

Notes on 1D bosons

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In this paper, we analyze the ground state energy of the quadratic form

$$\mathcal{E}(\Psi) = \int \sum_{i=1}^N |\nabla_i \Psi|^2 + \sum_{i<j}^N v_{ij} |\Psi|^2. \quad (0.1)$$

We assume that $v_{ij} := v(|x_i - x_j|)$ is a symmetric and translation invariant measure with a finite range, R_0 . Furthermore, we assume that v is of the form $v = v_{\text{h.c.}} + v_{\text{reg}}$, where v_{reg} is a finite measure, and $v_{\text{h.c.}}$ is a sum of hard core potentials.

1 Upper bound

1.1 The trial state

We provide the upper bound for the ground state energy, by using the variational principle with a suitable trial state. Since we are interested in an upper bound, we consider Dirichlet boundary conditions. For $b > R_0$, consider the trial state

$$\Psi(x) = \begin{cases} \omega(\mathcal{R}(x)) \frac{\tilde{\Psi}_F(x)}{\mathcal{R}(x)} & \text{if } \mathcal{R}(x) < b, \\ \tilde{\Psi}_F(x) & \text{if } \mathcal{R}(x) \geq b, \end{cases} \quad (1.1)$$

where ω is the suitably normalized solution to the two-body scattering equation, *i.e.* $\omega(x) = f(x) \frac{b}{f(b)}$ where f is any solution of the two-body scattering equation, $\tilde{\Psi}_F(x) = |\Psi_F|$ is the absolute value of the free fermionic ground state, and $\mathcal{R}(x) = \min_{i<j} (|x_i - x_j|)$ is uniquely defined a.e. Notice that defining $B = \{x \in \mathbb{R}^N \mid \mathcal{R}(x) < b\}$ we have that $\Psi = \tilde{\Psi}_F$ on B^c .

The energy of this trial state is then

$$\mathcal{E}(\Psi) = \int \sum_{i=1}^N |\nabla_i \Psi|^2 + \sum_{i<j}^N v_{ij} |\Psi|^2. \quad (1.2)$$

In the following we define some useful quantities:

We define the sets $B_{12} := \{x \in \mathbb{R}^N \mid \mathcal{R}(x) < b, \mathcal{R}(x) = |x_1 - x_2|\} \subset A_{12} := \{x \in \mathbb{R}^N \mid |x_1 - x_2| < b\}$. Up to a set of measure zero, B_{12} is the intersection of B with the set “1 and 2 are closest”.

Define also the quantities

$$\begin{aligned}
E_1 &:= \binom{N}{2} \int_{A_{12}} \sum_{i=1}^N |\nabla_i \tilde{\Psi}|^2 + \sum_{i<j}^N (v_{\text{reg}})_{ij} |\tilde{\Psi}|^2 - \sum_{i=1}^N |\nabla_i \Psi_F|^2, \\
E_2^{(1)} &:= \binom{N}{2} 2N \int_{A_{12} \cap A_{13}} \sum_{i=1}^N |\nabla_i \tilde{\Psi}_F|^2, \\
E_2^{(2)} &:= \binom{N}{2} \binom{N-2}{2} \int_{A_{12} \cap A_{34}} \sum_{i=1}^N |\nabla_i \tilde{\Psi}_F|^2.
\end{aligned} \tag{1.3}$$

We then have

Lemma 1. *Let $v \geq 0$, then*

$$\mathcal{E}(\Psi) \leq E_0 + E_1 + E_2^{(1)} + E_2^{(2)}. \tag{1.4}$$

Proof. Since v is supported in $B_b(0)$ and $\Psi = \tilde{\Psi}_F$ except in the region $B = \{x \in \mathbb{R}^N | \mathcal{R}(x) < b\}$, we may rewrite this, using the diamagnetic inequality, as

$$\mathcal{E}(\Psi) \leq E_0 + \int_B \sum_{i=1}^N |\nabla_i \Psi|^2 + \sum_{i<j}^N v_{ij} |\Psi|^2 - \sum_{i=1}^N |\nabla_i \Psi_F|^2, \tag{1.5}$$

with $E_0 = N \frac{\pi^2}{3} \rho^2 (1 + \mathcal{O}(1/N))$ the ground state energy of the free Fermi gas. Using symmetry under exchange of particles, and the diamagnetic inequality, we find

$$\begin{aligned}
\mathcal{E}(\Psi) &\leq E_0 + \binom{N}{2} \int_{B_{12}} \sum_{i=1}^N |\nabla_i \Psi|^2 + \sum_{i<j}^N v_{ij} |\Psi|^2 - \sum_{i=1}^N |\nabla_i \Psi_F|^2 \\
&\leq E_0 + \binom{N}{2} \int_{B_{12}} \sum_{i=1}^N |\nabla_i \tilde{\Psi}|^2 + \sum_{i<j}^N (v_{\text{reg}})_{ij} |\tilde{\Psi}|^2 - \sum_{i=1}^N |\nabla_i \Psi_F|^2.
\end{aligned} \tag{1.6}$$

where we have defined $\tilde{\Psi} = \omega(x_1 - x_2) \frac{\Psi_F(x)}{(x_1 - x_2)}$ on A_{12} , and used that $\Psi = 0$ on the support of $(v_{\text{h.c.}})_{ij}$ for all i, j . Since we have $v_{\text{reg}} \geq 0$, it follows that

$$\begin{aligned}
\mathcal{E}(\Psi) &\leq E_0 + \binom{N}{2} \int_{A_{12}} \sum_{i=1}^N |\nabla_i \tilde{\Psi}|^2 + \sum_{i<j}^N (v_{\text{reg}})_{ij} |\tilde{\Psi}|^2 - \sum_{i=1}^N |\nabla_i \Psi_F|^2 \\
&\quad - \binom{N}{2} \int_{A_{12} \setminus B_{12}} \sum_{i=1}^N |\nabla_i \tilde{\Psi}|^2 + \sum_{i<j}^N (v_{\text{reg}})_{ij} |\tilde{\Psi}|^2 - \sum_{i=1}^N |\nabla_i \Psi_F|^2 \\
&\leq E_0 + E_1 + \binom{N}{2} \int_{A_{12} \setminus B_{12}} \sum_{i=1}^N |\nabla_i \Psi_F|^2,
\end{aligned} \tag{1.7}$$

We may, by an inclusion-exclusion argument, estimate

$$\begin{aligned}
\binom{N}{2} \int_{A_{12} \setminus B_{12}} \sum_{i=1}^N |\nabla_i \Psi_F|^2 &\leq \binom{N}{2} \left(2N \left[\int_{A_{12} \cap A_{13}} \sum_{i=1}^N |\nabla_i \Psi_F|^2 - \int_{B_{12} \cap A_{13}} \sum_{i=1}^N |\nabla_i \Psi_F|^2 \right] \right. \\
&\quad \left. + \binom{N-2}{2} \left[\int_{A_{12} \cap A_{34}} \sum_{i=1}^N |\nabla_i \Psi_F|^2 - \int_{B_{12} \cap A_{34}} \sum_{i=1}^N |\nabla_i \Psi_F|^2 \right] \right) \\
&\leq \binom{N}{2} \left[2N \int_{A_{12} \cap A_{13}} \sum_{i=1}^N |\nabla_i \Psi_F|^2 + \binom{N-2}{2} \int_{A_{12} \cap A_{34}} \sum_{i=1}^N |\nabla_i \Psi_F|^2 \right]. \tag{1.8}
\end{aligned}$$

Thus we find $\mathcal{E}(\Psi) \leq E_0 + E_1 + E_2^{(1)} + E_2^{(2)}$ as desired. \square

1.2 The free Fermi ground state

We now construct the free Fermi ground state. The Dirichlet eigenstates of the Laplacian are $\phi_j(x) = \sqrt{2/L} \sin(\pi j x/L)$. Thus the free Fermi ground state is

$$\Psi_F(x) = \det(\phi_j(x_i))_{i,j=1}^N = \sqrt{\frac{2}{L}}^N \left(\frac{1}{2i}\right)^N \begin{vmatrix} e^{iy_1} - e^{-iy_1} & e^{i2y_1} - e^{-i2y_1} & \dots & e^{iNy_1} - e^{-iNy_1} \\ e^{iy_2} - e^{-iy_2} & e^{i2y_2} - e^{-i2y_2} & \dots & e^{iNy_2} - e^{-iNy_2} \\ \vdots & \vdots & \ddots & \vdots \\ e^{iy_N} - e^{-iy_N} & e^{i2y_N} - e^{-i2y_N} & \dots & e^{iNy_N} - e^{-iNy_N} \end{vmatrix}, \tag{1.9}$$

where we defined $y_i = \frac{\pi}{L} x_i$. Defining $z = e^{iy}$ and using the relation $(x^n - y^n)/(x - y) = \sum_{k=0}^{n-1} x^k y^{n-1-k}$ we find

$$\Psi_F(x) = \sqrt{\frac{2}{L}}^N \left(\frac{1}{2i}\right)^N \prod_{i=1}^N (z_i - z_i^{-1}) \begin{vmatrix} 1 & z_1 + z_1^{-1} & \dots & \sum_{k=0}^{N-1} z_1^{2k-N+1} \\ 1 & z_2 + z_2^{-1} & \dots & \sum_{k=0}^{N-1} z_2^{2k-N+1} \\ \vdots & \vdots & \ddots & \vdots \\ 1 & z_N + z_N^{-1} & \dots & \sum_{k=0}^{N-1} z_N^{2k-N+1} \end{vmatrix}. \tag{1.10}$$

Notice now that $(z + z^{-1})^n = \sum_{k=0}^n \binom{n}{k} z^{2k-n}$. Now for i from 1 to $N-1$ we add $\left(\binom{N-1}{i} - \binom{N-1}{i-1}\right)$ times column $N-i$ to column N . This of course does not change the determinant, and we find

$$\Psi_F(x) = \sqrt{\frac{2}{L}}^N \left(\frac{1}{2i}\right)^N \prod_{i=1}^N (z_i - z_i^{-1}) \begin{vmatrix} 1 & z_1 + z_1^{-1} & \dots & \sum_{k=0}^{N-2} z_1^{2k-N+1} & (z_1 + z_1^{-1})^{N-1} \\ 1 & z_2 + z_2^{-1} & \dots & \sum_{k=0}^{N-2} z_2^{2k-N+1} & (z_2 + z_2^{-1})^{N-1} \\ \vdots & \vdots & \ddots & \vdots & \vdots \\ 1 & z_N + z_N^{-1} & \dots & \sum_{k=0}^{N-2} z_N^{2k-N+1} & (z_N + z_N^{-1})^{N-1} \end{vmatrix}. \tag{1.11}$$

Now for $i = 1$ to $N-2$ we add $\left(\binom{N-2}{i} - \binom{N-2}{i-1}\right)$ times column $N-1-i$ to column $N-1$, continue this process, *i.e.* for $j = 3$ to N : for $i = 1$ to $N-j$ add $\left(\binom{N-j}{i} - \binom{N-j}{i-1}\right)$ times column

$N - 1 - i$ to column $N - j + 1$. Then we obtain

$$\Psi_F(x) = \sqrt{\frac{2}{L}}^N \left(\frac{1}{2i}\right)^N \prod_{i=1}^N (z_i - z_i^{-1}) \begin{vmatrix} 1 & z_1 + z_1^{-1} & (z_1 + z_1^{-1})^2 & \dots & (z_1 + z_1^{-1})^{N-1} \\ 1 & z_2 + z_2^{-1} & (z_2 + z_2^{-1})^2 & \dots & (z_2 + z_2^{-1})^{N-1} \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ 1 & z_N + z_N^{-1} & (z_N + z_N^{-1})^2 & \dots & (z_N + z_N^{-1})^{N-1} \end{vmatrix}. \quad (1.12)$$

The determinant is recognized as a Vandermonde determinant and thus we have

$$\begin{aligned} \Psi_F(x) &= \sqrt{\frac{2}{L}}^N \left(\frac{1}{2i}\right)^N \prod_{k=1}^N (z_k - z_k^{-1}) \prod_{i < j}^N \left((z_i + z_i^{-1}) - (z_j + z_j^{-1}) \right) \\ &= 2^{\binom{N}{2}} \sqrt{\frac{2}{L}}^N \prod_{k=1}^N \sin\left(\frac{\pi}{L} x_k\right) \prod_{i < j}^N \left[\cos\left(\frac{\pi}{L} x_i\right) - \cos\left(\frac{\pi}{L} x_j\right) \right] \\ &= -2^{\binom{N}{2}+1} \sqrt{\frac{2}{L}}^N \prod_{k=1}^N \sin\left(\frac{\pi}{L} x_k\right) \prod_{i < j}^N \sin\left(\frac{\pi(x_i - x_j)}{2L}\right) \sin\left(\frac{\pi(x_i + x_j)}{2L}\right). \end{aligned} \quad (1.13)$$

1.2.1 Reduced density matrices

We compute the one-particle reduced density matrix of the free Fermi ground state with Dirichlet b.c. in the usual way

$$\gamma^{(1)}(x, y) = \frac{2}{L} \sum_{j=1}^N \sin\left(\frac{\pi}{L} jx\right) \sin\left(\frac{\pi}{L} jy\right) = \frac{\sin\left(\pi\left(\rho + \frac{1}{2L}\right)(x - y)\right)}{2L \sin\left(\frac{\pi}{2L}(x - y)\right)} - \frac{\sin\left(\pi\left(\rho + \frac{1}{2L}\right)(x + y)\right)}{2L \sin\left(\frac{\pi}{2L}(x + y)\right)}. \quad (1.14)$$

Of course Wick's theorem applies to compute a general n -particle reduced matrix.

1.2.2 Taylor's theorem

For later use, we define the one particle reduced density matrix $\gamma^{(1)}(x, y)$ as well as the translation invariant part $\tilde{\gamma}^{(1)}(x, y)$

$$\begin{aligned} \gamma^{(1)}(x, y) &= \frac{\pi}{L} \left(D_N\left(\pi \frac{x - y}{L}\right) - D_N\left(\pi \frac{x + y}{L}\right) \right), \\ \tilde{\gamma}^{(1)}(x, y) &:= \frac{\pi}{L} D_N\left(\pi \frac{x - y}{L}\right) \end{aligned} \quad (1.15)$$

where $D_n(x) = \frac{1}{2\pi} \sum_{k=-n}^n e^{ikx} = \frac{\sin((n+1/2)x)}{2\pi \sin(x/2)}$ is the Dirichlet kernel. One obvious consequence is that $|\partial_x^{k_1} \partial_y^{k_2} \gamma^{(1)}(x, y)| \leq \frac{1}{\pi} (2N)^{k_1+k_2+1} \left(\frac{\pi}{L}\right)^{k_1+k_2+1} = \pi^{k_1+k_2} (2\rho)^{k_1+k_2+1}$. This bound will allow us to Taylor expand any $\gamma^{(k)}$, as all derivatives are uniformly bounded by a constant times some power of ρ . In fact the relevant power of ρ can be directly obtained from dimensional analysis. Alternatively Taylor expanding may be thought of as using the mean value theorem multiple times.

1.3 Some useful bounds

Lemma 2. $\rho^{(2)}(x_1, x_2) = \left(\frac{\pi^2}{3}\rho^4 + f(x_2)\right)(x_1 - x_2)^2 + \mathcal{O}(\rho^6(x_1 - x_2)^4)$ with $\int |f(x_2)| dx_2 \leq \text{const. } \rho^3 \log(N)$.

Proof. Notice that we have by translation invariance $\tilde{\gamma}^{(1)}(x, y) - (\rho + 1/(2L)) = \frac{\pi^2}{6}(\rho^4 + \rho^3 \mathcal{O}(1/L))(x_1 - x_2)^2 + \mathcal{O}(\rho^4(x_1 - x_2)^4)$. Furthermore, we have $\gamma^{(1)}(x_1, x_2) - \rho^{(1)}((x_1 + x_2)/2) = \tilde{\gamma}^{(1)}(x_1, x_2) - (\rho + 1/(2L))$. Now by Wick's theorem we find

$$\rho^{(2)}(x_1, x_2) = \rho^{(1)}(x_1)\rho^{(1)}(x_2) - \gamma^{(1)}(x_1, x_2)\gamma^{(1)}(x_2, x_1). \quad (1.16)$$

Using that $\gamma^{(1)}$ is symmetric, and that

$$\begin{aligned} \rho^{(1)}(x_1) &= \rho^{(1)}((x_1 + x_2)/2) + \rho^{(1)'}((x_1 + x_2)/2) \frac{x_1 - x_2}{2} \\ &\quad + \frac{1}{2}\rho^{(1)''}((x_1 + x_2)/2) \left(\frac{x_1 - x_2}{2}\right)^2 + \mathcal{O}(\rho^4(x_1 - x_2)^3), \end{aligned} \quad (1.17)$$

$$\begin{aligned} \rho^{(1)}(x_2) &= \rho^{(1)}((x_1 + x_2)/2) + \rho^{(1)'}((x_1 + x_2)/2) \frac{x_2 - x_1}{2} \\ &\quad + \frac{1}{2}\rho^{(1)''}((x_1 + x_2)/2) \left(\frac{x_1 - x_2}{2}\right)^2 + \mathcal{O}(\rho^4(x_1 - x_2)^3), \end{aligned} \quad (1.18)$$

where both expressions can be expanded further if needed, we see that

$$\begin{aligned} \rho^{(2)}(x_1, x_2) &= \rho^{(1)}((x_1 + x_2)/2)^2 - \gamma^{(1)}(x_1, x_2)^2 - \left[\rho^{(1)'}((x_1 + x_2)/2)\right]^2 \left(\frac{x_1 - x_2}{2}\right)^2 \\ &\quad + \rho^{(1)}((x_1 + x_2)/2)\rho^{(1)''}((x_1 + x_2)/2) \left(\frac{x_1 - x_2}{2}\right)^2 + \mathcal{O}(\rho^6(x_1 - x_2)^4) \end{aligned} \quad (1.19)$$

Notice that $\mathcal{O}(\rho^5(x_1 - x_2)^3)$ terms must cancel due to symmetry.

Now use the fact that $0 \leq \rho^{(1)} \leq 2\rho$, and $\rho^{(1)'} : [0, L] \rightarrow \mathbb{R}$, and $\int_{[0, L]} |\rho^{(1)''}| \leq \text{const. } \rho^2 \log(N)$, and finally that $\int_{[0, L]} |\rho^{(1)'}| \leq \text{const. } \rho \log(N)$, which follows from the bound on Dirichlet's kernel $\left\| D_N^{(k)} \right\|_{L^1([0, 2\pi])} \leq \text{const. } N^k \log(N)$, to conclude that

$$\rho^{(2)}(x_1, x_2) = \rho^{(1)}((x_1 + x_2)/2)^2 - \gamma^{(1)}(x_1, x_2)^2 + g_1(x_1 + x_2)(x_1 - x_2)^2 + \mathcal{O}(\rho^6(x_1 - x_2)^4), \quad (1.20)$$

for some function g_1 satisfying $\int_{[0,L]} |g_1| \leq \text{const. } \rho^3 \log(N)$. Furthermore, notice that

$$\begin{aligned}
& \rho^{(1)}((x_1 + x_2)/2)^2 - \gamma^{(1)}(x_1, x_2)^2 \\
&= (\rho^{(1)}((x_1 + x_2)/2) - \gamma^{(1)}(x_1, x_2))(\rho^{(1)}((x_1 + x_2)/2) + \gamma^{(1)}(x_1, x_2)) \\
&= \left[\rho + 1/(2L) - \tilde{\gamma}^{(1)}(x_1, x_2) \right] \left[-\rho - 1/(2L) + \tilde{\gamma}^{(1)}(x_1, x_2) + 2\rho^{(1)}((x_1 + x_2)/2) \right] \\
&= - \left[\rho + 1/(2L) - \tilde{\gamma}^{(1)}(x_1, x_2) \right]^2 + 2 \left[\rho + 1/(2L) - \tilde{\gamma}^{(1)}(x_1, x_2) \right] \rho^{(1)}((x_1 + x_2)/2) \\
&= 2 \left(\frac{\pi^2}{6} (\rho + 1/(2L))^3 (x_1 - x_2)^2 + \mathcal{O}(\rho^5 (x_1 - x_2)^4) \right) \left(\rho + \frac{1}{2L} - \frac{\pi}{L} D_N((x_1 + x_2)/(2L)) \right) \\
&= \frac{\pi^2}{3} \rho^4 (x_1 - x_2)^2 + g_2(x_1 - x_2)(x_1 - x_2)^2 + \mathcal{O}(\rho^6 (x_1 - x_2)^4),
\end{aligned} \tag{1.21}$$

where we have choosen $g_2(x) = \frac{\pi^2}{3} \rho^3 \left(\frac{\text{const.}}{2L} + \left| \frac{\pi}{L} D_N(x/(2L)) \right| \right)$ which clearly satisfies $\int_{[0,L]} g_2 \leq \text{const. } \rho^3 \log(N)$. Thus we conclude that

$$\rho^{(2)}(x_1, x_2) = \left(\frac{\pi^2}{3} \rho^4 + f(x_2) \right) (x_1 - x_2)^2 + \mathcal{O}(\rho^6 (x_1 - x_2)^4) \tag{1.22}$$

with $f = g_1 + g_2$, satifying $\int_{[0,L]} |f| \leq \text{const. } \rho^3 \log(N)$ □

Lemma 3. *We have the following bounds*

$$\begin{aligned}
& \rho^{(3)}(x_1, x_2, x_3) \leq \text{const. } \rho^9 (x_1 - x_2)^2 (x_2 - x_3)^2 (x_1 - x_3)^2, \\
& \rho^{(4)}(x_1, x_2, x_3, x_4) \leq \text{const. } \rho^8 (x_1 - x_2)^2 (x_3 - x_4)^2 \\
& \sum_{i=1}^2 \partial_{y_i}^2 \gamma^{(2)}(x_1, x_2, y_1, y_2)|_{y=x} \leq \text{const. } \rho^6 (x_1 - x_2)^2, \\
& \left| \partial_{y_1}^2 \left(\frac{\gamma^{(2)}(x_1, x_2, y_1, y_2)}{y_1 - y_2} \right) \right|_{y=x} \leq \text{const. } \rho^6 |x_1 - x_2|, \\
& \sum_{i=1}^2 (-1)^{i-1} \partial_{y_i} \left(\frac{\gamma^{(2)}(x_1, x_2, y_1, y_2)}{y_1 - y_2} \right) \Big|_{y=x} \leq \text{const. } \rho^6 (x_1 - x_2)^2.
\end{aligned} \tag{1.23}$$

Proof. The bounds follows straightforwardly from Taylor's theorem and symmetries of the left-hand sides. As an example, consider $\sum_{i=1}^2 \partial_{y_i}^2 \gamma^{(2)}(x_1, x_2, y_1, y_2)|_{y=x}$. Notice first that $\sum_{i=1}^2 \partial_{y_i}^2 \gamma^{(2)}(x_1, x_2, y_1, y_2)$ is anti-symmetric in (x_1, x_2) and in (y_1, y_2) . As we have previously argued that all derivatives of $\gamma^{(n)}$ are bounded by a constant times ρ^k for some $k \in \mathbb{N}$, we can clearly Taylor expand $\gamma^{(2)}$. Taylor expanding x_1 around x_2 and similarly y_1 around y_2 we see by the anti-symmetry that $\sum_{i=1}^2 \partial_{y_i}^2 \gamma^{(2)}(x_1, x_2, y_1, y_2) \leq \text{const. } \rho^6 (x_1 - x_2)(y_1 - y_2)$, where the power of ρ can be found by simple dimensional analysis. □

Lemma 4. *We have the following bounds*

$$\begin{aligned}
& \left| \sum_{i=1}^3 \left(\partial_{x_i} \partial_{y_i} \gamma^{(3)}(x_1, x_2, x_3; y_1, y_2, y_3) \right) \right|_{y=x} \leq \text{const. } \rho^9(x_2 - x_3)^2(x_1 - x_2)^2, \\
& \left| \sum_{i=1}^3 \left(\partial_{y_i}^2 \gamma^{(3)}(x_1, x_2, x_3; y_1, y_2, y_3) \right) \right|_{y=x} \leq \text{const. } \rho^9(x_1 - x_2)^2(x_2 - x_3)^2, \quad (1.24) \\
& \left| \left[\partial_y \gamma^{(4)}(x_1, x_2, x_3, x_4; y, x_2, x_3, x_4) \right]_{y=x_1}^{x_1=x_2+b} \right|_{x_1=x_2-b} \leq \text{const. } \rho^8 b(x_3 - x_4)^2.
\end{aligned}$$

Proof. The proof follows straightforwardly from Taylor's theorem and symmetries of the left-hand sides. \square

Remark 1. *We do not claim that the lemmas 3 and 4 are in any way optimal bounds.*

1.4 Estimating E_1

Recall the definition

$$E_1 := \binom{N}{2} \int_{A_{12}} \sum_{i=1}^N |\nabla_i \tilde{\Psi}|^2 + \sum_{i < j}^N (v_{\text{reg}})_{ij} |\tilde{\Psi}|^2 - \sum_{i=1}^N |\nabla_i \Psi_F|^2 \quad (1.25)$$

We now prove the bound:

Lemma 5.

$$E_1 \leq E_0 \left(2\rho a \frac{b}{b-a} + \text{const. } N(\rho b)^3 \left[1 + \rho b^2 \int v_{\text{reg}} \right] \right). \quad (1.26)$$

Proof. We estimate E_1 by splitting it in four terms $E_1 = E_1^{(1)} + E_1^{(2)} + E_1^{(3)} + E_1^{(4)}$. First we have

$$\begin{aligned}
E_1^{(1)} &= 2 \binom{N}{2} \int_{A_{12}} |\nabla_1 \tilde{\Psi}|^2 \\
&= 2 \binom{N}{2} \int_{A_{12}} \tilde{\Psi} (-\Delta_1 \tilde{\Psi}) + 2 \binom{N}{2} \int \left[\tilde{\Psi} \nabla_1 \tilde{\Psi} \right]_{x_1=x_2-b}^{x_1=x_2+b} d\tilde{x}^1.
\end{aligned} \quad (1.27)$$

The boundary term can be explicitly calculated and we find

$$\begin{aligned}
2 \binom{N}{2} \int \left[\tilde{\Psi} \nabla_1 \tilde{\Psi} \right]_{x_1=x_2-b}^{x_1=x_2+b} d\tilde{x}^1 &= \int \left[\frac{\omega(x_1 - x_2)}{|x_1 - x_2|} \partial_{x_1} \left(\frac{\omega(x_1 - x_2)}{|x_1 - x_2|} \right) \rho^{(2)}(x_1, x_2) \right]_{x_2-b}^{x_2+b} dx_2 \\
&\quad + \int \left[\left(\frac{\omega(x_1 - x_2)}{|x_1 - x_2|} \right)^2 \partial_{x_1} \left(\gamma^{(2)}(x_1, x_2; y, x_2) \right) \right]_{y=x_1}^{x_2+b} dx_2.
\end{aligned} \quad (1.28)$$

Since the function $\frac{\omega(x_1 - x_2)}{|x_1 - x_2|}$ is continuously differentiable and satisfies $\frac{\omega(x_1 - x_2)}{|x_1 - x_2|} = \frac{|x_1 - x_2| - a}{b - a} \frac{b}{|x_1 - x_2|}$ for $|x_1 - x_2| > b$, we see that

$$\partial_{x_1} \left(\frac{\omega(x_1 - x_2)}{|x_1 - x_2|} \right) \Big|_{x=x_2 \pm b} = \pm \frac{\frac{b}{b-a} - 1}{b} = \pm \frac{a}{b(b-a)}. \quad (1.29)$$

Using lemma 2, we find

$$\int \left[\frac{\omega(x_1 - x_2)}{|x_1 - x_2|} \partial_{x_1} \left(\frac{\omega(x_1 - x_2)}{|x_1 - x_2|} \right) \rho^{(2)}(x_1, x_2) \right]_{x_2-b}^{x_2+b} dx_2 \leq 2a \frac{b}{b-a} N \frac{\pi^2}{3} \rho^3 \left(1 + \text{const.} \frac{\log(N)}{N} \right). \quad (1.30)$$

Furthermore, we denote

$$\begin{aligned} & \int \left[\left(\frac{\omega(x_1 - x_2)}{|x_1 - x_2|} \right)^2 \partial_{x_1} \left(\gamma^{(2)}(x_1, x_2; y, x_2) \right) \right]_{y=x_1}^{x_2+b} dx_2 \\ &= \int \left[\partial_{x_1} \left(\gamma^{(2)}(x_1, x_2; y, x_2) \right) \right]_{y=x_1}^{x_2+b} dx_2 =: \kappa_1. \end{aligned} \quad (1.31)$$

Thus we have

$$E_1^{(1)} = \frac{\pi^2}{3} N \rho^3 (2a) \frac{b}{b-a} + \kappa_1 + 2 \binom{N}{2} \int_{A_{12}} \bar{\Psi} (-\Delta_1 \tilde{\Psi}). \quad (1.32)$$

Another contribution to E_1 is

$$\begin{aligned} E_1^{(2)} &= - \binom{N}{2} \int_{A_{12}} \left(2 |\nabla_1 \Psi_F|^2 + \sum_{i=3}^N |\nabla_i \Psi_F|^2 \right) \\ &= - \binom{N}{2} \int_{A_{12}} \sum_{i=1}^N \bar{\Psi}_F (-\Delta_i \Psi_F) - 2 \binom{N}{2} \int [\bar{\Psi}_F \nabla_1 \Psi_F]_{x_1=x_2-b}^{x_1=x_2+b} \\ &= -E_0 \binom{N}{2} \int_{A_{12}} |\Psi_F|^2 - \underbrace{\int \left[\partial_y \gamma^{(2)}(x_1, x_2; y, x_2) \right]_{y=x_1}^{x_2+b} dx_2}_{\kappa_1}, \end{aligned} \quad (1.33)$$

and using lemma 2 we find

$$E_1^{(2)} = -\text{const.} E_0 N \rho^3 b^3 - \kappa_1. \quad (1.34)$$

The last contributions are

$$\begin{aligned} E_1^{(3)} &= \binom{N}{2} \int_{A_{12}} \sum_{i < j}^N (v_{\text{reg}})_{ij} \left| \tilde{\Psi} \right|^2 = \binom{N}{2} \int_{A_{12}} v_{12} \left| \tilde{\Psi} \right|^2 + 2 \binom{N}{2} \int_{A_{12}} \sum_{2 \leq i < j}^N (v_{\text{reg}})_{ij} \left| \tilde{\Psi} \right|^2 \text{ and} \\ E_1^{(4)} &= \int_{A_{12}} \sum_{i=3}^N \left| \nabla_i \tilde{\Psi} \right|^2. \end{aligned}$$

First we notice that

$$\begin{aligned} & \binom{N}{2} \int_{A_{12}} \sum_{2 \leq i < j}^N (v_{\text{reg}})_{ij} \left| \tilde{\Psi} \right|^2 \\ & \leq \text{const.} b^2 \left(\int_{\{|x_1 - x_2| < b\} \cap \text{supp}((v_{\text{reg}})_{34})} v_{\text{reg}}(|x_3 - x_4|) \frac{1}{(x_1 - x_2)^2} \rho^{(4)}(x_1, x_2, x_3, x_4) \right. \\ & \quad \left. + \int_{\{|x_1 - x_2| < b\} \cap \text{supp}((v_{\text{reg}})_{23})} v_{\text{reg}}(|x_2 - x_3|) \frac{1}{(x_1 - x_2)^2} \rho^{(3)}(x_1, x_2, x_3) \right). \end{aligned} \quad (1.35)$$

By lemma 3 we have

$$\begin{aligned}
& \binom{N}{2} \int_{A_{12}} \sum_{2 \leq i < j}^N (v_{\text{reg}})_{ij} |\tilde{\Psi}|^2 \\
& \leq \text{const.} \left(N^2(\rho b)^3 \rho^3 \int x^2 v_{\text{reg}}(x) dx + N(\rho b)^3 \rho^5 \int x^4 v_{\text{reg}}(x) dx + N(\rho b)^4 \rho^4 \int x^3 v_{\text{reg}}(x) dx \right. \\
& \quad \left. + N(\rho b)^5 \rho^3 \int x^2 v_{\text{reg}}(x) dx \right) \\
& \leq \text{const.} N^2(\rho b)^5 \rho \int v_{\text{reg}} = \text{const.} E_0 N(\rho b)^3 \left(\rho b^2 \int v_{\text{reg}} \right),
\end{aligned} \tag{1.36}$$

and then we find that

$$\begin{aligned}
E_1 &= E_1^{(1)} + E_1^{(2)} + E_1^{(3)} + E_1^{(4)} \\
&\leq \frac{2\pi^2}{3} N \rho^3 a \frac{b}{b-a} + 2 \binom{N}{2} \int_{A_{12}} \left(\overline{\tilde{\Psi}}(-\Delta_1) \tilde{\Psi} + \frac{1}{2} \sum_{i=3}^N |\nabla_i \tilde{\Psi}|^2 + \frac{1}{2} v_{12} |\tilde{\Psi}|^2 \right) \\
&\quad + E_0 N(\rho b)^3 \text{const.} \left(1 + \rho b^2 \int v_{\text{reg}} \right).
\end{aligned} \tag{1.37}$$

Using the two body scattering equation this implies

$$\begin{aligned}
E_1 &\leq \frac{2\pi^2}{3} N \rho^3 a \frac{b}{b-a} + 2 \binom{N}{2} \int_{A_{12}} \frac{\overline{\Psi_F}}{(x_1 - x_2)} \omega^2(-\Delta_1) \frac{\Psi_F}{(x_1 - x_2)} \\
&\quad + 2 \binom{N}{2} \int_{A_{12}} \frac{\overline{\Psi_F}}{(x_1 - x_2)} \omega(\nabla_1 \omega) \nabla_1 \frac{\Psi_F}{(x_1 - x_2)} \\
&\quad + \binom{N}{2} \int_{A_{12}} \sum_{i=3}^N \frac{\overline{\Psi_F}}{(x_1 - x_2)} \frac{\omega^2}{(x_1 - x_2)} (-\Delta_i) \Psi_F \\
&\quad + \text{const.} E_0 N(\rho b)^3 \left(1 + \rho b^2 \int v_{\text{reg}} \right).
\end{aligned} \tag{1.38}$$

Furhtermore we have

$$\begin{aligned}
& \binom{N}{2} \int_{A_{12}} \sum_{i=3}^N \overline{\tilde{\Psi}} \frac{\omega}{(x_1 - x_2)} (-\Delta_i) \Psi_F \\
&= E_0 \binom{N}{2} \int_{A_{12}} \left| \frac{\omega}{(x_1 - x_2)} \Psi_F \right|^2 - 2 \binom{N}{2} \int_{A_{12}} \overline{\tilde{\Psi}} \frac{\omega}{(x_1 - x_2)} (-\Delta_1) \Psi_F.
\end{aligned} \tag{1.39}$$

By lemma 2 it follows that

$$\binom{N}{2} \int_{A_{12}} \left| \frac{\omega}{(x_1 - x_2)} \Psi_F \right|^2 \leq b^2 \int_{\{|x_1 - x_2| < b\}} \frac{\rho^{(2)}(x_1, x_2)}{|x_1 - x_2|^2} dx_1 dx_2 \leq \text{const.} b^2 \rho^4 L b = \text{const.} N \rho^3 b^3, \tag{1.40}$$

and by lemma 3 it follows that

$$\begin{aligned} 2 \binom{N}{2} \int_{A_{12}} \bar{\Psi} \frac{\omega}{(x_1 - x_2)} (-\Delta_1) \Psi_F &= \frac{1}{2} \sum_{i=1}^2 \int_{A_{12}} \left| \frac{\omega}{x_1 - x_2} \right|^2 \left[\partial_{y_i}^2 \gamma^{(2)}(x_1, x_2, y_1, y_2) \right] \Big|_{y=x} \\ &\leq \text{const. } N \rho^2 (\rho b)^3, \end{aligned} \quad (1.41)$$

so we find

$$\binom{N}{2} \int_{A_{12}} \sum_{i=3}^N \bar{\Psi} \frac{\omega}{(x_1 - x_2)} (-\Delta_i) \Psi_F \leq \text{const. } E_0 N (\rho b)^3. \quad (1.42)$$

Finally, again by lemma 3 we have

$$\begin{aligned} 2 \binom{N}{2} \int_{A_{12}} \bar{\Psi} \omega (-\Delta_1) \frac{\Psi_F}{(x_1 - x_2)} &= \int_{A_{12}} \left| \frac{\omega^2}{x_1 - x_2} \right| \left[\partial_{y_1}^2 \left(\frac{\gamma^{(2)}(x_1, x_2, y_1, y_2)}{(y_1 - y_2)} \right) \right] \Big|_{y=x} \\ &\leq \text{const. } N \rho^2 (\rho b)^3, \end{aligned} \quad (1.43)$$

and by using $\Delta\omega = \frac{1}{2}v\omega \geq 0$ which implies $0 \leq \omega'(x) \leq \omega'(b) = \frac{b}{b-a}$ for $|x| < b$, we find that

$$\begin{aligned} 2 \binom{N}{2} \int_{A_{12}} \bar{\Psi} (\nabla_1 \omega) \nabla_1 \left(\frac{\Psi_F}{(x_1 - x_2)} \right) &\leq \frac{1}{2} \sum_{i=1}^2 \int_{A_{12}} \left| \frac{\omega}{x_1 - x_2} \right| (-1)^{i-1} \omega'(x_1 - x_2) \partial_{y_i} \left(\frac{\gamma^{(2)}(x_1, x_2, y_1, y_2)}{y_1 - y_2} \right) \\ &\leq \text{const. } \frac{b}{b-a} N \rho^2 (\rho b)^3. \end{aligned} \quad (1.44)$$

Combining everything we get

$$E_1 \leq E_0 \left(2\rho a \frac{b}{b-a} + \text{const. } N(\rho b)^3 \left[1 + \rho b^2 \int v_{\text{reg}} \right] \right), \quad (1.45)$$

as desired. \square

1.5 Estimating E_2

Recall that $E_2 = E_2^{(1)} + E_2^{(2)}$ with

$$\begin{aligned} E_2^{(1)} &= \binom{N}{2} 2N \int_{A_{12} \cap A_{13}} \sum_{i=1}^N |\nabla_i \Psi_F|^2 \\ E_2^{(2)} &= \binom{N}{2} \binom{N-2}{2} \int_{A_{12} \cap A_{34}} \sum_{i=1}^N |\nabla_i \Psi_F|^2. \end{aligned} \quad (1.46)$$

We now prove the bound:

Lemma 6.

$$E_2 \leq E_0 (N(\rho b)^4 + N^2(\rho b)^6). \quad (1.47)$$

Proof. To estimate $E_2^{(1)}$ and $E_2^{(2)}$, we first split them in two terms each and use partial integra-

tion. Consider first $E_2^{(1)}$:

$$\begin{aligned} E_2^{(1)} &= \binom{N}{2} 2N \int_{A_{12} \cap A_{23}} \sum_{i=1}^N |\nabla_i \Psi_F|^2 \\ &= \binom{N}{2} 2N \left(2 \int_{A_{12} \cap A_{23}} |\nabla_1 \Psi_F|^2 + \int_{A_{12} \cap A_{23}} |\nabla_2 \Psi_F|^2 \right) + \binom{N}{2} 2N \int_{A_{12} \cap A_{23}} \sum_{i=4}^N |\nabla_i \Psi_F|^2. \end{aligned} \quad (1.48)$$

For the second term, we can perform partial integration directly, in order to obtain

$$\begin{aligned} \binom{N}{2} 2N \int_{A_{12} \cap A_{23}} \sum_{i=4}^N |\nabla_i \Psi_F|^2 &= \binom{N}{2} 2N \int_{A_{12} \cap A_{23}} \sum_{i=4}^N \overline{\Psi_F} (-\Delta_i \Psi_F) \\ &\leq E_0 N^3 \int_{A_{12} \cap A_{23}} |\Psi_F|^2 - N^3 \int_{A_{12} \cap A_{23}} \sum_{i=1}^3 \overline{\Psi_F} (-\Delta_i \Psi_F) \\ &\leq 2E_0 \int_{[0,L]} \int_{[x_2-b, x_2+b]} \int_{[x_2-b, x_2+b]} \rho^{(3)}(x_1, x_2, x_3) dx_3 dx_1 dx_2 - N^3 \int_{A_{12} \cap A_{23}} \sum_{i=1}^3 \overline{\Psi_F} (-\Delta_i \Psi_F). \end{aligned} \quad (1.49)$$

Using lemma 3 we find

$$2E_0 \int_{[0,L]} \int_{[x_2-b, x_2+b]} \int_{[x_2-b, x_2+b]} \rho^{(3)}(x_1, x_2, x_3) dx_3 dx_1 dx_2 \leq NE_0(\rho b)^6. \quad (1.50)$$

Furthermore, we find by lemma 4

$$\binom{N}{2} 2N \int_{A_{12} \cap A_{23}} \sum_{i=1}^3 \left(|\nabla_i \Psi_F|^2 - \overline{\Psi_F} (-\Delta_i \Psi_F) \right) \leq \text{const. } \rho^9 L b^6 = \text{const. } E_0(b\rho)^6. \quad (1.51)$$

Collecting everything we find

$$E_2^{(1)} \leq \text{const. } NE_0(\rho b)^6. \quad (1.52)$$

To estimate $E_2^{(2)}$, we use integration by parts

$$\begin{aligned} E_2^{(2)} &= \binom{N}{2} \binom{N-2}{2} \int_{A_{12} \cap A_{34}} \left(4 |\nabla_1 \Psi_F|^2 + \sum_{i=5}^N |\nabla_i \Psi_F|^2 \right) \\ &= \binom{N}{2} \binom{N-2}{2} \left(4 \int_{|x_3-x_4|<b} [\overline{\Psi_F} \nabla_1 \Psi_F]_{x_1=x_2-b}^{x_1=x_2+b} + \int_{A_{12} \cap A_{34}} \sum_{i=1}^N \overline{\Psi_F} (-\Delta_i \Psi_F) \right) \\ &= 4 \int_{x_2 \in [0,L]} \int_{|x_3-x_4|<b} \left[\partial_{y_1} \gamma^{(4)}(x_1, x_2, x_3, x_4; y_1, x_2, x_3, x_4) \Big|_{y_1=x_1} \right]_{x_1=x_2-b}^{x_1=x_2+b} \\ &\quad + E_0 \int_{A_{12} \cap A_{34}} \rho^{(4)}(x_1, \dots, x_4). \end{aligned} \quad (1.53)$$

By lemma 4 we get

$$4 \int_{x_2 \in [0, L]} \int_{|x_3 - x_4| < b} \left[\partial_{y_1} \gamma^{(4)}(x_1, x_2, x_3, x_4; y_1, y_2, y_3, y_4) \Big|_{y_1 = x_1} \right]_{x_1 = x_2 - b}^{x_1 = x_2 + b} = \text{const. } E_0 N (\rho b)^4. \quad (1.54)$$

Furthermore, by lemma 4 again, it follows that

$$E_0 \int_{A_{12} \cap A_{34}} \rho^{(4)}(x_1, \dots, x_4) \leq \text{const. } E_0 N^2 (\rho b)^6. \quad (1.55)$$

□

1.6 Localization

We will in this section localize in smaller boxes, in order to have better control on the error. The localization is straightforward with Dirichlet boundary conditions, as gluing the wavefunctions for each box together is simple, since the wavefunctions vanish at the boundaries. Thus we consider the state $\Psi_{\text{full}} = \prod_{i=1}^M \Psi_\ell(x_1^i, \dots, x_{\tilde{N}}^i)$, where $(x_1^i, \dots, x_{\tilde{N}}^i)$ are the particles in box i and ℓ is the length of each box. Of course $\cup_{i=1}^M \{x_1^i, \dots, x_{\tilde{N}}^i\} = \{x_1, \dots, x_N\}$ and $\{x_1^i, \dots, x_{\tilde{N}}^i\} \cap \{x_1^j, \dots, x_{\tilde{N}}^j\} = \emptyset$ for $i \neq j$, such that $M\tilde{N} = N$. The boxes are of length $\ell = L/M - b$, and are equally spaced through out $[0, L]$ such that they are a distance of b from each other. This is to make sure that no particle interact between boxes. Combining lemmas 5 and 6, the full energy is then bounded by

$$E \leq M e_0 \left(1 + 2\tilde{\rho} a \frac{b}{b-a} + \text{const. } \tilde{N} (b\tilde{\rho})^3 \left(1 + \rho b^2 \int v_{\text{reg}} \right) \right) / \|\Psi\|^2 \quad (1.56)$$

with $e_0 = \frac{\pi^2}{3} \tilde{N} \tilde{\rho}^2 (1 + \text{const. } \frac{1}{\tilde{N}})$ and $\tilde{\rho} = \tilde{N}/\ell = \rho/(1 - \frac{bM}{L}) \leq \rho(1 + 2bM/L)$ for $bM/L \leq 1/2$. Clearly we have $\|\Psi\|^2 \geq 1 - \int_B |\Psi_F|^2 \geq 1 - \int_{|x_1 - x_2| < b} \rho^{(2)}(x_1, x_2) \geq 1 - \text{const. } \tilde{N} (\rho b)^3$, where the last inequality follows from lemma 2. Thus, choosing M such that $bM/L \ll 1$ we have

$$E \leq N \frac{\pi^2}{3} \rho^2 \frac{\left(1 + \frac{2\rho ab}{b-a} + \text{const. } \frac{M}{\tilde{N}} + \text{const. } 2\rho abM/L + \text{const. } \tilde{N} (b\rho)^3 (1 + \rho b^2 \int v_{\text{reg}}) \right)}{1 - \tilde{N} (\tilde{\rho} b)^3}. \quad (1.57)$$

Now in fact, we would choose $\tilde{N} = N/M = \rho L/M \gg 1$, i.e. $M/L \ll \rho$. Setting $x = M/N$ we see that the error is

$$\text{const. } \left[(1 + 2\rho^2 ab^2/(b-a))x + x^{-1} (b\rho)^3 \left(1 + \rho b^2 \int v_{\text{reg}} \right) \right], \quad (1.58)$$

here we used that it will turn out to be the cases that $\tilde{N} (\rho b)^3 \leq 1/2$ so that we have

$$1/(1 - \tilde{N} (\rho b)^3) \leq 1 + 2\tilde{N} (\rho b)^3. \text{ Optimizing in } x \text{ we find } x = M/N = \frac{(b\rho)^{3/2} (1 + \rho b^2 \int v_{\text{reg}})^{1/2}}{1 + 2\rho^2 ab} \simeq$$

$(b\rho)^{3/2} (1 + \rho b^2 \int v_{\text{reg}})^{1/2}$, which gives the error

$$\text{const. } (b\rho)^{3/2} \left(1 + \rho b^2 \int v_{\text{reg}}\right)^{1/2}. \quad (1.59)$$

At last we choose $b = R := \max(\rho^{-1/5} |a|^{4/5}, R_0)$. Then for $(\rho |a|)^{1/5} \leq 1/2$

$$\frac{b}{b-a} \leq 1 + 2a/b \leq 1 + 2(\rho |a|)^{1/5}.$$

Thus we arrive at the following result

Theorem 1 (Upper bound). *Let the two-body potential $v = v_{h.c.} + v_{\text{reg}}$ as above, with two-body scattering length a . Then the bosonic N -body ground state energy satisfies the upper bound*

$$E \leq E_0 \left(1 + 2\rho a + \mathcal{O} \left((R\rho)^{3/2} \left(1 + \rho R^2 \int v_{\text{reg}}\right)^{1/2} \right) \right), \quad (1.60)$$

where E_0 is the free fermionic ground state energy.

Notice that

$$(R\rho)^{3/2} = \max \left((\rho |a|)^{6/5}, (\rho R_0)^{3/2} \right) \leq (\rho |a|)^{6/5} + (\rho R_0)^{3/2}.$$

Notice also that the result

$$E \leq N \frac{\pi^2}{3} \rho^2 \left(1 + 2\rho a + \mathcal{O} \left((R\rho)^{3/2} \left(1 + \rho R^2 \int v_{\text{reg}}\right)^{1/2} \right) \right) \quad (1.61)$$

holds only for $N \geq (\rho R)^{-3/2}$, but since the free Fermi, E_0 energy also contains a correction of order $\frac{1}{N}$, i.e. $E_0 = N \frac{\pi^2}{3} \rho^2 (1 + \text{const. } 1/N)$, the result remains true for $N < (\rho R)^{-3/2}$.

2 Lower bound

We will in this section provide a lower bound for the one dimensional dilute Bose gas. The proof is based on a reduction to a Lieb-Liniger model, and thus we will first recall some known features about this model

2.1 The Lieb-Liniger model

We will in this subsection for simplicity consider the Lieb-Liniger model on $\Lambda_L = [-L/2, L/2]$ instead of $[0, L]$, and we will in general write Λ_s for the interval $[-s/2, s/2]$.

Recall that the energy in thermodynamic limit of the the Lieb-Liniger model (with periodic

boundary conditions), is determined by the sytem of equation ((3.3) and (3.18)–(3.20) in [2])

$$\rho^3 e(\gamma) = \lim_{\ell \rightarrow \infty, n/\ell \text{ fixed}} \frac{E_{LL}(n, \ell, c = \gamma n/\ell)}{\ell}, \quad (2.1)$$

$$e(\gamma) = \frac{\gamma^3}{\lambda^3} \int_{-1}^1 g(x) x^2 dx, \quad (2.2)$$

$$2\pi g(y) = 1 + 2\lambda \int_{-1}^1 \frac{g(x) dx}{\lambda^2 + (x - y)^2}, \quad (2.3)$$

$$\lambda = \gamma \int_{-1}^1 g(x) dx. \quad (2.4)$$

The first lemma provides a rigorous lower bound for the thermodynamic Lieb-Liniger energy density.

Lemma 7 (Lieb-Liniger lower bound). *Let $\gamma > 0$, then*

$$e(\gamma) \geq \frac{\pi^2}{3} \left(\frac{\gamma}{\gamma + 2} \right)^2 \geq \frac{\pi^2}{3} \left(1 - \frac{4}{\gamma} \right). \quad (2.5)$$

Proof. Neglecting $(x - y)^2$ in the denominator of (2.3), we see that $g \leq \frac{1}{2\pi} + 2\frac{1}{\lambda} \int_{-1}^1 g(x) dx$. On the other hand (2.4) shows that $e(\gamma) = \frac{\int_{-1}^1 g(x) x^2 dx}{(\int_{-1}^1 g(x) dx)^3}$. Hence we denote $\int_{-1}^1 g(x) dx = M$, and notice that we have $g \leq \frac{1}{2\pi} (1 + \frac{2M}{\lambda})$. It is now easily verified that, $\int_{-1}^1 g(x) x^2 dx$ with M fixed and $g \leq \frac{1}{2\pi} (1 + \frac{2M}{\lambda}) = \frac{1}{2\pi} (1 + 2\gamma^{-1})$ is mininimized by $g = K \chi_{[-M/(2K), M/(2K)]}$, with $K = \frac{1}{2\pi} (1 + \frac{2}{\gamma})$. This gives us $\int_{-1}^1 g(x) x^2 dx = \frac{M^3}{3K^2}$ so that we have $e(\gamma) \geq \frac{1}{3K^2} = \frac{\pi^2}{3} \left(\frac{\gamma}{\gamma + 2} \right)^2 \geq \frac{\pi^2}{3} (1 - \frac{4}{\gamma})$ for $\gamma > 0$. \square

The next result concerns finite volume correction to the thermodynamic limit. Since we are interested in a lower bound, we consider the Neumann boundary conditions case denoted by a superscript "N". Dirichlet boundary conditions are denoted by superscript "D". Now in order to compare energies with different boundary conditions we introduce a cutoff function h , with the following properties:

1. h is real, symmetric, and continuously differentiable on Λ_{3L} .
2. $h(x) = 0$ for $|x| > L/2 + b$
3. $h(x) = 1$ for $|x| < L/2 - b$
4. $h(L/2 - x)^2 + h(L/2 + x)^2 = 1$ for $0 < x < b$.
5. $|\frac{dh}{dx}|^2 \leq \frac{1}{b^2}$, and $h^2 \leq 1$

Furthermore, we say that a symmetric, translation invariant measure, v , is decreasing if $v \circ \mathbf{c} \geq v$ for any contraction \mathbf{c}

Lemma 8 (Robinson's bound). *Let v be symmetric and decreasing, then for any $b > 0$ we have*

$$E_{\Lambda_{L+2b}}^D \leq E_{\Lambda_L}^N + \frac{2n}{b^2}. \quad (2.6)$$

Proof. The idea of the prove is given in [3] page 66, but we shall give a more explicit proof here. Let $f \in \mathcal{D}(\mathcal{E}_{\Lambda_L}^N)$. Define \tilde{f} by extending f to Λ_{3L} by reflecting f across each face of its domain in Λ_{3L} . Define then $V : L^2(\Lambda_L) \rightarrow L^2(\Lambda_{L+2b})$ by $Vf(x) := \tilde{f}(x) \prod_{i=1}^n h(x_i)$. It is not hard to show that V is an isometry, this is shown in [3] lemma 2.1.12. Also we clearly have $Vf \in \mathcal{D}(\mathcal{E}_{\Lambda_{L+2b}}^D)$. Let ψ be the ground state for $\mathcal{E}_{\Lambda_L}^N$. Then we define the trial state $\psi_{\text{trial}} = V\psi$. Without the potential, the bound (2.6) is obtained in lemma 2.1.13 of [3]. Thus we need only prove that no energy is gained by by the potential in the trial state. To see this, define $\tilde{\psi}$ to be ψ extended by reflection as above and notice that for $|x_2| < L/2 - b$ we have

$$\begin{aligned} & \int_{-L/2-b}^{L/2+b} v(|x_1 - x_2|) \left| \tilde{\psi}(x) \right|^2 h(x_1)^2 h(x_2)^2 dx_1 \leq \\ & \int_{-L/2+b}^{L/2-b} v(|x_1 - x_2|) \left| \tilde{\psi}(x) \right|^2 dx_1 + \sum_{s \in \{-1,1\}} s \int_{s(L/2-b)}^{s(L/2)} v(|x_1 - x_2|) \left| \tilde{\psi}(x) \right|^2 (h(x)^2 + h(L-x)^2) dx_1 \\ & = \int_{-L/2}^{L/2} v(|x_1 - x_2|) \left| \tilde{\psi}(x) \right|^2 dx_1, \end{aligned} \tag{2.7}$$

where we used that v is symmetric decreasing in the first inequality and that $h(x)^2 + h(L-x)^2 = 1$ for $L/2 - b \leq x \leq L/2$ which is just property 4.

$$\begin{aligned} & \sum_{(s_1, s_2) \in \{-1,1\}^2} s_1 s_2 \int_{L/2-s_1 b}^{L/2} \int_{L/2-s_2 b}^{L/2} v(|x_1 - x_2|) \left| \tilde{\psi}(x) \right|^2 h(x_1)^2 h(x_2)^2 dx_2 dx_1 \\ & = \sum_{(s_1, s_2) \in \{-1,1\}^2} \int_0^b \int_0^b v(|s_1 y_1 - s_2 y_2|) \left| \tilde{\psi}(L/2 - s_1 y_1, L/2 - s_2 y_2, \bar{x}^{1,2}) \right|^2 \\ & \quad \times h(L/2 - s_1 y_1)^2 h(L/2 - s_2 y_2)^2 dy_2 dy_1 \\ & \leq \int_0^b \int_0^b v(|y_1 - y_2|) \left| \tilde{\psi}(L/2 - y_1, L/2 - y_2, \bar{x}^{1,2}) \right|^2 \\ & \quad \times \sum_{(s_1, s_2) \in \{-1,1\}^2} h(L/2 - s_1 y_1)^2 h(L/2 - s_2 y_2)^2 dy_2 dy_1 \\ & = \int_0^b \int_0^b v(|y_1 - y_2|) \left| \tilde{\psi}(L/2 - y_1, L/2 - y_2, \bar{x}^{1,2}) \right|^2 dy_2 dy_1. \end{aligned} \tag{2.8}$$

In the third line we use the definition of $\tilde{\psi}$ as well as the fact that $|s_1 y_1 - s_2 y_2| \geq |y_1 - y_2|$ for $y_1, y_2 \geq 0$. In the last line we used property 4. of h . By combining the two bounds above, we clearly have

$$\begin{aligned} & \int_{-L/2-b}^{L/2+b} \int_{-L/2-b}^{L/2+b} v(|x_1 - x_2|) \left| \tilde{\psi}(x) \right|^2 h(x_1)^2 h(x_2)^2 dx_1 dx_2 \\ & \leq \int_{-L/2}^{L/2} \int_{-L/2}^{L/2} v(|x_1 - x_2|) \left| \tilde{\psi}(x) \right|^2 dx_1 dx_2. \end{aligned} \tag{2.9}$$

The result now follows from the fact that V is an isometry. \square

Lemma 9 (Finite volume corrections).

$$E_{LL}^N(n, \ell, c) \geq \frac{\pi^2}{3} n \rho^2 \left(1 - 4\rho/c - \text{const.} \frac{1}{n^{2/3}} \right). \quad (2.10)$$

Proof. By Robinsons bound, lemma 8, we have for any $b > 0$

$$E_{LL}^N(n, \ell, c) \geq E_{LL}^D(n, \ell + b, c) - \text{const.} \frac{n}{b^2}. \quad (2.11)$$

Since the range of the interaction in the Lieb-Liniger model is zero, we see that $e_{LL}^D(2^m n, 2^m \ell, c) = \frac{1}{2^m \ell} E_{LL}^D(2^m n, 2^m \ell, c)$ is a decreasing sequence. To see this, simply split the box of size $2^m \ell$ in two boxes of size $2^{m-1} \ell$, now there are no interactions between the boxes so by using the product state of the two $2^{m-1} n$ -particle ground states in each box as a trial state, we see that $E_{LL}^D(2^m n, 2^m \ell) \leq 2 E_{LL}^D(2^{m-1} n, 2^{m-1} \ell)$. Since we also have $e_{LL}^D(2^m n, 2^m \ell, c) \geq e_{LL}(2^m n, 2^m \ell, c) \rightarrow e_{LL}(n/\ell, c)$ as $m \rightarrow \infty$ [2], we see that

$$\begin{aligned} E_{LL}^N(n, \ell, c) &\geq e_{LL}(n/(\ell + b), c)(\ell + b) - \text{const.} \frac{n}{b^2} \\ &\geq \frac{\pi^2}{3} n \rho^2 \left(1 - 4\rho/c - \text{const.} \left(3b/\ell - \frac{1}{\rho^2 b^2} \right) \right), \end{aligned} \quad (2.12)$$

with $\rho = n/\ell$, where the second inequality follows from lemma 7. Optimizing in b we find

$$E_{LL}^N(n, \ell, c) \geq \frac{\pi^2}{3} n \rho^2 \left(1 - 4\rho/c - \text{const.} \frac{1}{n^{2/3}} \right). \quad (2.13)$$

□

2.2 Lieb-Liniger reduction

We will in this subsection provide a lower bound on the dilute bose gas by a Lieb-Liniger energy. The reduction is obtained by constructing a trial state for a Lieb-Liniger model in a smaller volume from the true ground state of the Bose gas.

Let Ψ be the ground state of \mathcal{E} , we then define $\psi \in L^2([0, \ell - (n-1)R]^n)$ by $\psi(x_1, x_2, \dots, x_n) = \Psi(x_1, R + x_2, \dots, (n-1)R + x_n)$ for $x_1 \leq x_2 \leq \dots \leq x_n$ and symmetrically extended.

Lemma 10. *For any function $\phi \in H^1(\mathbb{R})$ such that $\phi(0) = 0$ then we have*

$$\int_{[0, R]} |\partial \phi|^2 \geq \max_{[0, R]} |\phi|^2 / R \quad (2.14)$$

Proof. write $\phi(x) = \int_0^x \phi'(t) dt$, and find that

$$|\phi(x)| \leq \int_0^x |\phi'(t)| dt. \quad (2.15)$$

Hence $\max_{x \in [0, R]} |\phi(x)| \leq \int_0^R |\phi'(t)| dt \leq \sqrt{R} \left(\int_0^R |\phi'(t)|^2 dt \right)^{1/2}$ □

We can estimate the norm loss in the following way

$$\langle \psi | \psi \rangle = 1 - \int_B |\Psi|^2 \geq 1 - \sum_{i < j} \int_{D_{ij}} |\Psi|^2, \quad (2.16)$$

where we recall that $B = \{x \in \mathbb{R}^n | \min_{i,j} |x_i - x_j| < R\}$, and define $D_{ij} = \{x \in \mathbb{R}^n | \mathbf{r}_i(x) = |x_i - x_j| < R\}$ with $\mathbf{r}_i(x) = \min_{j \neq i} (|x_i - x_j|)$. Notice that D_{ij} are not symmetric in i, j and that for fixed i , D_{ij} are disjoint up to sets of measure zero. Finally notice also that $B = \cup_{i < j} D_{ij}$. To give a good bound on the right-hand side, we need the following lemma

Lemma 11. *Let ψ be defined as above, then*

$$1 - \langle \psi | \psi \rangle \leq \text{const.} \left(R^2 \sum_{i < j} \int_{D_{ij}} |\partial_i \Psi|^2 + R(R-a) \sum_{i < j} \int v_{ij} |\Psi|^2 \right). \quad (2.17)$$

Proof. Notice that by (2.14) we have for any $\phi \in H^1$,

$$||\phi(x)| - |\phi(x')||^2 \leq |\phi(x) - \phi(x')|^2 \leq R \left(\int_{[0,R]} |\partial \phi|^2 \right), \quad (2.18)$$

for $x, x' \in [0, R]$. Furthermore,

$$|\phi(x)|^2 - |\phi(x')|^2 = (|\phi(x)| - |\phi(x')|)^2 + 2(|\phi(x)| - |\phi(x')|)|\phi(x')| \leq 2(|\phi(x)| - |\phi(x')|)^2 + |\phi(x')|^2. \quad (2.19)$$

So for It follows that

$$\max_{x \in [0,R]} |\phi|^2 \leq 2R \int_{[0,R]} |\partial \phi|^2 + 2 \min_{x' \in [0,R]} |\phi(x')|^2. \quad (2.20)$$

Viewing Ψ as a function of x_i we have

$$2 \min_{\mathbf{r}_i(x)=|x_i-x_j|<R} |\Psi|^2 \geq \max_{\mathbf{r}_i(x)=|x_i-x_j|<R} |\Psi|^2 - 4R \left(\int_{\mathbf{r}_i(x)=|x_i-x_j|<R} |\partial_i \Psi|^2 \right). \quad (2.21)$$

Hence we find

$$\begin{aligned} 2 \sum_{i < j} \int v_{ij} |\Psi|^2 &\geq 2 \sum_{i < j} \int_{D_{ij}} v_{ij} |\Psi|^2 \\ &\geq \left(\int v \right) \sum_{i < j} \int \left(\max_{D'_{ij}} |\Psi|^2 - 4R \left(\int_{D'_{ij}} |\partial_i \Psi|^2 dx_i \right) \right) d\bar{x}^i \\ &\geq \frac{4}{R-a} \sum_{i < j} \left(\frac{1}{2R} \int_{D_{ij}} |\Psi|^2 - 4R \int_{D_{ij}} |\partial_i \Psi|^2 \right), \end{aligned} \quad (2.22)$$

where $D'_{ij} = \{x_i \in \mathbb{R} | \mathfrak{r}_i(x) = |x_i - x_j| < R\}$. Now, by (2.16), we see that

$$1 - \langle \psi | \psi \rangle \leq \text{const.} \left(R^2 \sum_{i < j} \int_{D_{ij}} |\partial_i \Psi|^2 + R(R - a) \int \sum_{i < j} v_{ij} |\Psi|^2 \right). \quad (2.23)$$

□

Choosing $R \geq 2|a|$ we have $\langle \psi | \psi \rangle \geq 1 - \text{const.} R^2 E$.

The following lemma will also be useful

Lemma 12 (Dyson). *Let $R > R_0 = \text{range}(v)$ and $\varphi \in H^1(\mathbb{R})$, then for any interval $\mathcal{B} \ni 0$*

$$\int_{\mathcal{B}} |\partial \varphi|^2 + \frac{1}{2} v |\varphi|^2 \geq \int_{\mathcal{B}} \frac{2}{R - a} (\delta_R + \delta_{-R}) |\varphi|^2, \quad (2.24)$$

where a is the s -wave scattering length.

Proof. This follows from the variational scattering problem, by comparing left-hand side to the minimizer of the scattering functional, see [1]. □

This lemma will essentially allows us to replace the potential by a shell potential of range R and strength $\frac{2}{R-a}$.

Lemma 13. *Let ψ be defined as above with $R > \max(R_0, 2|a|)$ and let $\epsilon \in [0, 1]$, then*

$$\int \sum_i |\partial_i \Psi|^2 + \sum_{i \neq j} \frac{1}{2} v_{ij} |\Psi|^2 \geq E_{LL}^N \left(n, \tilde{\ell}, \frac{2\epsilon}{R - a} \right) \langle \psi | \psi \rangle + \frac{(1 - \epsilon)}{R^2} \text{const.} (1 - \langle \psi | \psi \rangle). \quad (2.25)$$

where $\tilde{\ell} = \ell - (n - 1)R$.

Proof. Splitting the energy functional in two parts, and using lemma 11 on one term and Dyson's lemma on the other we find

$$\begin{aligned} & \int \sum_i |\partial_i \Psi|^2 + \sum_{i \neq j} \frac{1}{2} v_{ij} |\Psi|^2 \geq \\ & \int \sum_i |\partial_i \Psi|^2 \chi_{\mathfrak{r}_i(x) > R} + \epsilon \sum_i \frac{2}{R - a} \delta(\mathfrak{r}_i(x) - R) |\Psi|^2 \\ & + (1 - \epsilon) \left(\sum_{i < j} \int_{D_{ij}} |\partial_i \Psi|^2 + \int \sum_{i < j} v_{ij} |\Psi|^2 \right), \end{aligned} \quad (2.26)$$

where $\mathfrak{r}_i(x) = \min_{j \neq i} (|x_i - x_j|)$. The nearest neighbor interaction is obtained from Dyson's lemma by dividing the integration domain into Voronoi cells, and restricting to the cell around particle i .

By use of lemma 11 with $R > 2|a|$ in the last term, and by realising that the first two terms can be obtained by using ψ as a trial state in the Lieb-Liniger model, we obtain

$$\int \sum_i |\partial_i \Psi|^2 + \sum_{i \neq j} \frac{1}{2} v_{ij} |\Psi|^2 \geq E_{LL}^N \left(n, \tilde{\ell}, \frac{2\epsilon}{R-a} \right) \langle \psi | \psi \rangle + \frac{(1-\epsilon)}{R^2} \text{const.} (1 - \langle \psi | \psi \rangle). \quad (2.27)$$

□

The next lemma will bound how much mass is lost when going from the state Ψ of mass 1 to the state ψ

Lemma 14. *Let $C^{-1} = 8$ be the constant in lemma 11. For $n(\rho R)^2 \leq \frac{3}{16\pi^2} C$, $\rho R \leq 1$ and $R > 2|a|$ we have*

$$\langle \psi | \psi \rangle \geq 1 - \text{const.} \left(n(\rho R)^3 + n^{1/3}(\rho R)^2 \right). \quad (2.28)$$

Proof. From the known upper bound, and by lemma 13 with $\epsilon = 1/2$, it follows that

$$n \frac{\pi^2}{3} \rho^2 \left(1 + 2\rho a + \text{const.} (\rho R)^{3/2} \right) \geq E_{LL}^N \left(n, \tilde{\ell}, \frac{1}{R-a} \right) \langle \psi | \psi \rangle + \frac{C}{2R^2} (1 - \langle \psi | \psi \rangle) \quad (2.29)$$

Subtracting $E_{LL}^N \left(n, \tilde{\ell}, \frac{1}{R-a} \right)$ on both sides, and using lemma 9 on the left-hand side we find

$$\begin{aligned} & n \frac{\pi^2}{3} \rho^2 \left(1 + 2\rho a + \text{const.} (\rho R)^{3/2} \right) - n \frac{\pi^2}{3} \tilde{\rho}^2 \left(1 + 4\tilde{\rho}(R-a) - \text{const.} n^{-2/3} \right) \\ & \geq \left(\frac{C}{2R^2} - E_{LL}^N \left(n, \tilde{\ell}, \frac{1}{R-a} \right) \right) (1 - \langle \psi | \psi \rangle), \end{aligned} \quad (2.30)$$

with $\tilde{\rho} = n/\tilde{\ell} = \rho/(1 - (\rho - 1/\ell)R)$ Using now the upper bound $E_{LL}^N \left(n, \tilde{\ell}, \frac{1}{R-a} \right) \leq n \frac{\pi^2}{3} \tilde{\rho}^2$ on the left-hand side, as well as $2\rho \geq \tilde{\rho} \geq \rho(1 + \rho R)$ we find

$$\text{const.} n \rho^2 R^2 \left(\rho R + (\rho R)^{3/2} + n^{-2/3} \right) \geq \left(\frac{C}{2} - R^2 n \frac{4\pi^2}{3} \rho^2 \right) (1 - \langle \psi | \psi \rangle) \quad (2.31)$$

It follows that we have

$$\langle \psi | \psi \rangle \geq 1 - \text{const.} \left(n(\rho R)^3 + n^{1/3}(\rho R)^2 \right) \quad (2.32)$$

□

Remark 2. *For $n \leq \kappa(\rho R)^{-9/5}$ with $\kappa = \frac{3}{16\pi^2} C$ and $\rho R \leq 1$ we find*

$$\langle \psi | \psi \rangle \geq 1 - \text{const.} n(\rho R)^3 = 1 - \text{const.} (\rho R)^{6/5} \quad (2.33)$$

It is now straightforward to show the result

Proposition 1. *For assumptions as in lemma 14 we have*

$$E^N(n, \ell) \geq n \frac{\pi^2}{3} \rho^2 \left(1 + 2\rho a + \text{const.} \left(\frac{1}{n^{2/3}} + n(\rho R)^3 + n^{1/3}(\rho R)^2 \right) \right) \quad (2.34)$$

Proof. By lemma 13 with $\epsilon = 1$, we reduce to a Lieb-Liniger model with volume $\tilde{\ell}$, density $\tilde{\rho}$, and coupling c , and we have $\tilde{\ell} = \ell - (n-1)R$, $\tilde{\rho} = \frac{n}{\tilde{\ell}} \approx \rho(1 + \rho R)$ and $c = \frac{2}{R-a}$. Hence we have by Lemmas 9 and 14

$$\begin{aligned} E^N(n, \ell) &\geq E_{LL}^N(n, \tilde{\ell}, c) \langle \psi | \psi \rangle \\ &\geq n \frac{\pi^2}{3} \rho^2 \left(1 + 2\rho a - \text{const.} \frac{1}{n^{2/3}} \right) \left(1 - \text{const.} \left(n(\rho R)^3 + n^{1/3}(\rho R)^2 \right) \right) \end{aligned} \quad (2.35)$$

□

Corollary 1. For $\frac{\kappa}{2}(\rho R)^{-9/5} \leq n \leq \kappa(\rho R)^{-9/5}$ with $\kappa = \frac{3}{16\pi^2}C$ and $\rho R \leq 1$ we have

$$E^N(n, \ell) \geq n \frac{\pi^2}{3} \rho^2 \left(1 + 2\rho a - \text{const.} \left((\rho R)^{6/5} + (\rho R)^{7/5} \right) \right). \quad (2.36)$$

2.3 Lower bound of the dilute Bose gas for general particle number

So far, we have shown the desired lower bound only for the case where the number of particles are of the order $(\rho R)^{-9/5}$. In this subsection, we generalize this to any number of particles. We do this, by performing a Legendre transformation in the particle number, *i.e.* going to the grand canonical ensemble. First we justify that only particle numbers of orders less than or equal to $(\rho R)^{-9/5}$ are relevant for a certain choice of μ .

Lemma 15. Let $\Xi \geq 4$ be fixed and let $n = m\Xi\rho\ell + n_0$ with $n_0 \in [0, \Xi\rho\ell)$ for some $m \in \mathbb{N}$ with $\frac{\kappa}{2\Xi}(\rho R)^{-9/5} \leq \rho\ell =: n^* \leq \frac{\kappa}{\Xi}(\rho R)^{-9/5}$ with $\kappa = \frac{3}{16\pi^2}C$. Furthermore, assume that $\rho R \leq 1$ and let $\mu = \pi^2 \rho^2 \left(1 + \frac{8}{3}\rho a \right)$, then

$$E^N(n, \ell) - \mu n \geq E^N(n_0, \ell) - \mu n_0. \quad (2.37)$$

Proof. By corollary 1 we have

$$E^N(\Xi\rho\ell, \ell) \geq \frac{\pi^2}{3} \Xi^3 \ell \rho^3 \left(1 + 2\Xi\rho a - \text{const.} (\rho R)^{6/5} \right). \quad (2.38)$$

By superadditivity (positive potential) we have

$$E^N(n, \ell) - \mu n \geq m \left(E^N(\Xi\rho\ell, \ell) - \mu\Xi\rho\ell \right) + E^N(n_0, \ell) - \mu n_0. \quad (2.39)$$

Thus the result follows from the fact that

$$\frac{\pi^2}{3} \Xi^3 \ell \rho^3 \left(1 + 2\Xi\rho a - \text{const.} (\rho R)^{6/5} \right) \geq \pi^2 \rho^2 \left(1 + \frac{8}{3}\rho a \right) \Xi\rho\ell \quad (2.40)$$

□

We are then ready to prove the lower bound for general particle numbers.

Theorem 2 (Lower bound). *Let $E^N(N, L)$ denote the ground state energy of \mathcal{E} with Neumann boundary conditions. Then for $\rho R \leq 1$*

$$E^N(N, L) \geq N \frac{\pi^2}{3} \rho^2 \left(1 + 2\rho a - \mathcal{O}\left((\rho R)^{6/5} + N^{-2/3}\right) \right). \quad (2.41)$$

Proof. For the case $N < \kappa(\rho R)^{-9/5}$, the result follows from proposition 1.

For $N \geq \kappa(\rho R)^{-9/5}$ Notice that

$$E^N(N, L) \geq F^N(\mu, L) + \mu N, \quad (2.42)$$

where $F^N(\mu, L) = \inf_{N'} (E^N(N', L) - \mu N')$. Clearly we have

$$F^N(\mu, L) \geq M F^N(\mu, \ell), \quad (2.43)$$

with $\ell = L/M$ and $M \in \mathbb{N}_+$. Now let $\Xi = 4$ and choose M such that $\frac{\kappa}{2\Xi} (\rho R)^{-9/5} \leq n^* := \rho \ell \leq \frac{\kappa}{\Xi} (\rho R)^{-9/5}$ and $\mu = \pi^2 \rho^2 (1 + \frac{8}{3} \rho a)$ (notice that $\mu = \frac{d}{d\rho} (\frac{\pi^2}{3} \rho^3 (1 + 2\rho a))$). By lemma 15 we have that

$$F^N(\mu, \ell) := \inf_n (E^N(n, \ell) - \mu n) = \inf_{n < \Xi n^*} (E^N(n, \ell) - \mu n). \quad (2.44)$$

Now it is known from proposition 1 that for $n < \Xi n^*$ we have

$$\begin{aligned} E^N(n, \ell) &\geq n \frac{\pi^2}{3} \bar{\rho}^2 \left(1 + 2\bar{\rho} a - \text{const.} \left(\frac{1}{n^{2/3}} + n(\bar{\rho} R)^3 + n^{1/3}(\bar{\rho} R)^2 \right) \right) \\ &\geq \frac{\pi^2}{3} n \bar{\rho}^2 (1 + 2\bar{\rho} a) - n^* \rho^2 \mathcal{O}\left((\rho R)^{6/5}\right), \end{aligned} \quad (2.45)$$

where $\bar{\rho} = n/\ell$ (notice that now $\rho = N/L = n^*/\ell \neq n/\ell$) and where we used $\bar{\rho} < \Xi \rho$. Thus we have

$$F^N(\mu, \ell) \geq \inf_{\bar{\rho} < \Xi \rho} (g(\bar{\rho}) - \mu \bar{\rho}) \ell - n^* \rho^2 \mathcal{O}\left((\rho R)^{6/5}\right), \quad (2.46)$$

where $g(\bar{\rho}) = \frac{\pi^2}{3} \bar{\rho}^3 (1 + 2\bar{\rho} a)$ for $\bar{\rho} < \Xi \rho$. g is a convex, C^1 function with invertible derivative for $\Xi \rho a \geq -\frac{1}{4}$ (the case of $\Xi \rho a < -\frac{1}{4}$ is trivial, by choosing a sufficiently large constant in the error term). Hence we have

$$\begin{aligned} E^N(N, L) &\geq M(F^N(\mu, \ell) + \mu n^*) \geq M n^* \frac{\pi^2}{3} \rho^2 \left(1 + 2\rho a - \mathcal{O}\left((\rho R)^{6/5}\right) \right) \\ &= \frac{\pi^2}{3} N \rho^2 \left(1 + 2\rho a - \mathcal{O}\left((\rho R)^{6/5}\right) \right), \end{aligned} \quad (2.47)$$

here the equality follows from the specific choice of $\mu = g'(\rho)$. □

3 Ground state energy for the Fermi gas

From Theorems 1 and 2 the following result follows straightforwardly

Theorem 3. Let $E(N, L)$ be the ground state energy of the Bose gas with $v = v_{\text{h.c.}} + v_{\text{reg}}$, with $v_{\text{h.c.}}$ a sum of hard core potentials and v_{reg} a finite measure. Then

$$E(N, L) = N \frac{\pi^2}{3} \rho^2 \left(1 + 2\rho a + \mathcal{O} \left((\rho R)^{6/5} + N^{-2/3} \right) \right), \quad (3.1)$$

where a is the scattering length.

Theorem 4. Let $E_F(N, L)$ be the ground state energy of the Fermi gas with $v = v_{\text{h.c.}} + v_{\text{reg}}$, with $v_{\text{h.c.}}$ a sum of hard core potentials and v_{reg} a finite measure. Then

$$E_F(N, L) = N \frac{\pi^2}{3} \rho^2 \left(1 + 2\rho a_o + \mathcal{O}(\rho R)^{6/5} \right), \quad (3.2)$$

where a_o is the odd wave scattering length.

Proof. Consider the bosonic energy functional \mathcal{E}_∞ with potential $v_\infty = v + \infty \delta_0$, where $\infty \delta_0$ simply denotes a zero-range hard core potential, i.e. $\infty \delta_0$ imposes a Dirichlet boundary condition on all planes of intersection of particles. Consider then the unitary operator given by $U : f \mapsto (-1)^{\prod_{i < j} (x_i - x_j)} f$. Because of the Dirichlet condition in $\mathcal{D}(\mathcal{E}_\infty)$, we clearly have $U\mathcal{D}(\mathcal{E}_\infty) = \mathcal{D}(\mathcal{E}_F)$ with $\mathcal{E}_F(Uf) = \mathcal{E}_\infty(f)$, where \mathcal{E}_F is the Fermi energy functional with potential v . The ground state energy is then given by theorem 3 and the result follows. \square

It is easily verified that $a_o \geq 0$ for any $v \geq 0$, and hence we see that the first order correction to the Fermi ground state energy is positive as expected.

4 A remark on anyons

In the previous section, we saw that the fermionic ground state energy can be found from theorem 3 by means of a simple unitary operator. It turns out that this concept can be expanded to so called anyons exhibiting generalized exchange statistics. We first define the model of an anyon with statistics parameter κ . It turns out that in order for the model to exhibit non-trivial energy shifts from the corresponding bosonic model, a zero-range interaction is needed. The strength of this interaction, will be denoted by c . Let $\kappa \in [0, \pi]$ and define for each permutation $\sigma = (\sigma_1, \dots, \sigma_N)$ the sector $\Sigma_\sigma = \{x_{\sigma_1} < x_{\sigma_2} < \dots < x_{\sigma_N}\} \subset \mathbb{R}^N$, and consider the operator

$$H_N = - \sum_{i=1}^N \partial_{x_i}^2, \quad \text{on } \mathbb{R}^N \setminus \bigcup_{i < j} \{x_i = x_j\} \quad (4.1)$$

with domain

$$\mathcal{D}(H_N) = \left\{ \varphi = e^{-i\frac{\kappa}{2}\Lambda(x)} f(x) \mid f \in ((\oplus_{\text{sym}})_{\sigma \in S_N} C^\infty(\overline{\Sigma_\sigma})) \cap C_0(\mathbb{R}^N), \right. \\ \left. (\partial_i - \partial_j) \varphi|_+^{ij} - (\partial_i - \partial_j) \varphi|_-^{ij} = 2c e^{-i\frac{\kappa}{2}\Lambda(x)} f|_0^{ij} \text{ for all } i \neq j \right\} \quad (4.2)$$

where $c \geq 0$ and $\Lambda(x) = \sum_{i < j} \epsilon(x_i - x_j)$ with $\epsilon(x) = \begin{cases} 1 & \text{for } x > 0 \\ -1 & \text{for } x < 0 \\ 0 & \text{for } x = 0 \end{cases}$ and $|_{\pm,0}^{ij}$ means the function evaluated at $x_i = x_{j \pm, 0}$. Then the following proposition holds

Proposition 2. H_N is symmetric with corresponding quadratic form

$$\tilde{\mathcal{E}}_{\kappa,c}(\varphi) = \sum_{i=1}^N \int_{\mathbb{R}^N \setminus \bigcup_{i < j} \{x_i = x_j\}} |\partial_{x_i} \varphi(x)|^2 + \frac{2c}{\cos(\kappa/2)} \sum_{i < j} \delta(x_i - x_j) |\varphi(x)|^2 d^N x \quad (4.3)$$

Proof. Let $\varphi, \vartheta \in \mathcal{D}(H_N)$, then by partial integration we have

$$\begin{aligned} \langle \vartheta | H_N \varphi \rangle &= - \sum_{i=1}^N \int_{\mathbb{R}^N \setminus \bigcup_{i < j} \{x_i = x_j\}} \bar{\vartheta} \partial_{x_i}^2 \varphi \\ &= \sum_{i=1}^N \int_{\mathbb{R}^N \setminus \bigcup_{i < j} \{x_i = x_j\}} \overline{\partial_{x_i} \vartheta} \partial_{x_i} \varphi - \int_{\mathbb{R}^{N-1} \setminus \bigcup_{i < j} \{x_i = x_j\}} \sum_{i \neq j} \left(\bar{\vartheta} \partial_{x_i} \varphi|_{-}^{ij} - \bar{\vartheta} \partial_{x_i} \varphi|_{+}^{ij} \right) \\ &= \sum_{i=1}^N \int_{\mathbb{R}^N \setminus \bigcup_{i < j} \{x_i = x_j\}} \overline{\partial_{x_i} \vartheta} \partial_{x_i} \varphi + \int_{\mathbb{R}^{N-1} \setminus \bigcup_{i < j} \{x_i = x_j\}} \sum_{i < j} \left(\bar{\vartheta} (\partial_{x_i} - \partial_{x_j}) \varphi|_{+}^{ij} - \bar{\vartheta} (\partial_{x_i} - \partial_{x_j}) \varphi|_{-}^{ij} \right). \end{aligned} \quad (4.4)$$

Let $f, g \in C_0^\infty(\mathbb{R}^N)$ be the functions such that $\varphi = e^{-i\frac{\kappa}{2}\Lambda} f$ and $\vartheta = e^{-i\frac{\kappa}{2}\Lambda} g$. Then we have

$$\begin{aligned} \langle \vartheta | H_N \varphi \rangle &= \sum_{i=1}^N \int_{\mathbb{R}^N \setminus \bigcup_{i < j} \{x_i = x_j\}} \overline{\partial_{x_i} \vartheta} \partial_{x_i} \varphi + \int_{\mathbb{R}^{N-1} \setminus \bigcup_{i < j} \{x_i = x_j\}} \sum_{i < j} \left(\bar{g} (\partial_{x_i} - \partial_{x_j}) f|_{+}^{ij} - \bar{g} (\partial_{x_i} - \partial_{x_j}) f|_{-}^{ij} \right) \\ &= \sum_{i=1}^N \int_{\mathbb{R}^N \setminus \bigcup_{i < j} \{x_i = x_j\}} \overline{\partial_{x_i} \vartheta} \partial_{x_i} \varphi + \int_{\mathbb{R}^{N-1} \setminus \bigcup_{i < j} \{x_i = x_j\}} 2 \sum_{i < j} \left(\bar{g} (\partial_{x_i} - \partial_{x_j}) f|_{+}^{ij} \right) \end{aligned} \quad (4.5)$$

where the last equality follows from symmetry of f . Notice that by the boundary condition on $\mathcal{D}(H_N)$ we have

$$(\partial_i - \partial_j) \varphi|_{+}^{ij} - (\partial_i - \partial_j) \varphi|_{-}^{ij} = e^{-i\frac{\kappa}{2}(-1+S)} (\partial_i - \partial_j) f|_{+}^{ij} - e^{-i\frac{\kappa}{2}(1+S)} (\partial_i - \partial_j) f|_{-}^{ij} = 2c \varphi|_0^{ij} = e^{-i\frac{\kappa}{2}S} 2c f|_0^{ij} \quad (4.6)$$

where $S = \Lambda - \epsilon(x_i - x_j)$. By symmetry of f it follows that

$$\begin{aligned} e^{-i\frac{\kappa}{2}(-1+S)} (\partial_i - \partial_j) f|_{+}^{ij} - e^{-i\frac{\kappa}{2}(1+S)} (\partial_i - \partial_j) f|_{-}^{ij} &= e^{-i\frac{\kappa}{2}(-1+S)} (\partial_i - \partial_j) f|_{+}^{ij} + e^{-i\frac{\kappa}{2}(1+S)} (\partial_i - \partial_j) f|_{+}^{ij} \\ &= e^{-i\frac{\kappa}{2}S} 2 \cos(\kappa/2) (\partial_i - \partial_j) f|_{+}^{ij} \\ &= e^{-i\frac{\kappa}{2}S} 2c f|_0^{ij}. \end{aligned} \quad (4.7)$$

so that

$$2(\partial_i - \partial_j) f|_{+}^{ij} = \frac{2c}{\cos(\kappa/2)} f|_0^{ij}, \quad (4.8)$$

where we by $\kappa = \pi$ mean $f|_0^{ij} = 0$. Hence it follows that

$$\langle \vartheta | H_N \varphi \rangle = \sum_{i=1}^N \int_{\mathbb{R}^N \setminus \bigcup_{i < j} \{x_i = x_j\}} \overline{\partial_{x_i} \vartheta} \partial_{x_i} \varphi(x) + \frac{2c}{\cos(\kappa/2)} \sum_{i < j} \delta(x_i - x_j) \overline{\vartheta(x)} \varphi(x) d^N x, \quad (4.9)$$

where again $\kappa = \pi$ refers to $\langle \vartheta | H_N \varphi \rangle = \sum_{i=1}^N \int_{\mathbb{R}^N \setminus \bigcup_{i < j} \{x_i = x_j\}} \overline{\partial_{x_i} \vartheta} \partial_{x_i} \varphi(x)$ with Dirichlet boundary conditions on the planes of intersection. Now it is clear that starting from $\langle H_N \vartheta | \phi \rangle$, we can by the same steps arrive at (4.9), proving that H_N is symmetric. \square

Remark 3. Since $\tilde{\mathcal{E}}_{\kappa,c} \geq 0$, H_N has a self-adjoint Friedrichs extension, \tilde{H}_N , which we regard as the Hamiltonian for the one dimensional anyon gas with statistical parameter, κ , and a zero-range interaction of strength, c .

We regard in the following the potential $2c\delta_0$ with $c = \infty$ as a hard of zero range, in the sense, that it imposes a Dirichlet boundary condition on the planes of intersection. It is straightforward to include any potential of the form $v = v_{\text{h.c.}} + v_{\text{reg}}$. In the sense of remark 3, we see that our result applies to a general anyonic gas, in the following form

Theorem 5. Let $E_{(\kappa,c)}(N, L)$ be the ground state energy of anyon gas with $v = v_{\text{h.c.}} + v_{\text{reg}} + 2c\delta_0$, where v_{reg} is a finite measure with $v_{\text{reg}}(0) = 0$, and where $(\kappa, c) \in [0, 2\pi] \times [0, \infty]$. Then

$$E_{(\kappa,c)}(N, L) = N \frac{\pi^2}{3} \rho^2 \left(1 + 2\rho a_\kappa + \mathcal{O}(\rho R)^{6/5} \right). \quad (4.10)$$

Here a_κ is defined to be scattering length associated with potential $v = v_{\text{h.c.}} + v_{\text{reg}} + \frac{2c}{\cos(\kappa/2)}\delta_0$.

Proof. Let $\mathcal{E}_{\tilde{c}}$ denote the bosonic quadratic form with potential $v_{\tilde{c}} = v + 2c\delta_0$. By Proposition 2 with the observation that the quadratic form is independent of the phase-factors, we see that the unitary operator $U_\kappa : f \mapsto e^{-i\frac{\kappa}{2}\Lambda} f$, satisfies $U_\kappa \mathcal{D}(\mathcal{E}_{c/\cos(\kappa/2)}) = \mathcal{D}(\tilde{\mathcal{E}}_{\kappa,c})$ with $\tilde{\mathcal{E}}_{\kappa,c}(U_\kappa f) = \mathcal{E}_{c/\cos(\kappa/2)}(f)$. It then follows from Theorem 3 that the ground state energy is given by the desired formula. \square

In this setting, the results for bosons and fermions follows respectively as special cases of Theorem 5 with $\kappa = 0$ and $\kappa = \pi$, $c > 0$. Notice that the case $\kappa = \pi$, $c = 0$ does not reduce the usual fermions, as the kinetic energy at planes of intersection is unaccounted for in this model.

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