

## Quantum turbulent velocity statistics and quasiclassical limit

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(Received 26 October 2011; revised manuscript received 16 November 2011; published 5 December 2011)

Two research groups have measured turbulent velocity statistics in superfluid helium using different techniques. The results were in conflict: one experiment revealed Gaussian distributions (as observed in ordinary turbulence), the other experiment determined power laws. To solve the apparent puzzle, we numerically model quantum turbulence as a tangle of vortex filaments, and conclude that there is no contradiction between the two experiments. The transition from Gaussian to power law arises from the different length scales which are probed using the two techniques. We find that the average distance between the quantum vortices marks the separation between quantum and quasiclassical length scales.

DOI: [10.1103/PhysRevE.84.067301](https://doi.org/10.1103/PhysRevE.84.067301)

PACS number(s): 47.27.-i, 67.25.dk, 67.25.dg

Turbulence in superfluid helium ( $^4\text{He}$ ) [1,2] consists of a tangle of discrete, thin vortex filaments, each carrying one quantum of circulation  $\kappa = h/m$  (where  $h$  is Planck's constant and  $m$  the mass of one atom). This "quantum turbulence" [3,4] is also studied in superfluid  $^3\text{He}$  [5,6] and in atomic Bose-Einstein condensates [7]. The absence of viscosity and the discrete nature of the vorticity distinguish quantum turbulence from ordinary (classical) turbulence. Nevertheless, experiments have also shown remarkable similarities: the same pressure drop along the pipes [8], drag on a moving body [9], vorticity decay [10], and distribution of kinetic energy over the length scales (Kolmogorov energy spectrum) [11,12]. The relation between quantum turbulence and classical turbulence has thus become the focus of attention.

This report is concerned with the statistical properties of the components of the turbulent superfluid velocity field  $\mathbf{v}$ . In ordinary turbulence, experiments [13] and numerical simulations [14,15] confirm that velocity statistics are Gaussian. The usual interpretation of this property is the following [16]. At any time  $t$ , the velocity field  $\mathbf{v}$  at the point  $\mathbf{r}$  is determined by the vorticity field  $\boldsymbol{\omega} = \nabla \times \mathbf{v}$  via the Biot-Savart law [17]

$$\mathbf{v}(\mathbf{r}, t) = \frac{1}{4\pi} \int \frac{\boldsymbol{\omega}(\mathbf{r}', t) \times (\mathbf{r} - \mathbf{r}')}{|\mathbf{r} - \mathbf{r}'|^3} d\mathbf{r}'. \quad (1)$$

Thus, if the point  $\mathbf{r}$  is surrounded by many, randomly oriented vortical structures, Gaussianity results from the application of the central limit theorem.

In the last few years, the development of particle tracking visualization techniques suitable for liquid helium [18,19] has opened the way to the measurement of quantum turbulence statistics. Using solid hydrogen tracers, Paoletti *et al.* [20] at the University of Maryland deduced that, in superfluid helium, the velocity components of the turbulent velocity follow power-law distributions. Large velocity fluctuations are thus relatively more frequent than in ordinary turbulence, where these distributions are Gaussian [21]. The authors suggested that power-law distributions arise from vortex reconnections, clearly high-velocity events.

The experiment of Paoletti *et al.* motivated theoretical work on the problem. White *et al.* [22] solved numerically the Gross-Pitaevskii equation for a Bose-Einstein condensate and determined velocity distributions in a variety of quantum vortex systems at zero temperature: two-dimensional and three-

dimensional trapped atomic condensates, three-dimensional homogeneous condensates, Onsager's two-dimensional vortex gas. In all systems, they found power-law distributions, in agreement with Paoletti *et al.* [20], even in the absence of vortex reconnections. Using results from previous work by Min and Leonard [23] on the numerical analysis of vortex methods (later confirmed by Weiss *et al.* [24]), White *et al.* [22] concluded that the non-Gaussianity arises from the singular nature of the quantum vorticity, which causes an anomalously slow convergence to Gaussian behavior.

Further theoretical work at nonzero temperatures seemed to strengthen this conclusion. Baggaley and Barenghi [25] used the vortex filament model to numerically study intense vortex tangles. They confirmed the Kolmogorov spectrum and the power-law distributions of the velocity components. The vortex filament model was also used by Adachi and Tsubota [26], who found power-law distributions in counterflow turbulence (quantum turbulence driven by a heat flow).

In a recent experiment, Salort *et al.* [27] at Centre national de la recherche scientifique (CNRS) Grenoble measured the turbulent velocity in a superfluid wind tunnel using a small Pitot tube. They confirmed the Kolmogorov spectrum, but reported Gaussian velocity distributions, in apparent contradiction with Paoletti *et al.* [20] and with the numerical simulations [22,25,26].

To solve this puzzle, first we consider the size of the probe relative to the distance between vortices in the two experiments. The radius  $a$  of the tracer particles used by Paoletti *et al.* was  $a \approx 10^{-4}$  cm. The turbulence was created by a heat flux  $\dot{Q}$  which drove a counterflow current [28]  $v_{ns} = |v_n - v_s| = \dot{Q}/(\rho_s ST)$  between superfluid and normal fluid velocity components  $v_n$  and  $v_s$ , where  $\rho_s$  is the superfluid density and  $S$  the specific entropy. For example, at  $T = 1.9$  K the largest heat flux was  $\dot{Q} = 0.17$  W/cm<sup>2</sup>, corresponding to  $v_{ns} = 1.5$  cm/s, with  $\rho_s = 0.0831$  g/cm<sup>3</sup> and  $S = 0.709$  J/(gK). Using the relation  $L = \gamma^2 v_{ns}^2$  with  $\gamma \approx 140$  s/cm<sup>2</sup> as reported in Ref. [28], one finds  $\ell \approx 4.7 \times 10^{-3}$  cm, where  $L$  is the vortex line density (vortex length per unit volume) and  $\ell \approx L^{-1/2}$ . Paoletti *et al.* [20] took their velocity measurements during the decay of the turbulence, after switching off the heater, so the actual intervortex distance must have been larger than the above value of  $\ell$ . We conclude that, in the experiment of Paoletti *et al.* [20],  $a/\ell \ll 1$ ; this means that, although the tracer particles must have altered in some measure the motion of the vortex lines, the

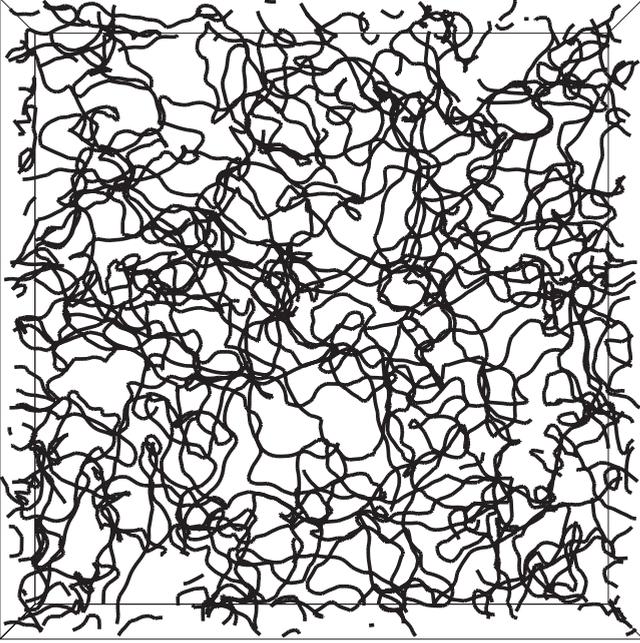


FIG. 1. Snapshot of the turbulent vortex tangle at  $t = 0.1$  s after the vortex line density has saturated, the box size  $D = 0.075$  cm.

velocity field was probed at very small length scales, between  $\ell$  and  $a$ .

In the experiment of Salort *et al.* [27], the nozzle of the Pitot tube had a diameter of 0.06 cm. The authors estimated [29] that the intervortex separation was between  $\ell \approx 5 \times 10^{-4}$  and  $20 \times 10^{-4}$  cm. We conclude that in this experiment  $a/\ell \gg 1$  (even without considering that the effective resolution in the streamwise direction, set by time dynamics of the probe, was perhaps much larger than  $a$  [29]). In summary, the experiment of Paoletti *et al.* [20] probed the velocity field between vortices, at length scales less than  $\ell$ , whereas the experiment of Salort

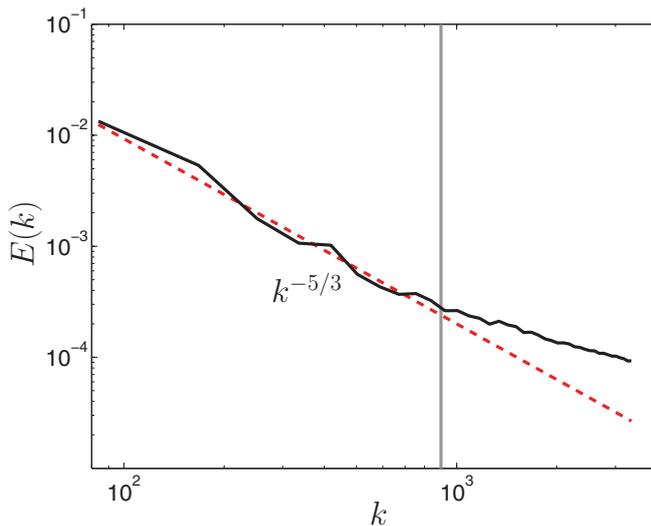


FIG. 2. (Color online) Energy spectrum  $E_k$  (arbitrary units) vs wave number  $k$  ( $\text{cm}^{-1}$ ) corresponding to Fig. 1. The dashed line is the Kolmogorov scaling  $E_k \sim k^{-5/3}$ ; the solid gray line shows the wave number corresponding to the intervortex spacing  $k_\ell \approx 900$   $\text{cm}^{-1}$ .

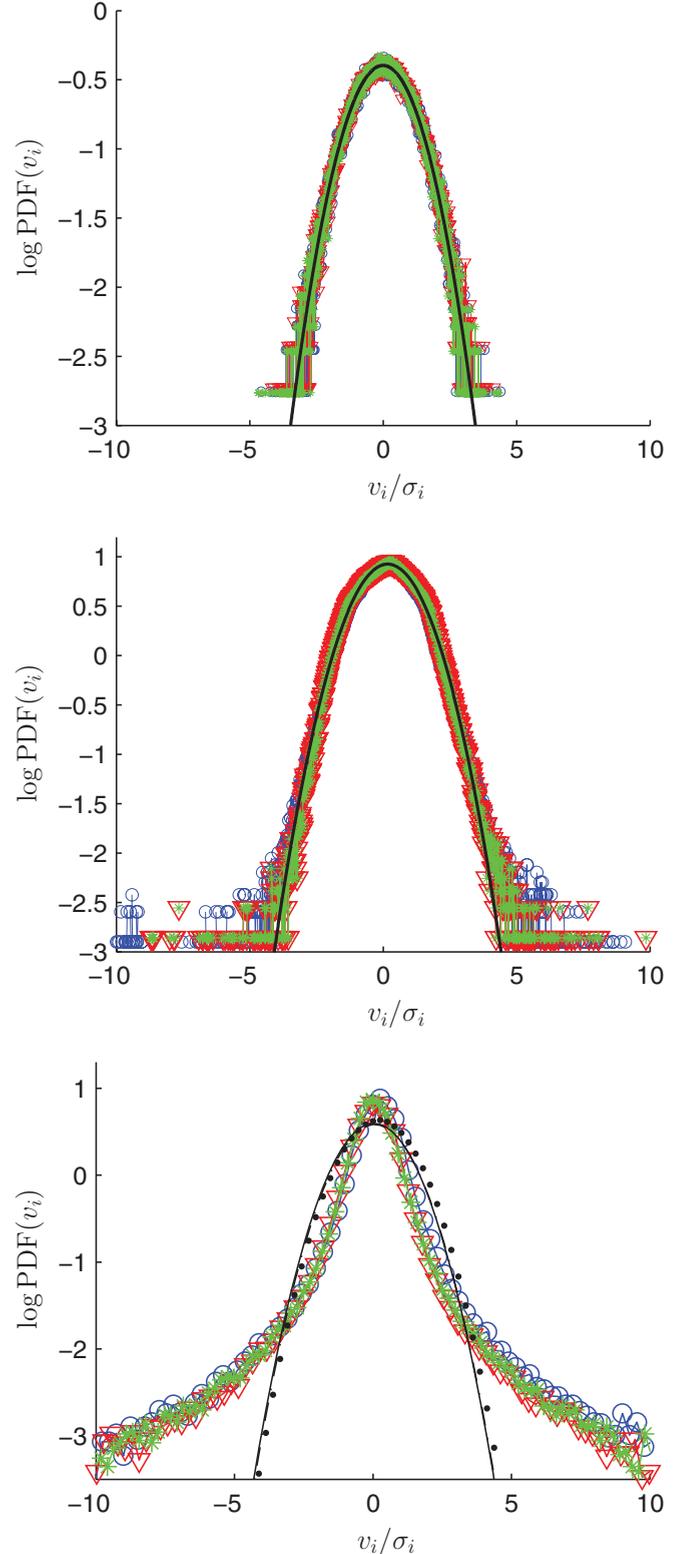


FIG. 3. (Color online) Probability density functions (PDF) of turbulent velocity components  $v_i$  ( $i = x, y, z$ ) vs  $v_i/\sigma_i$  calculated by averaging over regions of size  $\Delta = 2\ell$  (top),  $\Delta = \ell$  (middle), and  $\Delta = \ell/6$  (bottom). (Green) asterisks, (blue) circles, and (red) triangles refer, respectively, to  $i = x$ ,  $i = y$ , and  $i = z$  components. The solid lines are the Gaussian fits, defined by Eq. (4), where  $\bar{\sigma} = 0.041$  (top), 0.048 (middle), and 0.082 cm/s (bottom), respectively.

*et al.* [27] detected motion at scales larger than  $\ell$ , containing many vortex lines.

Second, we perform the following numerical calculation. In both experiments the length scales involved were much larger than the vortex core radius  $a_0 = 10^{-8}$  cm, so it is appropriate to use the vortex filament model [30]. We assume that the vorticity is concentrated in space curves  $\mathbf{s}(\xi, t)$  around which the circulation is  $\kappa = 10^{-3}$  cm<sup>2</sup>/s. Equation (1) reduces to

$$\frac{d\mathbf{s}}{dt} = -\frac{\kappa}{4\pi} \oint_{\mathcal{L}} \frac{(\mathbf{s} - \mathbf{r})}{|\mathbf{s} - \mathbf{r}|^3} \times d\mathbf{r}, \quad (2)$$

where the line integral extends over all vortex lines. The numerical techniques to discretize the vortex lines, to compute the time evolution, to desingularize the Biot-Savart integral, and to algorithmically perform reconnections when two vortex lines become close to each other are described in the literature [26,30] or in our previous papers [25,31]. The computational domain is a periodic box of size  $D = 0.075$  cm. The distance between discretization points along the vortex filaments is held at approximately  $\delta/2$  where  $\delta = 0.001$  cm. To speedup the evaluation of Biot-Savart integrals we use a tree method [32] with a critical opening angle  $\theta = 0.4$ . For the sake of simplicity, we assume that the temperature is  $T = 0$ . This means that no external forcing is needed to sustain the turbulence because the total kinetic energy is conserved during the evolution (at least for the time scale of interest here; the finite discretization and the reconnection algorithm introduce small energy losses which model phonon emission as described in Ref. [31]).

The initial condition at time  $t = 0$  consists of 100 straight, randomly oriented, vortex filaments discretized over  $N = 10^4$  Lagrangian points  $\mathbf{s}_j$  ( $j = 1, \dots, N$ ). During the evolution the vortex lines interact, become curved, reconnect, and a vortex tangle is quickly formed. We find that the vortex line density  $L$  initially grows, then saturates to the value  $L \approx 2.04 \times 10^4$  cm<sup>-2</sup>. We check that the average curvature saturates as well. Figure 1 shows the vortex tangle when we stop the calculation at  $t = 0.1$  s. We examine the energy spectrum  $E(k)$ , defined by

$$E = \frac{1}{V} \int \frac{1}{2} |\mathbf{v}|^2 dV = \int_0^\infty E(k) dk, \quad (3)$$

where  $E$  is the total energy per unit mass. Figure 2 shows that most of the energy is contained in the large scales, and that

the spectrum is qualitatively consistent with the Kolmogorov scaling  $E_k \sim k^{-5/3}$  in the region  $k \ll 2\pi/\ell \approx 900$  cm<sup>-2</sup>, in agreement with experiments [11,12] and with previous numerical calculations [25,33–35]. The shallow spectrum at large values of  $k$  is also consistent with existing similar calculations [34]. Second, we examine the velocity components and compute their probability density functions (normalized histograms, or PDF for short). Rather than sampling the values at points of the domain, we compute averages over regions of size  $\Delta$ , varying  $\Delta$ . This is done by calculating the velocity field, induced by the vortices, on a  $128^3$  Cartesian mesh, and then averaging cells over the appropriate length scale. The result is shown in Fig. 3, where we compare the data against their Gaussian fits

$$P_{\text{PDF}_g}(v_i) = \frac{1}{\sqrt{2\pi}\sigma^2} \exp(- (v_i - \mu)^2 / (2\sigma^2)), \quad (4)$$

where  $\mu \approx 0$  and  $\sigma$  is the standard deviation. It is apparent that, if  $\Delta < \ell$ , the PDFs are not Gaussian; by fitting  $F_{\text{PDF}}(v_i) \sim v_i^{-b}$  we obtain  $b = 3.2, 3.2$  and  $3.1$  for  $i = x, y, z$ , respectively, in agreement with the power-law statistics found experimentally by Paoletti *et al.* [20] and numerically by White *et al.* [22], Baggaley and Barenghi [25], and Adachi and Tsubota [26]. If  $\Delta > \ell$ , however, the distributions are Gaussian, and we recover the same (classical) statistics measured by Salort *et al.* [27].

In conclusion, the different velocity statistics observed by the Maryland and Grenoble experiments are consistent with each other. Taken together, these experiment and this work support the interpretation that, at scales larger than  $\ell$ , quantum turbulence exhibits quasiclassical behavior (in terms of both energy spectrum and velocity statistics), whereas at scales smaller than  $\ell$  (but still orders of magnitude larger than the quantum coherence length  $a_0$ ), the discrete nature of quantized vorticity affects the distribution of energy over the length scales and the frequency of high-velocity events.

#### ACKNOWLEDGMENTS

We thank J. Salort and P. E. Roche for providing us with experimental data and comments in advance of publication. This work was funded by the HPC-EUROPA2 Project No. 228398, with the support of the European Community (Research Infrastructure Action of the FP7), and by the Leverhulme Trust (Grants No. F/00125/AH and No. RPG-097).

[1] P. M. Walmsley and A. I. Golov, *Phys. Rev. Lett.* **100**, 245301 (2008).  
 [2] T. V. Chagovets and L. Skrbek, *Phys. Rev. Lett.* **100**, 2153 (2008).  
 [3] W. F. Vinen and J. J. Niemela, *J. Low Temp. Phys.* **128**, 167 (2002).  
 [4] Quantum Turbulence, in *Progress in Low Temperature Physics*, edited by B. Halperin and M. Tsubota (Elsevier, New York, 2008), Vol. 16.  
 [5] D. I. Bradley *et al.*, *Nature Physics* **7**, 473 (2011).

[6] V. B. Eltsov *et al.*, *Phys. Rev. Lett.* **99**, 265301 (2007).  
 [7] E. A. L. Henn, J. A. Seman, G. Roati, K. M. F. Mugalhaes, and V. S. Bagnato, *Phys. Rev. Lett.* **103**, 045301 (2009).  
 [8] P. L. Walstrom, J. G. Weisend, J. R. Maddocks, and S. W. Van Sciver, *Cryogenics* **28**, 101 (1988).  
 [9] M. R. Smith, D. K. Hilton, and S. W. Van Sciver, *Phys. Fluids* **11**, 751 (1999).  
 [10] S. R. Stalp, L. Skrbek, and R. J. Donnelly, *Phys. Rev. Lett.* **82**, 4831 (1999).  
 [11] J. Maurer and P. Tabeling, *Europhys. Lett.* **43**, 29 (1998).

- [12] J. Salort *et al.*, *Phys. Fluids* **22**, 125102 (2010).
- [13] A. Noullez, G. Wallace, W. Lempert, R. B. Miles, and U. Frisch, *J. Fluid Mech.* **339**, 287 (1997).
- [14] A. Vincent and M. Meneguzzi, *J. Fluids Mech.* **225**, 1 (1991).
- [15] T. Gotoh *et al.*, *Phys. Fluids* **14**, 1065 (2002).
- [16] P. A. Davidson, *Turbulence* (Oxford University Press, New York, 2004).
- [17] P. G. Saffman, *Vortex Dynamics* (Cambridge University Press, Cambridge, England, 1992).
- [18] T. Zhang and S. W. Van Sciver, *Nature Physics* **1**, 36 (2005).
- [19] G. P. Bewley, D. P. Lathrop, and K. R. Sreenivasan, *Nature (London)* **441**, 588 (2006).
- [20] M. S. Paoletti, M. E. Fisher, K. R. Sreenivasan, and D. P. Lathrop, *Phys. Rev. Lett.* **101**, 154501 (2008).
- [21] The Gaussianity of the distributions of the components of  $\mathbf{v}$  should not be confused with the non-Gaussianity of the distributions of the gradients of  $\mathbf{v}$ , or of the joint probability distribution of  $\mathbf{v}$  at two points, which are usually observed in ordinary turbulence.
- [22] A. C. White, C. F. Barenghi, N. P. Proukakis, A. J. Youd, and D. H. Wacks, *Phys. Rev. Lett.* **104**, 075301 (2010).
- [23] I. A. Min, I. Mezic, and A. Leonard, *Phys. Fluids* **8**, 1169 (1996).
- [24] J. B. Weiss, A. Provenzale, and J. C. McWilliams, *Phys. Fluids* **10**, 1929 (1998).
- [25] A. W. Baggaley and C. F. Barenghi, *Phys. Rev. B* **84**, 020504(R) (2011).
- [26] Hi. Adachi and M. Tsubota, *Phys. Rev. B* **83**, 132503 (2011).
- [27] J. Salort, B. Chabaud, E. L ev eque, and P.-E. Roche, Energy cascade and the four-fifths law in superfluid turbulence, HAL-00635578 (2011).
- [28] H. Adachi, S. Fujiyama, and M. Tsubota, *Phys. Rev. B* **81**, 104511 (2010).
- [29] P. E. Roche (private communication).
- [30] K. W. Schwarz, *Phys. Rev. B* **38**, 2398 (1988).
- [31] A. W. Baggaley and C. F. Barenghi, *Phys. Rev. B* **83**, 134509 (2011).
- [32] A. W. Baggaley and C. F. Barenghi, *J. Low Temp. Phys.* (to be published).
- [33] C. Nore, M. Abid, and M. E. Brachet, *Phys. Rev. Lett.* **78**, 3896 (1997).
- [34] T. Araki, M. Tsubota, and S. K. Nemirovskii, *Phys. Rev. Lett.* **89**, 145301 (2002).
- [35] M. Kobayashi and M. Tsubota, *Phys. Rev. Lett.* **94**, 065302 (2005).