Energy asymptotics for a fast rotating Bose-Einstein Condensate

AMPQ Seminar

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this presentation is available on `daniele.dimonte.it`
based on a joint work with **Michele Correggi**

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In the case of an N-body particle system, when $N \to +\infty$, if we assume condensation the state of the system can be described minimizing the following Gross-Pitaevskii energy functional:

$$\mathcal{E}_\omega^{\mathrm{phys}}[\Psi] = \int_{\mathbb{R}^2} \mathrm{d}\mathbf{r} \left\{ \frac{1}{2} |\nabla \Psi|^2 - \omega \Psi^* L_z \Psi + \frac{1}{\varepsilon^2} V(\mathbf{r}) |\Psi|^2 + \frac{1}{\varepsilon^2} |\Psi|^4 \right\}$$

$$E_\omega^{\mathrm{phys}} = \inf_{\|\Psi\|_2^2 = 1} \mathcal{E}_\omega^{\mathrm{phys}}[\Psi] = \mathcal{E}_\omega^{\mathrm{phys}}[\Psi_\omega^{\mathrm{phys}}]$$

- $V(\mathbf{r}) = r^s$, $s > 2$ is the trapping potential
- $L_z = -i(\mathbf{r} \times \nabla)_z = -i\partial_\theta$ angular momentum
- ω is the rotational speed of the condensate
- ε^{-2} in front of the quartic term is proportional to the 2-body scattering length for the interacting potential
- asymptotic $\varepsilon \to 0$ (corresponding to the Thomas-Fermi regime)
- asymptotic for ω as ε goes to 0

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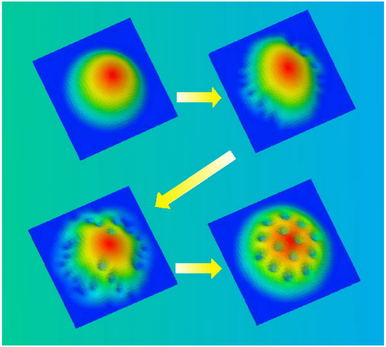
Increasing the rotational speed ω we can observe different behaviors:

- formation of quantized vortices in the condensate (related to superfluidity properties): change of the phase of $\Psi_\omega^{\mathrm{phys}}$
- different shapes of the condensate: change of the modulus of $\Psi_\omega^{\mathrm{phys}}$



ψ has a vortex in x_0

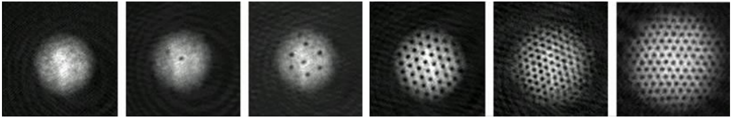
if around the point

$$\psi(x) \simeq e^{in\theta(x)} f\left(|x - x_0|\right)$$

Numerics by K. Kasamatsu, M. Tsubota, M. Ueda

First regime: $\omega \ll \varepsilon^{-1}$

- When $\omega = 0$ the minimizer can be taken as a strictly positive function (up to a $U(1)$ symmetry) and it's close to the minimizer of a Thomas-Fermi functional; its support is concentrated in an area around a ball centered in zero, and we can only see the effect of the trapping potential
- For small rotations $\omega < \omega_{c_1} = \omega_1 |\log \varepsilon|$ we can observe no effect on the state of the system; in particular $E_\omega^{\text{phys}} = E_0^{\text{phys}}$ and $\Psi_\omega^{\text{phys}} = \Psi_0^{\text{phys}}$ (Aftalion, Jerrard, Royo-Letelier, [AJR11])



Experiments from the Cornell Group, Jila research center

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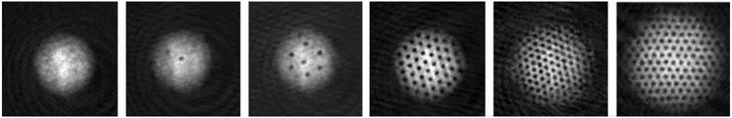

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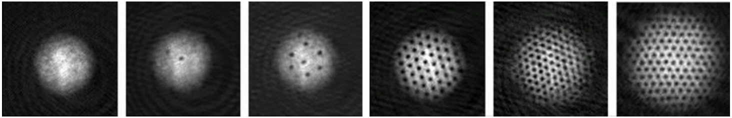
First regime: $\boxed{\omega \ll \varepsilon^{-1}}$

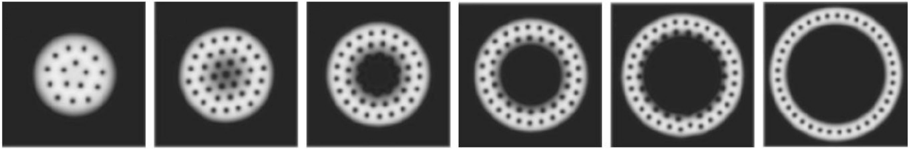
- As soon as $\omega \geq \omega_{c_1}$ vortices start to appear in the bulk of the condensate (Ignat, Millot, [IM06]) showing the contribute from the kinetic term
- As the second vortex appear the rotational symmetry is broken in the minimizer and is never restored, even for higher rotational speeds
- Increasing the rotational speed even more, for $\omega \gg |\log \varepsilon|$ the vortices become distributed uniformly (Correggi, Yngvason, [CY08])



Experiments from the Cornell Group, Jila research center

Second regime: $\boxed{\omega \sim \varepsilon^{-1}}$

- While $\omega \lesssim \omega_{c_2} = \omega_2\varepsilon^{-1}$ the condensate is still contained in a ball around zero and has vortices uniformly distributed in its bulk
- When $\omega = \omega_0\varepsilon^{-1}$ the Thomas-Fermi functional digs a hole in the origin, therefore the $\Psi_\omega^{\mathrm{phys}}$ becomes exponentially small in ε in a region close to the origin (Correggi, Pinsker, Rougerie, Yngvason, [CPRY12])



Numerics from Fetter, Jackson, Stringari [FJS05]

$$\mathcal{E}_\omega^{\mathrm{phys}}[\Psi] = \int_{\mathbb{R}^2} \mathrm{d}\mathbf{r} \left\{ \frac{1}{2} \left|\left(\nabla - i\mathbf{A}_{\mathrm{rot}}\right)\Psi\right|^2 + \frac{1}{\varepsilon^2}\left[r^s - \frac{1}{2}\varepsilon^2\omega^2 r^2 + |\Psi|^2 \right] |\Psi|^2 \right\}$$

$$\mathbf{A}_{\mathrm{rot}} = \omega \mathbf{r}^{\perp} = \omega\left(-r_2, r_1\right)$$

When $\omega \gg \varepsilon^{-1}$ the support of the Thomas-Fermi profile becomes concentrated in an annulus of mean radius equal to the minimum point of $r^s - \frac{1}{2}\varepsilon^2\omega^2 r^2$, which is going to infinity as ε goes to zero

Here the hypotheses of $s > 2$ becomes crucial, and if $s = 2$ as soon as $\omega \gg \varepsilon^{-1}$ the energy becomes unbounded from below

$$\mathcal{E}^{\rm phys}_{\omega}[\Psi] = \int_{\mathbb{R}^2} \mathrm{d}\mathbf{r} \left\{ \frac{1}{2} \left| \left(\boldsymbol{\nabla} - i\mathbf{A}_{\rm rot} \right) \Psi \right|^2 + \frac{1}{\varepsilon^2} \left[r^s - \frac{1}{2}\varepsilon^2\omega^2 r^2 + |\Psi|^2 \right] |\Psi|^2 \right\}$$

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We rescale the radius around this minimum point in such a way that

$$\boxed{\mathcal{E}^{\rm GP}_{\Omega}[\psi] = \int_{\mathbb{R}^2} \mathrm{d}\mathbf{x} \left\{ \frac{1}{2} \left| \left(\boldsymbol{\nabla} - i\mathbf{A}_{\Omega} \right) \psi \right|^2 + \Omega^2 W(x) |\psi|^2 + \frac{1}{\varepsilon^2} |\psi|^4 \right\}}$$

$$\mathbf{A}_{\Omega} = \Omega \mathbf{x}^{\perp}, \quad W(x) = \frac{x^s - 1}{s} - \frac{x^2 - 1}{2},$$

$$E^{\rm GP}_{\Omega} = \inf_{\|\psi\|_2^2 = 1} \mathcal{E}^{\rm GP}_{\Omega}[\psi] = \mathcal{E}^{\rm GP}_{\Omega}[\psi^{\rm GP}_{\Omega}]$$

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- The potential W is positive and has one only minimum in $x = 1$, $W(1) = 0$
- Ω is the rescaled rotational speed
- When $\omega \sim \varepsilon^{-1}$ also $\Omega \sim \varepsilon^{-1}$

Third regime: $\Omega \gg \varepsilon^{-1}$

- When $\Omega_{c_2} \leq \Omega \ll \varepsilon^{-4}$ it was proven in [CPRY12] that $E_{\Omega}^{\mathrm{GP}} = E_{\Omega}^{\mathrm{TF}} + \mathcal{O}\left(\Omega \left|\log(\varepsilon^4 \Omega)\right|\right)$, where E_{Ω}^{TF} is the ground state of

$$\mathcal{E}_{\Omega}^{\mathrm{TF}}[\rho] = \int_{\mathbb{R}^2} \mathrm{d}\mathbf{x} \left[\Omega^2 W(x) + \frac{1}{\varepsilon^2}\rho\right] \rho$$

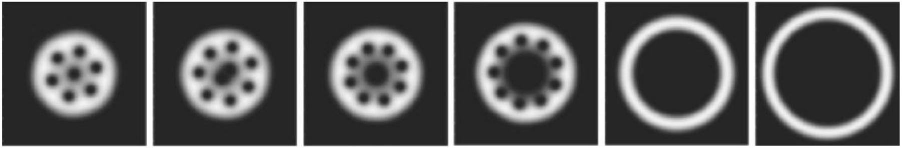
- Using the energy asymptotic it was possible to show also that the profile of the minimizer is exponentially small in ε outside a ring of radius 1 and of width $(\varepsilon\Omega)^{-\frac{2}{3}} = o(1)$
- Moreover, using the same asymptotic it is also possible to prove that the distribution of vorticity is uniform for $\Omega_{c_2} \leq \Omega \ll \varepsilon^{-4}$

- When $\Omega = \Omega_0 \varepsilon^{-4}$ the size of a single vortex becomes comparable to the width of the annulus where $\psi_\Omega^{\mathrm{GP}}$ is essentially supported
- Indeed below the threshold the size of a single vortex, that is the size of the region where $|\psi_\Omega^{\mathrm{GP}}|^2 \sim 0$, has a core radius ρ which is fixed by the energy to be of order $\rho \sim \Omega_0^{-\frac{1}{3}} \varepsilon^2$
- At the same time the width of the annulus is $(\varepsilon\Omega)^{-\frac{2}{3}} \sim \Omega_0^{-\frac{2}{3}} \varepsilon^2$
- For Ω_0 big enough the vortices don't fit in the annulus anymore and are expelled from the bulk of the condensate (**Giant Vortex state**)

Theorem (Correggi, Pinsker, Rougerie, Yngvason, [CPRY12])

If Ω_0 is big enough then $\psi_\Omega^{\mathrm{GP}}$ has no zeroes in the annulus, and therefore there are no vortices in the annulus; more precisely

$$\left|\psi_\Omega^{\mathrm{GP}}(\mathbf{x})\right| = \frac{1}{\sqrt{2\pi\varepsilon}} g_{\mathrm{gv}}(x)\,(1 + o\,(1))\,, \quad g_{\mathrm{gv}} > 0$$



Numerics from Fetter, Jackson, Stringari,[FJS]

An essential tool in [CPRY12] was proving the approximation of the energy in terms of a Giant Vortex energy; assuming $\Omega_0 \gg 1$

$$E_{\Omega}^{\mathrm{GP}} = \frac{E^{\mathrm{gv}}}{\varepsilon^4} + \mathcal{O}\left(|\log \varepsilon|^{\frac{9}{2}}\right)$$

$$\mathcal{E}^{\mathrm{gv}}[g] = \int_{\mathbb{R}} \mathrm{dy} \left\{ \frac{1}{2} |\nabla g| + \frac{1}{2}\Omega_0^2 (s+2) \mathrm{y}^2 g^2 + \frac{1}{2\pi} g^4 \right\}$$

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In particular the minimizer g_{gv} is strictly positive in the annulus $\mathcal{A}_{\mathrm{bulk}}$ where $\psi_{\Omega}^{\mathrm{GP}}$ is concentrated, so we can define u such that $\psi_{\Omega}^{\mathrm{GP}}(x) = \frac{1}{\sqrt{2\pi\varepsilon}} g_{\mathrm{gv}}(x) u(x) e^{i\lfloor\Omega\rfloor\theta}$, and in this case

$$\frac{E^{\mathrm{gv}}}{\varepsilon^4} \geq E_{\Omega}^{\mathrm{GP}} \geq \frac{E^{\mathrm{gv}}}{\varepsilon^4} + \frac{1}{2\pi\varepsilon^2} \int_{\mathcal{A}_{\mathrm{bulk}}} \mathrm{d}\mathbf{x}\ K(x) \left|\nabla u\right|^2 + \mathcal{O}\left(|\log\varepsilon|^{\frac{9}{2}}\right)$$

and the lower bound of this estimate reduces to estimate the positivity of the cost function; using the fact that for Ω_0 large enough the profile of g_{gv} is basically gaussian, they were able to prove

$$K(x) \geq C\left(1 + \mathcal{O}\left(\Omega_0^{-\frac{1}{4}}\right)\right) g_{\mathrm{gv}}^2(x)$$

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In our work we decided to focus more on the exact form of $K(x)$ to get a better description of the condition to have a lower bound

Using again a splitting of the energy one can get

$$E_{\Omega}^{\mathrm{GP}} = \frac{E^{\mathrm{gv}}}{\varepsilon^4} + \frac{1}{2\pi\varepsilon^2}\mathcal{E}[u] + \mathcal{O}\left(\varepsilon^{\infty}\right)$$

$$\mathcal{E}[u] := \int_{\mathcal{A}_{\mathrm{bulk}}} d\mathbf{x}\; g_{\mathrm{gv}}^2 \left\{ \frac{1}{2}\left|\nabla u\right|^2 + \mathbf{a}\cdot\mathbf{j}[u] + \frac{1}{2\pi\varepsilon^4} g_{\mathrm{gv}}^2 \left(1 - |u|^2\right)^2 \right\}$$

$$\mathcal{E}[u] \geq \int_{\mathcal{A}_{\mathrm{bulk}}} d\mathbf{x}\; K(x)\left|\nabla u\right|^2 + \frac{1}{2\pi\varepsilon^4} g_{\mathrm{gv}}^4 \left(1 - |u|^2\right)^2$$

$$K(x) := \frac{1}{2} g_{\mathrm{gv}}^2 - F(x)$$

Imposing the condition $K(x) > 0$ to get the lower bound gives us a critical value for Ω_0; in particular $K(x) > 0$ in $\mathcal{A}_{\mathrm{bulk}}$ if and only if $K(0) > 0$

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$$\mathbf{a}(x) := \left(\frac{\Omega + \beta_\star}{x} - \Omega x\right)\mathbf{e}_\theta,\ \mathbf{j}[u] := \mathrm{Im}\left(u^* \nabla u\right)$$

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Main Result

Critical velocity (Correggi, D, [CD15])

Let Ω_{c} be defined as the supremum of the solution of

$$\boxed{\Omega_0 = \frac{4}{s+2}\left[\mu^{\mathrm{gv}} - \frac{1}{2\pi} g_{\mathrm{gv}}^2(0)\right]}$$

where μ^{gv} is defined through $-\frac{1}{2} g_{\mathrm{gv}}'' + \frac{1}{2}\Omega_0^2 (s+2) \mathrm{y}^2 g_{\mathrm{gv}} + \frac{1}{\pi} g_{\mathrm{gv}}^3 = \mu^{\mathrm{gv}} g_{\mathrm{gv}}$; then if $\Omega_0 \geq \Omega_{\mathrm{c}}$ then

$$E_{\Omega}^{\mathrm{GP}} = \frac{E^{\mathrm{gv}}}{\varepsilon^4} + \mathcal{O}(1)$$

- It is possible to prove that there is a solution to the equation that defines Ω_c by considering the limits for Ω_0 going both to 0 and to $+\infty$; we espect this solution to be unique
- As in [CPRY12] the main consequence of this estimate is that $\psi_{\Omega}^{\mathrm{GP}}$ is strictly positive in $\mathcal{A}_{\mathrm{bulk}}$ and therefore the condensate has no vortices in $\mathcal{A}_{\mathrm{bulk}}$
- Therefore while $\Omega_0 \geq \Omega_c$ there are no vortices in the annulus so the phase transition already happened and this means that $\Omega_{c_3} \leq \frac{\Omega_c}{\varepsilon^4}$;
- It is still an open problem to show that the value we just found is in fact the real critical speed for the condensate, that is that in fact $\Omega_{c_3} = \frac{\Omega_c}{\varepsilon^4}$, and to prove this one should show that for any $\Omega < \frac{\Omega_c}{\varepsilon^4}$ there are vortices inside the annulus

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- It is possible to prove that there is a solution to the equation that defines Ω_{c} by considering the limits for Ω_0 going both to 0 and to $+\infty$; we espect this solution to be unique
- As in [CPRY12] the main consequence of this estimate is that $\psi_{\Omega}^{\mathrm{GP}}$ is strictly positive in $\mathcal{A}_{\mathrm{bulk}}$ and therefore the condensate has no vortices in $\mathcal{A}_{\mathrm{bulk}}$
- Therefore while $\Omega_0 \geq \Omega_{\mathrm{c}}$ there are no vortices in the annulus so the phase transition already happened and this means that $\Omega_{c_3} \leq \frac{\Omega_{\mathrm{c}}}{\varepsilon^4}$;
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Thanks for the attention!

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