (2015)
- [45] Bhowmik, A.; Mondal, P. K.; Majumder, S.; Deb, B., *Phys. Rev. A*, 93, Article 063852 pp. (2016)
- [46] Kanamoto, R.; Wright, E. M.; Meystre, P., *Phys. Rev. A*, 75, Article 063623 pp. (2007)
- [47] Wright, K. C.; Leslie, L. S.; Bigelow, N. P., *Phys. Rev. A*, 77, Article 041601 pp. (2008)
- [48] Bhowmik, A.; Mondal, P. K.; Majumder, S.; Deb, B., *J. Phys. B, At. Mol. Opt. Phys.*, 51, Article 135003 pp. (2018)
- [49] Bhowmik, A.; Majumder, S., *J. Phys. Commun.*, 2, Article 125001 pp. (2018)
- [50] Das, S.; Bhowmik, A.; Mukherjee, K.; Majumder, S., *J. Phys. B, At. Mol. Opt. Phys.*, 53, Article 025302 pp. (2020)
- [51] Tempere, J.; Devreese, J. T.; Abraham, E. R.I., *Phys. Rev. A*, 64, Article 023603 pp. (2001)
- [52] Marzlin, K.-P.; Zhang, W.; Wright, E. M., *Phys. Rev. Lett.*, 79, 4728 (1997)
- [53] Simula, T. P.; Nygaard, N.; Hu, S. X.; Collins, L. A.; Schneider, B. I.; Mølmer, K., *Phys. Rev. A*, 77, Article 015401 pp. (2008)
- [54] Nandi, G.; Walser, R.; Schleich, W. P., *Phys. Rev. A*, 69, Article 063606 pp. (2004)
- [55] Mukherjee, K.; Bandyopadhyay, S.; Angom, D.; Martin, A. M.; Majumder, S., *Atoms*, 9, 14 (2021)
- [56] Huang, S.; Miao, Z.; He, C.; Pang, F.; Li, Y.; Wang, T., *Opt. Lasers Eng.*, 78, 132 (2016)
- [57] Tao, S. H.; Yuan, X.-C.; Lin, J.; Burge, R. E., *Opt. Express*, 14, 535 (2006)
- [58] Yang, D.; Zhao, J.; Zhao, T.; Kong, L., *Opt. Commun.*, 284, 3597 (2011)
- [59] Franke-Arnold, S.; Leach, J.; Padgett, M. J.; Lembessis, V. E.; Ellinas, D.; Wright, A. J.; Girkin, J. M.; Öhberg, P.; Arnold, A. S., *Opt. Express*, 15, 8619 (2007)
- [60] Chin, C.; Grimm, R.; Julienne, P.; Tiesinga, E., *Rev. Mod. Phys.*, 82, 1225 (2010)
- [61] Köhler, T.; Góral, K.; Julienne, P. S., *Rev. Mod. Phys.*, 78, 1311 (2006)
- [62] Görlitz, A.; Vogels, J. M.; Leanhardt, A. E.; Raman, C.; Gustavson, T. L.; Abo-Shaeer, J. R.; Chikkatur, A. P.; Gupta, S.; Inouye, S.; Rosenband, T.; Ketterle, W., *Phys. Rev. Lett.*, 87, Article 130402 pp. (2001)
- [63] Nicolin, A. I., *Phys. Rev. E*, 84, Article 056202 pp. (2011)
- [64] Staliunas, K.; Longhi, S.; de Valcárcel, G. J., *Phys. Rev. Lett.*, 89, Article 210406 pp. (2002)
- [65] Engels, P.; Atherton, C.; Hofer, M. A., *Phys. Rev. Lett.*, 98, Article 095301 pp. (2007)
- [66] Maity, D. K.; Mukherjee, K.; Mistakidis, S. I.; Das, S.; Kevrekidis, P. G.; Majumder, S.; Schmelcher, P., *Phys. Rev. A*, 102, Article 033320 pp. (2020)

- [67] Zhang, Z.; Yao, K.-X.; Feng, L.; Hu, J.; Chin, C., *Nat. Phys.*, 16, 652 (2020)
- [68] Anglin, J. R.; Zurek, W. H., *Phys. Rev. Lett.*, 83, 1707 (1999)
- [69] Mukherjee, K.; Mistakidis, S.; Kevrekidis, P. G.; Schmelcher, P., *J. Phys. B, At. Mol. Opt. Phys.* (2020)
- [70] Kevrekidis, P. G.; Carretero-González, R.; Frantzeskakis, D. J.; Kevrekidis, I. G., *Mod. Phys. Lett. B*, 18, 1481 (2004)
- [71] Kevrekidis, P. G.; Frantzeskakis, D. J., *Mod. Phys. Lett. B*, 18, 173 (2004)
- [72] Fetter, A. L.; Svidzinsky, A. A., *J. Phys. Condens. Matter*, 13, R135 (2001)
- [73] Nguyen, J. H.V.; Tsatsos, M. C.; Luo, D.; Lode, A. U.J.; Telles, G. D.; Bagnato, V. S.; Hulet, R. G., *Phys. Rev. X*, 9, Article 011052 pp. (2019)
- [74] Abdullaev, F.; Bronski, J.; Galimzyanov, R., *Complexity and Nonlinearity in Physical Systems – a Special Issue to Honor Alan Newell. Complexity and Nonlinearity in Physical Systems – a Special Issue to Honor Alan Newell*, *Phys. D: Nonlinear Phenom.*, 184, 319 (2003)
- [75] Kwon, K.; Mukherjee, K.; Huh, S.; Kim, K.; Mistakidis, S.; Maity, D.; Kevrekidis, P.; Majumder, S.; Schmelcher, P.; Choi, J.-y., *Spontaneous formation of star-shaped surface patterns in a driven bose-einstein condensate* (2021)
- [76] Chen, C.-A.; Hung, C.-L., *Phys. Rev. Lett.*, 125, Article 250401 pp. (2020)
- [77] Law, K. J.H.; Kevrekidis, P. G.; Tuckerman, L. S., *Phys. Rev. Lett.*, 105, Article 160405 pp. (2010)
- [78] Allen, A. J.; Parker, N. G.; Proukakis, N. P.; Barenghi, C. F., *J. Phys. Conf. Ser.*, 544, Article 012023 pp. (2014)
- [79] Tsatsos, M. C.; Tavares, P. E.; Cidrim, A.; Fritsch, A. R.; Caracanhas, M. A.; dos Santos, F. E.A.; Barenghi, C. F.; Bagnato, V. S., *Phys. Rep.*, 622, 1 (2016)
- [80] White, A. C.; Barenghi, C. F.; Proukakis, N. P., *Phys. Rev. A*, 86, Article 013635 pp. (2012)
- [81] White, A. C.; Anderson, B. P.; Bagnato, V. S., *Proc. Natl. Acad. Sci. USA*, 111, 4719 (2014)
- [82] Madeira, L.; Cidrim, A.; Hemmerling, M.; Caracanhas, M. A.; dos Santos, F. E.A.; Bagnato, V. S., *AVS Quant. Sci.*, 2, Article 035901 pp. (2020)
- [83] Kraichnan, R. H.; Montgomery, D., *Rep. Prog. Phys.*, 43, 547 (1980)
- [84] Navon, N.; Gaunt, A. L.; Smith, R. P.; Hadzibabic, Z., *Nature*, 539, 72 (2016)
- [85] Navon, N.; Eigen, C.; Zhang, J.; Lopes, R.; Gaunt, A. L.; Fujimoto, K.; Tsubota, M.; Smith, R. P.; Hadzibabic, Z., *Science*, 366, 382 (2019)
- [86] Horng, T.-L.; Hsueh, C.-H.; Su, S.-W.; Kao, Y.-M.; Gou, S.-C., *Phys. Rev. A*, 80, Article 023618 pp. (2009)
- [87] LeBlanc, L. J.; Thywissen, J. H., *Phys. Rev. A*, 75, Article 053612 pp. (2007)
- [88] Rubio-Abadal, A.; Choi, J.; Zeiher, J.; Hollerith, S.; Rui, J.; Bloch, I.; Gross, C., *Phys. Rev. X*, 9, Article 041014 pp. (2019)
- [89] Jesacher, A.; Fürhapter, S.; Bernet, S.; Ritsch-Marte, M., *Opt. Express*, 12, 4129 (2004)
- [90] Ao, P.; Chui, S. T., *Phys. Rev. A*, 58, 4836 (1998)
- [91] Kasamatsu, K.; Tsubota, M.; Ueda, M., *Int. J. Mod. Phys. B*, 19, 1835 (2005)
- [92] Ville, J. L.; Saint-Jalm, R.; Le Cerf, E.; Aidelsburger, M.; Nascimbène, S.; Dalibard, J.; Beugnon, J., *Phys. Rev. Lett.*, 121, Article 145301 pp. (2018)
- [93] Chomaz, L.; Corman, L.; Bienaimé, T.; Desbuquois, R.; Weitenberg, C.; Nascimbène, S.; Beugnon, J.; Dalibard, J., *Nat. Commun.*, 6, 6162 (2015)
- [94] Navon, N.; Smith, R. P.; Hadzibabic, Z., *Quantum gases in optical boxes* (2021)
- [95] Christodoulou, P.; Galka, M.; Dogra, N.; Lopes, R.; Schmitt, J.; Hadzibabic, Z., *Nature*, 594, 191 (2021)
- [96] Ma, M.; Carretero-González, R.; Kevrekidis, P. G.; Frantzeskakis, D. J.; Malomed, B. A., *Phys. Rev. A*, 82, Article 023621 pp. (2010)
- [97] Nore, C.; Abid, M.; Brachet, M., *Phys. Rev. Lett.*, 78, 3896 (1997)
- [98] Saffman, P. G., *Stud. Appl. Math.*, 50, 377 (1971)
- [99] McCarron, D. J.; Cho, H. W.; Jenkin, D. L.; Köppinger, M. P.; Cornish, S. L., *Phys. Rev. A*, 84, Article 011603 pp. (2011)
- [100] Zeng, H.; Zhang, W.; Lin, F., *Phys. Rev. A*, 52, 2155 (1995)
- [101] Pethick, C.; Smith, H., *Bose-Einstein Condensation of Dilute Gases* (2008), Cambridge University Press: Cambridge University Press Cambridge
- [102] Bandyopadhyay, S.; Roy, A.; Angom, D., *Phys. Rev. A*, 96, Article 043603 pp. (2017)
- [103] Muruganandam, P.; Adhikari, S. K., *Comput. Phys. Commun.*, 180, 1888 (2009)
- [104] Egorov, M.; Opanchuk, B.; Drummond, P.; Hall, B. V.; Hannaford, P.; Sidorov, A. I., *Phys. Rev. A*, 87, Article 053614 pp. (2013)
- [105] Madelung, E., *Z. Phys.*, 40, 322 (1927)
- [106] Mithun, T.; Kasamatsu, K.; Dey, B.; Kevrekidis, P. G., *Phys. Rev. A*, 103, Article 023301 pp. (2021)
- [107] Kuznetsov, E. A.; Rasmussen, J. J., *Phys. Rev. E*, 51, 4479 (1995)
- [108] Reeves, M. T.; Anderson, B. P.; Bradley, A. S., *Phys. Rev. A*, 86, Article 053621 pp. (2012)

- [109] Kraichnan, R. H., *Phys. Fluids*, 10, 1417 (1967)
- [110] Kraichnan, R. H., *J. Fluid Mech.*, 67, 155-175 (1975)
- [111] Sreenivasan, K. R., *Rev. Mod. Phys.*, 71, S383 (1999)
- [112] Batchelor, G. K., *Phys. Fluids*, 12, II (1969)
- [113] Gauthier, G.; Reeves, M. T.; Yu, X.; Bradley, A. S.; Baker, M. A.; Bell, T. A.; Rubinsztein-Dunlop, H.; Davis, M. J.; Neely, T. W., *Science*, 364, 1264 (2019)
- [114] Johnstone, S. P.; Groszek, A. J.; Starkey, P. T.; Billington, C. J.; Simula, T. P.; Helmerson, K., *Science*, 364, 1267 (2019)
- [115] Reeves, M. T.; Billam, T. P.; Yu, X.; Bradley, A. S., *Phys. Rev. Lett.*, 119, Article 184502 pp. (2017)
- [116] Brachet, M. E.; Meneguzzi, M.; Politano, H.; Sulem, P. L., *J. Fluid Mech.*, 194, 333-349 (1988)
- [117] Kovalev, A. A.; Kotlyar, V. V.; Porfirev, A. P., *Phys. Rev. A*, 93, Article 063858 pp. (2016)
- [118] Proukakis, N. P.; Jackson, B., *J. Phys. B, At. Mol. Opt. Phys.*, 41, Article 203002 pp. (2008)
- [119] Aikawa, K.; Frisch, A.; Mark, M.; Baier, S.; Rietzler, A.; Grimm, R.; Ferlaino, F., *Phys. Rev. Lett.*, 108, Article 210401 pp. (2012)
- [120] Lahaye, T.; Menotti, C.; Santos, L.; Lewenstein, M.; Pfau, T., *Rep. Prog. Phys.*, 72, Article 126401 pp. (2009)
- [121] Cao, L.; Bolsinger, V.; Mistakidis, S.; Koutentakis, G.; Krönke, S.; Schurer, J.; Schmelcher, P., *J. Chem. Phys.*, 147, Article 044106 pp. (2017)

This reference list is based on information provided by the publisher or from digital mathematics libraries. Its items are heuristically matched to zbMATH identifiers and may contain data conversion errors. It attempts to reflect the references listed in the original paper as accurately as possible without claiming the completeness or perfect precision of the matching.