THE DISTRIBUTION OF SURFACE SUPERCONDUCTIVITY
ALONG THE BOUNDARY: ON A CONJECTURE OF X. B. PAN*

YANIV ALMOG† AND BERNARD HELFFER‡

Abstract. We consider the Ginzburg–Landau model of superconductivity in two dimensions in the large $\kappa$ limit. For applied magnetic fields weaker than the onset field $H_C^3$ but greater than $H_C^2$ it is well known that the superconductivity order parameter decays exponentially fast away from the boundary. It has been conjectured by X. B. Pan that this surface superconductivity solution converges pointwise to a constant along the boundary. For applied fields that are in some sense between $H_C^2$ and $H_C^3$, we prove that the solution indeed converges to a constant but in a much weaker sense.

Key words. superconductivity, surface, Ginzburg–Landau

AMS subject classifications. 82D55

DOI. 10.1137/050636796

1. Introduction. The Ginzburg–Landau energy functional of superconductivity is given in the form

$$J(\Psi, A) = \int_{\Omega} \left( -|\Psi|^2 + \frac{|\Psi|^4}{2} + |h - h_{ex}|^2 + \left| \left( \frac{i}{\kappa} \nabla + A \right) \Psi \right|^2 \right) dx_1 dx_2,$$

in which $\Omega \subset \subset \mathbb{R}^2$ is smooth, and $\Psi$ is the (complex) superconducting order parameter, such that $|\Psi|$ varies from $|\Psi| = 0$ (when the material is at a normal state) to $|\Psi| = 1$ (for the purely superconducting state). The magnetic vector potential is denoted by $A$ (the magnetic field is, then, given by $h = \nabla \times A$), $h_{ex}$ is the constant applied magnetic field, and $\kappa$ is the Ginzburg–Landau parameter which is a property of the material. The functional $J$ is invariant under the gauge transformation

$$\Psi \rightarrow e^{i\kappa \eta} \Psi, \quad A \rightarrow A + \nabla \eta,$$

where $\eta$ is a smooth function. We focus here on the properties, for a given $h_{ex}$, of the global minimizers of $J$ in $H^1(\Omega, \mathbb{C}) \times H^1(\Omega, \mathbb{R}^2)$ for type II superconductors (for which $\kappa > 1/\sqrt{2}$). Note that every global minimizer actually represents an orbit of minimizers associated to the group of transformations (1.2).

1.1. The onset of superconductivity. It is known both from experiments [18] and rigorous analysis [13] that for a sufficiently strong magnetic field the normal state ($\Psi \equiv 0$, $h = h_{ex}$) would prevail. If the field is then decreased, there is a critical field, depending on the sample’s geometry, where the material would enter the superconducting state. For samples with boundaries, this field is known as the onset...
critical field (or nucleation field) and is called $H_{C_3}$. This leads to the definition (cf. [19, 15, 10], for instance)

\[(1.3) \quad H_{C_3}(\kappa) = \inf\{h_{ex} > 0 : (0, \hat{A}) \text{ is the unique global minimizer of } \mathcal{F}\},\]

where $\hat{A} : \Omega \rightarrow \mathbb{R}^2$ satisfies $\nabla \times \hat{A} = h_{ex}$. The minimizer $(0, \hat{A})$ is unique in the sense that any other minimizer is gauge equivalent to it, i.e., it should be in the form $(0, \hat{A} + \nabla \eta)$. We note that for our choice of scaling in (1.1) we have $H_{C_3} \sim \frac{\kappa}{\beta_0}$ as $\kappa \to \infty$ for smooth $\Omega$ [17], where $\beta_0$ is approximately 0.59.

The simplest case in which the bifurcation from the normal state $(0, \hat{A})$ to the superconducting one was described is the case of a half-plane [20]. The analysis in this case is one dimensional: the linearized Ginzburg–Landau equations were solved on $\mathbb{R}_+$. A similar situation occurs in two dimensions: it was proved in [17] and [7] that the bifurcating mode in $\mathbb{R}_+^2$ is one dimensional and that the value of $H_{C_3}$ is exactly the same as in the one-dimensional case.

In addition, Saint-James and de Gennes [20] found that superconductivity appears first near the boundary for a half-plane, i.e., the order parameter $\Psi_\kappa$ decays exponentially fast away from the boundary. This phenomenon, which appears only in the presence of boundaries, is therefore called surface superconductivity. It was later proved for general two-dimensional domains with smooth boundaries [17, 7], that as the domain’s scale tends to infinity the onset field tends to de Gennes’ value, and that $\Psi_\kappa$ decays exponentially fast away from the boundary.

Another related problem that has been considered in the literature is the distribution of $|\Psi_\kappa|$ along the boundary near the critical field. In [4], this distribution was formally obtained. This led to the conjecture that $|\Psi_\kappa|$ should be maximal at the point of maximal curvature along the boundary. This was indeed proved a few years later [15, 16, 11, 12]. Furthermore, it was shown that $\Psi_\kappa$ decays exponentially fast away from the points of maximal curvature along the boundary.

1.2. Weakly nonlinear analysis. Suppose now that $h_{ex}$ is further decreased below $H_{C_3}$. While the minimizer $\Psi_\kappa$ still decays exponentially fast away from the boundary much after the nucleation in the highly nonlinear regime when $\kappa < h_{ex} < H_{C_3}$ [1, 19, 2], the exponential decay along the boundary disappears quite rapidly as $h_{ex}$ decreases. More precisely, if we introduce the distance to the nucleation field $\rho$ by

$$\rho(\kappa) = H_{C_3}(\kappa) - h_{ex},$$

then exponential rate of decay along the boundary (far from the points of maximal curvature) is guaranteed only when

$$\rho(\kappa) \xrightarrow{\kappa \to \infty} 0.$$

Furthermore, it was proved in [10] that if $\rho$ satisfies

$$\lim_{\kappa \to \infty} \rho(\kappa) = \infty; \quad \lim_{\kappa \to \infty} \frac{\rho(\kappa)}{\kappa^{1/2}} = 0,$$

then there exists $u \in \mathcal{S}(\mathbb{R}_+^2)$ such that

\[(1.4) \quad \int_{\Omega} \left| \frac{\Psi_\kappa(x)}{\kappa} - \frac{\rho}{\kappa^2} u \left( \frac{\kappa}{\sqrt{\lambda}} t(x) \right) \right|^2 \ dx = o(\rho \kappa^{-3}),\]

where $t = d(x, \partial \Omega)$, $\lambda = \kappa/h_{ex}$. 
This leaves open the situation when $\rho(\kappa)/\kappa^2$ does not tend to 0 as $\kappa \to \infty$ and in particular becomes of the order of $\kappa^2$. It is this last case which will be considered in this article.

1.3. Highly nonlinear analysis: Pan’s conjecture. Given some $\lambda \in ]\beta_0, 1[$, let $(\kappa_n, h_{ex}^n)_{n \in \mathbb{N}}$ denote a pair of sequences satisfying

$$\lim_{n \to +\infty} \kappa_n = \infty; \quad \lim_{n \to +\infty} \frac{\kappa_n}{h_{ex}^n} = \lambda.$$ 

In the above $\beta_0 = \lim_{\kappa \to \infty} \kappa/H_{C_3}(\kappa)$ (we provide a better definition of $\beta_0$ in the next section). In [19, Conjecture 1], Pan conjectures the existence of a function $\beta_0, 1[ \ni \lambda \mapsto C(\lambda) \in \mathbb{R}^+$ such that, for any sequence as above,

$$|\Psi_{\kappa_n}(x)| \to C(\lambda) \quad \forall x \in \partial \Omega. \quad (1.5)$$

While the conjecture appears to be correct in its essence—any minimizer, as the results in [10] and in the present contribution suggest, does tend in some weak sense to a constant along the boundary—we believe that either the convergence assumed in (1.5) cannot be uniform, or else that the global minimizer must be discontinuous in $h_{ex}$ and $\kappa$. Let us sketch the heuristic arguments supporting this belief. We first write the Euler–Lagrange equations associated with (1.1) (or the Ginzburg–Landau equations):

$$(1.6a) \quad \left( i \frac{\kappa}{\kappa} + A_{\kappa} \right)^2 \Psi_{\kappa} = \Psi_{\kappa} (1 - |\Psi_{\kappa}|^2),$$

$$(1.6b) \quad - \nabla \times \nabla \times A_{\kappa} = \frac{i}{2\kappa} (\Psi_{\kappa}^* \nabla \Psi_{\kappa} - \Psi_{\kappa} \nabla \Psi_{\kappa}^*) + |\Psi_{\kappa}|^2 A_{\kappa}.$$  

If $|\Psi_{\kappa}| > 0$ for all $x \in \partial \Omega$ (and this is indeed the case if we assume uniform convergence in (1.5)), then we can divide (1.6b) by $|\Psi_{\kappa}|^2$ and integrate over $\partial \Omega$ (the measure on $\partial \Omega$ being denoted by $ds$), to obtain the existence of an integer $N(\Psi_{\kappa})$ such that

$$\int_{\partial \Omega} \frac{\nabla \times (h_{\kappa} - h_{ex})}{|\Psi|^2} ds + \int_{\Omega} h_{\kappa} dx = \frac{2\pi}{\kappa} N(\Psi_{\kappa}),$$

where $h_{\kappa} = \nabla \times A_{\kappa}$ is the induced magnetic field. The integer $N(\Psi_{\kappa}) \in \mathbb{Z}$ is the winding number (or the degree) of $\Psi_{\kappa}$ around $\partial \Omega$, which is invariant under the transformation (1.2) since $\eta$ must be smooth.

In [9] it is proved that $\Psi_{\kappa}$ vanishes at isolated points or curves which should end on $\partial \Omega$. If $|\Psi_{\kappa}|$ does not vanish on the boundary, as implied by (1.5), then it is clear that $\Psi_{\kappa}$ can vanish only at isolated points. Thus, we can conclude that $N(\Psi_{\kappa})$ is the number of vortices of $\Psi_{\kappa}$, including multiplicities, in $\Omega$.

In [16], it is proved (see [19] for an extension to the case which is considered here) that, for any $\epsilon_0 > 0$, there exist $C > 0$ and $\kappa_0$, such that, if $\kappa/h_{ex} \in [\beta_0 + \epsilon_0, 1 - \epsilon_0]$ and $\kappa \geq \kappa_0$, then

$$\|h - h_{ex}\|_{L^\infty(\Omega)} + \|\nabla(h_{\kappa} - h_{ext})\|_{L^\infty(\Omega)} \leq C.$$

Hence there exists a constant $C$ such that

$$\left| N(\Psi_{\kappa}) - \kappa h_{ex} \frac{|\Omega|}{2\pi} \right| \leq C \kappa. \quad (1.7)$$
Suppose now that the minimizer is unique when varying \( h_{ex} \) and \( \kappa \) as above. It is in this case reasonable to think that \( (\Psi_{\kappa}, A_{\kappa}) \) varies continuously. If there exist \( \kappa_0, \epsilon_1 > 0 \) and \( C > 0 \) such that

\[
|\Psi_{\kappa}| \geq \frac{1}{C} \text{ on } \partial \Omega \ \forall \kappa \geq \kappa_0 \text{ s.t. } \frac{\kappa}{h_{ex}} \in [\lambda - \epsilon_1, \lambda + \epsilon_1]
\]

(which would be a consequence of a uniform version of (1.5)), then \( N(\Psi_{\kappa}) \) must be fixed, by continuity, for all \( \kappa \geq \kappa_0 \) such that \( \kappa/h_{ex} \in [\lambda - \epsilon_1, \lambda + \epsilon_1] \), and this is in contradiction with (1.7).

The above argument works not only for \( (\psi_{\kappa}, A_{\kappa}) \) but for any solution of (1.6). If indeed critical points of (1.1) are continuous functions of \( \kappa \) and \( h_{ex} \) in this regime, then (1.7) would contradict another conjecture of Pan (Conjecture 2 in [19]), implying that any solution of (1.6) converges to a constant along the boundary when \( \kappa \to \infty \) and \( \kappa/h_{ex} \in (\beta_0, 1) \). While the existence of continuous branches of critical points appears to be reasonable, two counterexamples come to mind while discussing the continuity of the global minimizer.

1. Serfaty [21] proves, for much lower external fields, that a large number of local minimizers of (1.1) in a disc, characterized by different winding numbers, exist for sufficiently large \( \kappa \) whenever \( \frac{1}{C} \kappa^{-1} \leq h_{ex} \leq C\kappa^{\alpha-1} \) for some \( 0 < \alpha < 1 \). In this regime of applied magnetic field values the magnetic field is nonuniform inside the domain, and hence the vortices are kept near the disc’s center, which minimizes the magnetic field term in (1.1).

While in the present case \( h_{ex} \) and \( \kappa \) have the same order, if we allow for an \( O(1) \) change in the applied magnetic field we might still encounter a global minimizer which turns into a local minimizer (or a critical point) and vice versa. Thus, this result suggests that the contradiction between (1.7) and the convergence to a uniform constant along the boundary might be explained by arguing that the global minimizer is discontinuous. However, unlike the case discussed in [21], no equivalent mechanism which keeps the vortices away from the boundary is presently known as the magnetic field uniformly converges to \( h_{ex} \) in \( \Omega [2] \).

2. Bauman, Phillips, and Tang [3] found radially symmetric solutions of the linearized version of (1.6). These solutions are characterized by a “fat” vortex at the disc’s center. The degree of the vortex is determined, to leading order in the large \( \kappa \) limit, by the magnetic flux through the disc. Thus, there is a sequence of critical flux values where the bifurcating mode changes its winding number. It is shown in [3] that the bifurcating mode is locally stable near the bifurcation for \( \kappa \) large enough.

Based on the results in [3] one can argue that the minimizer undergoes an abrupt change when the flux varies around one of the above critical values (and when \( \kappa \) is appropriately tuned to guarantee that weakly nonlinear analysis still holds). However, this result seems to follow from the special geometry, and, in general, for different geometries or away from the linear regime, nothing would hold the vortices in the center.

1.4. Statement of the main result. In the present contribution we focus on the case

\[
\lim_{\kappa \to \infty} \frac{h_{ex}(\kappa)}{\kappa} = \frac{1}{\lambda},
\]
with $\lambda$ close to $\beta_0$. We prove the following theorem.

**Theorem 1.1.** Let $\delta > 0$ be sufficiently small, so that $t = d(x, \partial \Omega)$ is a smooth function of $x$ for $0 \leq t \leq \delta$, and let

$$\Omega_\delta = \{ x \in \bar{\Omega} : d(x, \partial \Omega) \leq \delta \}.$$

Then there exist $\epsilon > 0$, a function

\[ [0, +\infty[ \times ]\beta_0, \beta_0 + \epsilon[ \rightarrow (\tau, \lambda) \mapsto U(\tau, \lambda) \in \mathbb{R}^+ , \]

a constant $C > 0$, and $\kappa_0$, such that, for $\kappa \geq \kappa_0$ and $h_{ex} = \frac{\kappa}{\lambda}$ with $\lambda \in ]\beta_0, \beta_0 + \epsilon[$,

\[
\int_{\Omega_\delta} \left| \Psi_\kappa(x) \right|^2 - U \left( \frac{\kappa}{\sqrt{\lambda}} t(x, \lambda) \right) \right|^2 \, dx \, dt \leq \frac{C}{\kappa^2},
\]

\[
\int_{\partial \Omega} \left| \frac{\partial \Psi_\kappa}{\partial \Omega} \right|^2 - U(0, \lambda) \right|^2 \, ds \leq \frac{C}{\kappa^{3/2}}.
\]

The function $U(\tau, \lambda)$ is defined for $\tau \in \mathbb{R}^+$ by

$$U(\tau, \lambda) = |f_\zeta(\lambda)|^2;$$

where $f_\zeta(\tau; \lambda)$ and $\zeta(\lambda)$ are associated to minimizers of a family of one-dimensional problems, which will be analyzed in section 2. The second statement in the theorem gives the $L^2(\partial \Omega)$ convergence of $\left| \Psi_\kappa \right|^2$ to a constant and is consequently a weak form of Pan’s conjecture.

The rest of the contribution is arranged as follows.

In section 2 we consider a one-dimensional differential operator and prove that it is positive for $\beta_0 < \lambda < \beta_0 + \epsilon$. In section 3 we use the results of section 2 to analyze a simplified two-dimensional minimization problem, which was proved in [19] to be a good approximation of the full Ginzburg–Landau model for $\beta_0 < \lambda < 1$. The last section gives the proof of Theorem 1.1.

**2. A one-dimensional problem.** Let

\[
\beta(z) = \inf_{\phi \in H^1_{mag}([0, +\infty[ \setminus \{0\} \rightarrow \mathbb{R}^+}} \frac{\int_0^\infty |\phi'(\tau)|^2 + (\tau + z)^2|\phi(\tau)|^2 \, d\tau}{\int_0^\infty |\phi(\tau)|^2 \, d\tau}.
\]

Here

$$H^1_{mag}([0, +\infty[) = \{ u \in L^2([0, +\infty[ ; u' \in L^2([0, +\infty[) \text{ and } \tau u \in L^2([0, +\infty[) \}. $$

It is well known (see [5]) that $\beta(z)$ has a unique local minimum at $z_0 < 0$, where

$$\beta(z_0) = \beta_0 = z_0^2.$$

Furthermore, $\beta(z) \xrightarrow{z \to -\infty} \infty$ and $\beta(z) \xrightarrow{z \to -\infty} 1$. Clearly, for $\beta_0 < \lambda < 1$ there exist $z_1(\lambda) < z_0 < z_2(\lambda)$, such that

$$|z_1(\lambda), z_2(\lambda)| = \beta^{-1}(\beta_0, \lambda).$$

It is also easy to show [6] that

\[
\beta''(z_0) = -2z_0 \phi^2(0) > 0,
\]

where $\phi$ is the minimizer of (2.1) whose $L^2(\mathbb{R}^+)$ norm is unity.
Let $f_z(\tau; \lambda)$ denote the minimizer of
\begin{equation}
E_{z,\lambda}(\phi) = \int_0^\infty |\phi'(\tau)|^2 + (\tau + z)^2|\phi(\tau)|^2 + \frac{\lambda}{2} |\phi(\tau)|^4 - \lambda |\phi(\tau)|^2 \, d\tau
\end{equation}
in $H_{\text{mag}}^1([0, \infty[)$. The Euler–Lagrange equation associated with (2.3) is
\begin{equation}
-f_z''(\tau; \lambda) + (\tau + z)^2f_z(\tau; \lambda) = \lambda f_z(\tau; \lambda)(1 - f_z(\tau; \lambda)^2).
\end{equation}

It has been proved in [19, Theorems 3.1 and 3.3] that whenever $z_1(\lambda) < z < z_2(\lambda)$, there exists a unique positive global minimizer to (2.3). Furthermore, let
\begin{equation}
b(z, \lambda) = \inf_{\phi \in H_{\text{mag}}^1([0, \infty[)} E_{z,\lambda}(\phi).
\end{equation}
Then there exists $\zeta(\lambda) \in ]z_1(\lambda), z_2(\lambda)[$, where $z \mapsto b(z, \lambda)$ attains its minimum over $\mathbb{R}$,
\[
b(\zeta(\lambda), \lambda) = \inf_z b(z, \lambda).
\]
Moreover,
\begin{equation}
\int_0^\infty (\tau + \zeta(\lambda))|f_{\zeta(\lambda)}(\tau; \lambda)|^2 \, d\tau = 0.
\end{equation}

Remark 2.1. Note that when $z \notin ]z_1(\lambda), z_2(\lambda)[$, then $b(z, \lambda) = 0$, and the minimizer of $E_{z,\lambda}$ is the 0-function. In particular,
\[
b(\zeta(\lambda), \lambda) < 0 \text{ if } \lambda > \beta_0.
\]

The following lemma will play a crucial role in the analysis of the two-dimensional problem in section 3.

Lemma 2.2. Let
\begin{equation}
\gamma(\alpha, \lambda) = \min_{\alpha \in \mathbb{R}} \gamma(\alpha, \lambda) = \frac{f_0^\infty |\phi'(\tau)|^2 + (\tau + \zeta + \alpha)^2|\phi(\tau)|^2 - \lambda(1 - f_{\zeta}(\tau; \lambda)^2)|\phi(\tau)|^2 \, d\tau}{\int_0^\infty |\phi(\tau)|^2 \, d\tau},
\end{equation}
with $\zeta = \zeta(\lambda)$.

Then there exists $\epsilon > 0$ such that, for $\lambda \in [\beta_0, \beta_0 + \epsilon[$,
\begin{equation}
\min_{\alpha \in \mathbb{R}} \gamma(\alpha, \lambda) = 0.
\end{equation}

Proof. We divide the proof into three steps.

Step 1. $\gamma(0, \lambda) = \gamma_{\alpha}(0, \lambda) = 0$.

Let $\mathbb{R}_+ \ni \tau \mapsto u(\tau; \alpha, \lambda)$ denote the positive minimizer of (2.7), whose $L^2(\mathbb{R}_+)$ norm is one. Then $u$ satisfies
\[
-u''(\tau; \alpha, \lambda) + (\tau + \alpha + \zeta)^2u(\tau; \alpha, \lambda)
\]
\begin{equation}
-\lambda(1 - f_{\zeta}(\tau; \lambda)^2)u(\tau; \alpha, \lambda) = \gamma(\alpha, \lambda)u(\tau; \alpha, \lambda),
\end{equation}
\begin{equation}
u'(0; \alpha, \lambda) = 0.
\end{equation}
For $\alpha = 0$, we multiply (2.9a) by $f_\zeta$ and integrate over $\mathbb{R}_+$ to obtain
\[ \gamma(0, \lambda) \int_0^\infty f_\zeta(\tau; \lambda) u(\tau; \alpha, \lambda) \, d\tau = 0. \]
Since both $u$ and $f_\zeta$ are positive, we have using (2.4),
\[ \gamma(0, \lambda) = 0, \quad u(\tau, 0, \lambda) = \frac{f_\zeta(\tau; \lambda)}{\|f_\zeta\|^2}, \]
where, for $p \in [1, +\infty]$, $\| \cdot \|_p = \| \cdot \|_{L^p(\mathbb{R}_+)}$. Next, we differentiate (2.9) with respect to $\alpha$ to obtain, having in mind (2.4),
\begin{align*}
(2.11a) & - u_\alpha'' + (\tau + \alpha + \zeta)^2 u_\alpha - \lambda (1 - f_\zeta^2) u_\alpha = \gamma u_\alpha + \gamma_\alpha u - 2(\tau + \alpha + \zeta) u, \\
(2.11b) & u_\alpha'(0) = 0,
\end{align*}
where $u_\alpha(\tau; \alpha, \lambda) = \left( \frac{\partial}{\partial \alpha} \right) u(\tau; \alpha, \lambda)$ and $\gamma_\alpha(\alpha, \lambda) = \frac{\partial}{\partial \alpha} \gamma(\alpha, \lambda)$. Multiplying (2.11a) by $u$ and integrating by parts, we obtain
\[ \gamma_\alpha(\alpha, \lambda) = 2 \int_0^\infty (\tau + \alpha + \zeta(\lambda)) |u(\tau; \alpha, \lambda)|^2 \, d\tau. \]
In view of (2.6) and (2.10), we thus have
\[ \gamma_\alpha(0, \lambda) = 0. \]
\(\text{Step 2.}\)
\[ \exists \epsilon_1 > 0 : \lambda < \beta_0 + \epsilon_1 \Rightarrow \gamma_\alpha(0, \lambda) > \frac{1}{2} \beta''(z_0) > 0. \]
To prove the above statement we notice that $z_1(\lambda) \uparrow z_0$ and $z_2(\lambda) \downarrow z_0$ as $\lambda \to \beta_0$. Hence, since $z_1(\lambda) < \zeta(\lambda) < z_2(\lambda)$, we have
\[ \zeta(\lambda) \xrightarrow[\lambda \to \beta_0]{} z_0. \]
Moreover, one gets from the fact that $f_z$ is a minimizer the property that
\[ \mathcal{E}_{z, \lambda}(f_z) \leq 0. \]
From this inequality and (2.1) we easily obtain
\[ \frac{1}{2} \|f_z\|^4 \leq \frac{(\lambda - \beta_0)}{\lambda} \|f_z\|^2, \]
\[ (2.16) \quad \| (\tau + z) f_z \|^2 \leq \lambda \| f_z \|^2, \]
and
\[ \| f_z \|_{H^1}^2 \leq (\lambda + 1) \| f_z \|^2. \]
Let $z = \zeta(\lambda)$. Since $|\zeta(\lambda)|$ is bounded in some right semineighborhood of $\beta_0$, it follows immediately from (2.16) that for $R$ large enough we get
\[ \| f_\zeta \|^2 \leq 2 \| f_\zeta \|^2_{L^2([0, R])}. \]
We now observe that
\[ \|f\|_4^4 \leq C(\lambda - \beta_0)\|f\|_{L^2([0, R])}^2 \leq C(\lambda - \beta_0)R^2\|f\|_2^2. \]
This first gives that
\[ \|f\|_4 \leq C(\lambda - \beta_0)^{\frac{1}{4}}, \]
and hence that
\[ \|f\|_2 \leq C(\lambda - \beta_0)^{\frac{1}{2}}. \]
By interpolation, we obtain
\[ \|f\|_{\infty} \leq C \|f\|_2^{\frac{1}{2}} \|f'\|_2^{\frac{1}{2}} \leq C'(\lambda - \beta_0)^{\frac{1}{4}}, \]
which implies that
\[ \lim_{\lambda \to \beta_0} \|f_{\lambda}(\cdot; \lambda)\|_\infty = 0. \]
Substituting the above and (2.15) into (2.7) yields
\[ \gamma(\alpha, \lambda) \to \beta(\alpha + \zeta_0), \]
where the convergence is uniform on every compact set in \( \mathbb{R} \). Since \( \gamma \) is holomorphic in \( \alpha \), its derivatives must uniformly converge as well, and hence
\[ \gamma_{\alpha\alpha}(\alpha, \lambda) \to \beta''(\alpha + \zeta_0), \]
from which (2.14) easily follows. We note that a tedious calculation shows that
\[ \gamma_{\alpha\alpha}(0, \lambda) = -2\zeta f'_{\lambda}(0; \lambda) + \frac{6\lambda^2}{\|f\|_2^2} \int_0^\infty f'_{\lambda}(\tau; \lambda) d\tau - \frac{2\lambda}{3} \int_0^\infty f'_{\lambda}(\tau; \lambda)[\lambda - (\tau + \zeta)^2] d\tau, \]
with \( \zeta = \zeta(\lambda) \), from which one can easily prove (2.14) as well.
From (2.14) we obtain that
\[ \exists \alpha_0 > 0 : \lambda < \beta_0 + \epsilon \Rightarrow \gamma(\alpha, \lambda) \geq 0 \forall |\alpha| \leq \alpha_0. \]
The last step would thus be to prove the above statement for \( |\alpha| > \alpha_0 \).

**Step 3. Proof of (2.8).**
From the definition of \( \gamma \) (2.7), it follows that
\[ \gamma(\alpha, \lambda) \geq \beta(\zeta + \alpha) - \lambda. \]
Clearly, for any \( \alpha_1 > 0 \), there exists \( \epsilon_2 > 0 \), such that, if \( \lambda \leq \beta_0 + \epsilon_2 \), then \([z_1(\lambda), z_2(\lambda)] \subset [z_0 - \alpha_1, z_0 + \alpha_1] \). We now take \( \alpha_1 = \alpha_0 \). This gives that \( \beta(\zeta + \alpha) \geq \lambda \) for all \( |\alpha| \geq \alpha_0 \), and (2.8) follows. \( \square \)
3. On two-dimensional models on half cylinders. We can now prove the following theorem.

**Theorem 3.1.** For \( \omega \in ]0, +\infty[ \) and \( \lambda \in ]\beta_0, +\infty[ \), let us consider the functional

\[
H_\omega \ni \psi \mapsto E_\omega(\psi, \lambda) = \int_{-\pi/\omega}^{\pi/\omega} \int_0^\infty \left[ \left| (i\nabla + \xi_1 i \partial_2) \psi \right|^2 + \frac{1}{2} \lambda |\psi|^4 - \lambda |\psi|^2 \right] \, d\xi_1 d\xi_2,
\]

where

\[
| (i\nabla + \xi_1 i \partial_2) \psi |^2 = |i\partial_1 \psi|^2 + |(i\partial_2 + \xi_1) \psi|^2,
\]

and

\[
H_\omega = \left\{ \psi \in H^1_{mag}(\mathbb{R}_+ \times ]0, L[ \times \mathbb{C}) \, \forall L > 0 \mid \exists \varphi \in \mathbb{R} : \psi(\xi_1, \xi_2 + 2\pi/\omega) = e^{-iz} \psi(\xi_1, \xi_2) \right\}.
\]

Let \( \psi_\lambda \) be the function

\[
(\mathbb{R}_+ \times \mathbb{R}) \ni (\xi_1, \xi_2) \mapsto \psi_\lambda(\xi_1, \xi_2) := e^{-i\zeta(\lambda) \xi_2} f_{\zeta, \lambda}(\xi_1; \lambda).
\]

Then there exists \( \epsilon > 0 \) such that

\[
E_\omega(\psi, \lambda) \geq E_\omega(\psi_\lambda, \lambda) \, \forall \lambda \in ]\beta_0, \beta_0 + \epsilon[ \, \forall \omega > 0, \, \text{and} \, \forall \psi \in H_\omega.
\]

**Remark 3.2.** Clearly \( \psi_\lambda \) is in \( H_\omega \) (take \( z = \zeta(\lambda) \)). Hence, the theorem states that \( \psi_\lambda \) is the global minimizer of \( E_\omega \) in \( H_\omega \).

**Proof.** Consider first functions in \( H_\omega \) which are given in the form

\[
(\xi_1, \xi_2) \mapsto \psi(\xi_1, \xi_2) := f_\zeta(\xi_1; \lambda) e^{-i\zeta(\lambda) \xi_2} v,
\]

with \( v \) periodic,

\[
v(\xi_1, \xi_2) = v(\xi_1, \xi_2 + 2\pi/\omega),
\]

and

\[
\zeta = \zeta(\lambda).
\]

Then

\[
E_\omega(\psi, \lambda) = \int_{-\pi/\omega}^{\pi/\omega} \int_0^\infty \left[ \left| (i\nabla + (\xi_1 + \zeta) i \partial_2) f_\zeta v \right|^2 + \frac{1}{2} \lambda |f_\zeta v|^4 - \lambda |f_\zeta v|^2 \right] \, d\xi_1 d\xi_2.
\]

Clearly,

\[
\int_{-\pi/\omega}^{\pi/\omega} \int_0^\infty \left| (i\nabla + (\xi_1 + \zeta) i \partial_2) f_\zeta v \right|^2 \, d\xi_1 d\xi_2
\]

\[
= \int_{-\pi/\omega}^{\pi/\omega} \int_0^\infty \left[ |v|^2 \left[ |f_\zeta|^2 + (\xi_1 + \zeta)^2 |f_\zeta|^2 \right] + f_\zeta^2 |\nabla v|^2 + \frac{1}{2} (f_\zeta^2)'' \frac{\partial}{\partial \xi_1} (|v|^2)
\]

\[
+ i(\xi_1 + \zeta) f_\zeta^2 \left( \frac{\partial v}{\partial \xi_2} - v \frac{\partial \bar{v}}{\partial \xi_2} \right) \right] \, d\xi_1 d\xi_2.
\]
Furthermore, integration by parts and (2.4) yield

\[
\int_{-\pi/\omega}^{\pi/\omega} \int_{0}^{\infty} \left[ |v|^2 \left[ f_{\xi}^2 \right] + (\xi_1 + \zeta)^2 |f_{\xi}|^2 + \frac{1}{2} \left( f_{\xi}' \right)' \left( \frac{\partial}{\partial \xi} |v|^2 \right) \right] \, d\xi_1 d\xi_2 = \lambda \int_{-\pi/\omega}^{\pi/\omega} \int_{0}^{\infty} |v|^2 f_{\xi}^2 (1 - f_{\xi}^2) \, d\xi_1 d\xi_2.
\]

Hence,

\[
\Delta E_\omega = E_\omega(\psi, \lambda) - E_\omega(f_\xi e^{-i\xi_2}, \lambda)
= \int_{-\pi/\omega}^{\pi/\omega} \int_{0}^{\infty} f_{\xi}^2 \left[ |\nabla v|^2 + i(\xi_1 + \zeta) \left( \frac{\partial v}{\partial \xi_2} - v \frac{\partial \bar{\xi}}{\partial \xi_2} \right) \right] \, d\xi_1 d\xi_2
+ \frac{1}{2} \int_{-\pi/\omega}^{\pi/\omega} \int_{0}^{\infty} f_{\xi}^4(1 - |v(\xi_1, \xi_2)|^2)^2 \, d\xi_1 d\xi_2.
\]

Using (3.5), we can write

\[
v(\xi_1, \xi_2) = \sum_{n=-\infty}^{\infty} v_n(\xi_1) e^{in\omega\xi_2}.
\]

Then

\[
\Delta E_\omega = \sum_{n=-\infty}^{\infty} \int_{0}^{\infty} f_{\xi}(\xi_1; \lambda)^2 \left[ \left| v_n'(\xi_1) \right|^2 + (n^2 \omega^2 + 2n\omega \xi_1) |v_n(\xi_1)|^2 \right] \, d\xi_1
+ \frac{1}{2} \int_{-\pi/\omega}^{\pi/\omega} \int_{0}^{\infty} f_{\xi}^4(1 - |v(\xi_1, \xi_2)|^2)^2 \, d\xi_1 d\xi_2.
\]

Consider now the functional

\[
u \mapsto \mathcal{J}(u, \alpha) = \int_{0}^{\infty} \left[ |f_{\xi}(\xi_1; \lambda)|^2 \left[ |u'(\xi_1)|^2 + (2\alpha^2 + 2\alpha(\xi_1 + \zeta)) |u(\xi_1)|^2 \right] \right] \, d\xi_1.
\]

Substituting \( w(\xi_1) = f_{\xi}(\xi_1; \lambda) u(\xi_1) \) and utilizing (2.4), we obtain

\[
\int_{0}^{\infty} |f_{\xi}(\xi_1; \lambda)|^2 |u'(\xi_1)|^2 \, d\xi_1 = \int_{0}^{\infty} \left[ - \left( w^2 \frac{f_{\xi}'}{f_{\xi}} \right)' + w^2 \frac{f_{\xi}''}{f_{\xi}} + |w'|^2 \right] \, d\xi_1
= \int_{0}^{\infty} \left[ |w'|^2 + [(\xi_1 + \zeta)^2 - \lambda (1 - f_{\xi}^2)] |w|^2 \right] \, d\xi_1.
\]

Consequently,

\[
\mathcal{J}(w/f_{\xi}, \alpha) = \int_{0}^{\infty} \left[ |w'|^2 + [(\xi_1 + \zeta + \alpha)^2 - \lambda (1 - f_{\xi}^2)] |w|^2 \right] \, d\xi_1 \geq \gamma(\alpha, \lambda) \int_{0}^{\infty} |w|^2 \, d\xi_1.
\]

Combining the above with (3.7), we obtain

\[
\Delta E_\omega \geq \sum_{n=-\infty}^{\infty} \gamma(n\omega, \lambda) \int_{0}^{\infty} f_{\xi}^2 |v_n|^2 \, d\xi_1 + \frac{1}{2} \int_{-\pi/\omega}^{\pi/\omega} \int_{0}^{\infty} f_{\xi}^4 (1 - |v|^2)^2 \, d\xi_1 d\xi_2 \geq 0,
\]

which proves, using (2.8), inequality (3.3) for every function in \( \mathcal{H}_\omega \) satisfying (3.4).
Note for later use that this implies

\begin{equation}
|E_\omega(\psi, \lambda) - E_\omega(f_\xi e^{-iz\xi_2}, \lambda)| \geq \frac{1}{2} \int_{-\pi/\omega}^{\pi/\omega} \int_0^\infty f_\xi(\xi_1; \lambda) (1 - |v(\xi_1, \xi_2)|^2)^2 d\xi_1 d\xi_2.
\end{equation}

To prove (3.3) for all $\psi \in H_\omega$, we consider now functions of the form

\begin{equation}
(\xi_1, \xi_2) \mapsto \psi_0(\xi_1, \xi_2) = f_\xi(\xi_1; \lambda)e^{-iz\xi_2}v, \quad \text{with} \quad v(\xi_1, \xi_2) = v(\xi_1, \xi_2 + 2\pi/\omega).
\end{equation}

Consider first the case when $\omega \in \mathbb{R}_+$ satisfies

\begin{equation}
\frac{\xi - z}{\omega} = \frac{p}{q}, \quad \text{for some pair} \ (p, q) \in \mathbb{Z} \times \mathbb{N}.
\end{equation}

Clearly, if $\psi_0$ satisfies (3.9) for some $\omega \in \mathbb{R}_+$, then it also satisfies (3.9) for $\omega/\hat{q}$, for every $\hat{q} \in (\mathbb{N} \setminus \{0\})$. Moreover, it is easy to show that

\begin{equation}
E_{\omega/\hat{q}}(\psi_0) = \hat{q}E_\omega(\psi_0), \quad E_{\omega/\hat{q}}(\psi_\lambda) = \hat{q}E_\omega(\psi_\lambda).
\end{equation}

We now choose $\hat{q} = q$, and observe that, according to (3.10), $\hat{\omega} = \omega/q$ satisfies

\begin{equation}
\frac{\xi - z}{\hat{\omega}} \in \mathbb{Z}.
\end{equation}

But in this case, $\psi_0$ admits the representation (3.4), and hence

\begin{equation}
E_{\hat{\omega}}(\psi_0) \geq E_{\hat{\omega}}(\psi_\lambda).
\end{equation}

Coming back to $\omega$ and using (3.11), we have the proof of (3.3) when $\omega$ satisfies (3.10) (with the additional condition that $z$ is fixed).

The proof of (3.3) in the general case follows immediately from the density of the rational numbers in $\mathbb{R}$. \qed

4. Surface superconductivity. Let $J$ be given by (1.1). Let $(\Psi_\kappa, A_\kappa)$ denote a minimizer of $J$ in $H^1(\Omega, \mathbb{C}) \times H^1(\Omega, \mathbb{R}^2)$. We prove in this section that $|\Psi_\kappa|^2$ is nearly a constant along the boundary, in $L^2(\partial\Omega)$ sense, as $\kappa \to \infty$, and for

\begin{equation}
\beta_0 < \lambda = \frac{\kappa}{h_{ex}} < \beta_0 + \epsilon,
\end{equation}

where $\epsilon$ is defined in (2.8).

To this end we need to adapt the results in [19]. Then let

\begin{equation}
x = F(t, s)
\end{equation}

denote a diffeomorphism from

\begin{equation}
D(\delta) = \{(s, t) : |s| \leq |\partial\Omega|/2, \ 0 \leq t \leq \delta\}
\end{equation}

to

\begin{equation}
\Omega_\delta = \{x \in \bar{\Omega} : d(x, \partial\Omega) \leq \delta\}.
\end{equation}

In the previous equation $t = d(x, \partial\Omega)$ and $s$ denotes the arclength along $\partial\Omega$. 

In order to formulate and prove the results of this section it is necessary to fix a specific gauge for \((\psi_\kappa, A_\kappa)\). To this end we first define the magnetic potential \(P_\kappa\) to be the solution of
\[
\begin{cases}
\nabla \times P_\kappa = \nabla \times A_\kappa - h_{ex} & \text{in } \Omega, \\
\nabla \cdot P_\kappa = 0 & \text{in } \Omega, \\
P_\kappa \cdot \hat{\nu} = 0 & \text{in } \partial \Omega.
\end{cases}
\]
(4.2)
(see, for example, [8] for the proof of existence of a unique solution for (4.2)). Moreover, the map associating the solution \(P_\kappa\) of (4.2) to the field \((h_\kappa - h_{ex})\) is linear continuous from \(L^p(\Omega)\) into \(W^{1,p}(\Omega)\) for any \(p \in [1, +\infty[\), and, using the Sobolev injection theorem, one can show that
\[
||P_\kappa||_{L^\infty(\Omega)} \leq C_\Omega ||\nabla \times A_\kappa - h_{ex}||_{L^\infty(\Omega)}.
\]
(4.3)
Then let \(e_1 = -\hat{\nu}\) denote an inward unit normal vector on \(\partial \Omega\) and let \(e_2\) denote a unit tangential vector. Further, let
\[
g = \text{Det}(DF) = 1 - t \kappa_r(s),
\]
where \(\kappa_r\) denotes the local curvature on \(\partial \Omega\). Let (see [19]) \(F\) be any vector potential such that \(\nabla \times F = h_{ex}\) and let \(a\) be defined by
\[
a = a_1 e_1 + a_2 e_2 = [F \cdot e_1] e_1 + [gF \cdot e_2] e_2.
\]
(4.4)
By [14], or the appendix in [12], there exists \(\hat{A}_\kappa\) such that if we substitute \(F = \hat{A}_\kappa\) in (4.4), we obtain
\[
a_1(s, t) = 0; \quad a_2(s, t) = h_{ex}[c_2 + t^2 \kappa_r(s)],
\]
where
\[
c_2 = \frac{|\Omega|}{|\partial \Omega|}.
\]
(4.5)
The gauge in (1.2) is now fixed by the condition that the \(\hat{A}_\kappa\) has in the new coordinates the normal form given above and that \(A_\kappa\) satisfies
\[
A_\kappa - \hat{A}_\kappa = P_\kappa.
\]
We now introduce the change of variables

\[
(\xi_1, \xi_2) = \left(\frac{\kappa \sqrt{\lambda}}{\sqrt{\kappa}}, \frac{\kappa \sqrt{\lambda}}{\sqrt{\kappa}} s\right)
\]
and prove the following lemma.

**Lemma 4.1.** Let
\[
\Psi_\kappa(\xi_1, \xi_2) = \begin{cases}
\Psi_\kappa(\sqrt{\kappa} \xi_1, \sqrt{\kappa} \xi_2) e^{-ic_2 \xi_2} & \text{for } 0 \leq \xi_1 \leq \frac{\kappa}{\sqrt{\lambda}} \xi_2, \\
\Psi_\kappa(\kappa \delta / \sqrt{\lambda}, \xi_2) e^{-ic_2 \xi_2} e^{-\xi_1 - \delta / \sqrt{\lambda}} & \text{for } \xi_1 \geq \frac{\kappa}{\sqrt{\lambda}} \xi_2
\end{cases}
\]
where \(c_2 = c_2(\Omega)\), and let
\[
\omega_\kappa = \frac{2\pi \sqrt{\lambda}}{\kappa |\partial \Omega|}.
\]
ON A CONJECTURE OF X. B. PAN

Then, as \( \kappa \) tends to \( +\infty \),

\[
J(\Psi_\kappa, A_\kappa) \geq \frac{1}{\kappa^2} E_{\omega_\kappa}(\hat{\Psi}_\kappa, \lambda) + O(1/\kappa^2).
\]

We will later prove (see (4.18)), that \( |E_{\omega_\kappa}(\hat{\Psi}_\kappa, \lambda)| \geq C\kappa \), and hence the correction term on the right-hand side of (4.6) is much smaller than the first term as \( \kappa \to \infty \).

Proof. In \([2]\) (see also \([16]\)) it was proved that for \( \lambda < 1 \), there exists \( \mu > 0 \) such that

\[
|\nabla(\nabla \times A_\kappa)| \leq Ce^{-\mu d(x, \partial \Omega)}.
\]

Consequently, for \( x \in \Omega_\delta \), we have

\[
|\nabla \times A_\kappa - h_{ex}|(x) \leq \int_0^{d(x, \partial \Omega)} |\nabla(\nabla \times A_\kappa)(t, s(x))| dt \leq C \int_0^{\infty} e^{-\mu\kappa t} dt.
\]

Hence, there exists \( C_1 > 0 \) such that

\[
\|\nabla \times A_\kappa - h_{ex}\|_{L^\infty(\Omega_\delta)} \leq \frac{C_1}{\kappa}.
\]

In view of (4.7) we can state the above inequality for the \( L^\infty(\Omega) \) norm of \( \nabla \times A_\kappa - h_{ex} \), and thus (4.3) gives that, for some \( C_2 > 0 \),

\[
\|A_\kappa - \hat{A}_\kappa\|_{L^\infty(\Omega)} \leq \frac{C_2}{\kappa}.
\]

Hence, for some \( C_3 > 0 \),

\[
\int_\Omega |\nabla \times A_\kappa - h_{ex}|^2 d\Omega \leq \frac{C_3}{\kappa^2},
\]

and

\[
\int_\Omega \left| \left( \frac{i}{\kappa} \nabla + A_\kappa \right) \Psi_\kappa \right|^2 dx = \int_\Omega \left| \left( \frac{i}{\kappa} \nabla + \hat{A}_\kappa \right) \Psi_\kappa \right|^2 dx
\]

\[
+ \int_\Omega |\Psi_\kappa|^2 |A_\kappa - \hat{A}_\kappa|^2 dx + \int_\Omega (A_\kappa - \hat{A}_\kappa) \cdot \left[ \frac{i}{\kappa}(\Psi_\kappa \nabla \Psi_\kappa - \Psi_\kappa \nabla \hat{\Psi}_\kappa) + 2\hat{A}_\kappa \right] dx
\]

\[
\geq \int_\Omega \left| \left( \frac{i}{\kappa} \nabla + \hat{A}_\kappa \right) \Psi_\kappa \right|^2 dx - 2||A_\kappa - \hat{A}_\kappa||_{L^\infty(\Omega)} ||\Psi_\kappa||_{L^\infty} \int_\Omega \left| \left( \frac{i}{\kappa} \nabla + \hat{A}_\kappa \right) \Psi_\kappa \right| dx.
\]

In \([2]\) it is shown that

\[
|\Psi_\kappa| + \left| \left( \frac{i}{\kappa} \nabla + \hat{A}_\kappa \right) \Psi_\kappa \right| \leq Ce^{-\mu d(x, \partial \Omega)}
\]

for some \( \mu > 0 \) when \( \lambda < 1 \). Hence,

\[
\int_\Omega \left| \left( \frac{i}{\kappa} \nabla + A_\kappa \right) \Psi_\kappa \right|^2 dx \geq \int_\Omega \left| \left( \frac{i}{\kappa} \nabla + \hat{A}_\kappa \right) \Psi_\kappa \right|^2 dx - \frac{C}{\kappa^2}.
\]
Combining (4.8) and (4.10) we obtain

\[ J(\Psi_\kappa, A_\kappa) \geq \int_\Omega \left( \left| \left( \frac{i}{\kappa} \nabla + \hat{A}_\kappa \right) \Psi_\kappa \right|^2 + \frac{1}{2} |\Psi_\kappa|^4 - |\Psi_\kappa|^2 \right) \, dx \quad - \frac{C}{\kappa^2}. \]

Using the coordinates (4.1) we obtain

\[ \int_{\Omega_0} \left( \left| \left( \frac{i}{\kappa} \nabla + \hat{A}_\kappa \right) \Psi_\kappa \right|^2 + \frac{1}{2} |\Psi_\kappa|^4 - |\Psi_\kappa|^2 \right) \, dx_1 dx_2 = \int_{D(\delta)} \left\{ \frac{1}{\kappa^2} \left| \frac{\partial \Psi_\kappa}{\partial t} \right|^2 + \frac{1}{g^2} \left( i \frac{\partial}{\partial s} + a_2 \right) |\Psi_\kappa|^2 + \frac{1}{2} |\Psi_\kappa|^4 - |\Psi_\kappa|^2 \right\} \, g \, ds dt. \]

Applying the transformation (4.5), we obtain

\[ \int_0^{\frac{2\pi}{\kappa}} \int_{\frac{-\sqrt{\kappa} \partial \Omega}{2\sqrt{\kappa}}} \int_{\frac{-\sqrt{\kappa} \partial \Omega}{2\sqrt{\kappa}}} \int_{\frac{-\sqrt{\kappa} \partial \Omega}{2\sqrt{\kappa}}} \int_{\frac{-\sqrt{\kappa} \partial \Omega}{2\sqrt{\kappa}}} \frac{\partial \phi_\kappa}{\partial \xi_1} \frac{\partial \phi_\kappa}{\partial \xi_2} \left\{ \left( \frac{\partial \Psi_\kappa}{\partial \xi_1} \right)^2 + \frac{1}{g^2} \left( i \frac{\partial}{\partial \xi_2} + \xi_1 - \kappa r(s) \sqrt{\frac{\kappa}{\lambda}} \right) \left( \frac{\partial \Psi_\kappa}{\partial \xi_1} \right)^2 + \frac{1}{2} \lambda |\Psi_\kappa|^4 - \lambda |\Psi_\kappa|^2 \right\}, \]

where \( \tilde{g} \) is defined by

\[ \tilde{g}(\xi_1, \xi_2) = 1 - \frac{\sqrt{\kappa}}{\lambda} \kappa r(\sqrt{\kappa} \xi_2/\kappa). \]

Since by (4.9), there exist \( \bar{\mu} > 0 \) and \( \tilde{C} \) such that on \( [0, \frac{\kappa}{\sqrt{\kappa}}] \times [-\kappa|\partial \Omega|/2\sqrt{\kappa}, +\kappa|\partial \Omega|/2\sqrt{\kappa}] \),

\[ \left| \left( \frac{i}{\partial \xi_2} + \xi_1 - \kappa r(\sqrt{\kappa} \xi_2/\kappa) \sqrt{\frac{\kappa}{\lambda}} \right) \frac{\partial \Psi_\kappa}{\partial \xi_1} \right|^2 + |\xi_1|^2 |\tilde{\Psi}_\kappa|^2 \leq \tilde{C} e^{-\bar{\mu} \xi_1}, \]

there exist \( \mu > 0 \) and \( C \) such that

\[ \left| \left( \frac{i}{\partial \xi_2} + \xi_1 \right) \frac{\partial \Psi_\kappa}{\partial \xi_1} \right|^2 \leq C e^{-\mu \xi_1}. \]

We thus obtain

\[ \int_0^{\frac{2\pi}{\kappa}} \int_{\frac{-\sqrt{\kappa} \partial \Omega}{2\sqrt{\kappa}}} \int_{\frac{-\sqrt{\kappa} \partial \Omega}{2\sqrt{\kappa}}} \int_{\frac{-\sqrt{\kappa} \partial \Omega}{2\sqrt{\kappa}}} \int_{\frac{-\sqrt{\kappa} \partial \Omega}{2\sqrt{\kappa}}} \frac{\partial \phi_\kappa}{\partial \xi_1} \frac{\partial \phi_\kappa}{\partial \xi_2} \left\{ \left( \frac{\partial \Psi_\kappa}{\partial \xi_1} \right)^2 + \left( i \frac{\partial}{\partial \xi_2} + \xi_1 \right) \left( \frac{\partial \Psi_\kappa}{\partial \xi_1} \right)^2 \right\} \, dx dx_1 dx_2 dx_3 = \int_0^{\infty} \int_{\frac{-\sqrt{\kappa} \partial \Omega}{2\sqrt{\kappa}}} \int_{\frac{-\sqrt{\kappa} \partial \Omega}{2\sqrt{\kappa}}} \left( \frac{\partial \Psi_\kappa}{\partial \xi_1} \right)^2 \, dx dx_1 dx_2 = O(1). \]

Using the above arguments for the remaining terms yields

\[ J(\Psi_\kappa, \hat{A}_\kappa) = \frac{1}{\kappa^2} \int_0^{\frac{2\pi}{\kappa}} \int_{\frac{-\sqrt{\kappa} \partial \Omega}{2\sqrt{\kappa}}} \int_{\frac{-\sqrt{\kappa} \partial \Omega}{2\sqrt{\kappa}}} \int_{\frac{-\sqrt{\kappa} \partial \Omega}{2\sqrt{\kappa}}} \int_{\frac{-\sqrt{\kappa} \partial \Omega}{2\sqrt{\kappa}}} \left\{ \left( \frac{\partial \Psi_\kappa}{\partial \xi_1} \right)^2 + \left( i \frac{\partial}{\partial \xi_2} + \xi_1 \right) \left( \frac{\partial \Psi_\kappa}{\partial \xi_1} \right)^2 + \frac{1}{2} \lambda |\Psi_\kappa|^4 - \lambda |\Psi_\kappa|^2 + O(\kappa^{-2}) \right\}. \]
so

\begin{equation}
\mathcal{J}(\Psi_{\kappa},\hat{A}_{\kappa}) = \frac{1}{\kappa^2} E_{\omega_{\kappa}}(\tilde{\Psi}_{\kappa},\lambda) + \mathcal{O}(\kappa^{-2}).
\end{equation}

Combining (4.12) with (4.11) yields (4.6).

We can now prove the main result of this work.

**Proof of Theorem 1.1.** Let \( \hat{\psi}_{\lambda,\kappa} : \Omega_{\kappa} \to \mathbb{C} \) be given by

\[ \hat{\psi}_{\lambda,\kappa}(x) = \psi_{\lambda}\left(\frac{\kappa}{\sqrt{\lambda}} t(x)\right) \exp\left\{ -ic_{2} \left(\frac{\kappa}{\sqrt{\lambda}} s(x)\right) \right\}. \]

Further, let \( \chi : \mathbb{R}_{+} \to [0,1] \) denote a smooth cutoff function satisfying

\[ \chi(t) = \begin{cases} 1 & t \leq \frac{1}{2}, \\ 0 & t \geq 1. \end{cases} \]

Then \( \chi(t(x)/\delta) \hat{\psi}_{\lambda,\kappa}(x) \) is in \( H^1(\Omega,\mathbb{C}) \), and it is not difficult to show that

\begin{subequations}
\begin{equation}
\mathcal{J}(\hat{\psi}_{\lambda,\kappa},\hat{A}_{\kappa}) \leq \mathcal{J}(\psi_{\lambda,\kappa},\hat{A}_{\kappa}) = -\frac{C_{\lambda} |\partial \Omega|}{\kappa \sqrt{\lambda}} + \mathcal{O}(\kappa^{-2}),
\end{equation}

where

\begin{equation}
C_{\lambda} = -\frac{\omega}{2\pi} E_{\omega}(\psi_{\lambda},\lambda).
\end{equation}
\end{subequations}

By Theorem 3.1 there exists \( \epsilon > 0 \) such that, for \( \beta_{0} < \lambda < \beta_{0} + \epsilon \), we have, for all \( \omega \),

\begin{equation}
C_{\lambda} = -\frac{\omega}{2\pi} \inf_{\psi \in \mathcal{H}_{\omega}} E_{\omega}(\psi,\lambda).
\end{equation}

Note that this implies, in particular,

\begin{equation}
C_{\lambda} = -\lim_{\omega \to 0} \frac{\omega}{2\pi} \inf_{\psi \in \mathcal{H}_{\omega}} E_{\omega}(\psi,\lambda).
\end{equation}

Combining (4.6) and (4.13) we obtain

\begin{equation}
\mathcal{J}(\Psi_{\kappa},\hat{A}_{\kappa}) = -\frac{C_{\lambda} |\partial \Omega|}{\kappa \sqrt{\lambda}} + \mathcal{O}(\kappa^{-2}),
\end{equation}

In [19, Lemma 7.3], Pan proves (4.16), for any fixed \( \beta_{0} < \lambda < 1 \), by using as a test functions the unknown minimizer of \( E_{\omega_{\kappa}} \) in \( \mathcal{H}_{\omega_{\kappa}} \) instead of \( \psi_{\lambda} \), and (4.15) as the definition of \( C_{\lambda} \). He also proves (4.16) when \( \lambda(\kappa) \to \lambda \) (with \( \lambda(\kappa) = \frac{\kappa}{\kappa_{\omega_{\kappa}}(\kappa)} \)) but with an additional \( \mathcal{O}((\lambda(\kappa) - \lambda)/\kappa) \) error. Note that when \( \lambda = \beta_{0} \), this result is no more useful since \( C_{\beta_{0}} = 0 \), and hence the leading order term of \( \mathcal{J} \) is unknown in this case (see [10] for results in this case).

By (2.5) and (3.3), we have

\[ C_{\lambda} = -b(\zeta(\lambda),\lambda), \]

which shows that \( C_{\lambda} > 0 \) for every \( \beta_{0} < \lambda < 1 \). Consequently, we have by (4.6) and (4.16),

\begin{equation}
E_{\omega_{\kappa}}(\Psi_{\kappa},\lambda) \leq E_{\omega_{\kappa}}(\psi_{\lambda},\lambda) + C.
\end{equation}
Thus, by (4.13b)

$$E_{\omega_{k}}(\tilde{\Psi}_{k}, \lambda) \leq -C_{\lambda} \frac{\partial\Omega}{\sqrt{\lambda}} + C,$$

which proves that indeed

(4.18) \[ |E_{\omega_{k}}(\tilde{\Psi}_{k}, \lambda)| \geq C_{\lambda}, \]

and that the correction term on the right-hand side of (4.6) is much smaller than the leading order term.

Let $w_{k}$ be defined by

$$\tilde{\Psi}_{k}(\xi_{1}, \xi_{2}) = f_{\gamma}(\xi_{1}; \lambda) w_{k}(\xi_{1}, \xi_{2}) e^{-ic_{2}\xi_{2}}.$$

Clearly, $w_{k}$ is periodic in $\xi_{2}$. Thus, by (3.8), we get

$$\left| E_{\omega_{k}}(\tilde{\Psi}_{k}, \lambda) - E_{\omega_{k}}(\psi_{\lambda}, \lambda) \right| \geq \frac{1}{2} \int_{-\pi/\omega_{k}}^{\pi/\omega_{k}} d\xi_{2} \int_{0}^{\infty} d\xi_{1} |f_{\gamma}|^{4}(1 - |w_{k}|^{2})^{2}.$$

Consequently, there exists $C_{0} > 0$ such that

$$\int_{-\pi/\omega_{k}}^{\pi/\omega_{k}} d\xi_{2} \int_{0}^{\infty} d\xi_{1} |f_{\gamma}|^{4}(1 - |w_{k}|^{2})^{2} \leq C_{0},$$

and hence, for suitable constants $C_{1}$ and $C_{2}$,

$$\int_{\Omega} \left| \Psi_{k} \right|^{2} - \left| \hat{\psi}_{\lambda,k} \right|^{2} \leq \frac{C_{1}}{\kappa^{2}} \int_{-\pi/\omega_{k}}^{\pi/\omega_{k}} d\xi_{2} \int_{0}^{\infty} d\xi_{1} |f_{\gamma}|^{4}(1 - |w_{k}|^{2})^{2} \leq \frac{C_{2}}{\kappa^{2}},$$

which proves (1.8a).

To prove (1.8b), we first notice that it is proved in [2] that

$$|\Psi_{k}| + \frac{1}{\kappa} |\nabla \Psi_{k}| \leq C,$$

and using the explicit form of $\hat{\psi}_{\lambda,k}$, we obtain

(4.19) \[ |\nabla(\left| \Psi_{k} \right|^{2} - \left| \hat{\psi}_{\lambda,k} \right|^{2})| \leq C_{\lambda}. \]

Evidently, as a consequence of the mean value formula, there exist $C > 0$ and $\delta_{0} > 0$, such that, for every $0 < \delta' \leq \delta_{0}$, there exists $0 \leq \delta'' \leq \delta'$ such that

$$\int_{t=\delta''} \left[ \left| \Psi_{k} \right|^{2} - \left| \hat{\psi}_{\lambda,k} \right|^{2} \right]^{2} ds \leq \frac{C}{\delta'} \int_{\Omega} \left[ \left| \Psi_{k} \right|^{2} - \left| \hat{\psi}_{\lambda,k} \right|^{2} \right]^{2} dx_{1} dx_{2}.$$

Furthermore, by (4.19), we have

$$\int_{\partial \Omega} \left[ \left| \Psi_{k} \right|^{2} - \left| \hat{\psi}_{\lambda,k} \right|^{2} \right]^{2} ds \leq C \int_{t=\delta''} \left| \left[ \Psi_{k} \right|^{2} - \left| \hat{\psi}_{\lambda,k} \right|^{2} \right]^{2} ds + C_{\lambda}\delta''.$$

Consequently, there exists $C > 0$ such that

$$\int_{\partial \Omega} \left[ \left| \Psi_{k} \right|^{2} - \left| \hat{\psi}_{\lambda,k} \right|^{2} \right]^{2} ds \leq \frac{C}{\delta' / \kappa^{2}} + C_{\lambda}\delta'.$$

Choosing $\delta' = \kappa^{-3/2}$ proves (1.8b).
Finally, we compare Theorem 1.1 with the results in [10, Remark 1.5]. As was already stated in the introduction, when $\rho(\kappa) = o(\kappa^{1/2})$ and tends to $\infty$ as $\kappa \to +\infty$, (1.4) holds. The function $u$ in (1.4) is given by

$$u(\tau) = \beta_0 \frac{|u_0(\tau)|^2}{\|u_0\|^4},$$

$u_0$ denoting the minimizer of (2.1).

We first note that, since as $\lambda \to \beta_0$, we have

$$f^2(\tau) \sim \frac{1}{\beta_0} u(\tau),$$

and since

$$\frac{\beta_0}{\beta_0} \sim \frac{\rho}{\kappa} \quad \text{as} \quad \kappa \to \infty,$$

(1.4) and (1.8a) match. The error in (1.4) is substantially smaller than in (1.8a). The difference is explained by the fact that $\psi_\kappa$ itself is small on $\partial \Omega$ when $\lambda \sim \beta_0$. Thus, if we extrapolate the error term in (1.4) to external fields for which $\rho/\kappa \approx 1$, it becomes $O(\kappa^{-2})$ exactly as in (1.8a).

Acknowledgments. The authors wish to thank the European program HPRN-CT-2002-00274 (Front Singularities) and their Scientists in Charge in France, Haim Brezis and Danielle Hilhorst, for providing support for the visit of the first author at the University of Paris XI in February 2005.

REFERENCES


